A COLD CATHODE PROTON SOURCE FOR THE SYNCHROCYCLOTRON

by

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I. SUMMARY

A cold cathode ion source which possesses to a high degree the requirements for a synchrocyclotron proton source has been developed. Two variations, one of electrode configuration and one of mode of operation, each produce currents sufficiently high to be of value either in steady or in pulsed operation.

The maximum consistently obtained total ion output currents in the cyclotron field (16,000 oersteds) were:
For the variation in electrode configuration (ejector anode)

Steady operation - 1.5 mA.

Pulsed operation - 1.3 mA.

For the variation in mode of operation (Asymmetric operation)

Steady - 10 mA.

Pulsed - 90 mA.

In the high magnetic field of the cyclotron the standard cold cathode oscillating electron discharge positive ion source under conditions comparable to those for the ejector anode figures above gave positive output currents never exceeding 0.2 mA. For increasing discharge current the output current reached a maximum, decreased and became negative. In pulsed operation output currents observed were always negative. This source, therefore, seems unsatisfactory for cyclotron or synchrocyclotron use.

The source using the ejector anode shows the same qualitative behaviour but gives a satisfactorily high maximum output current.

Asymmetric operation of the source showed no consistent indication of a maximum within the discharge current range covered.

The proton current is probably between 30 and 40 percent of the total ion current observed.

II. INTRODUCTION

1. General. Little discussion is necessary in these times of the need in nuclear physics for a satisfactory positive ion source for use with accelerating equipment. Suffice it to say that the problem becomes of greater importance in the construction of a frequency modulated cyclotron or synchrocyclotron (such as that being constructed at McGill) in which the average target current is a function not of the steady ion source output current but of the output during only a small fraction of each modulation cycle. Thus to achieve a high average target current the instantaneous output of the ion source must be high.

Previous cyclotron ion sources have served their purpose well and would still give a certain amount of satisfaction but it is desirable to obtain a greater ion current if possible. Other factors such as length of life, power supply and cost and upkeep enter into consideration but are of secondary importance.

The first cyclotron ion source used consisted of a heated tungsten filament located centrally in the cyclotron above the dees. Electrons emitted by this were accelerated downwards and produced ions by collision in the highly rarefied gas of the cyclotron vacuum. This was replaced by the arc type sources in which the ionization is produced, also by electron bombardment, in a constricted space at a somewhat higher pressure (10^{-2} - 10^{-3} mm of Hg) the ions being extracted by the electrostatic field into the cyclotron chamber (at a low pressure) accompanied by many neutral molecules owing to the pressure differential. Modifications of this are the most satisfactory of the sources which have been actually used in cyclotrons to date. A review of cyclotron arc sources has recently been given by Livingston (1).

Application to the cyclotron or synchrocyclotron of the oscillating electron ion source shown in this work to be very promising for these uses has not been reported in the literature. It is known from private communication that at least one other cyclotron group is investigating a source of this general type, but the results of their work are not available.

2. <u>Requirements of a Cyclotron Ion Source</u>. The necessary requirements of a cyclotron ion source are

(i) that it produce a sufficient current of the desired ions at or sufficiently close to a given point and that it be sufficiently reliable in its operation.

(ii) that it be sufficiently compact to be placed at the centre of the cyclotron between the dees, and that it not block the passage of the ions in the median plane.

(iii) that its operation be consistent with the operation of the cyclotron itself at a low pressure (10^{-4} to 10^{-5} mm of Hg), i.e., the available pumping speed must be able to take care of the outflow of neutral gas from the source.

In addition, none of its other characteristics must be incompatible with the operation of the cyclotron. In particular it must operate satisfactorily in the high magnetic fields of the cyclotron.

In the synchrocyclotron requirement (i) becomes more stringent. Only those ions emitted during a limited period near the peak of the frequency-time variation of the dee field will continue to be accelerated - i.e., will fall into phase stable orbits. Bohm and Foldy (2) have estimated the range of capture efficiencies for present cyclotron designs as being 0.1 to 2 percent. Capture efficiency is defined as the ratio of acceptance time to modulation period. Mr. D.W. Hone of this laboratory has calculated the capture efficiency of the McGill cyclotron as 0.7 percent, i.e., acceptance time of 14 microseconds with modulation frequency 500 cycles per second.

The desirable, but not essential, characteristics are

(i) that the current of the desired ions be as great as possible (within reason).

(ii) that the amount of other ions produced be as low as possible.

(iii) that the outflow of neutral molecules be as low as possible.

(iv) that the power consumption be moderate and that the requirements of additional high voltage and high frequency power be moderate.

(v) that the operation be as consistent as possible, the life without adjustments as long as possible, and the adjustments to be made as simple as possible.

(vi) that the ion beam have such a distribution of original directions and velocity as not to add to the problems of focussing.

It goes without saying that those sources which have been successfully used in cyclotrons meet the necessary requirements and fulfill the desirable characteristics at least reasonably well. Many other sources however, which have been found satisfactory for other uses do not meet the requirements for use in the cyclotron.

3. Consideration of various sources reported in the literature. Various forms of canal ray source (i.e. ions produced in a high voltage low pressure glow discharge) have been used in linear ion accelerating equipment but the large bulk and other lesser considerations make these unsuitable for cyclotron use.

The simple filament source mentioned above does not provide sufficient ion current for modern requirements due to the infrequency of ionizing collisions in the high cyclotron vacuum. Neither does it satisfactorily approximate a point source (vertically).

The low voltage arc as modified for the cyclotron by Livingston, Holloway and Baker (3) from the original designs of Tuve, Dahl and Hafstead (4) and Lamar, Sampson and Compton (5) improves the above simple form of source by surrounding the filament by an inverted truncated cone within which and just below the open tip of which the pressure is sufficiently higher than the main cyclotron vacuum to allow many times greater ionization - the hole at the tip being sufficiently small to maintain the pressure differential with the available pumping speed. The effective source of the ions is localised to the region below the tip of the cone.

A source is described by R. Planiol (6,7) in which ionization is produced by crossing at right angles an intense narrow beam of electrons with a dense cellimated beam of molecules (Hg, Cd, H_2) in an otherwise high vacuum. This gives the effect of a high gas pressure in the ionizing region. Extracting ions at right angles to both beams gives a very intense beam of ions (400 mA of cadmium; 20 mA of hydrogen in a preliminary trial) but the great size of the apparatus renders it unsuitable for cyclotron use as described. It is however not inconceivable that it might be modified for the cyclotron.

A cold electrode discharge (in the sense that no auxiliary power is supplied for heating) is described by K.G. McKay in a McGill thesis (8). The discharge occurs between a central wire cathode and a concentric ring anode in a coaxial magnetic field. High ion currents (several milliamperes) are observed in the discharge but no experiments were made on removal of positive ions from the discharge.

An ion source using an electrodeless radio frequency induced discharge has been recently described by Ward (9). This appears to perform excellently, giving satisfactory currents showing a relatively high percentage of protons. Unfortunately, it seems impractical for application to the cyclotron due to its relatively large size and the nature of its coupling with the oscillator.

The oscillating electron sources are of widely different construction. All depend on the magnification of the ionizing path of the electron by inducing its oscillation in the potential well formed by an anode between two cathodes in a magnetic field parallel to a line joining their centers. The principle of these sources is discussed more fully in Section IV dealing with the investigation of a cold cathode oscillating electron ion source.

Lorrain (10) working with such a cold cathode source raised the proton percentage in his ion beam from 10 percent using a pure hydrogen feed to 40 to 50 percent using a mixture of 90% hydrogen and 10% oxygen. This compares favorably with other sources, the average figure for most other sources for which a magnetic analysis has been done being about 10%. The use of this oxygen admixture would probably not be feasible with a hot cathode source as oxygen rapidly poisons emitting surfaces.

This figure of 40 to 50 percent appears to be a limit set by the intervention of atomic hydrogen in the production of atomic ions (protons), and would seem to be the upper limit in any source based on ionization by electrical bombardment (i.e., any electrical discharge) with the possible exception of Planiol's source (due to absence of surfaces for recombination near the ionizing region). Lorrain ascribed the effect of addition of oxygen to the hydrogen supply for his source to poisoning of the recombination of atomic hydrogen at the walls of the source. This made it possible to maintain a higher percentage of atomic hydrogen in the gas within the source.

The only type of source which might be free from this limitation is one not dependent on electron bombardment of gas molecules for the ionization. Such a source is that based on the system hydrogen-palladium. T. Franzini has shown that hydrogen dissolved in solid palladium metal behaves as though it exists at least partly in the form of free positive charges, probably protons, (11) and that when palladium saturated with hydrogen is heated there is a spontaneous emission of positively charged particles (12). On this he has based what he terms a "proton tube" (13). The first use of palladium as a proton source was by Y. Sigiura (14) who bombarded the end of a palladium tube containing hydrogen with electrons under 96 v. accelerating potential. He obtained 10^{-2} µA of protons which was sufficient for his experiments on diffraction of protons waves. By magnetic analysis the protons constituted 91 percent of his ion beam. H. Hulubei (15) used both direct heating (Joule heating) and electron bombardment, getting 100 to 750 µA by direct heating and 35 µA in preliminary experiments with electron bombardment. Unfortunately few experimental details are given.

Franzini's "proton tube" consists of a palladium tube, diameter 1.6 mm, wall thickness 0.15 mm, through which is passed a current of hydrogen at atmospheric pressure and which is surrounded by a high vacuum. The tube is heated by an electric current to temperatures of the order of 1100°C. A plate separated from the tube by 20 cm within the vacuum is at a negative potential of 14-24 kilovolts with respect to the tube. Positive ion currents (assumed by Franzini to be proton currents) of up to 300 µA were obtained. Errors due to secondary emission were avoided in this measurement by obtaining current through power delivered to a thermosensitive electrode under a known voltage drop. A rough magnetic analysis indicated a high degree of homogeneity in the beam.

Section III describes an investigation of the potentialities of the electron bombarded palladium source. Appendix I describes some work, not carried to any definite conclusion on the directly heated palladium source.

It might be noted that the work done here on the palladium sources was commenced before the definite accouncement that the McGill cyclotron was to be constructed as a synchrocyclotron. The palladium sources would not appear to be susceptible to pulsed operation, nor does the literature offer any promise of output currents as high as the peak values demanded by the synchrocyclotron.

III. INVESTIGATION OF THE PALLADIUM ION SOURCE

1. Palladium Sources.

The possibilities for the use of the system palladium-hydrogen in a proton source are two-fold. In both the palladium surface separates from the vacuum system a reservoir (or tube leading from a reservoir) of hydrogen at a higher pressure. The hydrogen diffuses through the metal from the reservoir to the vacuum side, the rate of diffusion depending on the temperature. A high potential gradient is established at the vacuum surface with the purpose of withdrawing from the surface any positively charged ions released there. The two variations are as follows.

(a) The palladium surface is heated directly (as by Joule heating) to a high temperature, positive ions being withdrawn into the vacuum by an electric field. The set-up becomes effectively a reversed diode in which protons play the part of electrons. This is the variation with which Franzini worked.

(b) The palladium surface is bombarded by electrons, the accelerating field for the electrons being the same as that for the protons. The electrons would provide a certain amount of heating and possibly aid in the ionization. This is the variation employed by Sigiura.

Both methods (a) and (b) were used by Hulubei.

Each of these methods has its advantages and disadvantages for our purposes. The second method was chosen for the first trial in this work chiefly since Hulubei's remarks indicated that it might be possible to operate at a lower temperature of the palladium. This seemed desirable since the higher the temperature of the palladium the greater the amount of neutral hydrogen diffusing through the palladium. At $400^{\circ}C$ this amount is about 150 litres per second at 10^{-5} mm pressure per square centimeter of surface and increases very rapidly with temperature. This figure is based on information given by Franzini for his palladium tube (12). Also in favor of low temperature running is the report that the permeability of palladium alters when exposed to hydrogen above $500^{\circ}C$ (16) due to a modification to surface structure. The disadvantage of this form is that the arrangement of an electron bombarded source as applied in the cyclotron would not be as simple as it would be in the case of the directly heated source since

(a) a filament is required as a source of electrons.

(b) the positive ions (moving in the opposite direction to the electrons) must leave the surface of the palladium parallel to the magnetic field since the electrons must follow (describe tight spirals about) the lines of force. The directly heated source would take the form of a small vertical tube centrally located between the dees.

2. Experimental.

(i) Vacuum System. For the experimental assembly a standard 1/2 litre three necked distillation flask with standard taper ground glass neck connections was taken as the main vacuum chamber (Fig. 44). The centre (larger) neck fitting bore a tungsten filament (two filaments from 60 watt Mazda bulbs 1 cm apart arranged vertically and connected in parallel) and the tube to the pumping arrangements and the vacuum gauges. By one of the smaller necks entered a glass tube to the end of which within the flask was sealed a vertical palladium tube, 5 cm in length, 1 mm outside diameter with 0.10 mm walls and closed at the lower end. The sealing on was done by soldering the palladium to copper electroplated on a chemically deposited film of silver on the drawn out end of the tube. Through the other neck was inserted a brass plate (5.5 cm x 1.5 cm) to serve as the ion collector.

The remainder of the vacuum system was completed by vacuum gauges, connecting tubing, a bulb containing phosphorous pentoxide (since dry ice-acetone mixture was the refrigerant used in the traps between the gauge and the system and the pump and the system), a cold trap, an oil diffusion pump and a Cenco Megavac pump. All glass blowing including the construction of the low-hold-up cold trap and an all-glass oil diffusion pump was done by the writer.

(ii) Pressure Measurement. For the main pressure measurement a tilting McLeod gauge was used. With this accurate measurement was not possible below 10^{-4} mm of Hg. A Pirani gauge (Distillation Products) was also included in the system but the original calibration was invalid and the sensitivity at low pressures was too low to be useful. Modifying the Pirani measuring circuit to a null point circuit in which the bridge was balanced by varying the energy input to the gauge filament (replacing the comparison gauge by a temperature invariant resistance) increased the sensitivity somewhat but the McLeod gauge still appeared equally satisfactory.

(iii) Leaks and leak testing. Leak testing by direct application of the probe of an Energex Tesla coil was found unsatifactory. Application of methyl alcohol to the suspected area while observing a discharge tube in the system was found to be more effective. This method was still considerably inferior to that later used in the investigation of the cold cathode discharge (q.v.). Diffuse leaks were detected in the ground glass joints of the system, apparently due to a separation on standing in the Dow-Corning silicone vacuum stop-cock grease used to lubricate and seal them. All semi-permanent joints were therefore surrounded by a collar of Apiezen Q sealing compound painted over with collodion. Stop-cocks and the rotating joint on the McLeod gauge were frequently and liberally regreased. With these precautions it was possible to maintain a pressure of $5 - 10 \times 10^{-5}$ mm of Hg and occasionally lower. This is a rough estimation only ,being below the accurate range of the McLeod gauge.

(iv) Electrical Circuit. (Fig. 45). A five ampere Variac was used as a filament supply. The plate was made negative with respect to one end of the filament by means of a power pack giving up to 300 v and the palladium tube was made positive with respect to the same point by a motor-generator set giving a variable voltage of 300 v to 1100 v. Meters read the current between the plate and filament and between the filament and the palladium tube.

(v) Hydrogen supply. A U-tube electrolytic generator was used electrolysing phosphoric acid solution. The upper end of this tube communicated through a stop-cock, rubber tubing and a length of thermometer tubing (as a safety measure in case of accidental opening to the vacuum system) with the glass tube leading to the palladium tube. Also by a T-tube, this was connected through a stop-cock to the Megavac pump to facilitate filling the tube with pure hydrogen.

(vi) Emission of filament and filament temperature. The resistance of the parallel filament arrangement was 7.2 ohms at room temperature. An ammeter was put in series with the filament and a voltmeter across the variac to follow the resistance changes and hence the filament temperature. With the system at its ultimate vacuum the filament passed 0.60 A at 63 v. This corresponds to a resistance of 105 ohms or temperature of 2740°C (17). At this temperature the filament to tube current (under 300 v accelerating voltage) was about 1 mA.

Acting on information that tungsten of light bulb filaments is thoriated for mechanical strength the filament was put through an activation cycle but no sign of increased emission was noted.

(vii) Experimental Results.

A. With hydrogen at a pressure of 780 mm of Hg in the palladium tube the following results were obtained. The plate was in all cases at a negative potential of 300 volts with respect to one side of the filament and the figure given below under "Tube potential" is the positive potential of the tube with respect to this same side of the filament. "Filament-tube current" consists chiefly of the electron current bombarding the palladium tube. "Plate-filament current" is the positive ion current plus any current due to secondary emission at the plate.

Pressure (mm of Hg)	Tube Potential (Volts)	Fil.-Tube Current (mA)	Plate-Fil. Current (μA)
10×10^{-5}	400	0.02	0.8
		0.04	1.8
		0.10	5.8
		0.20	12.7

Pressure (mm of Hg)	Tube Potential (Volts)	Fil.-Tube Current (mA)	Plate-Fil. Current (µA)
		0.40	25.7
		0.70	43.0
	700	0.02	0.4
		0.20	8.8
		0.70	33.0
		0.90	47.0
	1000	0.02	0.7
		0.20	8.0
		0.70	31.5

B. The palladium tube was evacuated by direct connection to the Megavac during a period of ten minutes (this necessitating preliminary turning off and cooling of the diffusion pump) and then air admitted at atmospheric pressure. Readings made immediately were substantially the same as those recorded above but seemed to be decreasing with time. After 15 minutes the following readings were made:

Pressure (mm of Hg)	Tube Potential (Volts)	Fil.-Tube Current (mA)	Plate-Fil. Current (µA)
5×10^{-5}	400	0.02	0.4
		0.20	11.0
		0.40	19.0
		0.70	31.0
		0.90	43.0
	1000	0.90	44.0

This makes it appear that the presence of hydrogen in the tube made little contribution to the observed ion current. In fact if the ion current be interpreted as ionization of the gas itself by the electrons the difference in pressure might account for the observed differences in ion currents in the two cases. The possibility remained however that the effect might be due to residual hydrogen in the palladium itself. For this reason the apparatus was left untouched for forty-eight hours (over the week-end) and then kept under evacuation by the Megavac (both the system and the palladium tube) for several hours. After this treatment results substantially the same as the above with air at atmospheric pressure in the palladium tube were obtained.

To definitely eliminate all possibility of effect from residual hydrogen in the palladium, the fitting holding the palladium tube was removed and a rubber stopper bearing a solid copper wire of approximately the same size as the palladium tube and similarly connected was substituted. This arrangement was quite vacuum tight. The following results were obtained:

Pressure (mm of Hg)	Tube Potential (Volts)	Fil.-Tube Current (mA)	Plate. Fil. Current (μA)
10×10^{-5}	400	0.1	16
		0.2	34 (?)
20×10^{-5}	400	0.3	26
		0.4	36
		0.5	42
		0.6	50
20×10^{-5}	1130	0.1	7
		0.2	19
		0.3	26
		0.4	34
		0.5	40
		0.6	48

From these results it is obvious that the observed ion current was almost entirely due to ionization of the gas in the system. This completely masked any possible contribution due to the hydrogen in the palladium tube, variations in the ionization due to pressure changes being too important. Use of a separate pump for evacuating the palladium tube (if one had been available) making it possible to maintain diffusion pump evacuation during the change over from hydrogen to air or vice-versa might have made it possible to detect any small contribution due to the hydrogen.

In any case it appears that with a bombarding electron current of this magnitude and potentials up to 1000 volts, no ion current of magnitude sufficient to be valuable for cyclotron use is obtainable.

In view of this no further work was done on this type of proton source. The cold cathode source seemed more promising, particularly in view of the fact that since the beginning of this investigation the definite decision to construct the McGill cyclotron as a synchro-cyclotron had been announced. A palladium source would not appear to be easily susceptible to the pulsed operation desirable in a synchrocyclotron.

Note: Preliminary calculations, the construction of a source model and the results of a preliminary trial in the investigation of a directly heated palladium source are described in Appendix I.

IV. INVESTIGATION OF THE OSCILLATING ELECTRON COLD CATHODE SOURCE.

1. The oscillating electron discharge. The arc sources commonly used in cyclotrons maintain low voltage discharges at low pressure by use of heated cathodes having a copious electron emission, each electron emitted making, at most, one ionizing transit between the electrodes. The same effect may be obtained with less copious electron emission or at lower pressures by causing the electrons to make many transits, as between two parallel negative electrodes separated by a hollow or pierced anode with a magnetic field parallel to the axis of the anode hole. Electrons emitted from one cathode or originating in the gas near one cathode are impelled toward the anode but are constrained to move in spirals about axes almost parallel to the magnetic field, so that those opposite the central region of the hole in the anode pass straight through on the first transit. Those passing through meet an opposing field on approaching the other cathode and are in large measure reflected and make another transit. Thus on the average each electron makes a large number of transits before reaching the anode and the probability of it making an ionizing collision is correspondingly increased. This makes possible copious ionization at low pressures by relatively few electrons. The electron is not necessarily lost for ionization after the first ionizing collision as

if favorably situated, it, and the new free electron created, may be reaccelerated.

This simple picture may be modified somewhat in the presence of a dense plasma where the electrons are free from the accelerating influence of the electrodes during the major part of their trajectories and subject to the intense but randomly directed inter-ion fields of the plasma.

L.R. Maxwell (18) introduced this principle. His ion source used a heated filament as one cathode, two parallel annular disc plates with holes opposite the filament as anode and second cathode, and a third parallel plate as ion collector. More recently Finkelstein (19), Von Ardenne (20) and Heil (21) have designed sources operating on the same principle, all incorporating heated filaments as sources of electrons.

In 1937 Penning investigated a cold cathode discharge of the same type as these, designing a vacuum gauge (22) and an ion source (23). Lorrain (10) has recently described a cold cathode discharge in which low voltage drop is attained by the use of magnesium electrodes. This is presumably due to low photoelectric work function of magnesium, or to the high secondary emission of magnesium oxide. Lorrain has also achieved a very high percentage of protons (40-50% in the output beam from his source by admixture of 10% of oxygen with the hydrogen feed.

Lorrain's source consisted of two flat-faced cathodes with the faces parallel and separated by a hollow cylindrical anode. The cathode faces were disc shaped and 1 cm in diameter (by measurement from a scale drawing in the paper mentioned). The anode dimensions used were 26 mm and 60 mm length and 20 mm and 13 mm inside diameter. The normal operating voltage was 200 volts subject to variation from 150 to 300 volts.

The writer's work on this type of source was begun following private discussions with Dr. Lorrain and prior to the publication of the above mentioned paper.

2. Considerations in applying this source to the cyclotron and synchrocyclotron. In considering application of an ion source of this type to the cyclotron a major decision must be made at the outset. Ion extraction from this source is possible in two ways - across the field through a hole drilled in the side of the anode or along the field through a hole in one of the cathodes in the manner of canal rays. In a fixed frequency cyclotron where the dee voltage is usually high sidewise extraction is quite possible, as with high voltage the initial ion path is large enough to clear a source of reasonable dimensions. In present synchrocyclotrons where because of the mechanical limitations in attaining high modulation frequencies the dee voltage is relatively low, sidewise extraction is impossible from any source of substantial dimensions. Fig. 43 gives a scale drawing of the initial 720° of the trajectory of a proton calculated for dee voltage 15,000 volts and dee

spacing 3 cm with a centrally located ion source assuming a uniform field between the dees. (This assumption is not strongly justified especially where one of the dees is grounded since in this case the ion source being at a fixed potential (probably grounded) would distort the field in its neighborhood, and in sidewise extraction would shield the area behind it). From this it appears that no ion source offering more than a few square millimeters cross section in the median plane would be possible. The possibility has been considered of a double cone anode with the cold cathode source, similar to the arrangement in some forms of low voltage arc source leaving the median plane completely unobstructed. This suggestion has also been made by Lorrain (10). It seems improbable that the discharge would pass readily at low pressure in such a source since the total discharge cross section would be limited by the size of the hole in the cone tips permitted by pumping speed limitations. In fact such a source seems to reduce to a double arc source operated under adverse conditions, namely in the absence of a filament. It is possible however that the asymmetric operation later described may represent a manner of inducing such a discharge.

A simpler solution appears to be to use end extraction placing the ion source below the median plane. The ions would be directed upwards toward the median plane along the lines of force. If this method is to be feasible the dee field must be capable of picking up these ions and their upward component of velocity must not be so great as to overcome the vertical focussing action of the magnetic and electric fields. That is, the ions must not be lost to the dees.

Loss to the lower dee edge before passing above its plane could be prevented by an electrostatic shield extending to this height. If the upward velocity component were too high the velocity could be reduced by a decelerating electrode before the particle left the region of the source.

Wilson (24) and Rose (25) have discussed focussing in the cyclotron. Wilson shows that there is a critical distance on either side of the median plane of the cyclotron such that an ion originating within this region will be retained by the focussing action of the electric and magnetic fields. Ions originating outside these limits will be lost by defocussing. In our case all ions will actually originate outside these limits but will be directed upward with a finite velocity. Until they reach the median plane after passing the lower dee edge these ions will be subjected to a decelerating component of dee field. Unless they have a very high initial velocity (which as pointed out above could be reduced) this will decrease their vertical velocity to zero before they reach the median plane. This point of zero velocity will correspond to Wilson's point of origin of the ions.

Thus it appears that it will only be necessary to adjust the vertical velocity of the ions to approximately the correct value to make location of the ion source below the dee edge feasible. Such an adjustment would probably be best done empirically. The decision having been made advantages of this arrangement immediately appear. The dee field will be picking up ions not from a plasma but from a cloud of ions of one charge so that the space charge limitation suspected in arc sources (1) will not appear. The high pressure point inevitably found in the neighborhood of the ion source aperture will be removed from the median plane, so that the initial ion paths will be described in a region of somewhat lower pressure.

With these points in mind it was decided to investigate endwise extraction from this type of source with regard to use as a cyclotron or synchrocyclotron ion source.

3. Experimental.

(i) Vacuum systems. Two vacuum systems were used in this work, one a relatively low speed system, and the other having a higher speed. These are described below.

(a) Low speed system. This was used for preliminary parts of this work in a small electromagnet and for the earlier trials in the cyclotron magnet. It consisted of a small vacuum chamber (Fig. 40), glass diffusion pump, and mechanical pump. Several preliminary experimental variations besides that here reported were used with this system, the various vacuum chambers being connected to the pumping system by metal collars fitting over the glass lead to the diffusion pump and sealed to the latter by Apiezon W wax (hard pitch). This material has been very useful everywhere in these experiments.

The diffusion pump was a Distillation Products Incorporated GF-25A glass three-stage self-fractionnating pump filled with Octoil. It was backed by a Welch Duo-Seal type 1405 mechanical pump, a phosphorus pentoxide trap being attached to the intervening lead. No cold trap was used.

The calculated pumping speed at the entrance of the lead to the diffusion pump was of the order of 10 litres/sec. (air).

(b) High speed system. At a later stage in this work the vacuum system was redesigned to make use of a high speed metal diffusion pump as this enabled a closer approach to actual cyclotron conditions.

This pump was a Distillation Products Incorporated MF-250 metal fractionnating pump. The rated pumping speed of this pump for air is 240 litres/sec. at 10^{-4} mm pressure. It was filled with Narcoil 10. The Welch Duo-Seal mechanical pump was again used as a backing pump.

A 3'4" length of 4" brass tube was used as a pumping lead with a cubical brass box 4 1/2" to the side as a vacuum chamber. The ion source proper sat on a Bakelite annulus which in turn rested in a circular hole in the top of the vacuum chamber. The connection between the brass tube and the diffusion pump was made at a rubber gasketed flange. The vacuum seals between the chamber, Bakelite, and ion source were made by Apiezon W wax. Both the enclosed model of the source (Plate III and Fig. 40) and the spacer model (Plate III and Fig. 41) were used with this system.

The calculated pumping speed at the junction of the pumping lead and vacuum chamber was 60 litres/sec. (air).

This vacuum system was used for some time with no baffles, but the results obtained were invalidated by a black insulating deposit which formed on the collector where the ion beam struck it. This deposit was at times 1/64" thick over the actual beam area and thick enough to provide electrical insulation to a wire probe for 1/2" around. Indications suggesting that this was due to decomposition of Narcoil vapor by the ion beam, a two plate baffle was inserted in the throat of the diffusion pump where it would be cooled by conduction from the sides. This appeared to decrease but not eliminate the deposit so a three plate optical baffle was inserted in the end of the 4" brass tube, this portion of the tube being surrounded by an insulated box which was kept filled with "dry ice". This completely eliminated the deposit thus confirming its origin in the backstreaming of Narcoil vapor from the pump. Similar observations have been reported by Stewart (26).

The optical baffle further cut down the total pumping speed. Although calculation of such a system is difficult the resultant speed should have been of the order of 40 litres/sec. (air) at the vacuum chamber. Measurement of the ratio of the pressure within the source to the chamber pressure with an extracting aperture of 1/4" diameter (pumping speed for air, 3.1 litres/sec) gave a value for the pumping speed at the chamber of 15 litres/sec. In this connection it is interesting to note a recent report (27) that the pumping speed of oil diffusion pumps for hydrogen is less than that for air rather than being greater in the inverse ratio of the square roots of the molecular weights as theoretically predicted. In this case the ratio of pumping speeds for the aperture and for the pump would not be the same for hydrogen as for air as was assumed above.

(ii) Pressure Measurements. Primary pressure measurements were made with a sensitive McLeod gauge constructed by the writer. This was of the double bulb type enabling it to measure up to two millimeters of mercury on the coarse scale and from 10^{-5} mm to 0.150 mm (0.01 μ to 150 μ) on the fine scales. On the fine quadratic scale a pressure of 10^{-5} mm was represented by a residual gas column of 2 mm. The gauge was of the all-glass type, a water aspirator being used to control the mercury level.

A Pirani gauge calibrated against this McLeod gauge was used for continuous measurement of pressure. As it was found that the calibration of this changed with time the McLeod gauge was connected to the same lead and frequent checks were made. The Pirani gauge was retained only because it gave a constant check on sudden changes of pressure. Separate calibration of the Pirani was necessary for air and for hydrogen-oxygen mixtures.

(iii) Leak Testing. All testing for leaks in the vacuum systems was done in the following manner. A discharge was initiated in the system evacuated by the forepump only, by wrapping a section of glass tubing in the system with metal foil connected by a wire to the probe of an "Energex" Tesla coil. Change in colour of the discharge and usually its partial extinction resulted when acetone was "squirted" from a long medicine dropper onto even the smallest of leaks. By this means any leak could be located exactly.

(iv) Electrical Circuit. The electrical circuit (Fig, 42) was essentially the same for all modifications of the source. The two essential forms of the source are shown in figures 40 and 41. Both consist essentially of two magnesium cathodes separated by a hollow axially symmetrical magnesium anode. A fixed D.C. potential is applied between the two cathodes and the anode in series with a rheostat and current measuring meter. The discharge current adjusts itself to such a value that the voltage drop in the series resistances is equal to the applied voltage minus the discharge voltage. In pulsed operation the place of the rheostat is taken by a set of four 6L6 tubes in parallel the grids being controlled by a standard phantastron pulsing circuit (built from designs supplied by Mr. J.S. Fraser of this laboratory) giving a pulse of duration variable from 5 to 90 microseconds and of repetition frequency variable from 796 per second to about 4000 per second. The change over from series rheostat to pulsing circuit is accomplished by throwing a D.P.D.T. switch which also replaces the voltmeter by a compensated attenuator for oscillograph measurement. For some measurements fixed grid bias for the 6L6's (0-300 v) was used but the stability was found to be increased by the use of cathode bias.

Bias on the grid, accelerator or collector was usually obtained by inserting a voltage supply (battery or power pack) between the cathode and the point in question. Occasionally self-bias through a resistor between the cathode and the point in question was used. All potentials mentioned are referred to the cathode as zero. Where the two cathodes are at different potentials the upper cathode is taken as the reference point. Except in the use of a center-grounded 220 v. D.C. supply in high current measurements, the upper cathode was always grounded.

For most measurements where discharge currents less than 100 mA. were used the operating voltage was supplied by a motor-generator set of voltage variable from 300 to 1100 v. When higher supply voltages were desired a small 450 v dynamotor was connected in series. For measurements when discharge currents were carried above this limit a large motor-generator set giving 400 v was set up in series with the 220 v D.C. lines.

(v) Hydrogen-oxygen supply. The hydrogen-oxygen mixture used was provided by an electrolysis apparatus (electrolyzing dilute phosphoric acid solution) the gases being mixed in the desired proportion in a 200 cc. reservoir with leads to the electrolytic apparatus, to a manometer tube, to a water aspirator, and to the adjustable Fowler leak leading to the ion source. For safety in handling, the mixture was usually kept at about 1/5 atmospheric pressure.

(vi) Fowler leak. (28). The Fowler leak consisted of a German silver tube 7 mm diameter by 12" long beaten out flat over the central six inches. The flattened section was bent in a curve the angle between the legs of which was variable from about 5° to 60° or 70° by means of a threaded rod passing through a nut pivoted on one leg and turning freely in a collar attached to the other leg. This permitted very satisfactory pressure control.

(vii) The Enclosed Model of Source. This succeeded a preliminary model in which the electrodes were separated by glass ring spacers, the vacuum system being confined to the actual space between the electrodes and the collecting chamber and pumps. The vacuum sealing of the electrodes to the spacers was done with Apiezon W wax. A discharge was obtained easily in this (in air) and it had the advantage of visibility, but the enclosed model was adopted as having the advantage of sturdiness.

The enclosed model also went through several stages before reaching the final form as shown in Fig. 40 and Plate III. Brief explanatory notes are given below on details not evident from the diagram or of which the purpose is not clear.

(a) Anode cooling. Cooling by means of a copper fin on on the end of the central conductor of a copper "co-ax" supporting the anode was found insufficient. The anode lead shown in Fig. 40 was drilled throughout its length by two 1/16" holes. These were so arranged as to coincide with two holes in the anode jacket when the lead was screwed into the latter. A partition in the jacket directed the water circulation around the jacket. The threads were sealed vacuum tight with Apiezon W wax or with soft solder.

Thus the source could be disassembled by heating the anode jacket and anode lead to melt the wax or solder. The water caused a parallel leakage path but only a milliampere or so of current flowed. Circulation of oil through the anode jacket to eliminate this leakage path was tried (using solder sealing for the threads) but the cooling was inefficient. In later stages the hollow copper jacket was replaced by a solid copper jacket of the same size. The anode lead, now closed by a copper tip which screwed into the jacket, was water cooled to within the copper tip. This is the form shown in Plate III.

(b) Glass anode lead insulator. This was included to prevent discharges from the anode lead to the outer coaxial member at cathode potential. These discharges had charred a Bakelite spacer causing shorting in a previous trial.

(c) Lavite insulators. Discoloration on the walls of the cathode enclosure indicated occurrence of parasitic discharges outside of the ion source proper. As these would falsify the value of the discharge current the lavite insulators were inserted to eliminate such discharges. The lavite insulators were machined from soapstone obtained from the Geology Department of McGill University and were baked at about 1100°C.

(viii) <u>The Spacer Model Source.</u> (Fig. 41). The primary purposes of this model were to allow for operation of the cathodes at different potentials, to improve the pressure measuring arrangements, to make replacement of the electrodes and centering of the cathodes easier and to allow for possible introduction of additional electrodes or change in electrode dimensions.

In Fig. 41 to show the largest number of important details in one diagram the anode jacket is rotated 45° clockwise and the lower cathode jacket 45° counterclockwise. Thus in the section taken of the top cathode and cathode holder four Stupakoff type GA Kovar-glass terminals with 1/4" hollow central conductor, through which the anode and lower cathode cooling leads slide smoothly, are not shown. These are soft soldered to the top cathode holder. The seal between the leads and central Kovar tubing is also made with soft solder.

While Kovar is somewhat magnetic these terminals are sufficiently far laterally from the discharge area to have little effect upon the field distribution, being in addition symmetrically located. The permeability of Kovar decreases greatly at high fields (29).

The lavite spacers for this source were machined from a higher grade of soapstone purchased from M. Kirchberger and Company, Brooklyn, N.Y. These were also fired at 1100°C in a Hoskins FH202 Electric Muffle Furnace. They were very close fitting, the pumping speed of the spaces left being so small compared to the extraction aperture that no sealing was necessary.

(ix) Anode shapes.

(a) The cylinder anode. The standard anode shape (i.e., the shape corresponding to that used by Lorrain and workers with hot cathode sources) is that shown in Figs. 40 and 41, and is item "j" of the upper picture and item "h" of the lower picture in Plate III. In the curves given at the end of this thesis (Figs. 1 to 38) this anode is referred to as the cylinder anode. All electrodes were of magnesium with the exception of one set of calcium electrodes.

(b) Ring anodes. These were given only a brief trial and then abandoned as with them the discharge voltage was slightly higher, the output current slightly lower for the same discharge current, and the minimum operating pressure higher than with the cylinder anode. These were used in one of the preliminary forms of the enclosed source. One was a toroid of cross section 1/16" diameter and outside diameter 1 1/16". The other (modified from this was of oval cross section, 1 1/16" outside diameter and 3/4" inside diameter.

(c) Bevelled anode. The outside length of this was 3/4". It was bevelled inwards at an angle of 45°, the inside length being 5/16" and inside diameter 5/8". The same remarks apply as in (b).

(d) Ejector anode. The form of this is best seen in Plate III where it is item "k" of the upper picture and item "g" of the lower. The purpose of the small central ring which when the source is assembled sits directly over the hole in the cathode is to provide a higher extracting field in the neighborhood of the hole and thus "eject" the ions. Comparison of Fig. 1 and Fig. 2 shows that it is effective in doing this.

(x) Cathode shapes.

(a) Flat cathodes. Flat cathodes with central holes in the extracting cathodes as illustrated in Fig. 40 and 41 and shown in Plate III ("e" and "g" of the upper picture, "f" and "i" of the lower) were used in all trials in this work from which the curves included were compiled. Various sizes of extracting holes were used 1/8" being the most common. The effect of variation in the size of the hole may be seen by a comparison of the various curves and in particular from Fig. 8. Doubling the size of the hole roughly doubles the output current. (N.B. Figure 8 is for a discharge in air as noted. All other curves are for a mixture of 90% hydrogen and 10% oxygen.)

The cathode face is 5/8" in diameter and is raised 1/8".

To test the possibility that the dip in the output current versus discharge current curves (Fig. 1 and Fig. 2) might be due to shift of the discharge to outer parts of the cathodes, two cathodes with off center holes, one with the hole halfway to the edge and one with the hole at the very edge of the cathode face (item "g" in upper picture,

Plate III), were prepared. With these cathodes essentially the same magnitude and variation of output current with discharge current were obtained.

(b) Projecting cathode. This is item "f" of the upper picture of Plate III. It is a closer approach to the cathodes used by Lorrain (10) but produced no significant change in output current (i.e. output current remained below 0.05 mA in the cyclotron field of 16000 gauss) the minimum discharge voltage with these cathodes was about 400 v even after "running-in" for some time. This compares with a voltage of 300-350 v for a well "run-in" source using flat cathodes. The cathode face was 3/8" in diameter and was raised 1/4".

(xi) Modes of operation. The normal mode of operation, that already investigated to some extent by other workers is that in which the cathodes are operated at the same potential. This has been termed here the symmetric mode of operation. The spacer model of source makes it possible to operate the source with the cathodes at different potentials. This mode of operation the writer has called asymmetric. The characteristics of the two modes of operation will be considered separately.

(a) Symmetric operation. Figs. 1-11, 27, 29 and 30 give curves dealing with symmetric operation. These curves represent a small but typical selection of the large number of readings taken.

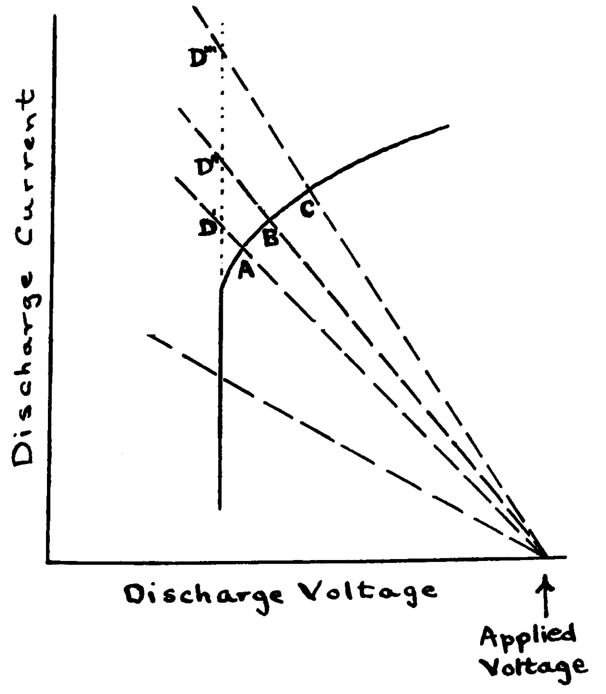
Cylinder anode. The discharge ignited readily in most cases with 1000 v supply voltage and often with less when the source had previously been operated and the apparatus had been left evacuated (with the forepump running.) In general the discharge struck more readily after the apparatus had been in use and under evacuation for some time. The apparatus was at times under constant evacuation for periods of one month or more.

The minimum discharge voltage after "running-in" was slightly higher in the cyclotron field (16,000 oersteds) than the value of 260-300 v indicated for low field in Fig. 3, ranging from 300-350 volts with no consistent trend. "Minimum discharge voltage" refers to the voltage at the flat portion on a curve of the type of Fig. 9. Minimum voltage could in general not be attained at less than 4 microns pressure even with a well run-in source. As observed by Lorrain and others the discharge is essentially a constant voltage discharge at such pressures. The second order dip of Fig. 3 is however a reproducible phenomenon corresponding to the decrease in output current.

A spark coil was used to start the discharge in the first stages of the work in the cyclotron field. For this purpose a large "retard coil" (900 henrys at 0.020A) was inserted between the anode and the remainder of the circuit (Fig. 42). This was shorted out by a knife switch in operation. With the switch open the coil protected the circuit meters from damage when the spark coil high voltage lead was applied to the anode to initiate a discharge in the source. A few seconds of this usually sufficed to start the source which usually started to run at a high voltage (as high as 700-800 v) and slowly approached normal running voltage. During the high voltage stage high output currents, up to 1 mA. were registered, even at as low as 450 v. The output current would rapidly fall to the usual low value as voltage decreased to normal.

In later stages of the work when sources were well run in the spark coil was seldom necessary.

At the lower pressures, 2 to 4 microns, there seemed to exist a maximum current which the discharge could pass stably in its normal constant voltage mode. Above this the discharge became unstable. This instability is illustrated in Fig. 11. The point D represents a region rather than a point. This behaviour can be explained on some basis such as that illustrated to the left. The solid line indicates the (assumed) stable voltage characteristic of the discharge, the dotted continuation an unstable continuation of the constant voltage discharge and the broken lines the load lines of different



series resistances, smaller the steeper the slope. Here again the high voltage discharges give higher output currents. It must be noted however that the actual readings of Fig. 11 were taken at low field (1700 oersteds). The same type of behaviour was observed in high field but the output currents were lower. Lorrain (10) also observes the high output currents in high voltage modes but observes that they are of little value due to low proton percentage.

In general it was not possible in the cyclotron field to obtain discharges which could be carried stably to high currents at pressures less than 4 microns. Low field results (e.g. Fig. 4) seem to indicate that stable discharges can be obtained at lower pressures in the low field, but as more reliance was placed on the constancy of the Pirani gauge calibration in these the pressure figures may be less reliable.

The most significant facts for the purpose in hand are shown in Fig. 2. The output current in all fields shows the same general behaviour, increasing from zero with increase in discharge current to a maximum value then decreasing. The maximum value is higher for lower field values. In the cyclotron field (16,000 oersteds) it has decreased to 0.03 mA. With increasing discharge currents it becomes negative and remains negative for the highest discharge currents used. That this maximum and drop off in the curves represents something fundamental in the discharge mechanism is indicated by the corresponding discharge voltage variation shown in Fig. 3 for low field. No consistent effect of this nature was observed in the high field, but neither was there a sharp maximum in the output current curve.

Fig. 10 (upper curve) shows the variation with field strength of the discharge current value corresponding to the maximum output current. The high field value is not included on this curve because of the resultant compression of the scale. Extrapolation of the curve as included predicts a maximum output current in the neighborhood of zero discharge current for fields of the order of 10,000 oersteds or more.

The minimum voltage shown by the source with calcium electrodes was 400 v. even at a pressure of 9 microns on the second day of running. Otherwise its characteristics were the same as those of the magnesium source.

Ejector anode. Fig. 1 gives the output current characteristics of the source with the ejector anode in symmetric running. The ejector anode appears to be a definite improvement over the cylinder anode. The essential shape of the characteristics is not changed but the height of the maximum is increased. There would appear to be no advantage (in fact a great disadvantage) in operating the source at high currents. This is borne out by the results in pulsing discussed later.

Fig. 5 shows the effect of the suppressor grid voltage. The minimum at -50 v. is presumably due to suppression of secondary electrons. The rise to the left is due to the extracting effect of the grid. Fig. 32 gives variation of output current with grid voltage at low field.

With the ejector anode the source seemed to start much more readily and to attain its normal operating voltage more rapidly. The normal operating voltage was lower than with the cylinder source, being 280-290 v. in the high field. The discharge would also pass at a somewhat lower pressure. These effects may have been due to the more intense field created at the surface of the cathode opposite the ejector bar, which would correspond to the starting electrode in some gas discharge tubes.

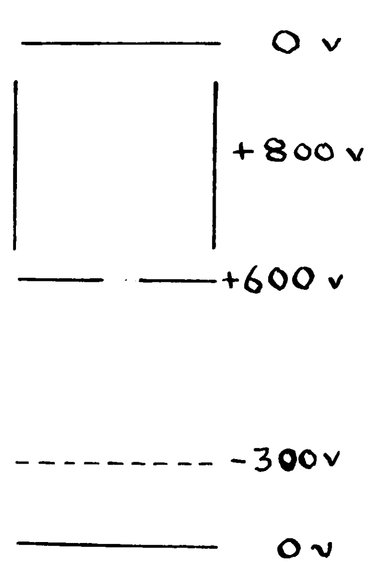
(b) Asymmetric operation. Figs. 12-26, 28-31, and 33-35 deal with asymmetric running.

The most obvious method of asymmetric running (i.e. operation with the two cathodes at different potentials) was to place a low impedance voltage supply between the two cathodes. This was done using storage cells. The results are given in Fig. 34. It appeared that any chance of increasing the output current lay in high positive voltage on the lower cathode, but sufficient storage cells were not readily available. Positive bias by means of a high leak resistance from lower to upper cathode seemed a simple solution. This is shown in the circuit diagram of Fig. 42. The result was a great increase in output current. See Figs. 13-15, 17, 19, 28, 30 and 35 for curves of operation with cathode self-bias in the high field. Except for Fig. 34, the cathode bias for all curves labelled "Asymmetric" is self-bias through a 276 kilohm resistor. The term "asymmetric" will in future unless otherwise stated refer to this particular arrangement. In most cases the larger the biasing resistor the higher was the output current observed for a given discharge current. Occasional exceptions were observed when some smaller value (50 kilohms occasionally) gave a slightly higher output than the 276 kilohms.

In considering these curves for asymmetric operation it must be borne in mind in order not to have a false idea of the extent of improvement obtained, that the collector is, unless otherwise specified, at the potential of the upper cathode, i.e. negative with respect to the lower cathode. This represents an extracting potential. To obtain a true comparison of the two modes of operation, the collector connection was removed from the upper cathode and made 330 volts negative with respect to the lower cathode. With this connection, both symmetric and asymmetric running were investigated. Fig. 30 indicates the comparison. While asymmetric running is definitely superior (output current over three times as great) symmetric running gives a higher output than observed in previous trials. It appears that bias on the collector is more effective than on the grid. A highly tentative explanation might be advanced for this if it were assumed that the source output current in symmetric running consisted of a mixture of electrons and positive ions. Under these circumstances the collector might be more effective in repelling the electrons than the grid, indicating an apparently greater efficiency of extraction.

Figs. 31 and 33 deal with asymmetric operation with the collector at the same potential as the lower cathode and various suppressor grid voltages. The output in these cases is negative.

This leads to a possible interpretation of the asymmetric discharge mechanism. This explanation is not advanced as a substantiated theory but merely as a speculation. Typical electrode voltages are shown in the diagram to the left. Motion of electrons downward, begun within the source at relatively high pressure may not cease at the lower cathode for those in line with the hole but may



continue out into the chamber vacuum (which is 0.5 microns for 10 microns in the source with a 1/8" cathode hole). Because the anode to lower cathode and lower cathode to collector voltages are accelerating to positive ions the electrons will be accompanied by positive ions from the source and those formed near the source opening. Electrons will be repelled by the combined action of the collector and negative grid, while positive ions will continue to the collector. This being of brass and having a suppressing voltage on the grid, secondary electrons from the collector will not contribute to the discharge mechanism. The ion source proper would seem then to be fulfilling the function of an emitting cathode and high pressure region in a source bearing a closer resemblance to that of Finkelstein (19) than to other oscillating electron discharges. A very perceptible hollow on the surface of the top magnesium cathode corresponding exactly to the hole in the lower cathode in size and position indicates that the intense discharge is largely confined to a central column. This observation is fully in keeping with the above theory. It also suggests a probable reason for the high ratio of output current to discharge current.

Since the collector plays no part in the discharge itself, this, although radically different in principle from the original discharge, would be equally satisfactory as an ion source. The effectiveness of suppressor voltage in increasing the output current (Figs. 17 and 18) confirms the fact that secondary emission from the collector plays no part in the discharge. For cyclotron use the grid would have to be replaced by a probably more effective ring electrode having a hole exactly of the beam size. This would be the electrode labelled "extracting electrode" in Fig. 43A.

(xii) Pulsed operation.

(a) Circuit and results. The use of the hard tube pulsing circuit shown in Fig. 42 was chosen because of its simplicity and flexibility. The use of a line type pulser was considered, but the idea was abandoned due to considerations such as those listed by Glasoe and Lebacqz (30), in particular the difficulty of matching where variation in load is desired.

In obtaining the higher values of pulsed current with this circuit (which was designed for exploratory observation of the pulsed behaviour of the source and with no intention of permanence or high efficiency) a certain steady conduction component was encountered when the grid bias voltage was decreased sufficiently. The applied pulse was of a fixed value of 150 volts (positive),, the grid bias being variable (either by varying the applied voltage in fixed bias, or by varying the cathode biasing resistor in cathode bias) to increase the pulsed current.through the tubes. Using fixed bias the steady conduction current for any bias setting could be accounted for by switching off the pulse. Using cathode bias curves were plotted of current against bias with the pulsing circuit on and off. The current at a given bias figure with pulse off gave the steady conduction component for that same bias.value with pulse on. The same method gives the steady component of output current.

Figs. 37 and 38 are plotted using values of discharge and output current corrected for this steady component. Along the right hand and top boundaries of the graphs are given the corresponding values of the instantaneous current in the pulse on the assumption that the pulse is perfectly square of uniform height and of the same length as the applied pulse.

Fig. 39 shows sketches of typical pulse shapes obtained in symmetric operation with the ejector anode. Voltage and current pulses obtained with the cylinder anode were essentially identical with those shown in this figure. Output current pulses indicated a negative output for all discharge currents used. The output current pulse sometimes had both a negative and a positive portion, the negative preceding the positive and being greater in magnitude. The traces of Fig. 39 were obtained using fixed bias. A DuMont type 241 cathode ray oscillograph was used to observe these pulses.

Plate IV shows photographs taken of pulse traces obtained in asymmetric operation of the source with calcium electrodes and a 3/16" extracting hole. A photograph of the applied pulse to the same horizontal scale is included for comparison. The voltage and current values shown against the traces are as measured from the negatives by comparison with 60 cycle sine wave calibrating voltage photographs taken at the same time. The pressure in the source was 8.5 microns, the discharge current meter read 10.5 mA and the output current meter read 0.65 mA. These values have been corrected for the steady component. The pulse length was 30 microseconds and the repetition frequency 796 per second. Grid voltage was zero.

The pulse shapes obtained with magnesium electrodes and other extracting hole sizes were essentially the same, although in some cases a slight delay in striking similar to that observed in symmetrical operation was observed.

It should be noted that, of necessity, due to the arrangement of the resistors across which voltage drops are taken for the oscillograph measurement, the positive direction differs on the traces for the discharge current and the output current. The positive direction is upward in Fig. 39 and Plate IV for output current, applied pulse, and discharge voltage and downward for the discharge current.

(b) Discussion of Results.

Symmetric Operation. From an inspection of the curves for pulsed symmetric operation of the discharge using the ejector anode (Figs. 36 and 37) it appears that the characteristics in pulsed operation are qualitatively similar to those for steady operation. The ion output both in the presence of accelerating potential and without acceleration rises to a maximum value as the discharge current increases then decreases and becomes negative for further increase in the discharge current. This same behaviour is evident in the traces observed on the oscilloscope.

When the peak values of the various currents are calculated from the meter readings using the known duty cycle (ratio of pulse length to repetition period of the applied pulse) assuming the current forms to be square the agreement between the values for pulsed operation and those for steady operation is seen to be somewhat more than qualitative. The maximum peak values of the pulsed ion current reached are of the same order of magnitude as the maximum steady ion current observed. This applies both with and without a negative (extracting) potential on the grid, and in high and low fields. The agreement is best in the high (cyclotron) field and with an accelerating potential. These statements are based on comparison of Figs. 36 and 37 with Fig. 1.

The accuracy of the above conversion from average meter reading to peak pulse current is limited by the apparent failure at low discharge currents of the source to strike immediately upon application of the voltage pulse. From the form of the observed trace (Fig. 39) it appears that this delay exceeds that required to charge up the capacity of the source, since the charging up portion is well defined and in many cases is practically complete within a fraction of the total delay. At higher discharge currents the discharge strikes sooner in the pulse, and eventually the delay becomes zero.

Assuming the delay to be due to ionization time of the source, the decrease in delay with rising current might be explained if the deionization time of the source were of the same order of magnitude as the repetition period. The deionization time would increase with discharge current and if the deionization period extended into the following pulse, a decrease in its ionization time might be expected.

The voltage traces in addition to this lag in the discharge also exhibit a partly discontinuous change in the height of the discharging portion as the discharge current is increased. This seems to coincide approximately with the change from positive to negative in the output current trace. No similar effect of comparable magnitude is observed in steady operation, so there may be no relation between the two phenomena.

The same remarks apply in general to the discharge using the plain cylindrical anode, both with flat and with projecting anodes. The output current was negative for all magnitudes of pulsed discharge current used. The form of the voltage and current traces on the oscilloscope was in general the same, the time lag in striking being, if anything somewhat greater.

From these results it appears that as in steady operation the ejector anode is a considerable improvement over the cylindrical anode. Because of the maximum on the output current characteristic however the maximum peak pulsed ion current obtainable is no higher than the maximum steady ion current.

Asymmetric operation. Comparison of Fig. 38 and Figs. 11-17, 27-30 and 35 shows that the asymmetric discharge exhibits the same general behaviour under pulsed operation as is shown in steady operation. Instantaneous discharge currents calculated from the duty cycle on the assumption of a square pulse shape run much higher than the currents used in steady operation. Correspondingly the instantaneous output currents also run much higher. The square pulse instantaneous value of the output current corresponding to the highest value recorded is 90 mA. This is for an instantaneous discharge current of 460 mA.

The assumption of squareness of the pulse is somewhat less justified in this case than in symmetric running.

The discharge current trace of Plate IV and other traces observed seem to rise stepwise. The output current pulse rises sharply but does not remain straight along the top of the pulse. This is probably the natural outcome of the shape of the current pulse. Some of the current pulses observed with magnesium electrodes showed a slight delay in striking the capacity charging portion being evident as in the symmetric case. In some cases also the output current pulse was more conical in shape, the sharp rise being absent. For this reason the pulse duration in synchrocyclotron use should probably be at least twice the acceptance time of the cyclotron.

4. The significance of the experimental results for cyclotron and synchrocyclotron application.

From the experimental results given above it appears that the cold cathode ion source investigated will give, either in the symmetric mode of operation with the ejector anode, or in the asymmetric mode of operation, a sufficiently high ion current to be promising for use in the cyclotron or synchrocyclotron. In addition both are capable of being pulsed at pulse lengths and at repetition frequencies of the order of those used in present synchrocyclotrons.

The asymmetric mode of operation gives a much higher ion output current. Other factors being equal it would than be the more desirable of the two developments. Taking the results for the source with calcium electrodes and a

3/16" extracting hole, the pulsed output was 90 mA or about 70 times the output current of the symmetric source with the ejector anode in pulsed operation. Its operating pressure for this reading was 8.5 microns. The pumping speed of the 3/16" extracting hole is roughly 2 litres/sec. at these pressures. A pumping speed of 1000 litres/sec. for evacuation of the cyclotron chamber could maintain the chamber pressure at 2×10^{-2} microns (2×10^{-5} mm) pressure against this alone. This is quite satisfactory as other accidental leaks would probably be of this magnitude. The upward velocity component of the ions would probably be higher than in the symmetric ejector case, the upper limit being the voltage drop between anode and extracting electrode (up to 1000 v.) but it has been shown that this would probably be no disadvantage. If it were found undesirable the ions could easily be decelerated. Thus none of the characteristics in asymmetric operation appear incompatible with synchrocyclotron conditions.

One important factor has not yet been discussed. Because of the necessity of performing this work in the limited space between the cyclotron pole faces, the usual methods of magnetic analysis of the proton beam were not feasible. Several possible methods were considered which would make use of the cyclotron field itself for a rough magnetic analysis, but time was not available to try these.

Because of the close similarity of our discharge conditions to those of Lorrain (10) it would seem that a fairly reliable estimate of proton percentage might be made by extrapolation from his curves for the variation of proton percentage with discharge pressure and magnetic field strength. For the mixture of 90% hydrogen and 10% oxygen used in this work his curves indicate by extrapolation a proton percentage of 60% at about 16,000 oersteds. His pressure variation curves give a proton percentage at 8 microns of about half the magnitude of that at 2 microns. This would lead to an estimate of 30% protons in the beam from the asymmetric calcium source, and perhaps 40% for the symmetric ejector anode case.

V. CONCLUSIONS

1. The standard form of oscillating electron cold cathode positive ion source with end extraction and for moderate extracting voltages has been shown to give no useful positive ion output in the high magnetic field of the cyclotron (16,000 gauss). The maximum positive ion current obtained was 0.03 mA.

2. The introduction of an anode of modified shape such as to provide a high field at the extracting hole produces an ion output current of 1.5 mA in steady operation and 1.3 mA peak in pulsed operation. This is with 300 volts extracting (negative) potential on a secondary electron suppressing grid. The probable proton percentage in this is 40%.

3. Operation of the discharge with the extracting cathode at a high positive voltage with respect to the other cathode, to which the power is supplied, this voltage being maintained by a biasing resistor between the two cathodes, produces a great increase in the ion output current. The highest ion current thus observed in steady operation was 10 mA, while in pulsed operation a peak output current of 90 mA was obtained. The discharge within the source appears to be largely concentrated in a column of the same cross section as the extracting hole.

4. Both of these forms of the ion source are concluded to have all the requirements for a synchrocyclotron ion source.

APPENDIX I

The directly heated palladium proton source.

The arrangement of a directly heated palladium proton source in the cyclotron would be particularly simple. Only a heated palladium tube centrally located in the cyclotron and parallel to the field would be required. The dee field would extract the ions from its surface. Its diameter could be sufficiently small not to interfere with the useful ion paths. Being incapable of pulsed operation it would probably not provide the high peak ion currents required by the synchrocyclotron.

An experimental set-up shown in Fig. 46, was constructed to test the possibility of such a source before the emphasis shifted to synchrocyclotron application. The arrangement of this is such as to make it tantamount to a positive ion magnetron. A straight palladium tube, hydrogen filled, and heated by passing an electric current through it, as a positive ion filament (anode) is surrounded by a coaxial cathode, the intervening space being evacuated and the whole being placed in a coaxial magnetic field. Because of this analogy to the standard magnetron it was hoped that if an ion current was obtained a rough magnetic analysis of the relative proportions of the various types of ion (H_1^+, H_2^+) present might be made possible by the different magnetic cut-off fields characteristic of the different

$\frac{e}{m}$ ratios of the ions. That is, a plot of current versus magnetic field strength at constant voltage should show more or less sudden decreases at field strengths characteristic of each of the ions (and the applied voltage), and the currents at these breaks should represent the total current, the total current minus the current of ion mass 1(i.e., protons), the total current minus the current of ions mass 1 and 2, etc. (assuming all singly charged).

Only preliminary trials of this model were made. In these no ion currents in excess of a zero current (0.09 mA) which flowed due to cooling water were observed with the palladium tube at about 1100°C, 10 cm. hydrogen pressure in the tube and 1100 v. between tube and collecting electrode.

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List of Symbols Used in Figures.

V = anode potential or discharge voltage

V_L= potential of lower, or extracting cathode

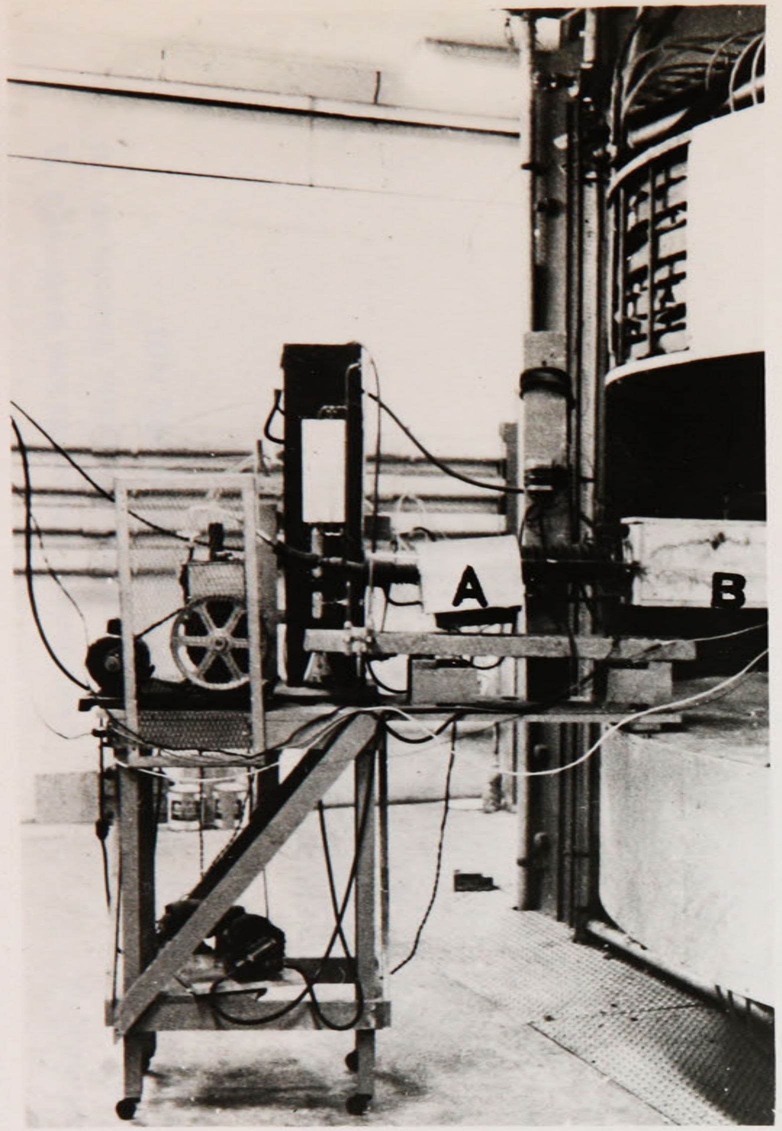
V_g= suppressor grid potential

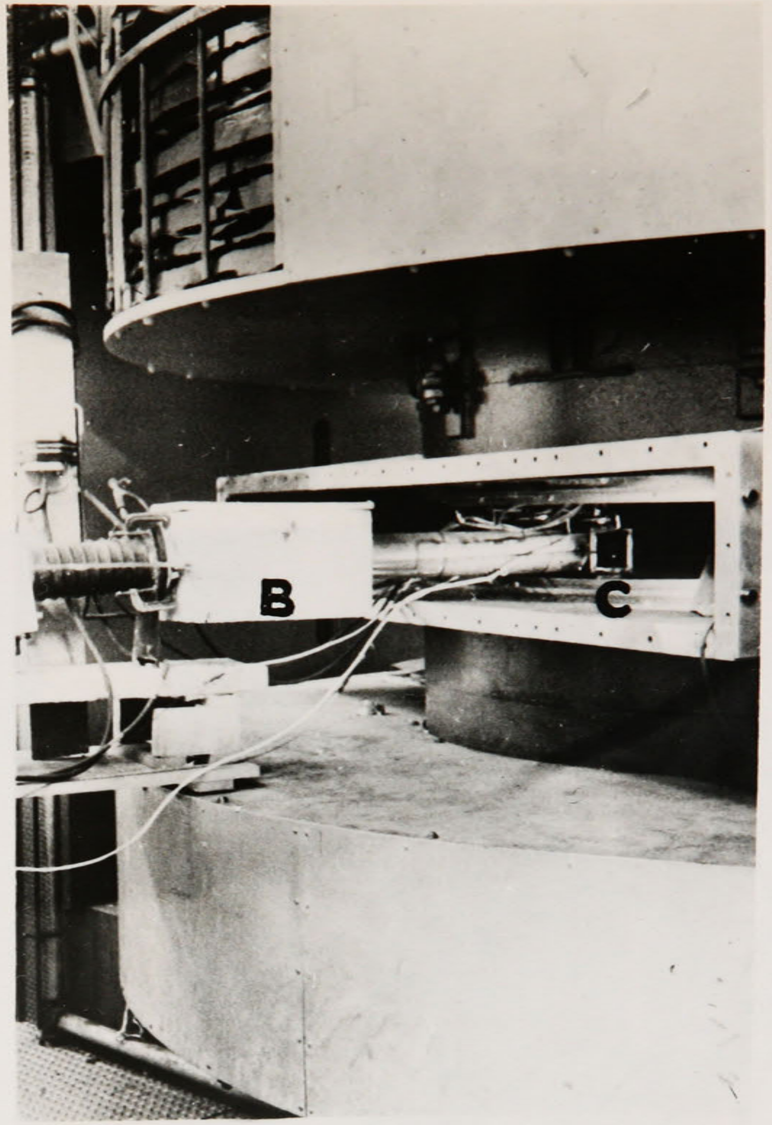
V_a= accelerator potential

V_c= collector disc potential (or where no collector disc was used potential of the vacuum chamber which served as collector).

i_T= total current to both cathodes. This is positive for electrons leaving cathodes or positive ions reaching cathodes.

i_o= collector current, also referred to in some figures as output current. This is positive for positive ions reaching collector or for electrons leaving collector.

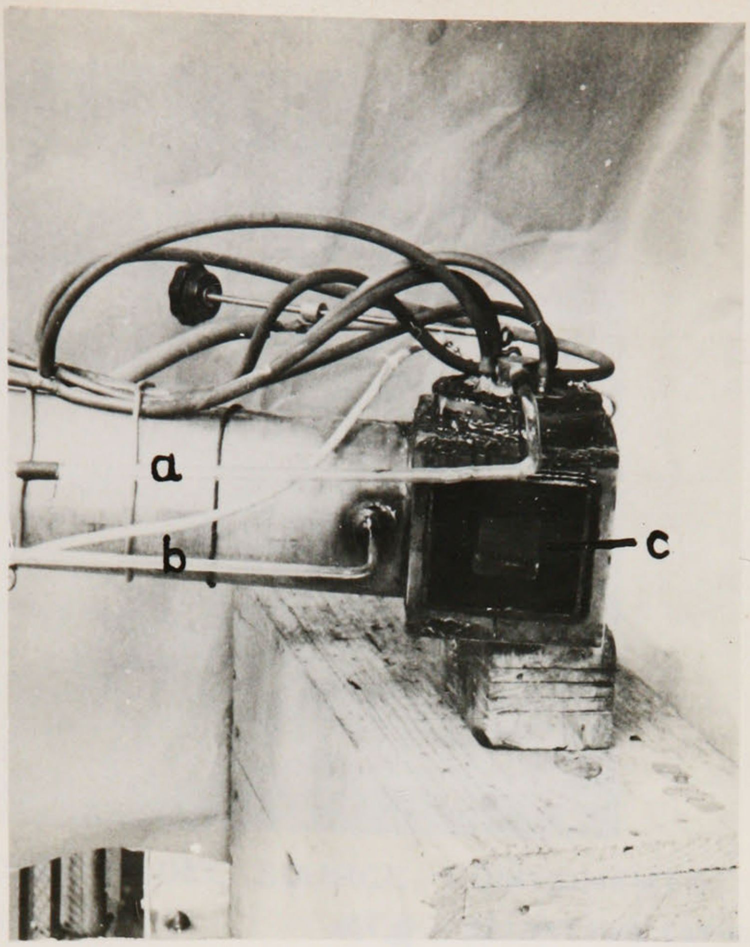


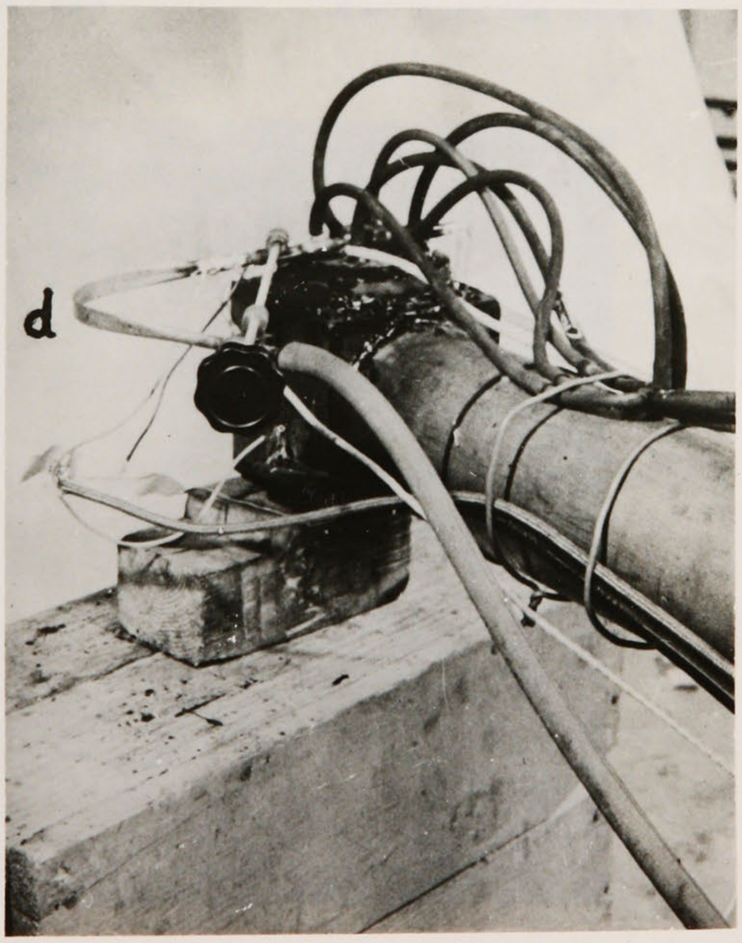


THE PUMPING SYSTEM IN POSITION IN THE CYCLOTRON MAGNET

A - DIFFUSION PUMP B - DRY ICE BOX C - ION SOURCE CHAMBER AND ION SOURCE

PLATE I

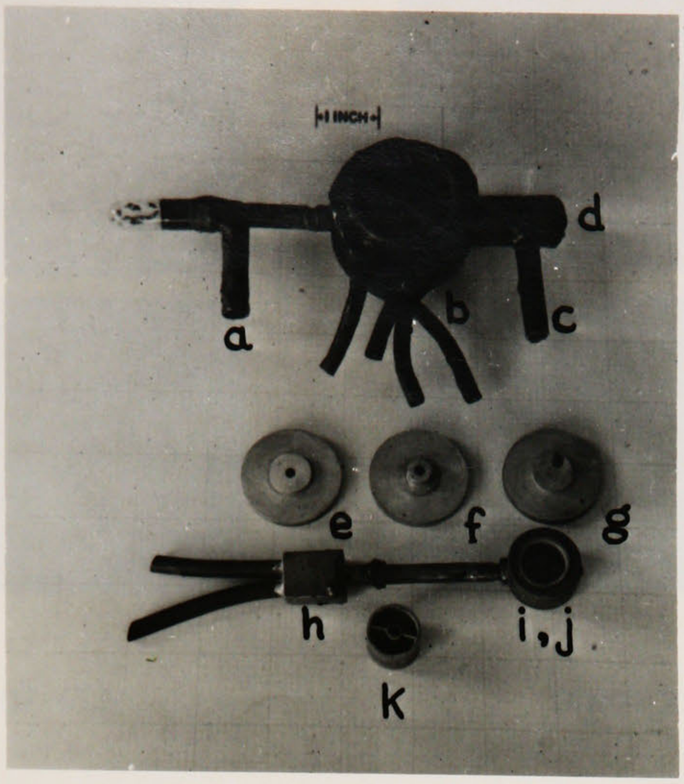




ION SOURCE VACUUM CHAMBER WITH SPACER MODEL IN POSITION

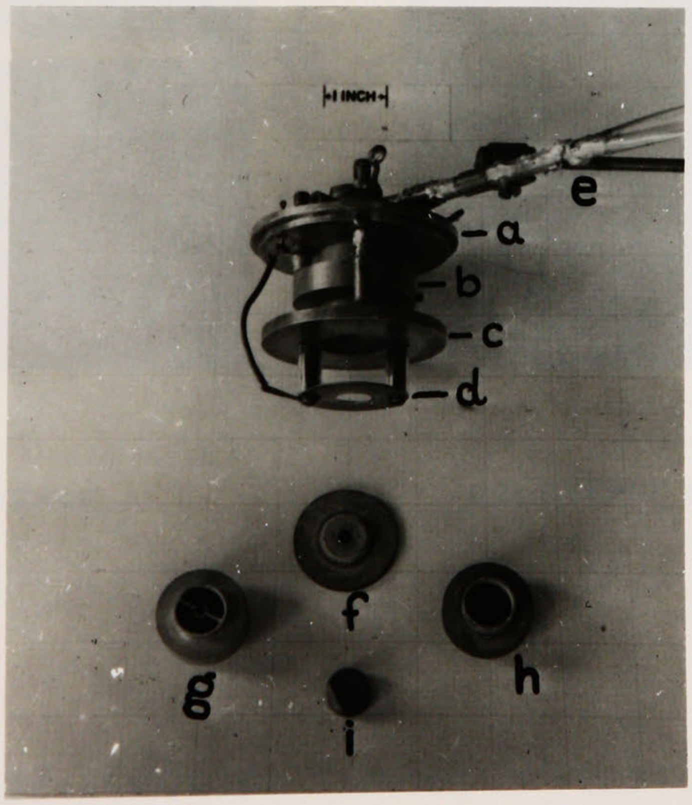
a. ION SOURCE PRESSURE MEASURING LEAD
b. CHAMBER PRESSURE MEASURING LEAD
c. WINDOW FOR OBSERVING BEAM
d. FOWLER VARIABLE GAS LEAK

PLATE II



ENCLOSED MODEL SOURCE-COMPONENTS

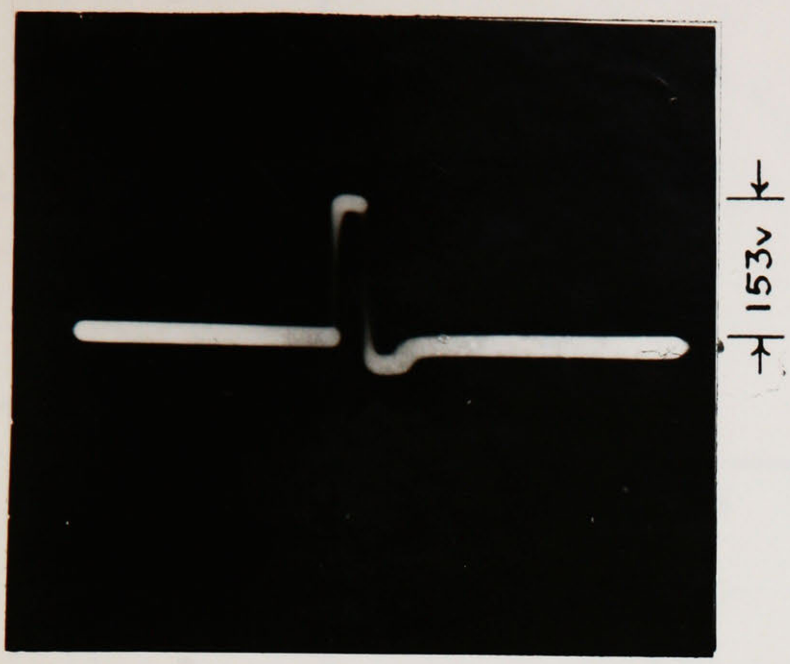
a – ATTACHMENT FOR McLEOD GAUGE
b – BODY OF SOURCE. CATHODE VISIBLE AT BOTTOM
c – ATTACHMENT FOR FOWLER LEAK
d – SHEATH FOR COAXIAL ANODE LEAD
e,f,g – EXTRACTING CATHODES
h – WATER COOLED ANODE LEAD
i,j – ANODE JACKET, CYLINDER ANODE
k – EJECTOR ANODE



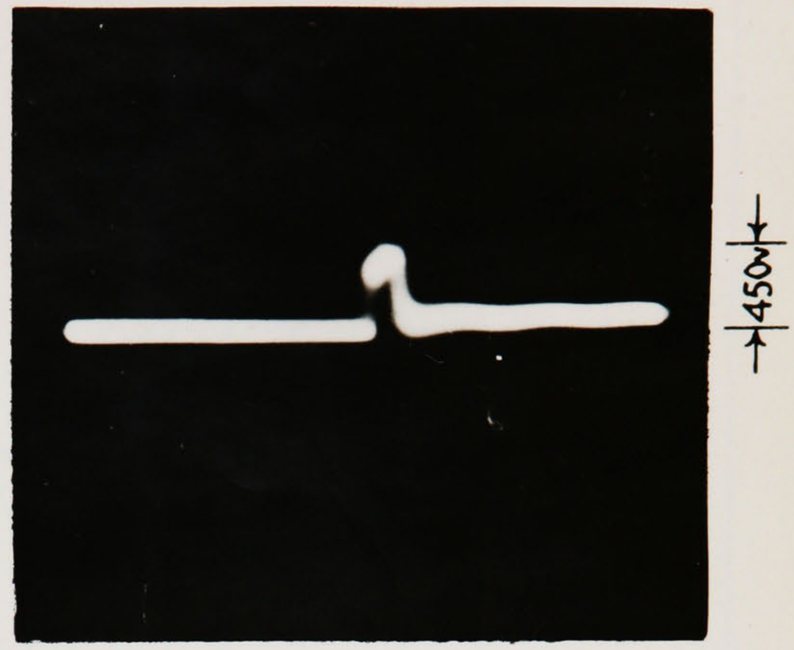
SPACER MODEL SOURCE AND ELECTRODES

a – TOP CATHODE HOLDER
b – ANODE JACKET
c – LOWER CATHODE JACKET
d – ACCELERATOR
e – FOWLER LEAK
f – LOWER CATHODE
g – EJECTOR ANODE
h – CYLINDER ANODE
i – TOP CATHODE (INVERTED, SHOWING BEVELLING FOR GAS INLET AND OUTLET TO McLEOD GAUGE.)

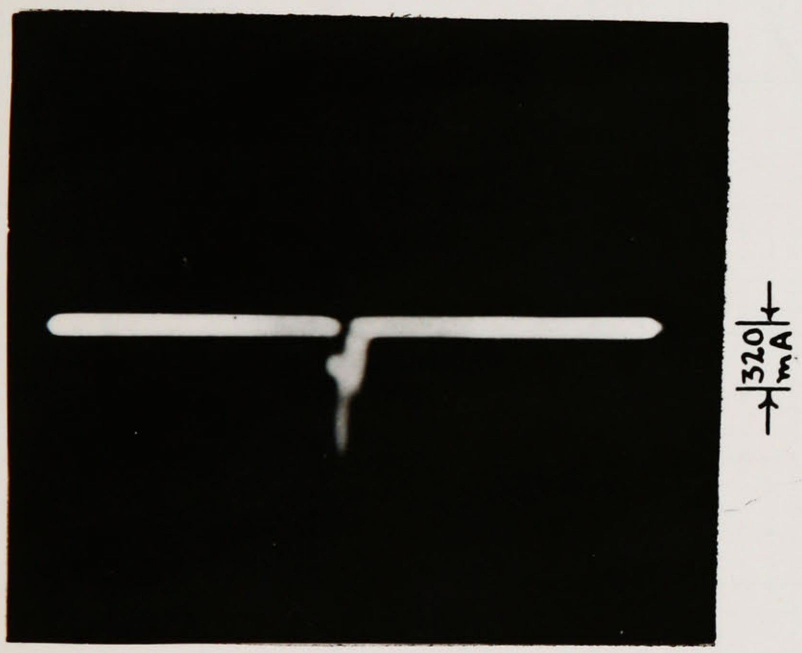
PLATE III



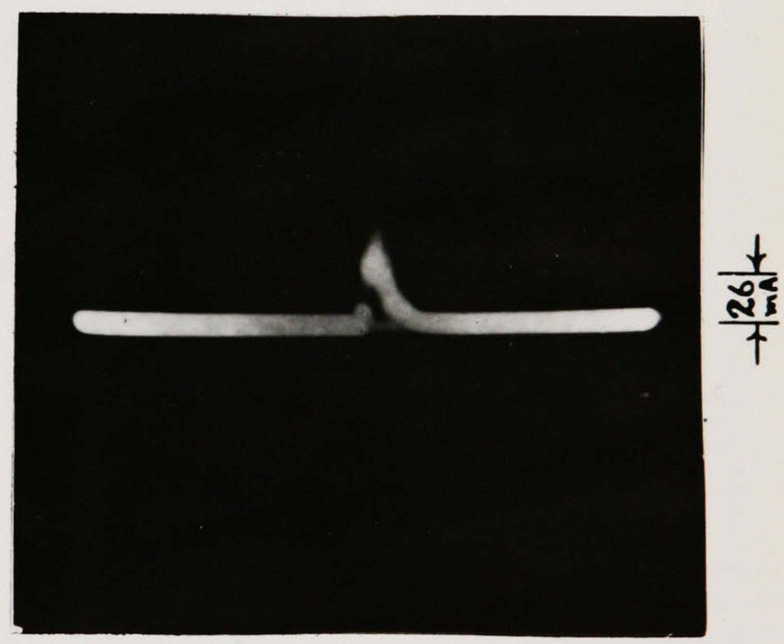
PULSE APPLIED TO GRID OF 6L6



SOURCE VOLTAGE TRACE



DISCHARGE CURRENT TRACE



ION OUTPUT CURRENT TRACE

PHOTOGRAPHS OF OSCILLOGRAPH TRACES IN PULSED OPERATION

ASYMMETRIC OPERATION, CYLINDER ANODE, CALCIUM ELECTRODES, 3/16 INCH HOLE.

H=16,000 OERSTEDS, P= 8.5 MICRONS, $V_G = 0$. BIASING RESISTANCE = 276 KΩ

REPETITION FREQUENCY = 796/SEC. PULSE LENGTH = 30 μSEC.

PLATE IV

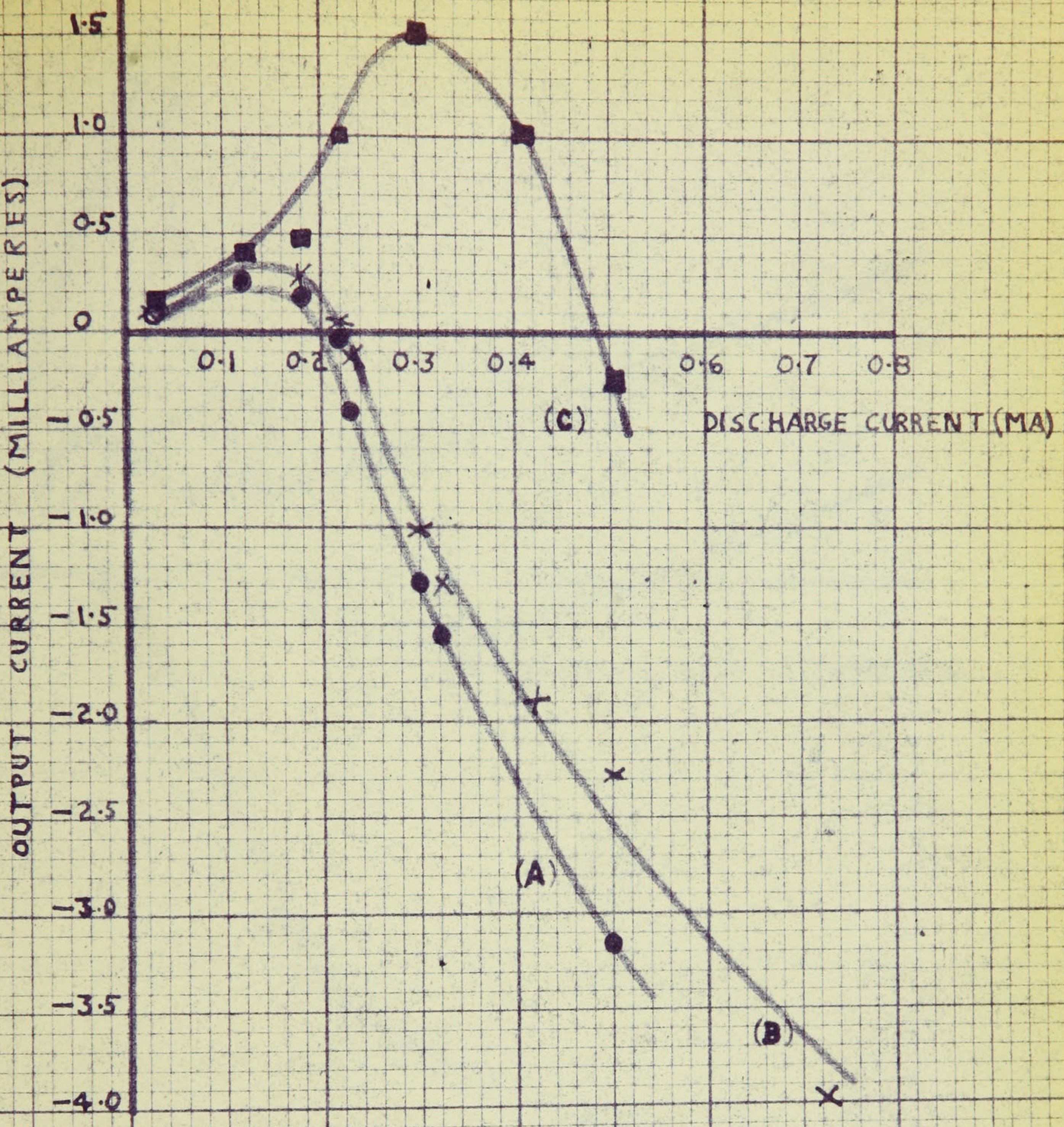


FIG. I

OUTPUT CURRENT vs DISCHARGE CURRENT

for various suppressor grid voltages - symmetric, ejector anode, 1/8" hole, $H = 16{,}000$ oersted, $p = 6$ microns, $V_c = 0$

A: V_g = value giving minimum i_o for given value of i_T
B: $V_g = 0$
C: V_g = value ($\geqslant$ -260 V) giving maximum i_o for given value of i_T. Unless otherwise indicated, V_g = -260 V, the upper limit of the power pack

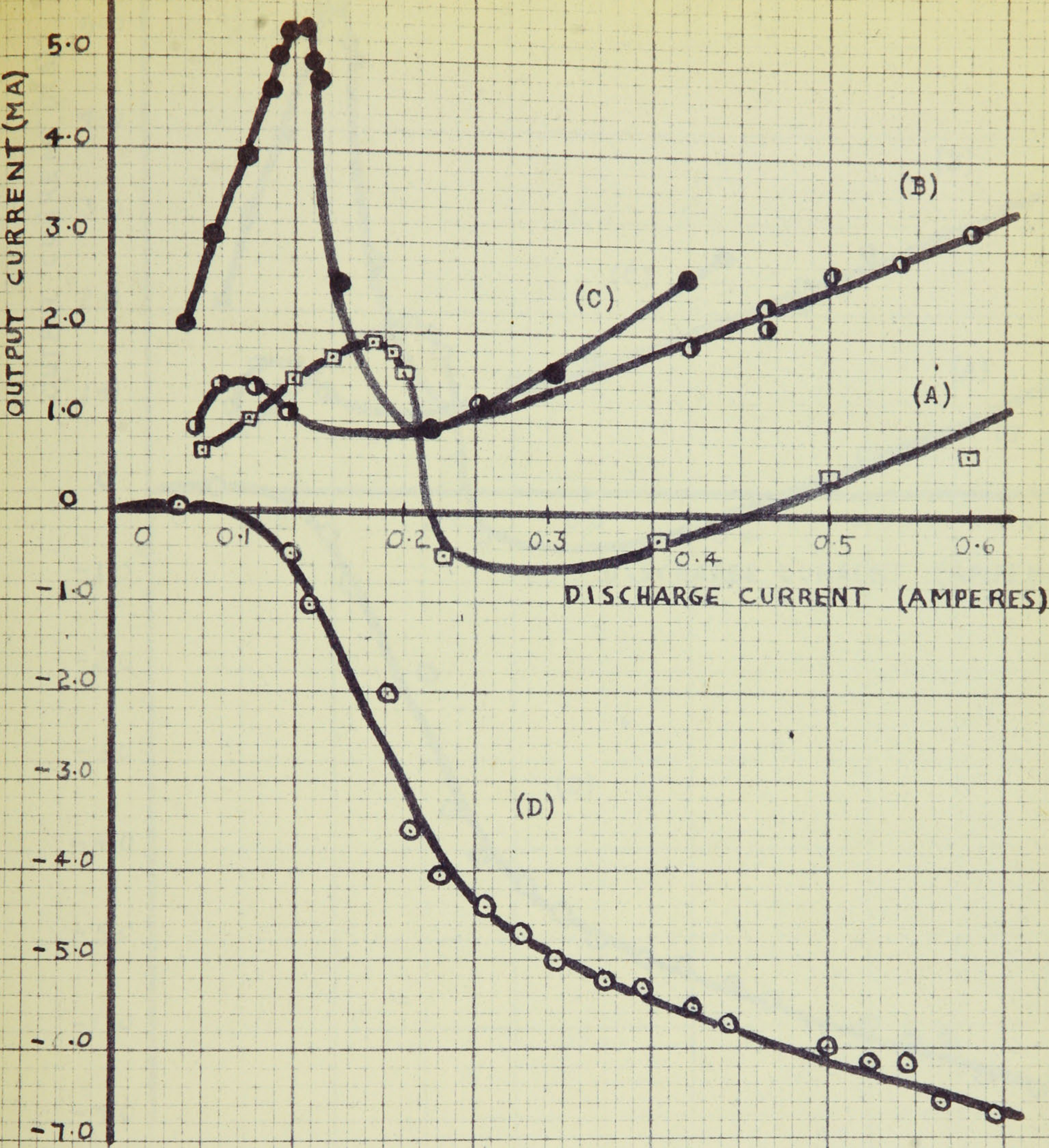


FIG. 2

VARIATION OF i_o vs. i_T TO HIGH DISCHARGE CURRENTS

cylinder anode, symmetric

	A	B	C	D
H (oersted)	400	1870	1870	16,000
p (microns)	3.5	4.4	3.0	4.2
V_c (Volts)	0	-100	-100	0
hole size	1/8"	5/32"	5/32"	1/8"

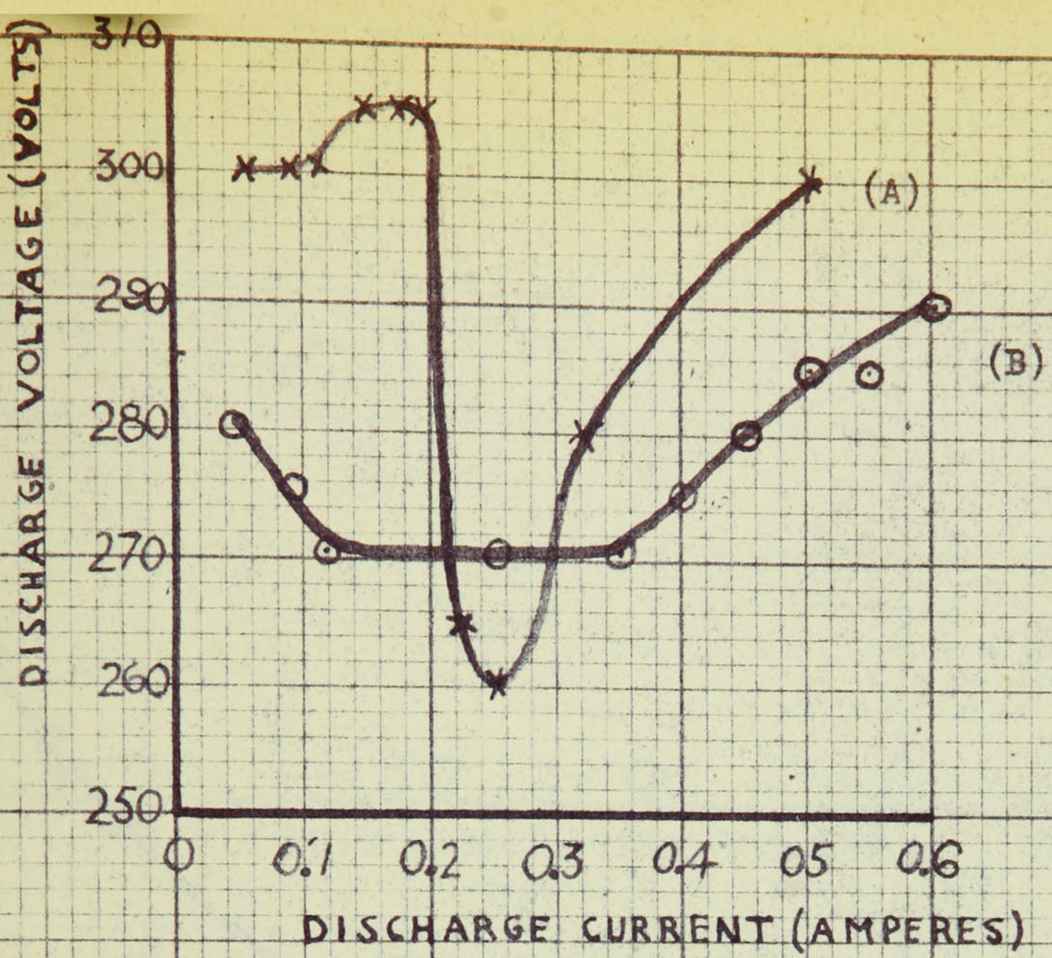


FIG.3

DISCHARGE VOLTAGE vs. DISCHARGE CURRENT

The letters indicate correspondence with Fig.2.

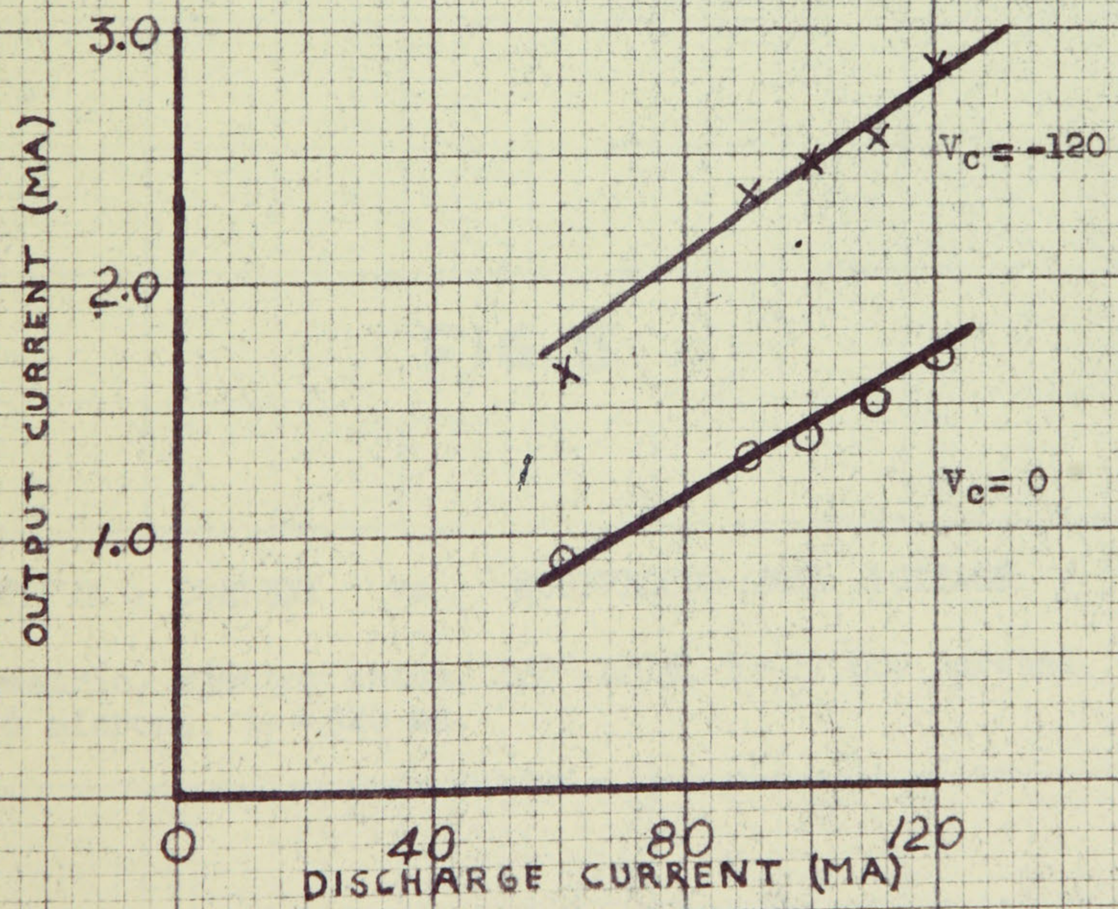


FIG.4

OUTPUT vs. DISCHARGE CURRENT

for two collector voltages -
symmetric, cylindrical anode,
5/32" hole, H = 1870, p = 1.2 microns

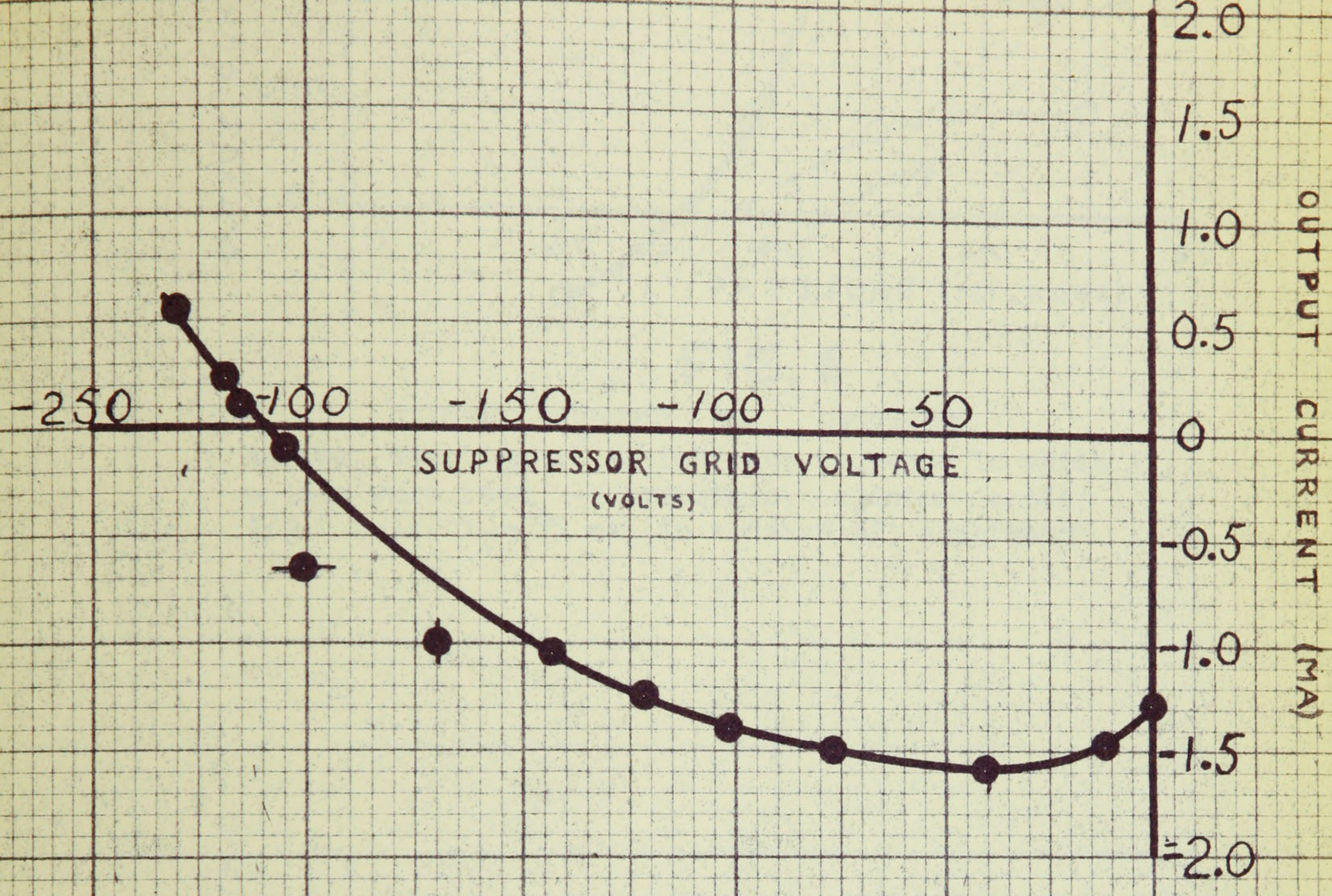


FIG.5

OUTPUT CURRENT vs. SUPPRESSOR GRID VOLTAGE -

symmetric, ejector anode, 1/8" hole, H = 17,000 oersted, p = 6 microns, i_T = 320 mA

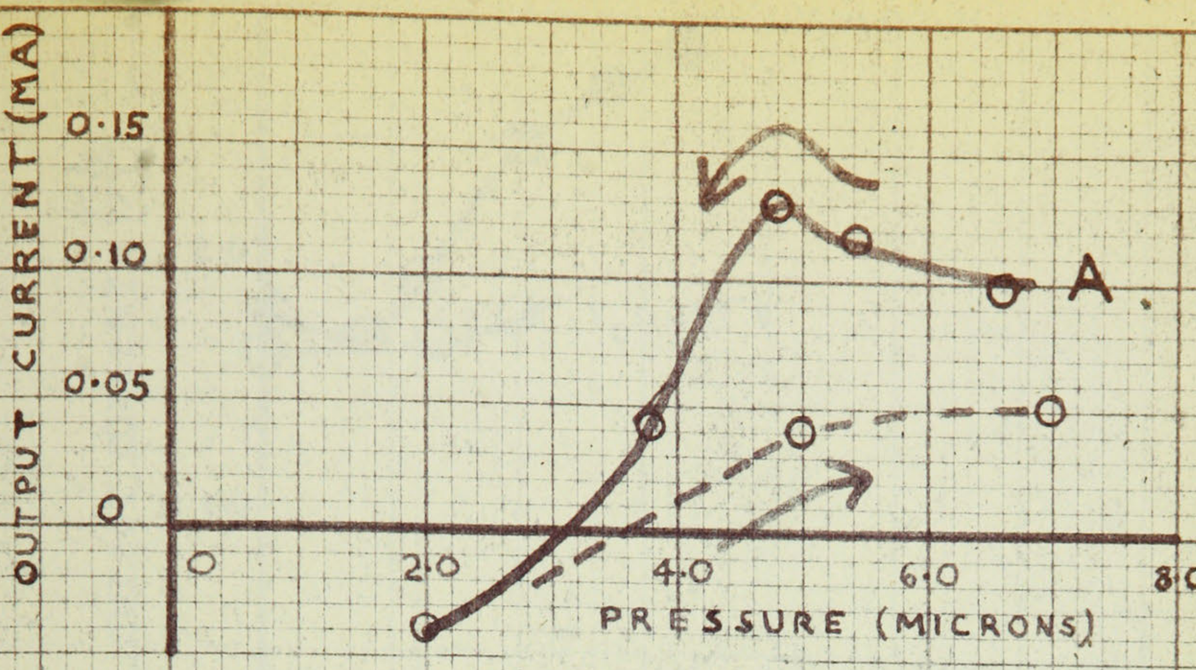


FIG. 6

OUTPUT CURRENT vs. PRESSURE

Arrows, starting at A, indicate sequence in which points were read - symmetric, ejector anode, 1/8 " hole, i_T = 85 mA, in absence of suppressor.

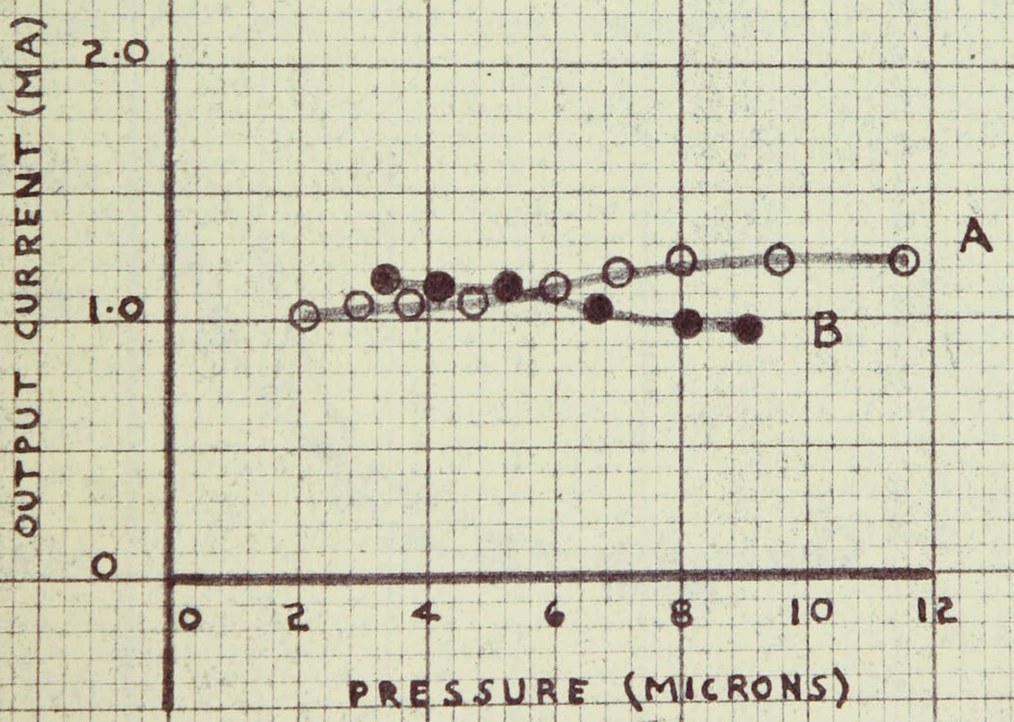


FIG. 7

OUTPUT CURRENT vs. PRESSURE

symmetric, cylinder anode, 5/32" hole, H = 1900 oersteds, i_T = 60 mA

A: $V_c = 0$ B: $V_c = -120V$

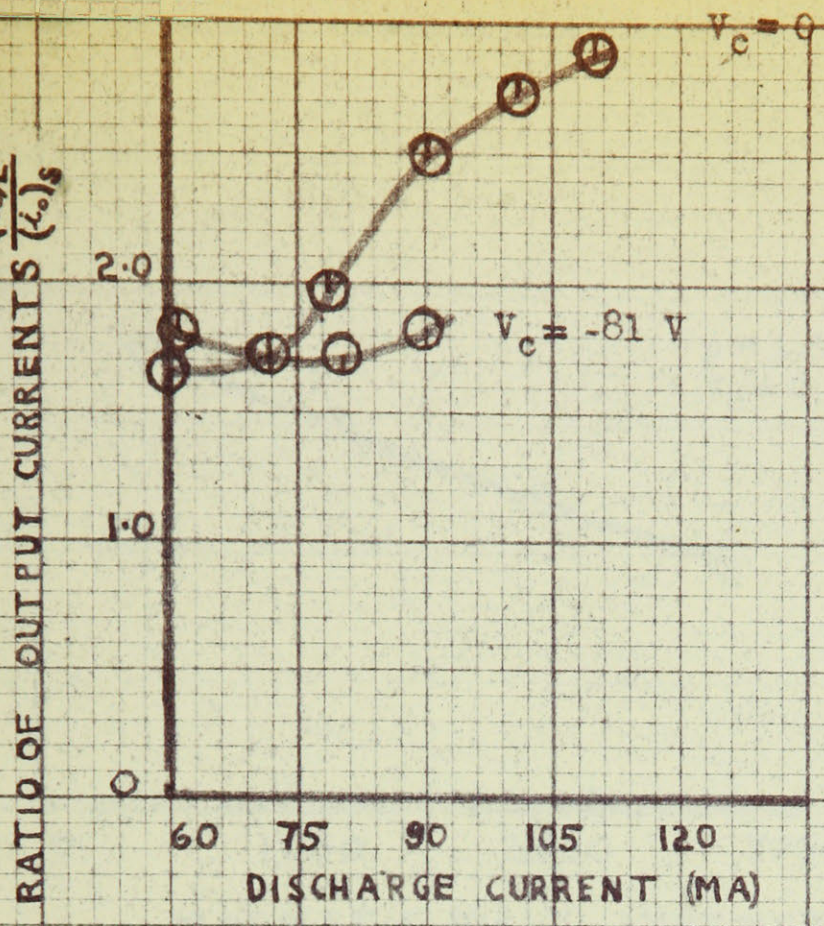


FIG.8

E F F E C T   O F   H O L E   S I Z E   (AIR)

cylinder anode, symmetric, H = 1700 oersted, $(i_0)_l$, $(i_0)_s$ represent output currents for the 7/32" and 5/32" hole respectively

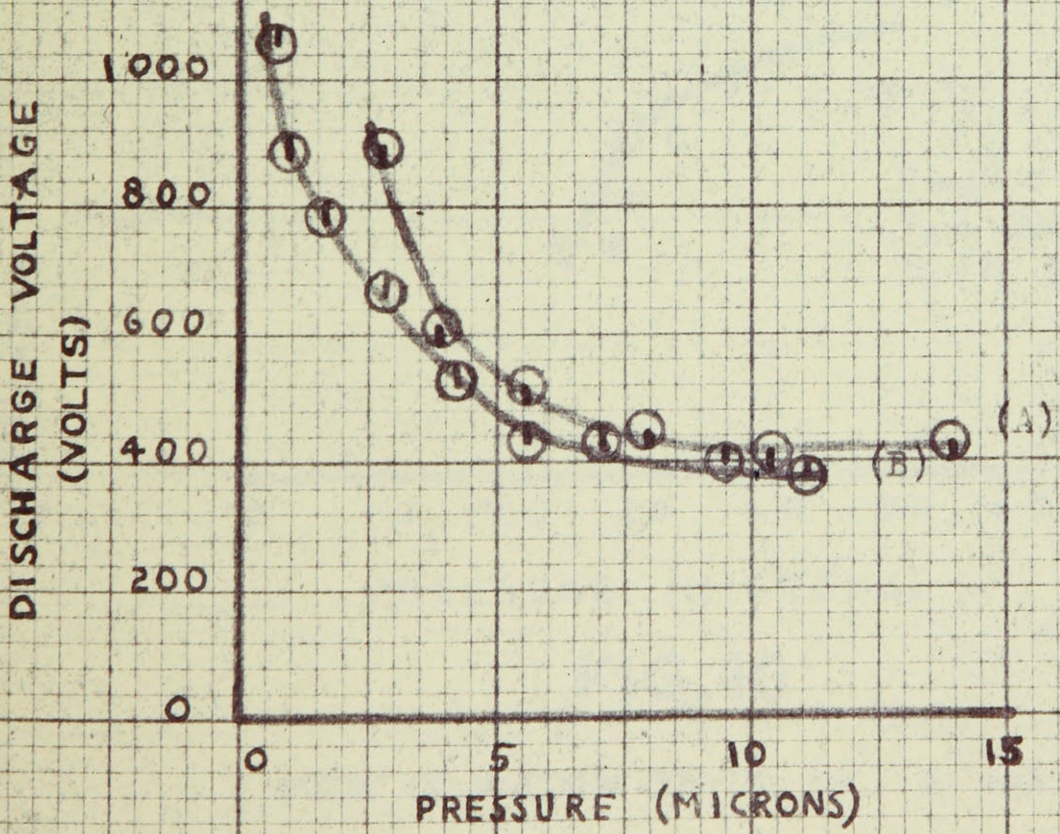


FIG.9

DISCHARGE VOLTAGE vs. PRESSURE of non-aged sources: symmetric, cylinder anode, A: Calcium source, 3/16" hole; B: Magnesium source, 1/8" hole, H = 16,000

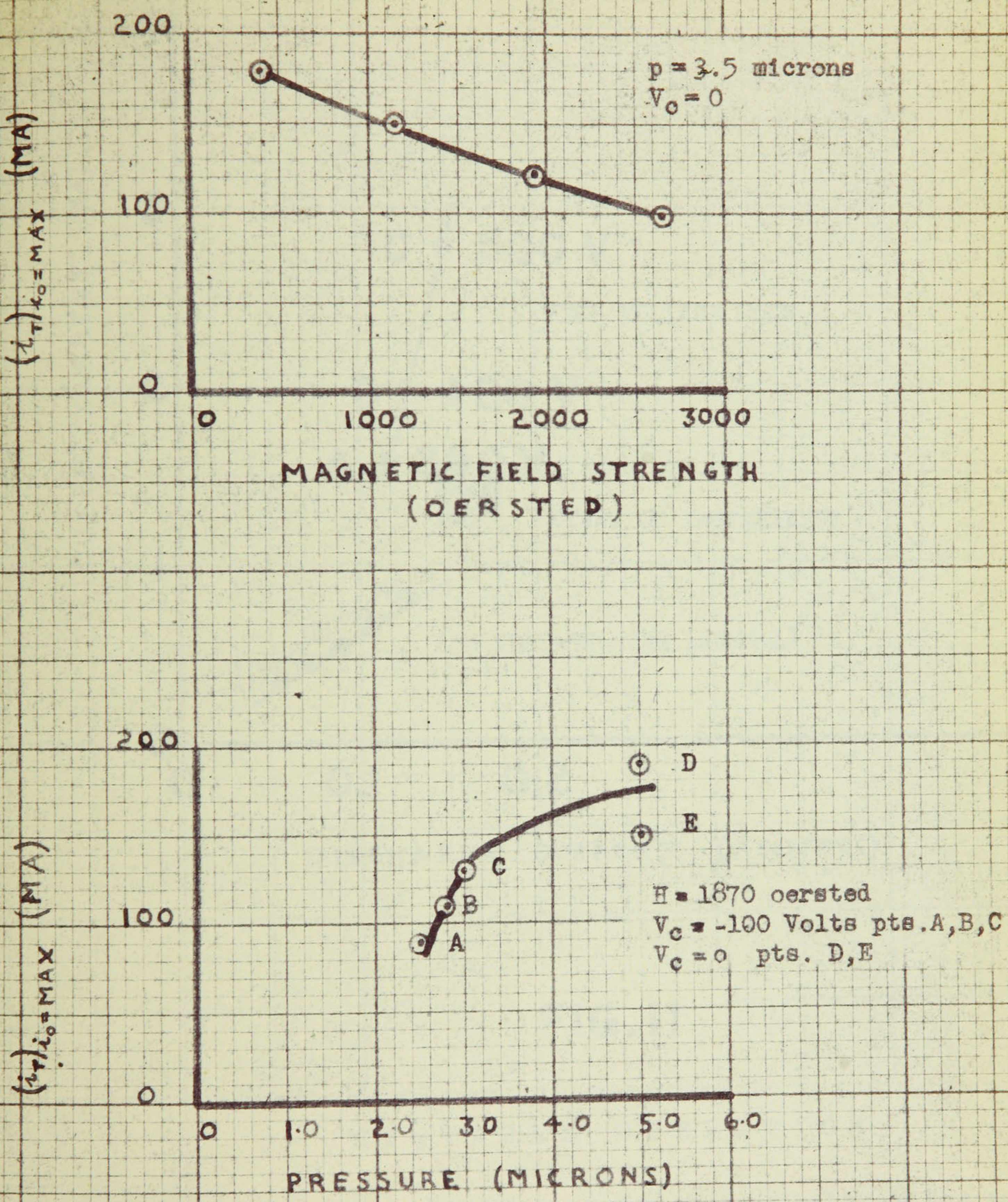


FIG. 10

POINT OF MAXIMUM OUTPUT vs. H and P

cylinder anode, symmetric

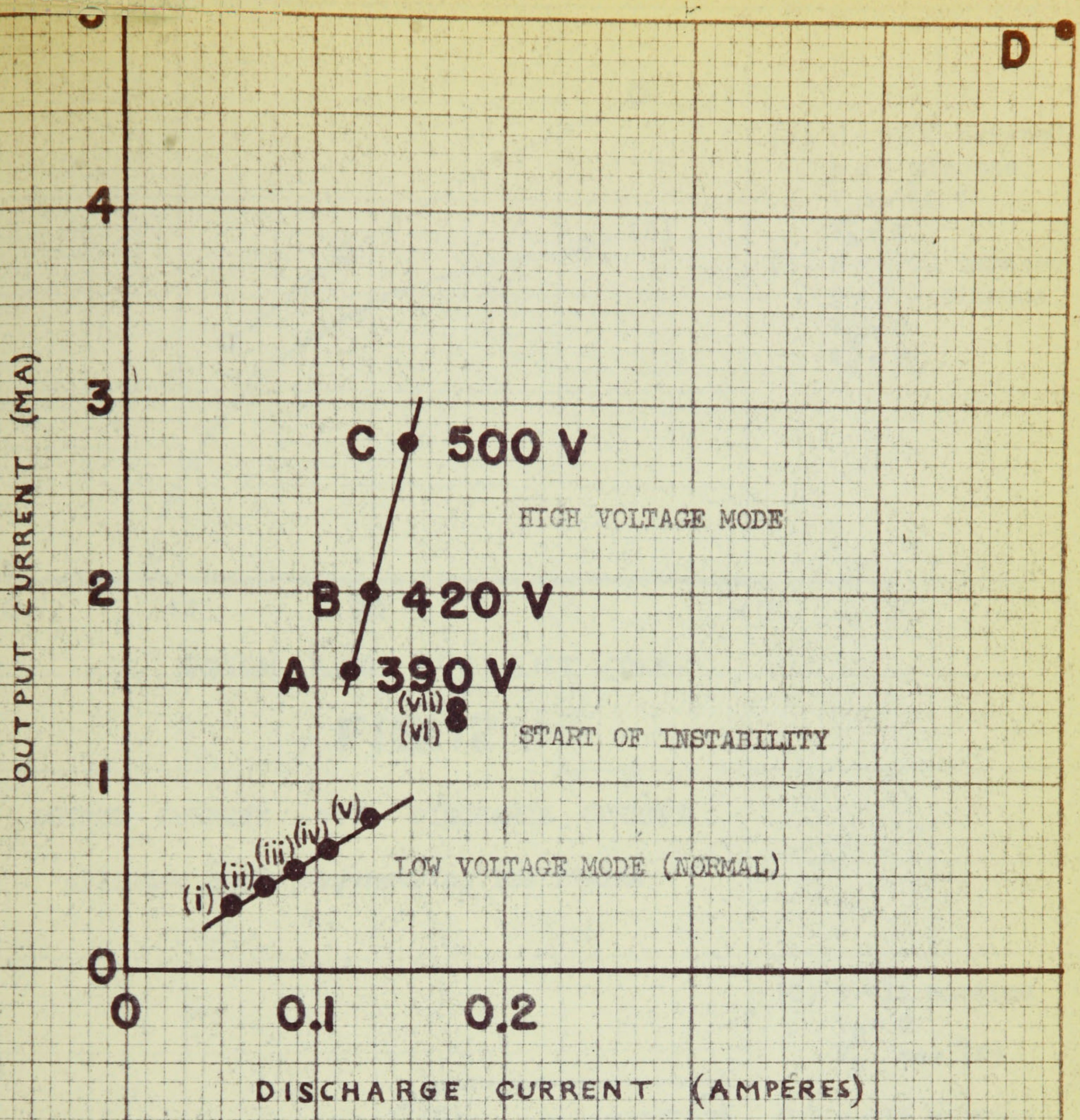


FIG. 11

UNSTABLE OPERATION

Readings (i) - (vii) are taken successively, as the series resistance R is decreased. Points A, B, and C are obtained on decreasing R further. From points A, B, and C frequent "kicks" to the point D (normal) occur.

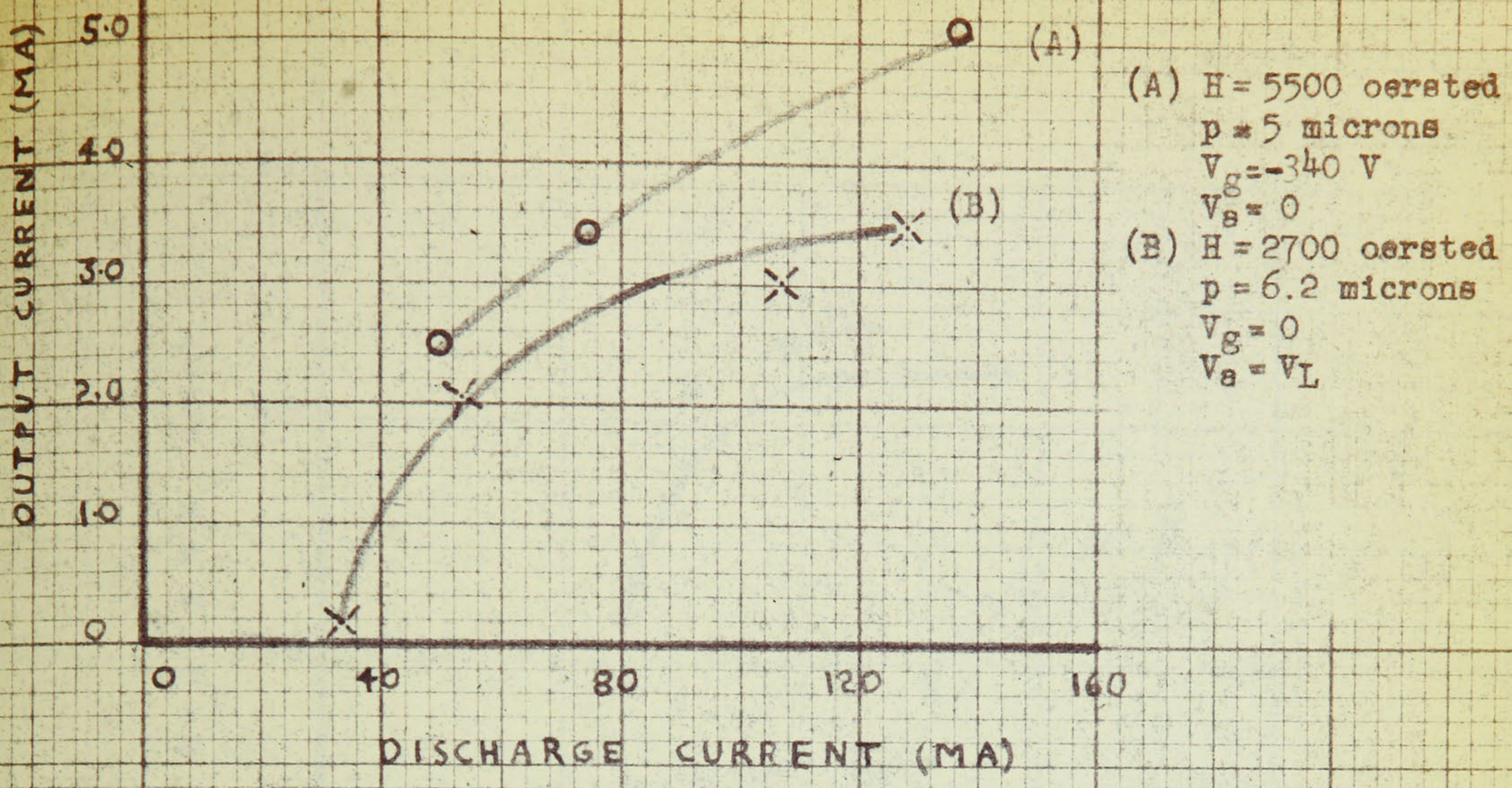


FIG. 12

OUTPUT CURRENT vs. DISCHARGE CURRENT

cylinder anode, asymmetric, low fields

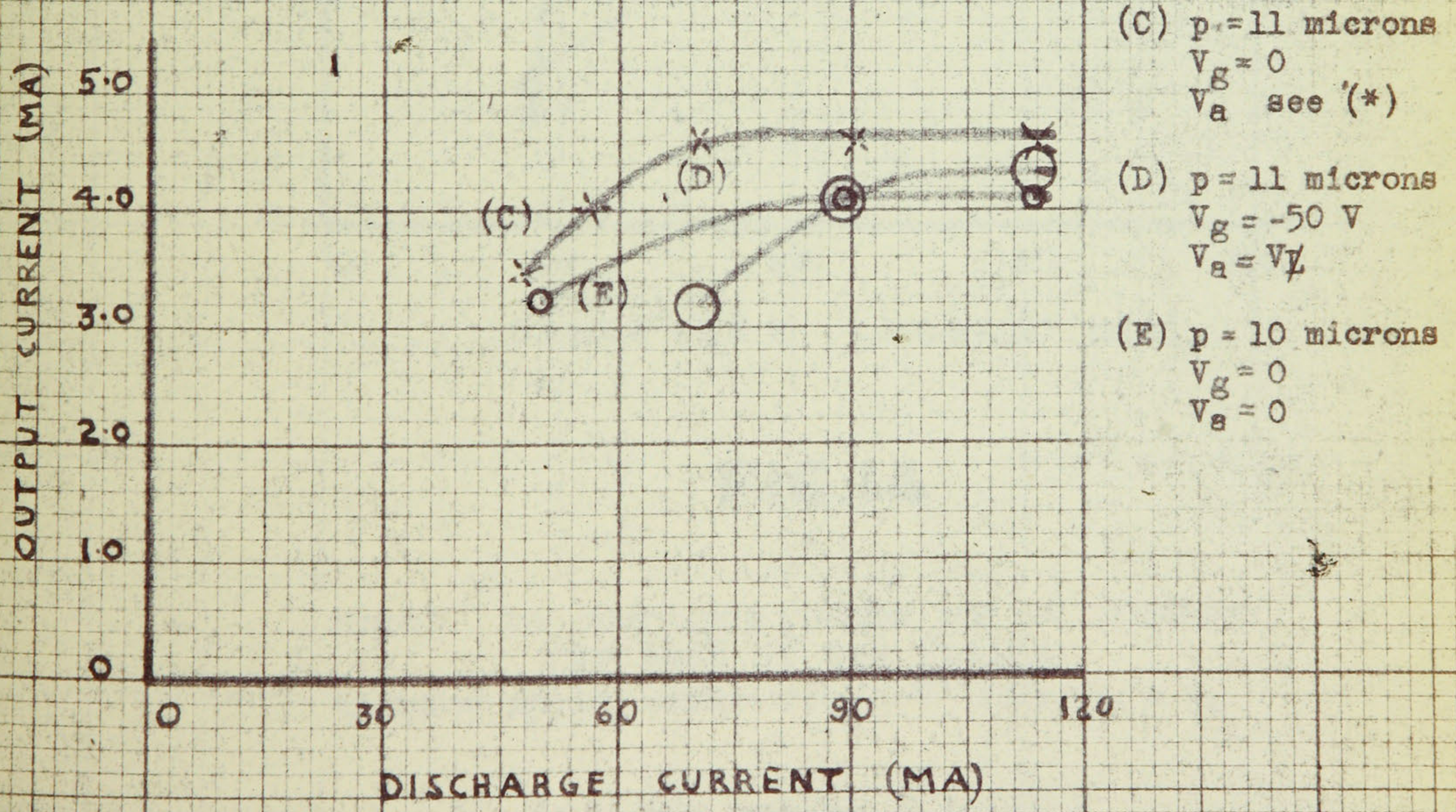


FIG. 13

OUTPUT CURRENT vs. DISCHARGE CURRENT

Cylinder anode, asymmetric, H = 17,000 oersted

(*) positive self-bias through 0.3 megohms

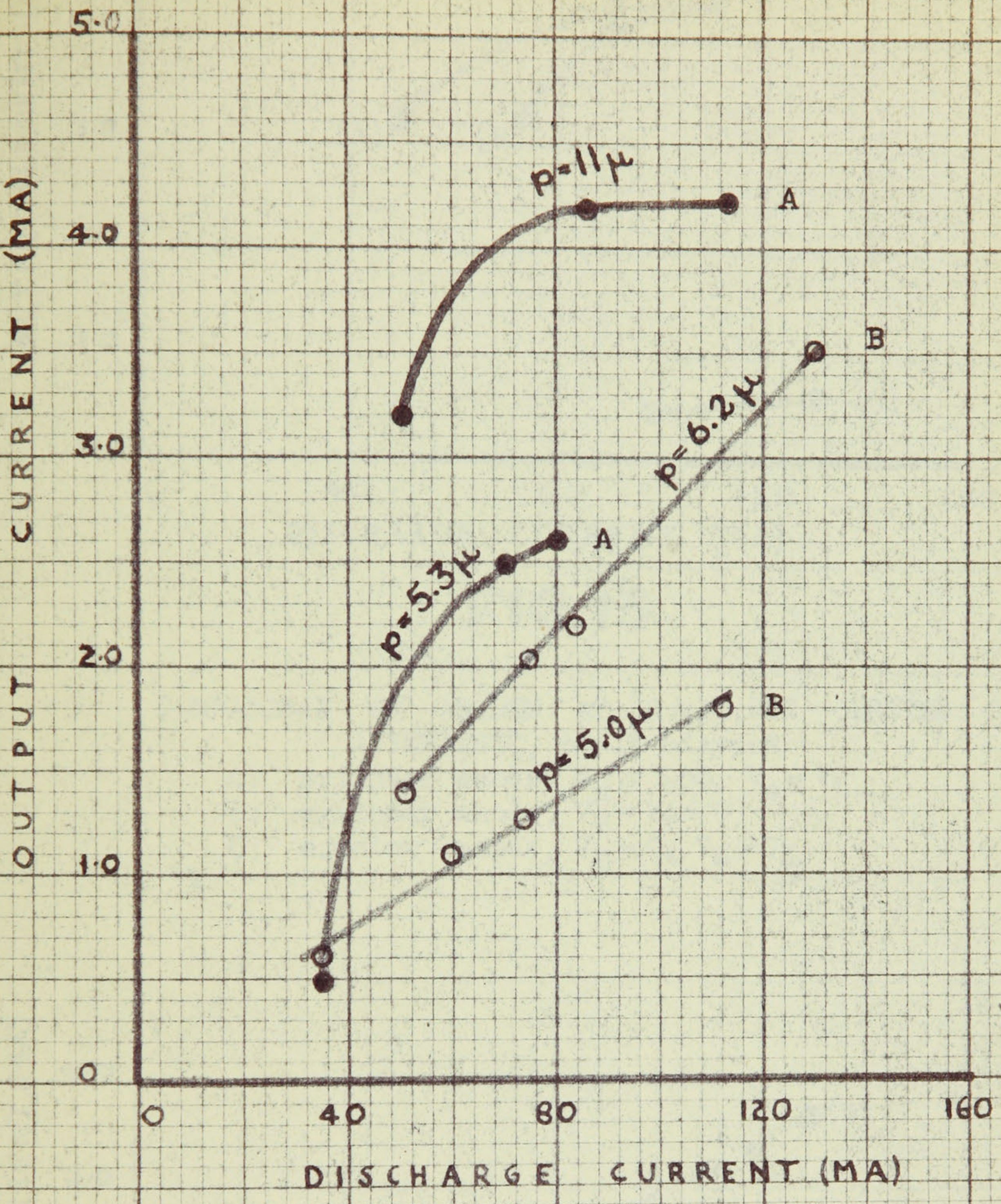


FIG.14

OUTPUT VS. DISCHARGE CURRENT FOR TWO PRESSURES
for each of two fields
cylinder anode, asymmetric, 1/8" hole, $V_a = V_L$

A: H = 16,000 oersted, V_g = - 50 V
B: H = 2,700 oersted, V_g = -330 V

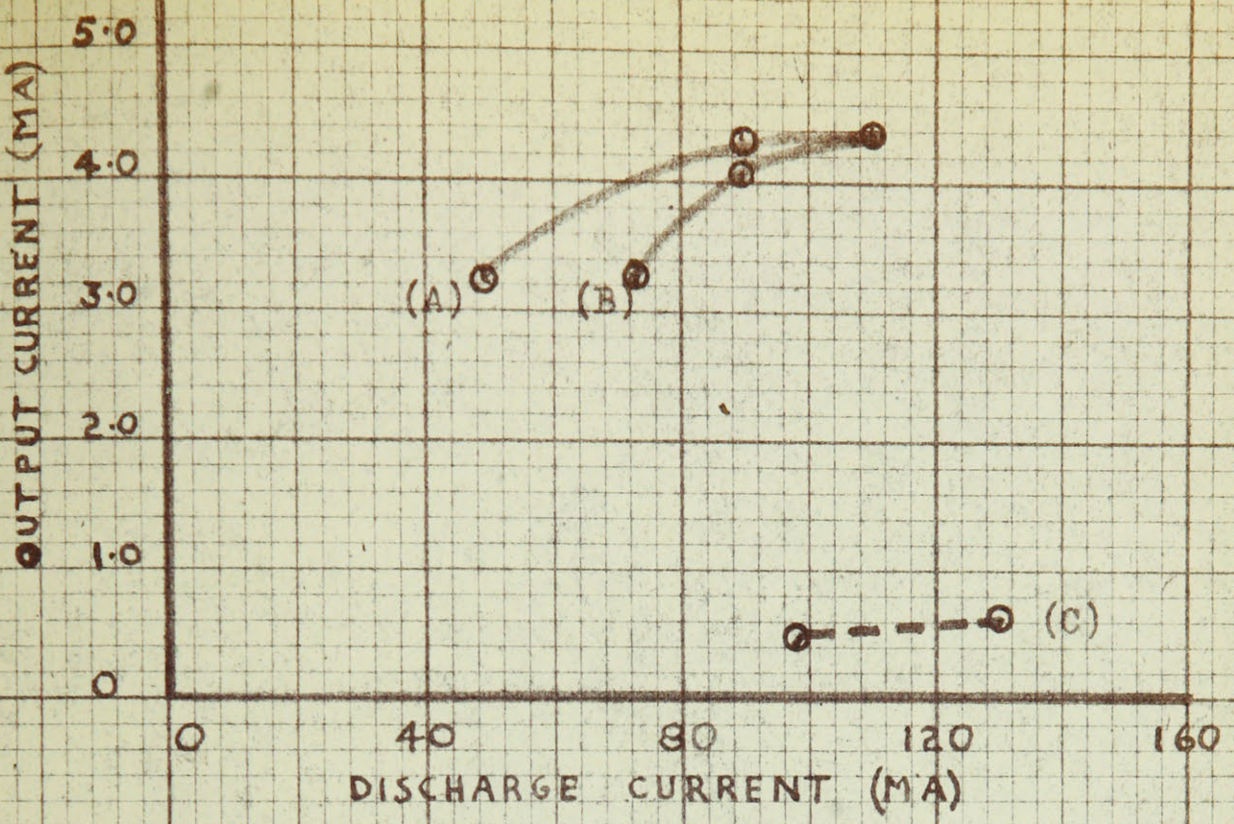


FIG. 15

COMPARISON OF ANODES AT H = 16,000 OERSTED
ASYMMETRIC, p = 11 microns
A: cylinder anode, $V_g = -50$, $V_a = V_L$
B: cylinder anode, $V_g = V_a = 0$
C: ejector anode, $V_g = 0$, $V_a = V_L$

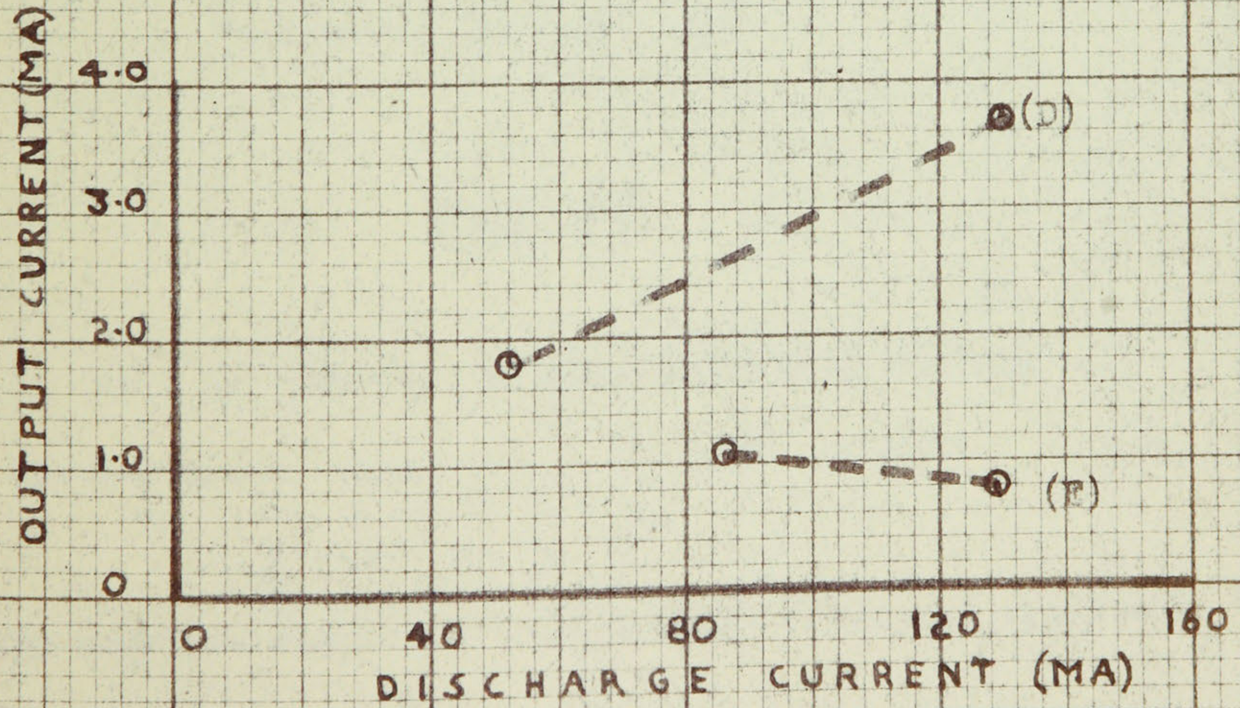


FIG. 16

COMPARISON OF SOURCES AT H = 2,700 OERSTED
asymmetric, p = 6.2 microns, $V_g = -330$ V
D: cylinder anode, $V_a = V_L$
E: ejector anode, $V_a = 0$

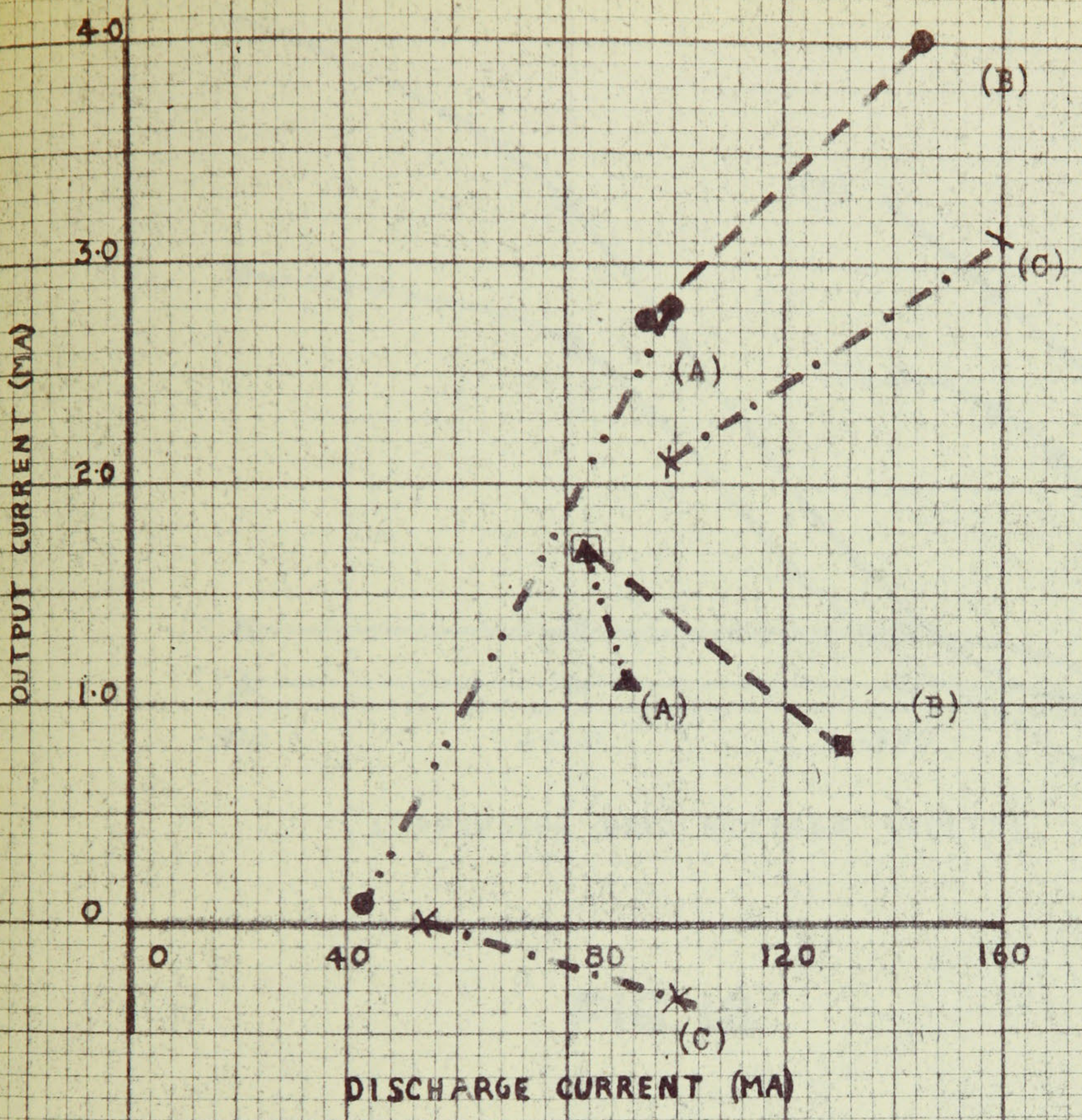


FIG. 17

i_o vs. i_T FOR VARIOUS SUPPRESSOR GRID VOLTAGES

ejector anode, asymmetric, H = 2,700 oersted

A: $p = 8.2$, $V_a = V_L$
B: $p = 6.2$, $V_a = 0$
C: $p = 9.8$, $V_a = 0$

(The negative slopes are exceptional; cf. Figs 12, 13 and 14.)

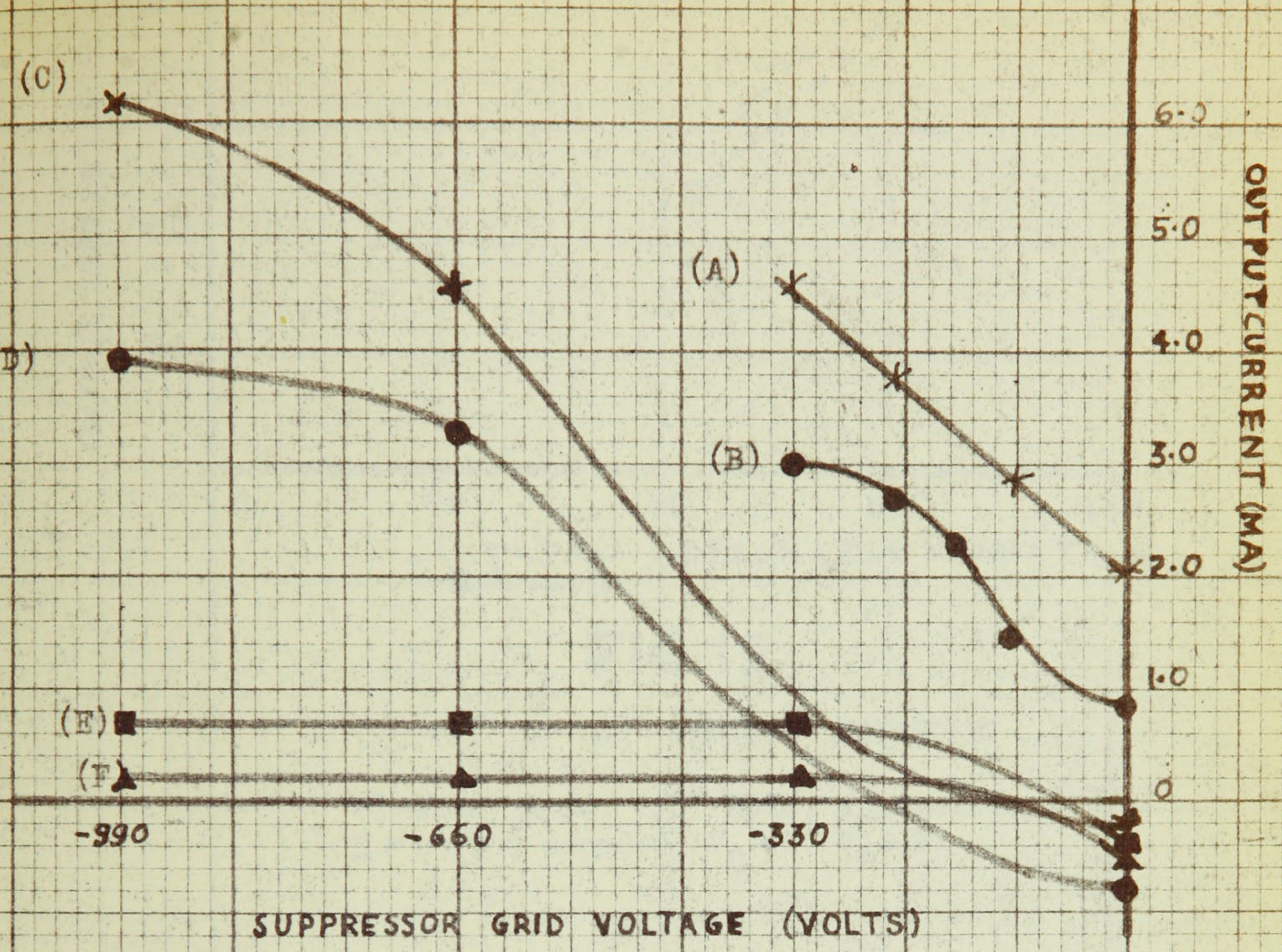


FIG. 18

OUTPUT CURRENT vs. SUPPRESSOR VOLTAGE (*)

ASYMMETRIC, $V_c = 0$

	A	B	C	D	E	F
i_T (mA)	67	49	89	137	80	60
H (oersted)	5500	5500	16000	2700	410	1140
V_a (Volts)	$\approx V_L$	$\approx V_L$	$\approx V_L$	0	0	V_L
anode type	--cylinder-		--------ejector--------			

(*) some of the points are obtained by interpolation in i_o vs. i_T curves

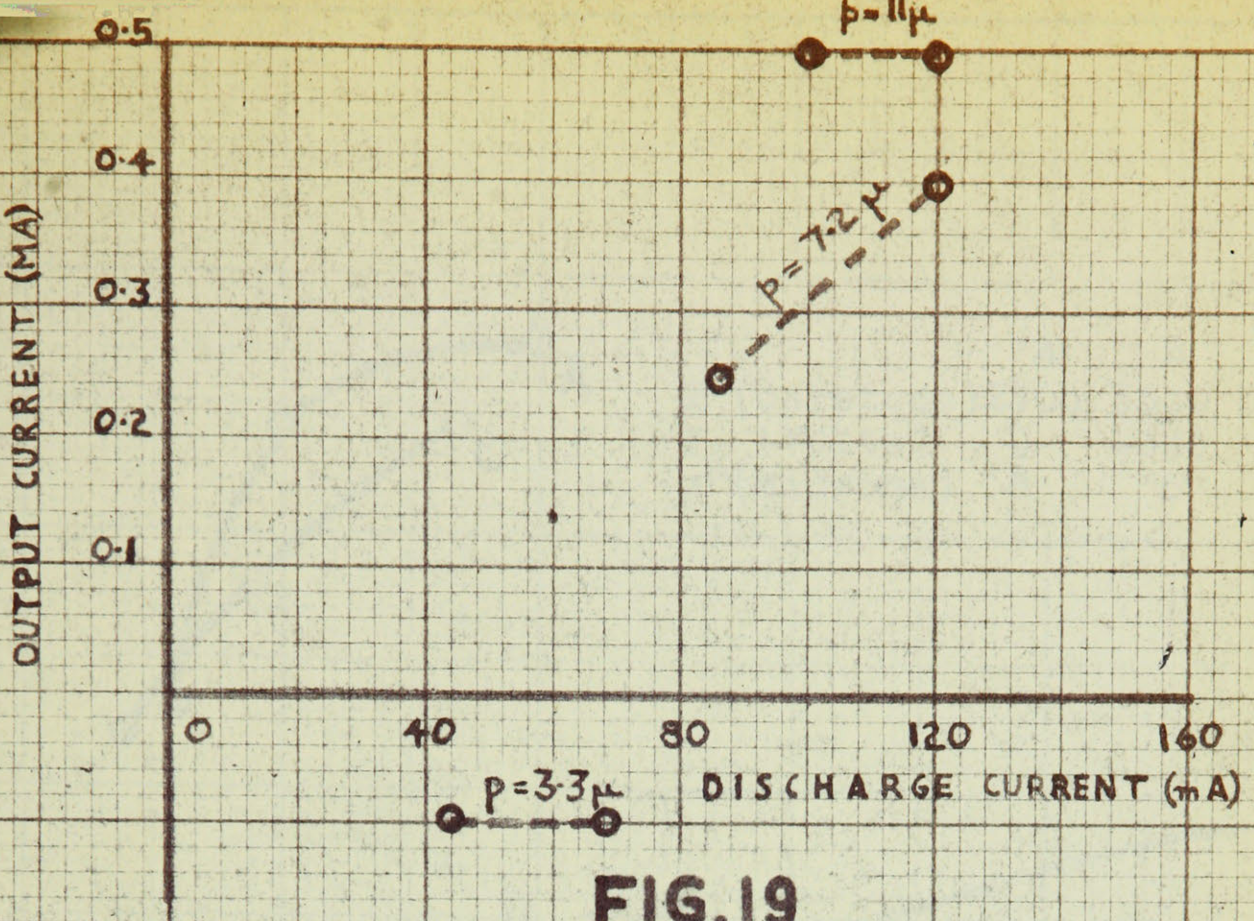


FIG.19

i_o vs. i_T AT VARIOUS PRESSURES

ejector anode, 1/8" hole, asymmetric, H =16,000 oersted, $V_g = 0$, $V_a = V_L$

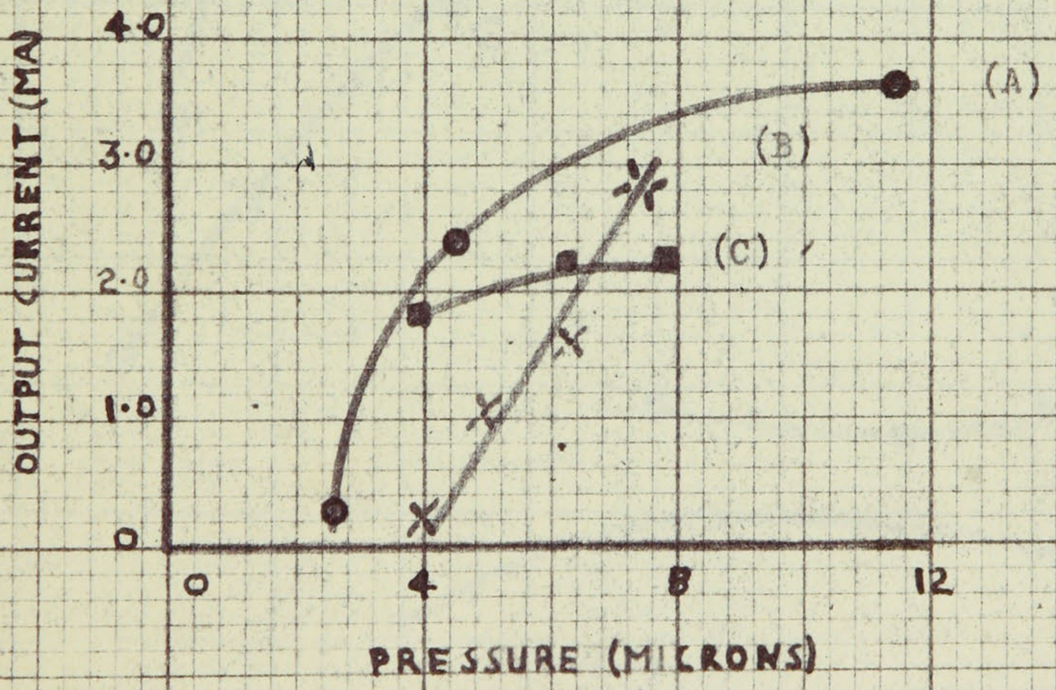
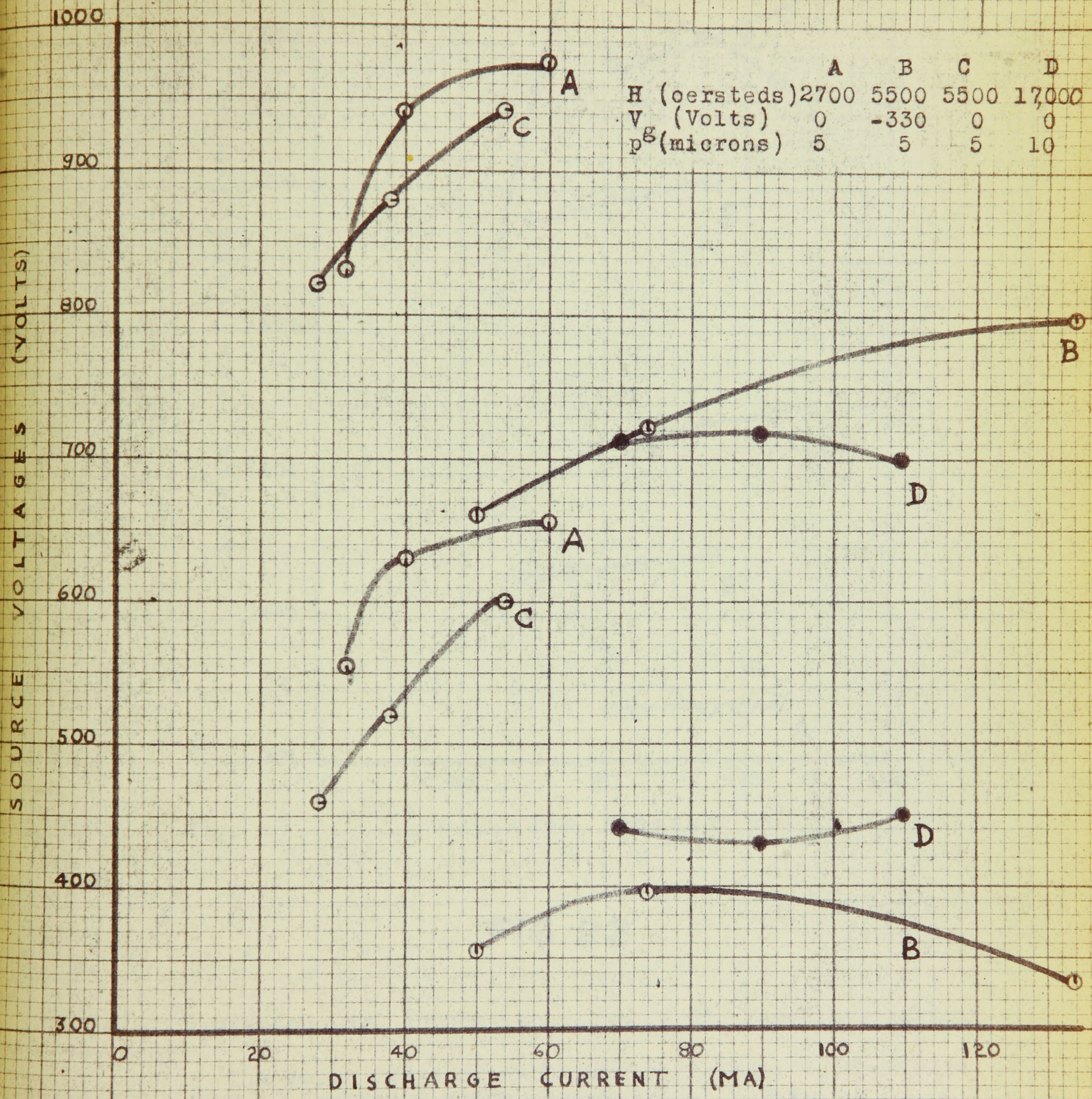


FIG. 20

OUTPUT CURRENT vs. PRESSURE
CYLINDER ANODE, ASYMMETRIC

	A	B	C
H (oersted)	16,000	2,700	2,700
i_T (mA)	70	61	112
V_g (Volts)	+50	+330	+330
V_a (")	$=V_L$	$=V_L$	0



VARIATION OF SOURCE VOLTAGES WITH DISCHARGE CURRENT

The upper curve of each pair represents V, the lower V_L - cylinder anode, 1/8" hole, asymmetric, $V_a = 0$

FIG.21

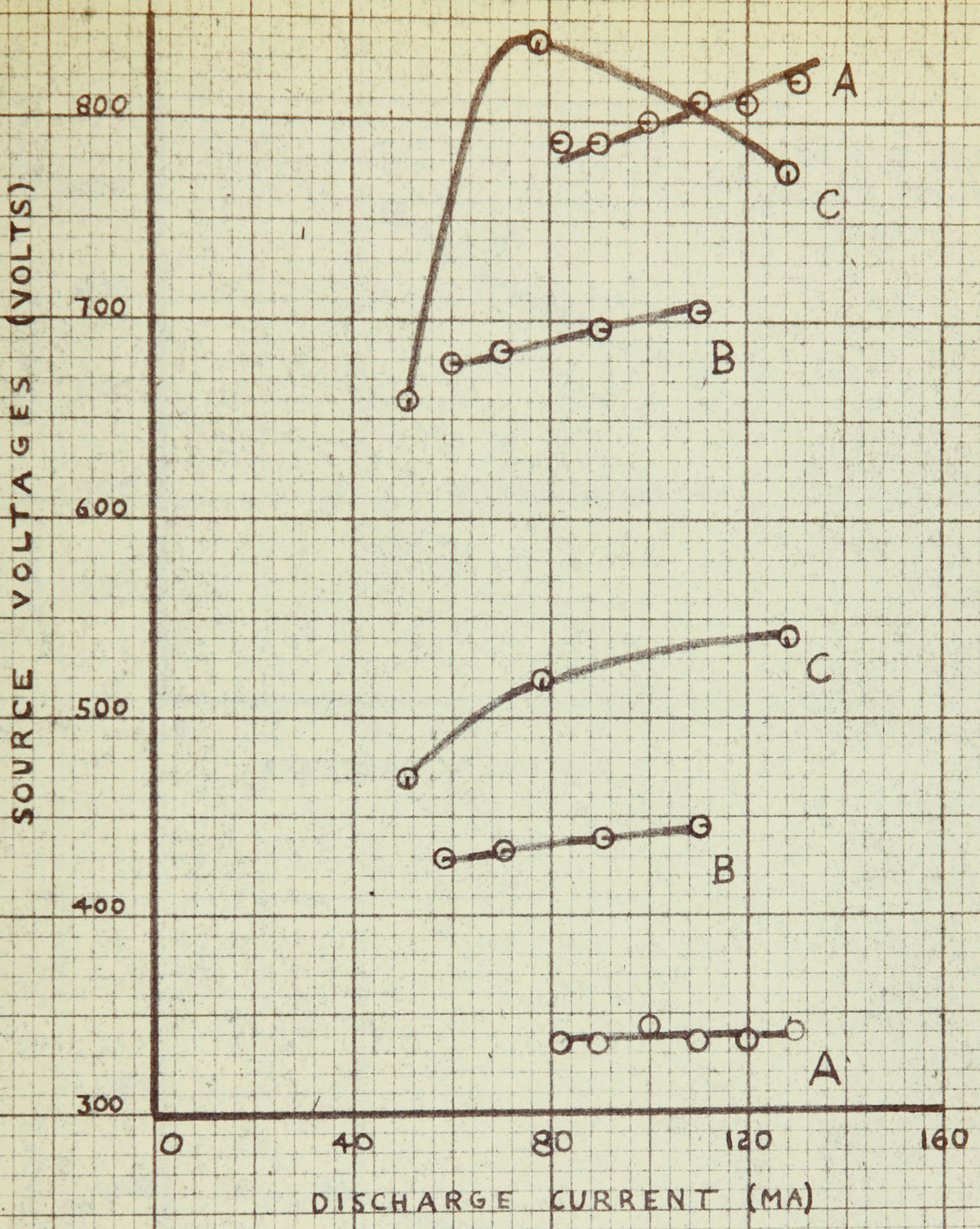


FIG. 22

VARIATION OF SOURCE VOLTAGES WITH DISCHARGE CURRENT

The upper curve of each pair represents V, the lower V_L - cylinder anode, asymmetric, $V_a = V_L$

	A	B	C
H (oersted)	17,000	17,000	2700
V_g (Volts)	-330	-50	-330

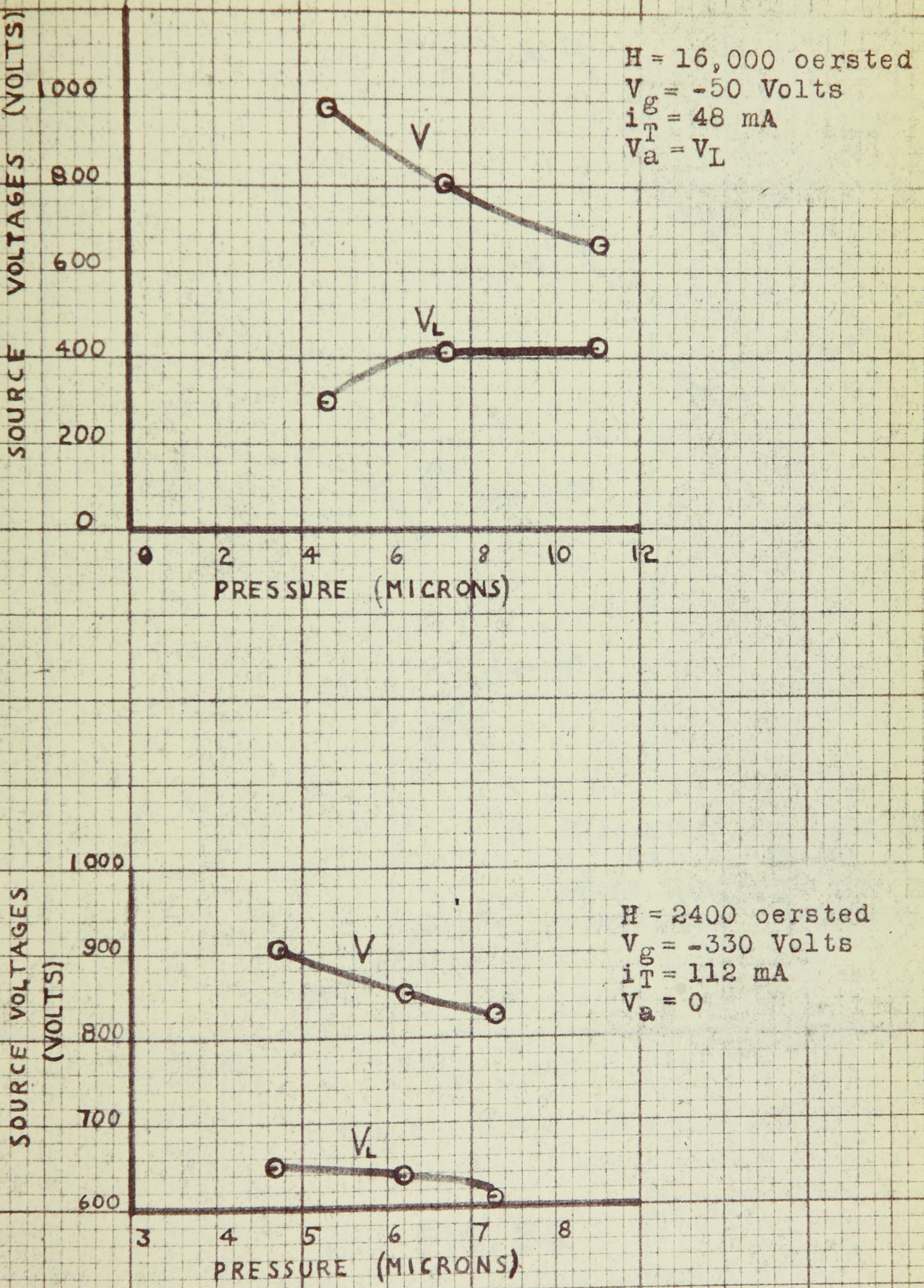


FIG. 23

VARIATION OF SOURCE VOLTAGES WITH PRESSURE
ASYMMETRIC, CYLINDER ANODE

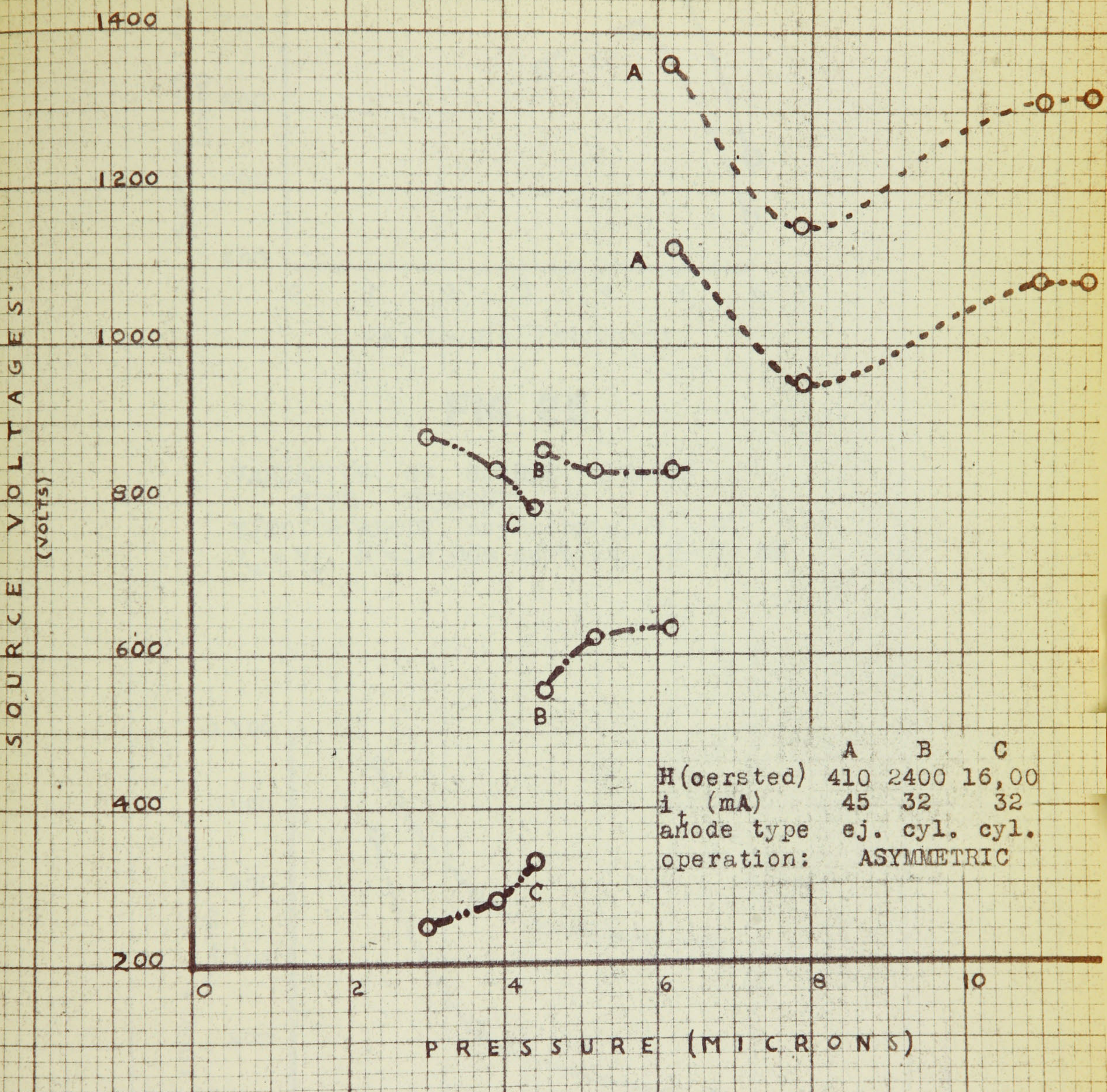


FIG. 24

VARIATION OF SOURCE VOLTAGES WITH PRESSURE

The upper curve of each pair represents V, the lower V_L. - $V_g = 0$ for all points

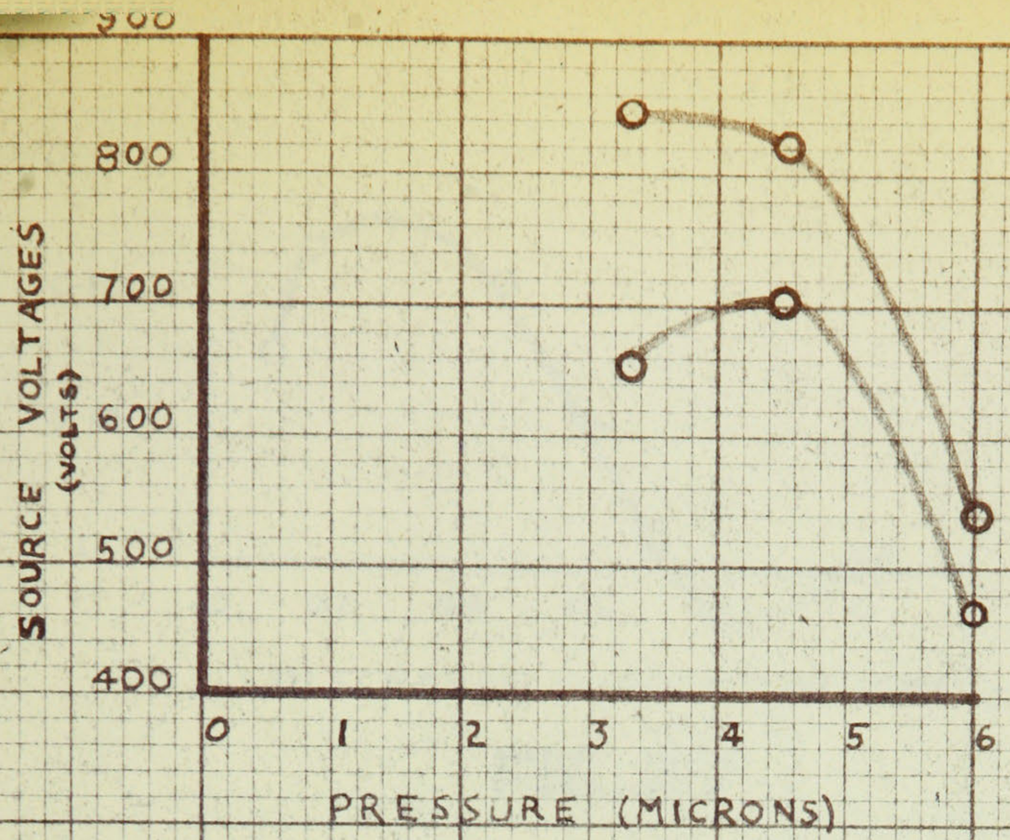


FIG. 25

VARIATION OF SOURCE VOLTAGES WITH PRESSURE
EJECTOR ANODE, asymmetric, $V_g = 0$, $V_a = V_L$, $H = 16{,}000$ oersted, $i_T = 74$ mA

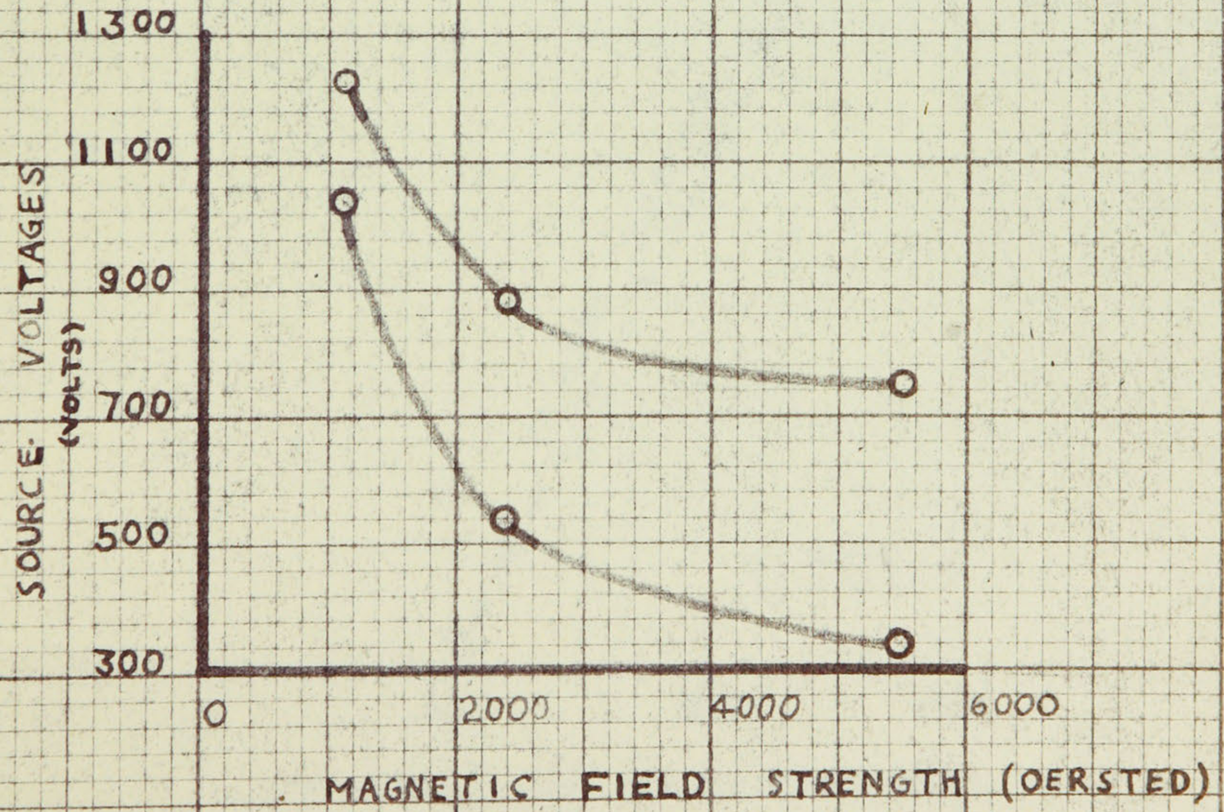


FIG. 26

VARIATION OF SOURCE VOLTAGES WITH MAGNETIC FIELD STRENGTH
cylinder anode, asymmetric, $V_g = 0$, $V_a = V_L$, $p = 6$ microns, $i_T = 40$ mA

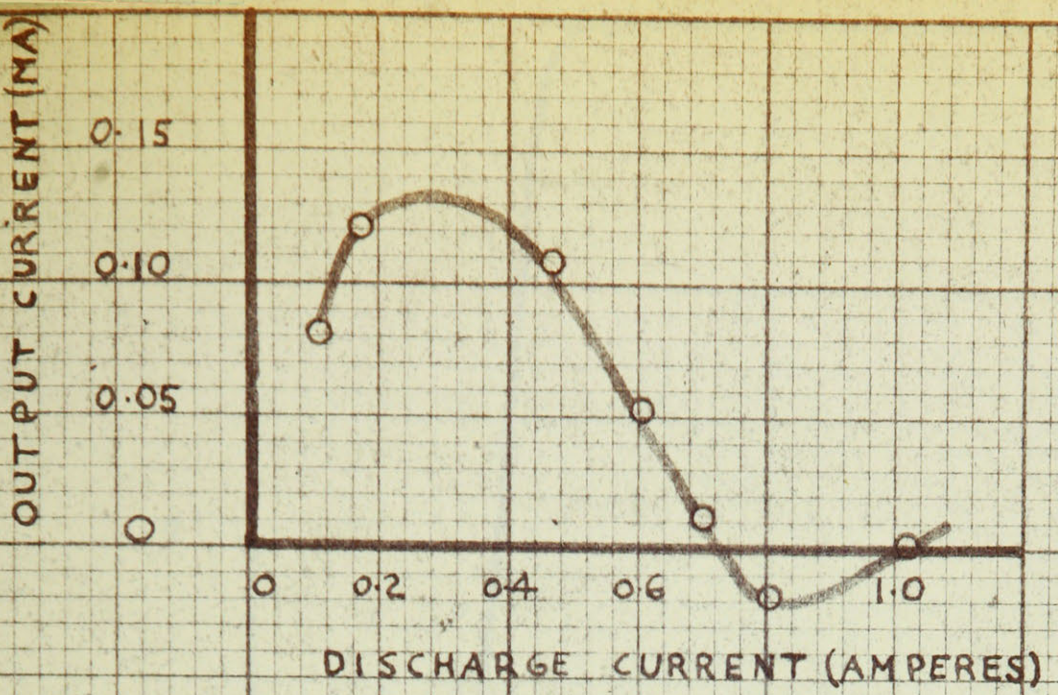


FIG. 27

OUTPUT CURRENT vs. DISCHARGE CURRENT

ejector anode, symmetric, p = 10 microns
H = 1130 oersted, V = 250-280 Volts, 1/8"

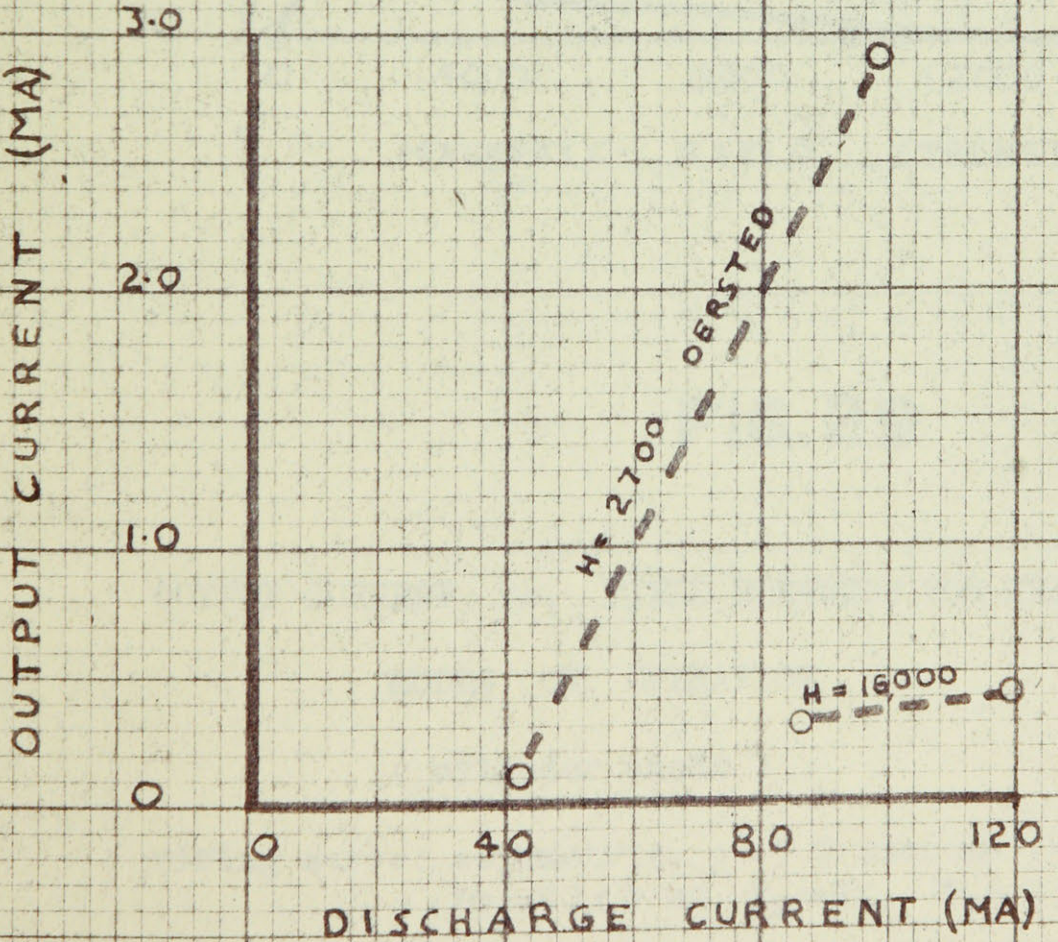


FIG. 28

OUTPUT CURRENT vs. DISCHARGE CURRENT
EJECTOR ANODE, ASYMMETRIC, P = 8.2 microns
H = 2,700, 17,000 oersted resp., $V_g = 0$, $V_a = V_L$

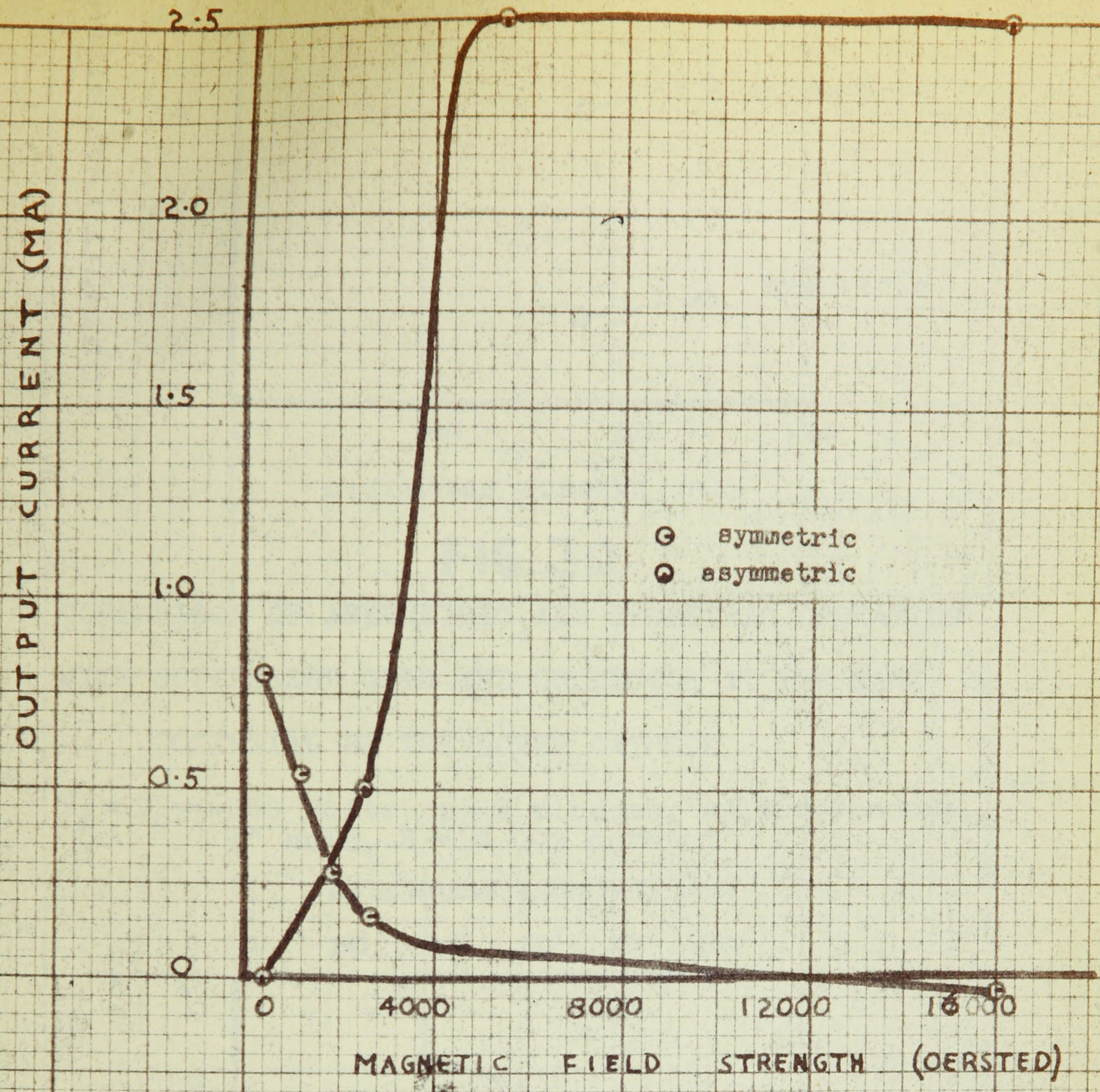


FIG. 29

OUTPUT CURRENT vs. FIELD STRENGTH FOR THE TWO MODES OF OPERATION

(cylinder anode)

rising curve: asymmetric, $p = 5.2$ microns (*), $i_T = 70 \pm 4$ mA, $V_a - V_L$, $V_c = 0$

falling curve: symmetric, $p = 3.5$ microns, $i_T = 70$ mA, in absence of accelerator

(*) the pressure is 7 microns for the point at 410 oersted

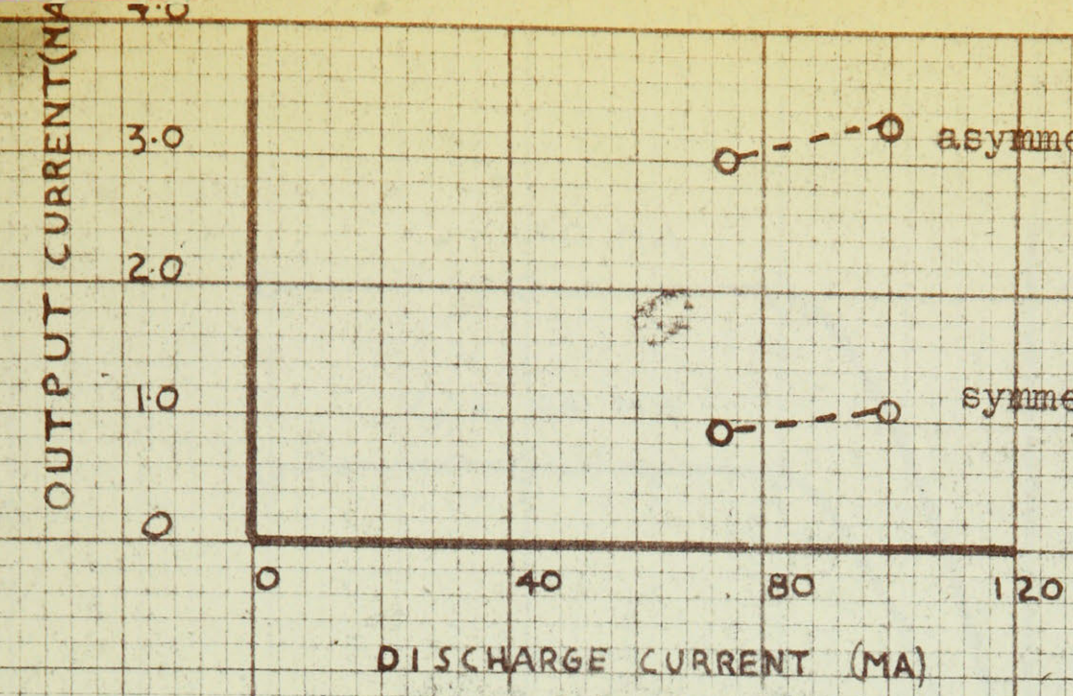


FIG.30

COMPARISON OF ASYMMETRIC AND SYMMETRIC OPERATION WITH SUPPRESSOR GRID AND COLLECTOR AT THE SAME POTENTIAL RE THE LOWER CATHODE

$V_g = V_c = -330$ Volts, $p = 9$ microns, cylinder anode, $\frac{1}{4}$" hole, $H = 16,000$ oersted

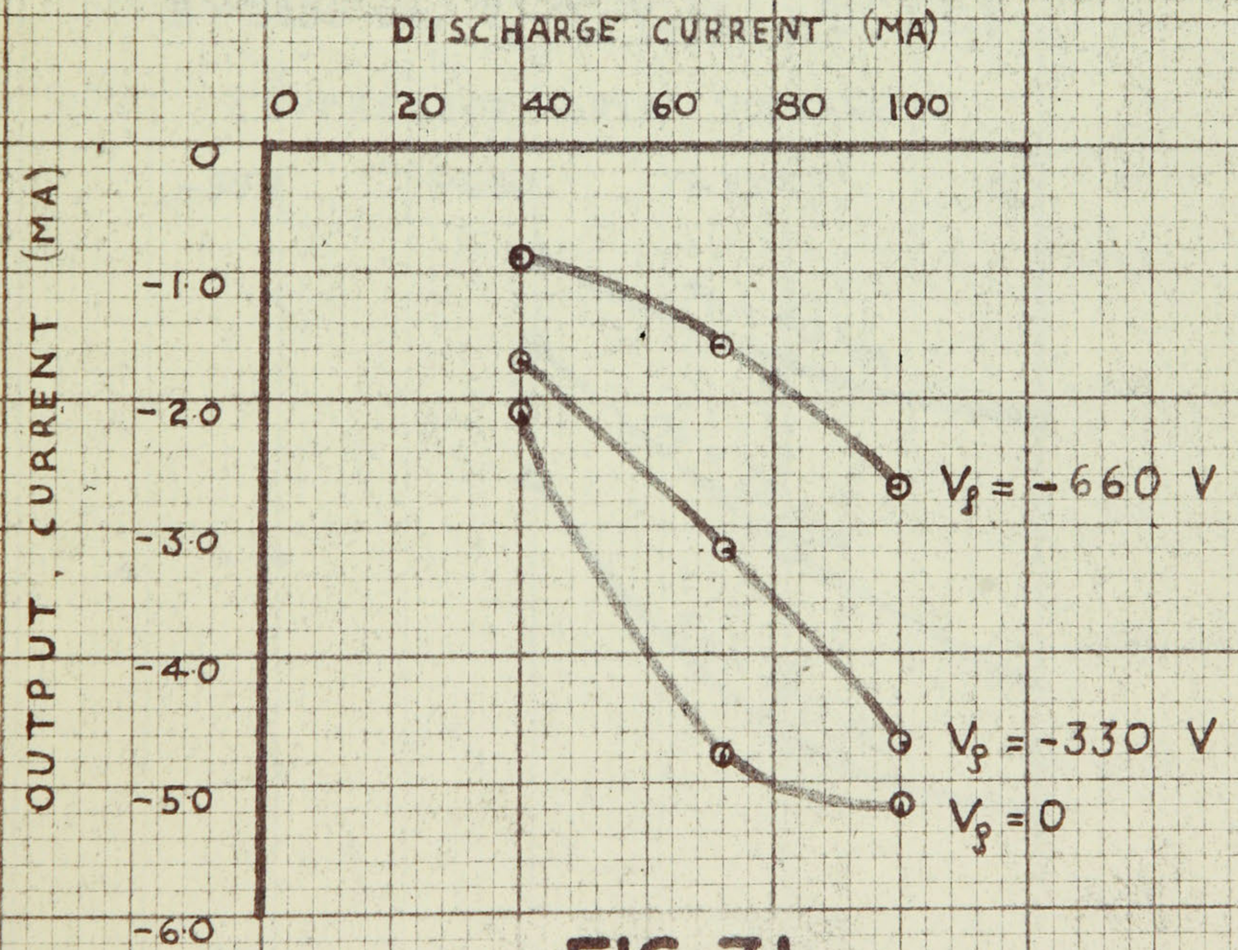


FIG.31

ASYMMETRIC OPERATION WITH COLLECTOR AT SAME POTENTIAL AS THE LOWER CATHODE AND VARIOUS GRID VOLTAGES -

cylinder anode, $\frac{1}{4}$" hole, $V_c = V_L$, $H = 16,000$

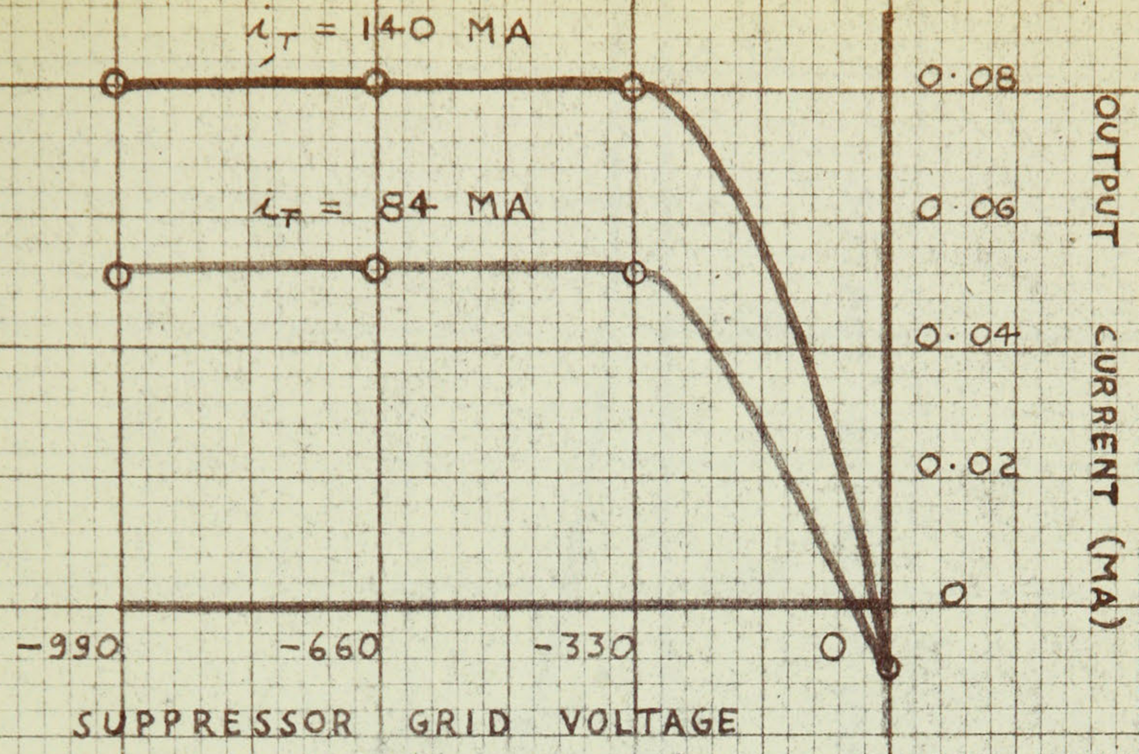


FIG.32

OUTPUT CURRENT vs. GRID VOLTAGE
ejector anode, symmetric, $p = 5.2\mu$
$H = 2400$ oe., $V_a = V_L = V_c = 0$, 1/8" hole

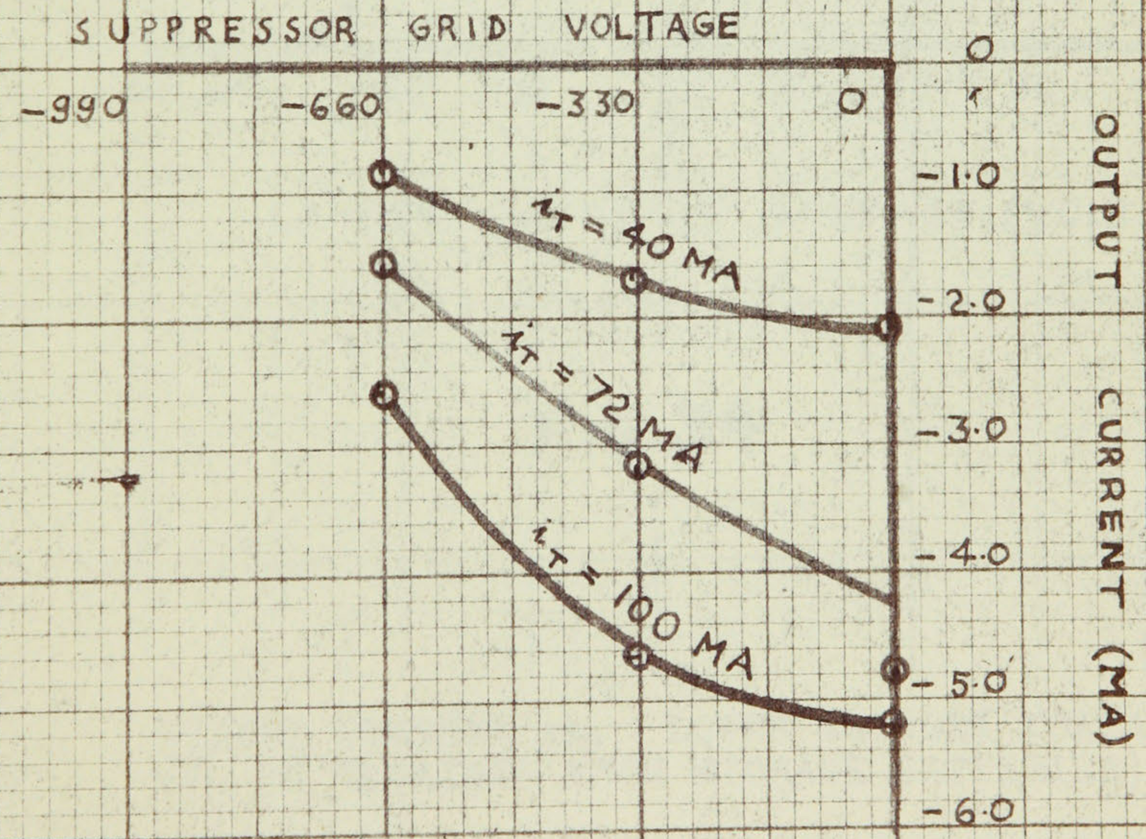


FIG.33

OUTPUT CURRENT vs. GRID VOLTAGE
WITH COLLECTOR AT POTENTIAL OF
LOWER CATHODE
$V_c = V_L$, $p = 9$ microns, $V_a = V_L$,
cylindrical anode, ¼" hole, asymmetric

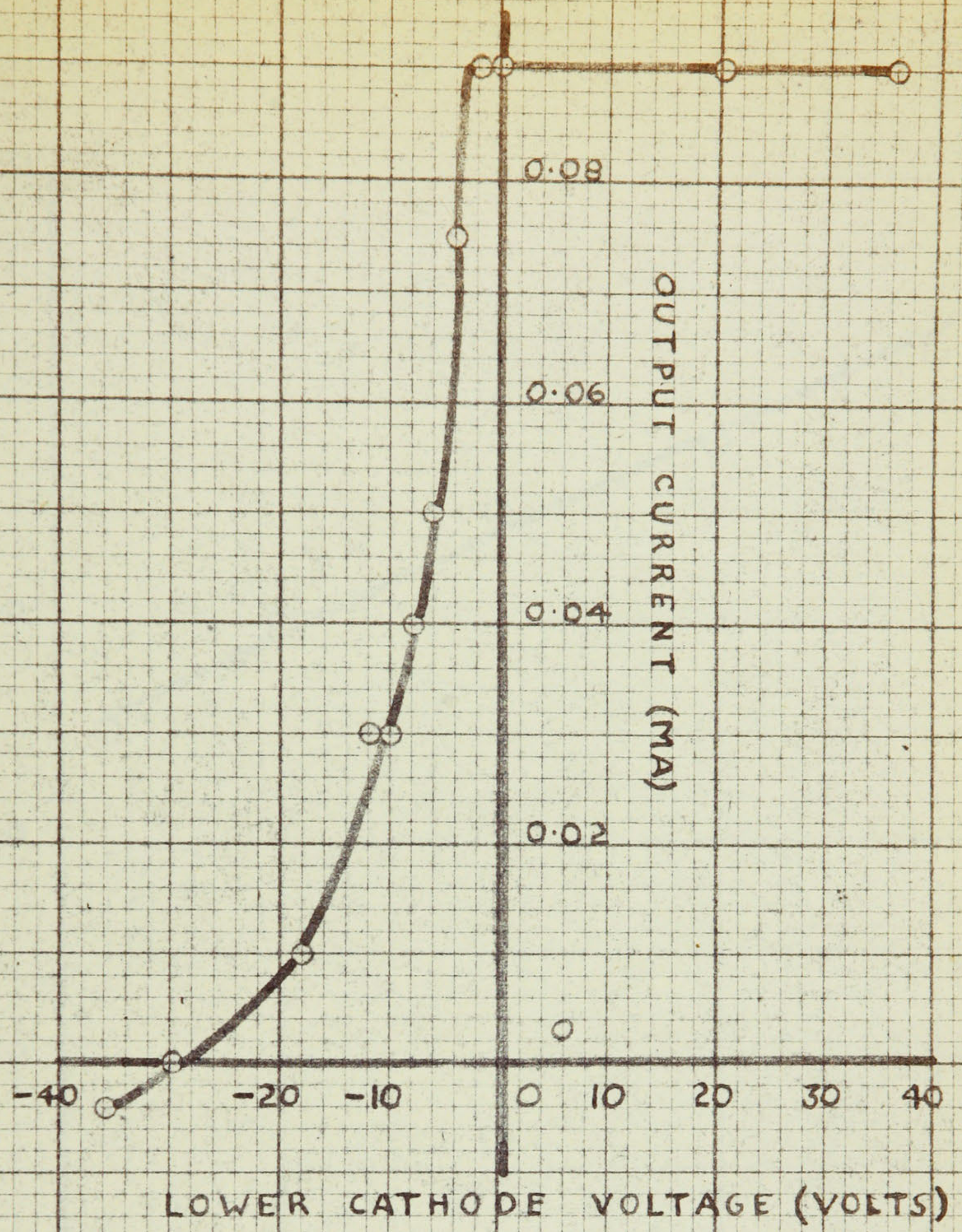


FIG.34

OUTPUT CURRENT vs. LOWER CATHODE VOLTAGE (V_L IS OBTAINED FROM STORAGE BATTERIES) -

cylinder source, 1/8" hole, asymmetric, $p = 9.5$ microns, $H = 16,000$ oersted, $V_a = V_g = 0$

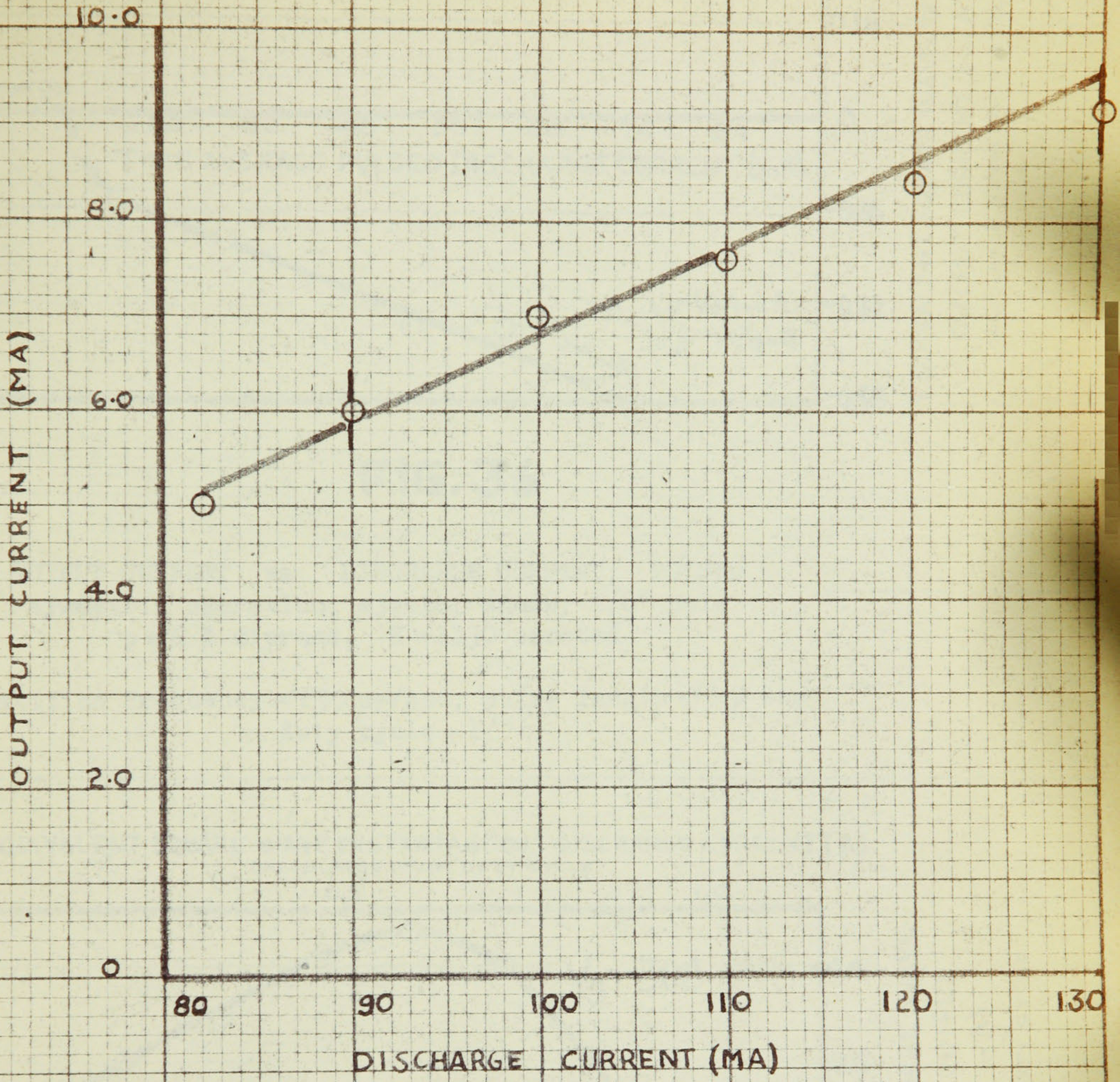


FIG. 35

OUTPUT CURRENT vs. DISCHARGE CURRENT

(cylinder anode, $\frac{1}{4}$" hole, asymmetric, H = 16,000 oersted, p=9 microns, $V_g - V_c = -330V$)

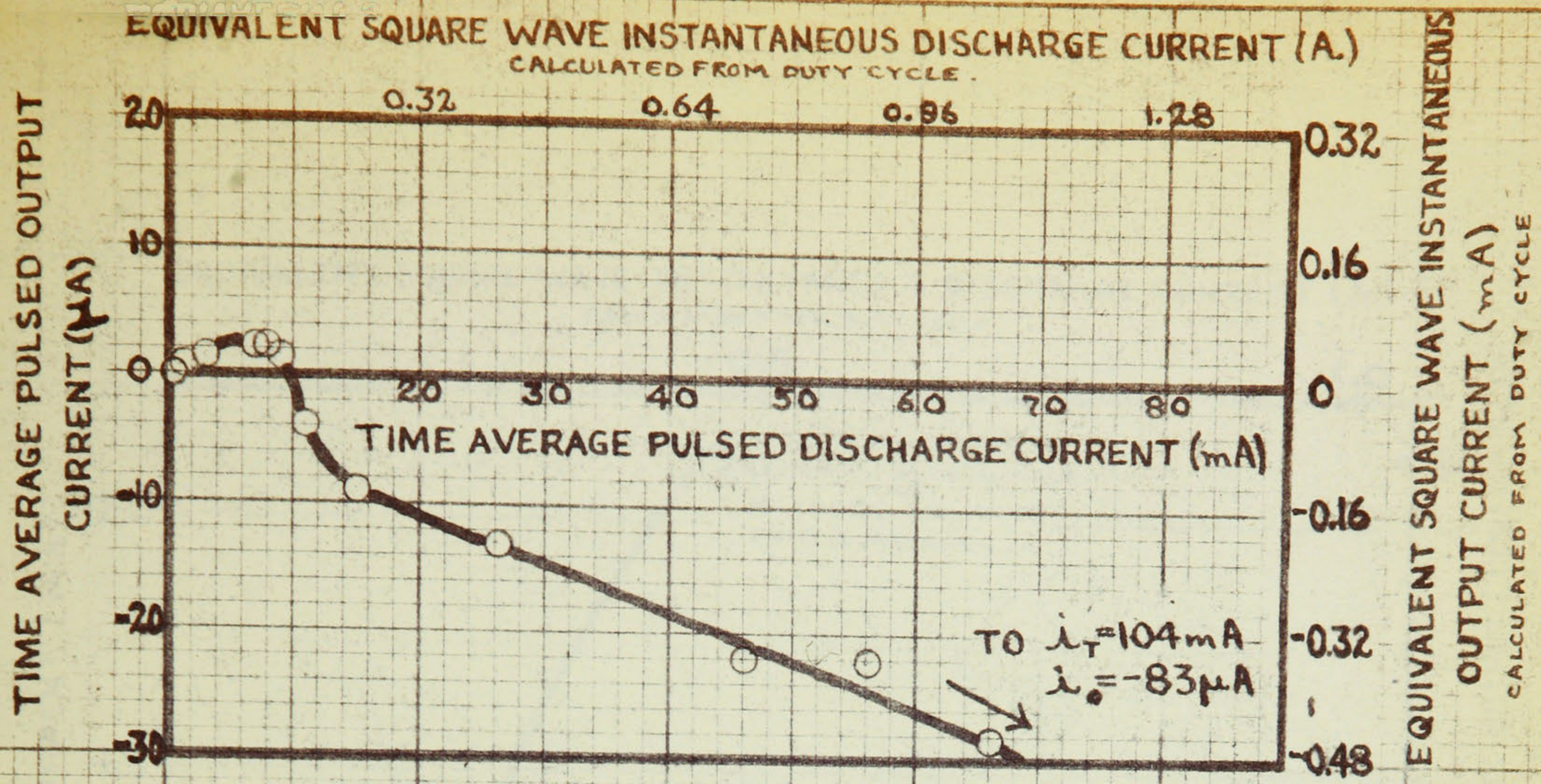


FIG. 36

OUTPUT CURRENT vs. DISCHARGE CURRENT; PULSED symmetric operation, ejector anode, 1/8" hole
p = 6.5 microns, H = 1130 oersted

repetition frequency = 850 cy/sec, pulse length = 75 μ sec
duty cycle = 1/16

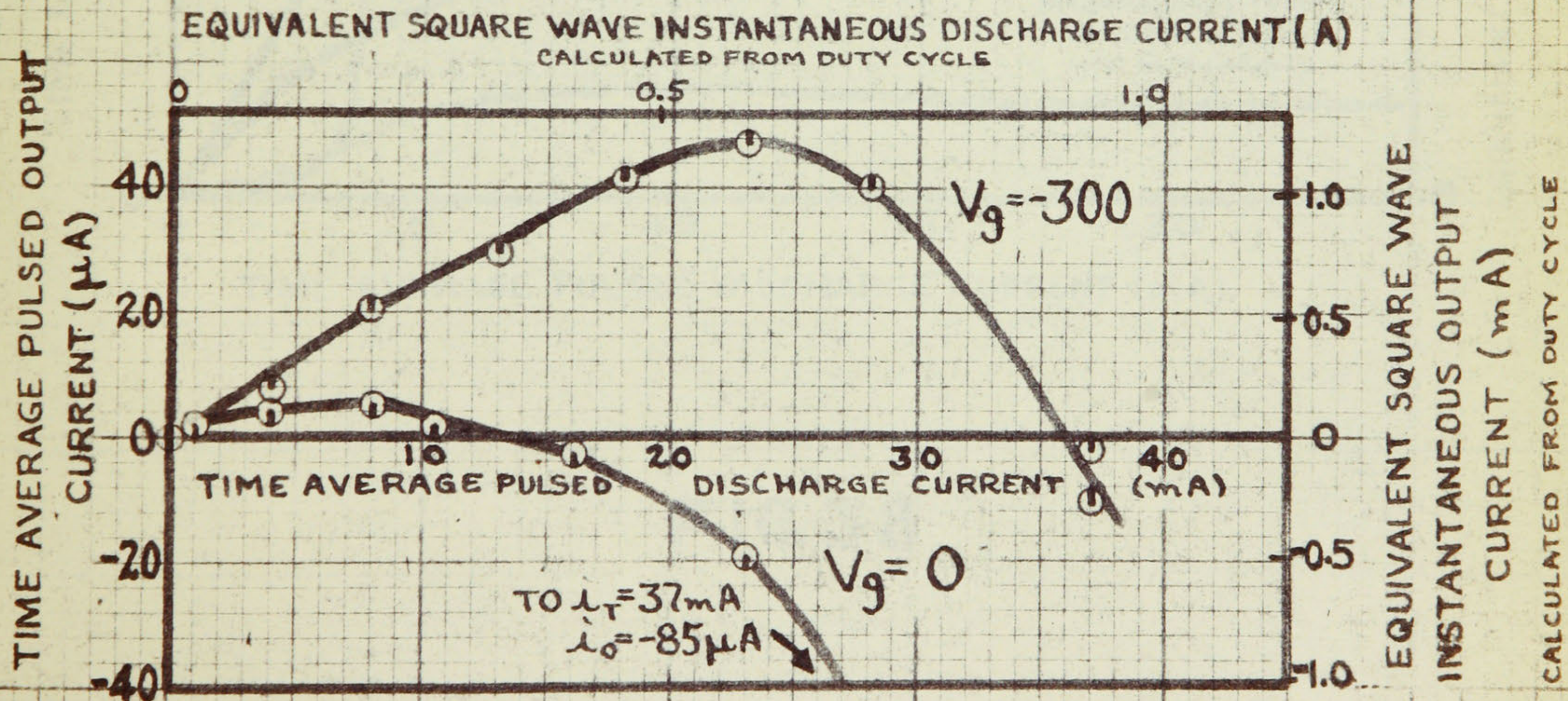


FIG. 37

OUTPUT CURRENT vs. DISCHARGE CURRENT; PULSED SYMMETRIC OPERATION, EJECTOR ANODE, 1/8" hole
p = 5 microns, H = 16,000 oersted
repetition frequency = 796 cy/sec, pulse length = 47 sec
duty cycle = 1/27

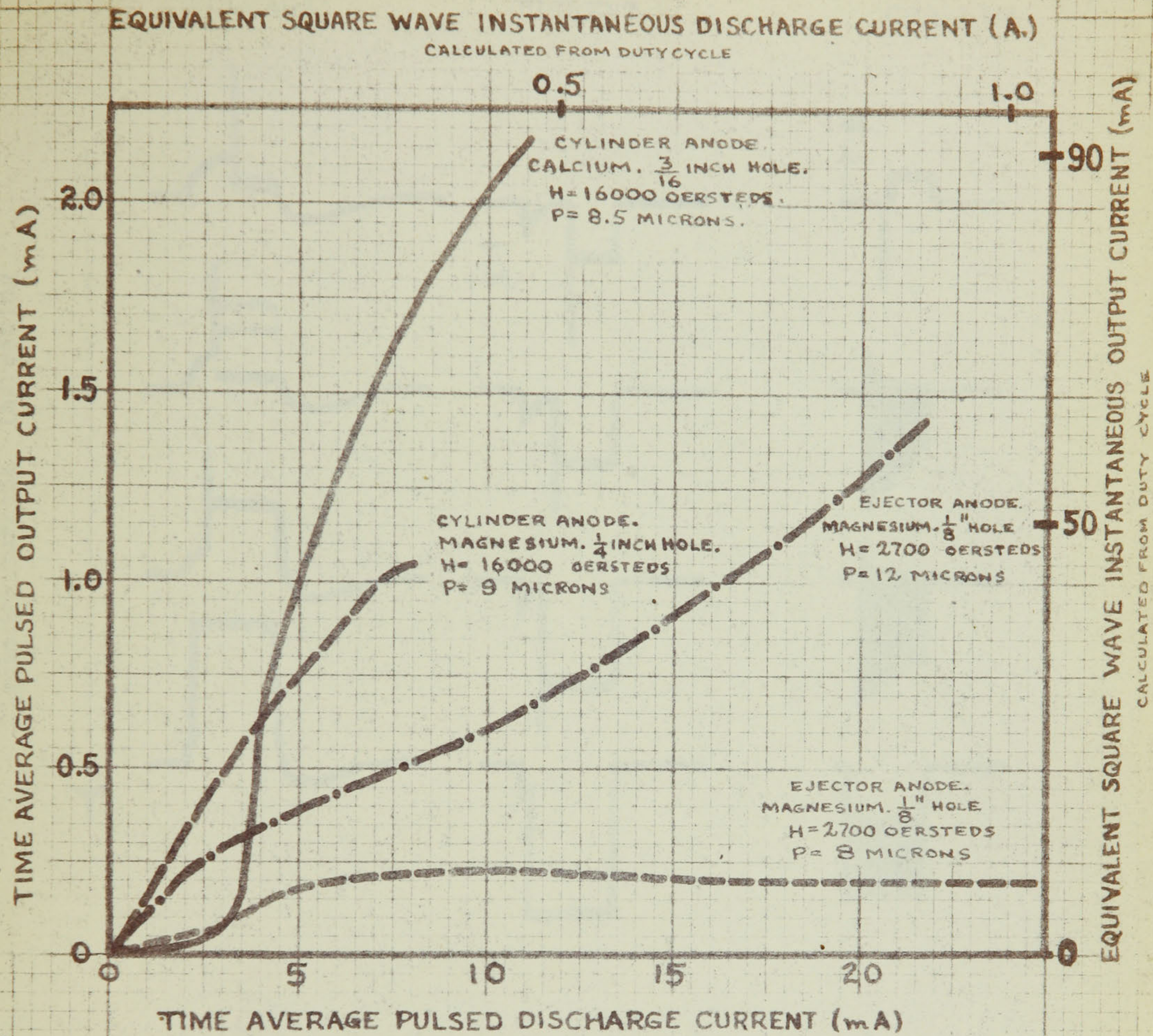


FIG. 38

OUTPUT CURRENT vs. DISCHARGE CURRENT; ASYMMETRIC PULSING

Repetition frequency = 796 cy/sec, pulse length = 30 μsec
Duty cycle = 1/42

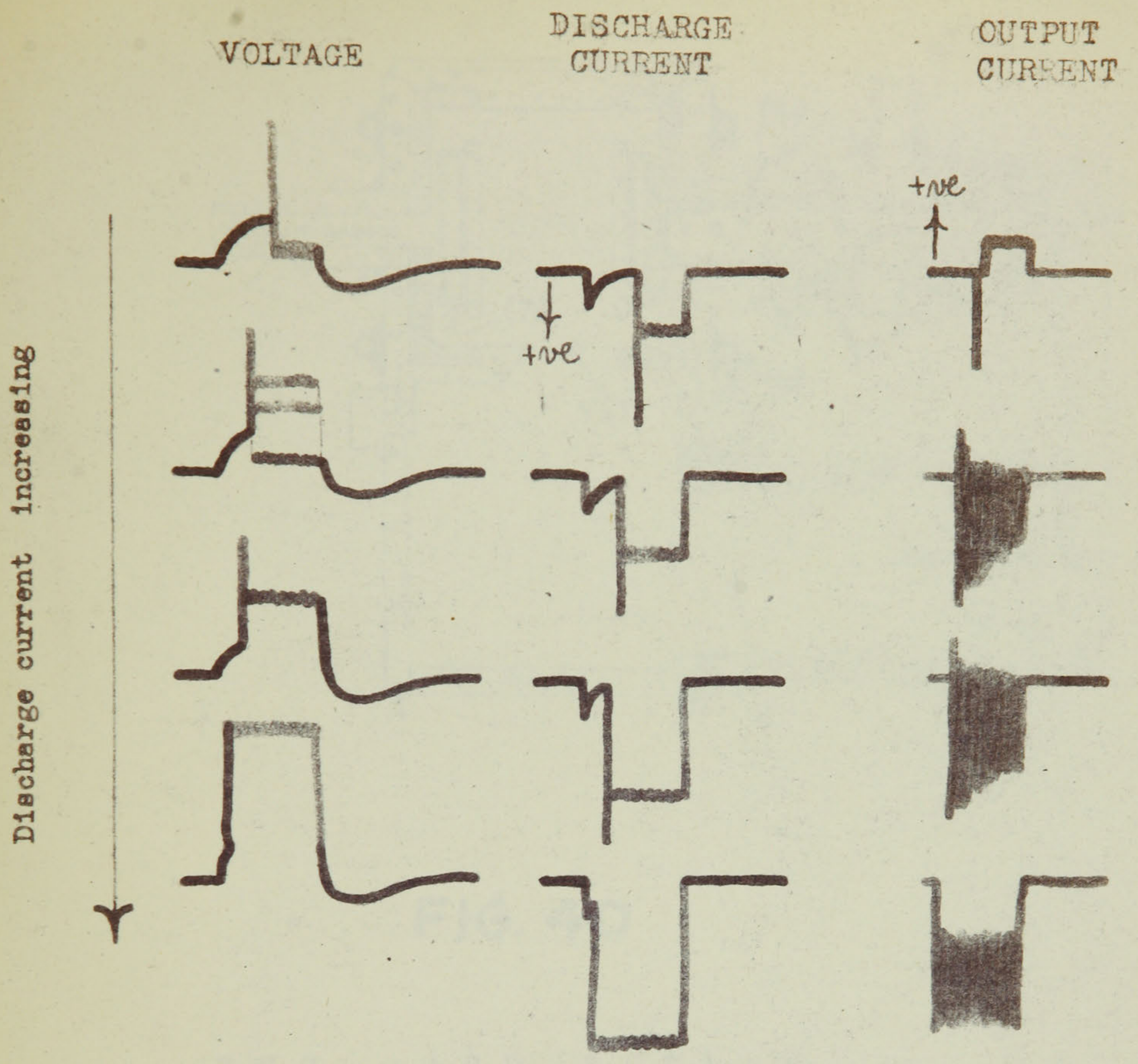


FIG.39

SKETCHES OF TYPICAL PULSE SHAPES — SYMMETRIC OPERATION

Ejector anode; no attempt has been made in these sketches to maintain a vertical scale. The shapes are qualitatively the same in high and low fields.

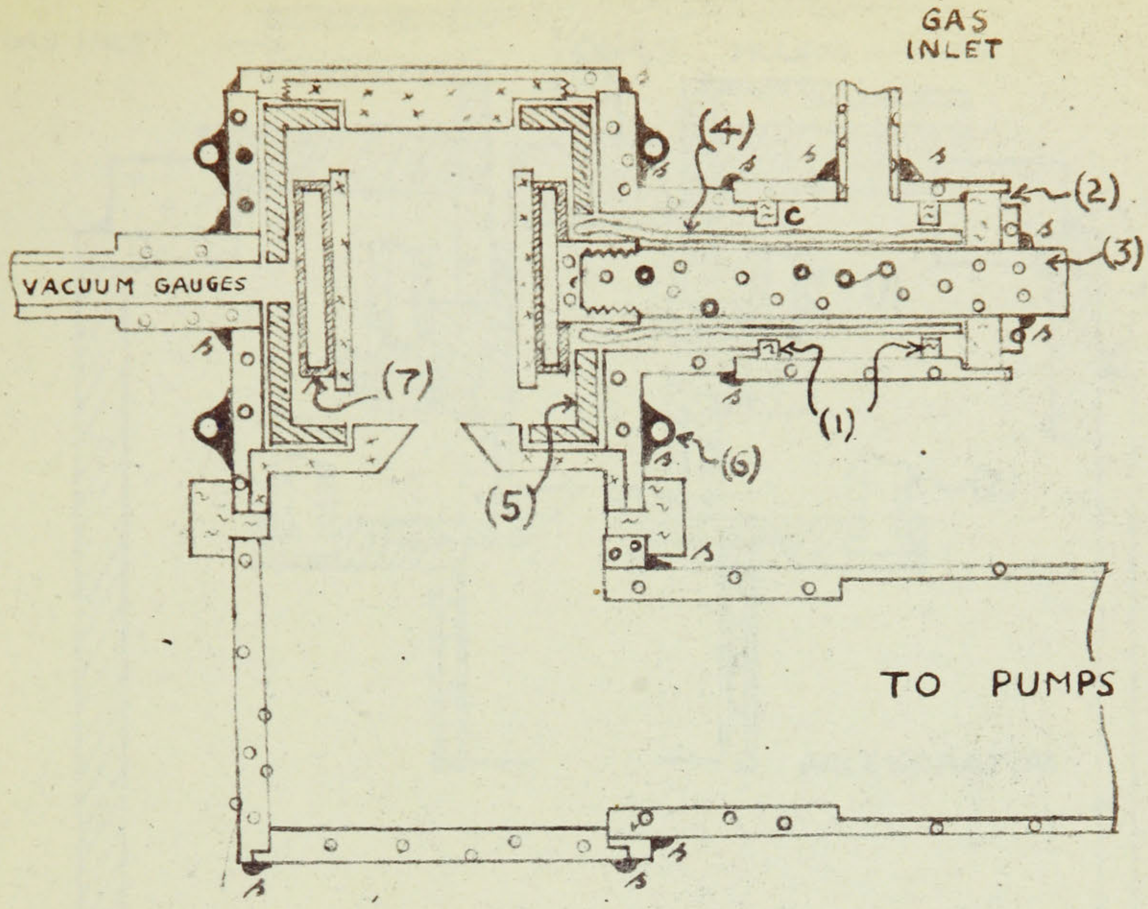


FIG. 40

E N C L O S E D   S O U R C E

(small vacuum chamber)

(1) Spacers

(2) Joint Apiezon-W sealed

(3) Lead for anode cooling cf. Fig.

(4) Insulator

(5) Lavite insulators

(6) Cathode cooling pipe

(7) Anode cooling jacket

s - soft solder

Lavite

Bakelite

Copper

Glass

Brass

Magnesium

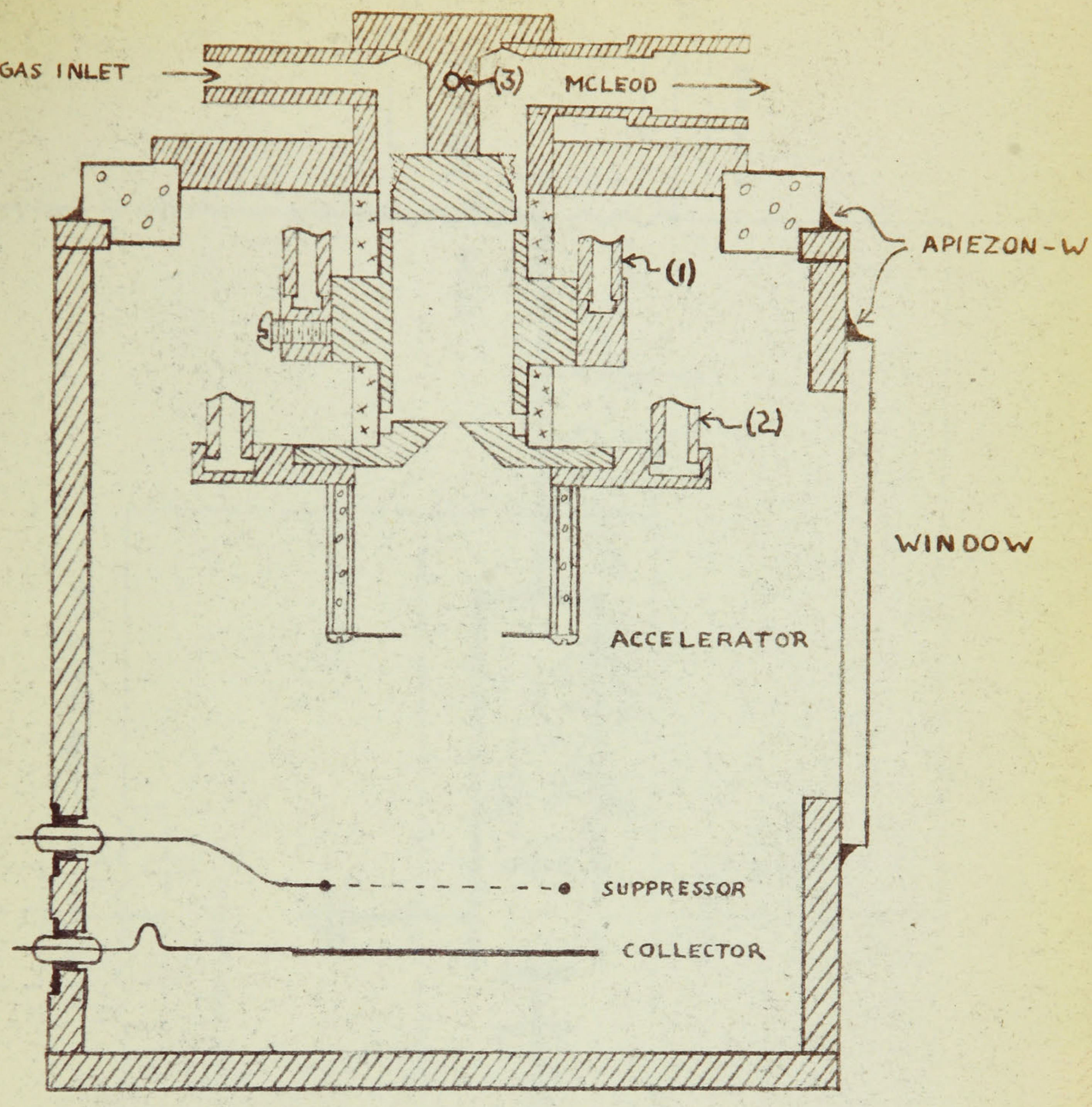


FIG. 41

SCALE: ACTUAL SIZE

SPACER MODEL SOURCE - LARGE VACUUM CHAMBER (cf. Plate III)

The top cathode is rotated 45° clockwise, the lower cathode 45° counter-clockwise.

Brass   Magnesium   Bakelite

Glass   Lavite

(1),(2) - Anode and lower cathode cooling and electrical leads

(3) - section of upper cathode cooling canal

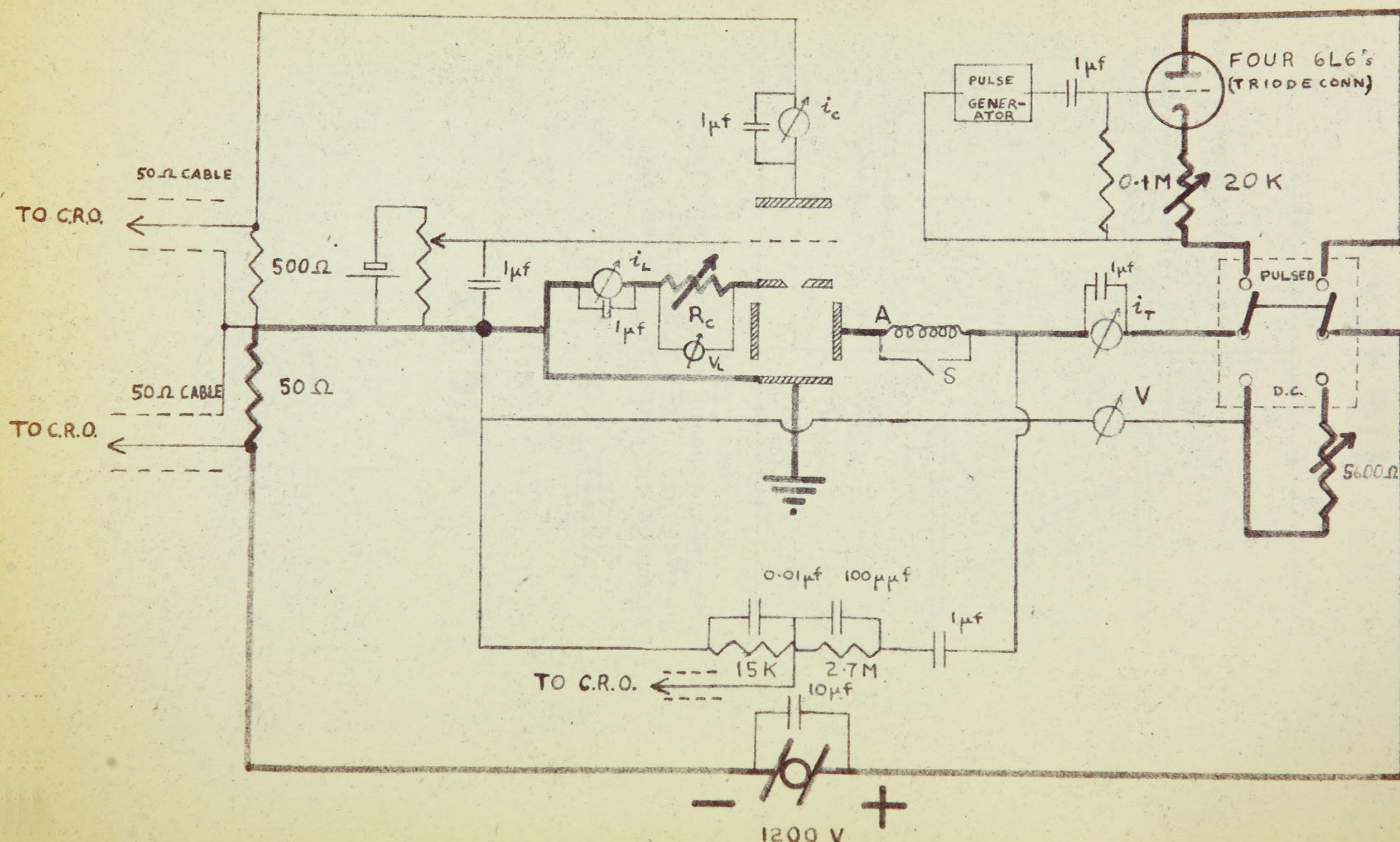


FIG. 42

ELECTRICAL CIRCUIT (schematic)

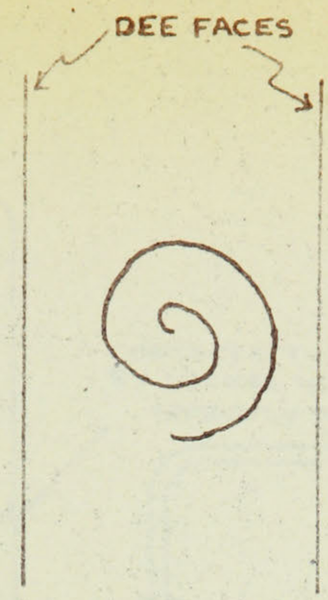


FIG.43

INITIAL ION - PATH

(Assuming uniform field given by
$E = E_m \cos t$; $E_m = 5000$ V/cm;
i.e. Dee spacing 3 cm for applied
voltage 15000 V)

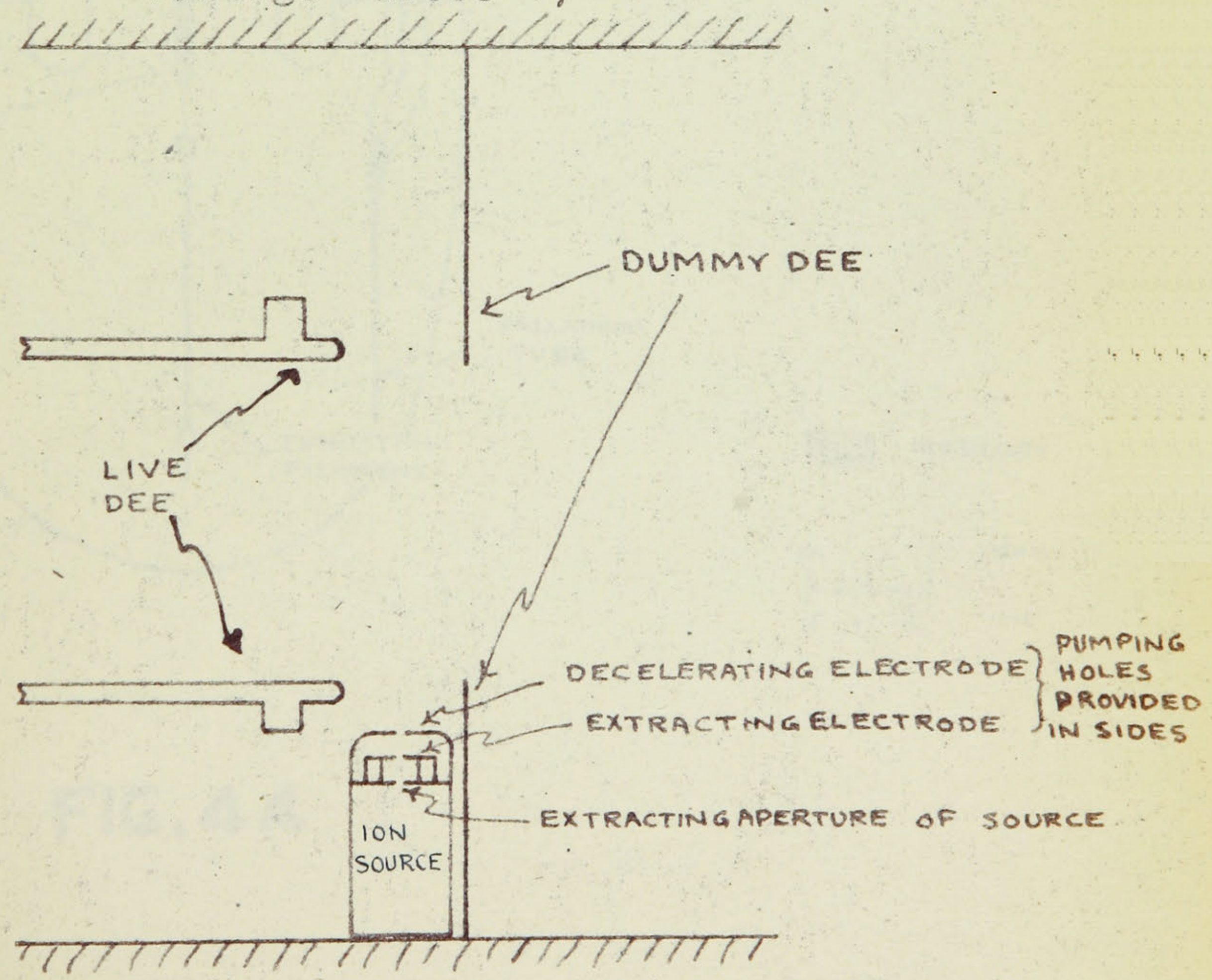


FIG.43A

POSSIBLE ARRANGEMENT OF ION-SOURCE
IN CYCLOTRON

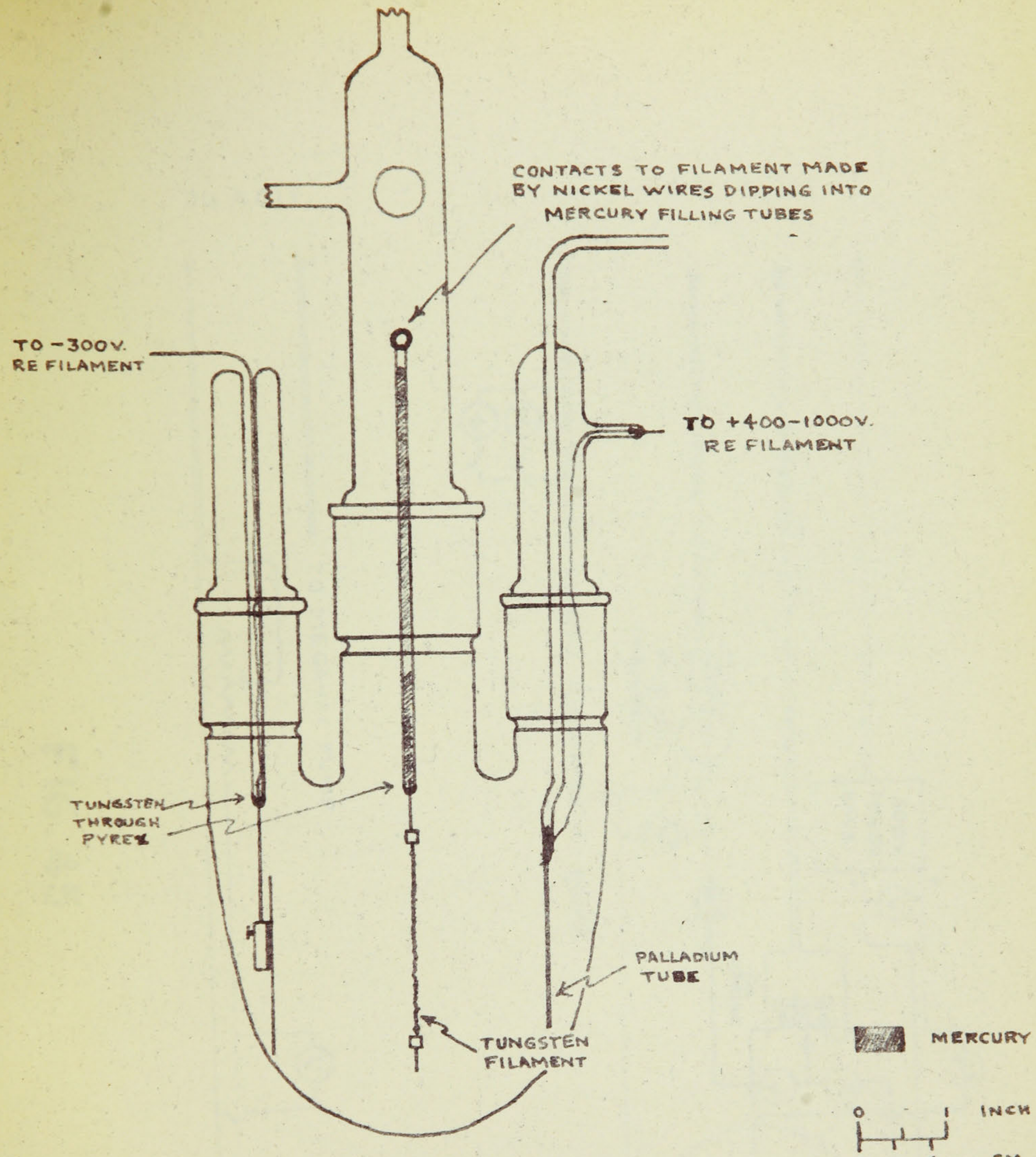


FIG.44

ELECTRON BOMBARDED PALLADIUM SOURCE

Experimental Model

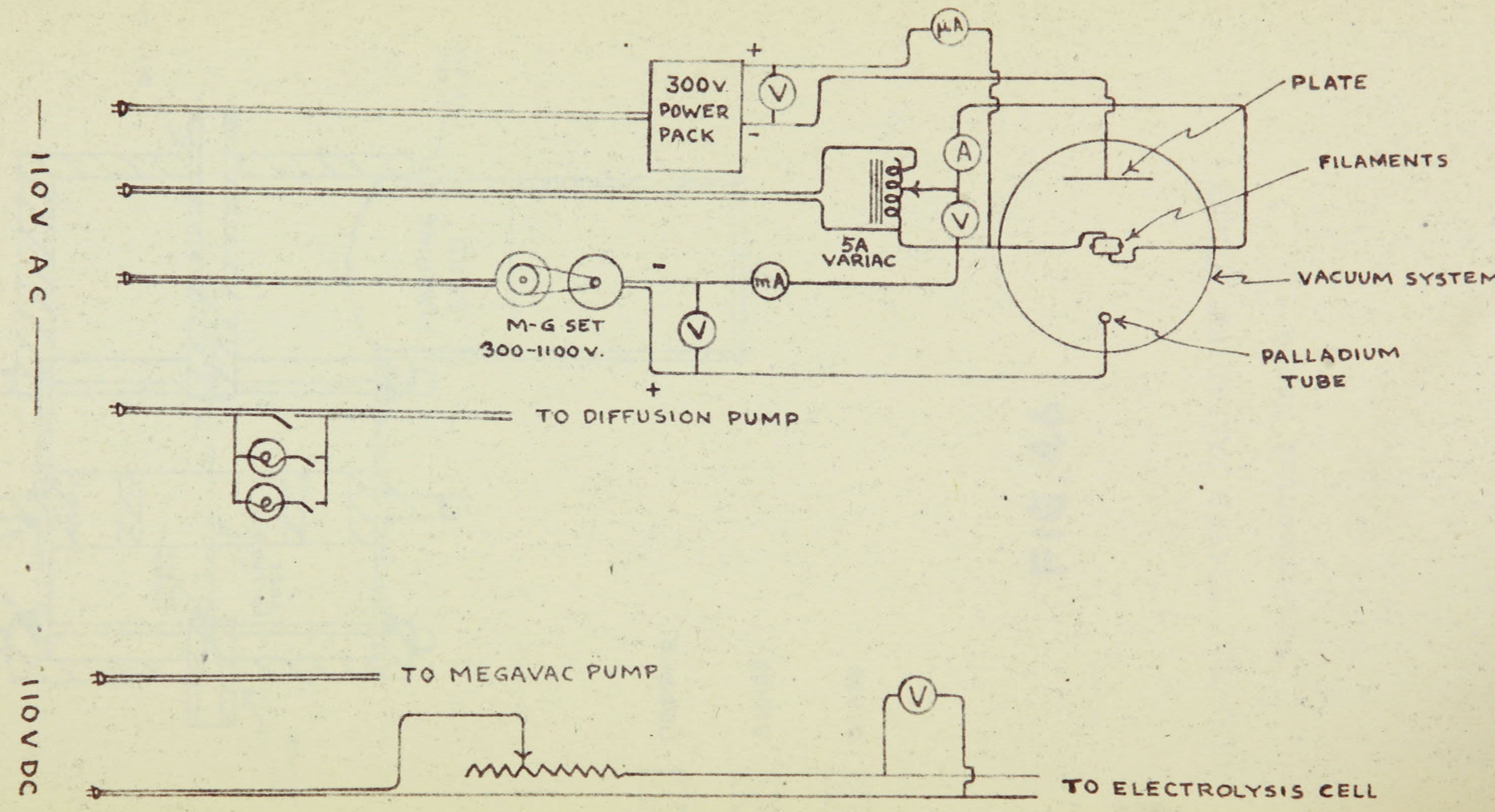


FIG. 45

ELECTRICAL CIRCUITS FOR ELECTRON BOMBARDED PALLADIUM SOURCE

10,000 Volt transformer for discharge tube and control circuit for Pirani gauge not shown

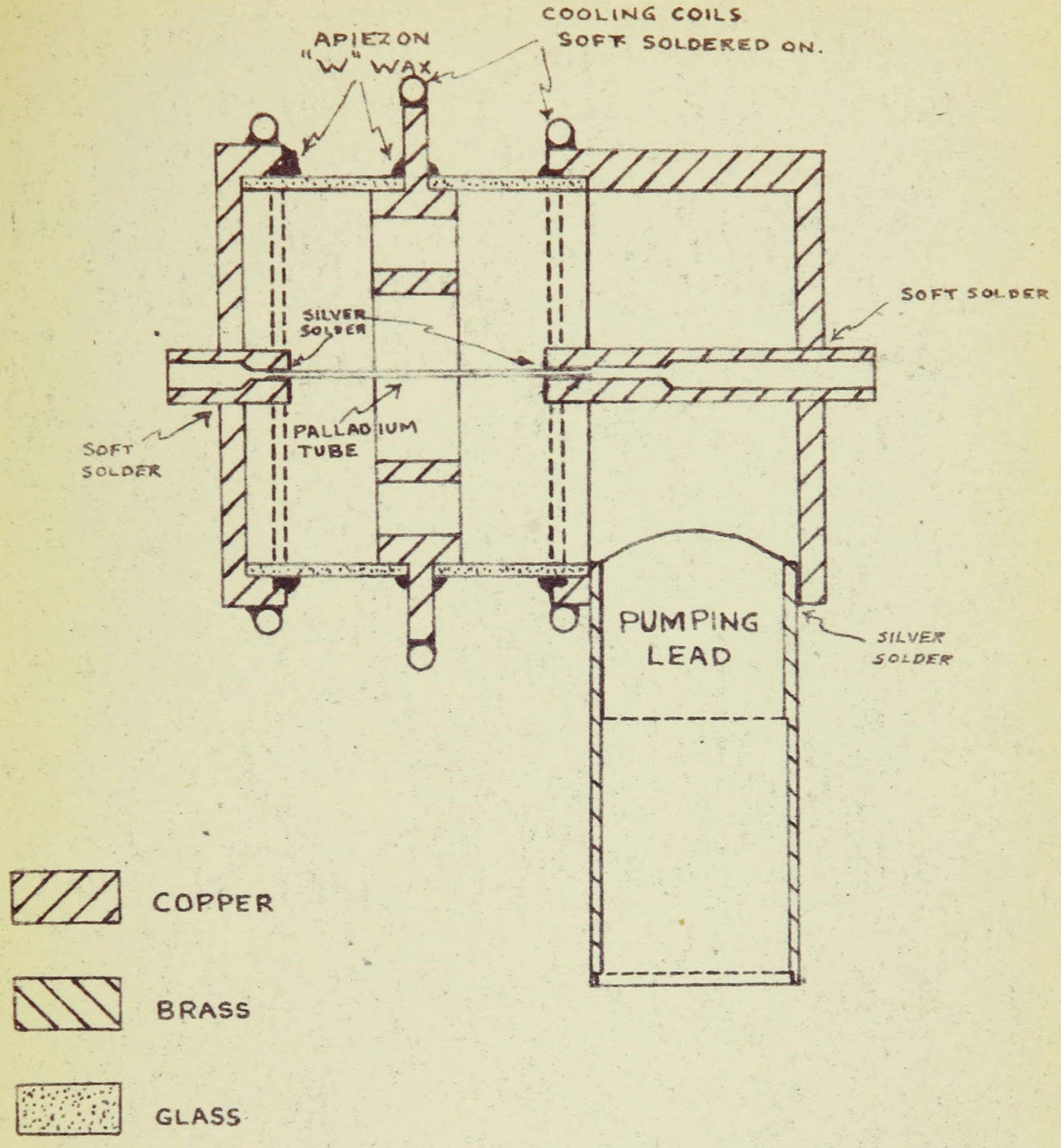


FIG.46

DIRECTLY HEATED PALLADIUM SOURCE

Experimental Model