THE UNIVERSITY OF MANITOBA

DUOPLASMATRON

ION SOURCE

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Abstract

A Duoplasmatron Ion Source to be used in the external injection system of the University of Manitoba cyclotron has been developed. Special efforts were made to cool internal parts of the ion source to improve performance. The encouraging preliminary results show that, for positive hydrogen ions, up to 100 mA of current can be obtained when using an expansion cup of 3/4" diameter. The effects of gas pressure and source magnetic field on the positive ion current were investigated.

The direct extraction of negative hydrogen ions from the duoplasmatron ion source has also been investigated. It was found that 150μA of H_1^- can be obtained by extracting off axis. The effect of the source magnetic field, the arc current, and the gas pressure on the negative hydrogen ion beam were investigated.

Acknowledgements

I am very grateful for the guidance and encouragement of my advisor, Dr. D.O. Wells, and for the support I received from the cyclotron director, Prof. K.G. Standing. Also thanks are due to Dr. S. Bunker and Dr. J. Nelson for their helpful discussions and advice.

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Section I

INTRODUCTION

I-1. The present ion source:

To improve the beam extraction from the University of Manitoba cyclotron, acceleration of negative ions has been used (1,2). After acceleration, the negative ions (H_1^-) are caused to deflect in the opposite direction and become self-extracting by stripping the two electrons from the accelerated negative hydrogen ions. This is accomplished by locating a thin foil at the outermost radius of the cyclotron. The beam energy can be varied by changing the radial location of the stripping foil. The use of this relatively simple method of beam extraction from the cyclotron has intensified efforts in developing negative ion sources for use in cyclotrons.

At present, the University of Manitoba cyclotron has a conventional ion source similar to that developed at Berkaley. Such a source employs a (PIG) discharge mechanism. Electrons from a hot cathode are accelerated across the median plane to an anticathode. Ionization takes place in the space between the cathode and anticathode and the resulting ions are accelerated in the conventional manner. This kind of ion source gives low ion current and high beam emittance.

The requirement of accelerating all the ions extracted from the ion source is:

$$E < A,$$

where E is the beam emittance and

A is the cyclotron acceptance.

This condition does not exist at present. Also, for negative ion acceleration, high gas flow and low pressure are needed (3), a condition difficult to obtain with the present configuration.

The disadvantages of the present ion source limit its use for cyclotrons because there are increasing demands for higher ion current for nuclear physics experiments.

Because of the above-mentioned disadvantages of the present type of ion source, axial injection was suggested at the UCLA cyclotron conference in 1962 (4). At the University of Manitoba, it has been decided to build an axial injection system for the cyclotron, using a negative hydrogen ion beam directly extracted from a duoplasmatron ion source.

I-2. Negative ion beams:

In principle, a negative ion beam can be produced by either a charge exchange process or direct extraction from an arc.

(a) Charge exchange processes:

Negative ions may be obtained from radio frequency ion sources as well as duoplasmatron ion sources by charge changing collisions. In a conventional, positive radio frequency ion source, ions are extracted from the discharge through a canal which restricts the gas flow from the source but allows sufficient current to be drawn from the plasma. Protons, extracted from the discharge, undergo charge exchanging collisions with the neutral gas atoms in the canal. When the product of the canal length and the mean gas pressure is high enough, a large number of the protons become neutral atoms. However, a small but significant number of protons pick up further electrons to become negative ions. A gas target thickness of 100 micron-cm. (5) is required to obtain a full yield of H_1^- ions. A current of 10μA has been obtained (5) by using this technique.

The cross sections for the charge exchange processes of interest are shown in the following table (5).

Cross section	Values calculated (cm^2/atom)
Electron capture $\sigma_{1,0}$	$4.32 \pm 0.11 \times 10^{-16}$
Electron loss $\sigma_{0,1}$	$0.440 \pm 0.044 \times 10^{-16}$
Electron attachment $\sigma_{0,-1}$	$0.120 \pm 0.012 \times 10^{-16}$
Electron detachment $\sigma_{-1,0}$	$5.75 \pm 0.41 \times 10^{-16}$

A duoplasmatron ion source (6) has also been used as the source of positive ions for use in the production of H_1^- by charge exchange. Thin foils or gases can serve as the electron donating matter. Because only a small percentage of the incident positive ions is converted to H^- ions, it is necessary to use an intense current of positive ions. This can be obtained from the duoplasmatron ion source. For an 80 mA, 30 KeV positive ion beam and a hydrogen target thickness of 180 cm, it is possible to get 700 μA of H^- beam with an emittance of 0.0065 rad. cm. $MeV^{\frac{1}{2}}$ (7).

However, the emittance of the negative ion beam obtained by this process is degraded from that of the initial proton beam by space charge forces, by scattering collisions, and by the kinematics of the attachment process. Furthermore, it is necessary to have a highly intense positive proton beam to get a reasonable H^- beam. Therefore, the charge exchange process for producing an H^- beam cannot be used in connection with the cyclotron injector.

(b) Direct extraction of H^- from the duoplasmatron:

Moak (8) noticed that negative ions (H^-) accompanied by a considerable number of electrons can be extracted directly from a duoplasmatron ion source by reversing the polarity of the extractor power supply.

Later, an attempt was made (7) to increase the yield of directly extracted negative hydrogen beam by variations in the geometry of the duoplasmatron ion source. Two parameters of the source were shown to have a marked effect upon the output beam intensity.

These parameters were the spacing between the intermediate electrode and the anode, and the source pressure.

The optimum distance between the intermediate electrode and the anode was found to be .9 inches, with the gas flow $\sim$ 200 atmos.cc/hr for the configuration used. A current of 70 μA of H^- ions at 20 KeV was obtained under these conditions. Since the negative ion beam was extracted from the centre of the arc, the electron load was too high. Electron loads of about 1 mA per μA of H^- were reported (7,8,9).

Collins (10) has shown that the efficiency of direct extraction of negative hydrogen ions from a duoplasmatron source can be increased by extracting the ions from the outer regions of the arc. Ion currents of 80 μA have been obtained with total source load of only 2 to 4 mA. The energy spread of the negative ions was found to be small. The reduction in the electron beam accompanying the the negative ions is due to the effect of the magnetic field in the extraction gap which affects the trajectories. The distortion of the field caused by the displacement of the intermediate electrode with respect to the anode and extractor assists in deflecting the electrons into the extractor electrode.

The duoplasmatron arc is a highly ionized plasma with electron density of 10^{14} to 10^{15} per cubic centimeter under an operating pressure of 10^{-1} Torr (10). Near the edge of the arc, the electron density is smaller and, consequently, the density of the gas is greater. Gas entering the arc plasma suffers many collisions with the electrons, resulting in many processes, some of which are listed in the following table.

Atomic process	Min. energy (eV)	Max. cross section (cm^2)	σ_{max} energy eV	Ref.
$H_2 + e \rightarrow H+H+e$	8.5	$.6 \times 10^{-16}$	12	12
$H_2 + e \rightarrow H_2^+ + 2e$	15.4	1.1×10^{-16}	80	13
$H_2 + e \rightarrow H^+ + H + 2e$	18.0	5×10^{-19}	120	14
$H_2 + e \rightarrow H^+ + H^+ + 3e$	46	5×10^{-19}	120	15
$H_2 + e \rightarrow H + H^-$	6.0	3.5×10^{-20}	14.2	16
$H_2 + e \rightarrow H^+ + H^- + e$	17.2	3×10^{-20}	Increasing at 38 eV	16

Schultz (15) studied the cross section for the production of H^- ions by electron impact in hydrogen gas. The cross section for H^- formation as a function of electron energy is shown (15) in fig. (1). The cross section below 13.6 eV is associated primarily with the reaction $H_2 + e \rightarrow H^- + H$, while above that energy the reaction $H_2 + e \rightarrow H^- + H^*$ predominates. The simultaneous production of H^- and H^+ can occur above 17.2 eV.

The reaction rate for a particular process depends on the energy distribution of the plasma electrons and the energy dependence of the cross section. There is little information known about the electron energy distribution in the duoplasmatron arc, but it is estimated that the mean energy is between 6 and 8 eV. Therefore, the reaction $H_2 + e \rightarrow H^- + H$ is thought to be important in the duoplasmatron arc. Since this reaction requires the presence of molecular hydrogen, conditions in the outer region of the arc should be suitable.

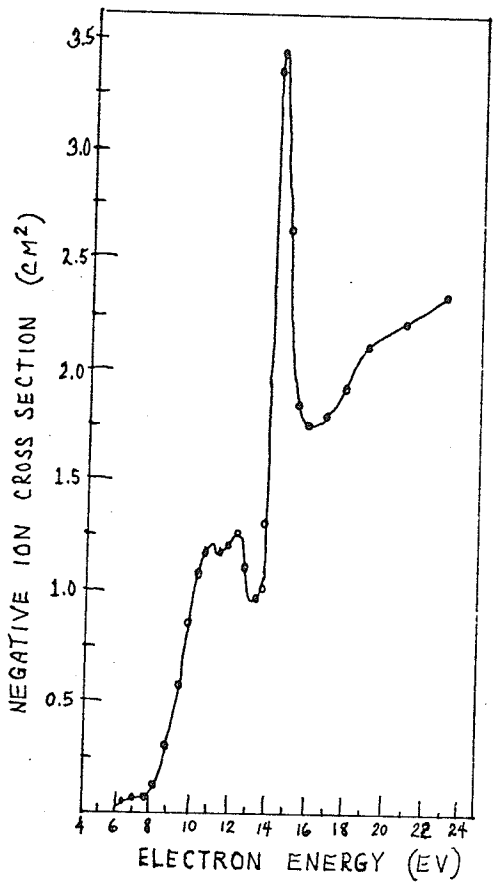

FIG. 1 NEGATIVE ION CROSS SECTION AGAINST ELETRON ENERGY IN HYDROGEN.

I-3. The duoplasmatron ion source:

Among the different types of intense ion sources, the duoplasmatron features high ionization efficiency, high current density and the possibility of yielding a beam with a reasonably good quality due to the focusing properties of its extraction system. Since the first type of duoplasmatron was introduced by Von Ardenne (16), subsequent developments have concentrated mainly on the extraction system, which is the most critical in ion source design. However, for the extracted beam to contain a high current density, it is also essential that the plasma be sufficiently ionized so that it can supply the ion emitting surface with the required current density. The mechanism by which intense ionization is produced within the arc chamber of the duoplasmatron makes it unique in satisfying such requirements.

In the basic duoplasmatron configuration (fig. 2), a low pressure arc is produced between a cathode and an anode. A conical intermediate electrode causes mechanical constriction of the plasma, while a strong magnetic mirror between the intermediate electrode and the anode causes magnetic constriction of the plasma. Thus a very dense plasma is created in the vicinity of the extraction aperture. Plasma penetration through the anode aperture permits a large area of plasma boundary to emit an ion beam upon application of a high potential to the extractor.

The normal arc discharge (one without constrictions) consists of three regions (17), the first of which is the "cathode drop",

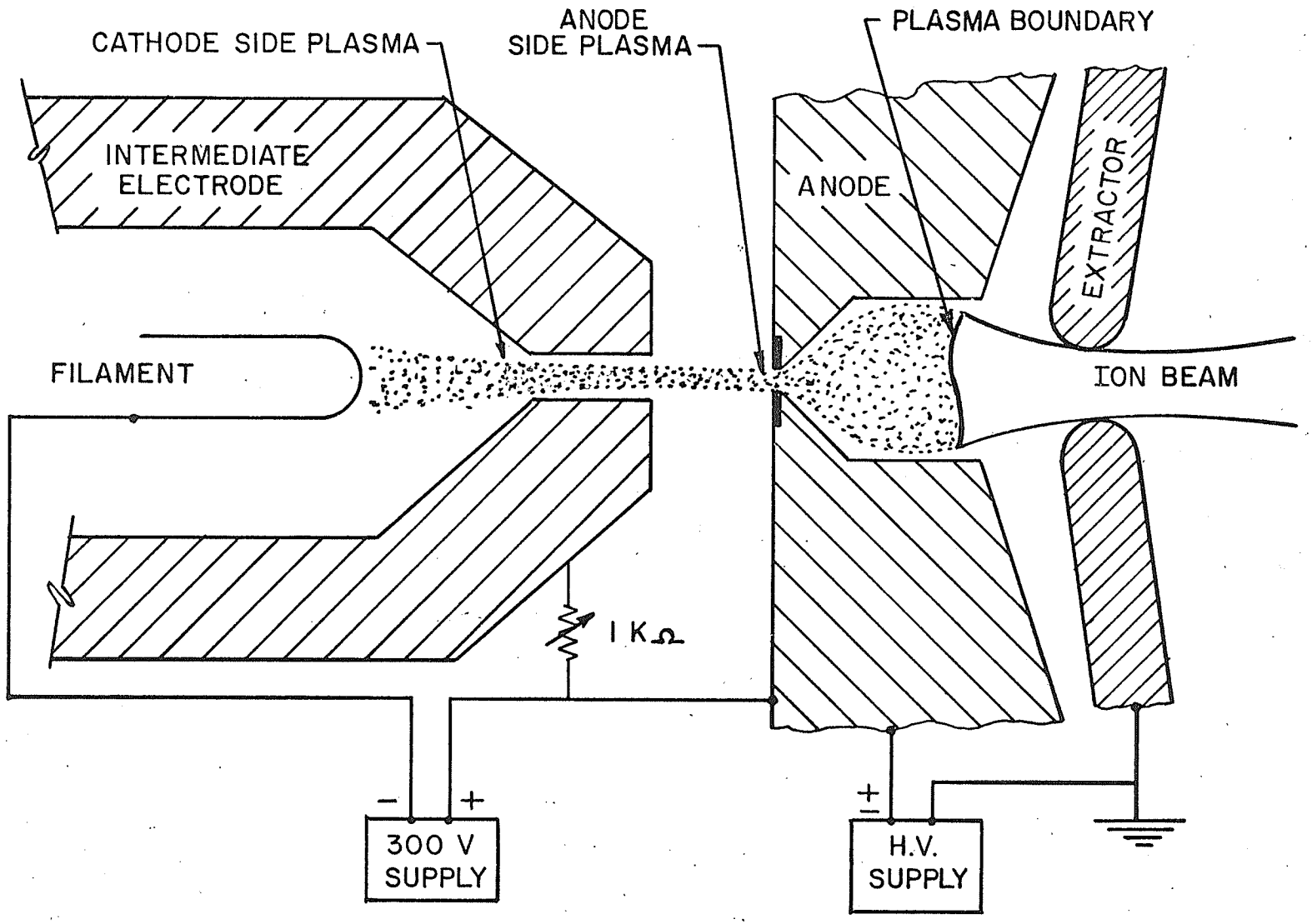

Fig. (2) Schematic Diagram of the Duoplasmatron Ion Source

where there is a potential difference approximately equal to the first ionization potential of the gas. It includes a strong positive charge near the cathode. The positive column, or plasma, exists at a short distance from the anode and is characterized by a small potential gradient and by charge neutrality. The third region is the "anode drop", near the anode, which contains an intense negative charge. The cathode electrons acquire enough energy to produce ionization in the positive column. After different collisions, they are scattered randomly but, due to their higher mobility, the electron temperature is higher than the ion temperature.

For a Maxwellian distribution of the plasma electrons in a Langmuir plasma, it was found that a stable ion sheath could be formed only when the ions reach the sheath with an energy at least equal to half the electron temperature (18).

$$\tfrac{1}{2}m_+v_+^2 = eV_o \gg \tfrac{1}{2}KT_e \qquad \ldots\ (1)$$

where m_+ is the mass of the positive ions,

v_+ is the velocity of the positive ions,

K is the Boltzman constant, and

T_e is the electron temperature.

The ion density in the sheath is then:

$$J^+ = n_+eV_+ = n_+e\sqrt{\frac{KT_e}{m_+}} \qquad \ldots\ (2)$$

The ion sheath protects the plasma from the walls or electrodes. Thus, the electric gardient due to the extraction potential is

supported by the sheath and not by the plasma.

With the presence of a strong magnetic field B, the plasma will be confined by a magnetic pressure (19).

$$P = - \frac{1}{8\pi} B^2$$

Such confinement will naturally reduce the diffusion losses of ions and electrons.

In a magnetic field, the diffusion coefficient is given by:

$$D = \frac{D_o}{1 + (w_c \tau)^2}$$

where D_o is the ordinary diffusion coefficient,

τ is the mean free time of particles, and

w_c is the cyclotron frequency.

The mechanical constriction and the magnetic field shaping forces the electrons into the central region of the plasma. Frequent collisions occur with the ions and the ion temperature approaches the electron temperature. The formation of a hot, dense plasma in the anode baffle space causes thermal ionization of any neutral particles which escape from the source. This process increases the gas ionization efficiency to a high value. With these mechanisms, we have a spherical luminous surface similar to a fire ball on the cathode side of the constriction (20). Two space charge limited flows exist; one for ions in the cathode direction, and one for electrons in the opposite direction (double layer). The double layer acts as a quasi cathode to supply the necessary extra electrons

to produce the anode current. A potential drop exists in the double layer rendering ionization in a cathode plasma due both to Townsend ionization and thermal ionization. Electrons oscillate up and down this potential hill. The energy needed for such plasma oscillation is absorbed from cathode fast electrons. The beam plasma interaction could yield electrons with up to 1000 eV energy and positive potential differences greater than 100 V. It has been shown (19) that the discharge pressure, p, and potential drop over the double layer are related by the equation:

$$N^{\frac{3}{4}}p = \text{constant}$$

Thus, the heating effect of the "fire ball" is greater for lower pressure until we reach the limit (10^{-2}torr), when the size of the plasma increases and it touches the walls, causing a sharp reduction of plasma temperature. This loss can be compensated for by increasing the filament current, but the efficiency in this case will be lower.

The second important procedure in the ion source, after the production of high density plasma, is the extraction of the plasma ions in the form of a beam of given energy and having the highest possible ratio of ion flux to atom flux.

For a beam of positive ions, extraction is from the positive ion sheath surrounding the plasma. This sheath is formed between the plasma boundary in the anode cup and the extraction electrode. By applying the proper polarity of high voltage on the extraction electrode, which is in the form of a Pierce electrode (21), an ion

beam is extracted.

One can cause the H^- ions formed in the sheath to be extracted by reversing the polarity of the potential applied to the extraction electrode and by adjusting the intermediate electrode position.

The plasma boundary is an elastic electrode, its shape and position being determined by the magnitude and shape of the electric field between it and the extraction electrode.

When maximum current is extracted from the plasma boundary, the beam should be space charge limited. The current density is then given by the Langmuir equation (for protons).

$$J = 5.45 \times 10^{-8} \frac{V_{ex}^{3/2}}{M^{\frac{1}{2}} d^2} \quad A/cm^2 \qquad \ldots\ldots (3)$$

where V_{ex} is the extraction voltage,

M is the molecular weight of the ions, and

d is the distance between the extraction electrode and the plasma boundary.

The total theoretical ion current is equal to the current density, J, multiplied by the area of the plasma boundary (cm^2).

It should be noted that equation (3) was derived for protons only but, in practice, the ion beam contains monatomic ions, diatomic ions, etc. Thus, for a hydrogen plasma, a positive beam would have H_1^+, H_2^+, and H_3^+ and a negative beam would have electrons H_1^-, H_2^-, etc. Then equation (3) should be modified to read:

$$J^+ = J_1 + J_2 + J_3 \qquad \ldots\ldots (4)$$

where J_1, J_2, and J_3 are the current densities of H_1^+, H_2^+, and H_3^+ respectively.

Then $$J = 5.45 \times 10^{-8} \left(\frac{K_1}{m_1} + \frac{K_2}{m_2} + \frac{K_3}{m_3} \right) \frac{V_{ex}^{3/2}}{d^2} \text{ A/cm}^2 \quad \ldots\ldots (5)$$

Where m_1, m_2, and m_3 are the masses of H_1^+, H_2^+ and H_3^+ respectively, and

K_1, K_2, and K_3 are the concentrations of H_1^+, H_2^+, and H_3^+ respectively.

When extracting negative ions, electrons are also extracted. So, equations (4) and (5) are modified to:

$$J^- = J_{H_1^-} + J_e \quad \ldots\ldots (6)$$

$$= 5.45 \times 10^{-8} \frac{K_1^-}{m_1} + \frac{K_e}{m_e} 2.335 \times 10^{-6} \quad \ldots (7)$$

where $J_{H_1^-}$ and J_e are the current densities of H^- ions and electrons respectively, and

K_1^-, and K_e are the concentrations of negative ions and electrons.

The principle of the expanded plasma was first introduced by Gabovich. The plasma passes through a small aperture in the anode which restricts the gas flow from the source to the extraction region, and leads to a big plasma boundary which results in a large ion current. This method has the advantage of giving ion beam with low divergence (23). By assuming that the ion current is space charge limited, the electric field near the extraction electrode is

$$E = 5 \times 10^3 \, s^{-\frac{1}{2}} V_{ex}^{\frac{1}{4}} I^{\frac{1}{2}} \text{ V/cm} \quad \ldots\ldots (8)$$

where I is the total extracted current, and

s is the area of the expanded plasma boundary (22).

Equation (8) indicates that the electric field can be decreased by increasing the area of the plasma boundary. This improves the design of ion sources with expanded plasma, since the extraction voltage will be small for the required ion current. This helps to reduce breakdown in the extraction region which occurs at higher extraction voltage.

The same principle should hold for direct extraction of negative ions from the source, provided a sufficient number of H_1^- ions can be produced in the ion sheath.

The object of this project was to determine the conditions necessary to produce the required intensity of negative hydrogen ions.

Section II

THE EXPERIMENTAL APPARATUS

II-1. The present duoplasmatron ion source:

A diagram of the duoplasmatron ion source used throughout this investigation is shown in figure (3). This ion source was designed and built in the Physics department at the University of Manitoba.

The intermediate anode, constructed of mild steel, has a canal 11 mm. in length and 5 mm. in diameter at its end. Since the plasma density in the canal is relatively high, cooling is provided from the circulation of freon in grooves cut directly in the electrode. The magnet is housed inside a stainless steel can with freon running through it. This housing is designed so that a space is left between it and the intermediate electrode for additional cooling with freon. This helps in cooling the intermediate anode, the filament flange, and the magnet.

The anode was designed so that expansion cups of different shapes and materials could be installed. These expansion cups are also cooled by freon. The distance between the anode and the intermediate electrode is 3 mm. The electrodes are insulated from each other by a pyrex ring, while the screws used to fasten the parts together are insulated by teflon sleeves.

The extraction electrode, made of stainless steel, has been shaped so that, combined with the expansion cup, it forms a Pierce electrode system. The extraction gap can be varied by putting spacers

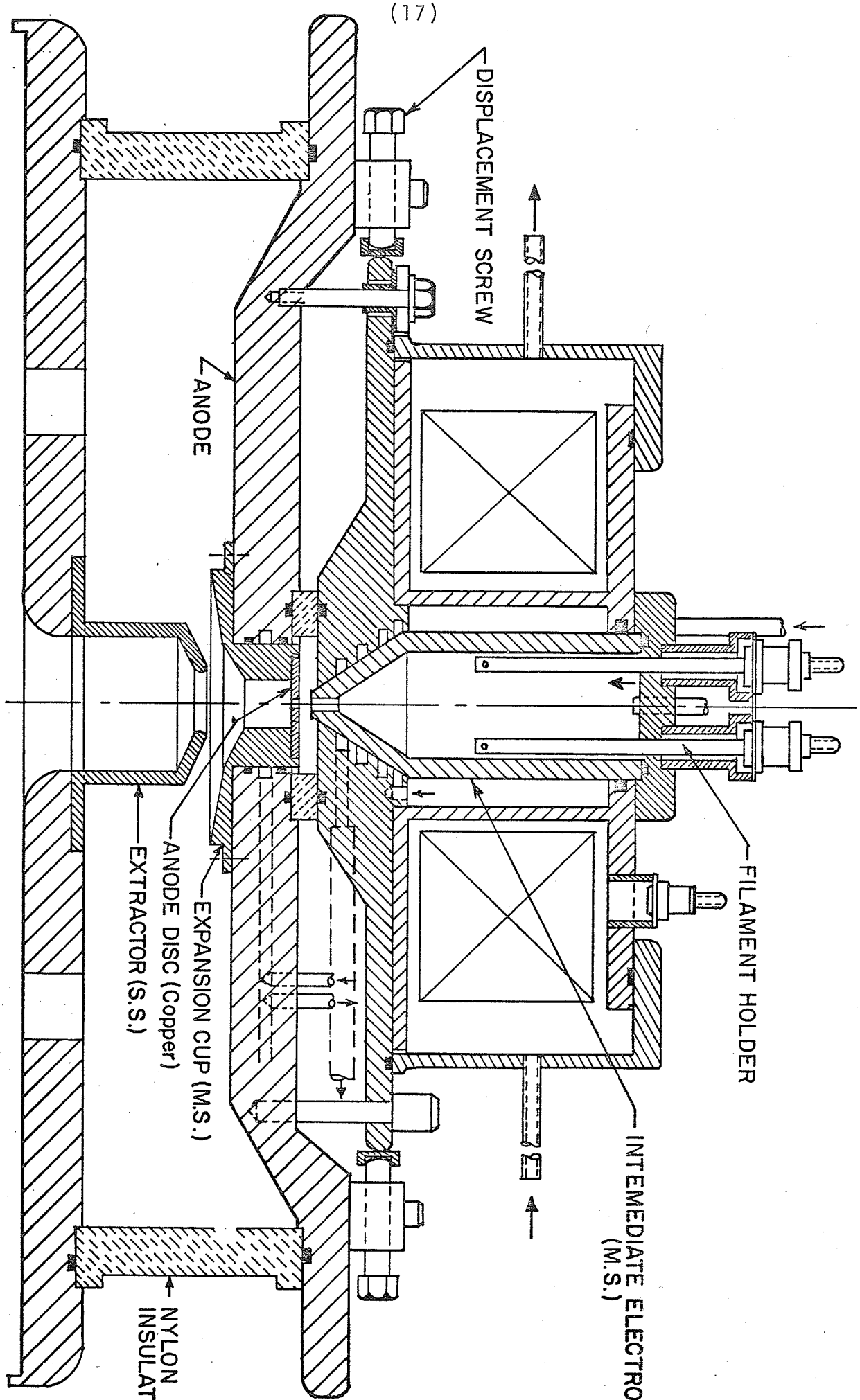

Fig.(3) Drawing of the Duoplasmatron Ion Source

under the extraction electrode.

Alignment of the intermediate electrode canal, the anode hole, and the extraction electrode is accomplished using two alignment screws.

Since the majority of negative ions are found off centre, the intermediate electrode can be moved slightly in two directions with respect to the anode. This is done by four screws through a block fastened to the anode and insulated from the intermediate anode by teflon sleeves.

An Ortec heat exchanger which uses freon as a coolant has been incorporated. The cooling lines are shown in the figure, while the direction of freon flow is indicated by the arrows in the figure.

Some experiments with the extraction system will be discussed later.

II-2. The experimental arrangement.

The ion source is fastened horizontally to a vacuum chamber. The system is evacuated by a 6" oil diffusion pump (2400 liters/sec.) which is backed by a 17.7 CFM mechanical pump. The base pressure in the vacuum chamber is 6×10^{-7} mm Hg.

The electrons which are extracted along with the negative ions are deflected by a transverse magnetic field of 100 Gauss produced by a magnet immediately following the extraction electrode. The ion beam is measured by a cooled Faraday cup.

A block diagram of the electrical circuit used in the experiment is shown in figure (4). All power supplies are isolated using a 30 KV isolating transformer. The power supplies are in a high voltage chassis which is isolated from the earth. The specifications of the power supplies are as follows: filament supply, 100 Amperes, 20V d.c.; magnet supply, 20 Amperes, 30 V d.c.; arc supply, a regulated current supply, 20 Amperes, 300 V. The rectifiers and transistors of the power supplies are cooled using deionized water.

The filament is an important part of the ion source due to the requirement of its having a long life. The filament used for the present ion source is an oxide coated type. Such a filament consists of a base metal coated with a mixture of metal carbonates. The carbonates are converted to oxides, and then to the pure metals by heating in order to produce good electron emitting materials. Filaments such as these have long lives and need little power for heating.

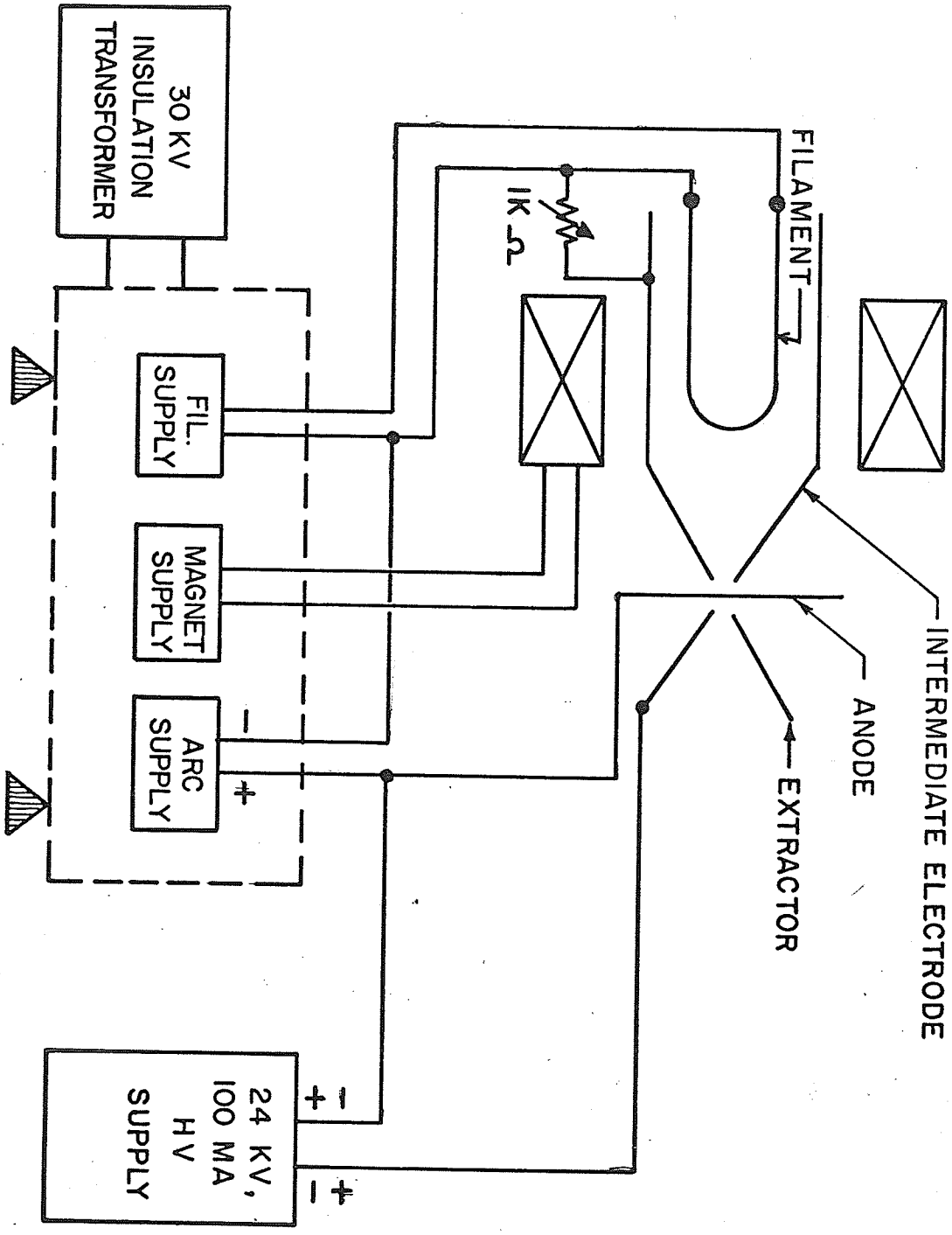

Fig.(4) A Block Diagram of the Electrical Circuit

The base metal used for the filament is pure nickel in the form of a minimesh with .005 cm. wire thickness and 0.005% transparency. The minimesh must be very clean since any small amount of impurities affects the activity of the filament and, accordingly, its life.

The emissive material consists of a mixture of 70 gm. cobalt-free Ni powder, 17.15 gm. $SrCO_3$ (pro analisi), and 12.85 gm. $BaCO_3$ (pro analisi). The powders are mixed for six hours in a porcelain container with 100 ml. amylacetate. After mixing, the amylacetate is allowed to evaporate until a pasty consistency is obtained. The mixture is then ready for use.

The filament consists of two layers of the nickel mesh 10 cm. in length and 1 cm. wide, with the edges spot welded together. Using a brush, the mesh is coated with a very thin layer of the carbonate mixture. The thickness of the layer should be such that the grid structure is just obscured. The filament is dried slowly, using a hair dryer. At this stage, the coating is extremely fragile. The filament is put in the source under vacuum for activation.

During the activation process, the carbonates are converted to oxides, and the oxides to pure metals. It is found that the degree of filament activity depends upon the care taken in this process. The activation process is started by slowly heating the filament in steps while keeping the pressure less than 10^{-4} Torr, until there is no further degassing. Then all the carbonates are presumably converted to oxides. At this stage, several 10 second flashes were made, then hydrogen was introduced and arc voltage applied. The arc was established, and a filament which showed an arc voltage greater than 80 V was considered to be good.

No definite lifetime for the filament is known, but it can be mentioned that the lifetime is approximately a few hundred hours if the filament is not exposed to air for a long time. If it has been exposed to air for a short time, it can be used again satisfactorily by cementing the cracks with a suspension of the mixture of carbonates in amylacetate.

II-3. The beam emittance:

The beam emittance is defined in the standard manner, based on Liouville's theorem. This states that if a group of particles is moving under the action of forces derivable from a Hamiltonian, the local density of the representative points in phase space remains everywhere constant. Then the hypervolume of the region containing all the points also remains constant. That is,

$$\text{div } n = 0$$

and $$\int dV_n = \text{const.}$$

where n is the local density of points in the phase space, and

dV_n is an n-dimensional phase space element.

For simplicity, it can be assumed that the three components of motion in phase space are confined to three planes, (x,p_x), (y,p_y), and (z,p_z), so that the integrals

$$I_x = \int dx dp_x,$$
$$I_y = \int dy dp_y, \text{ and}$$
$$I_z = \int dz dp_z$$

remain constant according to Liouville's theorem. The emittance of the beam is then proportional to this area. The emittance is conserved in any linear or nonlinear transport system.

It is convenient to use the normalized emittance (23) which is defined by

$$E = \frac{\text{Area of the two dimensional phase space}}{\pi} = E\beta\gamma \text{ cm-mrad.}$$

where $\beta = \frac{v}{c}$, and

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Because the extraction voltage is only 17 kV, γ can be neglected.

The simplest method of measuring the beam emittance is shown in figure (5). A thin plate with a series of pinholes in it is placed in the beam. The beam passing through each pinhole is received, after a suitable drift distance, on a photosensitive surface which produces a visible image after exposure to the beam. Almost any surface will produce some sort of image, but a clear image can be produced in a reasonable time by using copy paper of the type intended for copying machines. Negative paper is used because it is insensitive to visible light.

At first, two perpendicular rows of pinholes are used. Each row has six pinholes with a diameter of 13.5 thousandths of an inch and 5 mm. apart.

The technique of calculating the beam emittance is illustrated in figure (6). By plotting the distance between θ_1, θ_2 against the positions of the pinholes, an emittance curve can be obtained.

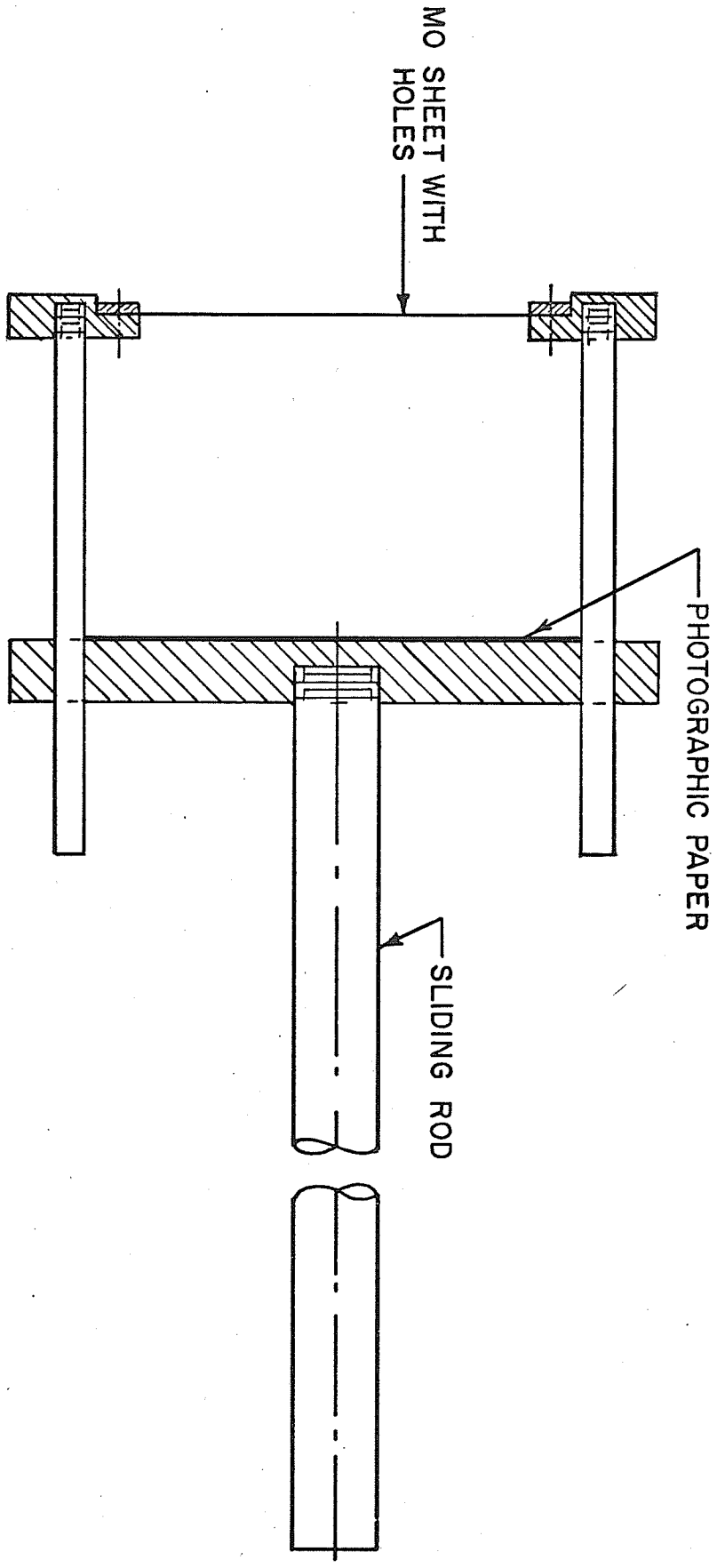

Fig. (5) Arrangement of Emittance Measuring Device

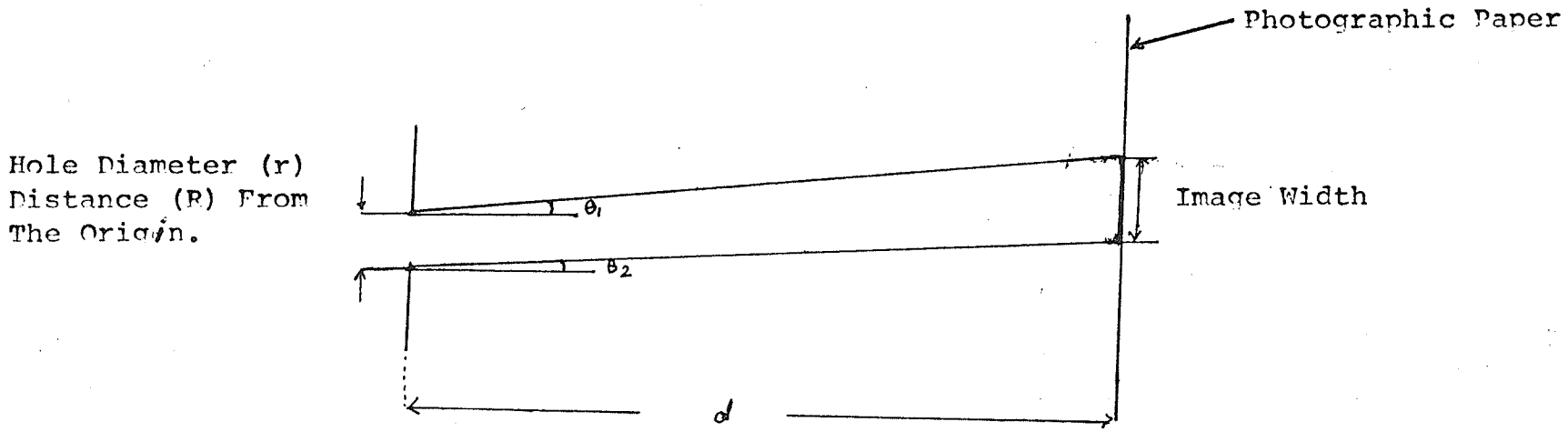

FIG.6. ILLUSTRATING DIAGRAM OF CALCULATING THE BEEM EMITTANCE.

Section III

EXPERIMENTAL RESULTS

III-1. Preliminary results:

During the early stage of testing the ion source, it was useful to start by extracting positive ions. The following preliminary results were taken by using a copper expansion cup 0.7 inches in diameter and 1 inch in length, placed 3 inches behind the extraction electrode. The diameter of the anode hole is 1 mm., and the extraction gap is 0.25 inches (see figure 3). The pressure was measured at the vacuum chamber and was not corrected for hydrogen.

Figures (7) and (8) show the relation between the extracted positive ion current and the extraction voltage at different pressures and discharge currents. The magnetic field was varied to get maximum current. Although 100 mA of positive ion current was obtained, the beam was quite divergent.

Figure (9) shows a family of curves demonstrating the relationship between the extracting ion current and the magnetic field strength at different extraction voltages. The discharge current and the pressure were kept constant. There is an optimum magnetic field for each setting of the extraction voltage. Increasing the magnetic field beyond its optimum value results in arcing in the extraction gap. This is probably due to the fact that the penetration of the magnetic field into the expansion cup deforms the shape of the plasma boundary.

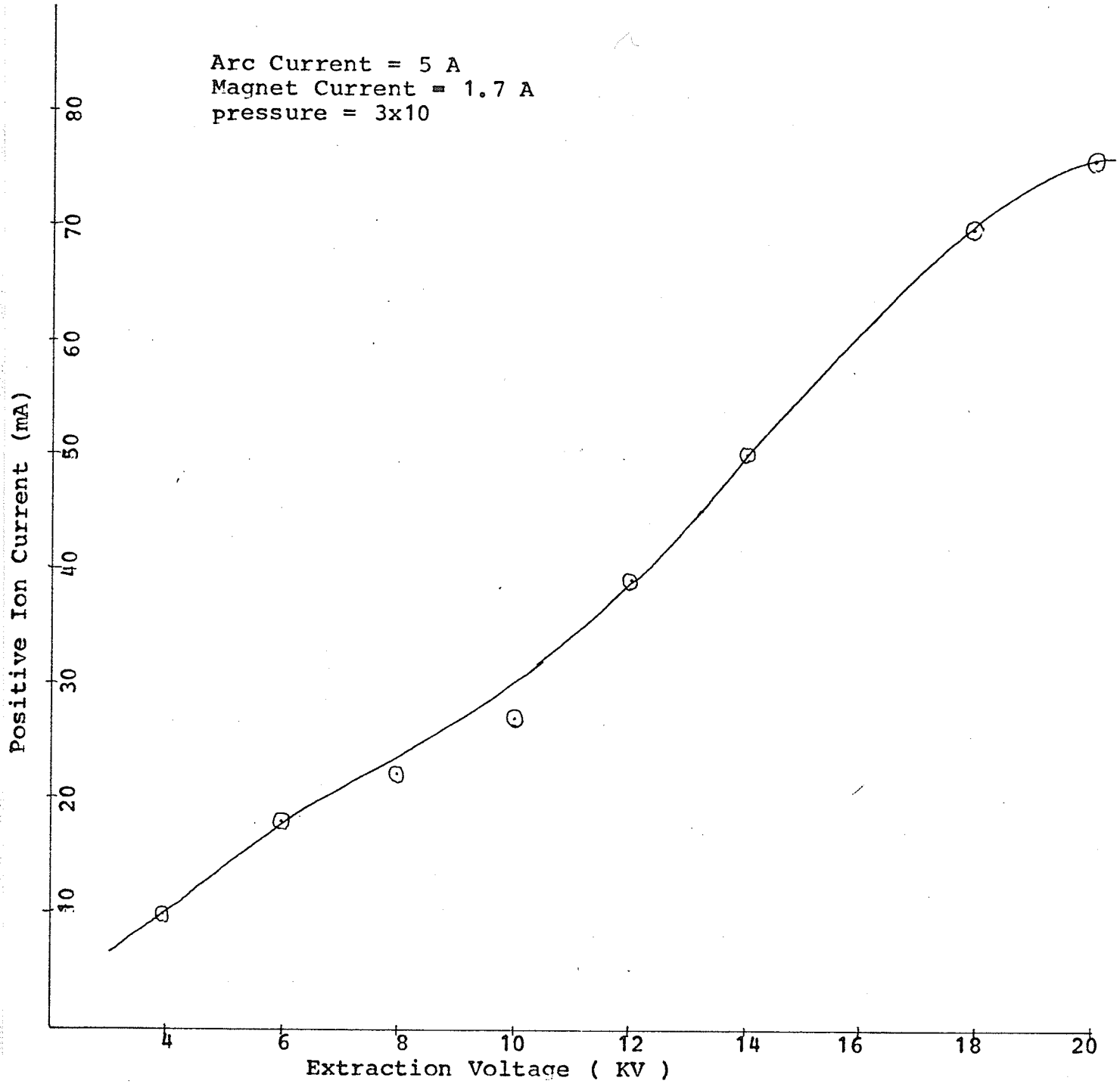

FIG.7. THE RELATION BETWEEN THE POSITIVE ION CURRENT AND THE EXTRACTION VOLTAGE.

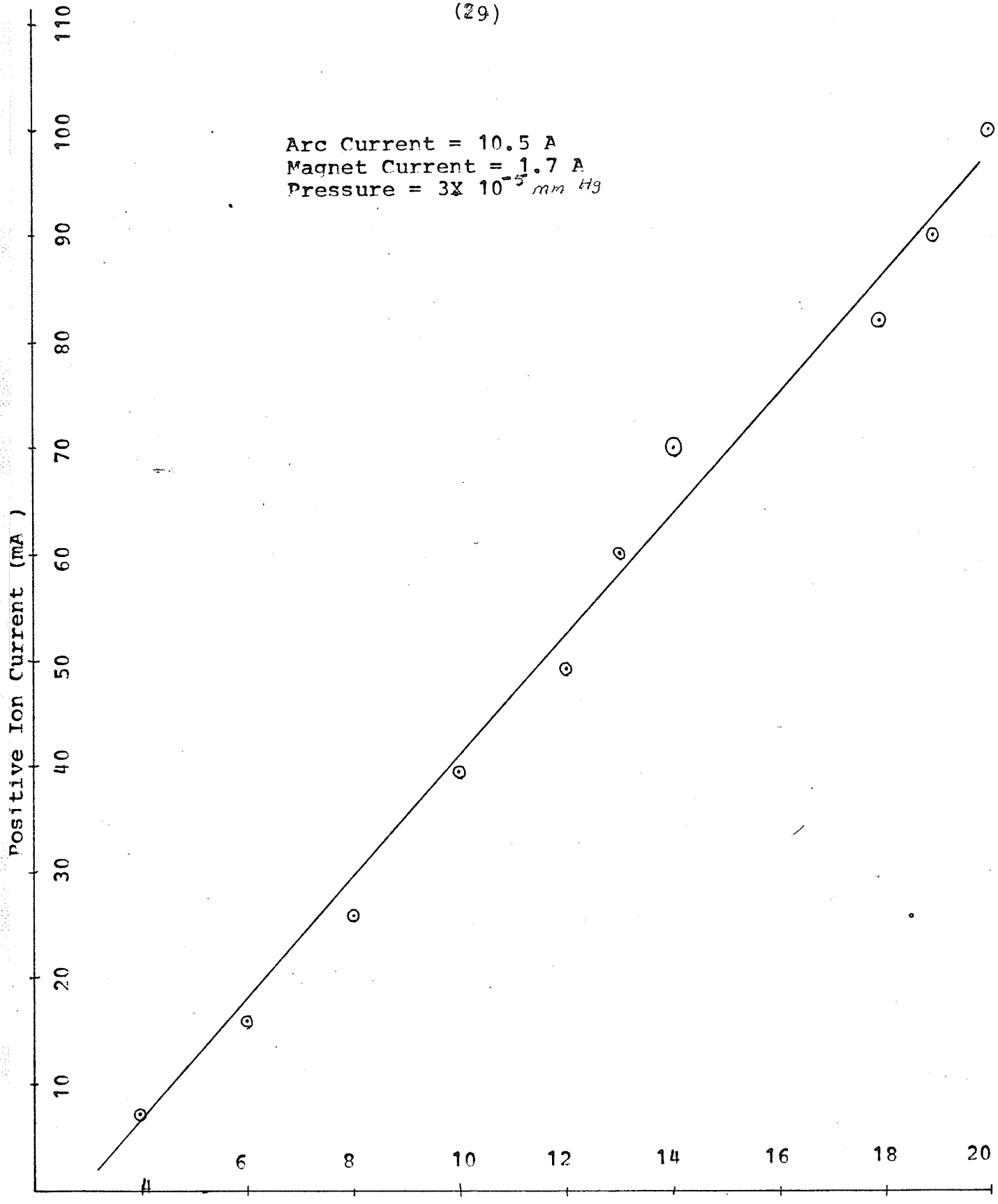

FIG.8. THE RELATION BETWEEN THE POSITIVE ION CURRENT AND THE EXTRACTION VOLTAGE.

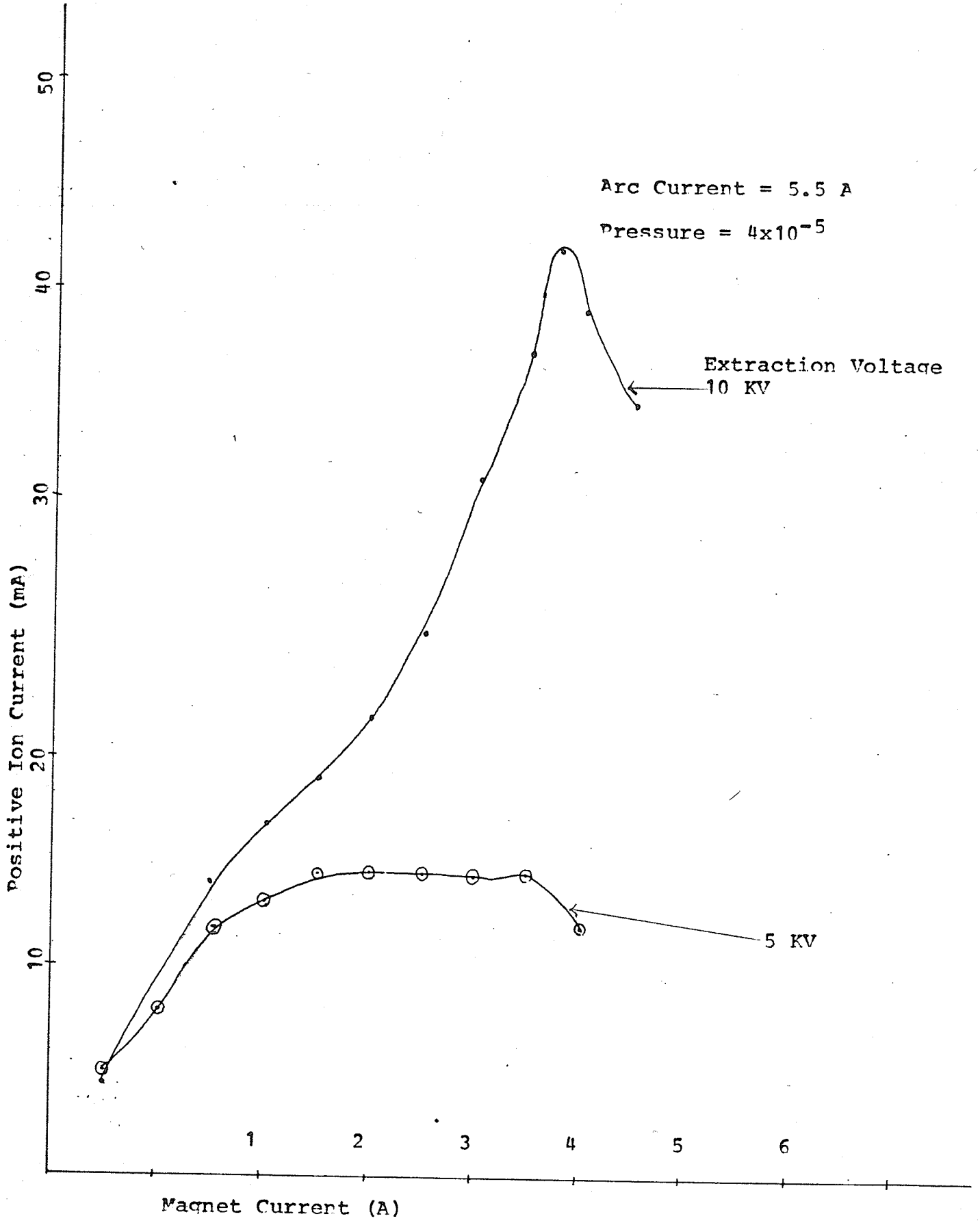

FIG.9. THE RELATION BETWEEN THE POSITIVE ION CURRENT AND THE ION SOURCE MAGNETIC FIELD.

Figure (10) shows the relation of the ion current to the gas pressure. There are two peaks in the curve. The peak at the high pressure is probably due to the formation of multi-hydrogen ions, (H_2^+ and H_3^+).

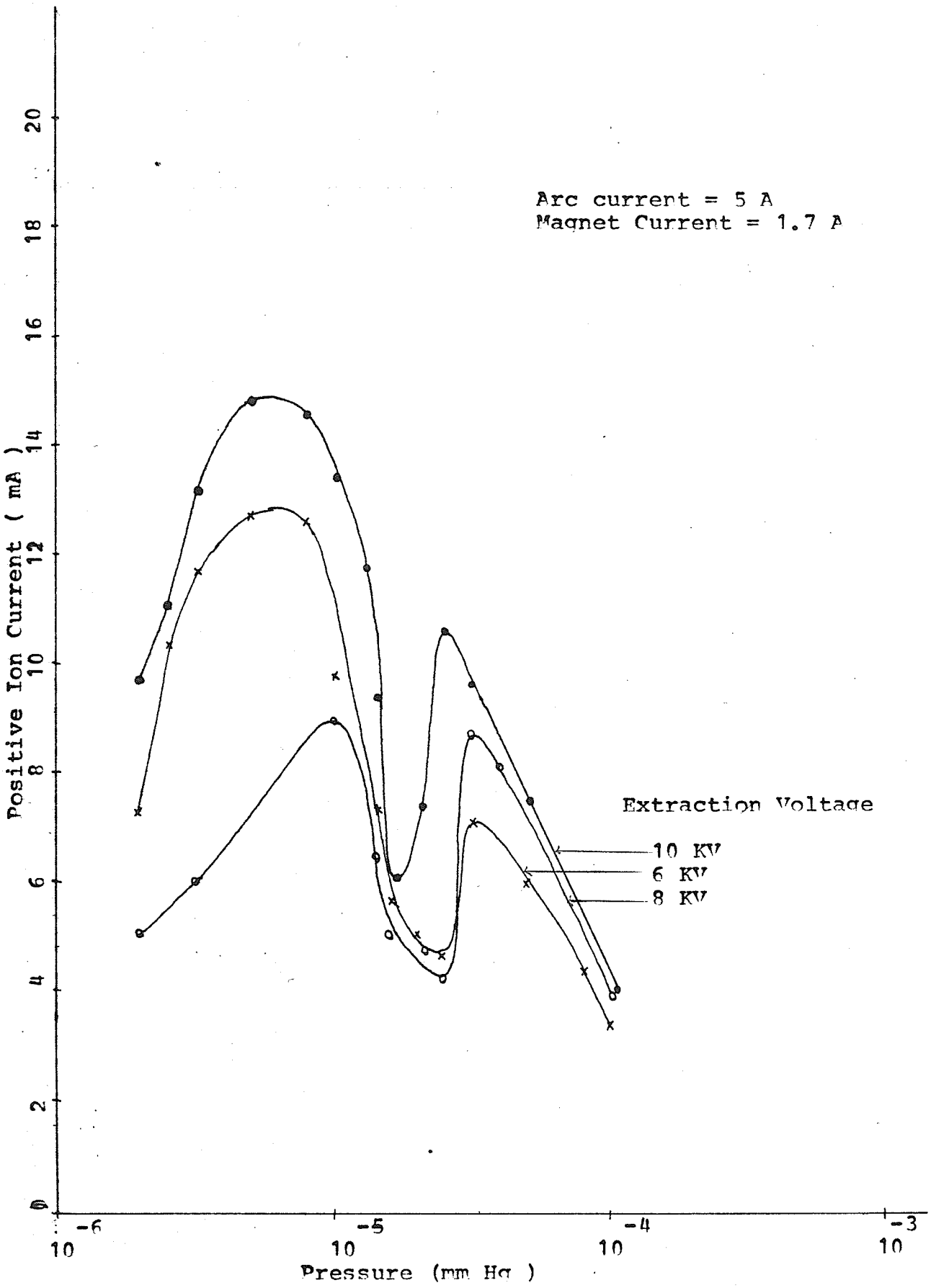

FIG. 10. THE RELATION BETWEEN THE EXTRACTED POSITIVE ION CURRENT AND GAS PRESSURE.

III-2. Results with a small expansion cup:

To avoid the large electron current extracted from the ion source when working with negative ions, a small expansion cup was installed. Also, an Einzel lens was used to properly focus the ion beam. The Einzel lens consists of three elements, with the extraction electrode used as the first element. This lens was designed so that its focal point is constant at different beam energies since the Einzel lens potential is the same as the extraction voltage.

Emittance measurements were taken for positive ions by using the above technique. For these measurements, a current of 3 mA of positive ions was extracted from an anode hole of .020 inches. The distance between the disc carrying the pinholes and the photographic paper was 47.4 mm. The holes were placed 5 inches from the Einzel lens. The size of the images of the pinholes on the photographic paper was measured using a travelling microscope, and the angles θ_1 and θ_2 given below (24) were computed using the following equations.

$$\theta_1 = \tan^{-1} \left[(y + \tfrac{1}{2}w) - (x + \tfrac{1}{2}d)\right] /L$$

$$\theta_2 = \tan^{-1} \left[(y - \tfrac{1}{2}w) - (x - \tfrac{1}{2}d)\right] /L$$

where d is the hole diameter,

w is the image width,

x is the distance between the axis and the hole centre, and

y is the distance between the axis and the image centre.

Figure (11) contains an emittance diagram of 1 mA beam current at 17 *Kv* beam energy. A normalized beam emittance of 0.2 mm-mrad. has been obtained.

III-3. Negative ion extraction using the small expansion cup:

During this study, it was found that the extracted electron beam ionized the residual gas immediately following the extraction electrode, causing breakdown in the region of the Einzel lens. Thus the work was done without benefit of this lens.

A further difficulty encountered concerned the emission of secondary electrons from the Faraday cup. If I_T is the true current hitting the Faraday cup, I_e the secondary electron current, and I is the measured current, then:

$$I_e = \gamma I_T \qquad \ldots\ldots (9)$$

$$I = I_T + \gamma I_T \qquad \ldots\ldots (10)$$

$$I_T = \frac{1}{1 + \gamma} \qquad \ldots\ldots (11)$$

where γ is the secondary electron emission coefficient, which depends on the beam energy and the target conditions.

Equation (11) was derived assuming that all secondary electrons escape from the cup. It reflects the fact that the current measured is much less than the actual extracted ion current. Many of the secondary electrons travel back to the ion source, causing breakdown. This fact explains why breakdown occurred in the extraction gap when alignment was not good or when the extraction gap was not at its proper value.

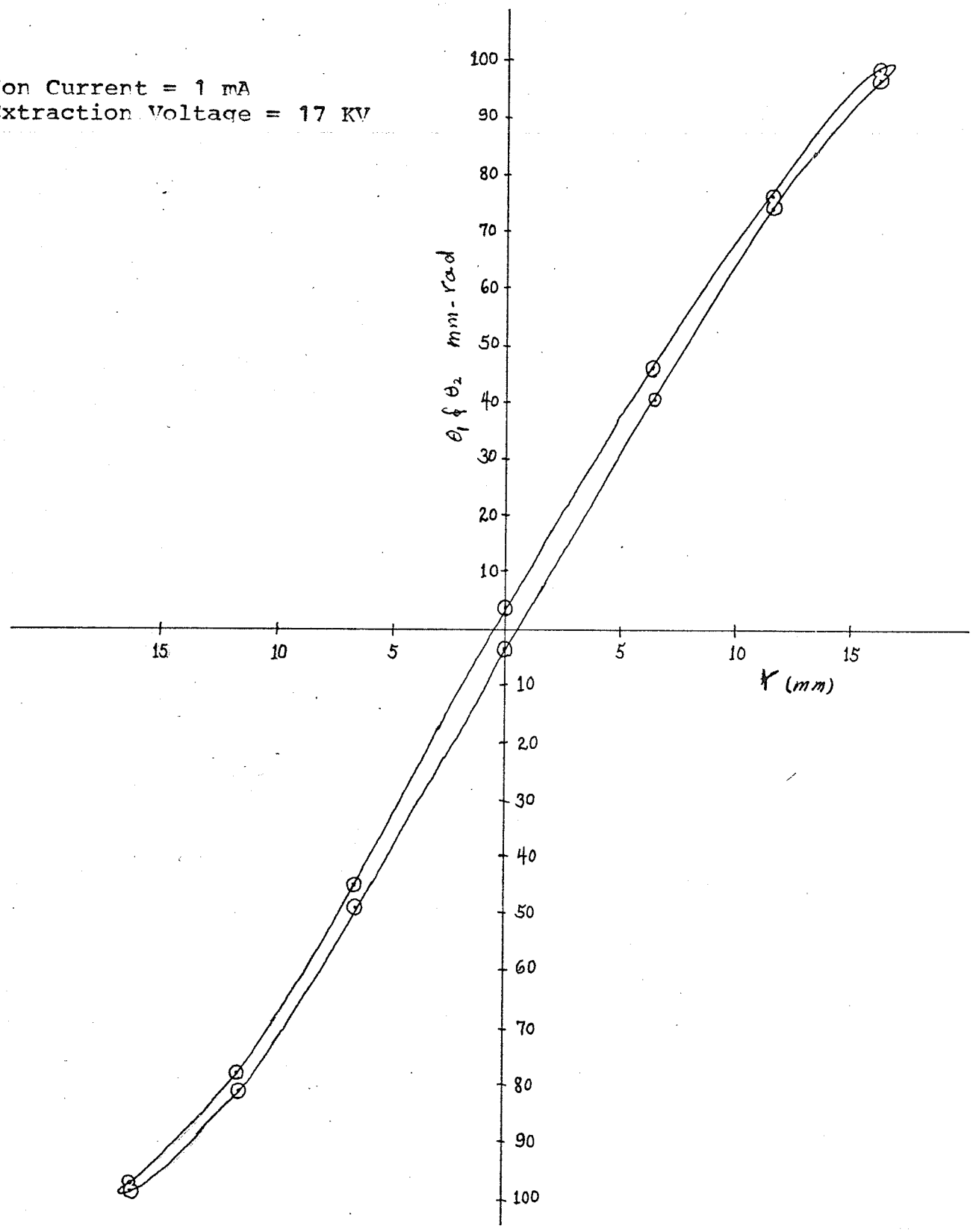

FIG.11 .EMITTANCE PLOT OF THE POSITIVE ION BEAM.

Due to the above difficulties, the Faraday cup was redesigned (figure 12). A ring has been placed in front of the Faraday cup and biased negatively to repel electrons from both directions. The entire system has been placed inside a shielding cylinder which is grounded. This collects electrons after deflection by the sweeping magnet located 2 inches downstream from the Einzel lens. When this design was used, ionization of the residual gas disappeared. However, some of the secondary electrons emitted from the shield still reached the Einzel lens, causing breakdown. By placing the sweeping magnet further from the Einzel lens (see fig. 13), these electrons were deflected through 30^{o} and removed from the system, thus avoiding breakdown. To rid the system of oil vapour coming from the diffusion pump, a coil of copper tubing through which cooling water is passed has been placed on the top of the diffusion pump to act as a baffle. This cooling system helps but it is not as effective as is desired, and it is intended to replace it by a baffle of better design. With the modifications mentioned, the behaviour of the Einzel lens was much improved.

To investigate the negative ion current from the ion source, it is essential to extract off axis to get the maximum number of negative ions while minimizing unwanted electron current. Arbitrary units have been used for measuring the displacement of the intermediate electrode. However, it should be mentioned that the distance of this movement is critical and that the alignment mechanism could be improved. Centre is defined by the location of

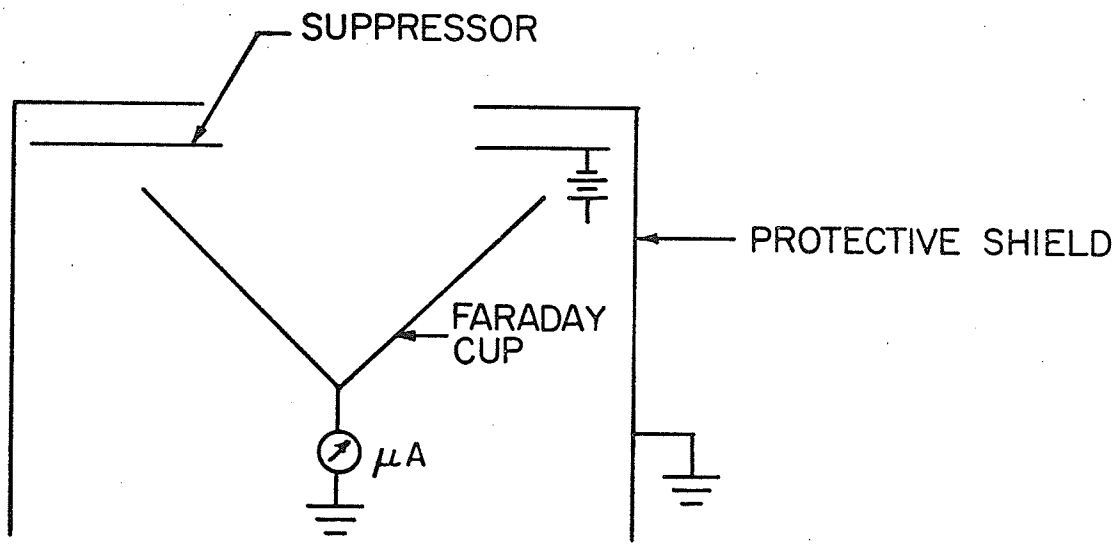

FIG. (12) Modified Faraday Cup

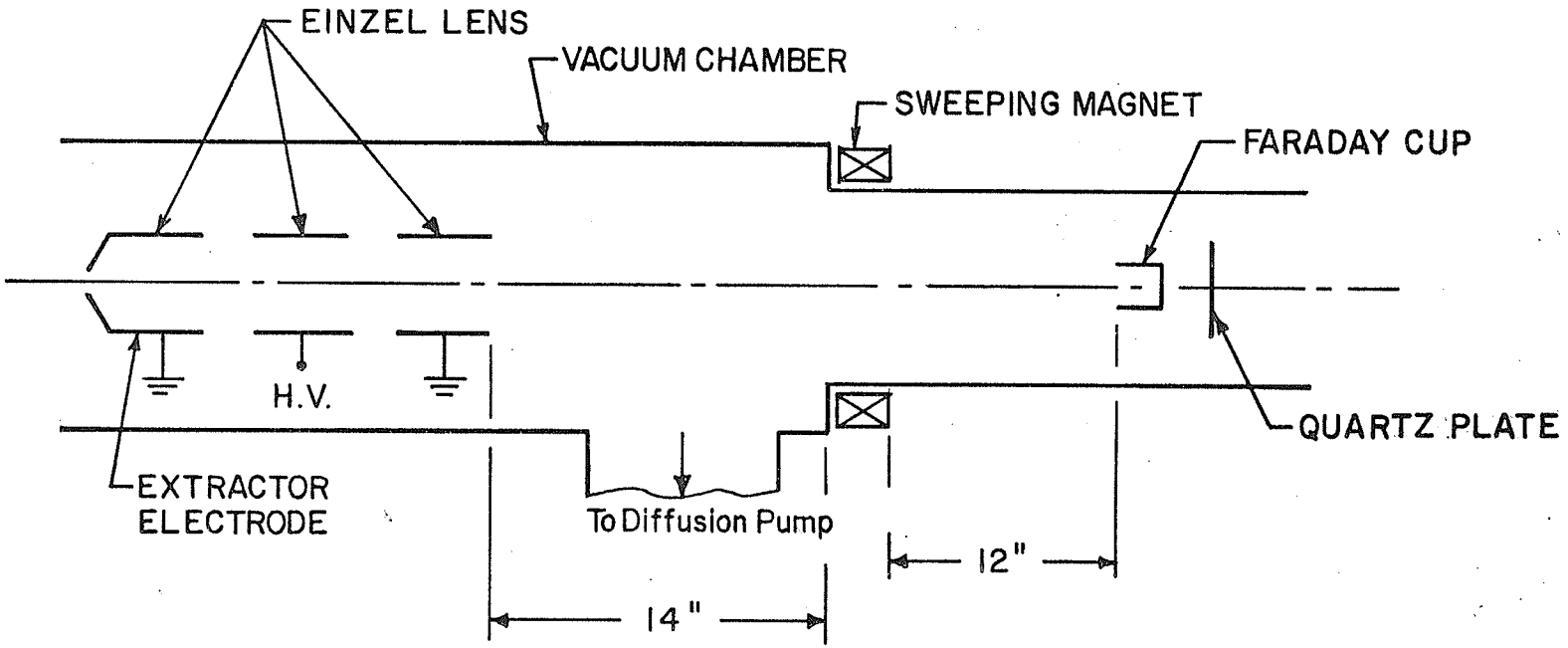

Fig.(13) Schematic Diagram Showing the Locations of the Einzel Lens, Sweeping Magnet, Faraday Cup, and the Quartz Plate.

the alignment pins. This is not necessarily the position where the anode hole is in best alignment with the intermediate electrode. Evidence for this misalignment is the fact that the discoloration on the anode disc is off centre, and that low positive ion beams are extracted when alignment is defined by these pins.

Figure (14) shows the effect of deflecting the electrons. The intermediate electrode was positioned for maximum negative ion production. The parameters which were kept constant during the experiment are listed on the diagram. The magnet current was set at 3.5 A (plateau) during all the following experiments.

Figure (15) shows the relation between the negative hydrogen ion and electron currents and the distance off centre of the intermediate electrode. It was found that the negative ion current has a peak as the electron current drops.

The effect of the source magnetic field, arc current, and gas pressure on the extracted negative ion current were investigated, and the results are shown in figures 16,17, and 18. The parameters which were kept constant for each experiment are shown in the figures. At high magnetic field (3A exciting current), H_1^- current appears to increase slowly, while it increases with increasing arc current. No attempt was made to extract negative ions at high arc current because of the dangers of high electron loading. The negative ion current has a peak at 1.9×10^{-6} mm. Hg pressure measured at the vacuum chamber.

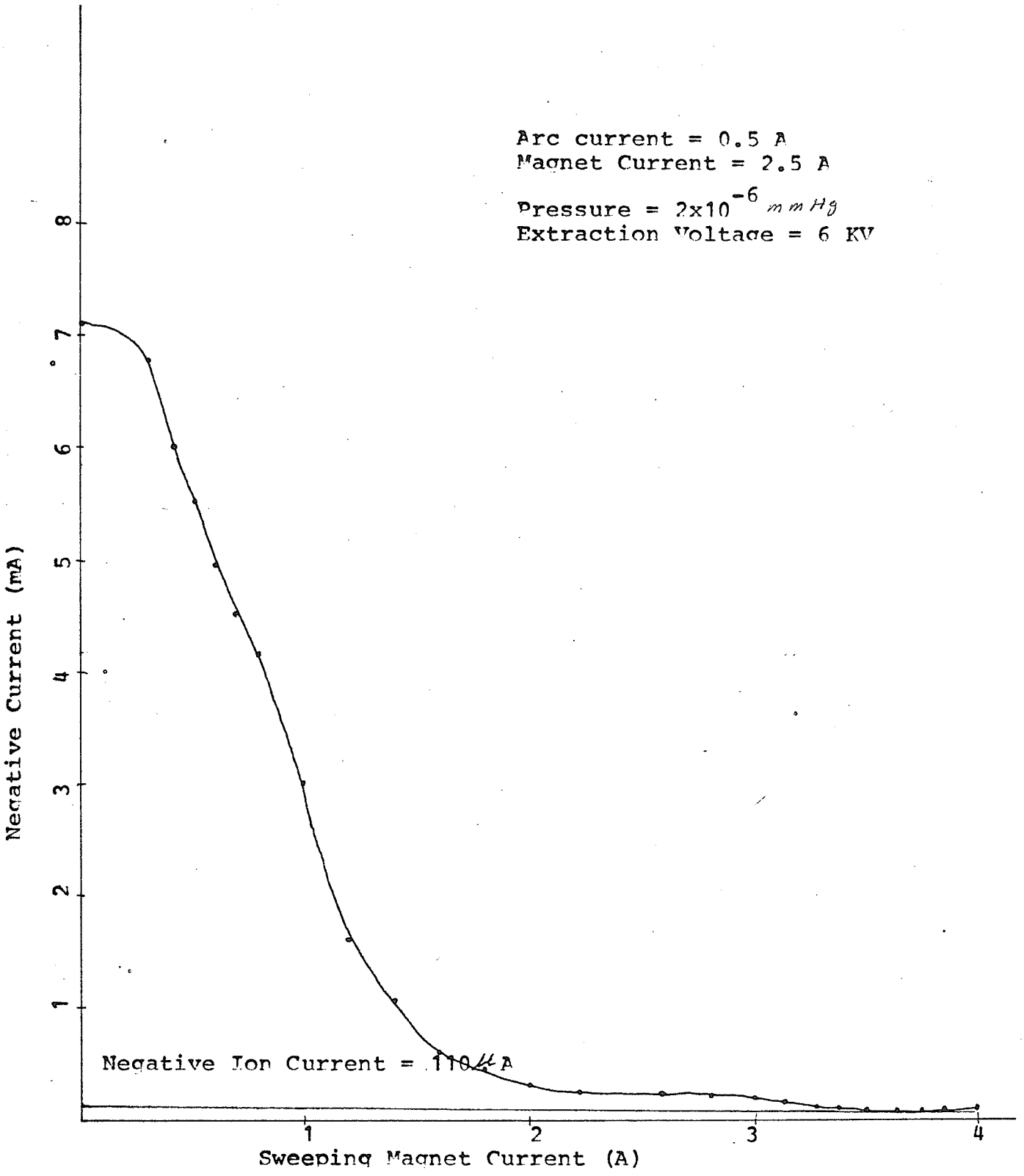

FIG.14. THERELATION BETWEEN THE NEGATIVE CURRENT AND SWEEPING MAGNET CURRENT.

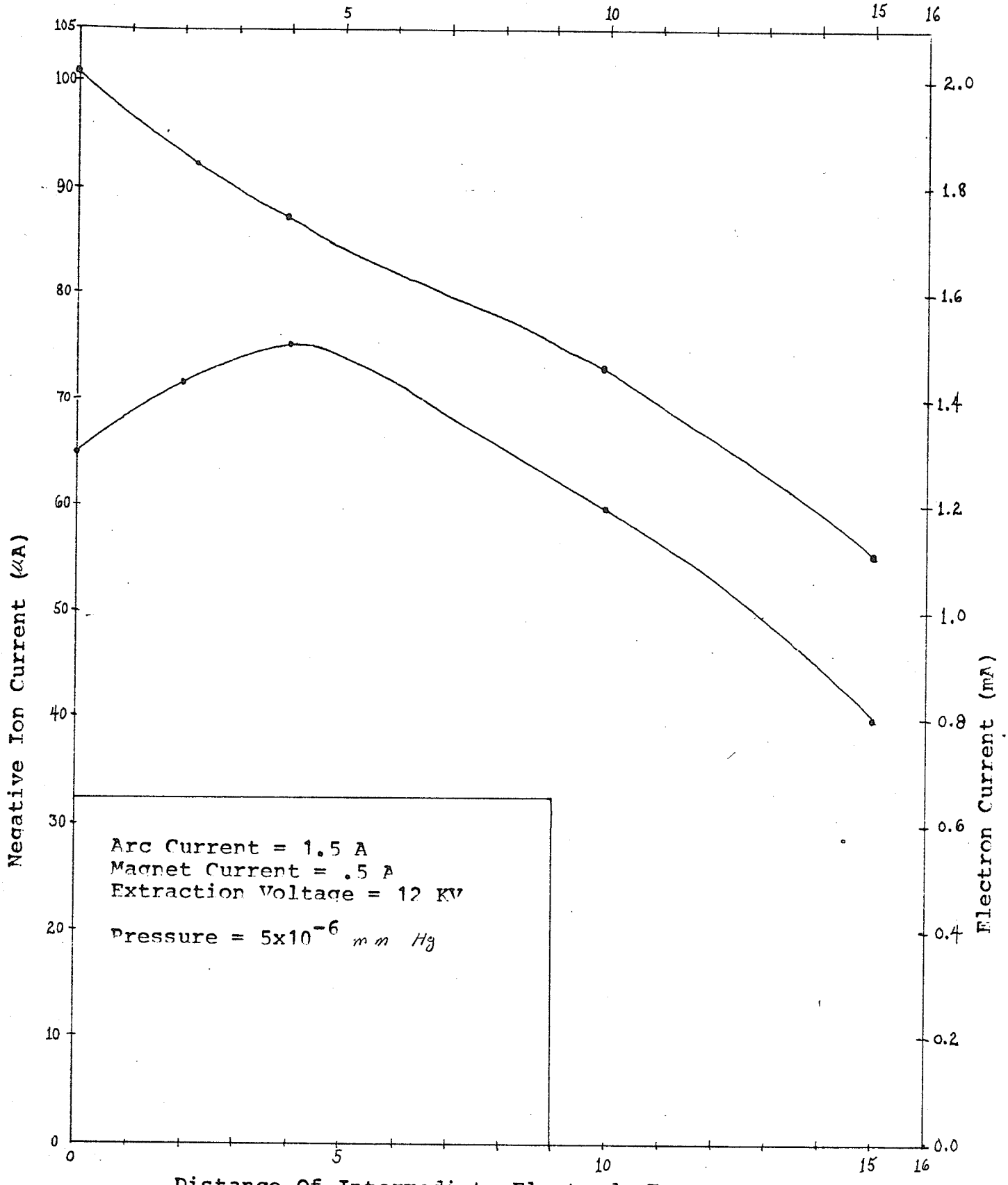

FIG. 15. THE RELATION BETWEEN THE NEGATIVE ION & ELECTRON CURRENTS AND THE INTERMEDIATE ELECTRODE DISPLACEMENT.

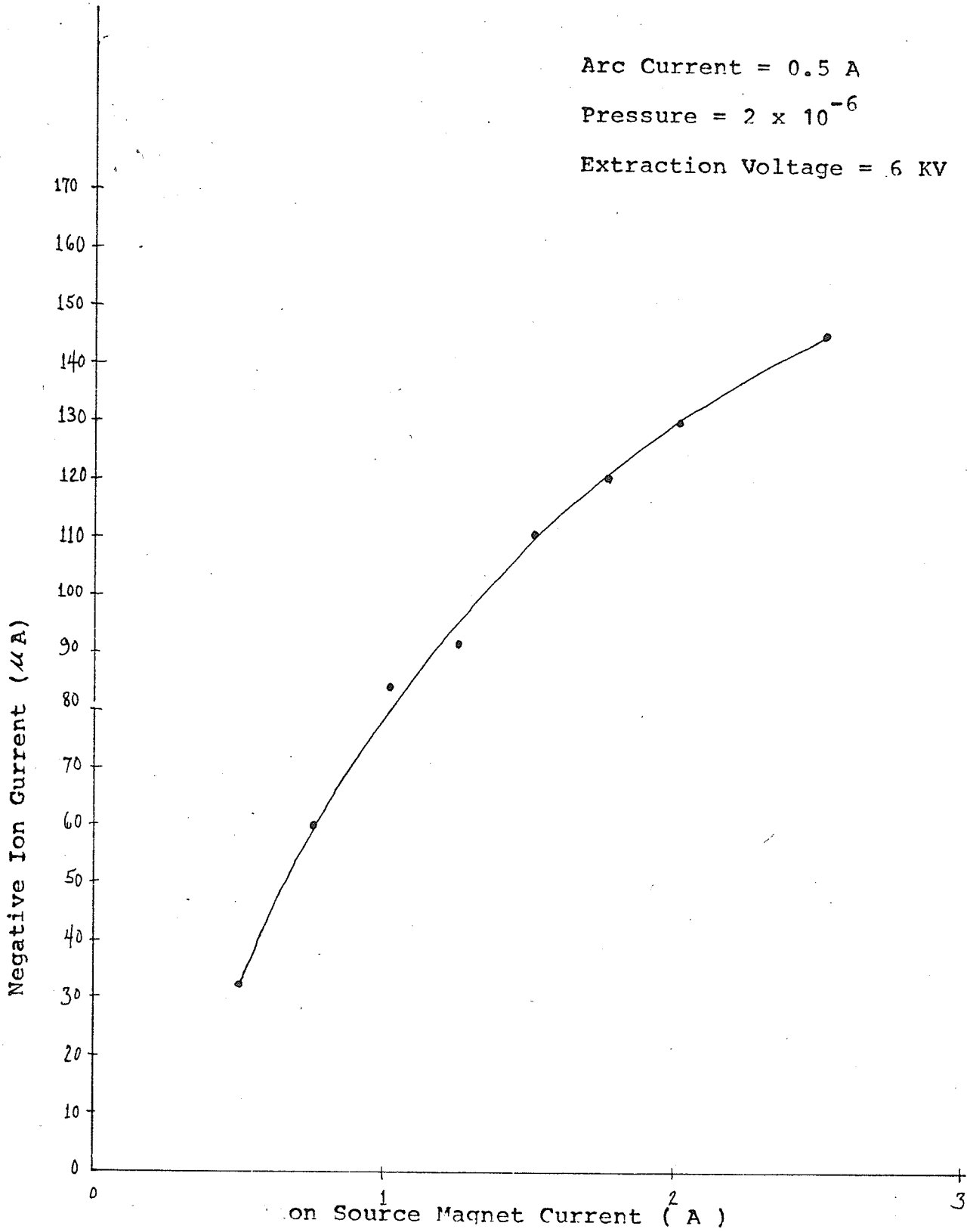

FIG.16. THE RELATION BETWEEN THE NEGATIVE ION CURRENT AND THE ION SOURCE MAGNET CURRENT

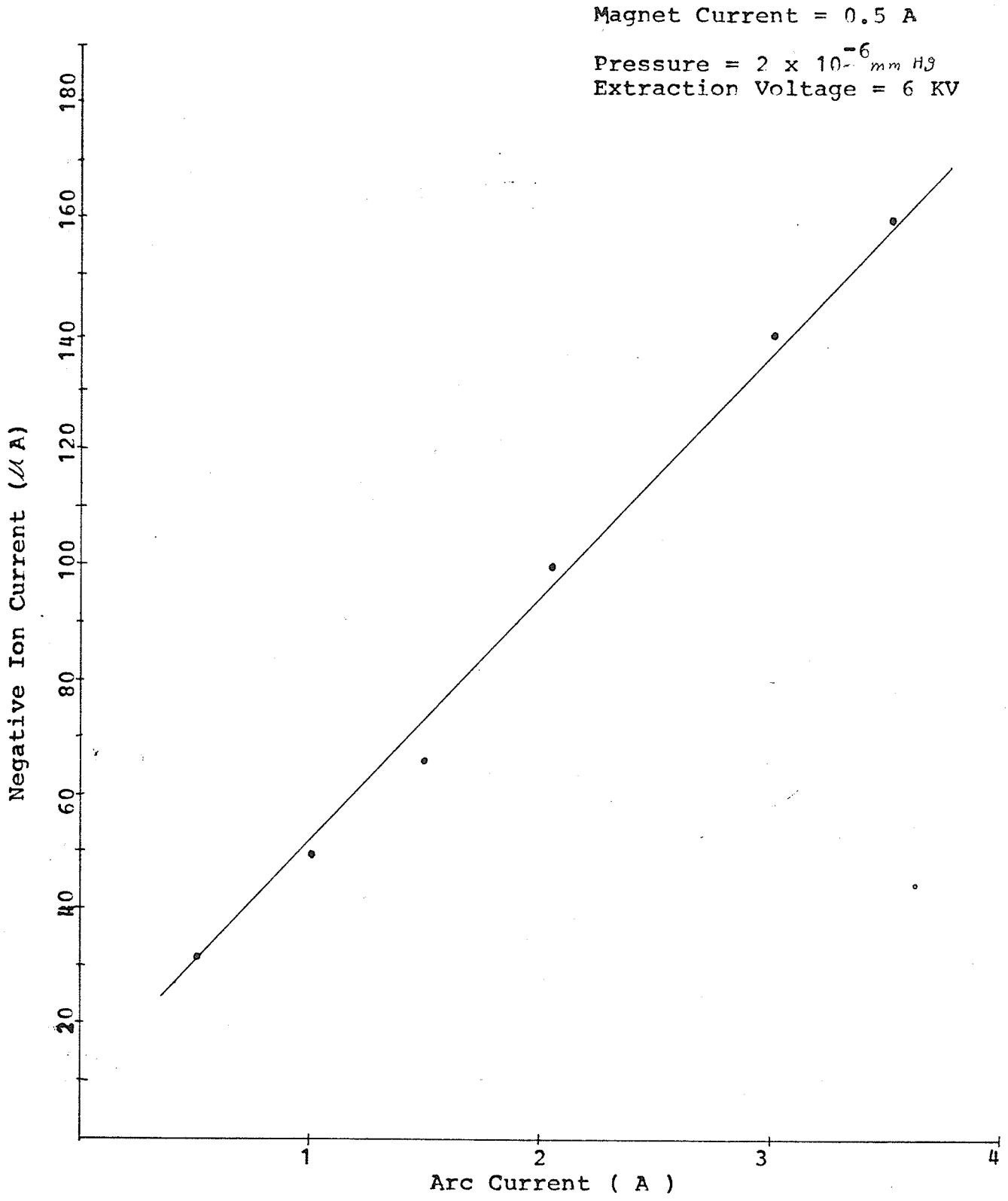

FIG. 17. THE RELATION BETWEEN THE NEGATIVE ION CURRENT AND THE ARC CURRENT.

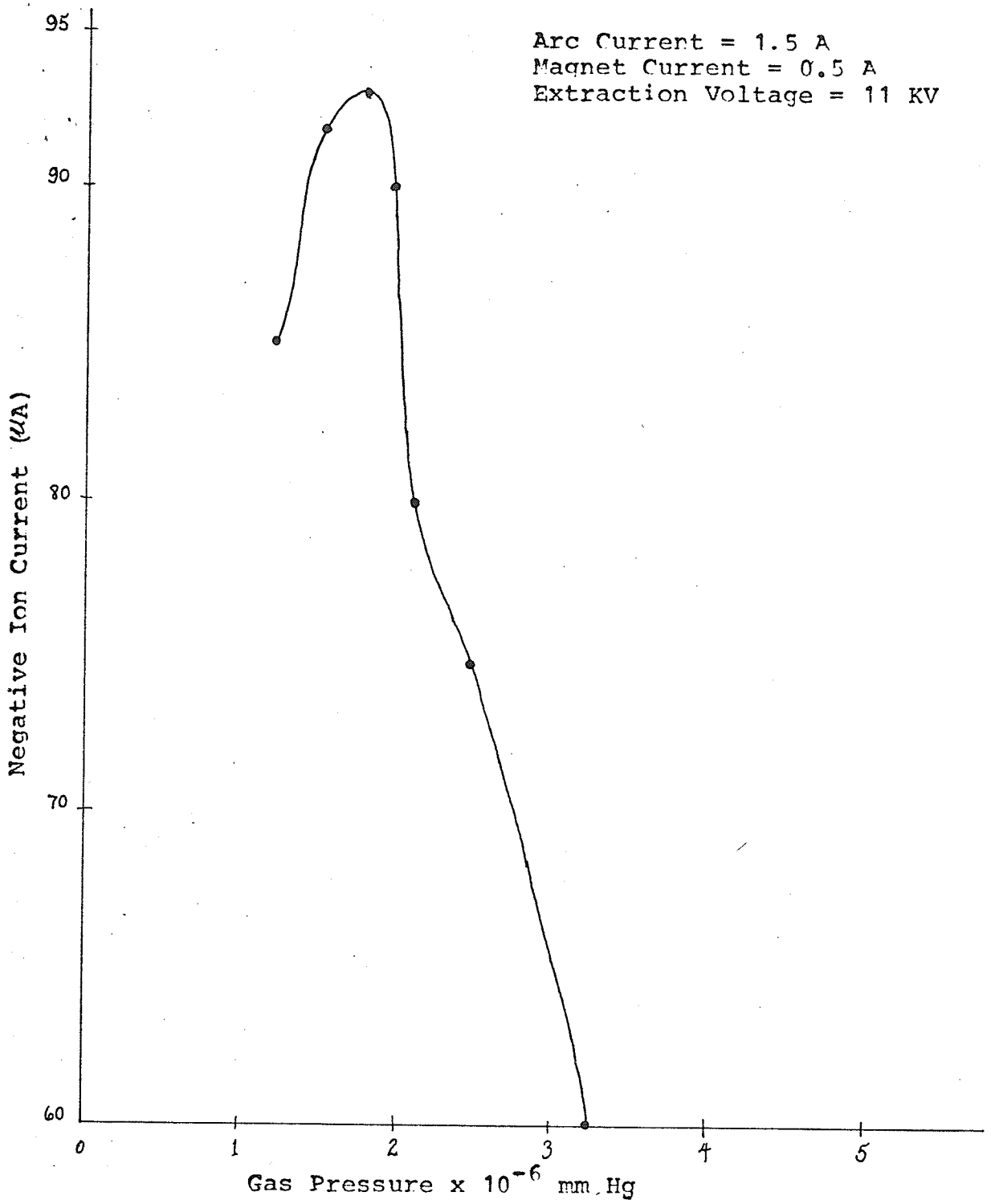

FIG.18. THE RELATION BETWEEN THE NEGATIVE ION CURRENT AND THE GAS PRESSURE.

Summary

The present development and investigation of the University of Manitoba Duoplasmatron Ion Source has given encouraging results.

In designing the ion source, special attention was given to the cooling of internal parts, such as the intermediate anode and the anode. As a result, there have not been any heating problems. The filament life is fairly long, which is of interest as far as the cyclotron operation is concerned. Tantalum was originally used for the anode disc. However, due to rapid deterioration, the tantalum disc was replaced by a copper one which was found to be more satisfactory.

The ion source was tested by first producing a positive hydrogen beam. 100 mA of positive beam can be obtained when using an expansion cup of 0.7" diameter and 0.8" length. The anode hole is 0.05". The effects of gas pressure and source magnetic field on the positive hydrogen current were investigated.

The ion source was then tested for the production of negative hydrogen beam (H_1^-). It was essential to use a small expansion cup with a small anode hole (0.020" in diameter). By displacing the the intermediate electrode off centre, up to 150 μA of negative hydrogen beam was obtained. The figure for the ion current may be 10%- 20% less than the actual current due to secondary electrons emitted from the Faraday cup.

The effects of changes in the arc current and gas pressure were also investigated. H_1^- current appeared to increase with increasing arc current, and it increased slowly by increasing the source magnet current above 3 A. It was noticed that the beam spot on a quartz plate was distorted if the source magnet current was increased above approximately 1 A. However, it is still possible to get 150 μA of

H_1^- beam by adjusting the gas pressure and the arc current, and leaving the magnet current below 1 A.

The results seem to be in reasonable agreement with those of other investigators.

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