THE PRODUCTION OF POSITIVE IONS
IN
RESONANT CAVITIES

Thesis by

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ABSTRACT

An extensive series of experiments designed to yield information on the mechanisms of ultra-high frequency discharges is described. The main conclusions are that such discharges exhibit a high negative space charge due to secondary electron emission from the walls of the cavity and that ion production is inhibited by the space charge trap so formed, that under certain conditions extremely intense electron beams may be obtained from a resonant cavity, and that fairly large ion currents may be obtained by the interaction of the emergent gas and the emergent electron beam in the exit orifice of the cavity.

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INTRODUCTION

This research is in a field in which there is still a great dearth of information. Consequently it was originally almost entirely exploratory in nature. As a result, a great number of observations were initially made to provide background information and clues regarding the mechanisms involved. Many of these early measurements, while not without interest, have now become of somewhat secondary importance to the main point of this thesis. In order to avoid obscuring the main trend of the thesis in a welter of detail, some of these measurements have been given in appendices. Other observations reported in appendices for the same reason are those describing general observations, providing detailed explanations for some of the effects observed, etc.

STATEMENT OF THE PROBLEM

Ion sources are integral parts of some of the most important analytical and research instruments now in use. Furthermore, it is very often the case that imperfect performance on the part of the ion source is the chief factor which limits the overall performance of the instrument as a whole. For that reason, the improvement of ion sources is an ever-current problem.

Obviously, sound ion source design must rest on an understanding of the mechanisms by which ions are produced and expelled from a source chamber. Even now, the operation of ion sources employing steady or slowly varying voltages very often eludes ready explanation, especially in the presence of magnetic fields and particularly in cases where high space charges are involved.

Even less well understood are discharges in which the fields employed are of sufficiently high frequency that transit times become important. The frequencies at which these effects enter depend, naturally, on the dimensions and operating pressure of the ion source under consideration; generally speaking, this frequency range extends upward from about 100 megacycles, and for ion sources of convenient dimensions ranges upward from about 300 megacycles. Only within very recent years have vacuum tubes been available from which reasonable amounts of power could be derived at these frequencies, and only during and since the recent war has there been appreciable interest in the mechanisms of ultra-high frequency ionization. Some work on this subject, started during the war, was done(1) to aid in the design of high-power wave guides in such a way as to prevent internal sparking. More recently, Margenau(2,3) and his co-workers(4,5), and Herlin and Brown(6,7) have extended both experimental and theoretical work to lower pressures in order to gain an understanding of some of the basic processes involved. Some of the observations about to be described have been made at pressures lower than any others of which the author has knowledge.

It is recognized that high-frequency discharges, employing frequencies up to a few megacycles, have been utilized(8), principally as spectroscopic arc sources, for many years. These so-called "electrodeless" discharges were much in vogue in such problems as hydrogen fine-structure studies; one such discharge tube was, in fact, built by the author* some years ago for this purpose. As far

*Described by Hsueh, Thesis, CIT 1944

as electronic transit times are concerned, however, these discharges are not materially different from direct-current discharges excepting that the use of a radio-frequency field permits of maintaining a high average internal electric field without the use of conducting bodies within the glass enclosure. Ultra-high frequency discharges as here considered, on the other hand, do seem to have some properties intrinsically different from those involving low frequency or steady fields. An investigation of these properties leading, if possible, to an improvement in general understanding of ultra-high frequency discharges, was the purpose of the work about to be described.

Investigations on the performance of ion sources have previously nearly always involved tests not of the ion source separately, but of the ion source as a functioning part of the apparatus in which it is ultimately to be used. This method automatically shows up any serious faults which the ion source may have and which might otherwise be overlooked, such as excessive gas consumption, faulty beam formation, and so forth. However, results obtained in such tests are indicative not of the performance of the ion source itself but of the combination, and data which might provide important information on the functioning of the ion source as such are sometimes lost. In this work, therefore, the ion source was tested as a separate entity, at reasonably low voltages, and with a reasonably large variety of electrode configurations, in order to obtain as much information as possible about the forces at play in the discharge itself; it is believed that the results to be reported here will justify this method adequately.

There were several reasons why it was felt that research on an ultra-high frequency ion source might prove fruitful. First, at ultra-high frequencies and with suitable geometry and gas pressures, the maximum energy acquired by an ion from the field is much less than that acquired by an electron, the maximum energy acquired by a particle depending inversely on its mass, as will shortly be shown. Consequently the method of ultra-high frequency excitation seemed to offer a means of exciting a discharge by a means to which the positive ions formed could be made relatively insensitive by an appropriate choice of parameters. Ions so formed could be drawn out by a superposed DC field or allowed to drift out of the ionizing region by diffusion, and it seemed as if some of the very troublesome effects of space charge might thereby be avoided. It will become amply evident in the course of this thesis that this hope was, at best, only partly capable of realization. Second, the method seemed to offer promise of permitting maintenance of a self-sustaining discharge at pressures much lower than could be permitted in a DC or low-frequency discharge. Such a possibility would greatly alleviate the problem of gas consumption which is present in nearly all gas ion sources. Third, during the early part of this work Hall[9], working at this Institute, developed an ultra-high frequency ion source whose mechanism of operation seemed to be imperfectly understood; partly to throw, if possible, more light on the mechanisms involved in Hall's source, and partly to correlate Hall's observations with the author's, some of Hall's work was essentially repeated and extended under comparable conditions.

OUTLINE OF THEORY

Theoretical treatments of ultra-high frequency ionization have thus far uniformly avoided providing for either space-charge effects or the effect of secondary electron formation at the walls of the cavity. Mierdel(10) has given a very simple treatment of the motion of a charged body in an alternating electric field, based on the hypothesis that the body is essentially free; that collisions of the body with gas molecules, the walls of the cavity, or anything else, are infrequent compared to the oscillation frequency of the field. Margenau(2) has challenged the validity of this hypothesis and has developed a theory applicable to higher pressures. We shall see that there is a large range of pressures in which discharges may be maintained under conditions in which the simple theory of Mierdel has as much validity as any thus far developed; since these are, by and large, the pressures in which we have been interested here, we will sketch Mierdel's theory briefly and indicate how it may be extended to cover secondary electron emission at the walls.

Consider a particle of mass m, charge q, situated in an electric field of intensity given by

$$E_y = E_o \sin (wt + \theta) \qquad (1)$$

Such a particle starting at $t = 0$ with $y = 0$, $\dot{y} = \dot{y}_0$, has a motion given by

$$y = \frac{qE_0}{mw^2}\left[\sin\theta - \sin(wt + \theta)\right] + v_0 t , \qquad (2)$$

where

$$v_0 = \frac{qE_0}{mw} \cos\theta + \dot{y}_0 . \qquad (3)$$

The motion of such a particle is clearly a superposition of two simple motions, the first being a uniform drift parallel in direction to the field, of magnitude

$$v_0 = \frac{qE_0 \cos\theta}{mw} + \dot{y}_0 , \qquad (4)$$

and the second being a sinuous motion in synchronism* with the field, of amplitude

$$a = \frac{qE_0}{mw^2} . \qquad (5)$$

In the absence of initial velocity, we have the maximum kinetic energy

$$T_{max} = \frac{(qE_0)^2}{2mw^2} \left(1 + |\cos\theta| \right)^2 , \qquad (6)$$

showing that in a situation in which the body is essentially free, an electron may acquire many orders of magnitude greater energy than a heavier charged body such as a proton. Superposition of a steady

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* The position of the charged body is in opposite phase to the field and the current formed by the motion of the charged body is 90° out of phase with the field, leading, if the charged body is positive. Both these effects are reversed in sign if the body is an electron.

field for withdrawing ions would modify these results along obvious lines.

It is to be noted from (2) that electrons coming into being without initial velocity at such times that cos $\theta = 0$ may oscillate sinusoidally in the field for a considerable number of cycles and in so doing may travel for a total distance much greater than the interelectrode spacings involved. It can be expected that there may be conditions in which this increased path length will lead to greater ionization probabilities per electron, and make possible operation at lower pressures, than would be the case in a steady or low-frequency field. This type of motion, and the ionization resulting from it, will be impaired by the superposition of a steady field due either to space charge or to a field imposed externally to the discharge itself. Some of the quantities of interest thus far developed are shown graphically in Figs. 1,2.

These derivations, based as they are on the suppositions that space charge and secondary emission may be neglected, have their greatest significance in furnishing information on the mechanism of initial breakdown at low enough pressures and in cavities large enough that collisions with the walls of the cavity are infrequent compared with collisions with gas molecules and that both are infrequent compared

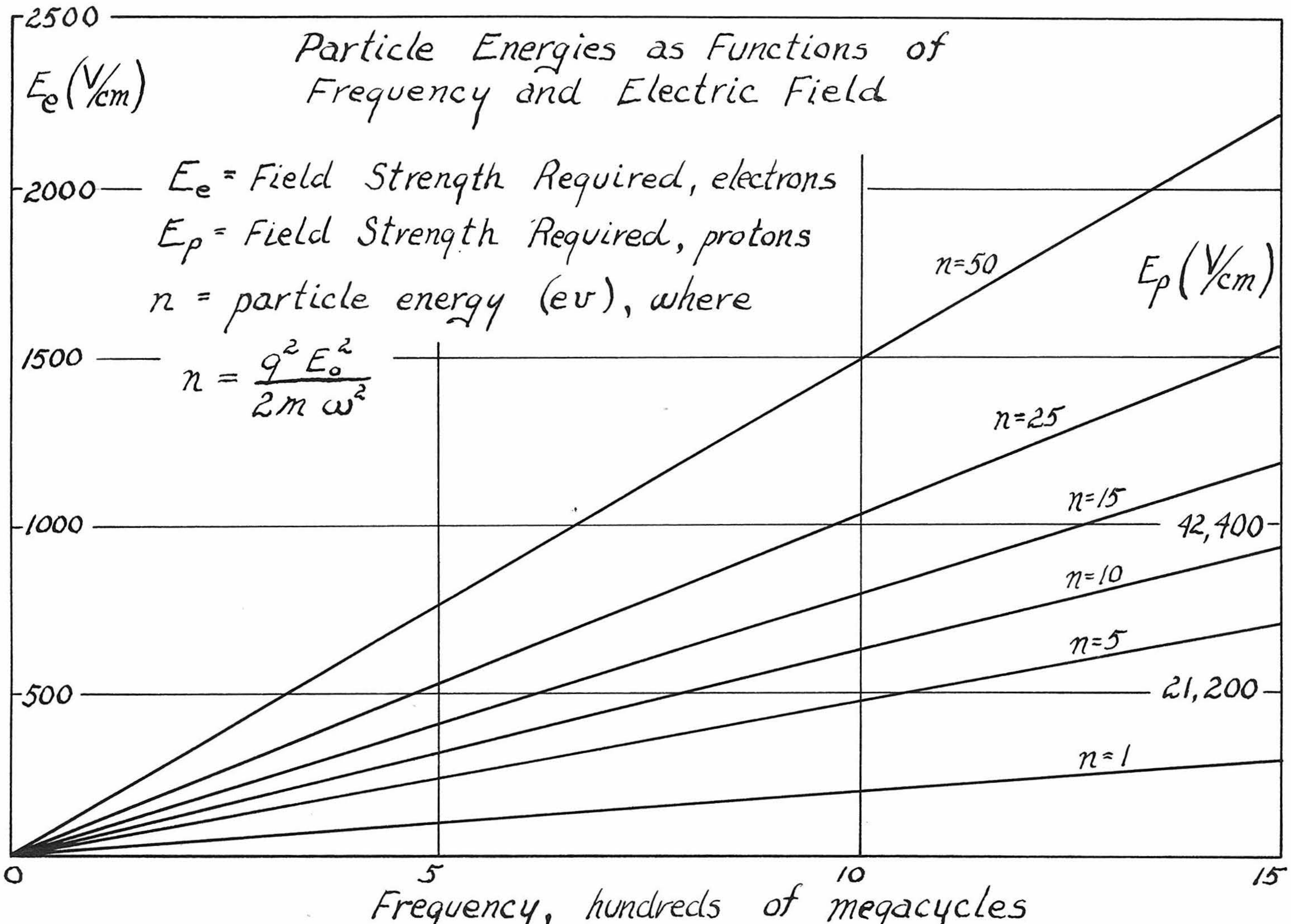
Particle Energies as Functions of Frequency and Electric Field
E_e (V/cm)
E_e = Field Strength Required, electrons
E_p = Field Strength Required, protons
n = particle energy (ev), where
$n = \frac{q^2 E_o^2}{2 m \omega^2}$
E_p (V/cm)
2500
2000
1500
1000
500
0
5
10
15
n=50
n=25
n=15
n=10
n=5
n=1
42,400
21,200
Frequency, hundreds of megacycles

Figure 1

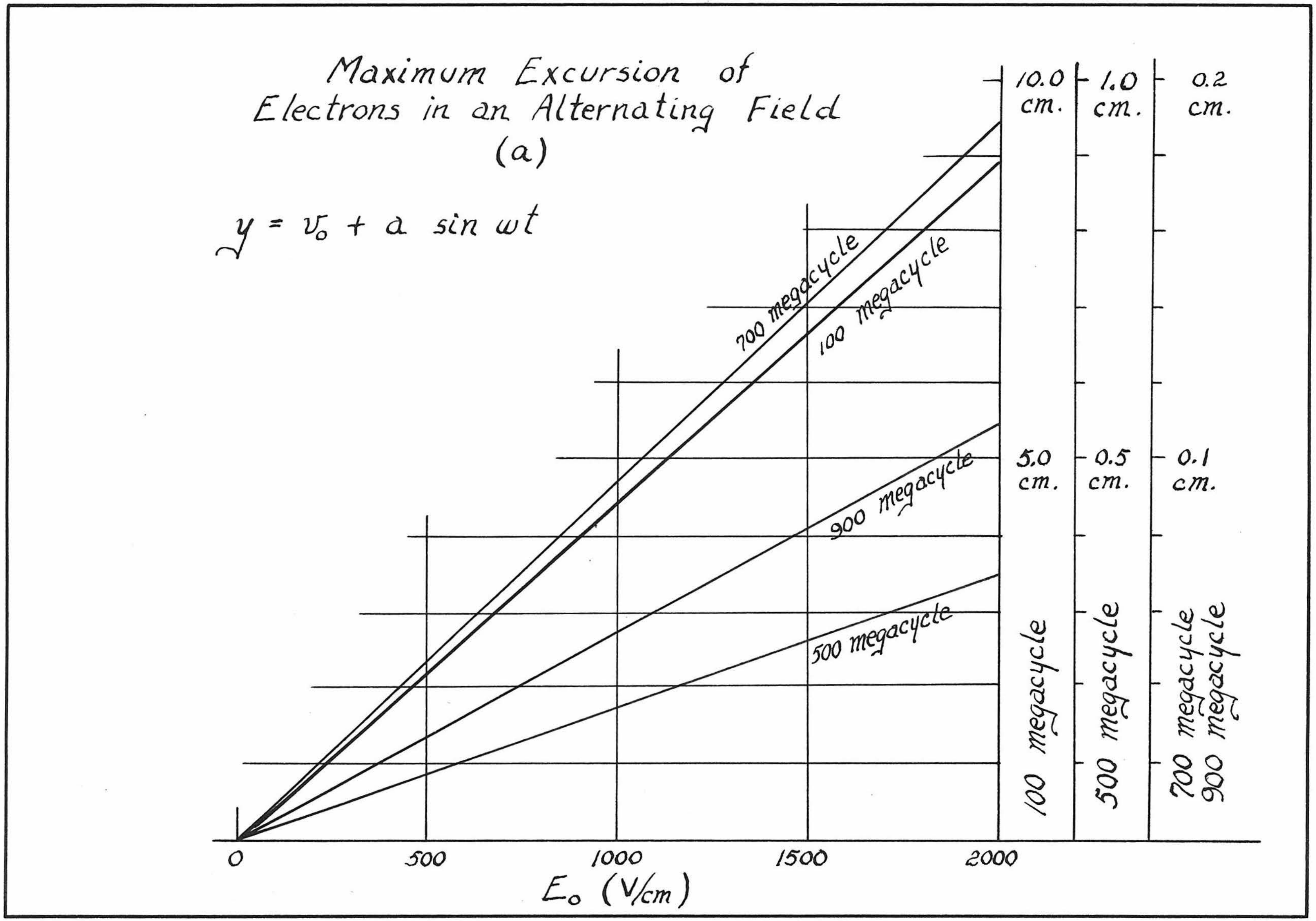
Maximum Excursion of
Electrons in an Alternating Field
(a)
y = v₀ + a sin ωt
700 megacycle
100 megacycle
900 megacycle
500 megacycle
10.0 cm.
1.0 cm.
0.2 cm.
5.0 cm.
0.5 cm.
0.1 cm.
100 megacycle
500 megacycle
700 megacycle
900 megacycle
0
500
1000
1500
2000
E₀ (V/cm)

Figure 2

to the frequency of the field. Although the results are not without validity in the situations to be described, ample experimental evidence will shortly be presented to support the conclusion that both space charge and secondary emission from the walls can play important roles.

It will be seen from figs. 1,2, that electrons which come into being essentially without initial energy are unlikely to acquire enough energy from a reasonably strong field to be effective in forming secondaries. Consider now an electron which has its origin as a secondary at one wall of a cavity, is accelerated to the opposite wall where it may, under favorable conditions, give rise to further secondaries. Assume a field strength of 580 volts (peak), frequency 550 megacycles. An electron for which $v_0 = 0$ (Eq. 1) acquires a maximum energy of 25 volts; if $\vartheta = 0$, $\cos \theta = 1$, the energy may be as high as 100 volts. If an electron has an initial energy of 25 volts* due to its origin as a secondary, it may

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* There is no general agreement in the literature of the subject of the most probable energy of secondary electrons; some authors (16) maintain that they are emitted with almost constant energy of five to ten volts; others (12) conceding that the energy is relatively constant but maintaining that it is nearer to 25 volts, while still a third view (11) is that they tend to be emitted with a constant fraction of the primary energy. Under the circumstances, the assumption that the secondary energy is about 25 volts seems as good as any.

acquire, under the most favorable conditions, an energy of 175 volts, requiring 0.75 cycle to develop the energy and travelling a distance of 8.7 millimeters in doing so. Clearly these are conditions easy to achieve in a practical situation and the electronic motions involved are of such magnitude that the phenomenon might be expected to occur in a cavity of reasonable dimensions. Also, it will be observed from (3) that electrons originating as secondaries on one side of the cavity at such times that $v_0 > 0$ will always cross the cavity; under the conditions given here, this will include somewhat more than half of all the secondaries produced, regardless of which side of the cavity they originate on.

Data are available on the secondary emission coefficients of many common materials; some of the more pertinent data, taken from Harries(11) are given in figs. 3,4. It will be noted that nearly all common materials, even aquadag, have secondary emission coefficients greater than unity for at least a restricted range of bombarding energies. It may also be noted that the admission of traces of gas to a cavity may be expected to contribute to breakdown by raising the secondary emission coefficient of the wall material(11) even though the gas may not be present in sufficient amount to play a directly important part in the gas discharge as such.

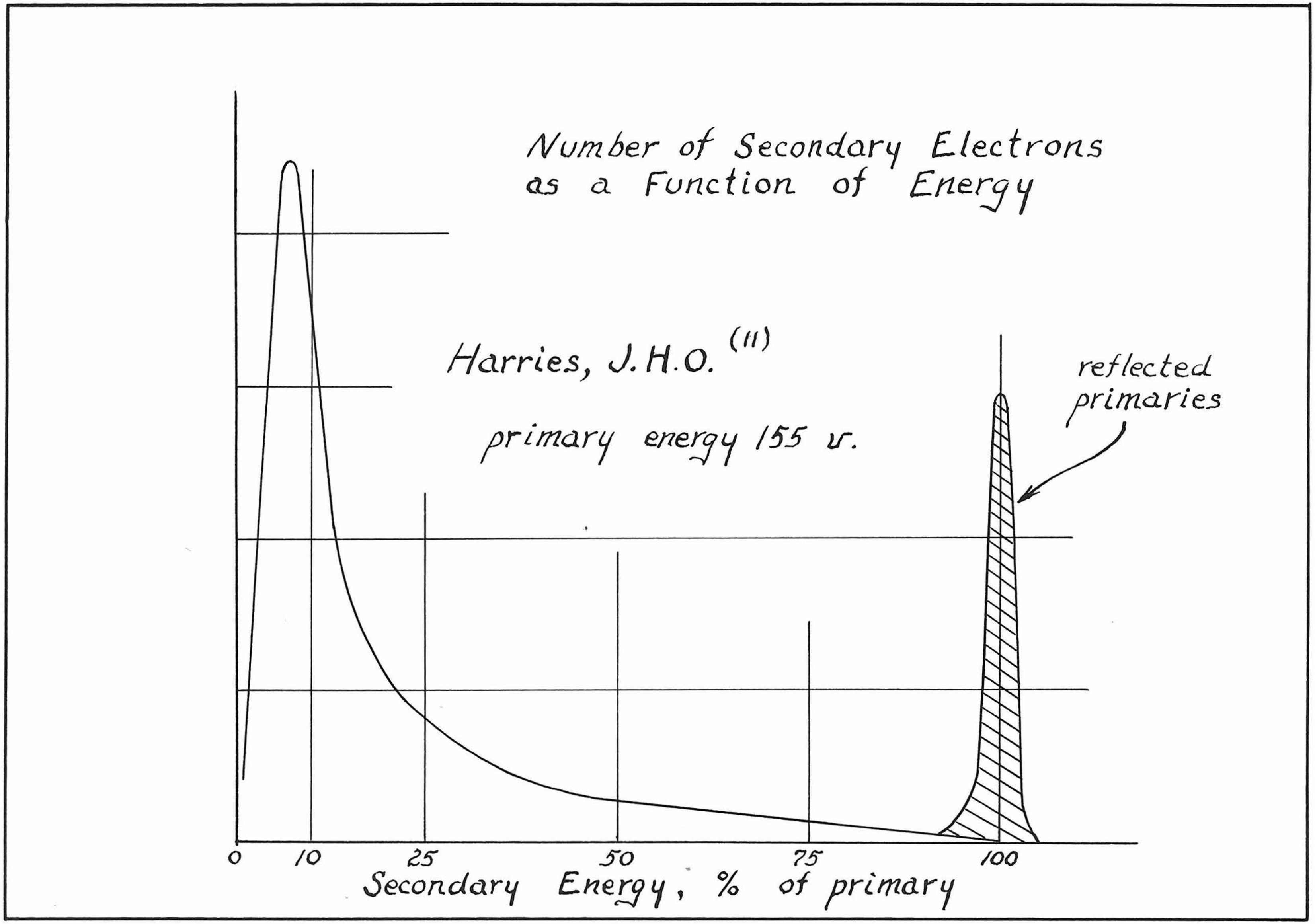
Number of Secondary Electrons
as a Function of Energy
Harries, J.H.O.[11]
primary energy 155 v.
reflected
primaries
0
10
25
50
75
100
Secondary Energy, % of primary

Figure 3

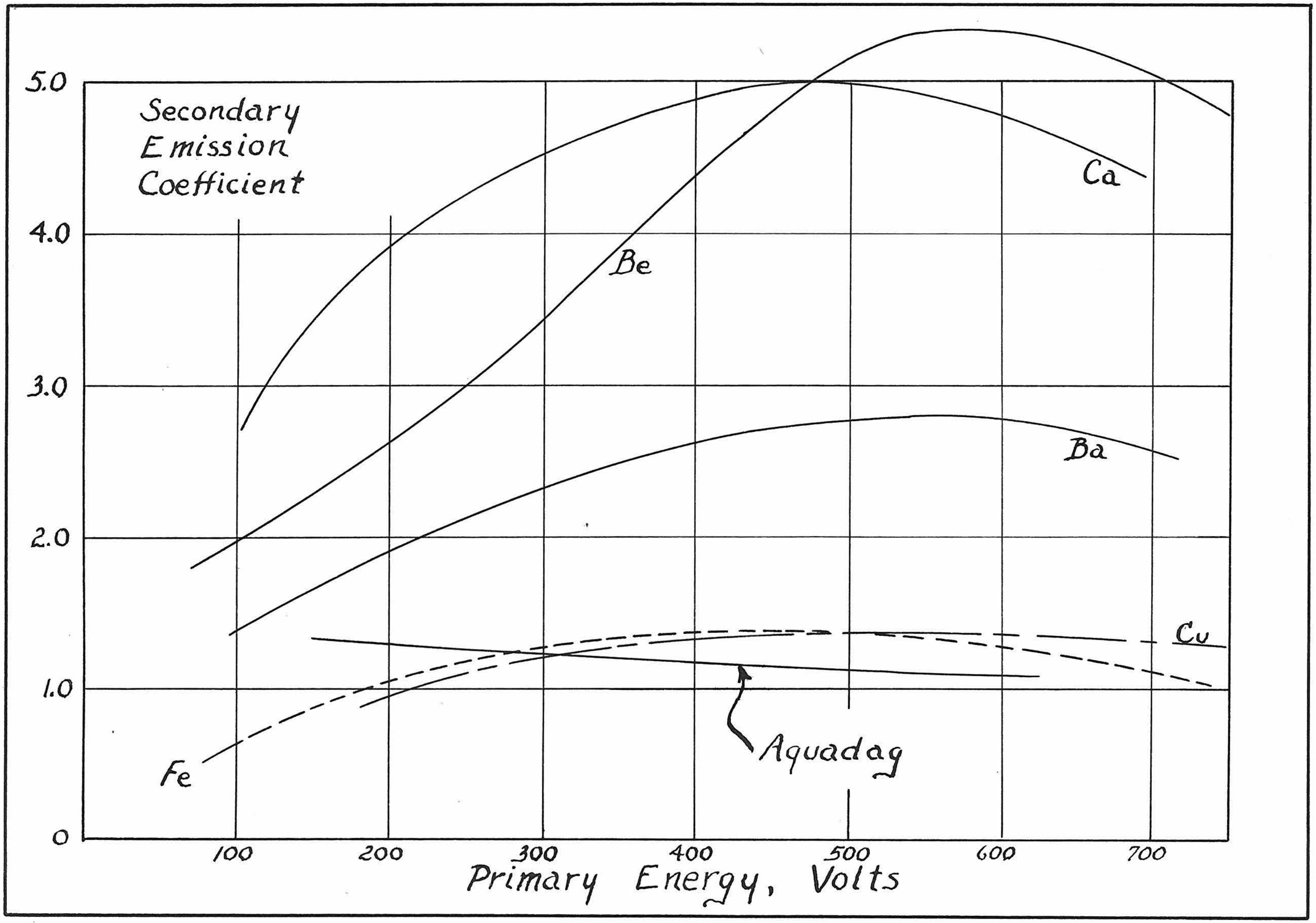
Secondary
Emission
Coefficient
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
500
600
700
Primary Energy, Volts
Ca
Be
Ba
Cu
Fe
Aquadag

Figure 4

This simple argument cannot, of course, be taken as evidence for or against the possibility of creating a self-sustaining pure electron discharge by secondary emission effects at high frequencies, nor is there enough information on the time lags involved in secondary emission available to permit performance predictions even if the theory were available.* Empirically, ample evidence for the possibility of pure electron discharges, maintained entirely by secondary emission, is to be found in high-power magnetron tubes, in some of which the electrons for operation are provided entirely by secondary emission once the tube has been started by initial heating of the cathode. Suffice it to say that secondary emission may not play a negligible role and discuss the apparent importance under the results.

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* Wang (14) and Greenblatt & Miller (15) have made some indirect measurements on this subject, concluding that at least some of the secondaries are emitted in less than 10^{-10} sec.

EXPERIMENTAL ARRANGEMENT

The source of rf power consisted of a three-stage continuous-wave oscillator-amplifier combination comprising a primary oscillator, an intermediate amplifier and "buffer" stage, and a final power amplifier, all working at the same frequency. All three stages employed double resonant cavities incorporating "lighthouse" tubes; the oscillator, an RCA 2C43 (five watt), the buffer, an RCA 2C40 (10-watt) and the final amplifier an Eimac 2C39 (100-watt). All three cavities were essentially identical except for the obvious differences in detail arising from the necessity of their accommodating different tubes. All consisted of brass tubing carefully machined and soldered to a heavy base plate, with the end covers machined for a tight press fit, and tuning plugs were machined from billets of brass or bronze. Sockets and other fittings for the tubes were machined from brass or copper billets. All three cavities were silver-plated on all inside surfaces. Tuning was accomplished by moving the tuning plugs by means of threaded bars passing through the base plate. A typical stage (the buffer) is shown in fig. 5.

Coupling between cavities was by means of RG8-U concentric cables, together with appropriately placed telescoping members of conventional type for tuning

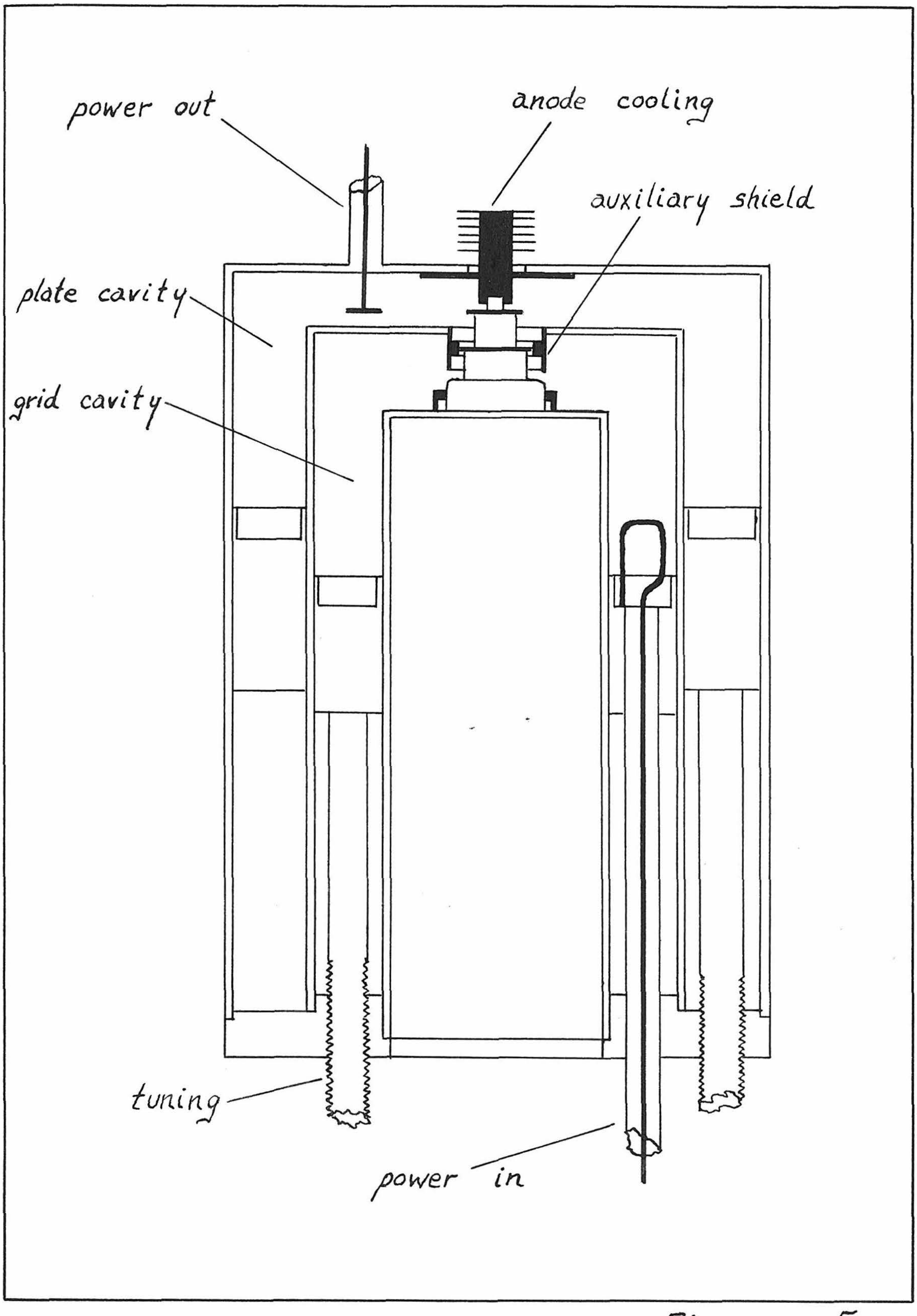
power out
anode cooling
auxiliary shield
plate cavity
grid cavity
tuning
power in

Figure 5

and impedance matching. In each case, coupling into a cavity was by means of a coupling loop inserted into the grid cavity and coupling out was by means of a capacitative probe inserted into the plate cavity.

It should be mentioned here that there is no necessity for a power source of this complexity as far as the operation of a practical ion source is concerned; a pair of 2C39 tubes working as a self-excited oscillator would almost certainly be adequate, for example. The three-stage combination described here was chosen partly because it was felt that the superior frequency stability of such a combination over a self-excited oscillator would make it possible to investigate more closely the changes in resonant frequency of the source cavity under varying conditions of excitation and partly because it was recognized that there might be many conditions of exploring the discharge properties in which a self-excited oscillator might become so over-loaded as to drop out of oscillation with consequent damage to the tubes, whereas this possibility would be largely avoided by isolation of the oscillator from the final stage.

To those who may wish, for one reason or another, to adopt a similar power supply, a few words here may be helpful. The first and most obvious is that a supply of this complexity must be mechanically well constructed to work at all; none of these stages produced much more power than was required to drive the succeeding one; construction had to be such that fine tuning was easy and that a cavity, once critically tuned, would stay in tune. Even when fully loaded, the plate cavities showed marked adverse effects if the tuning plugs were as little as a few thousandths of an inch out of position. Second, it is our observation that the 2C43 tube will not work properly as a power amplifier at these frequencies (550 to 900 megacycles) without neutralization, which is an added nuisance and was one of the reasons for deciding on the 2C40 since it will so operate. Third, the writer was advised that the 2C43 (and presumably the 2C40 as well) are very inefficient unless they are provided with auxiliary shields of the type shown in fig. 5. No certain explanation of this effect is to be found, but it is probably connected with dielectric losses in the glass envelope. The cavities used here worked poorly without these shields and worked well with them, but other changes were made at the same time the shields were installed so that it cannot be said definitely that the shields were the governing factor in this case. Fourth, to the extent to which these cavities may be treated as capacity-shunted transmission lines, their resonant positions to a fundamental frequency and its third harmonic are close together; since the oscillator shows a large third harmonic output it is not always easy to be sure whether the fundamental or its third harmonic is being tuned in the buffer. This leads to the advisability of making an actual frequency check on the buffer output to make sure one is not trying to drive the final stage at three times the desired frequency. Fifth, the resonant frequencies of these cavities will drift badly during a five or ten minute warming-up period, due probably to thermal buckling of the grids. A self-excited oscillator employing lighthouse tubes should, if heavily loaded, always incorporate some cathode bias or other current-limiting means to protect the tube from the results of drifting in and out of oscillation during the warmup period.

Frequency measurements were made in an air-filled tunable concentric line resonator of approximately three inch diameter. Frequency measurements were accurate to about 0.2%; it was not expected that any effects critically sensitive to frequency would be found (nor, in fact, were any such effects observed) and no attempt was made to measure the frequencies with great precision.

The vacuum system consisted of a bell jar of more or less conventional type evacuated through a specially constructed vacuum valve by a DPI VMF-100W oil diffusion pump, using Octoil as the pumping fluid. The bell jar proper consisted of a glass cylinder sealed at the top to a heavy steel plate and at the bottom to a narrow but stiff ring, the entire assembly being held together permanently by three steel tie rods and sealed with electricians' rubber tape and Glyptal varnish. The base ring of the bell jar was provided with a slightly undercut groove into which an O-ring was fitted, the undercut being to prevent the O-ring from falling out when the bell jar was lifted. The base plate was one-inch boiler plate, surface-ground at the area of contact between the plate and the base ring of the bell jar. The base plate was provided with twelve holes of diameter varying from $\frac{3}{4}$" to $1\frac{1}{4}$" into which brass plugs carrying various electrical leads, gas lines, etc., were fitted and sealed, the seals again being effected by O-rings, the plugs being slightly tapered on the outer end to prevent their being pushed in by atmospheric pressure. Electrical insulation inside the vacuum chamber was effected by stringing polystyrene beads on the wires. O-rings were used liberally throughout this apparatus, and in more than two years of use there were only three troublesome leaks, one in a warped glass stopcock, a second in an O-ring joint which had an extremely rough and gouged surface and which was cured by "buttering" this surface with a smooth coat of high-vacuum plasticine, and a third in a compression packing of conventional type which was cured by substituting an O-ring joint.

The basic discharge cavity was of the concentric line type, as shown in fig. 6. Gas was admitted directly to the cavity, and pressures, where reported, were measured by a Knudsen gauge connected directly to the discharge cavity. Various internal arrangements, different in detail, were tried during the course of the work; these will be described later in connection with the experimental results obtained with them. The short terminal stub shown was provided in order that the general shape of the field would not depend very much on the gap spacing, as might have been the case had the central pillar faced a flat end surface. The central pillar of the cavity could be moved in and out to investigate the effect of changes in gap spacing, and the tuning plug was adjustable from outside the bell jar. A ½" diameter hole through the wall of the cavity, sealed by mica held in place with "scotch" tape, served as an observation port.

For convenience in focussing the emergent beam, the re-entrant aspect of the top of the cavity should be eliminated in a practical ion source.

The capacitative probe shown in fig. 6 was inserted into the cavity for the purpose of making field strength

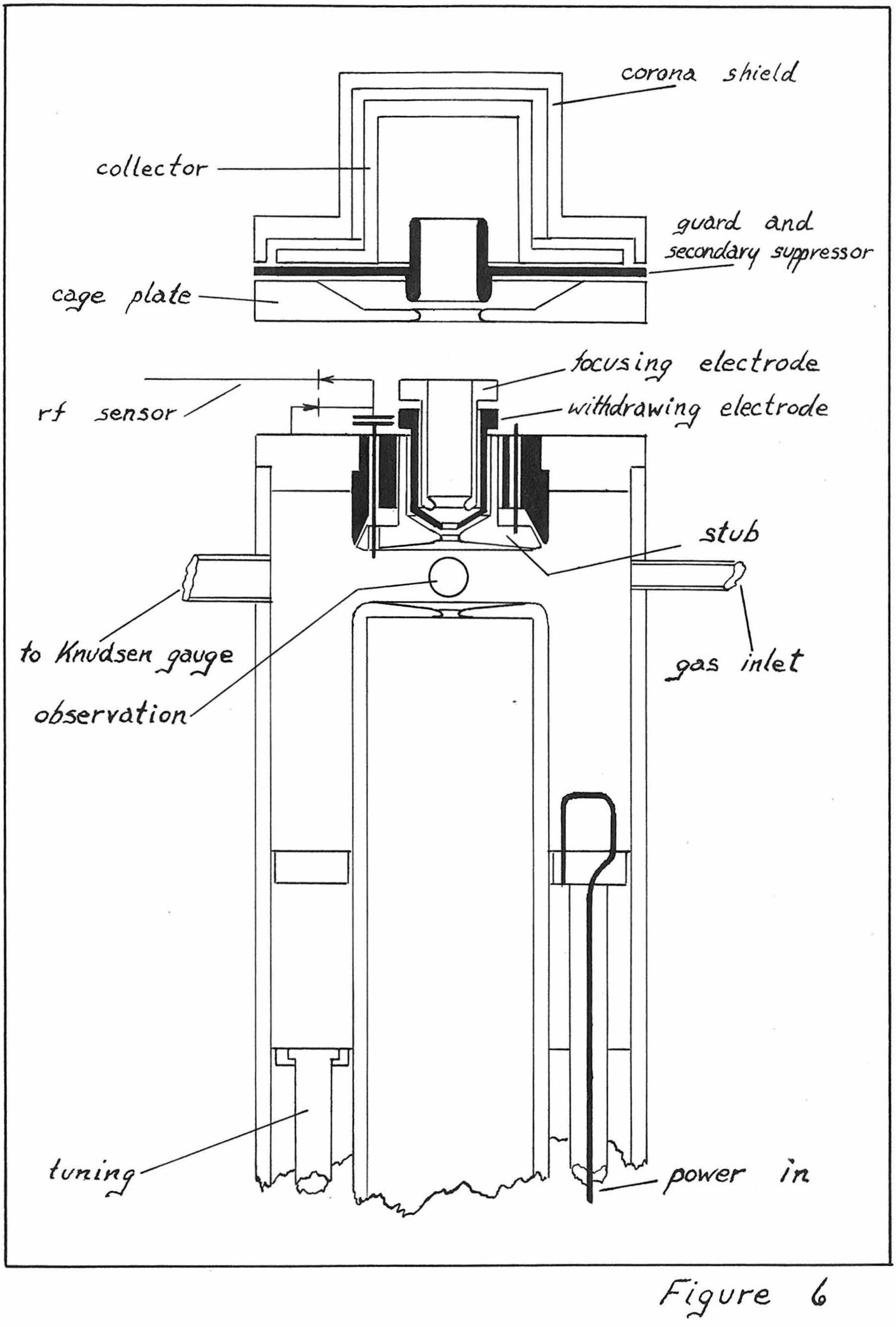
corona shield
collector
guard and
secondary suppressor
cage plate
focusing electrode
withdrawing electrode
rf sensor
stub
to Knudsen gauge
gas inlet
observation
tuning
power in

Figure 6

measurements. With a discharge in the cavity this probe was shielded to such an extent that it was most often useless; its utility was largely confined to indicating the no-load field strengths and hence serving as an aid to tuning and obtaining proper coupling.

EXPERIMENTAL OBSERVATIONS

The experimental observations of this work may be divided logically into three stages; first, a series of purely exploratory measurements, second, a series of measurements undertaken to investigate why the ion currents from the source were not as high as were expected nor as high as those which by that time were being reported by others in the field leading ultimately to an hypothesis regarding the mechanisms involved in the discharge, and third, a series of measurements undertaken principally to check the hypotheses which had been formulated as a result of the second stage of the work.

The first stage of the work was done with dry air as the ionizing medium, with no magnetic field, and with an all-metal (copper-plated steel) discharge chamber. The results of this stage, reported in detail in Appendix I, will only be summarized here. The main conclusions were:

I. That an ultra-high frequency discharge could be initiated and maintained, in a metal-lined cavity, at pressures ranging from 10^{-4} mm. Hg up to several tenths of a millimeter. Only rarely was it possible to initiate the discharge at very low pressures; more usually it was necessary to introduce a burst of gas to raise the pressure up to 2-3x10^{-2}mm, after which the pressure could be reduced and the discharge maintained. The ion yields showed essentially no frequency dependence in the range 600-900 megacycle, and no clear evidence for dependence on gap spacing in the range 10-16 mm. Measurements taken with 6.4 mm. gap spacing tended to be consistently lower than the others by about 25%.

II. No ions were ever observed in amounts over 5 microampere, and rarely over 1, without an auxiliary withdrawing potential, although electron currents over 100 microamperes were frequently observed with no steady potentials anywhere, even on the collector.

III. Ion currents to a collecting chamber of conventional type tended to be in the range 10-20 microampere.

IV. Ion currents showed a surprisingly small dependence on rf field strength or coupling.

V. The excitation of a discharge in the cavity changed the resonant point in a direction corresponding to the insertion of an inductive load, so that the net space current in the discharge was apparently negative. This is to be expected even in the absence of net space charge on account of the higher mobilities of electrons.

VI. The magnitude of the ion currents tended to depend on the magnitude of the withdrawing field; this suggested that the current was space-charge-limited, although the dependence could also be accounted for by a focussing effect.

VII. The initial energies of the ion beam, expressed as volts referred to the source chamber, ran as high as 120 volts. This indicates a high positive space charge in the presence of the withdrawing field and (II) above indicates an even higher <u>negative</u> space charge in its absence.

VIII. There is essentially no difference in ion current when the admitted gas is changed from air to hydrogen, which suggests that if space-charge effects are present, they are not governed by the conventional expressions which describe space-charge current limitation since if this were the case the current would show a definite dependence on the mass of the ion involved.

At the conclusion of the above phase of the work, and particularly in view of the mutual confusion among VI, VII, and VIII above, it was felt that an incompletely understood space charge effect of some sort was affecting the results. Consequently it was decided to introduce a beam of electrons from a hot filament into the discharge chamber from below, to attempt thereby to reduce the space charge (which was assumed to be positive) and thus enhance the ion beam intensity. It was observed at once that the sole result of electron injection was to reduce the intensity of the emergent beam, the beam intensity falling monotonically with increasing electron current injected. (Fig. 7.)

Here was a most unexpected result. Space charge formation is usually thought of as due to unequal mobilities of positive ions and electrons, the particles having the higher mobility being swept out of the discharge and leaving an excess of the less mobile particles behind. Under any ordinary conditions, one would expect the net space charge to be positive, yet here was evidence that the net space charge, in the absence of a withdrawing field, was strongly negative, and leading to an ion-trapping phenomenon in the potential well resulting from the negative space charge. This phenomenon is well known in mass spectrometry, where ionization is commonly produced by injecting a beam of electrons through the gas sample more or less transversely to the ionic orbit; if excessive electron current is employed, the ion yield is actually depressed due to the formation of just such a space-charge trap. The phenomenon is also well known to students of vacuum-tube theory[12].

The next experiment tried was the coating of the

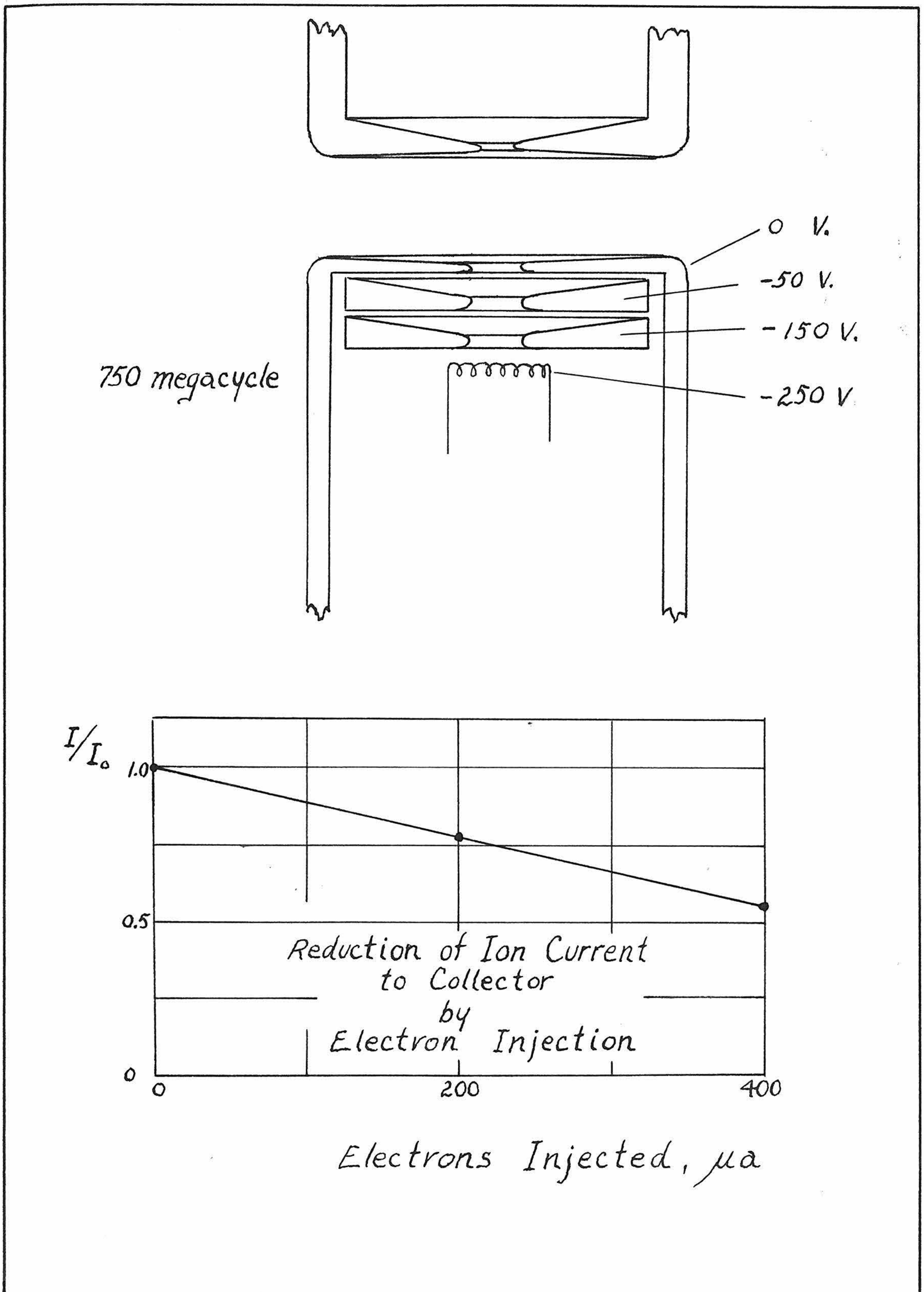
0 V.
-50 V.
-150 V.
-250 V
750 megacycle
I/I_0
1.0
0.5
0
0
200
400
Reduction of Ion Current to Collector by Electron Injection
Electrons Injected, μa

Figure 7

entire inside surfaces of the cavity with aquadag. Obviously, any electrons which were present in excess of the positive ions most probably had their origin as secondaries at the walls of the cavity; if they were present in sufficient numbers to interfere with ion escape by the formation of a space-charge trap, the seriousness of the effect might be reduced by coating the inside of the cavity with a material thought to be a comparatively poor secondary emitter.*

Two facts were noted as soon as this was done. The first was that there was no important change in ion current. The second was that the DC current to the insulated stub (Fig. 6) changed sign when the cavity was tuned through resonance, being negative when the cavity was off resonance and positive when the cavity was well tuned, although nothing else in the cavity was affected by the tuning process and no DC fields were present. There may be more than one explanation of this phenomenon, but one which we are willing to support is the following: under badly tuned conditions, electrons strike the stub with average energy low enough that the effective secondary emission coefficient of the surface is less than unity, and the net current is negative. As soon as the cavity is

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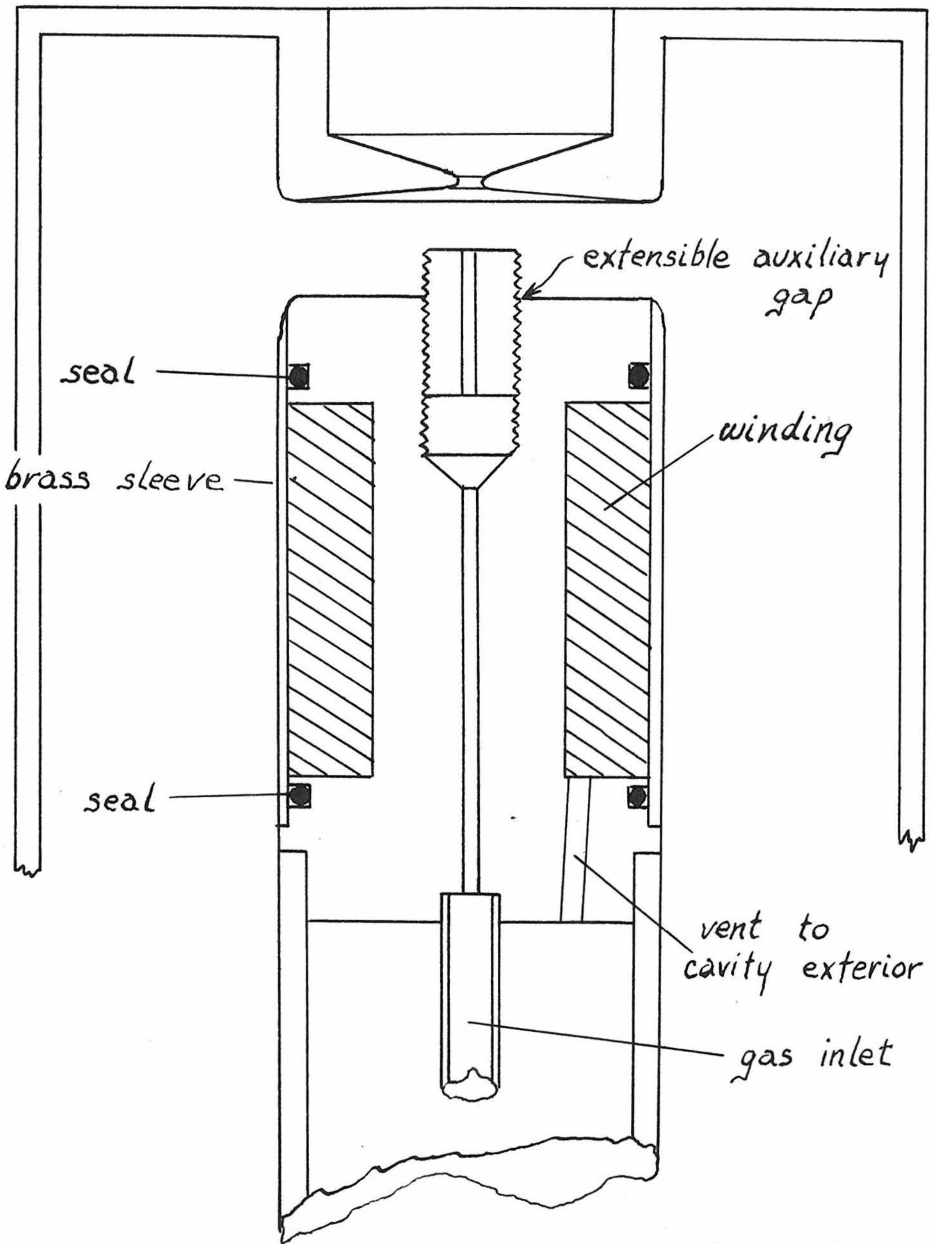
* Examination of figures 3, 4 shows that aquadag is not such a poor secondary emitter as was originally supposed; this error, however, has no bearing on the data about to be presented.

brought nearer to a properly resonant condition, the average electron energy is increased to the point where the secondary emission coefficient of the wall material for the average electron exceeds unity, and the current changes sign not because of any change in the sign of the bombarding particles, but because they arrive with such energy, and their escape in the absence of a DC biasing field is sufficiently probable, that there are more secondaries leaving the surface than primaries striking it. Consequently the positive sign of the current to the stub represents not a net positive current, but an excess of secondary electrons leaving the surface over primaries striking it. This explanation is borne out by a series of measurements with DC biasing fields within the cavity; these measurements, together with a more detailed discussion of the effect in this instance and also in the presence of an axial magnetic field, are given in Appendix II.

At about the time this stage was reached, Hall[9] reported a very interesting and successful ion source working on this same principle but considerably simpler in detail, employing a Pyrex bottle for the discharge and an axial magnetic field to confine it. The main purpose for which Hall's ion source was intended was admirable served; however, it raised several important questions. First, how was it possible to obtain ion currents exceeding those thus far observed here by factors of twenty to fifty, without a withdrawing field of any kind, when this work had thus far indicated that a withdrawing field was absolutely mandatory? Second, just what was the role played by the magnetic field and why did its employment result in such a large increase in ion yield in a system which already seemed to have a considerable degree of cylindrical symmetry?

The use of any insulating material in the discharge cavity had until now been avoided because it was felt that surface charges on such material would introduce electric fields of magnitude and shape which would be hard to predict or to explain, and which would consequently only confuse the results. However, it did seem to be clear that investigation of the effects of an axial magnetic field was required; accordingly, a solenoid (Fig. 8) was built for this purpose. The pillar of the discharge region was provided at this same time with a small (3/8" diameter) section which could be raised to concentrate the discharge, and investigations of the effect of the magnetic field, both in the entire gap and in the confined gap, were begun.

The first observation was that at pressures of about 10^{-3} mm. and below, a magnetic field of a few hundred Gauss would extinguish the discharge altogether. In one or two instances the magnetic field would blow



Note: Magnetic return path is through cavity walls, which are mild steel.

Figure 8

the discharge out within the gap but would leave a fringing discharge around the edges of the gap.
The second observation was that even magnetic fields not strong enough to extinguish the discharge altogether would impair the ion yield; the degree of impairment depended on pressure and withdrawing voltage, but there was no instance in which the magnetic field increased the ion yield by any amount which could not be ascribed to small instabilities in the source itself, and there was always at least one value of the magnetic field whose employment resulted in marked impairment of the ion yield regardless of the withdrawing voltage.

The next series of measurements was made with the auxiliary gap extended to develop a smaller, more concentrated discharge. Two effects, which had been more or less anticipated, were observed: first, the magnitude of the detuning effect due to the discharge was much reduced (by nearly a factor of ten) and second, the ion currents tended to be somewhat enhanced, being occasionally in the neighborhood of 40 microamperes. At gas pressures close to 100 micron, a magnetic field strength could be found at which the discharge exhibited a bright core approximately 2 millimeters in diameter along the axis of the discharge; the ion current in the absence of a magnetic field was in the neighborhood of 10 microamperes and was reduced to about three microamperes by the formation of the bright core just described.

It was known from previous measurements that the negative withdrawing field was necessary to the achievement of appreciable ion currents. It was felt that the above observations could be explained on the basis that the magnetic field made it more difficult for the withdrawing field to sweep electrons away from the exit aperture in sufficient numbers to remove, even locally, the space charge trap and hence permit ion currents to be maintained at the same values as in the absence of a magnetic field. Accordingly a series of measurements was undertaken to investigate the effect of the magnetic field on the conditions within the cavity itself. These measurements (discussed in detail in Appendix II) confirmed the hypothesis that an axial magnetic field intensifies the negative space-charge trap and inhibits ion production from within the high-frequency discharge itself.

Acceptance of these conclusions, however, immediately raises the question where the ion currents of several hundred microamperes reported by Hall were coming from. There was clearly no possibility that either these measurements or Hall's could be simply in error by an amount sufficient to explain the discrepancy in ion currents reported, and it was impossible to consider that an understanding of the phenomena involved had been arrived at in the presence of this direct contradiction between these results and Hall's. Consequently, it was decided to attempt to duplicate Hall's results under essentially identical circumstances. Several Pyrex bottles of the type described by Hall were obtained* and measurements with them begun.

The first measurements were disappointing. At the pressures previously most often used, the ion current increased with withdrawing voltage - it was still rising at a withdrawing potential of 700 volts - the ion currents even then were only in the neighborhood of 30 microamperes, and the only clear difference between the Pyrex and the metal cavities seemed to be that some ion current (5 to 7 microamperes) could be observed at pressures around 10^{-3} mm. with no withdrawing voltage applied. In view of the fact that surface charges on the Pyrex might give rise to almost any preassigned field distribution, this did not seem either surprising or important. Ion currents did not seem to depend much on the rf field strength, being nearly constant when the final amplifier plate voltage was changed from 400 to 700 volts, so that it seemed as if currents were being limited by space charge here just as they

---

* The first one used, which served as a pattern for the remainder, was kindly furnished by Mr. Holloway of the Kellogg Laboratory.

had been in the metal cavity. A little later, it was found possible to form an intense localized core in the discharge by a suitable choice of gas pressure and magnetic field; the formation of this core reduced the ion current from about 30 microamperes in the absence of the core to about 7 in its presence. Even in this condition, ion current seemed to be insensitive to rf field strength; the final amplifier plate voltage could be changed from 600 to 900 volts, and the cathode bias from 200 to 700 ohms, with no appreciable effect on ion current. It is important to note, however, that all these measurements were made with an ion withdrawing voltage of 400 volts or more (negative, of course, with respect to the body of the cavity).

It was at first thought that the failure to duplicate Hall's ion currents might be due to insufficient rf power supplied. This notion was dispelled very soon, however, by the observation that under extreme conditions of excitation the discharge assumed the bright yellow color of sodium vapor and that the Pyrex was badly pitted and eroded at the ends in only a few minutes' use, assuming a puffy appearance which one would expect from its having been melted locally in vacuum. Certainly Hall's conditions of excitation could not have been more violent than this without resulting in much faster deterioration of his capsules than was reported.

At last, more by accident than by design, it was observed that in the absence of any steady electrode voltages whatever, electron currents to the collector as high as two or three milliamperes could be obtained. Running down this clue, it was found that by adjusting the withdrawing and focussing voltages, the pressure, the magnet current, and the rf power input to optimum values, electron currents to the collector as high as twenty to thirty milliamperes could be collected; on several occasions, forty milliamperes were observed, and on one occasion, fifty. Furthermore, the current exhibited the expected critical sensitivity to tuning, to rf impedance match, to gas pressure, to amplifier plate voltage, and the remaining parameters involved. In this observation lies the confirmation of the hypotheses already presented regarding space charge and secondary emission, and the explanation of the puzzling discrepancies which seemed to exist between these measurements and Hall's.

At the time these high electron currents were observed, the hydrogen for the source was being generated by an electrolytic generator partly because a suitable hydrogen pressure regulator was not available and partly because it was felt that measurement of the generating current would provide information on the gas consumption rate if such information was desired.

The generating current in the situation under discussion was somewhat unsteady, but within a few percent of 200 milliamperes. The assumption that the electron currents observed would come from the ionization of the gas would require electrolytic generation of the gas, conveying this gas to the discharge bottle, dissociation of the gas (Hydrogen) into atomic ions and electrons, and collection of the resulting electrons, with the overall efficiency of the entire process running in the neighborhood of twenty-five percent. It was known that there was a large amount of gas leakage around the discharge bottle; this leakage was estimated at 80% and was certainly at least 50%. Visual observation of the effects of the discharge on the Pyrex bottle indicated strongly that there was end-for-end symmetry in the effects,* so that these two losses alone would require an overall efficiency for the remainder of the process of over 100%. Clearly, secondary emission from the interior walls of the Pyrex bottle is the only possible source of much the larger part of the electron currents observed.

The source of Hall's ion currents is now not far to seek. The exit bore of the Pyrex bottle was approximately 1 mm. (diameter) by 0.8 mm. long (somewhat variable from one bottle to another); if we assume

* Electrons are ejected backward as well as forward.

an average pressure within the bore of $4x10^{-2}$mm., and use Langmuir's ionization coefficient for 100 volt electrons of 0.038 ions per cm. per electron at 10^{-2}mm., we find ions produced, in the exit jet, at the rate of 15 microamperes per milliampere of electrons, and using the measured value of 40 milliamperes of electrons ejected, we find ions produced at the rate of 610 microamperes per millimeter of jet length; if one assumes an effective length for the gas-electron jet of 1.5 millimeters, one finds ion currents which agree with Hall's fully as well as could be expected from the approximate nature of the computations. More accurate computations can hardly be justified on the basis of available data; the exit gas jet is apparently mostly atomic as a result of the Hydrogen's having been dissociated in the discharge, and there are no data on ionization probabilities of electrons in atomic Hydrogen; Langmuir's coefficients for molecular Hydrogen have been used for lack of any other data. It is to be noted that ions formed by the mechanism described here would show all the sensitivity to gas pressure, rf field strength, tuning, and other factors, which have been reported by Hall for positive ions and reported here for electrons (but <u>not</u> for positive ions); this is further substantiation of the hypothesis.

Ion currents of this magnitude could not be brought to a satisfactory focus with the voltages and geometry available here; for the purpose of measuring total ion current, a special collector capable of collecting a considerable part of a fairly divergent beam was constructed. Unresolved ion currents to this collector as high as 350 to 400 microamperes could be collected without difficulty provided that the withdrawing voltage on the first gap was made zero or slightly positive.

The emergent ion beam was not subjected to mass analysis; however, visual spectroscopic examination showed the Balmer lines to be bright and clear compared to the band background, which is in general agreement with Hall's measurement of some 60% protons in the beam.

APPENDIX I

GENERAL PHENOMENA OF HIGH-FREQUENCY DISCHARGES

I GENERAL PROPERTIES

It was generally necessary to admit a burst of gas, raising the source pressure to about 2×10^{-2}mm Hg, to get the discharge started. After this was done, the pressure could be depressed to a very low value, usually to 2×10^{-4} and sometimes as low as $6\text{-}7 \times 10^{-5}$mm., before the discharge would go out. If the pressure was below about 10^{-3}mm. and the discharge was extinguished in any of a variety of ways (snapping the rf oscillator off and on, by excessive DC biasing voltages, or too high a magnetic field), the discharge would not generally reignite. Only at the highest rf field strengths obtainable was the discharge self-igniting at low pressures, and even then it was so infrequently so that we prefer to regard failure to ignite spontaneously at low pressures as the normal behavior, attributing exceptions to this rule to a possible surface contamination, an accidental gas burst, or other obscure cause.

There are apparently two main mechanisms involved in an ultra-high frequency discharge at low pressures. The first is the motion of electrons which have their origin in the main body of the gas and without much initial energy. At low pressures, only such of these as are formed with practically zero initial energy and at times near the instants when the field phase is optimum can have path lengths sufficient to have a reasonable chance of ionizing before they are carried out of the field by their initial energy of formation. The number of electrons formed by residual ionization (cosmic radiation or terrestrial radioactivity) having such low energies seems to be too small to permit self-ignition at low pressures. At higher pressures, electrons of even fairly high initial energy can have that energy degraded by multiple collisions to the point where a number of low energy electrons sufficient to initiate a self-sustaining discharge is produced.

Much the same type of argument may be advanced for electrons produced at the walls. Whether they have their origin as secondaries to a high-energy primary electron or as electrons ejected from the wall material by terrestrial or cosmic radiation, they are, as conventionally thought of, produced by an essentially high-energy process. High-energy electrons being relatively inefficient for secondary production, it is possible to imagine that these would also be ineffective in bringing a discharge into being at low pressures.

The foregoing may be summarized by saying that both of the processes which may of especial importance in a high-frequency discharge are essentially low-energy processes. The background effects to which discharge initiation is usually attributed, on the other hand, are most usually thought of as high energy processes (over a few hundred volts). Consequently these background phenomena are ineffective in initiating an ultra-high frequency discharge except at pressures where multiple collisions with gas molecules provide a mechanism for energy degradation. Once the discharge has started, the discharge itself affords an amply intense source of low energy electrons with which the discharge may be maintained.

It can be anticipated that both of the main sources of ionization in an ultra-high frequency field will be depressed by a super-posed DC field. Even electrons formed at propitious times will be quickly swept out of the ionizing region, whereas the emission of secondaries will be inhibited by the DC field which tends to drive at least half of them back into the surface from which they came. Data on the subject are presented in fig. 9. The data presented are typical; very many measurements of this effect were made and there was no circumstance in which a (more or less) uniform DC field had any other effect than to depress the ion currents. Furthermore it was repeatedly observed that superposition of too high a DC field, at low pressures, was sufficient to

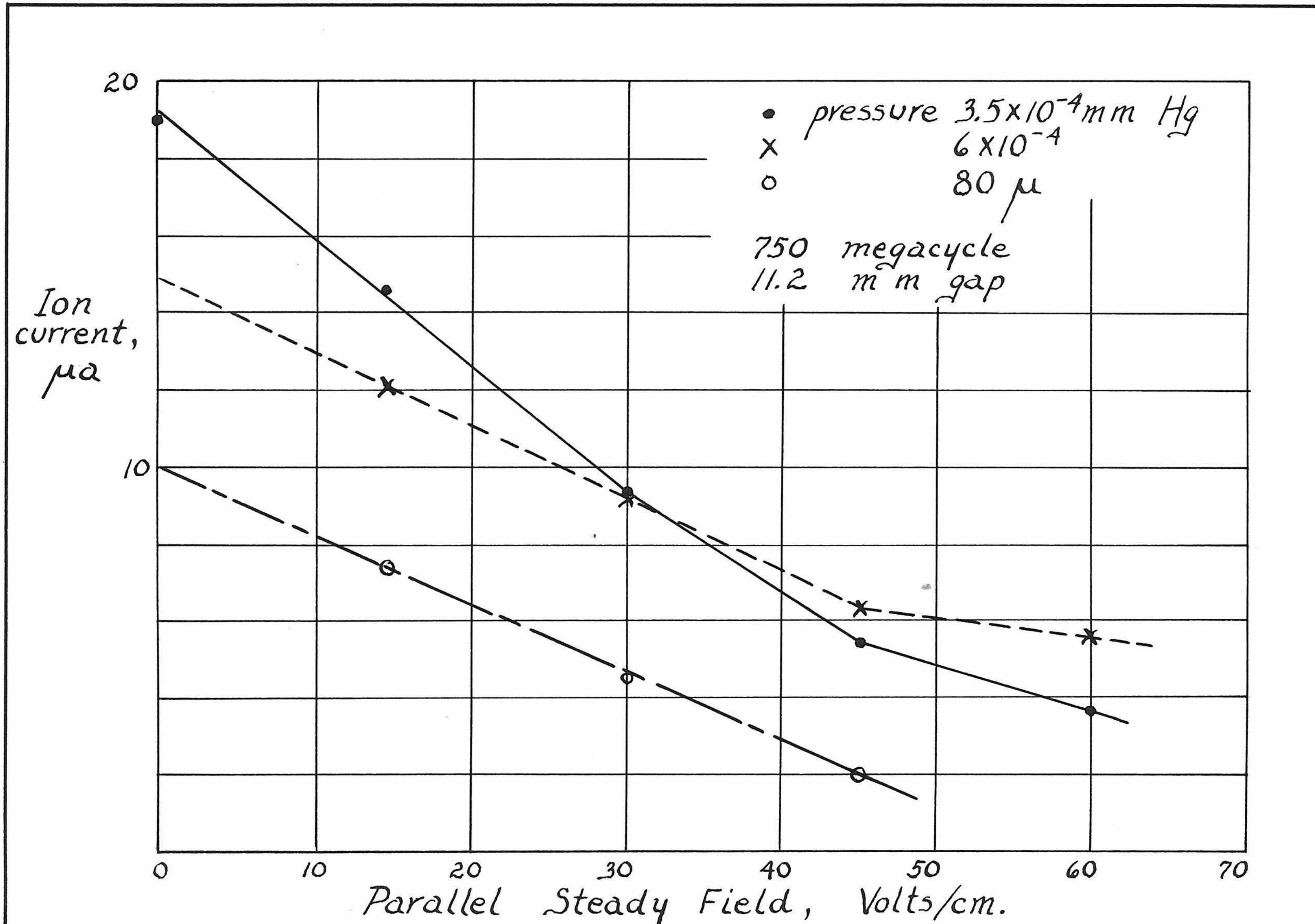

20
10
Ion current, μa
pressure 3.5x10⁻⁴ mm Hg
6x10⁻⁴
80 μ
750 megacycle
11.2 m m gap
0
10
20
30
40
50
60
70
Parallel Steady Field, Volts/cm.

Figure 9

extinguish the discharge altogether. In a few especially favorable cases it was possible to extinguish the main part of the discharge by superposition of a DC field and leave a discharge going in the fringing (weaker) part of the DC field; more usually the discharge was blown out altogether. It might have been possible to produce a fringing discharge fairly consistently had means been available to produce a smooth continuous variation of DC field strength; in this case the stub bias was increased in 25-volt increments by selecting one or another tap of a resistor string, so that the production of a fringing discharge was due more to chance than might otherwise have been the case.

The leakage field from the withdrawing electrode had much the same effect, though of course at much higher absolute voltages. In a few instances where particularly high withdrawing voltages were combined with narrow gap spacing, this leakage field would also produce fringing, or extinguish the discharge altogether.

II DETUNING OF THE SOURCE CAVITY BY THE DISCHARGE

It has been mentioned that either positively or negatively charged particles in an ultra-high frequency field move with velocities whose variable component is ninety degrees out of phase with the field, and that the currents originating in the motion of such charged particles have the effect of a reactive load on the cavity. It was repeatedly observed that the tuning plug positions for maximum no-load field strength and for maximum visual discharge liminosity or ion current were quite different. In every case the optimum cavity length was increased by the discharge, which indicates that the discharge has the effect of reducing the effective capacity of the gap (by coupling in an inductive load), which in turn is evidence that the currents are predominantly due to particles of negative sign. This was to be expected in view of the higher mobilities of electrons; the presence of m in the denominator of (5) indicates that space <u>currents</u> would be predominantly negative even if positive ions outnumbered electrons in the space <u>charge</u> by several fold. Consequently this observation cannot be taken as supporting any contentions regarding the net space charge in the gap.

The amount of detuning by the discharge is shown in Figs. 10,11. The flatness of some of the curves (at high pressures) can be partly accounted for by the fact that the sensing means (collected ion current) was largely space-charge saturated at high pressures. These curves would agree in general appearance, however, with a curve drawn on the basis of visual luminosity so that the reduced sensitivity of any of the discharge

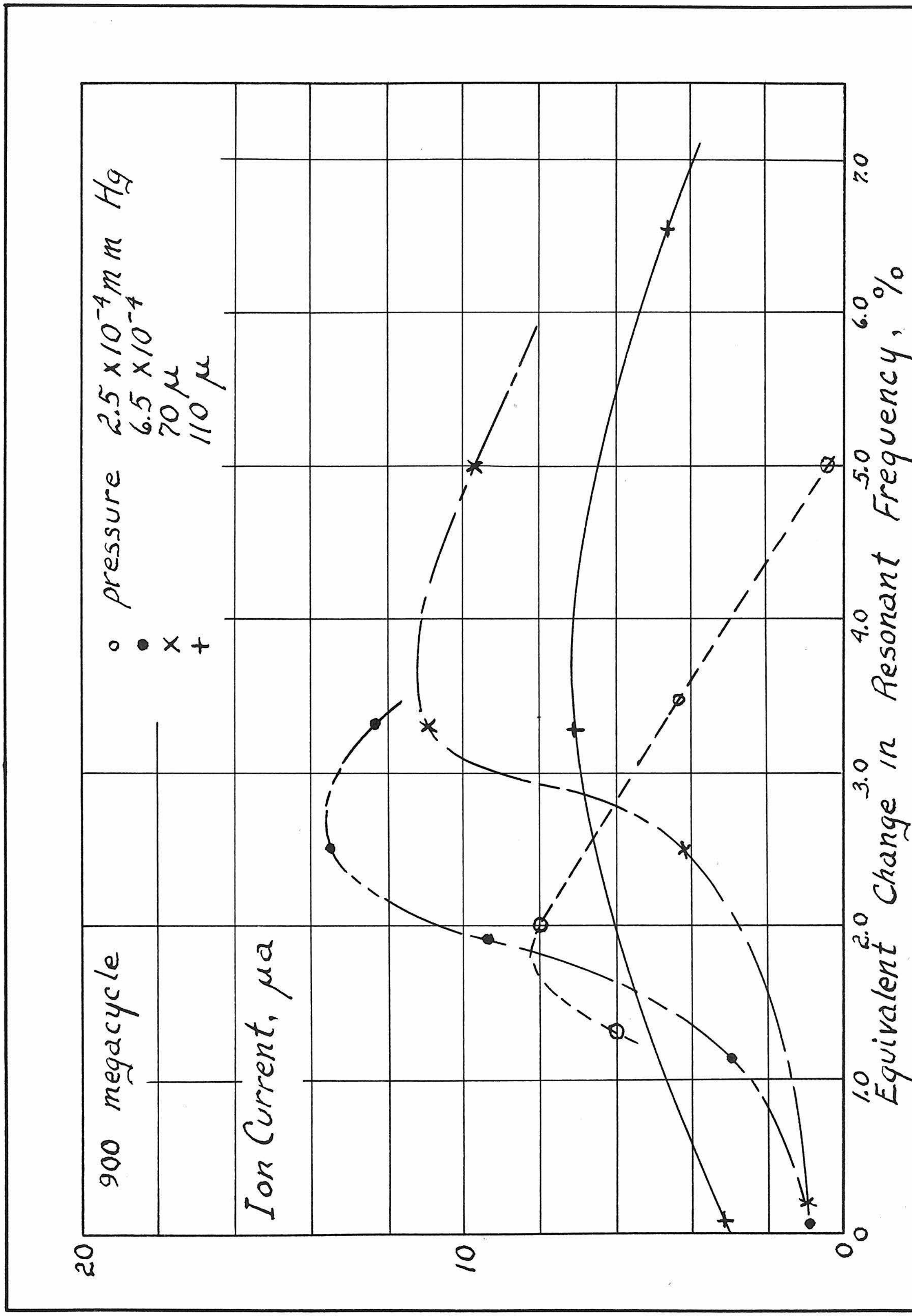
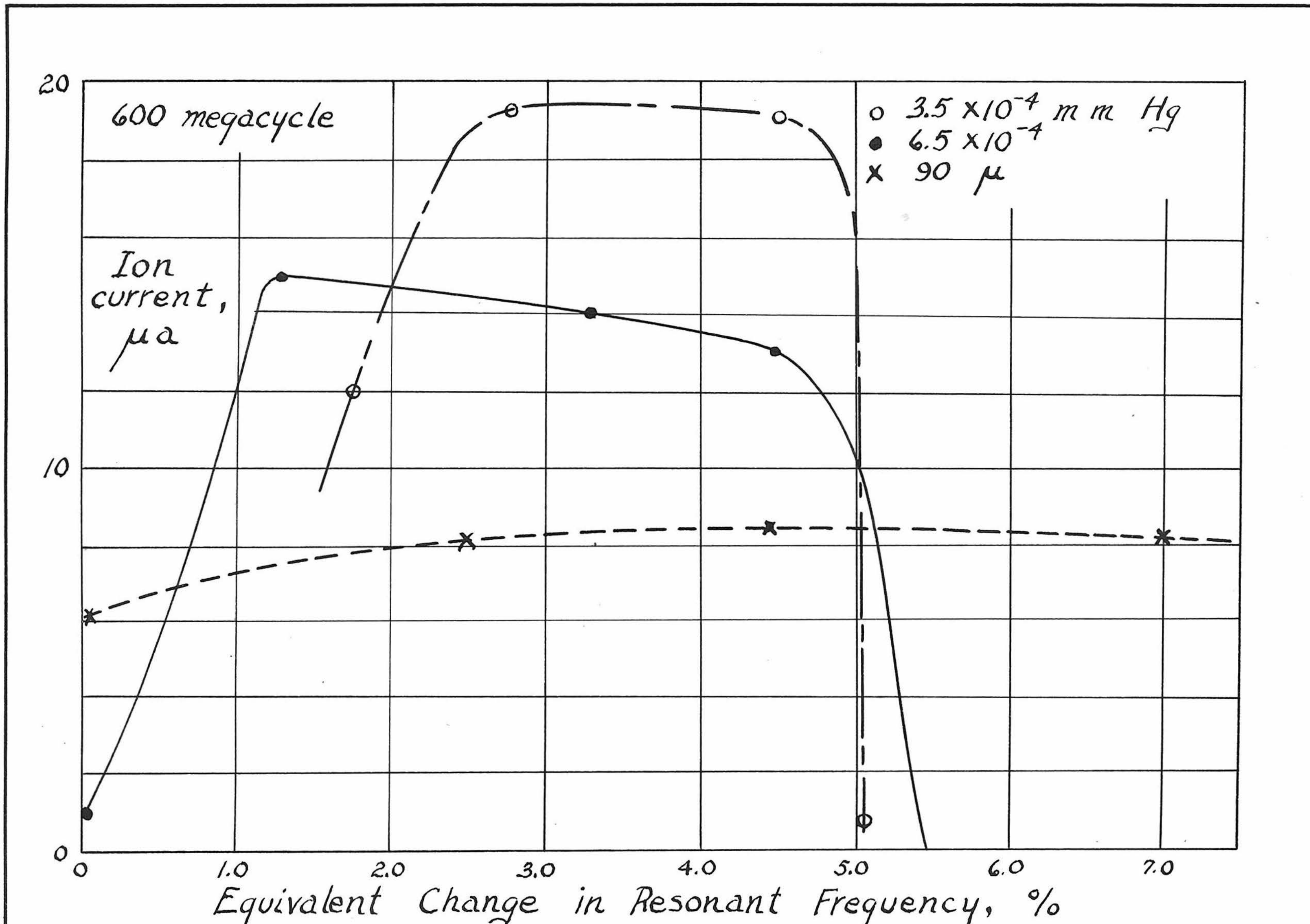

900 megacycle
Ion Current, μa
o ● × + pressure
2.5 x 10⁻⁴ mm Hg
6.5 x 10⁻⁴
70 μ
110 μ
20
10
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Equivalent Change in Resonant Frequency, %

Figure 10



600 megacycle
o 3.5 x10^-4 mm Hg
● 6.5 x10^-4
x 90 μ
Ion current, μa
20
10
0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Equivalent Change in Resonant Frequency, %

Figure 11

characteristics to tuning plug position at high pressures would seem to be very clear. This is easily explained on the basis of a broadening of the cavity resonance curve by a dissipative load, by which the ionization processes in the discharge may of course be represented.

III ION CURRENTS IN BARE METAL CAVITIES

The dependence of ion currents on tuning has just been discussed. The dependence on pressure is shown in Figs 12,13, where the currents shown are those obtained at optimum tuning plug positions for the particular conditions shown. Neither the presence nor the location of the maximum shown can be discussed very fully without considerably more information, both theoretical and experimental; obviously if the pressure is too low, no ion currents of any consequence can be formed, whereas at higher pressures the gas itself will interfere both with ionization, either by secondary emission from the walls or by the Mierdel[10] process, and with ion withdrawal from the cavity. It would seem that the location of this maximum might change with both high-frequency power level and frequency, although there is no evidence for such dependence here.

The dependence of ion current on withdrawing potential is shown in Fig. 14. There is little that can be said about these curves, or need be said, except that they show clearly that some type of space-

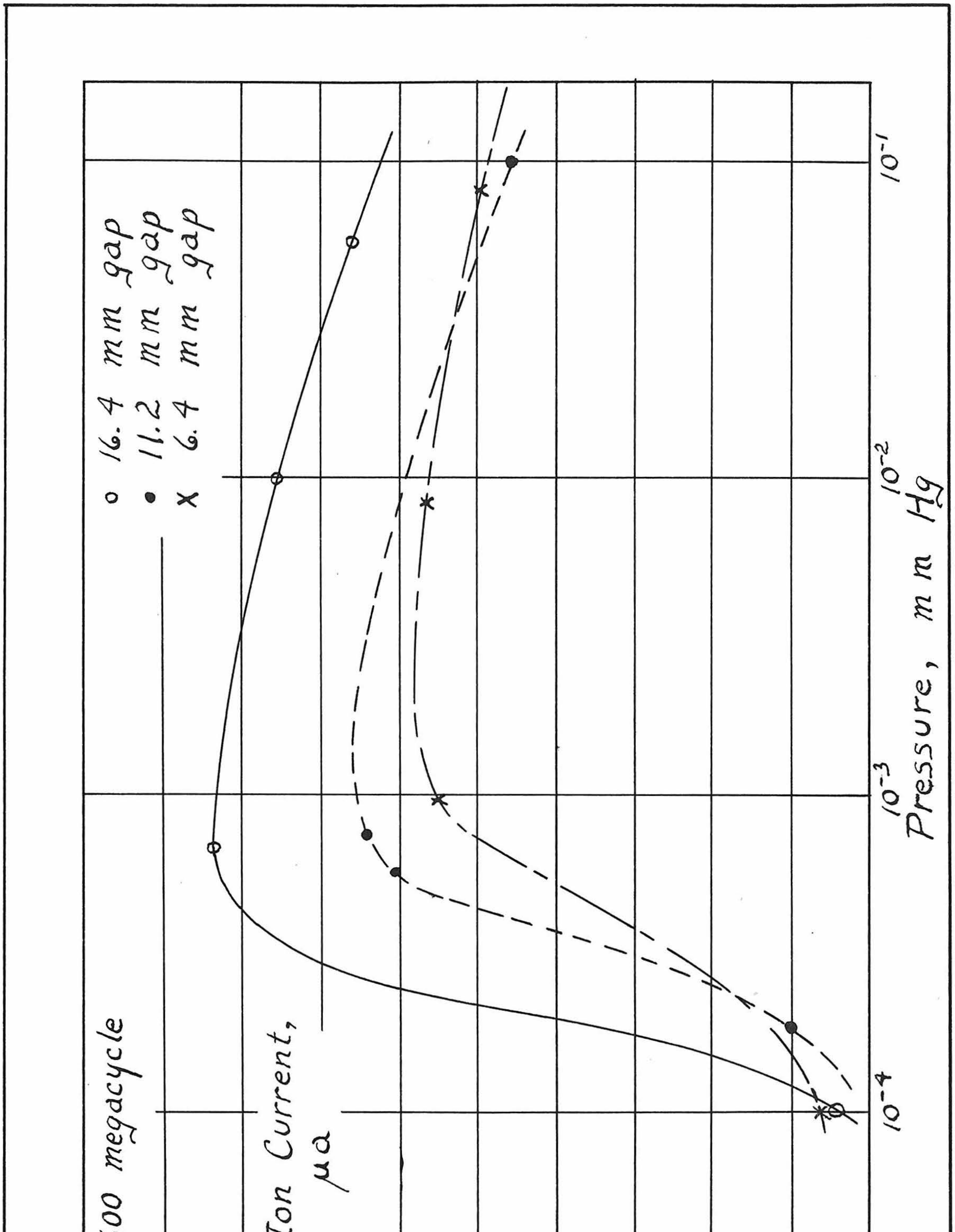

600 megacycle
Ion Current, μa
o 16.4 mm gap
• 11.2 mm gap
x 6.4 mm gap
Pressure, mm Hg
20
10
0
10^-4
10^-3
10^-2
10^-1

Figure 12

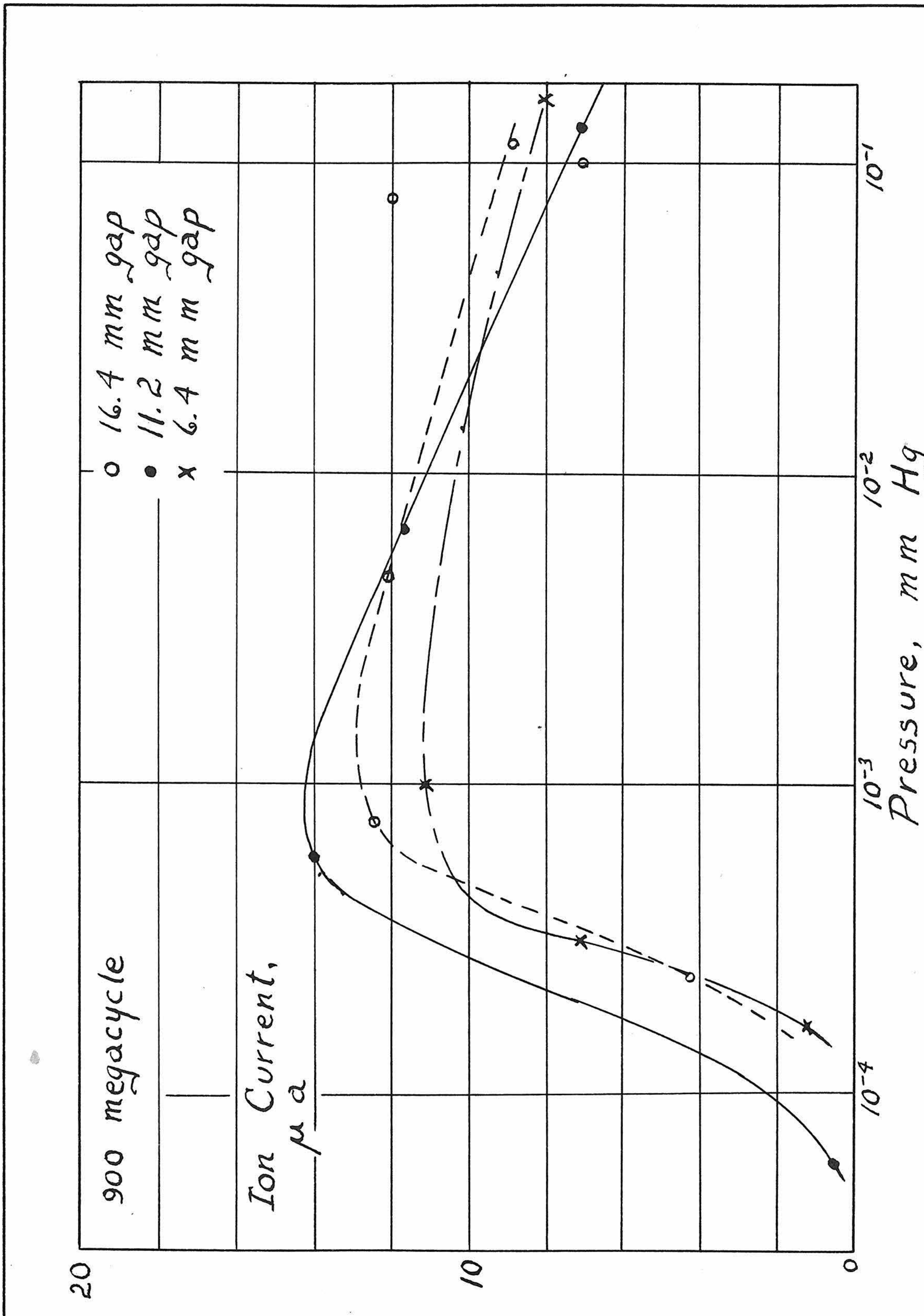

900 megacycle
Ion Current, μa
16.4 mm gap
11.2 mm gap
6.4 mm gap
Pressure, mm Hg
10^-4
10^-3
10^-2
10^-1
20
10
0

Figure 13

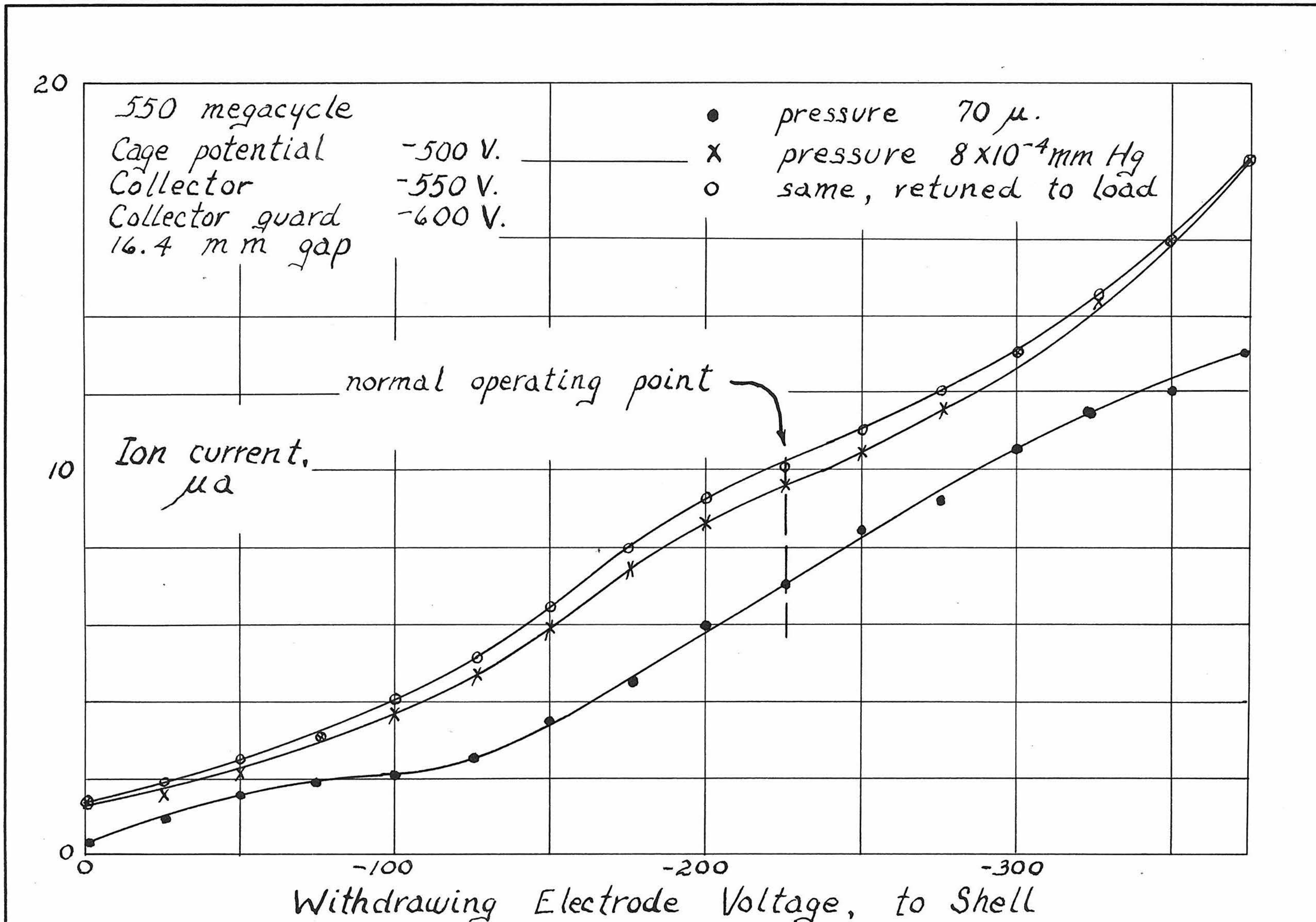

550 megacycle
Cage potential -500 V.
Collector -550 V.
Collector guard -600 V.
16.4 mm gap
• pressure 70 μ.
x pressure 8 x10⁻⁴ mm Hg
o same, retuned to load
normal operating point
Ion current, μa
20
10
0
0
-100
-200
-300
Withdrawing Electrode Voltage, to Shell

Figure 14

charge effect is involved; the fact that the ion current rises monotonically while the withdrawing electrode potential is taken all the way from the source cavity potential to the Faraday cage potential indicates against the supposition that the rise can be due entirely to a focussing effect.

IV INITIAL ENERGIES OF THE ION BEAM

In these measurements the ion beam originated in a space free of any DC fields except those due to space charge or to the leakage from the withdrawing electrode, and yet their combined kinetic and potential energies are as high as 125 volts with respect to the cavity in which they were formed. (Fig. 15) This measurement was one of the first ones which suggested that space charge was playing an important role in these phenomena; no ion currents of any importance had ever been observed without a withdrawing potential, yet once withdrawn, the ions were seem to have ample energy to escape except for some unexplained effect. The conclusion finally arrived at to explain this result is shown graphically in Fig. 16a,b. Fig. 16a shows the hypothecated potential distributions in the gap, in the absence of a withdrawing potential, due to ions alone, electrons alone, and their resultant. The

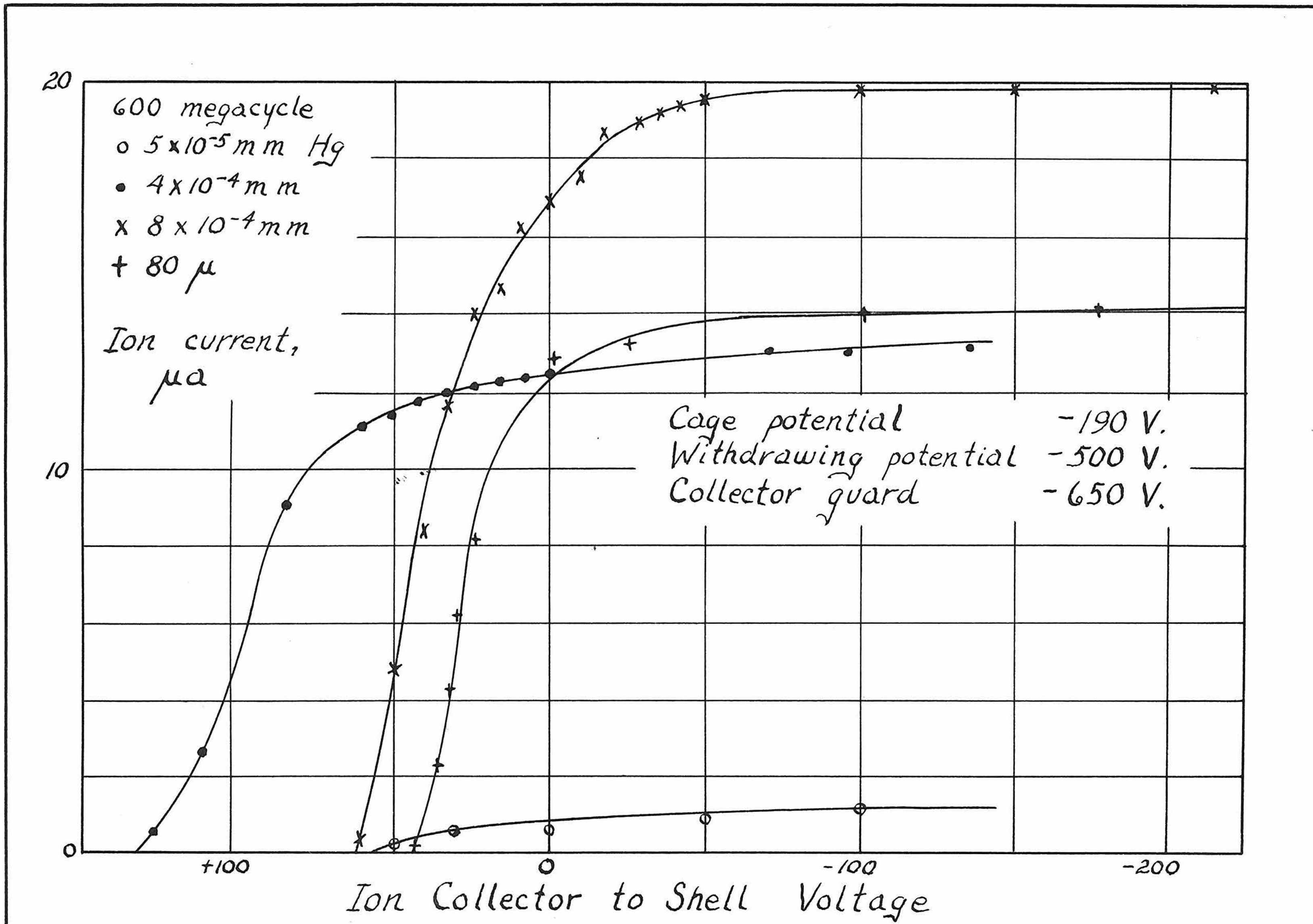

600 megacycle
o 5 x 10^-5 mm Hg
• 4 x 10^-4 mm
x 8 x 10^-4 mm
+ 80 μ
Ion current, μa
20
10
0
+100
0
-100
-200
Cage potential -190 V.
Withdrawing potential -500 V.
Collector guard -650 V.
Ion Collector to Shell Voltage

Figure 15

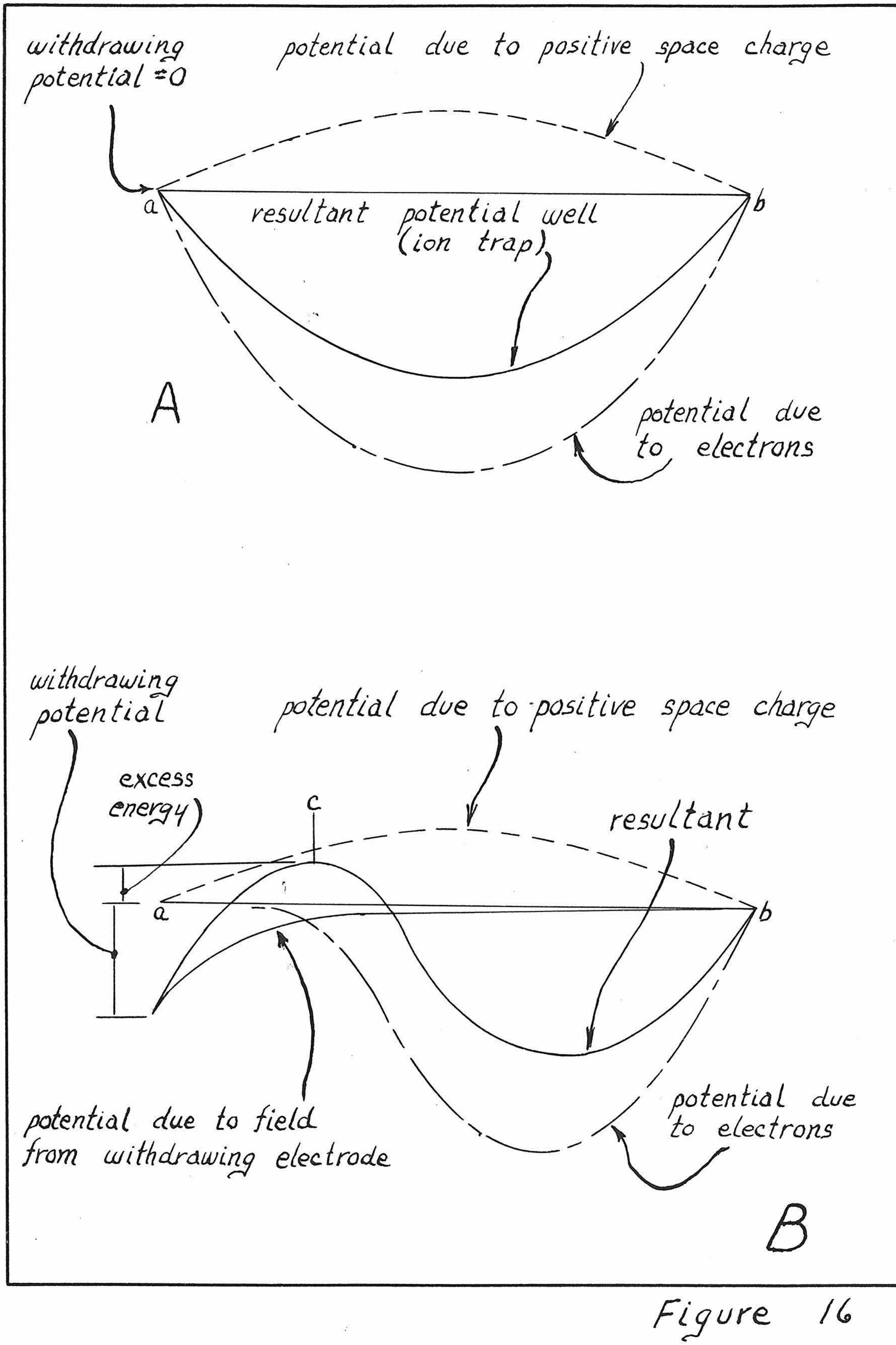

withdrawing potential = 0
potential due to positive space charge
a
b
resultant potential well (ion trap)
A
potential due to electrons
withdrawing potential
potential due to positive space charge
excess energy
c
resultant
a
b
potential due to field from withdrawing electrode
potential due to electrons
B

Figure 16

net potential clearly forms a well, or space-charge trap, from which the ions are unable to escape.*
Fig. 16b shows the same quantities in the presence of a withdrawing potential. The internal potential due to the leakage field from the withdrawing electrode is shown as a light solid line, the remaining potentials being shown as before. It is assumed that the leakage field does not disturb the positive space charge much (not comparatively, at least) but that the negative space charge is comparatively distorted due to higher electron mobilities. The net potential (heavy solid line) permits the escape of ions formed between points a and c, and some of these ions will be ejected from the cavity with anomalous energies as is readily seen from the position of point c above b. The extent of penetration of this stray field from the withdrawing electrode will depend on the electrode potential, which explains at least a part of the dependence of ion current on this potential which was discussed in the section just previous to this one.

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* Langmuir has shown that the potential due to a combined uniform field and uniform space charge is parabolic.

APPENDIX II

INTERNAL CONDITIONS IN THE CAVITY

One of the first observations which suggested that secondary emission might be playing an important part in the behavior of the discharge was the observation that the net stub current, in the absence of any DC fields, changed from negative to positive and back again when the cavity was tuned through resonance. Since the change affected only the rf field strength in the gap, it was difficult to believe that mostly positive ions might be collected at maximum field strength and then for the characteristics to change in some mysterious way so that mostly electrons would be collected at weaker fields; the supposition that the positive current is due to the fact that there are more secondaries leaving the stub than primaries striking it seemed much more plausible. It is known (11) that the secondary emission coefficient* of any material starts near zero at low bombarding energies, rises to at least one maximum, then falls again as the primary energy becomes high, and that the secondary emission coefficient of nearly all

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*The ratio of the number of secondary electrons ejected from a surface to the number of primaries striking it.

common materials exceeds unity* for at least a part of this range in primary energies. This fact makes it possible to give a ready explanation for the change in sign of the stub current; at high field strengths and high energies, the secondary emission coefficient of the wall material is greater than unity for a sufficient number of the primary electrons that the average current to the stub is positive, while detuning the cavity decreases the field strength and hence the average energy so that the secondary emission coefficient is less than unity and the stub current is of the sign to be expected from electrons.

It is possible to check this hypothesis by imposing a DC biasing voltage on the stub. If the current to the unbiased stub is positive and due to positive ions, it should be decreased by a positive bias; if due to excess secondaries it should be increased, because the positive potential will increase the number of primaries striking the surface, until the bias is so high as to interfere with the escape of the secondaries themselves. The argument is reversible; if the bias is negative, the current, if due to ions, should increase; if due to secondary emission, it should decrease. The results

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* At least when the surface is not clean and free from occluded gas, which is the situation here.

of actual measurements are shown in Fig. 17. It will be clear from a study of the figure that the hypothesis just given is confirmed in a generally satisfactory way. The question of current continuity will be dealt with shortly.

The effect of an axial magnetic field may now be discussed. The first gross observation was that the magnetic field has much the same effect on the discharge as a parallel steady electric field, in creating a fringing discharge or in extinguishing the discharge altogether.

The explanation which is believed to be correct is the following. At zero magnetic field, the space charge is self-limiting by virtue of electron circulation to the walls of the cavity; as soon as a negative space charge has built up to an appreciable level, electrons are ejected radially (transversely to the rf electric field) where they are collected on the inner walls of the envelope and can return as conduction electrons through the walls to the gap. It will be obvious that secondary emission at the envelope will play no part of importance in this phenomenon because the field at the envelope is essentially steady and any secondaries formed will be driven back into the surface from which they originated. This provides a sustaining mechanism for the secondary emission in the magnetic-field-free gap and makes the negative space charge self-limiting at a low level. As soon as

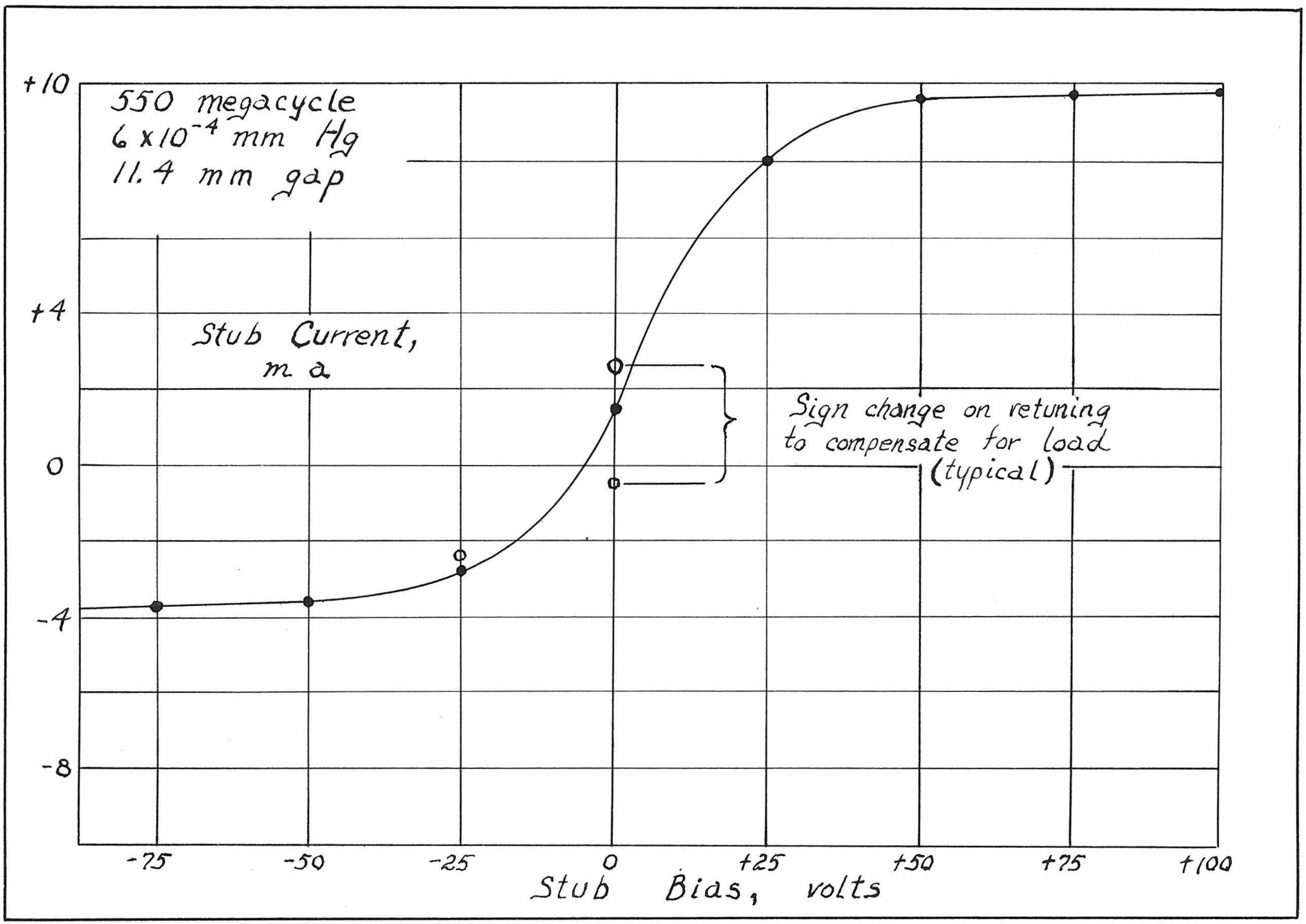
550 megacycle
6 x 10^-4 mm Hg
11.4 mm gap
Stub Current, m a
Sign change on retuning to compensate for load (typical)
+10
+4
0
-4
-8
-75
-50
-25
0
+25
+50
+75
+100
Stub Bias, volts

Figure 17

an axial magnetic field is applied, this electron circulation is inhibited, the electrons are trapped in the ionizing region, the negative space charge builds up to the point where there is a DC field high enough to extinguish the discharge (at low pressures) by mechanisms already discussed at length in Appendix I.

To obtain a check on this hypothesis, two measurements were made, the first being measurements of stub current and collected ion current as functions of the magnetic field, and the second being a measurement of the electron current collected at the wall as a function of magnetic field. Since the second of these measurements has the simpler interpretation we will deal with it first.

The experimental arrangement and the data are shown in Fig. 18. The data are generally confirmatory of the hypothesis just stated, as will be seen. This very clear and unambiguous confirmation is obtained only at low pressures, however; at higher pressures, and especially with a ten or fifteen millimeter gap, there is a sufficiently strong general discharge throughout the cavity to mask largely or completely the effect sought. This does not, of course, affect the validity of the conclusion.

Measurements of stub current and collected ion current as a function of magnetic field are shown in

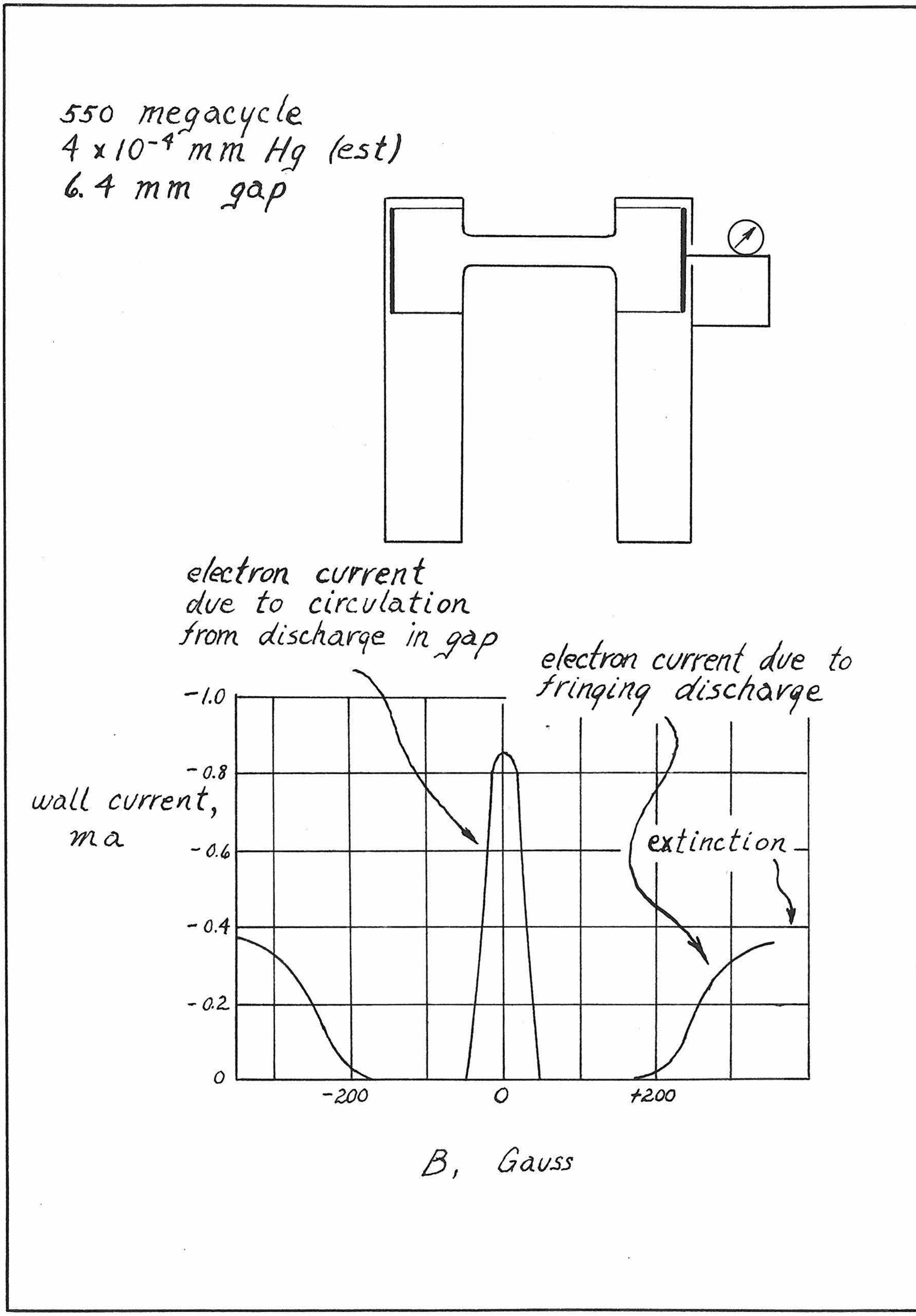
550 megacycle
4 x 10^-4 mm Hg (est)
6.4 mm gap
electron current due to circulation from discharge in gap
electron current due to fringing discharge
extinction
wall current, ma
-1.0
-0.8
-0.6
-0.4
-0.2
0
-200
0
+200
B, Gauss

Figure 18

Fig. 19. The simultaneous dip in ion current and stub current may have several explanations. One may say that the magnetic field acts in some unexplained way to depress the ionization in the cavity directly and hence to inhibit both electron current to the stub and the ion current to the collector. This explanation is refuted by two observations: first, that the electron currents ejected from the cavity show a generally rising tendency with increasing magnetic field (Fig. 20) and second, that the stub current was observed actually to change sign on one occasion, so that the drop in stub current seems most likely to be due to an increase in its secondary emission rather than due to a reduction in the number of primaries striking it. It was originally thought that the magnetic field might have some influence on the secondary emission coefficient of the gap material by influencing its state of magnetization, but this seems implausible because the effect of increasing electron current and decreasing ion current was also observed with the Pyrex bottle (stub current, of course, could not be measured in this case). It is now believed that the magnetic field, by inhibiting electron circulation, simply concentrates the discharge to such an extent as to operate it at a higher power density and consequently raise the average electron energy to the point where conditions for secondary emission become more favorable. Such an effect will show the general

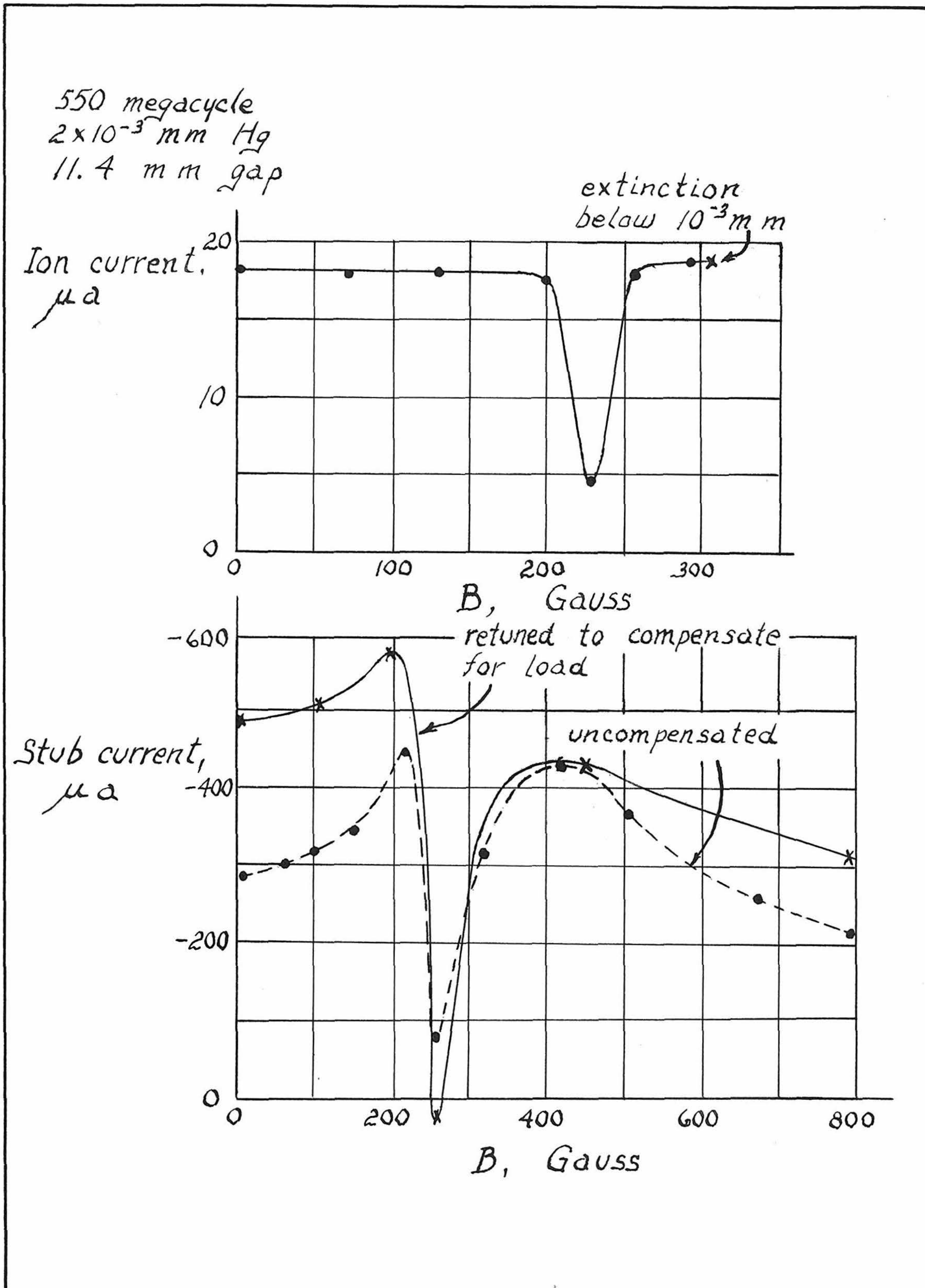
550 megacycle
2 x 10^-3 mm Hg
11.4 mm gap
extinction below 10^-3 mm
Ion current, μa
20
10
0
0
100
200
300
B, Gauss
retuned to compensate for load
uncompensated
Stub current, μa
-600
-400
-200
0
0
200
400
600
800
B, Gauss

Figure 19

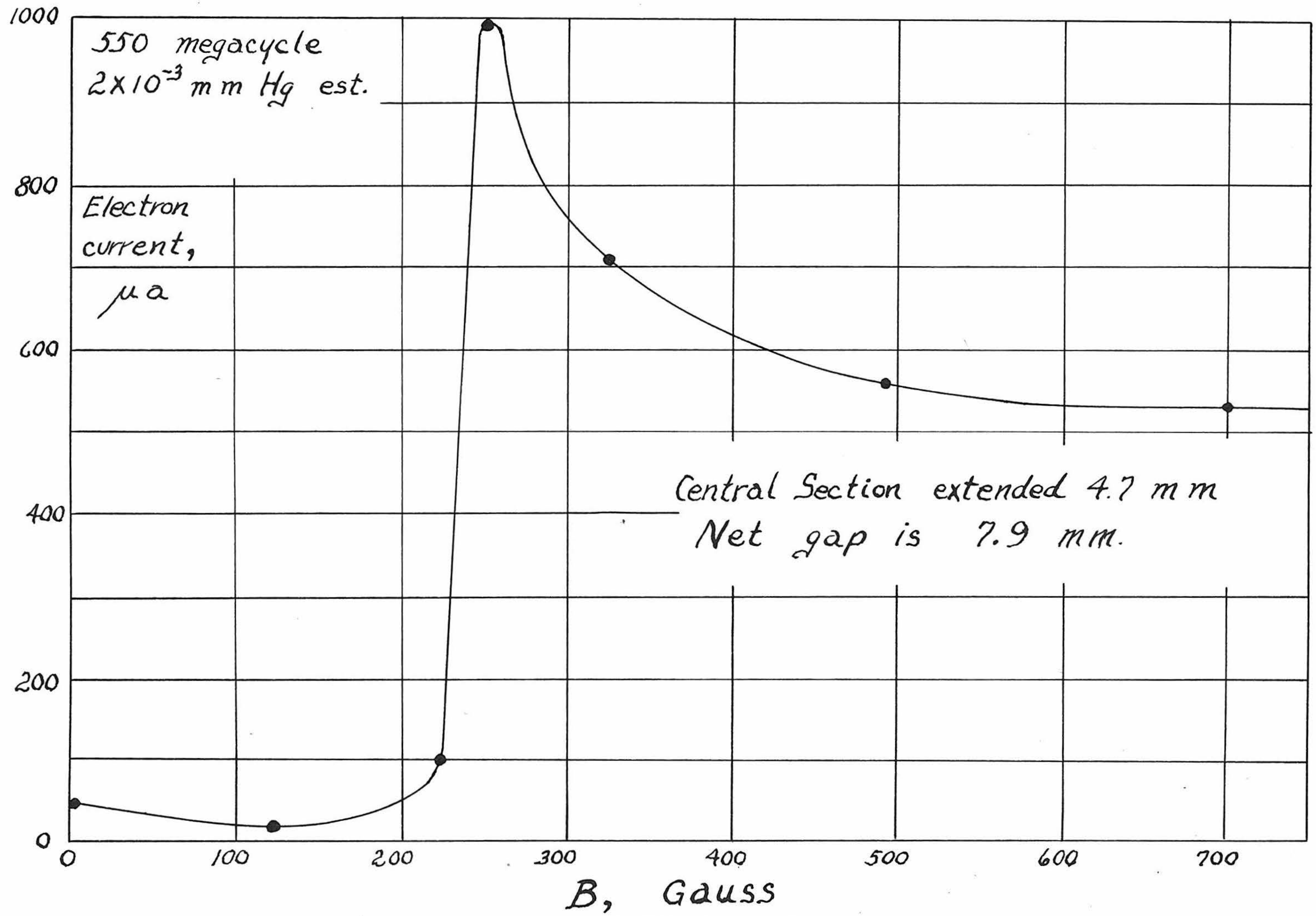
550 megacycle
2x10⁻³ mm Hg est.
Electron current, μa
Central Section extended 4.7 mm
Net gap is 7.9 mm.
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
B, Gauss

Figure 20

behavior seen here; the electon density will increase sharply at the point where the average electron energy is high enough to be effective in producing secondaries, but the imposition of higher than optimum magnetic fields will depress the yield of electrons because the space charge eventually becomes so high that the low energy secondaries cannot get across the gap to contribute to the process.

This phenomenon will also account in a qualitative way for the formation of axial jets in the discharge; it was observed both in the Pyrex bottle and in the metal cavity with the central pillar extended that under certain critical conditions of pressure and magnetic field, an intense jet would be formed on the axis of the cavity, the discharge continuing at about its usual brilliance in the remainder of the active volume. At higher pressures, intense localized cones would form about the two axial openings in the Pyrex bottle or in the end plates in the metal gap. It is known(11) that secondary emission is preponderantly normal to the emitting surface; secondaries emitted at the curved lips of the exit orifices are emitted transversely to the field, due to space charge, which tends to drive them back into the surface, and consequently secondary emission at the edges of these openings will be inhibited at higher fields than those for which the emission is inhibited on the plane surfaces of the gap.

There can be no question that the electron density in the immediate neighborhood of the exit orifice is markedly enhanced by jet formation. In the absence of any DC potentials, the formation of a reasonably intense jet in the cavity was always accompanied by the appearance of a visible exit beam of electrons moving toward the collector; with some accelerating potential on the electrodes, this beam was brightly visible with the room lights on. The beam was invariably composed principally of electrons, in amounts up to fifty milli-amperes under the most favorable conditions; it was always possible to get twenty milliamps or so without any trouble and with some care in picking optimum operating points for pressure, tuning, and magnetic field, thirty milliamperes or more could be obtained consistently.

Not only the intensity of the emergent electron beam, but its energy, depended on the value of the axial magnetic field. A crude magnetic analyzer was constructed during one phase of the work and placed in the path of the emergent beam; when this was first constructed it was believed that electron energies might be as high as several hundred volts and might be reaching the negatively biased collector and hence interfering with ion current measurements (for example, causing the dip in measured ion current on jet formation already alluded to). As soon as the magnetic analyzer was installed it was observed that the deflection of the emergent electron beam was markedly dependent on the axial magnetic field within the cavity, the deflection being a minimum at the field setting corresponding to jet formation. (This, of course, is without any withdrawing potentials). The two magnets were electrically isolated so that there was no chance of a change in the current in one affecting the other (the change was most strikingly evident with the analyzer magnet operating only on its residual field). Somewhat better measurements of initial electron energies are shown in Fig. 21 for various magnetic fields; these were done with the Pyrex bottle, with no withdrawing voltages, and with other potentials as shown.

Some measurements on the Pyrex bottle were made with a plain end bell on the cavity, as shown in Fig. 23, This end bell was constructed to permit better observation of the exit beam, although at the expense of the focussing means shown in Fig. 6. One observation of possible interest was that, at the lowest possible pressures (estimated to be about $4\text{-}5 \times 10^{-4}$mm.), the emergent beam was positive in sign and had considerable energy. The energy depended on both magnetic field and pressure. The dependence on magnetic field is shown in Fig. 22, where the energy estimate was based on the known repelling potential of the cage plate and the height of the positively charged cloud. The dependence on pressure could not

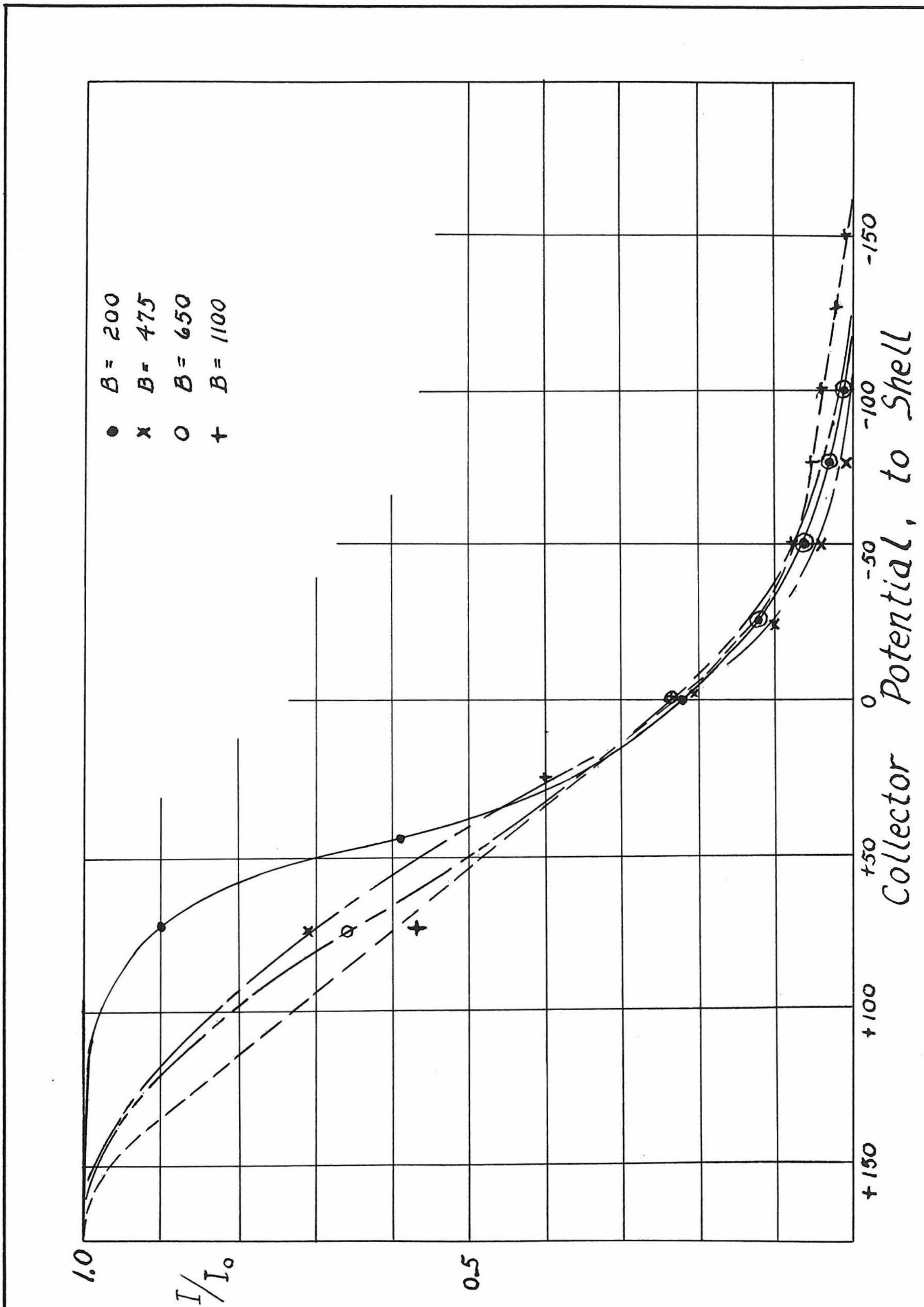
B = 200
B = 475
B = 650
B = 1100
I/I₀
1.0
0.5
+150
+100
+50
0
-50
-100
-150
Collector Potential, to Shell

Figure 21

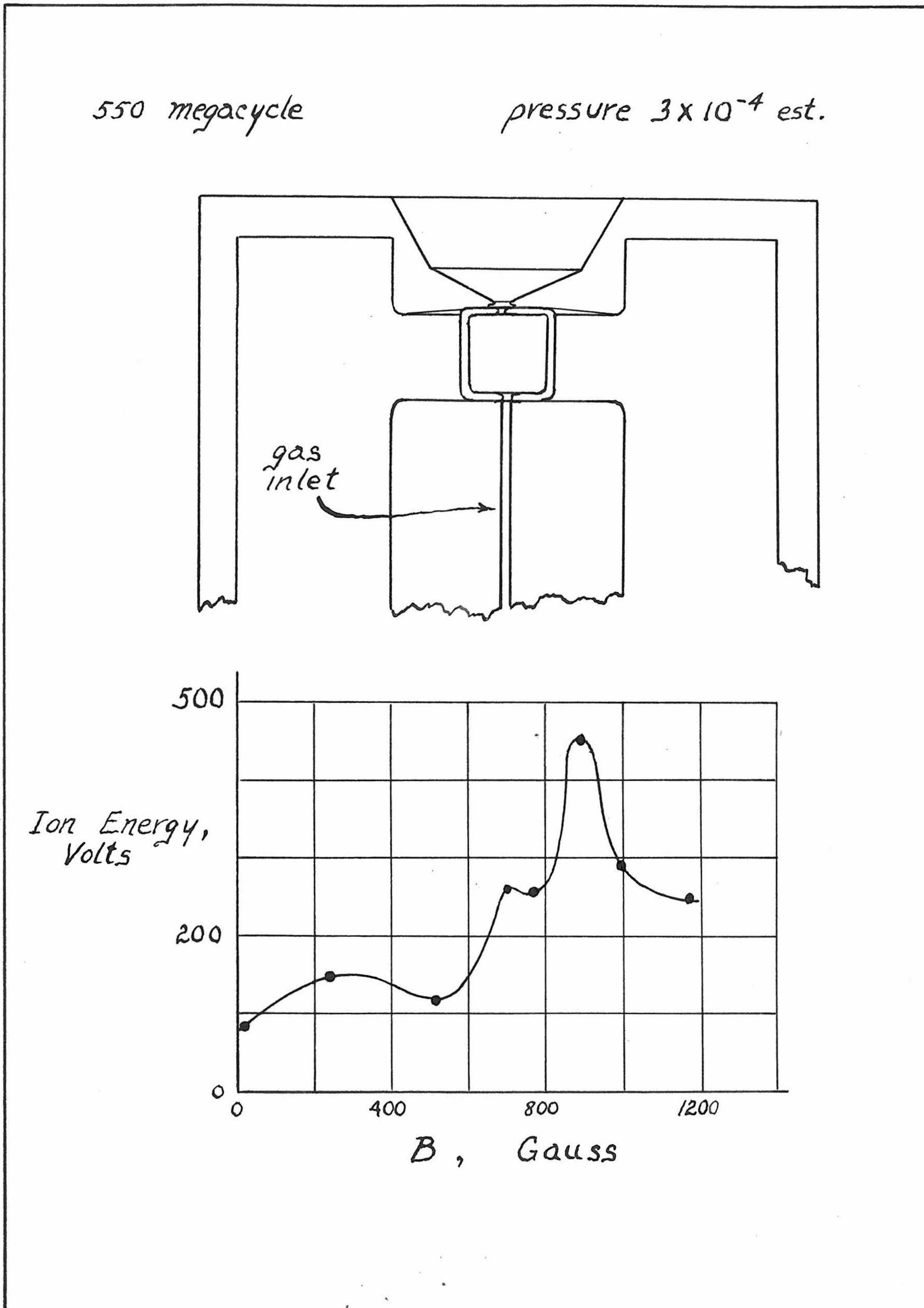
550 megacycle
pressure 3 x 10^-4 est.
gas inlet
500
200
0
Ion Energy, Volts
0
400
800
1200
B, Gauss

Figure 22

be measured, but the energy increased steadily as the pressure was reduced, all the way down to the point where the discharge was extinguished by insufficient gas, and decreased as the pressure was raised, the positive cloud disappearing altogether long before the electron beam became visible. If it is supposed that the Pyrex bottle was actually ejecting electrons but that the electron beam was not visible because of the low pressure in the bell jar at the time, secondary emission from the walls of the Pyrex will account for this phenomenon; electrons to replace those emitted are carried over the surface of the Pyrex from the metal discharge cavity and in so doing they bias the outside of the cavity strongly negative with respect to its interior, which results in a withdrawing field equivalent to the one which had to be imposed in the metal cavity. At higher pressures, the discharge becomes more intense, the Pyrex is heated to the point where its surface conductivity increases, and the electron flow gives rise to a smaller potential difference and a lower ion energy. These currents are in any case too unstable and too small to be of any practical value (or even measurable with the apparatus available; certainly they were under one microampere) and are reported here only for general interest.

CONCLUSION

Ultra-high frequency discharges exhibit two characteristics which differentiate them sharply from direct-current or low-frequency discharges: the first is that the oscillatory motion of some of the electrons is sufficient to make possible a discharge under lower pressures than those in which a direct-current discharge could be maintained, and the second is that the inhibition of secondary electron emission from the walls of the cavity is so much less effectual that secondary electron emission, and the high negative space charges associated with it, may play a role of governing importance at some pressures. The use of an axial magnetic field may prevent the dissipation of this negative space charge and thus lead to the formation of steady electric fields, which have their origin in space charge, large enough to blow out the discharge altogether at low pressures.

Space charge plays a governing role in determining the energy of an emitted ion beam; such a beam may have energy as high as several score volts, presumably of either sign, and depending on the parameters chosen, due to space charge or the action of withdrawing fields.

Under conditions favorable to electron ejection, ions observed are formed principally in the exit orifice of the source by interaction of the emergent gas beam with the electron jet; under such conditions, the use of a Pyrex bottle serves principally to ensure that the emergent gas stream will be largely in atomic, rather than molecular, form.

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