MASSACHUSETTS INSTITUTE OF TECHNOLOGY

CAMBRIDGE

February 4, 1958

Mr. Elias P. Gyftopoulos
35 Phillips Street
Arlington, Massachusetts

Dear Sir:

I take pleasure in informing you that you have been recommended by the Faculty for the Degree of Doctor of Science.

Very truly yours,

L. F. Hamilton

Secretary of the Faculty

DEPARTMENT OF ELECTRICAL ENGINEERING

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE 39, MASSACHUSETTS

December 21, 1956

Mr. E. P. Gyftopoulos
Room 24-090
M.I.T.

Dear Mr. Gyftopoulos:

Your doctoral thesis proposal entitled, "Fundamental Processes in High Vacuum Under High Voltages and High Electric Gradients" has been approved. This work will be done under the supervision of Professor J. G. Trump. Professors Gray and Van de Graaff have been appointed to cooperate with Professor Trump as readers.

The supervisor and readers of your thesis will carry the principal responsibility for evaluating the work you do. Consequently, they should be kept fully informed about the progress of your work and your future plans. Verbal reports to your supervisory committee should be supplemented by written summary reports. These may be made on forms available in Room 4-208 or by letter addressed to me. The intervals between reports should be determined by the progress you make.

Sincerely yours,

S. H. Caldwell
S. H. Caldwell
for the
Department Graduate Committee

SHC:mp
cc: Professors Trump
Gray
Van de Graaff
Wiesner

Merry Christmas
SHC

FUNDAMENTAL ELECTRICAL PROCESSES IN HIGH VACUUM

by

ELIAS PANAYIOTIS GYFTOPOULOS

Dipl. Eng., Technical University of Athens
(1953)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
January 1958

Signature of Author . . . .
Department of Electrical Engineering
January 22, 1958

Certified by. . . . .
Thesis Supervisor

. . . .
for the Chairman, Departmental Committee on Graduate Students

FUNDAMENTAL ELECTRICAL PROCESSES IN HIGH VACUUM

by

ELIAS PANAYIOTIS GYFTOPOULOS

Submitted to the Department of Electrical Engineering on January 22, 1958 in partial fulfillment of the requirements for the degree of Doctor of Science.

ABSTRACT

In an attempt to elucidate the processes which lead to electric instabilities in high vacuum, the charge carriers both before and during self-healing transients of a high voltage acceleration tube have been analyzed magnetically or magnetically and electrostatically. The analyzers used have been designed and constructed for the purpose of this investigation.

The energy spectrum of the electron current has been investigated and its time behavior established with total voltage across the tube and residual gas pressure as the variable parameters. It is found that during steady state electrons are formed at or near the electrodes and that self-healing instabilities are associated with pulsed discharges localized between one or more pairs of adjacent electrodes at various locations along the length of the tube. Pulsed discharges are always accompanied by a momentary rise of the residual gas pressure which may eventually result to a stable high voltage high vacuum discharge.

The energy and mass spectra of the negative ion current have been similarly investigated. It is found that negative ions are formed only during or on the verge of occurrence of transient instabilities. These ions originate from the vicinity of the same electrodes from which the electron pulses are extracted, and are H_1^-, O_1^-, $C\ell^-$ and some others. No negative heavy clumps of matter singly or multiply charged have been detected. However along with the negative ions some neutral particles have been recorded which seem to result from stripping of the electron charge of the former.

The energy and mass spectra of the positive ion current has been studied with voltage, residual gas pressure and gradient as the variable parameters. It is observed that positive ions of a great variety of mass numbers exist always in the dark current of acceleration tubes and originate from the vicinity of the electrodes. During self-healing transients positive ions were predominantly formed in the vicinity of the tube sections which undergo localized discharges. No positive heavy clumps of matter singly or multiply charged have been found. However along with the positive ions some neutral particles have been detected which probably result from electron attachment or charge exchange processes that the former are subject to during their acceleration.

A new mechanism for the initiation and growth of instabilities in single or multiple vacuum gaps is suggested which seems to be consistent with both prior experimental data and the results of the present research. The mechanism amounts to an exchange of positive and negative ions between cathode and anode which becomes critical when the voltage-gradient product is greater than a constant, characteristic of electrode materials, their surface conditions and their "electric" history. The negative ions are assumed to be formed by electron attachment to neutral particles produced in the vicinity of the cathode by positive ion sputtering.

Thesis Supervisor: John G. Trump
Title: Professor of Electrical Engineering

To my beloved FATHER

INDEX

ACKNOWLEDGEMENT

The author feels particularly happy to have this opportunity to express his deepest appreciation and gratitude to Dr. John G. Trump whose continuous inspiration, guidance and encouragement have been the greatest assets of this work.

He also wishes to sincerely thank and particularly acknowledge the kind and ever present advice and assistance of Dr. Trump's associate Robert W. Cloud.

His thanks are likewise extended to the entire staff of the High Voltage Research Laboratory and more specifically to Mr. Christos G. Andreadis, Mr. Robert Charpentier, Mr. Walter D. Wasson and Mr. Boris Subbotin for their valuable assistance given during various phases of the work.

Finally the author wishes to express his thanks to the drafting and machine shop groups of the Laboratory for Nuclear Science for their cooperation during the design and construction of the apparatuses; to Mrs. Grace Rowe and Mr. Percy Lund for diligently drawing the illustrations and to Mrs. Hazel Emerson for her fine work in typing the manuscript.

The generous sponsorship of the National Science Foundation is also gratefully acknowledged.

ILLUSTRATIONS

TABLES

INTRODUCTION

"Vacuum" is one of the most essential media for many disciplines of modern science and technology. In atomic and nuclear physics, the acceleration of energetic particles for probing the structure of matter takes place in high vacuum. In medicine, the production of X-rays for diagnostic and therapeutic purposes requires evacuated tubes. In industry, the production of energetic radiations for sterilization of drugs or for non-destructive materials testing involves acceleration in space which is in effect free of matter. In electronics, the vacuum tube is an indispensible component of innumerable devices and systems.

In these and many other applications of vacuum high voltages and high electric gradients are necessarily present. Consequently the imperative need for improving the understanding of the behavior of high vacuum under a wide range of electric stresses is evident.

Actually, since high vacuum is defined for all practical purposes as matter-free space, what one means by behavior of high vacuum under electric stresses is really the behavior of the materials which enclose the evacuated region rather than the high vacuum itself. However, because of the fact that any phenomena that may happen to the materials having a surface in the empty space will eventually have to be bridged through the vacuum gap, it is customary to talk about the behavior of high vacuum under electric stresses.

The interest in the insulating properties of vacuum is many decades old. A series of scientific papers has been written and a large amount of experimental data has been accumulated throughout the years. Many attempts have been made to elucidate the fundamental processes which lead to transient or irreversible instabilities in vacuum gaps, however up to date there is no sound theory which goes beyond the phenomenological description of the processes involved and which embraces all the available experimental evidence.

The High Voltage Research Laboratory group of MIT has a keen interest in understanding the mechanisms which initiate and sustain or quench instabilities of insulating vacuum gaps because the acceleration tube is a main component of the Van de Graaff accelerator. Under the leadership of Drs. J. G. Trump and R. J. Van de Graaff, the group has accumulated a vast experience with electrically-stressed vacuum configurations and for many years has made studies pertinent to the behavior of evacuated acceleration tubes.

This report is an account of the efforts of the author who undertook the task to continue the work of the HVRL group in the field of vacuum insulation and disclose the mechanisms which lead to the loss of the insulating properties of high vacuum gaps.

The first chapter of the report reviews the problem of vacuum insulation and prior experimental results. The second chapter defines the specific purpose of this investigation and describes the vacuum configuration selected for this study. The third chapter describes the apparatus and the experimental techniques. The fourth chapter reports the experimental results of the research. The fifth chapter presents a mechanism of high voltage breakdown in vacuum which seems to account for both the present observations and those of previous investigators. The final chapter includes an overall summary together with suggestions for further research in the field of vacuum insulation.

CHAPTER ONE

REVIEW OF THE PROBLEM OF VACUUM INSULATION

1.1 Definitions

a. Vacuum Insulation. Vacuum insulation exists between two metallic electrodes (Fig. 1) if the mean free path for encounters between the molecules of the residual gas is much larger than the distance d between the electrodes. The above statement implies that the voltage-holding ability of a vacuum-insulated gap is independent of the residual gas pressure, provided that the gas pressure is lower than a certain upper limit p_o which is a function of the separation d between the electrodes.

Evidently then the behavior of vacuum insulation under high electric stresses is primarily affected by the solid materials which are introduced into the empty space since few encounters can occur in the high vacuum itself.

b. Vacuum Breakdown. Vacuum breakdown in the form of an arc, a spark or flashover occurs when the voltage across the gap reaches an upper limit which depends on various factors to be subsequently discussed. The breakdown appears as a transition of the impedance of the gap from an extremely high level to a very low value accompanied by an increase of the residual gas pressure. The transition from high to low impedance across the gap is irreversible unless the voltage across the gap is withdrawn and the gas pressure is brought back to its normal value.

c. Dark Current and "Kicking" Effect. Dark current is the current that flows across the gap and which is probably sustained either by various external ionizing agents such as cosmic rays or by field emission from low work function contaminents of the electrode surfaces. Superimposed on the dark current are randomly distributed self-healing current transients which appear at a threshold voltage. These transients are called "kicks" or pulsed discharges and the phenomenon is described as "kicking" effect or current loading.

1.2 Voltage Holding Ability of Vacuum Insulated Gaps

The breakdown mechanism of vacuum gaps with small separations between the electrodes is fairly well accounted for by the widely known field emission theory.(1) According to this theory a self-sustained discharge, which leads to breakdown, can occur when the gradient at the cathode reaches the value of several million volts per cm. Thus the potential barrier at the surface of the cathode is lowered below the Fermi level and the free electrons of the metal can escape from it. Fowler and Nordheim(1) formulated the problem theoretically and give the following relationship for the field emission current:(1-3)

$$I = 6.2 \times 10^{-6} \frac{\mu^{1/2}}{(\phi + \mu)\,\phi^{1/2}} E^2 \exp\left[- \frac{6.8 \times 10^7 \,\phi^{3/2}}{E} \right] \quad (1.2.1)$$

where

I = current density in amp /cm^2

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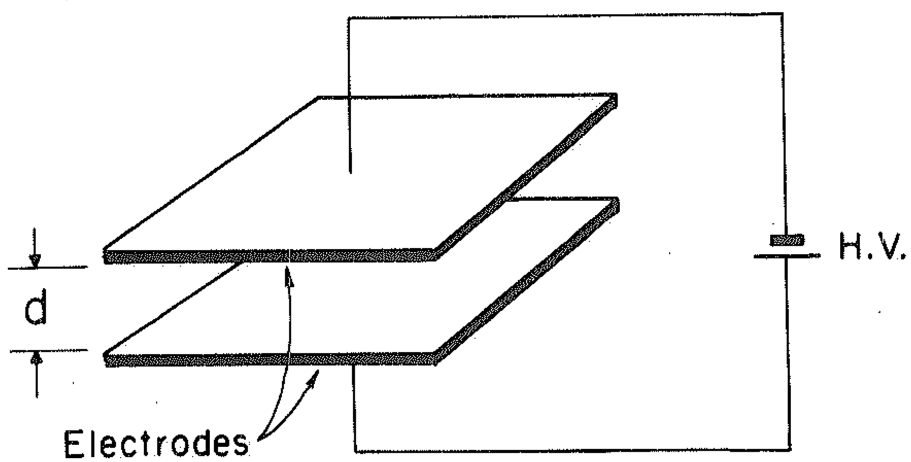
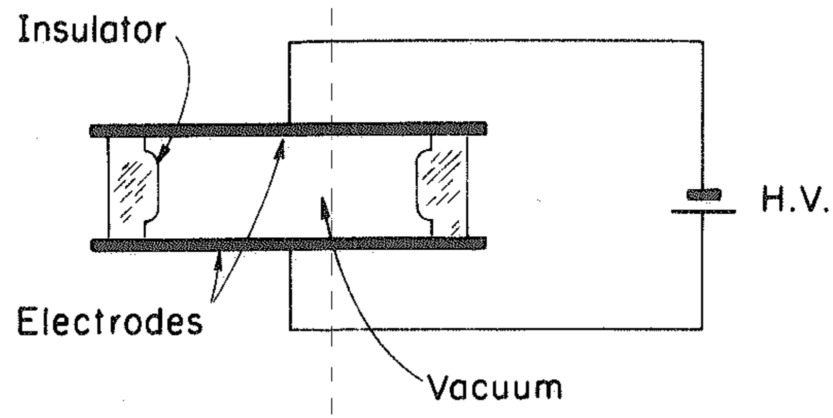
The theoretical value of the gradient necessary for field emission is of the order of 10^7 V /cm. assuming a perfectly smooth cathode surface.

The literature is full of data verifying the Fowler-Nordheim formula.(4-6) However, the experimental value of the gradient at which field emission occurs is lower than what theory predicts. This can be easily justified by



VACUUM IMMERSED GAP

Figure 1



VACUUM GAP ENCLOSED BY INSULATOR

Figure 4

the unavoidable field intensification which occurs at the cathode surface irregularities.

The breakdown mechanism of vacuum gaps with large separations between the electrodes is not the same as for small separations. This fact has been established by various experimenters[7-10] and is illustrated by Fig. 2 which shows the results that Trump and Van de Graaff[7] found during their high voltage vacuum breakdown experiments. It is evident that the threshold gradient, at which breakdown occurs in the case of gaps with large separations, is inadequate of itself to insure breakdown through the mechanism of field emission. One has to introduce other mechanisms which set in as the voltage across the gap increases to values above several tens of kv.

A possible mechanism was suggested by Van de Graaff[8] and amounts to an interchange of charged particles and photons between the anode and the cathode. Thus an electron starting from the cathode and accelerated by the voltage between the electrodes, impinges on the anode and gives rise to positive ions and photons. The positive ions and some of the photons return to the cathode and cause further electron emission. With the proper conditions the process becomes cumulative and leads to instability.

Quantitively the instability appears when

$$AB + CD > 1 \qquad (1.2.2)$$

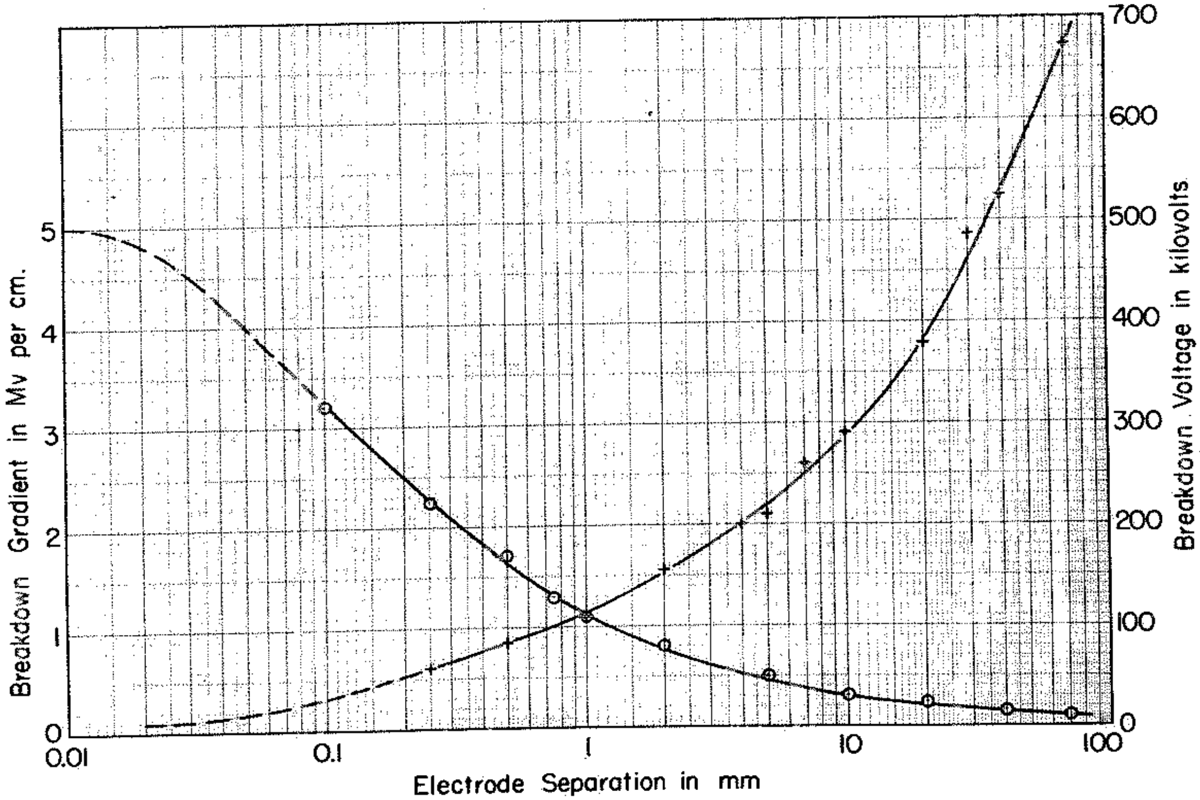
where

A = average number of positive ions per electron impinging on the anode.

B = average number of electrons per positive ion impinging on the cathode.

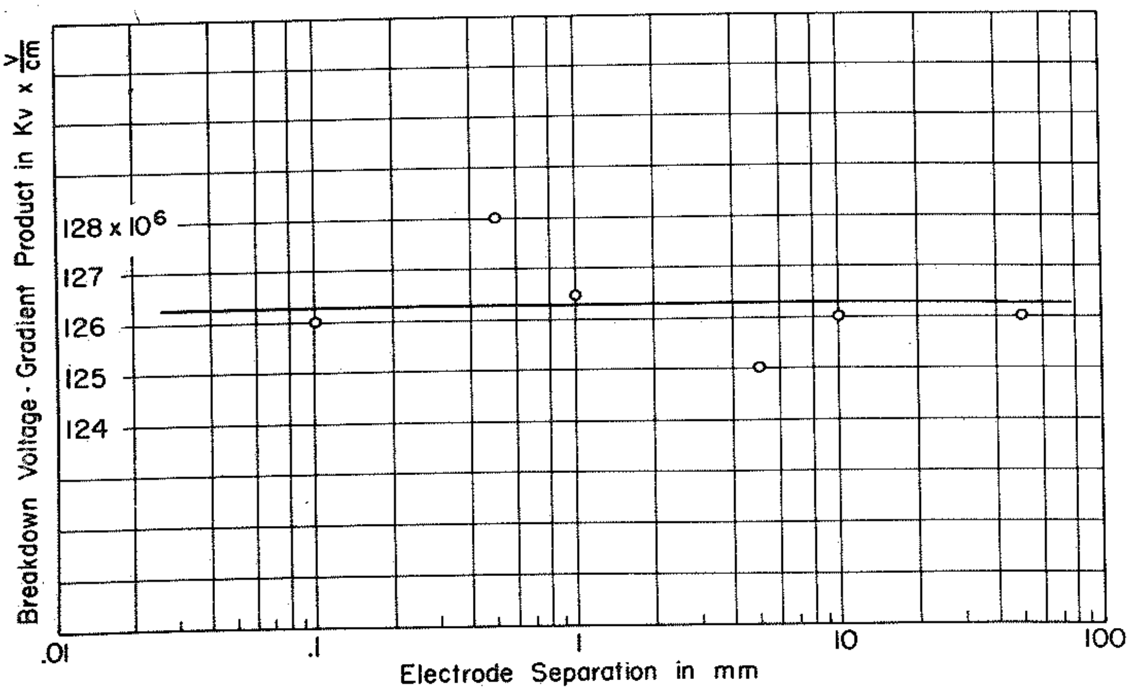
C = average number of "useful" photons per electron impinging on the anode.

D = average number of electrons per photon impinging on the cathode.



BREAKDOWN VOLTAGES AND GRADIENTS BETWEEN 1" STAINLESS STEEL BALL AND 2" STEEL DISK IN VACUUM

Figure 2



BREAKDOWN VOLTAGE GRADIENT PRODUCT FOR 1" STAINLESS STEEL BALL AND 2" STEEL DISK IN VACUUM

Figure 3

It would be expected that all coefficients A, B, C, D are functions of the energy of the particles involved or the total voltage across the gap, the materials used and their surface conditions.

The contribution to the mechanism by the processes described by the coefficients C, D is generally considered as negligible.(11) The values of the coefficients A and B have been determined experimentally(7) (12-16) and their product is found to be much smaller than one for a wide variety of voltages and gradients. Consequently an electron-positive ion exchange mechanism is now recognized as not adequate to explain the total voltage effect on vacuum breakdown.

Figure 3 is a plot of the data given in Fig. 2 of the product of the threshold gradient times the breakdown voltage versus electrode separation. It is worth noting that this product is essentially constant over all electrode separations. This fact was recognized by Fortescue and Heard and led Cranberg(17) to the formulation of his clump theory. According to this theory a clump of matter, loosely adhering to one electrode and in electric contact with it, is detached from the electrode by electrostatic repulsion. The detached clump is charged, the amount of charge being proportional to the gradient at the electrode surface, and accelerated along the vacuum gap. On impingement on the other electrode, if the energy density delivered by the clump is greater than a certain constant C, characteristic of the metals used and their surface conditions, breakdown may occur on account of local overheating resulting in thermionic emission. Obviously the energy of the clump is proportional to V x E, where V the voltage across the gap and E the gradient at the electrodes. Thus the onset of breakdown can be expressed as

$$V_{br} \times E_{br} > C' \qquad (1.2.3)$$

The latter condition appears to agree with the phenomenological experimental data of various research groups. However the validity of the hypothesis behind its derivation has not yet been established.

A series of experiments reported by Heard suggest that Cranberg's hypothesis is not valid. For instance Heard's experiments[18] show a direct dependence of the rise time of breakdown currents on the electrode separation; this would not be the case if Cranberg's hypothesis were true. Furthermore his data on material transfer from the anode to the cathode[19] indicate that the total charge transferred during a kick decreases with increasing gradients even though the total amount of material transferred is increased.

Theories related in general to the sputtering of particles from metallic surfaces by ion bombardment have a close bearing on the breakdown mechanism in vacuum but have not yet been examined in full detail. An attempt has been made by von Hippel[20] and some others but is not generally considered as very successful. The subject will be reviewed later on in this report.

1.3 Voltage-Holding Ability of Gaps Enclosed by Insulators

The voltage-holding ability of vacuum gaps whose electrodes are separated by insulators (Fig. 4) is affected adversely by the presence of the insulator.[21] However, by proper selection of the insulator material and corrugation of the surface exposed to the vacuum, the performance of the gap can be materially improved.[22] The discharge seems to be initiated at the insulator-cathode junction and proceeds along the insulator-vacuum interface but the breakdown mechanism is not fully understood in this case either.

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1.4 Voltage Holding Ability of Acceleration Tubes

In order to reduce the total voltage effect on the breakdown mechanism per unit length of vacuum gaps, modern acceleration tubes are sectionalized (Fig. 5). Thus, for a given distance between anode and cathode there is a series of vacuum gaps instead of just one single gap.

Various research groups and individuals found that the flashover voltage of sectionalized tubes under uniform field conditions is directly proportional to the flashover voltage of each section[22], the constant of proportionality being the number of the identical sections. Consequently the breakdown mechanism of sectionalized tubes must be the same as the breakdown mechanism of single vacuum gaps enclosed by insulators.

1.5 "Kicking" Effect in Single Gaps and Acceleration Tubes

The "kicking" effect has been studied by various people independently.

Clifford[23] found that in the case of single gaps the onset of pulsed discharges follows a relationship almost identical with the one established by Cranberg for breakdown. This led him to suggest that pulsed discharges may be the triggering mechanism of breakdown. Heard reports[24] that breakdown is entirely independent of the behavior of the prebreakdown dark current even though in a later paper[18] he shows that a kick may sometimes develop into a spark.

In the case of acceleration tubes the story is different. The central hole of the tube, necessary for the acceleration of charged carriers, makes the existence of the dark current spikes more pronounced and a serious limitation of the performance of the tube. This is to be expected since the central hole renders it possible for particles having the total energy of the tube to cooperate with the ones that move back and forth between the electrodes of the single sections and accentuate their effects. Further-

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Some other characteristics of the "kicking" effect reported in the literature are summarized below.

For single gaps Heard's experiments[24] showed that the dark current rises near the breakdown voltage but its rise is inhibited by the simultaneous increase of the residual gas pressure.

McKibben and Boyer[25] found that the electron current in a single gap increases rapidly at a certain threshold voltage. Furthermore when the electrons are prevented from reaching the anode the threshold voltage does not change.

For a sectionalized tube similar to the one shown in Fig. 5 but with a 3/4" pitch Green[26] reports the following:

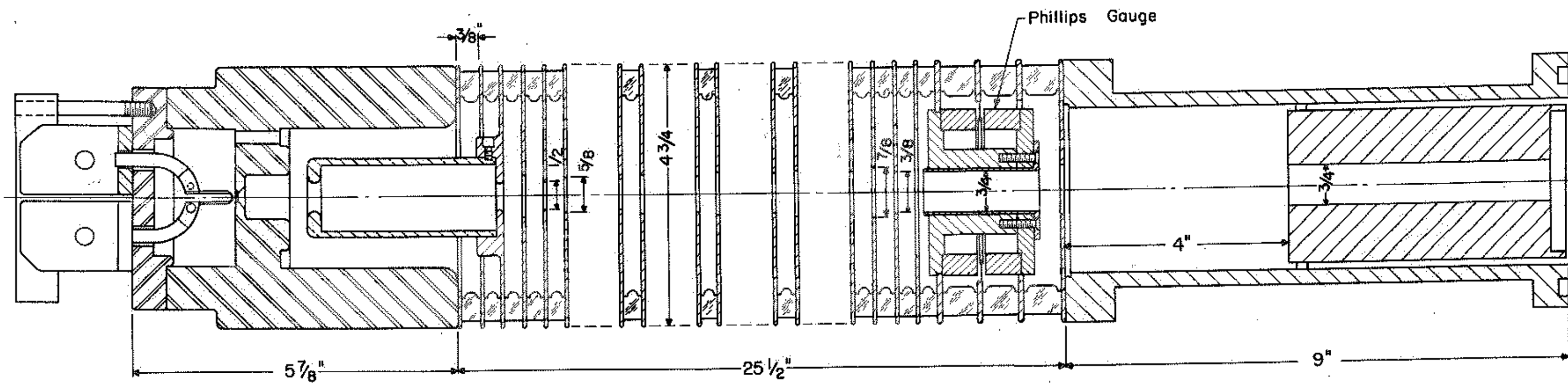
a. A kick is associated with an approximately three to ten per cent voltage reduction across the tube.

b. A kick is detected as a burst of electron current at the anode end of the tube. The amount of charge collected is equal to three to ten per cent of the charge stored in the generator-tube system. The positive charge collected at the cathode during a kick must be orders of magnitude smaller than the negative charge collected at the anode since it is not detectable by instruments similar to the ones used in the anode circuitry.

c. Recovery of the tube from a kick is quite fast.

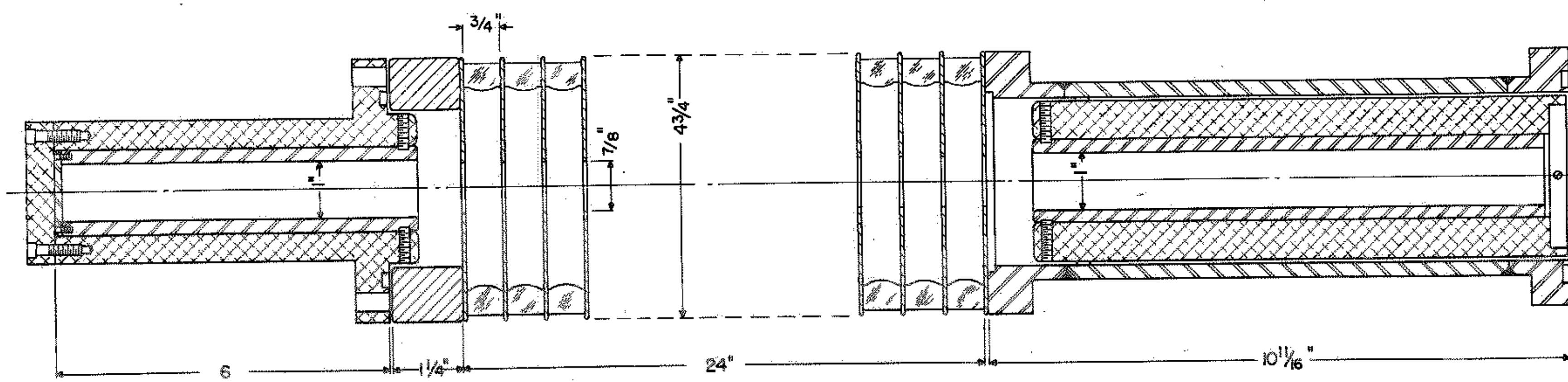
d. Kicks seem to originate all along the length of the tube.

On the same subject Chu[22] found that:



TEST ACCELERATION TUBE NO. 1

Figure 5



TEST ACCELERATION TUBE NO. 2

Figure 6

a. The threshold voltage for "kicking" is very sharp after conditioning and increases with conditioning.

b. The threshold voltage for "kicking" rises when the residual gas pressure is increased until the tube becomes conducting.

c. "Kicking" seems to originate mostly at the cathode end of the tube.

Harris[27] also found independently point (c) of Chu's results.

The mechanism of the "kicking" effect is not understood. McKibben and Boyer[25] suggested that it may be due to a chain reaction between positive and negative ions moving between anode and cathode but made no attempt to relate this mechanism with the known dependence of "kicking" on voltage and gradient.

1.6 Existence of Negative Ions in Acceleration Tubes

The existence of negative ions along with electrons in the dark current of acceleration tubes and single gaps has been reported by Harris,[22] McKibben[28], McKibben and Henshall[29]. Negative ions have also been detected under various experimental conditions by Arnot and Milligan[30], Sloan and Press[31], Sloan and Love[32] and many others.[33]

There are several modes of formation of negative ions,[33] some or all of which apply in various cases, depending on the conditions existing in the environment of their creation and the agents which promote it. With regard to the negative ion formation in high vacuum gaps there are no theories or suggestions up to date other than McKibben's[25] idea that they may be produced as secondaries due to positive ion bombardment. Such a mechanism though cannot lead to a chain reaction since the secondary negative ions produced by positive ion bombardment have been found to range between 10^{-3} to 10^{-4} per positive ion of energies 0 to 1 Mev respectively,[34] unless of course there was a copious number of positive ions per negative ion, which is rather doubtful.

1.7 Classification and Critiques of Mechanisms Leading to Instabilities of Vacuum Insulation

Since vacuum is a non-conducting medium, an instability can occur by one or a combination of the following processes:

a. Field emission from the cathode.

b. Thermionic emission from a spot on the cathode.

c. Positive-negative ion chain reaction.

d. Positive ion-neutral particles chain reaction.

From another point of view the processes may be classified in two groups.

The first group involves a single event which switches the vacuum gap from a high to a low inpedance level. Processes (a) and (b) for instance fall in this category. However, such a group of processes seems rather unlikely because for gaps with large separations the gradients at which instabilities occur are inadequate to justify field emission and thermionic emission is not evidenced experimentally. More specifically, the heating of a spot on the cathode is assumed to result from the bombardment by the incident positive charges, which implies that thermodynamic equilibrium is reached between the fast impinging ions and the metal surface. However, the assumption of thermodynamic equilibrium is doubtful as Kapitza[12] pointed out when he used it in order to derive his theory of secondary electron emission from metals under positive ion bombardment, a theory which is not experimentally verified. Actually Sternglass[35] presented quite recently a theory of secondary electron emission which is in excellent agreement with the experimental data and which does not assume thermodynamic equilibrium.

The second group postulates a chain reaction which switches the vacuum gap from a high to a low impedance level. Processes (c) and (d) fall in this category.

If the positive-negative ion exchange mechanism is considered as important, the question of primary interest is: "where and how are the negative ions created". The obvious answer is that negative ions result as secondaries from positive ion bombardment of the cathode, a process that has been studied experimentally and found to be subcritical. Other answers to the question raised above have not been suggested but are certainly worth looking into.

Now, if the chain reaction between charged and uncharged or neutral particles is considered, two distinct possibilities exist.

The first possibility is for the neutral particles to be very energetic. But in order for the neutral particles to become energetic they must have been charged some time during their lifespan across the gap and by some processes have lost their charge after they acquired their momentum. Hence the mechanism would require the production of ions and the detachment and attachment of electrons to neutralize and convert those ions to neutral particles. This has not previously been dealt with and will be reviewed later in this report.

The second possibility is for the neutrals to be in thermal equilibrium with the environment. The effectiveness of such neutrals, however, is questionable and hence need not be considered.

1.8 Summary of Vacuum Breakdown and "Kicking" Effect Data

In the previous sections an effort has been made to review the data and theories pertinent to vacuum breakdown and kicking effect or current loading. It is certain that many valuable contributions[36-38] to the field have been omitted from the discussion but it is equally certain that most of them fall in the same framework, which might be described as "statements of facts".

The known facts about the behavior of vacuum under high electric stresses may be summarized as follows:

VACUUM BREAKDOWN

Single Gaps

Spark breakdown occurs at a voltage which varies as the square root of the separation between the electrodes. This statement is equivalent to saying that breakdown takes place when the voltage and the gradient are such that $V \times E > C'$, where C' is a constant whose value depends on the metals used, their surface condition, and the energy stored in the system.

Breakdown seems to be independent of the behavior of the pre-breakdown current.

Sectionalized Tubes

Spark breakdown occurs at a voltage which is proportional to the number of sections of the tube, indicating that the performance of the tube is the same as the performance of its single gaps when the field is uniform along the tube.

Breakdown of sectionalized tubes may be taking place along the surface of the insulators because neither current nor X-rays are detected at either end of the tube.

PREBREAKDOWN KICKING OR CURRENT LOADING

Single Gaps

Pulsed discharges are superimposed on the small prebreakdown current. These pulses appear at voltages very close to the breakdown voltage and are randomly distributed.

The growth of the pulsed discharges seems to be inhibited by the increase of the gas pressure during the rise of the dark current.

There is no obvious correlation between the prebreakdown current behavior and the breakdown of the gap.

Sectionalized Tubes

Pulsed discharges are superimposed on the small prebreakdown current. These pulses appear at a voltage which varies as the 0.5 power of the number of sections used which is equivalent to the criterion $V_t \times E_e > C''$ where V_t the total voltage across the tube, E_e the local gradient and C'' a constant.

The threshold voltage for the occurrence of the pulsed discharges is increased with the increase of the residual gas pressure.

The pulsed discharges are always detected at the anode and never at the cathode.

The electrons associated with the pulsed discharges of both cases seem to be the eye-witnesses of the phenomenon rather than the parties immediately involved in it.

CHAPTER TWO

THE PROBLEM

2.1 Outline of the Problem

The High Voltage Research Laboratory group is interested in the insulating properties of high voltage acceleration tubes. Thus the author was assigned to continue the research of the group in the field of vacuum insulation using acceleration tubes rather than single gaps as experimental models.

The emphasis of the research was to be on the fundamental processes which lead to vacuum instabilities under high electric stresses rather than the accumulation of data.

In order to achieve this goal the following factors were selected for investigation and correlation:

a. Study the mass and energy spectra of both positive and negative heavy ion dark currents during steady state and unstable operations.

b. Examine the energy spectrum and time behavior of the electron dark current during steady state and unstable operations.

c. Ascertain the existence of neutral particles in the dark current and if time permits study their secondary effects.

d. Investigate the dependence of items (a), (b), and (c) on voltage across the tube, electrode gradients and residual gas pressure.

2.2 The test Units

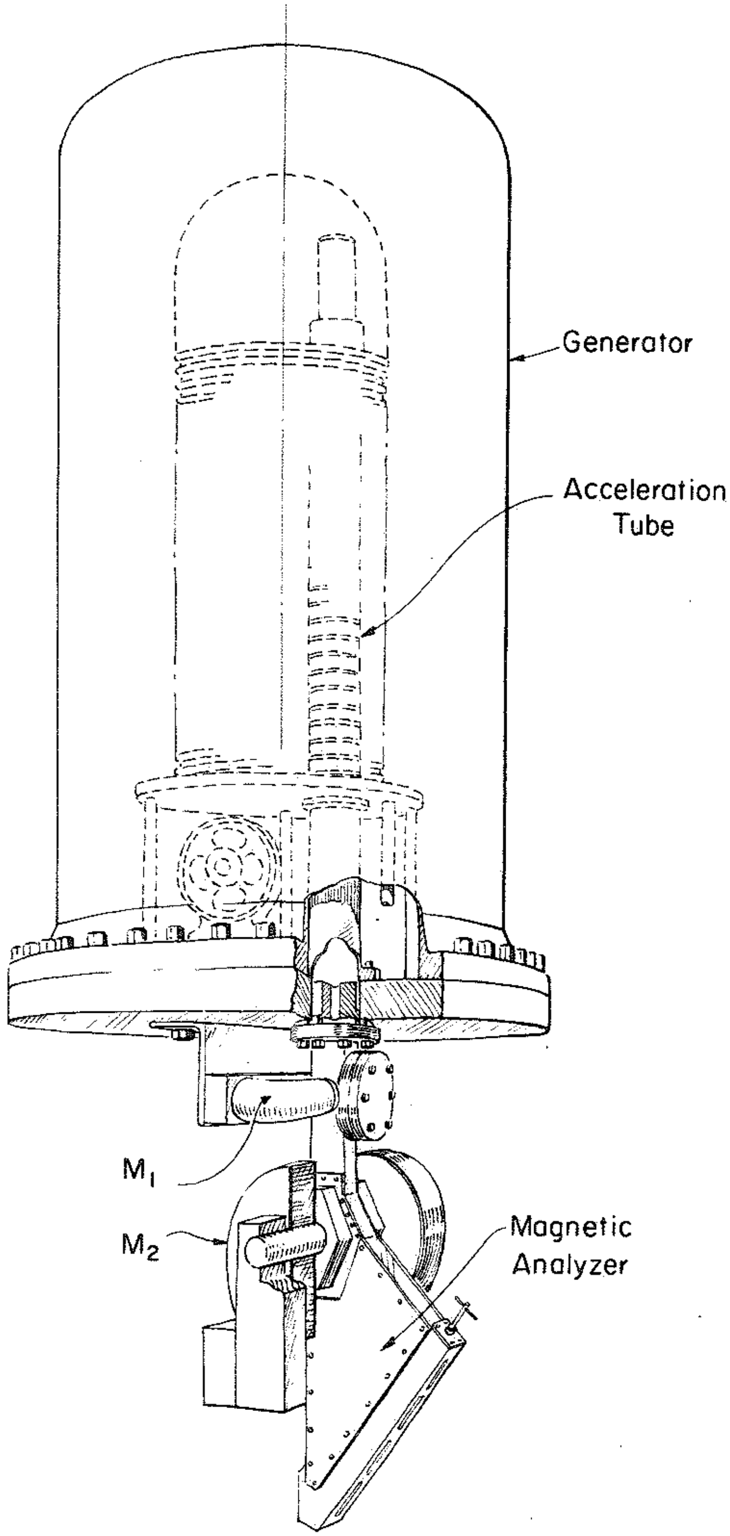
Two test acceleration tubes were built. The first is shown in Figure 5 and is similar to units commercially available. The other is shown in Fig. 6. The second tube is a special design for the purposes of this project; its main feature being its symmetry with respect to its mid-plane. This is necessary since the power source, which is subsequently described, did not allow simultaneous monitoring of the anode and the cathode. The design is also flexible enough to allow for changes of the anode or cathode materials by simply changing the sleeves of the anode and cathode extensions.

The electrodes of the acceleration tubes were made of highly polished aluminum and cleaned with methylene chloride and chemically pure acetone and then degreased in trichloroethylene vapors before assembly. The insulators were made of 7070 Pyrex glass rings, properly corrugated, washed in soap and water and rinsed in distilled water before assembly.

The tubes were assembled under sanitary conditions and once the parts were cleaned they were handled with greaseless gloves. The electrode-glass joints were made with vinylacetate, baked at 300°F. All parts were unoutgassed.

2.3 The Power Source

The power source is a 3 Mev pressurized Van de Graaff generator manufactured by the High Voltage Engineering Corporation of Burlington, Mass. The arrangement of the test tube and the power source is shown in Fig. 7.



GENERATOR AND ACCELERATION TUBE

Figure 7

CHAPTER THREE

THE EXPERIMENTAL APPARATUS AND TECHNIQUES

3.1 General Remarks

When this project was initiated it was not certain whether some of the factors under investigation were detectable and furthermore whether some of them existed at all or not. Thus, it was decided to build a simple magnetic analyser (Fig. 8) which at least would prove the feasibility of the program without too many expenses.

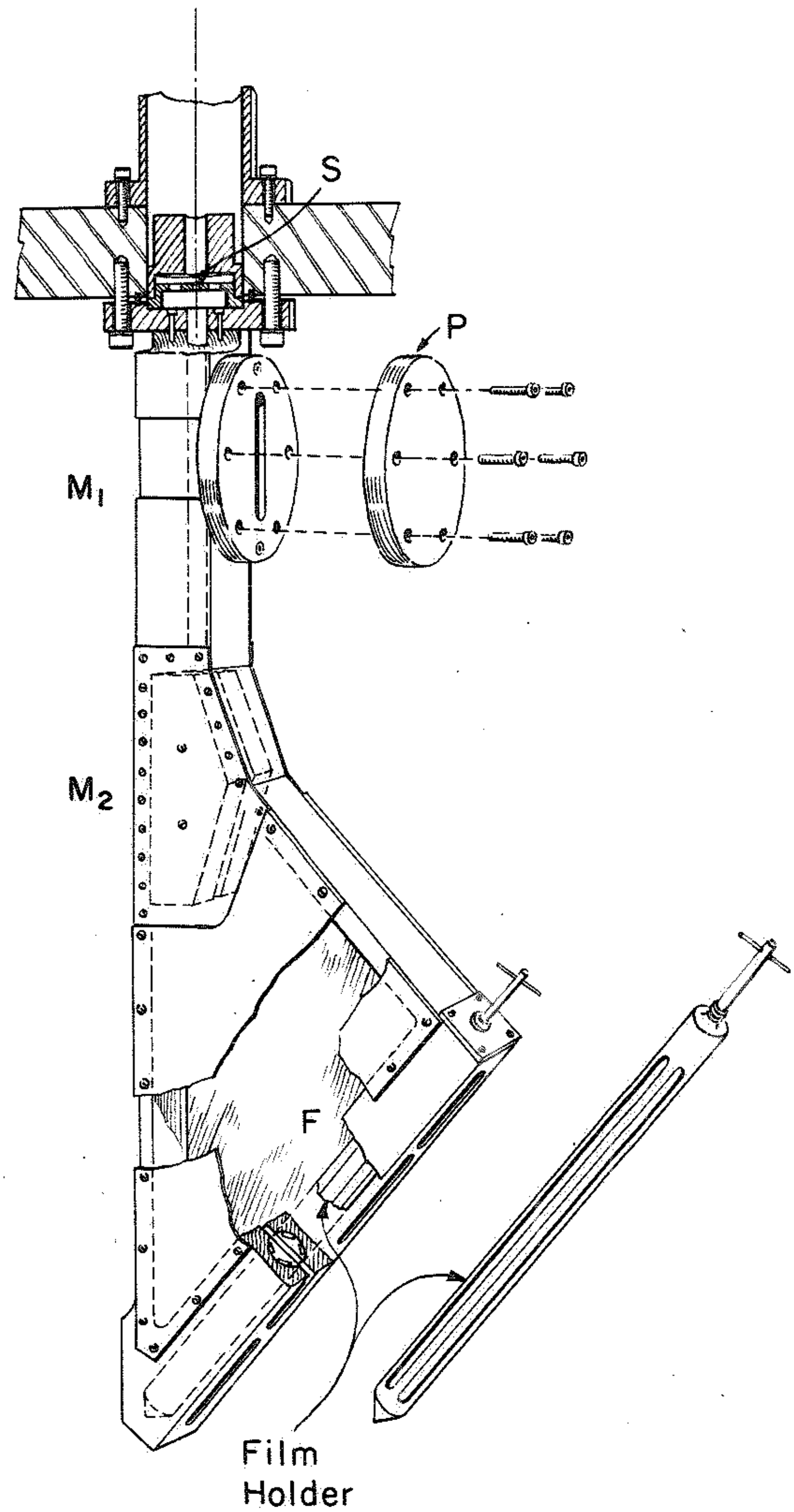
The results of the preliminary efforts proved both rewarding and encouraging even though their quantitative interpretation was not free of ambiguities. Consequently the electrostatic and magnetic analyser (Fig. 11) was designed and built.

In what follows the main features of both analysers and the techniques used are described in detail.

3.2 Magnetic Analyser

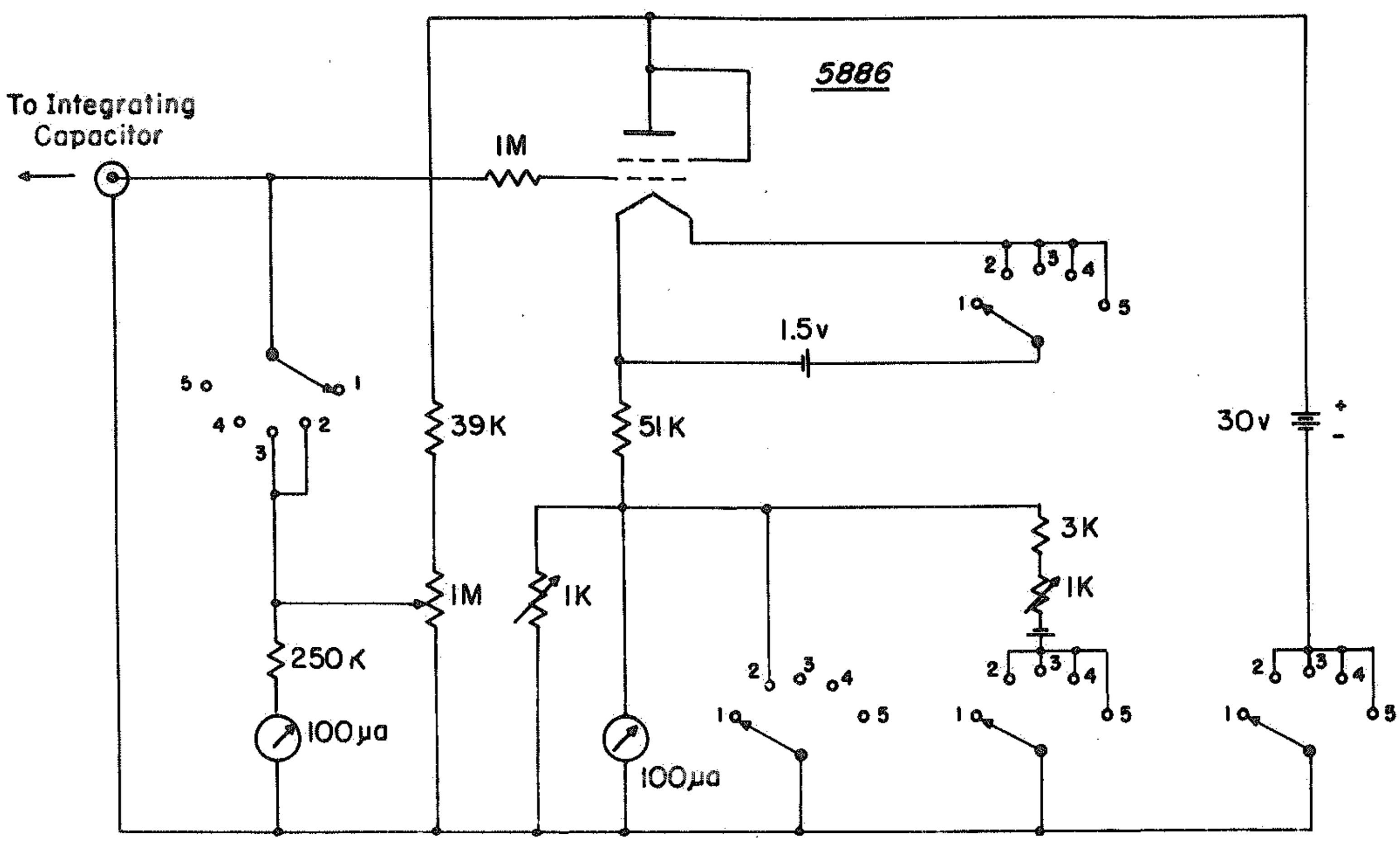
The analyser consists of a simple vacuum chamber attached under the generator as shown in Fig. 7. When the generator terminal is negative a sample of the beam of the dark current goes through the slit S (Fig.8). This sample passes through a magnetic field M_1 which deflects only the electrons on an insulated aluminum plate P on the side of a faraday cage-like slit on the wall of the chamber. The electronic current is either integrated by means of an integrating electrometer tube circuit (Fig. 9) or monitored on the screen of a Tektronix scope.

Any negative ions contained in the sample beam are not appreciably deflected by the magnetic field M_1 and continue drifting toward the magnetic field M_2. The latter is strong enough to deflect the negative



MAGNETIC ANALYZER

Figure 8



ELECTROMETER TUBE CIRCUIT

Figure 9

ions according to the value of the square root of the product of their mass and energy. The analysed negative ion beam is recorded (integrated) on a strip of sensitive film F. Two types of films are used, NTA nuclear track plates and Kodak X-ray type AA industrial film. Both give satisfactory results.

A similar setup is used when the terminal is positive but for the fact that no electrons are then detected.

Any neutral particles which are drifting along the tube and go through the slit S are unaffected by the magnetic fields and register at the photographic plate at the zero deflection position.

3.3 Calibration of the Film Strip F

The calibration of the positions on the film strip F is achieved by means of electrons emitted thermionically at the cathode and accelerated to a constant energy $T_e = 1.8$ Mev. The magnet M_1 is withdrawn and the electron beam is allowed to go through the magnetic field M_2. Assuming a uniform magnetic field, the radius of curvature of the beam in the magnetic field is

$$r_e = \frac{K_1}{B_e} \left[2m_oc^2 \, T_e + T_e^2 \right]^{1/2} \qquad (3.3.1)$$

where

K_1 = constant

B_e = magnetic field density

T_e = electron kinetic energy = 1.8 Mev

m_oc^2 = electron rest energy = 0.51 Mev

Evidently this radius corresponds to a definite position on the photographic plate.

In case heavy ions go through the magnet M_2, the radius of curvature is

$$r_i = \frac{K_2}{B_i} \left[A_i \; T_i \right]^{1/2} \qquad (3.3.2)$$

where

K_2 = constant = 42.85 K_1

B_i = magnetic field density

A_i = ion mass number to charge ratio

T_i = ion energy or acceleration voltage in Mev depending on whether the ions are singly or multiply charged, respectively.

If the magnet M_2 is used in the linear region of its magnetic field versus current characteristic and the radii r_e and r_i are equal then

$$A_i \; T_i = \frac{a^2}{42.85} \left[2m_o c^2 \;\; T_e + T_e^2 \right] \qquad (3.3.3)$$

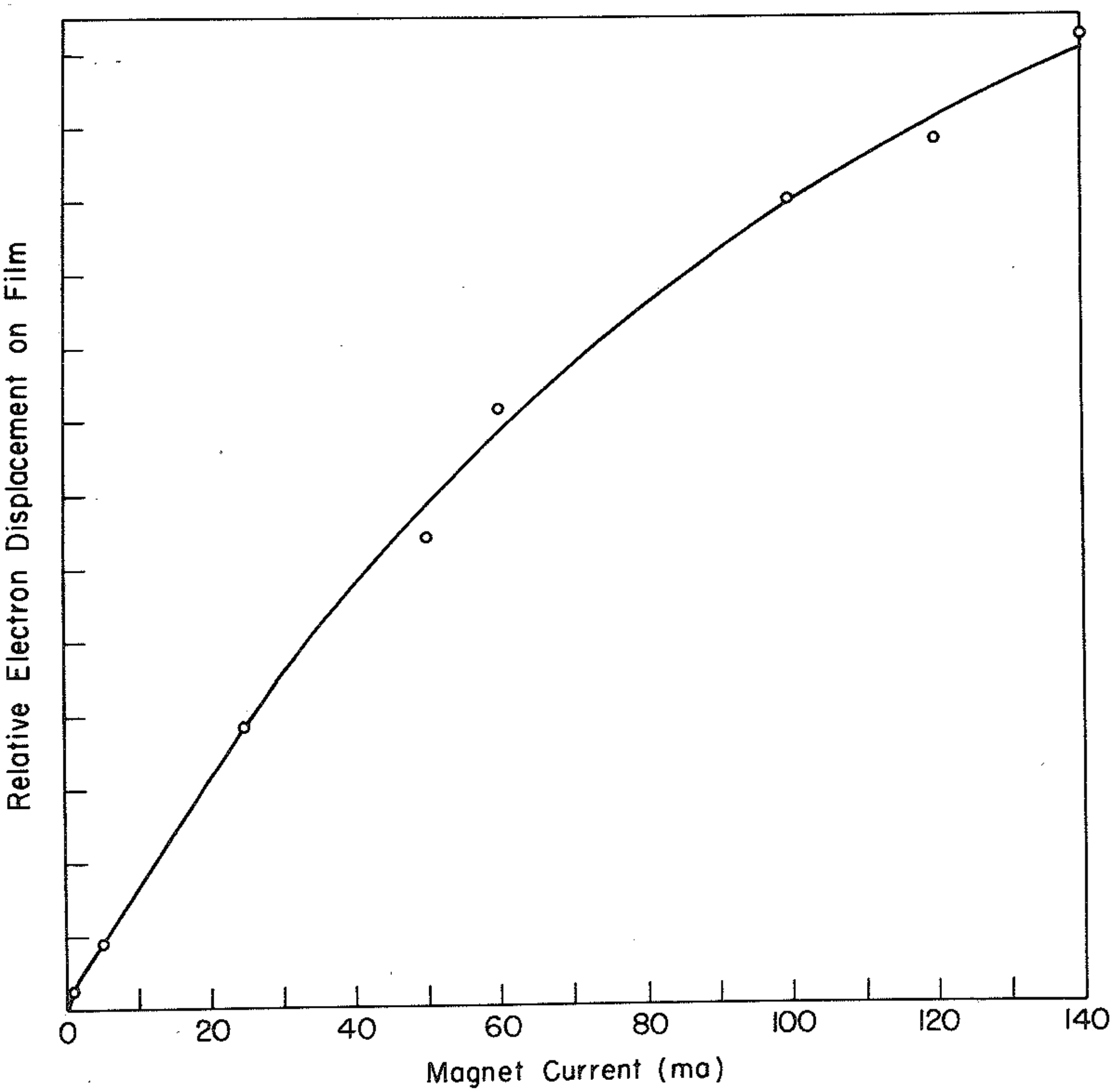
where $a = \frac{B_i}{B_e} = \frac{I_i}{I_e}$ = ratio of magnet currents when the ion and constant energy electron beam experiments are performed respectively.

Figure 10 is a plot of relative displacement of the electron beam on the film versus the magnet current from which the product A_i T_i is determined for a given position on the film and a given current I_i.

3.4 <u>Electrostatic and Magnetic Analyser</u>

The detailed features of the electrostatic and magnetic analyser are shown in Figure 11.

The beam coming down the acceleration tube goes through a small circular slit S_1 which may have different diameters from a few thousands of an inch up to 1/16" and whose position is adjustable so that the beam can be sampled all along the cross-section of the central hole of the tube. Under the slit S_1 there is a slit S_2, 1/16" x 1" which allows any beam



CALIBRATION CURVE FOR MAGNETIC ANALYZER I
BY MEANS OF 1.8 Mev ELECTRONS

Figure 10

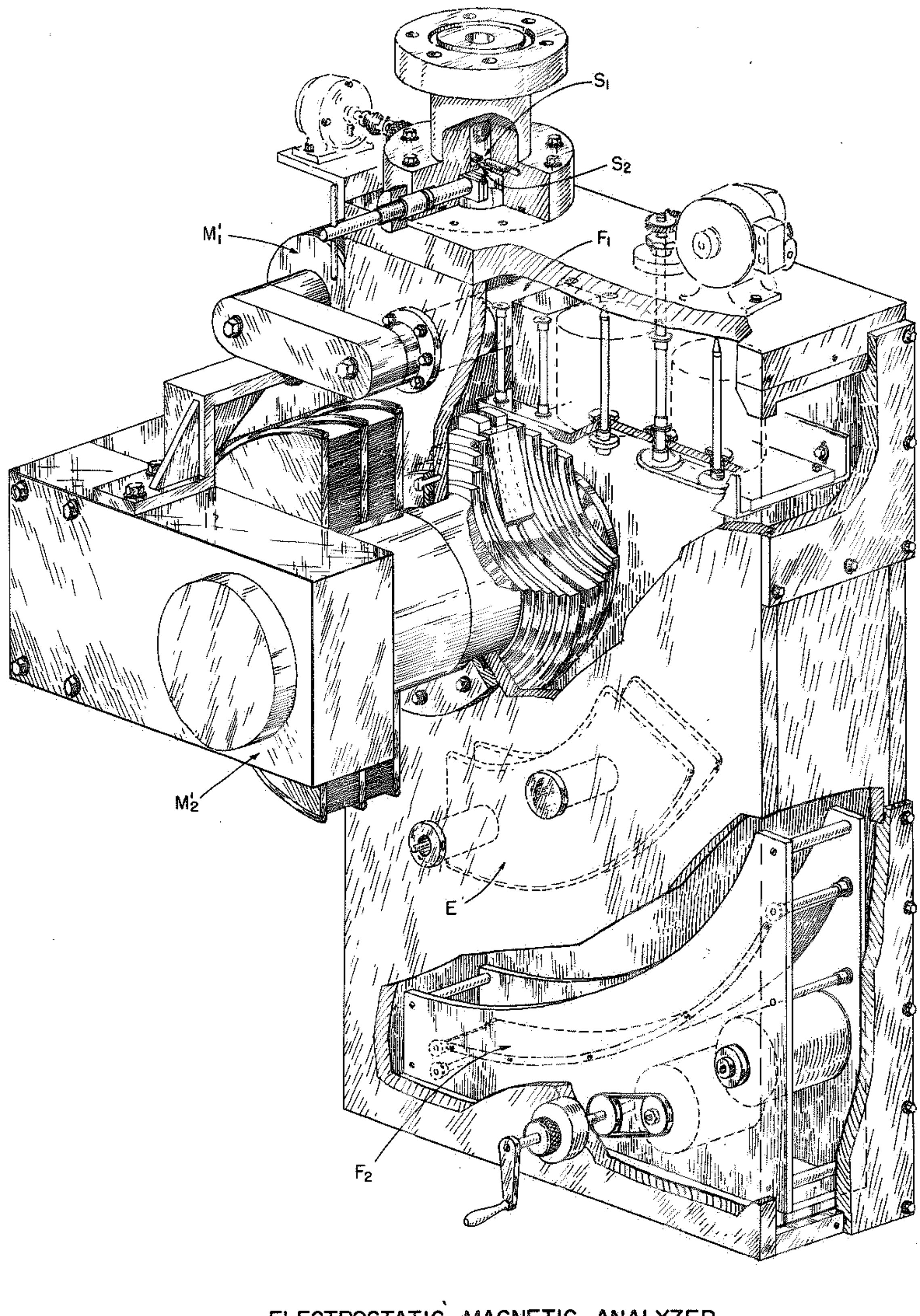
going through the slit S_1 to get in the analyser. The slit S_2 can be vacuum-tightly closed by means of a retractable shutter so that the vacuum systems of the tube and the analyser can operate independently if necessary.

When the generator terminal is negative, the electrons contained in the sample beam are deflected by the electromagnet M_1^1 and register on a continuously moving strip of 70 mm Kodak X-ray or DuPont Adlux film F_1. Thus the continuous component of the dark current sets up a background frame with respect to which the pulsed discharges register as darker spots or bands. The position of the darker spots indicates the energy or the origin along the length of the tube of the pulsed discharges, while the change in film density indicates the amplitude of the pulses.

The negative ions of the sample beam are not appreciably deflected by the magnetic field M_1^1 and pass through the magnetic field M_2^1 which spreads the ions according to the square root of the product of their mass and energy. Subsequently the analysed beam enters an electrostatic field E, parallel to the magnetic field M_2^1, which bends the negative ions in a direction perpendicular to the electrostatic field plates. The electrostatic deflection is inversely proportional to the energy of the ions.

All ions are integrated on a 70 mm stationary Kodak X-ray film strip F_2. Each point on the strip corresponds to a specific mass to charge ratio and energy for given magnetic and electrostatic field densities.

When the terminal of the generator is positive the sample beam going through the slit S_1 contains only positive ions which are recorded by a



ELECTROSTATIC-MAGNETIC ANALYZER

Figure 11

method similar to the one used for the negative ions.

3.5 Deflection of Electrons by Magnetic Field M_1^1

The deflection of the electrons by the magnetic field M_1^1 (Fig.12) is evaluated from the well known formula

$$\cot \frac{\theta}{2} = \frac{1}{BRc} \left[2m_oc^2\ T + T^2 \right]^{1/2} \qquad (3.5.1)$$

where

B = magnetic field density

c = velocity of light

m_oc^2 = electron rest energy

T = electron kinetic energy

Using the known numerical values equation (3.5.1) reduces to:

$$\cot \frac{\theta}{2} = \frac{1310}{B_1} \left[1.02T_1 + T_1^2 \right]^{1/2} \qquad (3.5.2)$$

where

B_1 = magnetic field density in gauss

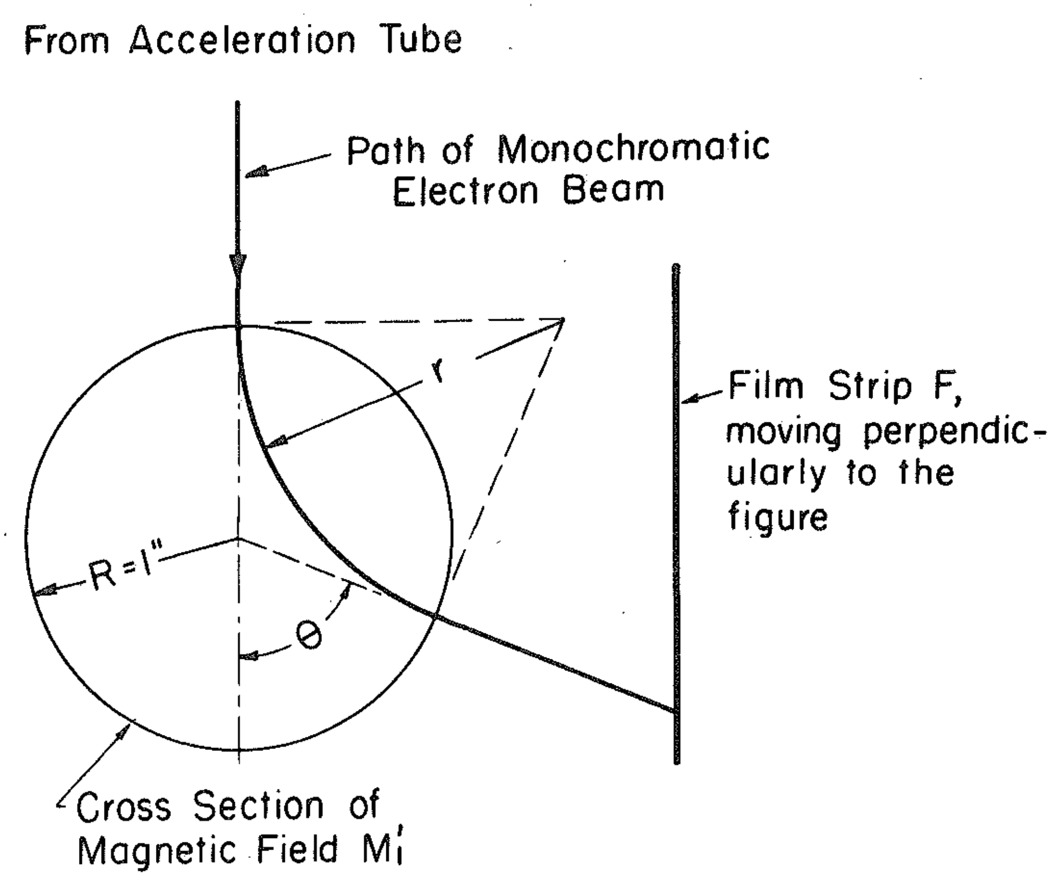
T_1 = electron energy in Mev

Figures 13 and 14 are plots of equation (3.5.2) with the magnetic field density and the angular deflection as a parameter, respectively. The interpretation of the spectra on the film F_1 is obvious for a given position of the electron camera with respect to the magnetic field M_1^1.

3.6 Deflection of Ions by Magnetic Field M_2^1

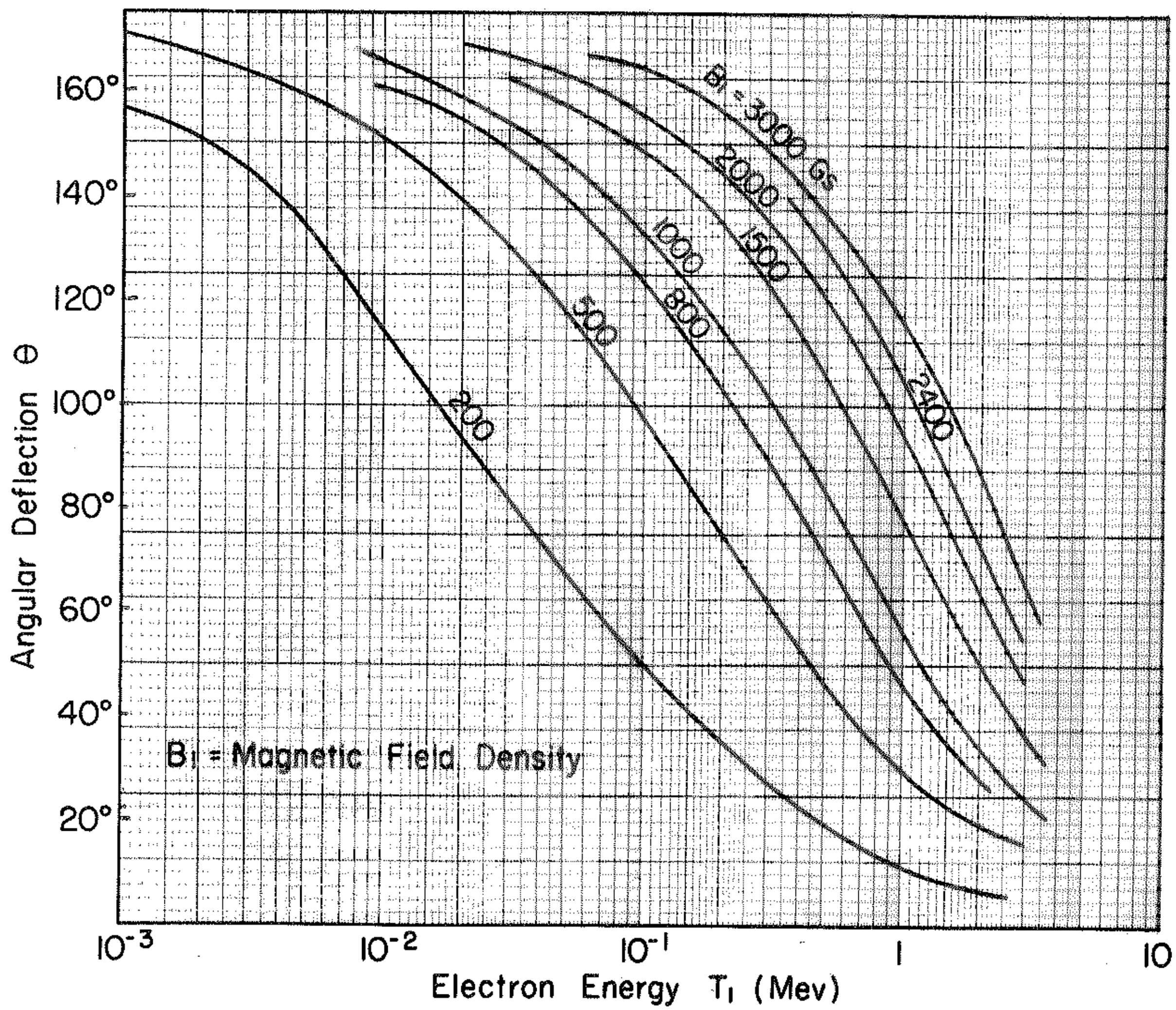
The deflection of the ions by the magnetic field M_2^1 (Fig. 15) is given by the formula

$$\cot \frac{\theta_1}{2} = \frac{1}{BR_1c} \left[\frac{2mc^2}{e}\ T \right]^{1/2} \qquad (3.6.1)$$



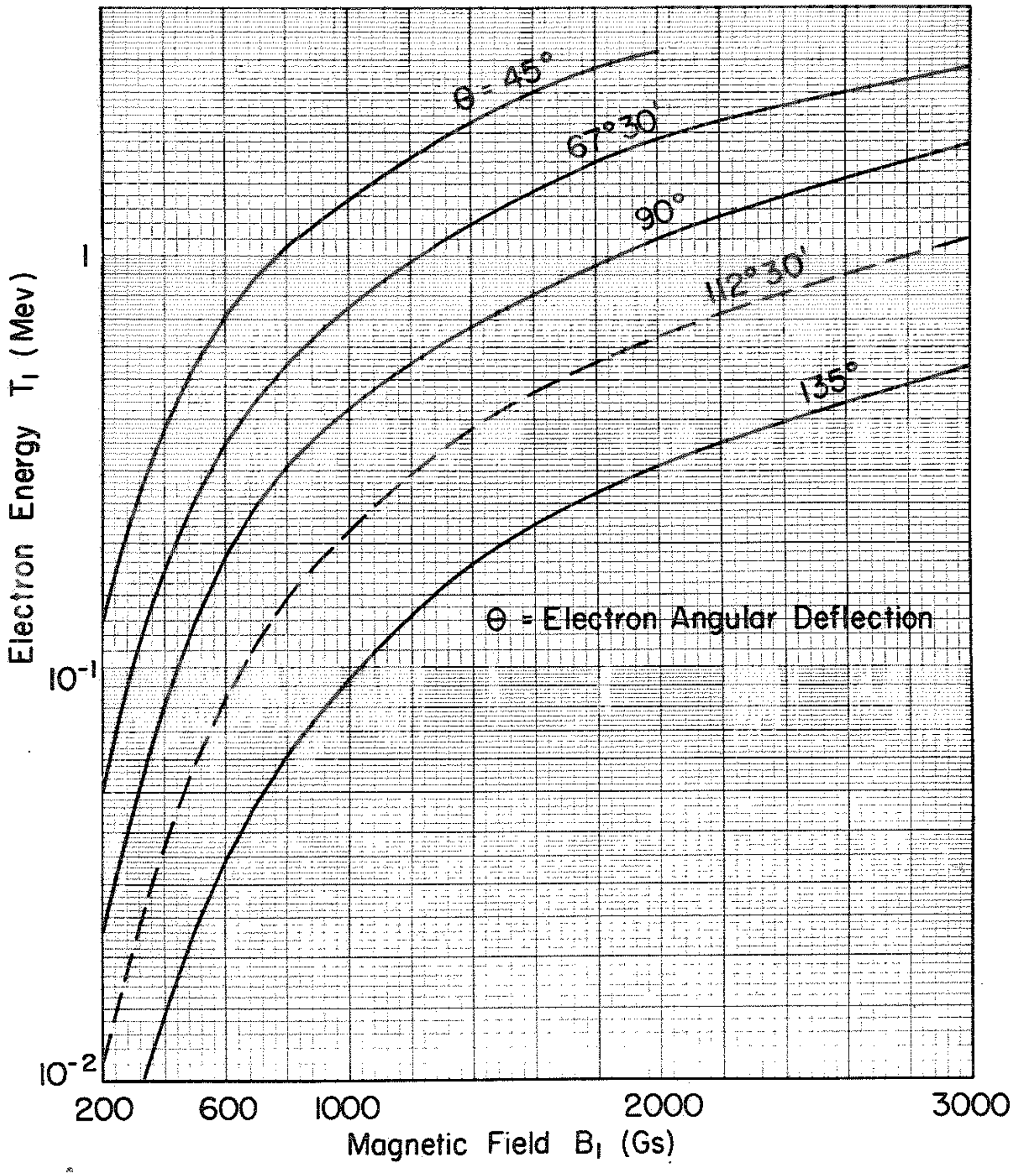
SCHEMATIC VIEW OF ELECTRON MAGNET AND FILM

Figure 12



ELECTRON MAGNET-ANGULAR DEFLECTION Θ vs ELECTRON ENERGY

Figure 13



ELECTRON MAGNET-ENERGY DISTRIBUTION OF SPECTRA

Figure 14

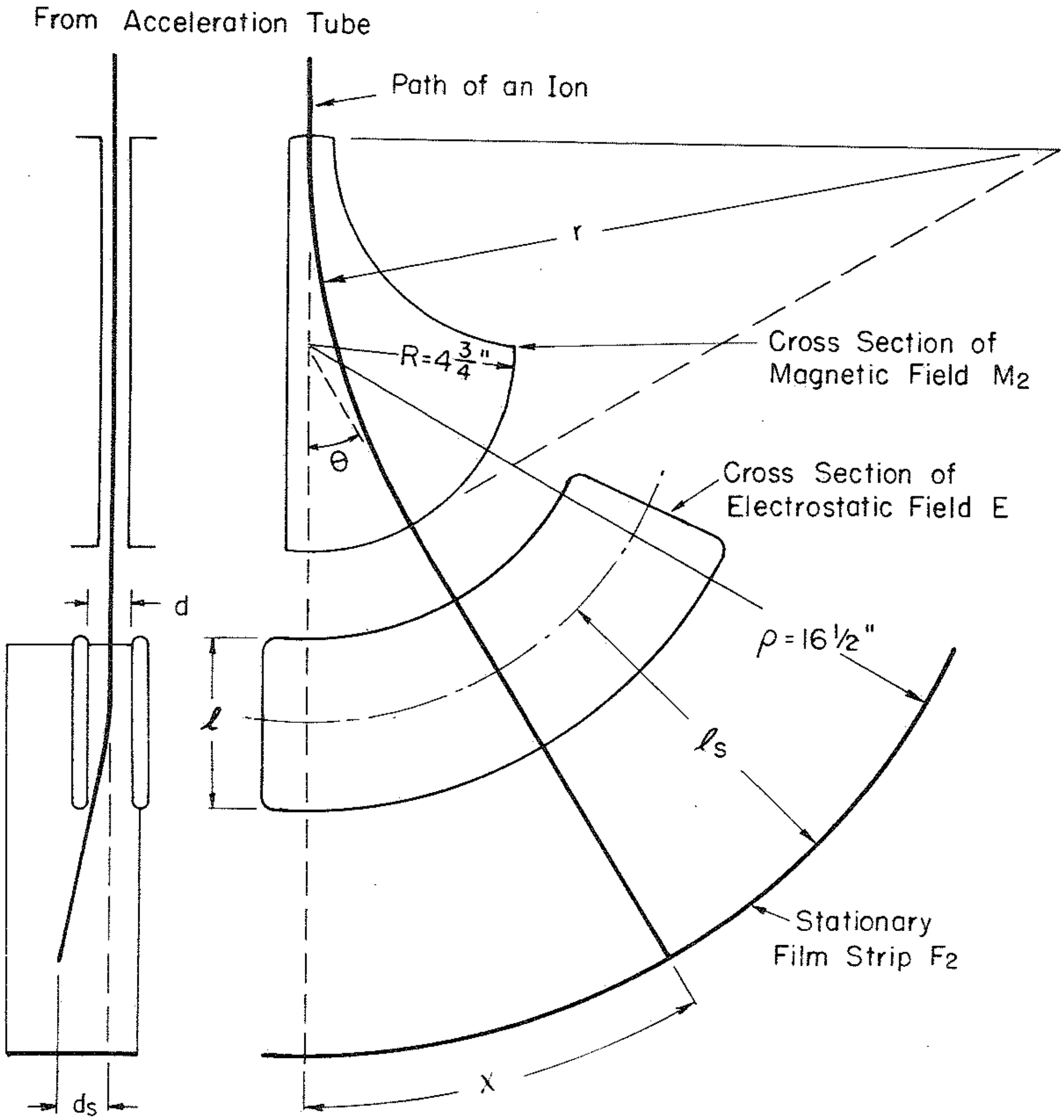

From Acceleration Tube
Path of an Ion
r
R=4 3/4"
θ
Cross Section of Magnetic Field M2
Cross Section of Electrostatic Field E
d
ρ=16 1/2"
ℓ
ℓs
Stationary Film Strip F2
X
ds

Figure 15

where

B = the magnetic field density

m = the ion mass

c = velocity of light

e = the ion charge

T = kinetic energy of ions or acceleration voltage in eV

Using the various known parameters the formula reduces to:

$$\cot \frac{\theta_1}{2} = \frac{1.11 \times 10^4}{B_1} \left[AT_1 \right]^{1/2} \qquad (3.6.2)$$

where B_1 is in gauss, T_1 in Mev and A is the ion mass number to charge ratio.

For a given deflection θ_1 the position x of the ion on the film strip (Fig. 15) is given by:

$$x = \rho \frac{\pi}{180} \theta_1 = 0.732 \, \theta_1 \text{ cm} \qquad (3.6.3)$$

Equation (3.6.2) and (3.6.3) have been plotted in Figures 16 to 18.

3.7 Deflection of Ions by Electrostatic Field

The deflection of the ions by the electrostatic field (Fig. 16) is given by the formula

$$d_s = \frac{1}{2} \ell s \frac{V}{T} \frac{\ell}{d} = 393 \frac{V}{T} \text{ (mm)} \qquad (3.7.1)$$

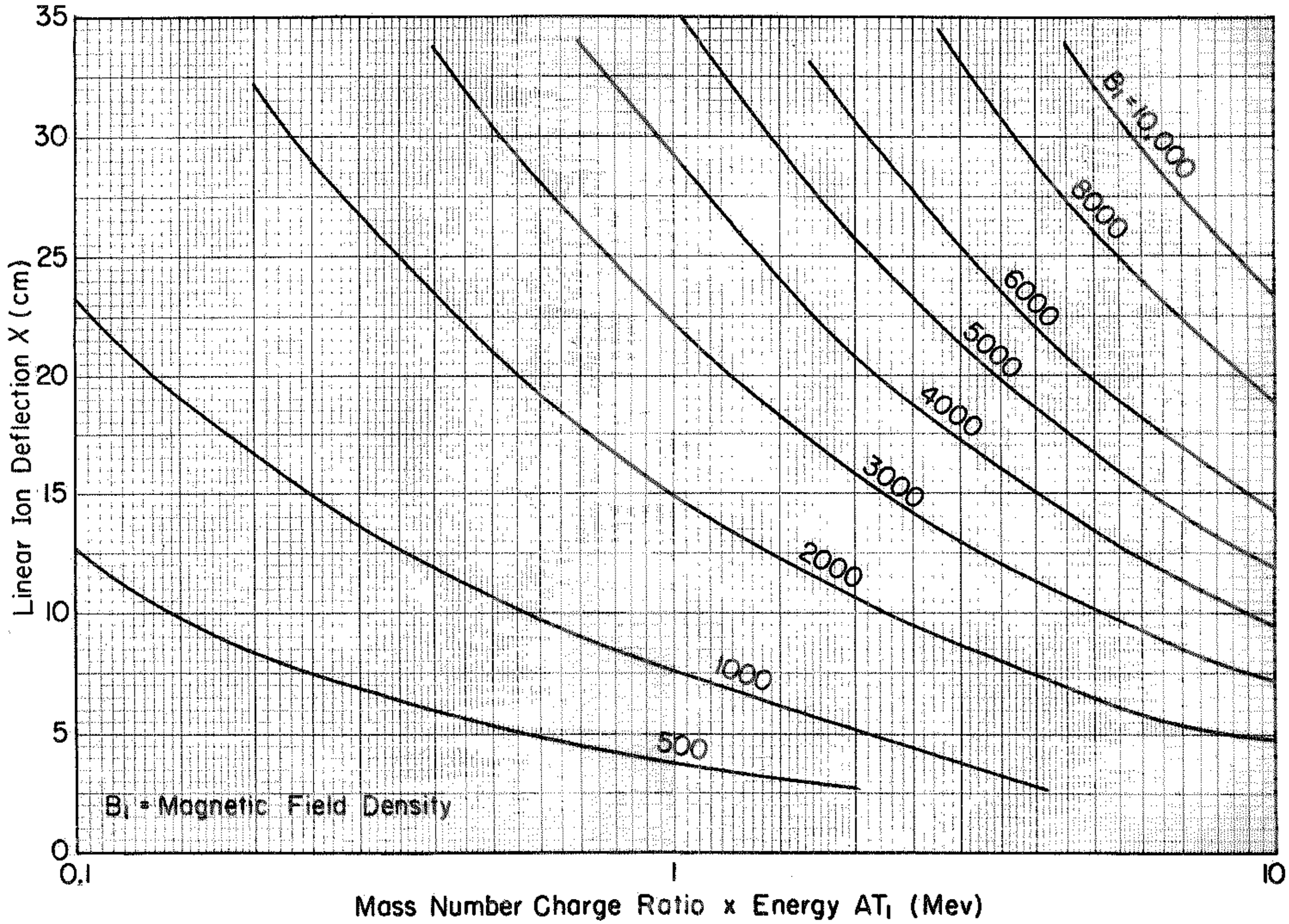
where

V = electrostatic plates potential difference in v

T = ion energy or acceleration voltage in eV

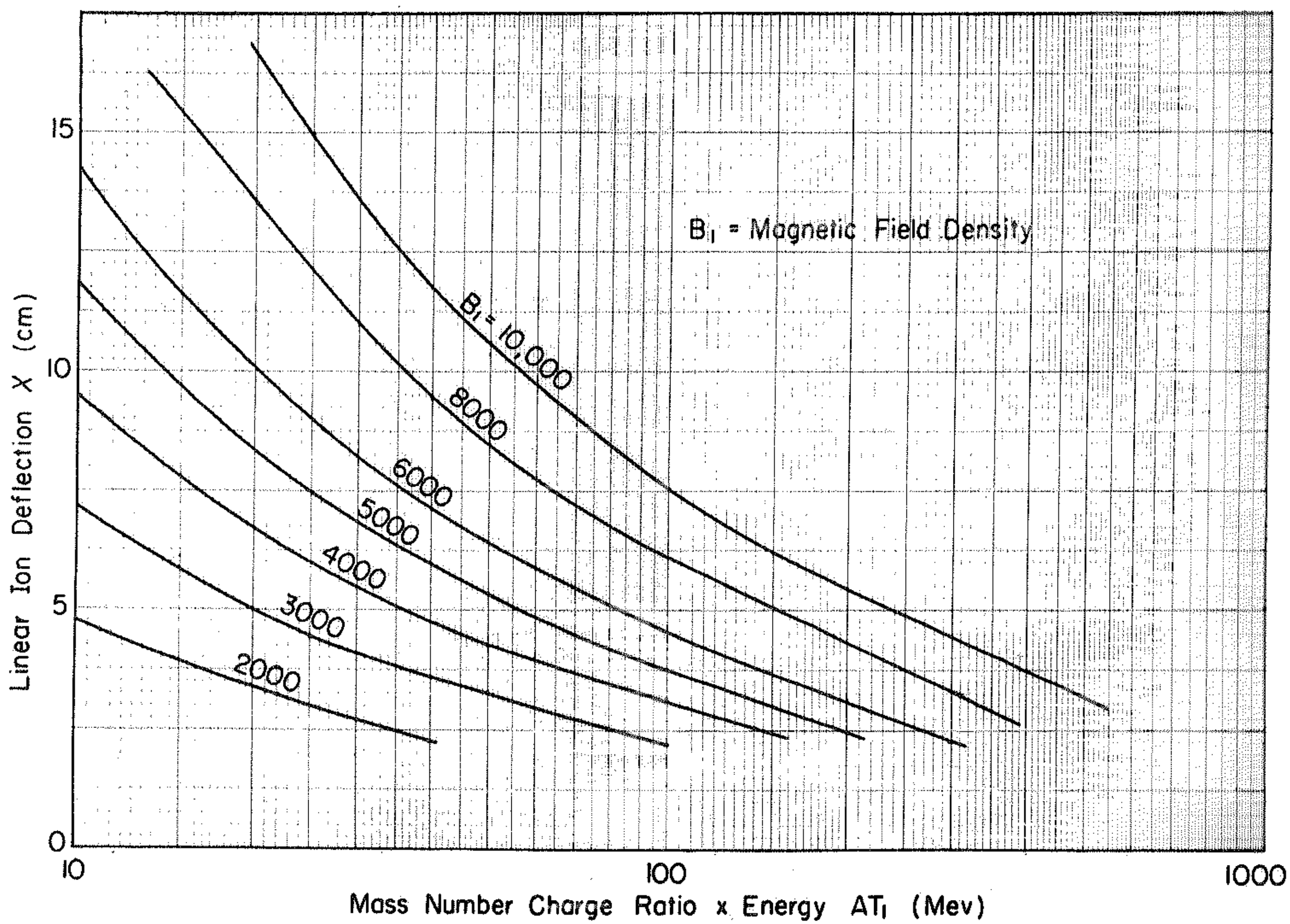
Equation (3.7.1) has been plotted in Figures 19 and 20.

Evidently then for given magnetic and electrostatic field densities every point on the film strip F_2 corresponds to an ion of a specific mass and energy.



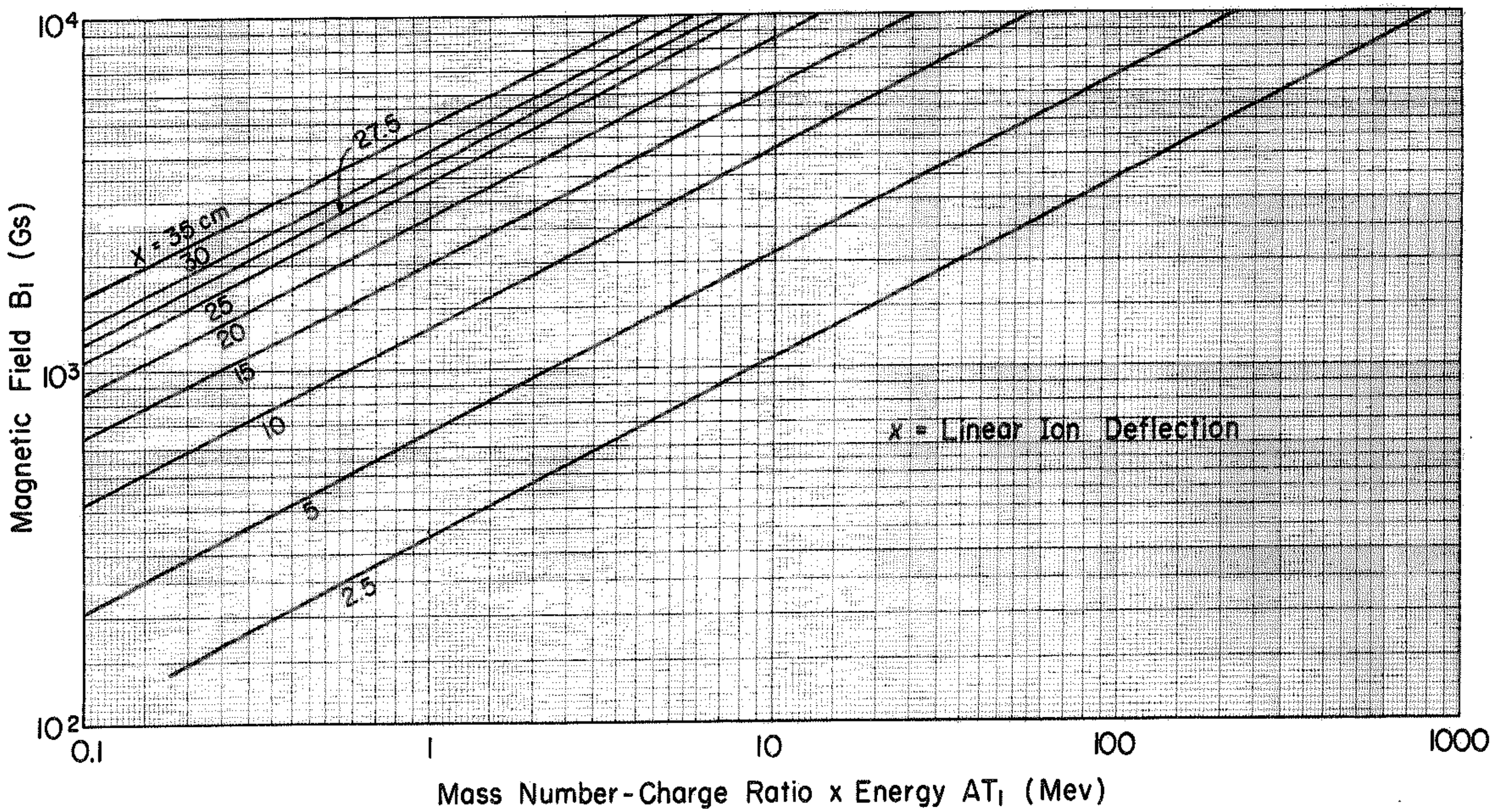
ION MAGNET - LINEAR ION DEFLECTION X vs MASS-ENERGY PRODUCT

Figure 16



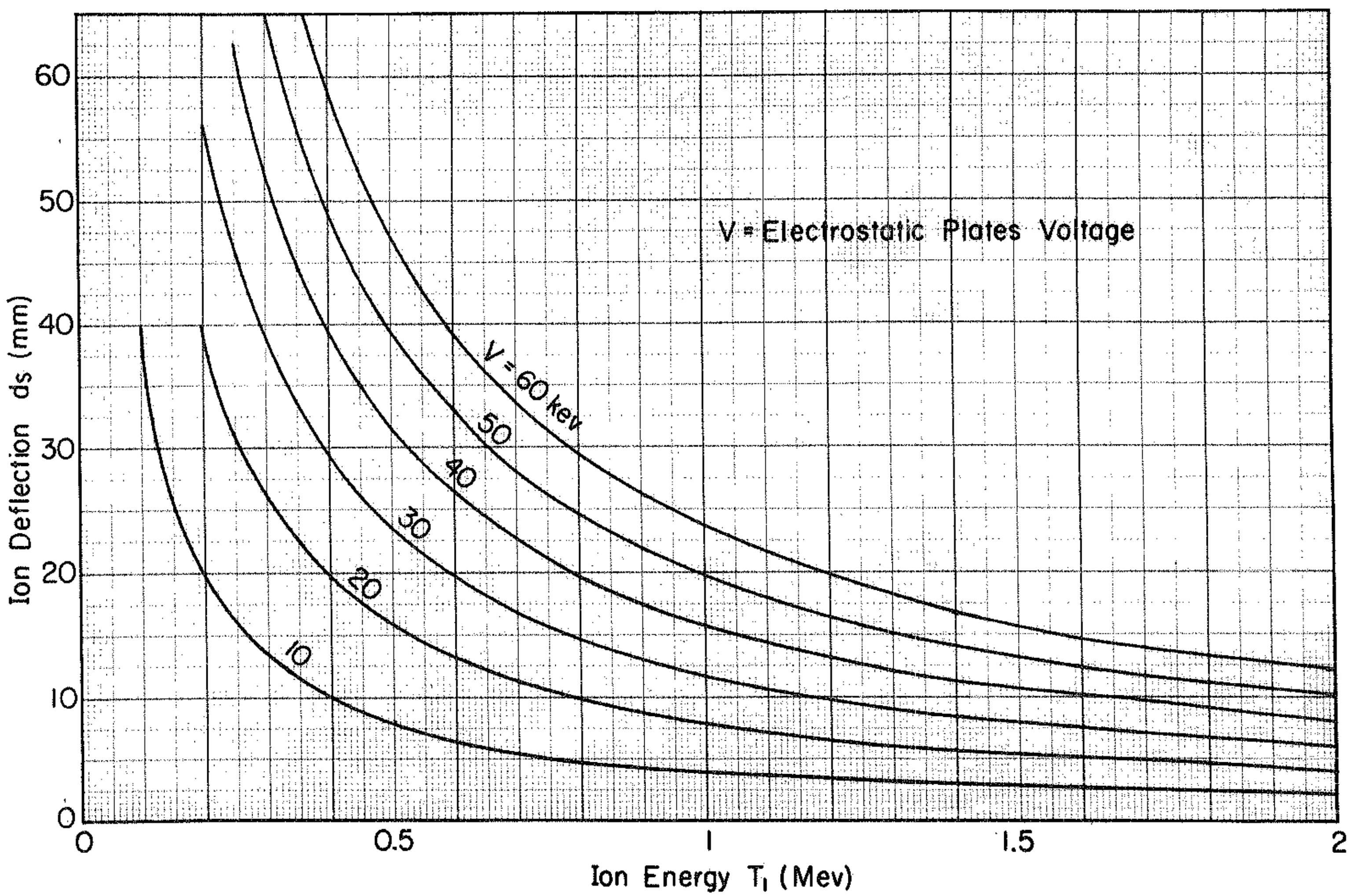
ION MAGNET - LINEAR ION DEFLECTION X vs MASS-ENERGY PRODUCT

Figure 17



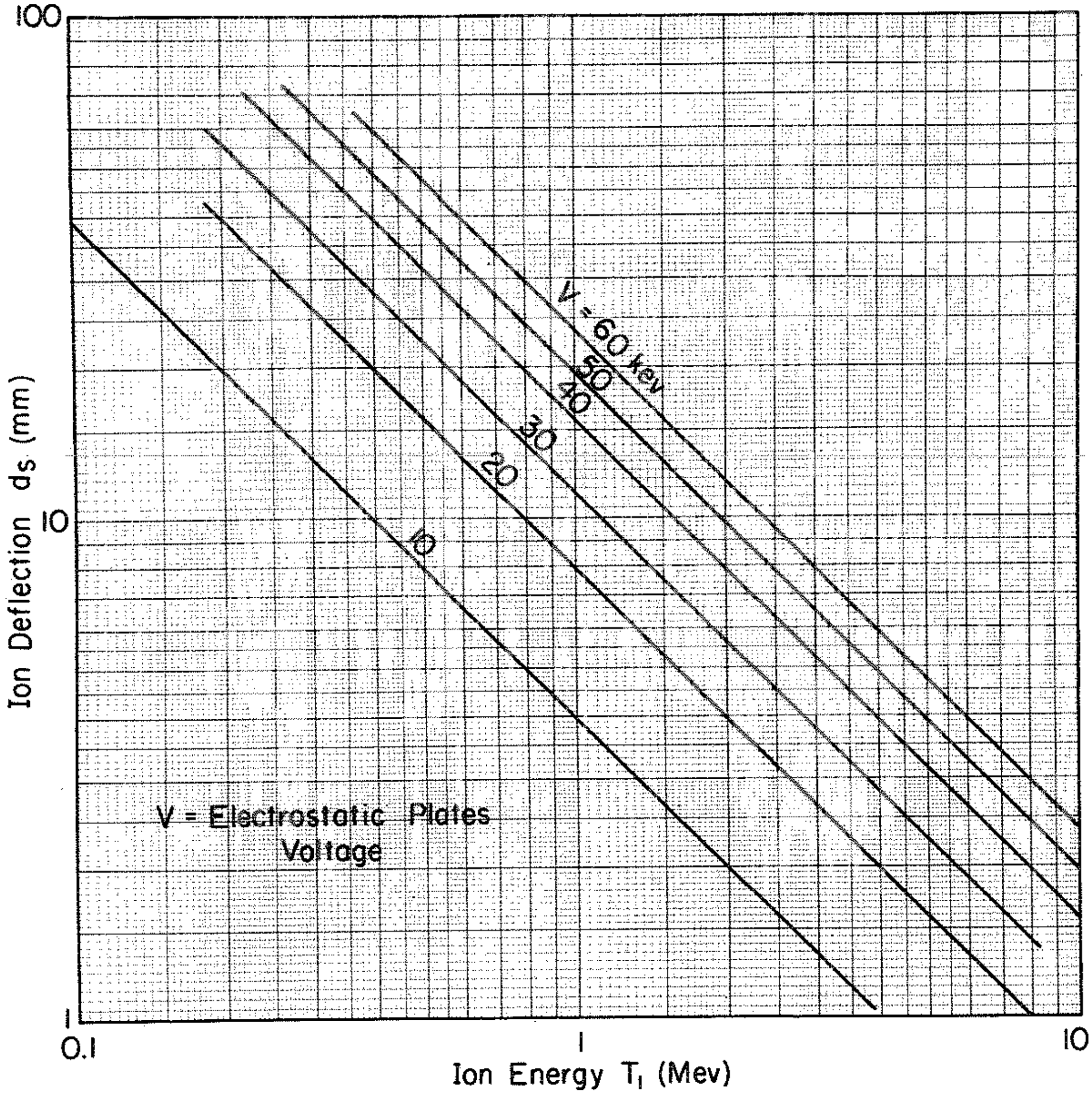
ION MAGNET - CONSTANT ION DEFLECTION CURVES

Figure 18



ELECTROSTATIC PLATES - ION DEFLECTION vs ENERGY

Figure 19



ELECTROSTATIC PLATES - ION DEFLECTION d_S vs ENERGY

Figure 20

3.8 Electromagnets and Their Power Supply

The d.c. power for the electromagnets is supplied from an electronic regulator which was built for this project and which is schematically shown in Fig. 21. The regulator diagram includes a system of relays for the automatic demagnetization of the electromagnets.

The electron electromagnet coil has three separate coils on one spool consisting of 600, 400, 200 turns, independent of each other. The ion electromagnet has two coils on each of its two spools. Each coil has 1000 turns so that there are 4000 turns in all. Both magnets have an air gap of 1/4".

3.9 Power Supply for Electrostatic Plates

The power supply for the electrostatic plates is a transformer rectifier gas insulated unit capable of 60 kv - 2 ma. Each of the deflection plates of the electrostatic field is at a potential higher than ground. This is achieved by putting a resistor across the power supply and grounding its mid-point. (Fig. 22)

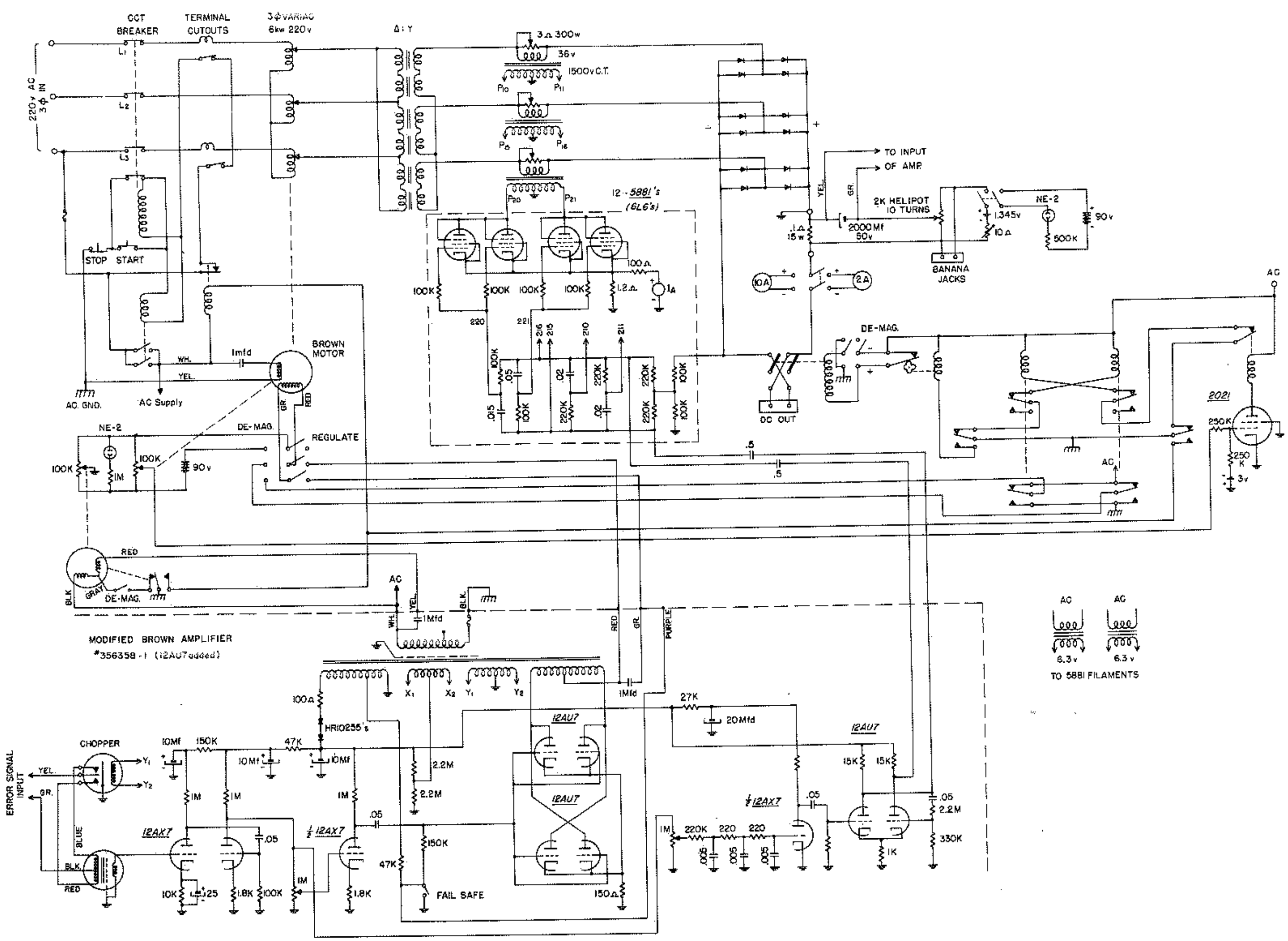
3.10 Vacuum Equipment

The acceleration tube and the electrostatic and magnetic analyser have separate pumping systems. Each vacuum system consists of a liquid nitrogen trap, a mercury diffusion pump, a dry ice trap and an oil forepump. (Fig. 23)

The vacuum is monitored by means of two ionization gauges and a Phillips gauge. A series of thermocouple gauges is also connected to the system for forevacuum measurements.

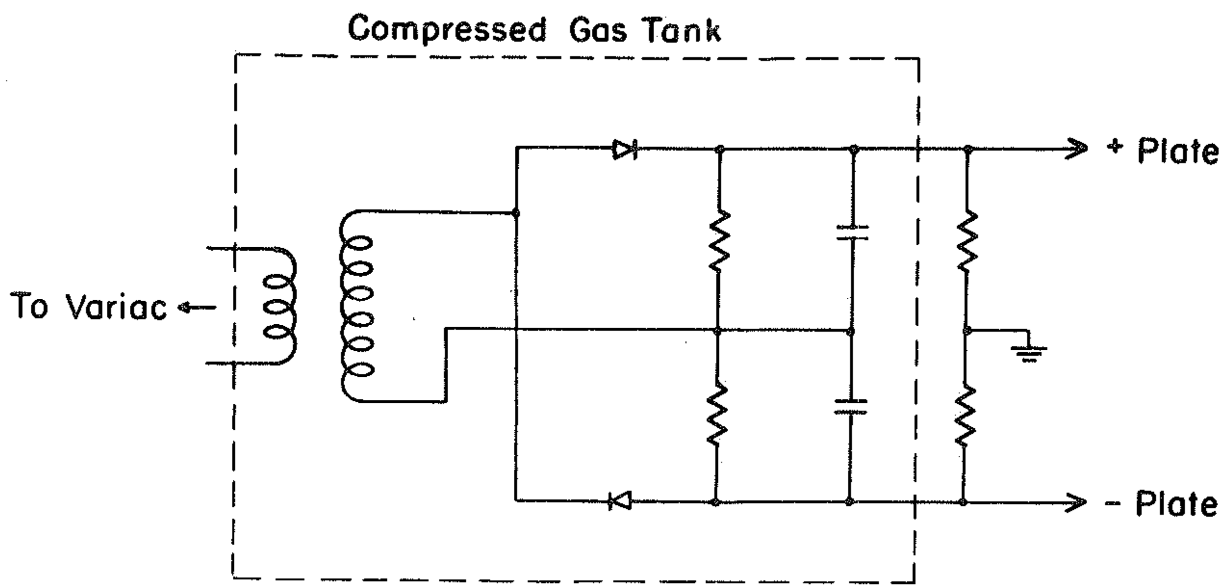
All gaskets are made of neoprene.

Figure 24 is a photograph of the generator and the analyser and



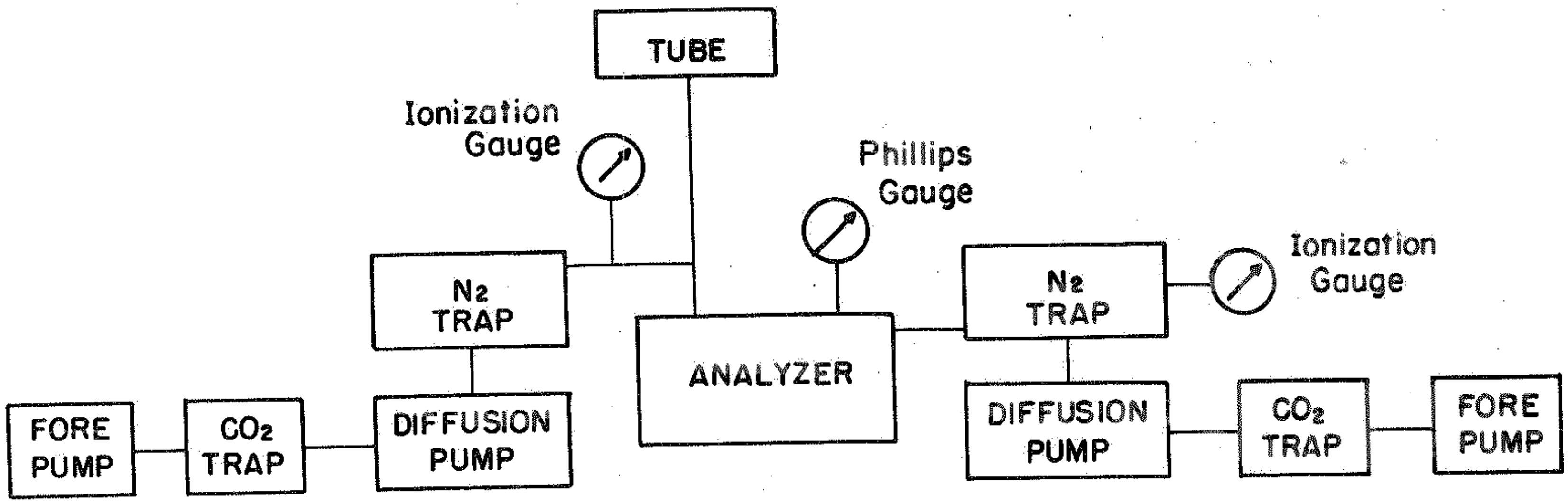
ELECTRONIC REGULATOR AND DEMAGNETIZING CIRCUIT

Figure 21



ELECTROSTATIC PLATES POWER SUPPLY

Figure 22



SCHEMATIC OF VACUUM SYSTEM

Figure 23

GENERATOR AND ELECTROSTATIC-MAGNETIC ANALYZER

FIGURE 24

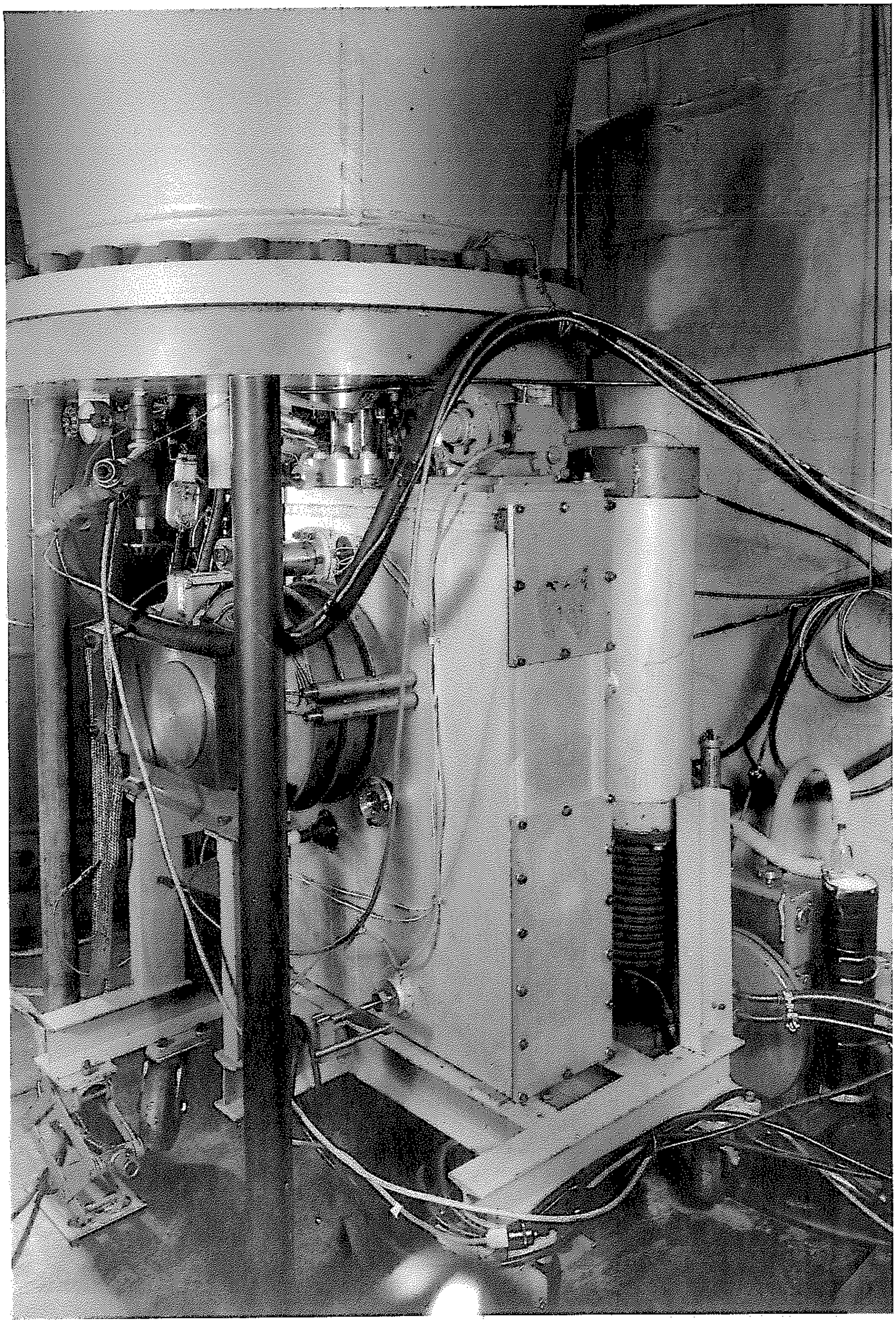
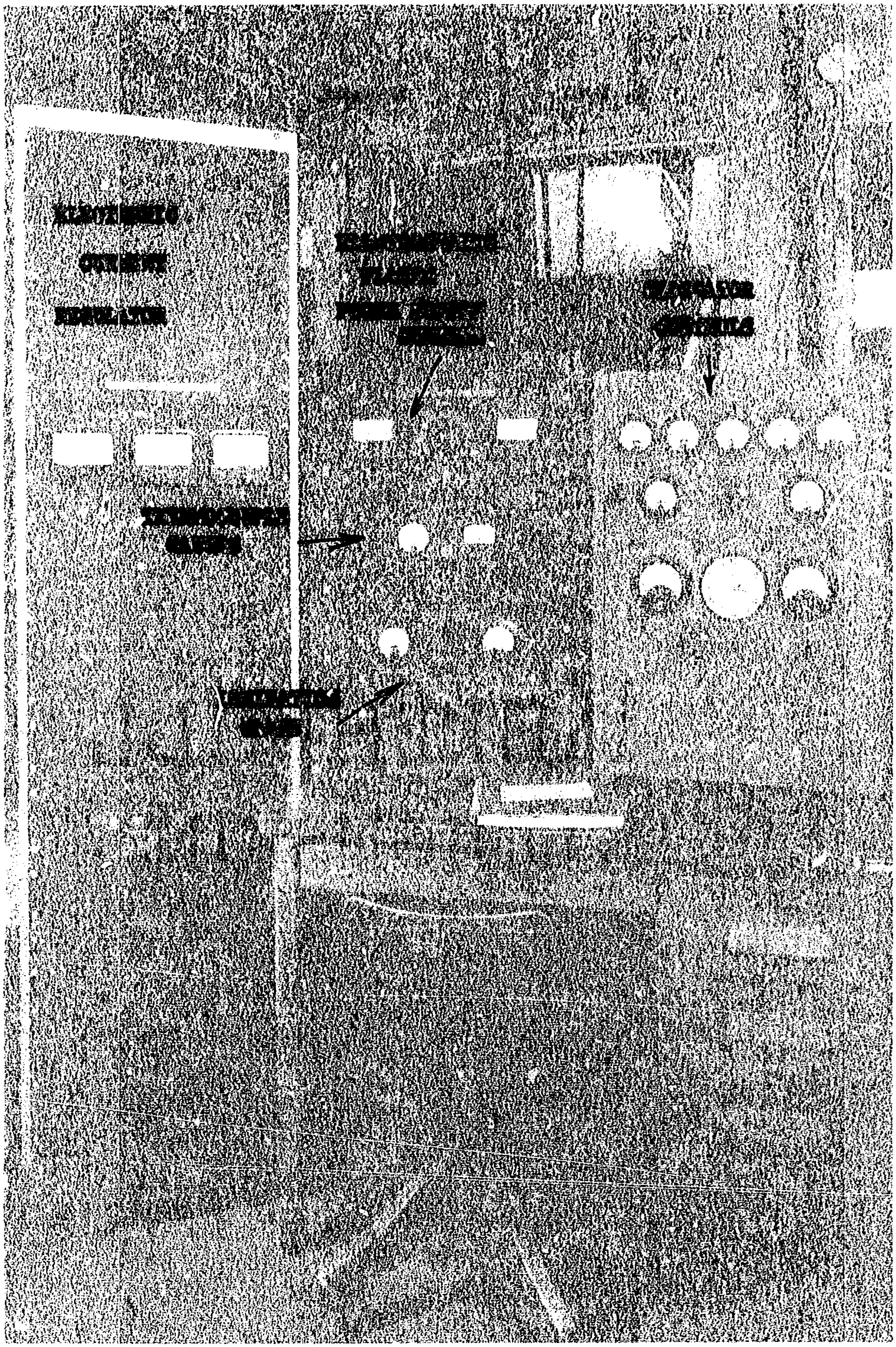
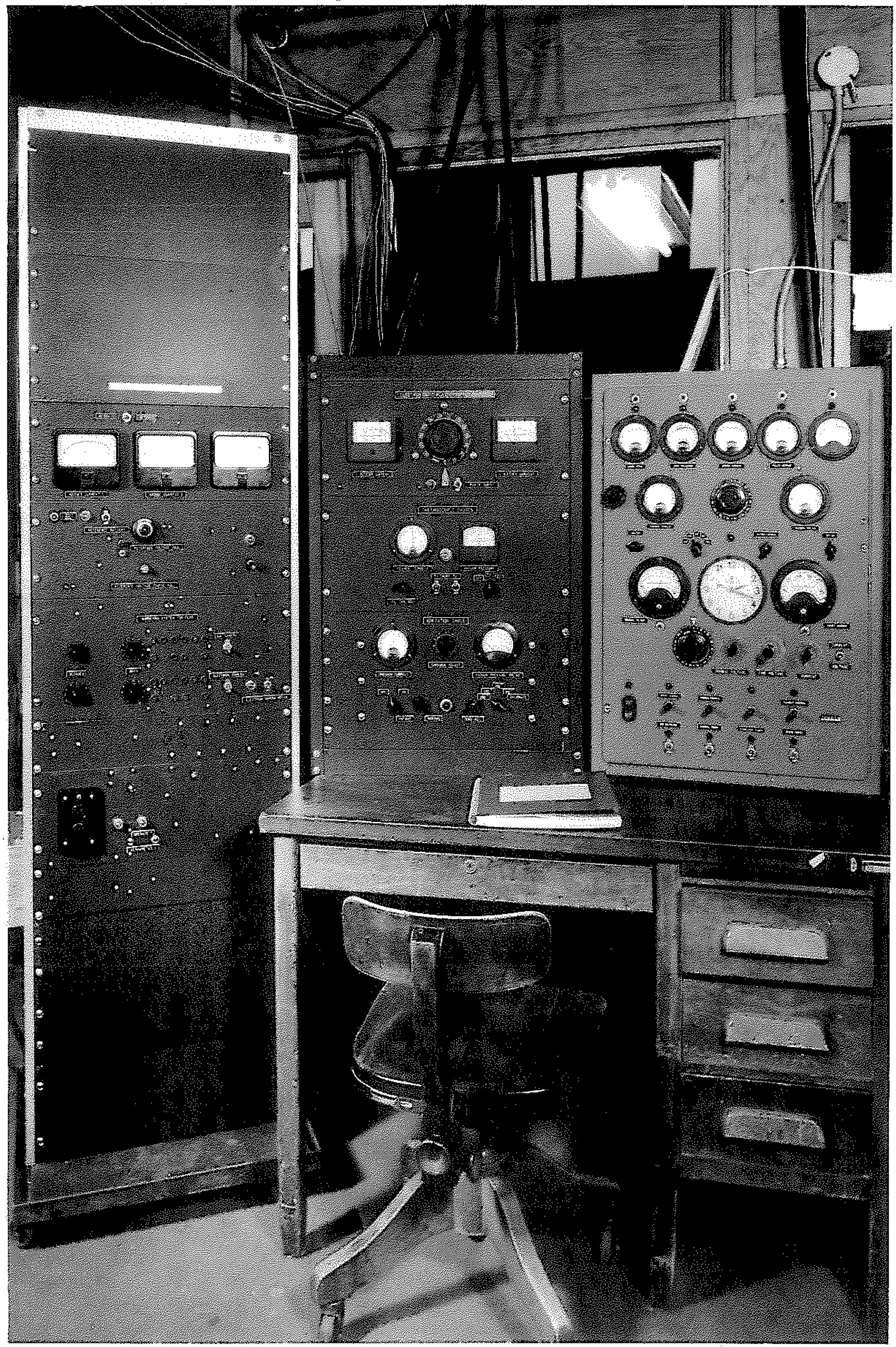


Figure 25 is a photograph of the control panels which are far from the generator for safety purposes against radiation hazards.



CONTROL PANELS

FIGURE 25



CHAPTER FOUR

EXPERIMENTAL RESULTS

4.1 General Remarks

The experimental results are classified in two groups. The first group is obtained by means of the magnetic analyzer I (Fig. 8) and the second by means of the electrostatic and magnetic analyzer (Fig. 11). All experimental data are pertinent to acceleration tube No. 1 (Fig. 5). Acceleration tube No. 2 has not been tested on account of unforseen time consuming difficulties with the vacuum systems and the films.

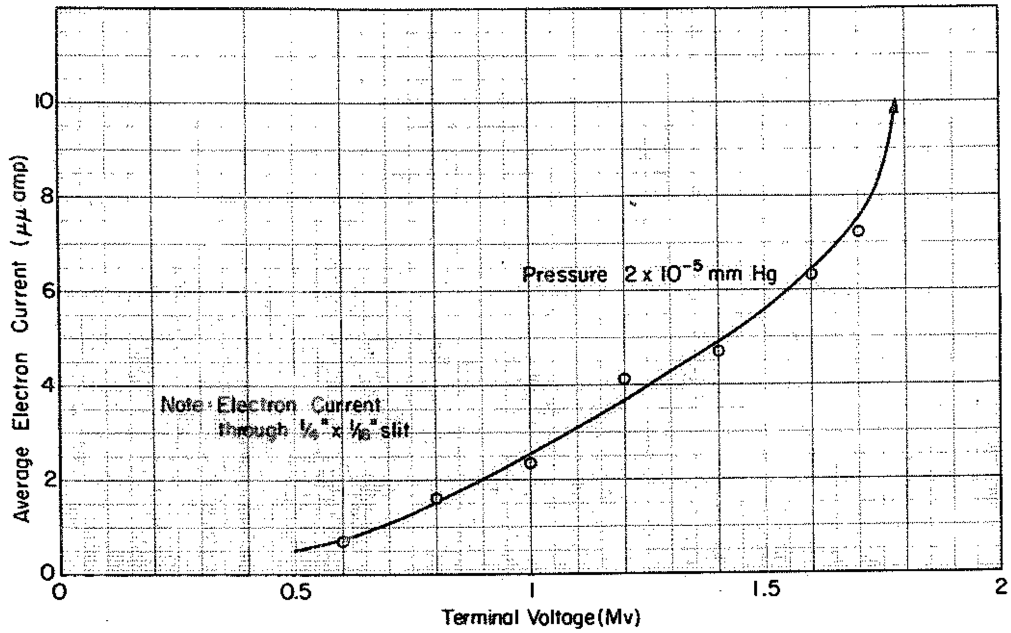
4.2 Experiments with Magnetic Analyzer I

4.2.1 Electron Dark Current and "Kicking" Effect Experiments

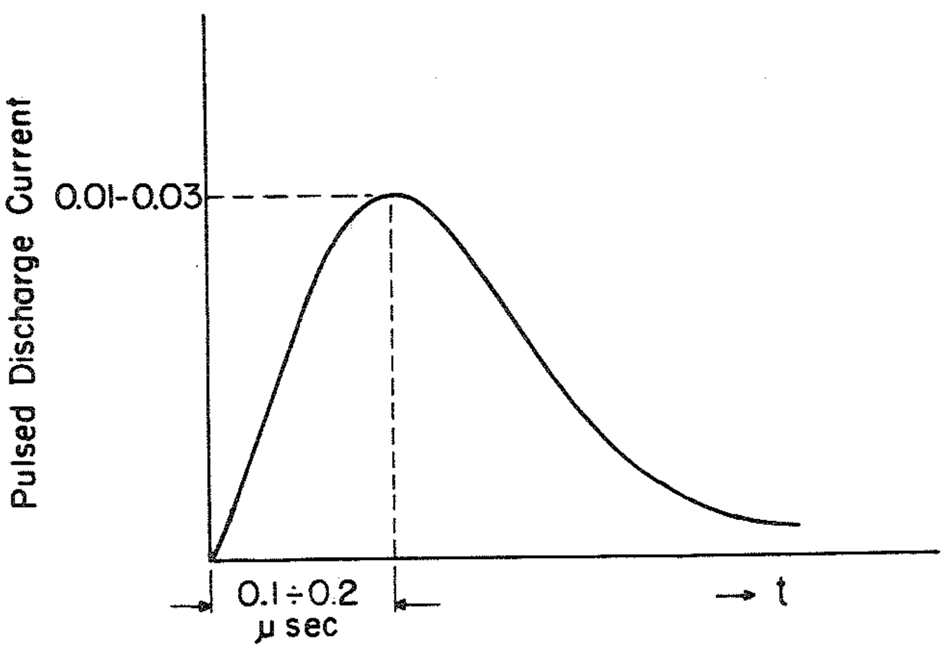
A sample of the electron dark current is collected at the plate P (Fig. 8) and is either integrated by means of a capacitor connected across the input of the electrometer tube circuit (Fig. 9) or monitored on the screen of a Tektronix oscilloscope.

The average electron current behavior as a function of voltage for a given residual gas pressure is depicted in Fig. 26. Mild "kicking" starts at voltages higher than 1.2 Mv. This is evidenced by a momentary decrease in the indication of the generating voltmeter and a momentary increase in the reading of the pressure gauge. At voltages 1.8 Mv or higher the "kicking" is rather violent causing the residual gas pressure to increase to a few times 10^{-4} mm Hg after two or three consecutive "kicks" and the tube to become highly conducting <u>without actually sparking</u>.

The average electron current is reduced when the residual gas



ELECTRON CURRENT VARIATION vs VOLTAGE
Figure 26



TIME BEHAVIOR OF PULSED DISCHARGE

Figure 27

pressure is increased in the range of 2×10^{-5} to 10^{-4} mm Hg. This is evidenced both by the decrease in the frequency of "kicking" and the increase in the threshold voltage at which "kicks" appear. Above the pressure of a few times 10^{-4} mm Hg the tube becomes highly conducting and stabilizes at the proper conditions for a high voltage vacuum discharge.

The time behavior of a single "kick" or pulsed discharge is schematically shown in Fig. 27. The rise time of the current is of the order of one to two tenths of a microsecond and the peak current varies between 0.01 - 0.03 a.

4.2.2 Negative Ion Dark Current Experiments

The negative ion spectra are studied with total voltage across the tube and residual gas pressure as variable parameters. For each value of the total voltage the magnetic field M_2 (Fig. 8) is adjusted so that H_1^- originating from the high voltage end of the tube register at the same position on the film F.

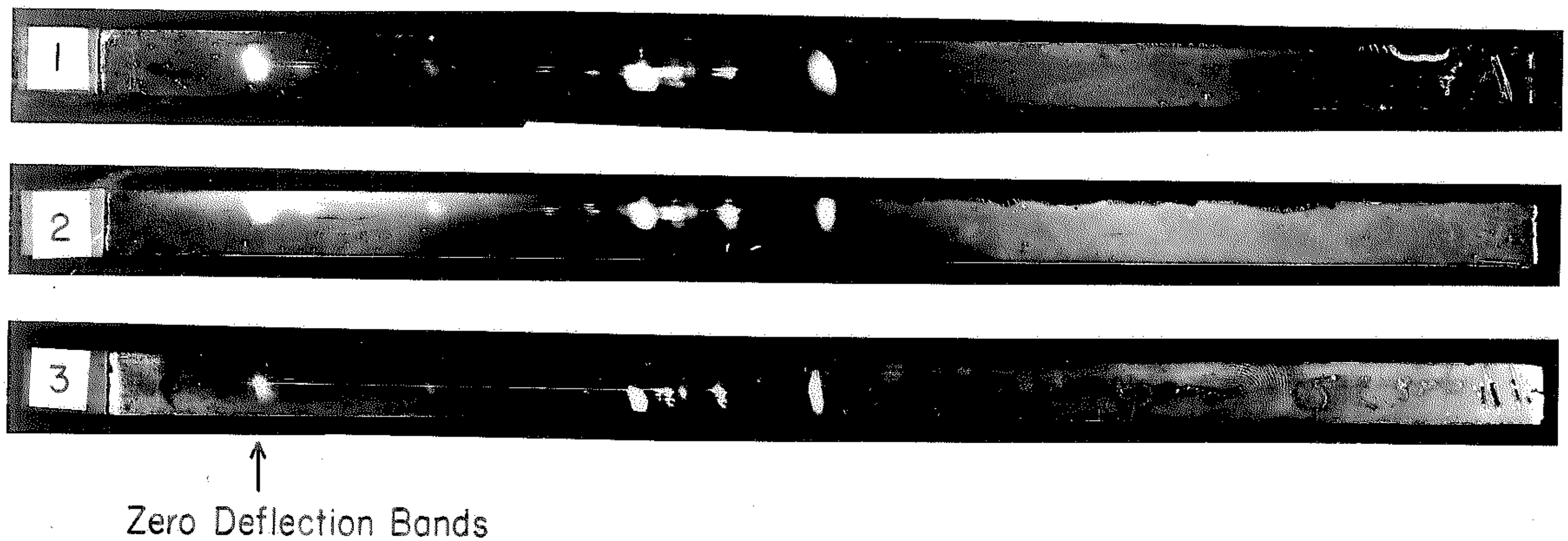
Some representative spectra of the magnetically analyzed negative ions are shown in Figs. 28 and 29 and the conditions under which they were taken are given in Table I. The interpretation of mass and energy of ions corresponding to different bands is not free of ambiguities with the exception of the H_1^- lines which seem to originate from the sections near the high voltage end of the tube.(Fig. 29). However, in spite of this difficulty the following conclusions can be drawn from the spectra.

1. There is a threshold voltage below which no negative ions are detectable. This threshold voltage coincides with the threshold volt-

TABLE I

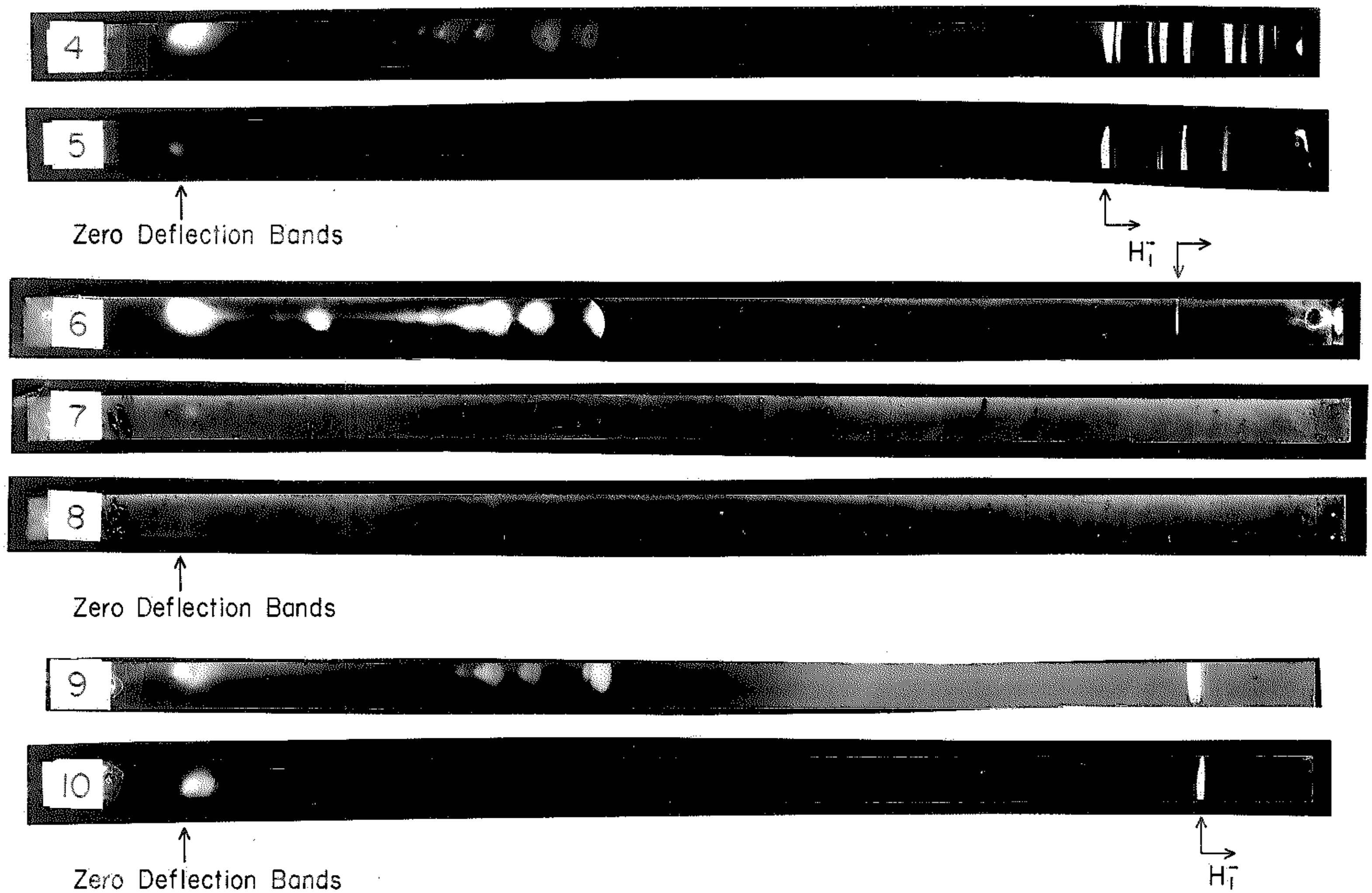
DATA ON NEGATIVE IONS SPECTRA

Figure	Spectrum Number	Terminal Voltage (Mv)	Exposure Time (min.)	Vacuum Pressure (mm Hg)	Remarks
28	1	1.2	20	2×10^{-5}	No negative ions below 1.2 Mv
28	2	1.3	17	"	
28	3	1.5	10	"	
29	4	1.5	2	1×10^{-5}	
29	5	1.5	0.5	"	
29	6	1.2	3	2×10^{-5}	Notice gradual disappearance of negative ions and zero deflection beam
29	7	1.2	3	7×10^{-5}	
29	8	1.2	3	3×10^{-4}	
29	9	1.6	1	2×10^{-5}	
29	10	1.6	1	3×10^{-4}	



NEGATIVE ION SPECTRA (see Table I)

Figure 28



NEGATIVE ION SPECTRA (see Table I)

Figure 29

age at which pulsed discharges are observed.

2. The negative ion current consists of ions of different mass numbers. The masses of the negative ions detected are not voltage dependent for a given gas pressure.

3. The negative ions originate in the vicinity of the electrodes since the spectra are discrete and not continuous.

4. The number of negative ions increases with tube voltage.

5. The negative ions gradually disappear with the increase of the residual gas pressure up to the point where the tube can sustain a high voltage vacuum discharge. However, the threshold pressure for the disappearance of negative ions of different masses is not the same.

6. Along with the negative ions there is a beam of particles which is not affected by the magnetic field. This beam consists of either heavy clumps of lightly charged matter or of neutral atoms and molecules and persists only as long as there are negative ions registering on the film.

4.2.3 Positive Ion Dark Current Experiments

The positive ion spectra are obtained by merely reversing the terminal polarity. Some representative spectra of the magnetically analysed positive ions are shown in Figs. 30 and 31 and the conditions under which they were taken are given in Table II. The essential conclusions about the positive ions are:

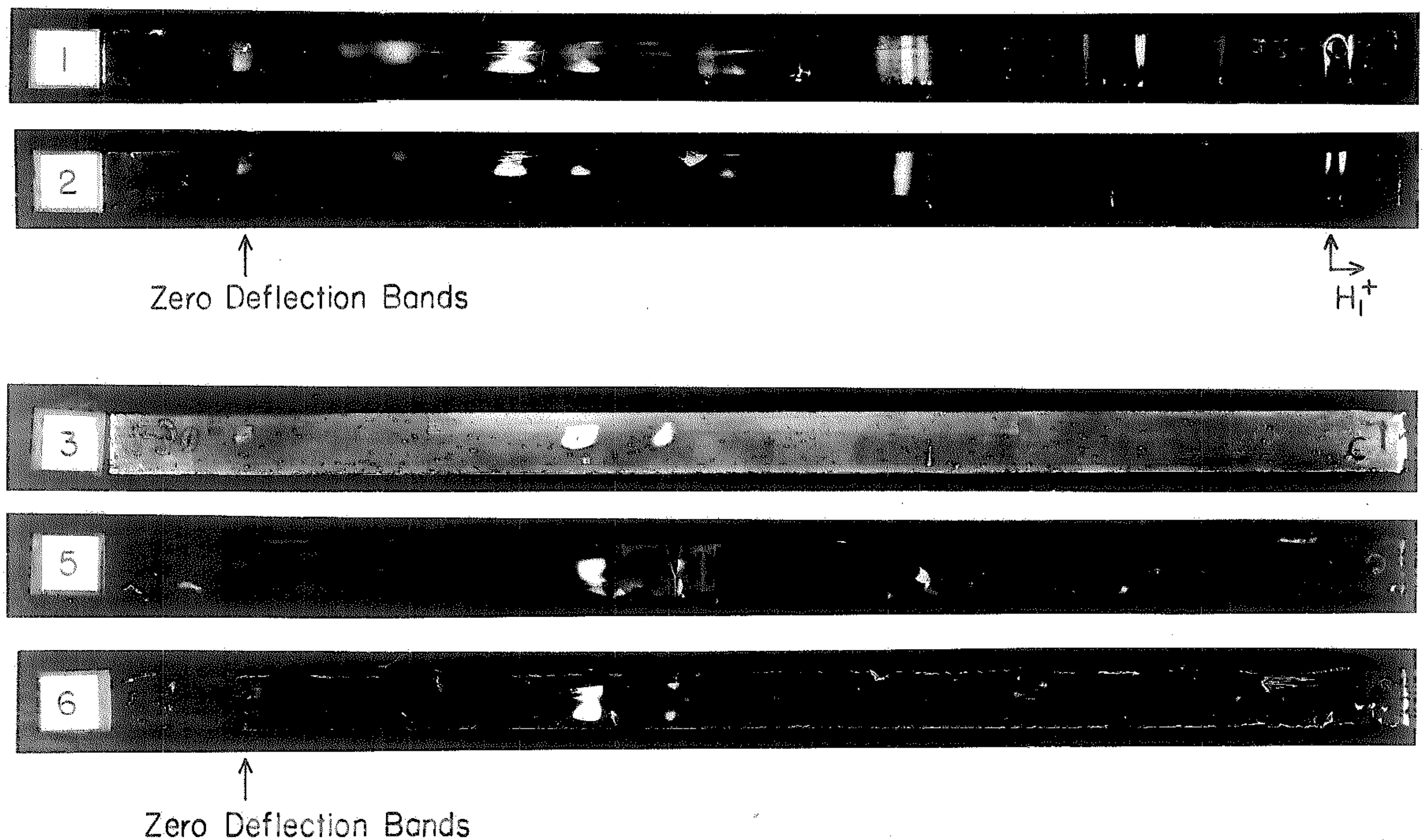
1. There does not seem to be a threshold voltage for the appearance of positive ions.

2. The positive ion current consists of ions of different mass numbers. The variety of spectral lines is greater in the case of positive

TABLE II

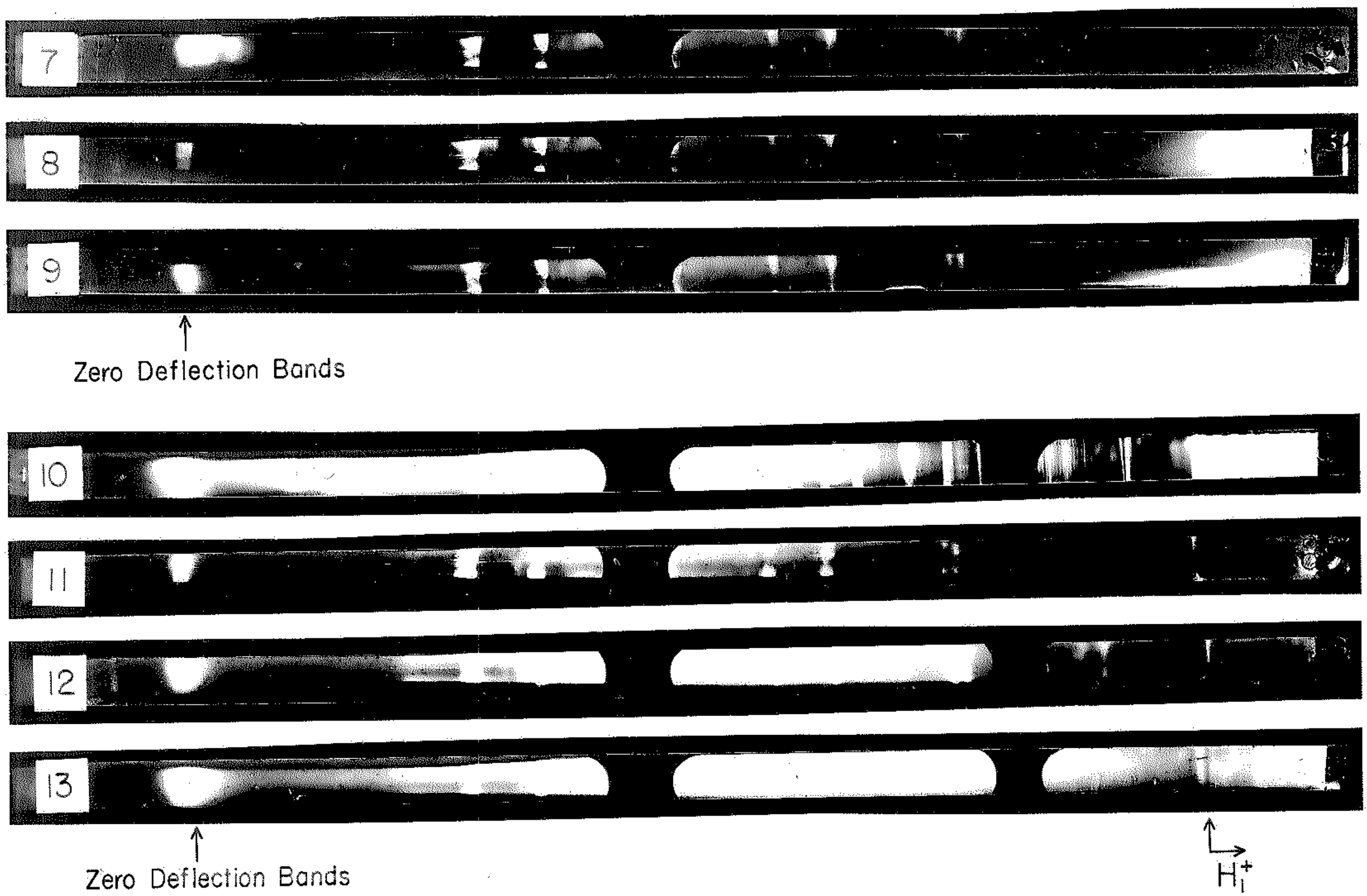
DATA ON POSITIVE IONS SPECTRA

Figure	Spectrum Number	Terminal Voltage (Mv)	Exposure Time (min.)	Vacuum Pressure (mm Hg)	Remarks
30	1	1.2	20	2×10^{-5}	
30	2	1.3	13	"	
30	3	0.4	15	"	
30	5	0.8	10	"	
30	6	1	4	"	
31	7	0.6	6	"	
31	8	0.8	3	"	
31	9	1	1	"	
31	10	1	3	2×10^{-5}	Tube is "kicking" at a lower voltage than when terminal is negative. Diffused spectra due to consecutive "kicks"
31	11	1	3	5×10^{-5}	
31	12	1	3	1×10^{-4}	
31	13	1	3	3×10^{-4}	



POSITIVE ION SPECTRA (see Table II)

Figure 30



POSITIVE ION SPECTRA (see Table II)

Figure 31

ions than in the case of negative ions indicating either a larger number of spots from which the positive ions originate or a greater variety of mass to charge ratios. However, this variety is neither pressure nor voltage dependent.

3. Most of the positive ions are formed in the vicinity of the electrodes as evidenced by the discrete character of the spectra. Incidentally some of the spectra appear continuous on account of consecutive pulsed discharges which resulted in a conducting tube.

4. The number of positive ions increases with voltage.

5. The positive ions spectra do not disappear with the increase of the residual gas pressure.

6. Along with the positive ions there is a beam of either extremely heavy clumps of lightly charged matter or neutral atoms and molecules.

4.3 Experiments with Electrostatic and Magnetic Analyzer

4.3.1 Electron Dark Current and "Kicking" Effect Experiments

Three series of measurements are performed during these experiments.

a. The total negative current associated with a "kick" and collected at the insulated adapter cavity (Fig. 11) is monitored on the screen of a Tektronix oscilloscope in order to establish its shape. It is found that a "kick" consists either of a single pulse (Figs. 32 and 33 - Table III) or of a train of superimposed pulses occuring at time intervals of one to several tenths of a microsecond apart (Figs. 34 and 35 - Table IV).

The essential conclusions from this series of experiments are:

1. The rise time of the pulsed discharges is of the order of a tenth of a microsecond.

2. The peak current of single "kicks" is of the order of a few amperes and decreases with increasing residual gas pressure (Fig. 36).

3. The current peaks of multiple "kicks" are spaced one to several tenths of a microsecond apart.

4. The threshold voltage for the appearance of "kicks" rises with the increase of the residual gas pressure (Fig. 37). Incidentally, the threshold voltage is greater during these experiments than is reported in section 4.2.1. The reason for this increase is not known. The only thing that happened between the two series of experiments is that the tube was not used for a period of 8 months.

5. All "kicks" are accompanied by a momentary decrease in the indication of the generating voltmeter by 50-200 Kev and a momentary increase of the residual gas pressure by 10^{-5} to 3×10^{-5} mm Hg.

TABLE III

DATA ON SINGLE PULSED DISCHARGE OSCILLOGRAMS

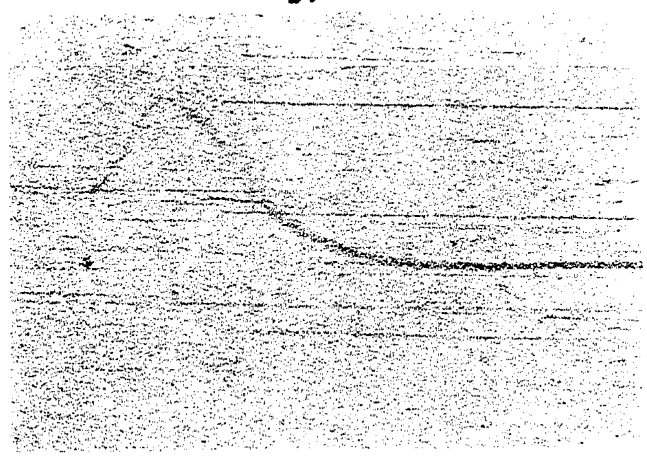
Figure	Frame Number	Residual Gas Pressure mm Hg x 10^5	Tube Voltage Mv	Sweep Speed μ sec/cm	Current Scale A/ cm
32	9-8	1	1.85	0.1	1.11
32	8-7	3	1.9	"	"
32	9-18	5	2.1	"	"
32	10-16	10	2	"	"
33	11-8	15	2.2	"	"
33	11-20	20	2.2	"	"

TABLE IV

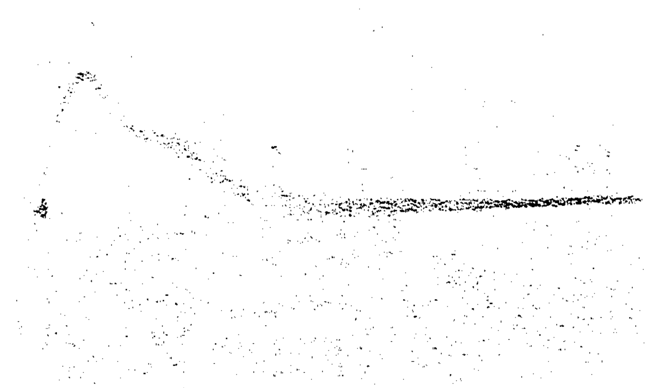
DATA ON MULTIPLE PULSED DISCHARGE OSCILLOGRAMS

Figure	Frame Number	Residual Gas Pressure mm Hg x 10^5	Tube Voltage Mv	Sweep Speed μ sec/cm	Current Scale A/ cm
34	9-10	1	2	0.1	1.11
34	8-5	3	2	"	"
34	9-17	5	2.1	"	"
34	10-11	10	2.1	"	"
35	11-7	15	2.3	"	"
35	11-14	20	2.2	"	"

#9-8



#8-7



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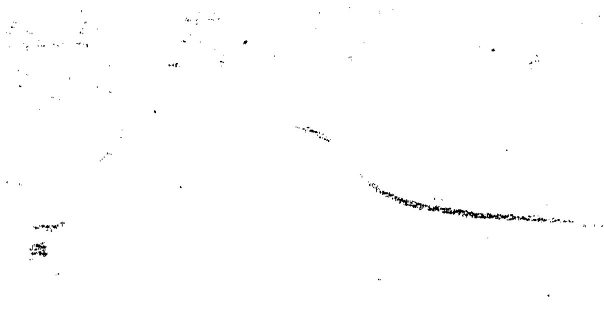
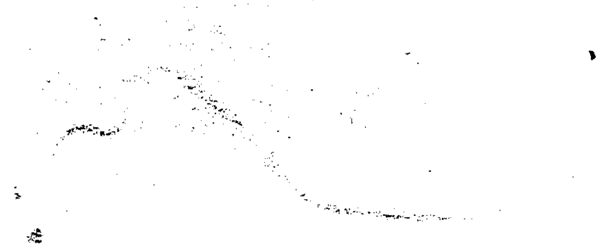
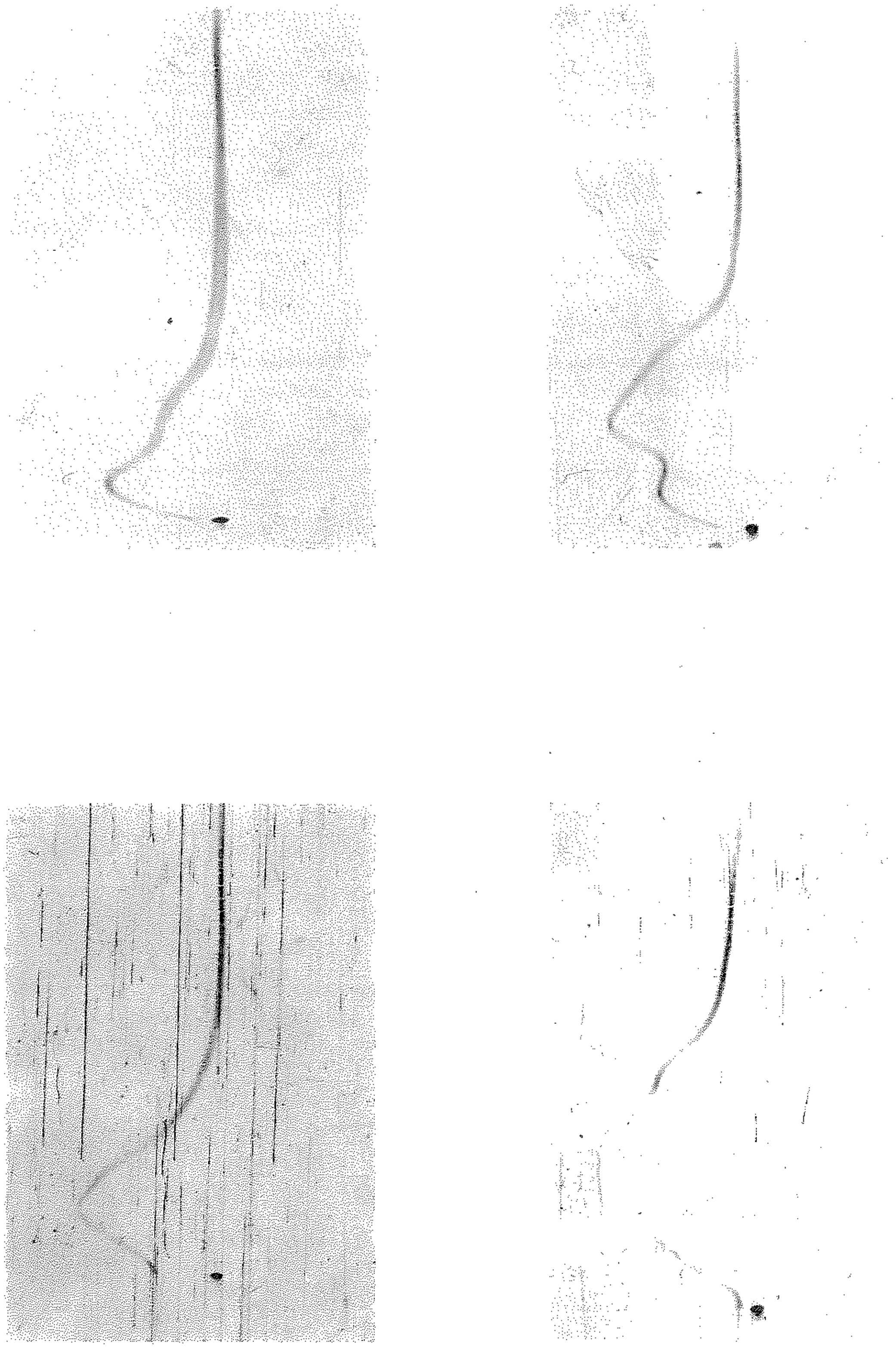


#10-16

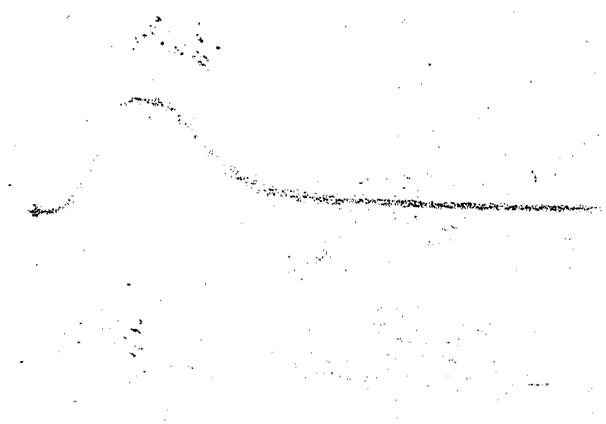


PULSED DISCHARGE OSCILLOGRAMS (See Table III)

Figure 32



#11-6



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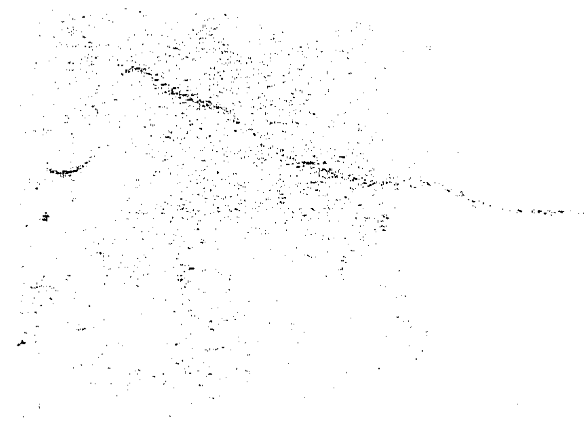
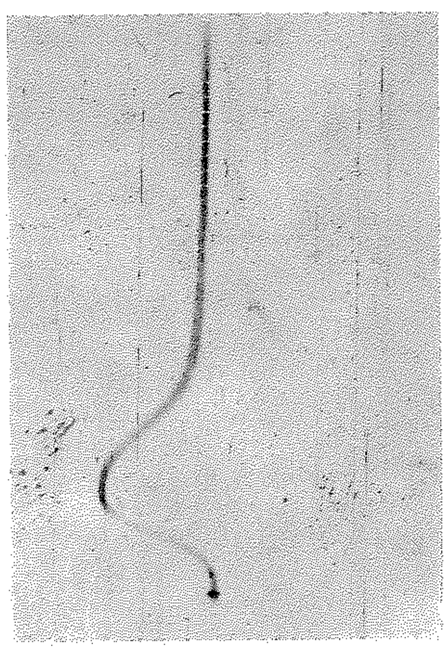
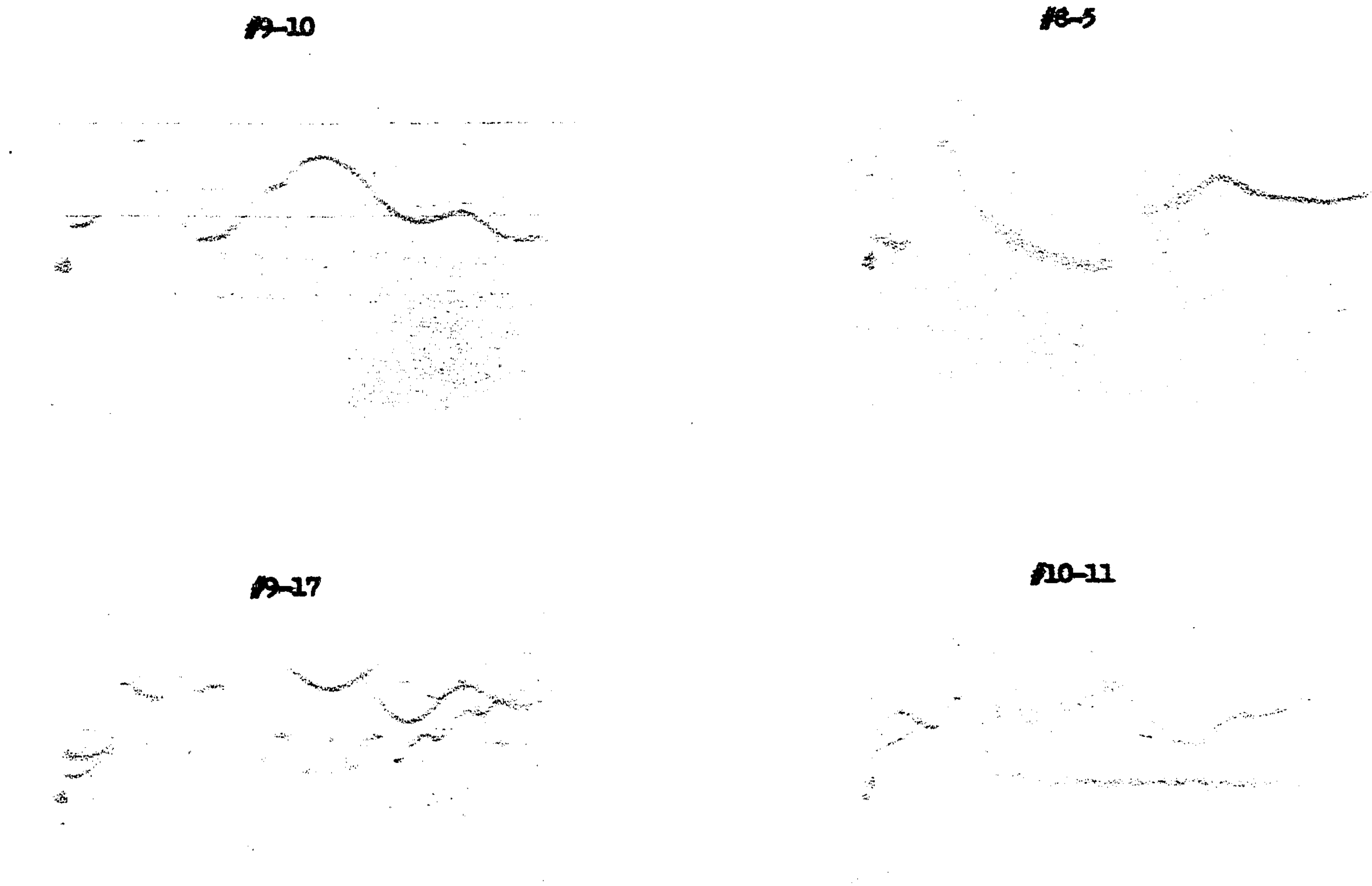


PULSED DISCHARGE OSCILLOGRAMS (See Table III)

Figure 32

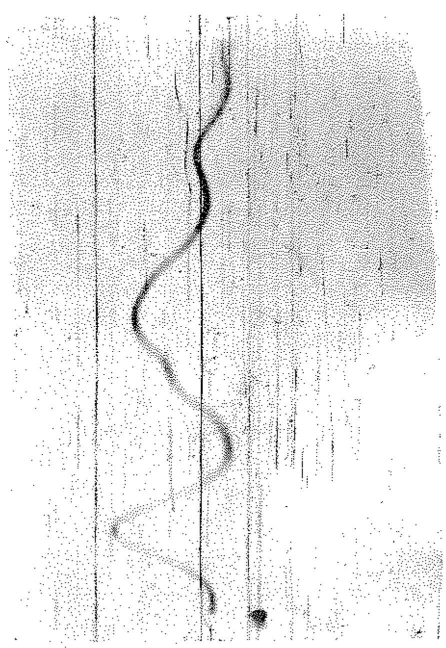
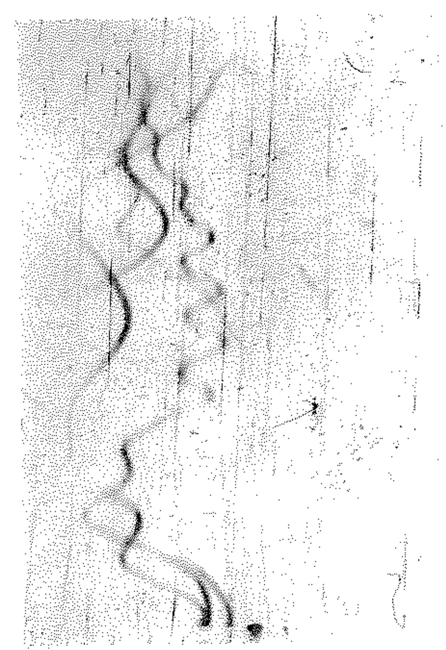




PULSED DISCHARGE OSCILLOGRAMS (See Table IV)

Figure 34



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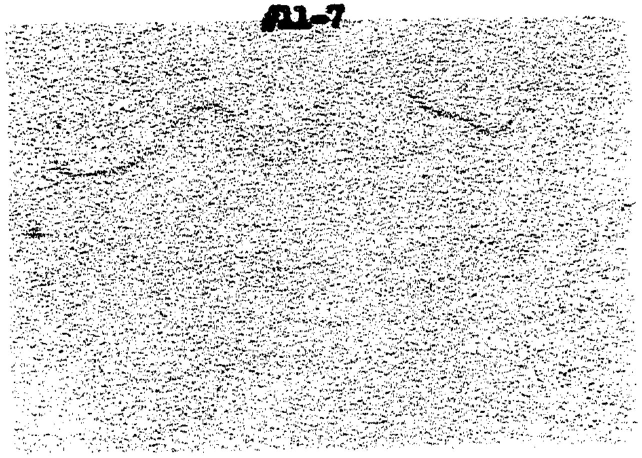

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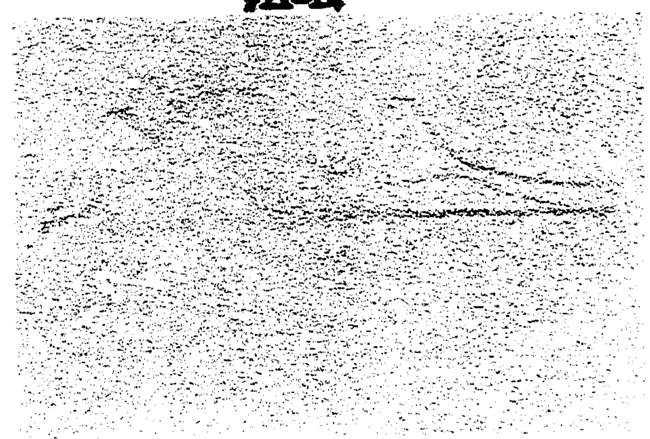
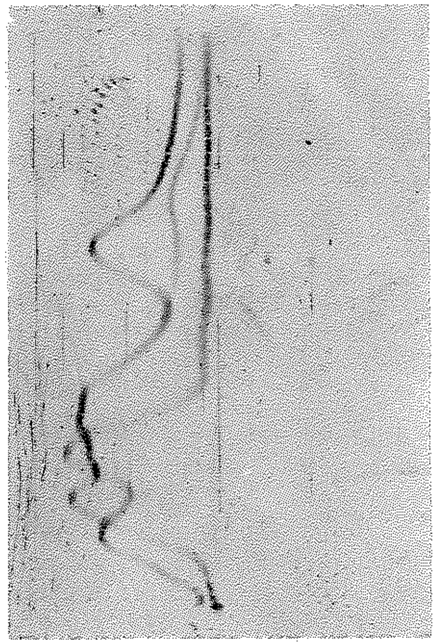
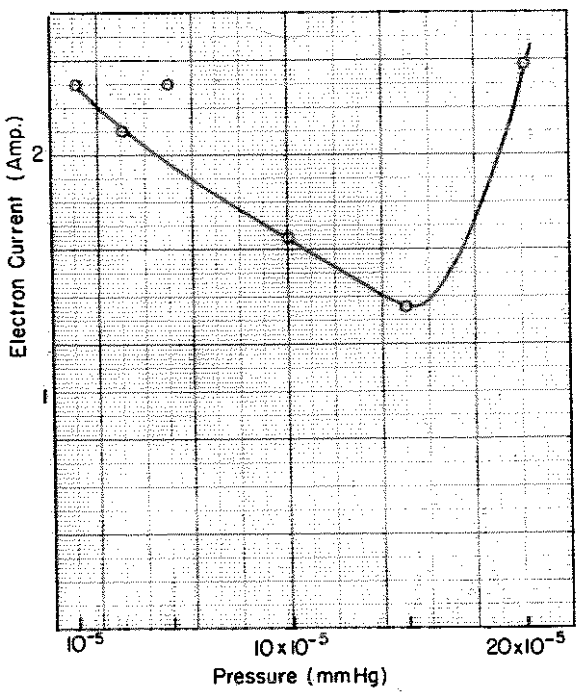


PULSED DISCHARGE OSCILLOGRAMS (See Table IV)

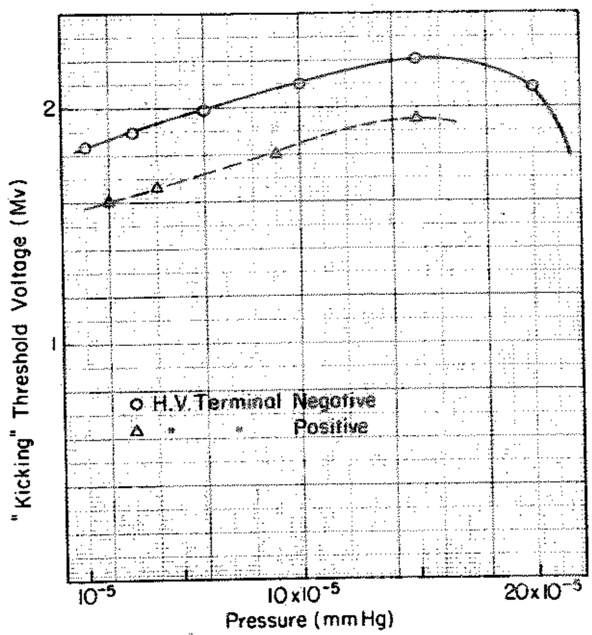
Figure 35





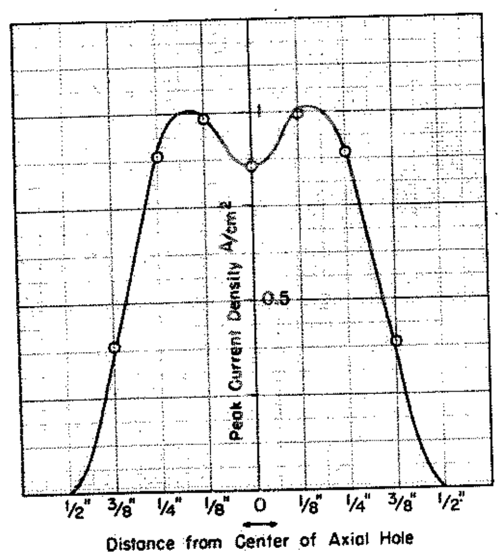
PEAK ELECTRON CURRENT DURING "KICKING" vs RESIDUAL GAS PRESSURE

Figure 36



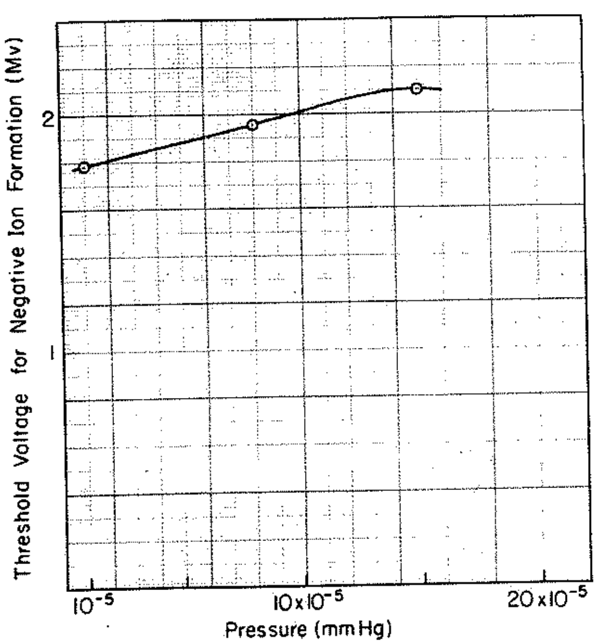
"KICKING" THRESHOLD VOLTAGE vs RESIDUAL GAS PRESSURE

Figure 37



PEAK ELECTRON CURRENT DENSITY AT THE ANODE DURING "KICKING"

Figure 39



THRESHOLD VOLTAGE FOR NEGATIVE ION FORMATION vs RESIDUAL GAS PRESSURE

Figure 42

b. A sample of the electron current associated with a "kick" is collected at a faraday cage placed in front of the magnet M_1^1 (Fig. 11) in lieu of the electron camera in order to find the current density distribution along the cross-section of the central hole of the tube. The sample is selected by properly positioning the slit S_1 (Fig. 11) and is monitored on the screen of the oscilloscope. Some representative pictures of samples through a 0.020" diameter slit are shown in Fig. 38 (see also Table V). Only single pulses are considered in order to facilitate the comparison. From these pictures it is concluded that:

1. The electron current density across the sampling line is fairly uniform (Fig. 39).

2. The sampling line is a good image of the entire cross-section of the hole of the tube since the area of the current density given by Fig. 39 over the cross-sectional area of the collecting cavity hole is comparable to the peak current of exposure No. 8 - 7 - Fig. 32.

c. Finally a sample of the electron current is integrated on a strip of stationary or moving film F_1 (Fig. 11) in order to establish the energy spectrum of the electrons. The sampling slit S_1 has a 0.040" diameter and is located at the geometric axis of the tube.

This series of experiments has not revealed the energy spectrum of the electron current when the voltage across the tube is lower than the threshold for pulsed discharges because if the film were too sensitive (Kodak photoflure blue sensitive) the x-ray background is untolerable while if the sensitivity of the film is smaller (Du Pont adlux or Kodak x-ray film) the exposure times required are not practical. Consequently only the electron current spectrum on the verge of or during instabilities is

TABLE V

DATA ON PULSED DISCHARGE CURRENT DENSITY DISTRIBUTION OSCILLOGRAMS

Figure	Frame Number	Residual Gas Pressure mm Hg x 10^5	Tube Voltage Mv	Slit Position from Axis	Sweep Speed μ Sec / cm	Current Scale A / cm
38	4-16	3	1.9	0	0.1	1.11
38	5-2	3	1.9	1/8"	"	"
38	6-13	3	1.9	1/4"	"	"
38	7-17	3	1.9	3/8"	"	"

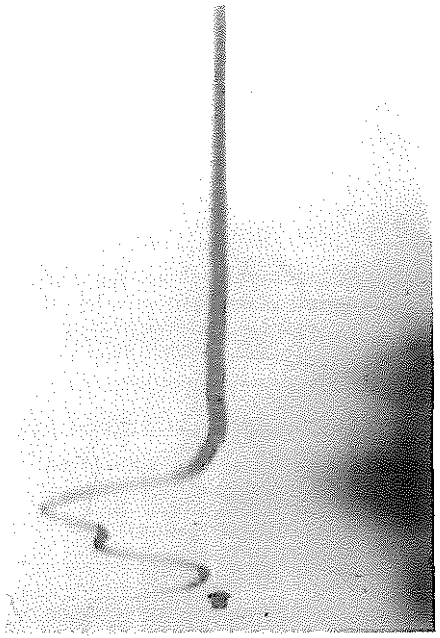
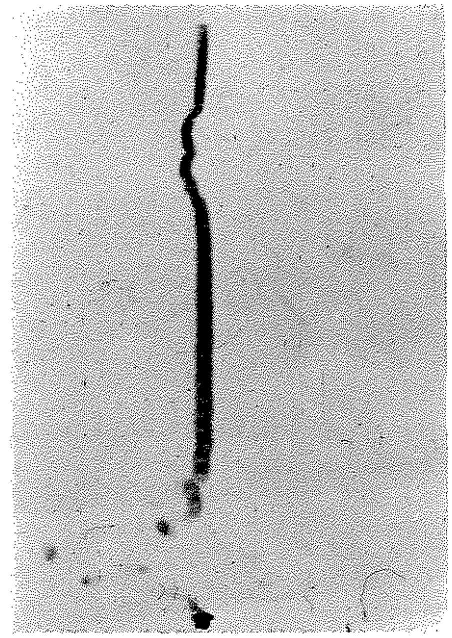
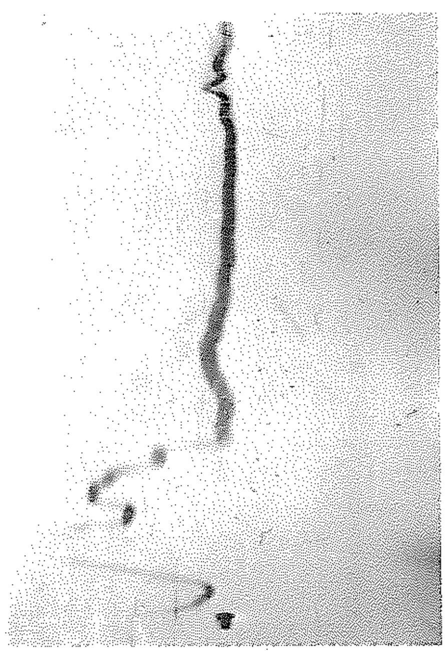
#5-2

#4-16

#6-13

#7-17

PULSED DISCHARGE OSCILLOGRAMS (See Table V)
Figure 38


investigated. Some representative spectra are shown in Figs. 40 and 41 (see also Table VI). The conclusions that may be derived from these spectra are:

1. The first pulsed discharge originates from one or two sections of the tube which are approximately 8" and 9 1/2" from the cathode. These two sections are 1 1/2" (or four single sections - see Fig. 5) apart and the discharge starts when they are at the 1.1 - 1.2 Mv level above ground or when the overall gradient along the tube is approximately $30\frac{kv}{cm}$.

2. A violent or multiple "kick" is associated with pulsed discharges which originate from more than two sections. However those sections are always 8" or more away from the cathode.

3. During the formative time of pulsed discharges electrons originate throughout the whole gas volume between the electrodes of the section which undergoes the discharge.

4. The energy width of a discharging section remains constant even when the discharge is fully developed. This might be interpreted as meaning that the voltage across the section does not collapse. However this may not be necessarily the case (see section 4.4).

5. The pulsed discharges are self-quenched.

4.3.2 Negative Ion Dark Current Experiments II

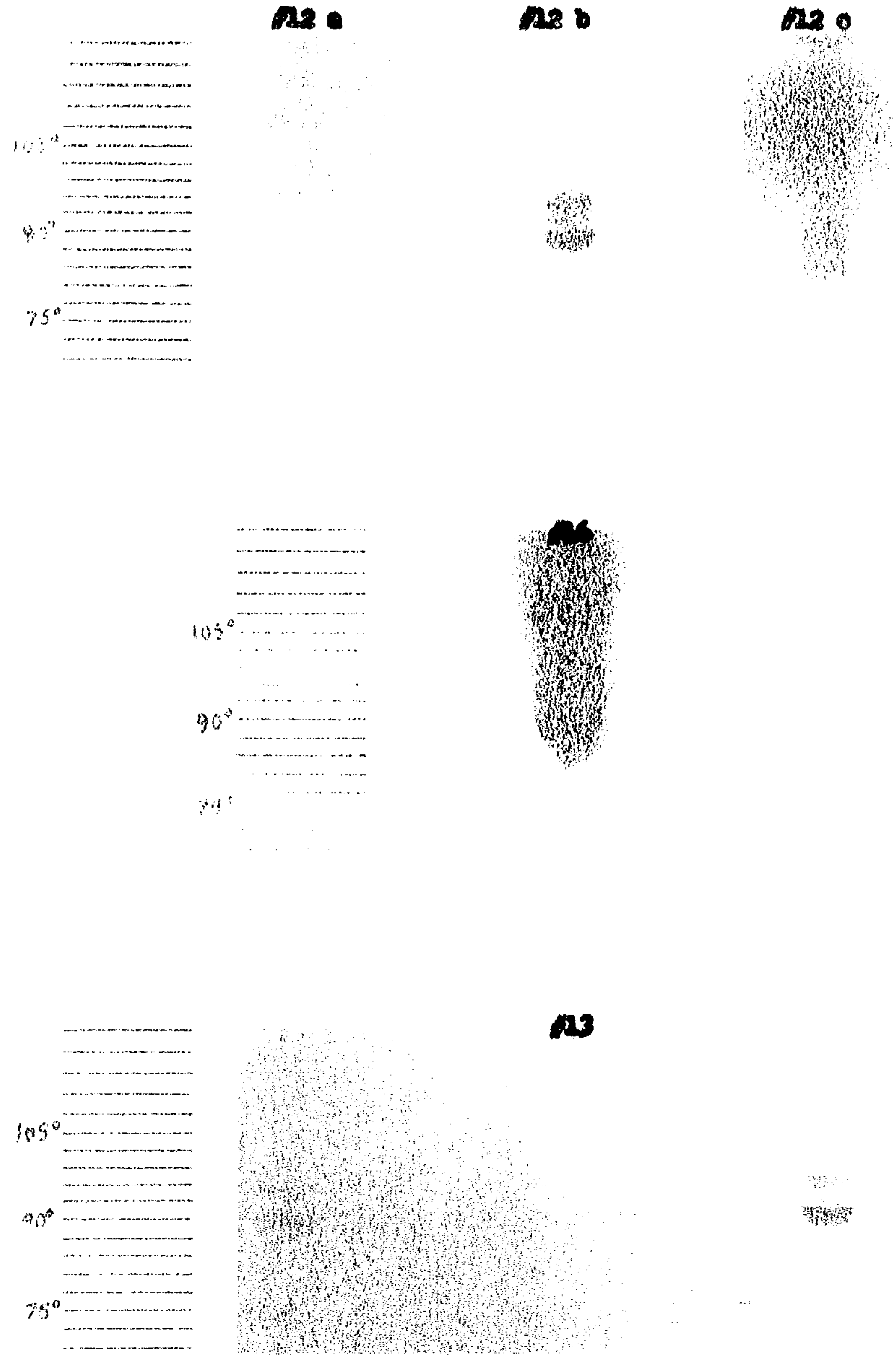
The negative ions spectra are studied with total voltage and residual gas pressure as variable parameters.

A series of exposures is taken in order to establish the threshold voltage for negative ion formation versus residual gas pressure. The results are given in Fig. 42. Then the negative ions are analyzed both magnetically and electrostatically and some representative spectra are

TABLE VI

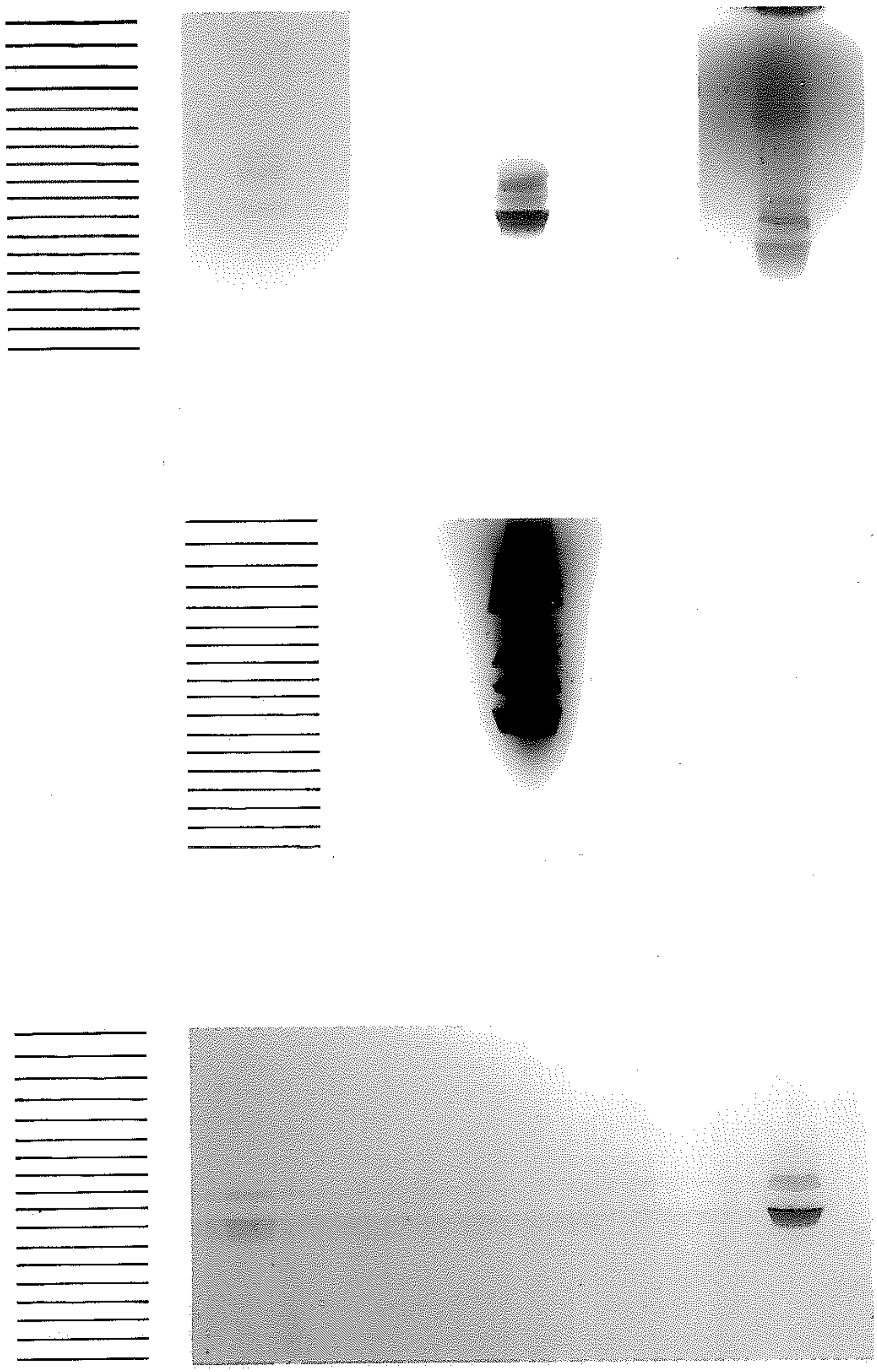
DATA ON ENERGY SPECTRA OF ELECTRONS

Figure No.	Spectrum No.	Tube Volt. Mv	Pressure mmHg 10^5	Film Type	Film Motion in/min.	Expos. Time min.	Press. Variat. mmHg 10^5	Voltage Variat. kev	Magnet. Field Gs	Max. Energy Mv
40	12a	1.8	1.5	Adlux	0	15	0	0	2250	1.2
This exposure may be interpreted as meaning either that many electrodes below the 1.2 Mv level were emitting electrons or that one mild discharge occurred during the 15 min. of exposure.										
40	12b	1.9	1.5	Adlux	2	2	2	50	2250	1.27
Spectrum of a mild "kick" that occurred during the exposure time. Nothing else was noticeable on 4" of film.										
40	12c	2.1	5	Adlux	2	2	3	100	2250	1.5
Same comments as for 40 - 12b.										
40	16	1.8	5	X-ray	5	2	10	200	2000	1.2
Spectrum of a violent "kick". Nothing else on 10" of film.										
40	13	1.9	3	X-ray	2	2	0	0	2250	1.3
Sections discharging are 1 1/2" apart.										
41	17a	2	6	X-ray	5	0.6	0	0	2250	1.35
Notice that both generating voltmeter and pressure gauge are insensitive to this self-healing discharge.										
41	17b	1.8	6	X-ray	5	1	20	300	2250	1.2
Spectrum of repeated violent "kicks". On the rest of the film only the two sections at the 1.2 Mv level were undergoing a mild discharge.										



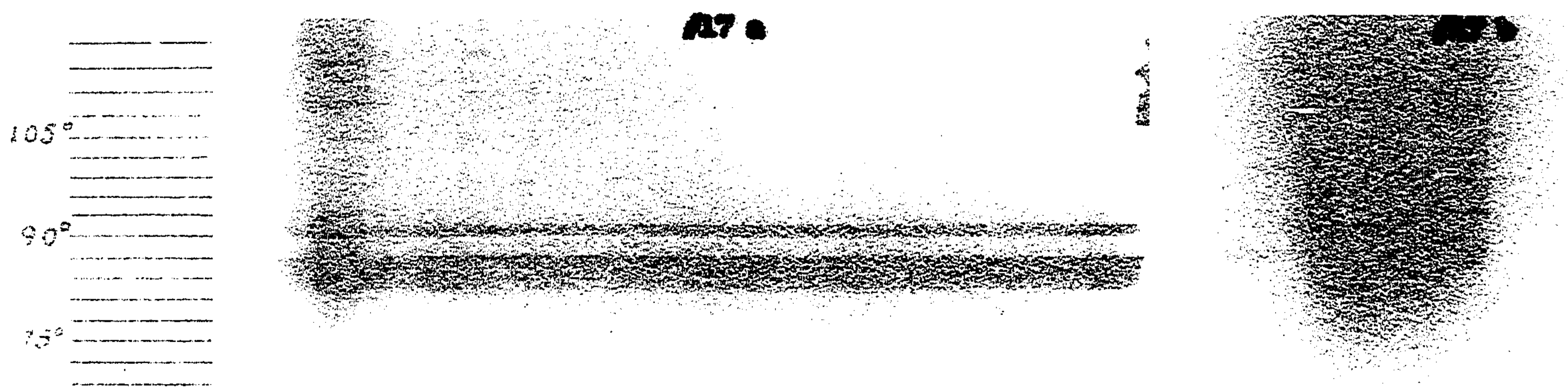
ENERGY SPECTRA OF ELECTRONS (see Table VI)

Figure 40



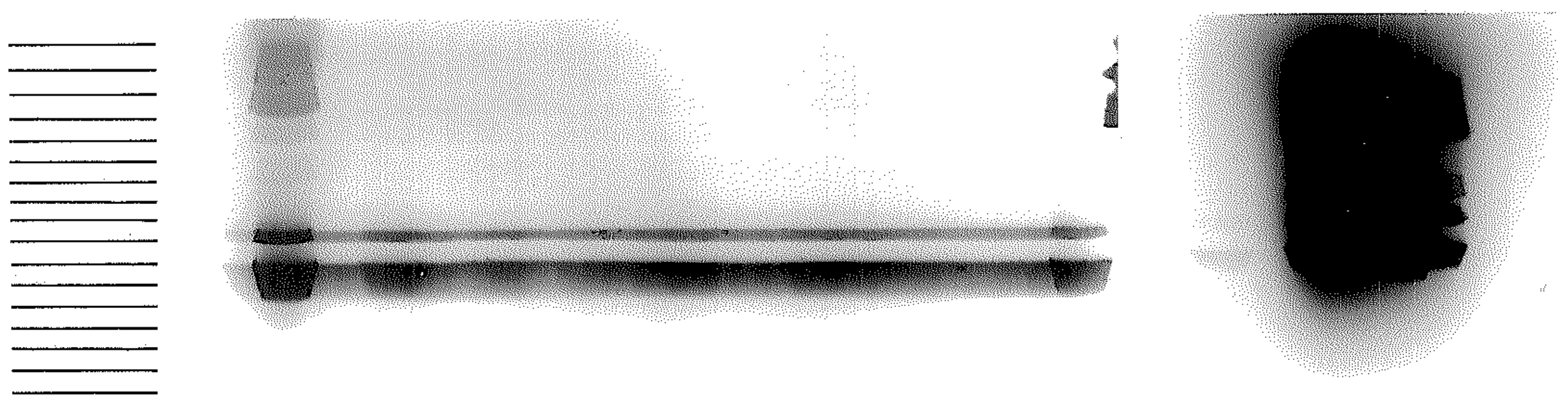
ENERGY SPECTRA OF ELECTRONS (see Table VI)

Figure 40



[illegible] SPECTRA OF ELECTRONS (see Table [illegible])

Figure 41



ENERGY SPECTRA OF ELECTRONS (see Table VI)

Figure 41

given in Fig. 43 (see also Table VII). The essential conclusions from the negative ion spectra are:

1. Points 1 through 5 of section 4.2.2 have been reestablished even though the threshold voltage for negative ion formation is higher than what is reported before.

2. Negative ions are first formed in the vicinity of an electrode which is about 8" from the cathode.

3. When a multiple "kick" occurs negative ions are formed in the vicinity of many more electrodes. Those electrodes are both closer than 8" to the cathode and farther than 8" from it, the latter being by far the preferred distances.

4. The negative ions are formed at the edges of the holes of the electrodes (Fig. 43 - No. 5). Notice that the circular shape of the holes is distorted on account of the fringing field of the electromagnet M_2^1.

5. No negative heavy clumps of matter singly or multiply charged have been detected. This is ascertained by comparing negative ion spectra taken with or without the electrostatic lense and noticing that no spots are missing.

6. The zero deflection spots are definitely due to neutral particles because they are not affected either by the magnetic or the electrostatic field. Evidently these neutral particles are formed by a detachment process from negative ions since they appear and disappear with the latter.

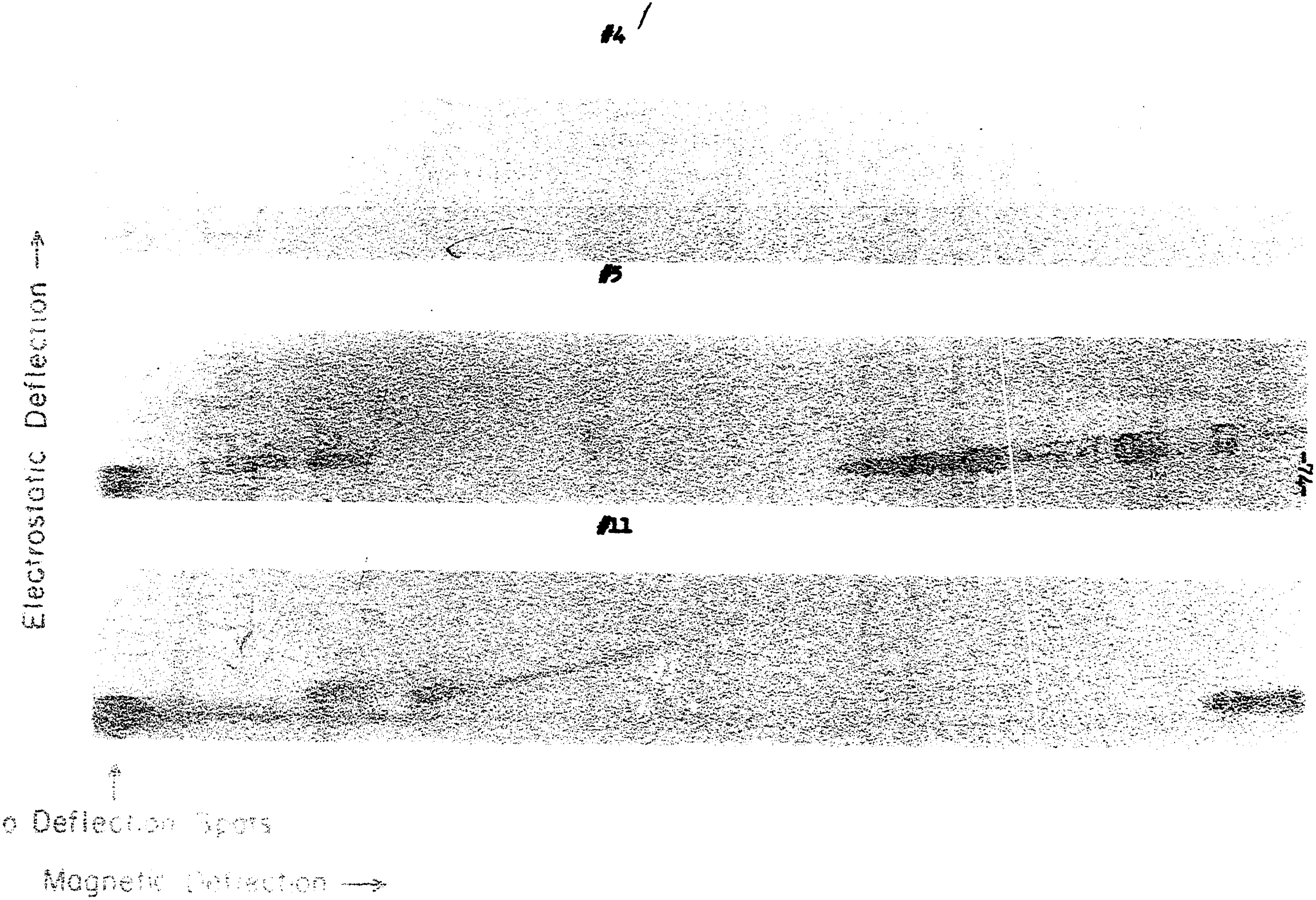
4.3.3. Positive Ion Dark Current Experiments II

The positive ions spectra are investigated with voltage, gradient and residual gas pressure as variable parameters. Four series of experiments are performed.

TABLE VII

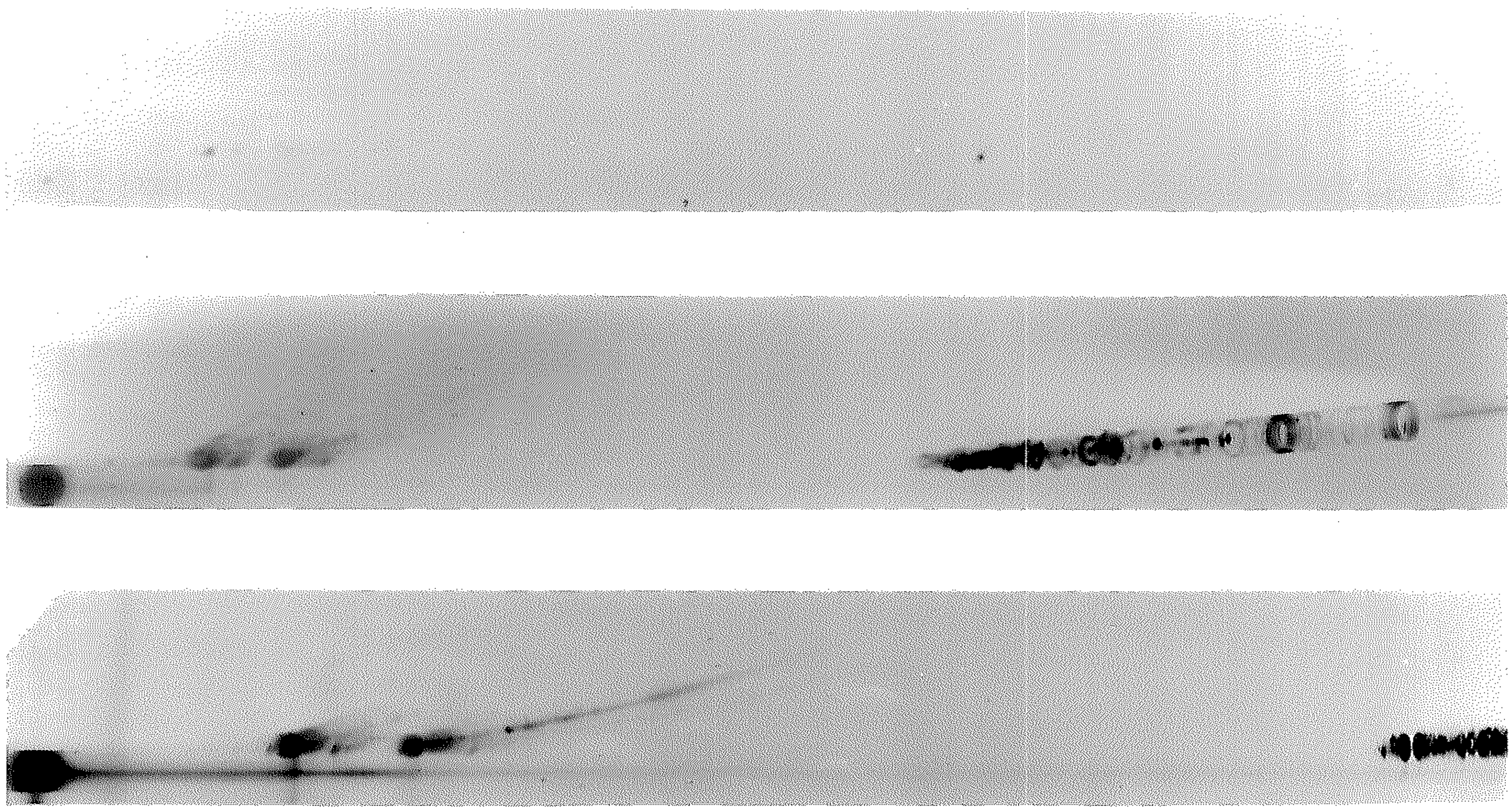
DATA ON NEGATIVE ION SPECTRA

Figure No.	Spectrum No.	Total Voltage Mv	Pressure mmHg 10^5	Exposure Time	Voltage Variation Kev	Pressure Variation mmHg 10^5	Magnetic Field Gs	Electr. Pl.Volt. Kev	Max. Energy Mev	Neg.Ions Detected
43	4	1.9	3	1	0	0	4000	25.2	1.27	H_1^- O_1^- 27^- 38^- Neutrals
Notice that all ions come from same electrodes as in case 13 - Fig. 40										
43	5	1.85	1.5	1	50	2	4000	25.2	1.54	H_1^- O_1^- Cl^- Heavier ions - Neutrals
"Kick" occurred during exposure. Only H_1^-, O_1^- which formed parabolas are easily detectable. Mass of other ions hard to interpret even though their variety is limited.										
43	11	1.8	5	1	100	3	6000	25.2	1.5	H_1^- O_1^- O_2^- Neutrals
"Kick" occurred during exposure.										



NEGATIVE ION [illegible] able VII)

Figure [illegible]



NEGATIVE ION SPECTRA (see Table VII)

Figure 43

a. The generator voltage is applied across the total length (24") of the tube. The positive ions are both magnetically and electrostatically analyzed. Some representative spectra are given in Fig. 44. (see also Table VIII) The main conclusions from these experiments are:

1. The positive ion current consists of ions of a great variety of mass numbers.

2. The positive ions originate mostly from one or two sections at approximately 8" and 16" from the anode (or high voltage end of the tube) particularly when the tube is on the verge of an instability.

3. During an instability most of the positive ions are formed at localized spots of the electrodes of #2 and the ones adjacent to them. Positive ions are also seemingly formed in the gas volume of the tube.

4. Conclusions 2 to 5 of section 4.2.3 have been reestablished.

5. No positive heavy clumps of matter multiply or singly charged have been detected. (see #5 of section 4.3.2)

6. The zero deflection spots are due to neutral particles since they are not affected either by the magnetic or the electrostatic field. Evidently these neutral particles are formed by an electron attachment or charge exchange processes from the positive ions.

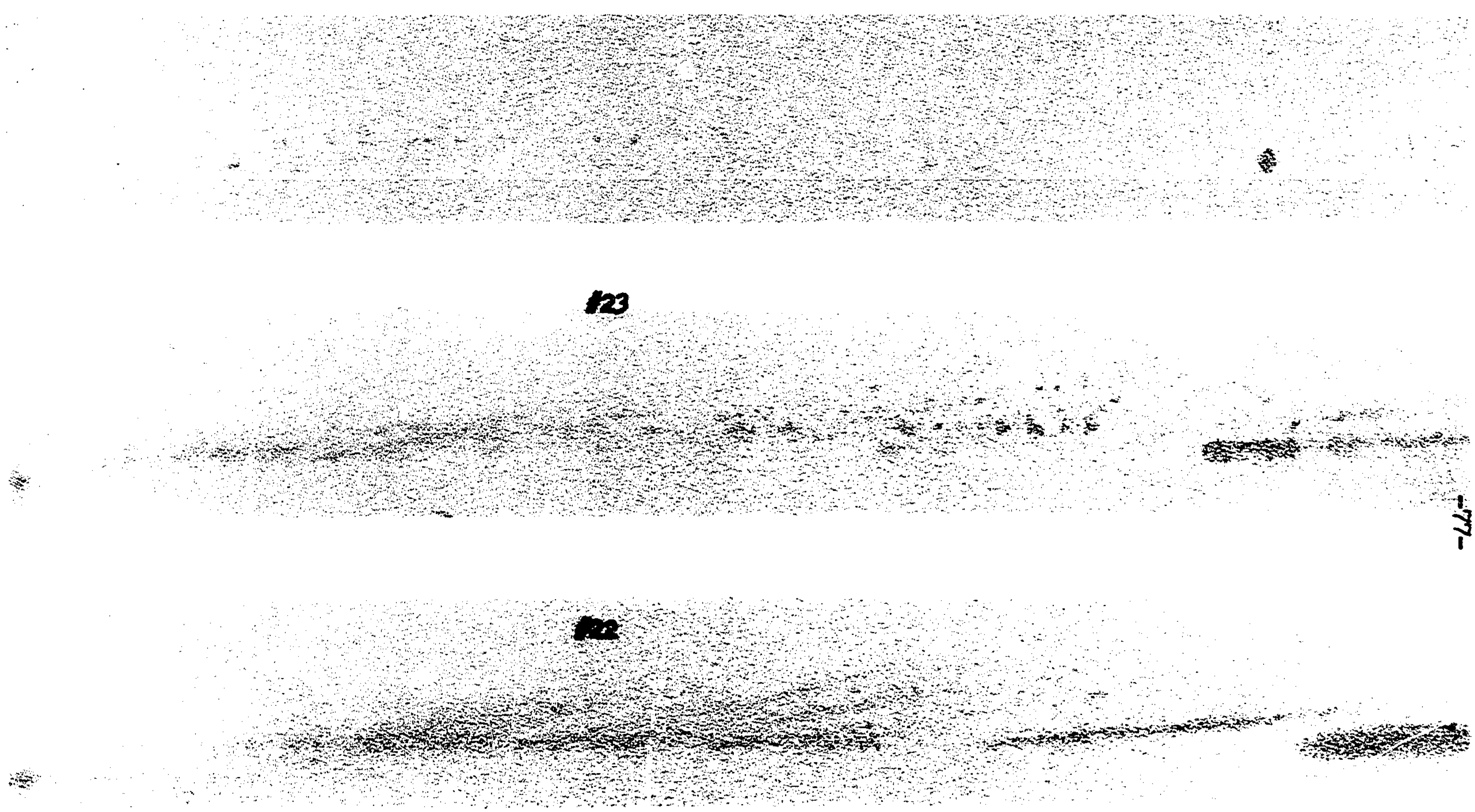
7. The threshold voltage for "kicking", when the high voltage terminal is positive, is slightly smaller than the same when the latter is negative (Fig. 37).

b. The generator voltage is applied across 16" of tube length, the top 1/3 of the tube closest to the high voltage terminal being shorted out. Figure 45 - Exposure 26 is a representative positive ion spectrum taken under these conditions. (see also Table VIII) It is worth noting

TABLE VIII

DATA ON POSITIVE ION SPECTRA

Figure No.	Spectrum No.	Tube Voltage Mv	Pressure mmHg 10^5	Exposure Time min.	Voltage Variation kv	Pressure Variation kv	Magnetic Field Gs	Electr. Pl.Volt. kv	Max. Energy Mev	Positive Ions Detected
44	19	1.5	4	1	0	0	5200	25.2	1	H_1^+ H_2^+ Li^{7+} CH^+ Al^+ AlO^+ $\frac{m}{e}$ =9,19,34,& 43 Neutrals
All positive ions originate from the 1 Mv and 0.625 Mv levels.										
44	23	1.8	6	0.5	50	4	5500	18	1.2	H_1^+ H_2^+ Li^+ C^+ CH^+ N^+ Al^+ and various other $\frac{m}{e}$ Neutrals
"Kick" occurred during exposure. Ions seem to originate from various levels below 1.2. However there are always pairs of levels 60 kv apart.										
44	22	1.8	4	0.5	100	10	5600	12.6	1.2	Same as #23
"Kick" occurred during exposure. Ion energies the same as #23.										
44	26	1.2	4	1	50	3	5000	18	1.2	Same as #23
Comments similar to #23. In spite of total voltage reduction ions originate from the same identical electrodes.										
44	37	0.8	2	1	0	0	4000	18	0.52	H_1^+ H_2^+ O^{++} Al^+
All ions originate from the 0.525 Mv and 0.39 Mv levels. These levels are 3" and 4 1/2" from the cathode (terminal negative) instead of 8" and 9 1/2" (see section 4.3.2 #3)										



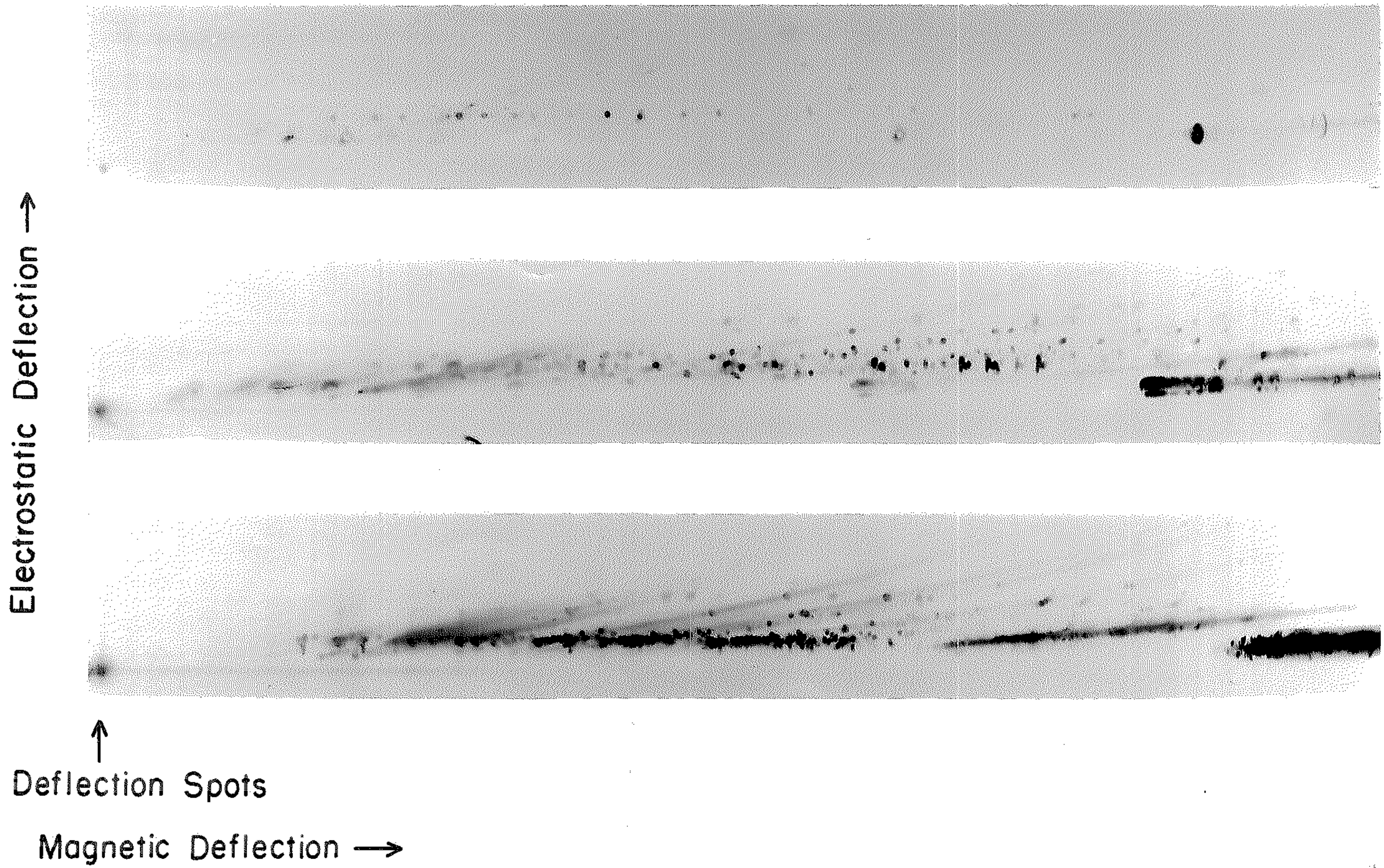
Electrostatic Deflection →

↑
Zero Deflection Spots

Magnetic Deflection →

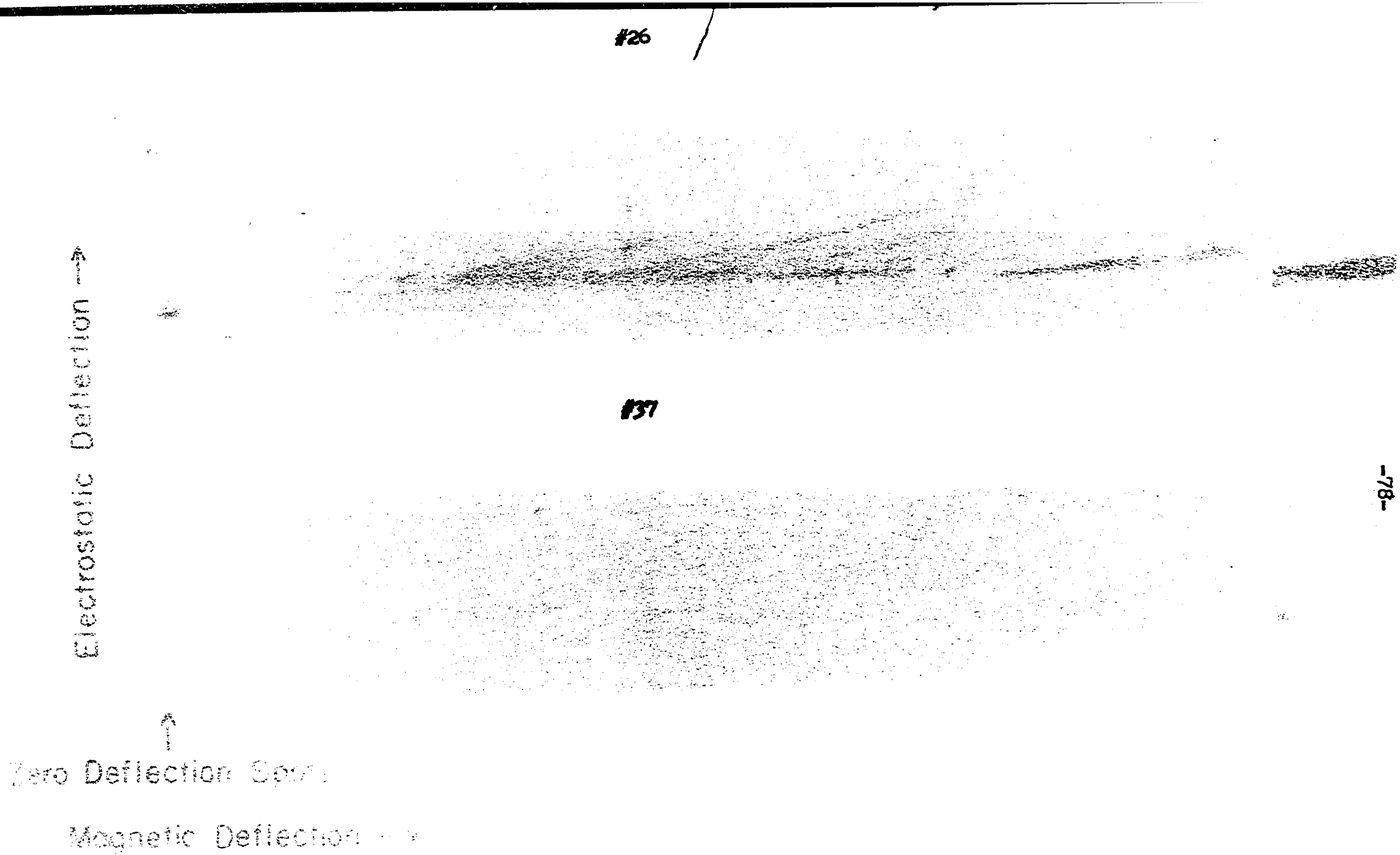
[illegible] Table VII

Figure [illegible]



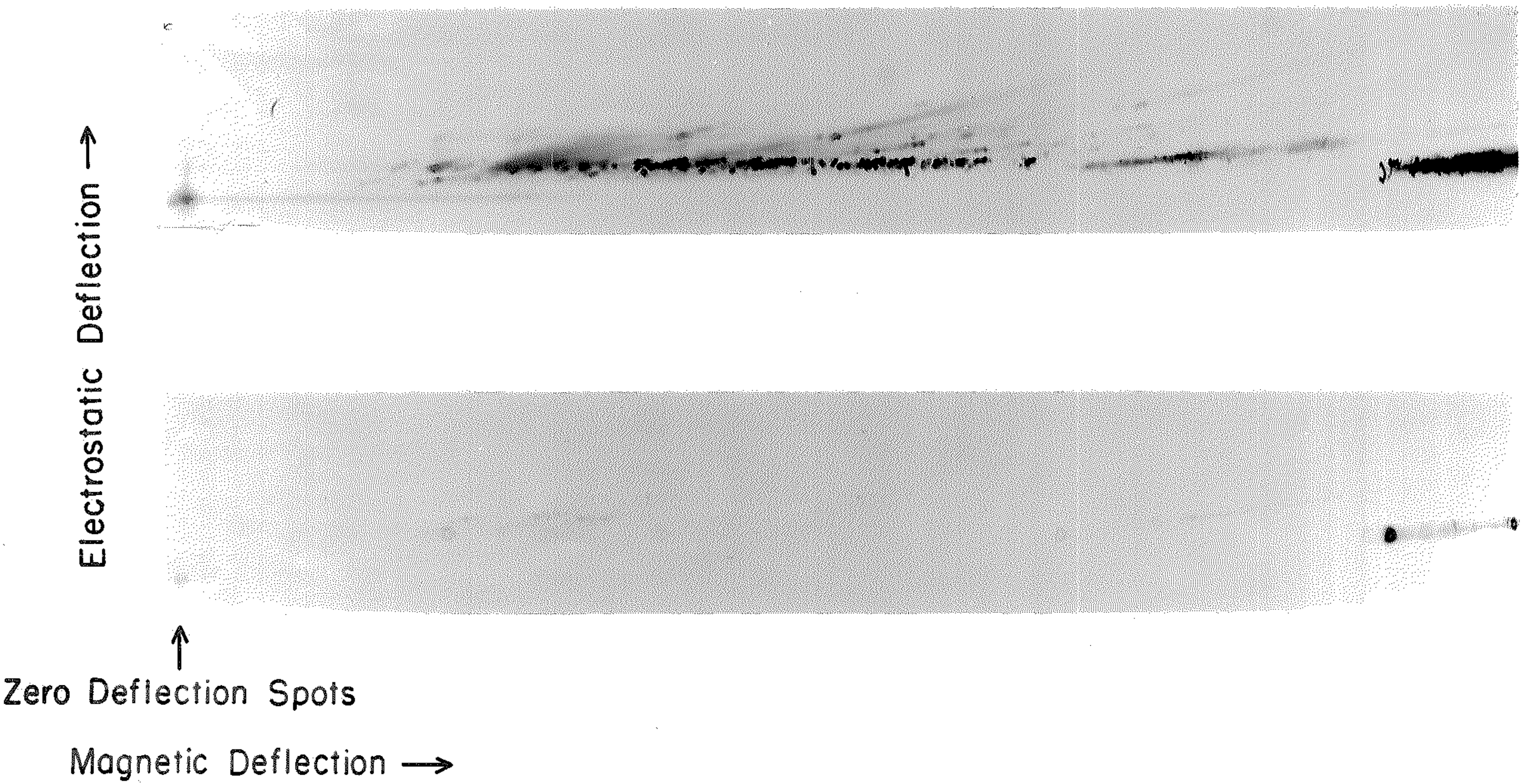
POSITIVE ION SPECTRA (see Table VIII)

Figure 44



POSITIV

Figure



POSITIVE ION SPECTRA (see Table VIII)

Figure 45

that discharges originated at the same identical sections as in case 4.3.3 (a) even though the voltage across the tube has been reduced proportionately to the reduction in tube length. This clearly indicates a dependence of the pulsed discharges on gradient rather than total voltage.

c. The generator voltage is applied across the 8" of tube length in the middle of the tube. Pulsed discharges are observed when the voltage is 0.6 Mv which implies that the pulsed discharges occur when the overall gradient across what might be called bad sections reaches the value of approximately 30 $\frac{\text{Kv}}{\text{cm}}$. No total voltage effect is again observed.

d. Finally the generator voltage is applied across 8" of tube length closest to the high voltage terminal, the remaining 16" of the tube being shorted out. Pulsed discharges start at 0.8 - 0.9 Mv and seem to originate from two sections (Fig. 45 - Exposure 37) 3" from the anode end of the unshorted tube length. Obviously the development of pulsed discharges in this group of sections is also gradient dependent and not voltage dependent, since no pulsed discharges originated from this section of the tube during experiments 4.3.3. (a).

4.4 Discussion and Summary of Experimental Results

a. The experimental data of sections 4.2 and 4.3 are qualitatively consistent. More specifically the following facts have been repeatedly observed.

1. Self-healing transients occur in acceleration tube No. 1 at a threshold voltage much lower than the breakdown or flashover voltage for which the tube is designed.

2. The threshold voltage is an increasing function of the residual gas pressure in the range of 10^{-5} to 2×10^{-4} mm Hg. and its absolute level depends on the "electric" history and age of the tube. Undoubtedly the variation of the voltage divider across the tube with time has also a decisive influence on the performance of the latter.

3. Self-healing transients originate from one or more sections of the tube which can be anywhere along its length.

4. These transient pulsed discharges are always associated with a rise of the residual gas pressure and a burst of electrons and positive ions and formation of negative ions. The number of negative ions formed is comparable to the number of positive ions as evidenced by the similar densities of the positive and negative ion spectra for equal exposure times. The pressure rise is 10^{-5} - 5×10^{-5} mm Hg per single pulsed discharge and consequently 3 or 4 consecutive transients result in a conducting tube. In this sense pulsed discharges are a severe limitation of the performance of the tube.

b. The quantitative correlation of the experimental results of section 4.3 reveals quite a few interesting properties of self-healing transients in acceleration tubes.

1. The oscillograms of pulsed discharges indicate that "kicks" are associated either with a single burst of electron current or a sequence of similar bursts. This may be interpreted in two ways. Either the electrons originate from one section whose voltage collapses and recovers in very short intervals of time or they are an image of discharges occuring at many sections and sequenced in time. Actually the first possibility

may be discarded because the electron and positive and negative ion spectra suggest that on the verge of an instability all charge carriers originate from one or two sections which are very close together while when a sizable discharge has developed charged particles originate from many more electrodes. Evidently then it is reasonable to assume that first a transient is initiated across one section. Then, as the discharge develops some of its debris are extracted by the electrostatic field and accelerated along the length of the tube. This debris presumably is capable to initiate discharges of other sections provided of course that the proper gradient conditions exist across the latter. Furthermore, if the picture described so far is correct, the time spacing between the current peaks of multiple pulsed discharges implies that the only debris which may be responsible for the transition of the discharge from one section to another is heavy ions. This is true because the time of flight of electrons is much shorter than the observed time intervals (App. A) while the time of flight of neutral particles is too long ($\sim$10 μsec/cm).

Actually the negative and positive ion spectra also suggest that both positive and negative ions are effective agents to initiate pulsed discharges provided that the proper gradient conditions have been established. This is true because regardless of terminal polarity the discharge has been found to propagate always from the "bad" section (which in this case happens to be 8" away from the high voltage end of the tube) towards the grounded end of the tube. The reason for this preferred direction of propagation has been found to be the fact that pulsed discharges are developed in the top 1/3 of the tube only when the overall gradient is 40 $\frac{kv}{cm}$ while in the middle 1/3 an overall gradient of 30 $\frac{kv}{cm}$ is adequate regardless of total voltage.

Viewed from another standpoint the previous discussion also indicates how the first pulsed discharge is initiated. It is observed that positive ions exist in the prebreakdown current of acceleration tubes. Some of these positive ions may impinge on the electrodes of the "bad" section, and, if the electric gradient is adequate, trigger a discharge. If such a localized discharge is to become self-sustained, it is evident that the secondary particles formed on account of the impingment of the positive ions on the electrodes must themselves be effective agents to produce positive ions. One possibility is that negative ions are created which proved as efficient as positive ions in promoting pulsed discharges.

2. The simultaneous gradual disappearance of both neutral particles and negative ions with rising residual gas pressure implies that the negative ion formation is inhibited by the increased gas pressure because if one assumes that the negative ions are formed but stripped of their electron by the increased gas density then one would expect to have neutral particles register on the film even without any negative ions. However this is not observed.

The other experimental evidence which supports the above conclusion is that the cross-section for stripping of negative ions is maximum when the latter have energies of many tens kev. Neutral particles which might be formed by stripping of negative ions would be very energetic and consequently as effective as the charged particles. Hence the residual gas pressure rise would have no effect on the performance of the tube. But this is not verified experimentally.

3. The electron and positive ion spectra suggest that the voltage across a section which undergoes a discharge may or may not collapse entirely.

The energy width or certain electron spectra appears constant with either constant or alternating densities for long periods of time. This indicates that either the charge of the electrodes between which the discharge occurs is being neutralized at a rate which can be sustained by the high voltage power supply or that the full development of the discharge is inhibited and the discharge temporarily quenched. In either case the voltage across the section does not collapse.

Conversely certain positive ion spectra taken during violent pulsed discharges show consistently pairs of ion spots which have energies differing by an amount equal to the voltage across one section. A possible interpretation of this phenomenon is that positive ions originating from one electrode at the beginning of the discharge appear to be coming from the next electrode because the voltage across this particular section collapsed entirely. Such an assumption is also supported by the fact that the charge collected at the anode during a single transient instability is of the same order of magnitude as the charge stored on two adjacent electrodes and furthermore such a transient is self-quenched.

4. The effective participation of the gas evolved during consecutive pulsed discharges in the development of a high voltage high vacuum discharge along the total length of the tube is self-evident. However a factor which has been overlooked and which is also evident is that the gas is formed at the surface of the electrodes and consequently there too may be an influential element of the development of instabilities.

CHAPTER FIVE

THE THEORY

5.1 General Remarks

From the review of the existing experimental evidence on vacuum breakdown and the explanations offered at various times by different people two facts are obvious:

a. Both self-healing and irreversible instabilities in a single or multiple vacuum gap are accompanied by an increase of the dark current and a rise of the residual gas pressure.

b. Theories on vacuum breakdown deal mostly with the mechanisms which initiate or sustain the rise of the dark current and consider the effects of the rising pressure as of secondary importance. More specifically these theories may be classified in two groups. The first group involves an exchange mechanism between positive and negative charge carriers which impinge on the cathode and anode and produce secondaries. The hypothesis usually made is that such a mechanism becomes critical at a certain voltage and gradient. The second group involves a combination of field and thermionic emission which set in at the breakdown voltage.

However, as it is previously pointed out, all measurements of secondary emission coefficients due to positive ion and electron bombardment over an extensive band of energies, fail to substantiate the validity of an exchange mechanism involving charge carriers.

Furthermore the breakdown gradients for gaps with large separations are orders of magnitude smaller than the gradients required for field emission and hence inadequate to justify a field emission initiating mechanism which would eventually develop into thermionic emission through conduction heating.

Consequently, either high vacuum electric instabilities result from phenomena involving primarily uncharged particles in cooperation with positive and negative ions and electrons or the modes of formation of the charge carriers suggested so far are not the appropriate ones.

Neutral particles which are in thermal equilibrium with the electrode materials are not effective agents to initiate an instability because if this were the case the instability would not be voltage or gradient dependent. However, such particles may assist the growth of an instability if their density is sufficiently high.

If the neutral particles have very high velocities then evidently the mode of their formation is some attachment or detachment process that positive or negative ions undergo during their acceleration across the vacuum gap, respectively. Consequently in order to explain the phenomenon of vacuum breakdown by means of energetic neutral particles one has to develop modes of formation of charge carriers with yields far above the ones resulting from secondary emission.

On the other hand if vacuum breakdown is initiated by charge carriers and the suggested theories have failed to reveal the appropriate modes of formation of positive and negative ions and electrons, then the explanation of vacuum instabilities that naturally suggests itself is again to investigate additional modes of formation of charge carriers.

In what follows a hypothesis will be outlined which introduces a new mechanism for the creation of negative ions, considers the residual gas pressure rise as an essential element of electric instabilities in vacuum and seems to account in a coherent manner for many, if not all, of the experimental data on high vacuum insulation.

Before presenting the hypothesis in detail the origin of electrons and positive ions in the prebreakdown current and the ejection of neutral particles from the cathode will be discussed.

5.2 Prebreakdown Electronic and Positive Ion Currents

Electrons and positive ions are always detected at the electrodes of a vacuum-insulated gap even when the voltage is far below its instability threshold value while negative ions are not.

One can postulate that the minute prebreakdown electron current is due to background cosmic radiation and stray radioactivity. Such ionizing radiation arrives randomly at the electrodes and results predominantly in the formation of secondary electrons. Some positive ions and neutral particles are simultaneously produced and possibly a few negative ions, even though the number of the latter must be comparatively small.

When voltage is applied between cathode and anode, the electrons and the positive ions are accelerated and as they impinge on the electrodes they produce secondary positive ions and electrons respectively. This process is externally sustained and as was previously stated cannot become critical under any voltage-gradient conditions. Consequently a steady state is reached in which the absolute current is observed to depend on the applied voltage and to consist of about 1000 times more electrons than positive ions.[9] [16]

In addition electrons may be released from the electrodes by high field emission. Such field emitted electrons are especially conspicuous from rough surfaces contaminated by low work function materials.

The above mechanisms for the origin of prebreakdown current are supported by the following experimental evidence:

The magnetic spectra of the electron and positive ion currents (Figs. 30, 31 and 40) clearly indicate that the bulk of these charged particles originate at the electrodes rather than in the gas volume of the acceleration tube. This is also to be expected since in high vacuum and at the energy range above several tens of Kev, the collision ionization cross-section by electrons is inadequate to account for the observed currents.

The relatively small number of positive ions shows that they are due primarily to electron bombardment since the probability for positive ion formation under electron bombardment[7] is of the same order of magnitude as the ratio of positive to negative prebreakdown currents. Viewed from another standpoint the latter ratio also suggests that the electrons are not solely due to positive ion bombardment since the secondary electron emission coefficient under positive ion bombardment (15) (35) is of the order of 10:1.

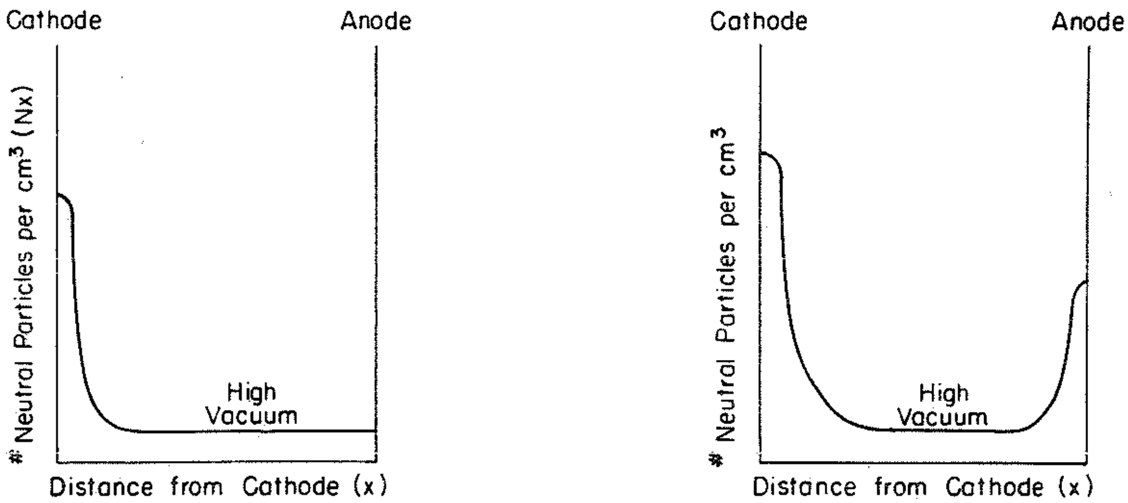
5.3 The Space-Mass Effect

In addition to the secondary emission of charged particles, bombardment of metallic surfaces by energetic positive ions results in the emission of neutral atoms and molecules[39] of the electrode material and of gaseous matter adsorbed or chemisorbed on its surface. This process is called "sputtering".

Different experimenters (40) (41) (42) have investigated the phenomenon with ions of energies ranging from 0 to 10 kev and found that the number of particles sputtered off the bombarded surface is directly proportional to the energy of the impinging positive ion. The constant of proportionality varies from metal to metal and is different for different sputtering ions. However, on the average, there is one sputtered particle per sputtering ion of a few hundred eV of energy.

The assumption is made here that the direct proportionality between the number of sputtered particles and the energy of the sputtering ions holds true even if the energy of the latter is up to several hundred kev. Accordingly, many neutral particles are given off from the spot hit by a highly energetic positive ion. These particles are emitted from a small area at the same instant and consequently produce a local pressure much higher than the vacuum pressure within a region of many molecular diameters from the emitting point. Thus the sputtered particles diffuse away from the surface with chaotic motion before they have a chance to reach the high vacuum region where no collisions can take place. This phenomenon might be called space-mass effect.

Figure 46 is a sketch of a possible matter density distribution profile across a vacuum gap connected to a high voltage source. This profile indicates that close to the cathode diffusion conditions exist for any neutral particles sputtered by the impinging energetic positive ions. The thickness of the relatively high density layer near the cathode depends of course on the voltage across the gap.

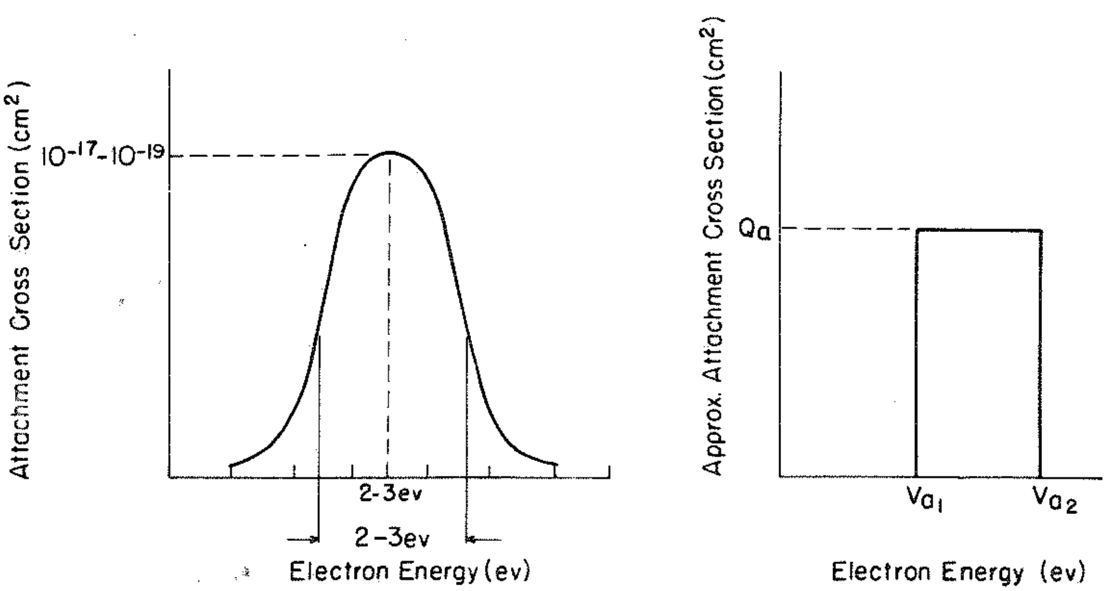


Before instability is initiated
(a)

During growth of instability
(b)

NEUTRAL PARTICLE DENSITY PROFILE

Figure 46



(a)

(b)

ELECTRON ATTACHMENT CROSS SECTION FOR NEGATIVE ION FORMATION

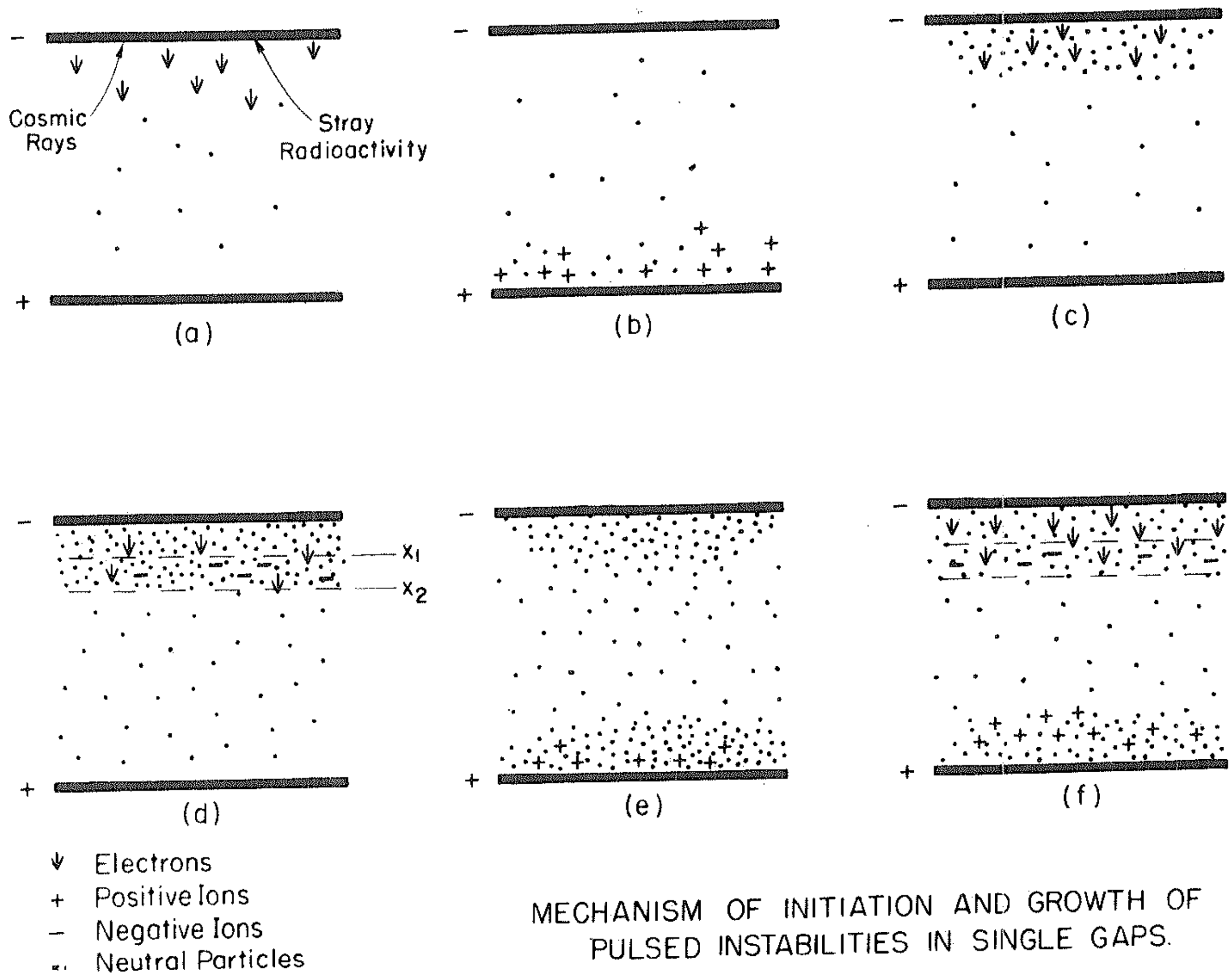
Figure 48

The fact that neutral particles are formed in electrically stressed vacuum gaps is suggested by many experimental observations[9] [19].

5.4 Mechanism of Initiation and Growth of Electric Instabilities in Single Gaps

It is postulated here that the initiation and growth of electric instabilities in a single gap (Fig. 1) is due to an exchange mechanism between positive and negative ions which impinge on the cathode and anode respectively. The negative ions are formed by electron attachment to neutral particles in the vicinity of the cathode. The mechanism is illustrated by the sequence of sketches of Fig. 47.

Consider a vacuum gap (Fig. 47a) whose separation is large enough so that the breakdown gradient is inadequate to justify consideration of the field emission mechanism. Electrons are formed at the cathode by the arrival of extraneous ionizing agents. These electrons are accelerated to the anode where on impingment produce secondary positive ions (Fig. 47 b). The latter are accelerated to the cathode and cause sputtering of neutral particles (section 5.3) and ejection of secondary electrons (Fig. 47 c). The secondary electrons move much faster than the neutral particles which diffuse away from the cathode with an average speed of the order of 10^5 cm/sec. However, if new positive ions arrive at the same general area of the cathode before the neutrals have a chance to diffuse very far, their secondary electrons will be traveling through the gas produced by the first positive ions. These electrons may then be attached to the neutral gas particles and give rise to negative ions (Fig. 47 d). However, in order for the attachment process to occur, the electrons must first be accelerated up to a resonance energy or, for a given gradient at the cathode, travel a definite distance. This is ill-



MECHANISM OF INITIATION AND GROWTH OF PULSED INSTABILITIES IN SINGLE GAPS.

Figure 47

ustrated by the resonance character of the attachment cross-section (33) (39) for negative ion formation (Fig. 48 a) versus electron energy, the peak, width and resonance energy of which depend on the specific negative ion formed.

The negative ions thus produced are accelerated to the anode where on impingment they sputter neutral particles and eject positive ions (Fig. 47 e). The positive ions are accelerated back to the cathode and the cycle is repeated (Fig. 47 f).

The process may become self-sustained if:

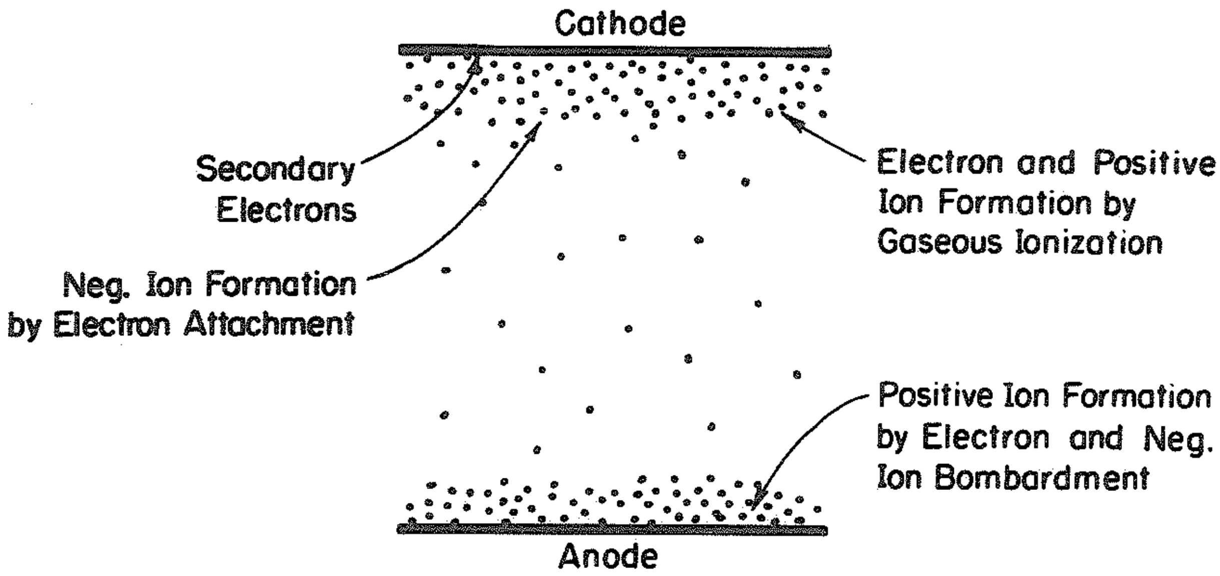
$$P_- P_+ > 1 \qquad (5.4.1)$$

where P_- = number of negative ions per unit area per positive ion

P_+ = number of positive ions per unit area per negative ion.

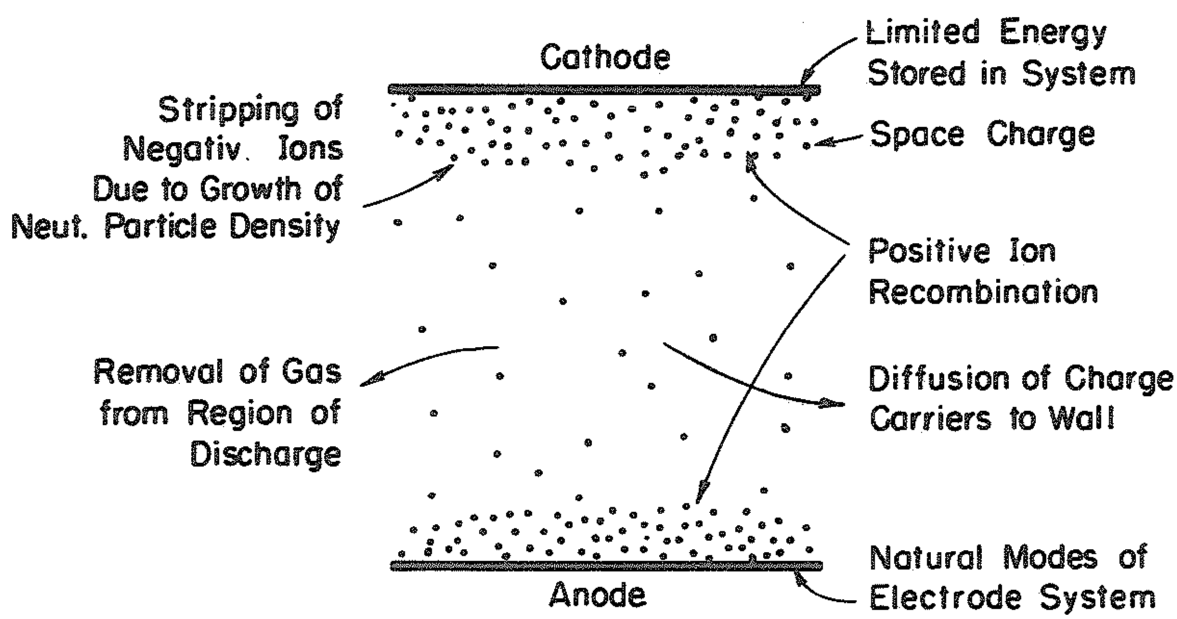
Condition (5.4.1) is the criterion for the initiation of an instability in vacuum gaps with large electrode separations. However, once the instability has been initiated it will keep growing with an increasing rate because other mechanisms start to assist it (Fig. 49 a). For instance the thickness and density of the gas layer in the vicinity of the cathode increases as the number of positive ions rises. Thus the secondary electrons may acquire enough energy, (10 ev or more), within this gas layer, to ionize the neutral particles and increase the number of ion pairs. The positive ions coming from the cathode pass also through the same gas layer and may ionize the gas molecules and increase the number of ion pairs.

Consequently the discharge may grow to the extent that all the electric charge stored in the electrode system is neutralized and the voltage across the gap collapses. This is vacuum breakdown.



AGENTS PROMOTING GROWTH OF INSTABILITIES

(a)



AGENTS IMPEDING GROWTH OF INSTABILITIES

(b)

Figure 49

Vacuum breakdown however is not the inevitable end point of a growing instability in a vacuum gap. This is due to the fact that the very growth of the instability introduces mechanisms which tend to prevent its further development and for that matter may quench it entirely. (Fig. 49 b) For instance the negative ions may be stripped of their electrons as they pass through the gas layer or the charge carriers may diffuse away from the channel in which the positive-negative ion exchange occurs, etc. Evidently then if the mechanisms which hinder the growth of the discharge prevail before the entire energy stored in the electrode system has been consumed, the instability will be quenched. This self-healing instability is the "kicking" effect.

5.5 Discussion of Coefficients P_+ and P_-

The effects of bombardment of metal surfaces by energetic negative ions have never been investigated. Consequently there is complete lack of experimental data on the coefficient P_+. However, it is reasonable to assume that, on impingment on the anode, the energetic negative ions sputter neutral particles and positive ions. This is substantiated by the fact that the negative ions are stripped of their electrons as soon as they hit the anode, since the work function of all metals is higher than the electron affinity of all negative ions[33] [39], and furthermore the neutral particles resulting therefrom are energetic enough to ionize some of the molecules which are subsequently ejected. Hence P_+ is probably of the order of unity or larger. (see also section 4.4)

Evidently the coefficient P_- is of the order of unity or smaller when an instability is initiated.

The number of negative ions formed by electron attachment is given by the formula

$$P_- = \int_0^{\infty} n_e \, Q \, N_x \, d\,x \qquad (5.5.1)$$

where n_e = number of electrons per unit area per positive ion

Q = attachment cross-section for negative ion formation

N_x = neutral particle density at the distance x from the cathode

Integral (5.5.1) is not easy to interpret qualitatively unless a density distribution function is assumed and the attachment cross-section is expressed analytically.

It is certain that the neutral particle density decreases very fast with distance from the cathode. Consequently a plausible distribution function may be:

$$N_x = \frac{kV}{x^2} \qquad (5.5.2)$$

where k = constant (see App. B)

V = positive ion energy or voltage across the gap

The attachment cross-section may be approximated by a square pulse (Fig. 48 b) so that:

$$Q = Q_a \left[u\,(V - V_{a1}) - u\,(V - V_{a2}) \right] \qquad (5.5.3)$$

where u(V) = unit step

Thus integral (5.5.1) becomes

$$P_- = n_e \, Q_a \int_{x_1}^{x_2} \frac{kV}{x^2} \left[u\,(x-x_1) - u\,(x-x_2) \right] dx =$$

$$= n_e \, Q_a \; k \, \frac{V_{a1} - V_{a2}}{V_{a1} \times V_{a2}} \left[V \times E \right] \qquad (5.5.4)$$

where $x_1 = \frac{V_{a1}}{E}$ and $x_2 = \frac{V_{a2}}{E}$

E = gradient at the cathode

The meaning of equation (5.5.4) is that when the voltage across the gap is high, a low gradient is adequate to render the coefficient P_- comparable to unity while if the voltage is low, a higher gradient is necessary.

5.6 Experimental Evidence Supporting Suggested Mechanism

The present research project has not investigated instabilities in single gaps hence the experimental results reported in Chapter Four cannot be immediately correlated with the mechanism suggested in section 5.4. However the literature is full of experimental data which seem to be consistent with many facets of the proposed mechanism.

1. The suggested mechanism of initiation of instabilities depends on voltage and gradient in a way similar to the one commonly accepted[17]. (See also App. B)

2. The mechanism is consistent with the experimental fact that an instability may or may not lead to gap breakdown[10][18].

3. The time constant of the initial growth of the suggested discharge mechanism is proportional to the time of flight of ions from cathode to anode and back (App. C). The latter is proportional to the gap separation and inversely proportional to the voltage across the gap. Actually such a dependence of the time constant of the initial growth of instabilities has been experimentally established[18].

4. The effectiveness of negative ions to yield secondary positive ions may be concluded from Chiles'[43] experiments who reports that the luminosity at the anode precedes that of the cathode. The time lags that he reports are equivalent to the time of flight of ions across the gap.

5. The suggested mechanism depends on the materials of the cathode, its surface condition and its "electric" history through the coefficient k

(equation 5.5.2). Such a dependence has been repeatedly verified[24].

5.7 Defects of Suggested Mechanism

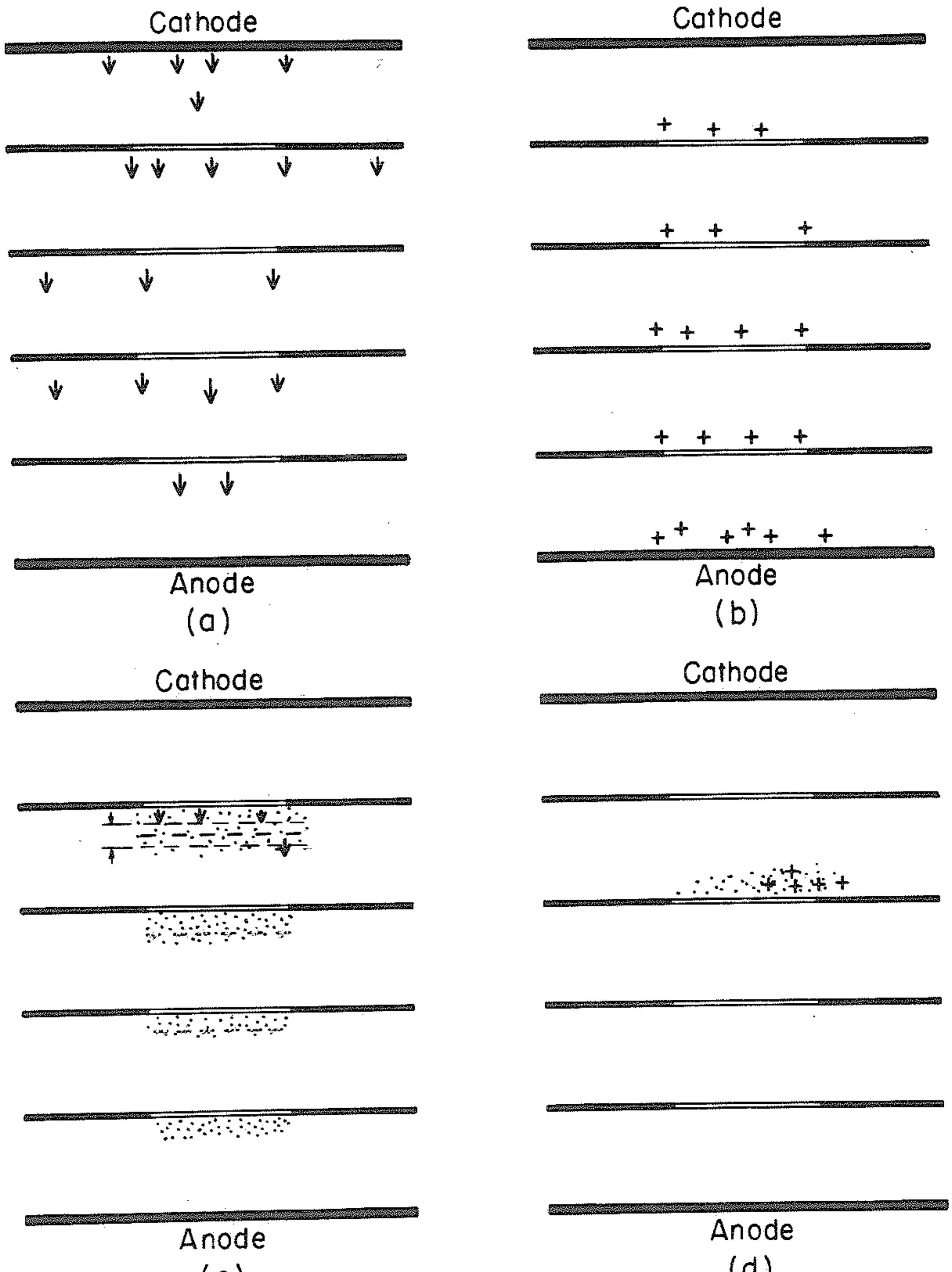
1. The suggested mechanism does not explicitly take into account the dependence of the threshold voltage for appearance of instabilities on the value of the high vacuum pressure.

2. The derivation of the dependence of the coefficient P_- on voltage and gradient is based on the arbitrary assumption that the density distribution varies as $1/x^2$. The reasonable result does not necessarily mean that the assumption is true.

5.8 Mechanism of Initiation and Growth of Pulsed Discharges in Acceleration Tubes

It is postulated here that the mechanism of initiation and growth of pulsed discharges in acceleration tubes is in many respects similar to the one presented in section 5.4. The mechanism is illustrated by the series of sketches of Fig. 50.

Electrons ejected by the arrival of extraneous ionizing agents (Fig. 50 a) are accelerated and on impingement on the electrodes induce the emission of secondary positive ions (Fig. 50 b). The positive ions bombard the electrodes and cause sputtering of neutral particles and secondary electrons (Fig. 50 c). Since all sections and electrodes cannot be "electrically" identical, negative ions may be formed by electron attachment in the vicinity of one of the electrodes (Fig. 50 c) if the proper conditions are satisfied (see section 5.4). Many of these negative ions are accelerated along the tube hole but some of them may impinge on the electrode adjacent to the one from which they originate and thus initiate a discharge of the type described in section 5.4. This discharge may or may not lead to a complete collapse of the voltage of



INITIATION AND GROWTH OF PULSED DISCHARGES
IN MULTIPLE GAPS
Figure 50

the specific section in which it occurs. However its electrically charged debris is extracted from it and accelerated along the hole of the tube and may assist the initiation and growth of similar discharges of other sections of the tube which are on the verge of an instability. The discharging sections need not be adjacent to each other.

The condition for the initiation of an instability in an acceleration tube is qualitatively similar to condition 5.4.1. However in this case the positive ions which induce the high density gas layer at the electrodes (Fig. 50 b) have energies ranging from that of one section to the one corresponding to the full voltage across the tube. Consequently one would expect pulsed discharges in acceleration tubes to occur at much lower gradients than in single gaps.

5.9 Experimental Evidence Supporting Mechanism of Section 5.8

The following experimental results reported in Chapter Four seem to be consistent with the suggested mechanism for initiation of pulsed discharges in acceleration tubes. (See particularly section 4.4)

1. Pulsed discharges are observed in acceleration tubes at voltages which are lower than the breakdown voltage.

2. Positive ions do originate from the electrodes.

3. Negative ions are formed only after a threshold voltage or overall gradient is reached and originate from the edges of the hole of the electrodes.

4. Negative ions are observed only when pulsed discharges are detected.

5. Pulsed discharges do originate from one or more sections of the tube which are not necessarily adjacent to each other.

6. Pulsed discharges originating from many sections are not simultaneous in time and the time intervals between consecutive pulses is of the same

order of magnitude as the time of flight of ions through few or many sections of the tube (Fig. A2). This time spacing of the pulses is much larger than the time of flight of the electrons (Fig. A1) and much smaller than the time of flight of the relatively slow neutral particles.

7. Pulsed discharges are self-healing. This may be due to either a complete collapse of the voltage of the section or sections which undergo the discharge or hinderance of the growth of the discharge by inhibiting mechanisms indicated in Figure A9 b including the fact that many charge carriers are drawn away from the region of the discharge by the electrostatic field.

However all these experimental results refer to one acceleration tube only and consequently do not represent a definite proof of the suggested mechanism.

Also it should be emphasized that the dependence of the threshold voltage for initiation of instabilities on the high vacuum pressure has not been explicitly considered.

A plausible explanation may be that when the residual gas pressure is raised positive ions are subject to an increased number of scattering collisions. Consequently the probability of having an adequate number of positive ions impinging on the same general area of the cathode, where the instability is initiated, is smaller. Hence a larger total number of positive ions or a higher voltage is necessary in order for a pulsed discharge to occur.

CHAPTER SIX

SUMMARY AND RECOMMENDATIONS

6.1 Summary

An electrostatic and magnetic analyzer has been designed and constructed. The instrument includes:

a. A magnetic field and a camera for electron energy spectral studies. The useful deflection angle of the magnetic field is from 60° to 120° on a strip of film 2" high. Consequently the resolution varies from 20 $\frac{kev}{cm}$ to 600 $\frac{kev}{cm}$ when the electron energy range is from 0-100 kev to 1 - 3 Mev respectively.

b. A system of magnetic and electrostatic fields and a camera for mass and energy spectral investigations of heavy ions. The useful area of the film is 50 cm for magnetic deflection by 5 cm for electrostatic deflection. The magnetic resolution varies from 0 to 100 $\frac{kev}{cm}$ as the mass number-charge ratio times the ion energy product varies from ∞ to 2 Mev. The electrostatic resolution is also highly nonlinear and has an average value of 30 $\frac{kv}{mm}$ in the energy range of 0.5 to 2 Mev.

The power supply for the electrostatic and magnetic analyzer and various other control circuits have been built.

Two acceleration tubes have been assembled. One is a commercial type and the other is a symmetric structure with respect to its mid-plane. Both ends of the second tube are easily accessible to permit the replacement of the anode and cathode materials.

Only one tube has been tested.

The energy spectrum of the electron current has been investigated and its time behavior established with total voltage across the tube and residual gas pressure as the variable parameters. It is found that during steady state electrons are formed at or near the electrodes and that self-healing instabilities are associated with pulsed discharges localized between one or more pairs of adjacent electrodes at various locations along the length of the tube. Pulsed discharges are always accompanied by a momentary rise of the residual gas pressure which may eventually result in a stable high voltage high vacuum discharge.

The energy and mass spectra of the negative ion current have been similarly investigated. It is found that negative ions are formed only during or on the verge of occurence of transient instabilities. These ions originate from the vicinity of the same electrodes from which the electron pulses are extracted, and are H_1^-, O_1^-, $C\ell^-$ and some others. No negative heavy clumps of matter singly or multiply charged have been detected. However along with the negative ions some neutral particles have been recorded which seem to result from stripping of the electron charge of the former.

The energy and mass spectra of the positive ion current has been studied with voltage, residual gas pressure and gradient as the variable parameters. It is observed that positive ions of a great variety of mass numbers exist always in the dark current of acceleration tubes and originate from the vicinity of the electrodes. During self-healing transients positive ions were predominantly formed in the vicinity of the tube sections which undergo localized discharges. No positive heavy clumps of matter singly or multiply charged have been found. However along with the positive ions some neutral particles have been detected which probably result from electron attachment or charge exchange processes that the former are subject to during their acceleration.

A new mechanism for the initiation and growth of instabilities in single or multiple vacuum gaps is suggested which seems to be consistent with both prior experimental data and the results of the present research. The mechanism amounts to an exchange of positive ions between cathode and anode which becomes critical when the voltage-gradient product is greater than a constant, characteristic of electrode materials, their surface conditions and their "electric" history. The negative ions are assumed to be formed by electron attachment to neutral particles produced in the vicinity of the cathode by positive ion sputtering.

6.3 Recommendations

The experimental results established are not conclusive in the sense that they are pertinent to only one acceleration tube. This is a severe limitation on the validity of the interpretations advanced particularly in view of the fact that high vacuum electrical instabilities are not well defined phenomena but statistical in nature. Consequently it is recommended that the following experiments be performed in order to emphasize or discount the importance of the data observed during this investigation.

1. Examine in more detail the dependence of pulsed discharges on gradient by continuing the short circuit tests with acceleration tube No. 1.

2. Increase purposely the gradient across combinations of pairs of electrodes at various locations of the length of the tube. Thus the ion spectra will indicate the sequence of propagation of the discharges and the oscillograms will definitely show the mechanism which promotes the pulsed discharges from one section to another.

3. Improve the instrumentation for the detection of changes of the indications of the generating voltmeter and pressure gauge because the time constant of the present time constant of the panel instruments used is too long.

4. Repeat the entire series of tests with acceleration tube No. 2.

5. Use different cathode and anode materials. If the mechanism for the propagation of discharges occurring far from the ends of the tube is correct then the cathode and anode materials should not influence the performance of the tube.

6. Investigate the initial growth of pulsed discharges more accurately. The Tektronix oscilloscope is not fast enough for this purpose.

7. Modify edges of electrode holes in a new tube in an effort to investigate the effect of local gradient on the development of pulsed discharges.

8. Measure absolute levels of positive and negative ion currents. Scintillation counting might be used to advantage.

9. Measure rate of sputtering under high energy positive ion bombardment.

10. Measure secondary positive ion formation under negative ion bombardment.

11. Investigate possibilities to avoid self-charging of films which proved to be a major difficulty of this investigation.

These are some of the tests and improvements that may lead to a better understanding of the fundamental electrical processes in high vacuum. If the evidence continues to be consistent with the suggested initiation mechanism then obviously the theoretical presentation should be improved. Time dependent diffusion theory may be used to great advantage.

Finally the problem of total breakdown by flashover of acceleration tubes should be reconsidered. It is questionable whether actually long acceleration tubes ever do break down because it has been observed that repetitive "kicking" always stabilizes to a high vacuum, high voltage discharge.

APPENDIX A

TIME OF FLIGHT OF ELECTRONS AND HEAVY IONS THROUGH ACCELERATION TUBES

a. Electrons

The time of flight of electrons in a uniform electric field E may be calculated from the momentum equation

$$\frac{dp_e}{dt} = eE \qquad \text{A1}$$

where p_e = electron momentum

e = electron charge

E = electric field gradient

Integrating A1 it is found that

$$p_e = e\,E\,t \qquad \text{A2}$$

if the initial momentum is assumed equal to zero. The electron momentum p_e is in general

$$p_e = \frac{1}{c}\left[e^2 E^2 L^2 + 2m_o c^2 e\,E\,L\right]^{1/2} \qquad \text{A3}$$

where L = distance traveled by electron

Consequently the time t required for an electron to travel a distance L is

$$t = \frac{1}{c}\left[L^2 \times \frac{2m_o c^2}{eE} L\right]^{1/2} \qquad \text{A5}$$

For an electric field gradient $E = 30 \frac{kv}{cm}$ equation A5 becomes

$$t = 3.33 \times 10^{-10} \left[L^2 + 34L\right]^{1/2} \qquad \text{A6}$$

where L = distance in cm and t = time in sec.

Equation (A5) is plotted in Fig. A1

b. Heavy Ions

The time of flight of heavy ions in a uniform electric field may be evaluated as follows:

$$\frac{d}{dt} (m_i v_i) = eE \qquad A6$$

Integrating equation A6 twice it is found that

$$m_i L_i = \frac{e\ E\ t^2}{2} \qquad A7$$

or

$$t = L_i \left[\frac{2m_i}{e} \quad \frac{1}{V_i} \right]^{1/2} \qquad A8$$

where t = ion time of flight

L_i = distance traveled by ion

V_i = potential difference across length L_i

If the potential difference across a distance of 2 cm is 60 kv and the distance $L_i = \eta$ x (sections of 2 cm separation) the equation A8 becomes

$$t = 1.2 \times 10^{-8} \quad \left[\eta\ A \right]^{1/2} \qquad A9$$

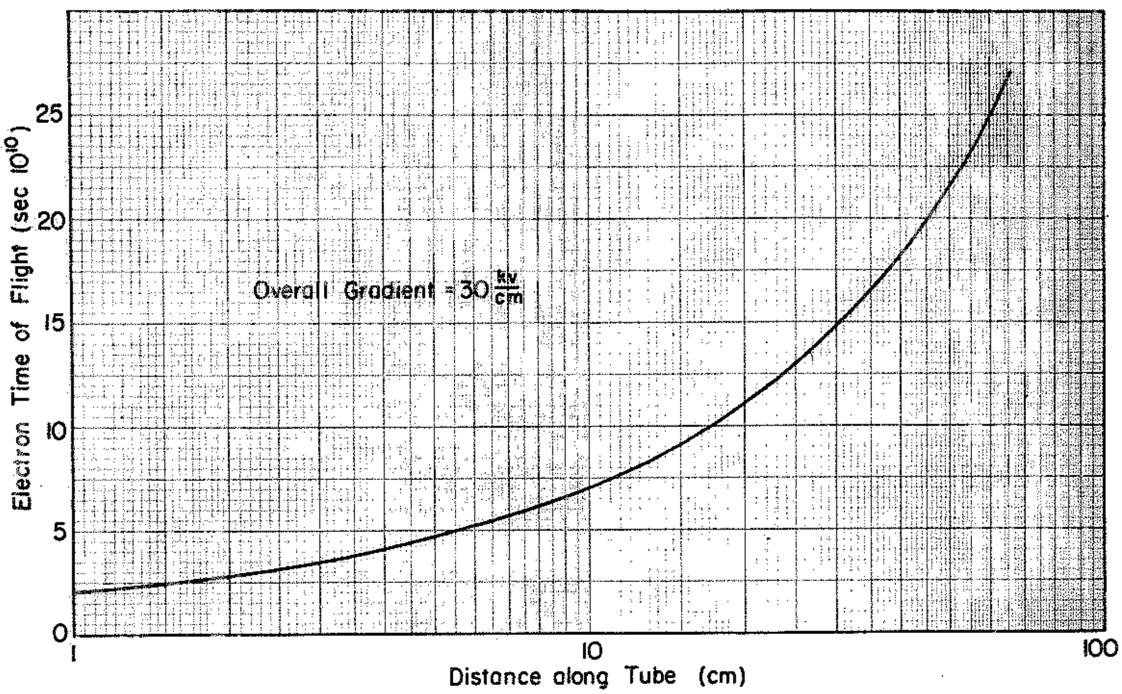
where

t = time in sec.

A = mass number to charge ratio

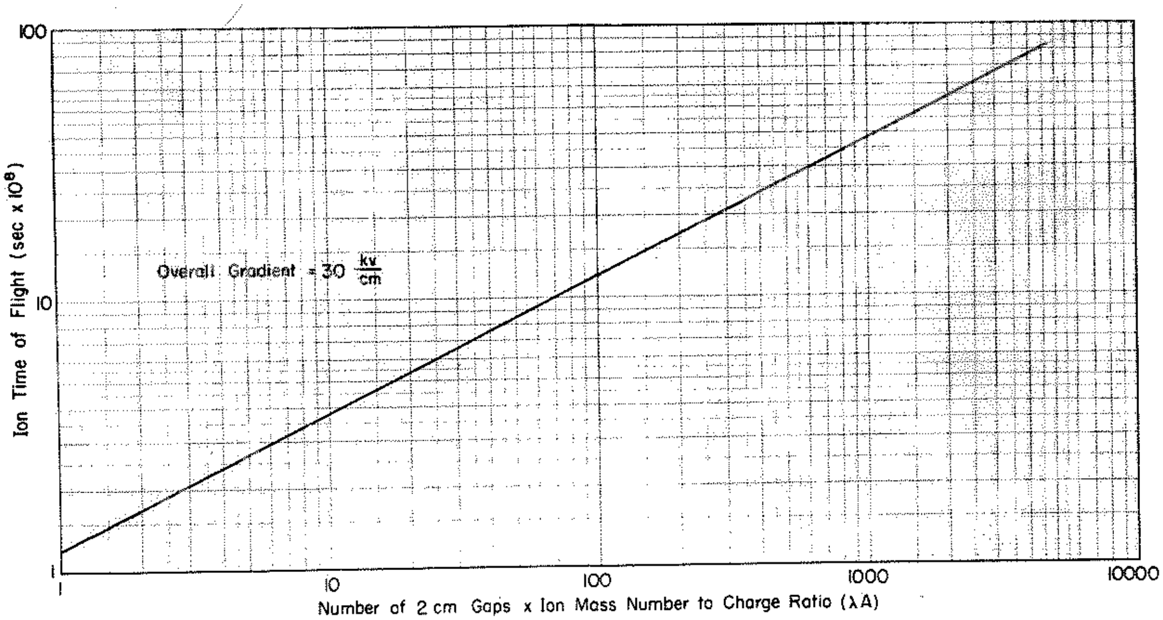
η = number of 2 cm sections traveled by ion

Equation (A9) is plotted in Fig. A2



ELECTRON TIME OF FLIGHT

Figure A1



ION TIME OF FLIGHT

Figure A2

APPENDIX B

NUMERICAL EVALUATION OF CRITERION FOR INITIATION OF INSTABILITIES

It is interesting to investigate whether the arbitrary assumption about the neutral particle density distribution of section 5.6 leads to reasonable quantitative results.

Assume that the number of neutral particles sputtered per positive ion are

$$N_n = k_1 V \qquad \text{B1}$$

where N_n = neutral particles per positive ion

k_1 = neutral particles per ev = $\frac{1}{500}$

V = positive ion energy (ev)

If the sputtered molecules are ejected instantaneously from a small cubicle which is p molecular diameters deep and whose sides are q molecular diameters long (Fig. B1 a) then a virtual cathode is formed p molecular diameters away from the real cathode (Fig. B1 b). Consequently, if the neutral particle density function is assumed as

$$N_x = \frac{kV}{x^2} \qquad \text{B2}$$

conservation of the ejected particles requires that

$$N_n = k_1 V = q^2 \frac{\pi}{4} d^2 \int_{pd}^{\infty} \frac{kV}{x^2} \, dx \qquad \text{B3}$$

or

$$k = \frac{4}{\pi} \frac{p}{q^2 d} k_1 \qquad \text{B4}$$

where d = molecular diameter.

Thus the criterion for initiation of instabilities (inequality (5.4.1) and equation (5.5.4)) becomes

$$V \times E \geq \frac{\pi q^2 d \, V_{a1} V_{a2}}{4 P_+ n_e Q_a p \, k_1 \, (V_{a2} - V_{a1})} \qquad \text{B5}$$

Assume that:

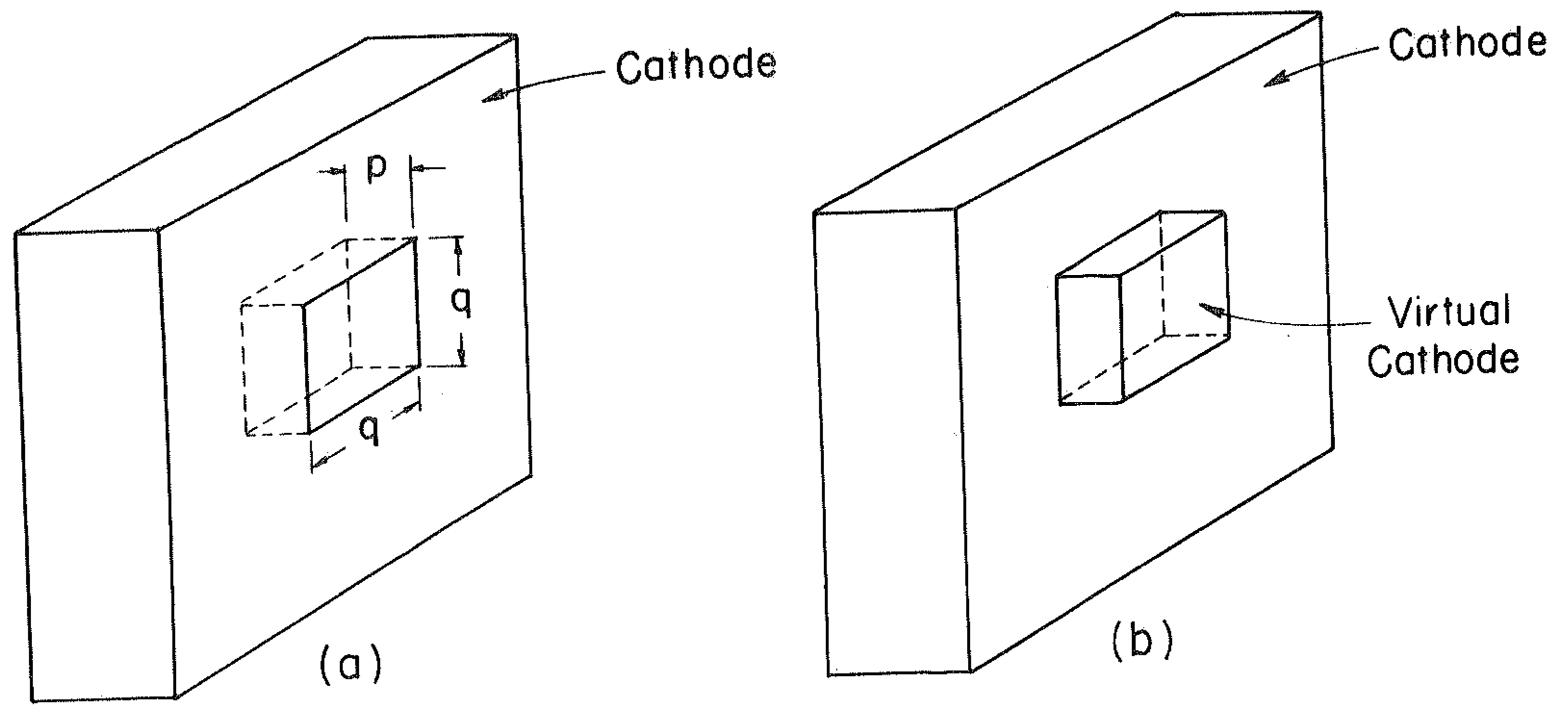
$q = 2p \qquad d = 10^{-8}\,\text{cm} \qquad V_{a1} = 1\ \text{ev} \qquad V_{a2} = 3\ \text{ev}$

$P_{+} = 5 \qquad n_e = 20 \qquad Q_a = 10^{-18}\ \text{cm}^2 \qquad k_1 = \frac{1}{500}\ (\text{ev})^{-1}$

Replacing these values in equation (B5), the instability criterion becomes

$$V \times E \geqslant \frac{\pi \times 4 \times 10^{-8} \times 3 \times 500}{4 \times 5 \times 20 \times 10^{-18} \times (3 - 1)} = 2.35 \times 10^{11}\ \frac{v^2}{\text{cm}} \qquad \text{B6}$$

This value of the voltage-gradient product is of the same order of magnitude as the one established by Trump and Van de Graaff(7) (Fig. 3).



CREATION OF VIRTUAL CATHODE BY SPUTTERING

Figure BI

APPENDIX C

INITIAL GROWTH OF POSITIVE AND NEGATIVE ION CURRENTS DURING AN INSTABILITY IN SINGLE GAPS

Assume that at time $t = 0$ the positive ion current leaving the anode is I_p. If T_p is the time of flight of positive ions from cathode to anode then at time $t = T_p$, $P_- I_p$ negative ions per second will be formed at the cathode by electron attachment to neutral particles. At time $t = 2\,T_p$ there will be $P_+ P_- I_p$ positive ions per second ejected from the cathode, etc.

Consequently if $P_+ P_- = f$ then at any instant of time t the rate of rise of the positive ion current is

$$\frac{dI_p}{dt} = \frac{(f-1)}{2T_p}\; I_p \qquad \text{C1}$$

or

$$I_p = I_{po}\; e^{\frac{(f-1)t}{2T_p}} \qquad \text{C2}$$

A similar expression can be easily derived for the negative ion current.

Evidently, the time constant of the initial growth of the positive and negative ion currents is

$$t = \frac{2T_p}{f-1} \qquad \text{C3}$$

As it is shown in Appendix A, T_p is equal to

$$T_p = d\left[\frac{2m}{e}\;\frac{1}{V}\right]^{1/2}$$

where d = gap separation

V = voltage across the gap

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BIOGRAPHICAL NOTE

Elias P. Gyftopoulos was born in Athens, Greece on July 4, 1927. He received his Diploma in Mechanical and Electrical Engineering from the Technical University of Athens in 1953. He served in the Royal Hellenic Navy from 1948 until 1951. In September 1953 he joined the staff of the High Voltage Research Laboratory of M.I.T. as a research assistant and became an Instructor in Electrical Engineering in 1954. He has acted as consultant to various industrial concerns and he is the author of an article on "Nuclear Power Plant Transfer Functions". He is a member of the American Nuclear Society and Tau Beta Pie.

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