AN EXPERIMENTAL STUDY OF COLLECTIVE EFFECT ACCELERATION OF ELECTRONS IN ELECTRON BEAMS.

A. Coutu

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An experimental study of collective effect acceleration of electrons in electron beams.

by Alain Coutu

Abstract

A discharge device was built to examine experimentally the acceleration by a collective space-charge effect in electron beams. The apparatus comprises a cathode at one end of a 100 cm long evacuated copper tube, a 7.9 cm long lucite tube in series with a velocity selector on the other end, and a 100 cm solenoid around the copper tube which produces a static magnetic field uniform through the grounded tube, but rapidly falling off towards the cathode and the lucite tubing. The emitted electrons form a cylindrical beam advancing in a screwlike manner towards the lucite tube. The decreasing flux there decelerates the angular velocity of the electrons; the absence of image-charges causes the development of a potential barrier which reduces the axial velocity of the arriving electrons. As a result of this simultaneous deceleration of angular and axial velocities the beam is reflected, and the electrons beyond the potential barrier become accelerated into the velocity selector. The apparatus operated with -500 V cathode potential relative to ground, 10 mA beam current and 300 G flux density, accelerated electrons to energies of at least 20 keV.

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ABSTRACT

A simple discharge device was built and operated to examine experimentally the acceleration by a collective space-charge effect in electron beams. The apparatus comprises a cathode at one end of a 100 cm long evacuated copper tube, a 7.9 cm long lucite tube in series with a velocity selector and collector electrode on the other end, and a 100 cm solenoid coil around the copper tube which produces a static axial magnetic field uniform through the grounded copper tube, but rapidly falling off towards the negative cathode and the lucite tubing. Under the influence of this magnetic field and the voltage applied to the cathode, the emitted electrons form a cylindrical beam advancing in a screwlike manner towards the lucite tube. The decreasing flux there decelerates the angular velocity of the electrons; the absence of image-charges causes the development of a potential barrier which reduces the axial velocity of the arriving electrons to zero. As a result of this simultaneous deceleration of angular and axial velocities the beam is reflected. In the process of this reflection the electrons beyond the potential barrier become accelerated into and through the velocity selector towards the collector electrode. The beam in front of the potential barrier recoils and disperses, another beam is formed and the whole process is repeated. The apparatus operated with -500 V cathode potential relative to ground, 10mA beam current and 300 G flux density, accelerated electrons to energies of at least 20 keV. The energies were measured with a specifically designed velocity selector.

CHAPTER 1

Introduction

In a paper by Heese and Raudorf (1969) the acceleration of electrons by an electrodynamic effect is reported and discussed. According to the paper, a cylindrical stream of electrons immersed in a longitudinal focusing magnetic field advances towards a coaxial tubular decelerator electrode which is negative with respect to the cathode. The retarding electric field there stops the arriving electrons and the running on of the succeeding electrons causes the charge density within the front portion of the beam to grow and the potential to drop. Finally a virtual cathode is formed, the potential of which is below that of the decelerator. The electrons ahead of the virtual cathode are accelerated into the decelerator as they traverse the potential difference between the decelerator and the virtual cathode.

The formation of the virtual cathode is brought about by stopping the front electrons. The acceleration process, therefore, will depend greatly on the method of decelerating the electrons which constitute the front portion of the beam.

The purpose of this work was to employ different methods of stopping the beam and to investigate in each case the resulting acceleration of electrons with the aid of a specially constructed velocity filter. Essentially three distinct methods were used. The first one differed from that reported by Heese and Raudorf (loc.cit) merely in that the decelerator was not connected to any external voltage source but kept "floating". By intercepting partially the electron stream during operation it charged up negatively with respect to the cathode and thus gave rise to the acceleration process in the same way as the decelerator electrode. The second method consisted in converting the axial velocity of the front electrons completely to angular velocity by letting the electron stream enter a coaxial magnetic field of rapidly increasing flux density (Billington and Raudorf 1954). Simpler and more efficient, however, than either method, proved the third one to be. For this reason, it was decided to report in the following only on the third method which differed from the others mainly in that both cathode and collector system were outside the applied focusing magnetic field. It is best explained in conjunction with the description of the device which served to test the method.

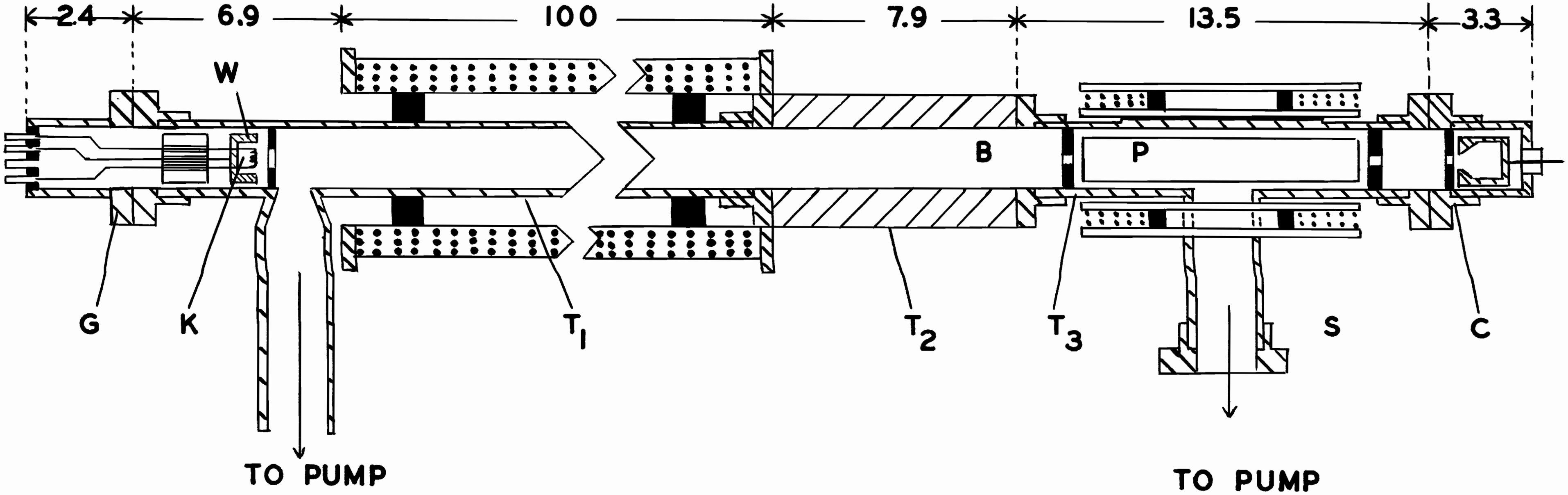

FIGURE 1. DISCHARGE DEVICE (ALL DIMENSIONS IN CM; DIAGRAM NOT TO SCALE)
K, CATHODE; W, WEHNELT CYLINDER; B, BAFFLE; G, ELECTRON GUN;
P, DEFLECTING PLATE; C, ELECTRON COLLECTOR; S, SELECTOR.

CHAPTER 2

Experimental Arrangement

A diagrammatical representation of the discharge device is given in figure 1. It is axially symmetric and essentially consists of the following components. An electron gun G on one end of a 100 cm long copper tube T_1 of 2 cm inner diameter, and a 7.9 cm long lucite tube T_2 of the same inner diameter on the other end, followed by a velocity selector S within a copper tube T_3 which is terminated by a collector electrode C. The metal housing, baffles B, and one of the deflecting plates P in the velocity filter are grounded, whereas the other deflecting plate, the collector C, cathode K and Wehnelt cylinder W of the electron gun are electrically insulated from the metal envelope. The main purpose of the baffles which are non-magnetic as all other parts of the system, is to assist in projecting a coaxial cylindrical electron beam of a maximum diameter of 0.5 cm.

The collector which is tubular in shape to suppress secondary emission, was connected to the input of a Keithley electrometer Model 610B, or a Tektronix oscilloscope Type 543A. A solenoid coil wound around the tube T_1, served to produce an axially symmetric longitudinal magnetic field within T_1. For evacuating the system, a mechanical fore-pump and a water-cooled oil vapour pump equipped with a liquid air trap were used. The experiments were carried out at pressures around 0.5 μ torr. A transformer supplied the filament power of about 25 watts. Independent regulated power supply units were employed for the d.c.

supply to the solenoid coil and the various electrodes. During operation the voltage applied to the cathode was negative with respect to ground.

CHAPTER 3

Operation

The operation of the device may be summed up as follows. Under the influence of the steady magnetic field, the electrons drawn from the cathode form, as they enter the focusing magnetic field, a cylindrical stream which is coaxial with respect to the applied magnetic field. The amount of the angular momentum of an electron at a point of its trajectory is proportional to the difference between the flux traversing the circle through the point considered around the axis of the system, and the flux traversing the circle defined by the point of emission on the cathode (Brillouin 1945). If the applied magnetic field is zero on the cathode, the angular velocity of an electron in the stream is proportional to the flux density of the uniform magnetic field within the solenoid coil. Hence the angular velocity is the same for all the electrons passing down the drift tube T_1. The cylindrical structure of the stream is controlled by the steady longitudinal field, and the space-charge density within the beam is uniform and proportional to the square of the flux density. The axial velocity of the electrons is also uniform and is the same for all electrons. In sum, the electrons projected into the focusing field form a cylindrical beam which rotates about its axis as a unit and advances in the same manner as a screw.

At the junction of T_1 and T_2, the electron stream emerges from the focusing magnetic field. The front electrons there encounter field conditions which are antisymmetric to those at the entrance of T_1. Consequently their angular velocity will be converted back to axial velocity. The absence of image charges in the plastic envelope, however, causes the potential to drop rapidly within the front portion of the beam. A potential barrier develops which blocks the passage into T_2 and against which the following electrons ram. Both space-charge density and potential barrier continue to grow until finally a space-charge limited virtual cathode is formed. Once the virtual cathode is set up, both angular and axial velocity of the beam are decelerated. The magnetic field which is associated with the beam collapses and induces during its collapse an axial electric field. This induced field is effective in the space between the virtual cathode and receiver. In the region within T_1 it is balanced by the electric field due to the non-uniform distribution of the space-charge along the beam caused by the run-on of the electrons. The electric field beyond the virtual cathode which is generated at the expense of the energy of the entire beam, draws electrons from the virtual cathode and accelerates them towards the receiver. During the discharge, the space-charge density decreases, and the virtual cathode disintegrates. The decelerated beam disperses under the influence of the radial interelectronic forces, another beam is formed and the whole process is repeated. Energy considerations show that the energy of the output electrons can be expected to vary from zero to a maximum value which depends on the potential of the virtual cathode.

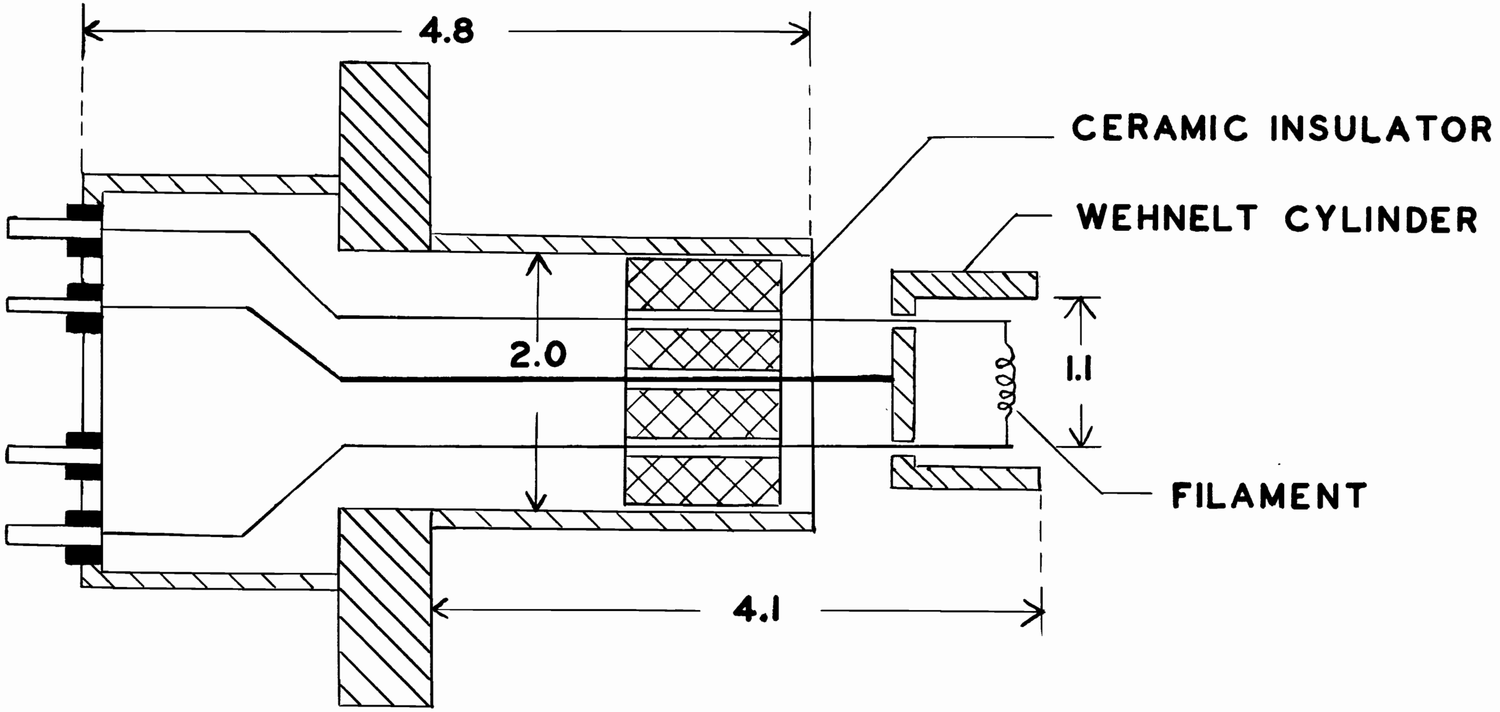

FIGURE 2. THE ELECTRON GUN
(DIMENSIONS IN CM)

CHAPTER 4

Design

In order to provide a wide range of experimental conditions, it was necessary to allow great variability in three important factors, viz, magnetic flux density, cathode potential, and emission current. Also the apparatus had to be constructed so that the major components were readily accessible. Neoprene O-rings were used at all demountable flanges and hard solder at joints. Although all discharge experiments were conducted under high vacuum, any adjustment to the cathode necessitated opening of the gun and exposing the cathode to the air. Oxide-coated cathodes and thoriated tungsten cathodes are susceptible to poisoning and easily damaged by ion bombardment. Hence it was decided to employ a directly-heated pure tungsten cathode in form of a simple spiral of 7 turns. Tungsten wire of 0.022 cm diameter was chosen to produce a cathode of reasonable rigidity. A Wehnelt cylinder of 1.1 cm diameter surrounded the filament spiral. Finally the whole cathode assembly was mounted on a multiple header as shown in figure 2, which sealed the cathode end of the drift tube T_1.

Coaxially inserted between the other end of T_1 and the metal housing of the velocity selector, was the 7.9 cm long piece of lucite tubing. In series with the velocity selector S followed the collector assembly C within a metal housing that was hermetically sealed by a terminal providing both support and electrical connection to the collector electrode (figure 3). The construction of the

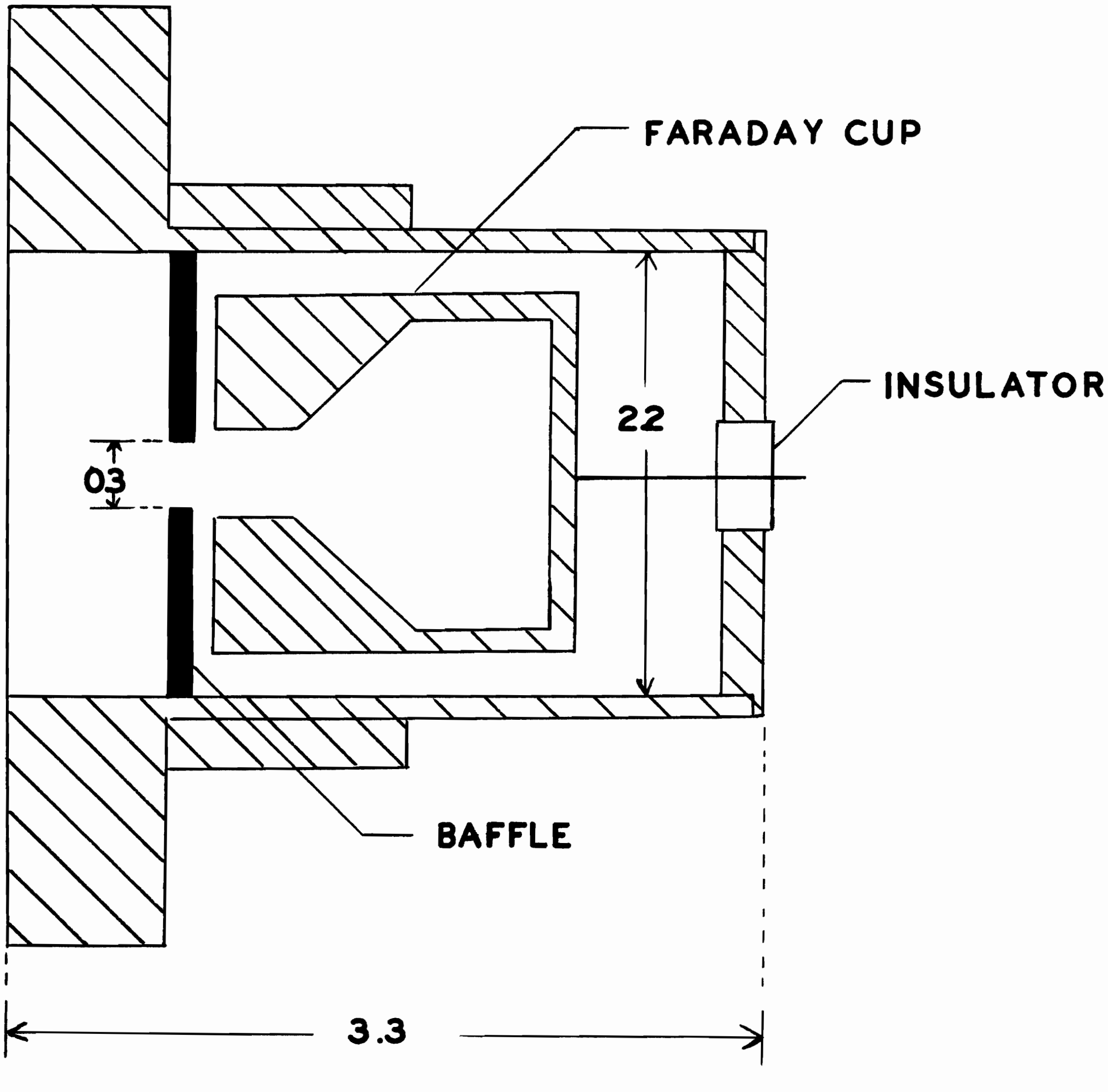

FIGURE 3. THE COLLECTOR
(DIMENSIONS IN CM)

plastic section and that of the collector system was straight forward and did not cause any difficulty worth while mentioning. The design of the velocity filter, however, posed problems. Their solutions are subsequently presented and discussed.

CHAPTER 5

The Velocity Selector

5.1 THOMSON'S CROSSED FIELDS METHOD

J. J. Thomson succeeded in measuring the ratio e/m for cathode rays by a method in which the effect produced by an electrostatic field $\underset{\sim}{E}$ was balanced by that due to a magnetic field $\underset{\sim}{B}$. Since the fields $\underset{\sim}{E}$ and $\underset{\sim}{B}$ were at right angle to each other (figure 4) and exactly cancelled out their separate effects on the electrons with velocity $\underset{\sim}{v}$, the net force:

$$\underset{\sim}{F} = e\,(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B})$$

was zero, giving the condition:

$$|\underset{\sim}{v}| = v = E/B$$

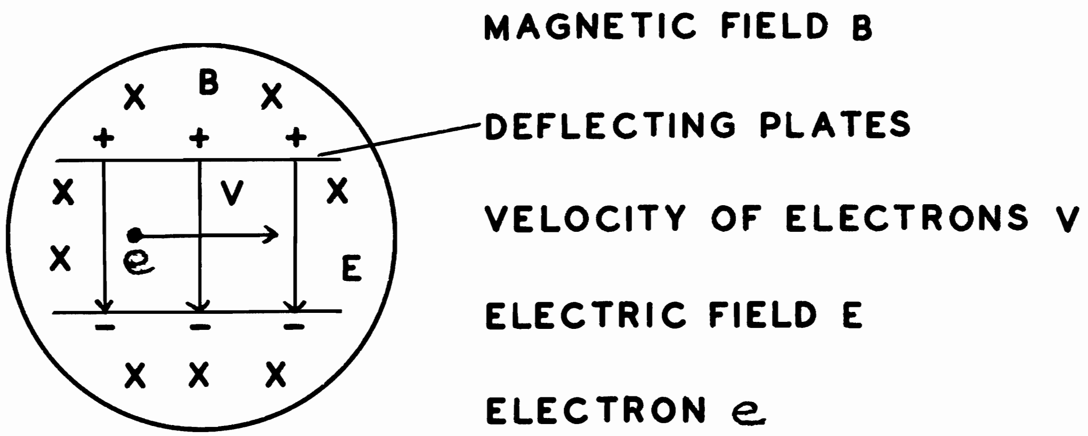

FIGURE 4. BALANCED ELECTRIC AND MAGNETIC FIELDS BETWEEN PLATES

The system of crossed electric and magnetic fields is often used as a velocity selector or filter. All electrons which possess the speed $v=E/B$, move in a straight line, and if their path is defined by a series of slits or apertures, only electrons with speeds $v = E/B$ can pass through the system. Conversely, if E and B are given, then the speed of the electrons traversing the filter is determined. Once the speed is known, the energy of the electrons can be computed. A velocity selector thus appears to be a simple device for measuring both velocities and energies of electrons. In order to obtain accurate results, it is necessary that the ratio E/B is the same at all points along the trajectories of the electrons. To achieve this would not be difficult if it were possible to produce fields which are uniform within a finite region and zero outside the region. Since this is not the case, one must ensure that the relevant electric and magnetic fringe fields fall off in such a manner that the constancy of the ratio E/B is preserved. This was to a high degree accomplished in the following way.

5.2 STUDY OF THE MAGNETIC FIELD

The uniform magnetic field was produced with Helmholtz coils. They consisted of a pair of coaxial, circular loops of the same radius a, equal in turns n, their centers separated by a distance a, and carrying the same current in the same clock sense. The radius a happened to be 3.67 cm and each coil had 118 turns of No. 18 gauge wire. The coil was energized with different currents and the flux density in each case measured (figure 5) along the

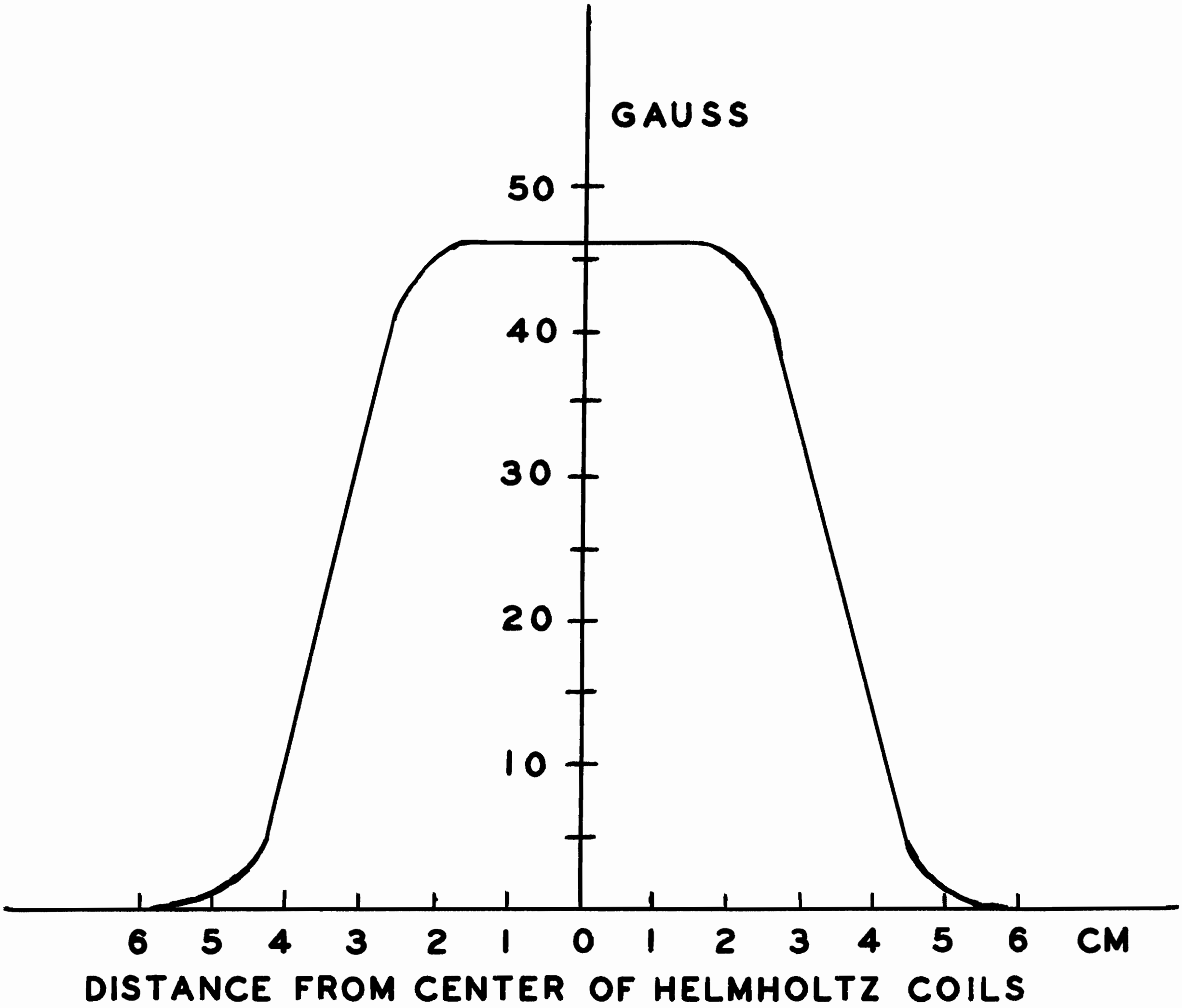

FIGURE 5. MAGNETIC FIELD OF HELMHOLTZ COILS ALONG THE AXIS OF T_3

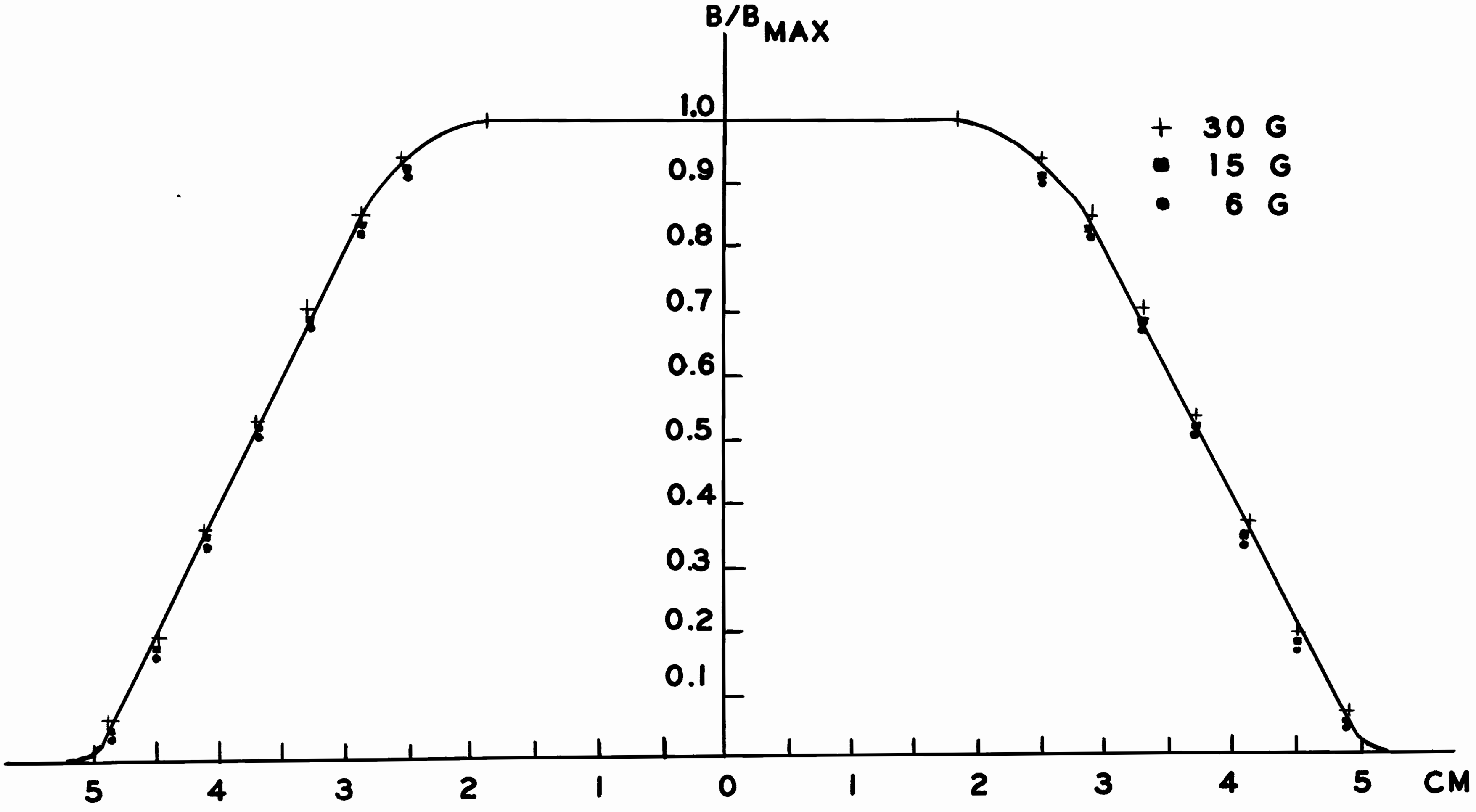

FIGURE 6. B/B_{MAX} ALONG THE AXIS OF T_3

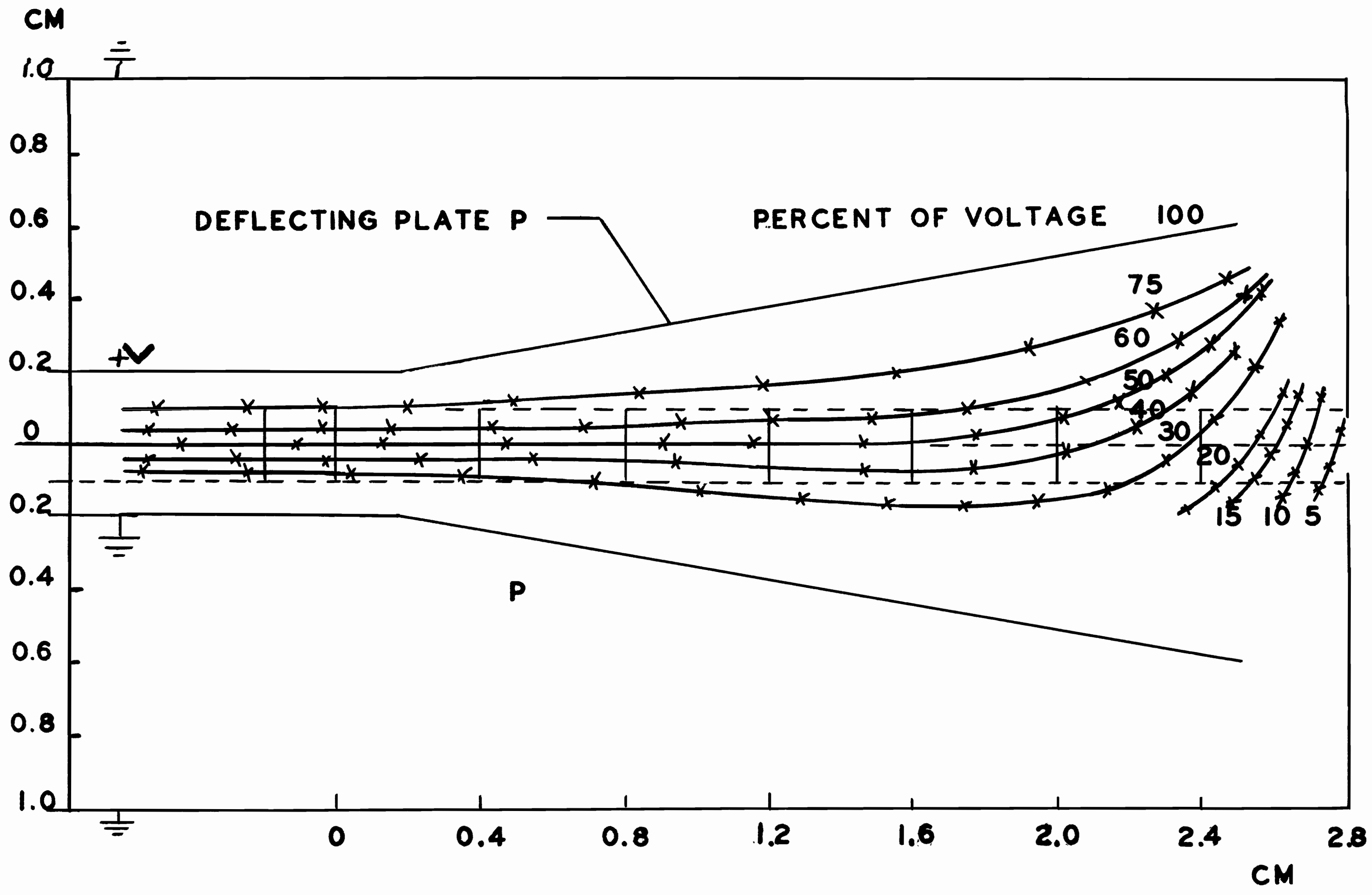

FIGURE 7. ELECTROLYTIC TROUGH-STUDY OF THE FRINGE FIELD

probable trajectory of an electron, that is, referring to figure 1, along the axis of T_3 between the openings of the two baffles in the velocity filter. The flux density at all points was found to be proportional to the energizing current. The results of these measurements are summarily presented in the figure 6 which shows the variation of the quantity B/B_{max} along the longitudinal axis of the velocity selector for three different values of B_{max}; B_{max} being the value of the uniform flux density at the center of the coils.

5.3 STUDY OF THE ELECTRIC FIELD

The problem was to produce an electrostatic field perpendicular to $\underset{\sim}{B}$ which is similarly modified by the edge effects as the magnetic field. A calculation showed that plane parallel plates would not be satisfactory. The end portions of the parallel plates were then altered, and the fringe field investigated by means of an electrolytic trough. Referring to figure 7, aluminum plates simulated the actual deflecting plates, a Cenco audio oscillator (1000 cps) served as voltage source, a probe plus an oscilloscope as detector. Starting with a tentative pair of deflecting plates, the equipotential lines were experimentally determined (figure 7), and the corresponding field lines constructed. Employing the method of successive approximation, the optimal shape for the plates was finally found. It is presented in figure 8 which shows the velocity selector viewed in the direction of the magnetic induction lines. Figure 9 presents the variation of E/E_{max} along the expected trajectory of the electrons in the velocity filter. Comparing the graphs in figure 6 and in

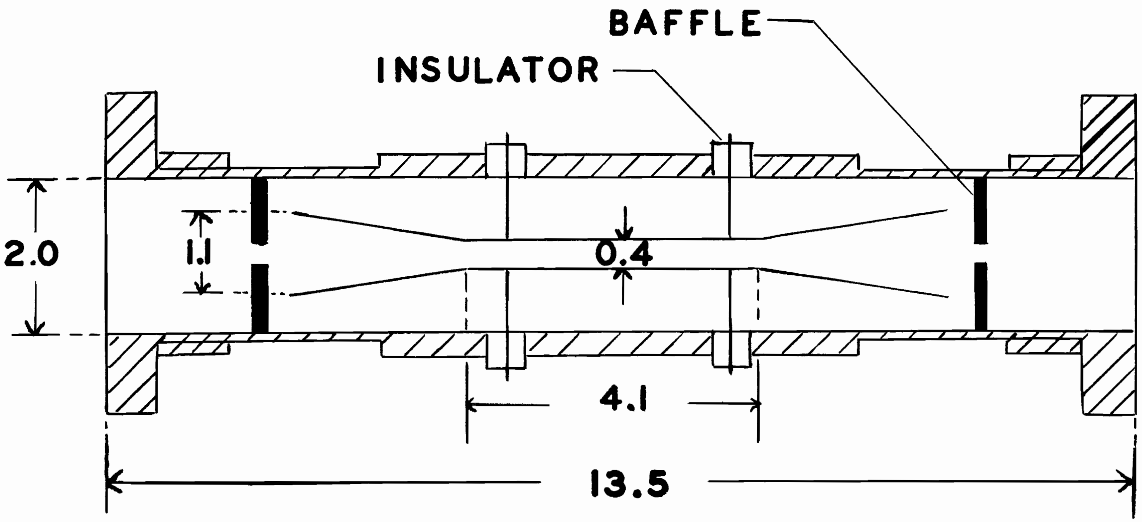

FIGURE 8. TOP VIEW OF VELOCITY SELECTOR
(DIMENSIONS IN CM)

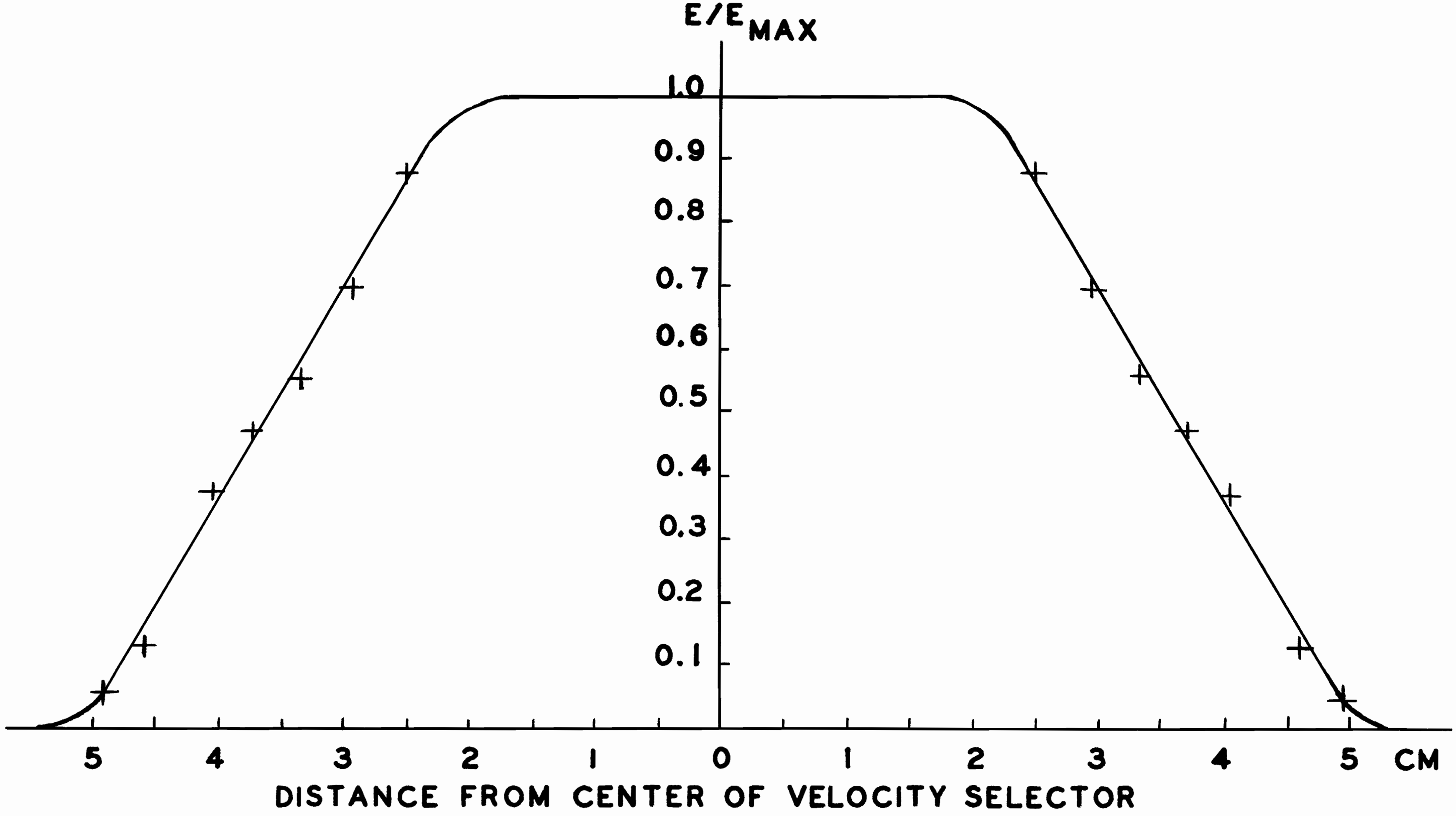

FIGURE 9. E/E_{MAX} ALONG THE AXIS OF T_3

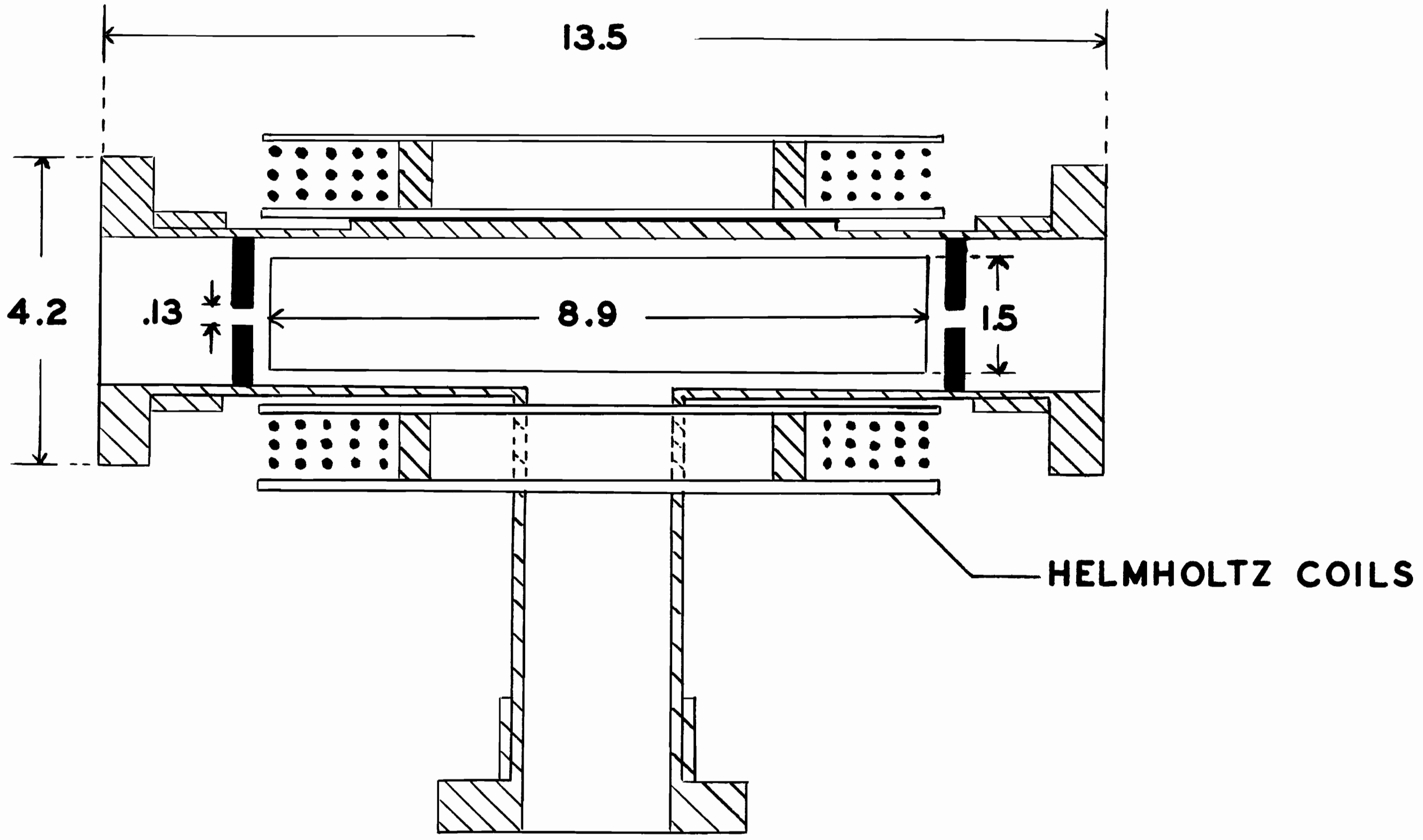

FIGURE 10. VELOCITY SELECTOR
(DIMENSIONS IN CM)

figure 9, it appears that the fringe portions of the electric and magnetic fields agree reasonably well.

5.4 DIMENSIONS OF THE VELOCITY SELECTOR

Referring to figures 10 and 8, the length of the deflecting plates was 8.9 cm and the width 1.5 cm. The parallel portion of the plates was 4.1 cm and 0.4 cm apart. The diverging section was 4.8 cm long, the separation between the ends being 1.1 cm. The plates were positioned by stainless steel rods which were insulated against the copper envelope by phenolite and sealed with epoxy. The spacing between the plates and the baffles at the entrance and exit of the velocity selector was 0.3 cm and the diameter of the apertures in the baffles was 0.13 cm. Regulated power supplies provided the voltage for the plates and the current for the Helmholtz coils.

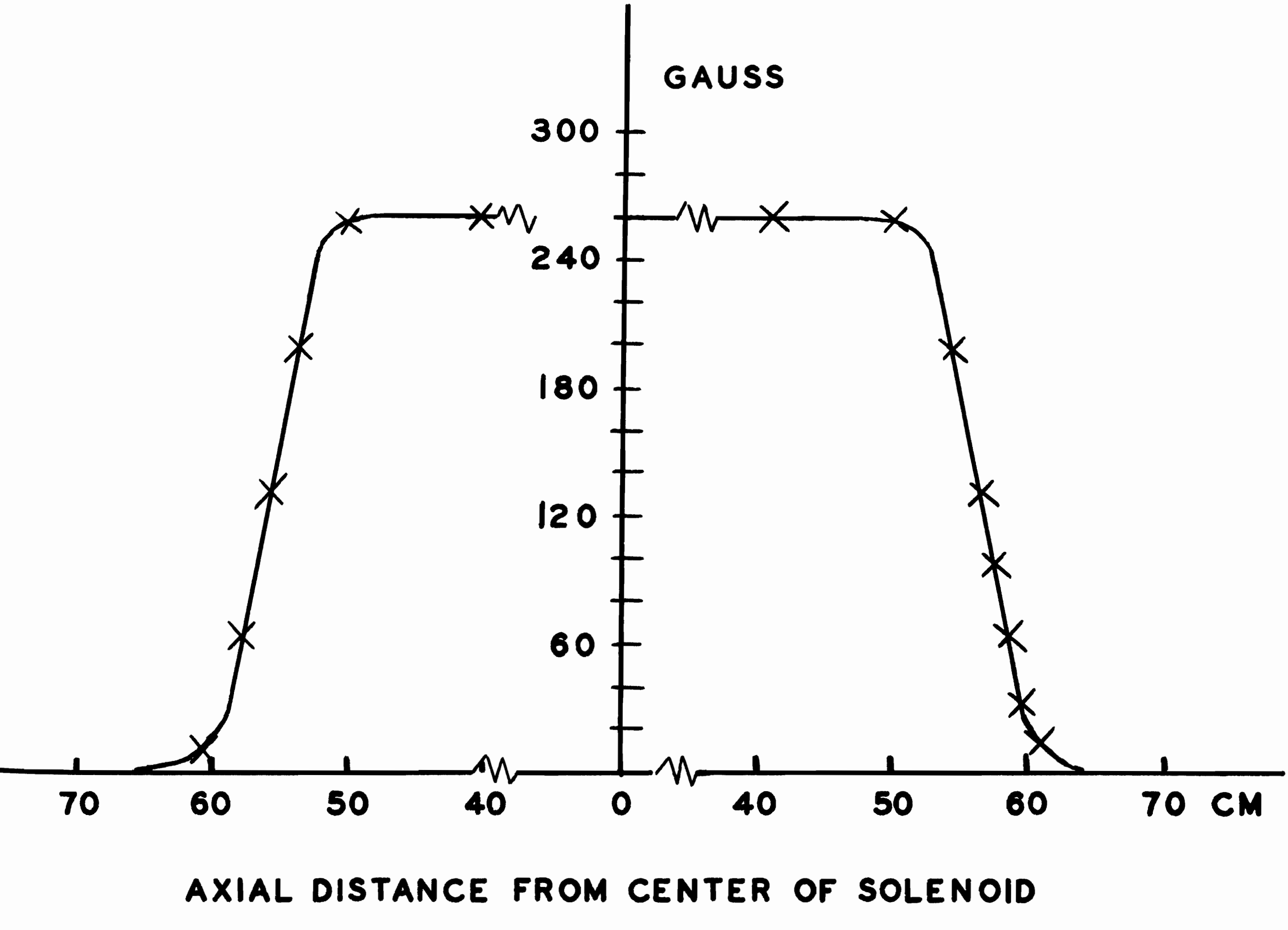

FIGURE 11. MAGNETIC FIELD OF THE FOCUSING SOLENOID

CHAPTER 6

Preliminary Measurements

6.1 FLUX DENSITY OF FOCUSING MAGNETIC FIELD

The solenoid focusing coil was energized and the flux density measured along the axis of the system with a calibrated gaussmeter. As expected the flux density was found to fall off rapidly towards the cathode and the lucite tubing, and to be constant throughout the drift tube T_1. A plot of the axial flux density within T_1 versus distance from the center of T_1 is presented in figure 11. The relationship between B_{axial} and the energizing current I was linear and given by the empirically found equation $B_{axial} = 45.0\ I$ gauss, where I is measured in amps.

A similar equation related the constant flux density B in gauss, due to the current I in amps through the Helmholtz coils, viz,

$$B = 32.4\ I \text{ gauss (figure 12)}$$

6.2 CALIBRATION OF THE VELOCITY SELECTOR

In order to calibrate the velocity selector, the electron gun was mounted coaxially with the velocity selector and collector assembly such that the distance between the cathode and first selector baffle was about 8 cm. Voltages ranging from -500 V to -2000 V relative to the grounded baffles in steps of 500 V were applied to the cathode. The emission current varied from

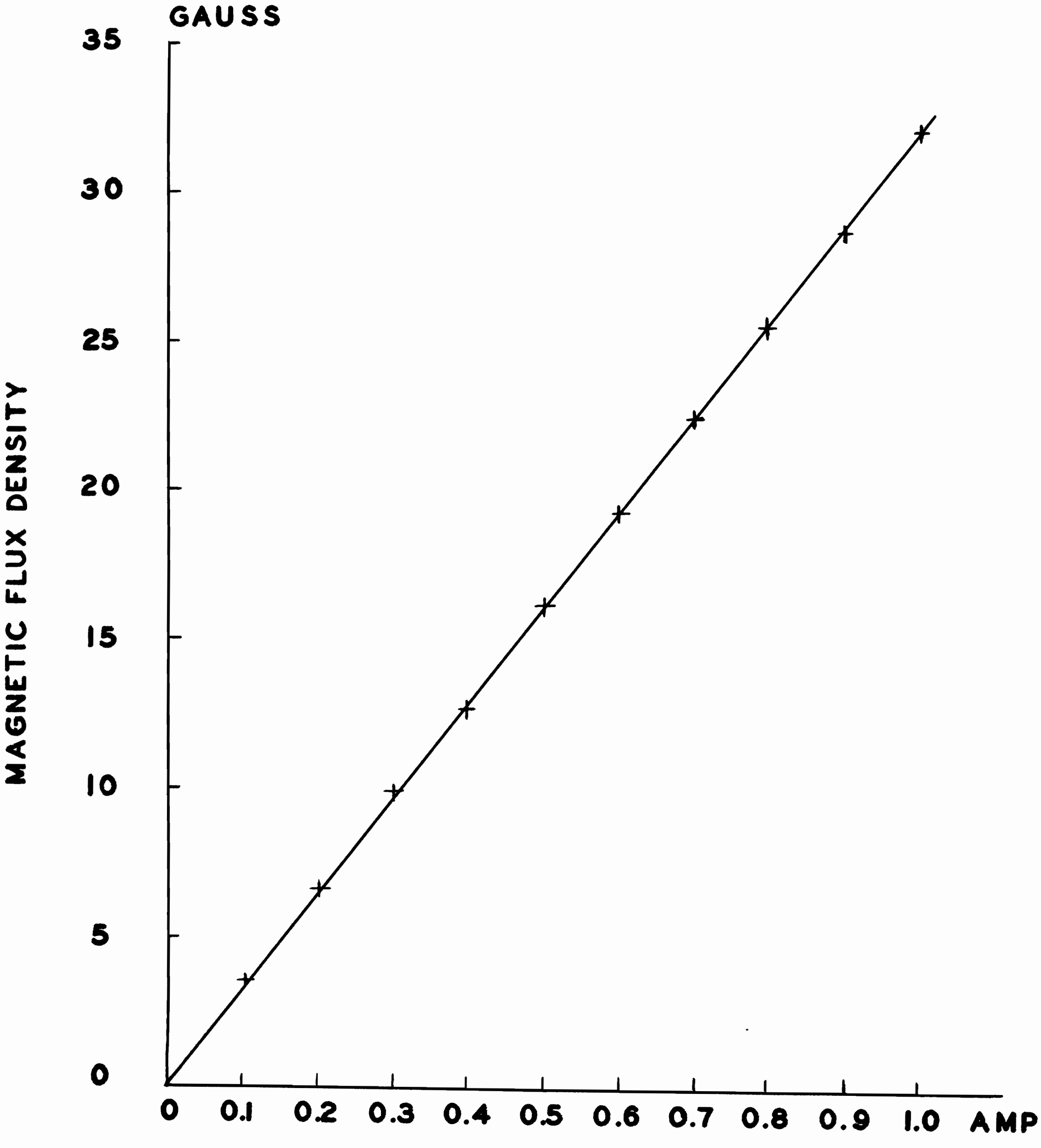

FIGURE 12 CALIBRATION CURVE OF THE HELMHOLTZ COILS

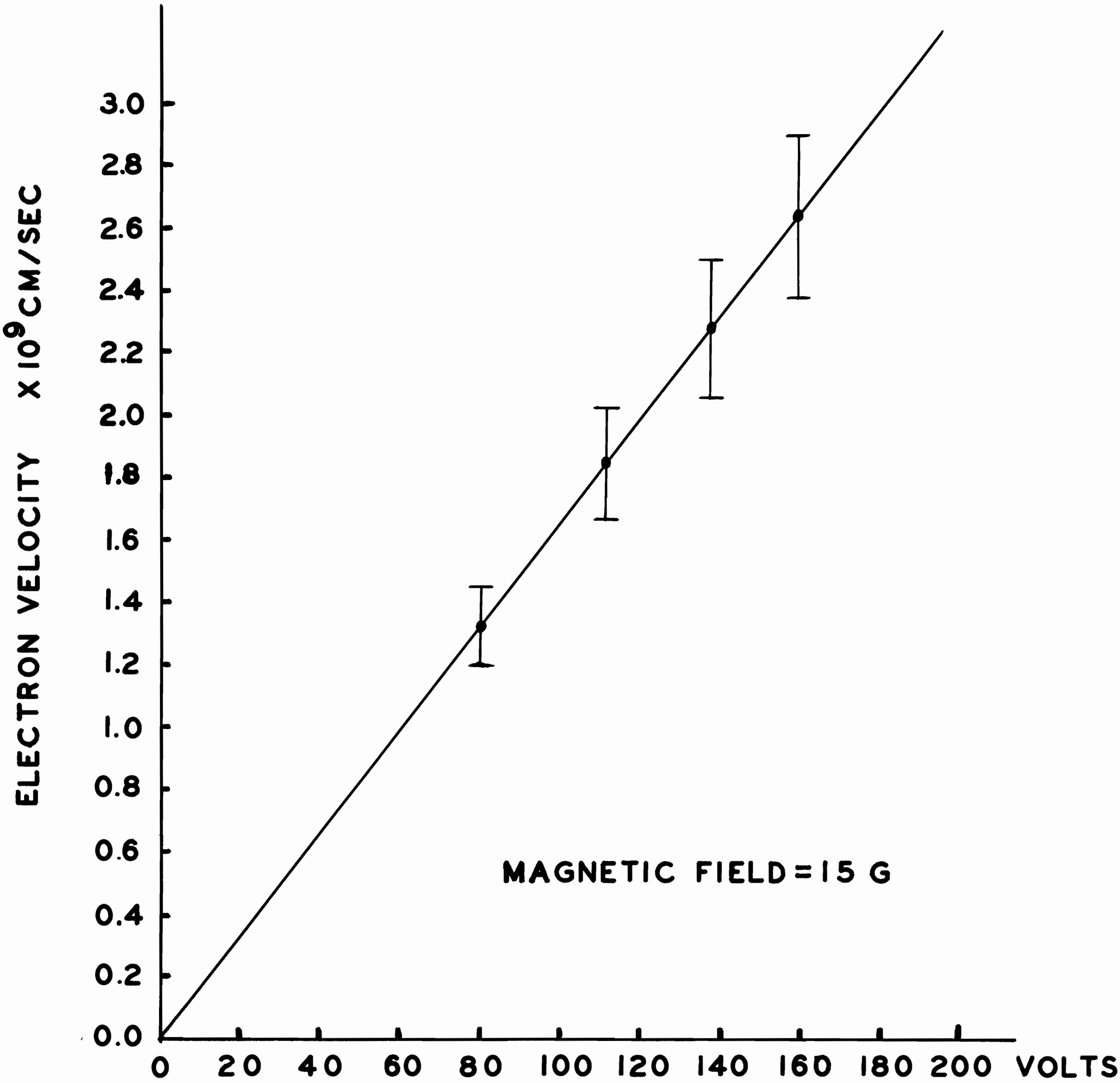

FIGURE 13A. ELECTRON VELOCITY VS PLATE VOLTAGE

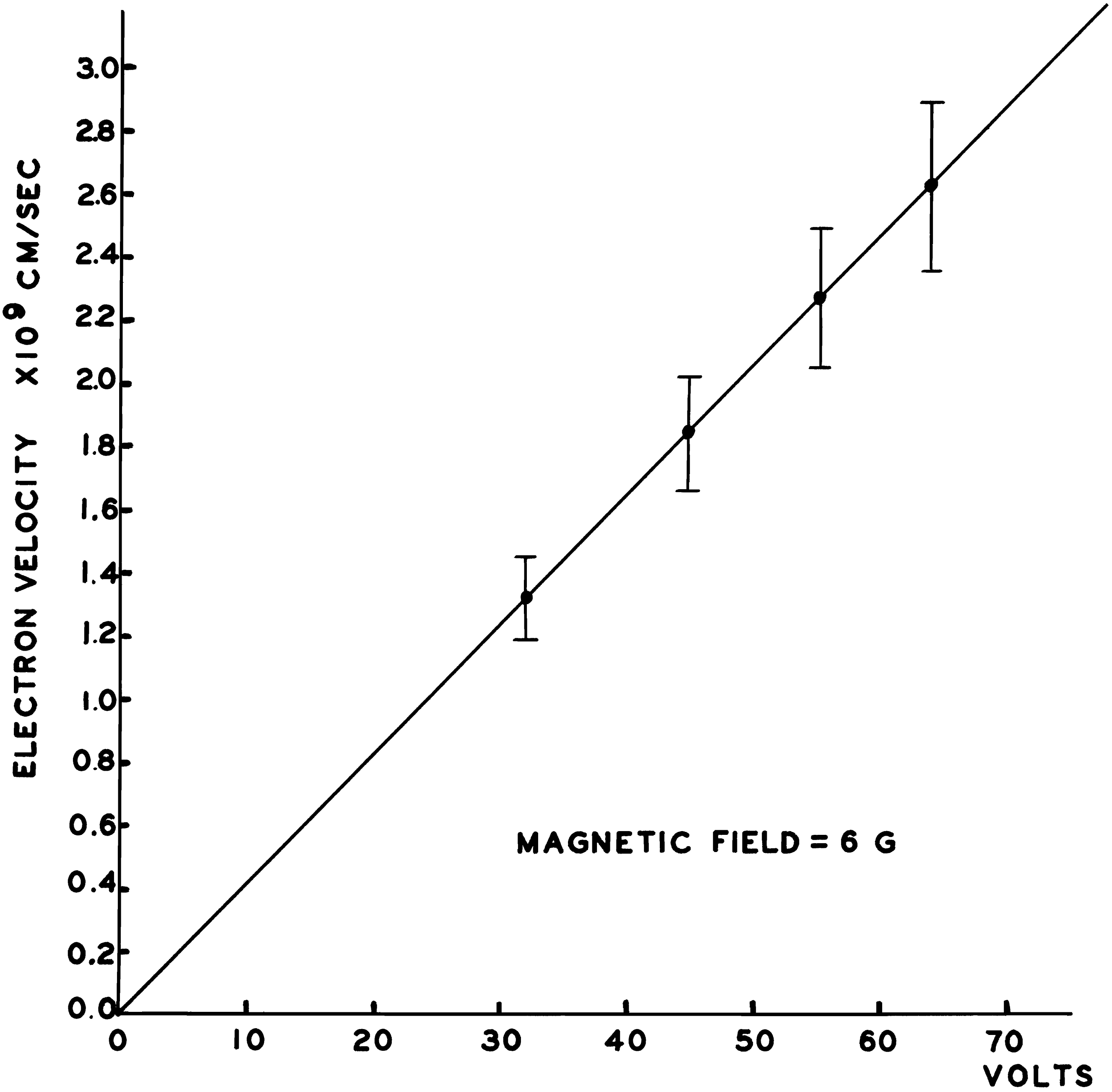

FIGURE 13B ELECTRON VELOCITY VS PLATE VOLTAGE

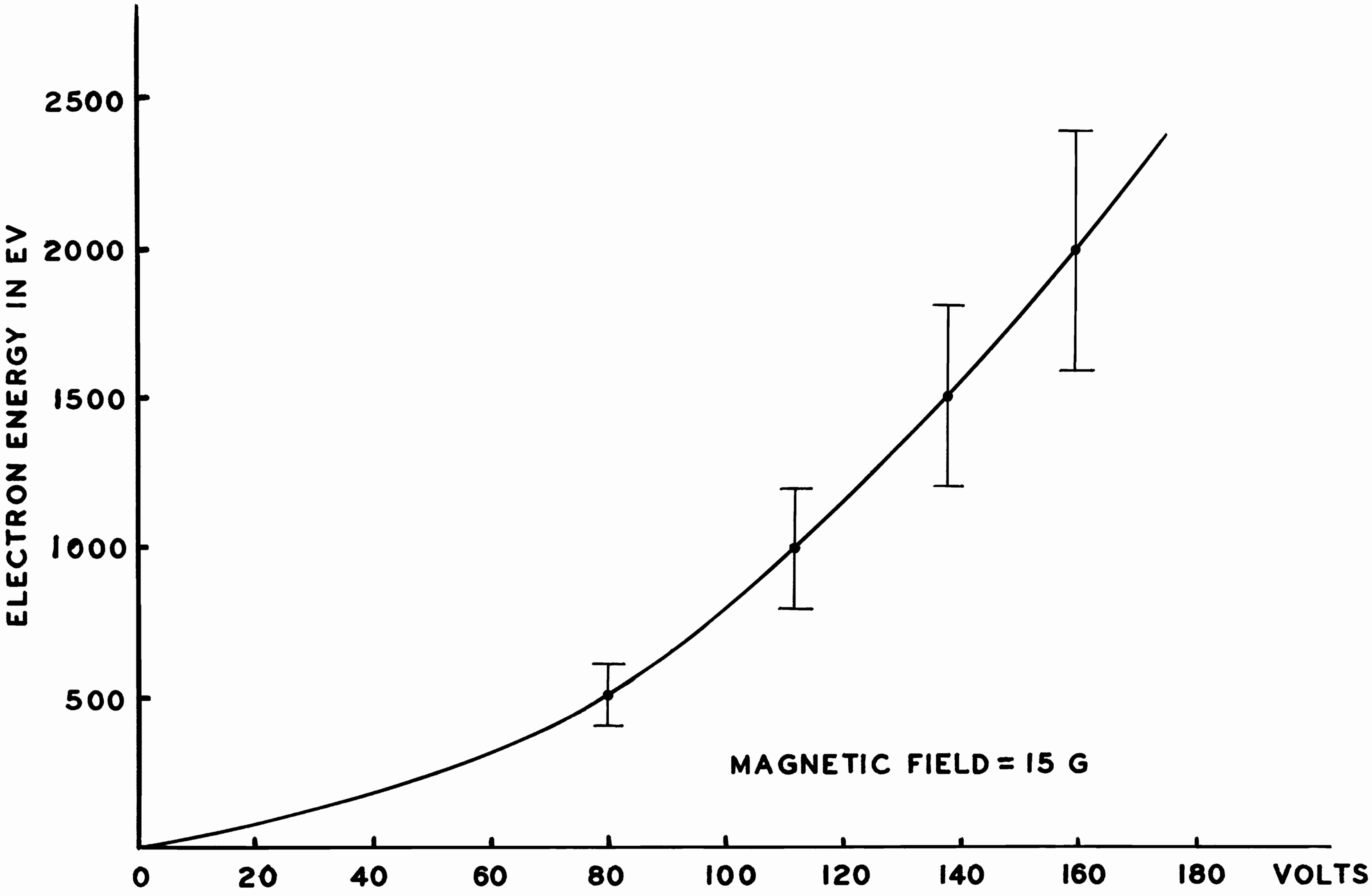

FIGURE 14A. ELECTRON ENERGY VS PLATE VOLTAGE

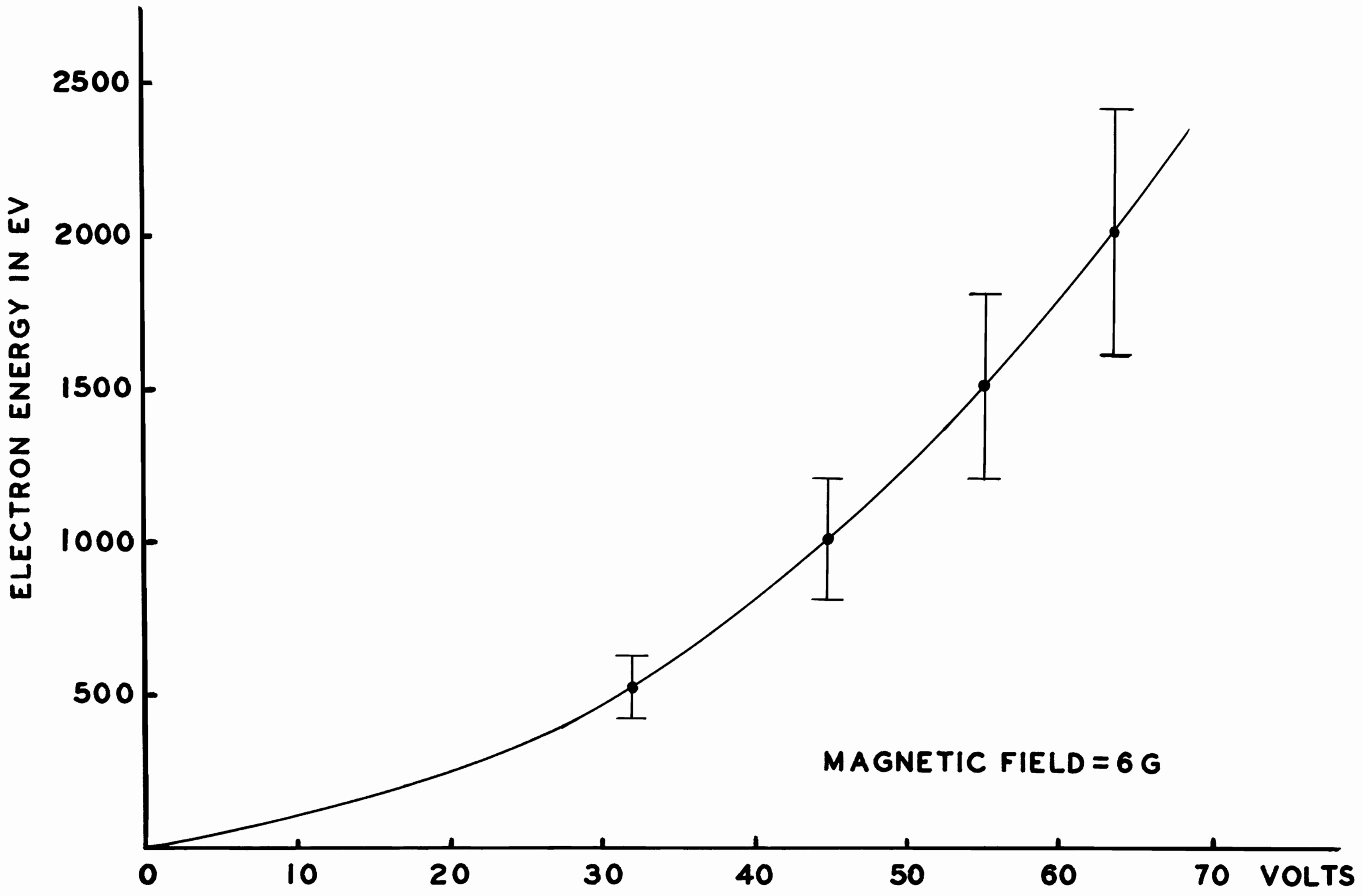

FIGURE 14B. ELECTRON ENERGY VS PLATE VOLTAGE

5 mA to 15.5 mA. The magnetic field $\underset{\sim}{B}$, generated by the Helmholtz coils, was kept constant at 15 gauss in the first series of measurements, and 6 gauss in the second series. The balancing electric field $\underset{\sim}{E}$ was calculated from the value of the voltages applied to the deflecting plates and the geometry of the plates. These measurements showed that for a given cathode voltage, i.e. given velocity of the electrons, the voltage across the deflecting plates of the velocity filter at which the collector current reached a maximum, agreed on the average with the theoretical value derived from $E = vB$. In other words, the values of the electron velocities obtained from a series of measurements of the voltages on the deflecting plates corresponded on the average to the actual values, that is to the values of the velocities determined by the cathode voltages. The deviation of the values, ascertained by the velocity selector from the actual values turned out to be ±10%. See figures 13A and 13B. Consequently, the error in the computation of the electron energies W from the voltages V_p between the deflecting plates amounted to ±20% as indicated in the plots of W versus V_p in figures 14A and 14B.

6.3 ELECTRON OPTICS

A convenient way of checking on the electron optics of the electron gun and the alignment of the various parts of the system is to measure the beam current at the end of the drift tube T_1 and compare it to the total current emitted by the cathode. For this purpose, a special collector assembly was connected to the flanges at the end of T_1 such that the collecting electrode was just within the focusing magnetic field. It was found that under operating conditions, 60 to 65% of the total current passed down the drift tube, the remaining portion was intercepted by the baffles, primarily by the baffle closest to the cathode. In view of the fact that the emissive surface of the cathode was neither plane nor equipotential, nor free of the magnetic field produced by the filament current, the distribution of the current, and hence the electron optics, was considered as being satisfactory.

Depending on the voltages applied to the cathode, the beam current ranged from 5 to 30 mA and was steady unless the cathode was pulsed.

6.4 FUNCTION OF THE LUCITE TUBE

According to the physical picture underlying the acceleration method, the insertion of the plastic tubing between drift tube and collector should introduce an instability in the discharge process. In spite of continuous operation of the cathode, the collector current should become intermittent for reasons given in section ''Operation'' of this work.

To examine whether this is the case, the 7.9 cm long tube was fitted between drift tube and collector assembly. The collector electrode was connected to the vertical input of a Tektronix oscilloscope, Type 543A. The voltage on the cathode was -300 V relative to ground and steady. As expected the output consisted of current pulses. The oscillogram in figure 15 illustrates the output voltage across a resistor of 1 KΩ between collector and ground. Neither the rate of recurrence nor the amplitudes of the output pulses appear to be uniform. This is not surprising in view of the inherent statistical character of the result of a collision between a beam of interacting electrons and a potential barrier set up by an electrodynamical space-charge effect. Successive beams cannot be expected to be identical in every respect, and fluctuations in the beam structure are likely to affect the entire discharge process, including deceleration, dispersion and reformation of the beam.

CHAPTER 7

Energy Measurements and Results

The energy W invested in the electron beam before its deceleration is given by $W = kIUt$, where k is a factor accounting for the interception of space-current by the baffles, I the emission current, U the voltage between drift tube and cathode, t the transit time, that is the time it takes the beam to travel from the cathode to the junction of drift tube and lucite tube. W being supplied by the external power supply, consists of magnetic energy W_m, kinetic energy W_k, and electric energy W_e. W_e is responsible for the dispersion of the beam after its deceleration and represents wasted energy which ultimately turns to heat.

During the deceleration or bunching period the charge Δq, which is small relative to the total electronic charge in the beam, is lifted to the energy level V, where V is the potential of the virtual cathode relative to ground. Energy preservation requires that $\frac{1}{2}V\Delta q = W-W_e$. After the bunching period, the small charge Δq becomes the object upon which the induced axial electric field, generated by the total moving charge in the beam, acts. As this charge gains momentum, the induced field collapses. During the discharge the space-charge density in the front portion of the beam decreases and the potential barrier recedes along the beam, becoming smaller and smaller until it vanishes. This "recoiling" of the potential barrier may be regarded as the reaction to the propulsion of the charge Δq.

FIGURE 15. OUTPUT PULSES WITH RAM EFFECT.

OUTPUT ACROSS 1,000 OHMS

BEAM STOPPED BY VIRTUE OF THE LUCITE TUBE

CATHODE VOLTAGE = -300 VOLTS

BEAM CURRENT = 5 MA.

FILAMENT CURRENT = 4.4 AMP.

FOCUSING MAGNETIC FIELD = 130 G

TIME SCALE = 0.1 MSEC/CM

SENSITIVITY = 0.05 VOLT/CM

The energy in electron-volts of the fastest electrons is V, provided losses due to radiation are negligible, and that of the slowest electrons is zero.

To measure the energies of the ejected electrons, the velocity selector was inserted between the lucite tubing and the collector assembly. The collector electrode was connected through a carefully shielded cable to a Keithley electrometer, Model 610B.

The output consisted of pulses similar to those in figure 15, but smaller in size because of the filter action of the velocity selector. The average output current as recorded by the electrometer was very low, particularly when the cathode was pulsed. Apart from a lesser repetition rate of the output, the pulsed operation of the device did not differ in any other respect from the continuous operation. For this reason the energy measurements were carried out with continuously operated cathode.

Several sets of measurements were taken under the following operating conditions: the cathode voltage -500 V with respect to ground and steady, the filament current was about 4.6 A, the total emission on the average 12 mA, and vacuum pressures around 0.5 μtorr. The optimal focusing magnetic field was found to be 240 gauss. The flux density in the velocity selector was kept constant during each set of measurements. In most of cases, it was 15 G, but 6 G and 30 G were also used. The voltage across the deflecting plates was varied in small steps and the output current I at each plate voltage V_p recorded. For each plate voltage the velocity and the energy of the electrons constituting the output current I were relativistically calculated.

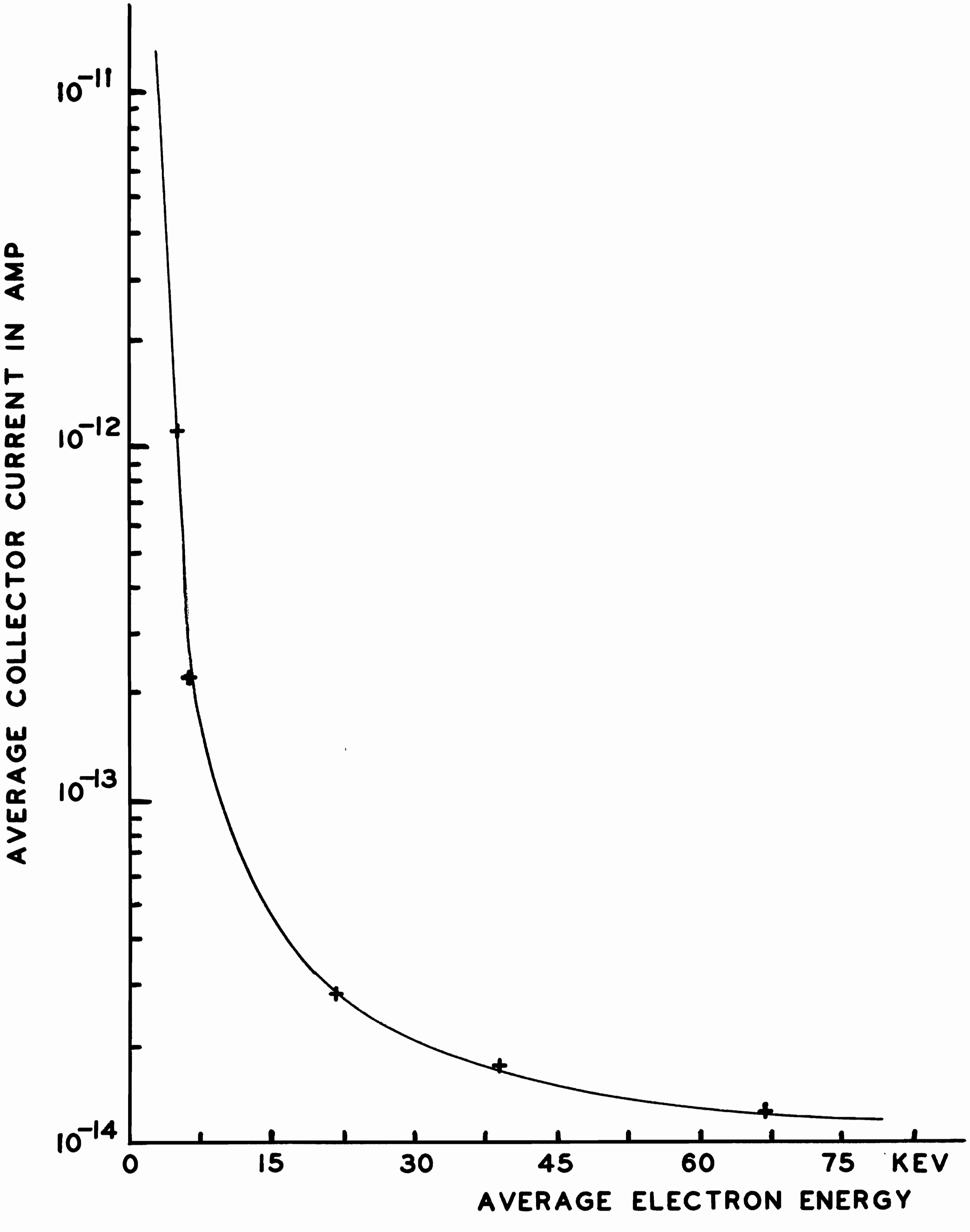

FIGURE 16. AVERAGE COLLECTOR CURRENT VS AVERAGE ELECTRON ENERGY

Finally the average values of I were formed using the data obtained from the series of measurements, and plotted versus the corresponding average energy values. The graph in figure 16 is such a plot presenting summarily the results of the energy measurements.

Since $I = g\rho v$, where ρ is the current density, v the electron velocity, and g a constant factor depending on the geometry of the velocity selector, it follows that $\rho \propto I/v$. The ratio I/v on the other hand, may be considered as dependent on the energy W and thus used to describe qualitatively the energy distribution of the electrons which make up the ejected charge Δq. Figure 16 in which I_{av} is plotted versus W shows that the number of electrons having energy W falls off rapidly with increasing W.

CHAPTER 8

Discussion

Summarizing, one can say that the method of stopping the beam employed in this work proved to be successful. The energy range of the accelerated electrons extends well beyond 20 keV, that is 40 times the energy of the electrons entering the drift tube.

To confirm the order of magnitude of these energies, the lucite tube was terminated with a thin mica sheet which could be passed only by electrons of at least 20 keV.

In fact, electronic current was registered by the electrometer when the device was operated. Deflecting the electron stream in the tube by holding a bar magnet against the tube, turning off the focusing magnetic field, or the filament current, invariably reduced the output to zero. The mica sheet was afterwards checked for holes with a helium leak detector, but no holes could be found.

The method of producing the desired space-charge effect by inserting a piece of plastic tubing appears to be simple and effective. Practically, however, it has a serious disadvantage. The slightest metallization of the inner or outer surface of the lucite tube makes the tube ineffective. After comparatively short operation, it has to be thoroughly cleaned to restore its efficiency.

Varying beam current, decelerator bias, cathode voltage and flux density have little effect on the energy range of the output electrons; a good vacuum, however, is important.

It should be mentioned that reversing simultaneously the polarity of the magnetic and electric fields in the velocity selector, had no appreciable effect on the output which showed that the axial symmetry of the device was satisfactory.

CHAPTER 9

Conclusion

Comparing the results reported above with those obtained by Heese and Raudorf (1969), it appears that the method of decelerating the electron beam with the aid of a dielectric tube is superior to that employing a negatively biased electrode to stop the beam. A more quantitative study of the influence of the beam deceleration method on the acceleration process would require an improved discharge device which permits independent change of the various operating parameters, such as cathode voltage, beam current, focusing magnetic field and electron optics.

CHAPTER 10

REFERENCES

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