THE DEFLECTION SYSTEM OF THE McGILL CYCLOTRON

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Graduate Studies and Research of McGill University

by

D.W. Hone

Radiation Laboratory

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TABLE OF CONTENTS

SUMMARY

The deflection method which is standard in fixed frequency cyclotrons[1] cannot be readily employed under present operating conditions in synchro-cyclotrons, mainly because the higher voltage potentials required cannot be maintained steadily without spark breakdown. Employing a pulsed electrostatic deflector and associated iron channel, the Berkeley, California, group have achieved some success in the ejection of deuterons from their 184-inch synchro-cyclotron.[2]

The work at McGill has led to a variation of Berkeley's method for application to protons, and results of the deflection experiments have so far met expectations in that 1 1/2% of the beam circulating at 36.1 inches (without deflector in) has been deflected to a radius of $(37.3 \rightarrow 37.6)$ inches.

Adaptation has involved the construction of a voltage pulser, of original design, whose output is characterized by an unusually fast time of rise for such high voltages (≈ 150 kilovolts) while retaining a precision of timing better than .01 μs. Improvements in the phasing of the initial trigger pulse for this pulser, in the vacuum conditions in the cyclotron, and adjustment of the deflector should increase the percentage deflection by a factor of 10.

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INTRODUCTION

The deflection method which is standard in fixed frequency cyclotrons[1] cannot be readily employed under present operating conditions in synchro-cyclotrons, mainly because the higher voltage potentials required cannot be maintained steadily without spark breakdown. Employing a pulsed electrostatic deflector and associated iron channel, the Berkeley, California, group have achieved some success in the ejection of deuterons from their 184-inch synchro-cyclotron.[2]

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In what follows a brief review of the conditions governing particle acceleration in the synchro-cyclotron will be carried out which will serve to provide an idea of the type of beam which one expects to be dealing with. This review will be followed by a discussion of alternative methods of deflection and then a description of the method first selected for trial and subsequent experimental work.

INVESTIGATION OF THE DEFLECTOR PROBLEM

The Ion Beam in a Synchro-Cyclotron

Protons, starting at the center of the cyclotron and being accelerated by the voltage on the dee, will at any radius be subject to the following equations.

$$He\,v = \frac{mv^2}{r} \qquad (1)$$

$$\text{or } \omega = \frac{He}{m} \qquad (2)$$

where H and e are in e.m.u. and m is the relativistic mass in grams.

$$m = m_o \frac{1}{1 - \frac{v^2}{c^2}} = m_o b \qquad (3)$$

The quantity b may be found as a function of r as follows

$$p = mv = He\,r \qquad (4)$$

$$= m_o \frac{1}{1 - \frac{v^2}{c^2}} \quad v = m_o \frac{v/c}{1 - \frac{v^2}{c^2}} \cdot c$$

$$\therefore \frac{p^2}{m_o^2 c^2} + 1 = \frac{v^2}{c^2} \; \frac{1}{1 - \frac{v^2}{c^2}} + 1$$

$$= \frac{1}{1 - \frac{v^2}{c^2}}$$

$$\therefore b = \left(\frac{p^2}{m_o^2 c^2} + 1\right)^{1/2} = \left(\frac{H^2 e^2 r^2}{m_o^2 c^2} + 1\right)^{1/2} \qquad (5)$$

From equation (2), (3), and (5) it is evident that the rotational frequency of the ion is a decreasing function of r, not only because m (through b) increases with r but also because H decreases with r, (H being a decreasing function of r is desirable for vertical focussing of the protons). Substitution of appropriate values of H, e, m, (for protons), r, and c to get ω vs r shows that a change of 10% in ω

occurs when going from r = 0 to r = 36. Also it can be shown that with 10 kv on the dee the ions will take about 3000 turns to get to r = 36", and that at, say, r = 15" the ions would slip in phase by π radians in about 40 turns, if the oscillator frequency were fixed at the r = 0 value, hence it is apparent that the frequency of the applied voltage must decrease in the same fashion as the ion rotational frequency. In the McGill case, the applied frequency is varied from 26.2 mc/sec. to 19 mc/sec., of which interval the portion from 25 mc/sec. to 22 mc/sec. is used for acceleration since these limits are the ion rotational frequencies at r = 0 and r = 36" respectively. It is apparent that the oscillator can accelerate only one particular group of ions at any given time and hence the ion beam consists of a succession of these groups, one per modulation cycle.

McMillan(4) and Bohm and Foldy(5) have considered the motion of the ions after they have been picked up and their results show that it is not necessary for an ion to start from the center of the cyclotron just when the accelerating voltage frequency equals the rotational frequency of the ion, but that it may start at any time, provided the difference between the two frequencies does not exceed certain values and that the ion crosses the dee gap at a time when the phase of the accelerating voltage is within certain limits. The theory leading to these conclusions has been developed in the paper by Bohm and Foldy(5) and appendix I is a brief summary of part of their paper.

The theory, as developed there, defines a so-called synchronous orbit, containing ions whose acceleration commences at such a time and phase that their energy gain per turn is just right to give them a frequency versus time characteristic equal to that of the applied voltage. The other ions which are successfully accelerated oscillate about the synchronous ions both in phase and radius and in this way each beam pulse attains an azimuthal and radial width.

From the theory also, an angle ϕ is defined such that the energy gain per turn of an ion is eV sin ϕ, where V is twice the dee voltage, and for the synchronous ions the gain is eV sin ϕ_s. ϕ oscillates about ϕ_s. For a known synchronous phase angle, ϕ_s, the maximum phase variation can be found from equation (21) as the difference between the two values of ϕ which make $\Delta E = 0$. The maximum radial variation is twice the value obtained from substituting the given ϕ_s in equation (24). The largest widths calculated in this way occur for $\phi_s = 0$ and one might think that adjustment of rotary condenser speed and dee voltage to approach this value of ϕ_s would provide the maximum beam current, but experimental evidence at Berkeley, California, indicated $\phi_s = 30^\circ$ gave optimum current. This led to an analysis[6] of the starting conditions in a synchro-cyclotron which showed that for ϕ_s between 0° and 30° the amplitudes of the phase and radial oscillations are so large that during the first oscillation a large number of ions are returned to the origin and fail to be picked up again, a number which is larger than any gain resulting from a low ϕ_s. Then, assuming the cyclotron as being adjusted for maximum beam, the equilibrium phase angle should be near 30° and the corresponding azimuthal and radial spread as calculated from equations (21) and (24) are

$$\Delta\phi_{total} \approx 180^\circ \text{ and } \Delta r_{total}\ (r = 36'') \approx .54 \text{ inches.}$$

Notice that these figures could be altered by operating conditions which forced ϕ_s to vary during acceleration because of inability to maintain a suitable dee voltage and/or a suitable applied frequency versus time characteristic. Lacking exact knowledge of these conditions, $\phi_s = 30^o$ and $\Delta\phi$, Δr as given above will be considered the most likely values of these parameters which will occur.

With $\phi_s = 30^o$ the average energy gain per turn of an ion is 1/2 eV and roughly suitable values of V and frequency modulation rate (assuming the duty cycle is 1/6 the total) to reach 94 Mev (Appendix II) are 10 Kilovolts and 200 cycles per second respectively. V = 10 Kilovolts means 5 Kilovolts dee voltage. This modulation rate is a reasonably high one to achieve with present modulation methods, and hence it is apparent that the dee voltage of synchro-cyclotrons must be much lower than in fixed frequency machines (c.f. 100 Kilovolts in Berkeley 60" cyclotron[2]). Such low dee voltages provide radial increases per turn of the order of 1 mil at r = 36 inches.

Additional Considerations.

In addition to the radial oscillations mentioned in the foregoing there is another type known as free radial oscillation[8],[10] which is due to the fact that the center of curvature of the ions may not be coincident with the axis of symmetry of the magnetic field, but instead moves around the axis at some radial distance which is usually of the order of an inch. The effect is to reduce the radius of curvature of the ion below the value of the radius at which it is detected by an amount equal to the amplitude of its oscillation. The magnitude of the effect is very difficult to measure although experiments now being carried out in the laboratory by Mr. William Henry indicate that the radius of the precession circle on which the centers of curvature move is from 1 to 2 inches when the ion is at r = 36 inches. The frequency of the oscillation is given by the expression $\omega_r = \sqrt{1-n}\,\omega$ where $n = -(r/H \times dH/dr)$ and ω is the ion rotational frequency which obtains at any given radius. No consideration was given to these oscillations in the initial deflector design since they are assumed to arise from the irregularities in the magnetic field which would be present in a poor magnet and the McGill magnet is considered to be very good. They also arise from off-center positioning of the ion source[7] which has not yet been tested in the McGill machine and which may be a contributing factor to the oscillation results being obtained.

Vertical oscillations, affecting the height of the beam, are also known to exist in the cyclotron and occur because the ions do not all originate in the median plane, and the magnetic field, decreasing with radius, focusses any such ions toward this plane. The amplitude of the vertical oscillations was taken to be 1/4 inch at r = 36 inches, based upon a reference to the M.I.T. cyclotron beam[1] where magnetic focussing is effective for only a short time.

An important, and at first unexpected, fact connected with the free radial and vertical oscillations is a resonant coupling between the two which occurs at certain values of n[10]. The result is a sharp increase in the vertical oscillations causing most of the beam to hit the dee and be lost. In the McGill cyclotron the beam decreases abruptly at 36.65 inches and at this point $n \approx 0.2$.

One other phenomenon should be mentioned as it affects the value one assumes for the radius of curvature of an ion. This is the non-coincidence of the axis of symmetry of the magnetic field and the geometric center of the pole pieces. The discrepancy amounts to about 3/8 inch and is a displacement nearly parallel to the mouth of the dee in a northerly direction. This fact was not discovered until deflection experiments had commenced.

Summary

The synchro-cyclotron beam consists of pulses which would arrive on an internal target at the rate of approximately 200 times a second. Each pulse covers 180° in azimuth and at $r = 36$ inches is approximately .54 inches wide in radius and may be expected to be of the order of 1/4 inch in height. Due to low dee voltages so far necessitated by frequency modulation the Δr per turn is about .001 inches at the outer radii.

Circumstances which have been discovered since the original design was carried out alter the deflection problem as will be seen later. These circumstances are the existence of large free radial oscillation and eccentricity of the magnetic field.

The discussion of the deflector problem which follows immediately will assume that the simple theory only, as outlined in the first portion of the review, is valid and that an ion at a radius r has a radius of curvature equal to r.

General Meaning of Deflection.

From equation (1), $Hev = mv^2/r$ and $Hr = p/e$. It will be noted from figure 1 that Hr has a peak at r = 37 3/4 inches and decreases rapidly for greater r. This means that an ion rotating in an equilibrium orbit at a radius of $r \leqslant 37\ 3/4$ inches can also rotate in an equilibrium orbit at some $r \geqslant 37\ 3/4$ inches, provided only that the Hr values for the two are the same. It is easily seen that the outer orbit is one of unstable equilibrium while the inner one is stable. The two cases depend on whether n, in $H = Ho/r^n$, is greater or less than 1 and it is seen that for $r \leqslant 37\ 3/4$ inches n is less than 1 while for $r \geqslant 37\ 3/4$ inches n is greater than 1.

Thus if an ion can be displaced from the inner orbit to the outer and retain some positive dr/dt it will continue to move so as to increase r. Normally it is sufficient to displace the ion from some orbit near the one where n = 1 to the latter place when it possesses sufficient radial velocity to reach and go beyond the outer equilibrium orbit. Notice in this connection that the beam should be forced to leave the influence of the magnetic field in a fraction of a revolution since n decreases so rapidly the ions otherwise tend to lose any collimation they may have. Deflection then is the problem of producing the desired displacement plus radial velocity.

Although it would seem that the displacement required could be made very small by waiting to pick the ions up at a radius near 37 3/4 inches, it is a fact that in the McGill cyclotron the beam current begins to drop off seriously at a radius of r = 36 inches (figure 2), corresponding to the beginning of a rapid change in n, and at r = 37 3/4 inches it is down by a factor of 10^{-3}. Hence the ions must be displaced a distance of the order of an inch or two to bring them to the region where n = 1.

Deflection Methods Considered

1. Electrostatic Deflection - Fixed Voltage.

This is the method used in most fixed frequency machines. There are two long flat electrodes bent into an approximate circle of radius somewhat greater than the last radius of rotation. These electrodes are separated by about 1/2 inch to form a curved channel whose entrance is at the last radius of rotation, and whose exit, 60° - 70° later, is at or beyond the radius where n = 1. A steady electric potential whose value is usually limited by sparking is applied between the electrodes such as to produce a field of about 35,000 volts/cm. The ions entering the channel have on the previous turn just missed the inner electrode so that on the next turn they must have gained sufficient increase in radius to take them outside, and clear the inner electrode. This condition is fulfilled in fixed frequency cyclotrons using reasonably thin ($\approx$20 mil) leading edges on the inner electrode, high dee voltages (100$\rightarrow$200 Kv) and low total energies ($\approx$50 Mev.)

In the McGill cyclotron the increase in radius per turn at 36 inches is, from Appendix II (using 5 Kv dee voltage and H = 15,730 gauss), 0.0010 inches. This means the inner wall of the channel entrance would have to be of the order of .0005 inches thick in order to allow an appreciable fraction of the beam to enter the deflector. The durability of such a thin piece of material (probably tungsten) under bombardment by the proton beam is not certainly known, and would be a matter for experiment.

The main feature of this type of deflection which discourages its use is the potential required between the electrodes to produce the necessary displacement of the ions. This may be calculated as follows.

Assume the ions must be moved outwards a distance of 1 3/4 inches from $r = 36$ inches after 90° of rotation. From equation (1) the radius of curvature of the ion at 36 inches is given by $r = mv/He$ and if the magnetic force is partially neutralized by an electric force of value xe then the new radius of curvature r' is given by

$$r' = \frac{mv^2}{Hev-xe} = \frac{m\omega^2r^2}{m\omega^2r-xe} = \frac{r}{1-\frac{x}{H\omega r}}$$

or

$$x = (1 - \frac{r}{r'})\, H\omega r.$$

Evaluating this last gives $x = 90$ Kv/cm. The field H is assumed to remain the same, which it very nearly is, over the radial increase considered. (The increase in radius of curvature means that the center of curvature shifts along the line of the radius at the beginning of the deflection, and remains fixed while the force is applied, so that after 90° the radial increase closely approximates the difference between the two radii of curvature.) This value of x requires a potential difference of 114 Kv on the electrodes separated by 1/2 inch. Such a potential difference is very difficult to maintain without sparking. Smaller electrode spacing would help, but it would require much more careful adjustment to allow for the fact that the ion path would not follow exactly the arc of the circle.

2. <u>Electrostatic Deflection - Pulsed Voltage</u>.

The sparking difficulty encountered with a high steady voltage could be expected to be considerably lessened and possibly entirely overcome by applying a voltage pulse which is at its maximum value for only a fraction of a microsecond. This expectation is borne out by experience at Berkeley, California, where a 200 Kv 0.2 μs. pulse is used successfully in the 184-inch cyclotron deflector system.[2]

Also, the use of a short pulse, if it were well timed and had a fast ($\leq$ .05 μs.) rise time, would allow the use of an inner electrode which was split along its median plane to leave a gap equal to the height of the beam. The voltage would not be applied until the beam was entering and leaving the deflector channel, when the ions would rotate undisturbed until on returning to the channel after one of their trips around they would find a deflecting electric field had been applied.

To investigate this method further, it is to be noted that one can count on deflecting only that portion of the ion beam which can be included in the deflector channel width which latter is limited in size by the maximum voltage one can produce and the electric field required for deflection. For an idea of the fraction of the beam which one might expect to get on this account we will assume 1/2 inch width of channel, since we have seen in the previous section this would require about 114 Kv, a voltage figure which is not too unreasonable. (These figures are approximate only, since for split electrodes the effective channel width is smaller than the electrode separation and the voltage would be higher.) From before we have the radial width of the beam at r = 36 inches is .54 inches, then 1/2 inch covers 92% of the beam.

The rise-time of the voltage pulse would have to be of the order of the rotational period which from equation (2),(3), and (5) is 0.045 μs. The timing of the pulse would have to be of the same order of magnitude plus or minus a few complete periods.

Then provided the required voltage pulse could be produced, this method promises a good percentage of beam deflected.

3. Magnetic Deflection.

It has been suggested[2] that the magnetic field be weakened over a selected arc length and radial width at the edge of the magnet by the insertion of suitably designed pieces of iron or conductors carrying current. The insertion of the iron would probably be the easier and the method would probably be satisfactory if one could obtain the required sharp decrease in magnetic field. The latter would have to be shaped such that ions circulating a few mils from the start of the fall-off would be unaffected.

Actually this method in combination with a pulsed electrostatic deflector is now in use[2], the electrostatic deflector being used to shoot the ions into the channel of a magnetic deflector which is thus enabled to be located at a larger radius, decreasing the shimming problem involved in counteracting the effect of the iron channel in the accelerating region of the cyclotron. A further aid to the latter problem is the fact that the ions enter the magnetic deflector with a considerable radial velocity so that the iron channel leaves the accelerating region faster than it would otherwise do so.

Using magnetic deflection alone there is no apparent reason why 100% deflection should not result, and since it is the best method from the point of view of ease of operation when once it had been developed it would seem to be the one which should have been investigated. But its development involved the use of the cyclotron for experimentation, and since the latter was not available in the initial stages of this problem, then method 2 was selected for trial.

DESIGN AND CONSTRUCTION OF APPARATUS

Design

The Electrodes. Since the electrode design governs the magnitude and power of the voltage pulse which is to be applied, it is discussed first.

The design is based on the fact that, for a given electric field strength needed to shift the ions outward a given distance, the electrodes are to produce this field over the width of the ion beam using as low a potential difference as possible. Since, from before, the radial extent of the beam is .54 inches and the field required to deflect the ions a distance of 1 3/4 inches is 90 Kv per cm., then if we were to use plane parallel electrodes the voltage difference required would be 114 Kv. However, using the open type of electrodes preposed this value would have to be increased and one of the first problems was to discover just what the multiplying factor would be.

Rather than make a theoretical prediction, electrolytic tray experiments were performed using enlarged-scale cross sections of various arrangements. Common properties of all the arrangements were that the channel width was chosen to be 1/2 inch and the vertical spacing of the inner bars which was taken to be 1/4 inch. The results of these experiments are given in figures 3 - 7.

Comparison of the graphs shows that figure 7 reveals a uniform field over the greatest width of channel and it is only a little lower than the higher fields in figures 3 and 5. In fact the field is uniform to within 5% over a distance of 0.4 inches and this would mean that we should have an opportunity of deflecting about 75% of the circulating beam. The increase in potential difference required to produce a given field with this arrangement over that using plane electrodes is a factor of 1.06. Hence the voltage pulse which would be required is 120 Kv. Since the energy (and power) needed to produce the voltage pulse depends on the capacity which the electrodes present to the source a capacity measurement was carried out on a set of straight bars placed between the pole pieces of the magnet. A value of 21 $\mu\mu$f. per meter was obtained with all electrodes ungrounded and 40 $\mu\mu$f. per meter with just the outer electrode grounded. (A later check on the actual model used yielded a result of 23 $\mu\mu$f. per meter, electrodes ungrounded.) The length of the electrodes was originally intended to be 120° of arc but certain space limitations imposed by the width of the dummy dee and the position of the probe, necessitated a reduction to 90° which means an electrode length of about 5 feet. Then the deflector electrodes were later built such that they consisted of an outer strip 1 1/4 inches X 1/4 inch X 5 feet and two 1/4 inch X 1/4 inch X 7 feet bars spaced 1/2 inch from, and inside of, the outer strip and separated vertically by 1/4 inch. They were bent to form arcs of circles such that the radius of curvature of the center of the channel was 37 3/4 inches. They require a potential difference of 120 Kv. to produce the required field and present a capacitive load of 23 $\mu\mu$f. per meter. Notice that although vertical oscillations might force the inner bars to a greater separation, this does not necessarily mean a decrease in efficiency of the deflector as one might expect, (the field in the median plane would become more non-uniform and would appear to decrease the radial coverage.), since vertical oscillations would mean that the ions spend more time near the upper and lower bars than in the median plane and one would expect the electric field to increase in value in these regions.

The Voltage Pulse. Ideally the pulse must be applied and rise to its full value while the ions are not in the deflector, and must last for a length of time which will allow that group of ions which has occupied the deflector channel in the previous turn to pass once through. Then we wish to be able to specify the required precision of firing (or what is the same criterion, the allowable time variation, called jitter), the time of rise, and the duration of the pulse. These specifications will be in addition to the magnitude, which we know, and the average and pulse power; the average power will require a knowledge of the repetition rate. These points will be considered separately but not necessarily in the order named.

Jitter.

This can be considered as arising from two sources and we will term the two resultant types, frequency and r.f. phase jitter, respectively, or radial and azimuthal jitter. The former means the variation in the timing of the pulse with respect to the frequency of the oscillator and the latter the variation with respect to some angular position through which the ions periodically pass.

A rough idea of the allowable magnitude of the radial jitter can be obtained as follows. Assume the ion beam is about 0.54 inches wide, the Δr per turn is .001 inches, and the frequency 21.8 megacycles/second. Then the beam will advance its own width in $.54/1.0\ 10^{-3} \times 21.8\ 10^{6} =$ 24.80 μs. and it will travel the effective width of the channel in $.4/.54 \times 24.08 = 18.5$ μs. so that the channel would be full of ions for approximately $24.8 - 18.5 = 6.3$ μs. and the pulse would be required to have a jitter of no more than $\pm$ 3.1 μs. Factors which will influence this figure are a change in Δr per turn due to different accelerating conditions requiring different average energy gains per turn, a possible effective lengthening of the pulse due to the radial oscillations which occur - some ions reaching the region of deflection on their maximum outward swing and others remaining behind due to the inward swing - and a change in the radial width of the beam depending upon whether the equilibrium phase angle ϕ_s increases at any time during the acceleration which would then result in a decrease of radial extent.

To demonstrate how this jitter time is translated for use in electrical circuits, if a resonant circuit is being used as the source of the trigger then it would have to be such as to resonate over a frequency band width of

$\pm \frac{d\omega}{dt} \times 3.1 = \pm 6.10^4$ radians/sec. (assuming a repetition rate of 200 c.p.s.)

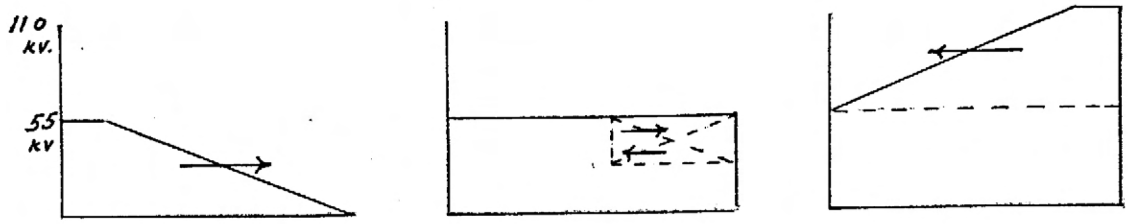
The second type of jitter is that associated with the desire to trigger at a particular phase of the r.f. cycle, ideally that phase at which there are no ions in the deflector. It can be seen roughly that satisfaction of this condition does not gain one a great deal. Since, assume the spiral and channel width of the deflector are such that an ion is in the channel for 45^o of its travel, then it is out for 315^o. If all the ions were bunched in azimuth and the time of rise of the voltage pulse were .001 μs. and if the pulse was allowed to occur at any phase of the r.f., only 12% of the ions would be lost on this account. In reality however a reasonable value of possible time of rise of a voltage pulse can be taken to be 0.03μs. which is 66% of the rotational period of the ions. Also the ions are not bunched in azimuth but can be expected to have a spread of the order of 180^o.

Taking account of these facts and calculating the amount of beam deflected with no phase jitter and with evenly distributed phase jitter, there results quantities whose ratio is approximately 3.5:1. This ratio is not bad enough to worry too much about at the present. However, since the r.f. phase jitter can arise from two sources, first during the pickup of a signal from the cyclotron, and second in the resulting triggering sequence which leads to the final pulse, it was considered desirable to try to eliminate jitter from one of these sources leaving only the other as a future problem. It was decided then to attempt to allow no more than 0.01 μs. jitter in the triggering sequence.

Time of Rise. It is apparent that the time of rise should be at least of the order of magnitude of the rotational period of the ions, which is 0.045 μs., and, in fact, if a large fraction of the ions are going to encounter the same deflecting field, the time of rise must be considerably less than this.

Experience with pulsers suggests that a 0.03 μs. rise time for a high voltage pulse is a reasonable limit and an estimate of beam deflection using 0.03 μs. rise time ($3/4.5 \times 360 = 240^\circ$), 180° azimuthal spread and uniformly distributed phase jitter yields a value for deflection of 9.4%. This estimate coupled with the fact that the deflector channel may cover only 75% of the radial width of the beam, gives an estimate of 7% for the deflected beam - this is about 14 times the size of any beam deflected from a synchro-cyclotron to date. Then a specification for rise time is 0.03 μs.

(1) Feeder + Deflector $\sim$ 0.0368 μs. (one way).
60 Kv. applied to the input with 0.03 μs. rise time.
Infinite impedance at termination of the deflector.
Pictured graphically is the voltage distribution on the line at the end of
(a) 0.036 μs. (b) 0.0518 μs. (c) 0.0736 μs.



$$\text{The average pulse power} = 1/2\ CV^2 = 1/2 \cdot \frac{0.0368.10^{-6}.3.10\ 23.10^{-12}}{0.0736.10^{-6}} \times (1.591 \times 60.10^3)^2 = 15.74 \text{ megawatts.}$$

The current rises from 0 to 414 amperes.
The peak pulse power = 414 X 60 X 10^3 = 24.84 megawatts
Average power = 213 watts.
Length of pulse at 60 kv. must be 0.0436 μs.

(2) Feeder + Deflector $\sim$ 0.015 μs.
120 kv. applied to input with 0.03 μs. rise time.
Infinite impedance at termination of the deflector
(a) after 0.015 μs. (b) after 0.030 μs.

$$\text{The average pulse power} = 1/2 \cdot \frac{0.015.10^{-6}.3.10^8.23.10^{-12}}{0.03.10^{-6}} (120.10^3)^2 = 25 \text{ megawatts.}$$

The current rises from 0 to 829 amperes.
Peak pulse power = 91.2 megawatts
Average power = 136 watts
Length of pulse at 120 Kv. must be 0.034 μs.

(3) Feeder + Deflector $\sim$ 0 + 0.0048 μs.
120 kv. applied to input end with 0.03 μs. rise time.
The deflector can be represented as a capacity of 33 $\mu\mu$f. which must be charged to 120 kv. in 0.03 μs.
Average pulse power = 1/2 $CV^2/0.03.10^{-6}$ = 8.0 megawatts.
The current = 132 amperes.
Peak pulse power = 14.5 megawatts
Average power = 43.8 watts.
Length of pulse at 120 kv. must be 0.034 μs.

Length of the Pulse. This is ideally just the time to allow a 180° spread of ions to pass once through the deflector which is 90° long. This results in a pulse length of 0.034 μs. (jitter and time of rise, if the former were better than 0.01 μs. and the latter faster than 0.02 μs., would have to be considered but these values are not likely to be exceeded.) This figure is not necessarily the pulse length which a modulator would have to deliver because it depends on the manner in which the pulse is transferred to the deflector. The manner of transfer also effects the average and peak pulse power and the voltage which is required so that we shall proceed to a brief survey of this.

Consider the + and - electrodes isolated from each other and from ground, -(this last since the capacity to be charged is thus reduced). Also consider the voltage to be fed via a transmission line of characteristic impedance equal to that of the deflector. (The impedance of the deflector is equal to 1/(velocity of light)(capacity per unit length) = 160 ohms), and take the rise time of the applied voltage to be 0.03 μs. There are three cases worth considering and these are summarised in the accompanying illustration. Where a line is designated "open", there is a resistor across the input end to serve as a d.c. load whose value is much greater than the characteristic impedance of the line. Cases occurring between (1) and (2) have voltages, input currents and powers of intermediate values.

From these results we see that case (1) requires the least modulator voltage to produce the desired potential difference on the deflector. This advantage outweighs the disadvantages of requiring more average power, current and pulse length than case (3), which is the next most suitable case. There is also another disadvantage in case (1) which should be mentioned and that is the high inverse voltages appearing across the source on return of the reflected wave from the load which could cause trouble if thyratrons were being used as switch tubes. However, if we select case (1) then the reflections become merely an argument to avoid the use of thyratrons.

Then to apply a 120 Kv. pulse to the deflector via case (1) with a rise time of 0.03 μs. and lasting for 0.034 μs. we would demand from a modulator a 60 Kv. output at up to 23 megawatts peak power and 213 watts average and having a rise time of 0.03 μs. with a pulse length of 0.044 μs. To allow for inefficiencies let us make the required voltage 150 Kv. and the powers then become 38.9 megawatts peak (24.6 megawatts average during the pulse) and 363 watts average with corresponding currents of 518 amps. peak and 48 ma. average.

The above allows us to set down the output requirements for the modulator which must produce the pulse, as follows.

(1) Amplitude - 75 Kv.

(2) Time of rise - 0.03 μs.

(3) Accuracy of timing (with respect to an initial trigger)- 0.01 μs.

(4) Duration at 75 Kv. - 0.044 μs.

(5) Repetition rate - 200 c.p.s.

(6) Power 38.9 megawatts Peak 363 watts average*

(7) Current 518 amps. Peak 48 ma. average*

* Averages include only rise time and useful pulse length since the voltage wave form at the end of the useful portion of the pulse will vary widely depending on the type of modulator employed.

The Modulator. When faced with the problem of designing a pulser one finds that there are roughly two main classes, the hard tube type and the soft tube or line type pulser. The main differences between the two being first, as the name implies, the type of switch used, and second the storage and use of the electrical energy. A hard tube pulser uses a capacity for a storage element and only a fraction of the energy stored is transferred to the load since one generally desires to maintain a nearly steady voltage during the pulse. The soft tube type transfers all the stored energy to the load during the pulse, and if a condenser serves as the storage element only the first portion of the energy transferred is of use, or if one employs a transmission line (real or simulated) for storage the energy transferred is 100% useful since the line also provides a square shape.

The first type of pulser is rarely considered for high power applications such as ours due to the large number of tubes required to carry the high currents.[(11),(12)] The second type is more suitable, but again because of the high power, the problem is not a simple one. Thyratrons are normally used as switches but their plate voltage is limited: (the best hydrogen thyratron, 5c22, is rated at 16 Kv. and 312 amps.) and we would require a pulse transformer to step up to 75 Kv. This is undesirable since a high power pulse transformer which will preserve a rise time better than 0.1 μs. is not known and its design would be a considerable problem. The only alternative was a spark gap and the one finally chosen was the series gap operated in air. Its efficiency is as good as any other, it can carry large pulse currents, eliminating parallel operations and its anode voltage is not limited in experimental work. Its breakdown promised to be so controllable as to allow the requirements for precision of firing and time of rise to be met and it is inexpensive to construct and maintain.

A word should be said here about the precision of firing of a spark gap since it is traditionally not at all precise. There was very little encouragement to be found in papers published (11),(13) on the result of spark gap pulser experimentation which took place during the war, but from two other papers (14),(15) which were concerned more with the phenomena of sparks it was learned that with over-voltages of 60-100% applied to gaps which were holding off a near-breakdown voltage and with application of ultra violet irradiation the breakdown could be initiated within 0.03 μs. of the arrival of the over-voltage. Although the experiments in the references involved carefully prepared electrodes and were concerned with single discharges as distinct from recurrent ones, they were considered sufficient justification to proceed with plans for a spark gap pulser.

Construction.

The Modulator.

General Description. A schematic diagram of the circuit is shown in figure 8 and pictures of the assembled components in figures 9, 10, 11.

The condensers (c_2, c_3) and (c_4, c_5) are charged in parallel and discharged in series, the chokes L_4 and L_3 behaving as inductances for the discharge period only. This type of circuit is known as the Marx connection and in this case provides an output voltage equal to twice that to which the storage condensers have been charged. A second voltage multiplication occurs during the charging process when after the pulse has passed and the gaps have deionized the chokes $L_1 + L_2 = L$ and the storage condensers form a series L-c circuit which includes a source of d.c. e.m.f. The voltage waveform across the condensers is oscillatory about a steady voltage of value E and by inserting the diode V_5 the condensers charge up in the first half cycle to 2E and are forced to remain in this condition until the switch S_1 is next triggered. If $\pi\sqrt{Lc}$ had been equal to or greater than the repetition rate the diode would not have been required and in the second instance the charging would not be sinusoidal but straight-line. Thus for a voltage E on the condenser c_1, 4E is delivered by the pulser and 8E appears on the deflector due to the doubling at the end of the transmission line. In practice a loss of 20% occurs between E and 8E, all of it in the actual discharge.

Selection of Components.

The values of the components are listed in the table accompanying the diagram. Since some of the larger equipment is either war surplus or, in the case of the X-ray transformer, a gift (from Philips of Montreal), it does not always fit the design requirements and this sometimes accounts for the use of more than one component in places where a single more suitable one might have been used if it had been more readily available. Although the quantity E was specified to be only 18 3/4 Kv. it was considered that it would be safer to design for a higher voltage and in fact for the purpose of calculating power ratings and insulation requirements a figure of 25 Kv. was selected. The discharge is a complete one so that the condensers c_2 to c_5 must be completely recharged each cycle and hence the average current rating for the various components involved must be

$$I = 1/2 \; \frac{c_2c_3}{c_2+c_3} + \frac{c_4c_5}{c_4+c_5} \; \frac{(2E)^2 \cdot 200}{E} = 400 \text{ cE if } c_2=c_3=c_4=c_5$$

These c's should be calculated on the basis that when they discharge in series the current taken from them during the pulse should not reduce the voltage across them by more than 1/10 the original value. Actually the condensers which were immediately available and which were the most nearly suitable were the ones listed in the table and as seen there their rating is nominally .01 μf. each, although they varied from this value by as much as 20% and the four largest were selected. They were such as to give a resultant for c of .0297 μf. (This value produces a 3.21% reduction in voltage during a time of rise of 0.03 μs. on a load of 160 Ω and a 9.3% reduction during a 0.044 μs. pulse on the same load).

Thus $I = 4 \times 2.97 \times 97.10^{-6} \times 25.10^{3} = 297$ ma. The only components which do not meet this current specification are the chokes L_1 and L_2, but for the present this is not at all serious. Two of these chokes are used in series and their cases are connected to h.t. because their insulation rating is unknown.

The resistor R_4 was selected so that it was 10 times the characteristic impedance of the deflector and so that the time constant CR_4 would be (10×0.074) μs.- but not so great that the gaps would have difficulty deionizing before the charging voltage was reapplied. Thus with $R_4 = 2200\Omega$ the first condition is realized and $CR_4 = 6.54$ μs. satisfies the second. For power dissipation six sixty-watt resistors are combined to give the proper value and air is blown over them. In this connection it should be noted that two Western Electric deposited carbon resistors were tested for this job and although the power and peak voltages applied were within their rating they broke down after a few minutes. (Sparking occurred along their surfaces, and had to be removed.) They were returned with a letter of explanation and the company replied recommending a slightly different type which we then ordered but have not tested since the wire wound power resistors have proved satisfactory so far.

The resistor R_6 is to protect the power supply components against short circuits (due to prefiring) which, in the testing stages at least, were quite common and which occur during normal operation due to occasional sparking at the deflector.

The Spark Gaps and Associated Circuit.

The way the circuit operates is as follows. Each half of S_1 and S_2 is set to hold off a voltage slightly less than E. When one switches on, the trigger voltage is adjusted to a value E or a little greater by turning up the h.t. on the 4c35 anode. The indication that the trigger voltage has reached this value is provided by the breaking down of the lower half of S_1 just on the trigger voltage. Now the variac T_3 is turned up until the power supply voltage equals E and, at this stage, since the trigger voltage effectively shorts the lower half of S_1, the upper half breaks down and hence also both halves of S_2 since 2E immediately appears across it. When this first discharge passes, the presence of the charging chokes L_1 and L_2 cause the condensers to be charged to 2E for the next pulse during which a pulse voltage of 4E appears across R_4 and similarly for all successive pulses. Actually the presence of R_6 decreases the voltage across c_1 as soon as the pulsing commences but T_3 can be turned up to account for this. One might be better off without R_6 since it effectively decreases the regulation of the power supply but the X-ray transformer has poor regulation anyway and hence it is felt that the beneficial effect of R_6 mentioned before outweighs its disadvantage.

The features in this circuit which operate to make the triggering precise are the method of voltage division, the introduction of the fourth electrode on S_1 and the mounting of the gaps.

Using capacitors for voltage division is not usual in this application and in fact reference (11) which devotes several pages to the subject does not mention it. The advantages of using capacitors rather than resistors are that the division of the voltage is independent of the repetition rate, their operation is more apparent - hence their design values are more easily selected - and in practice one can approach more nearly the theoretical maximum voltage operation of the gaps. The last advantage is the one which aids in precise triggering.

The fourth electrode on S_1 is a small tungsten wire (40 mil diameter) which is mounted on top of the center electrode and spaced about 1/32 inch away from it. When the trigger voltage is applied to the middle electrode (figure 8) the choke and condenser attached to the small electrode keep the latter at a steady potential, until the difference between the two electrodes is about 2000 volts or so and then a breakdown occurs between them. This small spark provides enough ultra-violet illumination of the lower gap so that initial ionization is present for breakdown in the application of the overvoltage. The breakdown of the lower gap in turn illuminates the top half of S_1, and it too breaks down with small delay. Since S_2 is mounted on top of and facing S_1 there is a minimum delay in its operation when the overvoltage arrives (via R_4). In figure 12 is shown a picture of the gaps mounted.

How well this arrangement decreases jitter is observed in figures 13 (a),(b),(c) which are 15 second exposures, with the repetition rate of the pulser being 150 c.p.s. The scope was triggered by the same signal which triggered the gaps.

The resistor R_2 is chosen so that the time constant R_2 $(c_7+c_6) = 1/10$ the repetition rate of the pulser and so that R_2 represents a load = 10 R_4. R_3 is similarly chosen 10 R_4. L_5 and c_6 are more or less arbitrary remembering c_6 should be kept as small as possible.

L_3 and L_4 were chosen roughly to satisfy the requirement that not more than about one tenth of the load current should build up in them during the pulse and then a final test was made by adding or subtracting to their values to produce a constant pulse amplitude. If sufficient current builds up in them they can oscillate with the condensers c_2-c_3 and c_4-c_5 and cause the gaps to fire and refire after the main pulse passes thus delaying deionization, and if their values are not well adjusted they will leave the condensers slightly charged sometimes one way and sometimes the other, which results in fluctuations of the final value of the charged potential.

There only remains to mention the blowing of the gaps. It was found that to work at voltages of more than about 8 Kv. per switch precautions had to be taken to ensure that a high velocity stream of air was directed across each gap and allowed to travel beyond it unobstructed for another 6 inches or so. The high velocity was provided by making jets (one for each gap) with small outlet diameters ($\gtrsim$ 1/16 inch). The velocity of the air is roughly .20 cubic feet/sec./gap (calculated from rate of fall of pressure in compressor tank). The gaps are shown separately in figure 12 and mounted, in figure 9.

The Sub-Modulator

The circuit diagram is shown in figure 13. The unit is located in the cyclotron room beside the modulator.

The hydrogen thyratron 4C35 is rated at 8 kv. hold-off voltage and 90 amps pulse current. Coupled with the 2.9:1 pulse transformer it can provide a 23 Kv. pulse with a time of rise of .1 μs. This is ample triggering for an E (in the modulator) of 25 kv. (160 kv. on deflector).

The 4C35 is fed by a one-shot cathode coupled multivibrator. The trigger pulse is 200 - 300 volts in amplitude with a rate of rise of about 1200 volts/μs., more than ample for precise timing (reference (11) quotes a figure of 600 volts/μs. as being necessary). The input to the multivibrator must be about -50 volts. Actually it is thought now that the multivibrator unit is more elaborate than is required, but when first built it was felt that hard tubes would be more jitter-free than thyratrons. Now, after some experience, it is considered that 884's or 2050's would allow precise control to better than .01 μs. and they would be much simpler. For that matter it is possible that the pulse taken directly from the trigger unit might be used on the 4C35.

Trigger Unit.

Figure 14 gives a schematic illustration of the circuit, which is due to Ray W. Jackson. The unit is incorporated in the pulse timing apparatus located in the control panel of the cyclotron. The only addition to it necessary was an 884 thyratron yielding a low impedance negative pulse to feed 100 feet of RG8U cable, leading to the sub modulator.

The trigger unit is fully described in Dr. Jackson's thesis.[16] In brief, it contains a circuit which resonates with the r.f., picked up on a probe in the dee lines, at any desired frequency in the range 26 to 21 megacycles/sec. Since this would produce two pips per modulation cycle, only one of which is desired (the one situated on the decreasing frequency side), a second circuit follows which discriminates between the two cases. It does so by virtue of the fact that the peak of each resonance is displaced from the centre frequency, one downward, for $d\omega/dt$ negative, and the other upward, for $d\omega/dt$ positive. The second circuit is tuned to the lower of the two frequencies and the result is rectified and amplified to give a negative output pulse of about 100 volts.

Voltage Transfer.

Three 18 ft. lengths of 52Ω, 30 kv. shielded cables were used for this purpose. The input end of them is seen in figure 10. They are connected at both ends in series such that the input and output impedances are 156Ω, i.e. almost equal to the deflector impedance. Although they would theoretically only stand 90 kv. across them, it is expected that higher voltages are safe as long as they are of the short durations ($\approx .05\mu s$) encountered here, and in fact up to 115 kv. has been applied so far without any sign of trouble.

The leads-through entering the vacuum chamber are shown in figure 15. The insulation is lucite and the stand-off portions are built up from lucite blocks with O-rings as vacuum seals. It was found that the cavity type of stand-off was necessary to prevent sparking along the insulator surface in the vacuum.

The leads going from the chamber wall to the deflector were two parallel lengths of 1/4 inch copper tubing, set with about 1/4 inch clearance between them to preserve the characteristic impedance of the deflector. The tubes slid over banana plugs at the input end and were held by screws to the deflector electrodes.

Output of Pulser

The voltage pulse was monitored at the ends of the cables where they are attached to the leads-through at the vacuum chamber wall (figure 15). As well as giving a direct indication of the pulse one expects to find on the deflector, this monitoring position is practically free from high frequency hash originating in the sparks and which is found to occur at the input ends of the cables.

The monitoring device was a capacitive voltage divider employing an unheated 8013 rectifier tube as a small high voltage capacitor. It was mounted on a small aluminum box and its lower third was shielded. A 200 $\mu\mu$f. mica condenser was placed inside the box to serve as the lower half of the dividing network. Three feet of shielded RG8U cable were employed to take the pulse to a Tektronix type 511 AD oscilloscope where it was applied directly to the deflection plates. Including all capacitances a voltage division of approximately 327:2 resulted.

A trigger pulse taken from a test unit was used to trigger the oscilloscope and the sub-modulator unit of the pulser.

Pictures of the oscilloscope traces are shown in figure 16. The sweep speed was .1 μs./cm., the repetition rate 150 c.p.s., and the exposure time was 15 seconds. The voltage on the modulator power supply was 9.3 Kv, implying a peak of 37.2 Kv. for the pulse on each cable. (This just happened to be the voltage at which the gaps were set at the time. Almost double this value of voltage has been used since).

The first two pictures are the positive and negative pulses respectively and the third results from connecting the monitor lead to the top gap of S_1. This provided a calibration pulse since the magnitude of the voltage here was known from previous measurements to be always twice the power supply voltage. Notice that the negative cable lead goes positive first, corresponding to the overvolting of S_2.

Tracings of the two pulses were fitted together and a plot of the potential difference between the two versus time yielded figure 17 which represents the time variation of potential difference between the two deflector electrodes. From this graph it is concluded that the time of rise of the pulse from 10% to 90% of its peak value (which is 80% of its possible peak value) takes .027 μs. and it remains above the 90% value for 0.045 μs.

The jitter time was not measurable from these traces but on magnification of the beginning of the sweep by a factor of 5 (provided for in the oscilloscope) the uncertainty appeared to be of the order of .005 μs. This is an upper limit since some of it may occur in the triggering of the oscilloscope sweep. The jitter increased noticeably when the power supply voltage was reduced by about 15%.

The Electrodes.

Experience showed that insulator materials such as lucite and mycalex were unsuitable for use in mounting the deflector electrodes, since once a spark or two had passed along the surface of these materials they tended to char and promote further sparking. The material selected finally was porcelain. Pictures of one of the deflectors used, (more than one had to be tried as it happened), illustrating the mounting are shown in figures 18, 19, and 20.

It was possible to clean and assemble the deflector outside of the vacuum chamber and then pass it through the hole in the vacuum chamber sidewall through which the deflector leads-through were put. The hole is 7 3/4 inches in diameter. For transporting the deflectors whose electrodes were four 1/4-inch square copper bars, a rigid 'back bone' consisting of 1 inch X 1/4 inch X 5 ft. dural metal was screwed to the three deflector supports, and removed when the particular deflector was in position.

The impulses on the deflector electrodes were such as to produce forces at the supports of 75 and 150 lbs and moments of 29 and 0 lbs.-ft. but the impulses were so short as to cause negligible movement. Since the effects were opposite for the positive and negative electrodes the net external effect on any support was practically zero.

EXPERIMENTAL WORK

Operating Conditions.

See Appendix II for general conditions. A few pertinent points which must be kept in mind will be mentioned here.

Due to the relatively high pressure which exists in the cyclotron vacuum chamber, the deflector voltages obtained were limited by breakdown and were not as high as they were planned to be. The poor vacuum appeared to be due to two causes which can be divided into two categories, each accounting for a rise in pressure of a factor of 2 to 3.

The first category contains just the one cause, which was the amount of H_2 required for steady operation of the ion source. The second category includes two causes and these are mainly connected with the deflector investigations. They are the continual introduction of fresh material during the early search for suitable insulators and during the later investigations of complete new deflectors, and the build up of gas in all the surfaces in the vacuum chamber, which attended the continual opening of the chamber needed for replacement and adjustment of deflector parts. This theory seemed to be justified when there was an interval of six months between the first set of deflector experiments and the next. The pressure had dropped to 10 $m\mu$., (20 with H_2 on) and after the deflector experiments had been in progress for a few days it rose to 28 $m\mu$. (55 with H_2 on). Actually the difficulty due to poor pressure seems to arise largely from the fact that the gas around the dee is ionized and promotes a 'blue glow' which serves to initiate breakdown at the deflector.

It was discovered after some weeks of experimenting that the ions were rotating as if the centre of the magnet field was about 3/8 inch away from the geometric centre of the pole pieces along a line at an angle of 24° to the dee mouth and bearing north. This would tend to increase the radius of curvature observed at the probe position by about .2 inches, but would decrease the one observed at the deflector entrance by about .3 inches. Thus the entrance of the deflector would have to be moved .3 inches from any radial position decided upon when assuming the field symmetrical.

In addition to the above, work done by W. Henry of this laboratory indicates that a free radial oscillation of from 1 - 2 inches amplitude exists in the region of r = 36 inches. This information indicated changes in the deflector cross section and positioning based on theory used at Berkeley, California(2) (although a clearer development of the theory given there can easily be worked out by using in place of their equation (3), the equation $\rho = c \cos(\omega_r t + \alpha) + \delta_2$ and by proceeding in the usual manner to apply initial conditions).

Then, taking account of the above factors, the deflector experiments consisted solely of putting deflector models into the cyclotron and testing for beam deflection; using the methods described below.

Notice that some of the experiments utilize a very long pulse, derived from rectifying the short one. This was to test the effect of a 'd.c.' voltage on the deflector. (It was found that a long pulse could be used without sparking, where, as noted before, d.c. voltage could not.)

Detection of the Cyclotron Beam.

The usual method for monitoring the beam is to read the current incident on a copper block mounted on the end of the cyclotron probe. A type H galvanometer (sensitivity, 0.004 μa per mm.) is the indicating device and the current measured in this fashion is of the order of .1 μa. A plot of the current versus radius at the outer radii using such a detector is given in figure 2. Note that it drops to zero at 36.65 inches, the radius where $n = -\left(r/H \cdot dH/dr\right) = .2$.

For the deflection experiments a more sensitive detector was desired and a d.c. current amplifier was constructed having a gain up to 10^4. This proved satisfactory except for the fact that its response was slow due to the combination of high input resistance at the electometer tube and high capacity of the shielded cable carrying the current to the control room, and also because there was a tendency at times to detect and amplify r.f. pickup from the deflector pulse, obscuring beam current readings.

Before any serious attempts were made to correct the faults of the d.c. amplifier a satisfactory detector was found consisting of an anthracene crystal on the end of a lucite rod which butted on a photo multiplier tube. The tube was mounted in an iron compartment, and this was attached to a brass pipe of a size to fit the regular probe opening in the cyclotron. The lucite rod projected from the brass pipe through a vacuum seal in a brass plug closing the end of the pipe. The rod and crystal were bound with aluminum foil and tape for light tightness. The size of the crystal was about 1/2 inch X 1/4 inch X 1/4 inch. The probe was built by Donald Tilley for another experiment but was kindly loaned for this work. This crystal detector proved to be stable, rapid in response and immune to spurious effects. Its sensitivity even when blackened by the heat of the beam was of the order of 5×10^3 (950 volts applied to the photo tube).

When deflection was detected and the deflector trigger tuned for best results a dental X-ray film was put in to demonstrate that the ions were actually being displaced as assumed. The results on the films were obscured slightly by X-rays from the deflector, but the ion beam was intense enough to cause solarization which stood out in contrast to the dark background. Orthographic process paper was also used, but it displayed no advantage over the X-ray film, and the latter came wrapped ready for use.

Deflection Trial Number 1.

Cross-section of deflector - see figure 7.

Radius of curvature (middle of channel) 37 3/4 inches

Entrance at 35.82 inches

Exit at 37 3/4 inches.

Deflector arc (as in all trials) 87°

Deflector voltage (11.0 X 8 X 4/5) = 70.4 kv.

Figure 21 is a plot of current vs radius with the deflector off and with it on. Actually the deflector 'off' meant only that the trigger tuning was off-tune and the deflector was still being pulsed but at a different place in the modulation cycle.

The results of this experiment were poor although one could not expect too much with such a low voltage and high pitch of deflector spiral since the ions would be slipping out of the deflector and receiving an inward 'kick' as they left.

Trial Number 2.

Cross-section - figure 7 except that the inner electrodes were separated by about 3/8 inch

Radius of curvature - as before

Facing Page 36.

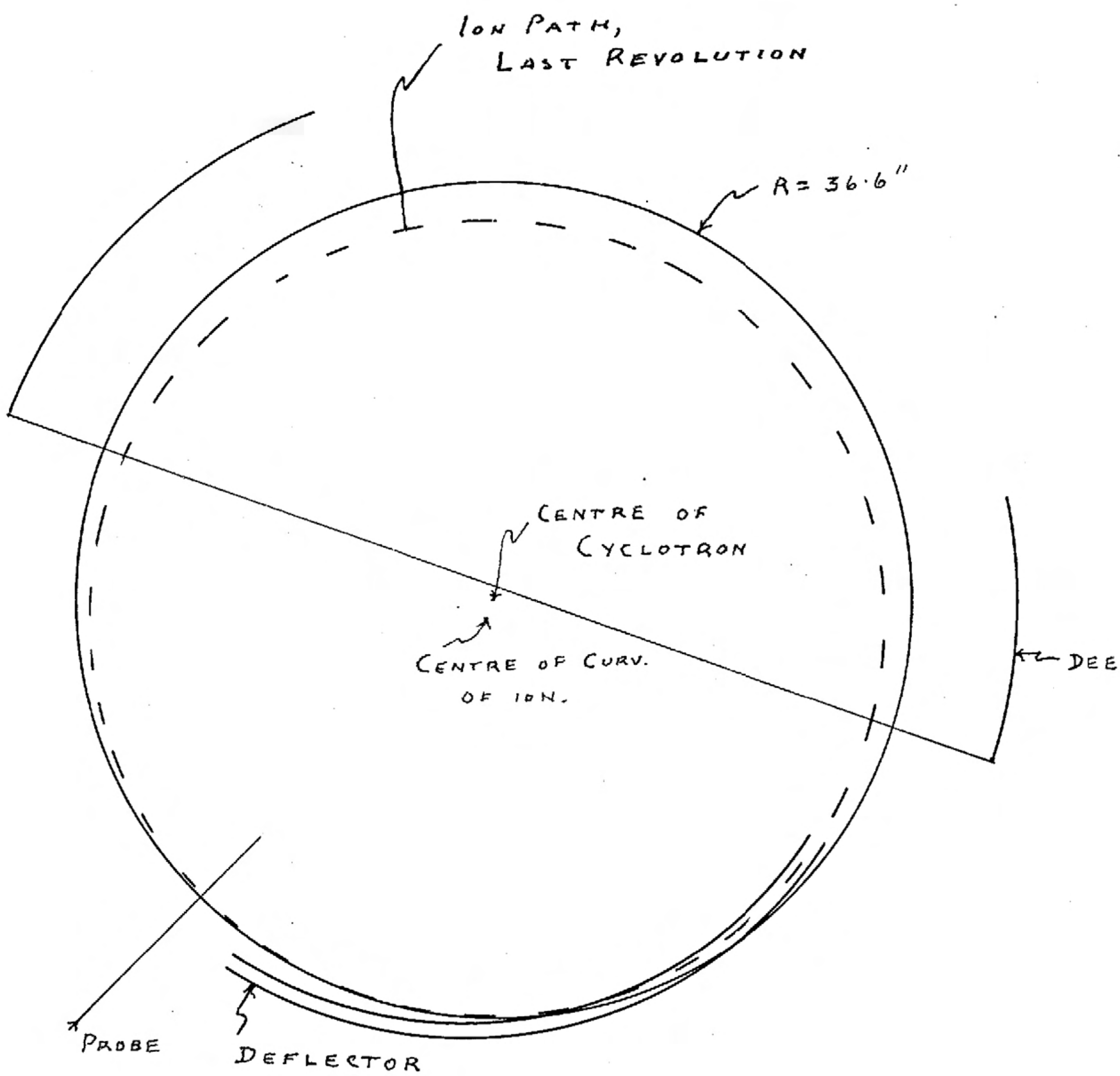


Diagram illustrating positioning of deflector, in trial 3, to take account of free radial oscillations.

Entrance at 36.6 inches

Exit at 37.5 inches

Deflector voltage 81 kv. and 102 kv.

The deflector and vacuum conditions were good enough to run for a minute or two at the higher voltage. Advantage was taken of this to insert an X-ray film, for a minute exposure, whose leading edge was at r = 36.5 inches. This value of r is 0.15 inches back of the main beam, remembering that the ions rotate off centre.

A plot of i vs r is shown in figure 21 and a reproduction of the film is in figure 24(a).

The results of this trial were considerably better than those of number 1 since between r = 37 inches and 37 1/4 inches a fraction of the beam that amounted to .43% of the ions circulating at 36.2 inches had been deflected at least .65 inches. The film shows deflection out to 37.4 inches.

After this experiment it was decided to assume a radial oscillation of 1 1/4 inches amplitude and trial number 3 resulted.

Trial Number 3.

Cross-section of deflector - figure 6 except that the vertical separation of the bars was made 9/16 inch

Radius of curvature 36.55 inches

Entrance of deflector at 35.4 inches

Exit at 37.60 inches

Deflector voltage 86.4 kv.

The calculations of the entrance and exit radii for the deflector were based on the theory given in reference (2).

Results are shown in figures 22 and 24(b), the film in the latter having been exposed 5 minutes.

These results show that 3.2% of the beam circulating at 36.1 inches is deflected to a radius of (37.4 to 37.65 inches) - a distance of at least 1 to 1.25 inches from where it was picked up. As a percentage of the beam which circulates at 36.1 inches without the deflector in, it amounts to 1.7%.

An experiment was done with both entrance and exit pulled out 1/2 inch and the results were exactly the same as for the above.

Trial Number 4.

Dimensions and position as for the first experiment of trial 3 but a long (RC = 330 μs.) +ve pulse derived from the rectification of the pulse on the +ve modulator lead applied to all four deflector bars.

See figure 23 for the results.

This experiment was done 'to see what would happen', as, with voltage applied in this fashion, the ions are pushed inward when they spiral out near the deflector and later, when they get beyond r = 35.6 inches, they are alternately pushed out and pushed in. The plot of i vs r demonstrates that some deflection occurs and it is a gradual process since otherwise there would be a decrease in current for $r \approx 36.6$ inches, as in figure 22. A film test confirmed this conclusion since no deflection appeared on the film. This type of deflection, although not producing as large an increase in current at r = 37.3 inches as in the previous experiment (.51% as compared with 1.7%), might prove to be of use later and is recorded here as a matter of interest.

Other combinations of long-pulse potentials were tried such as 1. all bars negative, 2. positive on inner bars, outer grounded, and 3. positive on outer, inner grounded, but all these gave negligible results.

CONCLUSIONS

The best results were obtained from trial number 3. They must be considered only as a first try since an increase of deflector voltage from 86.4 kv. to 96 kv., when the probe was at r = 37.6 inches, produced an increase in deflected beam of 30%. (The increased voltage could not be maintained steadily.) Hence it is apparent that, when conditions allow, a considerable increase in deflection should occur due to the application of higher voltages. Also, when one compares the results of trial 1 to trial 3 it is apparent that allowing for radial precession improves the deflection and, when more data is available concerning this effect or when it is possible to carry out a series of experiments to obtain optimum adjustment, a further increase should result.

Another factor which should multiply deflection, by 10 times or so, would be the correct phasing of the deflector voltage to time it correctly with the radial precession and with the r.f. phase (the effect of radial oscillation was not considered in the previous calculation of percentage deflection.)

To compare these results with deflection in other synchro-cyclotrons, there is only one known to have an external proton beam and that is the 184-inch cyclotron at the University of Berkeley, California.[9] From a circulating current of 1 μa.[17] the deflected beam is 10^{-10} amps, i.e. a deflection of .1%. In an article giving an account of the performance of their deflector as used for deuterons[2] it is apparent that the beam is reduced by a factor of 3 when passing through their magnetic channels since only 1 1/2% can enter the 1/4-inch wide channel and it is claimed that 1/2% emerges. Taking the same factor of reduction for the proton beam it would mean that .3% enters the channel. This is to be compared with 1 to 2% which would be possible in the McGill case.

The deflection which has been obtained is not yet satisfactory so far as having a beam outside the vacuum chamber is concerned, since the radius of curvature of an ion, decreased by an amount equal to the amplitude of the free radial oscillation, is too small to allow the ion to spiral out fast enough when the deflecting force is no longer present. A solution to this difficulty would be the introduction of an iron channel such as is used for the 184-inch cyclotron.[2] A similar device is being planned at the University of Chicago.[18]

One further note of importance is the vertical concentration of the deflected beam as apparent in figure 24.

APPENDIX I

To develop some relations first, we have that

$$E = mc^2 = m_o\, bc^2$$

$$\therefore\ \frac{dE}{dr} = m_o\, c^2 \frac{db}{dr} \tag{6}$$

but from (5)

$$\frac{db}{dr} = \frac{1}{b}\ \frac{p}{m_o c^2}\ \frac{dp}{dr} \tag{7}$$

and from (4)

$$\frac{dp}{dr} = e\ H + e^2 r\ \frac{dH}{dr}$$

$$= He\ (1 - n) \tag{8}$$

where

$$n = -\frac{r}{H}\ \frac{dH}{dr} \tag{9}$$

$$\therefore\ \frac{dE}{dr} = m_o c^2\ \frac{1}{b}\ \frac{He\ r}{m_o{}^2 c^2}\ He(1 - n)$$

$$= \frac{H^2 e^2 r}{m_o} \cdot \frac{1 - n}{b} \tag{10}$$

$$\therefore\ \Delta r = \frac{m_o}{H^2 e^2 r} \cdot \frac{b}{1-n}\ \Delta E \tag{11}$$

From equations (2) and (9) we have

$$\frac{d\omega}{\omega} = \frac{dH}{H} - \frac{dm}{m} = -\frac{n dr}{r} - \frac{dm}{m} \tag{12}$$

Equations (6), (7), (4), and (2) give

$$dE = \frac{pdp}{m} = vdp = \frac{vE}{c^2}\ \omega\ (1 - n)\ dr$$

whence

$$\frac{dr}{r} = \frac{dE}{E}\ \frac{c^2}{v^2}\ (1 - n) \tag{13}$$

Now

$$\frac{dm}{m} = \frac{dE}{E}$$

and combining this with (12) and (13), we have that

$$\frac{d\omega}{\omega} = -\frac{dE}{E}\left(1 + \frac{n}{1-n}\ \frac{c^2}{v^2}\right) = -K\ \frac{dE}{E} \tag{14}$$

(14) is an expression for the fractional change in ω as a function of the fractional change in E, the ratio $\frac{c^2}{v^2}$ and the behaviour of the magnetic field as described through the quantity n.

Now consider an ion being accelerated in the cyclotron such that it gains just that amount of energy which will change its frequency (through (14)) to keep it in step with the changing applied frequency. This ion is said to be travelling in a synchronous orbit and the subscript s will be used to denote the quantities associated with such an ion.

Let us say now that we have ions which are not in the synchronous orbit but whose ω, r, and E differ from those values associated with the synchronous ion by amounts $\Delta\omega$, Δr, and ΔE which are small compared to ω_s, r_s, and E_s respectively. Then from (14)

$$\frac{\Delta\omega}{\omega_s} = - \frac{\Delta E}{E_s}\left(1 + \frac{n}{1-n}\ \frac{c^2}{v_s{}^2}\right) = - K\,\frac{\Delta E}{E_s} \qquad (15)$$

The problem now is to show that there exist ions whose $\Delta\omega$ and ΔE execute stable oscillations about the equilibrium value E_s. Bohm and Foldy do this for the general case where acceleration is produced by a number of voltage gaps and by a changing magnetic induction. A summary of their development will be given with some remarks as to the application of the theory to the synchro-cyclotron.

It is assumed that these are i accelerating gaps located at azimuths θ_i, and $V_i \sin\left(\int\omega_s dt + \alpha i\right)$ is the potential on the i^{th} gap. If θ is the azimuth of the particle in its orbit, the phase ϕ is defined as $\phi = \theta - \int_0^t \omega_s dt + \alpha$. The energy gain on crossing the

i^{th} gap is $eV_i \sin(\omega_s dt + \alpha_i)$ or $eV_i \sin(\theta_i + \alpha_i + \alpha - \phi)$ and the energy gain per turn is the sum over i of these expressions. By adjusting α_i for each gap such that $\alpha_i = \pi - (\theta_i + \alpha)$, the energy gain per turn is given by $\Sigma e V_i \sin\phi = eV\sin\phi$, $V = \Sigma V_i$. Notice that for a synchro-cyclotron the gaps are located at $\theta_i = 0, \pi, 2\pi$ etc. and $V = V_1 + V_2 = 2V'$ where V' is the peak dee voltage.

Consider now the following. The work per turn done on the particle is equal to its energy gain per turn or

$$\frac{2\pi}{\omega} Fv = eV\sin\phi - e\frac{d\Phi}{dt}$$

(neglecting radiation loss which is justified in the case of 100 mev protons), where $-e\frac{d\Phi}{dt}$ takes account of the change in total magnetic flux enclosed by the orbit and F is the sum of the forces which act on the particle in a single turn. But

$$Fv = F\omega r = \omega\frac{d}{dt}(\text{angular momentum})$$
$$= \omega\frac{d}{dt}(r\ p)$$

and

$$\Phi = 2\pi r A$$

where A is the θ-component of the vector potential. (All units e.m.u.) Therefore the equation can be written

$$\frac{d}{dt}(r\ p + erA) = \frac{eV}{2\pi}\sin\phi. \qquad (16)$$

Before proceeding further let us develop a few more relations which will be necessary. From the definition of ϕ

$$\frac{d\phi}{dt} = \omega - \omega_s = \Delta\omega$$

and (14) gives

$$\frac{\Delta E}{\omega_s} = -\frac{E_s}{\omega_s K}\dot{\phi} \qquad (17)$$

Equations (8) and (10) and $E_s = mc^2 = \frac{He}{\omega_s} \cdot c^2$

give

$$\dot{p}_s = \frac{E_s}{c^2} \omega_s (1 - n) \dot{r}_s$$

and

$$\dot{r}_s = \frac{\dot{E}_s}{E_s} \frac{r_s}{v_s^2} c^2 \frac{1}{1-n} = \frac{\dot{E}_s}{E_s} \frac{c^2}{\omega_s^2} \frac{1}{(1-n)\, r_s}$$

whence

$$\dot{p}_s r_s = \frac{\dot{E}_s}{\omega_s} \qquad (18)$$

also

$$\Delta p r_s = \frac{\Delta E}{\omega_s} = - \frac{E_s}{\omega_s^2 K} \dot{\phi} \qquad (19)$$

Now in the left hand side of (16) replace r, p and A by $r_s + \Delta r$, $p_s + \Delta p$ and $A_s + \Delta A$ and obtain

$$\frac{d}{dt} \left(r_s p_s + r_s \Delta p + p_s \Delta r + e r_s A_s + e A_s \Delta r + e r_s \Delta A \right)$$

which, on recalling

$$H = - \frac{1}{r} \frac{\partial}{\partial r} (ra) \text{ and } Her = p,$$

gives l.h.s. $= \frac{d}{dt} \left(r_s p_s + e r_s A_s + r_s \Delta p \right)$.

Noting that

$$\frac{d}{dt} (r_s p_s + e r_s A_s) = \frac{eV}{2\pi} \sin \phi_s$$

from (16) and applying (19), equation (16) becomes

$$\frac{d}{dt} \left(- \frac{E_s}{\omega_s^2 K} \dot{\phi} \right) + \frac{eV}{2\pi} \sin \phi_s = \frac{eV}{2\pi} \sin \phi$$

or

$$\frac{d}{dt} \left(\frac{E_S}{\omega_s^2 K} \dot{\phi} \right) + \frac{eV}{2\pi} \sin \phi = \frac{eV}{2\pi} \sin \phi_s \qquad (20).$$

This is the same form as the equation for a pendulum having constant torque and hence ϕ is oscillatory about ϕ_s but not symmetrically so. It can be shown that the motion is unstable if ϕ reaches a maximum swing greater than $(\pi - \phi_s)$ and that ϕ increases without limit. In the case of an ion this might occur part way through the acceleration if for some reason ϕ_s were to increase, the ion would then slip out of the group being accelerated, and with a + ve increasing $\emptyset$ it would have an average energy gain of zero, and would remain at the same radius until scattered or decelerated on the rising portion of the r.f. modulation cycle, or picked up and accelerated further in the next accelerating sweep.

To solve (25) for $\dot{\emptyset}$

$$\frac{d}{dt}\left(\frac{E_s}{\omega_s^2 K}\dot{\emptyset}\right) = \frac{d}{d\emptyset}\left(\frac{E_s}{\omega_s^2 K}\frac{\dot{\emptyset}^2}{2}\right)$$

$$\therefore \frac{E_s}{\omega_s^2 K}\frac{\dot{\emptyset}^2}{2} - \frac{eV}{2\pi}\cos\emptyset = \frac{eV\sin}{2\pi}\emptyset_s \times \emptyset + c'$$

or

$$\dot{\emptyset}^2 = \frac{\omega_s^2 K}{E_s}\frac{eV}{\pi}\left\{\cos\emptyset + \emptyset\sin\emptyset_s + c\right\}$$

Putting $\emptyset = 0$ when $\emptyset = \emptyset$ max $= \emptyset m$ gives

$$\dot{\emptyset}^2 = \frac{\omega_s^2 K}{E_s}\frac{eV}{2\pi}\left\{\cos\emptyset - \cos\emptyset_m + (\emptyset - \emptyset_m)\sin\emptyset_s\right\}$$

The $\Delta E \sim \dot{\emptyset}$ can be obtained from this equation and (17)

$$\therefore \Delta E = \sqrt{\frac{E_s}{K}\frac{eV}{\pi}}\left\{\cos\emptyset - \cos\emptyset_m + (\emptyset - \emptyset_m)\sin\emptyset_s\right\}^{1/2}$$

while

$\Delta E \sim \dot{\emptyset}_{max} = (\pi - \emptyset_s)$ is

$$\Delta E = \sqrt{\frac{E_s}{K}\frac{eV}{\pi}}\left\{\cos\emptyset + \cos\emptyset_s + (\emptyset + \emptyset_s - \pi)\sin\emptyset_s\right\}^{1/2} \qquad (21)$$

From equation (13) the corresponding Δr is

$$\Delta r = r(1-n)\frac{c^2}{v^2}\sqrt{\frac{eV}{E_s K}\pi}\left\{\cos\emptyset + \cos\emptyset_s + (\emptyset + \emptyset_s - \pi)\sin\emptyset_s\right\}^{1/2} \qquad (22)$$

The maximum allowable ΔE and Δr for any given $\emptyset_s$ is obtained by putting $\emptyset = \emptyset_s$ in (21) and (22)

$$\therefore\ \Delta E_{max} = \sqrt{\frac{E_s}{K}\,\frac{eV}{\pi}}\ \left\{2\cos\phi_s + (2\phi_s - \pi)\sin\phi_s\right\}^{1/2} \qquad (23)$$

and

$$\Delta r_{max} = (1-n)\,\frac{c^2}{v^2}\sqrt{\frac{eV}{E_s K\pi}}\left\{2\cos\phi_s + (2\phi_s-\pi)\sin\phi_s\right\}^{1/2} \qquad (24)$$

A plot of the dimensionless quantity

$\Delta E\sqrt{\frac{\pi K}{E_s eV}}$ vs ϕ for various ϕ_s from equation (21) is given in Bohm and Foldy's paper. Although the contribution of $-\frac{d\Phi}{dt}$ to the energy gain achieved in a synchro-cyclotron is small (5000 volts in the McGill case) it plays a fairly important role in the development of the theory and may not be discarded at the beginning. (This may be seen on following through the expansion of the left hand side of (16)).

APPENDIX II

Note on Operating Conditions of McGill Synchro-Cyclotron.

Magnetic Field. The calculations requiring a knowledge of H vs. r used a curve which was obtained with 600 amperes in the magnetizing coils. This produced a centre-value for H of approximately 16,300 gauss, and a value at r = 36" of 15,730 gauss. This curve is shown in graph and was supplied by Dr. Murray Telford of this laboratory.

The curve is possibly only a good approximation now since in an effort to lower the beam which was found to be circulating above the median plane half of each of the lowest two pancakes of magnetizing coils were shorted out. To compensate for this, and for certain other reasons, the experiments in this paper were done with 650 amperes magnetizing current.

Repetition Rate. The design figure used in the calculations was 200 c.p.s. In the experiments this figure was never obtained, the first experiments being conducted at about 150 c.p.s. and the last ones at 70 c.p.s.

Dee Voltage. This ranged from 5.8 kv. to 6.5 kv. depending on how breakdown conditions in the cyclotron were.

Beam Current. Refer to graphs.

Pressure. For the deflector experiments, due to the fact that so much opening and closing of the vacuum chamber was necessary, and that the material in the deflector probably didn't have sufficient time to outgas, the pressure was fairly high, approximately 30 millimicrons without the ion source hydrogen on, and double this with the hydrogen on. The amount of hydrogen to be supplied to the ion source was just that which would produce reasonably steady operation, less than this the beam current readings fluctuated so badly as to be useless in a search for beam changes. The pressure gauge was located directly over one of the vacuum tank diffusion pumps which in turn were on the side of the bacuum chamber opposite to the location of the deflector so that the pressure readings represented minimum values of pressure at the deflector.

When it happened that the vacuum tank was left practically unopened for a period of six months, the pressure dropped to 9 millimicrons and 20 millimicrons without and with ion source gas respectively.

· Calculated Values for Some Parameters at r = 1" and r = 36".

Using equations (2), (5), and (11) we have the following

	Quantity		r = 1"	r = 36"
1	c	cm/sec.	$2.9979 \cdot 10^{10}$	
1	m_o	grams	$1.672 \cdot 10^{-24}$	
1	e	e.m.u.	$1.602 \cdot 10^{-20}$	
1	e/m_o	e.m.u./gram	9579	
2	H	gauss	16,300	15730
2	n		0	.0825
2	ΔE/turn	Kev.	5	5
1	m_oc^2	Mev.	938.18	
	b		1.0008	1.1006
	m	grams	$1.672 \cdot 10^{-24}$	$1.840 \cdot 10^{-24}$
	mc^2	mev	938.93	1032.56
	E_K	mev	.05	94
	ω	radians/sec.	$1.561 \cdot 10^{8}$	$1.369 \cdot 10^{8}$
		megacycles/sec.	24.8	21.8
	Δr/turn	inches	.10	.0010

[1] Values taken or calculated from results in reference.

[2] Values assumed from measurements.

The above figures do not take into account radial precession and assume the axis of symmetry of the magnetic field passes through the centre of the pole pieces.

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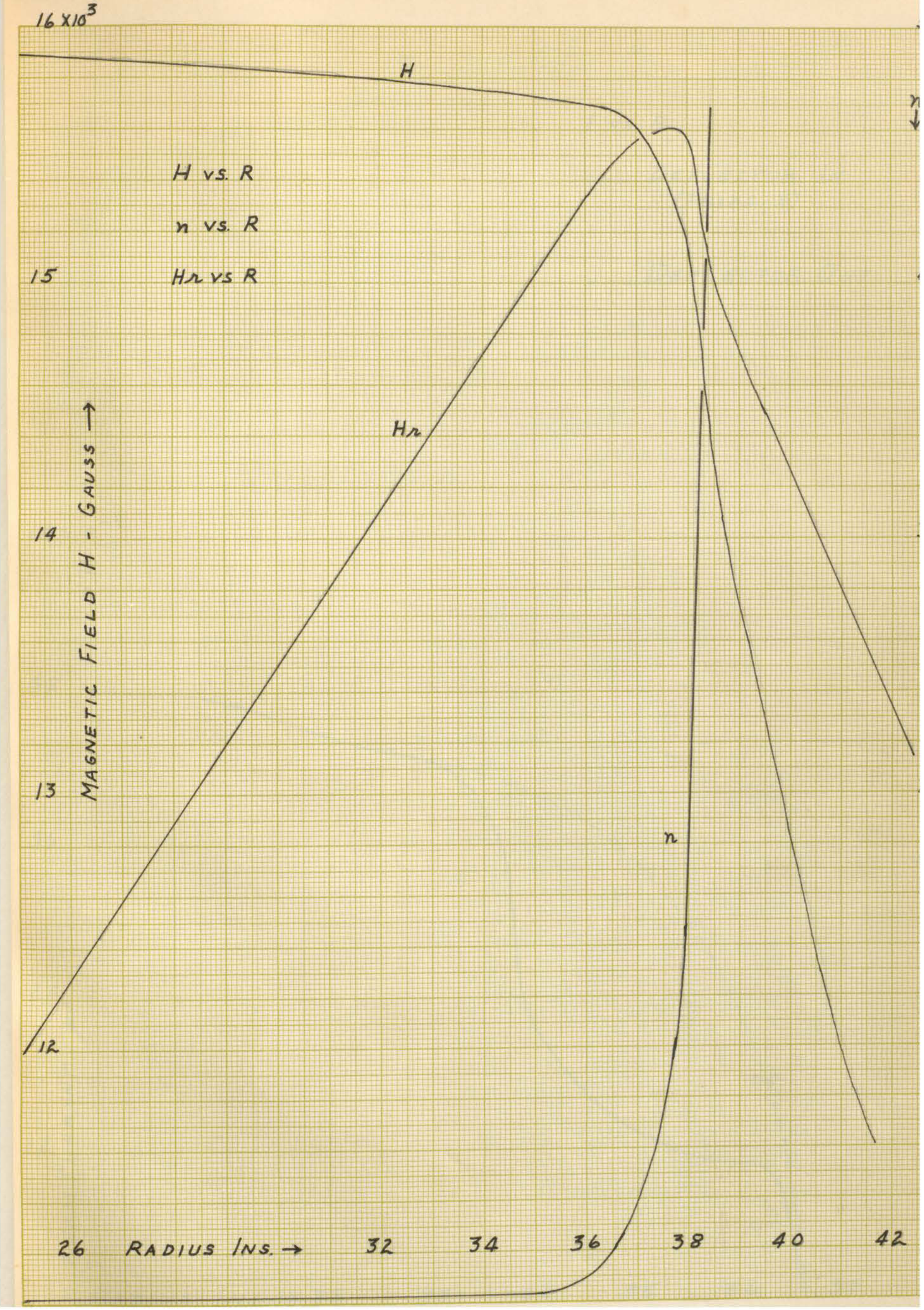
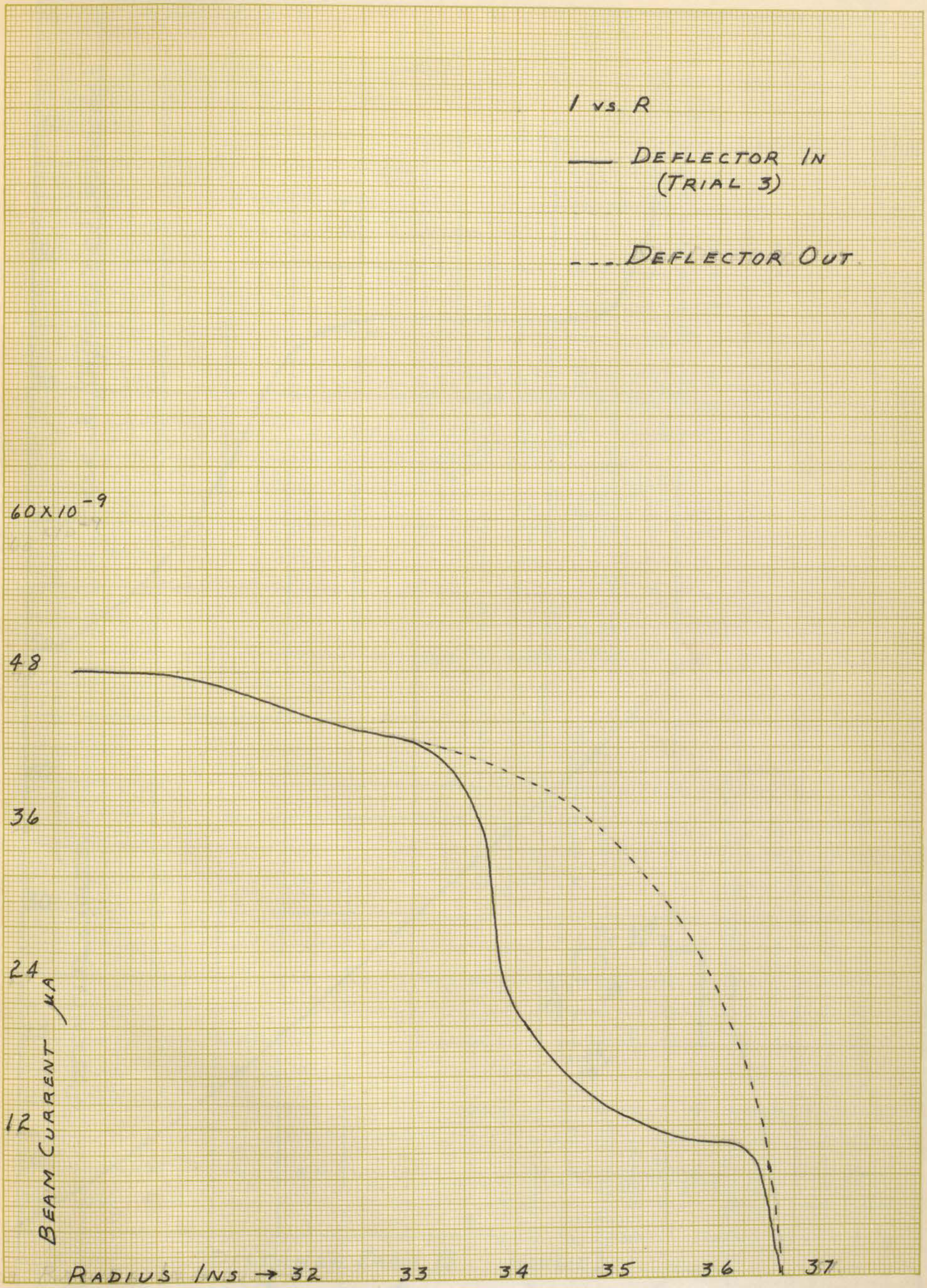

16 X10^3
H
n
H vs. R
n vs. R
Hr vs R
15
Hr
Magnetic Field H - Gauss →
14
13
n
12
26
Radius Ins. →
32
34
36
38
40
42



I vs. R
DEFLECTOR IN
(TRIAL 3)
DEFLECTOR OUT
60 X 10^-9
48
36
24
12
BEAM CURRENT μA
RADIUS INS → 32
33
34
35
36
37

FIGURE 2

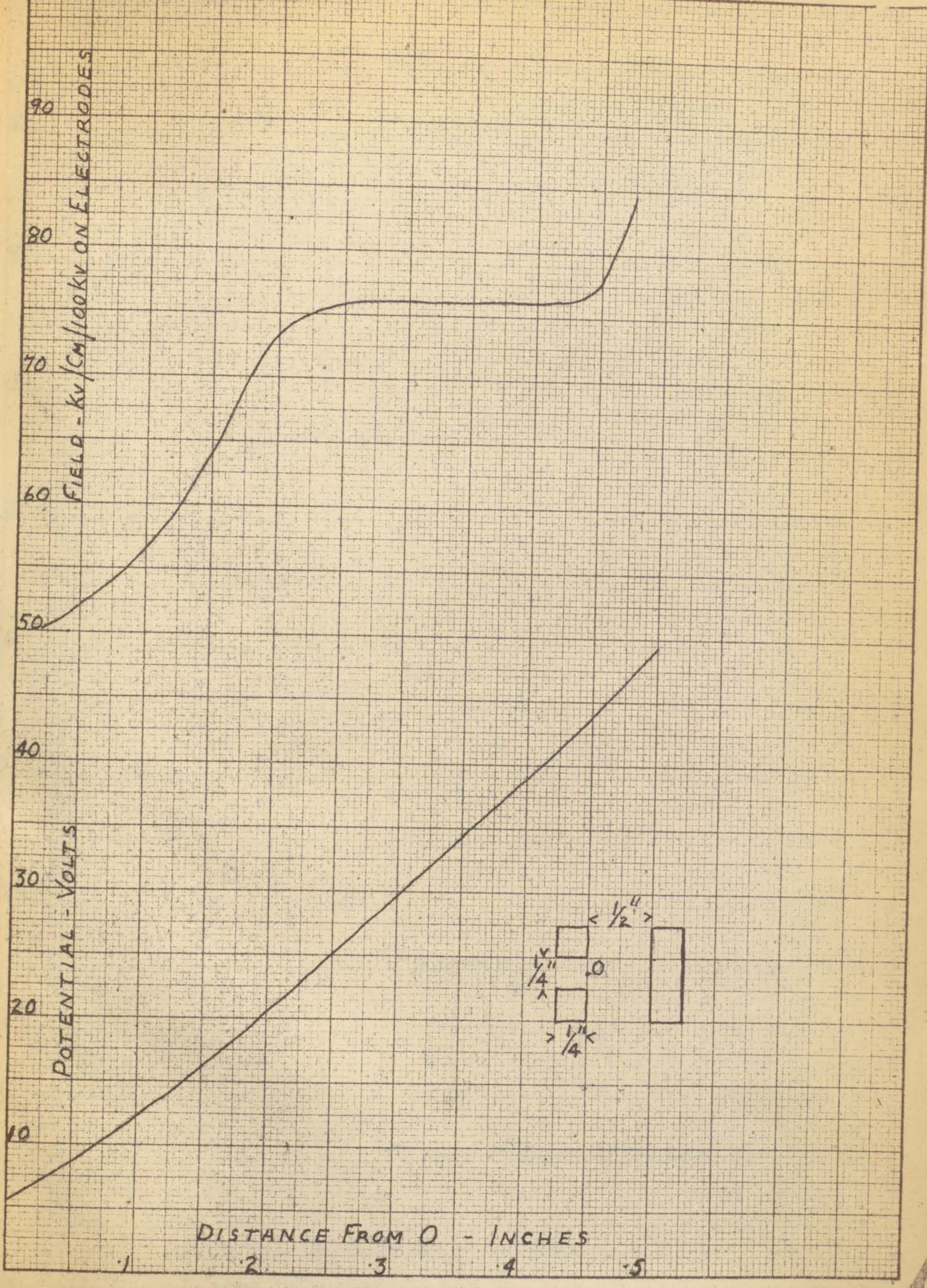

FIELD - KV/CM/100KV ON ELECTRODES
POTENTIAL - VOLTS
90
80
70
60
50
40
30
20
10
DISTANCE FROM O - INCHES
·1
·2
·3
·4
·5
1/2"
1/4"
O
1/4"

FIGURE 3

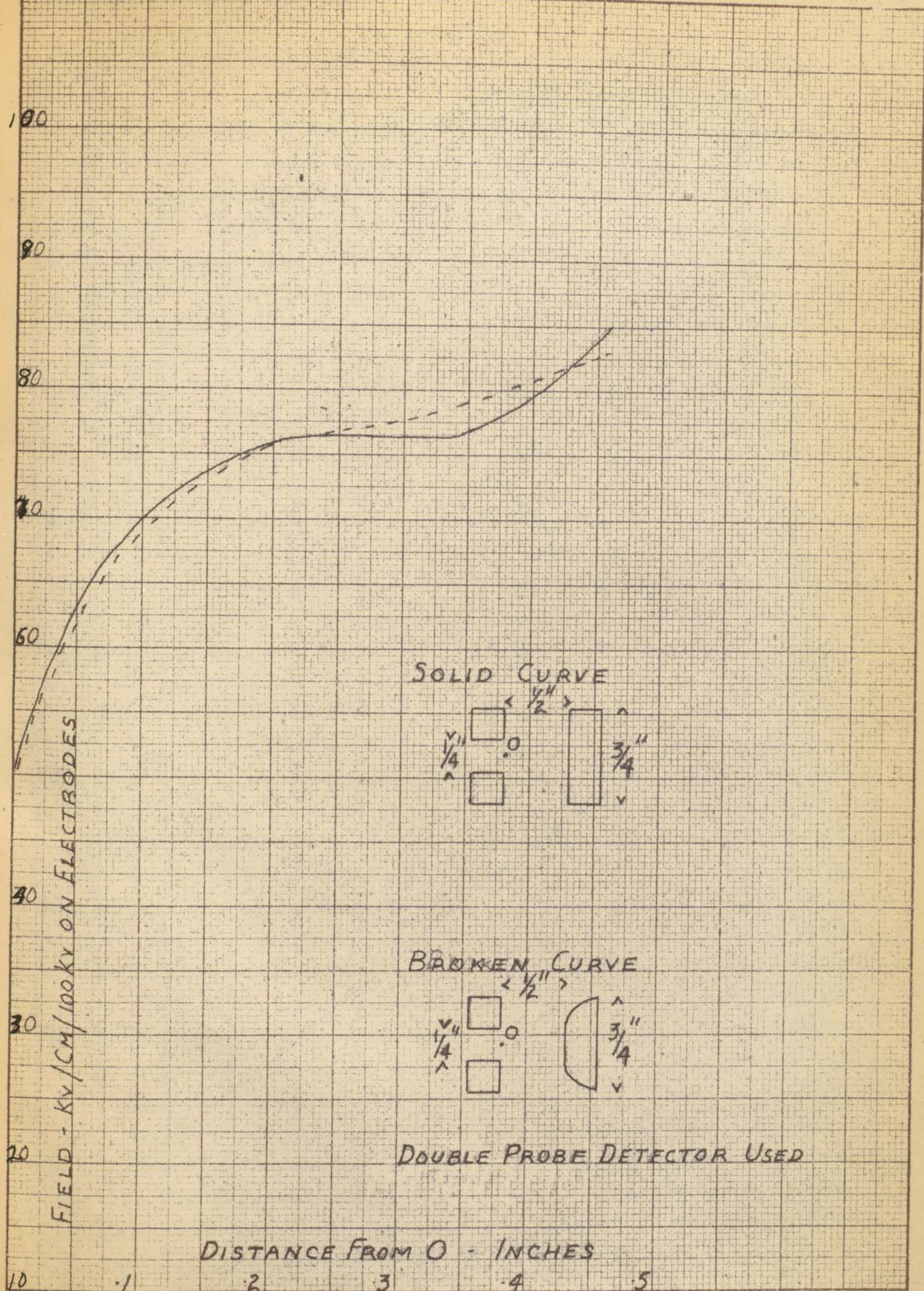

100
90
80
70
60
50
40
30
20
10
FIELD - KV/CM/100KV ON ELECTRODES
SOLID CURVE
1/2"
1/4"
O
3/4"
BROKEN CURVE
1/2"
1/4"
O
3/4"
DOUBLE PROBE DETECTOR USED
DISTANCE FROM O - INCHES
.1
.2
.3
.4
.5

FIGURE 5

FORM 200

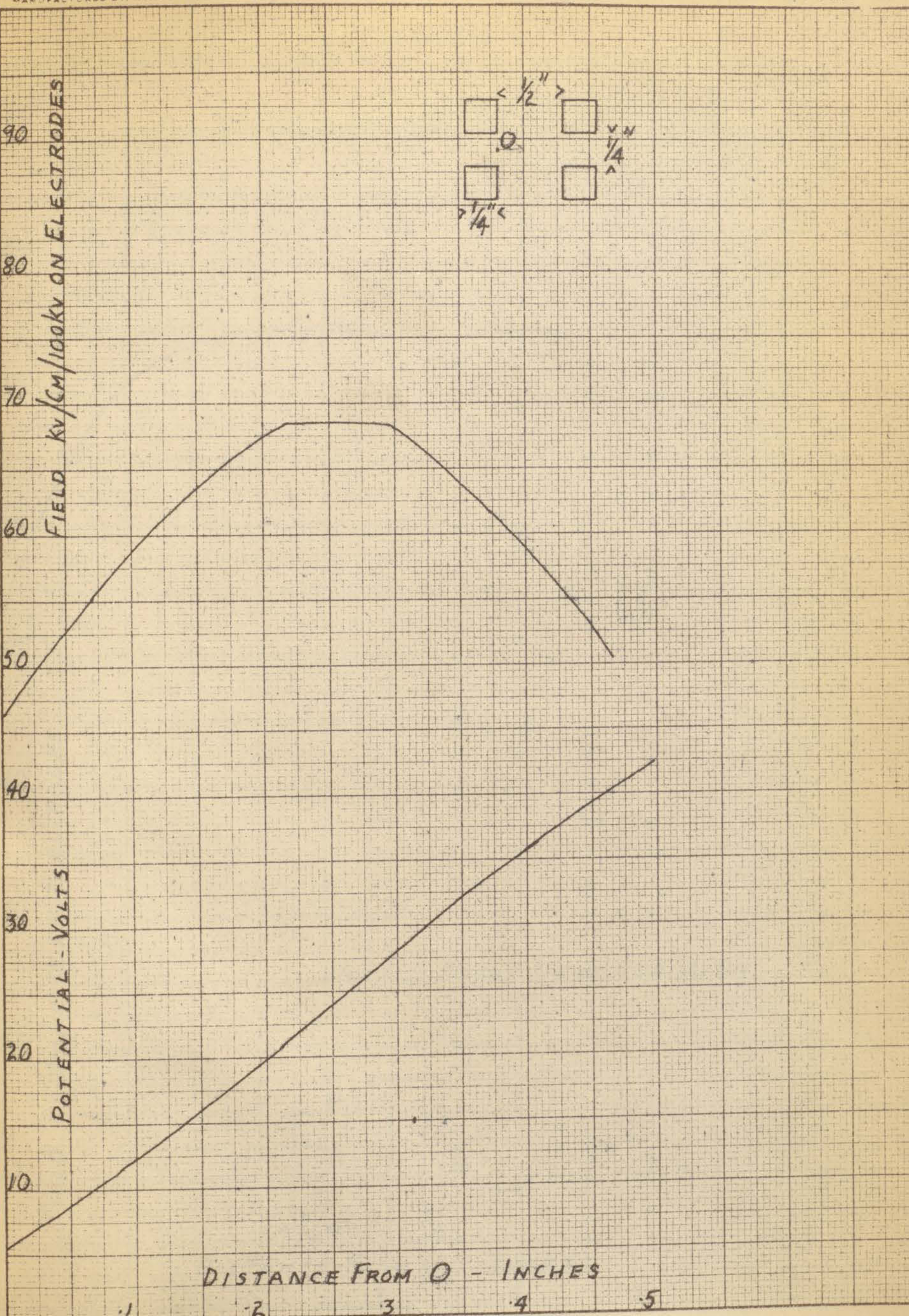


FIGURE 6

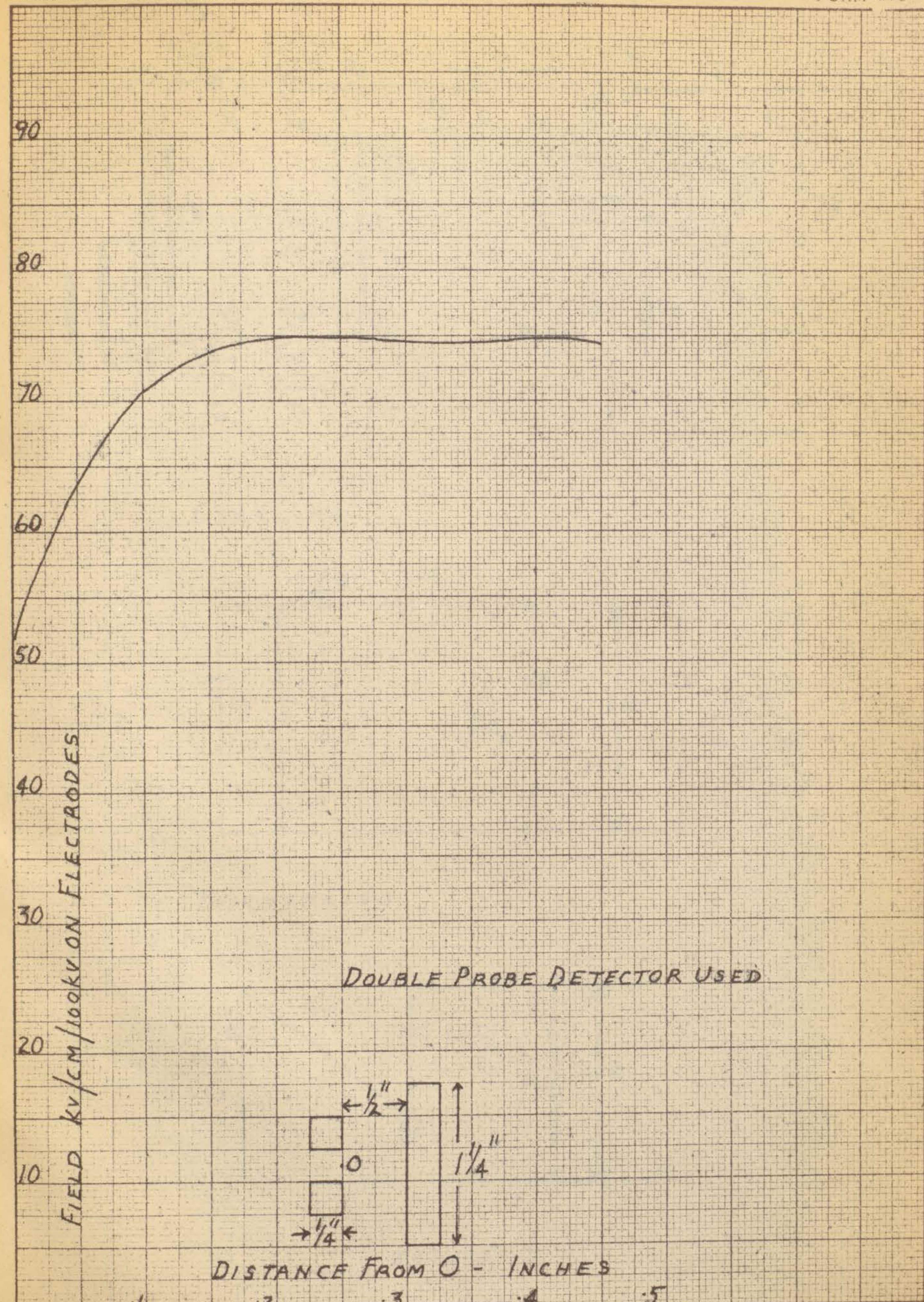
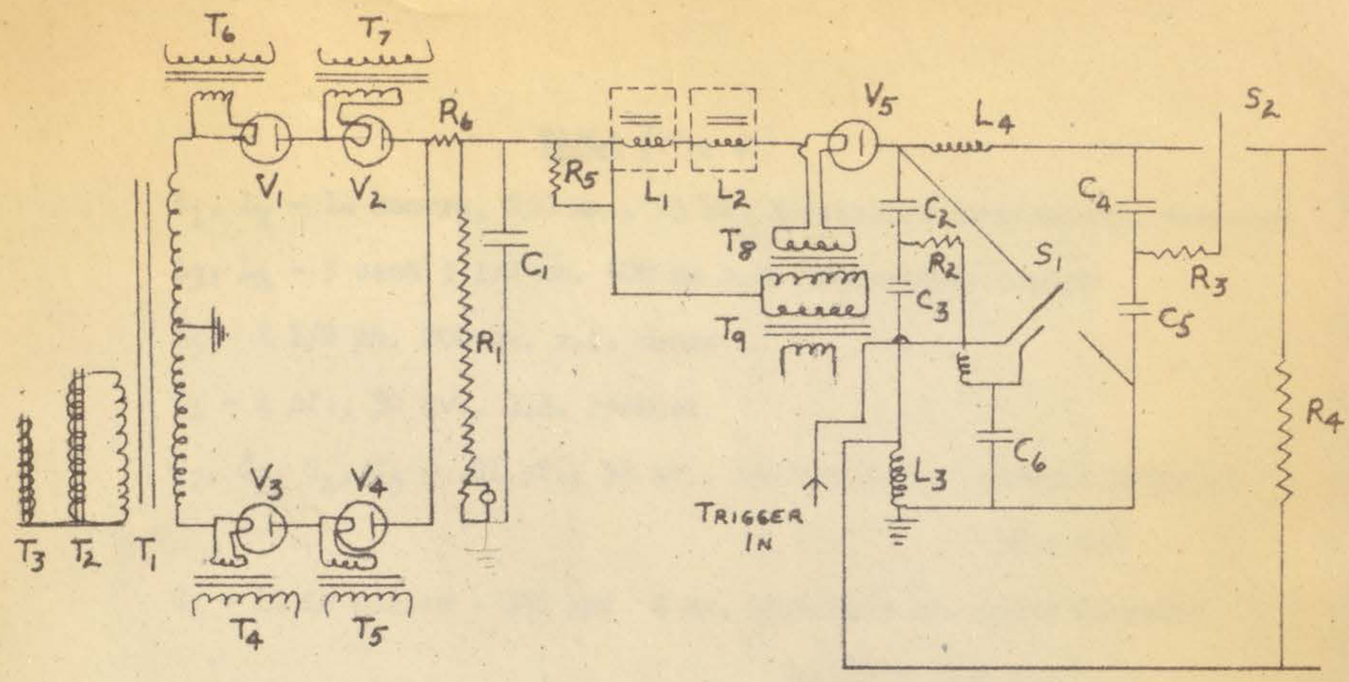
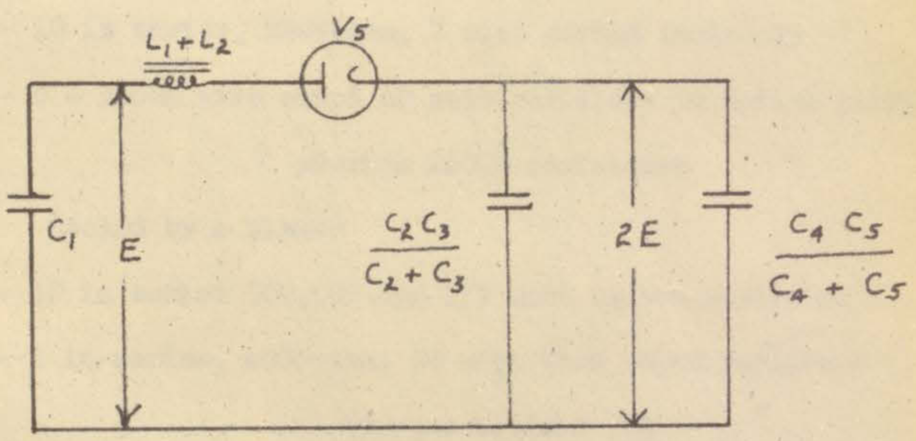

90
80
70
60
50
40
30
20
10
FIELD KV/CM/100KV ON ELECTRODES
DOUBLE PROBE DETECTOR USED
1/2"
1 1/4"
1/4"
O
DISTANCE FROM O - INCHES
·1
·2
·3
·4
·5

FIGURE 7

FULL CIRCUIT



CHARGING



DISCHARGING

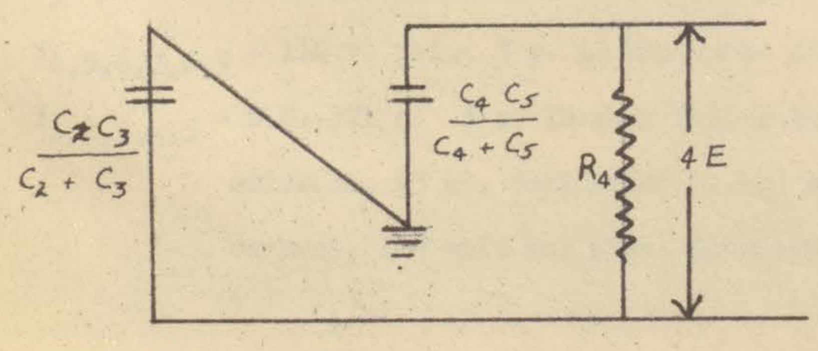


FIGURE 8.

TABLE (FIG. 8)

L_1, L_2 - 14 henrys, 250 ma., 25 kv. insulation (estimated). Ferranti

L_3, L_4 - 3 each 5 1/2 mh. 500 ma r.f. transmitter chokes

L_5 - 2 1/2 mh. 200 ma. r.f. choke

C_1 - 1 μf., 30 kv., G.E. Pyranol

C_2, C_3, C_4, C_5 - .01 μf., 30 kv., non-inductive Cornell Dubilier BT - 366

C_6 - 10 in series - 200 $\mu\mu$f 2 kv. working 5 kv. tests Cornell-Dubilier Type 15.

R_2 - 10 in series - 4700-ohm 2 watt carbon resistors

R_1 - 50 in series, 470,000 - ohm 2 watt carbon resistors

R_3 - 10 in series, 2200-ohm, 2 watt carbon resistors

R_4 - 6 - 3300Ω wire wound 60 watt resistors in series parallel to provide 2200Ω resistance

Cooled by a blower

R_5 - 10 in series 500,000-ohm 1/2 watt carbon resistors

R_6 - 2 in series, 4000-ohm, 50 watt wire wound resistors Sprague Koolohm 50K

T_1 - 2200 - 110 kv. 110 ma X-ray transformer - Kelley-Koit

T_2 - Autotransformer 1:2 step-up

T_3 - 2 Variacs in parallel - 110 v. to 110-135 v. at 18 amps

$T_{4,5,6,7,8,9}$ - 110 v. pri., 5 v. 10 amp, oil. 35 kv. insulation

$V_{1,2,3,4,5}$ - W.E. 371 B. 5 v. 10 amp. fil. 2 amps peak emission, 25 kv. peak inverse, 0.3 amps. average plate current, 100 watt max plate dissipation.

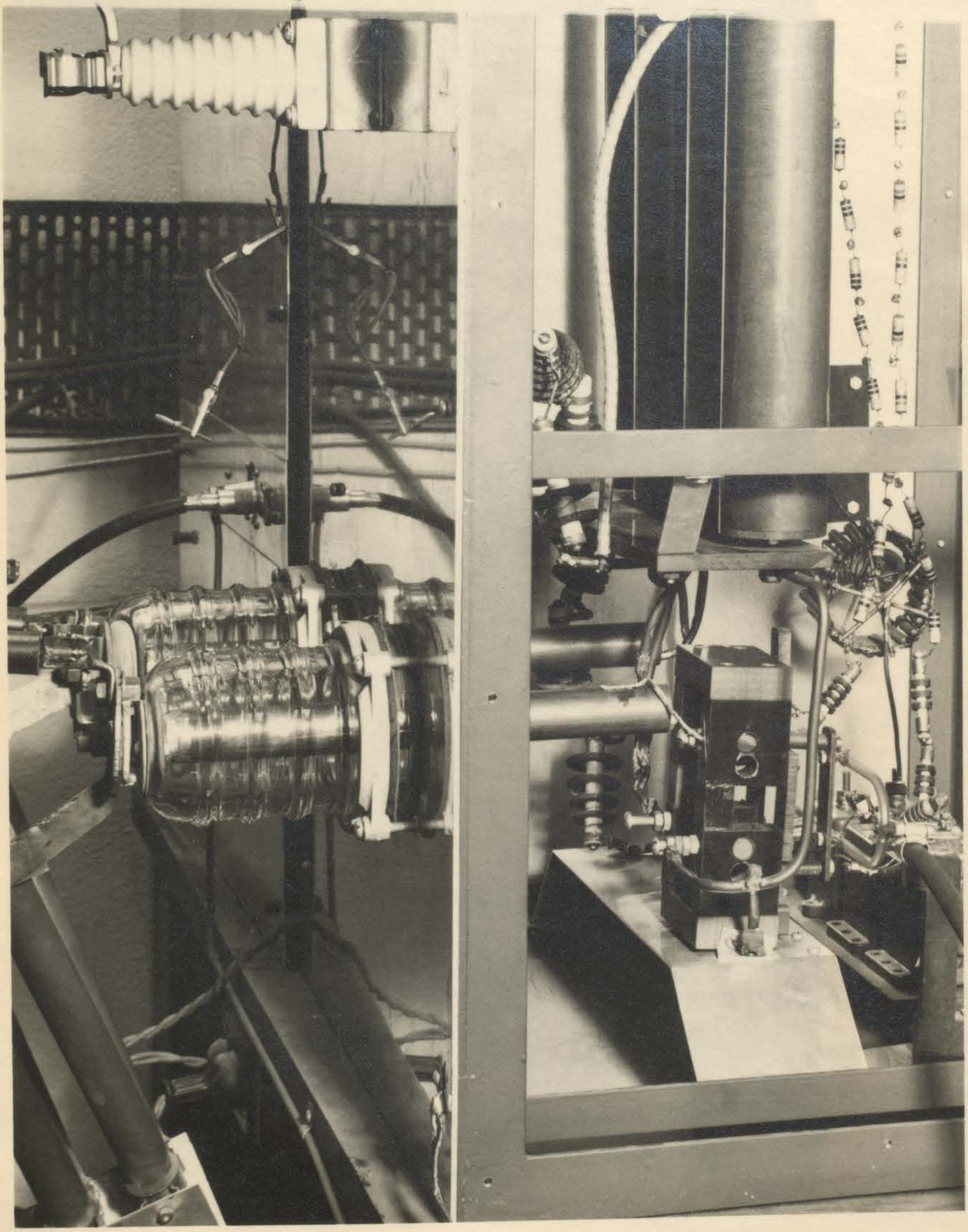


FIGURE 9

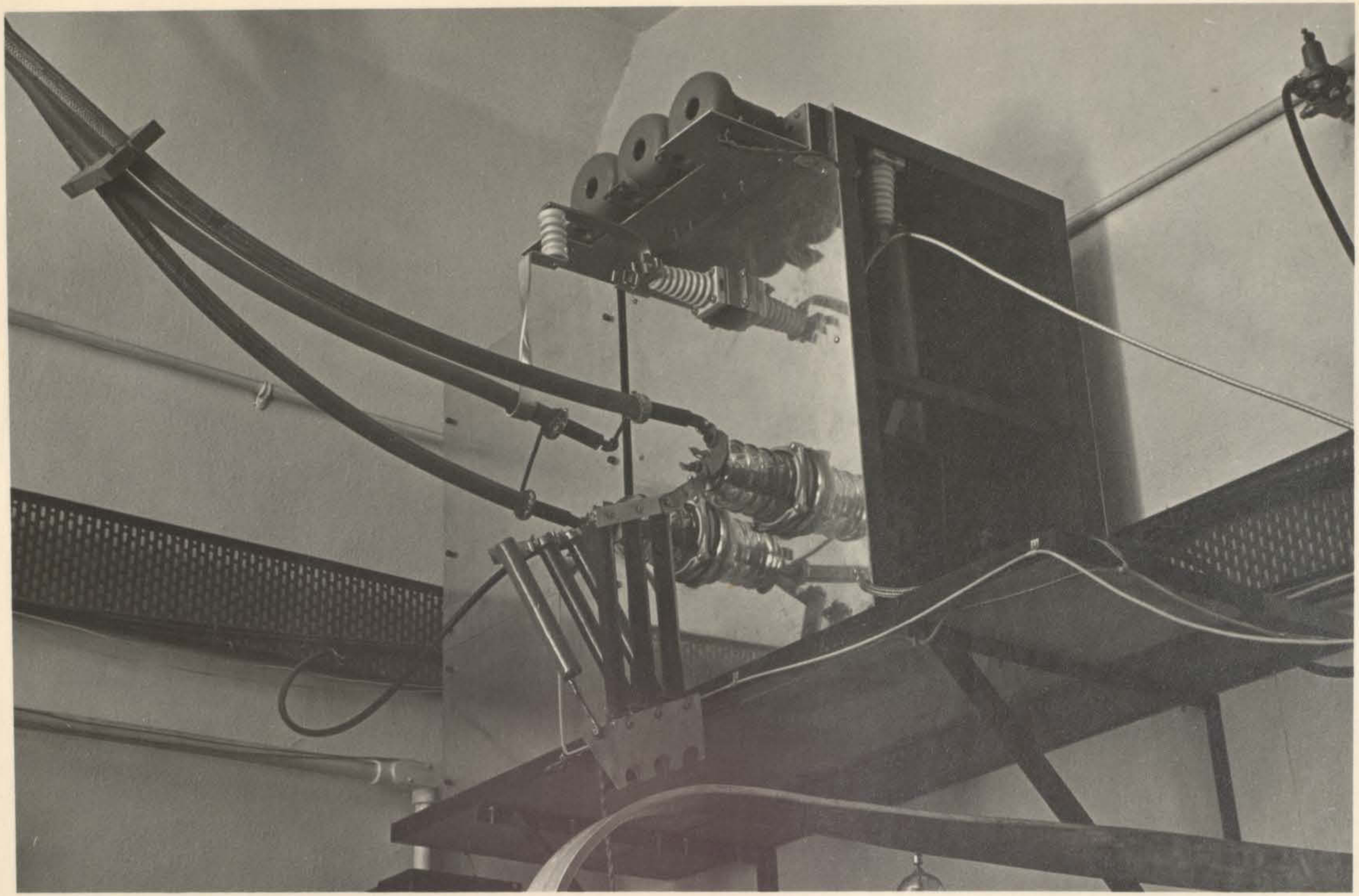


FIGURE 10

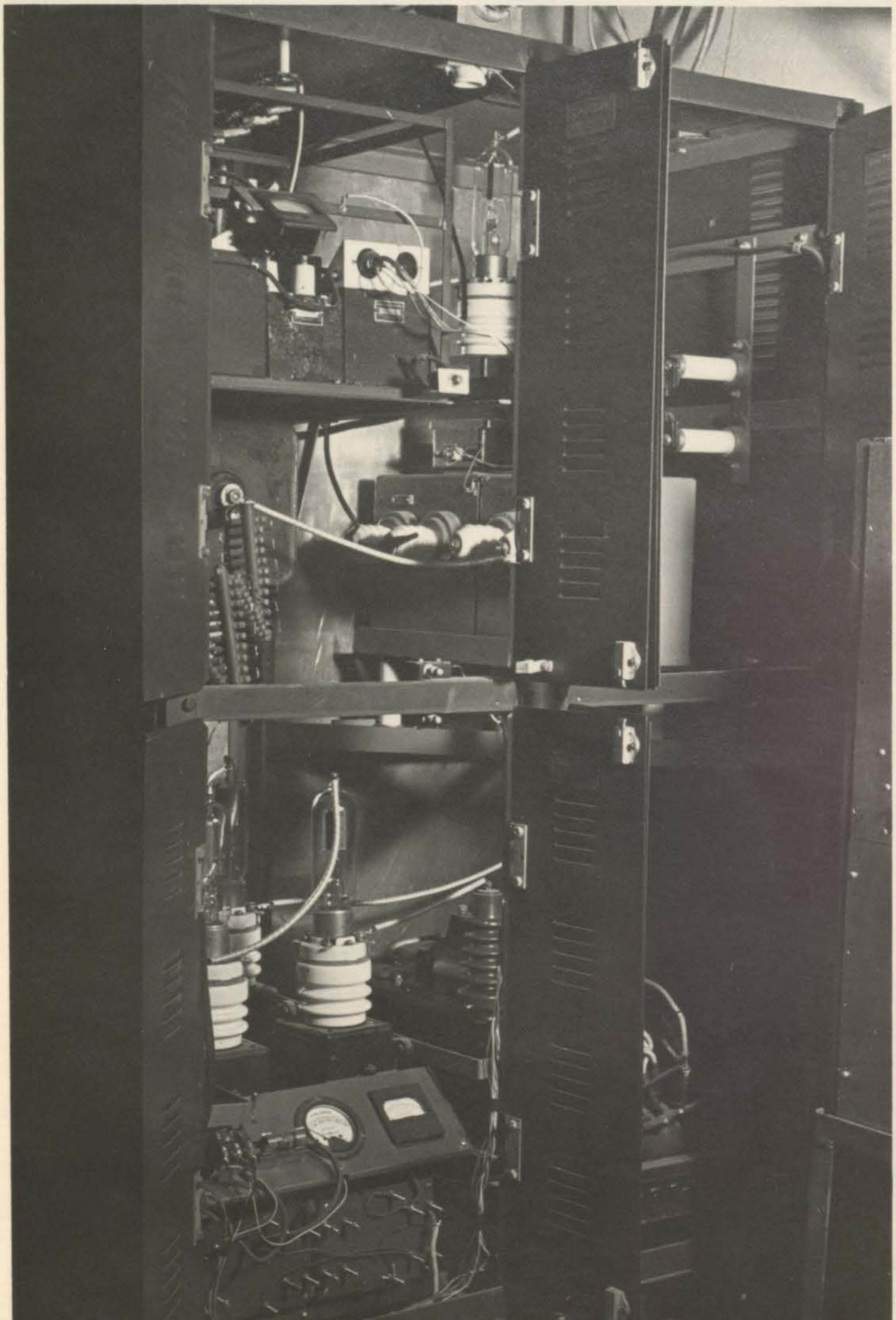


FIGURE 11

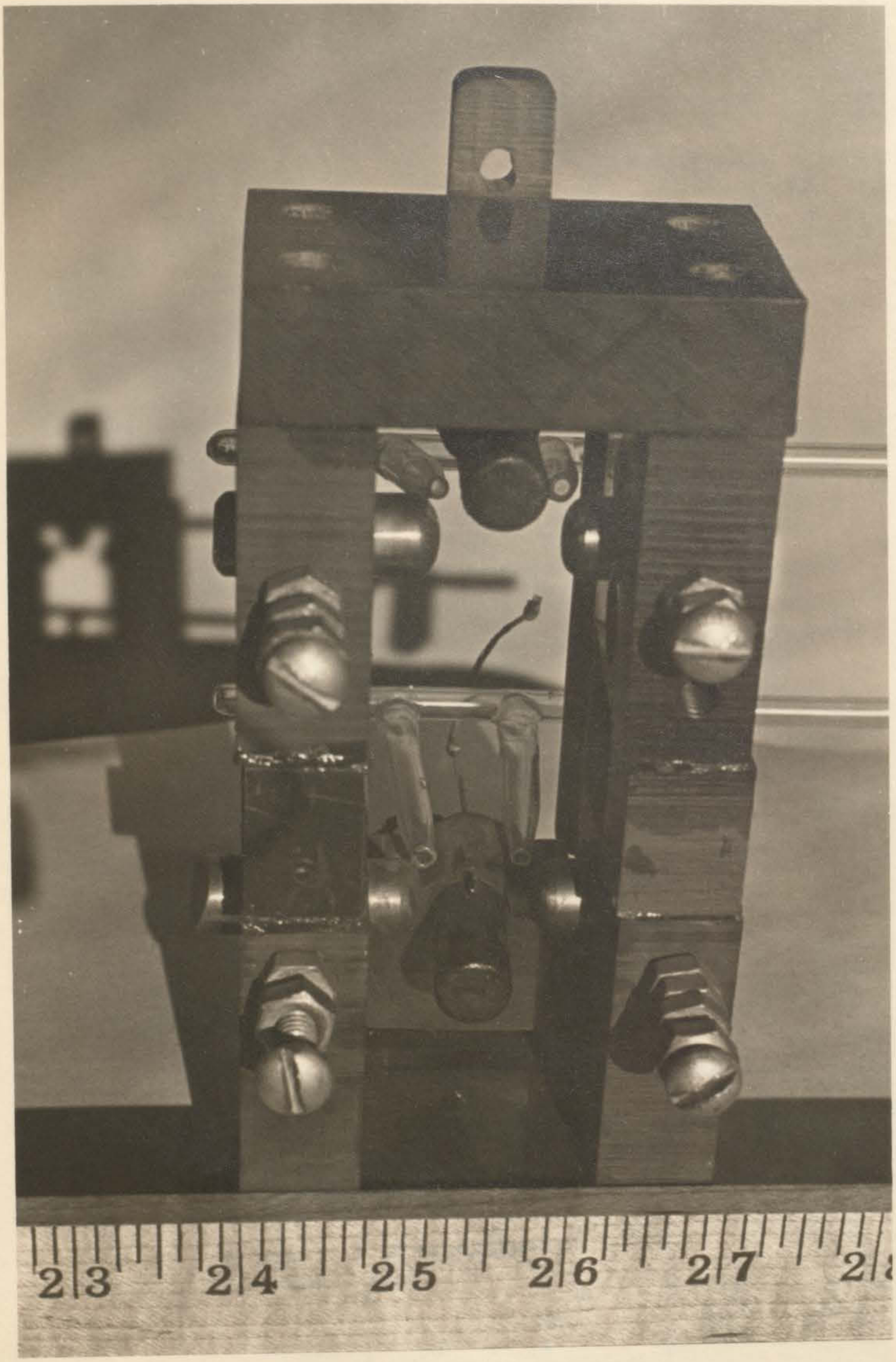


FIGURE 12

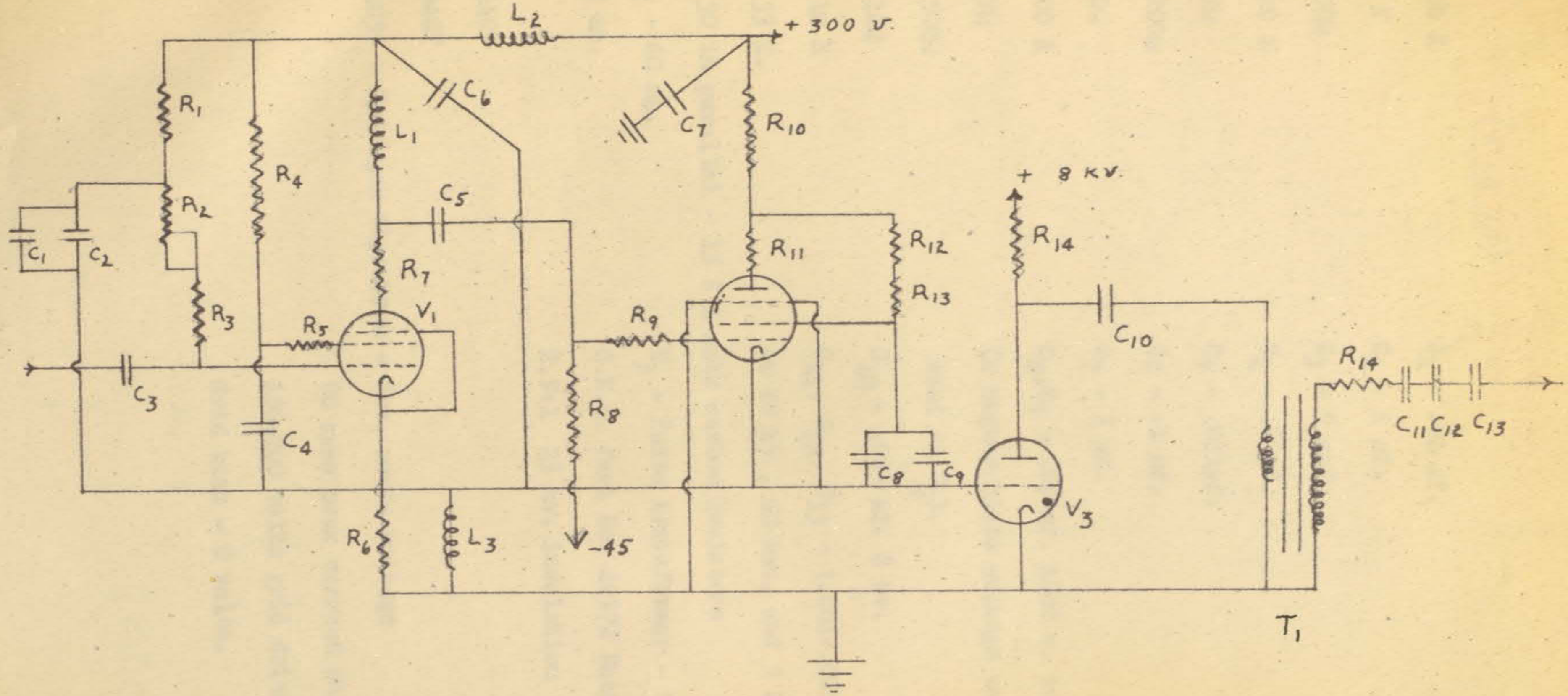

L2
+ 300 v.
R1
C6
L1
C7
R10
R4
+ 8 KV.
C5
R2
C1
C2
R12
R11
R14
R7
V1
R13
R3
R5
R9
C10
R14
C3
R8
C4
C11 C12 C13
C8
C9
V3
R6
L3
-45
T1

FIGURE 13

(FIG 13)

R_1 - 150 K

R_2 - 5 K

R_3 - 400Ω

R_4 - 120 K

R_5 - 47Ω

R_6 - 2200Ω

R_7 - 10Ω

R_8 - 100 K

R_9 - 47Ω

R_{10} - 500Ω

R_{11} - 10Ω

R_{12} - 10 K

R_{13} - 33 K.

C_1 - .01 μf.

C_2 - 1 μf.

C_3 - 5 μμf.

C_4 - .2 μf.

C_5 - .001μf.

C_6 - .1 μf.

C_7 - 1 μf.

C_8,C_9 - .05 μf. 1600 v. tubular paper (A higher plate voltage was originally used on V_2).

C_{10} - .003 μf. 8 kv.

C_{11}, C_{12}, C_{13} - (.001+.001+.003)μf. at 80 kv., 10 kv., and 5 kv. respectively

R_{14} - 30 in parallel - 15 K 1 watt carbon resistors

L_1, L_2 - 60 mh.

L_3 - 2 mh.

T_1 - Pulse transformer - Ferranti R.E.L. Part No. 28372 Ratio 2.9:1 23 kv. insulation

V_1 - 6AC7

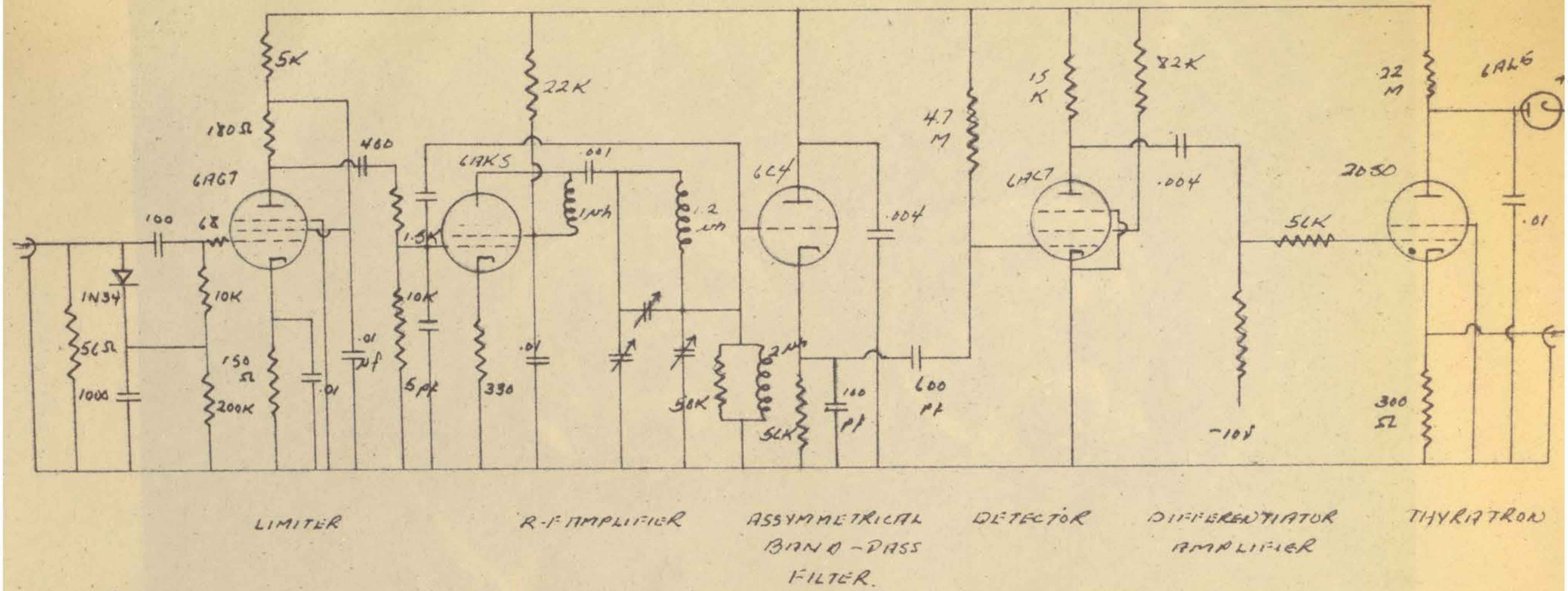
V_2 - 6AG7

V_3 - 4C35 - Hydrogen thyratron - 8kv. anode voltage

90 amps peak current on 50Ω load

150-200 volts grid drive

Grid bias - 0 volts.



5K
180Ω
6AG7
100
68
IN34
56Ω
1000
10K
150 Ω
200K
.01
.01 μf
400
22K
6AK5
.001
1μh
1.5K
10K
5pf
330
.01
1.2 μh
50K
6C4
2μh
5.6K
.004
100 pf
600 pf
4.7 M
15 K
82K
6AC7
.004
5.6K
-10V
.22 M
6AL6
2050
.01
300 Ω
LIMITER
R-F AMPLIFIER
ASSYMMETRICAL BAND-PASS FILTER.
DETECTOR
DIFFERENTIATOR AMPLIFIER
THYRATRON

FIGURE 14

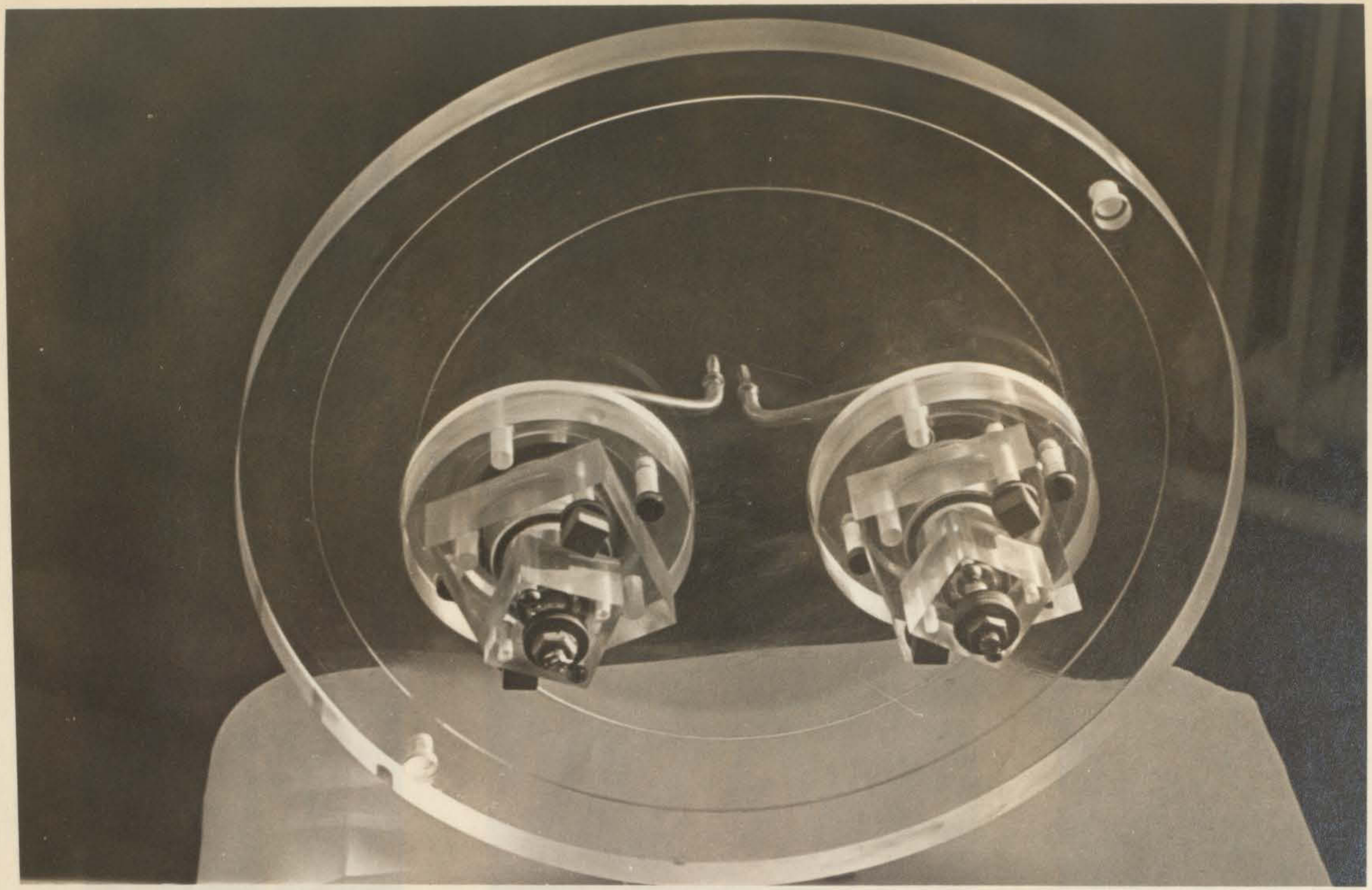


FIGURE 15

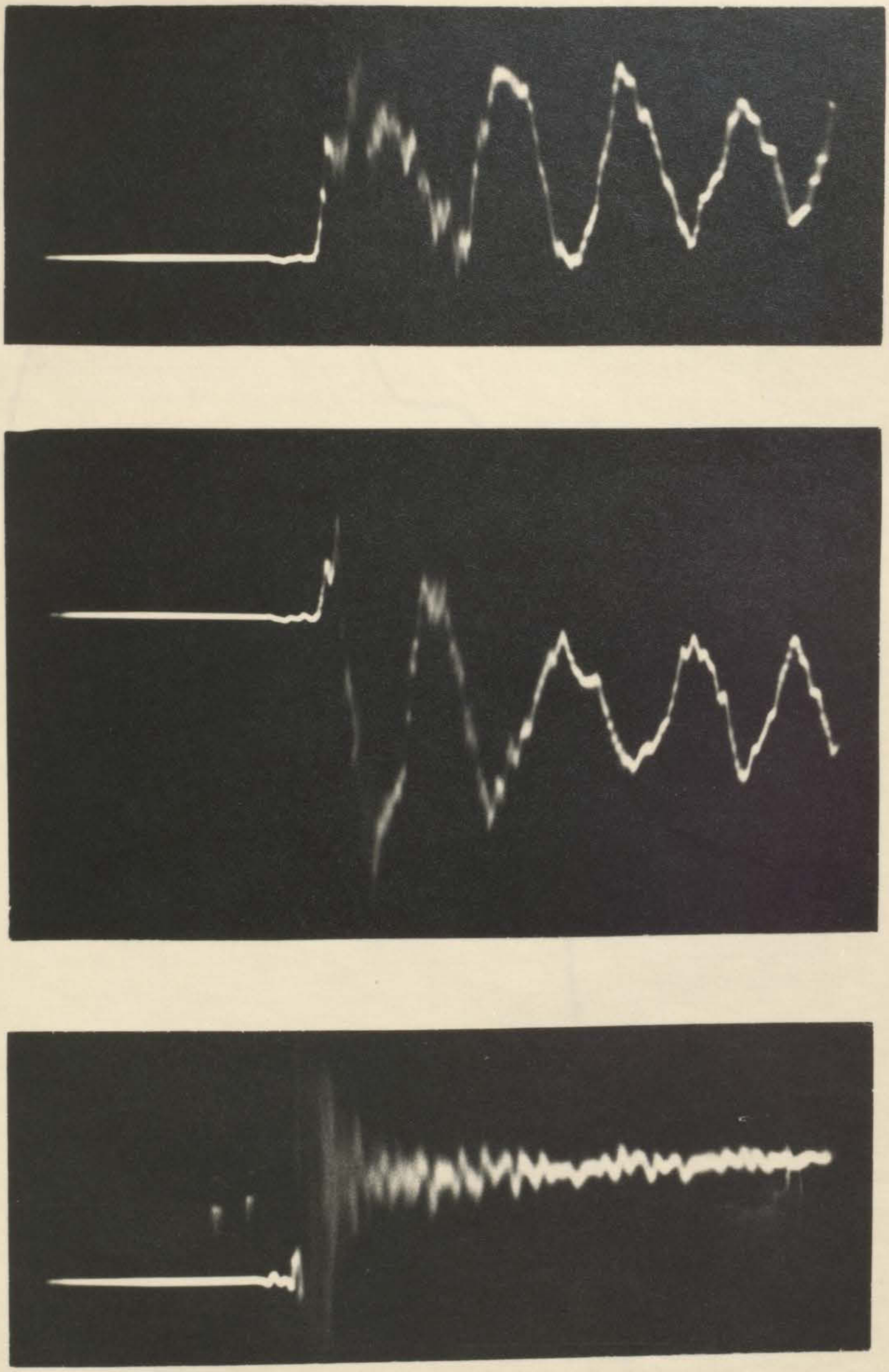
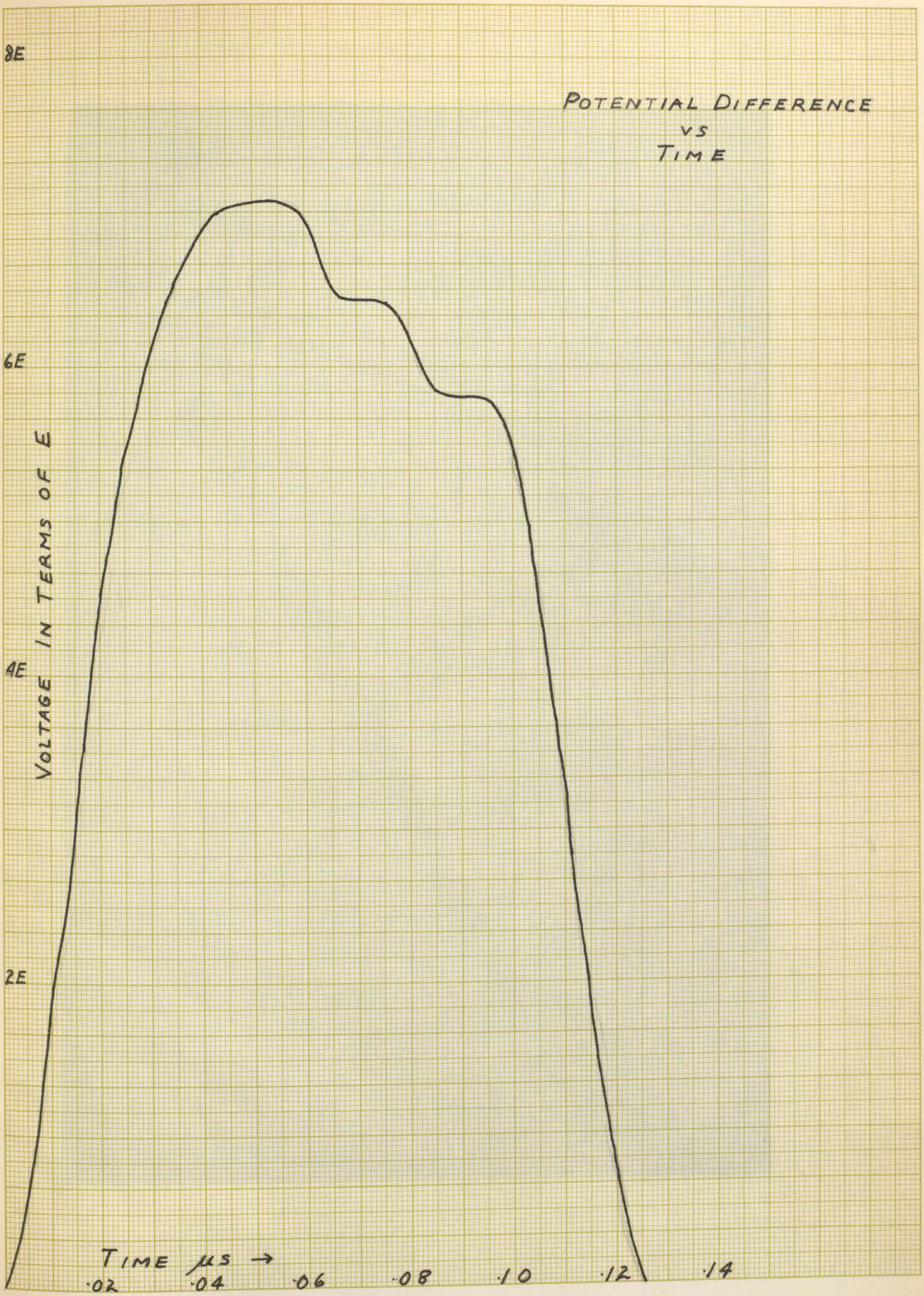
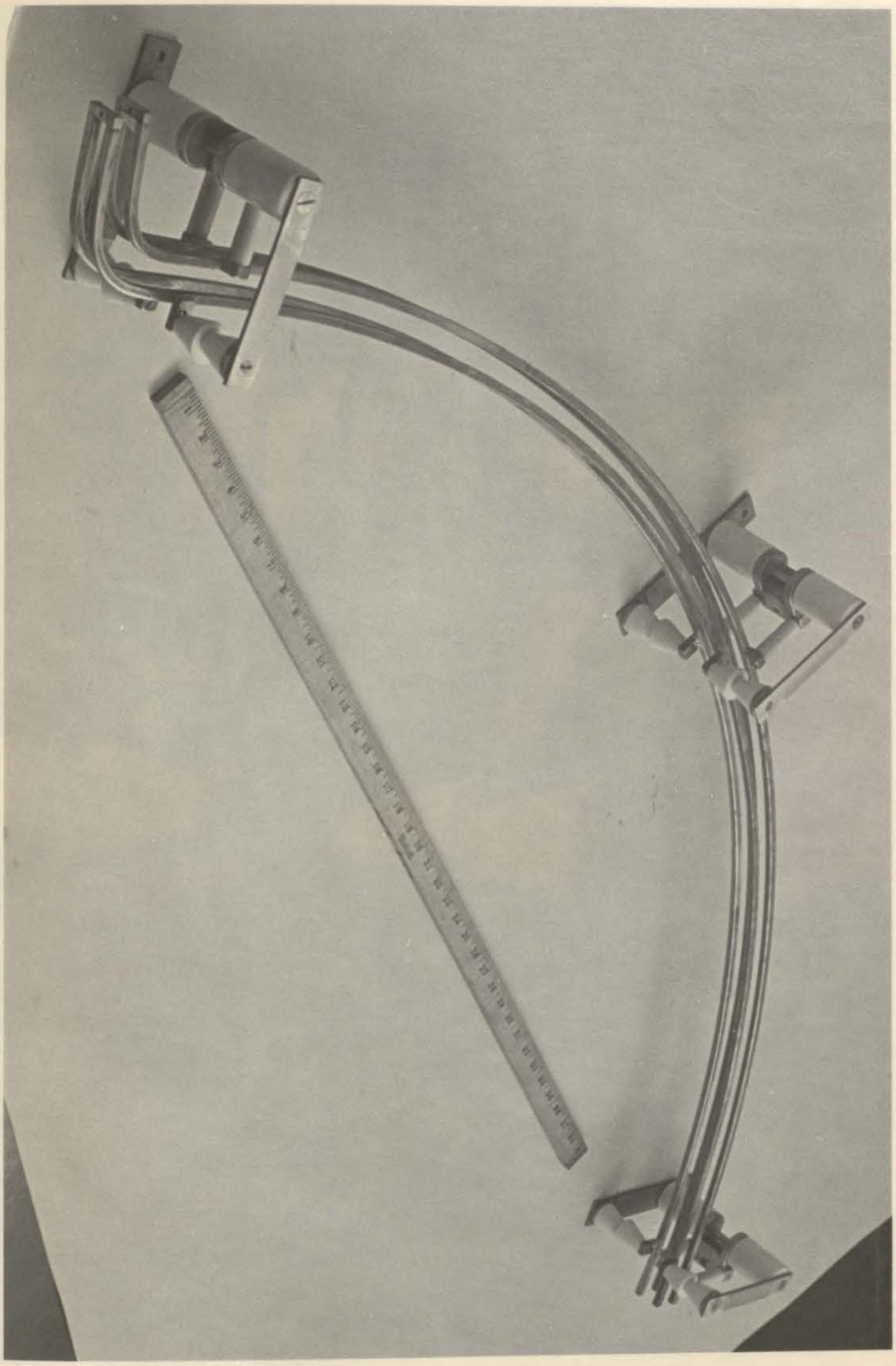


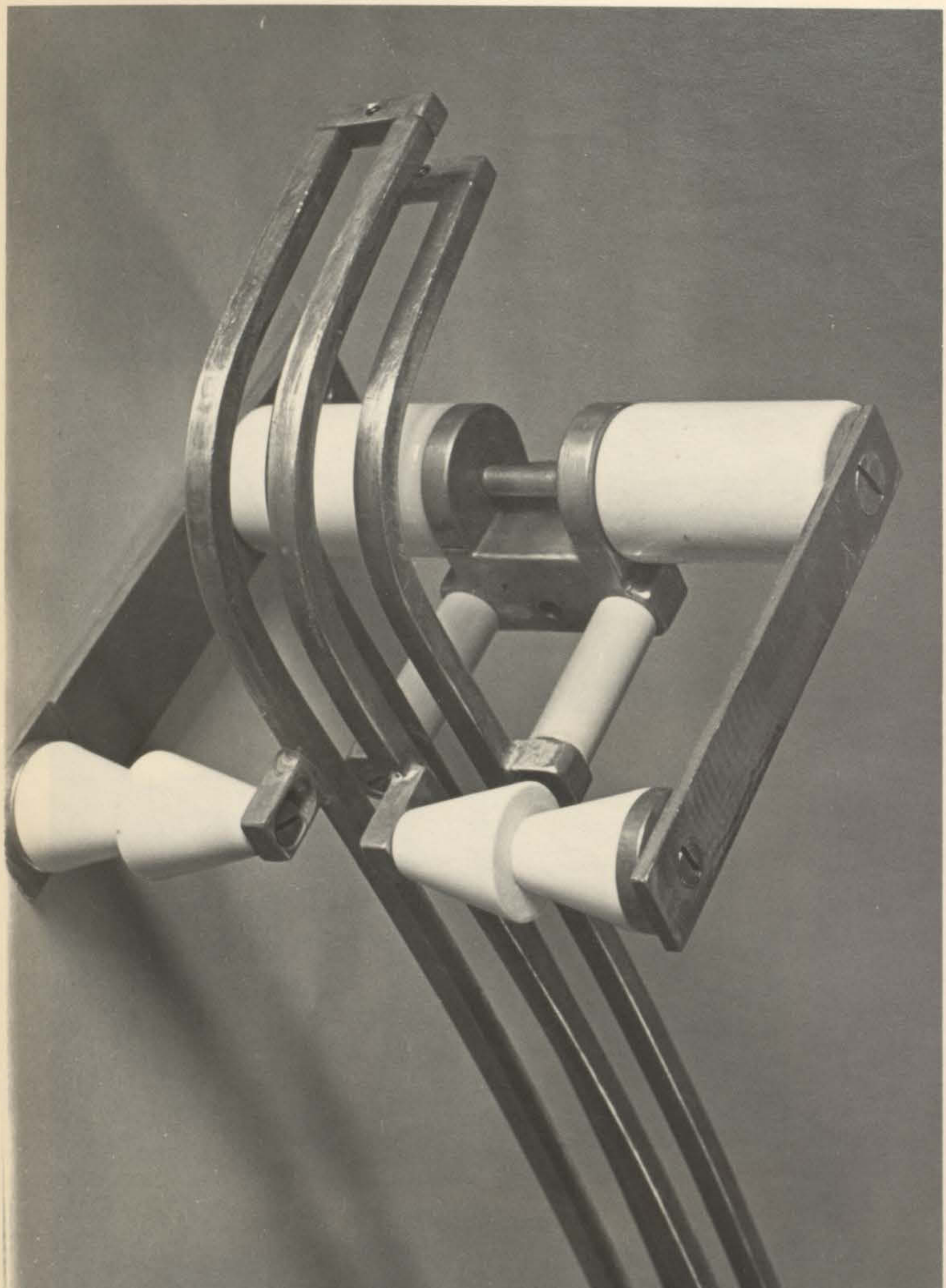
FIGURE 16

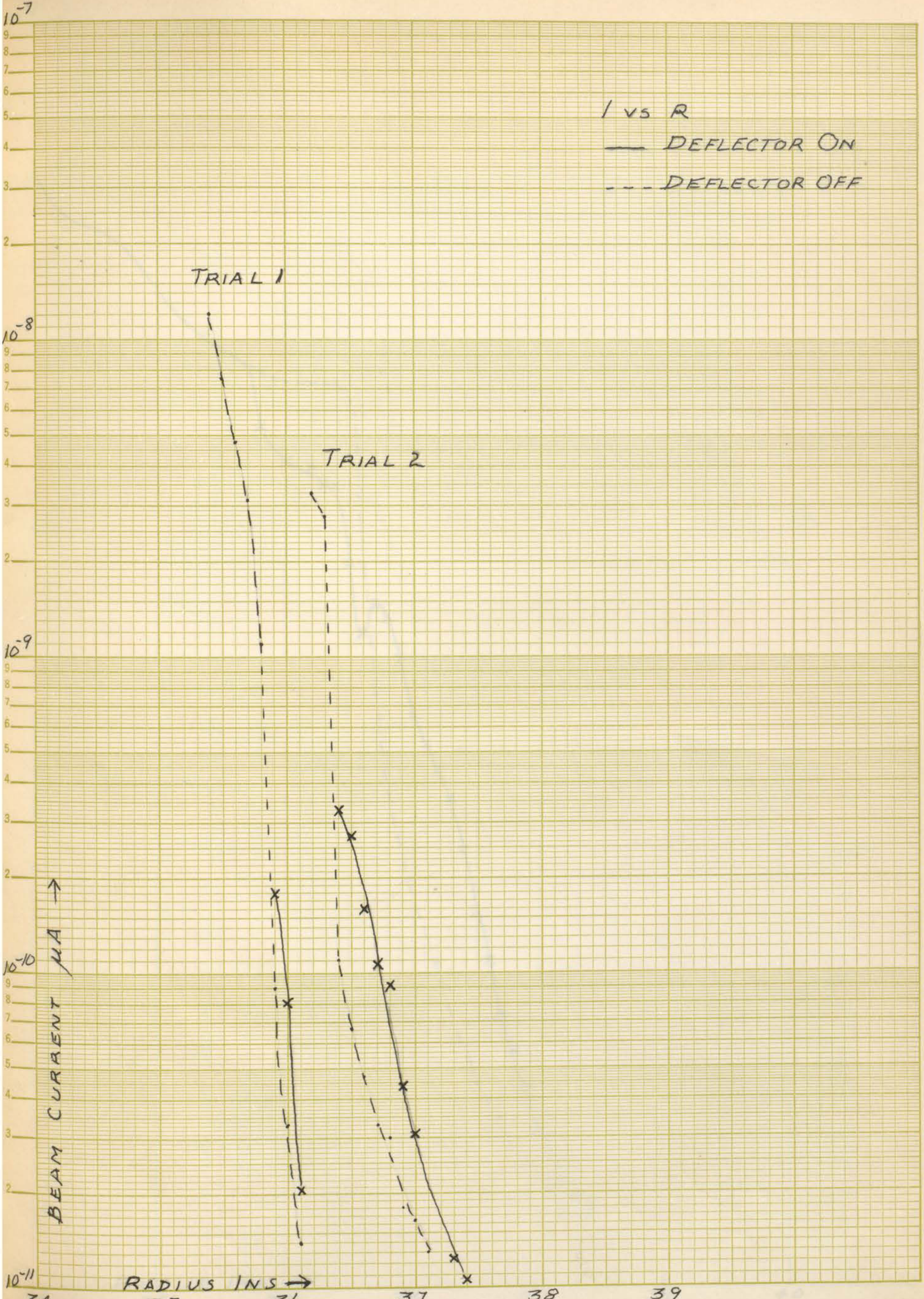


8E
6E
4E
2E
VOLTAGE IN TERMS OF E
POTENTIAL DIFFERENCE
VS
TIME
TIME μs →
·02
·04
·06
·08
·10
·12
·14

FIGURE 17

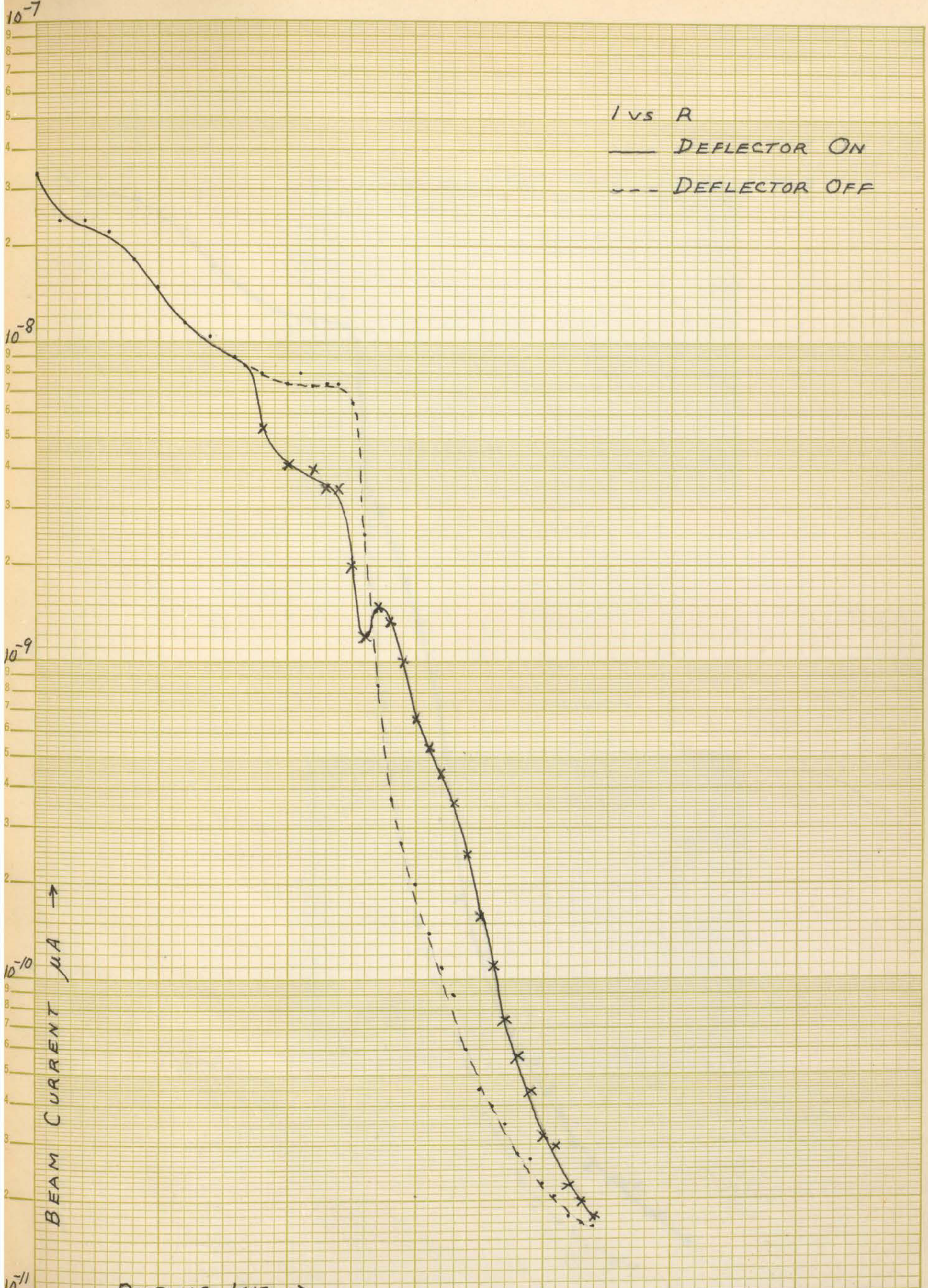






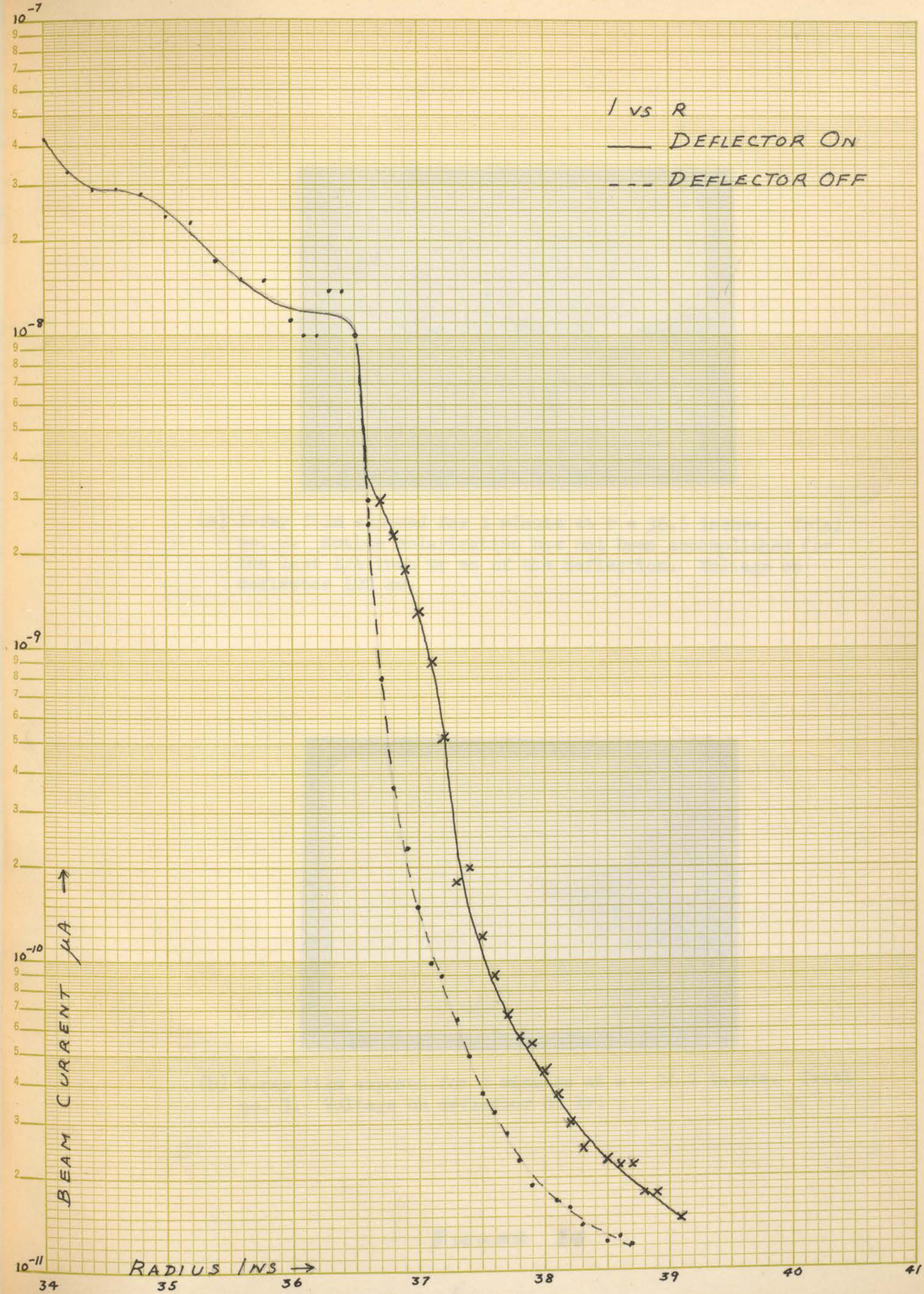
I vs R
DEFLECTOR ON
DEFLECTOR OFF
TRIAL 1
TRIAL 2
BEAM CURRENT μA →
RADIUS INS →
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
34
35
36
37
38
39

FIGURE 21



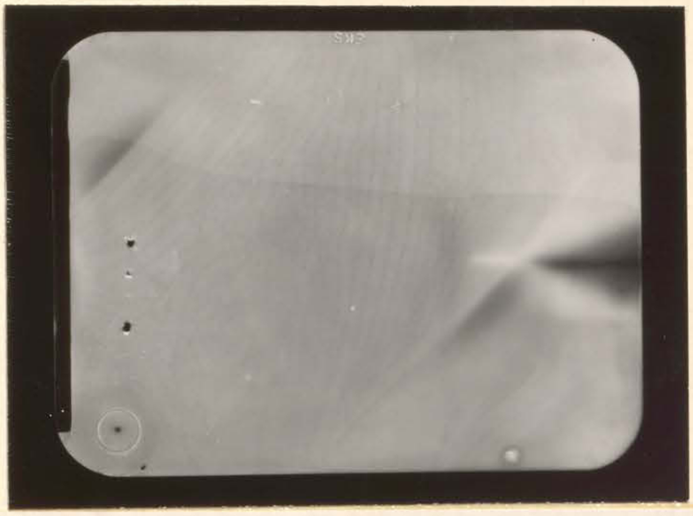
I vs R
DEFLECTOR ON
DEFLECTOR OFF
BEAM CURRENT μA →
RADIUS INS →
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
34
35
36
37
38
39
40

FIGURE 22



I vs R
DEFLECTOR ON
DEFLECTOR OFF
BEAM CURRENT μA →
RADIUS INS →
10^-7
10^-8
10^-9
10^-10
10^-11
34
35
36
37
38
39
40
41

FIGURE 23



(a) X-ray film exposed for 1 minute at r = 36.5 inches. Trial no. 2. Notice solarization has not been accomplished for the last 1/4 inch or so of the deflection. Voltage on deflector 102 kv.

(b) X-ray film exposed for 5 minutes at r = 36.2 inches. Trial no. 3. Voltage on deflector 86 kv.

FIGURE 24