A PRECISE A. C. NULL METHOD OF DETERMINING MAGNETIC FIELDS IN A BETA-RAY SPECTROMETER

A Precise A. C. Null Method
of Determining Magnetic Fields in
a Beta-Ray Spectrometer

by

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SCOPE AND CONTENTS:

This thesis is written in three sections; the first presents a critical survey of methods which have been used to measure magnetic fields; the second describes the construction of an A.C. null method capable of comparing two fields to one part in 30,000, and the third discusses its performance.

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INTRODUCTION

In order that the high resolution (defined as $\frac{\Delta p}{p}$ where p is the momentum and Δp is the full width of a peak at half maximum) yielded by the Siegbahn-type beta-ray spectrometer may be fully utilized in making energy determinations, magnetic field measurements must be made very accurately. The best resolution obtainable with the present machine is 0.2% and, since the true centre of a well defined electron peak can be located within a tenth of the half-width, an accuracy of 2 parts in 10,000 may be expected in the energy determination. To obtain such accuracy, the field measurement should be made with at least this precision.

At the present time a search coil with ballistic galvanometer is being used to measure the magnetic field. Since the accuracy inherent in this method is about 2 parts in 1000, the field measurement at present is the limiting factor in precise energy measurements.

The author was asked to undertake a study of methods of measuring magnetic fields and to develop one which would increase the accuracy to at least 2 parts in 10,000. The method selected was an A.C. generator null method that was developed by Hedgram in Sweden. It is expected that this device may be adapted for automatic stabilization of the field, though this development lies beyond the scope of this thesis.

Therefore, this thesis describes both the survey of possible measuring methods and the construction and operation of the chosen method.

SECTION I

SURVEY OF METHODS OF MEASURING STRENGTHS OF MAGNETIC FIELDS

The methods to be discussed will not be treated in detail but will be assessed on the basis of their ability to meet the following three conditions imposed by the Siegbahn spectrometer.

First, the field is not uniform but falls off in the radial direction with a gradient of 1% per cm. Second, the field magnitude is to be varied from 5 to 400 gauss. Third, the device must measure the field to better than 2 parts in 10,000.

There are two basic methods of measuring the strength of a magnetic field. One depends on the measurement of a quantity of electricity set in motion by a change of magnetic flux through a circuit. The other depends on the measurement of the force on a current-bearing conductor in the field. Still other methods are available which depend on the alteration of a physical characteristic of a substance when placed in a magnetic field. Each type of method will be discussed in turn. The one selected will be the last one to be described.

(A) Changes in Physical Characteristics

(a) Changes of Electrical Conductivity. When Kapitza (1) succeeded in developing magnetic fields up to 350,000 gauss, he found that for magnetic fields below a certain critical value the relative change in resistance of a conductor placed in the field was proportional to the square of the field, providing that the temperature was kept constant. For fields stronger than the critical value, the resistance tended to increase linearly with the magnetic field. This critical field value, for different elements, varied from 5,000 to 250,000 gauss. One element in which this effect is very marked is bismuth. Because of the dependence of the effect on the square of the field, making it very small at fields of a few hundred gauss, this method was felt to be unsuitable.

(b) A. C. Probe Method. It is known that the alternating current permeability of most magnetic alloys changes with super-imposed steady-state magnetic fields. In employing this principle Gregg (2) constructed a transformer from one of these alloys and applied a constant amplitude A.C. signal to the primary. The A.C. output appearing at the secondary was then a function of the steady-state field that existed in the core. Using a null method, he was able to obtain an accuracy of 1 part in 1000, but the method is only applicable to fields of less than 100 gauss, or to small variations in a large field.

(B) Force Exerted by a Magnetic Field

(a) Cotton (3), by means of a large chemical balance, employed the force of gravity on a mass m to balance the force that a magnetic field would have on a conductor carrying a current of i amperes and having a length l.

The equation used was

$$m\,g = H\,i\,l\,/\,10$$

For large fields the accuracy was found to be 1 part in 1000, but this limit was not obtainable with small fields.

(b) Optical Mechanical Probe. If a flat coil of wire be placed in a uniform magnetic field with its plane parallel to the lines of force, the current required in the coil to maintain its position against a constant mechanical torque is inversely proportional to the strength of the field.

Jones (4) used this principle to develop a rugged field-measuring device. In his design the position of the coil was established by means of an optical lever mounted on the coil. Although this instrument can be made to operate from 10 to 10,000 gauss, it was felt that it would be difficult to make measurements with the precision required in this work.

(c) Magnetron. The magnetron is a special form of the two electrode kenotron. It has a cathode which is a straight filament and an anode which is a cylinder concentric with the cathode. This tube is placed in a magnetic field so that the field is parallel to the axis of symmetry. In a given field there is a certain minimum value to the potential between anode and cathode required to allow any electrons to traverse the tube. This voltage is related to the tube radius and field through the equation

$$H = 6.72 \quad (V)^{\frac{1}{2}} / R$$

Using this principle Hull (5) has been able to measure fields between 20 and 500 gauss with an accuracy of 5 parts in 10,000. However, for fields of less than 20 gauss, it is difficult to get a precision of even 1 part in 100.

(d) Hall Effect in Germanium (6). A thin rectangular metal plate of thickness t cm., placed in the plane Z = 0 and with edges parallel to the X and Y axes, has a current I amperes flowing through it in the X-direction. A magnetic field H gauss in the Y-direction is super-imposed, causing the electrons in the sample to travel in curved paths to cause charging of the sides of the conductor. This charging continues until there exists a transverse electric field of the right magnitude to cancel the effect of the magnetic field and permit the electrons to pass through the solid, undeviated. The magnitude of this electric field in volts is given by the following equation:

$$V = R I H / t$$

where R is the Hall Coefficient in volt cm./ampere gauss. The effect is generally small, except in germanium which has a very large Hall Coefficient. Unfortunately, the coefficient is a function of field strength and temperature.

For fields from 3000 to 8000 gauss, this effect in a germanium crystal has been used to make measurements with an accuracy of about 2%.

(e) Proton Resonance (7,8). A proton sample (distilled water in a glass cell) is mounted within a small coil which is inserted in a magnetic field. The axis of the coil is at right angles to the direction of the field. If a R.F. signal, whose frequency f equals that of the Larmor precession of the protons, is set up in the coil, energy is absorbed by the protons and the signal is reduced in amplitude. The relation between this frequency and the applied magnetic field is

$$H = 2\pi f / \gamma = 234.87 \pm 0.29 \times 10^{-6} f$$

where γ is the gyromagnetic ratio of the protons.

The determination of H thus reduces to that of measuring a frequency and R.F. frequency measurements can be made to about 1 part in a million. Two serious limitations apply to this method. In the first place the field must be very homogeneous in order to give a sharp frequency response. In the second place, the frequency must be in a suitable region for generation and determination. In practice, this limits the method to fields of from 5000 to 20,000 gauss.

Using some special compounds it is possible to use the same principle with electron resonance. Since the gyromagnetic ratio of the electron is roughly 2000 times that of the proton, this means that the suitable region lies below 10 gauss.

(f) Magnetic Anistropy in Certain Crystals (9). Certain crystals, when suspended by a fibre or spring so that they may rotate about an axis perpendicular to the ternary axis and to the direction of the field, experience a torque when the field is applied. This torque is proportional to the square of the field times the sine of the angle between the ternary axis and the field direction. Commercial instruments based on this principle have been used for rough measurements from 5000 to 50,000 gauss. With fine suspensions and great care, fields of a few hundred gauss might be measured, but the accuracy would appear to be poor.

(C) Measurement of Quantity of Electricity Due to Motion of Conductor

(a) Mercury Jet Magnetometer. This method, developed by Kolin (10), utilises the E.M.F. induced in a conductor moving in a magnetic field. Mercury, flowing through a thin channel, in a direction at right angles to a magnetic field H, will induce a voltage E between the two sides of the channel, given by the following equation:

$$E = (\eta\, H\, \bar{\bar{v}}\, d)\, 10^{-8} \text{ volts}$$

where d is the diameter of channel, $\bar{v}$ is the average velocity of the mercury and η is a constant.

Although it gives a measure of the field over a region as small as one square mm. and can determine its direction accurately, it has not been developed to give an accuracy of better than 1% and, hence, is not suitable for our purpose.

(b) Ballistic Method. This is the most elastic and generally useful method in measuring magnetic field intensities. A small coil of cross-sectional area A, a number of turns n and resistance R, connected in series with a ballistic galvanometer of resistance Rg, is placed in a field of strength H, with its axis parallel to the field direction. The coil can be either moved quickly to a field-free region or flipped quickly through 180°.

In the first case (11,12) a total pulse of charge Q passes through the galvanometer, producing a deflection proportional to Q and hence to H. The following relationship can be shown to apply:

$$Q = K \theta = n A H / c(R + Rg)$$

where K is the ballistic constant of the galvanometer, θ is the galvanometer deflection and c is the velocity of light. The second case (13) leads to the same formula, except that the charge set in motion is doubled. The absolute accuracy of the Ballistic Method is limited to about 0.2%. For relative measurements, such as are required in the present application, the errors may be reduced to 0.1%.

The precision may be improved by use of a null method (14), that is, using the galvanometer to detect a balance between the voltages induced in two search coils. One coil could be placed in the field to be measured, the other in a reference field of known and variable magnitude, adjusted to give a null point. Unfortunately, this is a time-consuming process.

(c) Chattock Magnetic Potentiometer (15). If the ends of a helix are connected to a ballistic galvanometer and the difference in magnetic potential between the ends is changed quickly by the movements of one of the ends, the deflection of the galvanometer coil will be proportional to the change in magnetic potential between the ends. Therefore, holding one end fixed, and moving the other end quickly from the same point to a field-free region, a galvanometer reading is obtained which is proportional to the strength of the magnetic field.

This method can be used to measure directly the difference of magnetic potential between any two accessible points and, with reasonable care, it can be made accurate to 0.5%.

(d) Vibrating Coil Magnetometer. Caldecourt and Adler (16) are responsible for this device. An electronic oscillator is made to vibrate a shaft in a rotary fashion through a small angle about its longitudinal axis. The ends of the shaft carry small pick-up coils, one in a constant reference field, the other in an unknown field. A fraction of the voltage developed by the coil in the unknown field is compared to some fraction of that developed by the other. This difference is amplified and a servo-mechanism changes the voltage from the reference coil until a null is obtained. In this way, the ratio of the unknown field to the known field is found.

This is a very sensitive method with a claimed precision of 1 part in 10,000. The balance point is not a function of amplitude of oscillation and frequency, even though the coils are not precisely aligned and Caldecourt and Adler experienced no trouble with noise. However, the reference field must be independent of the unknown field. In our case, this would require a shaft over eight feet in length, compared with the 18-inch shaft of their device. The prospect of producing a 50-cycle oscillation frequency in such a shaft was not alluring, so the method was discarded.

(e) D.C. Generator. A coil, with effective area A driven with an angular velocity w, will develop an alternating E.M.F.

$$E = (A\ H\ w \cos wt)10^{-8} \text{ volts}$$

If the coil is connected to commutator segments, a D.C. voltage may be obtained which will be directly proportional to H.

Cork et al. (17) claim they can measure changes as small as 0.01 gauss in the region below 500 gauss. The limitation of this method seems to be the precision with which the rotational velocity of the driving motor can be kept constant. It was on this point that a device similar to that developed by Cork et al. failed when it was tried by Gale (18). For, despite the use of a synchronous motor, it was found that the line frequency was not stable enough to be used as a source of power for the motor.

(f) A.C. Generator. If, in the previous device, slip rings are used in the place of commutator segments, an A.C. voltage will be removed from the search coil. Several null methods have been developed using this A.C. voltage. Three such will now be discussed.

(1) The voltage obtained from a search coil in the spectrometer field is compared with the voltage produced by a search coil rotating in the field of a permanent magnet. A stabilizing circuit was built so that the current supplied to the spectrometer varied until the difference or error signal was zero. Katz et al. (19) claim stabilization of any field setting, between 500 and 6000 gauss, to be better than 1 part in 1000. This is below what we hope to achieve.

(2) An ingenious variation of the previous device has been developed simultaneously by Langer and Scott (20). Synchronous motors

were used whose relative phase of rotation could be varied. Brush noise was eliminated by bringing the signal from the search coils by means of a special transformer whose primary was attached to the shaft and whose secondary was at rest. Since these men were interested in weak fields, they took elaborate precautions to balance out the effects of the earth's field. Their claimed precision of 0.1% is below the goal which we have set for our spectrometer.

(3) A very elegant modification of the previous method has been developed by A. Hedgram (21). Since this is the one we decided to adopt, a detailed discussion of the method will be reserved for the next section of the thesis.

In place of mounting the coils on two separate shafts, both were mounted on the same shaft, one in the spectrometer field, and the other in a variable reference field. By means of a weak cross-field perpendicular to the reference field, accurate phase adjustment could be carried out. The absolute sensitivity claimed for this method is about 0.001 gauss and a minimum may be located with a precision of 1 part in 30,000 without difficulty.

Since both the range of fields for which this method was designed and the spectrometer for which it was to be used are similar to ours, this method seems to satisfy our requirements admirably.

SECTION II

DESIGN AND CONSTRUCTION OF APPARATUS

(A) Theory

A short analysis of the method will be given in order to emphasize the important factors in the design of the null detector. The basic principle is indicated in Fig. 1.

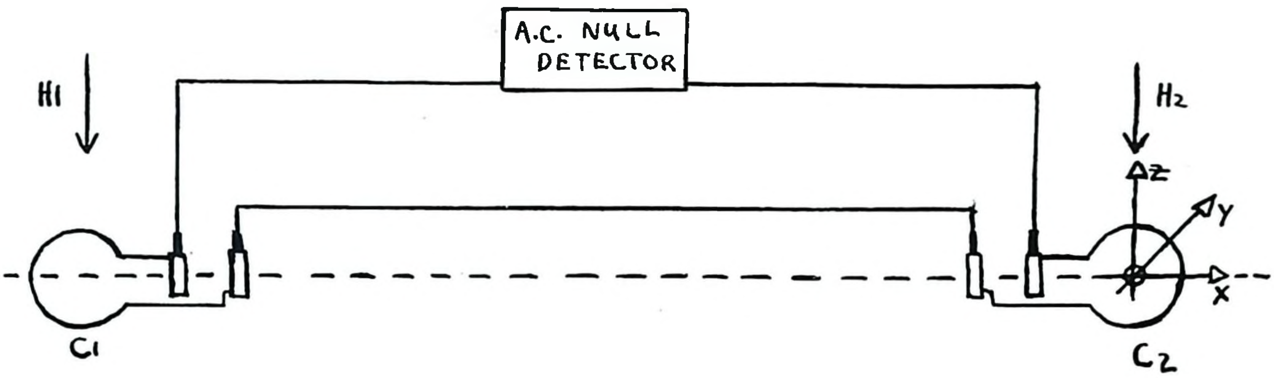

Fig. 1

Two flat coils, C_1 and C_2, are fixed to the same axle and rotate around the X-axis with an angular velocity w in the spectrometer field H_1 and the reference field H_2. Both H_1 and H_2 are to be parallel to the z-axis and in the same direction. H_2 is produced by an iron-free set of Helmholtz coils.

Assume for the moment that H_1 and H_2 are homogeneous, and that the relative position of the planes of the two search coils is so adjusted that the voltages induced in the two coils are π radians out of phase. The two fields are said to be balanced when H_2 is so adjusted that the detector shows a minimum. At the moment

$$H_1 = \frac{A_2}{A_1} H_2$$

where A_1 and A_2 are the effective areas of the coils.

Now H_2 is strictly proportional to the current I_2 through the Helmholtz coils. Therefore

$$H_1 = K I_2$$

Let the E.M.F. from the spectrometer coil be

$$E_1 \cos (w t + \theta)$$

and the E.M.F. from the Helmholtz search coil be

$$E_2 \cos w t$$

where θ is the phase angle shown in Fig. 2. Assume that a fraction y of the second signal is compared with the first. If these two signals are now mixed, the residual signal is

$$\Delta e = y E_2 \cos w t - E_1 \cos (w t + \theta)$$

Setting $$y E_2 - E_1 = \Delta e_o$$

it is readily seen from Fig. 2 that

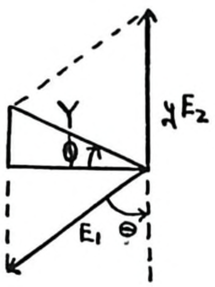

Fig. 2

$$\Delta e = Y \sin (w t + \phi)$$

$$\text{where } Y = \left[E_1 \, 4 \sin^2 \theta/_2 + \frac{\Delta e_o}{E_1} + \frac{4 \Delta e_o}{E_1} \sin^2 \theta/_2 \right]^{\frac{1}{2}}$$

Since in practice $\Delta e_o/_{E_1}$ and $\sin \theta/_2$ are both small, the last term is a third order quantity and may be neglected.

An inspection of the expression for Y shows that it may be minimized by changing either θ or Δe_o. Since we wish to have a sharp minimum Y when $\Delta e_o/_{E_1}$ is $\ll 1/2 \times 10^{-4}$, it is clear that $2 \sin \theta/_2$ must be of comparable magnitude. Hence θ will have to be less than 20 seconds of arc to get a sharp balance of the fields to one part in 10,000.

Because the effects of the earth's field cannot be completely eliminated, matters are not quite so simple as the above analysis would suggest. The earth's field at the centre of the Helmholtz coils can easily be neutralized to better than 0.1% by means of two pairs of compensating coils, used in the Helmholtz arrangement, with axes of symmetry respectively vertical and horizontal. The horizontal component of the earth's field at the spectrometer is small but not negligible and, as a result, the direction of the resultant field in the spectrometer changes slightly with the field strength in the gap. To obtain proper phasing conditions, it is necessary to alter slightly the direction of the resultant field at the Helmholtz coils. This is done by making small changes in the horizontal compensating field, primarily used to nullify the horizontal component. Such changes are much too small to affect the magnitude of either H_1 or H_2. Moreover, the spectrometer exerts a weak stray field at the Helmholtz position. As long as this field is strictly proportional to the field in the spectrometer gap, its effect is only to shift the constant of proportionality, as the following equations will indicate. We now have at the point of balance

$$H_2 = K I_2 + k H_1$$

whence

$$H_1 = K' V$$

where K' and k are constants and V is the voltage developed across a standard resistor in series with the Helmholtz coils.

The sensitive comparison of the two search coil signals can be made directly by amplifying the difference signal by a factor of 10^3 or 10^4

and adjusting to bring the amplified signal to zero. At this setting the potential across the standard resistance is proportional to the Siegbahn field.

An alternative and more elegant method involves passing the amplified error signal through a phase-sensitive detector and using the D.C. signal so obtained to control the magnet current. It was originally intended to use this method, but limitations of time have made it impossible to reach this goal.

(B) Mechanical Layout

Fig. 3 shows a schematic diagram of a vertical section through the apparatus. This apparatus, with its elaborate care in construction, was built after an earlier, simpler design proved mechanically inadequate. The Helmholtz coils A and B are mounted rigidly on a concrete block nine feet from the spectrometer gap. The vertical compensating coils are located at C and D and the horizontal compensating coils E and F are placed one in front and the other behind the plane of the diagram.

The Helmholtz search coil G is located precisely at the centre of the coils A and B. It is mounted on a short shaft which runs on rigid, oiled bronze bearings, with an adjustment to keep end-play to less than 0.002 inches. The details of this mounting are shown in Fig. 4. A similar mounting is used for the Siegbahn search coil H, which is located as closely as possible to a point 50 cm. from the axis of the Siegbahn magnet. The signals are removed from the search coils by means of brass slip rings and carbon brushes (not shown), since contact potentials have no effect.

The search coils are coupled to the driving mechanism, which is located midway between them, by two four-foot sections of aluminum tubing

1.625 inches in diameter. The ends of these tubes are coupled to the coil shafts and the drive shaft by means of flexible Cardan joints, K. These precautions were taken to reduce the vibration transmitted from the motor to the search coils.

The driving mechanism, mounted on its own rigid support, consists of a phase-shifting device, to be described later, and a stainless steel pulley. This pulley is coupled to the driving pulley of an 1800 r.p.m. 1/8 H.P. synchronous motor by means of a flat nylon belt. The pulley diameters were chosen to give a search coil angular velocity of 1500 r.p.m. This speed was chosen to reduce the resonance pick-up of unwanted signals, since the power frequency in the building is 60 cycle.

(a) Search Coils. Since the field in the Siegbahn is not uniform, it was decided to make the search coils with a small effective area and a large number of turns. The coils, consisting of 9,000 turns of B. & S. No.42 insulated copper wire, are wound on a bakelite spool, with a minimum diameter of 0.95 inches. The winding is 0.40 inches wide and 0.20 inches deep.

(b) Phase-Changing Device. The relative phase of the two search coils (G and H in Fig. 2) is controlled by a mechanical phase shifter (Fig. 5 and M in Fig. 3), which can be set to within one minute of arc. The fine phase control is imposed by varying the direction of the Helmholtz field, as described earlier.

The mechanical device, made out of stainless steel and 4 inches in diameter, consists of three discs mounted on a common shaft. The first two discs fit closely together and can be moved with respect to one another by steps of a third of a degree through 20 degrees, providing the coarse-phase adjustment. After clamping these discs rigidly, small changes in phase about any setting can be accomplished by causing a third disc to rotate slightly with respect to the second. This rotation is achieved by means of an eccentric which forces a conical plug radially out from the axis. This plug, working between stops on the second and third discs, forces them to move relative to each other. When the desired position is reached, a second clamp ensures that no further motion will occur. By reducing the taper of the plug and the amount of eccentricity on the eccentric disc, the device can be made as sensitive as desired. With a taper of 0.010 inches in 0.168 inches of movement, shifts of 20 seconds of arc can be made. In practice, it was simpler to get the phase correct to about one minute of arc and then to use the horizontal compensating coils for final adjustment.

(c) Reference and Compensating Field Coils. The reference field is provided by two coils (A and B in Fig.3), each with 5500 turns of B. & S. No.23 insulated copper wire and a mean diameter of 16 cm. The coils have a square winding cross-section of 5 cm., and are placed with their centres 8 cm. apart in the usual Helmholtz arrangement. Each coil has a resistance of 180 ohms. They were originally planned to be operated in series with each other and with the spectrometer magnet (resistance 600 ohms), but, since they became slightly warm at currents of 400 m.a. (i.e., the current needed to focus 3 Mev. electrons) they have been connected in parallel with each other and in series with the spectrometer magnet. They are mounted rigidly to maintain a constant proportion between the reference field and the current.

The vertical compensating coils C and D each have a diameter of 24 cm. and consist of 100 turns of B. & S. No.23 insulated copper wire. They are placed 12 cm. apart just above and below the coils for the reference field. The current necessary to neutralize the vertical component of the earth's field is approximately 50 m.a.

The horizontal compensating coils E and F are placed in vertical planes parallel to the rotating shaft. They each have a diameter of 33 cm. and consist of 100 turns of B. & S. No.23 insulated copper wire. They are placed 16.5 cm. apart and require approximately 20 m.a. to neutralize the horizontal earth's field.

(C) Electronic Control and Measuring Circuits

A narrow band amplifier and a phase-sensitive detector and their associated power supply will be described in this section. This power supply will also serve as a current supply for the compensating coils.

(a) Power Supply. The power supply shown in Fig. 6 is of conventional design (22). It was required to build a supply capable of delivering 225 m.a. at 290 volts (150 m.a. for filament current, 45 m.a. for the amplifier, and 30 m.a. for the power supply). The reference voltage is supplied by a 5651 voltage regulator tube, T4, which is supposed to be much more stable than the normal V.R. tube, though the operating levels for different tubes may vary by $\pm$ 5 volts about the manufacturers' rated value of 87 volts. Since individual tubes show this variation, the cathode resistor of T3, R9, must be adjusted until 150 m.a. flow through the heater line.

This power supply provides a convenient method of obtaining the current for the compensating coils C and D and E and F. Only a small fraction of the filament current passes through these coils because of the by-pass resistors R14 and R15. The helipots R16 and R18 permit a fine adjustment of the compensating coil currents without disturbing the filament current appreciably.

To couple the amplifier network to the existing Siegbahn current control, it was necessary to divide the 290 volt output between two points A and B. The D.C. levels chosen were + 130 volts and -160 volts, respectively.

The voltage output of the supply is free from ripple and stable to about 1 part in 20,000.

(b) Narrow Band A.C. Amplifier. The circuit shown in Fig.7 is a slight modification of a circuit described by J. M. Sturtevant (23). It consists of a cascaded pair of amplifiers sharply tuned to 25 cycles/sec. Actually, one member of the pair is tuned to a frequency of about 0.3 cycles per sec. below this value, while the other is tuned to a frequency slightly above 25 cycles/sec. The staggered combination has a nearly flat response over a one cycle/sec. band with sharp fall-off on both sides. Since both stages are essentially equivalent, only the first stage will be described.

The input signal is amplified by T5 and T8 and the output of T8 is fed back to the cathode of T5 by means of cathode followers T6 and T7. The T7 feed-back loop contains a twin-T filter which rejects the frequency to which the amplifier is tuned and passes all others. The T6 loop transmits all frequencies with the same attenuation, given roughly by R26/(R27 + R28). The attenuated signal from T6 provides the negative feed-back necessary for stability. T7, on the other hand, applies a very large negative feed-back signal to T5 for all signals passed by the filter, and therefore sharply reduces the gain of the amplifier for frequencies outside the passband.

For ideal operation, the following relation should exist between the components of the twin-T (see insert of Fig.7):

$$R_a = R_b = 2 R_c$$

$$C_a = C_b = 1/2\ C_c$$

$$\omega_o = 1/R_aC_a$$

where ω_o is the frequency to which the twin-T has been tuned.

The theoretical gain of the circuit at ω_o is

$$G(\omega_o) = (R27 + R28)(R26 + R25 + R29)/(R26 \cdot R29)$$

$$= 340 \text{ with the values given in Fig.7.}$$

The gain actually achieved is perhaps 70% of the value predicted by the theory which assumes that the g.m. of the tubes used is infinite.

The theoretical Q of the circuit is

$$Q = \frac{(R27 + R28)}{4 \cdot R29 \cdot R26}(R26 + R25)$$

For our choice of parameters, this is 10.

Adjusting R28, the overall gain of the staggered pair may be varied from 2400 to 15000. The larger figure is roughl_ a quarter of the gain expected, the discrepancy being due to the staggering of the tuned frequency and to attenuation in the coupling between stages. It is important that the cathode of T7 and T11 be maintained at 55 volts above point B. Potentiometers R41 and R61 provide adjustment for this purpose. The 60-cycle ripple appearing on the output corresponds to a 20 microvolt input. In order to reduce microphonics, the amplifier chassis was mounted on shock absorbers.

The twin-T network is tuned by feeding a signal of the desired frequency (25 ±.3 cycles per sec.) to the plate of T6 when power is being supplied to the amplifier. An oscilloscope is then connected to the cathode of T7. Resistors R33, R36 and R37 are varied until the signal passed by the filter is reduced to a minimum. Because of harmonics in the input signal, the frequency seen for this adjustment will be 50 ± .6 cycles per sec. Attempts to tune the amplifier by feeding the signal to the grid of T5 were not successful.

(c) Phase-Sensitive Detector (Fig.8). The output of the A.C. amplifier is taken either from P or Q (Fig.7) and passed through a coupling stage to T13 to a phase-sensitive detector (24) using tubes T14 and T15 to get full wave rectification. The coupling devise merely provides two signals of equal amplitudes 180 degrees out of phase. An A.C. signal of the same frequency as the input signal is applied to the grids of T14 and T15 through R and S. When the relative phases of the signals have the polarity as indicated in Fig. 8, T14a conducts on the first half cycle and T14b conducts on the second. As a consequence, C29 charges positively during both half-cycles. If the polarity of the input signal changes, then T15 conducts and C29 is charged negatively. Thus the grid of T16 is driven positively for signals of one phase and negatively for signals of the other. At a null point there is no voltage on the grid. The D.C. voltage appearing on C29 is roughly equal to the amplitude of the A.C. signal from P.

The A.C. signal applied to the grids of T14 and T15 must always be greater than the maximum A.C. signal applied to P. If this condition is not satisfied, the detector loses its sense of direction.

(D) Field Measurement

The disposition of the equipment when it is to be used for field measurement is shown in Fig.9. The Helmholtz coils and the Siegbahn coils are in series in the stabilized current circuit of the spectrometer. The current through the Helmholtz coils may be adjusted without affecting the Siegbahn coil current by means of the resistance network controlled by S3. The A.C. signal generated by the Siegbahn field in coil SC2 is balanced against the signal generated by the Helmholtz field in SC1 and the difference, or error signal, is fed to the A.C. amplifier through the mixing stage. The output of the amplifier is displayed on the oscilloscope.

With the vertical and horizontal components of the earth's field properly neutralized by means of the compensating coils (not shown), the Helmholtz coil current is adjusted until this signal passes through a minimum. The minimum will not be sharp unless the two search coil outputs are precisely out of phase (within ± 20"). The minimum signal is now reduced as far as possible by successive adjustments of the mechanical phase-shifter and this device is then clamped securely. The final phase adjustment is then made by varying the horizontal compensating field. These adjustments are so small that they will not affect the magnitude of the Helmholtz field but simply shift its direction through a few seconds of arc. When this adjustment has been properly made, the two search coil signals can be matched to within 1 part in 30,000.

When the null balance has been obtained by varying the Helmholtz current, the potential developed across a manganin resistor, R89, is measured on a Type K Leeds and Northrup potentiometer. This reading, which can be measured to 0.01% is proportional to the magnetic field in the Siegbahn gap. Although in principle this method seems to offer a precision of one part in 10,000 for the field measurement, the degree of reproducibility of the results does not support this conclusion. This matter will be discussed in detail in Section III.

The compensation for the earth's field is carried out by turning off the magnet current and shorting out SC2. The vertical and horizontal compensating coils are then adjusted to bring the signal appearing on the scope to zero. This adjustment at the Helmholtz coil can be made to one part in 2000. This does not mean that the earth's field has been compensated to this accuracy, since the residual field of the magnet at the Helmholtz is not negligible when the magnet is turned off.

In fact, unless the magnet is demagnetized carefully by successive reversals while the current through it is reduced, the compensating current required for the null will vary by several percent. With proper demagnetization, the compensating current is reproducible to one part in 1000.

The stray field of the Siegbahn magnet at the Helmholtz position can be readily measured by throwing switch S2 (Fig.7) from its normal position (b) used in field measurement to position (a) and by shorting out the Helmholtz coils. When this is done, a small fraction of the Siegbahn generator output is compared with the stray field of the magnet at the Helmholtz position and a null obtained in the usual manner by varying the helipot R19. The ratio of the stray field to the field present in the gap of the spectrometer can then be determined from the resistance values.

For the resistance values used, this ratio is

$$(4.91 + 0.123\ X)/10000$$

where X is the scale reading of the helipot at the null position (1500 full scale). The measured ratio is roughly 0.2%.

(E) A Proposed Method of Automatic Stabilization

The existing current control circuit for the Siegbahn is shown at the extreme right of Fig. 8. The inclusion of the Helmholtz coils in series with the Siegbahn magnet does not affect its operation. Since the field in the Siegbahn spectrometer is nearly proportional to the magnet current (within 10% if precautions for demagnetization are taken; within 40% if no care is exercised), it was felt that the Siegbahn field could be matched to the Helmholtz field by by-passing a controlled fraction of the magnet current through T17.

The electronics shown in Fig. 8 have been constructed with the above purpose in mind but phase shift and hysteresis effects made this approach more difficult than originally conceived and it was decided to concentrate our efforts on using the device for field measurement, as described previously.

SECTION III

A STUDY OF THE PERFORMANCE OF THE A.C. NULL METHOD OF MEASURING MAGNETIC FIELDS

The apparatus which has been described in Section II is only of value if it can measure the magnetic field in the spectrometer gap to better than 0.1% which is the limit of accuracy of the flip-coil method currently in use. It will become really valuable if it can make measurements to better than 0.05%.

Two conditions limit its performance: (I) the sensitivity with which a null can be established and (II) the reproducibility of the potentiometer reading associated with a given field. Each of these limitations is discussed in turn.

(A) Sensitivity

Under ideal conditions of adjustment of the magnitude and phase of the Helmholtz field, the A.C. signals generated may be made to cancel to better than 1 part in 30,000. This limit is set by the presence of a small 50 cycle/sec. harmonic in the output of the generator. At present such a null cannot be maintained over long periods because the current control circuit of the Siegbahn spectrometer is only stable to roughly one part in 10,000. Figure 10 shows how the null detector output varies as the Helmholtz current is varied near a null point. It is seen that the accuracy with which the null point can be determined depends somewhat on the absolute value of the spectrometer field; to within 0.01% at a field of 10 gauss and to within 0.005% at a field of 300 gauss.

Evidently, the sensitivity is quite sufficient for our purpose.

(B) Reproducibility

(a) Methods of Checking Reproducibility. With the condition of sufficient sensitivity having been achieved, it is necessary to make sure that the null method measurements can be reproduced accurately. To check this point, one must have available an independent method of measuring the field in the spectrometer gap. Two such methods are available. The potentiometer setting (determined when the null detector indicates a minimum) for a given Siegbahn field may be compared with the deflections of a ballistic galvanometer and flip-coil, placed in the same field. Since the latter method is only reproducible to 0.1%, the check on the null method can not be made more accurately than this. A laborious but more accurate check on the performance of the null detector can be obtained by scanning over photo-electron peaks produced by precisely known gamma rays, and comparing the points of inflection on the peaks so obtained with the value predicted from the known gamma ray energies.

(b) The Stray Field of the Siegbahn at the Helmholtz Position. It has already been shown that the stray field of the Siegbahn at the Halmholtz position is about 0.2% of the Siegbahn field (see p.23). An alternative method of determining this ratio involves (i) a determination of the Siegbahn field in the usual way; (ii) a reversal of the Helmholtz coil leads without disturbing the current setting of the Siegbahn coils. (The weakness of the method is perhaps the assumption that this alternative does not alter the Siegbahn current); (iii) A connection of the A. C. amplifier to the Helmholtz search coil with the search coil removed; (iv) an adjustment of the Helmholtz current to give a null signal. The ratio of the potentiometer reading for this setting to that for the total field is the desired quantity. This procedure gave a value of 0.20 ± 0.01%, which is in good agreement with the value found by the other method.

Since this ratio seems to be constant as demanded by the theory (page 13), it was decided to test the performance of the detector on some well known gamma rays.

(c) Determination of Peak Positions with the Null Detector. Figure 11 shows the Co^{60} peak at $H\rho$ 5504.7 gauss-cm. as converted in a 9 $mg./cm.^3$ uranium radiator. It is clear that the point of inflection can be located to within 0.01% and that much smaller increments in the field setting can be made than with the flip-coil measurements. This represents a marked improvement over the flip-coil method.

Unfortunately, the inflection point, as measured with this device, is a function of the previous treatment of the magnet core and shifts of the order of 0.3% may take place. Similar behaviour occurred for Cs peak at $H\rho$ 3088.4 gauss-cm. and for the Th peak at $H\rho$ 9396 gauss-cm. At very low fields the shifts are much larger, reaching values of a few percent. A great deal of effort has gone into attempts to account for these shifts without complete success. The remainder of this section of the thesis deals with this effect.

(d) Investigation of Hysteresis Effects. Since carefully scanning a peak requires at least three hours, it was decided to use the flip-co...

method as a reference and study the ratio of the flip-coil deflection to the null method potentiometer setting as a function of the flip-coil reading under various conditions. Fig. 12 shows how this ratio changes as the spectrometer field is gradually increased from zero (after careful demagnetization) to a maximum ($H\rho \sim 15000$) and then reduced to zero. The initial drop in the ratio below a deflection of 10 cm. may be eliminated if great care is taken in demagnetization. In the case when the field is being increased, the two methods agree to within 0.05% which is as good as one can expect, when it is considered that the flip readings are only accurate to 0.1%.

When the field is reduced, the two methods give quite divergent measurements, the difference reaching 01.6% at the lowest fields. Subsequent cycles without demagnetization follow the lower curve at least to a first approximation.

The following reasons for this behaviour have been postulated and examined.

(1) The fields at the flip-coil and Siegbahn search coil are not proportional.

It seems hard to believe that this could be so. However, some justification for this assumption could be found in view of the fact that within a distance of 25 cm. from the flip-coil there is a 1.5 inch hole in the lower pole face, an armco iron photomultiplier shield and a small amount of iron on a switch assembly.

That none of these had any effect on the curves of Fig.12 was readily proved by removing all of them.

Therefore it is believed that this postulate is not valid.

(ii) The stray field of the Siegbahn at the Helmholtz is not proportional to the field in the Siegbahn gap.

This postulate is very much more difficult to test than (i) because the stray field at the Helmholtz coil depends on the state of magnetization of the reinforcing iron in the ceiling and floor of the laboratory, in the electronic components and in the steel door jamb.

With the magnet current completely off, the field in the Siegbahn gap may be anywhere from $\sim$ .1 gauss to $\sim$ 3 gauss. In this range of fields, the field "shape" will certainly be variable and one might properly expect the (stray field/gap field) ratio to vary quite widely. However, we are not concerned with this region ($H\rho \sim 150$) but with electrons for which $H\rho$ is ~ 500 and the gap fields are therefore greater than 10 gauss. In terms of Fig. 12, a deflection of 20 cm. represents $\sim$ 14 gauss. For such fields, the field created by the current in the magnet coil controls the field shape of the magnet, since the thorium A line at this energy has good line shape. With such a situation, and without the presence of disturbing masses of ferro-magnetic material in the building, one would expect strict proportionality, as found by Hedgran (21) in his apparatus.

After a careful demagnetization cycle, Fig. 12 shows that near proportionality can be maintained for increasing fields. The evident departures from proportionality on the decreasing field portion of the cycle may probably be due to residual magnetism induced in the walls of the building.

(iii) The non-linearity of Fig. 12 is due to the interaction of the stray field of the Helmholtz with the walls.

Since the steel door jamb of the room is only 15 inches from the Helmholtz search coil, it seemed likely that the magnetization of this structure by the Helmholtz field could induce effects of the order of 1% at the search coil. This effect would be revealed as an apparent change in the vertical component of the earth's field at the Helmholtz, occurring whenever the Helmholtz current was increased to a maximum and then reduced to zero. With the spectrometer current at zero and with the A.C. amplifier coupled to the Helmholtz search coil, the Helmholtz coils were used to balance the "earth's" field before and after this cycle of variation in the Helmholtz current. Although the method was sensitive enough to detect a change of 0.1%, no changes were observed.

(iv) The non-linearity of Fig. 12 is due to the interaction of the stray field of the Siegbahn with the walls.

A repetition of the experiment of (iii) with the roles of spectrometer and Helmholtz coils reversed was used to look for changes at the Helmholtz search coil position. Changes as large as 4% of the vertical component of the "earth's" field were observed. Since this field is $\sim$ 0.5 gauss, changes of $\sim$ 0.02 gauss were recorded. This would cause a lack of proportionality at 10 gauss of 0.2%, which is not nearly enough to explain Fig.12.

It has recently been realized that abrupt changes in the state of magnetization of the door jamb can introduce quite large changes in the values of the vertical and horizontal components of the earth's field. Since some changes of this sort may have occurred during the preceding tests without the above fact being appreciated, it is clear that all of the tests ought to be repeated and new tests devised.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The device described in the above sections has been shown to be sensitive to field changes of 1 part in 30,000. In principle, it would seem to offer the possibility of measuring the field of the spectrometer and controlling it to within one part in 10,000. In order to achieve this, it will be necessary to eliminate a number of stray fields created by the ferromagnetic materials present in the walls of the laboratory.

The mechanical features of the apparatus seem to be very reliable and operate without attention. In particular, no trouble is experienced with brush noise, since the 25-cycle narrow band amplifier rejects such signals very well.

Even with the effects of stray fields now present, it appears that this method would offer a slight improvement in precision over the flip-coil now used. If the neutralization of these fields can be complete, field measurements accurate to 0.01% seem feasible.

The following suggestions for reducing the effects of the stray field are offered.

(a) Increase the Helmholtz field relative to the size of the stray field. This can be done only by making the physical size of the Helmholtz coils and the search coil smaller. A highly stabilised and independent power supply for the Helmholtz coils would be very useful and eventually be used for automatic control of the Siegbahn field.

(b) It may be possible to shield the Helmholtz coils from the stray fields in the room by means of a large cylindrical sheet of mu-metal or hypernik surrounding the Helmholtz assembly.

(c) Move the Helmholtz assembly further from the door jamb to reduce its effect. A shift of about one foot might be practicable.

(d) Make the current controls of the vertical and horizontal components totally independent.

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PARTS LIST

C1 - 10 m.f.
C2 - 20 m.f.
C3 - 0.1 m.f.
C4 - 1 m.f.
C5 - 0.25 m.f.
C6 - 1 m.f.
C7 - 1 m.f.
C8 - 8 m.f.
C9 - 8 m.f.
C10- 0.05 m.f.
C11- 0.05 m.f.
C12- 0.1 m.f.
C13- 0.01 m.f.
C14- 1 m.f.
C15- 0.25 m.f.
C16- 1 m.f.
C17- 1 m.f.
C18- 8 m.f.
C19- 8 m.f.
C20- 0.05 m.f.
C21- 0.05 m.f.
C22- 0.1 m.f.
C23- 0.01 m.f.
C24- 1 m.f.
C25- 0.25 m.f.

C26 - 40 m.f.
C27 - 1 m.f.
C28 - 1 m.f.
C29 - 1 m.f.
F1 - 2 amp fuse
L1 - 10-200K
M1 - 0 250 m.a.ammeter
R1 - 0.15 K
R2 - 0.15 K
R3 - 5.1 K
R4 - 5.1 K
R5 - 12.5 K
R6 - 510 K
R7 - 15 K
R8 - 510 K
R9 - 10 K[*]
R10-12.5 K
R11- 1000 K
R12 - 82 K
R13 - 0.8 K
R14 - 0.15 K
R15 - 0.05 K
R16 - 1 K[**]
R17 - 68 K
R18 - 0.05 K[**]

R19 - 100 K[†]
R20 - 4700 K
R21 - 200 K[Δ]
R22 - 500 K[Δ]
R23 - 1000 K
R24 - 100 K
R25 - 1 K[Δ]
R26 - 1 K[Δ]
R27 - 50 K[Δ]
R28 - 250 K[x]
R29 - 15 K[Δ]
R30 - 500 K[Δ]
R31 - 51 K
R32 - 47 K
R33 - 20 K[x]
R34 - 100 K[Δ]
R35 - 100 K[Δ]
R36 - 20 K[x]
R37 - 50 K[Δ]
R38 - 10 K[x]
R39 - 10 K
R40 - 500 K[Δ]
R41 - 2 K[x]
R42 - 2.2 K
R43 - 10 K

PARTS LIST (Cont'd.)

R44 - 20 K
R45 - 1000 K
R46 - 100 K
R47 - 1 KΔ
R48 - 1 KΔ
R49 - 300 KΔ
R50 - 15 KΔ
R51 - 500 KΔ
R52 - 51 K
R53 - 47 K
R54 - 100 KΔ
R55 - 20 Kx
R56 - 100 KΔ
R57 - 20 Kx
R58 - 50 KΔ
R59 - 10 Kx
R60 - 10 K
R61 - 3 Kx
R62 - 500 KΔ
R63 - 2.2 K
R64 - 10 K
R65 - 20 K
R66 - 1000 K
R67 - 47 K
R68 - 2 KΔ

R69 - 2 KΔ
R70 - 510 K
R71 - 510 K
R72 - 10000 K
R73 - 10000 K
R74 - 10000 K
R75 - 10000 K
R76 - 10 K
R77 - 65 KΔ
R78 - 30 KΔ
R79 - 0.47 K
R80 - 140 K
R81 - 1 KΔ
R82 - 0.1 K
R83 - 0.075 K
R84 - 0.25 K
R85 - 0.4 K
R86 - 2 K**
R87 - 2 KΔ
R88 - 0.1 K**
R89 - standard resistor (manganin, approx. 2.15 ohms)
S1 - on,off switch
S2 - double pole, double throw switch

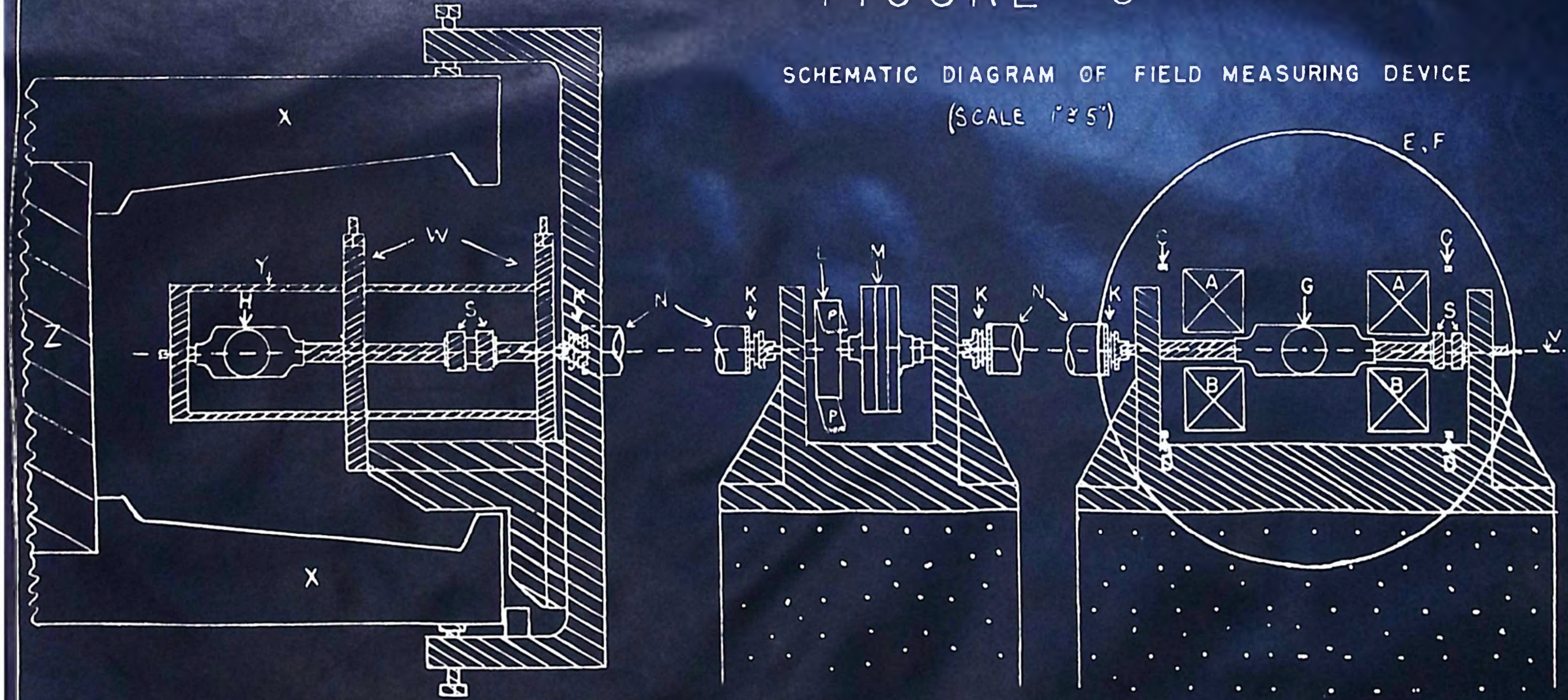
S3 - multiple switch
T1 - 5T4
T2 - 6AS7
T3 - 12SL7
T4 - 5651
T5 - 12SJ7
T6 - 12J5
T7 - 12J5
T8 - 12SJ7
T10 - 12J5
T11 - 12J5
T12 - 12SJ7
T13 - 12J5
T14 - 12SL7
T15 - 12SL7
T16 - 12SH7
T17 - 6B4
T R1 - 278 x 60

* wire wound potentiometer
** 10 turn helipot Type A
+ 15 turn helipot type B
x carbon potentiometer
Δ Nobeloy, 1 watt

FIGURE 3

SCHEMATIC DIAGRAM OF FIELD MEASURING DEVICE

(SCALE 1"≅5")



- CONCRETE
- BRONZE CASTINGS
- OTHER BRONZE (BRASS)

A, B - HELMHOLTZ COILS

C, D - VERTICAL COMPENSATING COILS

W - CLAMPS FOR Y

E, F - HORIZONTAL COMPENSATING COILS

G - HELMHOLTZ SEARCH COIL

H - SIEGBAHN " "

K - FLEXIBLE COUPLING

L - PULLEY

X - POLE FACES OF SIEGBAHN (IRON)

Z - COILS OF SIEGBAHN

M - MECHANICAL PHASE SHIFTER

N - ALUMINIUM TUBE

P - NYLON BELT

S - BRASS SLIP RINGS

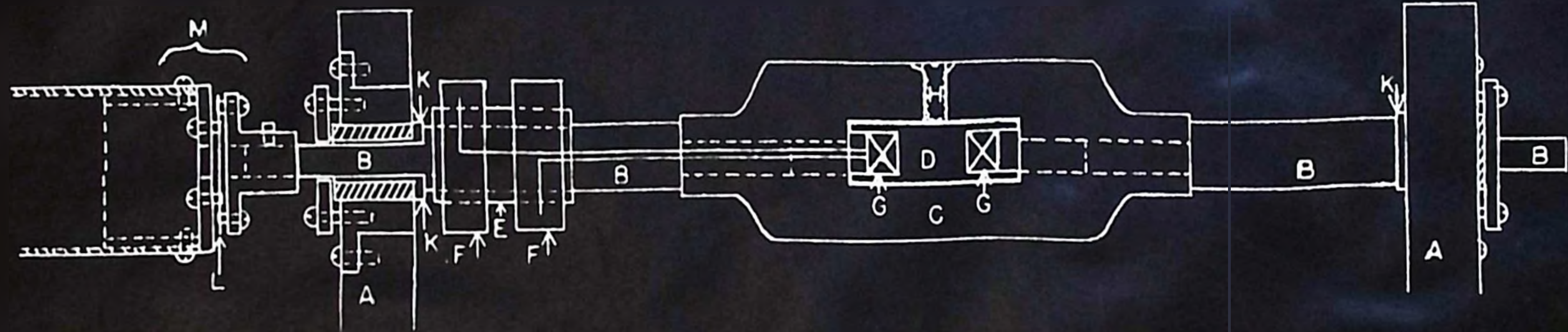
V - AXIS OF ROTATION

Y - BRASS CYLINDER

FIGURE 4

DETAILS OF THE SEGMENT ROTATING IN THE HELMHOLTZ FIELD

(DRAWN TO HALF SIZE)



(oil bronze hatching) - OIL BRONZE BEARINGS

(aluminium hatching) - ALUMINIUM TUBE

A - BRONZE CASTING

B - BRONZE ROD

C - BAKELITE FRAME

D - BAKELITE SPOOL

E - RUBBER

F - BRASS SLIP RINGS

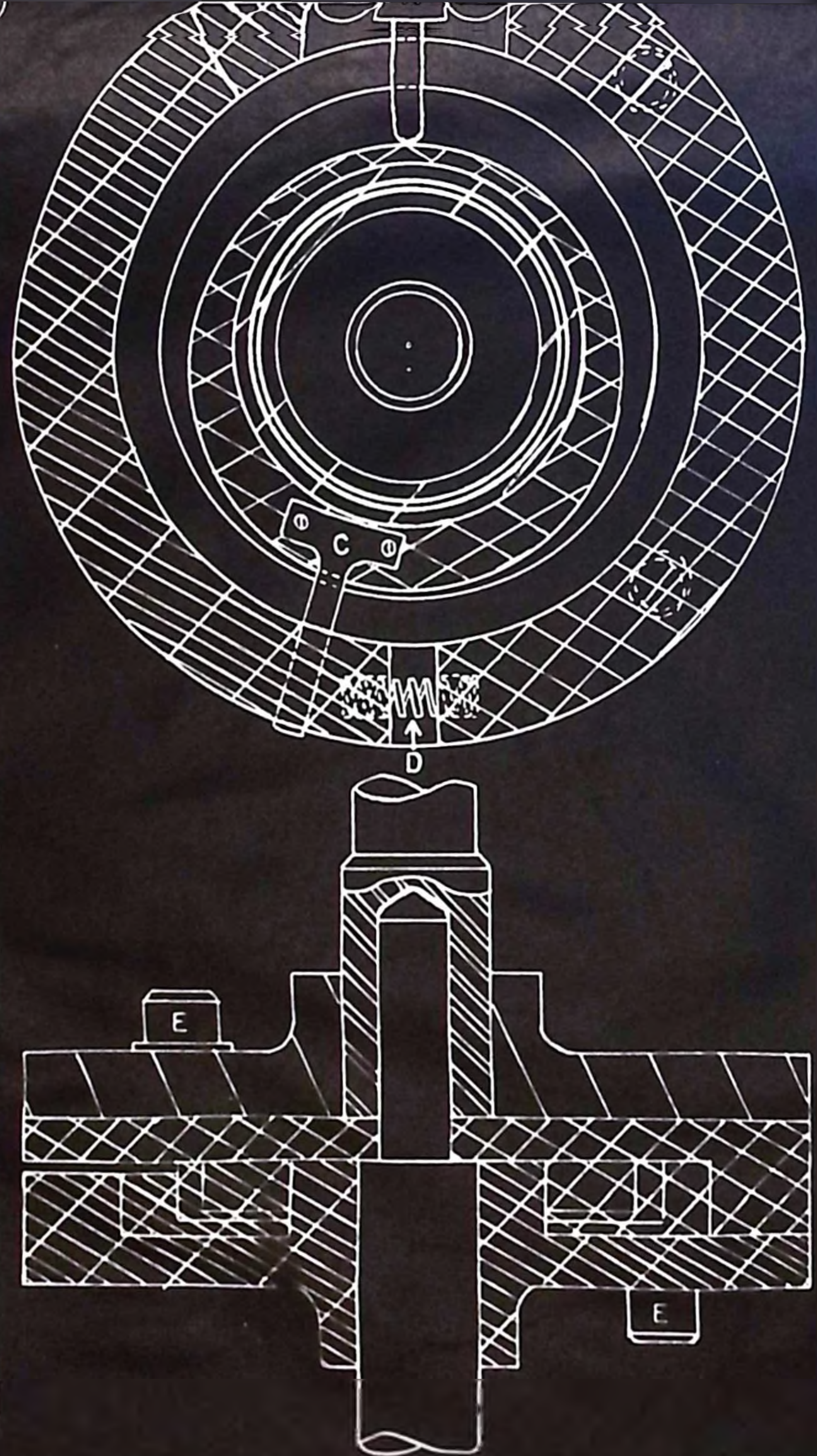
G - SEARCH COIL WINDINGS

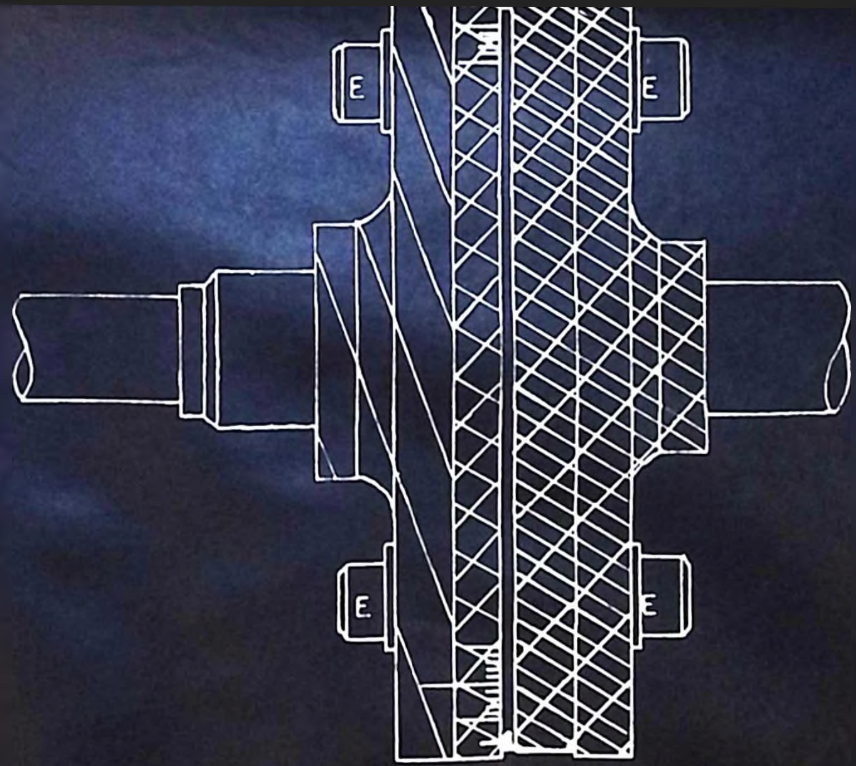
H - BRASS SCREW

K - STAINLESS STEEL COLLAR SWEATED ON B

L - 0.010" NICHROME SHEET

M - FLEXIBLE COUPLING (CARDAN JOINT)



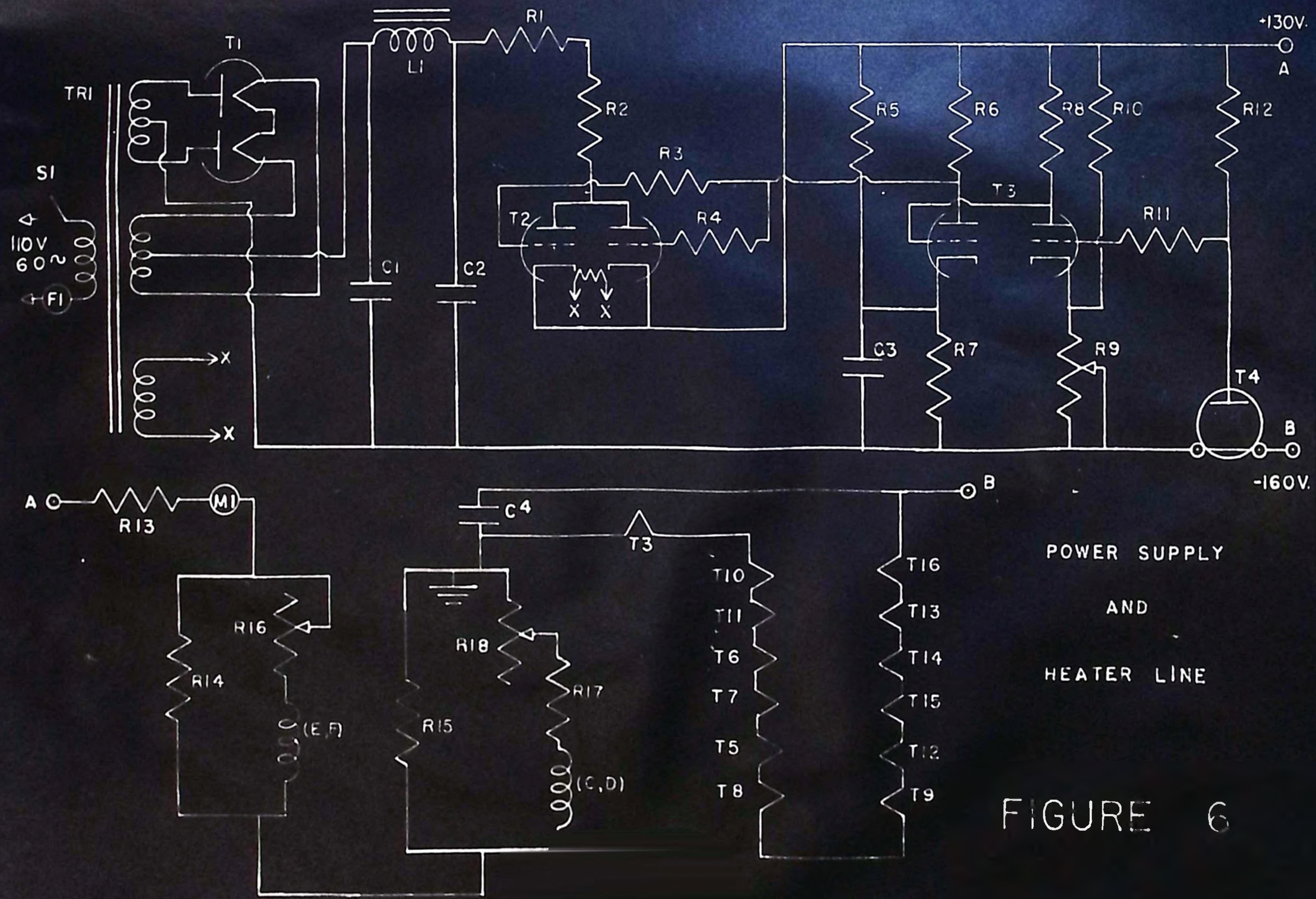


- DISC 1
- DISC 2
- DISC 3
- ECCENTRIC
- BALL-BEARING RACE

A - TAPER PIN
B - ROLLERS
C - POINTER
D - SPRING
E - SCREWS (CLAMPS)

FIGURE 5

MECHANICAL PHASE SHIFTE
(FULL SCALE)



+130V.
A
T1
TR1
L1
R1
R2
R3
R4
R5
R6
R8
R10
R12
R11
S1
110V
60~
F1
T2
C1
C2
X X
T3
C3
R7
R9
T4
X
X
B
-160V.
A
R13
M1
B
C4
T3
R16
R14
(E,F)
R18
R15
R17
(C,D)
T10
T11
T6
T7
T5
T8
T16
T13
T14
T15
T12
T9
POWER SUPPLY
AND
HEATER LINE

FIGURE 6

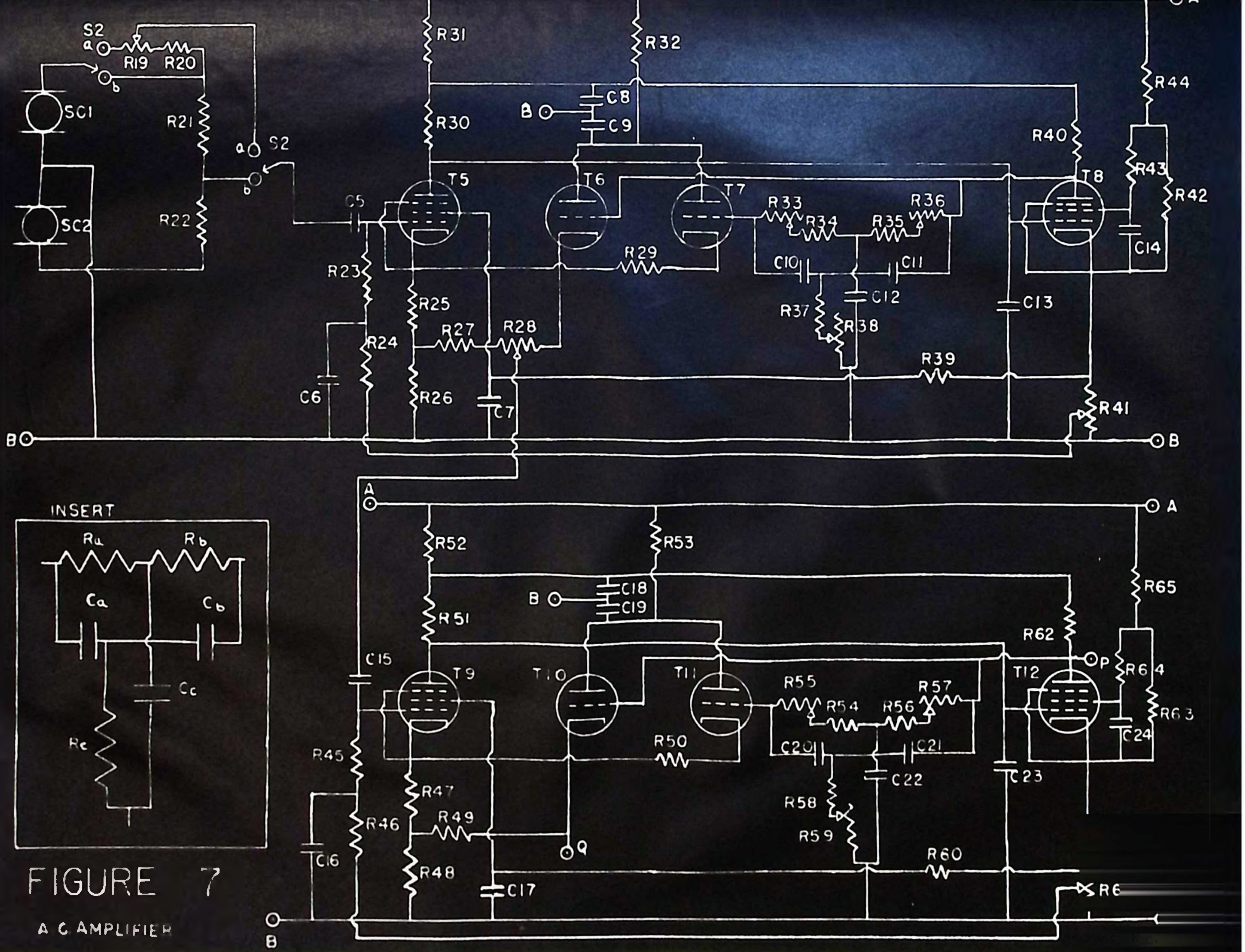
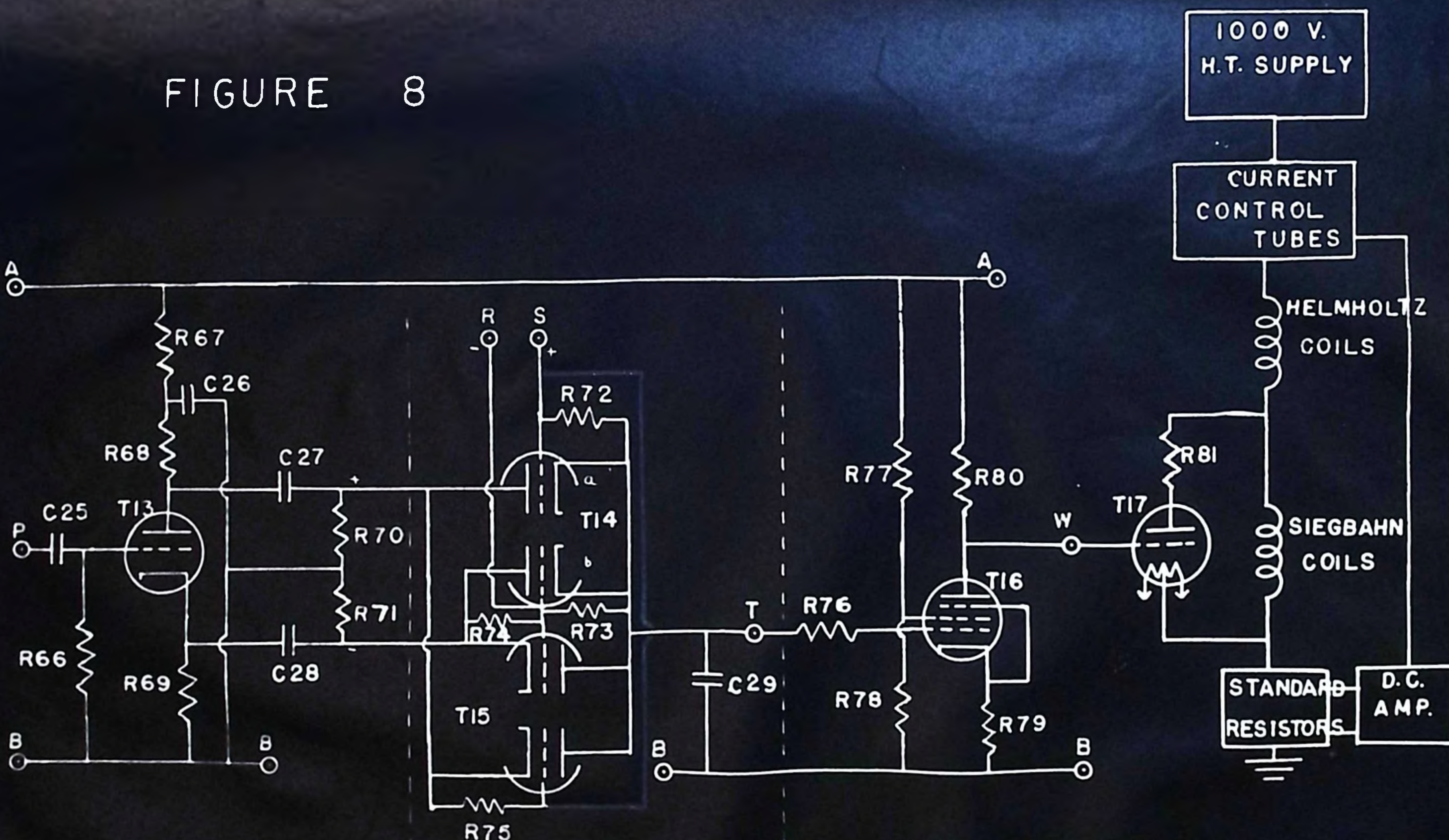


FIGURE 7

A C AMPLIFIER

FIGURE 8



COUPLING DEVICE

PHASE SENSITIVE DETECTOR

PROPOSED METHOD OF AUTOMATIC STABILIZATION

FIGURE 9

FIELD MEASURING EQUIPMENT

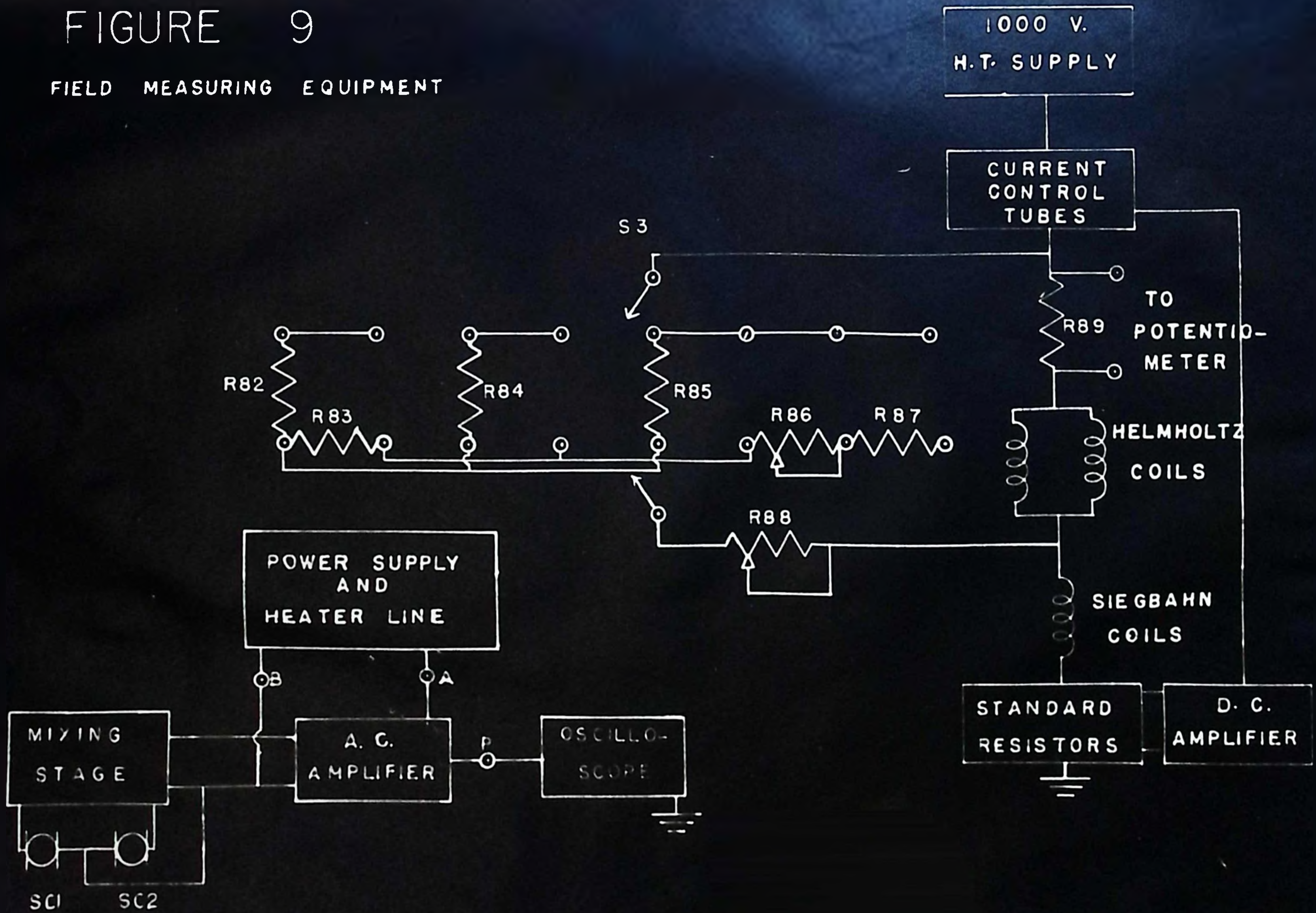


FIGURE 10 SENSITIVITY OF BALANCING

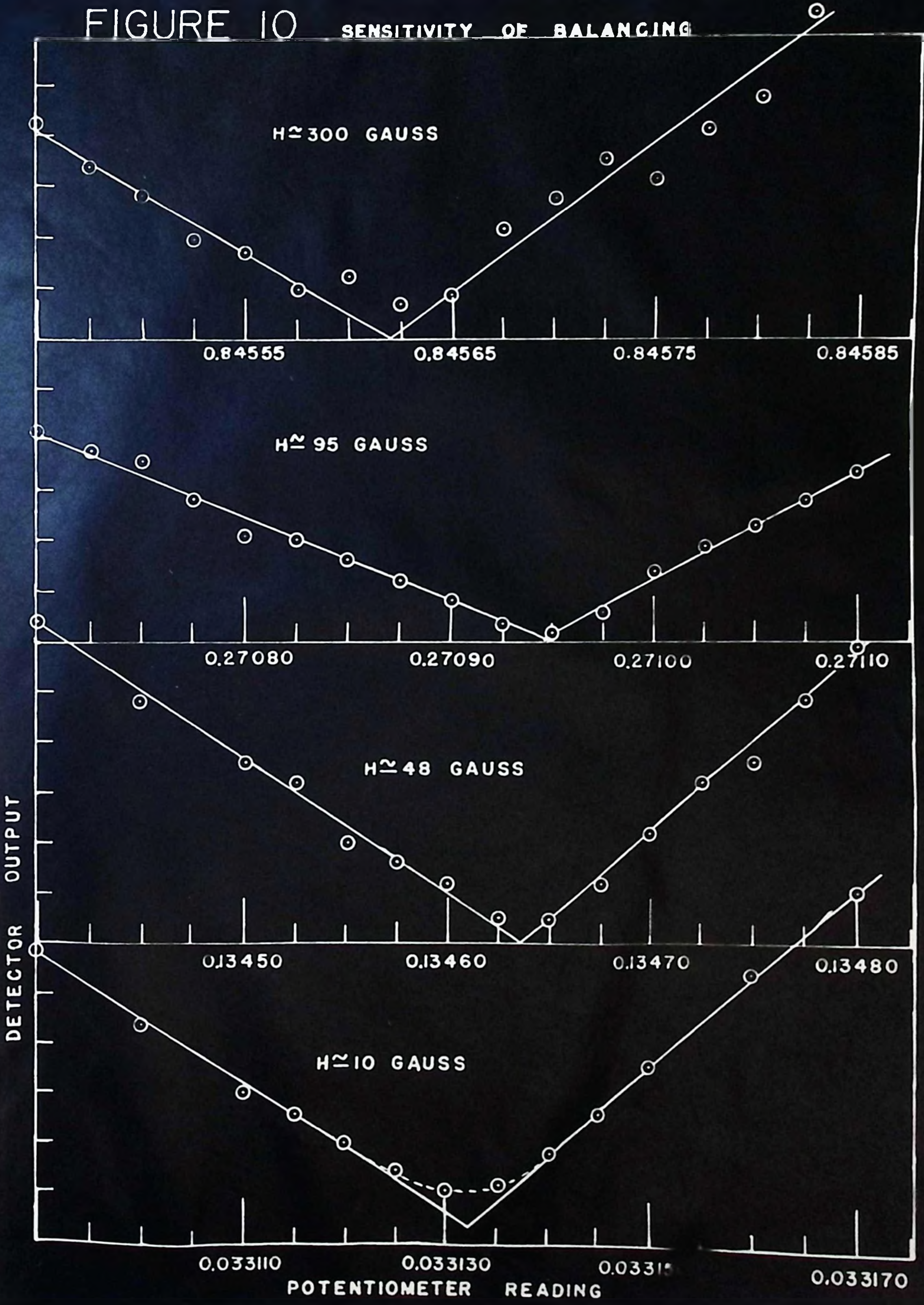
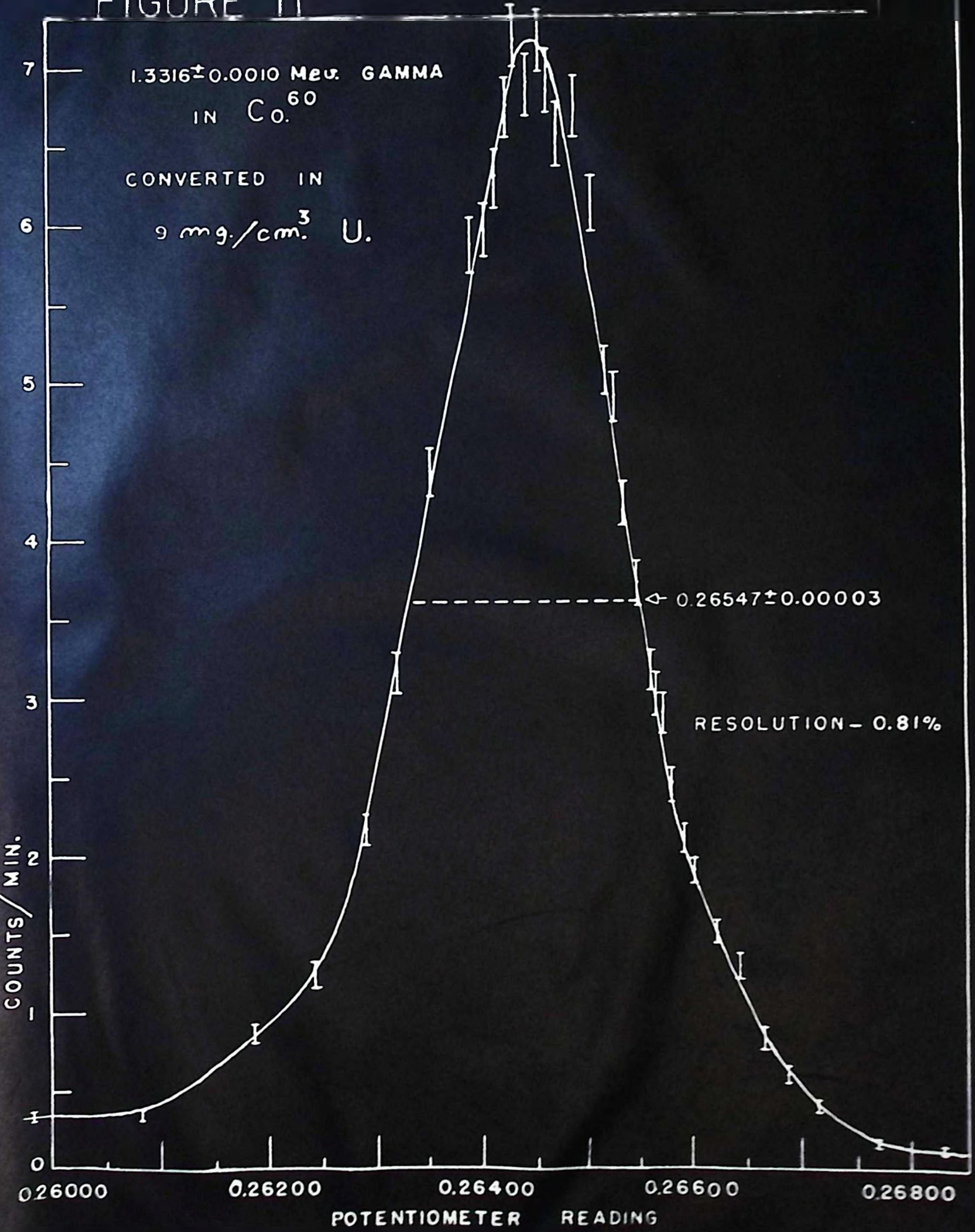


FIGURE 11


1.3316±0.0010 Mev. GAMMA
IN Co^{60}
CONVERTED IN
9 mg./cm.³ U.
0.26547±0.00003
RESOLUTION – 0.81%
COUNTS / MIN.
0
1
2
3
4
5
6
7
0.26000
0.26200
0.26400
0.26600
0.26800
POTENTIOMETER READING

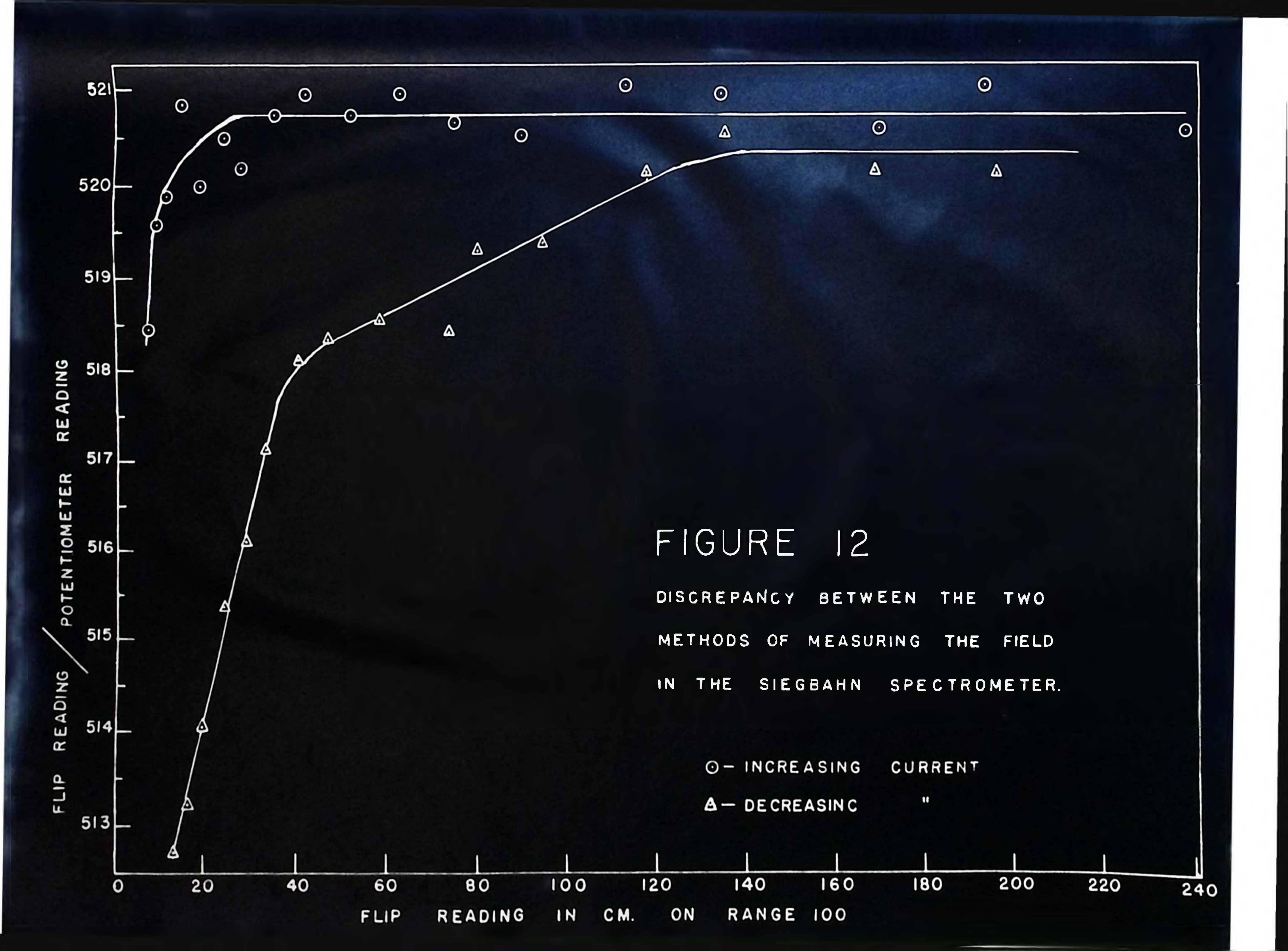


FIGURE 12
DISCREPANCY BETWEEN THE TWO
METHODS OF MEASURING THE FIELD
IN THE SIEGBAHN SPECTROMETER.
⊙ – INCREASING CURRENT
Δ – DECREASINC "
FLIP READING / POTENTIOMETER READING
FLIP READING IN CM. ON RANGE 100
521
520
519
518
517
516
515
514
513
0
20
40
60
80
100
120
140
160
180
200
220
240