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MAGNETIC EFFECTS IN A
ROTATING SUPERCONDUCTOR

A thesis submitted to the Faculty of the
Rice Institute in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

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Houston, Texas
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MAGNETIC EFFECTS IN A ROTATING SUPERCONDUCTOR

Introduction

Certain metals (e.g., lead, tin, mercury), when cooled below a critical temperature characteristic of each, suddenly lose their resistance completely, even to the extent that if a current is set flowing in a closed loop of one of these metals, it will persist without any measurable decrease for as long as one maintains the temperature below its critical value. This was the first property of what is now called the superconducting state of a metal to be discovered (Kammerlingh Onnes, 1911)¹⁾, and it has important consequences on the law of electromagnetic induction. For if the resistance of a superconductor be really zero, then the electric field within the superconductor must be zero, since a potential gradient would require finite resistance. Then one can conclude from the law of induction

$$\text{curl } \vec{E} = - \frac{\partial \vec{B}}{\partial t}$$

that $\vec{E} = 0$, and that consequently $\vec{B} = \text{constant}$ in a superconductor. This means that whatever magnetic field exists in a superconductor at the time it passes through the transition will be 'frozen in' and will thereafter remain constant, independent of any further changes in external fields.

The concept of an infinite conductivity is not strictly correct, since the electrons still possess inertia. One

of the early attempts to develop the electrodynamics of superconductors took into account the inertia of the electrons by writing an "acceleration equation" for the motion of free electrons in an electric field. This equation, when expressed in terms of the macroscopic current density \bar{J} and electric field \bar{E} , can be written as

$$1) \quad \lambda \dot{\bar{J}} = \bar{E} \quad \lambda = m/ne^2$$

where n is the volume density of superconducting electrons, m the mass, and e the charge of the electron. This equation was thought of as replacing Ohm's law for superconductors.

If one assumes the relations $\bar{B} = \mu_0 \bar{H}$ and $\bar{D} = \epsilon_0 \bar{E}$ for a vacuum hold in a superconductor, then equation (1) together with the two Maxwell relations

$$2) \quad \text{curl } \bar{E} = -\frac{\partial \bar{B}}{\partial t}$$

$$3) \quad \text{curl } \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t}$$

can easily be shown to lead to the equation

$$4) \quad \nabla^2 \dot{\bar{B}} = \frac{\mu_0}{\lambda} \dot{\bar{B}}$$

for \bar{B} within the superconductor, which when integrated with respect to time gives

$$\nabla^2 (\bar{B} - \bar{B}_0) = \frac{\mu_0}{\lambda} (\bar{B} - \bar{B}_0)$$

where \bar{B}_0 is the magnetic induction which exists at the time the body becomes superconducting. The solutions of this equation for $\bar{B} - \bar{B}_0$ fall off exponentially from the surface of the superconductor, so that essentially they give $\bar{B} = \bar{B}_0$ everywhere inside. This was assumed to be

the case for a superconductor until in 1933 Meissner²⁾ discovered that when a substance goes superconducting it kicks out any magnetic flux which it might contain at that time, so that $\bar{B} = 0$ seems to be the more proper description of the magnetic field in a superconductor. This is a quite fundamental property of superconductors, and is more satisfying from a theoretical point of view than $\bar{B} = \bar{B}_0$, since it provides thermodynamically reversible magnetic behavior in a superconductor. One might assume then that $\bar{B} = 0$ is the proper description of the 'pure' superconducting state characterized by complete reversibility in its magnetic behavior.

F. and H. London³⁾ have developed a set of equations which describe the electromagnetic behavior of the pure superconducting state. By assuming a new relation between the supercurrent and the magnetic induction

$$5) \quad \text{curl } \lambda \bar{J} = -\bar{B}$$

in addition to the acceleration equation (1), they arrive at the equation

$$6) \quad \nabla^2 \bar{B} = \frac{\mu_0}{\lambda} \bar{B}$$

for the magnetic induction in a superconductor. In effect, this amounts to setting $\bar{B} = 0$, since the solutions to this equation differ from zero only in a thin layer at the surface of the order of 10^{-5} cms. thick. Thus the significant properties of the pure superconducting state are properly described by the London equations.

The above considerations have only been applied to simply connected superconductors. In the case of a multiply connected superconductor, such as one which has the shape of a doughnut, it can be shown that these equations admit only solutions for which the magnetic flux through the hole is constant, in accord with the persistent current experiments which have been performed.

A further property of superconductors is the fact that their superconducting state will be destroyed by a sufficiently strong magnetic field. This critical field is characteristic of each metal, and depends on the temperature, the dependence on temperature being of the form

$H_c = \alpha (T_c^2 - T^2)$, where T_c is the critical temperature. It is also found that a current will destroy superconductivity, but this is felt to be due to the magnetic field produced by the current (Silsbee's hypothesis)¹⁰⁾. This has been verified experimentally.

From an experimental standpoint the London equations do not apply except under ideal conditions. What is actually observed experimentally⁴⁾ is a Meissner effect varying anywhere from zero, as depicted by the acceleration theory, to complete, as described by the London theory. A variety of experiments have been performed on these hysteresis effects (i.e., the existence of 'frozen in' flux in superconductors), and in general it is found that they depend on the degree of impurity, on the crystal structure of the specimen, and on its geometrical shape.

Mendelssohn⁵⁾ has made a study of 'frozen in' fields in hollow and in solid specimens of mercury, tin, lead, tantalum, and various alloys. He found that in tin single crystals, and in polycrystalline tin and lead, the 'frozen in' flux amounted to from 6% to 15% of the total flux threading the specimen at the time of transition, and that in general the amount of 'frozen in' flux increases with the degree of impurity, even to such a degree that some of the alloys (e.g., lead plus 10% bismuth) froze in all of the flux. Of all the substances he investigated only mercury seemed to show complete reversibility, corresponding to the pure superconducting state, which would be characterized by a complete Meissner effect. This state seems to be closely approached by a single crystal of extremely pure metal in the form of a long, thin rod.

Apparently there exists an intermediate state for superconductors in general for which the behavior ranges from that which one would expect according to the acceleration theory to that depicted by the London equations. Gorter⁶⁾ and London³⁾ have proposed a model to explain the structure of the intermediate state of the superconductor. They suppose that as the metal passes into the superconducting state annular superconducting regions are formed within, which crowd the magnetic flux within their 'holes' closer together as they grow until a point is reached when the magnetic field strength in these 'holes' exceeds the critical field strength, thereby preventing the further

growth of these superconducting regions. The flux which remains in these 'holes' gives rise to the permanent magnetic moment, which is 'locked in' by the surrounding superconducting regions. In this manner a state intermediate between perfect diamagnetism ($\bar{B} = 0$) and perfect conductivity ($\bar{B} = \bar{B}_0$) is achieved.

Several investigators^{7),8),9)} have treated the problem of a rotating superconductor, but the most thorough investigation is that to F. London. All agree in that if one brings a superconductor into a state of rotation starting from rest below its transition temperature, a weak magnetic field will be generated due to the lagging behind of the superelectrons with the lattice of the metal, since they assume no interaction between the two systems. However, London concludes on the basis of his theory that one would also expect the appearance of the same magnetic field independently of whether one cools the superconductor below its transition temperature while rotating or brings it into a state of rotation after cooling below the transition temperature, a result entirely unexpected on the basis of the acceleration theory used by Becker in his treatment. Thus an experimental investigation of this idea would be of importance in clarifying fundamental theoretical ideas concerning superconductors. The present experiment was designed to detect these magnetic effects, which would be of the order of 10^{-4} gauss for a superconductor rotating at 6,000 r.p.m.

However, at the present time effects of this order of magnitude have been obscured by first order effects of an interesting nature. The results given in this thesis will be concerned solely with these first order phenomena.

The following phenomena have been observed in the present experiment:

a) The perfect shielding of a superconducting lead can, in its hollow, to changes in an external magnetic field.

b) The Meissner effect in a solid specimen of chemically pure tin.

c) A large positional effect, i.e. large changes in the magnetic field around the specimen of tin as it is turned through a complete revolution after being cooled below its transition temperature in an external magnetic field.

d) The destruction of this positional effect by rotating at high speeds (6,000 - 8,000 r.p.m.), the decrease in magnitude depending on the total time and possibly speed at which the specimen is rotated.

a) and b) represent well known properties of superconductors. c) and d) are not well known, and only further experimentation can determine their true nature.

EXPERIMENTAL EQUIPMENT AND METHOD

Detecting Equipment

The equipment used to detect the magnetic effects described is the airborne magnetometer developed by the Navy during the war and kindly supplied to the Rice Institute Low Temperature Laboratory through the cooperation of the Office of Naval Research.

The sensitive element of this equipment is a small coil wound in a single layer around a core of magnetic material of high initial permeability which saturates in a low magnetizing field (of the order of 1 gauss). If the coil exists in a unidirectional field, then the current through the coil required to produce saturation is different in one direction from what it is in the other. Furthermore, if the initial permeability is high, the further change of flux through the coil after the saturating current is reached will be negligible, so that essentially the flux remains constant after the saturating current is reached. If a current from a high impedance source is sent through the coil, the flux through the coil on the positive half swing of the current will be different from that on the negative half swing, due to the unidirectional field which exists in the coil, and consequently the flux in the coil will exhibit an anti-symmetrical wave form. The voltage developed across the coil will also exhibit an anti-symmetrical wave form. It is easily seen that the Fourier analysis of an anti-symmetrical wave will contain a second

harmonic, whereas that of a symmetrical wave will contain none. This second harmonic which is generated by the unidirectional field is used as the measure of that field. An analysis of this detector coil, based on simplifying assumptions concerning the magnetization curve of the core, shows that the magnitude of the second harmonic is proportional to the field in which the coil is located.

A block diagram of the complete equipment used in the experiment is shown in Fig. 1. Instead of one, three of these detector elements were used in the experiment in order to measure the magnetic effects in three mutually perpendicular directions. The current was supplied by a 1,000 cycle, push-pull, tuned plate oscillator with an automatic volume control and buffer amplifiers on its output to isolate the oscillator from the load. The output from the oscillator is fed through a 1,000 cycle filter to eliminate any harmonics it might contain, especially the second harmonic. The output from the filter contains three leads, each of which leads through an inductance coil to a series resonant circuit consisting of a detector coil and a series capacitor shunted by a resistance to ground. The resonant circuits provide a strong current through the coils necessary for proper operation. A three-way switch enables one to switch the input of a 2,000 cycle filter to any one of the three channels, designated by H_x , H_y , and H_z . The 2,000 cycle output from this filter

is fed into a resistance-coupled amplifier whose output is measured with a vacuum tube voltmeter and at the same time observed on an oscilloscope. The amplifier has two stages, in between which is located another 2,000 cycle filter to reduce further any 1,000 cycle component still present.

Although the signal read on the voltmeter will be proportional to the field in the detector for large fields (.1 gauss), this will not be true for extremely small fields (10^{-4} gauss), since the magnitude of the second harmonic generated will be of the same order of magnitude as the 1,000 cycle component which is left after filtering, and also because some 2,000 cycle voltage is generated in the inductance coils, which have iron cores. Hence, on eliminating the field at one of the detectors, one finds that the voltage on the voltmeter does not go to zero, but rather approaches a minimum value. Furthermore, since the detectors are non-directional by nature, one finds that on reducing the field to zero, and then increasing the field in the opposite direction, the voltmeter readings will pass through a minimum value and then start to increase again, as shown in curve A of Fig. 15. Hence one should take as the true measure of the field the difference between the voltage measured and the minimum value obtainable. A calibration curve on the H_2 detector, made with a small solenoid in which the detector was placed, in fields up to

0.4 gauss, is shown in Fig. 2. What is plotted is the strength of the H_z signal against the difference between the current in the solenoid required to produce a minimum voltage and the current at which the voltage was read. This is not the same curve that one would get by starting in a field free space with zero current in the solenoid due to the fact that the solenoid does not produce a uniform field. However, the difference that would result would not be too great, and the curve shown is good enough to indicate the right order of magnitude. The scale in gauss is based on the constants of the calibrating solenoid. The fact that the curve begins to level off at high fields is not due to any non-linearity of the response of the detectors, but rather to saturation in the amplifier. All of the effects recorded in the experiments were in the linear range of this curve. The same curve was also run on the H_x and H_y detectors, and they all agree to within 10%. On the basis of the curve the components of the earth's field within the experimental chamber at the detectors H_x , H_y , and H_z were found to be 0.17, 0.18, and 0.33 gauss, respectively.

The nature of the way in which these detectors measure a magnetic field should be emphasized. What is measured as a voltage is proportional to the total flux along the direction of the detector axis. Thus any field which produces a net flux of zero, such as a field at right angles

to the coil, will not be detected at all. Furthermore, because of the non-directional property of the detectors, any change of field which only changes the direction of the total flux will not be noticed unless during the process of changing the signal is observed going through its minimum value. To use one of these detectors as an accurate magnetic field indicator, one would have to know the exact nature of the field being measured.

Rotor Framework

The rotor was placed in a housing which was attached to a framework designed to fit down into the experimental chamber of the Rice Institute Collins Cryostat. The motor which turned the rotor was placed at the top of this framework underneath a top plate which sealed off the hole leading to the experimental chamber. The motor had to be placed at the top to avoid freezing and also to keep from heating the cold region of the cryostat when running. The motor at the top was joined to the rotor at the bottom by means of a phosphor bronze wire under tension through two textilite spacers placed along the framework and used to cut down on the vibration of the wire. Phosphor bronze wire was used to avoid having any moving magnetic materials in the framework. The use of wire rather than a solid shaft was found necessary due to the difficulty of alignment with a solid shaft. The shaft of the motor was extended up to the top plate with a small disk on its end. By observing this disk through a lucite plate at the top

with a stropotac, one could measure the speed of the motor as well as visually estimate the rest angle of the rotor below.

The tin sample was made of chemically pure tin, containing not more than 0.05% impurities, and cast in a vacuum. It was then cut down to a cylindrical form with well rounded edges and placed in the hollowed space between two pieces of textilite which screwed together to form a container. The tin is known not to have any flaws because it is the same sample which was used by Mr. William Overton of the laboratory for sound pulsing experiments which would have detected any flaws. Further, in the magnetic experiments described in this thesis, there is no evidence of lack of homogeneity or of flaws in the tin rotor.

It was felt necessary to have, as closely as could be obtained, a field free space which, moreover, stayed constant with time. With this end in mind the equipment was designed so that the rotor and measuring devices would be entirely surrounded by a lead can, so that once the lead can had gone superconducting, no further changes of field would take place. No magnetic materials were located within the lead can other than the detector elements themselves, including the bearing which held the rotor shaft at the bottom.

The three detector elements were mounted mutually perpendicular to each other inside the rotor housing.

The H_z detector was stuffed in cotton inside a small calibrating coil wound on a core of textilite. The cotton was used to eliminate microphonics in the detector when the rotor was rotating. The rotor housing was insulated from the framework by a textilite plate in order to be sure that no stray currents could flow around the detector elements and produce spurious magnetic effects.

A photograph (Fig. 3) of the rotor assembly shows the significant details of its construction. A is the textilite container for the tin specimen. B is the calibrating solenoid for the H_z detector. The detector elements H_x and H_y are shown at C. D is the lead plate which forms the top of the lead can. E is the textilite plate used to insulate the rotor housing from the rest of the framework. G shows a housing used to place the thrust bearing which supports the tension in the wire, I, at a good distance from the detector elements because of the small amount of magnetic material it contained. H is a coupling device to join the wire to the rotor. F is a capillary tube for measuring the vapor pressure. A photograph of the assembly with the lead can soldered to the lead plate with Wood's metal is shown in Fig. 4.

In Fig. 5 is shown a photograph of the complete experimental equipment. A is a 350 volt regulated power supply which supplies voltage to a voltage dividing circuit at B, which in turns supplies the various voltages required

to operate the oscillator unit C. D is the amplifier; E, the vacuum tube voltmeter; and F, the oscilloscope. G is a microammeter used to measure the current in the calibrating solenoid, and H is the rotor gear which was placed inside the cryostat.

In order to eliminate the earth's field at the detectors H_x and H_y , two pairs of Helmholtz coils wound on a square framework 18" x 18" were placed outside the cryostat in the x- and y-directions. Since these coils were at right angles to each other, the fields at the H_x and H_y detectors could be minimized independently. To eliminate the z-component of the earth's field a solenoid was wound around the outer jacket of the cryostat itself. A top view of the arrangement of the coils about the jacket is shown schematically in Fig. 6. The off-centering of the experimental chamber with respect to the solenoid on the outer jacket and the fact that the jacket is made of iron are undesirable features of the arrangement; however, these features could not be avoided.

EXPERIMENTAL RESULTS

Run II

The results reported were taken on two different successful runs, designated by I and II. Only the data taken on run II will be given in detail, since the results of run I are in general the same, and were of exploratory nature.

Just above the transition temperature of the lead can the field inside the cryostat at the three detectors was eliminated as well as possible by steady currents in the external Helmholtz coils. This was somewhat difficult for two reasons:

a) The cryostat itself was running so that the vibration of the machine produced random fluctuations of the detector signals.

b) A vacuum pump behind the cryostat was running, giving a fluctuating signal at the detectors. However, by looking at the pattern of these signals on the oscilloscope, it was possible to recognize the signal due to the steady field. Under these conditions, the following detector output readings were taken:

$$H_x = 0.10 \text{ volts} \quad H_y = 0.08 \text{ volts} \quad H_z = 0.08 \text{ volts}$$

These output voltages correspond to magnetic fields of less than 10^{-3} gauss. When the lead can passed through its transition temperature of 7.2° K , the signals changed within an interval of only a few seconds to the new set of readings:

$H_x = 0.85$ volts $H_y = 1.10$ volts $H_z = 0.08$ volts.
From the changes that took place in these signal strengths, one can conclude that a significant reorientation of the magnetic field distribution took place, which may be due to a large inhomogeneity of the magnetic field within the lead can, i.e., the magnetic field was only eliminated at the detector elements and could have been much different from zero at other regions within the lead can. Thereafter the detectors were completely oblivious of any further changes in the external field around the lead can, a result in accord with the perfect shielding property of superconductors.

The field within the lead can does not live up to one's expectations, since it seemed to change with time. About 15 minutes after the second set of readings was taken, the following set was recorded:

$H_x = 0.83$ volts $H_y = 1.05$ volts $H_z = 0.20$ volts.
The possible error in these readings is only ± 0.02 volts, so that the difference in readings represents a real change in the magnetic field distribution. However, the rotor was turned on from time to time to prevent its freezing up, and this change of field may represent an effect of the rotation on the magnetic field within the can.

After the lead can went superconducting at 7° K, the cryostat was run for over two hours to liquefy some four liters of liquid helium at 4° K. The cryostat was then shut down, and a set of readings taken at various positions

of the rotor in order to look for possible positional effects above the transition temperature (about 3.7° K) of the tin. These values are recorded in the following table. A denoting the angle of the rotor with respect to an arbitrary direction which was used throughout the experiment.

A (degrees)	H _x (volts)	A (degrees)	H _y (volts)	A (degrees)	H _z (volts)
45	0.90	200	2.05	180	0.16
270	0.90	45	2.05	45	0.17
90	0.90	160	2.05	90	0.16
140	0.90	200	2.05		

The angle A was measured by estimating the angle of the indicator at the top of the motor. Since the motor shaft was attached to the rotor at the bottom by means of a phosphor bronze wire, there is a possibility of a difference between two readings representing the same angle at the indicator because of different amounts of twist in the wire. A check outside the cryostat showed this difference to be within the error of estimation of the angle at the indicator, but this may not have been true at the liquid helium temperatures at which the readings were taken.

The table shows that there exists no positional effect of the rotor above the transition temperature of the tin.

It also shows a marked difference from the magnetic field readings taken two hours earlier. This cannot be ascribed to changes in the associated electronic equipment, since the strengths are not affected in the same manner.

Next, a set of measurements to detect any rotational effects while the tin was in the normal state was taken, giving the following table:

W (r.p.m.)	H _x (volts)	H _y (volts)	H _z (volts)
0	0.83	1.85	0.18
6400	0.20	3.30	0.15
3500	0.10	1.80	0.15
0	0.84	2.90	0.18

It is seen from this table that large signals have been generated by the rotation, especially in the x- and y- directions. The existence of this rotational effect above the transition temperature of the tin makes it impossible to make any conclusions concerning rotational effects due to superconductivity. It is probably due to eddy currents of a complicated nature induced in the rotor by its motion in a magnetic field. It seems strange that H_z showed a relatively small change on rotation, which furthermore seemed to be independent of speed. This may be due to the fact that H_z is close to the minimum value on the calibration curve (Fig. 14, curve A), where the sensitivity falls off. On stopping the rotor, H_y showed another big change. Again there seems to be an effect of the rotation on the magnetic field.

The tin was taken below its transition temperature and brought back up a total of three times, and a study of positional effects in the superconducting state before and after rotation was made. These trials are designated by the numbers 1, 2, and 3.

Trial I By pumping on the bath of liquid helium in which the rotor was immersed, the temperature was lowered from 4.2° K to 3.2° K, which is well below the transition temperature of 3.7° K for tin. The temperature was observed by measuring the vapor pressure of the liquid with an open tube manometer, and by a calibrated carbon resistor thermometer. At 3.7° K, as read on both thermometers, sudden changes took place in the H_x , H_y , and H_z readings, which leveled off to a constant value in an interval of a few seconds. These changes represent the Meissner effect taking place in the tin and are recorded, together with the position of the rotor, on Figs. 7, 8, and 9. The arrow \downarrow is used to designate the Meissner effect due to lowering of the temperature. On finally warming back up, the Meissner effects are recorded as: "reading below" \uparrow "reading above."

As soon as the temperature was well below the transition temperature, curves A of Figs. 7, 8, and 9 were taken. They show the magnetic field determined by the detectors as a function of the rest position of the superconducting rotor. A word of explanation concerning curve A of Fig. 7 should be given at this point. An extra peak has been drawn in on this curve (dotted portion) without much apparent justification. There are several good reasons for believing that this is the true shape of the curve as far as variations in the voltmeter readings are concerned:

The H_x and H_y detectors are both mounted tangentially to the rotor at right angles. Consequently the positional effect observed in one should also be observed in the same manner in the other, except for a phase difference of 90° . The H_y variations are clearly of sinusoidal nature. Hence the H_x variations should also be sinusoidal and 90° out of phase with respect to the H_y readings. By assuming that the field at the H_x detector has changed direction during the process of turning through one complete revolution one would then have an extra peak in the volt-meter readings because of the non-directional property of the detector elements. One would get the true magnetic field variations by reflecting this additional peak in the line $H_x = 0.1$ volts, which corresponds to zero magnetic field. It is easy to see that on doing this one obtains a sine curve, whose peaks are then 90° out of phase with the corresponding peaks in the H_y readings. The steep slope of the curve to left of 120° and the fact that one reading was taken at practically zero field seem to be sufficient evidence for the assumption that this change of direction has taken place. The various positions of the rotor were obtained by turning the motor on and off quickly to change its position, and by reading the angle off the indicator at the top. It is seen from these curves that wide variations in the readings have taken place due to the position of the rotor, whereas above the transition tempera-

ture no observable positional effect was found. It might be argued that since the magnetic field within the lead can had shown changes before, that an effect of this kind was being observed, or that there is a relaxation time associated with the sudden change in the rotor position, and the readings would return to their equilibrium values corresponding to a pure Meissner effect if one waited awhile. To test this hypothesis, the rotor was left stationary for five minutes on one of the readings (the value 1.45 for H_x at 15°). No change took place in the H_x reading during this time interval, although a change of 2% could have been detected. This is convincing evidence that these positional effects are real and permanent, and not due to any time variations of the magnetic field, since they were all taken within a time of the order of ten minutes.

Next, the motor was turned on, and the data in table C below was taken in order to observe any rotational effects. Just as before, when the tin was in the normal state, large

C		A		B	
W	H_z	W	H_x	W	H_y
(r.p.m.)	(volts)	(r.p.m.)	(volts)	(r.p.m.)	(volts)
0	0.28	0	1.45	0	1.10
7500	0.29	5900	0.33	6000	1.67
6700	0.29	5600	0.40	5100	1.65
5750	0.29	4600	0.58	3750	1.65
5100	0.30	3400	0.70	3700	1.72
4300	0.35	2400	0.78	0	1.82
3000	0.30	0	0.22		
0	0.27				

changes in the readings of the detectors took place on rotating. What is observed in this case is probably a mixture of the magnetic effect of the type generated above the transition plus the effect that the positional variation of magnetic field would have on rotation at high speeds. The nature of this signal is then quite complex, and only further experimentation can decipher its true origin.

After turning the motor off, a few observations on the positional effect in the H_z detector were made. The results are shown as curve B on Fig. 9. Since the possible error in readings is ± 0.02 volts, a straight line has been drawn through these points, although there is probably some positional effect still remaining. Then the rotor was turned again, and the data shown in table A were taken. On turning the motor off, the positional effect was studied in the H_x detector, and the results shown in curve B of Fig. 7 were taken. Although a straight line has been drawn through the points it is clear that some positional effect still remains, since the two points which do not fall on the curve differ by more than the experimental error. It is easily seen by a comparison with curve A of the same figure that a curve of this type could be fitted between these points just as well. The same process repeated with the H_y detector rendered table B and curve B of Fig. 8. It is clear from this curve that the positional effect has now been completely destroyed, since the points were taken

at positions of the rotor where peaks had occurred before rotation.

The temperature was allowed to rise slowly through the transition value, and the magnitudes of the Meissner effect was recorded as shown on the figures. It is seen from the readings to which H_x , H_y , and H_z return that the field within the can has changed strongly, especially as regards H_y . This leads to further confusion concerning the behavior of the field within the lead can, but it certainly does not alter the fact that the positional effect exists and rotation will destroy it.

Trial II The system was taken below the transition temperature, and the magnitude of the Meissner effect was recorded as shown in Figs. 10, 11, and 12. Then curves A, shown in these figures, were taken. The rotor was rotated for several minutes at 6,000 r.p.m. and turned off, after which curves B were taken. Here again the assumption of a change in direction of the magnetic field at H_x has been made on curves A and B of Fig. 10. It is seen from the curves B of these figures that the positional effect has been practically destroyed in all three directions at the same time, since in this case the positional effect was taken on all three detectors after the same amount of rotation. The specimen was then taken up through its transition temperature, and the Meissner effect was recorded.

The voltmeter readings all returned to the same values which they had before going down, except for negligible changes. In this case the field within the can has not changed appreciably during the process of going below the transition, rotating, and coming back up. Yet, the decrease of the positional effect after rotation is clearly shown, the same as in Trial I. Apparently then, the destruction of the positional effect by rotating is independent of any field changes which might take place within the lead can, since it was observed with and without these changes having taken place.

Trial III The same process was repeated again, with the difference that only positional effects in H_2 were determined, and more accurate time measurements were made. No detectable Meissner effect was observed on the transition down. A more detailed set of data was taken on the positional effect, as shown in Fig. 13, which shows definitely that a sine wave pattern is followed as the rotor is turned through one revolution. The points (●) were taken before rotating. Then the rotor was turned on and rotated at 10,000 r.p.m. for 10 seconds, after which the points (○) were taken. Then, in succession, rotations for 20, 40, 80, and 120 seconds were made; each was followed by a rough check on the positional effect, as shown in the figure. Only the curves representing no rotation and 270 seconds of rotation have been drawn in, since not enough points were

taken to justify detail curves on the others.

It can be seen that the general trend is again toward decreasing amplitude of the positional effect until it is finally destroyed. There is some evidence that the final destruction takes place suddenly, but this will have to be investigated more carefully to make certain. Once again, the field returns to its original value above the transition to within the accuracy of measurement at these small values.

This trial differs significantly from trials I and II in that the rotor was cooled down at a different position. In the first two trials the rotor was cooled down at 100° , and in both cases the peaks of the curves occurred at the same angles in an entirely reproducible way. If the magnetic moment producing the positional effect is determined by imperfections or impurities in the lattice of the metal then one would expect these peaks to occur at the same angle of the rotor independently of the position at which it is cooled. An opportunity to test this hypothesis was presented in trial III, where the rotor was cooled down at 315° . In this case it may be seen that the peak in the H_z curve occurs at a new position, contrary to what one would expect according to the hypothesis of imperfections of the tin lattice. On the other hand the peaks of curves A of Figs. 12 and 13 both occur at approximately the same angle as measured from the angle at which the rotor was cooled. This indicates that the magnetic moment producing the potential effect is set into the specimen only by the

external field, and not by lattice defects or impurities. This important aspect of the experiment will certainly require more detailed proof in future experiments.

Discussion of Detector Sensitivity

It was suspected that the lead can had an effect upon the sensitivity of the H_2 detector below its transition temperature. A calibration curve was run on the H_2 detector below its transition temperature, using the calibrating solenoid. A similar curve was run on the detector above the transition temperature of the lead. The results are shown as curves A and B respectively in Fig. 14. The differences are striking. The sensitivity (slope of the curve) above the lead transition temperature is greater and falls off over a much smaller interval of current than it does below the transition. This difference is obviously due to the superconductivity of the lead can. What seems to be taking place is a reaction of the lead walls to the change of flux created within the can by the calibrating solenoid, which acts in such a manner as to reduce the flux through the solenoid which would ordinarily be produced by a current flowing in it. This effect could be reduced probably by having the solenoid further removed from the wall of the can, but this would be rather difficult under the crowded conditions which already exist within the can.

One further feature of these curves should be noticed. Above the Pb transition the minimum value of signal strength obtainable with the solenoid was 0.043 volts, while below the minimum it was only 0.10 volts, approximately twice as big. This must be due to the fact that the field of the solenoid plus that of the reaction of the lead can is more inhomogeneous than the field of the solenoid by itself. Furthermore, the field within the lead can is probably more inhomogeneous below the transition temperature. It seems reasonable to assume that the detector still has the same sensitivity that it had above the lead transition, so that the voltmeter readings are still proportional to the total amount of flux through the detector core in the direction of its axis.

Run I

The experimental arrangement in this run differs from that of run II in that only the z-component of the earth's field was eliminated, leaving a large horizontal component frozen in within the lead can. The gain of the amplifier was lower than in run II by a factor of 13. Readings were taken on the positional effect, but the angle of the rotor was not estimated. The situation in this run is further complicated by the fact that such a small component of field was frozen in the z-direction that changes in direction of the field at the detector could take place without

changes in the magnitude of the signal generated. This was actually observed on several of the Meissner effect readings.

The results in general are in accord with what was found in run II. The field within the lead can remained the same throughout the experiment within the limits of error. However, due to the small field that was frozen in, some change might have taken place which was not detected due to low sensitivity.

A Meissner effect was observed at all times on passing through the transition temperature of the tin. Large positional effects were found below the transition temperature and before rotation. After rotating at 8,000 r.p.m. for several minutes, the positional effects were decreased, in some cases to zero. In general the destruction of the positional effect seemed to depend on the total time during which the rotation took place. However, several times sudden drops in the signal strength were observed while rotating, followed by a decrease in the positional effect. This indicates that the destruction of the positional effect by rotation does not take place in a continuous manner with time, but perhaps takes place in a series of sudden transitions of random size.

Several other interesting observations which are important were made. On two different trials Meissner effects were observed when the tin sample was cooled below

its transition while rotating (6,000 r.p.m.), which shows that the transition into the superconducting state is not prohibited by rotation. Identical changes took place on both occasions, and the positional effect recorded after turning the motor off below the transition was four times smaller than the positional effect when the tin was cooled while stationary. Furthermore, the positional effect which remained after cooling while rotating was destroyed by further rotation.

It was also found that by sending a strong current (13 ma., corresponding to a field of 0.4 gauss) through the calibrating solenoid, and thereby creating a stronger field at the tin specimen while it was cooled, a stronger positional effect would be created, which could also be destroyed with sufficient amount of rotation.

INTERPRETATION OF RESULTS

Of the preceding experimental results there are two significant features which have been established:

a) When the tin specimen is cooled down below its transition temperature in an external magnetic field, and is then moved to different angular positions, wide variations in the magnetic field surrounding the specimen take place. Moreover the peaks in these variations seem to occur at the same angle as measured from the position at which the rotor was cooled and not at the same angle of the rotor with respect to the lead can. This indicates

that the positional effect is not determined by lattice defects or impurities.

b) After rotating the specimen for several minutes, these variations are damped out, the degree of damping depending on the total time of rotation and probably on the speed at which the rotation took place. The fact that one obtains a Meissner effect on increasing the temperature after the positional effect has been destroyed by rotation assures one that it is still in the superconducting state, and has not been driven into the normal state by rotation, in which state there is no positional effect. It also shows that the current loop in the specimen required to produce the Meissner effect does not move with the specimen as it is turned, but rather stays fixed with respect to the external field. Definite proof of the fact that rotation does not prevent the transition into the superconducting state is provided by the observation of a Meissner effect taking place when the specimen is cooled while rotating.

It seems reasonable to assume that the positional effect is due to a frozen in magnetic flux. It has been shown that it is not due to the Meissner effect and so the frozen in flux is maintained by a current loop which stays fixed on the rotor. As to why this frozen in moment is destroyed by rotation one can only speculate at the present time.

The present experiment has been of an exploratory nature, and must be improved in order to establish the details of the positional effect. The lead can may not be necessary to shield against external fields, and should be removed on the next experiment. Furthermore, to eliminate possible error in the angle measurements, a rigid shaft should be put into the gear to replace the wire, and an accurate angle measuring device installed which will also enable one to turn the rotor around slowly to test the positional effects. It is hoped to answer the following questions in a quantitative manner:

a) How does the amplitude of the positional effect depend on time and speed of rotation?

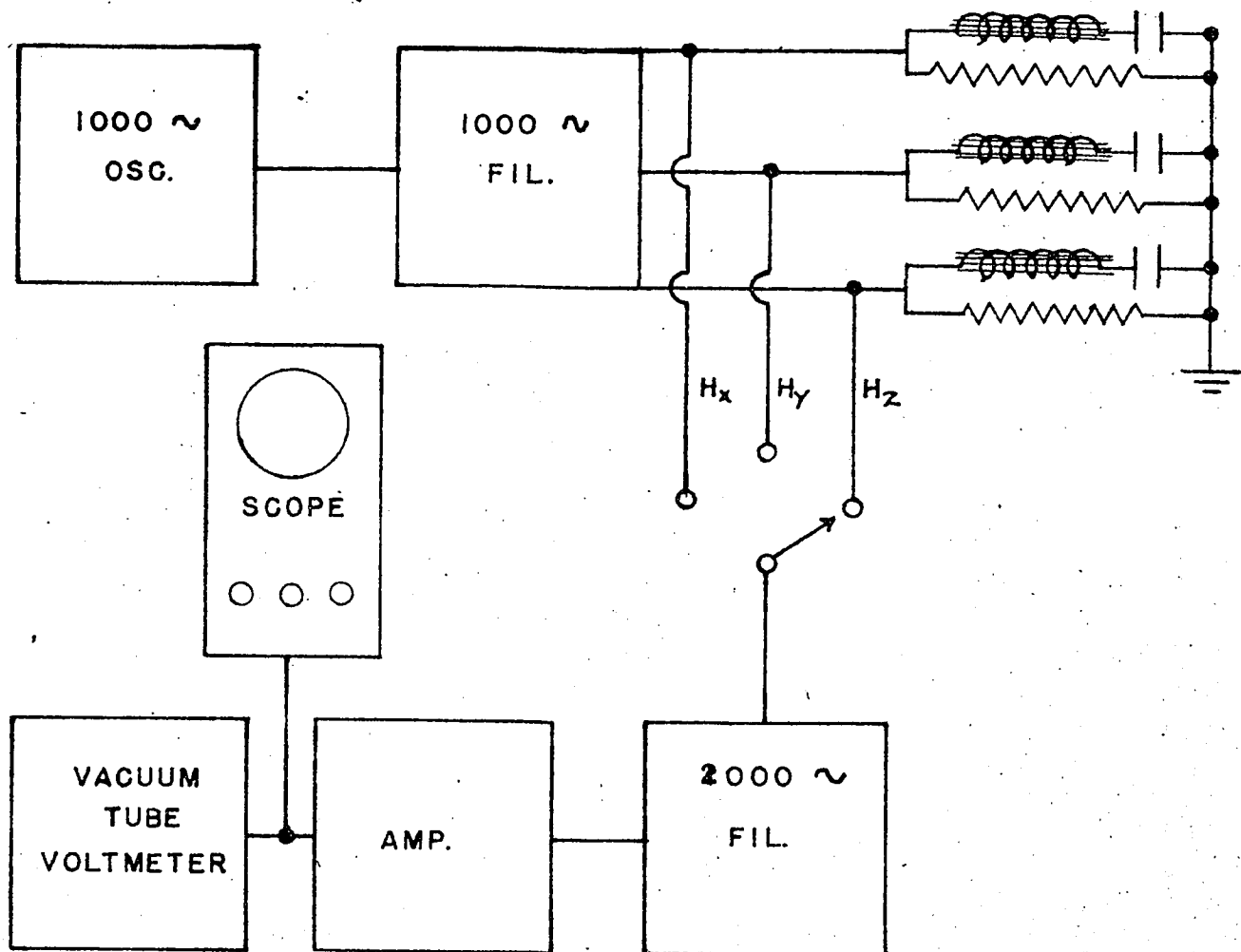
b) Does the Meissner effect depend on the position at which the rotor is cooled down? (This was obscure because of the shift of field within the lead can).

ACKNOWLEDGMENT

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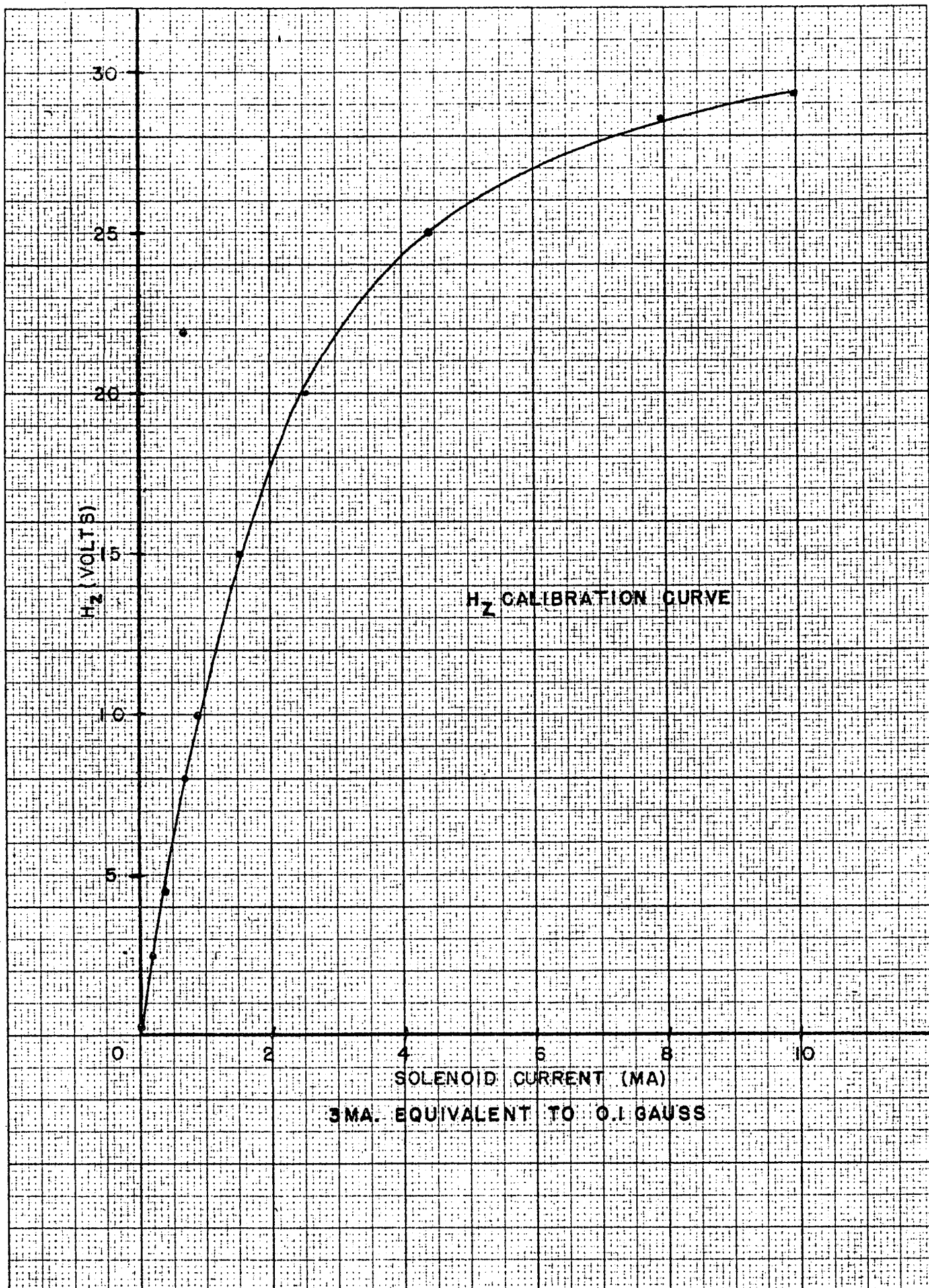
To the other members of the Low Temperature Laboratory, and especially to Mr. Perry Alers and Mr. Robert F. Blunt, the author is indebted for their assistance in carrying out the experiment. The skilled craftsmanship of Mr. Earl Harmering and Mr. J. F. Van der Henst of the Machine Shop is appreciated. The author is also grateful to Mrs. Anne Phillips for valuable assistance in proof reading. This work was supported by the joint program of the Atomic Energy Commission and the Office of Naval Research.

FIG. 1



BLOCK DIAGRAM OF EQUIPMENT

FIG. 2



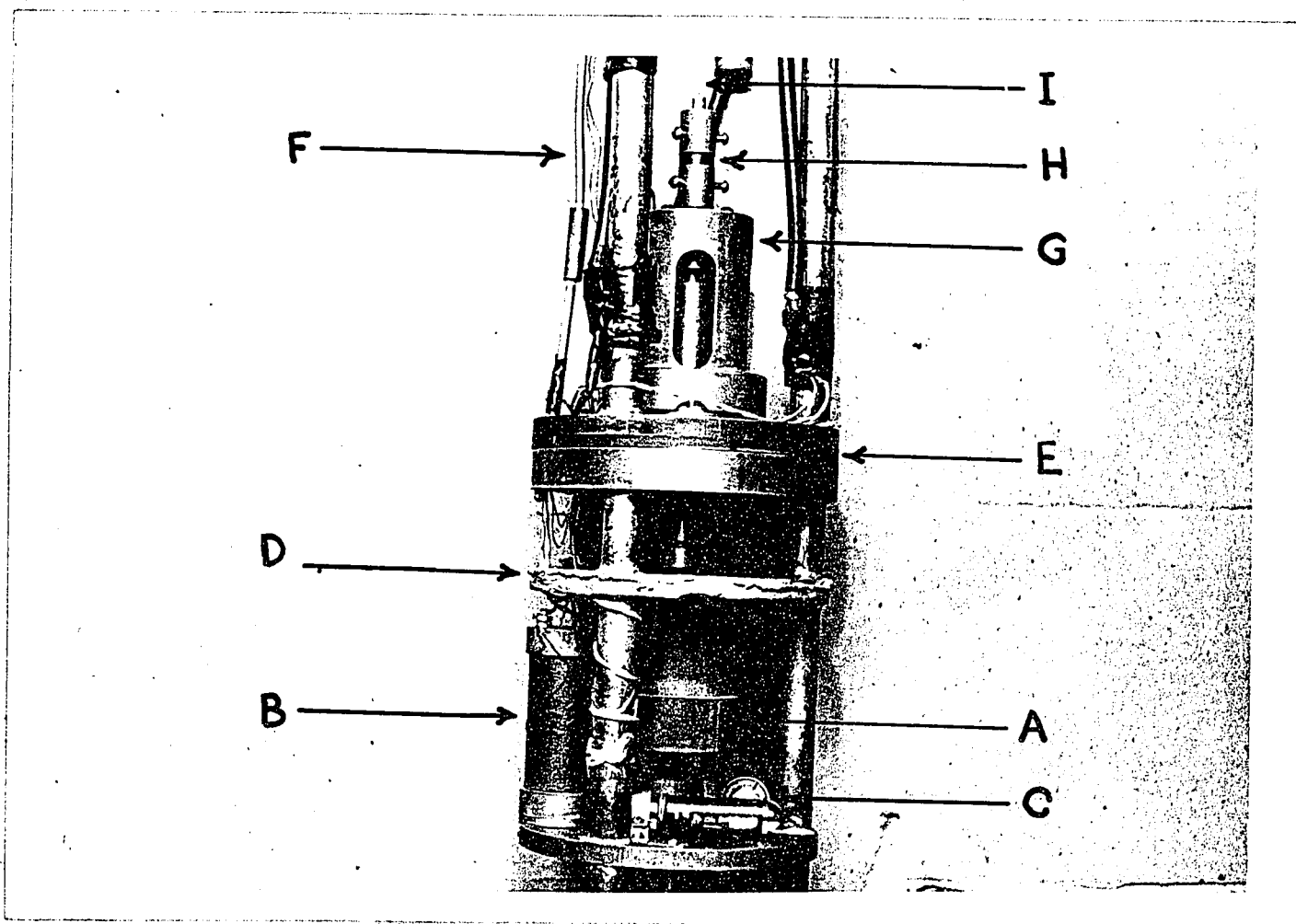


Fig. 3 - Photograph of rotor assembly with lead can removed

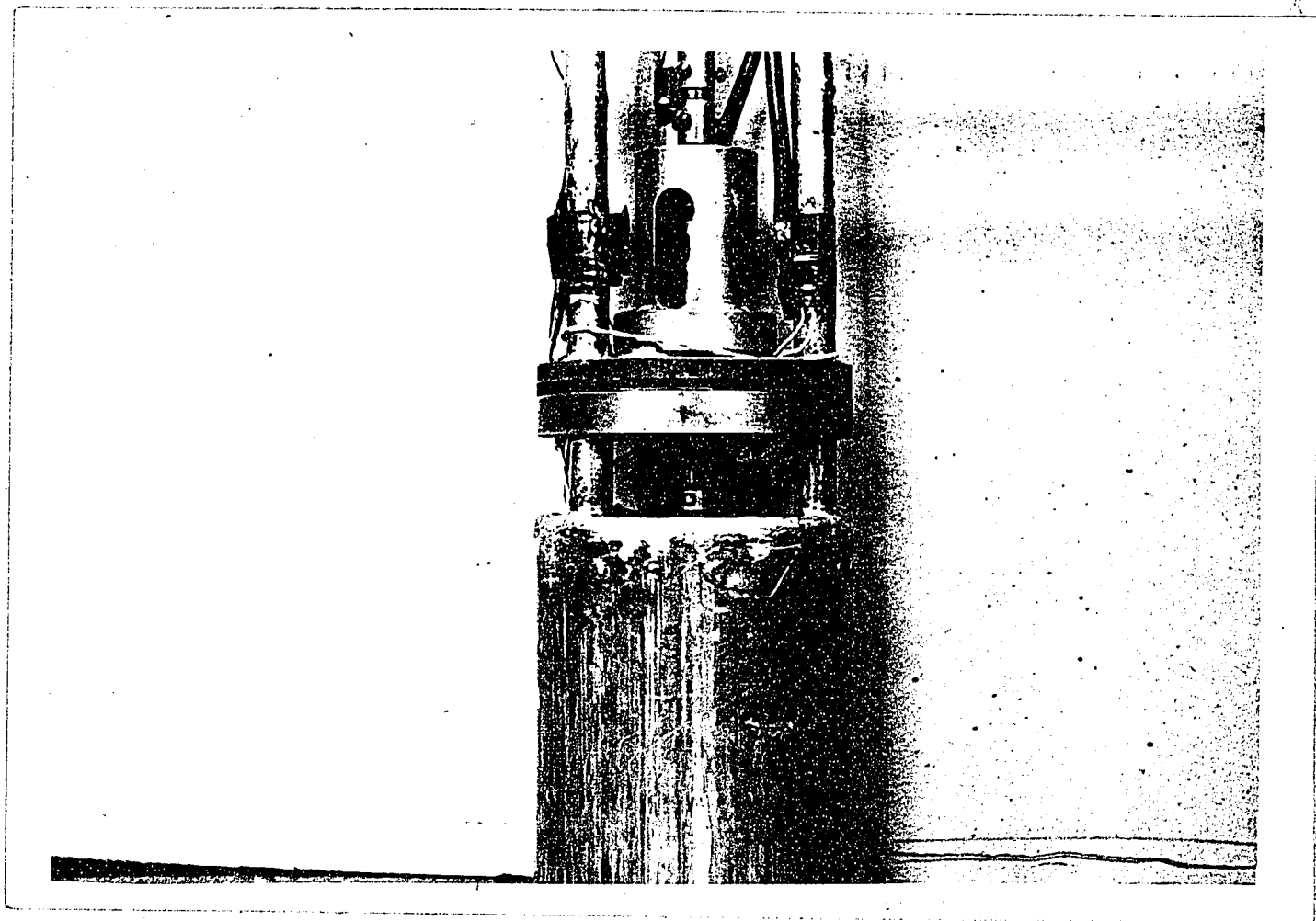


Fig. 4 - Photograph showing lead can
surrounding rotor assembly

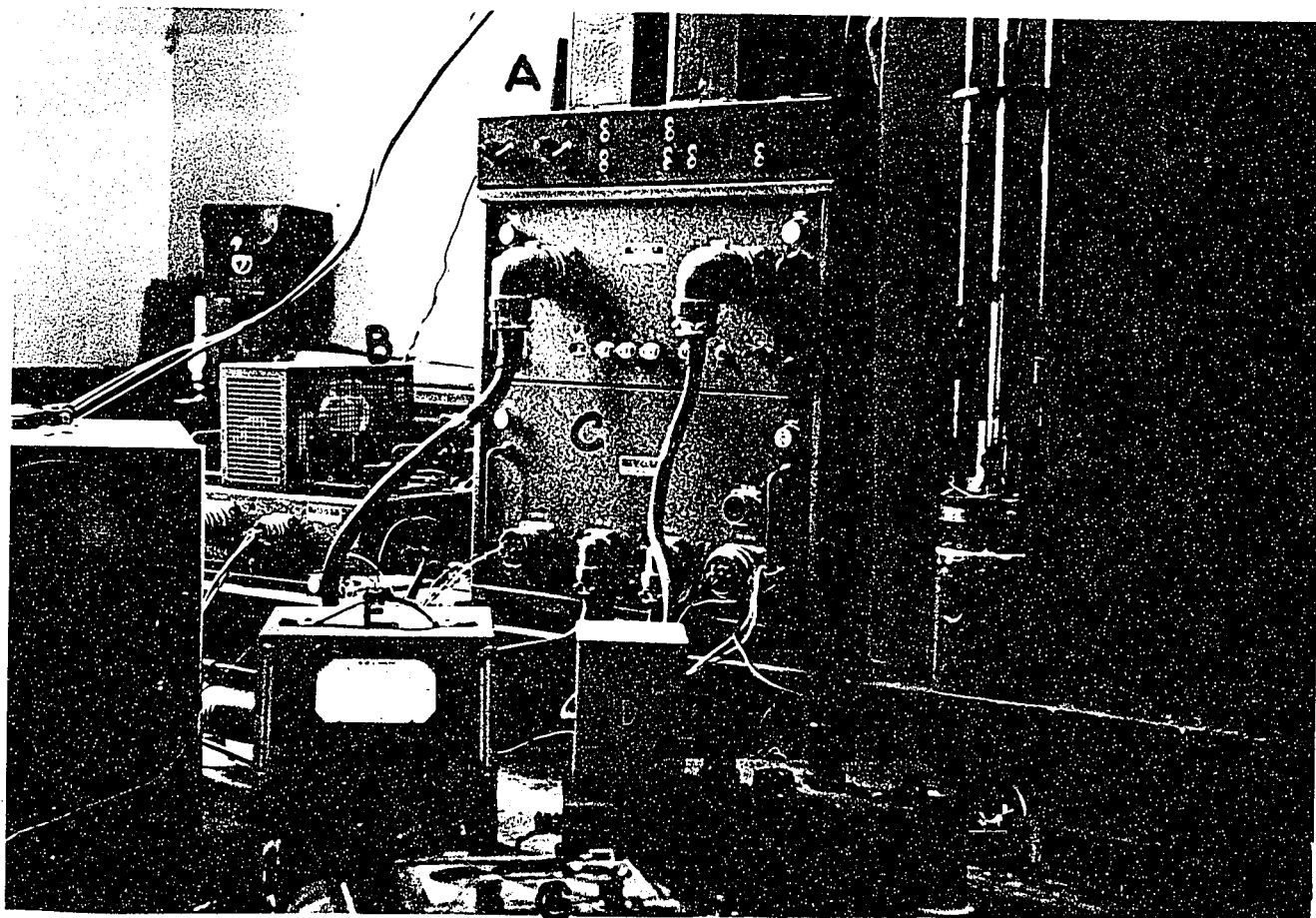
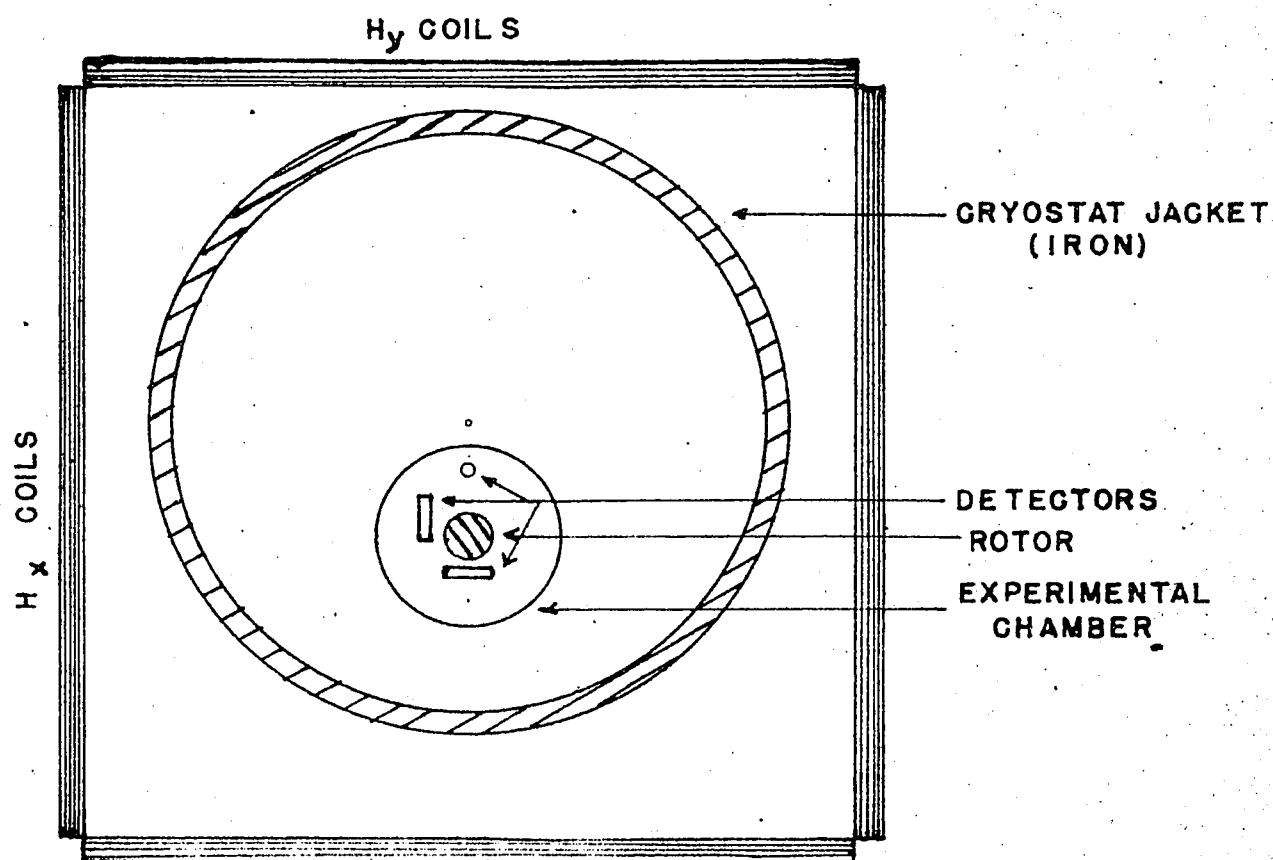


Fig. 5 - Photograph of experimental equipment

FIG. 6



EXPERIMENTAL ARRANGEMENT
(SCHEMATIC)

FIG. 7

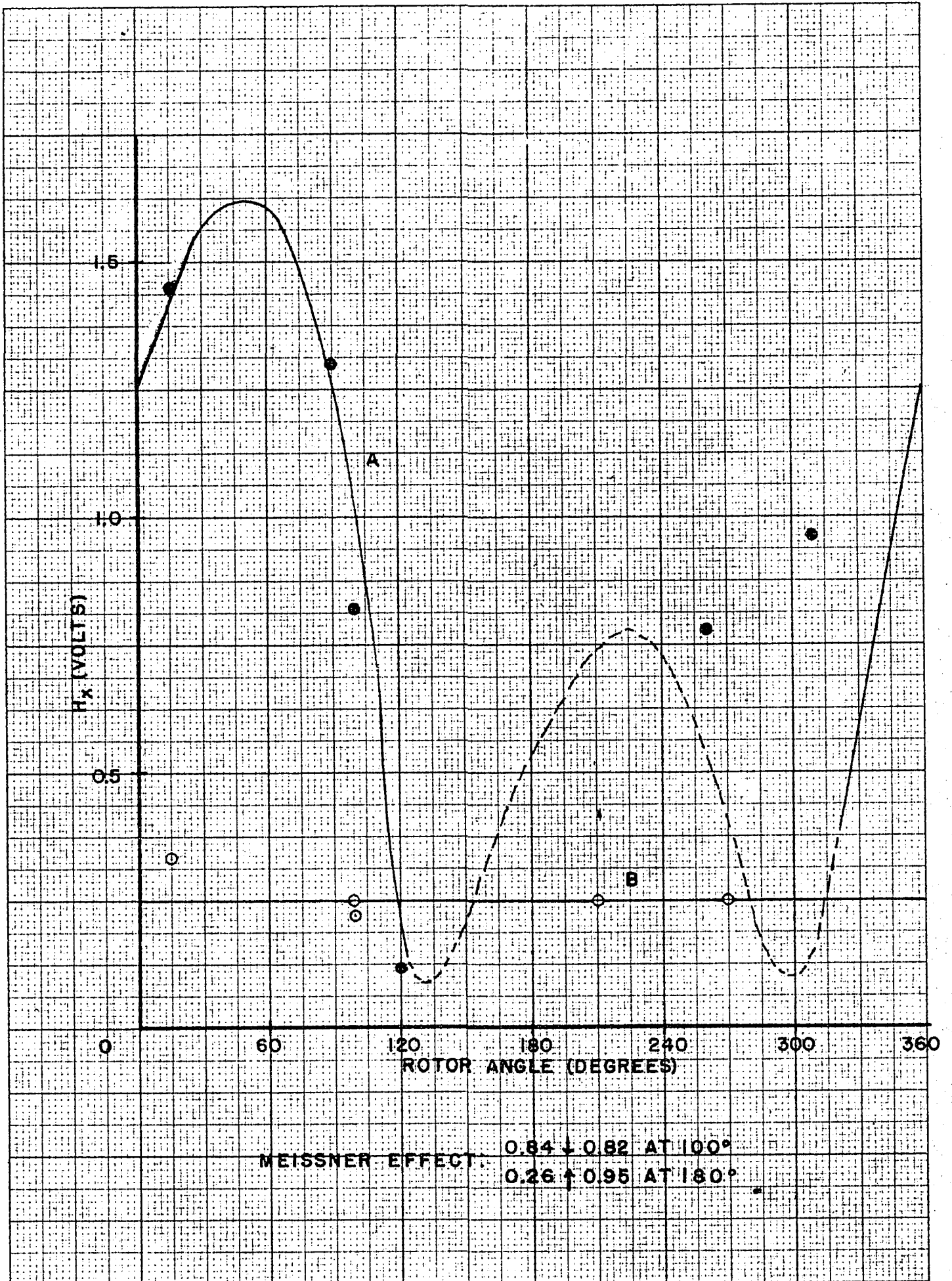


FIG. 8

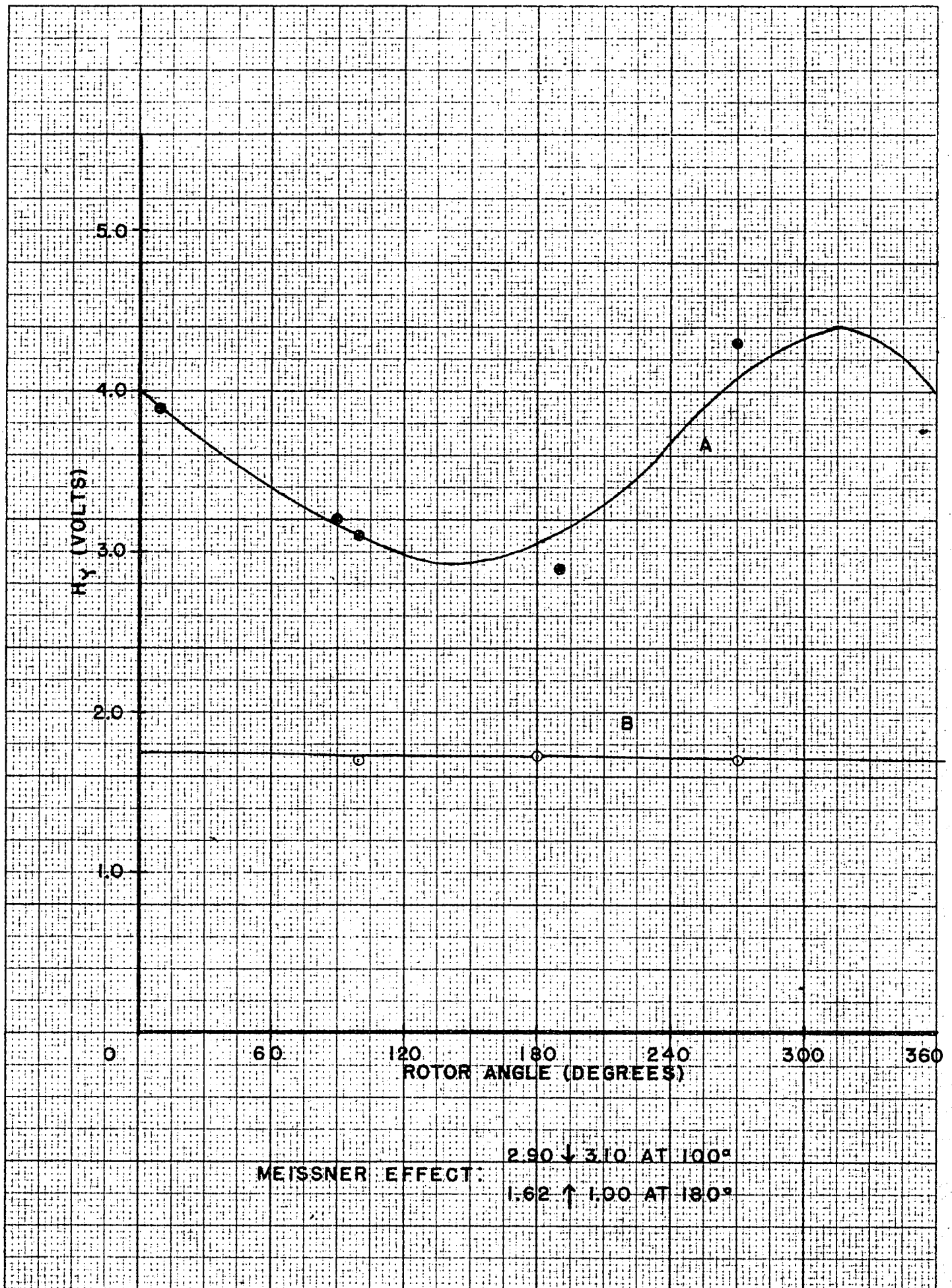


FIG. 9

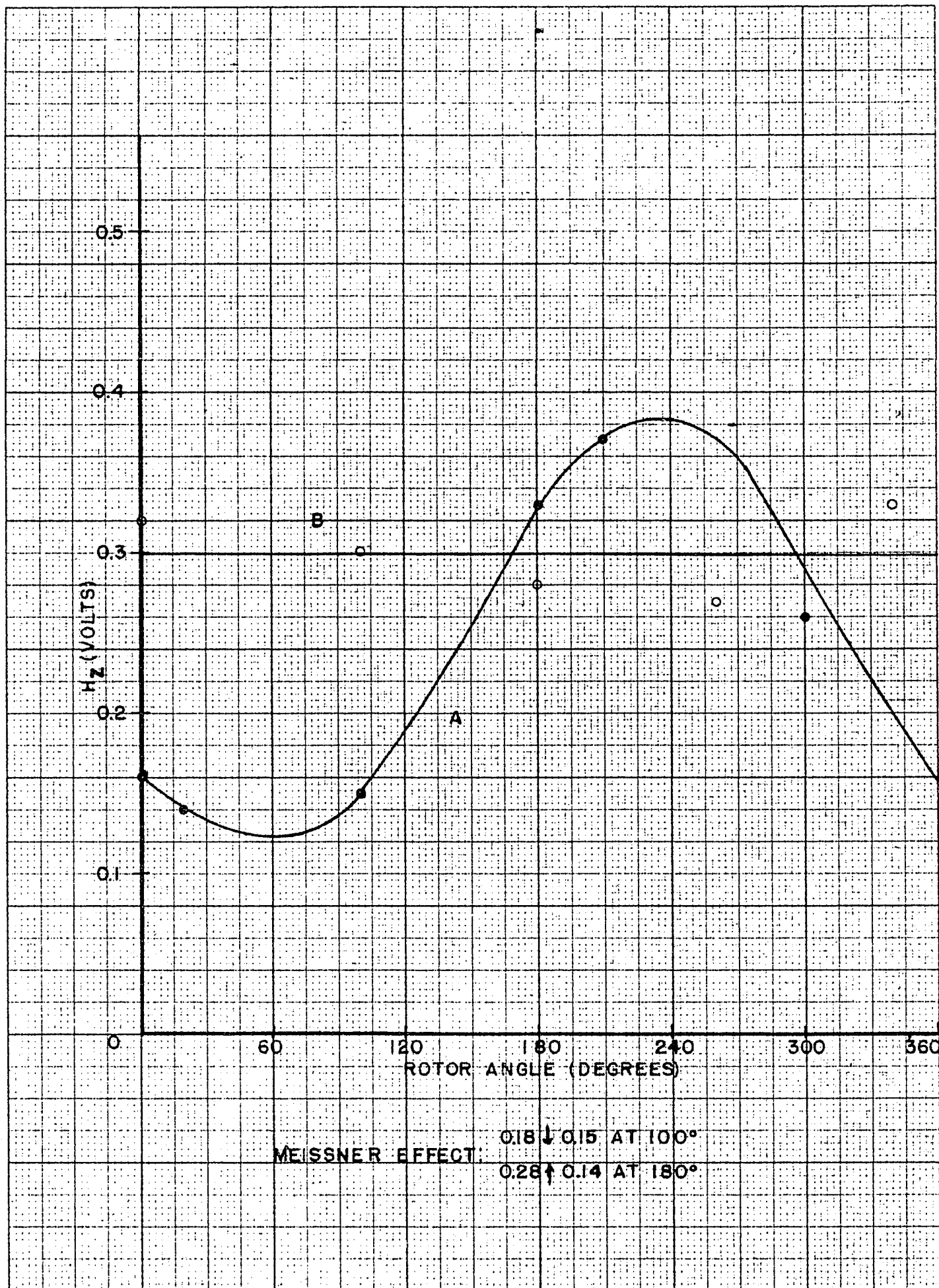


FIG. 10

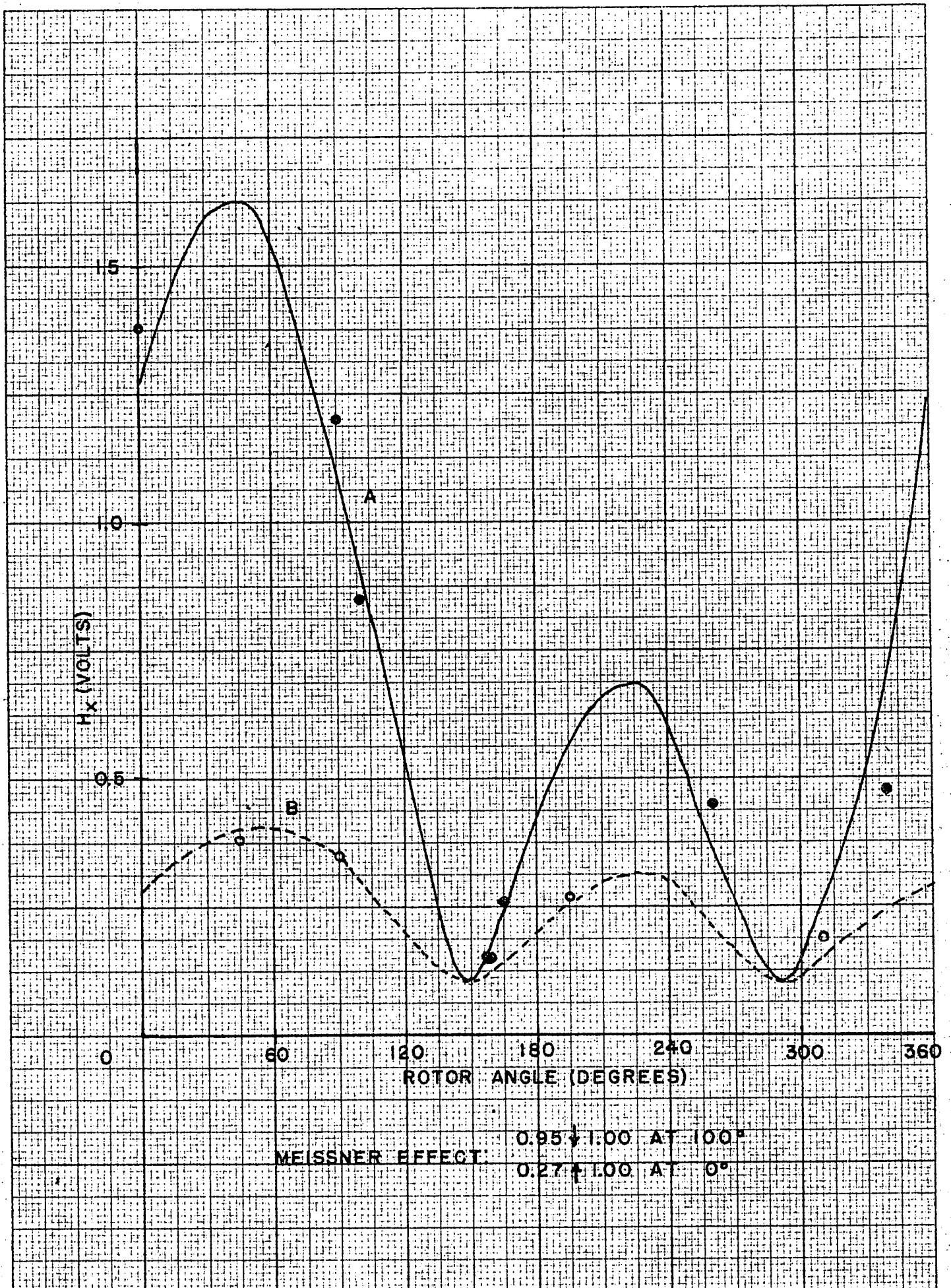


FIG. 11

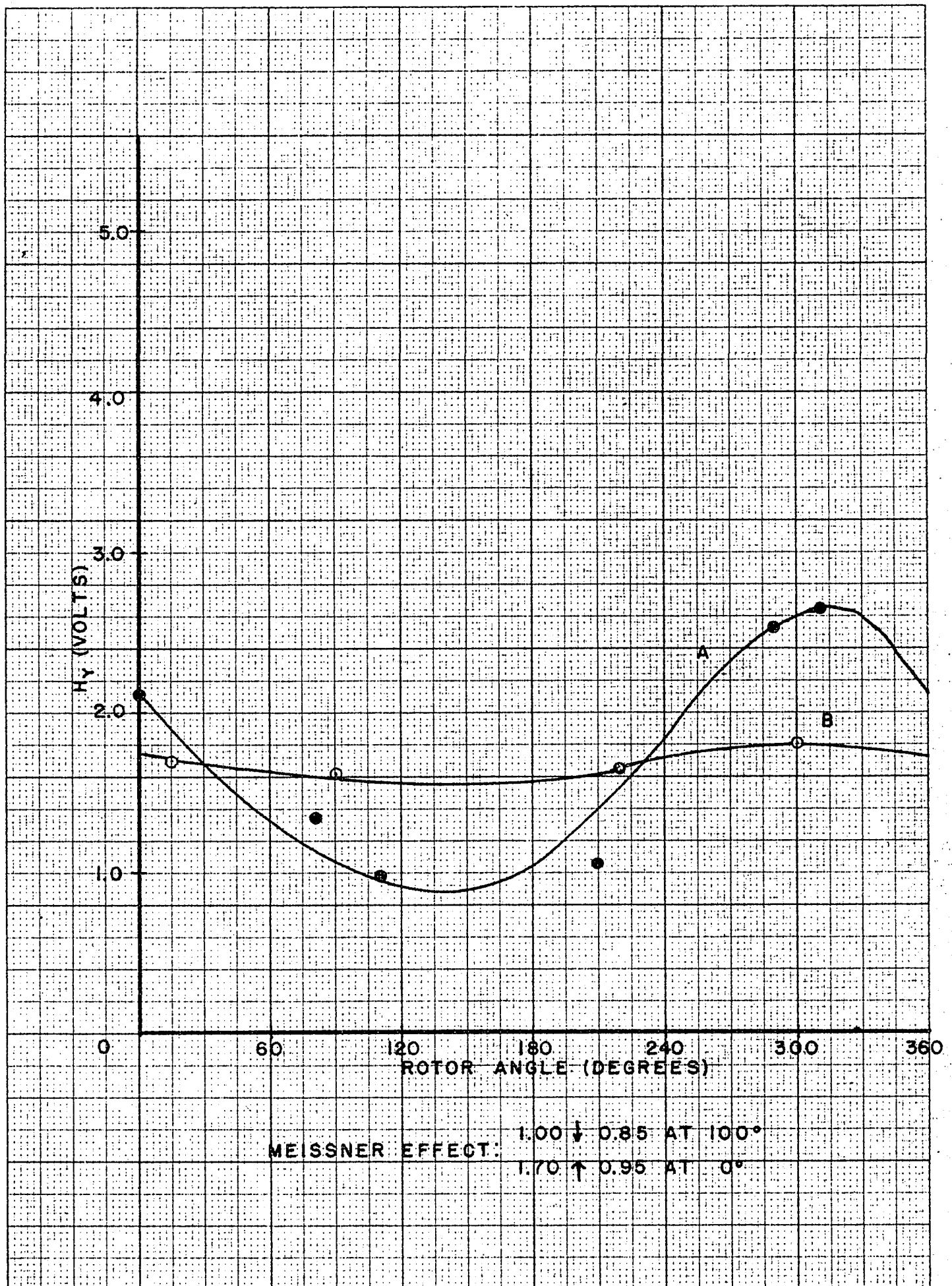


FIG. 12

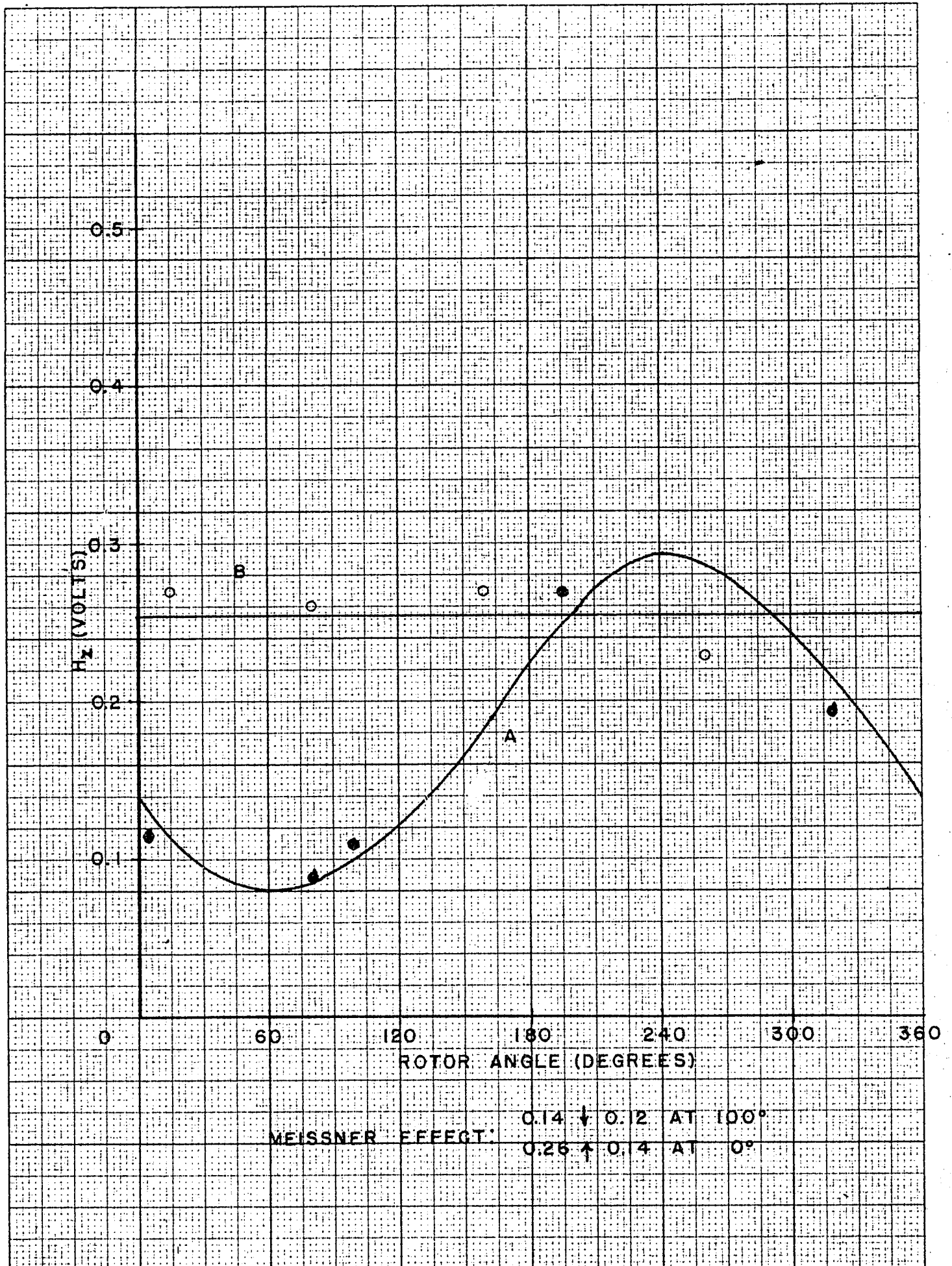


FIG. 13

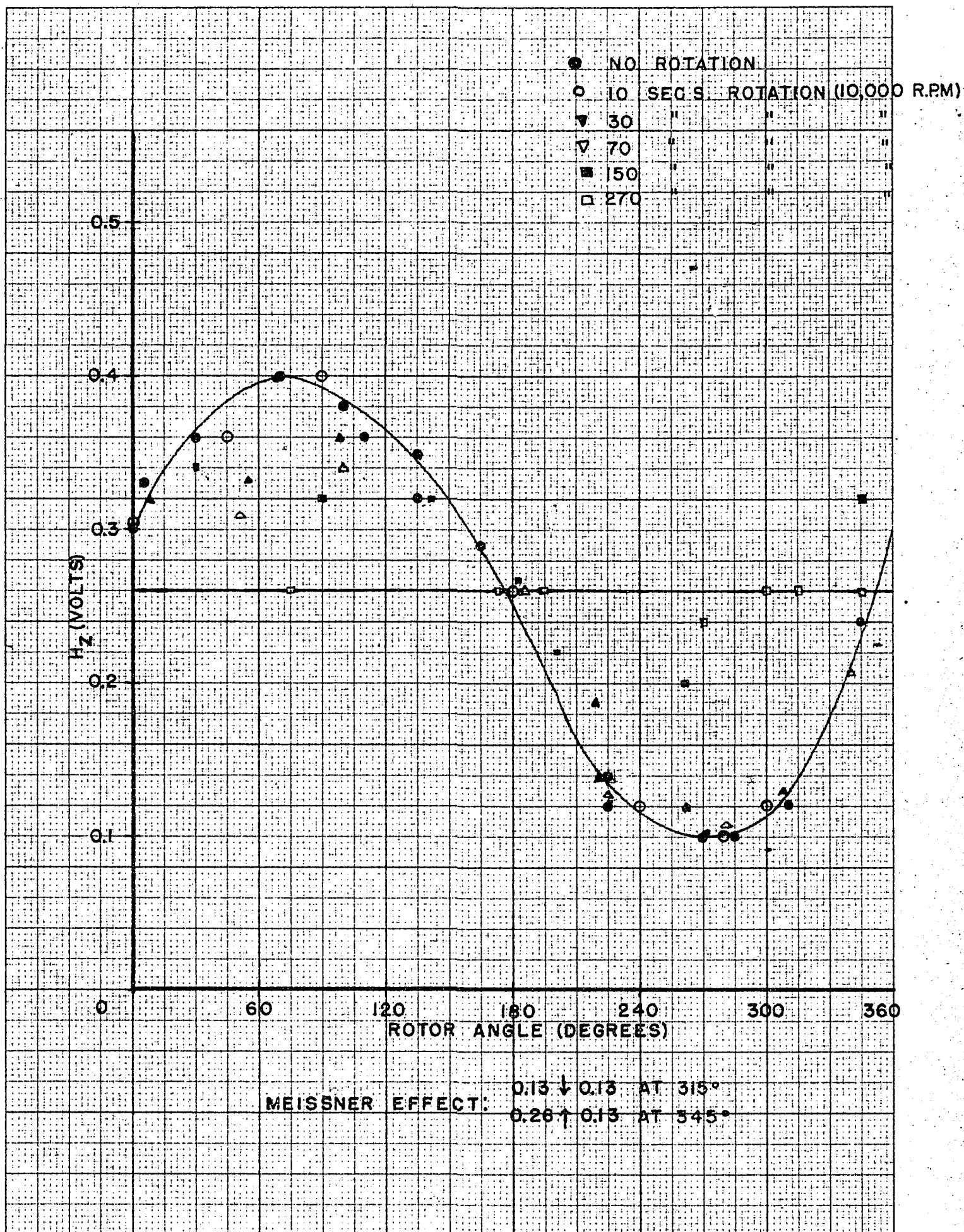
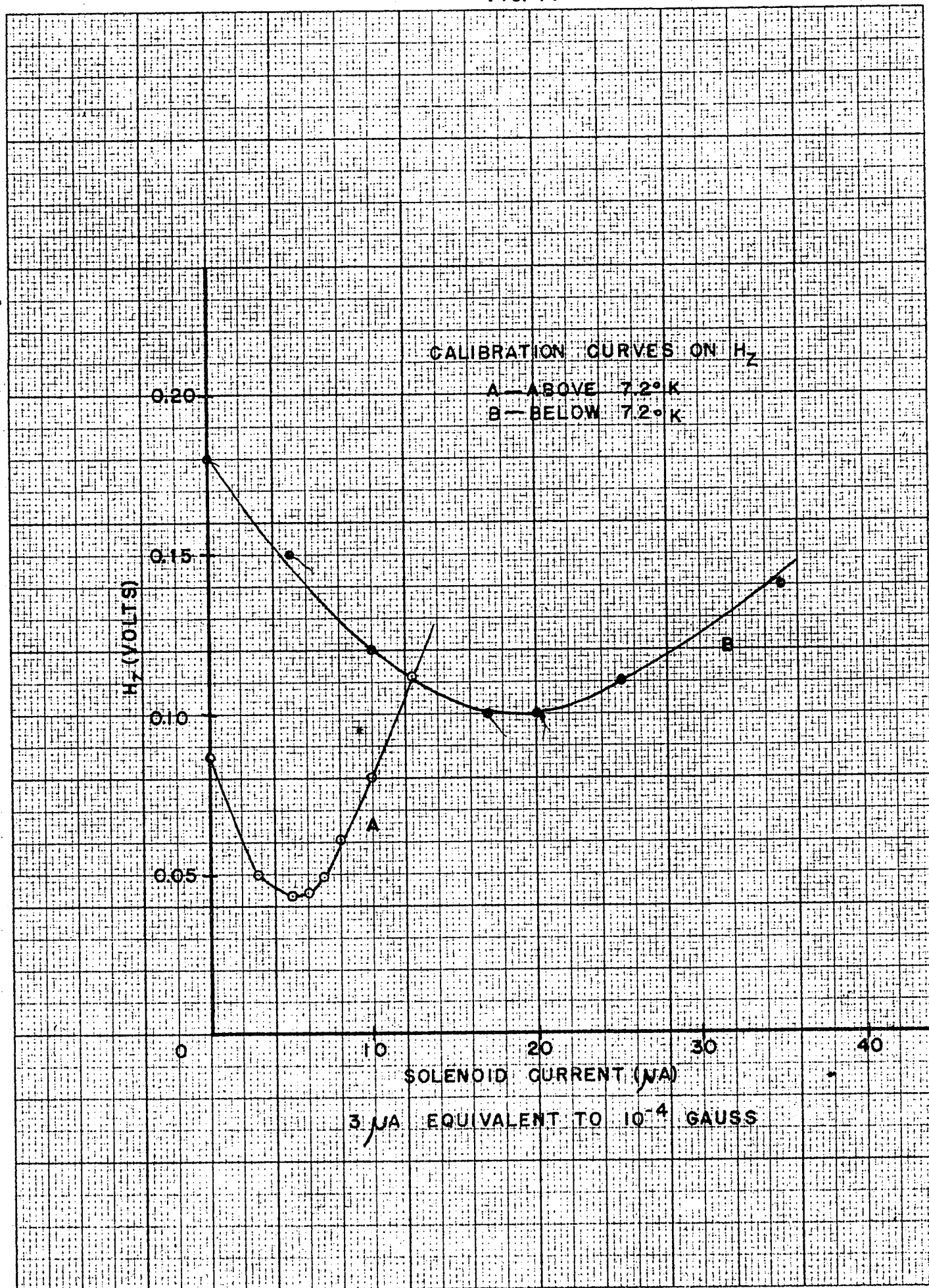


FIG. 14



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