CONSTRUCTION OF A LARGE ELECTROMAGNET SUITABLE FOR THE ZEEMAN AND PASCHEN-BACK EFFECT

By

MICHAEL HAWRANICK

Bachelor of Science

Moravian College for Men

Bethlehem, Pennsylvania

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THESIS AND ABSTRACT APPROVED:

Alvin Pershing
Thesis Adviser

Frank M. Durbin
Faculty Representative

Dean of the Graduate School

PREFACE

The purpose of this thesis was to plan and supervise the construction of a large electromagnet to be used in connection with the grating Spectrograph. With this magnet one can then study the Zeeman and the Paschen-Back effects.

ACKNOWLEDGMENT

I wish to express my sincere appreciation to those people responsible for the completion of this project. I am indebted to "Pop" Hopkins of the Research and Development Laboratory, who machined all parts, and Gordon Smith who offered timely suggestions and helped secure needed materials.

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CHAPTER I

MAGNETIC FIELD EFFECT

When a source of light is placed between the poles of a powerful electromagnet, a single spectral line breaks up into several components.[1] The number of components depends on the particular spectral line which is examined, and this number is not the same when the light is viewed in the direction of the magnetic field as it is when the light is viewed at right angles to the field.

Faraday placed a sodium flame between the poles of a strong electromagnet and examined the light with a spectroscope.[2] He failed to observe any effect upon the light due to the magnetic field. Professor P. Zeeman of Holland repeated the experiment in 1896, using a spectroscope of higher resolving power, and found that, when the field was turned on, the spectral line was resolved into components. When the light was viewed at right angles to the field there were three components. One component was in the position of the original line and was plane polarized with the electrical vibration along the direction of the magnetic field. The other components had frequencies one greater, the other less, than the original frequency and they were plane polarized with electrical vibrations at right angles to the magnetic field.

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[1] Alpheus W. Smith, The Elements of Physics, pp. 710

[2] Norman E. Gilbert, Electricity & Magnetism, pp. 567

When the light was viewed along the direction of the magnetic field, only two components appeared. These were displaced by the same amounts as before but were circularly polarized in opposite directions.

In his original paper announcing his discovery, Zeeman discusses the phenomenon of separation in terms of a mechanical ether, but finally decides in favor of an explanation in terms of the electrical theory of matter, which had recently been developed in its complete form by Lorentz.[1] Lorentz pointed out that this phenomenon is in harmony with the electron theory of matter and radiation proposed by himself.[2] He predicted, from theoretical considerations, that the light from the above mentioned lines should be polarized by the magnetic field, circularly polarized if viewed in a direction parallel to the field, and plane polarized if viewed in a direction which is at right angles to the field.

These predictions were later verified by Professor Zeeman by means of Nicol prisms as analyzers.

In order to make a distinction between Zeeman effect and Paschen-Back effect, a further distinction between "weak" and "strong" fields must be made.[3] The term "weak" is relative, since fields in excess of 10,000 oersteds are usually

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1. Richtmyer & Kennard, Introduction to Modern Physics, p. 76

2. Harvey E. White, Introduction to Atomic Spectra, p. 149

3. Richtmyer & Kennard, op. cit. p. 386

necessary to produce observable Zeeman patterns. A magnetic field is said to be "weak" (or strong) according as the separations of the Zeeman components of each of the several lines of a multiplet group are small (or large), compared with the separation of the lines of the multiplet from one another. For example, the D lines of sodium in a field of 30,000 oersteds show Zeeman separations which are small compared with the separation between D_1 and D_2. Therefore, for the D lines of sodium, a field of 30,000 oersteds is a "weak" field. In lithium, however, the separation of the two components of the first line of the principal series is of the order of 0.3 cm^{-1}. A field of 30,000 oersteds produces Zeeman separations several times larger than this doublet separation. For lithium, therefore, a field of 30,000 oersteds is a "strong" field.

The distinction can also be made by considering the internal fields within the atom.[4] If the field is weak as compared with the fields due to the spin and orbital motion of the electron, the atom gives rise to the Zeeman effect. When the external field becomes greater then these internal fields, the internal motions are greatly perturbed and the atom gives rise to the Paschen-Back effect. The term "Zeeman effect" is sometimes used to include all magnetic effects.

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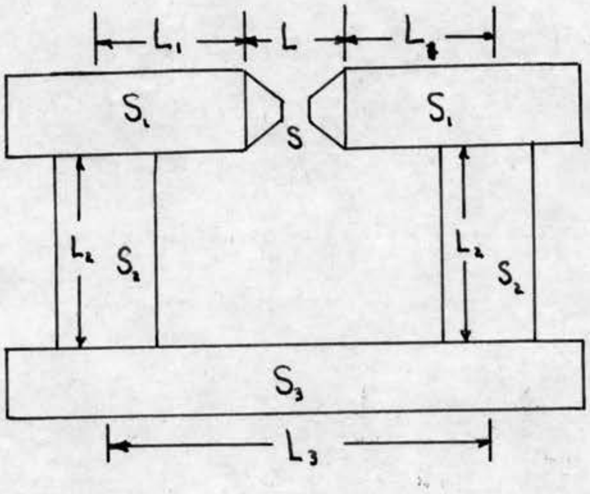
[4] Harvey E. White, op. cit. pp. 162-163

CHAPTER II

EQUATION of the MAGNETIC CIRCUIT

The magnetic circuit is made of soft iron whose permeability μ is roughly 2000 or more. For this type of iron the permeability at low fields is constant at about 100. As the field increases, μ increases rapidly and may reach values of 4000 or 5000. Above the knee of the B-H curve the permeability rapidly decreases. At very large fields the iron becomes magnetically saturated and here the permeability approaches unity.[1]

In order to calculate the expected value of B (flux density) in the space between the pole-pieces, the following method was used.[2]



The above drawing represents the electromagnet where L stands for length and S, cross sectional area. From the

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[1] Norman E. Gilbert, Electricity & Magnetism, p. 216

[2] Sydney G. Starling, Electricity & Magnetism, p. 295

formula for reluctance of a magnetic circuit, $R = \frac{1}{\mu}\frac{L}{S}$ the reluctance of the entire magnetic circuit can be found by taking each portion of the circuit separately and finding its reluctance. The total reluctance will then be the sum of the reluctances of these portions.

reluctance of air gap------------ $\frac{L}{S}$ (where $\mu = 1$)
reluctance of pole-pieces-------- $\frac{2L_1}{\mu S_1}$
reluctance of cores-------------- $\frac{2L_2}{\mu S_2}$
reluctance of yoke--------------- $\frac{L_3}{\mu S_3}$

The total magnetic reluctance is then-

$$\frac{L}{S} + \frac{2L_1}{\mu S_1} + \frac{2L_2}{\mu S_2} + \frac{L_3}{\mu S_3}$$

From the formula, $\text{flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}$

or $$N = \frac{\frac{4\pi nI}{10}}{\text{reluctance}};$$

then if there are nI ampere turns-

$$\frac{4\pi nI}{10} = N\left(\frac{L}{S} + \frac{2L_1}{\mu S_1} + \frac{2L_2}{\mu S_2} + \frac{L_3}{\mu S_3}\right).$$

The value of B (flux density) in the air gap is, $\frac{N}{S}$, and since the permeability here is unity, this is also the strength of the field in the gap.

The magnet is wound with 5,420 turns of copper wire and if the current used is 5 amperes, then all quantities except one in the above formula are known. If the equation is solved for $\frac{N}{S}$ we get,

$$\frac{N}{S} = B = \frac{\frac{4\pi nI}{10}}{S\left(\frac{L}{S} + \frac{2L_1}{\mu S_1} + \frac{2L_2}{\mu S_2} + \frac{L_3}{\mu S_3}\right)}.$$

Substituting all quantities into the equation,

where $n = 5420$

$I = 5$

$L = 1$ cm

$S = 1$ cm^2

$L_1 = 20$ cm

$S_1 = 50$ cm^2

$L_2 = 22$ cm

$S_2 = 180$ cm^2

$L_3 = 44$ cm

$S_3 = 90$ cm^2

$\mu \doteq 2000$

$$B = \frac{(1.26)(5,420)(5)(2000)}{2000 + .8 + .24 + .49} \doteq 34,120 \text{ Gauss}$$

The above calculation is only an approximation, since the circuit is very imperfect from the magnetic point of view and also the taper of the pole-pieces requires a refinement in the dimensions of S and L. It did, however, provide a result which is reasonably close to the experimental value later obtained.

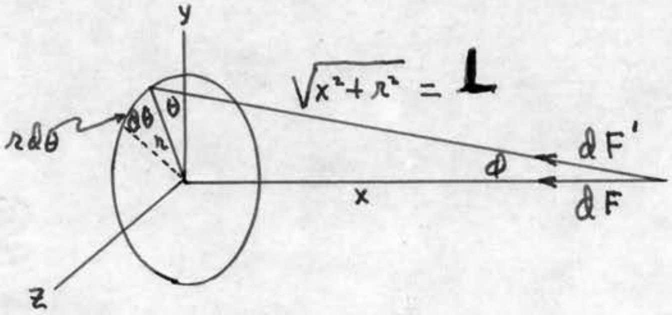
Before the number of ampere turns were known, the above formula was helpful in approximating that number which is required to produce a stated magnetic flux density. Hence, the formula was solved for nI, and from this an estimate of n could be made. When this estimate was made, and the diameter of the wire known, it was then a simple matter of calculating how much wire was to be used and how large to make the coils.

CHAPTER III

FORM of CONE
to give
MAXIMUM CONCENTRATION of FIELD

The magnetic force in the space between the pole-pieces is made up of two parts:[1] (1) the electromagnetic force directly produced there by the current in the magnet coils; and (2) the force due to free magnetism, distributed for the most part over the pole faces. The first of these forms a comparatively small part of the whole, and its value is nearly uniform at small distances from the axis. Therefore, in consideration of the conditions which will secure the greatest strength in the field at the neck, it is necessary only to deal with that part of the force which is produced by free magnetism.

The free magnetism of the pole faces may be treated as made up of a series of co-axial circular rings in planes normal to the axis of the pole-pieces. If M is the whole free magnetism of one of these rings and r its radius, the magnetic force F due to it at a point in the axis at a distance x from the plane of the ring can be calculated from the following diagram.[2]



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[1] James A. Ewing, Magnetic Induction in Iron and other Metals, p. 139

[2] Merit Scott, Mechanics - Statics and Dynamics, p. 171

From the diagram, $dF = dF' \cos\phi$

and $$dF' = \frac{M}{2\pi r}\,\frac{r\,d\theta}{(r^2 + x^2)}$$

also $$\cos\phi = \frac{x}{\sqrt{r^2 + x^2}}$$

Therefore, $$F = \int dF' \cos\phi = \int_0^{2\pi} \frac{M}{2\pi r}\,\frac{r\,d\theta}{(r^2 + x^2)}\,\frac{x}{(r^2 + x^2)}$$

$$= \frac{Mx}{(r^2 + x^2)^{3/2}} = \frac{Mx}{L^3}$$

This force F will be a maximum when $\frac{dF}{dx} = 0$.[1]

$$\frac{dF}{dx} = M\left[\frac{(r^2 + x^2)^{3/2} - (r^2 + x2)^{\frac{1}{2}}\,(2x)\,(x)}{(r^2 + x^2)^{6/2}}\right]$$

$$= M\left[\frac{L^3 - 3Lx^2}{L^6}\right] = M\left[\frac{1}{L^3} - \frac{3x^2}{L^5}\right]$$

Placing $\frac{dF}{dx} = 0$ requires that $\frac{1}{L^3} - \frac{3x^2}{L^5} = 0$

This occurs when $x = \frac{r}{\sqrt{2}}$

but $\tan\phi = \frac{r}{x} = \frac{r}{\frac{r}{\sqrt{2}}} = \sqrt{2}$

and $\phi = 54^\circ\ 44'$, the semi-angle of the cone.

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[1] James A. Ewing, op. cit. p. 140

Therefore a series of co-axial rings will be most advantageously disposed for producing force at a point on the axis if they lie on a cone having its vertex on the axis, with a semi-angle of 54° 44'.

The greatest force will be produced when the pole-pieces themselves are saturated, so that the intensity of magnetization reaches its limiting value in all parts of the metal. In that case, the distribution of density from ring to ring is uniform.

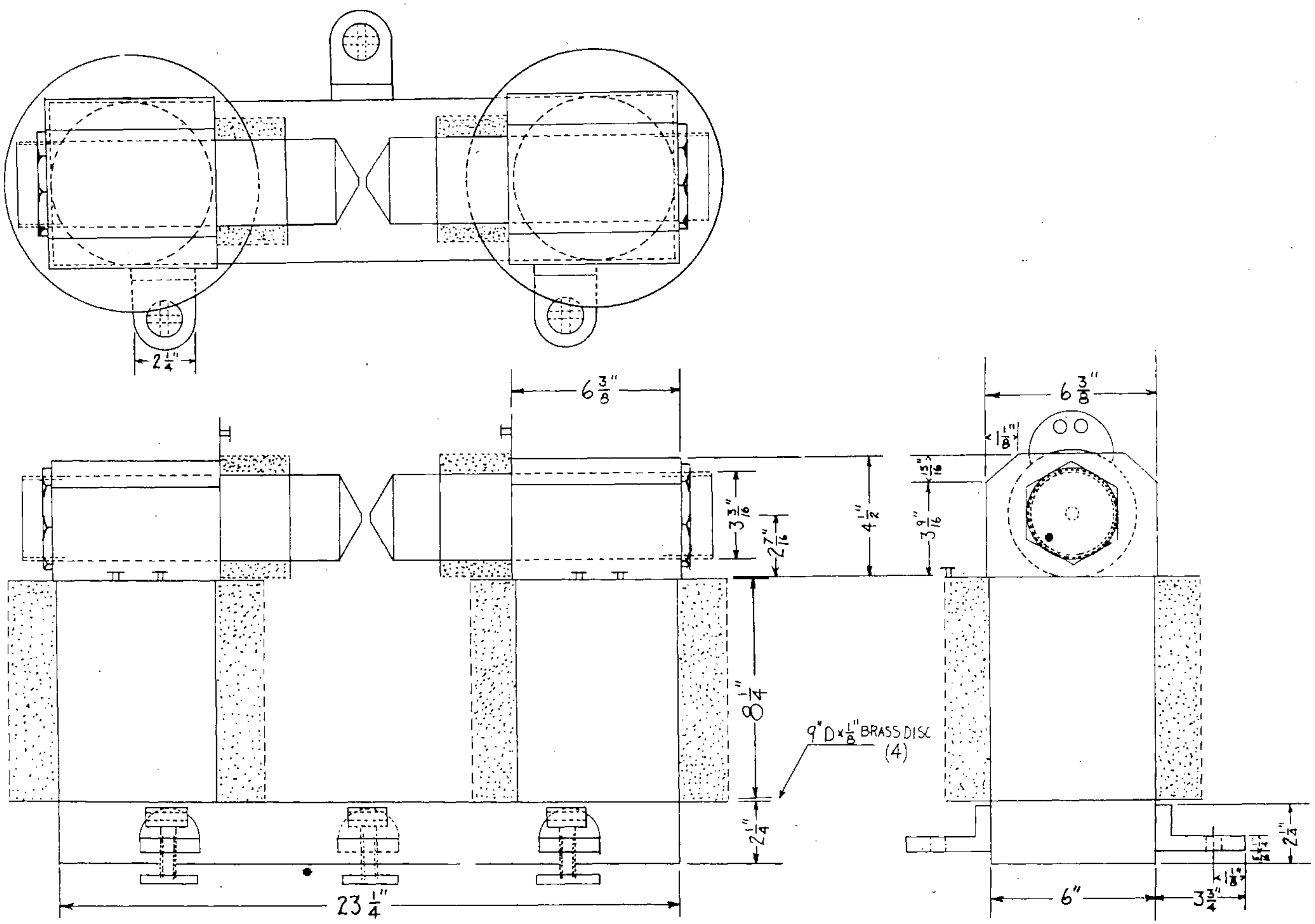
CHAPTER IV

DESCRIPTION of ELECTROMAGNET

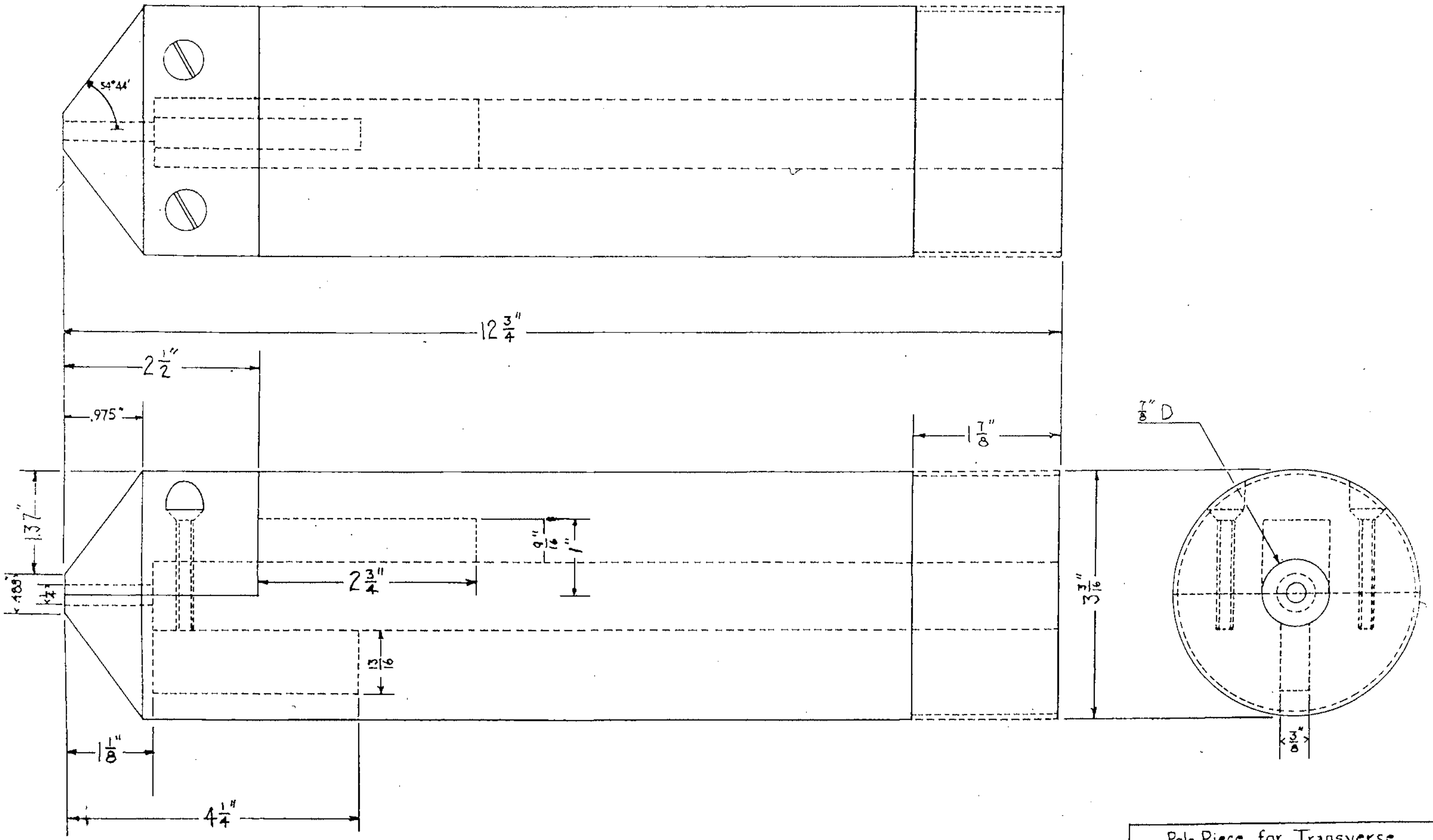
This magnet is made from soft iron with a low carbon content, thoroughly annealed. The yoke and cores contain about .01% to .02% carbon. The pole-pieces have a slight trace of manganese so that they could easily be worked by the machinist. The core and shaft, into which the pole-pieces enter, are one solid piece and are bolted to the yoke. Adjustments are provided for raising and lowering the magnet. S ize #14 American Wire Gauge round copper wire was used to wrap the cores of the magnet. This wire has an allowable current carrying capacity of 20 amperes and a diameter of .0641 inches. Insulating paper is used between each layer of wire and both ends of the wire are fastened to terminals which are themselves insulated from the magnetic curcuit. The small auxillary coils are wrapped in a similar manner and can be removed if necessary. The large coils cannot be removed. Four pole-pieces are provided, two of which are designed to house any conventional type spectrum tube. With these two, the light can be viewed transversely. The other two are for longitudinal viewing.

In order to obtain longitudinal and transverse viewing experimentally, the magnet must be turned trough 90 degrees. Despite the rather large weight of the magnet, this can be accomplished with little effort since it rests on a hard, smooth surface.

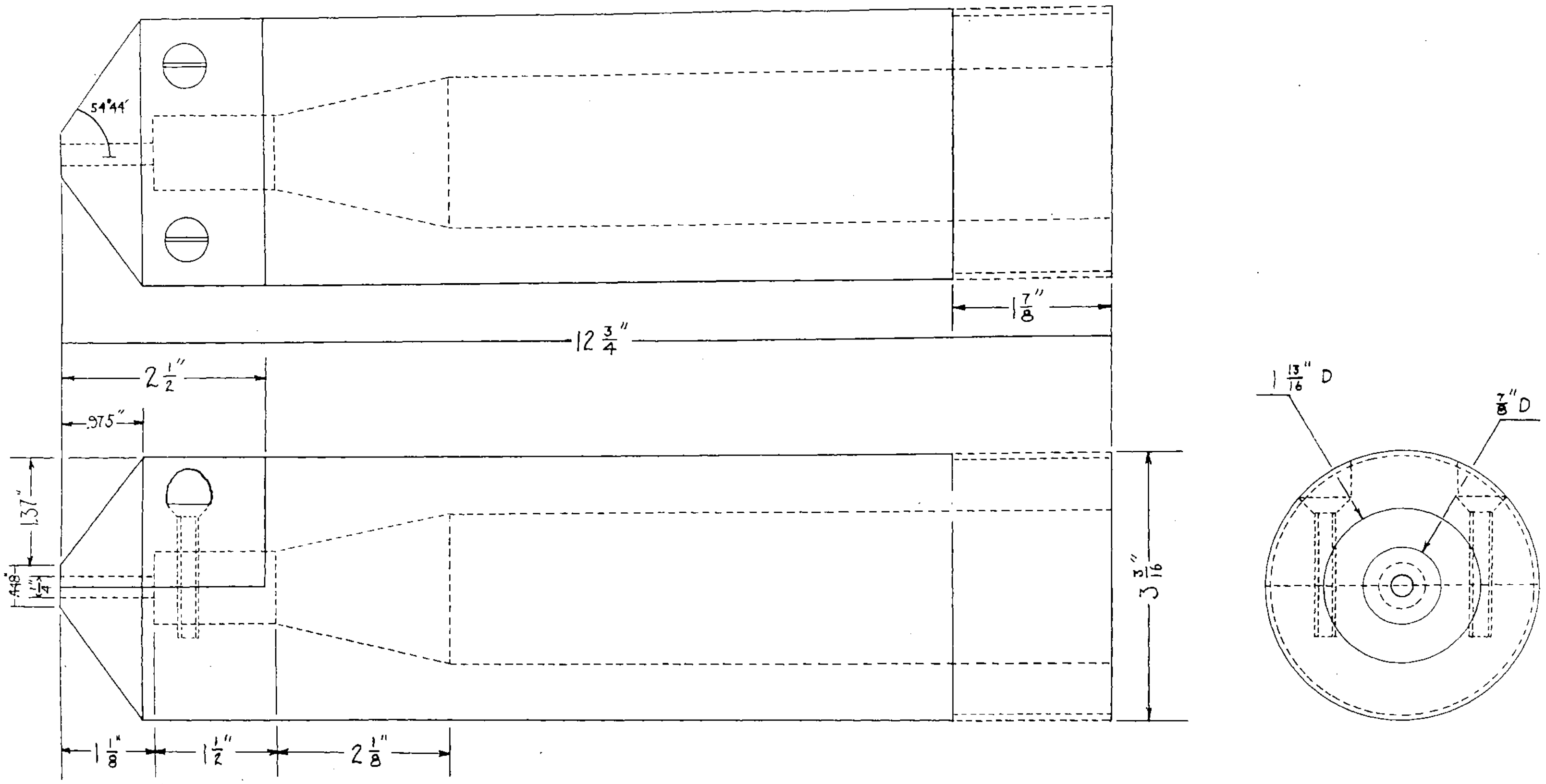
The pole-pieces are threaded on one end and are provided with a large nut, so that they can be separated to any desired distance. The other end of the pole-pieces is tapered with a semi-angle of 54° 44' to give a maximum concentration of the field. The pole-pieces have a clearance in the shaft of .015 inches and each weighs about 20 pounds. The entire magnet, less pole-pieces weighs 437 pounds. There are 5,420 turns of wire in all; 4800 of which are consumed by the large coils.



M. HAWRANICK   PHYSICS DEPT.

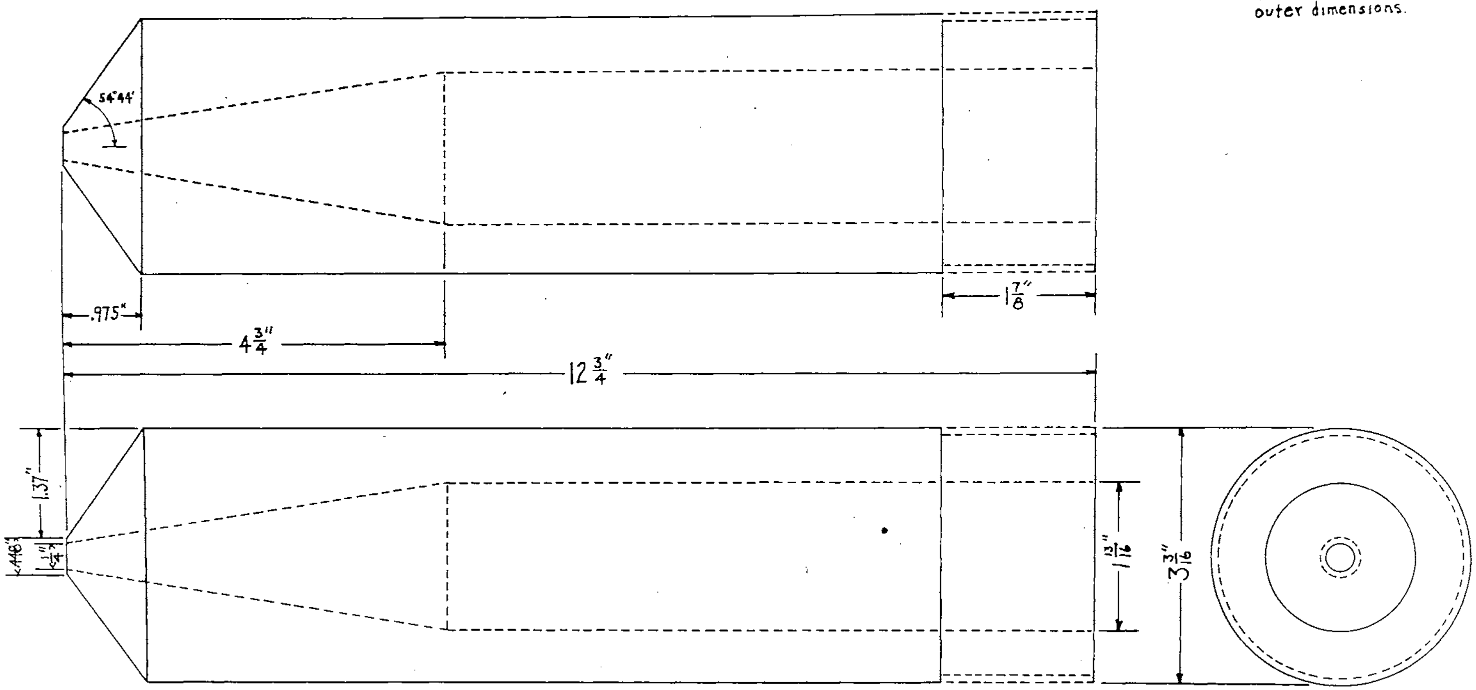


Pole Piece for Transverse Viewing
M. HAWRANICK Physics



Split Cone
M. HAWRANICK Physics Dept.

Note: This is one pole piece of a pair. Second has no internal cutaways ie. a solid cone with same outer dimensions.



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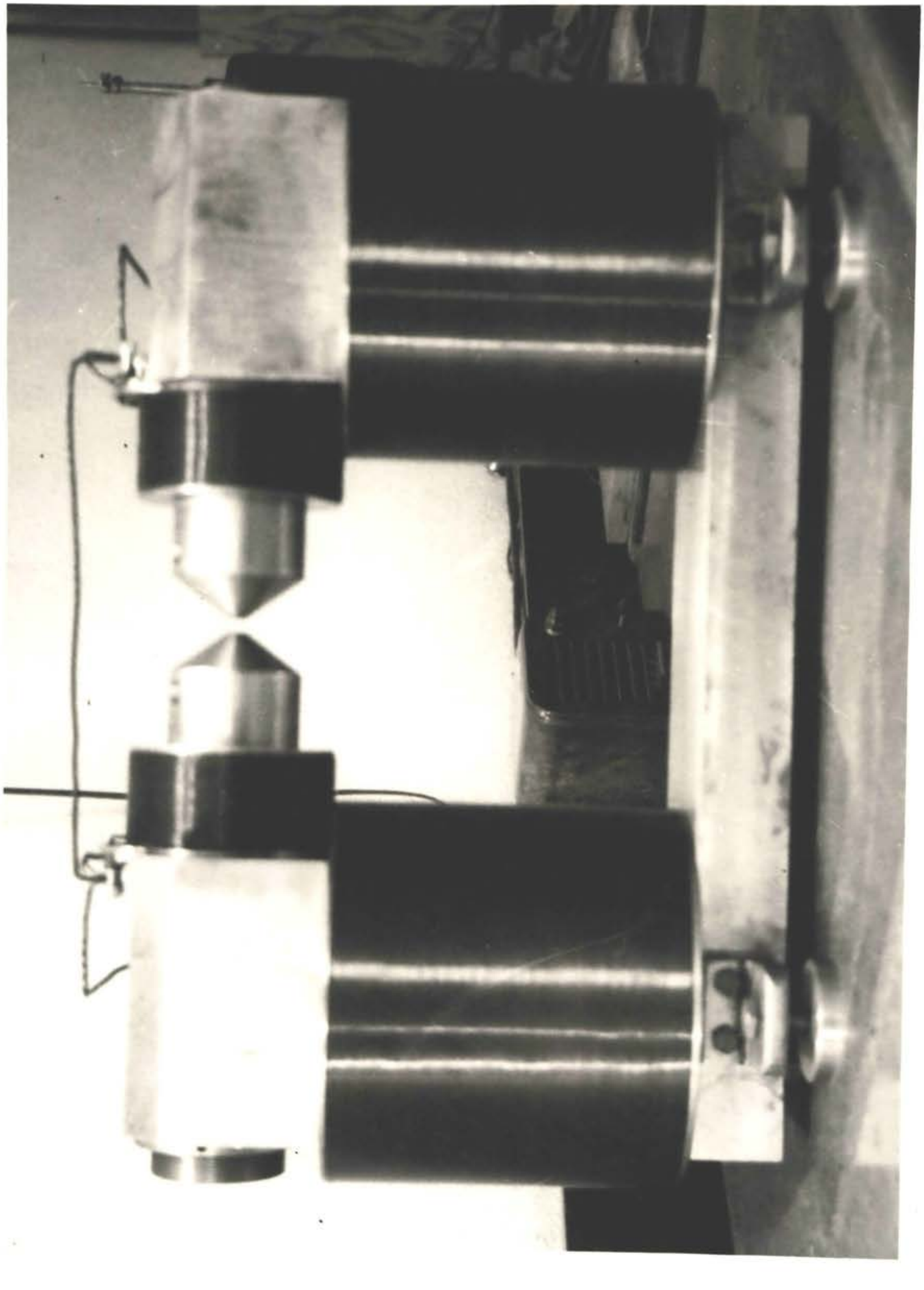
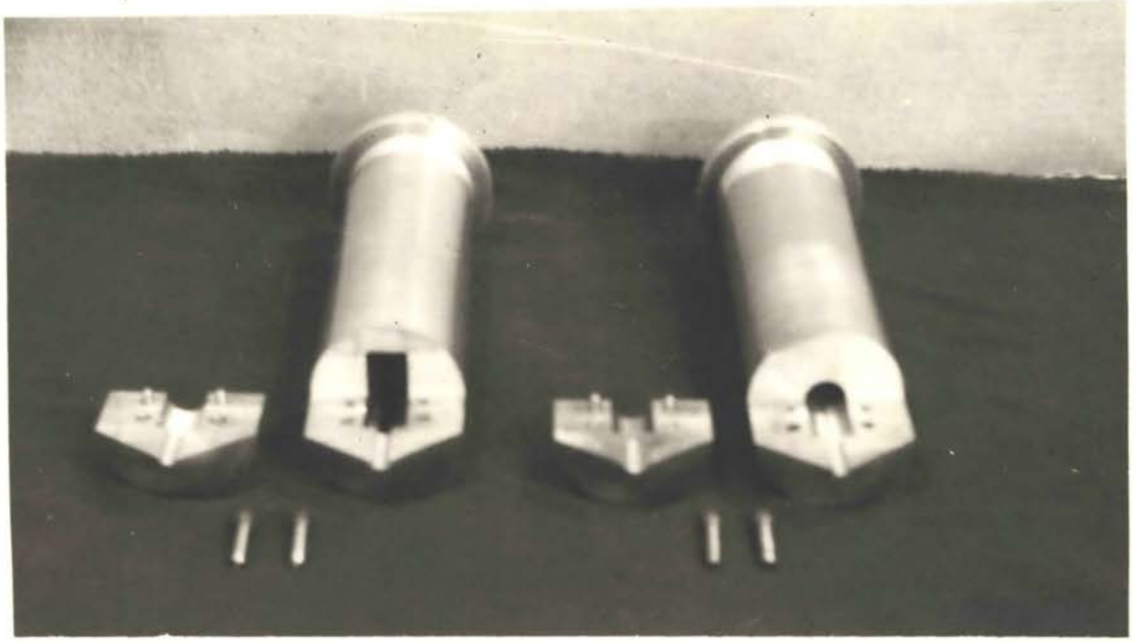
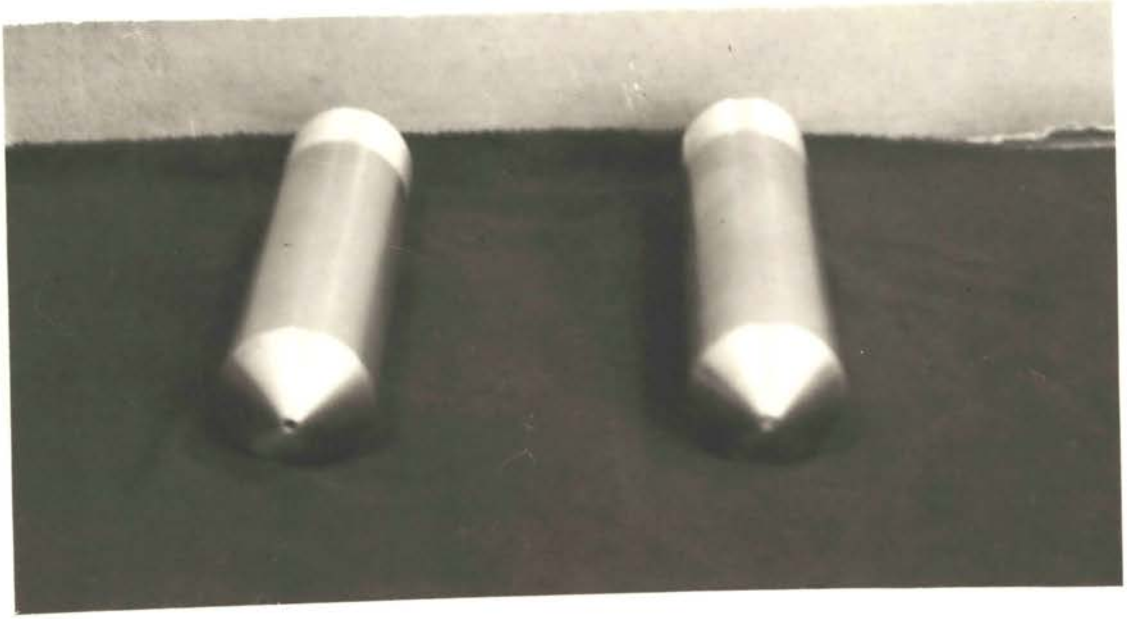
Pole Piece For Longitudinal Viewing





Pole-pieces for Transverse Viewing



Pole-pieces for Longitudinal Viewing

CHAPTER V

MEASUREMENT of FLUX DENSITY

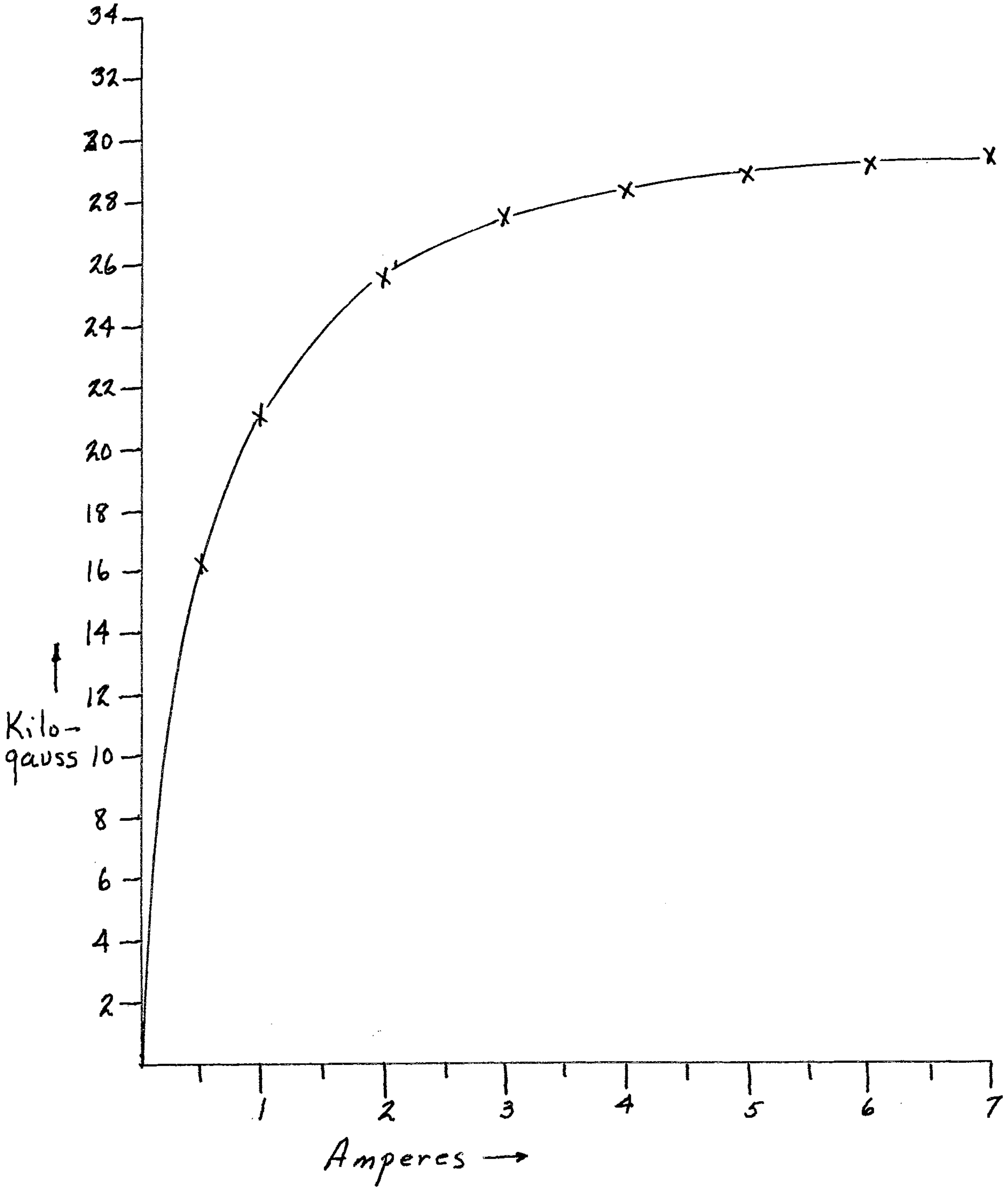
Numerous methods of measuring the value of a magnetic field are described in literature, but many of them could not be applied to this case where the pole separation is one millimeter. The method used here was one where the ballistic galvanometer deflection for an unknown field was compared to the deflection produced from a known field when an exploring coil was jerked from between the pole-pieces. This necessitated winding a coil whose thickness was less then a millimeter, and whose outer diameter was that of the truncated part of the cone formed by the pole-pieces. Because of its dimensions, the coil could not be wound on a form and used. Furthermore, it had to be wound with fine wire in order to acquire as many turns as possible for an appreciable galvanometer deflection. A suitable arrangement consisted in winding the coil on a form, removing it, and then inserting it between several layers of scotch tape. In this way 52 turns were wound and the measured thickness was considerably less than a millimeter.

In the experimental arrangement, the exploring coil was placed in series with a resistance and then connected to a ballistic galvanometer. The series resistance was used so that the galvanometer would not be overdamped and also to keep the deflections within the range of the scale.

With the field on, a gauss meter was inserted between the pole-pieces and a known field was produced. The guass meter could read the value of B directly, but since its maximum reading was 5,000 gauss it could not be used to measure fields beyond this. When the field was known, the exploring coil was inserted and jerked from the field. This produced a deflection on the galvanometer and the number of gauss per millimeter deflection could be calculated, and used as the galvanometer constant. Since the deflection of the galvanometer is proportional to the amount of flux cut by the coil, the flux density for any value of current can be found by multiplying the deflection produced, by the constant of the galvanometer. $B = kd$

Results obtained by this method show that the B - H curve (or what amounts to the same thing, the B - I curve) begins to "level off" at about 3 amperes. A further increase of I beyond 3 amperes does not produce too great an increase in B.

Magnetization Curve for Magnet.



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NAME OF TYPIST: MRS. MICHAEL HAWRANICK

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