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DESIGN AND
CONSTRUCTION OF A
LABORATORY ELECTROMAGNET

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Arthur Jerome Luck

1950

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DESIGN AND CONSTRUCTION OF A
LABORATORY ELECTROMAGNET

by

Arthur Jerome Luck

A Thesis

Submitted to the Graduate School of Michigan
State College of Agriculture and Applied
Science in partial fulfilment of the
requirements for the degree of

MASTER OF SCIENCE

Department of Physics

1950

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Arthur J. Luck

CONTENTS

	Page
I. Introduction	1
II. Design of the Electromagnet	3
III. Construction of the Electromagnet	12
IV. Operation of the Electromagnet	17
V. Bibliography	21

I. INTRODUCTION

The design of electromagnets follows general principles which are widely known; the manner of application of these principles is determined by the purpose for which the electromagnet is to be used. The electromagnet described in this thesis was intended for use as a general laboratory magnet, providing fields of moderate intensity, in a fairly large volume.

Fundamental approaches to the problem of magnet design have been made at intervals spanning a considerable period of time. Ewing¹ has considered the case of what is generally thought of as the typical electromagnet. The field is produced in the space between the ends of cylindrical pole pieces, and the magnetization is axial. It has been shown that, in this case, the maximum flux density attainable is of the order of 19,000 gauss. This represents the contribution to the flux density due to the magnetization of the core material, so that greater values might be realized by increases in the magnetizing field component.

Fabry² has shown that the magnetic field intensity produced by an air-core coil is given by:

$$H = G \sqrt{\frac{W\lambda}{\rho a}}$$

1. Ewing, J.A. "Magnetic Induction in Iron and other Metals" p. 146
2. Fabry, C. Production De Champs Magnetiques Intenses Au Moyen De Bobines Sans Fer. Journal De Physique 2, p. 129. 1910

where W = power dissipated

ρ = resistivity of winding material

λ = a conductor-to-winding-space ratio

G = a factor determined by the geometry of the coil.

A = cross-sectional area of the core

Bitter³ has shown that, under the conditions of greatest efficiency, and with an optimum (non-uniform) current distribution, the constant "G" reaches a limiting value of 0.272. In the matter of maximum efficiency in the utilization of iron, it is shown⁴ that the direction of magnetization should be not axial, but in such a way that:

$$\sin^2 \alpha = cr$$

where α is the angle between the direction of magnetization and the coil axis, and r is the distance from the center of the coil. This implies an equatorial sort of distribution of the iron, so that, instead of making up a core for the magnetizing coil, it makes up a shell enclosing the coil. When iron is used in this manner, it is shown that the maximum contribution of the iron to the flux density is of the order of 68,000 gauss, rather than the 19,000 suggested by Ewing.

3. Bitter, F. "Design of Powerful Electromagnets"
Review of Scientific Instruments 7 (479) 1936

4. Bitter, F. "Design of Powerful Electromagnets"
Review of Scientific Instruments 8 (318) 1937

II. DESIGN OF THE ELECTROMAGNET

The air-core electromagnet has manifest advantages. In addition to low cost and simplicity of construction, it possesses excellent stability with respect to current changes. Also, the field intensity is directly proportional to the current, making determination of operating conditions easy. From the information given above, it is a simple matter to determine the power requirements for an air-core electromagnet having the desired characteristics.

Assuming a core area of 10 sq. cm., a space factor of 0.75, an optimistic value of 0.2 for G , and windings of annealed copper, the power required, in watts, is:

$$W = 0.57 \times 10^{-3} H^2$$

so that, if a field intensity of 10,000 oersteds is desired, the power required is of the order of 50 kilowatts. A power input of this magnitude would involve serious cooling problems. Channels for a coolant would be required, reducing the space factor of the coil. So it seems that this power estimate is probably well below what would actually be required.

It is apparent that, although the air-core electromagnet is appropriate to the production of intense fields in relatively small volumes, the magnet of moderately low power and large dimensions must depend primarily upon the magnetization of iron for its flux density.

If we consider Fabry's equation for an air-core coil as applying to a coil which is to magnetize an iron core, it is apparent

that, since the field intensity varies as the square root of the power input, the maximum power efficiency will be at the smallest power input. Moreover, cooling problems become troublesome if the power input is large.

A third factor which is of importance in the design of an electromagnet is stability with respect to variation in current. A variation in the magnetizing current should produce a minimum variation in the flux density produced by the magnet. If possible, this condition should be achieved without the use of complicated control equipment. These considerations all point to the use of iron in a condition of maximum saturation. A relatively weak magnetizing field will then suffice to produce the required flux density; the cooling problem will be simple to solve, and, when the iron making up the magnetic structure is well past the knee of its magnetization curve, the stability of the magnet will approach that of an air-core coil.

The immediate application of the electromagnet seemed to be in connection with research in radio-frequency and microwave spectroscopy. Discussion with individuals working in these fields, and reports of work in progress, indicated that a maximum available flux density in the region of 10,000 gauss should be entirely adequate. This value is well within the limit of 19,000 gauss stated by Ewing for axial magnetization, so that a conventional electromagnet design seemed appropriate.

An important difficulty in using magnetic fields for resonance experiments lies in the stringent requirement for uniformity and constancy

of the field, both in time and in space. The time variation may be minimised by the use of iron in the saturation region. Unfortunately, highly saturated pole faces produce quite non-homogeneous fields. Ewing⁵ has shown that the homogeneity of the field may be improved by the shaping of pole faces. The pole-face shape for maximum homogeneity - a truncated cone with semi-vertical angle of $39^{\circ}14'$ - differs from that for maximum field intensity. But the maximum intensity attainable by the use of this sort of pole-face is still well above that required here.

Since the form of pole-face required for the greatest ultimate usefulness was uncertain, it was decided to build the magnet with simple flat pole-faces, to be capped at some later date with pole pieces to meet specific requirements. In order to provide adequate homogeneity of the field between these faces, the diameter of the cores was made as large as conditions would permit. A six inch diameter was chosen, this being the largest size which could be handled and machined without great difficulty.

The utilisation of iron in an electromagnet represents a compromise between theory and practice. The distribution suggested by Bitter tends toward an 'ironclad' structure. Certain mechanical difficulties attend the use of iron in this fashion. The most important of these is the matter of access to the working space of the magnet. This problem has been solved, for powerful electromagnets,

5. Ewing, J. A. "Magnetic Induction in Iron and Other Metals"
p. 148

in satisfactory fashion by Dreyfuss, in the Uppsalla electromagnet⁶, and by Bitter, in the Arthur D. Little Electromagnet⁷.

In the present case, where extreme efficiency in the use of iron is of no great importance, and where flexibility of arrangement seems of the utmost importance, it was decided to use an extremely open type of construction.

There appeared also to be a strong possibility that flux densities much less than 10,000 gauss might be required on occasion. So it was decided that some arrangement for producing saturation of a large part of the magnetic circuit, at lower values of flux density, should be provided.

The magnetic material most often used in the magnetic structures of magnets of this type is Armco iron, a highly purified soft iron. Although its performance at moderate values of saturation is excellent, it can be seen from the curves in Fig. I that, at high flux densities, cast steel and SAE 1020 steel equal and even surpass pure iron in maximum permeability. So it was decided to construct the magnet frame, in so far as possible, of SAE 1020 steel.

Determination of the characteristics of an iron-core electromagnet under widely varying conditions is rather difficult. Two factors are responsible for this difficulty. One is the variation

6. Snellman and Burge: "The Uppsalla Electromagnet" Journal of Scientific Instruments, and of Physics in Industry 26, 10 (331) Oct. 1949

7. Described in a brochure published by Arthur D. Little, Inc. in February, 1950

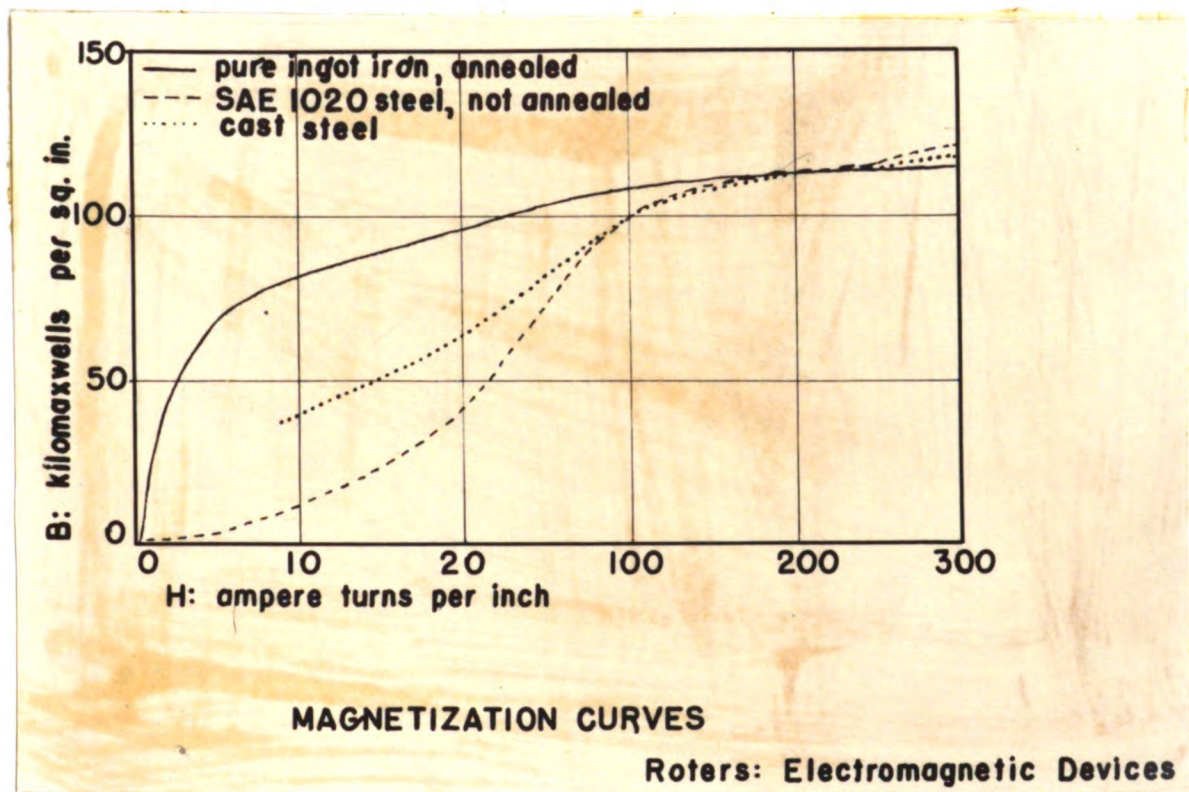


Fig. I

in the permeability of the core material over a range of operating conditions. This variation is complicated in character, and cannot be expressed analytically. The other factor is what might be termed the "flux leakage". Roters⁸ suggests an approximate method of determination of this factor. The basis of this method is the breaking down of the total leakage into geometrically simple paths. The leakage through each path is evaluated or approximated, and the total leakage taken as a summation of the individual parts.

A convenient way in which the flux leakage may be expressed is by means of a "leakage coefficient". This is a ratio of the overall permeance of the air gap, including all leakage paths, to the permeance of the useful path. The permeance of the useful path is:

$$P_1 = \frac{\pi \mu r_1^2}{g}$$

The permeance due to the fringing about the edges of the pole pieces is:

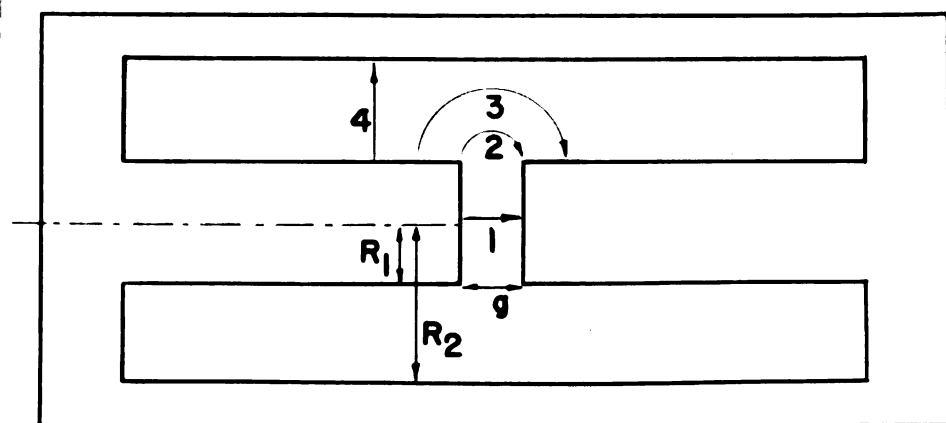
$$P_2 = 1.63 \mu (r_1 + g/4)$$

The permeance due to the path between the external (cylindrical) surfaces of the pole pieces is:

$$P_3 = 2 \mu r_1 \ln \frac{4(r_2 - r_1)}{\pi g}$$

The symbols above relate to those shown in Fig. II.

8. Roters: "Electromagnetic Devices" p. 139



FLUX PATHS

Fig. II

A fourth leakage path exists between the cylindrical surface of the core, and the outer frame. But, since the outer frame to be used is open in character, the leakage along this path is neglected. The leakage coefficient is:

$$\nu = \frac{P_1 + P_2 + P_3}{P_1} = 1 + \frac{1}{\pi r_1} \left[1 + \frac{g^2}{r_1} + 2g \ln \frac{4(r_2 - r_1)}{\pi g} \right]$$

The effects of flux leakage may be further interpreted by computing an "equivalent area" A' of the air-gap. This may be considered to be the area which would be required to produce the total permeance, assuming the flux to be uniformly distributed between two parallel pole faces, separated by the actual air gap length. From this description, it follows that the equivalent area is given by:

$$A' = \nu A$$

where A represents the actual area of the pole face. From this equivalent area may be computed the total flux required to produce a particular flux density in the useful air gap:

$$\Phi = BA' = \nu BA$$

Since ν is a function of g , the air gap length, the total flux requirement varies over a wide range, depending upon the air gap length. Fig. III shows the variation of A' with g , for the design used.

Once a value for the total flux has been obtained, the required cross-sectional area of the magnetic structure may be determined from the magnetization curves of the materials used. In order to produce

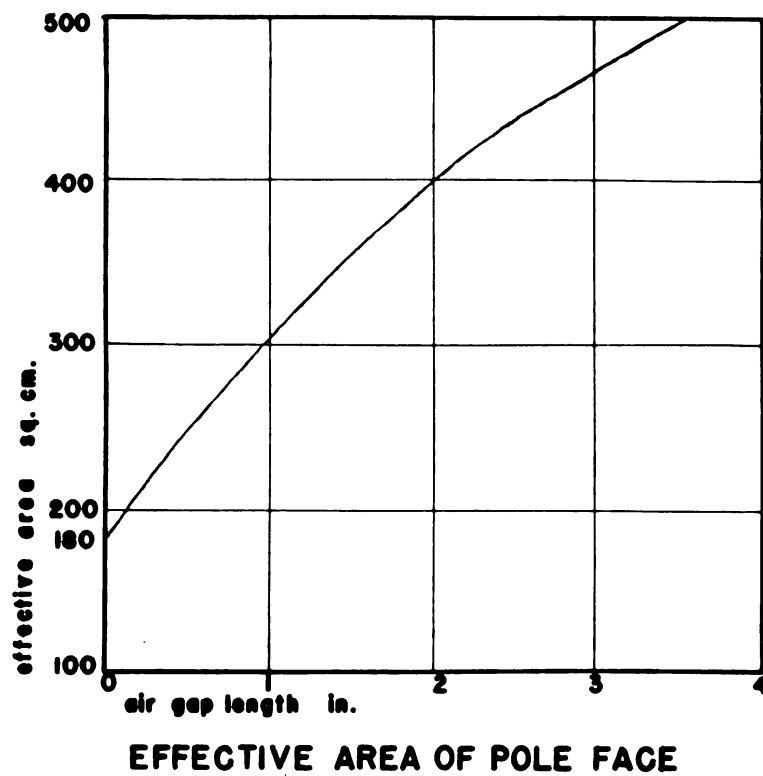


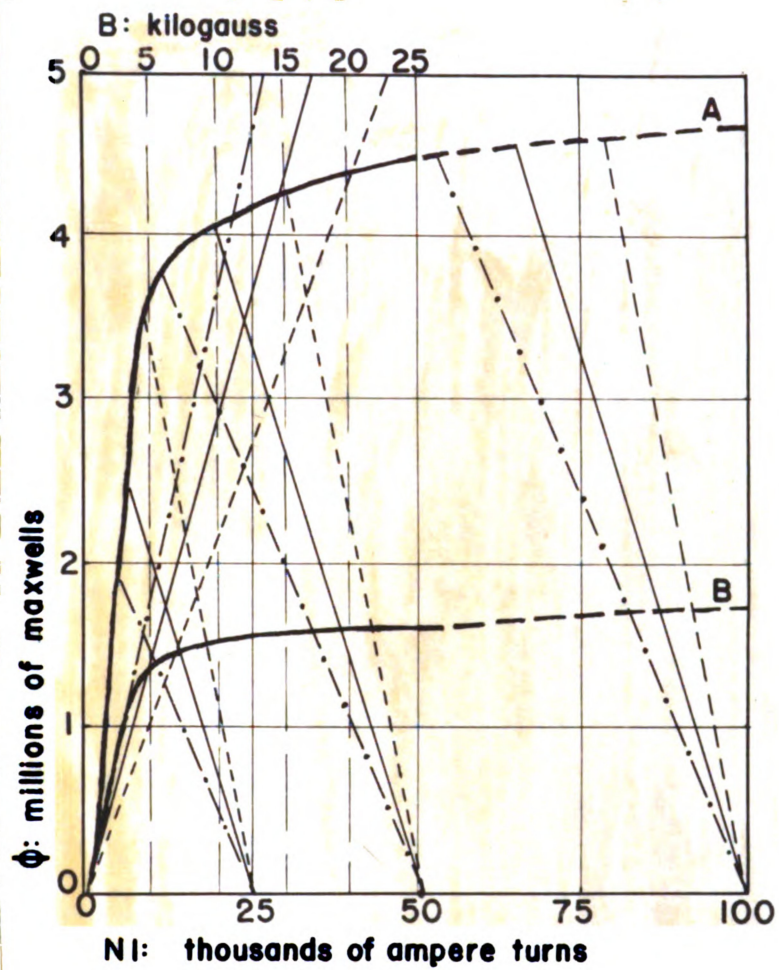
Fig. III

homogeneity of the flux between the pole faces, the material in that locality should remain at a low state of saturation. On the other hand, in order to produce stability with respect to current variation, the magnetic structure in general should be completely saturated. An obvious method of producing this situation is to make the pole faces of some material with a much higher value of saturation flux density than the rest of the structure.

In order to evaluate the performance of tentative designs under various conditions, a graphical method was adopted. As a starting point, a typical magnetization curve for an iron-and-air structure was used. This gives the ampere-turns requirement for a specified total flux, as a sum of the excitation required for the iron part of the structure, plus that for the air portion of the structure. The total permeance of the air gap, including the leakage paths, is used here.

Superimposed upon this is a second set of curves, representing the flux density produced for a given total flux. These are a family of straight lines, one for each air gap length. The members of the family vary in slope because of the variation of effective area of the pole face for different values of gap length.

This combination of curves constitutes a useful nomograph, with which it is possible to determine, for a specified design, both the excitation requirements for some particular performance, and the performance which may be expected for a given excitation. The set of curves for the design adopted is shown in Fig. IV.



CALCULATED PERFORMANCE

A: all four filler rods in place

B: no filler rods

air gap lengths: - - - - - 0.5 inch

————— 1.0 inch

- . - . - . 2.0 inch

Fig. IV

For example, it may be desired to find the ampere-turns required for a flux density of 10,000 gauss, at a gap length of 1 inch. The procedure is as follows: On the $B-\Phi$ curves, follow the 1-inch line to its intersection with the 10,000 gauss line. Then move horizontally in either direction to the intersection with the appropriate iron magnetization line. From that point downward along a line parallel with the slope for a 1-inch gap length to the NI scale, finding the excitation required to be some 35,000 ampere turns. The operations may, of course, be carried on in the reverse direction, depending upon the information supplied. A great utility of this sort of representation is that it provides a comprehensive and compact diagram of the limits of performance of a given design.

The problem of cooling the magnetizing windings is a grave one, in magnets of high power dissipation. In order to preserve a reasonable space factor, liquid cooling is generally resorted to. Water cooling presupposes an adequate supply of pure, soft water; insulation problems nevertheless appear. An alternative is oil cooling. This presents no insulation problems, but generally requires the use of heat exchangers.

Where the power involved is small, air cooling seems to be an entirely adequate method. Shaw⁹ describes an electromagnet comparable with that discussed here, which was successfully air cooled.

9. Shaw, E. J. "Design and Construction of an Electromagnet for Investigation of the Magnetic Properties of Atoms and Molecules". Review of Scientific Instruments, 2(611) 1931

Although the use of air as a coolant requires that a considerable portion of the winding space be devoted to air passages, in a magnet of relatively low power, the sacrifice in space factor may be more than balanced by the increase in convenience of operation. A liquid-cooled magnet requires a considerable time to reach temperature equilibrium, due to the relatively large heat capacity of the coolant. In an air-cooled magnet, temperature equilibrium is reached quickly.

The eventual design evolved into an open H-type form. This construction is superior to a U-shaped structure in that the forces acting upon the poles do not cause misalignment of the pole faces. In addition, flux leakage is minimized. The longitudinal frame members are tubular, themselves presenting a rather small cross-sectional area. Therefor this portion of the structure, which makes up a considerable portion of the total path length, may be highly saturated at relatively small values of total flux. For larger values of flux, filler rods may be inserted into the tubes, providing the necessary increased cross-sectional area.

A further advantage of the open design is the extreme accessibility to the working space of the magnet. Access is possible from the top and bottom, as well as both sides. The tubular frame members may be utilized as supports for equipment to be used in connection with the magnet. An assembly drawing of the magnet is shown in Fig. V.

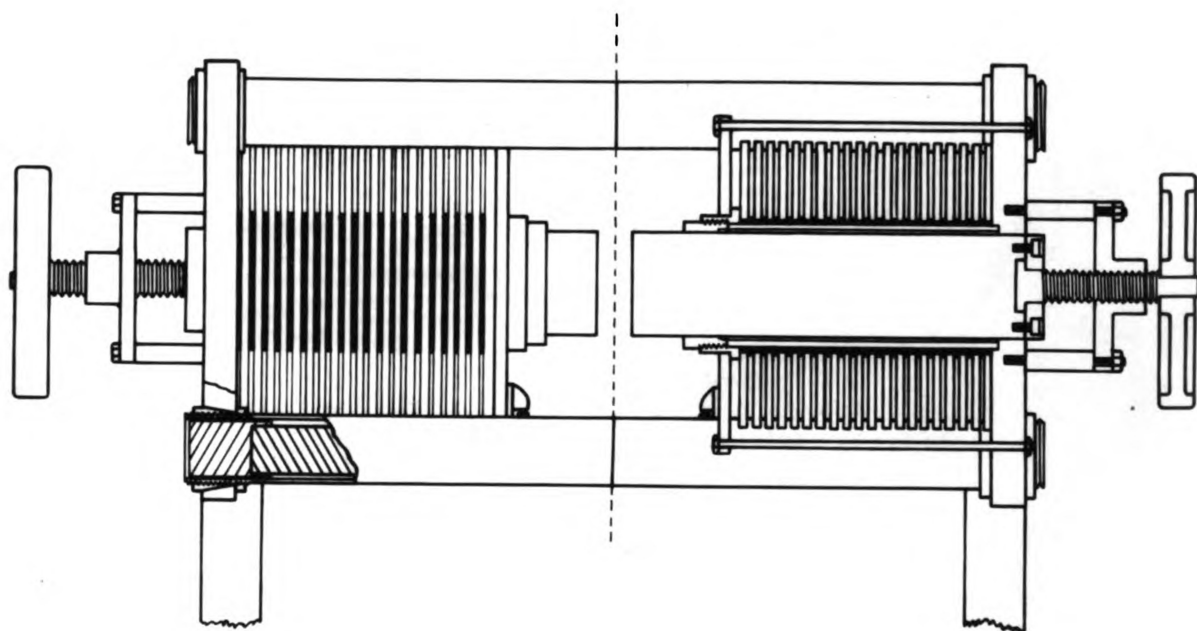


Fig. V

III. CONSTRUCTION OF THE MAGNET

In order to decrease the amount of heavy machine work required, stock sizes of standard materials were used, in so far as was possible. SAE 1020 steel, which was used for the major portion of the frame, is available in a large variety of sizes in round, cold-drawn bars. These are drawn through dies, so that the accuracy of dimension and the surface finish are comparable with that of a ground cylinder. Six-inch diameter stock of this type was used for the cores of the magnet; these required only a facing-off operation.

The rectangular end plates were cast of low-carbon steel, carbon content specified less than 0.20 percent. This material produced a clean casting. Distortion in casting was small, and the metal was easily worked. The tubular longitudinal frame members were made of standard-weight welded steel pipe, of 4 inch nominal size. Assembly of the pipes to the frame was by means of threaded collars, which were made from standard steel pipe couplings. The holes in the end plates through which the pipes pass were given a rather extreme taper - about 7 degrees. Great care was taken in preparing the pattern, so that a hole was produced in the casting which required little in the way of finishing. The tapers were ground slightly, and the collars individually fitted to the holes. Using a stop nut on the inner face of the end plate, and the tapered locking collar on the outside, a joint was produced which appears mechanically strong, and yet permits adjustment of the alignment of the end plates by screwing the two collars up or down the threads on the pipes.

The only major machining operation needed on the cast steel end plates was the boring of the hole to receive the six-inch diameter cores. The end plates were mounted face-to-face, in the same orientation that would be used in the final assembly, and the two bored simultaneously on a horizontal boring mill. A clearance of 0.005 inch was allowed in the operation. Ewing¹⁰ states that the reluctance of a smoothly machined joint is equivalent to that of an air-gap several thousandths of an inch long, even when the surfaces are in firm contact. So it was felt that there would be no object in specifying an extremely small clearance.

The internal surfaces of the welded steel pipe were found to hold to consistent dimensions. Specifications for standard 4 inch welded steel pipe state an internal diameter of 4.026 inches. However, the swaging effect of threading the ends of the pipes reduced the inside diameter of the threaded portions by about .015 inch, making a free but close fit on a 4 inch cold-drawn steel bar. The filler rods, to be inserted into the pipes, were made up of lengths of 3 inch cold-drawn steel bar, fitted at the ends with four inch lengths of 4 inch diameter steel bar. Thus, good contact is maintained at the ends, yet the bars can be inserted and withdrawn easily. No difficulty was encountered in fitting the filler rods, except in the case of one of the four pipes, in which a projecting weld was found near one end. One of the four pipes had the threads

10. Ewing, J.A. "Magnetic Induction in Iron and Other Metals"
p. 288

on one end extended for a length of about ten inches. This makes it possible to manipulate the bar in such a way that the locking collars and stop nuts may be removed, and the pipe slid out without disassembling the entire frame. This permits easy access to the coils, in case of some need for adjustment or servicing.

The central solid steel cores are supported at the outer ends by the holes bored in the cast steel end plates. The inner ends are supported in steel bushings, which were machined from a 6-inch standard steel coupling and two short lengths of extra-strong steel pipe. These bushings are in turn held in place by aluminum clamping discs, which also act as end-plates for the windings. The discs rest on jack screws, bearing on the two lower longitudinal frame members. The alignment of the pole faces may be adjusted by means of these screws. The aluminum discs are clamped in the horizontal direction by four brass rods passing back through the cast steel end plates.

Control of the air-gap length is by means of two large lead screws, bearing handwheels at their outer ends, and passing through threaded plates back of the end plates. Since the force acting upon these screws may be of the order of five tons, the mechanism must be quite strong. The lead screws were machined from three-inch diameter steel bar, with a pitch diameter of two inches. The length of thread engagement in the end plate is two inches. It appeared that the weakest portion of this structure would be

found in the screws which hold the cap on the outer end of the core, where the lead screw is attached. For this reason, eight hardened steel cap screws of the highest quality were used in each end. The lead screw pitch is ten threads to the inch, providing a smooth control of the positions of the pole faces. The range of adjustment permits a gap length of eight inches; wide enough so that the cores may be capped with pole pieces of special design and material.

Welded steel pipe, of 6 inch nominal size, was used to carry the windings. Since the inside diameter of this pipe is about 6.060 inches, adequate clearance was provided for the six-inch cores. The pipes were welded to the end plates, concentric with the cores. The weld provides sufficient strength to support the windings, so that the windings may be placed in position and removed with no difficulty. These pipes also act as stops for the bushings which support the inner ends of the cores. Since the pipes and bushings are made of low carbon steel, they also form part of the magnetic structure, augmenting slightly the cross-sectional areas of the cores for a large portion of their lengths.

The coils are wound in pancake style, of .500 inch by .040 inch copper ribbon. The insulation consists of a coating of heavy Formex, covered with a wrapping of Formex impregnated glass fiber. This insulation is capable of withstanding much higher temperatures and voltages than are expected in normal operation; the current carrying capacity of the wire is considerably in excess of that required. The choice of this wire was determined by its

availability; however, the resulting rather low resistance of the magnet reduces the power dissipation.

Each pancake consists of 70 turns; inside diameter of the pancake is 7 inches, and the outer diameter is about 16 inches. The winding operation was performed under a tension of about 30 pounds, in a rig using a variable speed motor driving a 70:1 reduction worm gear. The combination of the worm gear on the winding reel, and a friction brake on the spool, made it possible to stop winding at any point without losing tension.

A skeleton type winding reel was used, making it possible to remove each finished pancake from the winder, and fasten the ends with no difficulty. The reel was then removed from the coil, and winding of the next coil could be resumed while the previous coil was being treated. Sodium silicate was originally used to coat the pancakes. Although the results appeared good at first, subsequent drying of the coating made the film too brittle, and it tended to chip and peel. Clear pyroxylin lacquer was later used as a binding material, with good results.

The inner turn of each coil was bent and flattened to a right angle, and the inner end was brought out so that all connections between coils could be made externally. A total of 42 pancakes were wound, providing a total of 2940 turns. The coils are connected in series in two sections of 21 coils each. The sections are brought out to separate terminals, so that they may be used either in series or in parallel. The series resistance is about 4 ohms; in parallel, the resistance is about 1 ohm.

The coils are mounted on the 6-inch steel pipes welded to the end plates. The inner turns of the coils clear the surface of the pipe by about a quarter inch; the coils are held concentric with the pipe by means of small maple wedges spaced about the inner diameters. The coils are held apart from one another axially, by means of maple spacers cemented to the coils near their peripheries. The spaces thus produced, about one quarter inch wide, serve as cooling passages for air. The surface available for cooling is approximately 15,000 square inches - a highly adequate surface to dissipate the $1\frac{1}{2}$ kilowatt or so involved in normal operation, without resort to forced draft.

The weight of the electromagnet is approximately 3000 pounds. To provide the necessary strength and rigidity, a frame of heavy 4 inch steel channel was welded directly to the cast steel end plates; this frame is proportioned so that the air gap is at a convenient table-top height.

The weight of the magnet is distributed by the frame over an area of actual floor contact of about 400 square inches, so that no special provisions are needed to protect the floor surfaces. However, a floor strength adequate to support a static load of 300 pounds per square foot is required.

IV OPERATION OF THE ELECTROMAGNET

The electromagnet has been operated at several points in its operating range, using the motor-generator set installed for

general use in the Physics-Mathematics building. A Fluxmeter was used to determine the flux density in the air gap. With all four of the filler rods removed, and an air-gap length of 1 inch, saturation occurred in the region between 5000 and 6000 gauss, with excitation of about 20,000 ampere turns. With all four of the filler rods in place, saturation occurred at about 10,000 gauss, with excitation of about 60,000 ampere turns. Increase of excitation to 120,000 ampere turns produced a flux density of about 12,000 gauss, indicating that operation in that range is quite stable.

The flux densities associated with saturation in the various operating conditions appeared to be in good agreement with those given by the calculated performance curves. However, the excitations required were considerably higher than those anticipated. This is probably due to the reluctance of the joints in the magnetic structure, which were not computed. The power actually required for operation at the planned maximum flux densities is small enough so that no new problems of supply, control, or heat dissipation have been introduced.

Although the power requirement for the maximum operation of the electromagnet is modest, problems of power supply are encountered. The current required for saturation, with series operation of the coils, is of the order of 20 amperes. The motor-generator set which is available for general use in the Physics-Mathematics building is capable of supplying currents of several times that amount, at appropriate voltages. However, one difficulty lies in the fact that

this power supply is in fairly constant demand, and operates at a fluctuating load. A second difficulty is that of control current. In order to vary the flux density produced by the magnet, it is necessary to vary the current supplied to the coils. Using a remote set of generators, a large resistor bank would be necessary to handle the total current. It was decided that an entirely separate power supply for the magnet would be needed. The possibilities considered were:

1. Storage batteries
2. Dry-disc rectifiers
3. A Motor-Generator set

The third of these possibilities was chosen, partly because of availability, but mainly because the output of a generator is easily controlled by varying its field excitation. In this way, variation of the rather large magnet current may be accomplished by the variation of a small generator field current. In addition, the slight ripple in the generator output, being high in frequency, is easily filtered.

The circuit connections for the operation of the magnet are shown in Fig. VI. The generator is a compound wound machine, rated to have an output of 50 volts at 40 amperes. Since the voltage is rather low, the coil sections of the magnet are used in parallel. The shunt field is separately excited, probably from the general set of storage batteries. Since the resistance of the shunt field of the generator is about 25 ohms, the excitation

requirement will be about 2 amperes at 50 volts. A rheostat capable of handling this is placed in series with the shunt winding.

Connected in series with this shunt field is the secondary winding of a low voltage, high current transformer. The resistance of this winding is about 1 ohm. This transformer is for use in modulating the flux density of the electromagnet, as is generally required for the observation of resonance phenomena. Taps on the secondary, and a rheostat in series with the primary winding of the transformer make it possible to vary the degree of modulation; switches are provided to remove the transformer completely from the circuit, in cases where modulation is not required.

In order to indicate thermal equilibrium, a small ceramic thermistor, forming one arm of a Wheatstone Bridge, is placed within one of the air cooling passages. It is not anticipated that heating will be a problem, since continuous operation at a current of 20 amperes produced no perceptible rise in the temperatures of the coils. Currents up to 40 amperes, with series operation, were maintained for approximately 10 minutes; only a slight increase in temperature was noted.

At the time of writing, the power supply has not been completed. After completion, it is planned to obtain calibration curves for the various conditions of operation, using a nuclear induction form of fluxmeter.

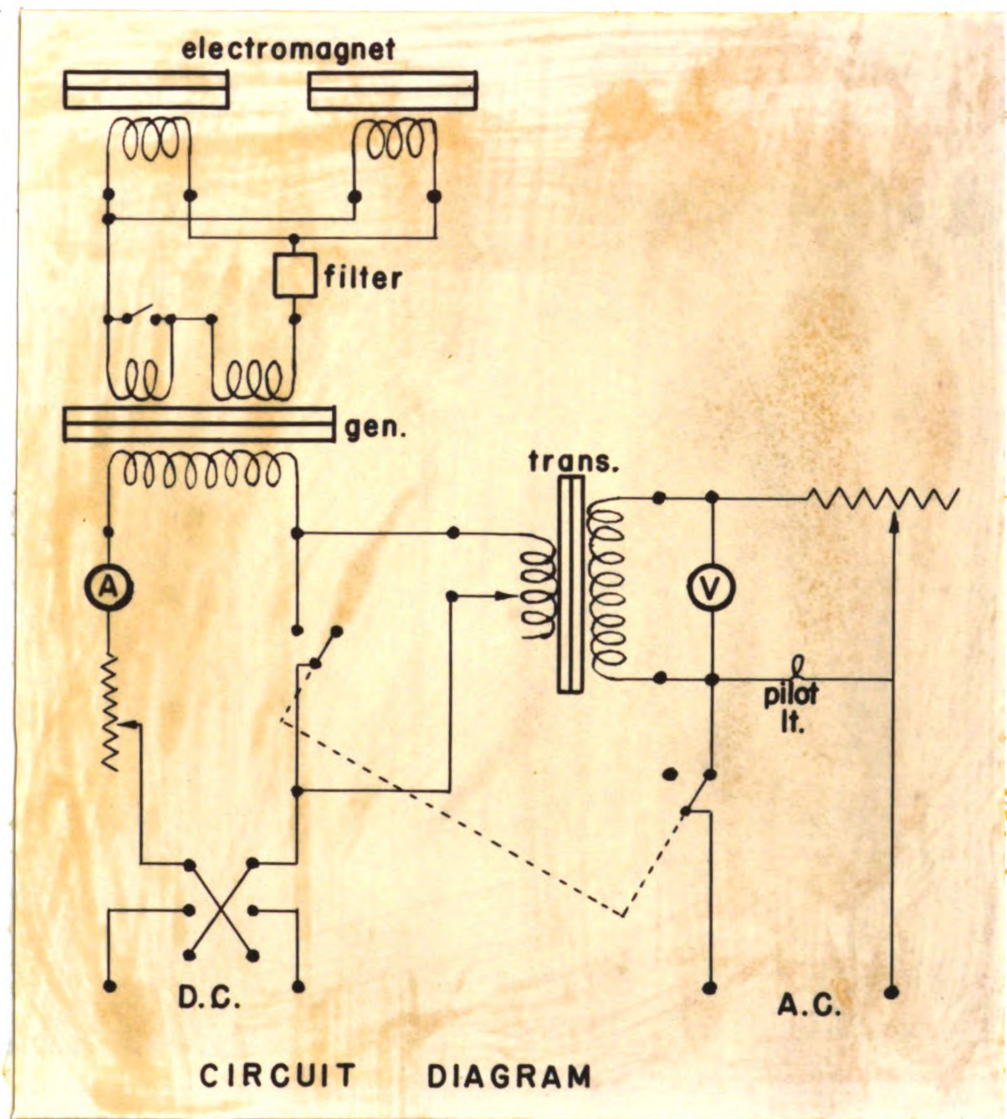
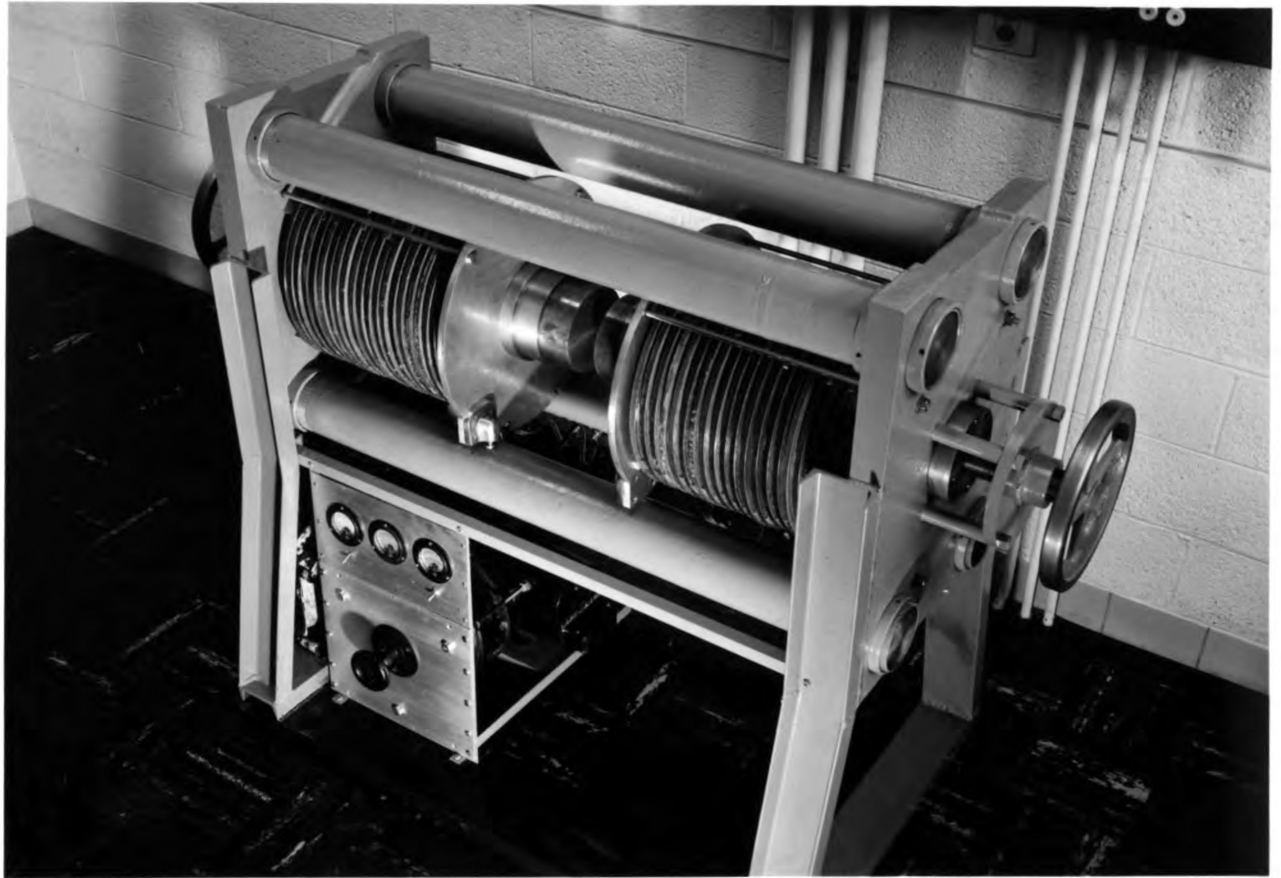


Fig. VI



THE COMPLETED ELECTROMAGNET

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