

New Developments in HIGH-MAGNETIC

By Francis Bitter



Hypothetical map, taken from 1628 Latin edition of *De Magnete*, shows deviations of marine compasses caused by adjacent land masses. If magnetic pole is at A, arrows on center circle indicate compass deviations at points where they appear.

(Courtesy New York Public Library Rare Books Division)



William Gilbert (1540-1603), author of *De Magnete*, an early synthesis of information about magnets.

(Courtesy New York Public Library)

THREE hundred and fifty years ago, long before Newton was born, at a time when the motions of freely falling bodies were first being carefully observed and analyzed, William Gilbert, the physician of Queen Elizabeth I, was collecting facts about magnets. These he published in his famous book *De Magnete*. Magnets were, at the time, thought of as curios having occult and magical properties. These Gilbert reviewed, but in addition he performed a most extraordinary feat of synthesis. He collected data on the orientation of compass needles carried around the surface of the earth by mariners and showed that the enormously varied observations could all be described by means of one basic assumption, that the earth itself was a magnet.

Let me begin, however, by emphasizing the spirit in which Gilbert approached his work. Here is a brief excerpt from his book:

PREFACE TO THE CANDID READER, STUDIOUS OF THE MAGNETICK PHILOSOPHY

Clearer proofs being afforded by trustworthy experiments and by demonstrated arguments than by the probable guesses and opinions of the ordinary Professors of Philosophy; so, therefore, that the noble substance of that great magnet, our common mother (the earth), hitherto quite unknown, may be better understood, we propose to begin with a study of common magnetic stony and iron material and with magnetic bodies and with the nearer parts of the earth which we can reach with our hands and perceive with our senses, then to proceed with demonstrable magnetic experiments, and so penetrate for the first time into the innermost parts of the earth. . . .

Many things in our reasonings and hypotheses will, perchance, at first sight seem rather hard when they are foreign to the commonly received opinions. Yet I doubt not that hereafter they will yet obtain authority from the demonstrations themselves. . . .

Gilbert's experimental accomplishments are summarized by the illustrations in Figs. 1 and 2. In Fig. 1 we see a magnetized sphere. This was, of course, mined in the magnetized condition and carefully shaped into the spherical form. Gilbert noted that the direction of magnetization coincided with the direction of the earth's field and thereby initiated an experimental technique

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FIELD RESEARCH

for studying the earth's field which is being assiduously followed today. He constructed compass needles and dip needles with which he examined the field of this "terrella" and came to the conclusion that its field was sufficiently similar to the observed field of the earth to warrant the assumption that the earth is a big magnet with its poles considerably displaced from the axis of rotation. He examined the fields surrounding magnetized bars in detail, as is illustrated in Fig. 2, and so foreshadowed the mapping of magnetic fields by drawing "lines of force".

Gilbert also occupied himself with the medicinal and biological effects of magnets. Here is a further excerpt (from Book 1, Chapter 14 of his work):

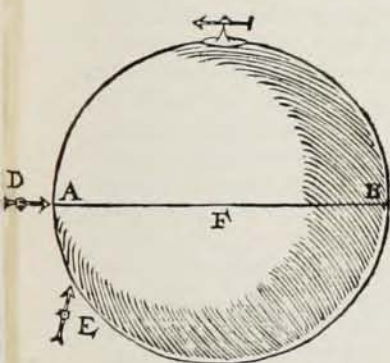


Fig. 1 (above). Gilbert's terrella, and the location of its poles. The magnetic versorium (compass needle) on top of the sphere is pointing along a meridian circle; the versorium at D points directly to the center of the sphere and hence to the pole A, in contrast to the versorium at E.

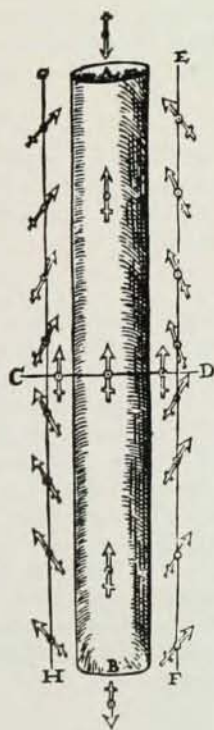


Fig. 2 (right). An illustration taken from Gilbert's *De Magnete*, showing the behavior of a compass needle near an elongated lodestone.



Francis Bitter, former associate dean of science at the Massachusetts Institute of Technology, resigned from that post last year in order to accept primary responsibility for the design and construction of the MIT Magnet Laboratory which is to be established in Cambridge, Mass. A specialist in subjects involving high magnetic fields, he has been named to serve as chairman of the new laboratory's Policy Committee.

CONCERNING OTHER POWERS OF LODESTONE AND ITS MEDICINAL PROPERTIES

Dioscorides prescribes lodestone to be given with sweetened water three scruples weight to expel gross humors. Others relate that lodestone perturbs the mind and makes folks melancholic and mostly kills. Gartias ob Horto thinks it not deleterious or injurious to health. The natives of East India tell us, he says, the lodestone taken in small doses preserves youth, on which the aged king Zeilam is said to have ordered the pans on which his victuals were cooked to be made of lodestone. . . .

Plutarch and Claudius Ptolemy and all the copyists since their time think that a lodestone smeared with garlic does not allure iron. Hence, some suspect that garlic is of avail against any deleterious power of the magnet. Thus, in philosophy, many faults and idle conjectures arise from fables and fablehoods. Some physicians have opined that the lodestone has power to extract iron of an arrow from the human body, but it is when whole that the lodestone draws, not when pulverized. Thus, vainly and preposterously do the Sciolists look for remedies while ignorant of the true causes of things. The application of a lodestone for all sorts of headaches no more cures them (as some make out) than would an iron helmet or a steel cap. To give it in a draft to dropsical persons is an error of the ancients or an impudent tale of the copyists, though one kind of ore may be found which like many more minerals purges the stomach, but this is due to some defect of that ore and not to any magnetic property. . . .

This, then, is the beginning of magnetic research and the development of magnets. It involved primarily three investigations:

- (a) The magnetic properties of matter.
- (b) The earth's magnetism.
- (c) Magnetic influences on living matter.

The next great step in the development of magnets came two hundred or more years later when Oersted discovered the connection between magnetic fields and electric currents. Within a very short time Ampère had thought of intensifying magnetic effects by passing currents, not along straight wires, but along wires bent into the form of a spiral or "solenoid" as he first called a cylindrical coil. The coil was a "canal" for conducting magnetic flux, and the word "solenoid" is taken from

the Greek name for a canal. Very shortly thereafter, W. Sturgeon¹ built and demonstrated to the Royal Society the first iron-core electromagnet by wrapping a conductor around a horseshoe-shaped bar of iron and passing a current through the winding. A sketch of this first instrument is shown in Fig. 3. Then, as magnets were gradually improved, the magnetic properties of matter were explored and classified. The magnet used by Faraday² in his researches on magnetism is shown in Fig. 4.

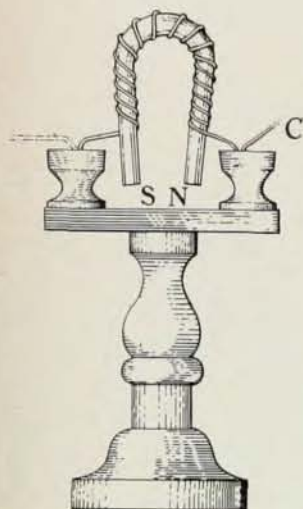


Fig. 3 (left). One of the first electromagnets, demonstrated to the Royal Society by Sturgeon in 1825.

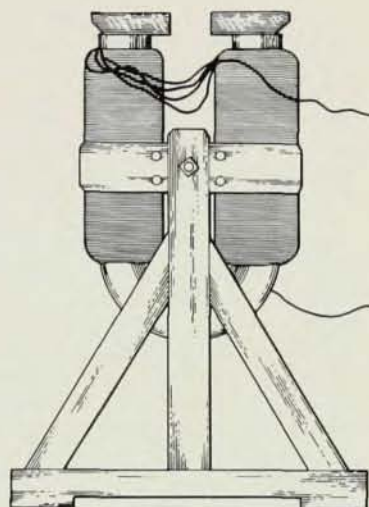


Fig 4 (right). Sketch of magnet used by Michael Faraday.

This is basically the iron-core magnet in use today except for relatively minor changes. For experiments in which very homogeneous and constant fields are required, as, for instance, for nuclear-magnetic-resonance experiments in which the resonances are exceedingly sharp, a very rigid frame with very flat and carefully adjusted poles is required, and a well-regulated power supply must be used. If strong fields over 20 000 gauss are desired, it has been found desirable to taper not only the poles, but the core of the magnet itself to provide a greater cross section for the leakage flux which enters the iron yoke back from the pole faces. Such a core is shown in Fig. 5. The coils of such magnets customarily dissipate a good many kilowatts, and must be water cooled. A detailed comparison of iron-core electromagnets is notoriously difficult, particularly as extensive data are available in only a very few instances. We shall here attempt to point out what, in general, can be expected of an electromagnet, and omit discussion of fine points or the relative merits of details of design. In a later section we shall take up a comparison of iron-core magnets with solenoids.

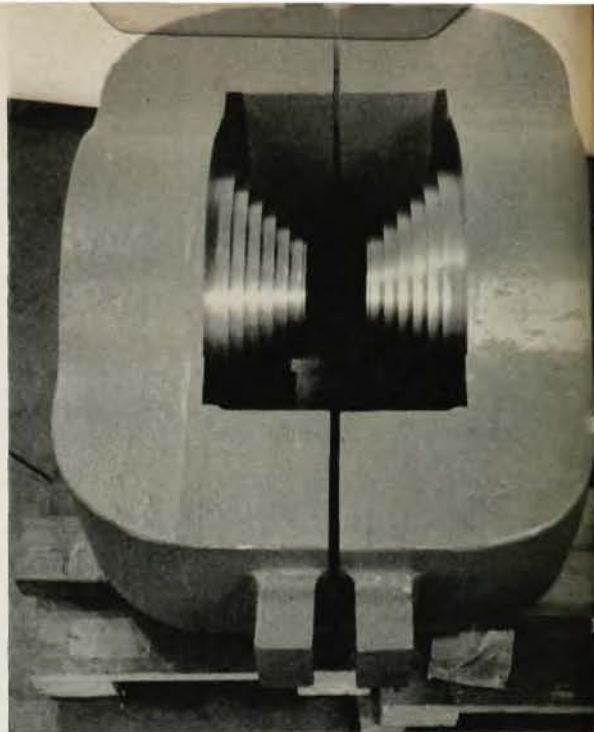


Fig. 5. Core and yoke of a modern electromagnet. (Courtesy of the Harvey-Wells Corp. and the Naval Ordnance Laboratory)

IN selecting a magnet for use in a particular laboratory, one of the most important considerations is the power available. A review of data on a variety of magnets indicates that, in the range of 20 to 50 kilogauss, they fall into two classes—the commonly used laboratory instruments weighing around two or three tons, and the very large magnets weighing 30 tons or more, such as the Uppsala magnet³ and the Paris magnet.⁴ Their performance is usually specified in terms of the magnetizing current, or the ampere turns in the windings for a given level of performance, but this is not of as much interest to the user as the power required. It is interesting to note that the ampere turns can be expressed in terms of the power used as follows:

$$Ni = G_0 \sqrt{W_r / \rho},$$

where G_0 is a geometry factor, r is a scale factor such as the mean radius of the coils, and ρ is the resistivity of the conductor. It turns out that for most magnets we may write

$$Ni = k \sqrt{W},$$

where k is of the order of 1000 if W is in watts. For the smaller magnets k is actually around 900 to 1200, and ranges up to 1500 for the very large Paris magnet.

Performance of iron-core electromagnets in terms of power consumption is summarized in the following tables. Gaps of 2 inches and 1 inch have been chosen as being of the greatest interest. The higher fields in smaller gaps are actually seldom used. Smaller magnets, in the 2–3-ton range, will in general produce fields comparable to those quoted in Table 1 for the iron-core magnet manufactured by Arthur D. Little, Inc.⁵ Much larger magnets may be expected to produce fields comparable to those quoted in Table 2 for the Uppsala magnet.

Table 1.
Performance of 2-3-ton magnets

Pole gap	2"		1"	
Pole diameter	5 $\frac{3}{4}$ "	1"	5 $\frac{3}{4}$ "	1"
Power in kilowatts	Field in Kilogauss			
10	18.5	19.0	25.5	29.5
20	22.5	22.8	28.0	31.8
50	24.9	26.0	30.2	33.0
100	26.2	27.0	31.5	35.0

Table 2.
Performance of magnets weighing 30 tons or more

Pole gap	2"		1"	
Pole diameter	4 $\frac{1}{2}$ "	2 $\frac{1}{4}$ "	4 $\frac{1}{2}$ "	2 $\frac{1}{4}$ "
Power in kilowatts	Field in Kilogauss			
20	30	31	34.5	39
50	33.5	35	38	43
100	37	39	40.5	45
150	38	40	42	46.5
200	39	41	43	48
300	41	42.5	44	49

In order to produce stronger fields it is necessary to go to air-core solenoids carrying extremely large currents. For coils operated at room temperature this requires a tremendous amount of power as compared to iron-core magnets. In the early 1930's Kapitza⁶ overcame this difficulty by using pulsed currents. These techniques have been in use since that time and are currently producing useful fields of the order of many hundreds of kilogauss over useful volumes and remaining more or less constant for times of the order of milliseconds.⁷

Another approach to the problem is to operate the coils at low temperature where the electrical resistance is greatly reduced, thus reducing the required power consumption.⁸ A most promising development in this connection is the discovery of superconducting materials that retain their superconducting properties even in high fields and in the presence of high current densities.⁹ While these materials are so new that their fabrication into high field solenoids has not as yet been accomplished, it is clear that superconducting solenoids will add greatly to our capacity for producing magnetic fields, particularly when strong magnetic fields in large volumes are needed for long periods of time.

Solenoids to be operated at room temperature require

power in the megawatt range in order to produce magnetic fields appreciably larger than those that can be made with large iron-core electromagnets. A useful approximate relationship is the following:

$$B \text{ (kgauss)} = 100 \left(\frac{\text{Mw}}{\text{radius of experimental volume in cm}} \right)^{\frac{1}{2}}$$

A magnet laboratory having available 1.7 megawatts of dc power (10 000 amperes at any voltage up to 170 volts) was set up at MIT about twenty-five years ago and (with the exception of the war years) has been operating ever since.¹⁰ It turns out that at this level the problems of strength and cooling are not severe and have been met in a variety of designs. The plate construction used at the MIT laboratory has proved to be very satisfactory. It is illustrated in Fig. 6. There are at present some dozen magnet laboratories in various parts of the world having available a few megawatts of dc power and producing fields of the order of 50 to 100 kilogauss in solenoids having inner diameters ranging from 1 to 4 inches.

The contributions of magnetic research, apart from engineering applications, have been primarily in making possible our understanding of the structure of matter. During the first quarter of this century when the quantum theory was being developed, the work on the Zeeman effect of atomic spectra indicated how these new ideas could be applied, and so led to the unraveling of the structure of atomic energy levels. In addition, the statistical interpretation of magnetic susceptibilities led, during these years, to the establishing of new basic ideas about the structure of solids. More recently the development of radio-frequency and microwave techniques has made possible a whole new set of magnetic observations involving resonances between oscillating

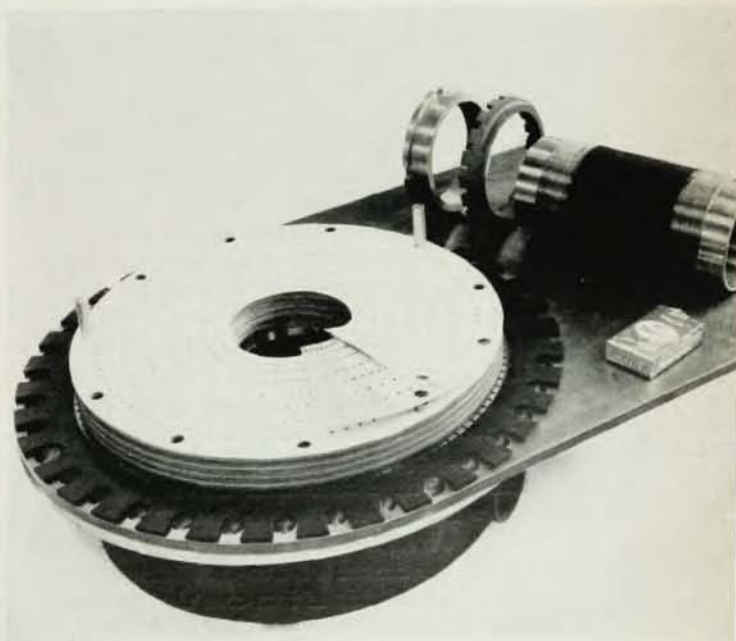


Fig. 6. The plate construction of high-performance solenoids in use at the MIT laboratory.

electromagnetic fields and magnetic dipoles and free charges in solids and in conducting gases.

LET us now look tentatively into the future. During the last several years the collaboration of a group at the MIT Lincoln Laboratory with the existing magnet laboratory has been extraordinarily stimulating. As a result of this collaboration funds were applied for and have been made available by the Air Force through its Office of Scientific Research to establish a new National Magnet Laboratory at MIT. Plans for this laboratory are now taking shape and will be reported on in detail elsewhere. However, since this is a turning point in the development of magnets for research, some preliminary comments regarding the planned facilities should be made at this time.

The MIT National Magnet Laboratory is under the direction of Benjamin Lax who also heads the Lincoln Laboratory group mentioned above. The assistant director is Donald Stevenson. Henry Kolm and Bruce Montgomery have played a major part in the development of plans. The laboratory is to house motor generators capable of producing up to 8 megawatts of dc power continuously, 12 megawatts for 15 minutes and controlled pulses up to 32 megawatts lasting a few seconds. The laboratory will provide initially for connections to about a dozen magnets, and room for expansion to a larger number is available. Four magnets can be operated simultaneously and independently up to the 2-megawatt level. All the supporting facilities for a modern laboratory are being made available. The laboratory is to be located on Albany St. near the MIT campus, immediately next to the existing nuclear reactor. It is hoped that it will be in operation early in 1963. Its facilities are to be made available to our entire scientific community.

The imminence of this new laboratory has stimulated a variety of thoughts about the development of magnets for research. To begin with, at the existing 2-megawatt level, there is first of all the matter of the use of iron. It is clear that at low power levels of the order of 1 to 10 kilowatts it is best to use the available power to produce magnetomotive force or ampere turns to magnetize iron. Under these circumstances the iron plays a predominant role in producing the magnetic field. At higher power levels, certainly in the megawatt range, the power had better be used to produce the magnetic field itself at the center of a solenoid, and iron, if it is to be used at all, must play a secondary part wrapped around the outside of the coil.

The magnitude of the contribution of the iron around an iron-clad solenoid has not been investigated in detail, but such experiments as exist and such theoretical calculations as have been made indicate that the contribution will be slight, of the order of 10 000 to 20 000 gauss. The question arises as to the power level at which the performance of iron-clad solenoids may be expected to exceed that of iron-core electromagnets. To illustrate the situation, data on the performance of both

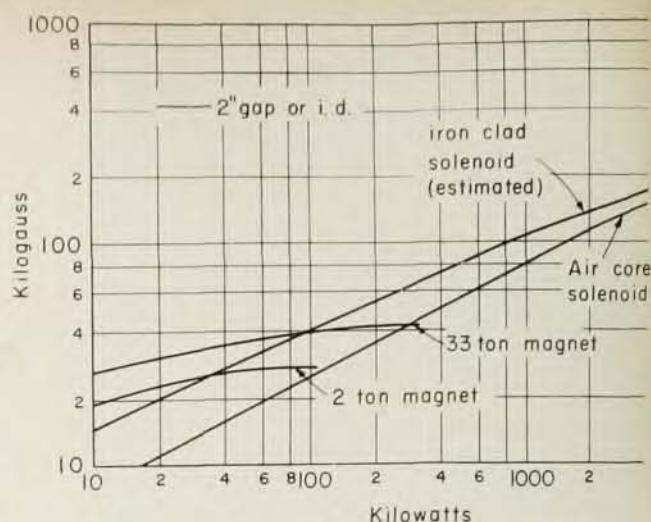


Fig. 7. Comparison of iron-core electromagnets with iron-clad solenoids.

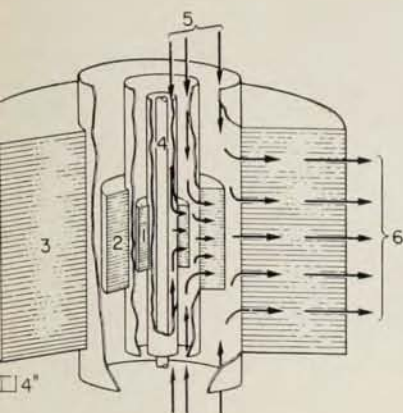
types of magnets is combined in Fig. 7. For purposes of comparison a gap between the poles of 2 inches in an electromagnet is compared with the performance of a coil having a 2-inch inner diameter. This seems to be a practically useful dimension, particularly when Dewars for low-temperature work are brought into consideration. From this figure it appears the dividing line comes roughly at 100 kilowatts. Below 100 kilowatts the iron-core magnets outperform the solenoids, whereas at high power the solenoids outperform the magnets. It is interesting to note that a laboratory having available a few hundred kilowatts of power may do well to consider using a variety of small iron-clad coils rather than a single large electromagnet.

Magnets are currently being designed specifically for the new laboratory. Perhaps the most important of these is a magnet to produce up to 250 000 gauss. Two relatively minor modifications of present construction have led to a promising initial design. The first of these is to construct the magnet out of several coaxial solenoids and to limit the current density in the inner solenoids to values that are acceptable from the point of view of strength. This helps to achieve the desired purpose, but at the cost of more power than would otherwise be required. The second is to use radial slots within the plates of the structure and to use these specifically to provide cooling surface. The axial holes of the current designs, shown in Fig. 6, act also as canals to carry the cooling water from one side of the magnet to the other. A design by Bruce Montgomery that would accommodate the greater power and water flow, and that should provide almost 250 kilogauss with the available 12 megawatts, is shown in Fig. 8. This design, while more complex than anything attempted so far, does not involve any drastically new or untested principles of construction. The cooling can be carried out without requiring greater heat-transfer coefficients than in the present magnets, and the general stress level will involve safety factors comparable to those in magnets used in the present magnet laboratory.

For some experiments, notably nuclear-magnetic-reso-

Fig. 8. Preliminary design by Bruce Montgomery of 250-kgauss magnet made up of three coaxial solenoids labeled 1, 2, and 3. Central tube, about 1" i.d., for experimentation is marked 4. Water enters axially as indicated by 5, and flows out radially, 6, at rate of 3000 gal/min. Performance of individual solenoids would be as follows:

- | | |
|---------------------------------------|-----------------------------|
| 1. i.d. 1.5"; o.d. 3"; length 3.0"; | 4 lb; 45 kgauss; 400 kw. |
| 2. i.d. 3.5"; o.d. 7.0"; length 7.0"; | 32 lb; 65 kgauss; 2 Mw. |
| 3. i.d. 7.5"; o.d. 30"; length 15"; | 2500 lb; 140 kgauss; 12 Mw. |



nance experiments, extremely homogeneous and constant fields are required. Up to the present, investigations have been confined to the range of 10 to 20 kilo-gauss because only iron-core magnets with cylindrical cores have so far produced fields of sufficient homogeneity. Two approaches to increase this range present themselves. The first is the development of the Helmholtz coil concept of coils having flat fields in the neighborhood of a central point. The second is the development of Maxwell's concept of an ellipsoidal current sheet having equal currents in equal axial increments of length and producing a uniform field within the ellipsoid.

In order to produce high fields a lot of power must be used, and the effective use of power requires a lot of copper. The obvious modification of the Helmholtz coil concept is to find the current distribution within a massive coil which maximizes the field per unit power at its center, subject to additional conditions about the field uniformity, for example that

$$\left(\frac{\partial^2 H_z}{\partial z^2} \right)_{z=0} = 0.$$

This leads, as one might expect, to a current density distribution having two maxima, one on either side of the central plane. The numerical solution has been

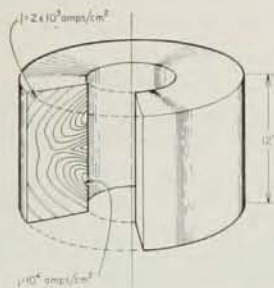


Fig. 9. Sketch of a magnet to give a field of 51 kgauss using 1.7 Mw uniform to one part in 10 000 over the central two centimeters. Contour lines of equal current density ranging from 2000 to 10 000 amp/cm² are shown.

worked out for a coil having an inner diameter of six inches and a length of one foot. It is illustrated in Fig. 9. This leads to a central field given by¹¹

$$H = 51\,000(1 - 9 \times 10^{-5} z^4 \dots) \text{ gauss,}$$

where z is the axial distance from the center in centimeters.

While ellipsoidal magnets have been constructed, the use of plates seems to offer new possibilities for a practical approach to the ideal condition. Such a stack having an ellipsoidal inner and outer surface as shown in Fig. 10 would have a perfectly uniform internal field except for the very slight wrinkles produced by the insulation between turns. However, in order to provide access, holes must be left at the ends, and the optimum practical magnet will no doubt make use of a constant current distribution in ellipsoidal envelopes in the central sections and cylindrical ends with an axially varying current density. Indications are that an appreciably more homogeneous field can be made in this way than with a design based on special current distributions as in Fig. 9. The uniformity to be achieved will depend on the degree to which the practical considerations, especially the cooling arrangements, interfere with the approach to the theoretical ideal. The experimental cavities within both magnets shown in Figs. 9 and 10 are large for two reasons. First, to minimize effects due to inhomogeneities in the field near the windings, and second, to leave plenty of room for low-temperature shields, possibly superconducting shields, to help keep the field of the solenoid constant and to allow for small correction coils to provide a final adjustment.

IN conclusion, we may well look back to William Gilbert's original program and ask how completely we have carried it out. Part (a), dealing with the proper-

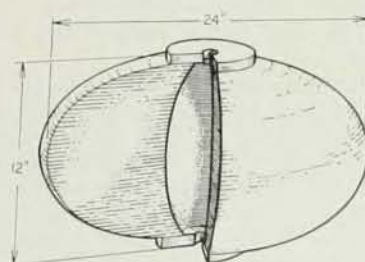


Fig. 10. An ellipsoidal magnet, consisting of a stack of plates connected as in Fig. 6, to produce a uniform internal field. A magnet having the dimensions shown could produce a field of the order of 50 kgauss with 1.7 Mw.

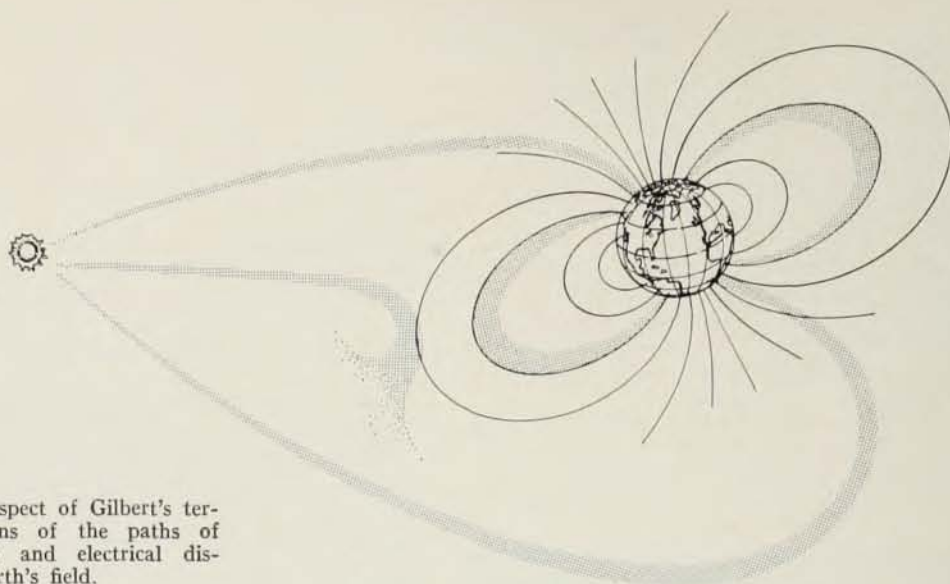


Fig. 11. A new aspect of Gilbert's terrella—investigations of the paths of charged particles and electrical discharges in the earth's field.

ties of matter, we have certainly carried far beyond Gilbert's anticipations. We have had great success in elucidating the properties of matter. Regarding the second part, (b), involving the terrella, we have made some progress. But, both as regards the detail of the inner magnetic structure of the earth and of stars and planets, and as regards the fields in space around these magnetized bodies, there is a great deal more to be done. The paths of charged particles and the forms of electrical discharges in the fields of astronomical bodies, still involve many unanswered questions.¹² Fig. 11 illustrates this aspect of Gilbert's terrella, which will doubtless be further exploited during the coming decades.

Lastly, there is the third aspect of magnetism which Gilbert considered; namely, the biological effects of magnetic fields. Here, I quote from a recent review by Don Stevenson of papers on this subject received at the National Magnet Laboratory.

Magnetic fields are now known to produce effects in biological systems from man down to the lowest forms of life. D'Arsonval, in 1896, was the first to report that flashes of light may be seen when the head is placed in a magnetic field. This phenomenon called a magnetic phosphene, has been studied more recently by several investigators.

A striking series of experiments on mice has been reported by Barnothy. He found that in certain cases the effects of gamma irradiation on the blood could be counteracted by exposure to a magnetic field of a few thousand gauss. Magnetic field treatment had several salutary effects on the growth and spread of transplanted cancers in mice. In addition, certain magnetic field treatments of healthy mice increased longevity by a significant amount. Under other magnetic field conditions he noted detrimental effects such as loss of fertility, abnormal changes in liver and spleens, retarded growth and early mortality.

Brown and co-workers have reported detailed studies of the responsiveness of certain snails to the earth's field and to artificial fields of the same order of magnitude.

Other workers have reported on disturbances in embryonic development, on paramagnetism of DNA and RNA, and on the magnetic properties of muscle fibers. Studies have been made of magnetic effects on the growth of bacteria, yeast, the roots of plants, and tissue cultures.

Interest and activity in the field is increasing. This activity is indicated by two recently compiled bibliographies: one containing about 40 items and the other 60. An informal group has been set up to provide better communication of results and ideas between interested researchers. This group, under Dr. R. O. Becker of the Veteran's Administration Hospital, Syracuse, N. Y., is publishing a newsletter and compiling a bibliography.

The work which Gilbert started is, in many respects, still in its initial stages. Magnets different from any that have so far been available can now be constructed and operated. Scientists using these magnets may be expected to open many doors for us to pass through in our search for knowledge.

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