ELECTRO-MAGNETS.

IN this article it will be shown what a great advantage results from constructing electro-magnets on scientific principles, instead of making them according to everyday notions, and to give an idea which is the best form to adopt for producing very strong magnetic fields.

To understand the matter we must first consider the magnetic circuit, which is very analogous with the simple electric circuit. Just as when we have an electric current flowing in a copper rod, say, we know that the current is flowing round a complete circuit of which the rod forms only a part, so in the case of an iron rod magnetised by a current flowing round it, we consider that magnetism flows round a complete circuit of which the iron rod forms only a part. Fig. 1 is an ordinary bar electro-magnet; and in Fig. 2 B represents a cell and C A a copper rod the ends of which are joined by a great many thin wires of high resistance.

Now the flow of current in Fig. 2 is exactly analogous with the flow of magnetism in Fig. 1. The cell replaces the coil of

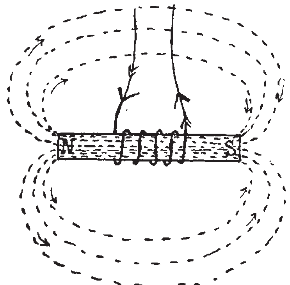

FIG. 1.

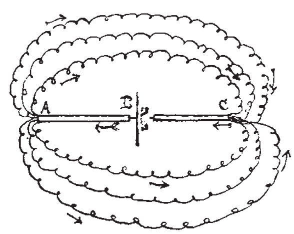

FIG. 2.

wire on the magnet, for whereas the cell sends the current in Fig. 2, the current flowing through the coil sends the magnetism in Fig. 1 through the iron rod, corresponding with the copper rod, and to complete the magnetic circuit the magnetism passes through the air in paths shown by the dotted lines, Fig. 1, back to the south pole of the magnet; so that the magnetic circuit in this case is formed partly of iron and partly of air.

The current flowing in the coils of wire on the magnet produces what is called a "magnetomotive force," which is proportional to the current and to the number of turns of wire; and a certain fraction of this quantity is used to send the magnetism through the iron rod and the remainder to send it through the air, or, in other words, every little piece of the magnetic circuit requires a certain magnetomotive force to drive the magnetism through it, and the sum of all these, taken all round the circuit, is the whole magnetomotive force due to the current in the coils; just as a certain part of the electromotive force of the cell is used to send the current through the copper rod and the remainder to send it through the thin wires forming the rest of the circuit. In fact, even the law governing the production of magnetism in a magnetic circuit is very similar to Ohm's law for the flow of current in an electric circuit, namely, that the amount of magnetism produced is equal to the magnetomotive force producing the magnetism, divided by the magnetic resistance, or "reluctance," as it is called, of the entire magnetic circuit. Hence, if the amount of magnetism is to be as large as possible it is just as important that the reluctance of the entire circuit should be small as it is that the current and number of turns of wire be large.

Now the reluctance of any little bit of a magnetic circuit, say from S to N, Fig. 1, for example, is proportional to the length of the piece, inversely proportional to its cross section, and also inversely proportional to the magnetic conductivity, called permeability, of the material. Therefore, to make the reluctance of our circuit small, we have to make: (1) its length small, (2) its cross section large, (3) and make it of a material whose permeability is as large as possible.

But the important thing is that the reluctance of the whole of the magnetic circuit must be small, not only of any particular part of it. For example, in Fig. 1, making the diameter of the iron bar large simply makes the reluctance of the circuit from S to N small, while the reluctance of the rest of the circuit, from N through the air to S is still very large, because the permeability of air is very small compared with that of iron. But if the bar is bent round into a ring, Fig. 3, then the reluctance of the whole circuit is reduced, and consequently a larger amount of magnetism will be produced in the bar for the same current flowing round it, and the density of the flow—that is, the strength of the magnetic field in the air space—will be very much increased.

There seems to be a popular idea that if a magnet is to produce as strong a field as possible it must be wound with an enormous number of turns of wire and a very large current sent round the coils, and that nothing else is of the least consequence. The following is a description of a large electro-magnet, made only about three years ago, which well illustrates this. It formed part of an electrical instrument intended to be used in connection with submarine telegraphy, the sole function of the magnet being to produce a very strong magnetic field. This result was certainly not obtained because it was not properly designed.

The magnet consists of two iron cores, 6 centimetres in diameter, each wound with about 1500 turns of wire, making the outside diameter more than 16 centimetres. To illustrate the

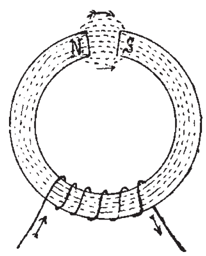

FIG. 3.

uselessness of this great amount of wire compared with the cross section of the iron, it has been found by experiment that if only one-third of the ordinary current is sent round the coils the strength of the magnetic field is thereby reduced only 15 per cent. If therefore the magnet had been wound with one-third the number of turns the cost of materials would have been about halved, and the power used to excite it only one-third, and even a less reduction than 15 per cent. in the strength of the field would have resulted.

The cross section of the piece of iron joining the two cores, *i.e.* "the yoke," is less than half that of the cores, and consequently the density of the flow of magnetism in the yoke is very large, and this means that the yoke will offer a great resistance to the magnetism for two reasons: (1) because the area is small, (2) Because the density being so large the permeability will be very small, for the magnetic conductivity gets rapidly less the greater the density; in fact, in this case the reluctance is so large that when the magnet is excited with its ordinary working current it produces a field of only 7900 C.G.S. units, and it can be calculated that the magnetomotive force used to send the magnetism through the yoke is then more than four times that required for the air gap, whereas in a properly designed magnet nearly all the magnetomotive force is used to send the magnetism through air gap and pole pieces. Doing what has been done here is exactly analogous with trying to send the strongest current that you can through an electrical apparatus by connecting to it the most powerful battery obtainable with two very long thin high-resistance wires. Analogy, therefore, shows us that the cross section of the yoke should have been made at least equal to that of the cores.

In order to see what sort of saving might have been effected, I have designed a magnet (Fig. 4) to produce the same effect as this one.

It consists of a cast steel ring, rectangular in section, the wire being wound on ten bobbins made of thin wrought iron, and not straight on the ring, for convenience in winding.

The design is made by starting with the assumption that a magnetic field exists of the strength desired in an air gap of the dimensions of the last magnet. Then the flow of magnetism at the section *a a*, Fig. 4, is calculated, ditto for section *b b*, where it is greater than at *a a*, by the amount which leaks out of the iron between these two sections. Similarly, the flow is obtained at all the sections, *c c*, *d d*, &c., round the circuit, the area of the iron at all these sections being made such that the density of flow has a value for which the magnetic conductivity of the cast steel is high. When the density of the flow is found, having a previous knowledge of the magnetic quality of the steel we can get the permeability for each section. Then the product of current, into number of turns of wire, necessary to force the magetism through all the different sections into which the magnetic circuit has been divided can be found, and, adding all these together, we can obtain the current that must be sent round the magnet a given number of times to produce the desired effect. The following table gives the flow, density of flow, &c., at the different sections (Fig. 4), the "ampere turns," *i.e.* current, into number of turns, given in column 5, being for the particular section, together with the similar one, on the other side of the ring.

For Magnet, Fig. 4.

Section at.	Flow of mag. C.G.S. units.	Area of section, sq. cm.	Density of flow, C.G.S. units.	Current × No. of turns required for section. Ampere turns.
			For air gap	6360
aa	32,000	4·0	8,000	
				very small
bb	64,000	7·2	8,900	
				120
cc	126,000	7·2	17,500	
				70
dd	147,000	12·9	11,400	
				130
ee	200,000	12·9	15,500	
				320
ff	225,000	12·9	17,500	
				140
gg	249,000	18·0	13,800	
				160
hh	270,000	18·0	15,000	
				170
ii	270,000	18·0	15,000	
			TOTAL ...	7470

Column 2 shows what a large amount of magnetism leaks out from the one side of the ring and passes over to the other, not passing through the air gap at all. Column 3 shows how the

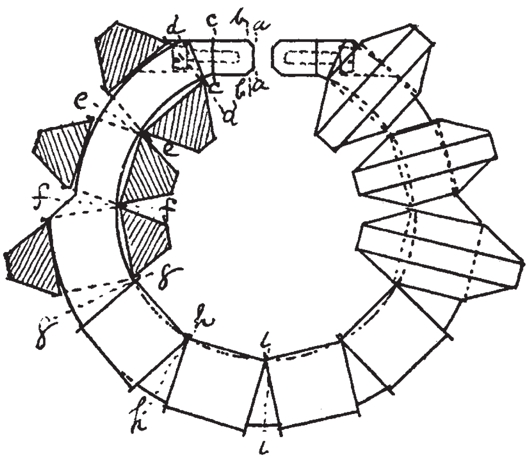

FIG. 4.—(Scale, quarter full size).

area of the iron has to be increased, owing to this leakage, for sections further away from the air gap. The current for this magnet is to be 5·4 amperes, and this flowing 1,500 times round should allow an ample margin to produce the field required.

It is interesting to compare the leading particulars of these two magnets.

Table comparing Two Magnets.

	Original magnet.	New design, Fig. 4.
Strength of field, C.G.S. units	7900	8000
Length of air gap, cm.	1	1
Area of air gap, sq. cm.	4	4
Exciting current, amperes	15	5·4
Turns of wire	3000	1500
Product of current, into number of turns, ampere turns	45,000	8100
Length of wire, yards	1140, No. 11	450, No 16.
Weight of wire, lbs.	139	17
Weight of iron in magnet, lbs.	41	15½
Total weight, iron and copper, lbs. ...	180	33
Cost of iron and copper— Iron @ 2·2*d.* per lb.; copper @ 1*s.* per lb.	£11 9 0	£2 11 0
Cost of working magnet continuously, per year, with current at 6*d.* per Board of Trade unit	£130 0 0	£25 0 0

Since the magnet was intended to work in connection with a submarine cable, it is quite safe to say it would require current throughout the year, and then, as the above table shows, there would be a saving of more than 100*l.* a year by using the magnet, Fig. 4, if the current could be got at 6*d.* per Board of Trade unit—it would, however, very likely cost much more under these conditions—to say nothing of the saving in first cost.

Another example of the importance of having sufficient iron in the magnetic circuit is afforded by the alterations that were made to an electro-magnet belonging to the Central Technical College. The cross section of its yoke was less than half that of the cores, due to the fact that the magnet was made before the theory of the magnetic circuit was understood. Recently a new yoke of proper cross section was made for the magnet, and it was found by experiment before and after the alteration that under precisely the same conditions the strength of the field had been just doubled simply by adding a few pounds of iron in the right place.

But at the same time it should be remembered that the magnetic properties of different specimens of iron vary enormously, and it is important that any iron which is to be used for a magnet should first be tested. Fig. 5 shows a very convenient apparatus for doing this. It consists of a massive iron frame into which you can slide a bar of the sample to be tested, the bar passing through a thin brass tube on which a known number of turns of wire are evenly wound. Also a few turns of fine wire are wound on the middle of the tube, shown at T, Fig. 5,

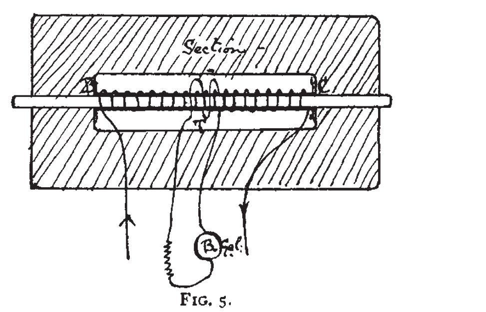

FIG. 5.

and connected to a ballistic galvanometer. A current is sent through the large coil, causing magnetism to flow through the bar, returning by the massive frame the cross section of which is so large that practically the whole of the magnetomotive force due to the current is used to send the magnetism through the bar; therefore, dividing the total ampere turns by the length of the bar we obtain the ampere turns necessary to send the magnetism through one centimetre of that specimen of iron. Several different strengths of current are sent through the magnetising coil, and in each case the flow of magnetism produced is measured by suddenly switching off the current, consequently causing the magnetism passing through the secondary circuit connected to the ballistic galvanometer to rapidly die out, and in doing so a quantity of electricity, proportional to the amount of magnetism, is sent through the galvanometer, thus giving a measure of the amount of magnetism. Fig. 6 shows the difference between three specimens of iron—I. cast iron, II. wrought iron, III. best cast steel for magnets.

The curves show how rapidly the magnetic resistance of iron rises as the density of magnetisation is increased, and therefore the importance of not allowing the density to exceed about

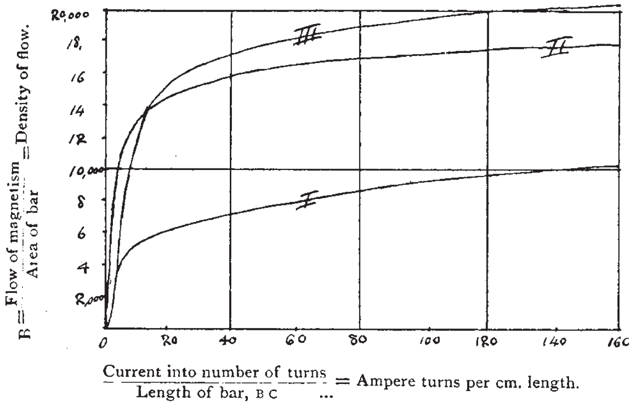

FIG. 6.

16,000 C.G.S. units. These curves are very useful in designing, because from them the ampere turns necessary to produce a certain density of magnetisation in a particular kind of iron can at once be found. It is most important to use the best steel, such as curve III. represents, for making magnets that are to produce very strong fields. With regard to what is meant by a very strong field, a field up to 20,000 C.G.S. units is moderately easily reached. But at about this limit saturation of the iron sets in and it becomes much more

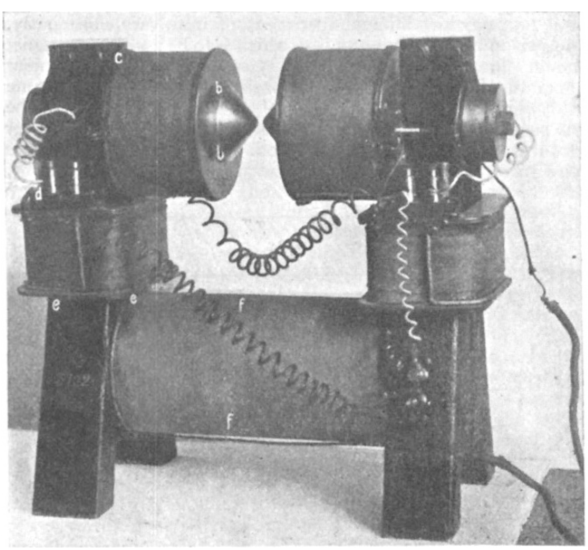

FIG. 7.

difficult to go higher. A field of 30,000 units is a very strong field; the cost of the magnet rises very rapidly if a stronger field than this is required. A field of 40,000 is about the strongest field obtainable. To go above this would require such a large additional expenditure in materials and power, compared with the small increase in the field, that it is not practical.

Fig. 7 shows a photograph of a good type of magnet to produce a very intense field. In this magnet the density of flow in the pole pieces is very great, so great, in fact, that the permeability of the pole pieces is not much greater than that of air; consequently a very large leakage of magnetism occurs, which makes the calculations very laborious. An idea of the amount of leakage that occurs is got from the fact that the flow of magnetism in the lower cylinder, Fig. 7, is fifty times greater than the flow across the air gap under working conditions, whereas in the case of the magnets of dynamo machines the flow in the yoke would not generally be more than 1·4 times the flow in the air gap, because they produce only relatively weak fields of about 6000 units. Owing to this great leakage the calculations cannot be made so accurately for this magnet, Fig. 7, as for dynamo magnets. In making the final calculations for this magnet it was necessary to divide the magnetic circuit in the pole pieces up into a great many sections, only two millimetres apart, finding the ampere turns necessary for each section, because the density changes so rapidly in the pole pieces, and also because the ampere turns required for the pole pieces are much greater than those required for the air gap, which cannot be helped, because the magnet was designed to produce a very intense field in a small air gap.

The following table gives the results of the final calculations:—

For Magnet, Fig. 7.

	Distance of section from pole tip in cm.	Section at.	Total flow of magnetism at section.	Area of section, sq. cm.	Density of flow of mag., C.G.S. units.	Product of current, into number of turns required for each section.
					For air gap	8900
In pole piece	0	—	27,500	0·785	35,000	4,340
	0·2	—	53,000	1·54	34,400	3,500
	0·4	—	81,500	2·7	30,100	4,140
	0·8	—	139,500	5·7	24,500	763
	1·2	—	208,500	10·5	20,000	175
	2·2	—	375,500	27·3	13,800	24
	3·2	*bb*	535,000	52·75	10,150	660
		cc	925,000	52·75	17,500	183
		dd	1,054,000	80·0	13,100	540
		ee	1,206,000	80·0	15,100	894
		ff	1,374,000	85·0	16,100	
					TOTAL...	24,119

This magnet was originally intended to produce a field of 35,000 C.G.S. units, in an air-gap $\frac{1}{8}$-inch long, for which the above calculations were made; but they show that the magnet will not be able to produce so strong a field as this, because it is wound so that it may be connected straight on to 200-volt mains, with all coils in series, or 100-volt mains with two sets of coils in parallel, and then there are 22,400 ampere turns available, whereas at least 24,120 are required.

Recently this magnet was made by the Electric Construction Company for the Solar Physics Laboratory, South Kensington, and the strength of the field produced under the conditions assumed in the above calculation was found to be 32,000 C.G.S. units, showing that the theoretical calculations agree fairly well with practice, considering the very high value of the field.

When the length of the air-gap was reduced to 2 millimetres, and the exciting current doubled, the maximum strength of field attained, for a short time, was nearly 38,000 C.G.S. units, which corresponds to a pull, between the pole pieces, of no less than 830 pounds per square inch! T. L. JAMES.