A New Method for Obtaining a Uniform Magnetic Field

JOHN WESLEY CLARK
University of Illinois, Urbana, Illinois
(Received June 6, 1938)

TWO methods are in common use at present for obtaining the uniform magnetic fields so necessary to nuclear research; large electromagnets with iron cores, and Helmholtz coils. Iron core magnets are very satisfactory, but somewhat expensive and bulky; and when the field must be varied, an air core coil is advantageous since the current through it is a measure of the field. When a field is required which is constant in the direction of the lines of force, the Helmholtz coil is very satisfactory; but if (as is usually the case) it is necessary to have the field vary but little in a direction perpendicular to that of the lines of force, the Helmholtz coil is not satisfactory unless of dimensions large compared to those of the region of constant field. Besides, the concentrated windings necessary in a Helmholtz coil present some difficulty in cooling if one attempts to obtain very large fields.

The method described in the present paper avoids some of the above-mentioned difficulties. It can be shown[1] that the field inside a spherical coil is accurately a constant, if the windings are so distributed that each unit of length, measured along the axis of the windings, contains the same number of turns. In fact, the field inside an ellipsoidal magnet, wound in this fashion, is accurately a constant, even if the three axes are unequal and if the axis of the windings coincides with none of the axes of the ellipsoid. For the simple case of an ellipsoid of revolution, with the axis of the windings coincident with the axis of revolution, the field inside is certainly constant, and in building up such a magnet, one need not be particularly careful to make it exactly spherical. This fact has been made use of in certain moving magnet galvanometers of very old design; but, probably on account of the difficulty of winding wire on a spherical form, a magnet of this sort has to the best of the author's knowledge never been made on a large scale before.

In connection with a research problem at the University of Illinois, it became necessary to have a magnetic field, constant within less than one percent, over a cylindrical volume some twenty inches in diameter and four inches high, with the field running perpendicular to the large dimension. Calculation of a Helmholtz coil to accomplish this proved to be rather difficult; and particularly on account of the rather small value of the field required, 200 oersteds or less, it seemed unnecessary to use a water-cooled coil. The spherical magnet poved a very satisfactory solution of this problem.

The expression relating ampere-turns to field in such a magnet is: $H=8/3\pi ni$, where i is in *ab*-amperes, and n is the number of turns per centimeter. To obtain a field of 100 oersteds requires then 119 ampere-turns per centimeter, or 3620 ampere-turns per foot.

If one assumes that an open coil can radiate 101 watts per square foot, one obtains at once one of the equations that must be satisfied by the coil: $W/A=E^2/RA=101$ watts/sq. ft., where A is the total area of the coil in square feet, and R is the total resistance. But $R=rL$, where r is the resistance in ohms per foot of the wire to be used, and L is the total length of the wire in the coil. On performing a simple integration, one finds that $L=9.9\ na^2$, where a is the radius of the coil in feet.

One now obtains from the condition for radiation the equation:

$$E^2=12600\ nra^4; \tag{1}$$

and from the fact that we must have a field of 100 oersteds, we obtain a second equation which restricts the design of the coil:

$$E=3500\ ra^2. \tag{2}$$

For practical reasons, the value of E was taken to be 250 volts; and because of the size of the apparatus to be used inside the coil, a was taken to be 15 inches. Eq. (2) now determines the value of r: 4.46 ohms/1000 feet. In a wire table, we

[1] Mascart and Joubert, *L'Éléctricité et le Magnetisme*, Vol. 1 (G. Masson, Editeur, Paris, 1882), p. 546.

find that the resistivity of No. 16 copper wire is 4.49 ohms/1000 feet at 50°C. From Eq. (1) we obtain the value of n as 415 turns/foot or 34.6 turns/inch. No. 16 wire can lie about 15 turns to the inch; so we will need about $2\frac{1}{2}$ layers of wire for this coil. In order to be able to reach higher values of field, let us double the number of turns per inch; this about doubles the permissible current. We now have the necessary design data for the coil.

$$n = 830 \text{ turns/foot}$$
$$i = 3620/830 = 4.35 \text{ amp.}$$
$$L = 12800 \text{ ft.}$$
$$R = 57.5 \text{ ohms}$$
$$W = 1090 \text{ watts.}$$

The coil was wound on a wooden form. White pine planking $1\frac{1}{8}''$ thick was used; 24 circles of the proper sizes were cut out, each in six sections, and nailed together with copper nails. Strips of $\frac{1}{32}''$ black fiber were placed between the layers, leaving a $\frac{1}{2}''$ flange projecting to hold the wire on. 80 turns of No. 16 D. C. C. copper wire were wound on each layer. At the top and bottom, where it is impossible to approximate a sphere with short sections of cylinders such as these, a small cone was used as a base for the wire. When completed, the magnet proved to be a prolate spheroid, about one inch longer than it was wide. But, as noted above, this has no effect on the uniformity of the field. Long brass bolts were run through each half of the completed sphere to strengthen it. The lower half was set upon a $\frac{1}{4}''$ brass plate, which in turn was fastened to three $\frac{1}{2}''$ bolts which were run through holes in the table, which held the magnet, and held with nuts on both sides. The long brass bolts which hold the top half of the magnet together end in brass rings which are fastened to a pulley which lifts it up when it is necessary to work inside the magnet. The whole arrangement is mechanically strong, and while not very convenient to work with, is about as convenient as the inherent nature of a completely enclosed coil will permit. 3″ holes at the top and bottom of the coil permit the entrance of electrical and vacuum connections. Fig. 1 shows the appearance of the completed magnet.

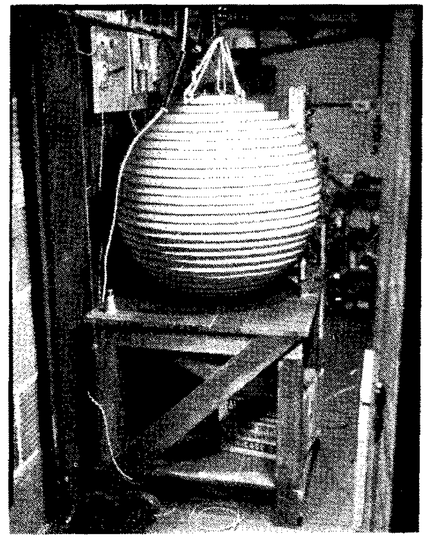

FIG. 1. The spherical magnet.

The field was explored to see what effect the approximation to a geometrical sphere used had upon it. A ballistic galvanometer was used, connected to two small search coils in parallel

TABLE I.

Search coil "*B*" at center of magnet; search coil "*A*" moved along north and south horizontal diameter of magnet:												
Distance from center, inches:	−10	−8	−6	−4	−2	−1	1	2	4	6	8	10
Deflection, mm:	−1	−1	0	0	0	0	0	0	0	0	−1	−1
Search coil "*B*" at center of magnet; search coil "*A*" moved along east and west horizontal diameter of magnet:												
Distance from center, inches:	−10	−8	−6	−4	−2	−1	1	2	4	6	8	10
Deflection, mm:	0	0	0	0	0	0	0	0	0	$-\frac{1}{2}$	−1	−2
Search coil "*B*" at center; coil "*A*" moved around central plane of magnet at 10″ from center:												
Angle, measured from east:	0°	45°	90°	135°	180°	225°	270°	315°				
Deflection, mm:	−1	−2	−1	0	0	0	−1	−1				
Search coil "*B*" 10″ east of center; coil "*A*" moved along vertical axis of magnet:												
Distance from center, inches:	−13	−12	−11	−9	−7	−5	−4	−3	−2	0		
Deflection, mm:	8	3	3	$2\frac{1}{2}$	$2\frac{1}{2}$	3	3	2	2	2		
Distance from center, inches:	2	4	6	10	12							
Deflection, mm:	2	2	2	$2\frac{1}{2}$	6							
Search coil "*B*" at center; coil "*A*" moved in circle radius 10″ around axis of magnet, 2″ below central plane:												
Angle, measured from east:	0°	45°	90°	135°	180°	225°	270°	315°				
Deflection, mm:	−1	−2	−1	0	0	$-\frac{1}{2}$	−1	−1				
Search coil "*B*" at center; coil "*A*" moved in circle radius 10″ around axis of magnet, 2″ above central plane:												
Angle, measured from east:	0°	45°	90°	135°	180°	225°	270°	315°				
Deflection, mm:	$-1\frac{1}{2}$	−2	0	0	0	0	−1	−2				

A positive deflection means that the field is greater at coil "*A*" than "*B*." Above readings corrected for the difference between the two coils. Deflection with one coil alone would be 22.9 cm under these conditions. Radius of magnet = 15″.

opposed. The readings were taken by rapidly reversing the current in the magnet, since it would have been difficult to have used a "flip" coil under the circumstances. The coils were made as nearly identical as possible; 2000 turns of No. 40 silk covered wire wound on brass forms, $\frac{7}{16}''$ i. d. by $\frac{3}{4}''$ long. In spite of the care with which they were made, the coils made a deflection of 0.3 cm even when placed right together. Taking this into account, we obtained the values in Table I. Under these circumstances, the deflection due to one coil alone would be 22.9 cm.

To check the absolute value of the field, one of the above coils was used with the same galvanometer. The field in the round magnet was compared with that of a standard solenoid with this arrangement, and it was found that $H=22.1$ oersteds/amp., in satisfactory agreement with expectation.

To see what effect, if any, the damping of the galvanometer by the search coil across it had upon its sensitivity, it was verified by varying the current in the standard solenoid that the deflection was proportional to the field; then placing one coil in the solenoid, and the other in parallel with it some distance away, it was shown that the sensitivity was proportional to the external resistance—at least if the latter be not varied over too great a range.

So we see that in this way it is rather easy to obtain a field uniform to within better than one percent. The cost of building such a magnet is not great; negligible compared with that of an iron core magnet of comparable size. The most serious limitation upon it is the small fields obtainable; and by cooling by forced air or water, it would not be difficult to obtain fields of several thousand oersteds.

In conclusion, the author wishes to thank Professor H. M. Mott-Smith for his helpful advice on this project, and Dr. F. W. Loomis for the material used.

OCTOBER, 1938 R. S. I. VOLUME 9

The Growing of Large, Single Crystals of Potassium Bromide

Katherine Chamberlain
Wayne University, Detroit, Michigan
(Received June 22, 1938)

THE method of growing potassium bromide crystals described here is essentially that developed by Kyropoulos[1] and Korth.[2] It has been found necessary, however, to spend a very considerable amount of time working out certain details not previously published and the following is offered in the hope that it may be of assistance to others who are interested in growing such crystals.

The method involves the use of furnaces of the pot type of sufficient depth so that the surface of the melted salt is several inches below the top of the furnace and enough power is supplied so that the furnace may be left uncovered during the entire period of crystal growth. The potassium bromide fumes can thus be carried off as fast as they are formed by a strong up-draft provided by the ventilating hood surrounding the furnace. This greatly lengthens the life of the furnace windings. Another advantage of the open furnace is that observation of the crystal is possible throughout the entire period of growth. Inspection of the crystal with a focusing flashlight when it first appears enables one to determine whether it is single and, if it is not, power can be increased to melt the unsatisfactory part. Throughout the entire period of growth, new crystals are liable to start at the boundary whenever the main crystal begins to grow a little too fast and if one observes this as soon as it occurs, it is a simple matter to increase power slightly and melt away the undesirable portion. In fact, close observation during the entire period of growth makes possible manual adjustment of

[1] Kyropoulos, Zeits. f. Physik **63**, 849–854 (1930).
[2] Korth, Zeits. f. Physik **84**, 677–9 (1933).