DESIGN OF MAGNETS PRODUCING STRONG MAGNETIC FIELDS

J. K. SINHA AND (MISS) R. KAUR

Solid State Physics Laboratory, Delhi

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The importance of high magnetic fields and the methods for generating them have been discussed. The design details of a 25 kW solenoidal magnet have been presented.

High magnetic field is a very powerful tool for conducting investigations in many branches of science. Its numerous applications as a research tool are dependent on its two essential manifestations—the alignment of magnetic dipoles and the deflection of moving charges.

Some of the important scientific studies which must employ high magnetic fields for their investigations are being enumerated. A magnetic field represents a loss-less confining force that deflects moving charged particles and acts normal to itself and the direction of motion. As such it finds use in cyclotron and other circular particle accelerators and also serves to deflect and analyse particles of terrestrial and cosmic origin in cloud chambers, photographic track plates and mass spectrographs. An analogous application which has recently received much attention is in controlled thermonuclear reactions where charged ions can be concentrated by high magnetic fields—an application of the Pinch effect. Pinch effect is the name given to manifestations of the magnetic self attraction of parallel electric currents having the same direction. Since 1952, the Pinch effect [1,2] in a gas discharge has become the subject of intensive study as it presents a possible way of achieving the magnetic confinement of a hot plasma necessary for the successful functioning of a thermonuclear or fusion reaction.

The use of magnetic fields to obtain very low temperatures is well-known. Besides, by observing the response of magnetic dipoles in a solid, one can use them as probes to investigate the internal fields in the solids. Paramagnetic and anti-ferromagnetic resonance measurements have contributed greatly to our understanding of the solid-state and many of these measurements require extremely high applied external fields to compete with the natural internal fields. All these phenomena follow basically from the capacity of the magnetic field to align the magnetic dipoles.

These resonance studies have resulted in the creation of a range of devices which have added newer dimensions to the respective technological fields. The study of electron paramagnetic resonance has produced molecular amplifier called the Maser which is a microwave amplifier having the lowest noise-factor achieved so far. This has been used to extend the range of radio-astronomical telescopes many-folds. The ferromagnetic resonance studies have resulted in a range of non-reciprocal devices such as circulators, parametric amplifiers, and isolators which have advanced radar, communication and microwave technologies. A tunable far-infrared detector[3] and submillimeter source[4] are other important devices requiring high fields for their operation.

METHODS OF PRODUCING MAGNETIC FIELDS

In view of their important applications the following techniques for generating high magnetic fields are reviewed: (*i*) Conventional iron-cored magnets, (*ii*) Conventional conductors wound into solenoids, (*iii*) Pulsed fields of short durations and (*iv*) Superconductors in solenoids cooled with liquid helium.

IRON-CORED ELECTROMAGNETS

At low fields the iron in an electromagnet provides a resistanceless path for the magnetic flux. The magnetomotive force of all windings around the iron core, however placed can, therefore, be used to overcome the magnetic reluctance of the gap between poles. The magnetic reluctance of the iron may be neglected and all the ampere turns of the windings may be considered to be acting on the pole-gap. However, on sufficiently increasing the ampere turns, iron approaches saturation and there the magnetic reluctance of the iron gradually increases until finally its magnetic properties are different from the vacuum only in that the iron is uniformly magnetized to saturation. The value of saturation field for iron and steel usually employed in electromagnets is of the order of 25 K.O. Although iron saturates at about 25 K.G. the field in the air gap can be arranged to be as high as 70 K.O.

Between the air gap and the cores there must, therefore, be interposed some link which while requiring a minimum possible expenditure of magnetomotive force will form the means of reducing the air induction from this high value to a value for the induction in iron of about 20 K.G. or so. This link consists of pole pieces which are, therefore, vital elements in the design of electromagnets. Inspite of the lengths of their magnetic paths being small, the air gap plus the pole pieces in correctly dimensioned magnets require by far the greater part of the total ampere turns. Theory and experiments have shown [5,6] that the conical pole pieces with apex angle of the order of 120° give satisfactory results.

De Klerk & Gorter[7] have suggested that a useful volume of magnet efficiency is the relation between the maximum obtainable field H_{max} and the ratio of the useful volume *i.e.*, to the volume V of the iron in the magnet. It has been found that all efforts to increase the maximum field lead to an enormous increase in the volume ratio. A typical 14-ton magnet will produce 53 K.O. in a 1 cm gap and 68 K.O. in a 2 mm gap. The production of 80 K.O. in a gap of 2 mm requires a magnet weighing 100 tons while a field by 1000 K. O. in the same gap requires at least a 10000 ton magnet[8] . Hence it appears that for fields exceeding 50 K.O. in a gap of the order of 1 cm, the iron-cored electromagnets are both inconvenient and uneconomic.

SOLENOIDAL MAGNETS

The second method of generating the magnetic field is by the use of solenoidal currents. Such a solenoid dissipates far more energy than a corresponding magnet at low fields. However, in the field range above about 40 K.O. the solenoid provides a more attractive solution than the iron magnet both because of the comparative power requirements and because it has the advantage of not requiring an exponential increase in volume with field as with the electromagnets.

It is through this method that the fields exceeding 250 K.O. have been obtained. In principle there is no limit to the value of the magnetic field that can be obtained as the fields inside the solenoid are directly proportional to the current. The practical limit imposed here is due to the availability of power, the current carrying capacity of the solenoid, mechanical strength and the speed of cooling as heat has to be taken away at a fast rate if used even for a few seconds.

The basic mathematical analysis of coil shape and current distribution has been developed principally by two authors Cock croft[9] and Bitter[6]. Bitter's analysis, however, is most complete and due to extensive studies carried out by him, these magnets have also come to be known as Bitter magnets. One such Bitter magnet has also been designed by the authors at their laboratory. However, the value of the magnetic field chosen is rather low due to the limitations of facilities. The details of design are given later.

Various types of coil constructions have been suggested by various workers namely Bitter[6], Wood[10], Montgomery[11] etc., but the basic design considerations in all these constructions have been the procurement of maximum field for any particular level of power used, effective cooling and mechanical strength. Details of the various coils can be found in some of the reviews [8, 12] available on the subject. However, a discussion of the general problems associated with the design of these solenoidal magnets follows.

The design problems of these magnets are clearly associated with the powers employed in the solenoid. Bitter[13] has categorized these problems in three distinct groups *viz.*, (*i*) problems associated with tho solenoidal magnets handling powers in the vicinity of one megawatt (*ii*) special problems arising corresponding to the powers in the vicinity of 10 megawatts and (*iii*) problems that may arise for powers in the vicinity of 100 megawatts.

Solenoidal magnets in the power range of one megawatt

One need consider only air-core coil designs, for power level of about 1 megawatt and fields of about 100 K.O. Different types of coil design [6, 10, 11] are attempted mainly with a view to use the power as effectively as possible and to have the proper cooling. Solenoidal magnets in this power range can now be relatively simply produced and after being connected to the bus system and the water cooling system are capable of considerable repositioning due to the availability of flexible connections. New methods of de-ionization and filtration of the coolant have been tried and now sufficient experience has been gained so that these magnets can be used for hours at a stretch.

Solenoidal magnets in the power range of 10 megawatts

Until very recently, magnets operated at this power level were exploited only in pulsed magnets. However, Montgomery[11] at MIT has succeeded in a coil design with a very much improved cooling facility which can give a field of 205 K.O. in a clear bore of 2·25″ with a power dissipation greater than 10 megawatts. By introducing two iron pole pieces along the axis of the coil and holding them a short distance apart, steady fields of about 255 K.O. have been produced. This condition, of course, leaves a very small working space of 1/64″ diameter and 1/64″ high.

It is well known[12] that for fields in the vicinity of 250 K.O. or more, mechanical problems begin to be important due to the outward barrel forces creating tensile stress in the conductors. Hence, plastic deformations might occur in the vicinity of 250 K.O [13]. Using a *Cr.-Cu*, *Zn-Cu* coil, the limit may be raised to 300 K.O. It has, however, been suggested by Bitter[13] that the plastic deformations should not lead to catastrophic consequences provided temperature rise is not unduly large. This is because of (*i*) strain hardening that sets in and (*ii*) capability of the coil to support considerably greater stresses as would a thick walled cylinder with internally applied pressures. Even at pressures which would cause a *Cu* or *Zn-Cu* cylinder to fail, a strong confining structure, for instance a steel cylinder with steel ends to house the current-carrying coil, should make possible the production of much large fields from the usual coils. Another solution to this difficulty is simply imposing the design condition that the tensile stress shall always be less than the breaking point. The result is to alter the current distribution and to limit it near the centre of the coil resulting in a less efficient coil. It implies that the power required per oersted rises. In principle it should be possible to generate very high fields by this method.

Another very important consideration in these magnets is the requirement of not only uniform but also a constant field. The current regulation of the power supply is certainly not better than a few parts in 10^4 which would lead to the fluctuations in a field of 100 K.O. magnet of a few tens of oersteds. It is hoped that a superconducting shield in the central portion of the magnet can hold the field extremely constant and the coil can be so designed that the superconducting currents themselves will not materially affect the homogenity.

Solenoidal magnet with 100 megawatt power

In concluding the discussions in liquid coated magnets, mention must be made of the objective of obtaining fields of the order of 100 megaoersteds. Pulsed power of short duration in this range is already a reality which is discussed later. It may be mentioned that even with the currently available technology, high field magnets using such power levels are possible. However, as we move up from 300 K.O. towards half a million oersteds, new exploratory work will be needed. Here we will be moving to the area of research in magnetic design. Clearly cryogenic and superconducting magnets are most promising and will eventually play an important part. Combination of such magnets with water cooled magnets are among the interesting possibilities to be investigated for achieving this aim.

Cooling fluids

With conventional solenoids, water cooling is usually favoured and, provided dimineralized water of controlled conductivity is used, no troubles due to leakage currents and electrolysis need occur. Other cooling fluids have been used such as kerosene and dowtherm, but they do not offer any advantage and usually bring a train of special problems of their own.

Cryogenic solenoids *i.e.*, the coils operated at liquid nitrogen or liquid hydrogen temperatures have also been tried. It is clear, of course, that a reduction in the resistivity of the material used will lead to a considerable reduction in the specific dissipation required to produce a magnetic field. However, the overall power consumption in a system of this type should include that required to produce the cryogenic liquid. From the detailed investigations of Sydoriak & Roberts[14] it was found that water is, in fact, one of the most favourable media; only liquid hydrogen appears comparable in efficiency.

PULSE MAGNETS

The power requirements for producing very strong fields in normally conducting solenoids become prohibitive and the cooling problems seem unsurmountable above 250,000 oersteds. Both of these problems can be overcome by using Kapitza's[15] pulsed field technique. If the field need be generated only for a very short time then clearly neither heating nor continuous power requirements need be a serious consideration. A very large number of experiments can, in fact, be carried out during short field pulses and a great deal of highly interesting experimental work has been done in the recent years using such pulsed magnetic fields.

Kapitza succeeded at the Cambridge University in producing 500,000 oersteds for several milliseconds by drawing a battery of strong cells through a very small solenoid, and later succeeded in producing 300,000 oersteds in a larger solenoid powered by the short circuit current of a 2 megawatts a.c. generator.

In general, various forms of energy storage have been used; the kinetic energy of a rotary dynamo, special accumulators, large inductance coils and banks of condensers. Out of these, the capacitor discharge system is comparatively cheap and reliable. A bank of capacitors having a large capacitance is charged slowly, and then, at a given point discharged through a suitably designed coil via ignition switches.

In any real coil a part of the field energy resides outside the working space and some energy is always dissipated as Joule heat during the discharge. The resistive dissipation heats the coil and melting of the coil eventually sets an upper limit to the time during which the field can be maintained. It has been shown[8] that for copper the longest pulse that may be used with a coil of internal radius 1 cm to produce a field of 100,000 oersteds is about 1 second. Fields of 1 megaoersted cannot be maintained for more than 10 milliseconds before such a coil melts.

The difficulties present in the ordinary solenoids due to electromagnetic stresses are also present here and our finding is that difficulties due to the distortion of the coils by the electromagnetic forces arise in ordinary wire wound solenoids at fields of about 150 K.O. By using glass fibre reinforcement Cott has made coils which will survive fields as high as 400,000 oersteds. Beyond this limit single turn coils or strongly supported helical coils turned out of a single piece of high strength alloy such as beryllium-copper have allowed Furth & Wanier[16] and Foner & Kohn[17] to reach fields of 750 K.O. for 100 μ sec. or more.

It may be mentioned that provided the restrictions of space and time be acceptable, pulsed field systems are extremely useful tools; but there is no question of these being anything but complementary to steady field systems until the practicable limits of steady field systems are reached.

SUPERCONDUCTING MAGNETS

Fair amount of research is now being concentrated on the development of superconducting magnets capable of giving very high fields. It has been known for a long time that many metals are superconductors[18] *i.e.*, below a critical temperature T_c they lose all traces of electrical resistance.

In the case of a solenoid using the superconductor winding, therefore, there is the great advantage of having almost a negligible resistance. Hence a considerably large number of turns can be wound and a high magnetic field obtained at a relatively low power due to the generation of the super current.

However, the use of superconducting wires for obtaining high fields have been limited in the past due to the relatively low values of critical magnetic field H_c and the critical current I_c. H_c and I_c are respectively the field and the current at which the superconducting materials lose their superconductivity.

It has been found that the more strained and impure the superconductor, the higher the magnetic field required to completely destroy its superconductivity. It has also been shown that some alloys and inter-metallic compounds have quite high critical temperatures in zero field; for example the compound niobium-tin has a critical temperature of 18°K. These alloys and inter-metallic compounds have been found to have quite high value of H_c at liquid helium temperatures. Some extensive work in USA by Kunzler[19] and others on the alloys of molybdenum with rhenium and niobium with zirconium showed that when wires of these materials were hard drawn and hence in a relatively strained condition very high values of critical fields could be obtained.

In 1961, Westinghouse introduced the world's first high field superconducting solenoid. This solenoid generated 43 K.O. and contained approximately one mile of 10 mil. diameter Nb-Zr wire. Magnetic fields of nearly 60 K.O. have been reported by Hulon *et al.*[20] and by Hake *et al.*[21].

The inter-metallic compound niobium-tin (Nb_3Sn) has proved to be very promising. The wires prepared from this compound are somewhat brittle; their critical temperature in zero field is about 18° K[22]. It has been shown by graphical extrapolation that at the absolute zero the critical field could be as high as 500 K.O. but at 1·50°K. it has been shown to be about 210 K.O. in pulsed field measurements. A solenoid using this wire and capable of giving 100 K. O. has been reported by Martin *et al.*[23].

Another intermetallic compound with a high transition temperature is vanadium gallium (V_3Ga). Wernick *et al.*[24] have obtained evidence that V_3Ga has a critical field in excess of 500 K. O. Like niobium-tin, vandadium-gallium is very hard and brittle and before the full potential of either material can be realised, better methods of producing them in the right condition will have to be devised.

The upper limit of applicability of the superconducting magnets can be very considerably increased if the suggestions made recently by Jaccarino and Peter[25] should prove correct. These authors have predicted that superconductivity may exist in certain ranges of very high magnetic field in some ferro-magnetic materials. This effect might increase the maximum fields at which superconductivity can exist to many millions of oersteds.

There are several practical problems in the operation of these superconducting magnets. All of these, however, are concerned with the problems of heat dissipation from the various mechanisms which result in the destruction of the coil. All these problems have been satisfactorily solved. Further details on these magnets may be obtained from some of the review[8,12] papers on the subject.

The magnitude and nature of the magnetic field required are dictated by the experiment but the choice of technique is governed largely by economic factors; for example, at 100 K.O. a superconducting solenoid has the power advantage of 100 to 1 over the conventional solenoids. This advantage, however, is obtained at the cost of a few hundred litres of liquid nitrogen per hour as these superconducting magnets have to work at about liquid helium temperatures. It has now been found that below 70 K.O. and in comparatively small bores, the natural choice is now the use of superconductors. At present niobium- *Zr* wire is the natural choice in this field region because of its tractability and strength but it is expensive. Niobium-tin is more attractive as a superconductor and should be less expensive if better methods of fabrication of this material are developed. Nevertheless, in the low field region, superconducting solenoids are here to stay, particularly where applications of high fields in instruments are considered.

DESIGN OF A 'BITTER' SOLENOID GIVING A FIELD OF 18 K.O. IN ONE INCH GAP

Finally, an aircored solenoidal magnet designed in our laboratory is discussed.

From considerations of obtaining as large a value of the magnetic field as possible Bitter[6] came to the conclusion that a magnet consisting of a suitable opening to permit the access to the centre of the coil where the field is produced would correspond to the most efficient arrangement. The advantages of such a construction are that in this way the maximum possible iron is magnetized in approximately the optimum direction and that the field produced by the coil is added to the field produced by the iron. The coil furnishes the magnetomotive force for magnetizing the iron. Since the coil in general furnished the major part of the field, full attention has to be given to its construction and design.

There are various types of coils which can be designed. In the present case a cylindrical coil with tapered ends has been chosen in which the current density is inversely proportional to the radius. This arrangement is simply obtained by rolling up a flat tape whose width gradually increases from the inside to the outside of the roll. It has been shown[6] that for this case, the electric field H is given by :

$$H = G\,(W\lambda)^{\frac{1}{2}}\,/\rho a_1 \tag{1}$$

Where W is the power applied, ρ is the specific resistance of the material in ohm.cm, λ is the space factor *i.e.*, the fraction of the volume of the coil occupied by conducting material and a_1 is the inner radius of the coil. G in equation (1) is given by

$$G = \left\{ K\,\pi/25\,(k^2+1)\,(\alpha-1) \right\}^{1/2} \log_e \alpha \tag{2}$$

where. $K = b/a_2$ and $d = a_2/a_1$, b being the half of the maximum width of the coil and a_2 being the outer radius of the coil. (See Fig. 1).

The procedure in designing the solenoid is to choose the value of the power W to be applied together with the values of the working voltage and current. This enables the determination of the total resistance of the coil. The minimum and maximum widths of the coils are now chosen taking into account the volume in which the field is required and the value of G that will result from this choice. Once the minimum and the maximum widths are chosen, the mean width can be found. If the thickness of the tape is chosen, the cross-sectional area of the tape can be determined and the length of the tape can be calculated from the formula

$$R = \rho . l / A, \tag{3}$$

where R is the resistance of the coil, ρ is the specific resistivity in ohm. cm, l is the length of the tape and A is the area of cross-section.

The values of the length and thickness of the *Cu* tape being known, it is possible to calculate the total number of turns by giving due allowances for the outer radius of the tape. The space factor λ is known by calculating the volume of the coil and the air space. In this case λ was found to be equal to $0{\cdot}8$.

All the parameters of the one inch gap solenoidal magnet which have been calculated corresponding to the applied power 25 kW at 250 volts and 100 amperes are given below—

Inner radius of the coil	1·25 cm.
Outer radius of the coil	18 cm.
Length of the coil	743 m.
Total resistance of the coil	2·5 ohms.
Number of turns	1154.
Minimum width of the *cu*-tape	0·9 cm.
Maximum width of the *cu*-tape	9·2 cm.
Thickness of the *cu*-tape	0·01 cm.
Thickness of the insulation	0·005 cm.

Expected field in one inch gap over the length of 0·9 cm $\simeq$ 16 KG.

The iron surrounding the coil is made in two halves. These two halves are bolted through an iron ring which holds the wound copper tape in position. This ring also serves as a terminal for the current. Due precautions have been taken everywhere for electric and water insulation as water has been chosen as the coolant. Here the coil is cooled by water flowing over outer surface only at the rate of approximately eight gallons

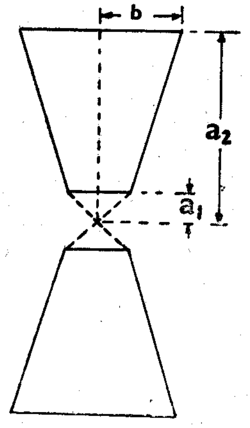

Fig. 1—Parameters of the solenoidal magnet.

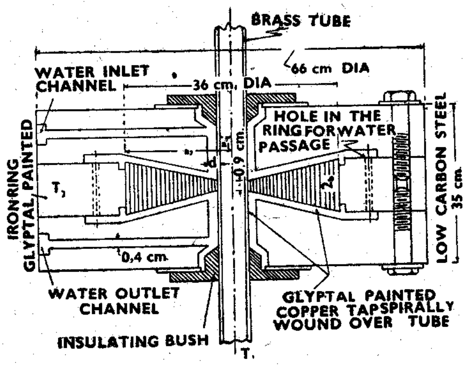

Fig. 2—Cross section of the solenoidal magnet with dimensions.

per minute. The pressure at which the water is to be forced at the inlet is calculated by the simple application of Bernoulli's theorem, assuming the exit pressure to be equal to the atmospheric pressure and the velocity of the inlet to be equal to zero. This gives the pressure at which water is to be passed at the inlet to be equal to 20 lb p.s.i.

The cross section of this solenoidal magnet giving all the dimensions is shown in Fig 2. It can be seen that the water flows here on one side of the coil along with the conductor and then to the otherside through suitable holes made in the ring. This design follows almost the same pattern as one of the early designs of Bitter.

It is worth mentioning that at this power level an iron-cored electromagnet would have been more efficient. However, this first attempt of the design of the solenoidal magnet is intended for getting the familiarity with the practical problems normally encountered in the design of such magnets. After the fabrication and successful operation of this magnet it will really be worthwhile to undertake the design of more powerful solenoidal magnets.

CONCLUSION

It may now be concluded that due to its being a common requirement in many major branches of science, high magnetic field research has now emerged as a very important and interesting field of study.

For the fields of the order of 30 K.O. or less it is probably economical to go in for the design of conventional electromagnets but for fields exceeding this value, the solenoidal magnets—both normal and superconducting—will be more efficient and practicable. At the present state of technology the maximum steady fields that have been achieved is of the order of 250 K.O. using powerful solenoids. Probably some of the superconducting magnets may also give the fields of that order. For fields beyonds 500 K.O., it seems that for a long time to come pulsed systems will remain the only way for producing them, of course, the length of the pulse can be traded in for the magnitude of the field.

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