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HIGH FIELD SUPERCONDUCTING MAGNETS*

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W. B. Sampson

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Introduction

Although a few superconducting magnets^{1,2} were built earlier, the history of such devices really began in 1961 when it was announced that substances had been found that would remain superconducting in very high magnetic fields.^{3,4} A number of workers immediately began to build small solenoids of the new materials and plan the construction of large coils. It soon became apparent, however, that magnets made from long lengths of material did not perform nearly as well as tests on short samples indicated they should. This phenomenon became known as "current degradation" and a number of suggestions were put forward to explain it. In spite of this "degradation" it did prove possible to build small (1-2 in. I.D.), relatively high field (50-60 kG) solenoids and these magnets were soon in everyday use in the laboratory. The degradation phenomenon, however, was worse in larger magnets or multiple coil assemblies (split-pairs) and proved to be

* Invited paper presented at Intermag Conference, Stuttgart, Germany, April 1966.

1. G.B. Yntema, Phys. Rev. 98, 1197 (1955).
2. S.H. Autler, Rev. Sci. Instr. 31, 369 (1960).
3. J.E. Kunzler et al., Phys. Rev. Letters 6, 89 (1961).
4. T.G. Berlincourt et al., Phys. Rev. Letters 6, 671 (1961).

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an almost insurmountable obstacle in the building of such coils. Most of the early magnets were made with various alloys of NbZr because it is easier to handle than the intermetallic compound Nb₃Sn. As the technology of producing Nb₃Sn in readily usable form developed, the fields available in small solenoids increased considerably but the basic problems for large magnets remained. The properties of the three most commonly used superconductors are shown in Fig. 1 where the solenoid degradation is evident.

Recently a better understanding of the effects of magnetic and thermal transients has led to techniques of construction that allow large solenoids which are not degraded to be built. This report discusses these techniques with particular reference to very high field solenoids (greater than 100 kG) and indicates the possibilities presented by currently available superconductors.

Solenoid Stabilization

Superconducting solenoids which do not show degradation but operate at or near the short sample critical current are usually referred to as being "stable" and the methods used to obtain this performance are referred to as coil stabilization. A number of such stabilizing techniques have been discovered and they are discussed in some detail below.

Metallic interleaving. A considerable improvement in the critical current of a magnet can be realized by using a metallic interleaving between the layers of the coil.⁵ This effect is most pronounced in coils wound from Nb₃Sn ribbon but some improvement can also be realized for solenoids wound from NbZr wire. The resistivity of the interleaving material is very important, and in general the performance of the coil improves with increasing conductivity of the interleaving material (see Fig. 2). The most commonly used interleaving materials are anodized aluminum foil and Mylar-clad copper foil usually about 1 mil thick. The stabilizing action of these foils is thought to be due to a combination of two effects, the first being the improved cooling of the interior of the coil by thermal conduction along the

5. W.B. Sampson, Rev. Sci. Instr. 36, 565 (1965).

Fig. 1 The critical current (4.2°K) as a function of magnetic field for short samples of the three most common superconductors used in magnet construction. The dashed curves represent typical operating levels actually achieved in solenoids.

Fig. 2 The effect of the electrical conductivity of metallic interleavings (insulation) on the low field performance of Nb_3Sn solenoids.

foil to the helium bath which tends to reduce the height of temperature spikes produced during "flux jumps". The second effect is a damping action by eddy currents induced in the foils which increases the time scale of flux jumps and results in a lower maximum temperature being reached. This reduces the likelihood that a particular flux redistribution will lead to a quench of the whole coil.

Multiple conductors. Another method of achieving improved performance in larger coils is to parallel a number of small conductors to form a superconducting cable. This technique was first used by Charles Laverick of Argonne National Laboratory in the construction of a coil system for a helium bubble chamber.⁶ After stranding, the cable is usually impregnated with indium to form a strong, easy to handle conductor. In some cases copper wires are included in the cable to act as shunts during transients when short sections of wire may go normal. As well as improving the performance, this technique markedly reduces the inductance of the coil, shortening the charging time. Cross sections of such cables are shown in Fig. 3.

This method has been extended by Z.J.J. Stekly⁷ and co-workers to produce a fully stabilized composite conductor. The conductor is composed of nine 0.010 in. diameter NbZr wires imbedded in a copper ribbon and is shown in Fig. 3. The amount of copper used has been chosen in such a way that the rated current of the superconductors can be carried in the copper without the local temperature going above the critical temperature of NbZr. This means that a coil constructed of this material, if properly cooled, can be driven beyond its critical current without going normal.⁸

Magnetic field stabilization. When a degraded solenoid is operated in an externally applied background field its critical current may be greater than that obtained in the absence of such a biasing field.⁹ The critical

6. C. Laverick and G. Lobell, Rev. Sci. Instr. 36, 825 (1965).

7. A.R. Kantrowitz, Z.J.J. Stekly, Appl. Phys. Letters 6, 56 (1965).

8. Z.J.J. Stekly and E.D. Hoag, Proc. Intermag Conf., Stuttgart, Germany, April 1966 (in press).

9. E.R. Schruder et al., Appl. Phys. Letters 4, 105 (1964).

Fig. 3 NbZr cables and fully stabilized NbZr ribbon conductor.

current usually increases with background field until the short sample current is reached for the total field. This effect is believed to be due to the fact that the biasing field removes the low field regions from the coil where the flux jumps responsible for degradation are the most numerous. To take advantage of this effect a solenoid is built in a number of concentric sections and the outer sections used to apply a stabilizing field to the inner sections. In this way a large portion of the coil can be operated at maximum possible current. Figure 4 shows the behavior of the various sections of a four-stage coil designed for particle physics experiments. An advantage of this method of construction is that the current density in the whole coil is not limited by the short sample current of the high field section which may be less than the normal degraded current. A disadvantage is, of course, the added complexity of a number of power supplies and leads.

Superfluid stabilization. It has recently been found that a considerable improvement is realized in Nb_3Sn coils by operating below the superfluid transition temperature of He^4 (2.18°K).¹⁰ This effect is especially noticeable in very degraded coils where a substantial increase in current occurs just below the lambda point. A less dramatic but appreciable improvement occurs even for coils which are not degraded at 4.2°K (see Fig. 5). This is due to the increase in the short sample current at the lower temperatures.

High Field Solenoids

With a number of approaches available, the problem in designing very high field solenoids is to choose the best combination of techniques to produce the highest field with the least volume of superconducting material (i.e., at the least cost). Overall current density is of prime importance in the design of these coils. In Fig. 6 the relative volume of conductor required to produce 100 kG is plotted against current density. It can be seen that even for relatively large coils (2 meters I.D.) the volume rises rapidly with decreasing current density. The absolute volume of conductor,

10. W.B. Sampson et al., Appl. Phys. Letters 8, 191 (1966).

Fig. 4 Magnetic field stabilization of interior sections of a composite solenoid. The field applied by the external sections raised the current in the inner section until short sample current is achieved.

Fig. 5 Improvement of coil performance at low temperatures. The stability of the solenoid is also improved in superfluid helium.

Fig. 6 The relative volume of superconductor required to construct a 100 kG solenoid as a function of overall current density.

of course, increases as the cube of the inner radius. This strong dependence of size on current density virtually rules out the use of conductors heavily stabilized by normal material except perhaps as outer sections of a composite coil. Since a high field coil will almost certainly be operated in sections using different materials for the separate coils, magnetic field stabilization can be used on the inner sections so that little or no stabilizing material is needed there. For the outer sections the amount of normal material used in stabilization must be kept to the minimum required to produce the highest overall current density. Cladding Nb_3Sn ribbon with very pure and well annealed copper can produce high current densities in the 30-80 kG range. Such a conductor is shown in Fig. 7. It is made up of three strands of RCA Nb_3Sn ribbon bonded between two layers of 0.001 in. copper. This material was used in the construction of a 5 in. bore coil and the critical current for the composite found to be 431 amperes equal to 143 amperes per ribbon, which is in excellent agreement with the typical short sample currents for this material at the maximum field of 68 kG. The solenoid is shown in Fig. 8. The high current density is evident in the modest external dimensions; the outer diameter is only 7 inches. Similar coils constructed with half-inch-wide copper-clad G.E. ribbon have been equally successful. The use of superfluid stabilization promises to be of significant help in producing very high field coils. The fact that the critical current increases more rapidly with decreasing temperature than expected and that the relative improvement is greater at higher fields (at least up to 80 kG) indicates that the currents at 170 kG and 1.5°K may be twice the 4.2°K critical current. One can only guess at how high a field may be possible until measurements on short samples are available at low temperatures and in the 200 kG region.

Applications to High Energy Physics

Since sufficient evidence is now available to indicate that superconducting coils can be produced in almost any size or shape, it is interesting to look at some of the proposed applications of these coils. In the immediate future these magnets will be largely used at high energy physics laboratories where high fields and large magnetic volumes are always in demand.

Fig. 7 Critical current of composite Nb_3Sn ribbon as a function of applied magnetic field.

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Fig. 8 Solenoid constructed from composite Nb₃Sn ribbon.

One of the most obvious places where a superconducting magnet could be used is to provide the field for a bubble chamber. The existence of a cryogenic environment should considerably reduce the problems of keeping such a magnet below its critical temperature. At the present time superconducting magnets are being seriously considered for two large chambers at Argonne and Brookhaven National Laboratories. Figure 9 is a view of the proposed Brookhaven chamber. The inside diameter of the coils will be 16 feet!

Unlike the bubble chamber application a great deal of the magnetic apparatus used in high energy physics is only large in one dimension. This includes such devices as dipoles, quadrupoles and synchrotron magnets, which are usually long compared to their aperture. In general the field patterns produced by such devices can be duplicated by arrays of superconductors arranged around a circular or elliptical pipe. Recent calculations¹¹ have shown that field configurations of very high precision can be obtained with relatively simple winding geometries. Furthermore, suitable reverse windings, concentric with the primary ones, can be employed to exactly cancel the external field.¹² In Fig. 10 a schematic drawing of such an array is compared with a conventional synchrotron magnet. The difference in weight and volume is obvious. An additional advantage of such magnets is that a considerably greater fraction of the stored energy is contained in the beam tube so that the power supply can be smaller under a given set of circumstances. The first magnet of this general type (a quadrupole) has been constructed and tested.¹³ While there is no doubt that dc magnets (quadrupoles, bending magnets, etc.) can be successfully constructed, more work is required before we can answer the question of whether or not pulsed magnets of the synchrotron type can be operated economically.

11. R.A. Beth, BNL Accelerator Dept. Internal Report AADD-102 (1966).

12. R.A. Beth, BNL Accelerator Dept. Internal Report AADD-103 (1966).

13. P.G. Kruger, Proc. Intermag Conf., Stuttgart, Germany, April 1966 (in press).

PROPOSED HYDROGEN BUBBLE CHAMBER	
DATE	11-1-68
BY	W. J. B. / J. B. B.
FOR	U.S. DEPARTMENT OF ENERGY
PROJECT	11-1-68-14-318

Fig. 9 Proposed 14-foot hydrogen bubble chamber with superconducting magnet.

Fig. 10 Comparison of conventional and superconducting synchrotron magnets.

Existing Problems

In case this report has left the impression that there are no problems remaining in the construction of superconducting magnets, it might be wise to mention some of the unusual properties of these devices which will give trouble as increasingly complicated and refined coils are designed. These properties are related to nonlinear effects in the coil.

The most obvious of these effects are flux jumps (sudden rapid changes in magnetic field). In an application where the field must be varied continuously and smoothly these discontinuities would present great difficulty. Fortunately under some circumstances these flux jumps can be swept out of the coil in the first charging and will not appear during subsequent cycles as long as the solenoid is not driven normal.

Another nonlinear effect is illustrated in Fig. 11, where the field vs. current curves of the solenoid are seen to be different when the coil current is sweeping up or down. This is assumed to be caused by diamagnetic currents set up in the superconductor which tend to counteract field changes. The large residual fields possible in Nb_3Sn magnets are shown in the insert to Fig. 11. Fields as high as 6 kG have been trapped. This, of course, is a considerable difficulty when conditions require the field to return to zero as in adiabatic demagnetization magnets. Also shown in Fig. 11 is the residual field retained in the magnet as a function of the maximum field obtained before returning to zero current. It may be that the much lower trapped fields in NbZr magnets are due to the fact that such magnets are usually severely degraded and do not reach or come close to the short sample current. At any rate these nonlinearities pose serious problems to the magnet designer. It is to be hoped that such effects will prove to be predictable so that they can be considered in the design calculations.

Conclusions

It is evident that the art of constructing superconducting magnets has come a long way since 1961 and it is almost certain that such magnets will be largely responsible for providing the large volume, high field magnets of the future.

Fig. 11 Deviations from classical behavior in Nb_3Sn solenoids. The magnetic field is not directly proportional to current. The inserts show the spatial distribution of trapped field along the axis of the solenoid and the amount of trapped field as a function of maximum field obtained.

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