Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

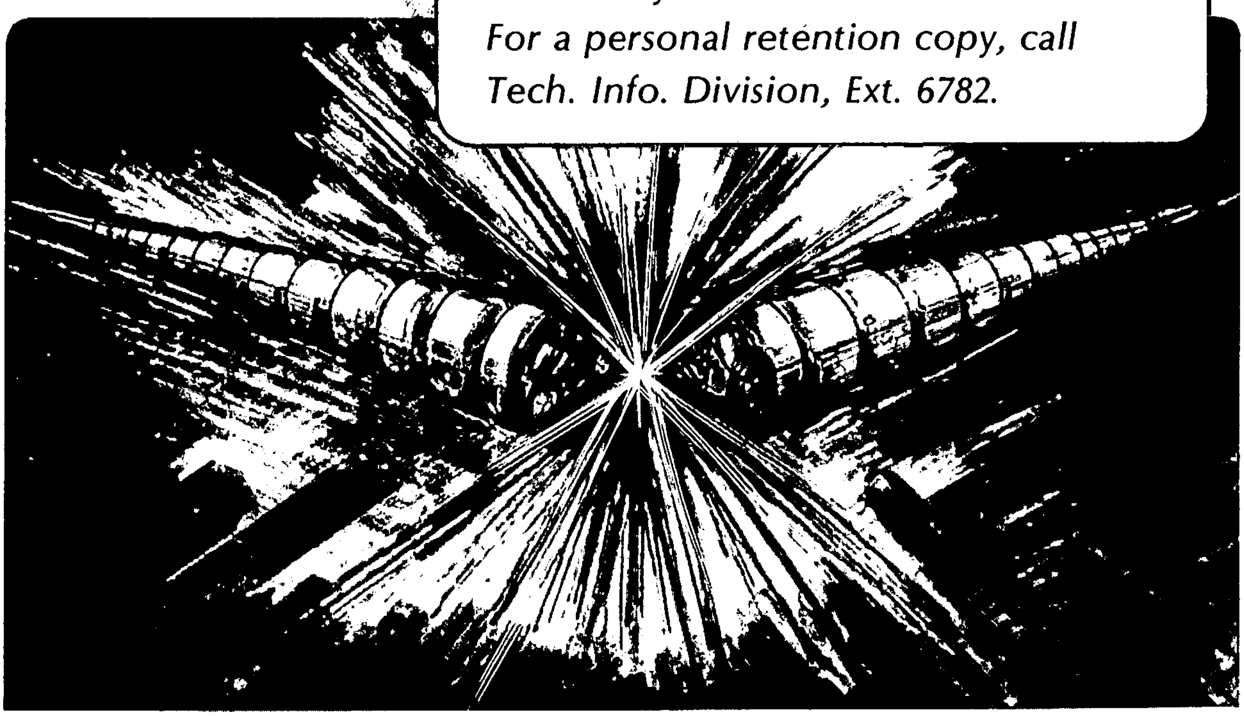
Accelerator & Fusion Research Division

Presented at the Ninth International Cryogenic
Engineering Conference, Kobe, Japan,
May 11-14, 1982

HIGH-FIELD SUPERCONDUCTING ACCELERATOR MAGNETS

C. Taylor, R. Meuser, S. Caspi, W. Gilbert,
W. Hassenzahl, C. Peters, and R. Wolgast

May 1982



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

LBL-14400
SUMAG-68

HIGH-FIELD SUPERCONDUCTING ACCELERATOR MAGNETS*

C. Taylor, R. Meuser, S. Caspi, W. Gilbert, W. Hassenzahl
C. Peters, and R. Wolgast

May 1982

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

HIGH-FIELD SUPERCONDUCTING ACCELERATOR MAGNETS

C. E. Taylor, R. B. Meuser, S. Caspi, W. S. Gilbert, W. V. Hassenzahl, C. Peters, and R. C. Wolgast

Lawrence Berkeley Laboratory, University of California, U.S.A.

The next generation of accelerators for high-energy physics will require high-field, small-bore dipole magnets: in the region of 10 T and 40-mm diam. For such magnets, there is a great incentive to attain high overall current density through increasing the current density within the superconductor and minimizing the copper stabilizer. Both Nb-Ti operating at 1.8 K and Nb_3Sn at 4.2 K are candidate superconductors. Two programs in the U.S. and one in Japan are directed toward the development of such magnets. The program at LBL is described below.

INTRODUCTION

The magnetic field of a next-generation, high-energy physics accelerator must be high if the circumference is to be minimized. This is desirable in order to minimize costs associated with land and right-of-way acquisition, tunnel and shielding construction, cryogenic distribution system, vacuum system, etc. For example, for 10 T and 30 TeV, the circumference is 80 km.

In October 1981, an ICFA Workshop on "Possibilities and Limitations of Superconducting Magnets for Accelerators" was held at Protvino, USSR [1]. Problems of magnet design, refrigeration, and accelerator parameters were considered. Some of the major conclusions were:

(1) A field of 10 T is a reasonable goal and is attainable by using either Nb-Ti or improved ternary alloys at 1.8 - 2.0 K, or by using Nb_3Sn or other A-15 materials at 4.2 - 4.5 K. The advantage of Nb-Ti is high strength and ductility; disadvantages are: An operating temperature of 2 K requires a more complex and expensive refrigeration system; the coil has a lower tolerance for radiation heating because of low heat capacity of metal at 1.8 K compared to 4.2 K. The advantage of Nb_3Sn is 4.5 K operation; disadvantages are: Nb_3Sn is mechanically brittle, so excessive strain will damage the conductor; the conductor, including inter-turn insulation, must be reacted at 700 C after winding.

(2) Electrical insulation must withstand pressure of 100 - 150 MPa.

(3) Several types of coil designs will work for 10 T depending upon insulation stresses, cooling conditions, quench protection, mechanical deformation, manufacturing technology, and cost. Magnetic iron adds only about 5 percent to the field.

(4) There is no inherent limitation on the size of the accelerator imposed by cryogenics. Refrigeration will be supplied by many distributed plants.

In this paper we discuss some of the technical considerations for 10-T accelerator magnets and present two example designs.

TECHNICAL CONSIDERATIONS

Current Density Required in the Windings A multi-TeV accelerator beam can in principle be very small (~20 mm diam), depending on design of the injection and extraction system, and on beam-cooling technology. The magnet cost is strongly dependent on magnet size. How small is reasonable? We believe that a 40-mm accelerator bore diameter (~60-mm winding diam) is feasible and is a reasonable goal for intital research and development. However, the combination of high field and small bore requires higher-current-density superconductors than used in present accelerator magnets. Fig. 1 shows how the required volume of superconductor, expressed in ampere-turns, varies with overall current density and coil inside diameter for an idealized "cosine-theta" winding (uniform radial winding thickness, current density varies as cos θ). For an idealized "intersecting ellipse" configuration the dependence on current density is more severe. The curves are for a design point of 400 A/sq mm, which we have used for our example designs. Higher current densities may be possible with new superconductor developments.

Current density in the superconductor Fig. 2 shows representative critical current density in the non-stabilizer cross section of Nb-Ti and Nb_3Sn [2]. It is clear that Nb-Ti must be refrigerated to a much lower temperature than Nb_3Sn to have a useful current density at 10 T.

Nb-Ti Various reported measurements on Nb-Ti are: Larbalestier [3], from 1050 to 1350 A/sq mm at 10 T, 2 K; Segal, et al [4], over 1000 A/sq mm at 10 T, 1.8 K; and for experimental material that has been "cold" extruded, greater that 1600 A/sq mm at 10 T, 1.8 K have been reported [2]. Experimental quantities of the ternary alloy Nb-Ti-Ta have given 1400 A/sq mm at 10 T, 4.2 K [4]

Nb_3Sn Multifilamentary Nb_3Sn has been fabricated by a number of methods. The only process that has been used on a large scale is the "bronze" process. Fig. 2 shows that the 10 T, 4.2 K current density is relatively low. However, by addition of more tin than allowed by the conventional 14-to-15-percent-tin bronze alloy, much higher current densities have been produced in experimental materials. Current density reached using external diffusion of tin from electroplated external layers is much higher, as shown in Fig. 2 (also see Walker, et al [5]); these processes seem to be limited, by practical diffusion distances, to small strands (diam < 0.5 mm). However, there are active developments of methods to distribute nearly pure tin throughout wires of large diameter that, if successful, should produce practical cables with the high current density shown in Fig. 2.

Thus with expected improved material, design current density in the superconductor of at least 1000 A/sq mm from Nb-Ti at 2 K and Nb_3Sn at 4.5 K seems reasonable for future accelerators.

Copper stabilization Copper must be added to the conductor to limit quench voltages and to ensure stable operation. The minimum amount of copper required for stabilization is not known; the only reliable way to determine this limit is to construct model magnets, since many variables such as insulation and structural details also influence stability. The FNAL cable uses a copper-to-superconductor ratio of 1.8. With 1.8 K operation and somewhat lower current density at 10 T, a copper to superconductor ratio of 1.0 is expected to be stable.

Quench Protection A consequence of minimum stabilizing copper is very rapid heating following a quench; for example, at a current density of 1000 A/sq mm in the superconductor, and a copper-to-superconductor ratio of 1.0, the maximum safe discharge time is about 0.4 sec. (approximately equal to L/R for discharge to an external load R). At 10 T, a 40-mm aperture (60-mm coil inside diam) magnet with an overall current density of 400 A/sq mm in the windings will have a stored energy as large as 5 MJ for a 5-m-long magnet. If we choose a maximum discharge voltage of 2 kV, for example, the operating current must be 12.5 kA; ie, we must use a large cross-section conductor to have few turns and low inductance. Thus, we must wind very-small-bore coils with large cables -- a difficult task. It will also be difficult to design reliable insulation, in a limited space, for several kV.

EXAMPLE DESIGNS

Two representative types of 10-T winding designs for a 40-mm-diameter accelerator aperture are described: A "layer" or shell type winding (Fig 3) in which the cable is edge-wound on nesting cylindrical surfaces, and a "block" design (Fig 4).

Layer design Several advantages of the layer design are: The conductor is efficiently located close to the useful aperture; the ends of the windings are compact (Fig. 5), and it is convenient to grade the winding by using different cable in the lower-field outer windings. Disadvantages are: Wedge-shaped conductors or separate wedges are required to make the winding solid, and maximum magnetic pressure is developed at the midplane in the highest-field region -- an especially important factor for Nb_3Sn conductors.

The layer design has been widely used for accelerator magnets with lower fields. Design studies for a four-layer, 10-T, 50-mm-bore-diameter magnet made at FNAL includes a winding configuration similar to that shown in Fig. 3 and is described in detail in another paper in these proceedings [6]. A low-current-density, large bore, six-layer design for 10 T was made earlier. [7]

Block design The advantages of the "block" design are: Rectangular cable (no wedges); maximum magnetic pressure is developed in the low-field region. Disadvantages are: "Turned-up" ends are more complex (Fig. 6): placement of conductor is slightly less efficient; graded windings require joints within the block; and maximum stress in the windings is higher.

Fig. 7 shows the location and magnitude of the maximum principal stress in the 10-T layer and the block designs. Zero-shear-stress surfaces are assumed: between layers in the "layer" case and on the horizontal surfaces on the outside and between layers 2 and 3 in the "block" case. In both cases, sufficient pre-load is applied to preclude tensile stresses under magnetic loads.

Common features Both designs have a laminated, non-magnetic, close-fitting structure to hold the windings in position, axial tie bars to support the end-to-end magnetic load, and a magnetic iron yoke that also acts as the main support structure for radial magnetic forces. A design with thermal insulation between the coil and the iron has much less mass to cool down, but additional structure is required. It is not yet determined whether warm iron, cold iron, or no iron is the preferred design for a large accelerator; it is much easier to maintain the required high field uniformity ($\Delta B/B = 1\text{-}4 \times 10^{-4}$ at a diam of 25 mm) without saturated iron nearby.

EXPERIMENTAL PROGRAMS

There are two experimental programs in the U.S. and one in Japan directed toward the development of small-bore, high-field accelerator magnets.

The FNAL program, which is part of a cooperative effort between KEK and FNAL, is to build a 4-layer magnet using a Nb-Ti-Ta alloy, now under development [6].

The LBL program includes two models under construction. One is also a 4-layer design similar to Fig. 3 using Nb-Ti cable, no fiberglass, and very little epoxy. The other is a four-block design similar to Fig 4 [7], using a high-current cable with 12 strands of 1.7-mm-diam wire, fiberglass insulated, and epoxy-impregnated after winding and reaction.

The KEK program in Japan [2,9] follows both the Nb-Ti and Nb_3Sn approaches.

Major goals of these early model programs is to determine the minimum amount of copper required for stability and to investigate quench-propagation behavior.

CONCLUSION

Based on design studies and material tests, we have concluded that 10-T, small-bore accelerator dipole magnets are feasible, but extensive design and model testing are required.

ACKNOWLEDGEMENT

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

REFERENCES

1 Proceedings of the Workshop on 'Possibilities and Limitations of Superconducting Magnets for Accelerators'; International Committee on Future Accelerators (ICFA), International Union of Pure and Applied Physics. Sevpukhov, USSR, Oct 1981 (to be published).

2 Hirabayashi, H. '8-10 T Dipole Magnets at KEK', ICFA Workshop (see Ref. 1).

3 Larbalestier, D. C. 'Niobium-Titanium Superconducting Materials', in S. Foner and B. Schwartz (eds.), Superconducting Materials Science, ch. 3. Plenum Publishing Corp., 1981.

4 Segal, H. R.; Hemachalan, K.; de Winter, T. A.; and Stekly, Z. J. J. 'Developmental Nb-Ti Conductor for High-Field Applications', IEEE Trans. on Magnetics, vol MAG-15, no 1, Jan 1979.

5 Walker, M. S., et al 'Properties and Performance of Fine-Filament Bronze-Process Nb_3Sn Conductors', IEEE Trans. on Magnetics vol MAG-15, no 1, Jan 1979.

6 Ishibashi, K. and McInturff, A. D. 'Stress Analysis of Superconducting 10-T Magnets for Synchrotrons', Proc. of the Eighth International Cryogenic Engineering Conf., Kobe, Japan, May 1982.

7 Taylor, C. E.; Meuser, R. B.; and Wolgast, R. C. 'Preliminary Design of a Nb_3Sn Dipole Magnet'; ICFA Workshop (see Ref 1).

8 Taylor, C. E., and Meuser, R. B. 'Prospects for 10-T Accelerator Dipole Magnets', IEEE Trans. on Nuclear Science, vol NS-28 no 3, June 1981.

9 Hirabayashi, H.; Shintomi, T.; and Wake, M. 'Stress Analysis in a High-Field Dipole Magnet Design', Proc. of the Eighth International Cryogenic Engineering Conf., Kobe, Japan, May 1982.

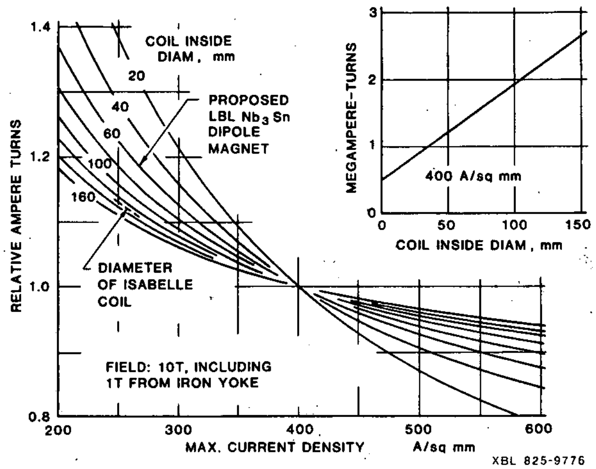


Fig. 1 Effect of coil inside diameter and current density on ampere-turns required (idealized cosine-theta winding).

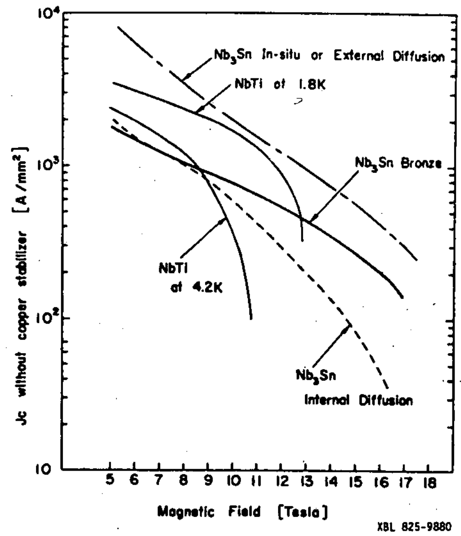


Fig. 2 Critical current density in non-stabilizer region of Nb-Ti and Nb_3Sn superconductors.

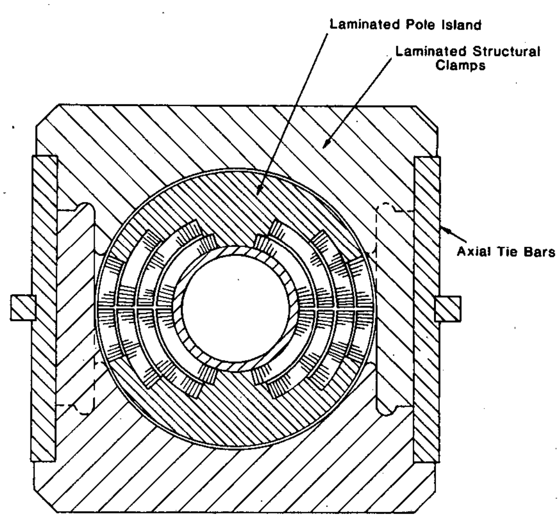


Fig. 3 "Layer"-type magnet cross-section.

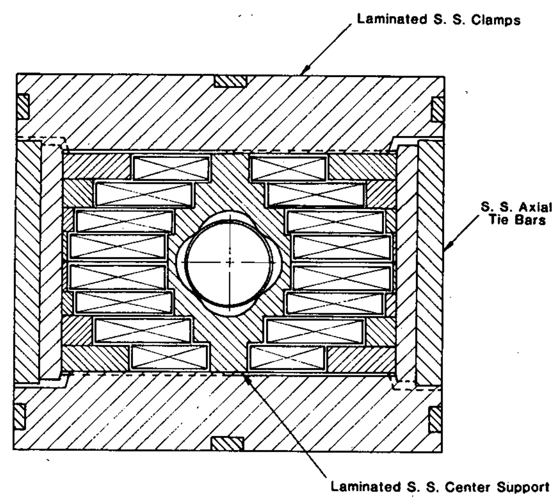


Fig. 4 "Block"-type magnet cross-section.

Figures 5 and 6 are on the following page.

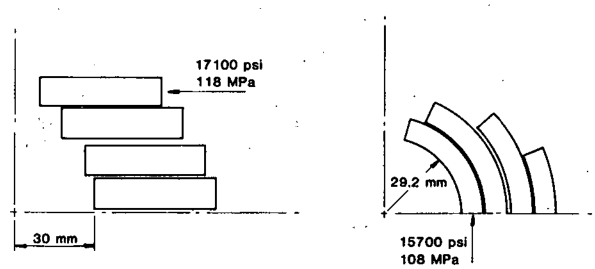


Fig. 7 Magnitude and position of maximum principle stress in 10-T layer- and block-type magnets. Stresses are averaged over face of conductor.

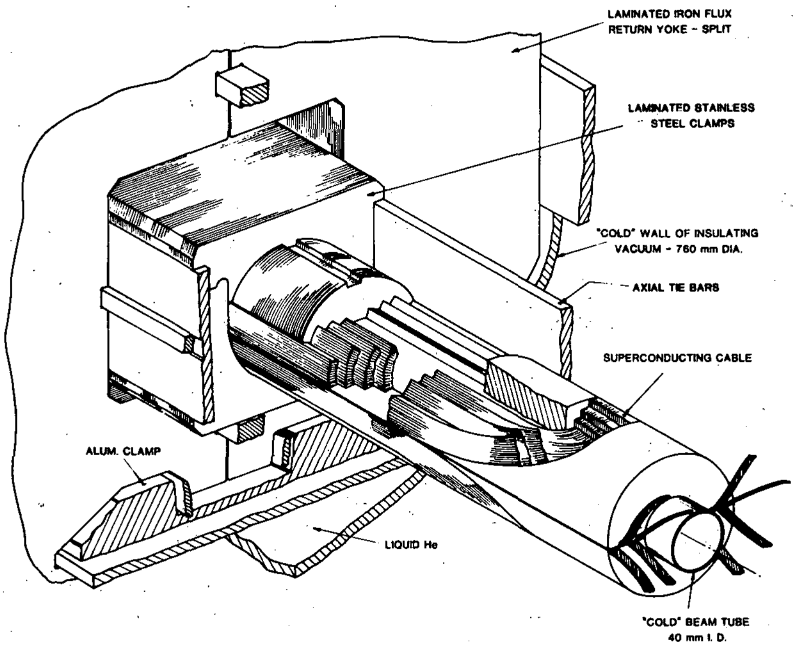


Fig. 5 "Layer"-type magnet end region.

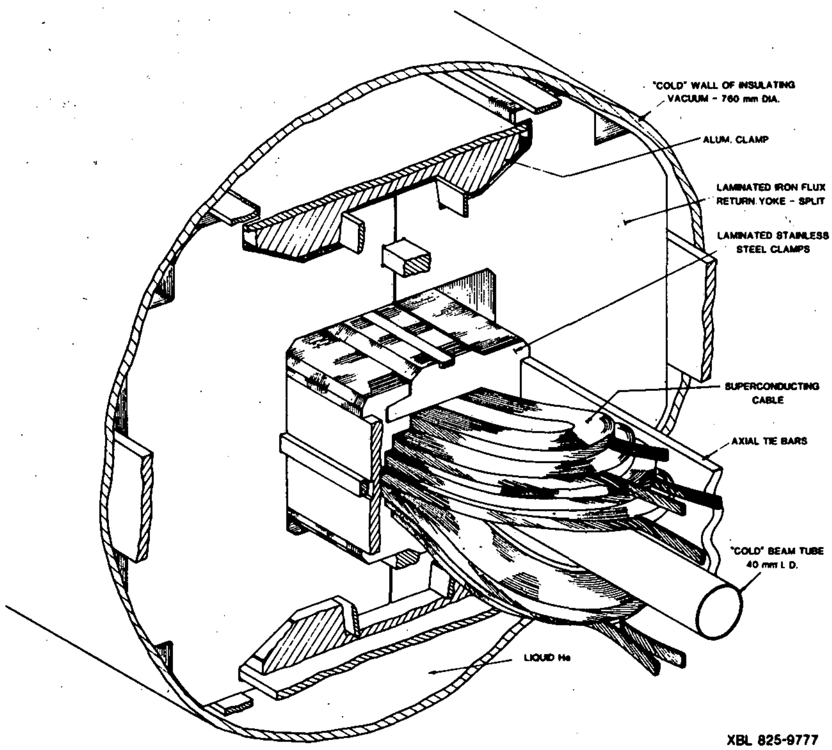


Fig. 6 "Block"-type magnet end region.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720