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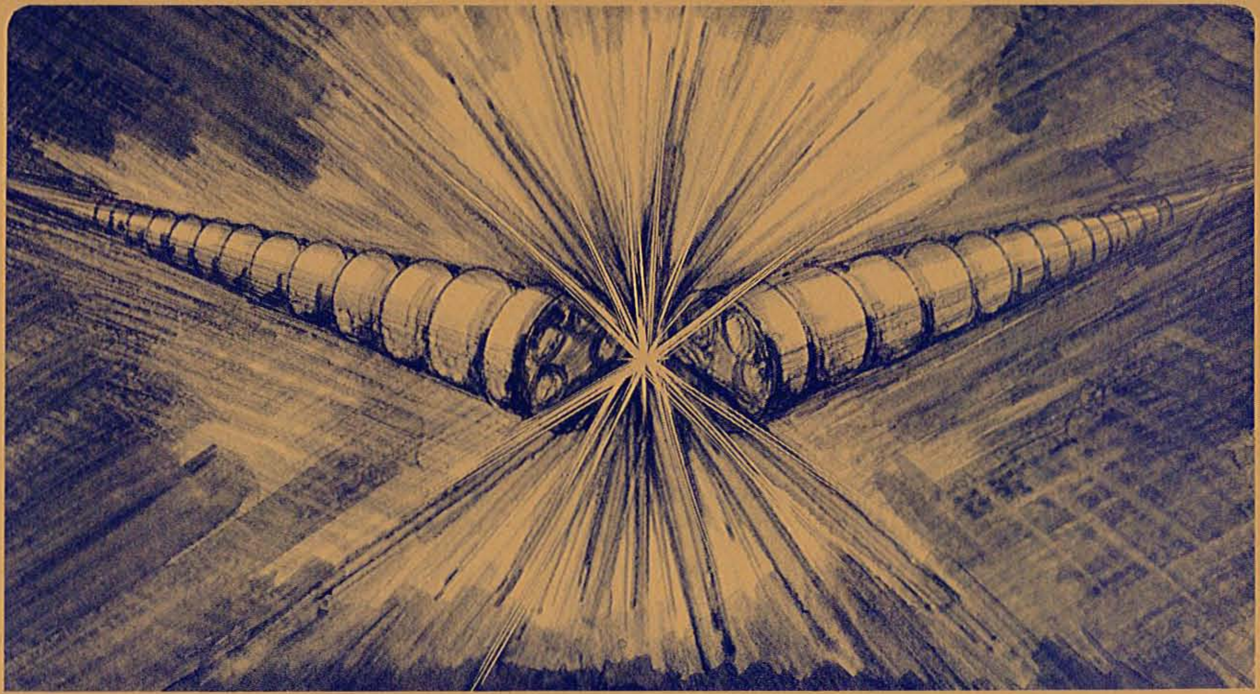

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TECHNICAL CONSIDERATIONS

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

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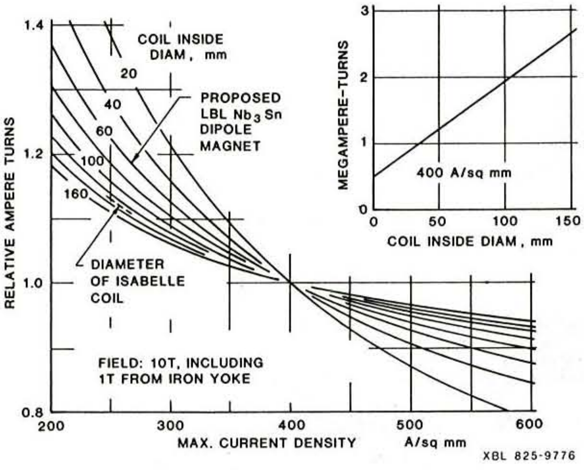


Fig. 1 Effect of coil inside diameter and current density on ampere-turns required (idealized cosine-theta winding).

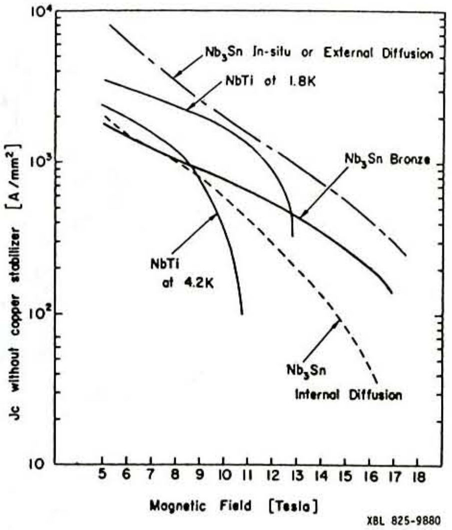
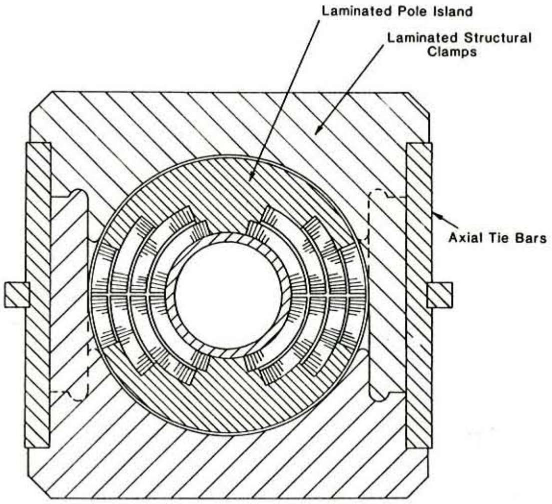


Fig. 2 Critical current density in non-stabilizer region of Nb-Ti and Nb_3Sn superconductors.



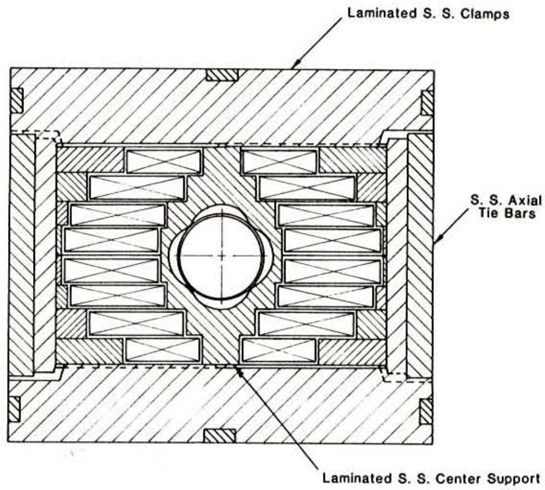


Fig. 3 "Layer"-type magnet cross-section. Fig. 4 "Block"-type magnet cross-section.

Figures 5 and 6 are on the following page.

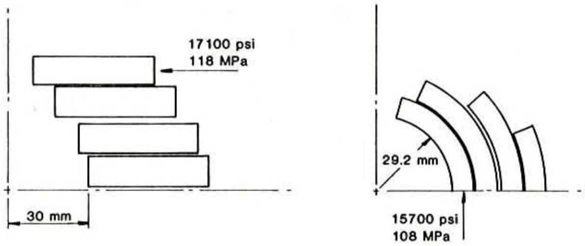


Fig. 7 Magnitude and position of maximum principle stress in 10-T layer- and block-type magnets. Stresses are averaged over face of conductor.

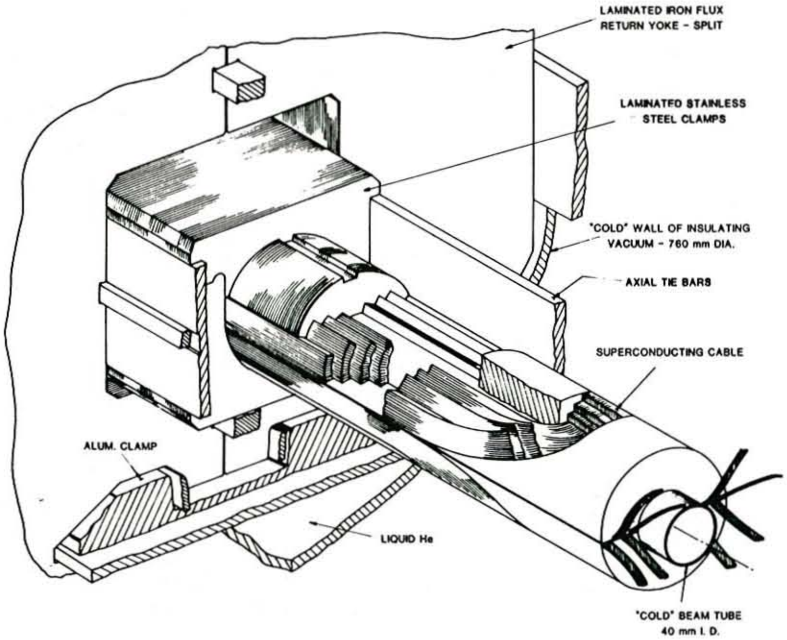


Fig. 5 "Layer"-type magnet end region.

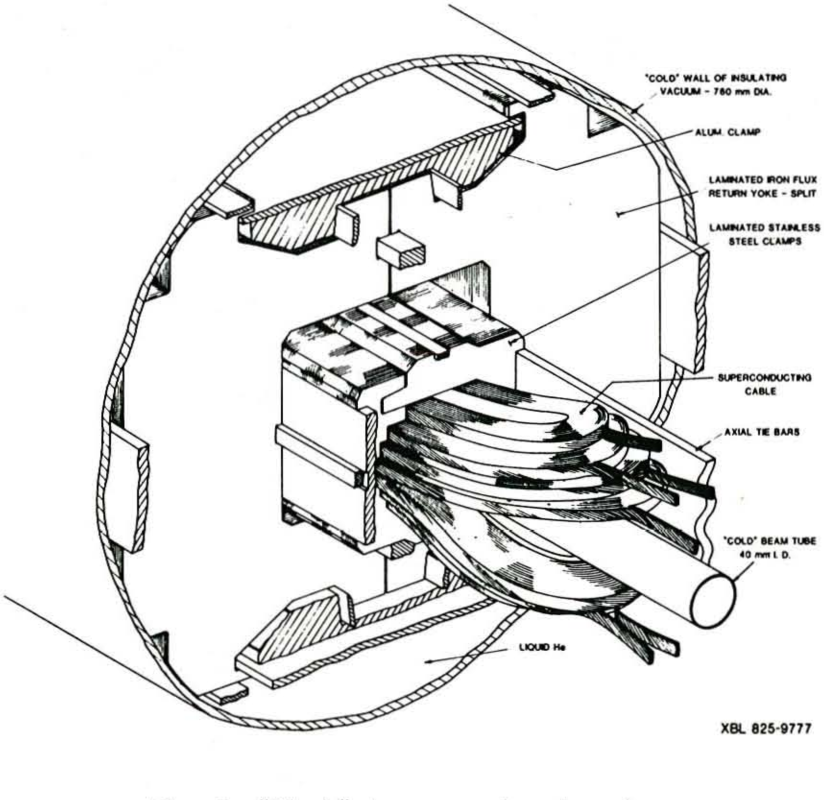


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Fig. 6 "Block"-type magnet end region.