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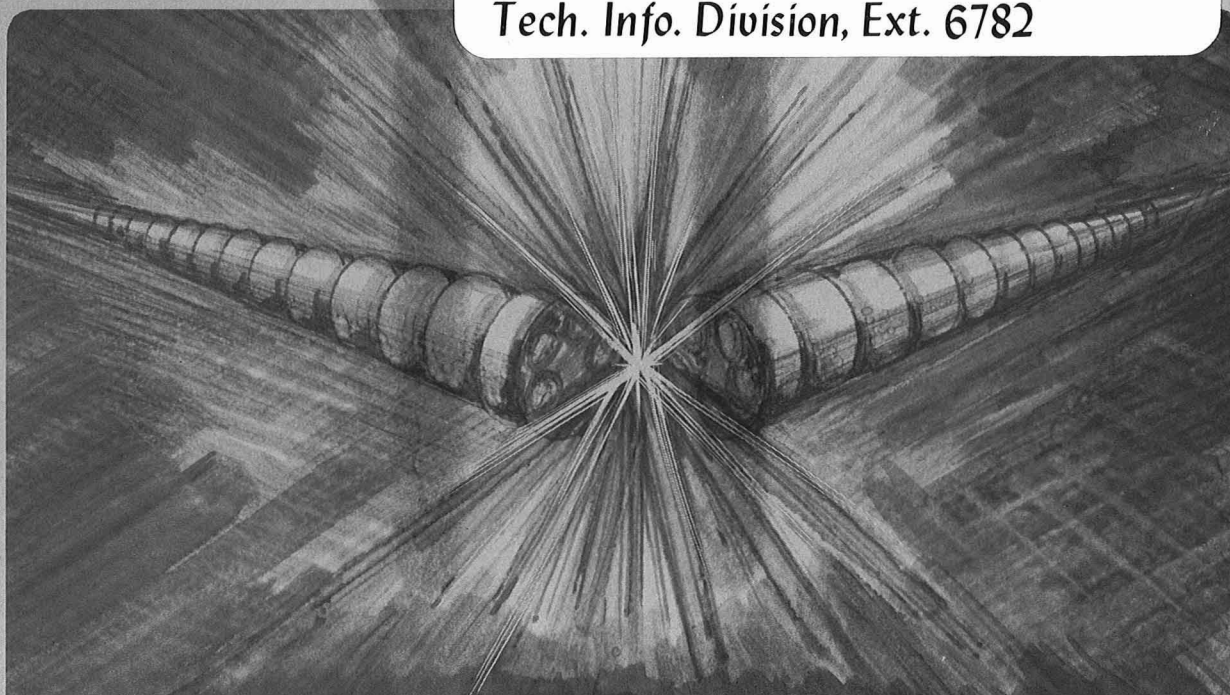
PRELIMINARY DESIGN OF A Nb_3Sn 10-T DIPOLE MAGNET

C.E. Taylor, R.B. Meuser, and R.C. Wolgast

October 1981

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Preliminary Design of a Nb₃Sn 10-T Dipole Magnet

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We present here a preliminary design for a small-bore (7 cm) 10-T dipole magnet based on Nb₃Sn at 4.4 K. It is not an optimized design but shows what is possible with presently-available bronze-process superconductors.

Construction Principles

Figs. 1, 2, and 3 show the general arrangement of windings for a 7-cm-bore dia. with a "three-block" winding design. Each "block" is wound of flattened cable in a spiral-in-spiral-out double pancake with an electrical crossover at the inside.

Unreacted cable is spiral-wrapped with fiberglass or quartz insulation, wound into a double-pancake winding, and then reacted. After reaction, each double-pancake winding is vacuum impregnated. Electrical connections are made on the outside of the impregnated winding by soldering a Nb-Ti cable to the Nb₃Sn cable. The windings are then stacked around a center structure and clamped from the sides with a split collar system consisting of stacked laminations.

In the illustrations a cold-iron support system is shown; the split stainless steel collars are thin and are secured at top and bottom by keys; the magnetic forces are transmitted to the split iron yoke. A stainless steel tie-bar placed along each side of the coil supports the axial magnetic forces acting on the ends and serves as a pad to transmit the large horizontal forces to the iron; the thermal elongation of the tie-bars nearly matches that of the windings; thus the windings, collars, and tie-bars can slide axially as a unit within the iron during cooldown and warmup without subjecting the windings to changes in strain. The clamped coil assembly, with tie-bars, is centered in the iron by two keys located in the mid-plane.

The iron yoke is split vertically and held together with a tie bar on top and bottom. These tie bars are aluminum alloy and are designed to maintain a nearly constant pre-load on the windings during cooldown and warmup. The iron is supported axially by tie bars, independent of the winding support system.

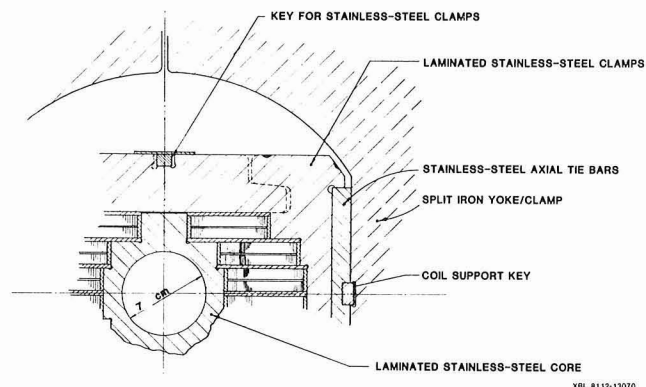


Fig. 2. 10-T, 70-mm-bore dipole; winding cross section

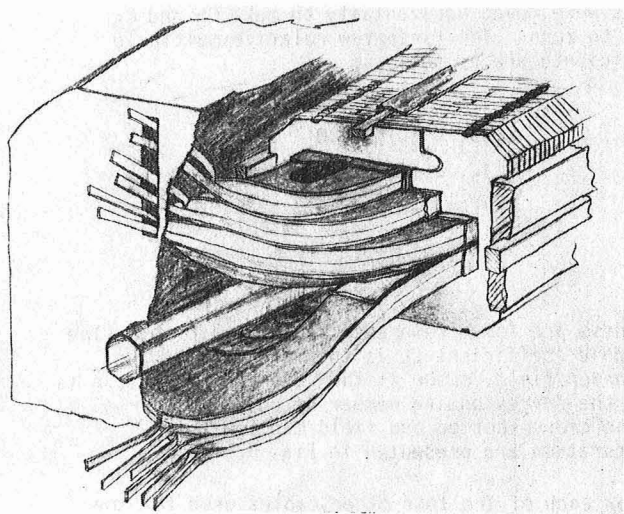


Fig. 1. 10-T, 70-mm-bore dipole; general arrangement.

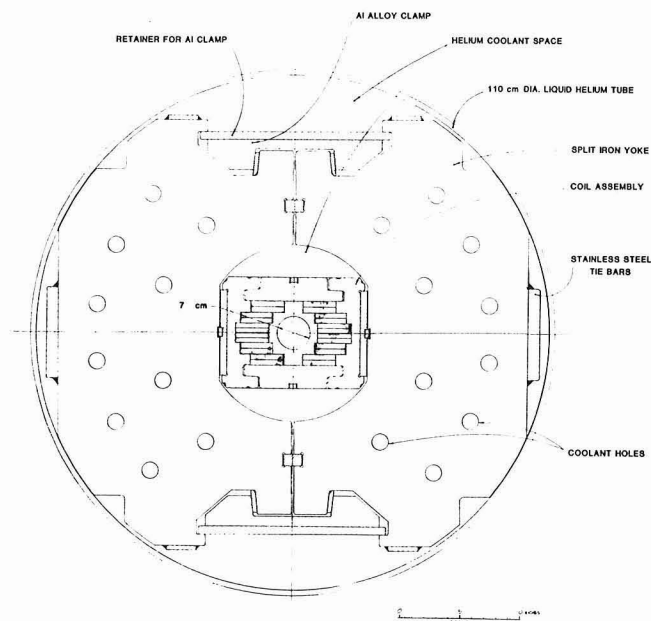


Fig. 3. 10-T, 70-mm-bore dipole; overall cross section.

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This winding can also be used with a separate cryostat surrounded by warm iron; in that case the stainless-steel clamps must be much thicker in order to limit the coil deflections, and the cryostat supports must be carefully designed to maintain field quality and limit heat leak. A discussion of the relative merits of warm and cold iron is beyond the scope of this paper.

The average outward magnetic pressure of the windings against the clamps is about 85 MN/m^2 , with the maximum of about 106 MN/m^2 occurring on the upper windings. The total outward force is about 10 MN/m . The maximum vertical magnetic pressure at the mid-plane of the winding occurs at a distance from the inner coil radius of about .4 of the total block thickness and is about 30 MN/m^2 .

The conductor is assumed to be a bronze-process Nb_3Sn cable with J_c of 700 A/mm^2 in the Nb plus bronze. If we assume that 50 percent of the cable is superconductor (Nb + br), 45 percent is Cu, and 5 percent is other metal, and we assume a reasonable insulation thickness, the overall current density is 285 A/mm^2 at 10 T (245 A/mm^2 at the maximum field of 10.6 T). The total cross-section of the windings, including insulation, is 185 cm^2 .

Significant reduction in superconductor, structure, and iron, results from decreasing the bore diameter. For example, Fig. 4 shows a 3.8-cm-bore magnet; a comparison of the materials required per meter of magnet is shown in Table 1.

TABLE I
Material Required per Meter Length

	7 cm bore	3.8 cm bore
Stainless Steel	600 Kg	300 Kg
Magnetic Iron	5000 Kg	2560 Kg
Cable	96 Kg	68 Kg

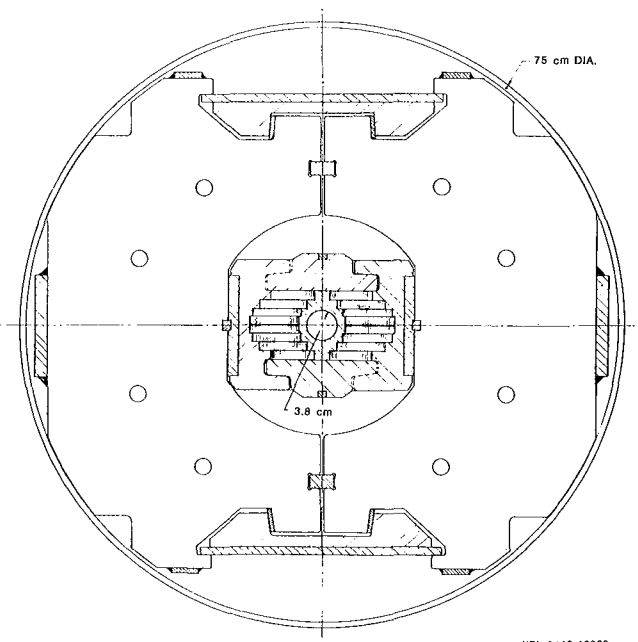


Fig. 4. 10-T, 38-mm-bore dipole; overall cross section.

The cost of the smaller magnet will be significantly less. Therefore, it seems desirable to develop a very-small-bore magnet for a large accelerator.

The horizontal widths of the windings at the midplane is about 64 mm, or .91 and 1.7 times the bore diameter, respectively, for the 70 and 38 mm bores. This results in rather inefficient use of conductor in these small magnets. 700 A/mm^2 is a reasonable current density for presently available materials; however current density of 1000 to 1500 A/mm^2 at 10 T is possible if experimental fabrication methods can be scaled to large-volume production; these higher current densities will result in significant increases in efficiency of the small magnets.

Grading

A study was undertaken to determine the effect of grading upon the total conductor requirements and other parameters. (The results presented here are preliminary in nature, and merely a first step in the design process.)

Dimensional characteristics of the conductor used in the study are as follows:

Space factor of uninsulated conductor, 0.88; insulation thickness, each of four sides, 0.13 mm (0.005 in.); overall depth of insulated conductor, 9.017 mm (0.355 in.).

No. of strands	Strand diameter		Overall width	
	in.	mm	in.	mm
27	0.0256	0.649	0.0556	1.413
23	0.0300	0.762	0.0636	1.614
19	0.0363	0.922	0.0748	1.901
15	0.0460	1.168	0.0921	2.340
11	0.0627	1.593	0.1220	3.098

For the un-graded coil, block widths were selected to give an approximation to an overlapping-ellipse configuration. The upper two blocks were moved horizontally to make C_3 and C_5 equal to zero. The first few relative multipole coefficients are as follows:

$$\begin{aligned} C_3/C_1 &= C_5/C_1 = 0 \\ C_7/C_1 &= +2.0 \times 10^{-4} \\ C_9/C_1 &= -2.8 \times 10^{-4} \\ C_{11}/C_1 &= +0.8 \times 10^{-4} \end{aligned}$$

These are for a reference radius of 30 mm. (The multipole coefficient C_n is the magnitude of the n -th order field vector at the reference radius; n is twice the corresponding number of poles.)

The cross-section and field map for this configuration are presented in Fig. 5.

For each of the four other cables used for the inner parts of the blocks, the block widths were adjusted to give the same aperture field, the field plotted, and the position of the dividing line between the two conductors was adjusted to make both conductors critical at the same current. The block positions were not readjusted to preserve the field quality. The resulting configurations are illustrated in Fig. 6.

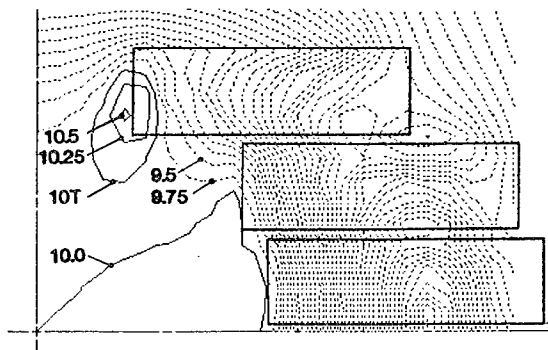


Fig. 5. Cross section (first quadrant) and field map for ungraded 10 T dipole magnet.

The effects of grading on the total superconductor cross section are as follows:

Strands, inner regions	Relative total super- conductor cross-section
27, ungraded	1
23	0.83
19	0.71
15	0.65
11	0.62

Mechanical stresses were calculated for a "slippery conductor" model (zero shear stresses) using 27 and 21 strand conductor. In turn, the conductor displacements, for linear stress-strain

behavior, and the corresponding changes in field quality were calculated. It was assumed that the pre-stress was sufficient to prevent the inner edges of the layers from separating from the coil form, an essential feature. The results are as follows:

Required prestress: 67 MPa (10 kpsi)
 Max horizontal stress: 106 MPa (15 kpsi)
 Max vertical stress: 27 MPa (4 kpsi)
 Max horizontal displacement: 1.3×10^{-3} mm
 Max vertical displacement: 24×10^{-3} mm

n $\Delta/C_0/C_1$ at $r=30$ mm
 3 21×10^{-6}
 5 4×10^{-6}
 7 etc. $< 1 \times 10^{-6}$

* for $E = 69$ MPa (10×10^6 psi), This reference elastic modulus of 69 MPa (10^7 psi) is greater by a factor of 2 to 3 than that which can be expected, and so the above values are proportionally smaller than can probably be achieved in practice.

Conclusion

This preliminary result shows that a "block" winding design can produce a theoretical field uniformity of about 10^{-4} . The effects of winding deformation on field uniformity are small. The effects of structure deformation were not considered but are expected to be small with a "cold iron" structure. Reducing the bore diameter will result in significant reduction in weight of materials required (and, therefore, cost). However, J_c should be increased from ~ 700 A/mm² to ~ 1000 - 1500 A/mm² for efficient use of conductor for bore diameter smaller than 7 cm.

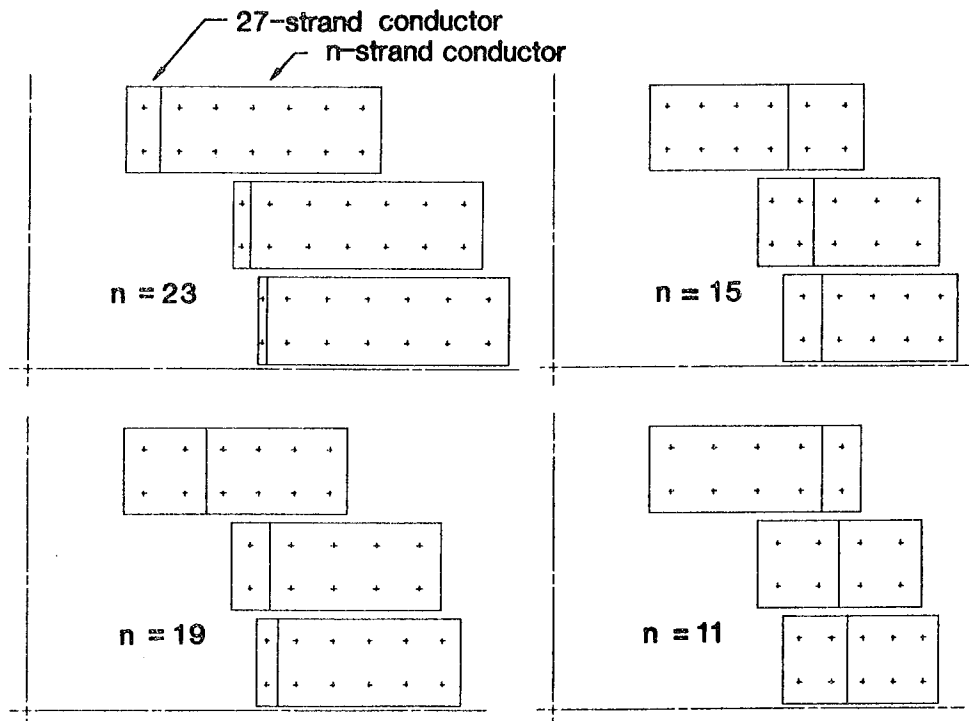


Fig. 6. Cross sections of graded-conductor 10-T dipole magnets.