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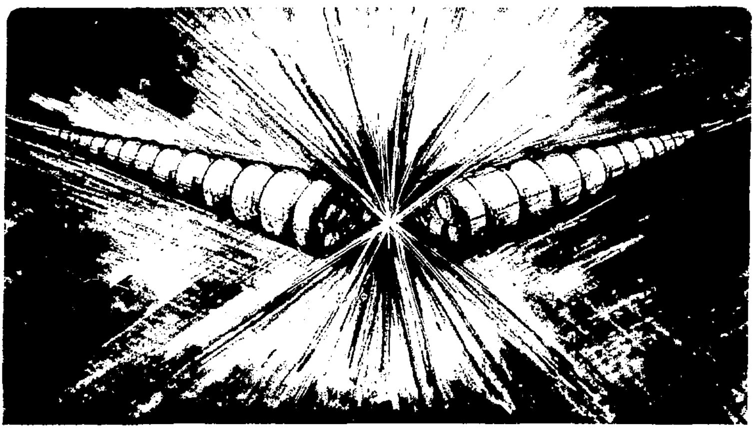

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PROSPECTS FOR 10T ACCELERATOR DIPOLE MAGNETS*

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Introduction

A next-generation major accelerator will require the highest possible field to minimize the circumference; however, there have been no proven designs for suitable magnets with fields substantially higher than 5T. A number of successful 4 to 5T dipole magnets have been built in recent years; these have involved long and difficult development projects. The 3" bore 4.25T magnets for the Doubler are being produced by the hundreds at Fermilab, and a number of prototypes of the 5.2" bore 5T ISABELLE magnets have been built. Successful short, ~5T models have been made at SACLAY, KEK, and Serpukhov. and a number of model magnets with lower fields have been built at many laboratories. Field uniformity achieved in these magnets is about

$$\frac{\Delta B}{B} \approx 10^{-3}$$

We can certainly expect 10T magnets with higher field uniformity to be a challenging development task.

We briefly discuss the general problems of high-field (10T) magnets in terms of superconductor performance and mechanical limitations.

Superconducting Materials

Fig. 1 shows current density vs. field intensity for several candidate superconductors.

We show here only the "commercially available" materials: Nb-Ti, Nb-Ti-Ta, and Nb_3Sn. Current density is based on superconductor area for Nb-Ti and Nb-Ti-Ta, but includes the area of superconductor, bronze, and Ta diffusion barrier material for Nb_3Sn. A realistic design, with stabilizing Cu, insulation, space for helium, and structural materials, would have much lower overall current density than shown; however, Fig. 1 is useful to compare the materials because the relative overall current density will not be changed significantly by addition of insulation, stabilizer, etc. The Nb_3Sn curve represents commercial bronze-process multifilamentary wire produced in large amounts(1). The shaded region includes the wide range of properties that have been produced in small batches and represents improvements that might reasonably occur with future development.

Above about 8T, Nb_3Sn has slightly higher current density than Nb-Ti at 4.2K, and above 9T Nb_3Sn is clearly superior. At 9T and 4.5K Nb_3Sn has about twice the current density of Nb-Ti; however, when the temperature is decreased to 1.8-2K, the current density of Nb-Ti is dramatically increased, whereas the current density of Nb_3Sn is increased only slightly; thus at 9T, Nb-Ti at 1.8K has about twice the current density of Nb_3Sn at 4.2K. At 11T the relative current densities of Nb-Ti at 1.8K and Nb_3Sn at 4.2K are comparable.

Addition of various materials to Nb-Ti can further increase the current density and extend its

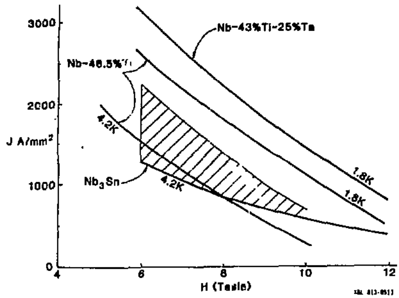

Figure 1. Short-sample characteristics of commercially available superconducting materials at 4.2K and 1.8K.

usefulness to about 13T. A curve for Nb-43%Ti-25%Ta is shown; however Ta is costly, and considerable effort is being expended to find lower-cost materials to enhance the J_c of Nb-Ti(2).

Nb_3Sn and other A-15 Materials

Nb_3Sn is expected to exhibit more electrical stability in high-current-density magnets (i.e. less tendency to "train") because of its high critical temperature. Unfortunately, it is a brittle material and fractures easily under tension. However, because it is formed at high temperature (~750C), usually in the form of fine filaments (~5μ) imbedded in a bronze matrix, the Nb_3Sn undergoes very high compression as the bronze cools from ~750C. In this condition the composite conductor (Nb_3Sn + bronze) can withstand considerable tensile strain without breaking the superconducting filaments. Fig. 2 shows typical behavior of critical current vs. tensile strain(3); if tensile strain exceeds ~0.7-0.8 percent, permanent deterioration occurs. Since we can limit the strain in a magnet structure to values less than this limiting strain, Nb_3Sn can, in principle, be useful if the magnet winding is very stiff, well confined and thus cannot deflect more than the surrounding structure will allow. However, this strain limit will severely restrict the manner in which the conductor can be bent during coil fabrication without degredation; for example, to be bent around a 50mm diameter, the conductor can be no more than about 0.2mm thick.

A wider conductor in the form of flattened cable of the Doubler size (~1.5mm thick) must be wound prior to reaction, which requires insulation that can withstand the reaction temperature. Unfortunately, after reaction the bronze surrounding the Nb_3Sn filaments is depleted of Sn and is fully annealed, as is the stabilizing Cu. Therefore, the conductor has a much lower strength than a similar Nb-Ti cable that

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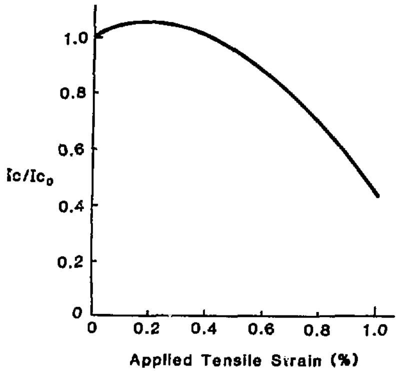

Figure 2. Strain degradation of single-strand LCP - type Nb_3Sn conductor.

can be hardened by cold work. When we compressed a stack of reacted cable, it yielded continuously above a few kpsi; at 15kpsi the compression is ~4 percent and at 30kpsi it is 6.5 percent. If the cable were well confined and had no space to spread into, the stack would be much stiffer. In contrast, unreacted cable can be very stiff depending on the degree of annealing before cabling.

During reaction at ~750C the conductor and insulation must be reasonably 'loose'; then after cooling, the winding must be compressed into its final shape. The brittle Nb_3Sn could be damaged during this operation. We have measured critical current at 10T of bare cables (not epoxy inpregnated) that we squeezed after reaction to 15,000 psi in a direction normal to the flat side, and preliminary results indicate no significant degredation (at $\rho \approx 10^{-11}\Omega$-cm), even though the cable had been permanently yielded 4 percent in the direction of squeezing; however at 30,000 psi the cable was severely damaged.

There has been very limited experience with Nb_3Sn in accelerator magnets. Using the wind-before-react method and epoxy impregnation, a quadrupole has been built at CERN(4) with an expected overall current density in the winding of 300A/mm^2 at 4.2K with B_{max} = 7.4T; a 3.5T, 6.2cm-bore dipole was built and tested at KEK(5), and models are planned at several laboratories. Experiments on prereacted, thin braids have been made at BNL and several dipoles have been made using the general winding method developed for ISABELLE(6).

There are many other A-15 superconductors which are promising for very high fields; however, none appear to be competitive with Nb_3Sn at 10-12T. Unfortunately, all are mechanically brittle. The addition of small amounts of Hf to the Nb and Ga to the bronze results in large increases in J_c of Nb_3Sn for fields above 10T(7).

Stresses in the Winding of 10T Dipole Magnets.

We believe that stresses and deflection within the windings of 10T magnets will be major design limitations. Several types of winding configuarations have been investigated, and all have high compressive stresses within the windings.

Example of a 10T 1.8K, Nb-Ti Design

As an example, we show a comparison of several six-layer configurations, to be operated in helium II. The conductor is a flat, Rutherford-type, Nb-Ti cable having a copper-to-superconductor ratio of 1.5, 27 strands, and a cable void volume of 10 percent. The inside radius of the innermost layer is 40mm, and the inside radius of the iron is 200mm. The cable is wrapped with two layers of film insulation (Mylar, Kapton), and is wound "dry" (no epoxy). The conductor is graded in pairs of layers so that the critical current is the same in each pair; this grading results in a saving in superconductor of about 20 percent. The strand diameter in the inner pair of layers is 0.025in; that in the outer layers is smaller, the size depending on the local field intensity.

The short-sample curve for Nb-Ti at 1.8K in Fig. 1 was used in this study, but the critical current was decreased by a factor of 0.97 to account for the J_c in strands being lower than the published short-sample data, and a factor of 0.90 to account for the J_c in cables being less than that of the sum of the strands. The field intensity in the aperture is 10.9T at "short sample", giving a margin of safety at 10T of about 40 percent.

The innermost two layers, and the outermost four, are two mechanically independent coils. The inner coil has a "block-type" or "cosine theta" configuration. Circumferential magnetic forces are transmitted to the wedge-shaped spacers, and from them to tube segments; this "compartmenting" prevents the circumferential forces from accumulating, and reduces the stresses in those layers to about half of those for a non-compartmented design.

Several configurations for the outer layers were investigated(8) as illustrated in Fig. 3, along with the circumferential stresses ca. The stresses for cases 1 and 2 are uncomfortably high (22 to 25 kpsi). The stresses for case 4, having block-type windings, are much lower, particularly if they are compartmented, but such coils are not easy to construct. Case 3, a "60-degree" configuration has moderate stresses, which can be reduced to about 15,000 psi by a slight adjustment of the angles. A safety margin on the prestress, to ensure that no part of the coils will tend to go into tension, will increase the stresses somewhat.

Compression tests have been made at LBL on 23 strand cable with 0.027in. dia. strands (FNAL - Doubler size) insulated with Mylar and Kapton film. This conductor has been used, without epoxy, in 3in bore-dia layer magnets at LBL(9). Fig. 4 shows stress vs. strain for this combination; after the conductor has been squeezed into place and heated (100C) to aid compacting of the insulation, the effective Young's modulus of the stack of conductors is high (~6 x 10^6 psi at 77K). A high modulus is desirable to minimize elastic motion of the windings during operation.

A more complete design, based on Case 3, is shown in Fig. 5. The inner coil is surrounded by a ring-and-collet system which pre-stresses the coil.

The four-layer outer coil is either wound directly on the inner coil's ring-and-collet system, a layer at a time, or is constructed independently of the inner coil, and the inner coil inserted into it. The outer coil is surrounded by a thick ring-and-collet system, which pre-stresses the outer coil and accomodates the magnetic bursting forces.

The coil system is contained in a vessel which also contains the helium II. This vessel is surrounded by a 4K helium-cooled shield, and that in turn by a 77K nitrogen-cooled shield, both shields being in vacuum and surrounded by superinsulation. Finally there is the vacuum-vessel wall and then the iron shield.

Several rectangular-aperture configurations were also investigated[10]. The stresses are somewhat lower than for the design shown in Fig. 5, but the amount of superconductor required is much greater.

Refrigeration at 1.8K

There have been many small 1.8K refrigerators built and operated, but none in the multi-kW range. Three relatively large systems (~300W) were built and operated about 10 years ago with compressor power requirements ranging from 1200W/W at 1.8K with supplemental liquid nitrogen pre-cooling[11] to about 2000 without liquid-nitrogen[12]. (It is estimated that an improved cycle might require as little as 700W/W at 1.8K.)

With careful design, the heat input to the 1.8K region can be limited to hysteretic losses in the conductor. These losses depend on conductor design and pulse rate, but might be as low as 1W per m of length. The remaining heat leak into the magnet is removed at ~4.2K requiring about 500W/W at 4.2K. Therefore the total compressor power for the combined 1.8K–4.2K system might be no more than 1.5 times that of a 4.2K "conventional" system.

To maintain a reasonably uniform temperature of 1.8K around a ring of several km circumference will probably require many separate 1.8K refrigeration stations. From Ref. 13 Warren[14] derived the following equation for the distance between cooling stations, L(m): for a given heat input along the conduit of q/ℓ (W/m), maximum temperature difference of ΔT(K), and conduit cross-section of A(m^2),

$$L = 5\,(\Delta T)^{0.23}\left(\frac{A}{q/\ell}\right)^{0.77}$$

For example, for 1W/m, a maximum temperature difference along the ring circumference of 0.05K, and distance between cooling stations of 200m, the cross-sectional area of HeII required to conduct the heat is 280cm^2. This area is probably best provided within the magnet cryostat rather than in a separate conduit; to reduce the number of stations to 25 would require 700 cm^2; thus, there is a tradeoff between cryostat size and multiplicity of He II refrigerators. A 10km ring might have about fifty 1.8K cooling stations, each with 200W capacity if the pulsed losses can be as low as 1W/m. Such a refrigeration system poses no fundamental technical problems but it adds significant additional complexity to the accelerator. It will be important to design and develop a reliable HeII refrigeration system along with development of the magnet.

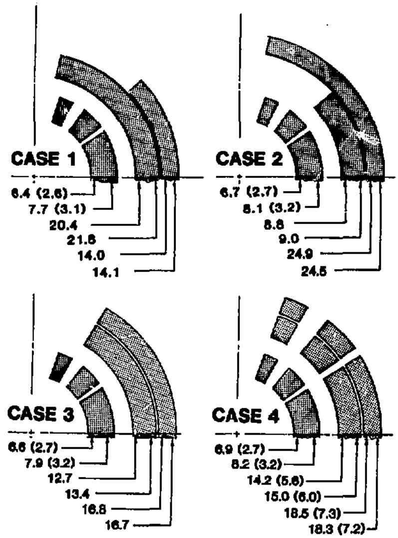

Figure 3. Coil cross sections considered in design study for Nb-Ti conductor at 1.8K, and circumferential compressive stresses (kpsi). Stresses in parentheses are the maximum stresses in each layer, for compartmented coils.

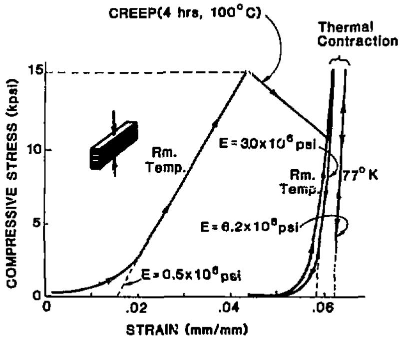

Figure 4. Effect of accelerated creep on stiffness of insulated Nb-Ti cable.

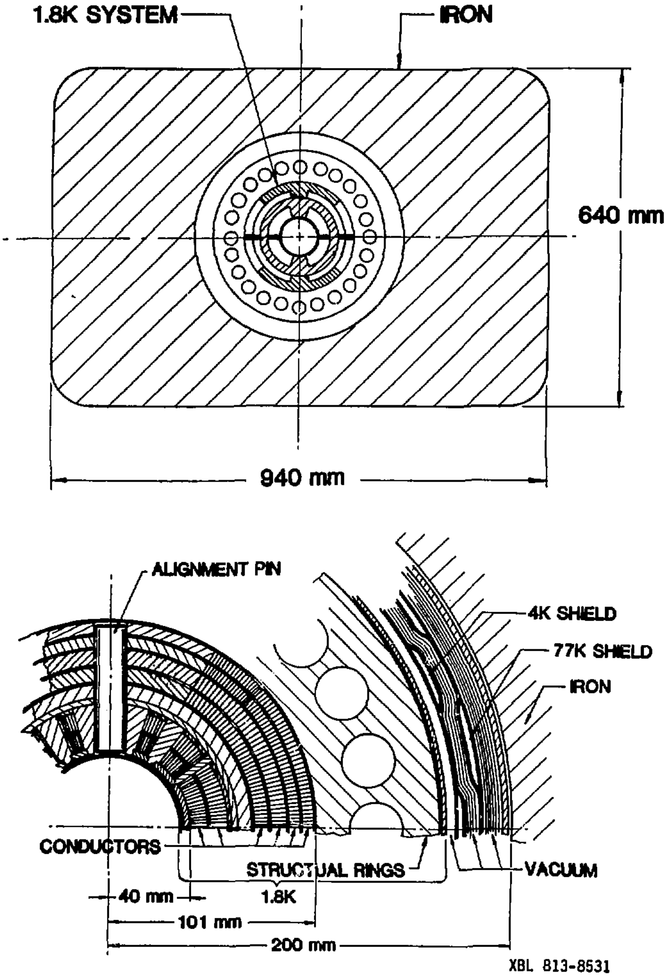

Figure 5. Cross-sections of six-layer dipole magnet using Nb-Ti at 1.8K.

costs[15] was based on present costs of superconductor and reasonable guesses about refrigerator costs and fabrication costs; the cost per T-m compared to "present day" 5T, 4.2K Nb-Ti magnets are indicated as follows:

Superconductor	Temp.	Field	Relative Cost per T-m
Nb-Ti	4.2K	5T	1
Nb-Ti	1.8K	10T	1.6
Nb-Ti-Ta	1.8K	10T	1.9
Nb_3Sn	4.2K	10T	2.5

There seems to be a significant advantage for Nb-Ti at 1.8K. However, this difference will be narrowed by graded designs, by development of lower-cost Nb-Ti-X alloys, and by development of lower-cost, high-J_c Nb_3Sn and other A-15 conductors. In the absence of experimental verification of magnet designs and more complete system studies, these cost comparisons must be considered very approximate. The optimum field intensity will, of course, be determined by comparing the increased cost of "bending power" at high fields with decreases in other costs such as tunnel construction, land, etc.

Conclusion

10T dipole magnets will be considerably more complex than 5T magnets. Compressive stresses in the windings are a major design consideration; however, present day materials can probably be used. Reasonable designs can be made for Nb-Ti at 1.8K; however, the He II refrigeration system is a major complexity. Nb_3Sn magnets will require much more development because of strain limitations, low strength after reaction, and high cost of present materials; however there is future potential for higher J_c and lower cost. Therefore, improved Nb_3Sn conductors for accelerator dipoles should be a major development goal for two main reasons: refrigeration can be simpler at 4.2K than at 1.8K and, for fields much greater than 10T, Nb_3Sn or other A-15 materials will be necessary.

References

1. P.A. Sanger, E. Adam, E. Ioriatte and S. Richards, "Critical Properties of Multi-filamentary Nb_3Sn Between 8 and 14 Tesla", IEEE Transaction on Magnetics, Vol. Mag-17, No. 1 January 1981.

2. David G. Hawksworth, David C. Larbalestier, "Further Investigations of the Upper Critical Field and the High Field Critical Current Density in Nb-Ti and its Alloys", IEEE Transaction on Magnetics, Vol. Mag-17, No. 1, January 1981.

3. R.M. Scanlan, R.W. Hoard, D.M. Cornish, and J.P. Zbasnik, "Mechanical Properties of High-Current Multifilamentary Nb_3Sn Conductors", Filamentary A15 Superconductors, Ed. by M. Suenaga and A. Clark, Plenum Press, 1980, p. 221.

4. A. Asner, Ch. Becquet, D. Hagedorn, Ch. Niqueletto and W. Thomi, "Development and Testing of High Field, High Current Density Solenoids and Magnets, Wound with Stabilized Filamentary Nb_3Sn Cable and Reacted After Winding", IEEE Transactions on Magnetics, Vol. Mag-17, No. 1, January 1981.

5. K. Ishibashi, M. Koizumi, K. Hosoyama, M. Kobayashi, and T. Horigami, "Nb_3Sn Dipole Magnet by Wind and React Process", IEEE Transactions on Magnetics, Vol. Mag-17, No. 1, January 1981.

6. W. B. Sampson, S. Kiss, K.E. Robins and A.D. McInturff, "Nb_3Sn Dipole Magnets", IEEE Transactions on Magnetics, Vol. Mag-15, No. 1 January 1979.

7. A. Tachikawa, "Developments of A15 Filamentary Composite Superconductors in Japan", Filamentary A15 Superconductors, Ed. M. Suenaga, A. Clark, Plenum Press, 1980, p. 1.

8. R. Meuser and A. Kennedy, "10-Tesla Dipoles with Circular Aperture", Lawrence Berkeley Laboratory Engineering Note M5689, Mar. 6, 1981.

9. C. Taylor, R. Althaus, S. Caspi, W. Gilbert, W. Hassenzahl, R. Meuser, J. Rechen, R. Warren, "A Novel Epoxy-Free Construction Method for Fabricating Dipole Magnets and Test Results", 1981 Particle Accelerator Conference, March 1981, Lawrence Berkeley Laboratory LBL-11752.

10. R. Meuser, "10-Tesla Dipoles with Rectangular Aperture", Lawrence Berkeley Laboratory Engineering Note M5690, March 6, 1981.

11. W. Daus, and J. Ewald, R., "A Refrigeration Plant With 300W Capacity at 1.8K", Cryogenics, Oct. 1975, p. 591.

12. W. Baldus, "Helium II Refrigerator for 300W at 1.8K", Ad. Cryo. Eng., Vol. 16, p. 163.

13. G. Bon Mardion, Claudet, G., and Seyfert, P. "Steady State Heat Transport in 'Superfluid Helium at 1 Bar", Proceeding of the Seventh International Engineering Conference, IPC Press 1978.

14. R. Warren, Lawrence Berkeley Laboratory Engineering Note M5330, April 17, 1979.

15. Hassenzahl, W., "A Comparison of Nb-Ti, Nb_3Sn, Nb-Ti-Ta, Superconductors for High-Field Accelerator Dipoles", 1981 Particle Accelerator Conference, March 1981, Lawrence Berkeley Laboratory LBL-11744.