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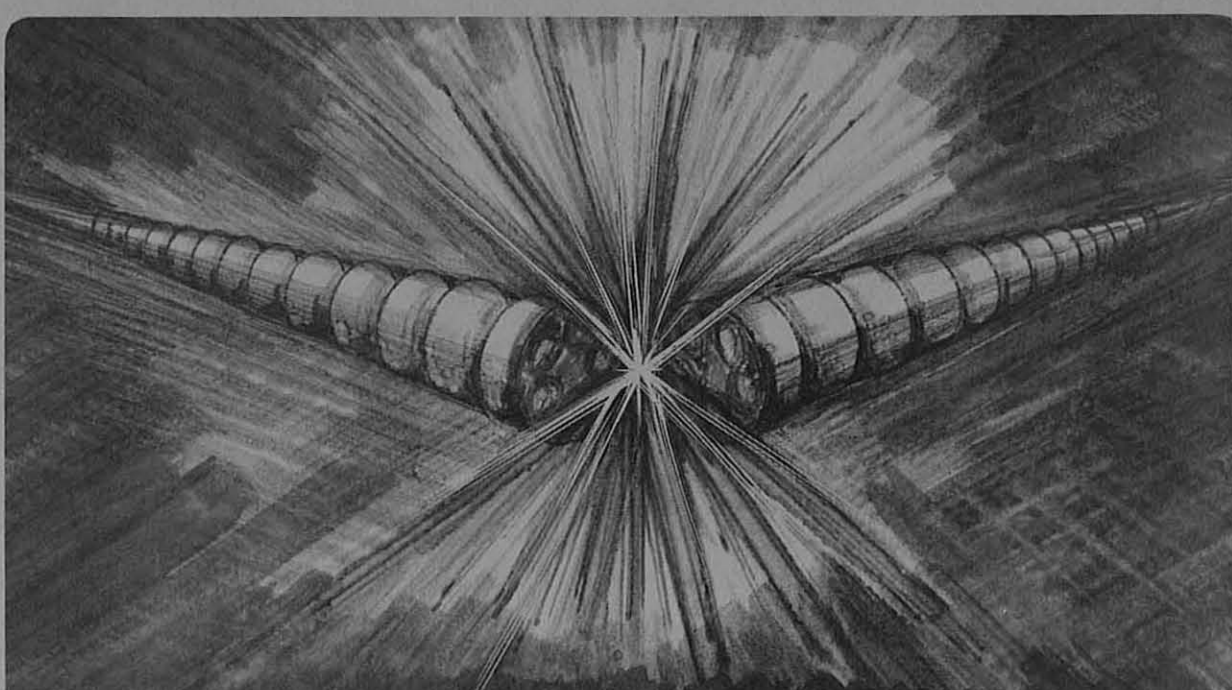

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Summary

Recent progress in technology of high-current- density cables for SSC model magnets is summarized. NbTi cable with J_c up to 50% higher than Tevatron cable can be expected. Magnetization effects can be predicted and corrected with several new techniques. Development of Superconductor with 2-3 μm filament diameter and high J_c is expected.

Introduction

With the successful operation of the Tevatron at 800 GeV, with 990 superconducting magnets, 774 dipoles and 216 quadrupoles, superconducting accelerator magnets can be considered a proven technology for large-scale applications. However, with large proposed accelerators such as the SSC, cost considerations require us to minimize the amount of materials needed. Aperture and magnetic field intensity have a large influence on cost of superconducting magnets, as does performance of superconducting wire. In the past two years, a preliminary development program at several laboratories, aimed at next-generation high energy physics accelerators, has resulted in several significant advances in technology that have a direct bearing on new designs. Superconductor performance, training behavior, and field quality are important for accelerator magnets; these are particularly important for high-field magnets because of cost. A simple scaling of the cost of superconducting cable and iron with field and aperture for a two-layer magnet design based on collared coils and cold iron is shown in Fig. 1. These values include only costs of cable and iron and are intended only for relative comparisons of 2-layer cold iron dipoles. The cost per tesla-meter of "bending power" of these two materials increases approximately with $B^{1.3}$ and directly with aperture. At higher fields, for a given accelerator energy, the magnet costs‡ may dominate the total accelerator facility cost.

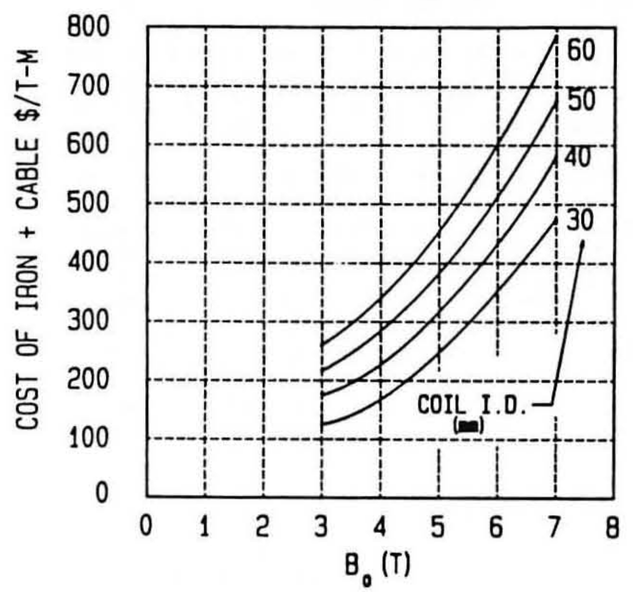

Fig. 1.

The incentive for higher fields is that the tunnel circumference and cost is inversely proportional to field, and careful optimization must be done to select the field intensity that minimizes total cost.

Consideration of a high-field alternative for the SSC[1, 2] has resulted in several new developments that will affect future magnet designs; this report is a summary of work in progress in the areas described as follows.

High Current-Density NbTi Superconductor

In the past two years, it has been discovered that the commercial NbTi produced on a large scale for superconducting wire can be easily made with a much-improved compositional homogeneity on a microscopic scale and that, with this "high homogeneity" material, multiple heat treatments can increase J_c very substantially.[3] Because of interest in high-field SSC magnets, these improvements have been rapidly incorporated into large-scale commercial production in the past two years,[4] and now we can with confidence design magnets with cable having critical current density at least 30% greater than was possible for the Tevatron project.

In addition to increased J_c, the more homogeneous material appears to be much less susceptible to breakage during wire drawing resulting in delivery of long continuous lengths (up to about 500,000 ft. from a 10 inch billet) which makes cabling easier. If we compare J_c of NbTi wires at 5 T, 4.2K, the "old" J_c was about 1800 A/mm^2† and the "new" is about 2500 A/mm^2. There is hope that further processing improvements, shown to give over 3000 A/mm^2 in laboratory pilot tests can soon be realized in production.

Fine Filament Superconducting Wire

A phenomena long observed in all superconducting magnets is that magnetic flux that penetrates a superconducting wire becomes trapped. This is due to currents induced within a filament that flow in a direction to oppose any change in magnetic field penetrating the filament. These currents are generally very strong (because of the very high critical current density) and flow in generally opposite directions on opposite sides of a superconducting filament. Measurement of this phenomena in various cables is given by Sampson and Garber[5]; field distortion caused by the effects have been observed for many years. In accelerator-type dipole magnets Green[6] described a simple method of predicting the distortion in terms of the usual multipole expansions. The distortions are nearly inversely proportional to filament size. Fig. 2 shows, in the curves marked "no correction", the observed sextupole component of field measured at LBL in a 4-cm bore 6.5 T model magnet wound with high J_c cable with relatively large

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‡Total magnet costs include additional construction materials and labor, and are higher than shown in Fig. 1; however, the scaling of total cost with field intensity should be similar to that shown.

†ranging up to about 2,000 A/mm^2 for the best material.

filaments (~20 μm). For a 20 TeV SSC with 1 TeV injection energy, injection must occur at .325 tesla where the field distortion caused by "magnetization" (expressed in terms of the sextupole component of the distortion) will be about 0.4% at a radius of 1-cm. This is much too large to be correctable using the usual correction windings located near the focussing quadrupole magnets, and must either be corrected locally along the length of each magnet or greatly reduced by developing cable with very small filaments.

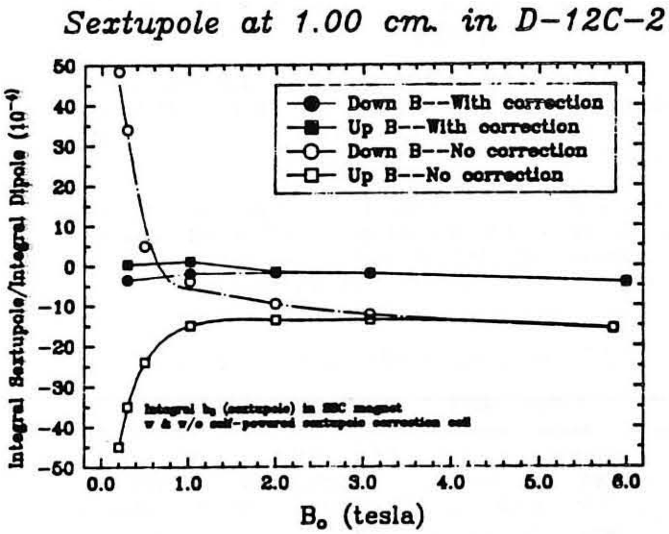

Fig. 2.

Figure 3 shows the effect of filament size on magnetization as predicted using the approximate method of Green[6]. If filaments of 2 to 3 μm can be achieved economically, then it will be possible to compensate for the remaining distortion in the SSC using conventional correction magnets.

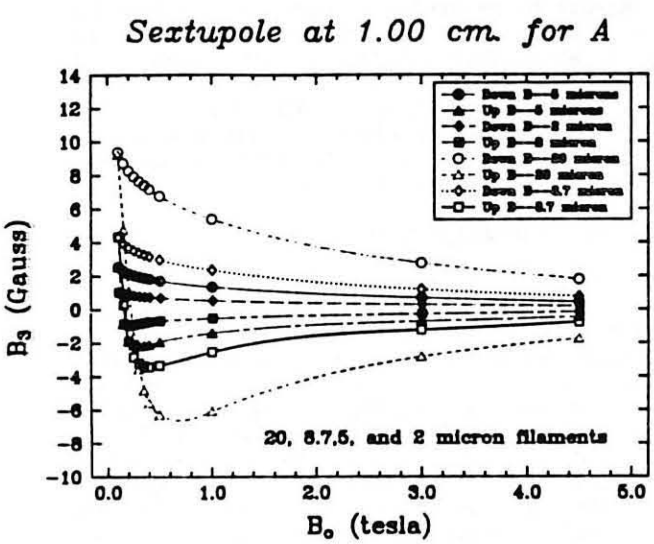

Fig. 3.

Unfortunately, this requires a very large number of filaments, about 50,000 in a strand of the size now used for cables in this type of magnet (0.65-mm - 0.80-mm dia.); it is not practical to assemble production size billets (up to 12 inch dia.) with this number of filaments using present Industry practices. (About 4,000 has been achieved.) However, multifilamentary rods can be drawn and rebundled for a second extrusion to achieve the required number. Several methods for accomplishing this economically are being developed. When NbTi in a copper matrix is heated to the normal extrusion temperature (about 550°C), a thin layer of brittle copper-titanium compound forms that does not deform smoothly during the wire drawing process; this is of no consequence for large filaments (10-20 μm) if care is taken to control the temperature and the heating time at extrusion, but it prevents uniform drawing to very small filament diameter. However, a thin barrier can be used to prevent this compound from forming on the filaments[7] and is now being used commercially. Low temperature extrusion can also be used. Some examples of deleterious effects that can be caused by copper-titanium compounds are described in these proceedings.[7,8]

At present, pilot quantities of wire have been commercially produced having 2-3 μm filaments with current density equal to that of larger filaments; full size billets are in process.

Cable Development

To balance the current density in a two-layer winding, it is convenient to use a flattened cable with a large aspect ratio. For the 6.5 T 4-cm bore SSC model described by Peters et al.,[9] a 23 strand inner cable and a 30 strand outer cable is used. The 30 strand cable proved more difficult to make than the more conventional 23 strand cable. After some development of improved methods using an experimental cabling machine at LBL, 30 strand cable can now be reliably produced in industry and experimental cables with 36 strands have been produced. There is probably an upper limit (perhaps about 40) to the number of strands that can be wound conveniently into a flattened cable without introducing a rigid core for internal support.

Winding Magnets with Prereacted Nb_3Sn Cable

Nb_3Sn (and other similar compounds) have better superconducting properties at fields above 10 tesla than NbTi. However, great care must be used to avoid damage to this brittle material during winding into coils. To avoid this problem, many small solenoids and several experimental accelerator-type magnets have been wound with unreacted cable; after winding, the completed coil is then heated to about 700°C to form the superconductor, however, turn-to-turn insulation compatible with the reaction temperature must be used.

At BNL, a 4.5-m long developmental SSC dipole magnet was designed with enlarged "dog-bone" ends to allow gentle bending of prereacted Nb_3Sn cable at the coil ends without serious damage. A NbTi version of this design was built and tested.[10] Internal tin cable[11] made by IGC was insulated using the Kapton-epoxy-fiberglass system that was used on the Tevatron and CBA magnets. After winding, the coils were compressed and molded in a fixture to cure the epoxy. As predicted, winding can be done without excessive damage; however, problems were encountered in the coil molding operation and the molding procedure is being modified.[12] The internal-tin superconductor used in this magnet has a high current density (about 1200 A/mm^2 at 10 T, 4.2K) as expected; however, magnetization (as described earlier) is excessive because the filaments, although small (about 3 μm dia.) are not individually isolated after reaction. It appears that the problem can be cured without serious decrease in current density if sufficient inter-filament spacing is used.[12]

Magnetization Correction

If magnetization effects cannot be conveniently reduced to the required magnitude, it is, of course, possible to place correction coils continuously along the magnet. Since the field distortion is generally small, this winding need occupy less than 1-mm of radial space and would itself be superconducting. For a large machine such as the SSC, it appears feasible to utilize automated methods for reducing the cost of such windings. Coils are being built at BNL using a method for accurately and rapidly placing wire up to .012" dia. on a flexible surface which can then be wrapped on a bore tube.[13]

If the correction winding is made with superconductor, it can be "self-energized" instead of utilizing an external power supply.[14] Figure 2 shows the measured sextupole field component of a 4-cm bore 1-m model dipole magnet with such a self-energized coil wound on the bore tube. These coils perform as expected, and will correct field distortions as needed by individual magnets; however, the effects of repeated cycling, magnet quenches, etc., must be understood before such a scheme could be practical.

Another passive correction scheme being investigated at Fermilab has "dummy" superconductors that do not carry the main magnet current, placed at appropriate locations within the magnet bore. The magnetization included in this material can nearly cancel that induced in the main windings.[15].

The recent development of magnet technology for the SSC, spurred by the desire to minimize cost, should be of use in many other applications.

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