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D. Dell'Orco, R.M. Scanlan, A. Lietzke, S. Caspi, J.M. van Oort, and A.D. McInturff

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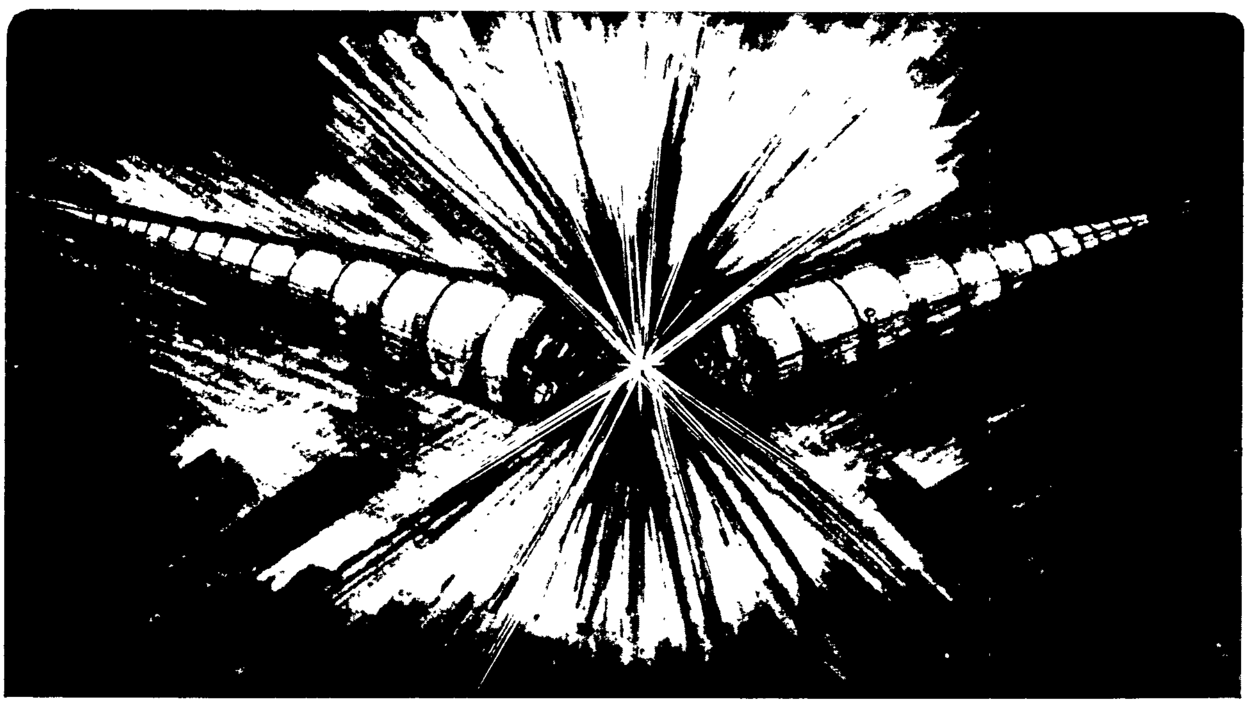

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Fabrication and Component Testing Results for a Nb_3Sn Dipole Magnet*

D. Dell'Orco, R. M. Scanlan, A. Lietzke, S. Caspi, J. M. van Oort, and A. D. McInturff
Lawrence Berkeley Laboratory
University of California
Berkeley, California

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Fabrication and Component Testing Results for a Nb3Sn Dipole Magnet

D. Dell'Orco, R. M. Scanlan, C. E. Taylor, A. Lietzke, S. Caspi, J. M. van Oort, and A. D. McInturff
Lawrence Berkeley Laboratory

***Abstract*—At present, the maximum field achieved in accelerator R&D dipoles is slightly over 10T, with NbTi conductor at 1.8 K. Although Nb_3Sn has the potential to achieve much higher fields, none of the previous dipoles constructed from Nb_3Sn have broken the 10T barrier. We report here on the construction of a dipole with high current density Nb_3Sn with a predicted short sample limit of 13T. A wind and react technique, followed by epoxy impregnation of the fiberglass insulated coils, was used. The problems identified with the use of Nb_3Sn in earlier dipole magnets were investigated in a series of supplemental tests. This includes measurement of the degradation of Jc with transverse strain, cabling degradation, joint resistance measurements, and epoxy strength tests. In addition, coil assembly techniques were developed to ensure that adequate prestress could be applied without damaging the reacted Nb_3Sn cable. We report here the results of these tests and the construction status of this 50 mm bore dipole.**

I. Introduction

In an earlier paper [1], we reported on the preliminary design of a Nb_3Sn dipole. This design was based on our experience with NbTi dipoles, and a number of similar design features were used. The conductor was a Rutherford cable, and the keystone angle was chosen according to the guidelines developed for the NbTi cables. The magnet coils are prestressed during assembly, and the prestress is maintained during cooldown by the use of a split iron yoke and aluminum bars. As might be expected, some of the design features adopted from the earlier NbTi magnets worked well for this magnet, and others needed to be modified to take into account the different properties of Nb_3Sn. In this paper, we report the results of a series of optimization studies which have led to the present magnet fabrication approach. The key issues are cable design, cable insulation, Nb_3Sn heat treatment conditions, end spacer, pole piece, and wedge material, joint design, and coil impregnation.

II. Conductor Development and Testing

The main goal of the conductor design was to maximize the overall current density, while still respecting the need for fabricability, protection, and insulation integrity. Two sources of conductor, both based on the internal tin approach, were developed. The construction details of these conductors were different, although the critical currents were similar. Teledyne Wah Chang Albany (TWCA) provided a modified jelly roll Nb_3Sn conductor with a high volume fraction of Sn and a Nb diffusion barrier in order to produce a high Jc. Intermagnetics General Corporation (IGC) provided a conductor with a low copper to noncopper ratio, a moderately high volume fraction Nb and Sn, and a Ta diffusion barrier. Two different conductors, one for the inner layer cable and one for the outer layer cable, were ordered from each supplier. Keystoned cables were made from these wires, with the parameters listed in Table I.

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TABLE I
Cable Parameters

Original Cable	Inner Cable	Outer Cable
Strand No.	37	47
Strand diameter (mm)	0.75	0.48
Cable width (mm)	14.1	11.52
Keystone Angle(deg)	1.11	0.87
Mid-thickness (mm)	1.60	1.11
Cu/Sc ratio	0.4	1.15

Final Cable	Inner Cable	Outer Cable
Strand No.	37	47
Manufacturer	IGC	TWCA
Strand diameter (mm)	0.75	0.48
Cable width (mm)	14.45	11.63
Keystone Angle(deg)	0	0
Mid-thickness (mm)	1.369	0.873
Cu/Sc ratio	0.43	1.0

Wires were extracted from the cables and the critical current measured. In addition, the critical currents of these cables were measured as a function of applied strain in the test facility at Twente Univ. [2]. These tests indicated a large degradation in critical current due to the cabling operation, and also a large dependence of critical current on the applied transverse strain [3]. Subsequently, cables were made without keystoning and the tests repeated. These cables showed little cabling degradation and improved strain dependence [4] so the magnet cross section was redesigned to use a rectangular cross section cable. The properties of the final cables used in this magnet are shown in Table I. Micrographs of strands removed from the cables showed the cause of the Jc degradation to be severe deformation of the filament bundles on the narrow edge of the keystoned cables (Fig. 1). Micrographs of strands removed from the rectangular cross section cables showed no sheared bundles of filaments. However, strands of the TWCA inner layer material still showed some breaks in the Nb diffusion barriers at the edge of the rectangular cross section cable (Fig. 2).

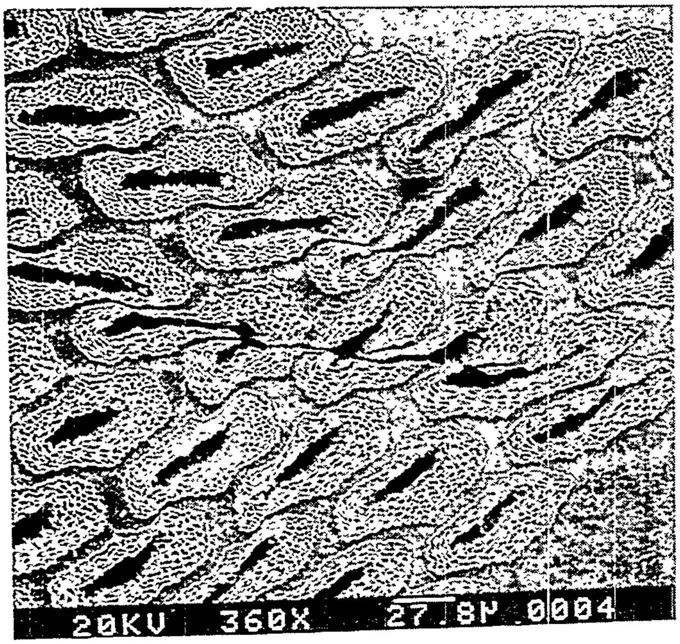

Fig.1 Transverse section micrograph of filament bundles at the narrow edge of the keystoned cable, which show severe deformation and shearing of the bundles.

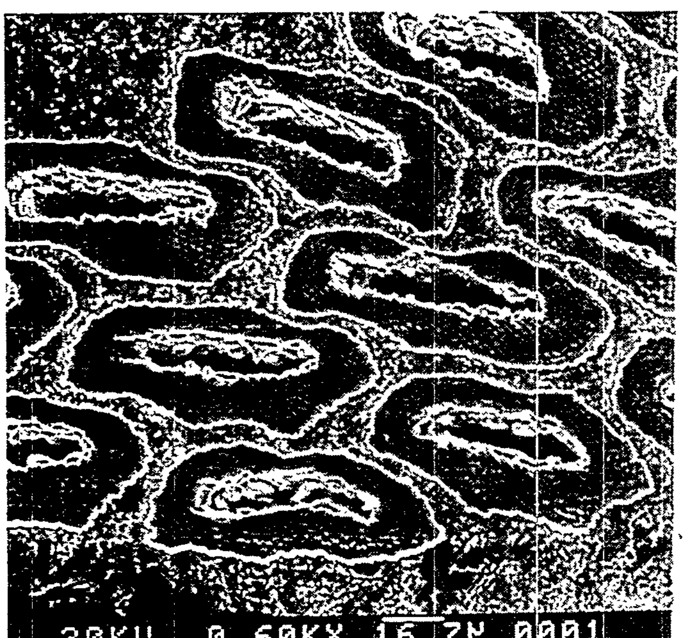

Fig. 2. Transverse section micrograph of filament bundles for the rectangular cables, which show some necking down and breaking of the Nb diffusion barriers.

Since the inner strands of IGC material did not show any breaks in the diffusion barriers, this material was chosen for the inner layer coils. The reason for the difference in behavior of the diffusion barriers in the two wires is not clear, since several factors are different. The IGC wires have a hybrid the TWCA wire was assembled from 96 elements, each with a separate barrier, whereas the IGC wire was assembled with a single barrier surrounding all the subelements, and the barrier was thicker than the barrier in the TWCA wire. Also, the deformation mode appeared different in the two cases, with more severe local deformation of the barrier for the TWCA wire. For the outer layer cable, the TWCA strand was used, since it has higher Jc and the diffusion barrier in this case (54 elements) was not broken during cabling.

III. Joint Development and Testing

The two inner layer coils are wound from a single length of cable, as are the two outer layer coils. However, joints are required to attach NbTi cables to the Nb_3Sn cables at the coil ends. This joint must be reliable and reproducible, since it is made before epoxy impregnation and afterward is thermally isolated from the helium coolant. In order to insure the quality and reproducibility of this joint, a procedure was developed and then verified on a series of test joints. The procedure starts with the coil reaction step, in which the conductor is formed into the final shape and restrained during reaction by a fixture. After reaction, this fixture is carefully removed and replaced with a clean, high conductivity copper fixture. The Nb_3Sn cable, NbTi cable and copper pieces are all coated with flux; Pb-Sn eutectic solder strips are placed between each component in the copper fixture. Heat is applied to the joint by means of a resistance heater, and the temperature monitored by thermocouples. The resistance heating is terminated when the solder strips melted and the copper splice box can be closed. In order to test this procedure, a series of joints 70, 100, 130 and 160 mm in length were prepared and tested. The joint resistances varied in a predictable manner from a value of 0.37 nΩ at zero field for the longest (130 mm) joint, to 1.3 nΩ at 6 T (4.2K) for the shortest joint (70 mm). The resistance as a function of joint length is shown for various background fields in Fig. 3.

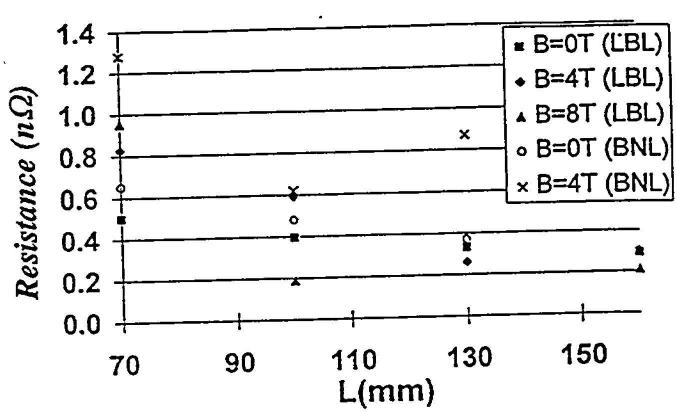

Fig. 3. Joint resistance as a function of joint length for several background field levels. BNL and LBL refer to measurements made at Brookhaven and Lawrence Berkeley Laboratories, respectively.

The condition most closely simulating the situation in the magnet (100 mm length, 2T 4.2K), yields an expected joint resistance of about 0.6 nΩ, or about 0.025 W at 6000 A heating per joint. This heat is transmitted to the helium bath by the copper channel and the NbTi cable which extend outside the epoxy impregnated coil.

IV. Epoxy Impregnation Development and Testing

The assembly process chosen for this magnet is wind-react-epoxy impregnate. Since the Nb_3Sn cable cannot withstand the assembly stresses and the Lorentz forces during operation, the coil windings must be reinforced by a combination of glass fiber and epoxy. The strength of this reinforcing matrix, in combination with the reacted Nb_3Sn cable, has been measured in a series of mechanical property test samples. For this application, the epoxy must have a low viscosity, long pot life, good toughness, and be compatible with glass fiber reinforcement. In addition, we require good cryogenic performance. After preliminary screening, the epoxy chosen for more extensive testing was CTD-101 [5]. The test specimens consisted of stacks of cables, which were insulated, heat treated, and epoxy impregnated under the conditions specified for the actual magnet coils. Both inner layer and outer layer cables were used to prepare test samples; also, samples of pure epoxy and epoxy plus glass fiber were tested. Compression tests were performed at ambient temperature and at 77 K. For properties at 4.2 K, we rely on the test data provided by the epoxy manufacturer [6]. The values obtained for Young's modulus and thermal expansion for both inner and outer cable samples are shown in Table II. The Young's modulus values agree well with values calculated by using a rule of mixtures; however, the measured coefficient of expansion does not agree with the rule of mixtures. Additional tests were performed to find the maximum compressive load the composite stacks could withstand before the epoxy began to show cracking; loads of at least 100 MPa could be applied before the epoxy cracked.

TABLE II
Mechanical Properties of Cable/Insulation/Epoxy Composites

	Young's Modulus at 293K (GPa) Measured	Calculated	Young's Modulus at 77K (GPa)	Contraction between 293-77K (%)
Outer Cable Stack	33	37	36	0.26
Inner CableStack	38	40	42	0.29

V. Insulation

An important requirement for the insulation is that it withstand the Nb_3Sn reaction heat treatment. Glass fiber is an attractive option, since it is readily available in many forms and is inexpensive. Initial tests at the two reaction heat treatments provided by the conductor manufacturers showed a somewhat surprising result. At 680 C, the insulation remained intact and could be handled to some extent. However, after the 740 C heat treatment recommended by IGC, the insulation was extremely fragile and crumbled under the slightest handling or abrasion. Alternatives such as ceramic or quartz fibers were considered, but both suffered from limited availability and relatively high cost. The solution adopted for this magnet was to use a less than optimum heat treatment for the IGC conductor, in order to be able to use the glass fiber insulation. Two types of glass fiber insulation were evaluated--a braid that was formed around the cable and a sleeve that was made and then slipped onto the cable. The sleeve was adapted for this magnet after we demonstrated a method for applying the sleeve on the cable lengths required for this magnet (500 m).

The sizing applied by the manufacturer left a heavy residue of carbon when the cable was reacted in an argon atmosphere. Removal of the sizing with a treatment in a partial atmosphere of oxygen has been used for previous wind and react Nb_3Sn magnets [7], and we made some trials with this approach. However, this approach was abandoned due to problems with oxidation of the copper matrix and incomplete carbon removal in the less accessible areas of the coils. Instead, the manufacturer's sizing was removed by heating in air, and then another sizing, one that could be volatilized in argon without leaving a heavy carbon residue, was applied.

Initial winding tests with this insulation showed that occasional shorts could still develop due to abrasion by the metal components of the coil, especially the end spacers and the wedges. This problem was solved by applying a ceramic insulation coating on these metal pieces; plasma sprayed aluminum oxide 0.1 mm thick provided a coating with good adherence to the metal pieces and good bonding to the epoxy, as well with good insulating properties.

VI. Metal Pole and End Spacer Development.

The requirements for these components of the coils are: high modulus, so that the forces are transmitted from the coils to the structure with minimum strain on the Nb_3Sn windings; compatible with the coil reaction conditions; non-magnetic; and with a thermal expansion coefficient that matches that of the coils. An aluminum bronze alloy was chosen to meet these requirements. Several different approaches for fabrication of these pieces were evaluated [8]. The wedges were made by conventional machining, as were the pole pieces. However, the end spacers could not be machined by conventional methods due to their complex shapes. Electrical discharge machining and milling with 5-axis machines were evaluated, as well as a two-step process whereby the shapes were machined in wax and then cast using the lost wax process. All three methods can be used, but due to cost and schedule considerations, the parts at present are being made by casting.

VII. Magnet Protection

This magnet has a relatively high inductance (45 mH), which means that protection issues must be addressed. In order to limit the magnet terminal voltage, most of the stored energy will be absorbed in the magnet windings rather than being extracted with an external dump. Protection heaters have been designed to dissipate the energy over a large volume of the magnet, in order to keep the coil hot spot temperature low. These heaters are fabricated from a polyimide/stainless steel composite sheet, with the heater traces formed by a photoresist/etching process. After etching, a top sheet of polyimide is bonded to the package to produce an insulated unit 120 to 150 microns thick. These heater packages are then bonded into the coils during the epoxy impregnation step. With a quench detection level of 0.25 V, the temperature of the coil hot spot should be limited less than 300 K.

VIII. Construction Status and Test Plans

Three test coils have been constructed and evaluated with regard to insulation integrety, conductor position, end spacer shape, soundness of epoxy impregnation, joint fabrication, and coil reaction. Sections of these test coils will be instrumented with strain gages and used to verify the coil prestressing approach. Coil radial prestressing is accomplished by a continuous wire wrapping over the yoke and a thin split shell. Magnet axial constraint is accomplished by 150 mm thick stainless steel end plates welded to a thick cylinder outside the wire wrap.

The final Nb_3Sn coils are being fabricated at present, with assembly planned for early 1995 and final magnet testing in May 1995.

Summary

1. Fabrication of keystoned cable resulted in unacceptably large critical current degradation. The magnet was redesigned to use rectangular cross section cable with small critical current degradation.

2. Soldered joints between Nb_3Sn and NBTi cable have been made and tested. These joints have the required low resistance for use in epoxy impregnated coils.

3. The techniques required for wind and react Nb_3Sn and NbTi cables have been made and tested. These joints have the required low resistance values for use in epoxy impregnated coils.

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