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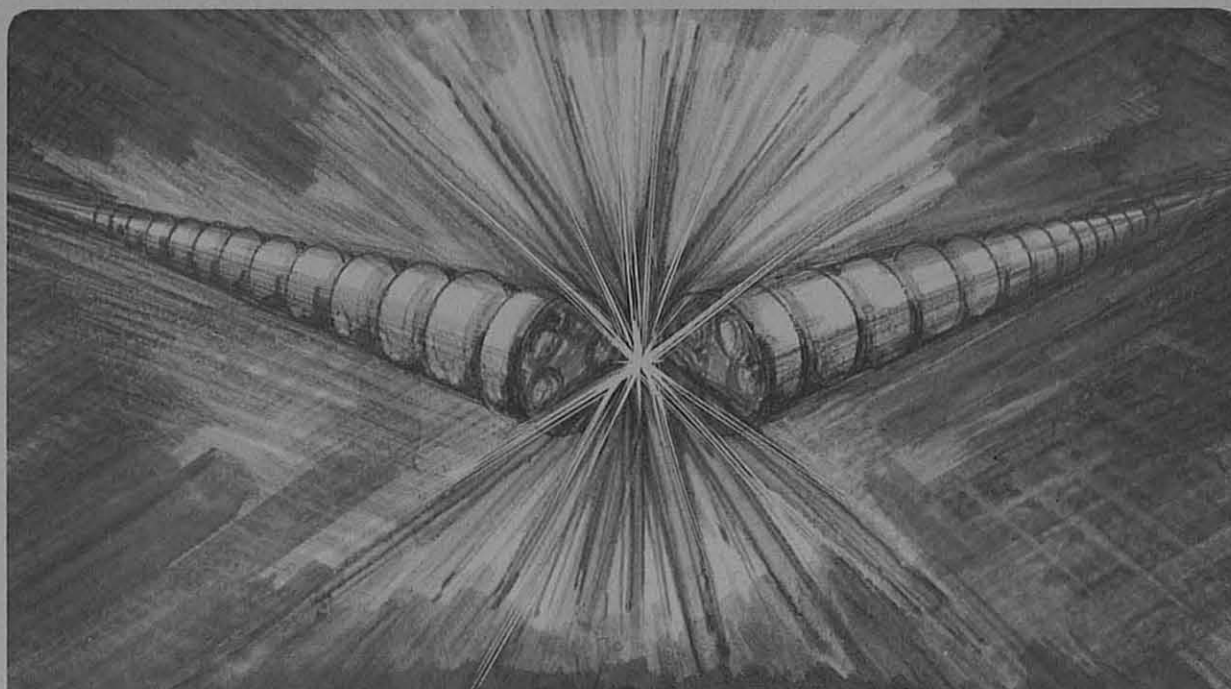
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Abstract

A 5 cm bore dia., 1-m-long dipole model magnet was constructed by winding un-reacted cable, followed by reaction and epoxy-impregnation. Experience and test results are described on the 1.7 mm dia. internal-tin wire, the eleven-strand flattened cable, fiberglass insulation, and construction of the magnet. Each half of the magnet has two double-pancake-type windings that were reacted in a single operation. The two double-pancakes were then separately vacuum impregnated after soldering the flexible Nb-Ti leads to the Nb₃Sn conductors. No iron flux return yoke was used. In initial tests a central field of 8.0 T was reached at 4.4 K. However, evidence from training behavior, and 1.8 K tests indicate that premature quenching, rather than critical current of the cable, limited the field intensity. The magnet was reassembled and more rigidly clamped; additional test results are reported.

Introduction

Several designs have been proposed for dipole magnets with field strengths in the range 9-10 T. One approach utilizes Nb-Ti binary or Nb-Ti-Ta ternary alloys operating at 1.8 K. Another approach is based on Nb₃Sn operating at 4.2 K; the Nb₃Sn designs can be sub-divided further into a wind-and-react approach or a react-and-wind approach. The react-and-wind approach has been employed at Brookhaven National Laboratory and several dipole magnets with fields up to 4.8 T have been constructed.¹ Work on a higher field react-and-wind magnet is continuing at BNL in support of the Superconducting Super Collider study.²

This paper will describe results on a Nb₃Sn dipole using the wind-and-react approach. The primary advantage of this approach is that virtually all the handling of the conductor is complete before the components are reacted to produce the brittle Nb₃Sn intermetallic compound. A disadvantage of this approach is that insulation capable of withstanding the 700°C reaction temperature must be utilized. The construction techniques used in winding this dipole will be compared with those used in similar wind-and-react Nb₃Sn dipoles³ or quadrupoles,⁴ and the test results on this dipole will be discussed.

Conductor and Magnet Design

The design for the Nb₃Sn dipole has been described in detail in an earlier publication,⁵ so only the main points of the design will be reviewed. To achieve a cost-effective dipole, a small bore (40 mm) and a high field (10 T) are chosen as initial

design parameters. Analysis of magnets with these parameters showed that a rather high critical current density (J_c approximately 1200 A/mm² at 4.2 K and 10 T) is required. The current density that is presently available commercially in conventional bronze-process Nb₃Sn is about 800-900 A/mm² at 10 T.⁶ Consequently, an important part of this dipole development program has been the development and scale-up of the internal-tin approach⁷ for fabrication of Nb₃Sn with high current density.

The choice of insulating materials for use in a Nb₃Sn wind-and-react coil is limited due to the necessity for the insulation to withstand the 700°C reaction temperature. Woven fiberglass tape (type "S") was chosen as a material that is capable of withstanding the Nb₃Sn reaction temperature and is flexible enough to be wrapped around the 11-strand cable.

This combination of fiberglass, annealed Cu, and Nb₃Sn produces a very low strength, low modulus coil pack.⁸ Furthermore, calculations of the stresses introduced at 10 T in this dipole design predict an average compressive stress of 83 MPa (12,000 psi) along the midplane, and local compressive stresses of over 138 MPa (20,000 psi). In order to prevent the turns from being over-strained during operation, the windings are filled with epoxy after the Nb₃Sn reaction step. The mechanical properties of this cable-fiberglass-epoxy system were evaluated in a series of compression tests at 300 K and 77 K.⁸ The results of these tests indicated that, although the epoxy could prevent local excessive straining of the windings, it is necessary to apply an additional constraint on the entire coil. This constraint is achieved by molding the coil to precise dimensions and then enclosing the coil winding with a mechanical support system (Figure 1).

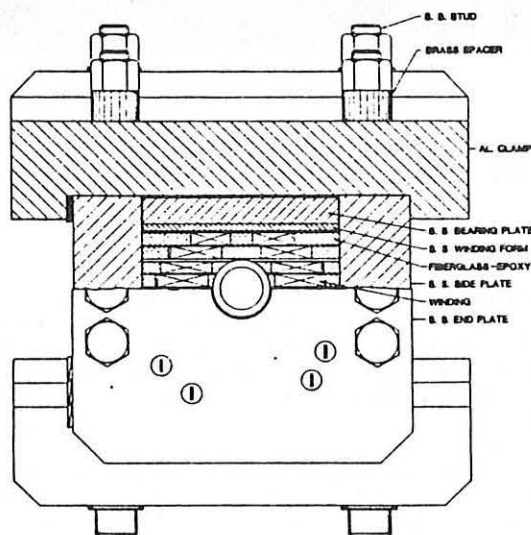


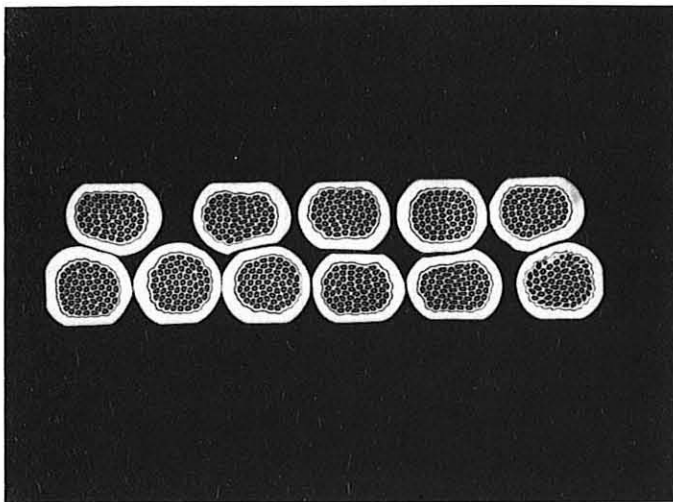
Figure 1. Cross section of the dipole magnet showing construction details.

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Conductor Fabrication

The tin content in the conventional bronze approach is limited for ductility reasons to about 14 wt percent, and this in turn limits the amount of Nb_3Sn which can be formed. By using a pure tin (or Sn 0.3 wt percent Cu) core inside a copper-niobium multifilamentary composite, the components can be processed reliably up to an effective bronze composition of approximately 30 wt percent Sn. Exploratory work on this approach by Intermagnetics General Corp.⁷ had shown promise, so a conductor with the following specifications was ordered: 1.7 mm strand size, 50 percent Cu, a target J_c (10 T) = 1200 A/mm², and a minimum J_c (after cabling) = 975 A/mm². The conductor was fabricated by loading a Sn core into a hollow extrusion consisting of a Cu matrix and Nb filaments. This composite is cold drawn and cut into 61 pieces which are re-bundled inside another hollow extrusion consisting of a diffusion barrier on the inside and high purity Cu on the outside. This rod is then drawn down to produce the 1.7 mm diameter strand material for subsequent cabling. The conductor fabrication process is described more fully in these proceedings.⁹

This 1.7 mm diameter wire was used to produce 300 m of 11-strand Rutherford-type cable compacted to approximately 80 percent (Figure 2). After cabling, the material was annealed for 3 hr at 200°C in order to soften the copper and facilitate winding.



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Figure 2. Transverse section micrograph of 11-strand cable used in construction of dipole magnets.

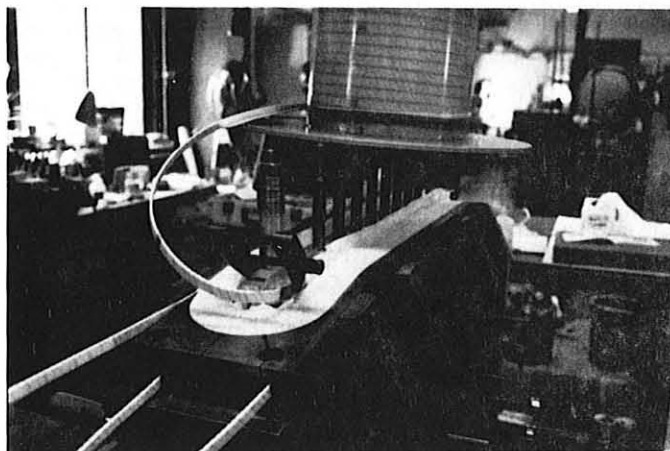
Magnet Fabrication

The coil configuration chosen (Figure 1) consists of flat race-track layers with the ends inclined in order to clear the bore tube. There are four layers per pole, and each of the double pancakes is wound from a single piece of cable with a cross-over at the inside.

The cable was insulated on-line during the winding process with tape which had been cleaned after weaving with detergent and enzymes to remove most of the starch sizing. After this treatment the insulation is somewhat fragile but can be wound to produce a coil free from shorts. The glass

insulation dimensions are $14 \pm .4$ mm wide by $.09 \pm .01$ mm thick. The insulation is half-lap wrapped onto the cable and the final dimensions are 3.25 mm by 11.3 mm.

A winding base with a 508 mm straight section and ends sloped downward at 10° was mounted on a winding table (Figure 3). Stainless steel pole pieces are attached to this base, and the four layers are wound with a winding tension of 425 N. Three layers have 14 turns while the fourth layer has 11 turns.



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Figure 3. Partially completed winding showing fiberglass-wrapped cable (white) and bent ends to allow clearance for the bore tube.

After winding is complete, the remaining sides and ends of the stainless steel coil forms are assembled around the coils and the coils are compressed an average of 1.2 percent from the lightly-clamped dimensions. Next, the coils are loaded in a vacuum furnace and thermocouples attached in preparation for reacting the components to form Nb_3Sn . The ends of the cable strands are fused to prevent leakage of molten tin during the heat treatment. The heat treatment consists of 200 hr at 200°C, 24 hr at 375°C, 240 at 580°C, and 100 at 700°C. The metallurgical changes occurring in each step and the effect on critical current are discussed in another paper in these proceedings.¹⁰ After reaction, the coil forms are removed and the coils are inspected. The insulation showed some color change (from the original white to a grey-green), but the turn-to-turn insulation remained adequate. Aside from the color change, the insulation shows no signs of deterioration. In addition, no tin leakage is observed at the ends of the strands.

In preparation for epoxy impregnation, the steel pole pieces and picture frames are removed and replaced with fiberglass-epoxy pieces coated with mold release. During this procedure, special fixtures and careful handling are used to prevent damage to the reacted Nb_3Sn . Prior to potting, Nb-Ti cable leads are spliced onto the Nb_3Sn cable leads. The splice joint is made over the 500 mm straight section on the outer turn by carefully moving this turn away from the adjacent conductor and inserting a piece of Kapton sheet behind and under the turn. Next, the insulation is removed, the copper surface cleaned and tinned with solder (62 wt percent Sn, 2 wt percent Ag, .35 percent Sb, balance Pb). A pair of pre-tinned NbTi cables are then soldered to the outer side of the Nb_3Sn

conductor. Finally the joint is cleaned and insulated with fiberglass sleeving.

In preparation for potting, aluminum forms sealed with rubber O rings are installed, and the coil is pumped in a vacuum chamber. After baking for 12 hr., epoxy is introduced into the coil and cured 50°C for 5 hrs, 60°C for 8 hrs, and 80° for 8 hrs. The epoxy is a mixture of 50 parts Epon 826, 50 parts DER 736, catalyzed with 25 parts Tonex. After potting, the two layers wound from a single length of cable become a rigid pair. Electrical measurements taken on the coils before and after potting showed no change in resistance or inductance.

After the potting fixtures are removed, the following instrumentation is installed. Aluminum blocks are prepared with strain gages mounted on four sides and connected in a bridge. One block is installed in a slot on each fiberglass-epoxy picture frame enclosing each coil. Voltage taps are connected across each splice joint and each layer, for a total of 7 taps for each coil. The potted layer pairs are installed on each side of a stainless steel bore tube insulated with a layer of 0.25 mm thick mylar. Coil compression is accomplished with stainless steel side plates and aluminum bars top and bottom. The initial assembly was clamped to achieve a moderate horizontal compression of 34 MPa (5000 psi). This value was chosen for the initial tests because of concern about possible damage to the Nb₃Sn. After the assembly clamps were removed the compression decreased to about 17 MPa (2500 psi).

Magnet Test Results

The magnet was tested in our test cryostat¹¹ and utilized our newly modified 15,000 ampere power supply, extraction system, and current leads. By monitoring the coil voltage taps when the magnet goes resistive, we can deduce which section caused the quench. A reasonably slow ramp rate of about 60 A/s (or 0.04 T/s) is used in these tests.

Training started at 7.0 tesla and proceeded at a reasonable rate to 8.0 tesla in some twenty quenches (Figure 4). The quenches were distributed over all the layers and didn't start at the inside turns. On the 8.0 tesla (12,000 ampere) quench, the extraction rack didn't perform and all the stored energy was dumped in the magnet. Afterwards the peak current achieved was about 300 amperes lower. As shown in Figure 4, quenches in helium II at 1.8 K did not occur at higher currents, or fields. This is an indication that the magnet was not at its short sample limit but was limited either by conductor movement or possibly heating in the Nb₃Sn to Nb-Ti current splices.

A comparison of strand short sample critical current, cable short sample critical current, and magnet performance is shown in Figure 5. The cable critical current data are incomplete due to problems of sample motion in the test fixture and the availability of a small uniform field volume for the test. The split-solenoid test magnet has a small high-field region of only 5 cm diameter with 1 percent uniformity. Thus, current transfer voltages are present in the results. With 2.5 cm voltage tap spacing, a critical current of 6000 A at 12 T was measured, using a criteria of 0.4 μ V/cm. Attempts to obtain a value at 10 T were not successful due to sample quenching, but the current reached before quenching is in excess of 9000 A. The 12 T value lies on the line for the specification value and extrapolates to a value of 11000 A at 10 T.

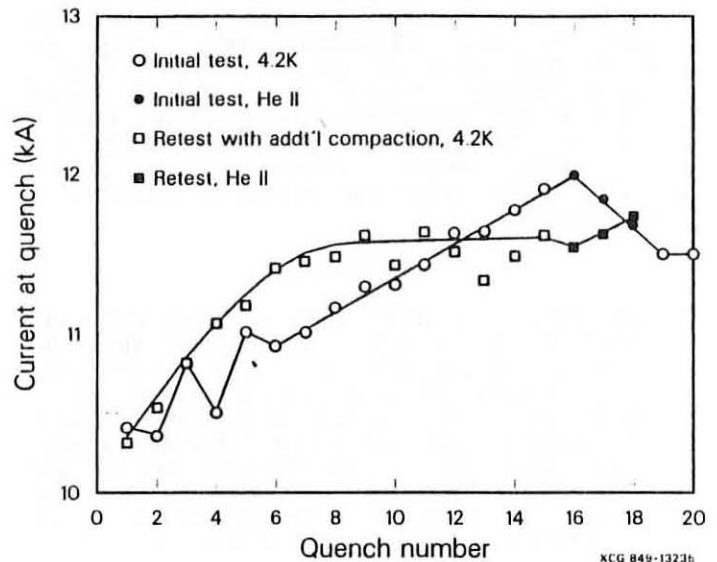


Figure 4. Record of maximum current for each magnet quench. The second test with additional prestress reached approximately the same current and field level as the first test.

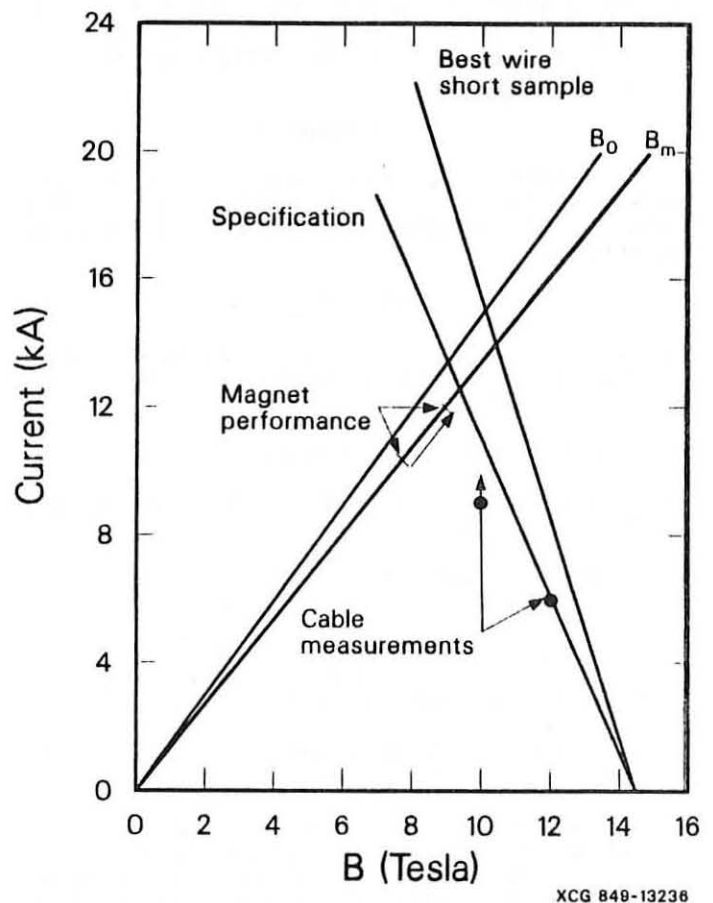


Figure 5. Critical current data for a single strand (multiplied by 11 strands) and cable, compared with magnet load lines - the B₀ is measured dipole field and B_m is the calculated maximum field.

In an attempt to eliminate the possibility that conductor motion was limiting performance, the magnet was re-clamped, with an increased preload of 55 MPa (8000 psi), and the test sequence repeated.

This test produced results that were almost identical with the first except that the peak current was some 300 amperes less. Thus, we conclude that conductor motion is not limiting magnet performance. The possibility that the quench behavior is due to heating in the splices remains unresolved. The joints are completely potted and hence poorly cooled. However, system noise prevented us from obtaining accurate measurements of joint resistances.

Conclusions

1. The successful performance of this wind-and-react dipole to 8.0 T demonstrates that the internal-tin approach is capable of producing long lengths of high quality Nb₃Sn superconductor. Prior to this demonstration, there was concern that the molten tin-copper alloy would burst through the diffusion barrier and contaminate the coil windings, or that the Nb₃Sn layer produced during reaction might be non-uniform along the conductor length.
2. The wind-and-react approach can be used, in conjunction with epoxy impregnation, to produce a dipole which is structurally sound and can be trained with a reasonable number of quenches.
3. The details of splice joint preparation for Nb₃Sn wind-and-react coils are important, and this may be limiting the performance of this particular magnet.

Acknowledgments

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