BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Note

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Title: Construction and Test of Nb_3Sn Coil MCA003

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Construction and Test of Nb_3Sn Coil MCA003

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A Nb_3Sn coil made with pre-reacted cable wound into the midplane slot of an aluminum cylinder was successfully tested on Thursday August 23, 2001. This marks the first success for this approach to building high field magnets. The approach was originally conceived as a candidate for dipole and/or quadrupole magnets for the collider ring of the proposed Muon Collider, or for special purpose magnets is this or other machines.

Many of the parts and techniques for this coil are borrowed from the helical magnet program, where 96 slotted coils 2.4 m long, half with seven windings each and half with nine windings each, have been built with NbTi superconductor. Here, a cylinder 610 mm long with seven slots was used (Figure 1). Drawings of the cylinder and its dimensions are shown in Figures 2 and 3. Only the mid-plane slot was wound with superconductor (108 turns) in this test. As is done in the helical program, the winding was wrapped with Kevlar, cured, wrapped with fresh Kevlar, then tested in a vertical dewar in the wire short sample measurement lab in B902. In this configuration, at the peak current reached by the coil (826 A) the field at the center of the coil is 0.65 T, but substantially higher at the winding and in the end. The measured short sample performance of this cable is shown in Figure 4.

Figure 1 The cylinder used for this coil, showing also the slots milled into the surface.

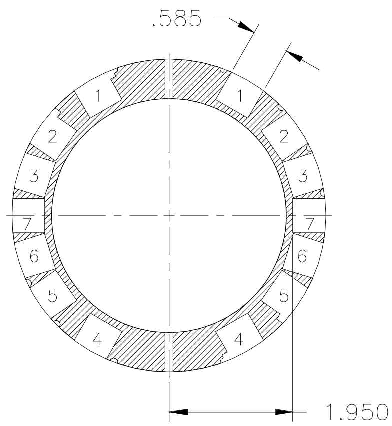

Figure 2 Cross section of the cylinder. Dimensions are in inches.

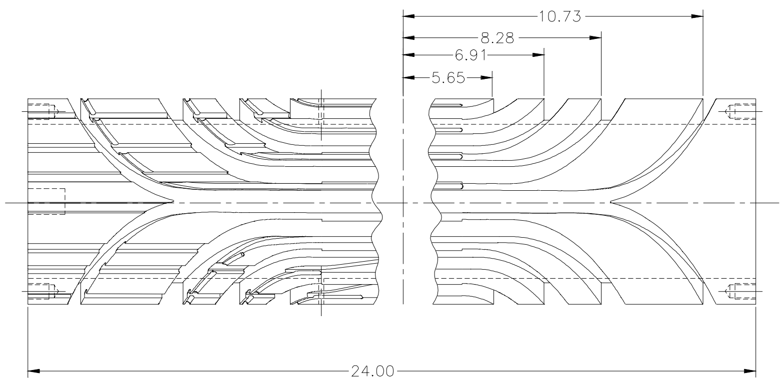

Figure 3 Side view of the cylinder. Dimensions are in inches.

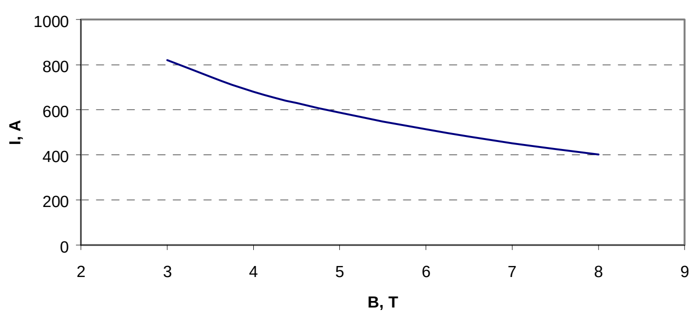

Figure 4 Measured short sample current of the 6-around-1 cable.

The cylinder being used was originally obtained be E. Kelly in May 1999. J. Schmalzle organized the machining of the cylinder. The layout of slots was drawn by K. Power, based on the design used for the inner coil of the helical magnets, but without the slot rotation used there. G. Morgan modified the specification for helical ends to designate the straight ends needed here. The cylinder was machined in Central Shops in October 1999. It has been used in several earlier trials of this technique that were not successful because the Nb_3Sn cable used had its wires sintered together and was thus too brittle.

The Nb_3Sn used is made from 0.6 mm surplus wire originally purchased in the ITER fusion program. Its copper to non-copper ratio is 1.6 to 1. At the request of W. Sampson and A. Ghosh, it was drawn to 13 mil and 7 mil diameter wires under the supervision of E. Gregory at IGC. Some 4000 feet of the 13 mil wire arrived at BNL in May, 1999. The wire used in this coil was made into a 6-around-1 one mm diameter cable at NEEW in August 2000 (some of the wire had been made into a 6-around-1 cable earlier at NEEW). At the same time, a 2 mm diameter, 100 strand cable made of 7 mil strand in five, 20 wire bundles was also made. A coil will be made with this 2 mm cable later. The process at NEEW was modified from the earlier cabling run by having each individual wire coated with Mobil One oil, rather than just a drip of this oil on the wire bundle as it passes into the shaping die on the cabler. This thorough coating of the wire ensured that there would be no sticking together of the wires in the subsequent long, high temperature reaction that forms the Nb_3Sn compound. The reaction began in November 2000 and was completed about a month later. Figure 5 is a picture of the cable after the reaction, still on its reaction drum. The cable is indeed quite flexible after the reaction and showed no tendency to break with normal handling.

Figure 5 The 6-around-1 cable after the reaction to form Nb3Sn. The cable is wrapped loosely and has graphite sheets between layers to reduce the liklihood of adjacent wires sticking to one another.

By May 2001, the cable had been wrapped with Kapton at NEEW and was ready for winding onto the slotted cylinder. W. Themann and J. Famiglietti completed this by the end of June including the needed oven-curing of the epoxy. The techniques used for this task were those learned in the helical magnet program but with some modifications: the cable was handled more carefully than would be the case with NbTi, less pressure was applied to the press plates during winding, and only about half the usual tension was used in applying the Kevlar overwraps, both the one before curing and the one after curing. Even with this reduced tension, the cable seated well into the slot in the straight section of the tube, with only a nominal exposure of the press plates above the top of the slot. In the ends, however, the cable bundle was not well seated. At the very end, the press plate was barely engaging the top of the slot. Future changes will include a widening of the slot at the end to allow space for the extra arc length required by the cable as it gets pushed inward to a smaller radial position. The resulting void at the ends will be filled with epoxy subsequent to the cure. Figure 6 shows a drawing of the conductor arrangement in a slot. Figure 7 shows the completed coil.

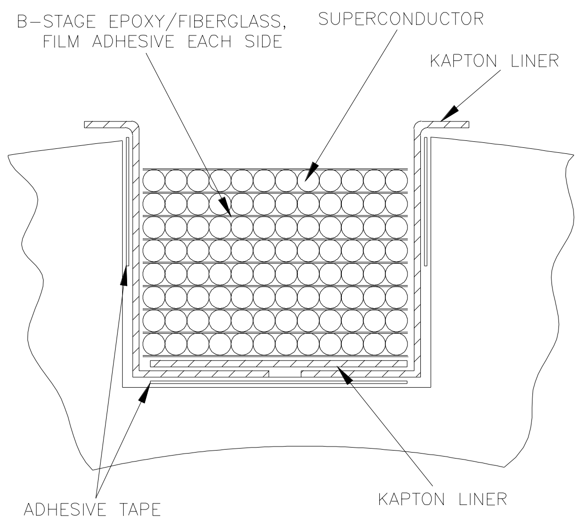

Figure 6 Detail showing the arrangement of cable turns in the slots of the cylinder.

Figure 7 The completed coil after curing but before the final over-wrap with Kevlar. In this test, only the midplane slot was filled with (108 turns) conductor.

The results of the quench tests, conducted by A. Ghosh and E. Sperry on August 23, 2001, are shown in Figure 8. After one training quench, the coil went to its peak current of 826 A. At this current, the central fields is calculated to be 0.65 T, but in this geometry, the peak field at the coil in the straight section is 3.75 times larger, or 2.44 T. In the end, the field enhancement is perhaps 20 % (no 3D calculation available), or 2.93 T. Referring to Figure 4, 820 A is approximately the short sample limit of the cable at 3 T.

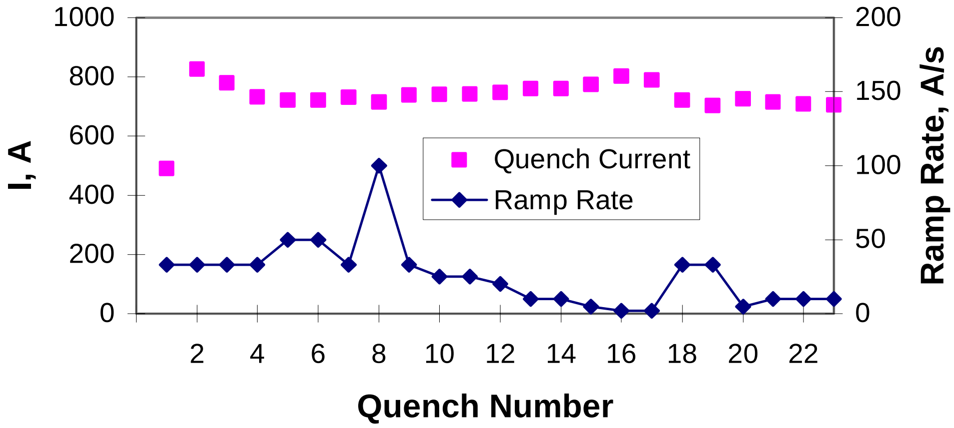

Figure 8 Quench performance of the Nb_3Sn coil. The 2nd quench reached the maximum value of 826 A, approximately the short sample limit of the conductor. Subsequent quench currents were somewhat erratic. This may be because the coil turns are not as solidly anchored in the epoxy/fiberglass matrix as would be desirable.

Subsequent testing showed somewhat erratic behavior of the quench current, some ramp rate dependence and some degradation with repeated quenching. Because the center conductor of the cable is not part of the weave, some eddy currents and perhaps some resistance to current-sharing is expected. The erratic quench level and the degradation may be caused by the deficit of epoxy in the ends of the coil, allowing the cable to delaminate in local places and move around under the Lorentz force. Future coils would preferably be built with a prepreg material more heavily loaded with epoxy (the helical windings are known to be somewhat short on epoxy, as revealed by inspection of those windings that have been opened to make repairs.) Additional coils will have to be built and tested to better understand quench performance.

The coil has demonstrated pre-reacted Nb_3Sn can be made into a magnet of this slotted design without serious damage to the conductor. Care was exercised by the experienced technicians who put the turns in place, but the this care was not unreasonable. Since the Lorentz forces in this concept are all contained in the individual slots and do not build to put excessive pressure on any of the conductor, which would likely degrade the performance of this material, there is good reason to believe that a high field magnet made of many slots filled with such conductor is within reach.

Additional work is needed and can be fruitfully done on this concept, much of it inexpensively because of the flexibility of the design and the re-use of components. Near term, additional windings could be added to the existing mid-plane winding. However, before that is done, it would be prudent to widen the slots in the ends, which would mean replacing this mid-plane winding. More epoxy should be used in the windings, which means finding a prepreg material that differs from that being used in the helical program. Subsequently, the 100 strand cable already available could be tried. In the intermediate term, improved superconductor that would allow higher current could be purchased. Ramp rate effects are not a concern in the magnets of the muon collider since the magnets do not ramp, so the usual compromise now being made in the fabrication of Nb_3Sn, a compromise that ensures small filament diameters at the expense of high critical current, need not be made here. Various cable geometries should be tried to identify an optimum layout: small diameter strand cabled into ~2 mm cables with various amounts of sub-bundling into favorable patterns; low copper-content superconductor strand mixed in the cable with pure copper wires; etc. The development of flexible Nb_3Sn cables by S. Pourrahimi in Boston, recently selected for DOE Phase II SBIR funding, may make some interesting cables available to this program. An optimum recipe for reacting the Nb_3Sn wire being used needs to be established. If these various projects validate the design, then additional cylinders can be added to the program and a magnet exceeding 10 T could be attempted.