

A  $\text{Nb}_3\text{Sn}$  High Field Dipole\*

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## Abstract

A dipole magnet approximately 1 meter long with an 8 cm bore has been fabricated from cable made from  $\text{Nb}_3\text{Sn}$  multifilamentary strands. The coil consists of four layers of conductor wound in pairs to eliminate internal joints. Each set of layers is separately constrained with Kevlar-epoxy bands and the complete assembly clamped in a split laminated iron yoke. The inner coil pairs were wound before heat treating while the outer coils were formed from pre-reacted cable using conventional insulation. A  $\text{NbTi}$  version of the magnet was fabricated using SSC conductor to test the construction techniques. This magnet reached a maximum central field of 7.6 Tesla, at 4.4K which is very close to the limit estimated from conductor measurements. The  $\text{Nb}_3\text{Sn}$  magnet, however, only reached a maximum field at 8.1T considerably short of the field expected from measurements on the inner cable.

## Introduction

In recent years the fabrication techniques for superconducting accelerator magnets have reached the point where magnet performance is limited by conductor properties for the ductile alloy composites such as  $\text{NbTi}$ . This is true despite the fact that the current density in these materials has almost doubled due to improvements in wire manufacturing procedures.

The brittle compound  $\text{Nb}_3\text{Sn}$  has significantly better inherent critical properties than any of the alloy conductors but has been plagued by mechanical problems which make coil fabrication difficult. The application of multifilamentary  $\text{Nb}_3\text{Sn}$  composites to dipole magnet design is an obvious next step in the continuing development of superconductors for high energy accelerators and detectors.

A number of dipoles have been built from this difficult material over the past fifteen years.<sup>1-5</sup> The most successful of these magnets has achieved a field of almost 10T at 4.3K<sup>5</sup>. The magnets described in this paper were built to test certain fabrication techniques and to provide background field for measuring cable conductors for the SSC and RHIC projects. The bore size (8 cm) and length (1 m) were chosen to match the exiting short sample measuring apparatus. The iron yokes were adapted from parts originally made for the C.B.A. project at BNL and the cable parameters were derived from 4 cm SSC magnet models.

## Magnet Construction Details

The dimensions of the four layers in the magnet are given in Table I. Assembly methods were identical for both the  $\text{Nb}_3\text{Sn}$  and  $\text{NbTi}$  coils. The upper and lower inner double coils were clamped on a stainless steel bore tube by 25 mm thick aluminum rings spaced at 50 mm intervals. The space between these clamps was then wound with Kevlar epoxy to apply prestress to the coils. After curing the clamps were removed and the Kevlar epoxy-fiberglass bands ground to fit the inner diameter of the outer coils. This procedure was then repeated and the outer bands ground to match the inner diameter of the iron yoke. The Kevlar applies azimuthal force to each layer of conductors and the yoke prevents the coil from distorting under the influence of the magnetic forces. Since there are no internal joints the coils can be easily connected in series by pre-shaped cross connectors at the end of the magnet in a low field region. These connectors as well as the cables used to attach to the main current leads were made from  $\text{NbTi}$  cable for both types of magnets. A cross section of the magnet is shown in Fig. 1. The yoke was fabricated from standard C.B.A. blocks which are formed from thin low carbon steel laminations glued together under high pressure.

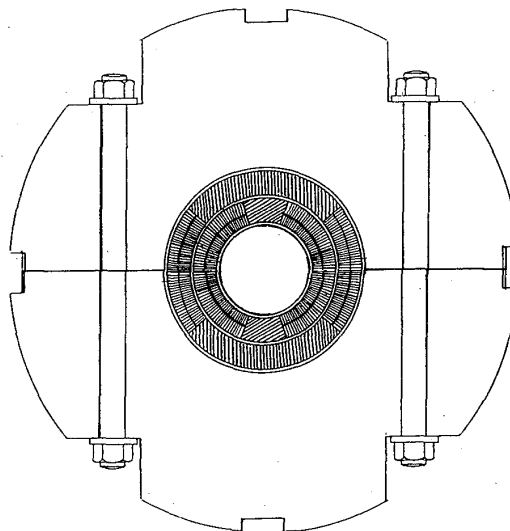


Fig. 1 Cross section of high field, four layer, dipole.

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Table I

Inner Diameter	Coil #1	81 mm
Outer Diameter	Coil #2	121 mm
Inner Diameter	Coil #3	125 mm
Outer Diameter	Coil #4	165 mm
Inner Diameter	Yoke	175 mm
Outer Diameter	Yoke	508 mm
Length of Uniform Field		760 mm
Overall Length of Magnet		1066 mm
Weight of Magnet		~1100 kg

## Coil Winding Details

Table II is a comparison of the coils for the  $\text{Nb}_3\text{Sn}$  and  $\text{NbTi}$  magnets. Fig. 2 is a cross section of a coil. While each set of coils has the same nominal dimensions the number of turns is different due to the thickness of the insulation used on the "wind and react" inner coils of the  $\text{Nb}_3\text{Sn}$  magnet. A ribbon made from "S-glass", 10 mm wide and 0.1 mm thick was used to insulate this coil with a 50% overlap to give an effective thickness of 0.2 mm. All other coils were insulated with conventional Kapton and B-stage epoxy-fiberglass insulation and molded in a high pressure fixture. The inner  $\text{Nb}_3\text{Sn}$  coils were given the same heat treatment as the cable used in the outer coils. A low pressure Argon atmosphere ( $10^{-3}$  mmHg) was maintained in the furnace during the four-step procedure (200 hours at 220°C, 48 hours at 340°C, 24 hours at 580°C and 150 hours at 650°C). The outer cable was treated with Mobil "1" synthetic oil to prevent sintering and heat treated on a 1 meter diameter stainless steel drum with alumina-paper separators. The inner coils were reacted as wound in a special fixture which maintained their shape during the heat treatment. A description of the outer conductor, a low magnetization Modified Jelly Roll, is contained elsewhere in these proceedings.<sup>7</sup> The inner cable is also a MJR type conductor but contains a higher percentage of niobium and is designed to produce very high overall current without regard for filament coupling.<sup>6</sup> A micro photograph of the wire used in the outer conductor is shown in Fig. 3. The cables used in the  $\text{NbTi}$  version of the

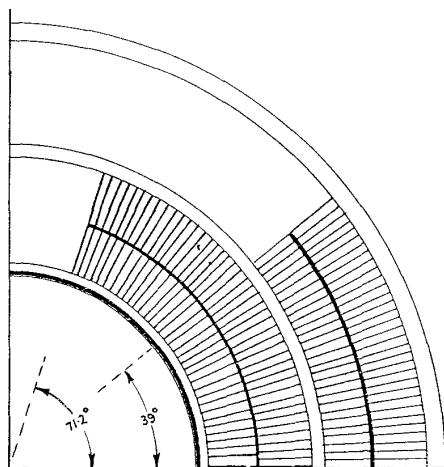


Fig. 2 Details of winding configuration for high field dipoles.

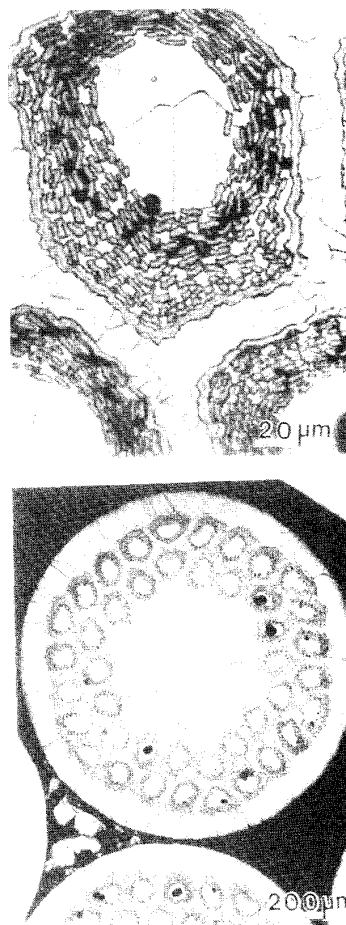
Fig. 3 Microphotograph of modified Jelly Roll Conductor used in outer coils of  $\text{Nb}_3\text{Sn}$  dipole.

Table II

	$\text{Nb}_3\text{Sn}$	$\text{NbTi}$
Turns, Coil #1	30	34
Turns, Coil #2	37	43
Turns, Coil #3	28	34
Turns, Coil #4	32	39
Inner Cable Current, 8T	8500A	4200A
Outer Cable Current, 6T	8200A	6700A

magnet are identical to inner and outer SSC cables. A thermally activated superconducting switch was installed on each magnet so that they could be operated in the persistent mode.

Performance of  $\text{NbTi}$  Magnet

The first quench in the  $\text{NbTi}$  dipole occurred at 3100 amps (7T central field, 7.3T peak field). The magnet trained up gradually to 3500 amps after 15 quenches (7.8 T central field 8.27 peak field). Analysis of the rate of growth of the normal zone from voltage signals indicated that all the quenches were in the coil ends and approximately evenly distributed among the four coils. The decay rate observed at 7.5T was 25 gauss/hr

very close to the rate expected from the coil inductance and the total resistance of the cable-to-cable soldered joints. The load line for this dipole intersects the cable critical current at 3600 amps so that the magnet achieved 97% of expected peak field. It has been used to provide background field for cable measurements for the past nine months, replacing an earlier 6T dipole that had been in daily use for fourteen years.

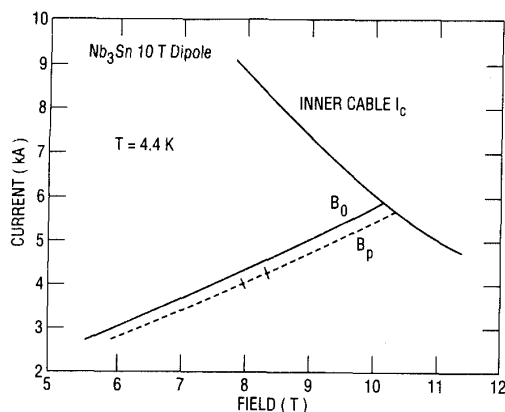


Fig. 4. Magnet load line and conductor critical current for the  $\text{Nb}_3\text{Sn}$  dipole.

#### Performance of $\text{Nb}_3\text{Sn}$ Magnet

Fig. 4 shows the expected performance of the  $\text{Nb}_3\text{Sn}$  dipole which should reach a central field of 9.8T (10.2 T peak field) if limited only by the characteristics of the conductor. The first quench, however, occurred at approximately 4000 amps ( $B_0 = 7.6\text{T}$ ;  $B_p = 8.0\text{T}$ ) originating in the end turns of the outer coil much like the early quenches in the alloy composite magnet. The coil appeared to be training in a similar fashion but on the fourth quench (the first one to occur in the inner coils) at 4350 amps something apparently happened which limited the current on subsequent quenches to slightly less than 4000A. Observations of the decay rate while in the persistent mode indicated that a significant field dependent resistance had developed in the windings as shown in Fig. 5. This resistance could not be localized due to the lack of internal voltage taps on the coils.

When the magnet was disassembled there was no indication of any damage due to arcing or overheating on either the inner or outer coils. The inner windings, however, had moved away from the pole pieces by a significant amount leaving a gap of almost 2 mm. Clearly the inner coils were under-compressed during assembly and probably should have been epoxy impregnated to prevent such gross motions. It is not clear at this time if the coil performance was limited by the resistance observed in current decay studies or by the large azimuthal motions of the inner coils. Reassembly of this magnet with a more complete set of voltage monitoring leads and a suitable method of controlling inner coil motion will be required to answer this question.

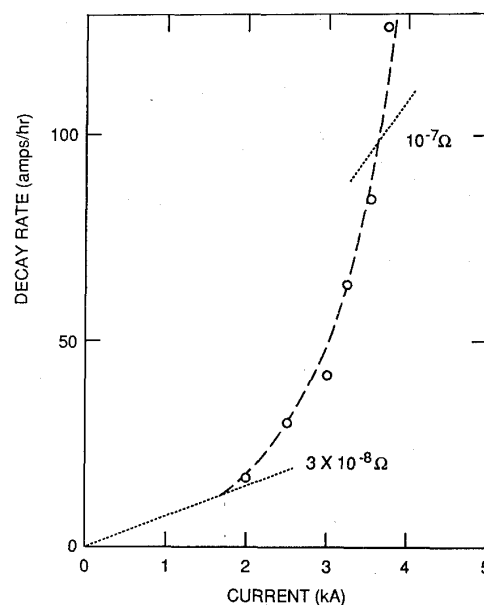


Fig. 5. Internal resistance as a function of magnet current for the  $\text{Nb}_3\text{Sn}$  dipole.

#### Conclusions

While the performance of this  $\text{Nb}_3\text{Sn}$  dipole was somewhat disappointing, it did reach 85% of the short sample limit. Improvements in the method of assembly combined with the steady progress in conductor development should make it possible to reach 10T in the near future.

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