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Fabrication and Test Results of a Prototype, Nb_3Sn Superconducting Racetrack Dipole Magnet

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***Abstract*—A prototype, Nb_3Sn superconducting magnet, utilizing a racetrack coil design has been built and tested. This magnet represents the first step in a recently implemented program to develop a high field, accelerator quality magnet. This magnet was constructed with coils wound from conductor developed for the ITER project, limiting the magnet to a field of 6 - 7 Tesla. Subsequent magnets in the program will utilize improved conductor, culminating in a magnet design capable of producing fields approaching 15 Tesla. The simple geometry is more suitable for the use of brittle superconductors necessary to eventually reach high field levels. In addition, fewer and simpler parts are used in fabricating these coils compared with the more conventional cosine theta cross section coils. The general fabrication steps, mechanical design and quench performance are discussed.**

I. Introduction

The ongoing program for the development and utilization of brittle superconductors for accelerator magnets at LBNL has been recently focused on coils with a simple racetrack geometry. High field, low cost magnets are the most likely option for significantly lowering the overall cost of a new high energy collider. A simple racetrack coil geometry offers a means of utilizing high performance, brittle superconductors as well as cost effective construction techniques. In particular, the Common Coil approach is well suited for collider design [1,2]. The concept, shown schematically in Fig. 1, consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions.

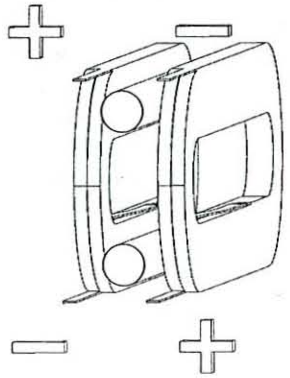

Fig. 1. Common Coil Geometry

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The ultimate goal of the program is to develop accelerator quality dipoles with fields up to 15 T. This will be approached by building a few lower field magnets to demonstrate the feasibility of the design, develop fabrication techniques and understand relevant performance parameters. Ultimate success in the high field regime will depend on the development of high quality, low cost superconductor. The maximum field for the first model is limited by the available conductor.

II. Design

The design and early fabrication stages have been described in some detail in an earlier paper [3]. Brief summaries of the component design are given for completeness. The physical parameters are summarized in Table I.

TABLE I

Racetrack Coil Specifications

Coil Geometry	Two-layer pancake
Number of turns	40
Coil Radius	40 mm
Coil Length (straight section)	50 cm
Coil Spacing (horizontal)	40 mm
Bore Spacing (vertical)	150 mm
Central Field	approx. 6 T

A. Conductor and Cable

The cable is made from 0.808 mm diameter strand manufactured by Teledyne Wah Chang Albany (TWCA) for the ITER project, which has a J_c of about 610 A/mm^2 at 12 T and 4.2 K. Short sample measurements of single strands indicate a bore field of 6.4 T at short sample. A single measurement of a bifilar cable sample gives a lower value of 5.7 T. There is some suspicion that the cable sample may have been damaged during preparation. Another measurement is planned in the near future.

Thirty strands are wound into a Rutherford style cable with a rectangular cross section, 1.45 X 12.34 mm. The cable is insulated with a nominal 0.13 mm thick sleeve of woven S-2 glass. To reduce carbon deposits during reaction, the factory sizing is baked out and replaced with a palmitic acid sizing which leaves less carbon residue. However, there is still a minor problem with low coil resistivity. The simplicity of the racetrack design might make it possible to attempt winding a coil without sizing.

B. *Coil Module*

The fundamental component of this design is the coil module, which consists of a double-layer coil contained in a support structure. The coil module components are shown in Fig. 2.

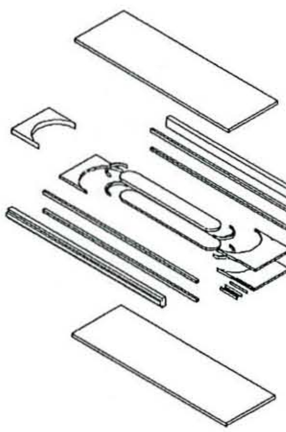

Fig. 2. Coil module components.

The preliminary design is for a 10 mm aperture magnet (40 mm coil spacing) with emphasis on maintaining the simplicity of the racetrack geometry.

C. *Support Structure*

The magnet structural support is designed for modular coil assembly, Fig. 3.

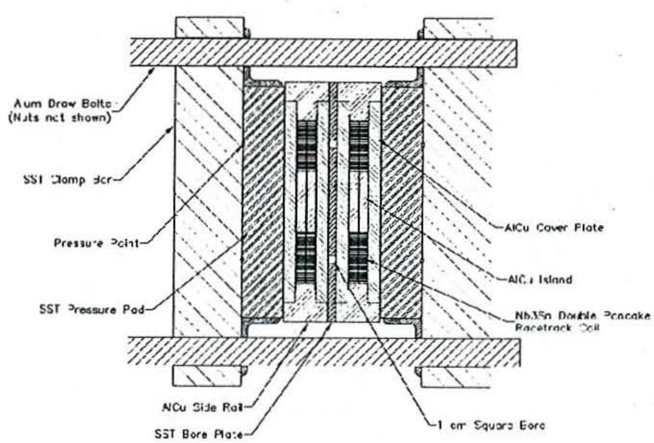

Fig. 3. Coil module support structure.

End forces and vertical forces (forces in the plane of the racetrack coils) are supported within the coil module. A vertical prestress of 50 MPa is applied through 50 mm thick aluminum-bronze rails running the full magnet length in the coil package and an end preload of 50 MPa is applied using a series of setscrews loaded against the end shoes. To apply horizontal prestress and structural support, the coil packages are sandwiched between stainless steel clamping bars pulled together by aluminum tension rods. The horizontal preload is 16 MPa at room temperature and increases to 30 MPa at liquid helium temperatures. This simple support structure allows easy change-out of coil modules and independent control of vertical and horizontal prestress. Future tests of this magnet will be done under varying preload conditions.

III. FABRICATION

A. *Coil Winding*

The double-layer coils are wound around a center island (pole piece) on a flat plate with a ramp between layers to avoid internal splices. All metal parts which will be in contact with the coil are made from aluminum-bronze in order to survive the high temperature heat treatment and because of it's relatively high heat transfer coefficient compared to other materials such as stainless steel. During the winding process, strips of stainless steel foil are wrapped around the cable in strategic locations to provide voltage taps. All metal parts are insulated with 0.086 mm thick strips of mica paper to augment the electrical integrity of the coil and provide a parting plane if needed. A 10 mm spacer is inserted after the 6^{th} turn to reduce the field in the coil end.

B. *Reaction*

After winding, the coil straight section is compressed to a predetermined size by bolting spacer bars and side rails, into the upper and lower plates. The ideal coil size is determined by 10-stack measurements of insulated cable. It is important to minimize the amount of epoxy between the coil turns and thus control the mechanical properties of the composite coil. Optimal compression is achieved at a pressure between 14 and 20 MPa. End shoes are then added and the leads are carefully supported in their final positions. The pole piece is made in two parts with a gap to allow for differential thermal contraction of the conductor and components during reaction. The lead-end shoe and pole piece section are fixed in place, while the return end of the coil is allowed to move. The coil is placed in a stainless steel retort under an Argon atmosphere and reacted according to the manufacturer's recommended reaction cycle, for a two week period.

C. *Instrumentation*

Following reaction, a pair of NbTi cables are spliced to the fragile Nb_3Sn leads. The splice regions are eventually safely contained in the impregnated coil package Capitance gauges are installed in the coil to monitor coil stress during fabrication and testing. Finally, a 0.13 mm laminated sheet of Kapton, stainless steel and copper, containing the heater strips, readout traces and pads for the voltage taps is added to each layer, followed by a 0.13 mm sheet of glass cloth. The coil temperature and joint performance are monitored with a 1/8 watt 100 ohm carbon resistor/thermometer mounted on the cable on the coil side of the NbTi/Nb3Sn splice.

D. Epoxy Impregnation

The reacted coil is strain sensitive and must be reinforced with a glass fiber and epoxy matrix. The stainless steel side rails and plates used during reaction are replaced with similar parts made of aluminum-bronze, designed to closely fit the post-reaction dimensions of the coil. Strips of mica paper are added between the outer turn of the coil and the surfaces of the side rails and end-shoes for electrical insulation. Also, the mica provides a shear plane, intended to prevent stick-slip motion under Lorentz loading. In addition, the plates, side-rails and end-shoes are mold released. The completed package is then vacuum impregnated, providing a robust module for insertion into the horizontal support structure. All surfaces in contact with the coil remain after potting, providing good surface matching and reducing the necessity for stringent part tolerances, another potential cost saving feature of this design. A cross section of the coil module support structure, is shown in Fig. 4.

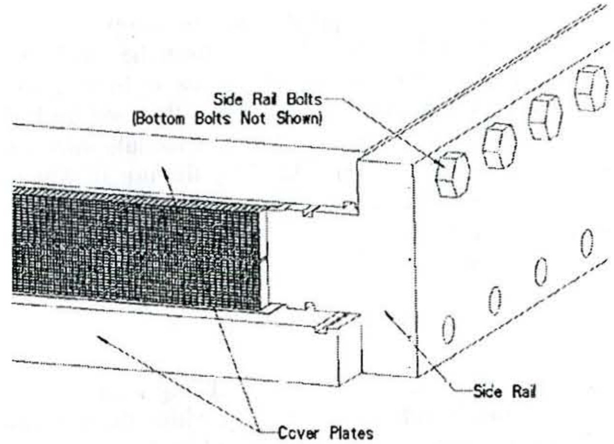

Fig. 4. Cross section of coil module structure.

E. Coil Preloading

Prior to epoxy impregnation a 1 mm shim is inserted between the side rail and cover plate. After potting, the shim is replaced with a smaller shim to achieve the desired vertical preload. This method prevents the development of shear stress when vertical and horizontal prestress is applied simultaneously. The shim can be changed to vary the vertical prestress independently of the horizontal support.

E. Final Assembly

A diagram of the support structure components is shown in Fig. 5.

The coil packages and support structure components are stacked and aligned via pins. The load from the side bars is transferred and controlled through the use of bearing rods and balls. This technique greatly reduces the need for high tolerances. The minor variations in coil module thickness and uniformity are accommodated by the use of Kapton shims between the coil modules and pressure pads. The nuts on the aluminum tension rods are then tightened to obtain the desired preload.

IV. Test Results

As of this writing, the magnet is being cooled down prior to testing. Results are anticipated within the next few days. The headered magnet is shown in Fig. 6.

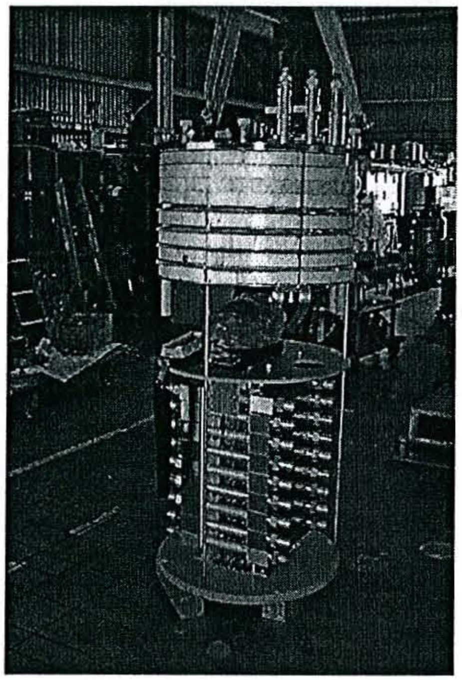

Fig. 6. Magnet mounted on cryostat header.

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