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An R&D Approach to the Development of Long Nb_3Sn Accelerator Magnets Using the Key and Bladder Technology

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***Abstract*—Building accelerator quality magnets using Nb_3Sn for next generation facilities is the challenge of the next decade. The Superconducting Magnet Group at LBNL has developed an innovative support structure for high field magnets. The structure is based on an aluminum shell over iron yokes using hydraulic bladders and locking keys for applying the pre-stress. At cool down the pre-stress is almost doubled due to the differences of thermal contraction. This new structure allows precise control of the pre-stress with minimal spring back and conductor over-stress. At present the support structure has been used with prototype magnets up to one meter in length. In this paper, the design of a 4-meter long, 11 Tesla, wind-and-react racetrack dipole will be presented as a possible step toward the fabrication of long Nb_3Sn accelerator magnets.**

***Index Terms*—Nb_3Sn, superconducting magnets.**

I. INTRODUCTION

NIOBIUM TITANIUM (NbTi) has been the conductor of choice in superconducting accelerators from Fermilab's Tevatron to CERN's Large Hadron Collider (LHC) [1]. However, several next generation facilities demand fields well beyond the working limit of NbTi conductors. In particular, powerful dipole and quadrupole magnets will be required during the next decade to reach the ultimate luminosity upgrade target of $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the LHC [2]. A new Department of Energy program, the LHC Accelerator Research Program (LARP), has been established for the development of high field magnet technologies suitable for the LHC upgrade and other future accelerators [3].

Among potential conductors for next generation high field magnets, Niobium Tin (Nb_3Sn) is in the most advanced state of development. Nb_3Sn is a brittle inter-metallic compound belonging to the A15 crystallographic family. It is formed during a heat treatment (reaction) reaching temperatures up to 650°C. In the reacted state, Nb_3Sn is brittle and extremely sensitive to mechanical stress. In order to use this material effectively, two fabrication methods have been developed.

The first method, called react-and-wind, requires the conductor to be reacted prior to winding [4], [5]. Due to difficulties in handling the conductor in such a brittle state, the react-and-wind method presents serious challenges in the area of coil design and fabrication. On the other hand, if this technique can be successfully developed in short models, the technology could easily be applied to long magnets.

The second method, called wind-and-react, uses un-reacted cable (when conductor is still ductile) and reacts the coil module after winding. In recent years this method has seen significant advances in the performance of short prototypes [6]. A record dipole field of 16 T was achieved using the wind and react method [7]. However, converting wind and react techniques to long accelerator magnets poses additional challenges. The challenges include thermal effects during reaction, handling of reacted conductor, impregnation of long coils, fabrication and assembly of long magnet structures, stress variation during cool-down, and containment of Lorentz forces. All these length dependent issues need to be addressed in the early stages of the magnet development.

For this reason, we propose to fabricate a 4-meter long dipole magnet with a compact cross section aimed at investigating the technical issues involved with long Nb_3Sn coils. The magnet adopts the design of the SM (subscale magnet) series [8], and extends it to a length of four meters.

Following a brief description of the subscale magnet design, this paper deals with the fundamental R&D aspects related to the fabrication of a long SM magnet, including reaction and impregnation of the coil, manufacturing of the components, and assembly and cool-down of the support structure.

II. SUBSCALE MAGNET PROGRAM

In 2001, LBNL implemented a subscale magnet program to test the performance of advanced magnet concepts under realistic conditions. The cross section of the sub-scale magnet is shown in Fig. 1: the outer diameter is 240 mm and the longitudinal length is 305 mm. The Rutherford-type superconducting cable is insulated with a continuous woven sleeve of fiberglass. A double-layer coil module is wound around a single magnetic steel pole (island) in a flat racetrack configuration and vacuum impregnated with epoxy resin (VI). Two of these modules are assembled in a dipole configuration and compressed by steel pads.

The support structure is based on the key and bladder technology [9]. It consists of magnetic steel yokes, an aluminum shell, and a set of four steel keys. The two bladders generate the primary force needed to spread the yokes apart tensioning the

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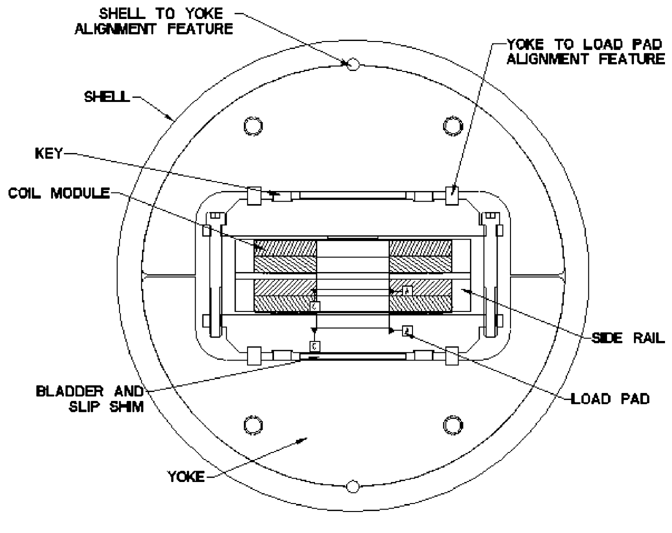

Fig. 1. Subscale magnet cross-section.

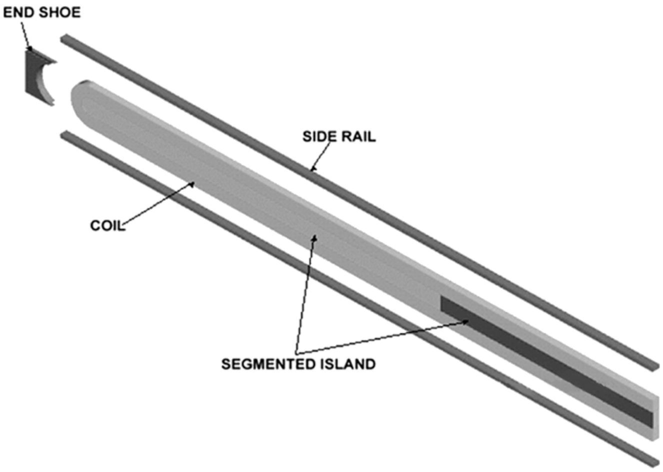

Fig. 2. Exploded view of the long SM coil module return end.

shell. This also compresses the coil pack. Once the keys lock the structure, the bladders are depressurized and removed. During cool-down (293 K to 4.2 K), the shell generates additional preload on the coil-pack, as a result of the different thermal contractions of aluminum and magnetic steel. The magnet can reach a peak field in the conductor above 11 T at a current of 10 kA. Up to now, LBNL has manufactured fifteen sub-scale coil modules and performed six dipole magnet tests [10]–[13]. More recently four SM coils have been implemented in a quadrupole magnet [14].

The SM design is suitable to address the critical issues related to long Nb_3Sn magnets, in preparation for the fabrication of the 4-meter long LARP models. At the same time, this task can be carried out at an affordable cost thanks to reduced conductor volume, minimal tooling, and compatibility with existing test facilities.

III. LONG SUBSCALE MAGNET

A. Coil Module

1) Conductor and Insulation: The Rutherford cable of a SM coil is comprised of twenty 0.7 mm diameter strands. After re-roll the compaction of the cable is typically 87% and the un-insulated cross section is 7.9 mm by 1.3 mm. A 4-meter SM style coil will require a total cable length of 340 meters. Each required strand length should be increased by four percent to accommodate length lost due to cabling. The mass of conductor material required per coil is 70 Kg. A crucial step in the cable manufacturing process is the annealing. Annealing cable at 200°C for 4 to 6 hours will reduce the amount of contraction during the reaction process.

S-Glass is the preferred insulation for Nb_3Sn magnets. S-glass can withstand the extreme reaction temperatures and acts as a capillary agent during impregnation. For magnets of length less than one-meter, insulation is typically a sleeve. The sleeve is installed on the cable after the annealing process. It would be advantageous to investigate alternative methods of insulating cable with S-glass. The co-wound method installs S-glass tape between turns during winding. This will insulate the cable turns from each other. An additional layer of S-glass should be placed above and below the un-insulated portion of the coil module. Another method of insulating the cable would be a spiral wrap. The spiral wrap method installs S-glass on the conductor during winding between the tensioner and the winding form. The spiral wrap can be quarter lap, half lap, or three quarter lap depending on the coil design.

2) Coil Module Support Structure: For ease in manufacturing and cost effectiveness, a long Nb_3Sn magnet should be assembled using modular components. The coil module will consist of a segmented island, a return end shoe, a lead end shoe, and two side rails. The end shoes and side rails are used during pre-reaction loading of the coil in conjunction with the reaction fixture to guarantee proper coil geometry. The end shoes and side rails must also provide a smooth uniform sealing surface for impregnation. These features are also used during coil assembly and pre-load as a means of transmitting force to the coil.

3) Island: The island should be manufactured in segments to enable manufacturing tolerances to meet specifications and to reduce manufacturing costs. For an island manufactured of magnetic steel a gap of one millimeter per meter length will remove any risk of conductor damage due to the contraction or expansion (see Fig. 4) of Nb_3Sn cable during reaction [15]. This gap could be eliminated if the coefficient of thermal expansion (CTE) of the island material is similar to that of the conductor. The island should also have sufficient features for precision assembly.

B. Manufacturing Process

1) Coil Winding Procedure: The winding procedure should incorporate voltage and resistance checks while the winding is in progress. Winding a 4-meter coil module will require the island to be mounted stationary while the winding head moves around the coil module. The winding head will also need to keep the proper tension (178 N) on the cable while winding is in progress.

Currently there is suitable equipment for winding long magnets available at several institutions.

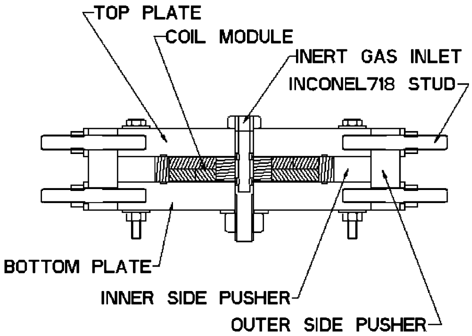

Fig. 3. Cross-section of SM reaction fixture.

2) Coil Reaction Fixture: The reaction fixture is a crucial component of magnet manufacturing. The coil reaction fixture consists of a top and bottom plate, two side inner pushers, two side outer pushers, an inert gas inlet, and the Inconel 718 fasteners (Fig. 3). The reaction fixture will act as a support structure before and after heat treatment. Before reaction, the support structure is used to compress the coil to a theoretical dimension calculated from a 10-stack compression test at 14 MPa. Post reaction, the fixture must rigidly support the coil to prevent irreversible strain during removal from the oven and handling.

The reaction fixture must be manufactured from materials that can withstand the required temperatures while maintaining structural integrity. The fixture must also be modular in order to reduce manufacturing costs. The plates, rails, and pushers should be made of 316 stainless steel, which has a yield strength of 155 MPa at 650°C. The fasteners used to push the side rails inwards toward the top and bottom plate should be made of Inconel 718, which has a yield stress of 980 MPa at 650°C. In addition to the Inconel fasteners an additional hydraulic pusher may be required to compress the coil depending on the amount of fluff encountered during winding [18].

3) Coil Reaction Procedure: The reaction schedule will be 210°C for 100 hours, 345°C for 48 hours, and finally 650°C for 50 to 180 hours. This schedule may vary depending on the desired conductor properties. The oven used to react the coil module should have uniform temperature profile. Any temperature gradient greater than 5°C may cause a nonuniformity of the superconducting properties (RRR). The oven should also have adequate access in order to insert and remove the coil from the oven using the reaction fixture and a secondary strong back. At present there is an existing reaction oven at Texas A&M that would be suitable for reaction of long magnets with minimal modification.

4) Handling of the Reacted Coil Module: Once a coil module is reacted it becomes sensitive to strain. Strain due to bending or handling in excess of 0.5% may result in substantial degradation of conductor critical current [16]. For this reason all fixtures used in reaction, impregnation, and assembly must be rigid. The key areas where there are possibilities for strain damage to occur are: removal of reacted coil module from the reaction oven; transfer of the reacted coil module from the reaction fixture to the impregnation fixture; transfer of the reacted coil module from the impregnation fixture to the support structure; loading of the support structure; transporting any of the aforementioned fixtures.

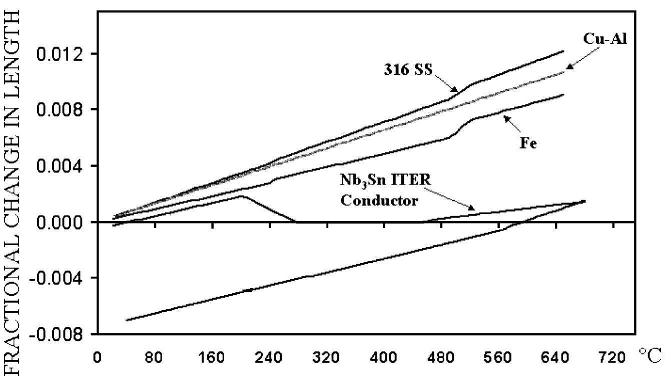

Fig. 4. Comparison of SM materials during reaction.

Depending on coil geometry and design length, rigidity should be engineered into the impregnation and reaction fixtures to prevent strain or deflection.

5) VI for Long Magnet: It is standard practice to impregnate a reacted Nb_3Sn coil using epoxy and S-glass to fill voids and add strength. Each section of the impregnation fixture will need a strong back for rigidity and features to allow for fluid sealing between each modular piece. Allowances should also be made for fluid sealing between the impregnation fixture and the coil module. Once the entire structure is assembled it should be placed at an angle of at least 10° in the vacuum vessel. The vacuum vessel may be modular to accommodate magnets of different lengths. It is recommended that the impregnation fixture have multiple fill points as well as multiple reservoirs for back filling to eliminate any chance of voids in the epoxy. The required heating per meter length of magnet is approximately three kilowatts. This is necessary to initiate curing of the epoxy. All sections of the impregnation fixture that will be removed from the coil module after impregnation must be mold released. At present there is an existing potting vessel at Texas A&M that would be suitable for impregnation of long magnets with minimal modification.

6) Shell, Yokes, and Load Pads: The support structure for a four-meter Nb_3Sn magnet will be modular to ensure correct machining tolerances and cost effectiveness. The shell, yoke, and load pads will all be manufactured in sections. The section components will have features that allow them to be assembled with pins. In this manner a magnet of any length can be assembled from standard components.

7) Magnet Alignment Features: The proposed alignment features for a four-meter long SM magnet would be from the shell to the yokes and from the yokes to the load pads (see Fig. 2). An additional alignment feature from the load pad to the coil module can be incorporated into the design. Similar alignment features have been successfully incorporated in the manufacture and testing of SQ-01 [14].

C. Assembly Procedure With Key and Bladder Technology

Pre-stress of superconducting magnets can be applied directly through the support structure. The bladders are placed between the yoke and the load pad. The bladders can be pressurized to 70 MPa with a maximum stroke of 4 mm [17]. Once the desired load has been achieved the keys are inserted between the yokes

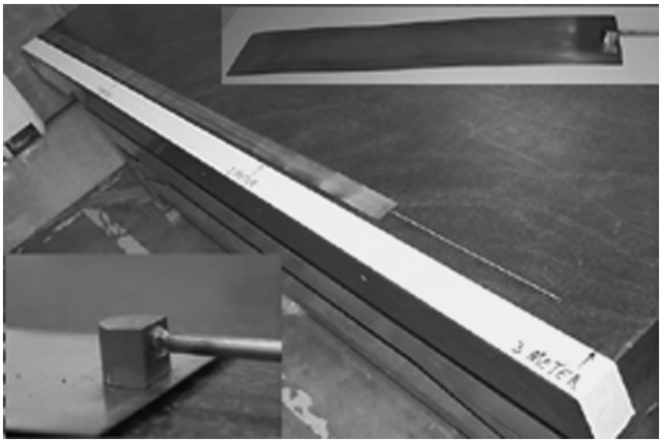

Fig. 5. (Left) pressure block, (Middle) 2.5 meter bladder, (Right) sub-scale bladder.

and load pads. Releasing the pressure from the bladders causes the aluminum shell to apply the pre-load to the coil modules. This process has become standard for all magnet assemblies requiring pre-load at LBNL.

D. Cooldown Issues

The azimuthal stress variation during cool-down in SM magnet shells has been monitored with strain gauges. All measurements showed the same mechanical behavior: an increase of shell tension of the order of 100 MPa, independent from room temperature stress and not significantly affected by friction between the shell and yoke. The reproducibility of the measured cool-down effect allowed predicting precisely the final shell stress, and consequently the coil compression. The same contribution is expected in a long prototype.

The effect of cool-down on the shell axial stress is more difficult to predict. In fact, the shell behavior along the axis strongly depends on the friction between shell and yoke. Assuming perfect sliding, the shell shrinks and no stress is produced. If, on the other hand, the contraction is partially prevented by friction, the cool-down causes an axial tension in the shell. Studies of longitudinal behavior during the cool-down are currently being carried out, both computationally and numerically [19].

IV. CONCLUSIONS

The SM type coil and support structure is a viable option for examining the issues associated with long Nb_3Sn magnets. The implementation of key and bladder technology allows precise control over conductor stress both at room temperature and cool down. The mechanical simplicity and cost effectiveness of the SM type magnet will provide an opportunity to develop sound methods and processes for manufacturing accelerator quality Nb_3Sn magnets.

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