### Title

An approach for faster high field magnet technology development




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### Publication Date

2002-02-15

# An Approach for Faster High Field Magnet Technology Development

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**Abstract— The Superconducting Magnet Program at LBNL has developed a magnet design supporting our new Subscale Magnet Program, that facilitates rapid testing of small superconducting racetrack coils in the field range of 10-12 Tesla. Several coils have been made from a variety of $Nb_3Sn/Cu$ cables, insulated, wound, reacted, potted and assembled into a small reusable yoke and shell loading structure. Bladder and key technology have provided a rapid, efficient means for adjusting coil pre-stress during both initial assembly, and between thermal cycles. This affords the opportunity to test moderately long cable samples under "magnet conditions" on a time scale considerably closer to that for traditional short-sample cable tests.**

**We have built and tested four coils with the initial aim of determining the feasibility of reducing overall conductor costs with "mixed-strand" cables. Details of cost reduction improvements, coil construction, magnet structure, and assembly procedures are reported, along with the relative performance of the mixed-strand coil.**

***Index Terms*— Common Coil Magnet, mixed-strand cable, $Nb_3Sn$, racetrack coil.**

## I. Introduction

Lawrence Berkeley National Laboratory has implemented a Subscale Magnet Program. The new Subscale Magnet Test Facility was fabricated to support the program. The facility includes a 381mm-ID x 1524mm-deep vertical cryostat, with support structure and magnet support header. The program tests the performance of various types of superconducting cables in a medium-to-high field environment as well as investigates magnet structural design modifications, in small scale, before implementing them into our large-scale program. The magnet structural components were mass-produced and standardized for rapid coil module assembly.

Three of the four coil modules initially built (two baseline coils, one mixed strand coil and a comparison coil), have been tested. Presently, two more coil modules with mixed $Nb_3Sn/Cu$ strand coil variations have been reacted and are presently being assembled. Also, a coil module with a new woven ceramic insulator is being reacted.

Manuscript received August 6, 2002. This was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Department of Energy, under Contract No. DE-AC03--76SF00098.

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## II. The Conductor

The Subscale Magnet Program utilizes superconducting $Nb_3Sn$ strands produced by Oxford and IGC. The cables were wound with 20 strands of 0.7mm diameter. The nominal cable cross-section used by the Subscale Magnet Program is 7.9mm x 1.3mm. The cable is sheathed in a continuous, woven, fiberglass sleeve. Coil modules are wound in 2 layers in flat racetrack coil configuration around an iron pole-island – each layer having 22 turns each. (Fig. 1). Each double-layer coil module requires 22m of cable (5 kg).

The two baseline coil modules (SC01 & SC02) were used in the inaugural test of the new Subscale Magnet Test Facility. They were both wound with $Nb_3Sn$ cable – with the same strand as was used in LBL's 14.7 Tesla RD-3B large-scale magnet. The winding and assembly, prior to reaction, took about 2-3 days.

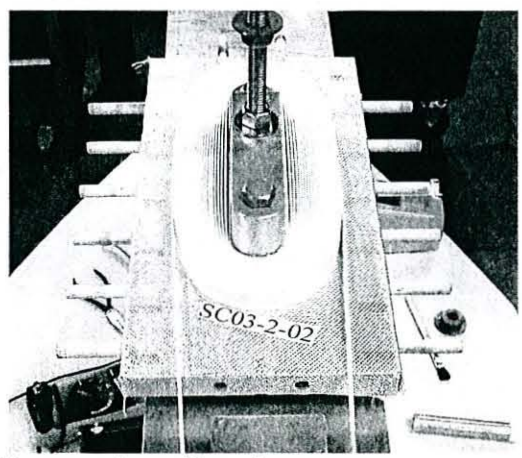


Fig. 1. 2 layers wound around iron pole.

The next coil module (SC03) was wound with a "mixed-strand" cable consisting of 21 strands - 14 $Nb_3Sn$ strands cabled with 7 strands of pure copper. Due to the difference in elastic modulus between the SC and the Cu strands, decabling was evident throughout the whole length of the cable. Coil winding tension was cut in half, from 178N to 89N, to minimize decabling. Even with the lower tension, "popped" strands were observed.

Coil module SC04 was wound with 20 $Nb_3Sn$ strands and was intended as a comparison to the SC03 mixed strand module.

All four coil modules were reacted simultaneously (Fig. 2) and vacuum-potted two at a time.

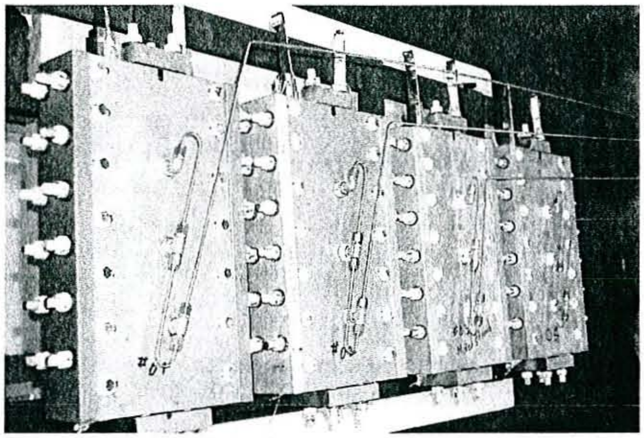

Fig. 2. 4 coil modules reacted simultaneously.

## III. Coil Support Structure

In previous common coil racetrack configurations, the cable was wound around an iron pole-island. Normally, separate side rails or rectangular bars were used to compress the straight sections of the coil layers to a prescribed load. The coil ends were supported by separate end shoes. (Fig. 3). A coil is compressed at least four times – for reaction, potting, skinning and final assembly.

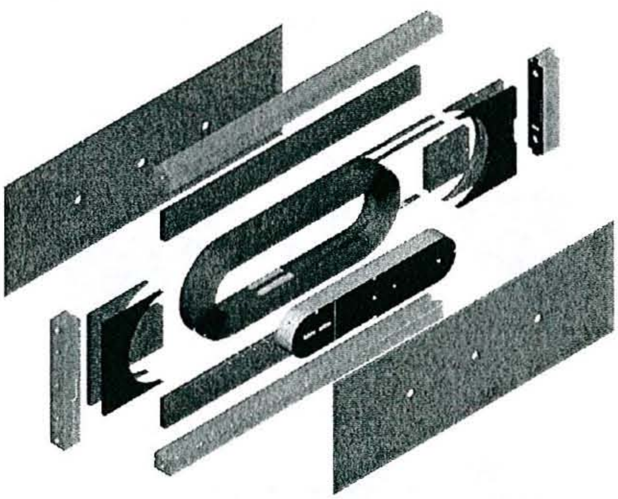

Fig. 3. Full-scale RD-3 components (former configuration)

The Subscale Magnet design has incorporated a "horseshoe"-type coil support system (Fig. 4) where the return-end shoe and the side rails are integrated into one component. A traditional end shoe is used at the lead-end. A push-block is used to axially pull against the horseshoe while simultaneously pushing on the lead-end shoe – in boot-strap fashion. In the past, there were undesirable situations where the feathered-ends of the end-shoes deformed the outer turn of the coil. Half of these "pinch-points" were eliminated with this new design.

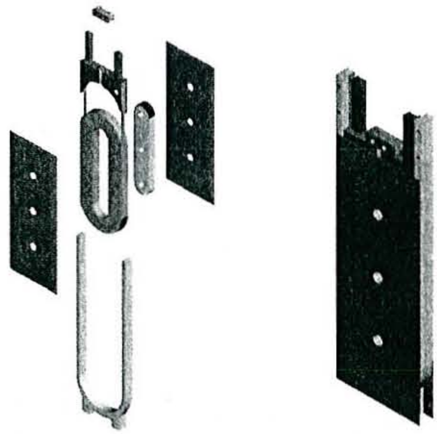

Fig.4. Sub-scale components (new configuration)

Machined to the same thickness as the dual layers, the horseshoe also provides a continuous sealing surface for epoxy impregnation – improving containment of the epoxy within the coil region during potting. The same horseshoe remains with the assembly from reaction through impregnation, becoming an integral part of the final coil module.

During the "skinning" process, the coil module was compressed in a hydraulic press to preload the coils. While in a state of compression, the skins were welded to the horseshoe to keep the coils in a compressed state. This process took about 4 hours.

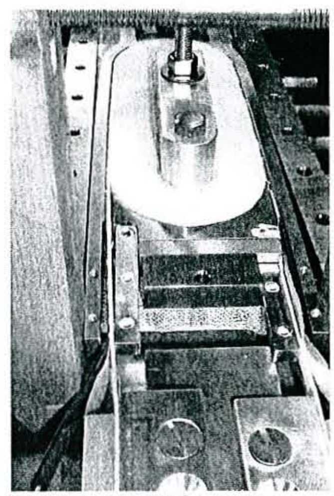

Fig. 5. Subscale module being prepared for reaction.

## IV. Coil Module Instrumentation

The design philosophy of the subscale magnets was to produce, in short order, coil modules to test numerous types of superconducting cables. Any voltage taps within the coil would entail the incorporation of a voltage-tap trace to bring the voltage-tap leads out of the coil module.

The subscale coil modules were designed with minimum instrumentation. There were two voltage taps at each of the two lead splices and one spot heater (for quench propagation studies) in the outer-most turn at the low-field point of the lead-end. (Fig. 6).

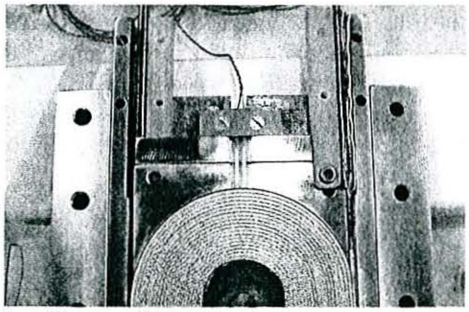

Fig. 6. Voltage Taps at splice and Spot heater.

Presently, there are no plans to install voltage taps within the coil. With this minimum instrumentation, we could only determine when and which coil module quenched during testing.

## V. Assembly

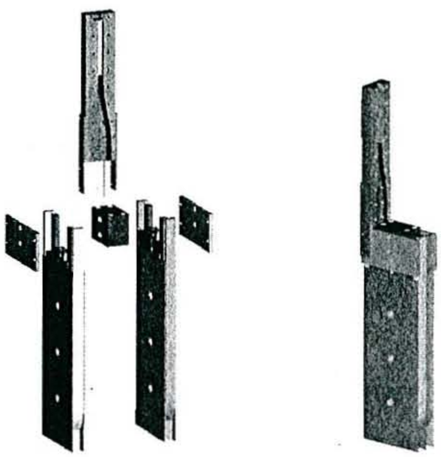

Fig.7. Subscale Magnet Dual Modules with splice.

The test magnet was composed of two coil modules - one base-line coil module and one test coil module, externally spliced in series. (Fig. 7). The modules were structurally pinned together by three NEMA G-10-sleeved pins and isolated from each other by a 0.254mm sheet of NEMA G-10. This package was sandwiched between two steel load pads, 19.0mm thick. Twelve bolts compressed and held this "coil pack" together prior to insertion into the magnet loading structure. (Fig. 8).

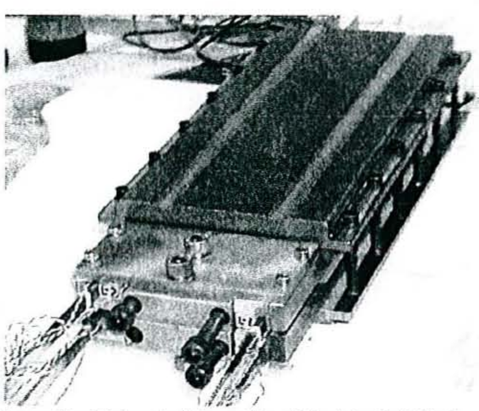

Fig. 8. Pre-Assembled Subscale Magnet Dual-Module Coil-Pack.

The magnet loading structure was composed of 6 laminations of 50.8mm thick steel yoke-plates inside a 12.7mm thick, aluminum cylindrical shell of 215.1mm-ID x 304.8mm-long. Using bladder and key technology [1], the magnet loading structure was slowly stretched until it was possible to insert the prescribed thickness keys (corresponding to a predetermined shell stress) between the coil pack and the yoke assemblies. The bladders were deflated and removed, leaving the coil pack compressed at its room-temperature pre-stress. (Fig.'s 9 & 10).

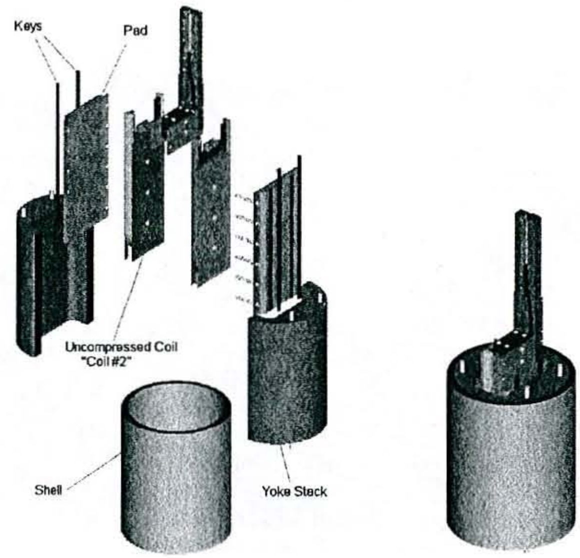


Fig. 9. Sub-scale Coil Pack w/ Loading Structure.

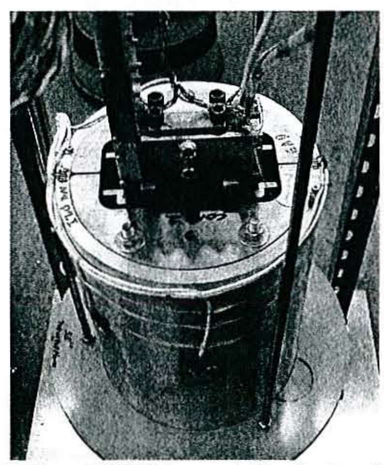

Fig. 10. Subscale Magnet SM-01 in cryostat header assembly.

During cool-down, the aluminum shell of this assembly contracts further to produce the final preload on the coil pack – to prevent the coil pack from separating at 12.5 Tesla. After warm-up, it only takes less than 3 hours to adjust the preload of the coil pack by re-introducing the bladders, inflating and changing out the keys.

## VI. Test Coil Modules

The first two "base-line" coil modules tested in the SM01 magnet test were wound with the same $Nb_3Sn$ conductor. Coil

#1, named SC01, was assembled like our large-scale coil modules – with pre-stress and welded skins.

A new, cost and time saving procedure was employed for Coil #2 (SC02) coil module. This second, "free-skinned", module was assembled like the first except no preloading or skin welding was administered. While the coil was free-standing, the skins were laid in and only tack-welded in the corners, just to keep them in place during handling. The yoke and shell loading structure was used to provide the compression forces required, after cool-down, to keep the coils immobile by friction. These assumptions were simulated and confirmed by ANSYS analyses. (Fig. 11).

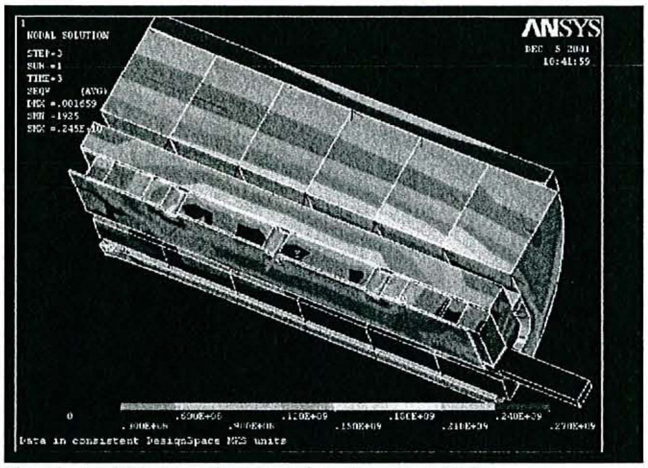


Fig. 11. ANSYS Analysis: Von Mises Stresses at 4.2K

## VII. Test Results

Instrumentation on the loading structure was comprised of full-bridge, temperature-compensated strain gages around the aluminum cylindrical shell. These strain gages measure azimuthal strain as well as longitudinal strain on the shell. The monitored stresses in the shell directly loads the coil pack. Shell strains were recorded while the magnet was being installed in the structure (during the bladder and keying process), in the cryostat (during cool-down), testing, and warm-up. (Fig. 12).

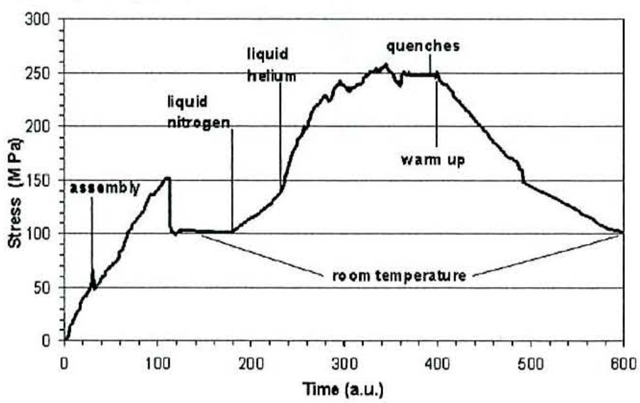


Fig. 12. Shell Longitudinal Stress Time-History (arbitrary time units). [2]

The first test, designated as SM01A, was on a highly loaded coil-pack with a shell stress of 103MPa at room temperature. After cool-down, the shell structure generated 248MPa at 4.2K. Figure 13 shows the training performance of these coils under two load conditions (SM01A & SM01B). The heavily pre-stressed coil started well but improved slowly to 95% of its calculated short sample value. It was decided to decrease the coil-pack loading after the thermal cycle.

In the SM01B magnet test, the SM01 Magnet Assembly was cooled down again and tested. The shell stress was lowered to 1.5MPa at room temperature. After cool-down, the resulting shell stress was 90MPa at 4.2K. After several quenches, starting at higher currents than SM01A, the coils reached 100% of short sample.

The "free-skinned" SC02, during the test of SM01B, only quenched once, while the bulk of the quenches occurred in the preloaded/welded coil (SC01) before reaching 100% short sample.

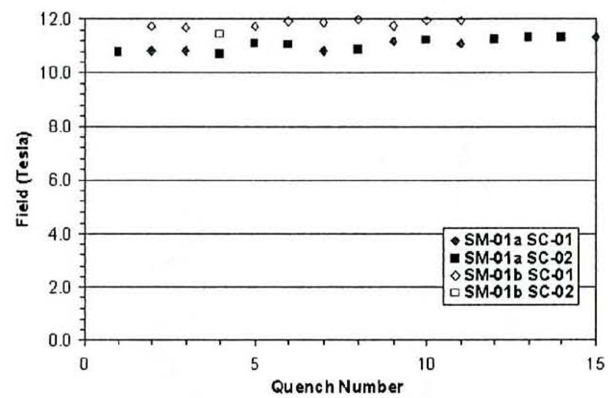


Fig. 13. Quench History of the SM01A & SM01B tests.
Short Sample = 11.9T. SM01A reached 95% of short sample. SM01B reached 100% of short sample. [2]

Data is still being analyzed to catalog other characteristics of $Nb_3Sn$ coil behavior from the initial tests of the subscale coils.

## VIII. Conclusion

It takes a little more than one month to produce a test coil module - from coil winding, through three weeks of reaction, to final installation prior to testing. Due to the favorable results from SM01B, our next large-scale magnet will incorporate the horseshoe design & "free skin" procedure. LBNL's fully operational Subscale Magnet Test Facility is expected to perform numerous investigations on superconducting cable performance and magnet characteristics. This can be attributed to the rapid assembly and fabrication techniques implemented in the Subscale Magnet Program.

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[2] L.Chiesa & S.Caspi, "Strain Gauge Measurements on Subscale Magnet SM-01", SC-MAG 757, Lawrence Berkeley National Laboratory, Dec., 2001.