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Fabrication of a Short-Period Nb_3Sn Superconducting Undulator

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***Abstract*— Lawrence Berkeley National Laboratory develops high-field Nb_3Sn magnets for HEP applications. In the past few years, this experience has been extended to the design and fabrication of undulator magnets. Some undulator applications require devices that can operate in the presence of a heat load from a beam. The use of Nb_3Sn permits operation of a device at both a marginally higher temperature (5-8K) and a higher J_c, compared to NbTi devices, without requiring a larger magnetic gap. A half-undulator device consisting of 6 periods (12 coil packs) of 14.5 mm period was designed, wound, reacted, potted and tested. It reached the short sample current limit of 717A in 4 quenches. The non-Cu J_c of the strand was over 7,600 A/mm^2 and the Cu current density at quench was over 8,000 A/mm^2. Magnetic field models show that if a complete device was fabricated with the same parameters one could obtain beam fields of 1.1 T and 1.6 T for pole gaps of 8 mm and 6 mm, respectively.**

***Index Terms*— Nb_3Sn, Superconducting Undulator**

I. INTRODUCTION

Superconducting undulators (SCU's) have the potential to enable a new generation of insertion devices with enhanced brightness and broadened energy range, representing significant improvements over existing radiation sources. The most promising (though aggressive) technology is based on Nb_3Sn superconductors.

An R&D effort was initiated at LBNL in 2002 to investigate performance characteristics and technological issues associated with the implementation of SCU's at the Advanced Light Source (ALS) [1]. Preliminary analysis considered both NbTi and Nb_3Sn superconductors. Due to geometric constraints, high coil-pack current densities significantly enhance performance of SCU's. The R&D effort at LBNL therefore concentrates on the use of high critical current Nb_3Sn [2], which has the potential to provide the best performance. State of the art Nb_3Sn conductors are a by-product of active research within LBNL's high-field dipole program [3].

The decision to focus on Nb_3Sn superconductor for undulator designs was reinforced after collaborative discussions with researchers from fellow light sources determined that image current heating may severely limit the performance of SCU's [4]. The relatively high critical temperature (T_c) of Nb_3Sn serves to mitigate the risks associated with uncertainties in the magnitude of the image current heating and in the performance of the magnets' cryogenic system without the need for an intermediate liner that adversely affects the magnetic gap, limiting ultimate performance.

The R&D effort at LBNL has resulted in 3 prototype devices. The first device, with a 30 mm period, concentrated on basic fabrication details and magnet protection [5]. The second, a 14.5 mm device, included a number of design modifications/improvements based on experience from the first device [6].

A key feature of the second device was the implementation of NbTi trim coils to provide field perturbations for phase error correction on future devices. The trim coils achieved center-field perturbations of >1% at all field levels, as anticipated by models. The test demonstrated perturbation amplitude sufficient to provide a mechanism for active phase-error correction in future devices.

The performance of the first two devices indicated that they were limited in some cases by magnetic instabilities and in others by mechanical disturbances. Two possible origins for

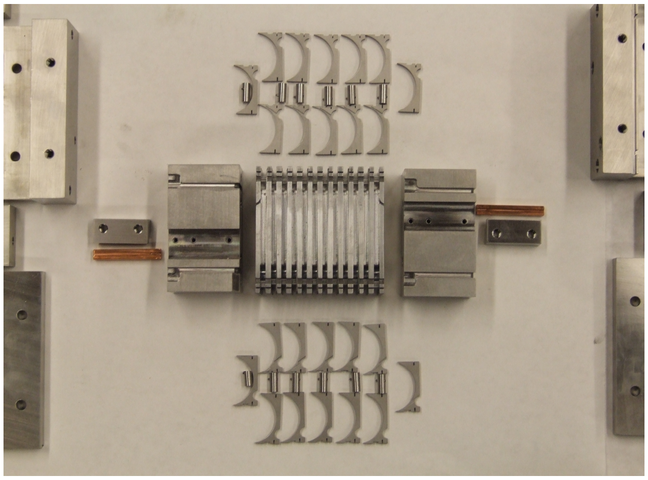

Fig. 1. Main sections of the Nb_3Sn SCU prototype and its components. The main coil is separated into its three sections: the yoke section in the middle of two independent stainless steel end block sections, which provide mechanical support and enable the Nb_3Sn to NbTi splice.

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these instabilities are the conductor effective filament diameter D_{eff} and cracking in the epoxy. The D_{eff} (in the MJR strand used in our prototypes D_{eff}~40 microns) affects the heat deposition due to flux motion; a possible mechanism to mitigate this magnetic instability is to provide dynamic stability by increasing the conductivity (residual resistivity ration RRR) of the copper stabilizer [7, 8]. The low RRR ~20-40, of the Cu matrix of the first two devices limited their ability to dynamically stabilize the conductor. The heat treatment has therefore been modified for the third prototype to increase RRR while minimizing reduction in critical current.

Inspection of the first and second prototypes indicated significant epoxy cracking on the surfaces, which penetrated to the windings. It is possible that the sudden release of energy associated with the formation of a crack in the epoxy near the conductor would provide a signature similar to that seen in mechanical instabilities. Fabrication of filler pieces should minimize the potential for epoxy crack formation during cooldown and energizing. Therefore, in the third device end shoes have been added to fill the larger volumes of epoxy and glass at the end of each coil (see Fig. 1, 2).

II. Nb_3Sn SUPERCONDUCTORS FOR SCU'S

The impressive critical current density (J_c) performance of Nb_3Sn is well established [9], and has been successfully leveraged in a number of high-field magnets. SCU's can also capitalize on the J_c of Nb_3Sn, provided the conductor is stable under operating conditions and magnet protection issues can be overcome. SCU's are characterized by relatively low peak conductor fields (typically 4-6T). Leveraging the current carrying capacity of state of the art Nb_3Sn conductors at these fields results in extremely high copper current densities during a quench, suggesting possible protection issues.

State of the art Nb_3Sn strands can carry 3 times as much current as bronze-processed conductor at all fields, due in part to the quality of the Nb_3Sn (i.e. more volume fraction near the stoichiometric composition of 25 at. %) and in part to the larger Nb_3Sn fraction in the wire cross-section. The conductors are fabricated with processes that utilize almost 100% Sn cores in a Nb-Cu matrix. Strand processing options under these conditions are limited: besides requiring that the temperatures stay below the melting point of Sn, the wires cannot be rolled into tape (e.g. made rectangular) without a reduction in critical current [10]. This is most likely due to the non-uniform tin distribution that results from rolling a twisted wire. Therefore, one must accept the lower fill factor associated with round wire to retain the high J_c.

Magnetic instabilities in state of the art Nb_3Sn can be partially alleviated by providing dynamic stability [11], i.e. providing high RRR copper in the conductor matrix. Experience at LBNL shows that appropriate tailoring of the heat treatment cycle can provide significant increases in RRR with nominal decrease in critical current [7].

III. MAGNET DESIGN AND FABRICATION

The J_c performance of Nb_3Sn is tempered by manufacturing difficulties. First, Nb_3Sn is a brittle inter-metallic compound, capable of withstanding only small (~0.5% tensile) strains [12] before suffering irreversible damage. Undulators must therefore follow a wind-and-react approach due to the small bending radii (large strains) associated with winding a coil. Second, the reaction process subjects the coils to temperatures of 635-650C. The design must allow for proper staging of fixtures and assembly unique to Nb_3Sn -based magnets:

- A special reaction fixture is used during heat treatment, capable of allowing continuous flow of argon gas to purge sizing and other contaminating volatiles. The Nb_3Sn leads are supported by fixtures capable of withstanding the reaction cycle.
- The lead fixtures are carefully removed and Nb_3Sn-NbTi joints fabricated. New (electrically insulating) fixtures clamp the joint to eliminate any movement of the joint and neighboring Nb_3Sn conductor.
- A special potting fixture is used to allow steady, thorough vacuum epoxy impregnation. The coil must be handled with care between reaction and vacuum impregnation; once the coils are epoxy impregnated they are reasonably robust.

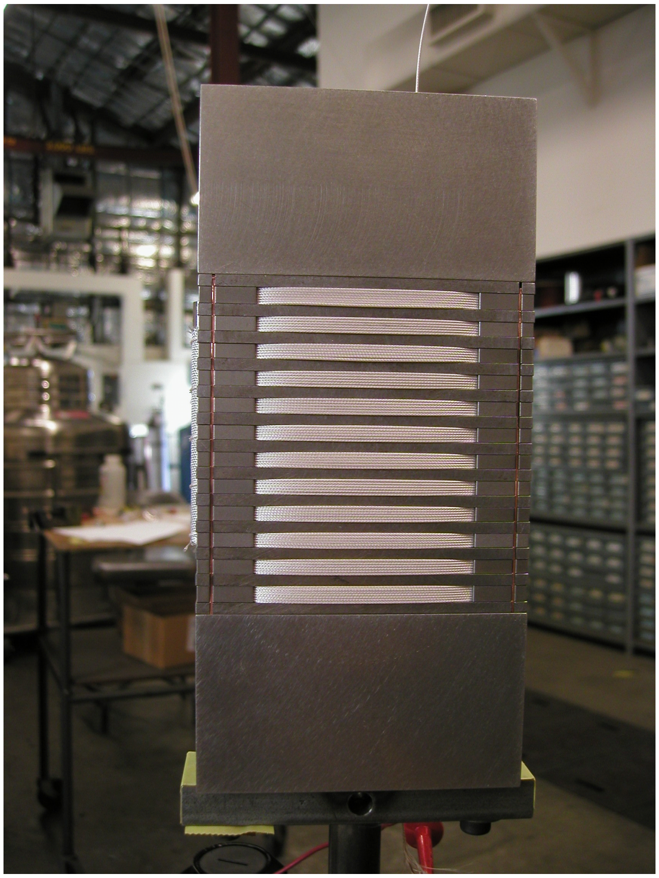

Fig. 2 Beam side of the wound 30-cm long device.

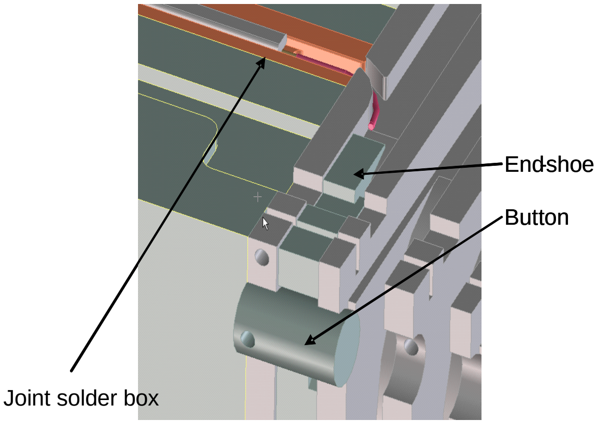

Fig. 3. A winding model with a Nb_3Sn wire coming from the NbTi to Nb_3Sn solder box for making the wire connection into the first coil pack. A winding button and its end shoe are also shown.

The design, fabrication, and testing of prototype devices is essential to building the experience needed to reliably produce Nb_3Sn SCU's. The R&D effort to date at LBNL has concentrated on a wide variety of magnet design issues, as outlined below.

The first prototype addressed basic magnet design issues, with an emphasis on fabrication issues and magnet protection. The resulting 30 mm period device is described in [2]. Key issues that were addressed include:

- Selection of a superconductor with acceptable short-sample J_c in the field range of interest (5-6T).
- Design of a winding methodology that is independent of period length, scalable to arbitrary length devices, does not require internal splices, and minimizes fabrication complexity.
- Design of a (scalable) protection system capable of protecting the conductor during a quench, despite copper current densities greater than $4kA/mm^2$.

The second prototype was designed with a 14.5 mm period and focused on:

- Improving upon the winding methodology and fabrication methods, based on the experience of the first device. The button (Fig. 3) approach to winding reversal, developed for the first device, was further improved. The new technique allows for constant tension on the conductor making the winding process faster and less prone to mistakes. The new procedure is independent of the number of periods, i.e. yoke length. The winding method developed here can easily be extended to a device 1-2m long.
- Design, fabricate and test the addition of a trim coil that will serve as a basic element in a phase error correction scheme for future SCU devices.

The third prototype, also with a 14.5 mm period, builds on the experience from the previous devices, with the following modifications:

- Incorporated a singe strand, providing lower-current operation compatible with use in a cryocooled system.

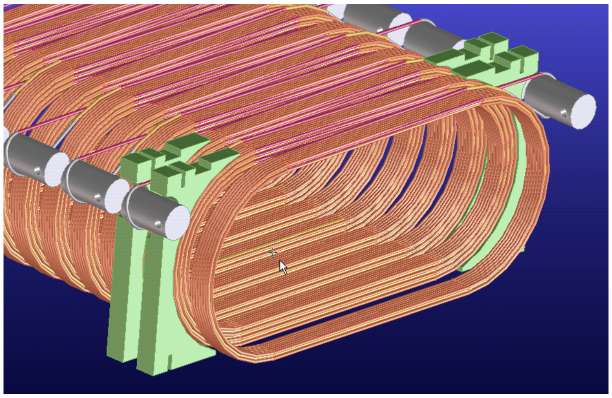

Fig. 4. CAD model showing the windings in the coil packs along with the buttons for reversing the winding direction and four end shoes. (The steel yoke and end blocks are not shown.)

- Incorporated stainless steel end shoes to minimize epoxy cracking, a potential source of premature quenching in the previous prototypes.
- Improve the RRR of the Cu in the conductor matrix to improve dynamic stability. The heat treatment peak temperature was lowered from 650 C to 635 C, and the time at peak temperature reduced to 48 h, increasing RRR to 100 with only a ~10% loss of I_c.
- Two wire insulations were considered. One was S-glass woven onto the wire and the other was a commercial trial ceramic Al_2O_3 coating (provided under contract by nGimat Co.™). The S-glass sleeve had a wall thickness of about 70 microns while the Al_2O_3 coating was about 10-20 microns thick. Although the ceramic holds promise to improve the effective current density by reducing the fraction of area occupied by insulation, the Al_2O_3 coated wire was not used in a prototype due to incomplete coverage of sufficient length of strand. Only the S-glass insulated strand was used.

The lead reaction fixtures were modified to provide more robust holding of the single wire entering and exiting the yoke (see Fig. 3). The lead-box solder assembly and support, seen partially in Fig. 3, was modified to bring the Nb_3Sn lead out parallel to the device. The design accommodates any differential thermal issues between the split assembly and the yoke and provides a Cu block that is reacted along with the assembly and ensures the Nb_3Sn lead has continual support after reaction and prior to soldering the NbTi lead and potting.

Based on our experience with the first two devices and an analysis of the stored energy and system inductance for this short-period and short-length prototype, we concluded that the device is self-protected, i.e. the high quench propagation velocity would distribute the stored energy sufficiently rapidly to avoid excessive localized temperature rise that may damage the device.

IV. MAGNET PERFORMANCE

The single yoke device was tested in March of 2006. It reached the expected short sample current (to within the

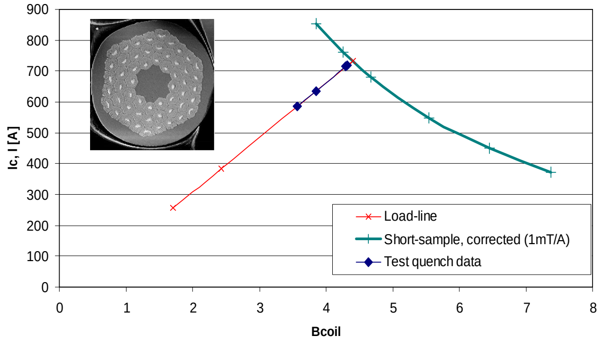

Fig. 5. Critical current as a function of field for the strand used in LBNL's 3rd Nb_3Sn undulator prototype. The load line for the present device is also shown along with the performance of the device (i.e. the quench currents). Superimposed in the plot is a photograph of the modified-jelly roll (MJR) conductor with a diameter of 0.48 mm used.

margin of error of peak field modeling, short sample measurements, and their self-field correction) in 4 quenches. The first quench occurred at 585A followed by another at 585A, then 635A, 717A and 714A (Fig. 5). All of the runs had the same ramp rate of ~1 A/s. Modeling predicted that the peak field on the conductor at the highest quench current of should be 4.3T. This was consistent with the test results.

The RRR of the device was measured to be ~100. This was much higher than for the previous two devices that both had RRR's of ~20. The increase appears to have alleviated the stability issues encountered on the previous devices.

The modifications (i.e. end shoes to reduce epoxy volume, higher RRR via heat treatment) incorporated in this device alleviated the issues thought to have limited the performance of prior devices. As discussed earlier, the modified heat treatment (i.e. lower temperature from 650 to 635 C, and shorter time, from 100 / 80 for the first two devices to 48 h) increased the RRR of the Cu matrix and improved dynamic stability of the strand. The other significant modification was the addition of stainless steel end shoes at both ends of each coil pack, as seen in Fig. 2, 3, and 4. The shoes eliminated the large volumes of glass and epoxy that were prone to cracking. The device was not limited by flux jumps in the strand, and no mechanical or thermal effects arising from cracking of the epoxy were observed.

The device has not yet been disassembled to visually inspect for cracks in the epoxy. When it is determined that the device will not be tested again, the cover plates, which were mold released prior to potting, will be removed from both surfaces and the coil windings will be inspected.

V. CONCLUSION

LBNL's experience with Nb_3Sn superconducting magnet technology is being extended to insertion devices. The design, fabrication, and results of the single-yoke prototype presented here is the culmination of a series of devices.

The self-protecting device went to its expected short sample current within 4 quenches with the highest quench current being 717A. At this current the non-Cu J_c was 8250 A/mm^2 and the current density in the Cu was 7600 A/mm^2. Magnetic field models show that if a complete device were fabricated with the same parameters one could obtain beam fields of 1.1 T and 1.6 T for pole gaps of 8 mm and 6 mm, respectively.

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