fabrication of a short-period Nb3Sn superconducting undulator

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Abstract—Lawrence Berkeley National Laboratory develops high-field Nb3Sn 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 Nb3Sn permits operation of a device at both a marginally higher temperature (5-8K) and a higher Jc, 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 Jc of the strand was over 7,600 A/mm2 and the Cu current density at quench was over 8,000 A/mm2. 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—Nb3Sn, 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 Nb3Sn 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 Nb3Sn 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 Nb3Sn [2], which has the potential to provide the best performance. State of the art Nb3Sn conductors are a by-product of active research within LBNL’s high-field dipole program [3].

The decision to focus on Nb3Sn 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 (Tc) of Nb3Sn 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
these instabilities are the conductor effective filament diameter $D_{\text{eff}}$ and cracking in the epoxy. The $D_{\text{eff}}$ (in the MJR strand used in our prototypes $D_{\text{eff}} \approx 40$ 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 ratio RRR) of the copper stabilizer [7, 8]. The low RRR $\approx 20-40$, 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$_3$Sn SUPERCONDUCTORS FOR SCU’S

The impressive critical current density ($J_c$) performance of Nb$_3$Sn 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$_3$Sn, 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$_3$Sn conductors at these fields results in extremely high copper current densities during a quench, suggesting possible protection issues.

State of the art Nb$_3$Sn strands can carry 3 times as much current as bronze-processed conductor at all fields, due in part to the quality of the Nb$_3$Sn (i.e. more volume fraction near the stoichiometric composition of 25 at. %) and in part to the larger Nb$_3$Sn 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$_3$Sn 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].
The design, fabrication, and testing of prototype devices is essential to building the experience needed to reliably produce $\text{Nb}_3\text{Sn}$ 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 single strand, providing lower-current operation compatible with use in a cryocooled system.
- 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 $\text{Al}_2\text{O}_3$ coating (provided under contract by nGimat Co.™). The S-glass sleeve had a wall thickness of about 70 microns while the $\text{Al}_2\text{O}_3$ 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 $\text{Al}_2\text{O}_3$ 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.

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
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 717A. At this current the non-Cu \( I_c \) 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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**REFERENCES**