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Fabrication and Test of a Racetrack Magnet Using Pre-Reacted Nb_3Sn Cable

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***Abstract*— A racetrack magnet, using Nb_3Sn superconducting cable reacted before winding, has been fabricated and tested at Fermilab. It consists of two flat racetrack coils, connected in a common-coil configuration, separated by a 5 mm thick fiberglass plate. Synthetic oil was used to prevent sintering of the strands during the heat treatment. The coils were wound and vacuum impregnated in the mechanical structure. The turn-to-turn insulation, consisting of Kapton® and pre-impregnated fiberglass tapes as wide as the cable, was wound together with the bare cable in order to form a continuous inter-turn spacer. The coils were instrumented with voltage taps, temperature sensors, spot heaters and quench heaters. The maximum current achieved was 12675 A which is 78% of the short sample limit at 5.1 K (minimum temperature in the coil during 75 A/s ramp). Measurement of the temperature margin revealed a low degradation in the innermost turns. Quench performances at different temperatures and ramp rate effects have been measured and are presented and discussed.**

***Index Terms*— Nb_3Sn, React-and-Wind technology, Superconducting magnets, Superconducting materials.**

I. Introduction

A single layer common coil dipole magnet, using Nb_3Sn conductor and the React-and-Wind technology, is under development at Fermilab [1]. As part of this R&D effort, two small racetrack magnets, wound with pre-reacted conductor, have been fabricated and tested They have been employed to develop and test all the procedures required for the fabrication of magnets using pre-reacted Nb_3Sn, to study different insulations suited for this technology, and to practice with the impregnation of coils inside the mechanical structure (a feature required by the single layer common coil). The design and the test results of the first racetrack magnet (HFDB-01) have been presented elsewhere [2]. HFDB-02 has several new features, including a different conductor, different insulation and a new technique to apply the insulation and wind the coil. In this paper those new features, the fabrication of HFDB-02, and the test results are presented and discussed.

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II. Magnet design

HFDB-02 consists of two racetrack coils, wound with pre-reacted Nb_3Sn cable, connected by a NbTi cable in a common coil configuration (i.e. the current is flowing in opposite directions in the two coils). Each coil, 0.73 m long, has 28 turns. There is one spacer in the ends and no spacers in the straight section. The coils are separated by a 5 mm thick G10 plate. All parts inside the winding are made of G10 (with the fiberglass sheets coplanar with the winding), the end shoes are made of bronze, and stainless steel is used for all parts of the mechanical structure (main plates, side and end pushers). More details may be found in [2]. Fig. 1 shows the second coil during the insertion of the end shoes.

The Rutherford cable had 41 0.7 mm diameter strands made by Oxford Superconducting Technologies (ORE-151 and 152 with 54 subelements and 46.5% copper). Virgin strand samples, reacted with the cable, showed an average critical current of 1866 A/mm^2 at 12 T, 4.2 K. The measured cabling degradation was 2%. The short sample limit, in a magnet wound with pre-reacted Nb_3Sn, depends on the bending strain. This strain is determined by the geometry of the coil and of the reaction spool, and may increase by more than a factor two if there is any sintering of the strands during the reaction [3]. The inner diameter of the ends of HFDB-02 is 180 mm. The cable was reacted on a stainless steel spool with an inner diameter of

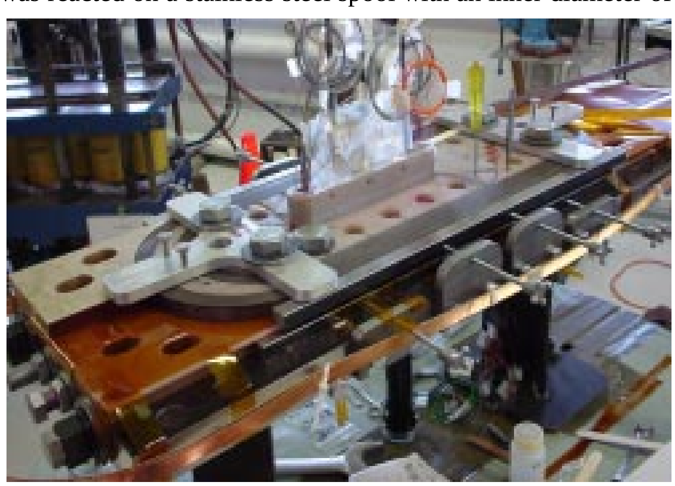

Fig. 1. HFDB-02 after the winding of the second coil. The cable and the insulation, still connected to their tensioners, may be seen in the top right corner.

360 mm, in order to have approximately the same bending in both the ends and the straight sections of the magnet. The maximum bending strain (i.e. the maximum strain in the outermost filaments), occurs in the innermost turn in the ends. It is 0.22%, or 0.47% in case of sintering. According to measurement [4], the expected critical current degradation due to this bending at 10 T is about 6 %, or 15 % in case of sintering. Therefore the total degradation of the conductor, in case of sintering, should be 17% at fixed field, equivalent to a 5% degradation on the magnet load line. The corresponding maximum field at 4.5 K is 10.2 T at 16870 A reached in the 14^{th} and 15^{th} turn in the straight sections.

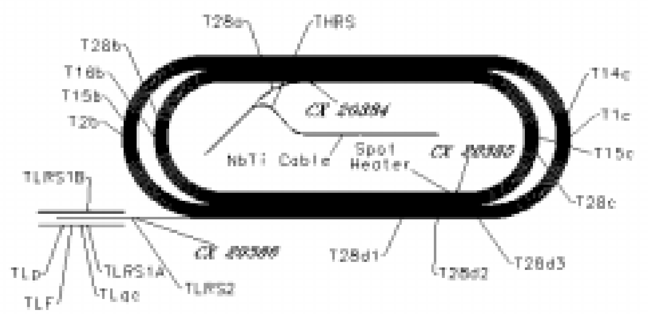

Fig. 2. Position of voltage taps, spot heater and temperature sensors on the second coil. The number in the voltage tap's name indicates the turn.

III. Fabrication

The cable was made at LBNL adding 5% synthetic oil (Mobil-1) to the oil normally used for cabling. Measurement of the degradation due to bending, in cable samples, showed that the amount of oil introduced in this way may not be sufficient [3]. A larger amount was therefore added by doing a vacuum impregnation of the cable, inside a plastic bag, with 100% Mobil-1 oil. The cable for each coil was subsequently wound on a single-layer stainless steel spool, using mica-glass tape to separate the turns. The reaction was performed in an Argon atmosphere, inside a retort, using the heat treatment suggested by OST. The coils were wound and subsequently impregnated in the mechanical structure. One of the two main plates was installed on a rotating table, the first coil was wound on it, the G10 interlayer plate was inserted, then the second coil was wound on it (Fig.1) and the rest of the mechanical structure was assembled (top main plate, side and end pushers).

The ground insulation consisted of four layers of 127 μm thick Kapton® strips over the main plates (thick so as not to be damaged during the winding of the coil), of 330 μm thick Kapton® toward the ends and of G10 shims (3.5 or 6 mm thick) toward the sides. The turn-to-turn insulation consisted of one layer of pre-preg tape, 150 μm thick, and one of Kapton® tape, 75 μm thick. Both tapes had the same width as the cable and were wound together with the cable (i.e. not wrapped around the cable). The cable was wound under a tension of 10 kg while 15 kg of tension were applied to the insulating tapes (which had previously been wound on the same spool). The tension applied to the insulating tapes was sufficient to keep the coil compact during the winding, without the need of side pushers, allowing a short winding time (less then four hours per coil). Copper shims were set on the sides of the splices. In order to have sufficient cooling, the splice regions were designed to have those shims in direct contact with the helium. This was achieved by extending the shims outside of the lead end, and by providing for holes perpendicular to the magnet at the location of the splices to the NbTi junction.

Both coils were instrumented with a spot heater on the innermost turn, two temperature sensors (Cernox-HT, set in the coil before the impregnation), and 19 voltage taps (Fig. 2). An additional temperature sensor was located close to the lead end splice of the second coil. Unfortunately its wires were damaged during the cleaning after impregnation. Grooves for the wires were made in the G10 islands and in the G10 interlayer plate. Quench heaters, consisting of stainless steel strips glued on Kapton foils, were set on the top of each coil during the fabrication of the magnet. Twelve bolts were instrumented with strain gauges.

Both coils were wound smoothly. An unexpected problem occurred during the instrumentation of the second coil. The T-shaped tools set in the ends (Fig. 1), used to keep the cables in position during the winding, were removed in order to solder the voltage taps. Overnight the outermost turns of the coil, in the lead end, raised by almost 1 mm. A G10 plate and a clamp were used to apply moderate pressure to re-seat these turns, but they rose again when the pressure was released. It was decided to remove 200 μm from the Kapton® foils of the quench heaters covering this area, and to proceed with the assembly.

After the winding and instrumentation of the second coil, the top main plate was set in place. Subsequently the side and end pushers were installed and used to compact the coils before the impregnation. During the assembly of the magnet all parts were painted with mold-release varnish (with a few exceptions like the quench heater face toward the coil). A layer of high temperature grease was set on all bolts and nuts before use and all exposed parts were covered with a silicone rubber (GE RTV 21) after installation. Another silicone rubber (GE RTV 157) was used to fill holes that were to remain free from epoxy (for instance the cooling channels). The magnet was placed in a slightly inclined tank and vacuum impregnated with epoxy (CTD-101K) in a temperature controlled oven at 60 °C. The temperatures of the oven and of the magnet were monitored during the five hours of the impregnation. After the impregnation, epoxy was cleaned from the outside of the mechanical structure. The side and return end pushers were removed, cleaned of epoxy and set back in place to apply the pre-stress. The lead end pusher was also to be removed, but it was glued by epoxy to the current leads, despite the application of mold-release varnish and silicone rubber before the impregnation. Because of the risk of damaging the leads, it was decided to remove this pusher only after the first thermal cycle (if a lack of support on the lead end was shown during the test). A partial cleaning of the surface behind the pusher was executed from the sides. The pre-stress was applied in steps of ¼ of the total load (Table I), first on the sides and ends, then on the main plates. In order to reduce the pre-stress losses during the cooldown, aluminum bolts were used in the sides and thick invar washers in the ends. After the first thermal cycle the lead end pusher was removed without great difficulty, and the pre-stress was re-applied and increased in the ends (Table I). Further details about the fabrication may be found in [5].

TABLE I
LOADS IN FIRST/SECOND THERMAL CYCLE

Bolt location	# of bolts	Load/bolt preload (kN)	Load/bolt cooldown (kN)	Energization gain @12 kA (kN)
Main plate	57	21/21	8/17	20/16
Side pusher	32	9/10	10/10	-0.7/-0.6
End pusher	8	7/15	6/10	0/0.7

IV. TEST AND ANALYSIS

HFDB-02 was tested at Fermilab in the vertical magnet test facility [6] at 4.5 K and at lower temperatures. Two thermal cycles were performed and the effect of different ramp rates explored (from 20 to 500 A/s, i.e. from 12 to 302 mT/s). A 30 mΩ dump resistance and quench heaters were used for protection.

The quench history is shown in Fig. 3. Initial studies were performed at a nominal temperature of 4.5 K. The first quench occurred at 9273 A, followed by quenches at 11079 A and 10914 A, before reaching what appears to be a plateau near 12000 A in the next several quenches. This current is significantly below the estimated short sample limit of 16870 A (shown as the dashed line on the figure). Quenches were recorded at ramp rates of 5, 300, and 500 A/sec. The quench current dependence on ramp rate was quite modest: a drop of only 1500A from the plateau was observed at the 500 A/s rate. Lowering the magnet temperature to 2.5 – 3.5 K range did not improve the quench current; in fact, the lower temperature quenches occurred at currents (11447-11738A) below those measured at 4.5 K. Following the lower temperature studies, the magnet was warmed to room temperature.

Studies of quench heater performance and of spot heater induced quenches at fixed currents and locations were also carried out during the first test cycle. Voltage taps were located near the spot heaters to allow study of quench development; thermometers were also mounted on the coil near the spot heaters. These studies will be discussed elsewhere [7]. The spot heaters were also used to slowly heat the coil in a small region, while measuring the temperature on the adjacent thermometer, allowing a determination of temperature margin at fixed currents. Measurements were performed at 7, 10 and 11.5 kA in the first coil and at 11.5 kA in the second coil. An ANSYS model was used to evaluate the

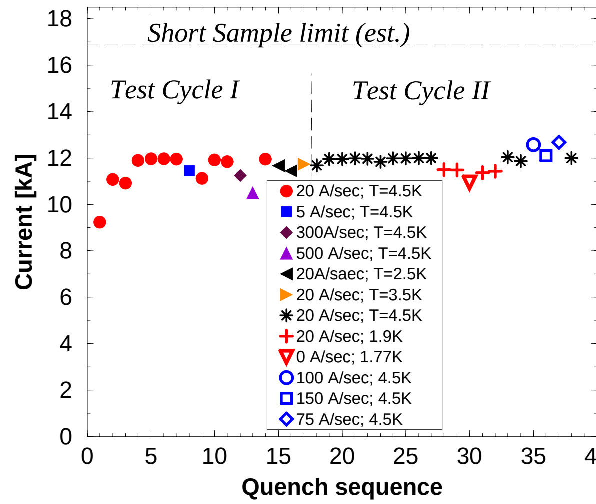

Fig. 3. Quench history of HFDB-02

temperature in the cable hot spot, knowing the temperature measured at the sensor and the power generated by the heater. Different models of the critical surface were used to evaluate the expected temperature margin and to compute the degradation. The results of this study [8] show that the conductor in front of both spot heaters reached the short sample limit.

The first two quenches were located in the first coil, in a region that includes one side of the first turn from the coil end to the voltage tap at the lead splice. All subsequent quenches, with one exception, originated in the second coil, in a voltage tap segment that included turns 2 through 14. The one exception was a quench (#9) in the second coil, in the voltage tap segment that included half of the first turn from the tap at the lead splice to the opposite end of the magnet.

The first quench of the second test cycle was at 11675 A, roughly 300A below the plateau current reached in the first cycle. The second quench returned to the same plateau current as did the next eight. The magnet temperature was then lowered to 1.9 K for superfluid studies and five quenches were recorded in the temperature range from 1.7 to 1.9 K. As before, the magnet quench current decreased with lowered temperature, a somewhat surprising result. The temperature was raised back to 4.5 K and the quench current returned to the plateau region. Ramp rate tests at intermediate rates of 75 – 150 A/s were performed to complete the studies begun in the first test cycle. The highest current (12675 A) was reached at 75 A/s.

All quenches in the second test cycle occurred in the same location as the preponderance of quenches in the first thermal cycle: the voltage tap segment including turns 2 through 14. Of the total of 38 quenches recorded, 35 were in this same location. Unlike the first magnet of this design, HFDB-01 [2], there were almost no voltage spikes associated with quenches.

The typical voltage rise in the quenches was 210 V/s, much larger than in the quenches induced by spot heaters (about 25 V/s), and corresponding to a quench propagation velocity of 43 m/s (in each direction).

The resistance of the lead splice was 0.7 and 0.85 nΩ in the first and second coil respectively, and 2.2 nΩ in both the inner splices. The loads in the bolts, after the cooldown and at 12 kA, are shown in Table I. The instrumented side bolts recorded a loss of load during magnet energization. These bolts are in the end regions and this behavior may be caused by a poor pre-stress of the ends, or by an unexpectedly large shrinkage of the G10 end insert. FEM analyses are on course to better understand this behavior.

There are at least two interesting features of the test data. The first is the ramp rate dependence of the quench current and the second is its temperature dependence. A plot of quench current versus ramp rate is shown in Fig. 4. The current reaches a maximum value at a ramp rate of about 75 A/s with a noticeable fall off on either side. This behavior is suggestive of 'resistive heating' where slower ramp rates result in longer heat generation times and thus higher temperatures at the location of some isolated resistance, typically a splice. However, in the present case the quench origin is not directly associated with a splice, suggesting the existence of a damaged area. A few factors suggest that this degradation may be in the outermost turns: the fast propagation of the quench to the first turn (less than 20 ms), the fact the conductor in the center of the coil never experienced a quench despite the higher field, and the low degradation on the innermost turns as measured using the spot heaters.

A thermal model of the magnet cross section showed that the hysteretic losses should generate a temperature increment of the order of 1-2 K at 75 A/s. During the tests the following temperature increments were measured at 4.5 K bath temperature on the innermost turn: 0.2 K at 20 A/s ramp rate and 0.6 at 75 A/s. Higher temperature increments were measured at 3.5 K and 2.5 K, but the increments were negligible at 1.77 K. Those results suggest that some helium was in contact with the innermost boundary of the coils. The thermal model showed that this cooling should not significantly affect the temperature in the central and outermost turns of the coil due to the poor transverse thermal conductivity of the coil [9].

An analytical model of the coil heating and cooling has shown that DC heating and hysteretic and additional AC losses may resolve in a ramp rate dependence of the quench current similar to the one measured [10]. Further studies and comparisons with measured AC losses are on course.

The negative correlation between temperature and quench current is seen in Fig. 4. A linear fit to the data results in a slope of –200 A/K over a range from 4.5 to 1.7 K. The reduction of the thermal conductivity and capacity of the materials, and the distance of the cooling from the "damaged" turns, may explain a smaller than expected increment of the quench current at temperatures below 4.2 K. The addition to these factors of the larger amount of the hysteretic loss at lower temperature is the most plausible cause of this negative correlation, but we have not yet been able to develop a model that can predict the measured values of the quench current.

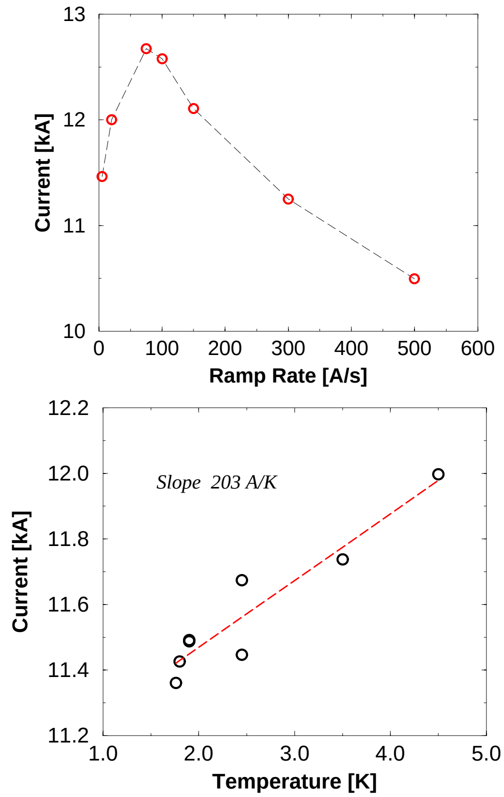

Fig. 4. Quench current versus ramp rate (dI/dt) TOP, and versus bath temperature BOTTOM.

HFDB-02 was partially disassembled after the second thermal cycle. The top plate and the quench heater from the second coil were removed to check this coil. No sign of damage could be seen and the impregnation was complete.

Acknowledgment

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