TECHNOLOGY DEVELOPMENT FOR REACT AND WIND COMMON COIL MAGNETS*

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Abstract

High field common coil magnets [1,2] using brittle High Temperature Superconductors (HTS) or Nb_3Sn cables provide new challenges with respect to the design and manufacturing of coils. We are developing the scaleable techniques that can be used in the production of common coil or other magnets with similar designs [3,4]. By utilizing a cost-effective rapid turnaround short coil program, it is possible to quickly develop and test the new conductors and learn the design and manufacturing concepts needed for them. The flexible nature of a rapid turnaround program required the development of a standard coil cassette for different size cable, allowing coils to be used as building blocks for testing in different magnet configurations. Careful attention is given to the design of the coil structure: The inner bobbin the wire is wound on, the coil winding process, insulation integrity, epoxy vacuum impregnation, and final assembly into a test magnet. This paper will discuss the manufacturing techniques and design rules learned from the rapid turnaround program, and test results to date.

1 INTRODUCTION

The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) is developing alternate magnet designs and technology for future accelerators. The common coil program has been tailored for the quick learning of techniques necessary for the successful handling and use of brittle superconductors and associated technology for use in high field magnets. With the rapid turnaround process, it has been possible to develop in parallel both the design constraints and the manufacturing techniques necessary for the successful application of reacted HTS and Nb_3Sn cables. For practical reasons, the rapid turnaround program forces the development of low cost R&D techniques for manufacturing coils and magnets, as high cost tooling is typically expensive and has a long lead time.

Since the critical current density of presently available HTS is not sufficient for generating high fields by itself, the test fixturing and magnet support structure have been designed to handle a hybrid magnet of up to 6 coils. Three coil pairs in any combination of HTS and Nb3Sn may be powered.

2 MAGNET DESIGN

To achieve rapid turnaround, a 10 turn coil was selected. The length of the pole straight is 300 mm (1 foot); one entire coil requires approximately 11 meters of cable. The coil design was further simplified by using only a single layer of conductor, eliminating the layer transition and its associated cost and complexity.

Fig. 1: Magnet support structure and high current testing setup.

2.1 Magnet Design Layout

- The location of the inner lead was chosen to allow cassettes to be connected either in concert or opposed, depending on orientation during assembly. The design is flexible enough to allow from one to six coils in any electrical or magnetic configuration. In addition, the coils can be configured either as a single bore or dual bore common coil.

- The pole radius of 70 mm was chosen to develop a magnet design with small volume and small strain on the cable during the winding process.

- The bend radius of the center lead is also set to 70 mm. This places the lead along the coil midplane in the low field area of a common coil so that NbTi can be used for flexible splice connections.

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- Both ends of the conductor were stabilized by soldering to a second conductor at the point where it exits.

2.2 Cable Insulation

To be compatible with epoxy impregnation, a glass cloth insulation was chosen for the cable wrap. Initial testing was performed with a 0.003 inch (75 microns) thick, .5 inch (1.25mm) wide ribbon helically wrapped with a 50% overlap, providing a 12 mil (.3mm) insulating gap between conductors. The insulation wrapping was done on existing equipment, at much lower tensions to accommodate the brittle conductor. At present, a 2 mil (50 microns) cloth ribbon is being used, giving an 8 mil (.2mm) conductor spacing. Impregnated insulation test samples of each cloth thickness were evaluated through liquid nitrogen temperature cycles, demonstrating turn to turn dielectric strength in excess of 2 kV. Additional insulation configurations are being evaluated, including tape between the two turns and braid on the cable for testing of 2 and 4 mil (50 and 100 microns) conductor spacing insulations, aimed at further increasing available current densities.

2.3 Epoxy impregnation

To eliminate voids, vacuum impregnation was used. The epoxy chosen was chosen for it's low viscosity and long pot life. Impregnation was performed through the use of a molding fixture with attached heater strips. Temperatures for injection and curing were controlled using simple controllers.

3 OBSERVATIONS

3.1 Epoxy limitations

Unfilled epoxies by nature tend to have rather high thermal coefficients of expansion (TCE), typically 3 to 5 times the rates of the metals and conductors used in magnet design. Because of this difference, any unreinforced epoxy volumes exceeding 20 mils (.5mm) have been found to crack when exposed to cryogenic temperatures. Therefore, unreinforced sections of thicknesses above 10 mil (.25mm) should be avoided where significant stress can be encountered.

The common coil design has a significant advantage over the cosine theta design for impregnated designs. When a cosine theta coil is wound, the compound bend the conductor is forced into will squeeze the conductors whenever the cable bend tries to increase the strand pitch, and "birdcages" the conductors on the opposite side of the pole. While the squeezing is manageable, the birdcaging condition tends to hollows the cable, causing a significant epoxy impregnation cross section ***within the cable*** which will crack normal to the conductors during cooldown and energizing if the epoxy is sufficiently thick. This could be a source of quenching in the ends of impregnated cosine theta magnets.

The most significant rule learned is to never rely on the impregnation epoxy to fill any "fluff" in the design. Voids as small as ¼ to ½ mm can compromise the integrity of the structure at cryogenic temperatures.

3.2 Winding Rules

Since the conductors used are already reacted, they are very brittle, requiring extreme care throughout the entire manufacturing process. During winding, cable tension is kept low, typically 10 lbs., as compared to 40 lbs. typical of NbTi winding. Such low cable tensions are unable to locate the cable against the winding bobbin where the straight sections begin. Tooling clamps providing normal forces against the conductor have been used, but they must be released and replaced during every turn of the winding process. External clamping also causes a buildup of cable stresses as the number of turns increase, causing excessive working and straining of the cable. New clamping methods eliminate the excessive working of the cable, preventing the turn to turn force buildup, and provides for the fabrication of high field coils with a saggitta that could be variable along the so called straight section of the magnet. This development is critical to the magnets for neutrino factory storage ring magnets [3].

3.3 Impregnation tooling limitations

The impregnation mold fixturing, although adequate for the coil structure, requires the use of expensive custom mold designs. Changing the coil geometry significantly requires the fabrication of new mold tooling. For consistency with a rapid turnaround program, we are implementing new impregnation tooling using vacuum bag technology. This technology, already used in industry for aviation, boating, and furniture, allows a significant flexibility in adapting to changes in the coil designs. Modified coil designs can be accommodated with a minimum tooling change, eliminating the delays and cost associated with each custom tooling.

3.4 Insulation limitations

All insulations tested to date provide sufficient dielectric withstanding. Care, however, must be exercised in placement of insulation, as well as it's interaction with the impregnation epoxy. For example, a crack propagating through the epoxy will continue through a layer of polyimide. Multiple layers of insulation will also crack through if they were in place prior to impregnation.

4 A FLEXIBLE TESTING SETUP

4.1 Testing Configuration

The flexible nature of the common coil program required the development of a testing setup capable of supporting many different magnet configurations. To achieve this goal, a second testing tophat has been built and tested. By incorporating 6 gas cooled leads, four of them 10 kA and two 6 kA, many different testing configurations can be used. As an example, a 20 kA Nb3Sn background field with an independently wired 6 kA HTS core; or by wiring in series, a 20 kA background current with from 14 to 26 kA center current.. The main power supplies at BNL can supply 30 kA. This capability meshes well with the various conductor types used to date, as well as with the cables already in the queue.

Incorporated into the test system is the ability to monitor voltage taps throughout the coils, as well as the ability to generate spot heater quenches for propagation studies.

5 Nb_3Sn COIL TEST RESULTS

Coils have been made with two Nb3Sn cable types to date. The first, a chrome plated ITER conductor reached 8250 amps with one training quench. The second coil pair with similar cable, instrumented with 24 taps for quench studies, failed to quench within the current limit of the test system (9700 amps); peak field of 4.2 Tesla. In an attempt to force a ramp rate dependent quench, ramp rates up to 1500 amps/sec were tried. One plateau quench occurred after a 400 amp/sec ramp to 9700 amps, and none occurred at 1500 amps/sec. The next ramp rate used, 62,000 amps/sec caused a quench at 6,500 amps; this occurring in a solder filled stabilizing splice where eddy currents are expected.

A third coil set, made of a higher performance Nb3Sn, quenched consistently at 3000 amps, indicative of cable damage within one of the coil cassettes. Testing of the good coil will commence, and another coil will be fabricated after an autopsy of the damaged coil.

6 HTS COIL TEST RESULTS

HTS React & Wind coil design is similar to Nb3Sn coil except that it uses a narrower 18-strand cable instead of 30-strand cable used in Nb3Sn coils. To minimize damage on the more brittle HTS cable, insulation and winding of HTS coils was done by hand. The tooling has since been modified to handle HTS conductors. All HTS coils are heavily instrumented to obtain a detailed information about each turn of cable (~1 meter). The coils were independently powered to allow testing by themselves, as a common coil, and in the muon collider configuration. Fig. 2 shows the V-I characteristics for each turn in coil #2. In HTS, the critical current (I_c) is typically defined as the current required to produce 1 μV/cm voltage drop in the cable. It is clear that there is some turn-to-turn variation in I_c of the cable. However, the inner-most turn with smallest radius did not have the lowest Ic. This indicates that the bending radius of 70 mm was not a predominant source of degradation.

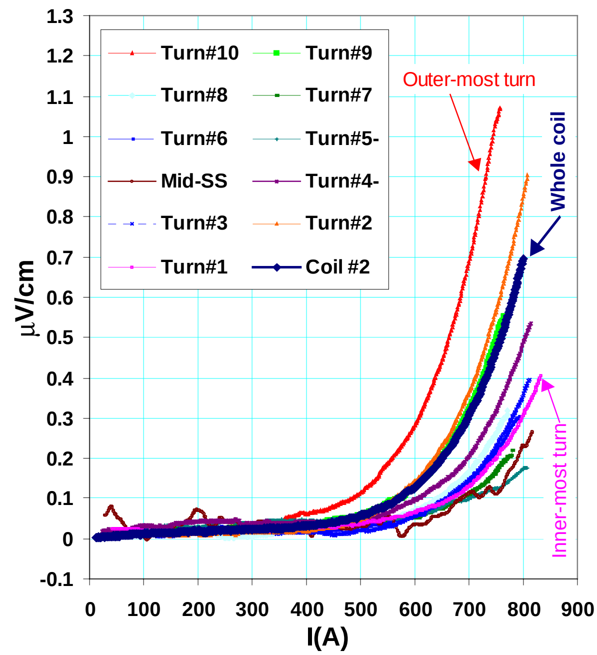

Figure 2: HTS results of coil #2 in common coil configuration.

7 ACKNOWLEDGMENT

We acknowledge the contributions of the technicians responsible for the success of this program. Their expertise in manufacturing process and good observational skills provide the excellent feedback system required in a rapid development system. In particular, Ed Weigand, Mich Williams, Daniel Sullivan, Joseph Gormley and Hal VanDeroef. Part of the cable used in these tests was supplied by Lawrence Berkeley Laboratory. The HTS cable was purchased from Showa Electric Corporation .

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