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Development and Test of Nb_3Sn Cos-theta Dipoles Based on PIT Strands

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***Abstract*—Fermilab is involved in the development of new generation high-field accelerator magnets using state-of-the-art Nb_3Sn strands produced using different technologies. Two 1-m long models - mirror configuration and dipole magnet - were fabricated recently at Fermilab based on powder-in-tube (PIT) Nb_3Sn strands with small effective filament size. This paper describes the parameters of superconducting strands and cable, the details of magnet design and fabrication procedure, and reports the results of PIT coil testing.**

***Index Terms*—Superconducting accelerator magnets, high field dipole, Nb_3Sn strands and cables, Powder-in-Tube technology**

I. Introduction

FERMILAB is involved in the development of new generation high-field accelerator magnets exploring different design and technological options. One of the possible magnet designs is based on Nb_3Sn cos-theta coils and the wind-and-react technology. The single-bore dipole model design was developed based on the two-layer shell-type coil with a 43.5 mm bore and cold iron yoke [1]. Studies and optimization of magnet quench performance were done using magnet half-coils and magnetic mirror configuration [2]. The first three 1-m long dipole models, and a mirror configuration, were fabricated using cable made with the Modified Jelly Roll (MJR) process. These magnets displayed a large degradation of magnet quench current at the level of 50-60% of the expected short sample limit [3,4]. Detailed analysis and special experiments showed the cause to be large magnetic instabilities in the MJR high-J_c Nb_3Sn strands used in those models [5,6]. Further experimental studies performed at Fermilab on different Nb_3Sn strands, cables and small magnets confirmed this conclusion [7-10].

To improve the magnet quench performance and reach the maximum field in this magnet design, more stable Nb_3Sn strands with an effective filament size of ~50 microns produced using powder-in-tube (PIT) technology were used. The 28-strand PIT cable first was tested in a small common coil racetrack magnet SR01 which reached its short sample limit at 4.5 K and maximum field in the coil of 10 T [10]. Two PIT cos-theta half-coils were then wound. The first one (coil #12) was first tested in a mirror configuration HFDM03 and then both coils were used in dipole model HFDA05.

This paper describes the parameters of superconducting strands and cable, the details of magnet design and fabrication procedure, and reports the results of testing magnets with PIT coils. In this paper we focus on magnet quench performance. The results of magnetic measurements performed in the dipole model will be reported elsewhere.

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II. Magnet Design

The dipole model design is based on the two-layer shell-type coil with a 43.5 mm bore and cold vertically-split iron yoke. The magnet coils are made of a keystone Rutherford-type cable with 28 Nb_3Sn multi-filament strands, each 1 mm in diameter. Magnet 3D view is shown in Fig.1. The magnetic mirror configurations use the same mechanical structure with vertically or horizontally split yoke in which one of the two half-coils is replaced with the iron half-cylinder (magnetic mirror). Details of the magnet design and technology are described in [1,2].

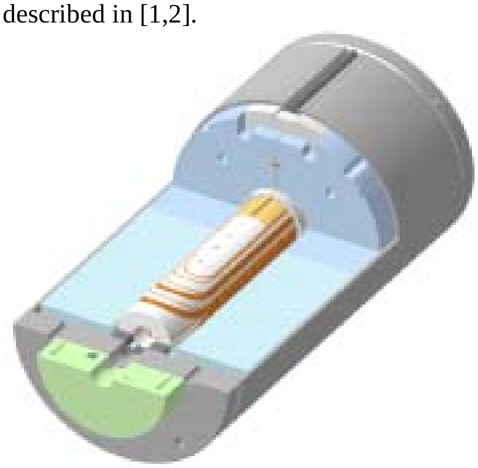

Fig.1. 3D view of HFDA dipole (lead end).

A. Strand and Cable

To avoid instability problems at low fields, the strand was made by SMI (Netherlands) using the Powder-in-Tube process. The filament diameter in round strands is approximately 50 μm. Rutherford-type cable was manufactured at Fermilab. Fig 2 shows the cross-sections of PIT round strand and 28-strand cable before reaction.

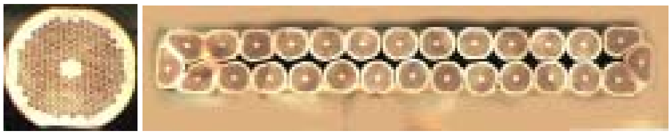

Fig.2. Cross-sections of PIT round strand and 28-strand cable.

The cable insulation system consists of 1 layer of 0.125 mm thick and 12.7 mm wide dry ceramic cloth, spiral wrapped with 1 mm gaps, surrounded by 1 layer of 0.125 mm thick and 12.7 mm wide ceramic cloth with factory pre-preg using CTD-1008 binder [11], spiral wrapped with 1mm gaps.

B. Coil Design and Fabrication

Coils are wound using the coil-on-coil procedure, where the inner coil is wound and cured, inter-layer insulation is added (3 layers of 0.125 mm ceramic sheet), then the outer coil wound over the cured inner coil. Both coils are then cured together. CTD-1008 liquid binder is painted on each inner and outer coil before curing. Inner and outer coil layers are made from one continuous length of cable, eliminating the need for an inter-layer splice. End parts are made of Al bronze using water jet techniques.

A thin layer of mica is placed between each wedge surface and the insulation. The mica is used so that the cable does not stick azimuthally to the wedges. It is believed that, during excitation, the mica helps prevent the epoxy from cracking between the wedges and turns, which may cause quenches. An identical mica sheet is also placed over the pole piece on the inner coil, over the straight section, for the same reason.

Coil curing was done in a closed cavity mold manufactured to the nominal coil size at 150ºC for ½ hour. The mold cavity was shimmed to a size 125 µm smaller azimuthally per side than the nominal coil size. Under a pressure of 20 MPa, the azimuthal coil size after curing was 1.1 mm and 0.7 mm smaller than nominal for coils #12 and #13, respectively. The 0.4 mm difference between the coil sizes after curing was attributed to the fact that the binder used on coil #13 was already partially cured before the coil was wound. The final coil size was achieved during the reaction and impregnation processes and was nearly identical for the two coils.

Ground insulation, consisting of 3 layers of 0.125 mm ceramic sheet, was installed before reaction. Quench protection heaters were made of 0.025 mm by 12.7 mm wide stainless steel strips. One was inserted in each quadrant, between the first and second layers of ground wrap, after the coil is reacted. Each coil pair was reacted using this cycle: ramp up 25ºC per hour from room temperature to 655ºC, followed by 170 hours plateau at 655ºC. Four round strands and four extracted from the cable were placed as witness samples in the reaction fixture along with the coil. The witness samples were tested at the Fermilab short sample test facility to estimate the coil short sample limit.

After reaction but before impregnation, the Nb_3Sn mid-plane leads were spliced to flexible NbTi cable. This splice was made within the longitudinal confines of the coil end part, to prevent the Nb_3Sn cable from being subjected to any motion. Each coil was impregnated with CTD101K epoxy at 60°C, in the same tooling used for reaction. After impregnation, the fixture was placed in an oven and cured at 125°C for 21 hours..

C. Magnetic Mirror Configuration HFDM03

We used a horizontally split yoke approach for HFDM03, as shown in Fig. 3. Coil prestress was provided by mid-plane radial and azimuthal shims. The coil pre-stress range was determined by taking into account two contradictory requirements: one calls for high pre-stress in order to support the turns at the maximum Lorentz forces, while the other requires that the pre-stress be limited due to high sensitivity of PIT strand critical current to transverse pressure [12].

Fig.3. HFDM03 cross-section (return end view).

D. Dipole Model HFDA05

The design and assembly procedure for HFDA05 was similar to the design and procedures of our previous HFDA models [3] except that the end plates and skin which were bolted instead of welded (see Fig.4). The coil prestress was provided by radial shims installed between the coil and coil-yoke spacer and additional radial shims installed between the spacer and the iron yoke near the coil mid-plane.

Fig.4. Dipole model HFDA05 (lead end, before installation of end plate and half-coil splicing).

Coils in HFDM03 and HFDA05 had voltage taps installed on the outer layer and on the each block of the inner layer as well as across all Nb_3Sn/NbTi lead splices.

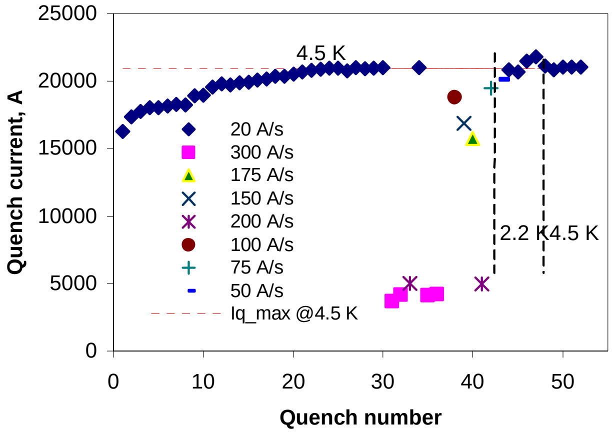

Fig.5. HFDM03 quench history.

III. Test Results and Discussion

Magnetic mirror HFDM03 and dipole model HFDA05 were tested in the Vertical Magnet Test Facility at Fermilab in boiling liquid helium.

A. Quench history

The quench history of mirror magnet HFDM03 is shown in Fig.5. Training quenches at 4.5 K with the current ramp rate of 20 A/s were followed by ramp rate studies, magnet training at 2.2 K, and finally quenching the magnet again at 4.5 K.

The first quench in HFDM03 at 4.5 K was at 16.2 kA. The magnet exhibited slow but steady training. It took 20 quenches to reach the current plateau at 20.6 kA. In order to confirm that the magnet reached its short sample limit at 4.5 K it was cooled down to 2.2 K. Although the quench behavior at 2.2 K was quite erratic, the magnet current increased to 21.8 kA, exposing the magnet to higher Lorentz forces than it was at 4.5 K. A few quenches taken again at 4.5K confirmed that the magnet had reached its short sample limit at 4.5 K. The short sample limit calculated based on the witness strand and cable tests was within the range 17.3-20.6 kA. This range includes additional Ic degradation and present uncertainty due to PIT cable compression in the coil [12]. The maximum field in the coil reached during the test was ~10 T.

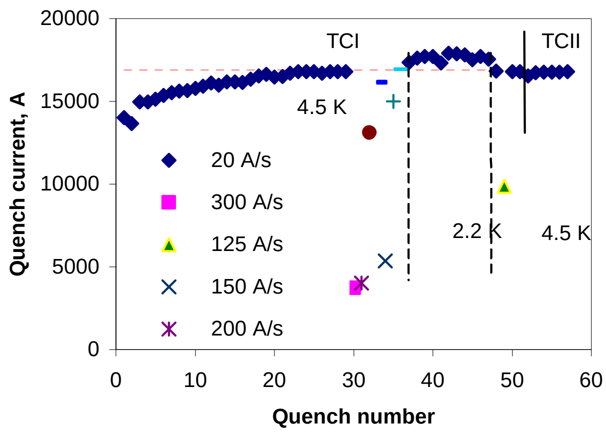

Fig.6. HFDA05 quench history.

Based on signals from the voltage taps, all quenches occurred inside the coil body in the high field region. Some of the quenches might have started close to the transition from the first to second pole blocks of the coil inner-layer since the two segments were quenched at about the same time.

The quench history of dipole model HFDA05 is shown in Fig.6. The magnet training procedure was similar to the HFDM03 test procedure described above. The first quench at 4.5 K was at 14.0 kA. After 23 quenches the magnet reached a stable current plateau at 16.8 kA. After a few quenches at 2.2 K the magnet current increased to 17.9 kA. When the magnet was excited again at 4.5 K it quenched at 16.8 kA. After a thermal cycle to room temperature the magnet showed small, short re-training with the first quench only 3% below the short sample limit. In both thermal cycles all the training quenches occurred in the inner-layer pole block of the new half-coil the maximum field. Training data show that the magnet has reached its short sample limit at 4.5 K. The short sample limit based on the witness strand tests was within the range 16.2-18.7 kA. The maximum field in the bore (coil) at 4.5 K was 9.5 T (9.9 T) and at 2.2 K was 10.0 T (10.4 T).

Fig. 7 summarizes the magnet quench performance during training at 4.5 K. The quench current for each magnet was normalized on its maximum value reached after training at this temperature. Based on the quench location these data could be interpreted as training curves of coil #12 (HFDM03) and coil #13 (HFDA05). As it follows from Fig.7 the training curves of both coils are similar. Since coil #12 never quenched in HFDA05 one could conclude that even after its re-use in HFDA05 it remembered its training. This behavior differs from the behavior of non-impregnated coils used in NbTi magnets.

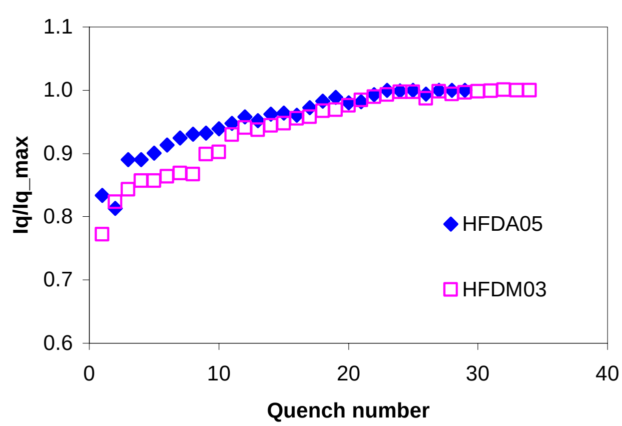

Fig.7. Magnet training summary at 4.5 K.

Coil azimuthal stresses and longitudinal end forces in both models were monitored during fabrication and cold testing in each excitation cycle using resistive and capacitive gauges installed in the coil and on the magnet skin. Azimuthal coil pre-stress remained at 4.5 K after cooling down. Moreover, the strain gauge data indicated no unloading of the coil up to the maximum reached currents. Coil deformation due to the Lorentz force was elastic throughout the test current range.

B. HFDA05 temperature dependence of magnet quench current

The dependence of magnet quench current vs. temperature for HFDA05 is presented in Fig. 8. This dependence was measured during the second thermal cycle after the completion of magnet training at 4.5 K and 2.2 K. The line shows the short sample limit for this magnet design calculated using Summers parameterization [13] with B_{c2}=28 T and T_c=16 K. Excellent correlation of experimental and calculated data confirms that the magnet reached its short sample limit at all temperatures from 2.2 K to 4.5 K.

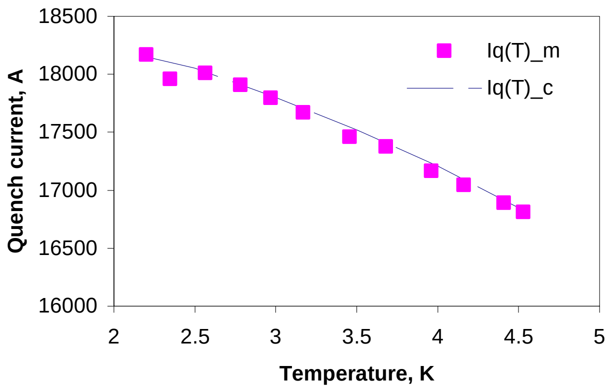

Fig.8. Temperature dependence of HFDA05 quench current.

C. Ramp rate dependence

Ramp rate dependences at 4.5 K of HFDM03 and HFDA05 normalized on their maximum quench current at dI/dt=20 A/s are shown in Fig 9. Quench current decreases with increasing ramp rate following a continuous function. This behavior is another confirmation that the magnets are at critical current limits. The shape of this dependence at low current ramp rates suggests that the ramp rate dependence is dominated by the eddy currents losses in the cable which are quite large in these two coils (see Fig.10). At ramp rates higher than 200 A/s the quench current drops dramatically and practically does not change with the current ramp rate. This behavior indicates that the magnet is limited by high losses and insufficient coil cooling conditions.

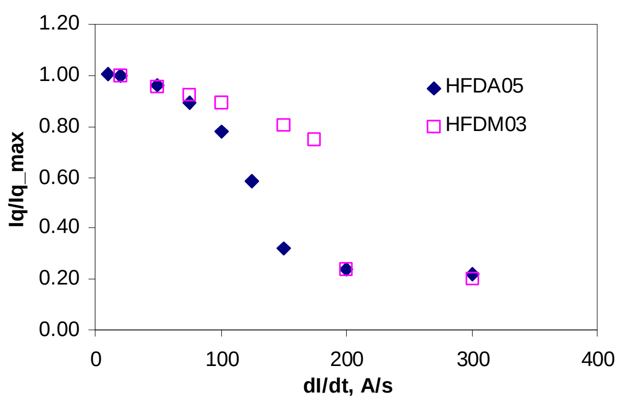

Fig.9. Ramp rate dependence of magnet quench current at 4.5 K.

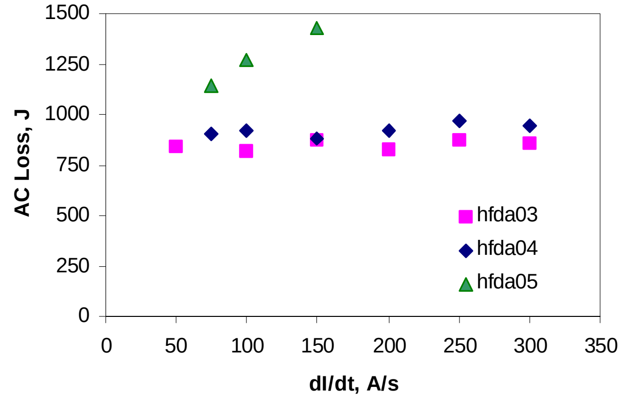

Fig.10. AC losses vs. the current ramp rate in the triangular current 500-6500-500 A.

IV. Conclusion

Successful fabrication and tests of the two cos-theta magnets based on PIT Nb_3Sn strands have proven an importance of the conductor stability for magnet quench performance predicted by the stability analysis of Nb_3Sn strands and cables [5-6] and allowed to reach 10 T magnetic field. The mechanical structure developed for these magnets demonstrated reliable performance at fields up to 10 T. The Nb_3Sn coil and magnet fabrication technologies are robust and reproducible.

Acknowledgment

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References

[1] G. Ambrosio et al., “Development of the 11 T Nb3Sn Dipole Model at Fermilab”, IEEE Trans. on Applied Superconductivity, v. 10, No. 1, March 2000, p.298.

[2] D.R. Chichili et al., “Design, Fabrication and Testing of Nb3Sn Shell Type Coils in Mirror Magnet Configuration”, CEC/ICMC 2003, Alaska, September 22-25 2003.

[3] N. Andreev et al., “Development and test of single-bore cos-theta Nb3Sn dipole models with cold iron yoke”, MT-17, IEEE Trans. on Applied Superconductivity, v. 12, No. 1, p. 332, March 2002.

[4] S. Feher et al., “Test Results of Shell-type Nb3Sn Dipole Coils”, MT-18, Japan, October 2003.

[5] V.V. Kashikhin, A.V. Zlobin, “Magnetic Instabilities in Nb3Sn Strands”, Fermilab Technical note, TD-03-032, July 21, 2003.

[6] V.V. Kashikhin, A.V. Zlobin, “Magnetic instabilities in Nb3Sn strands and Cables”, this conference 5LB02

[7] E. Barzi et al., ”Transport Critical Current of Nb3Sn Strands at Low and High Magnetic Fields”, this conference 2MB04

[8] G. Ambrosio et al., ”Critical Current Measurement of Nb3Sn Rutherford-type Cables for High Field Accelerator Magnets”, this conference 2LR03.

[9] E. Barzi et al., “ Study of Current Carrying Capability of Nb3Sn Cables in Self-field Using a SC Current Transformer”, this conference 1LX06.

[10] S. Feher et al., “Cable Testing for Fermilab`s High Field Magnets Using Small Racetrack Coils”, this conference 2LR05.

[11] D.R. Chichili et al., “Fabrication of Nb3Sn Shell-Type Coils with Pre-Preg Ceramic Insulation”, CEC/ICMC 2003, Alaska, September 22-25, 2003.

[12] E. Barzi et al., “Sensitivity of Nb3Sn Rutherford-type cables to transverse pressure”, EUCAS2003, Napoli, Italy, September 15-20 2003.

[13] L.T. Summers et al., “A model for the prediction of Nb3Sn critical current as a function of field, temperature, strain, and radiation damage”, IEEE Trans. Magn., vol. 27, no. 2, Mar 1991, pp. 2041 – 2044.