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Nb_3Sn Accelerator Magnet Technology Scale Up Based on Cos-theta Coils

F. Nobrega, A.V. Zlobin, G. Ambrosio, N. Andreev, E. Barzi, R. Bossert, R. Carcagno, S. Feher, V.S. Kashikhin, V.V. Kashikhin, M.J. Lamm, I. Novitski, Yu. Pischalnikov, C. Sylvester, M. Tartaglia, D. Turrioni, R. Yamada

***Abstract*—After successful testing of a 1 m long dipole mirror magnet and three dipole models based on two-layer Nb_3Sn coils, Fermilab has started a Nb_3Sn technology scale-up program using the dipole mirror design and the developed Nb_3Sn coil fabrication technology based on the wind-and-react method. The scale-up will be performed in several steps starting from a 2 m long coil made of Powder-in-Tube (PIT) strand. This will be followed by 4 m long Nb_3Sn coils made of PIT and RRP strands that will be fabricated into dipole mirror magnets and tested. This paper presents a summary of Fermilab's wind-and-react short model program. It includes details on the 2 m and 4 m long, 2 layer Nb_3Sn dipole mirror magnet design, mechanical structure, and fabrication infrastructure.**

***Index Terms*—Superconducting accelerator magnets, high field dipole, Nb_3Sn strands and cables, technology scale up**

I. INTRODUCTION

FERMILAB is involved in the development of a new generation of high-field accelerator magnets which will succeed the present generation based on NbTi superconductor limited by an operation field level of 7-9 T at 4.5-1.9 K and temperature margin. At present, the work is focused on magnets based on a Nb_3Sn superconductor [1]. This material potentially allows the operating field to be increased up to 15 T at 4.5 K and temperature margin by a factor of 3-5. Due to superconductor brittleness, Nb_3Sn magnets require development of new design and technological approaches and the use of non-traditional structural materials.

One of the possible approaches is based on the wind-and-react technology and traditional shell-type (cos-theta) dipole coils that have been extensively studied at Fermilab during the past six years [2]. After successful testing of a 1 m long dipole mirror magnet and three dipole models based on two-layer Nb_3Sn coils, Fermilab has started a Nb_3Sn technology scale-up program using the developed dipole design and the Nb_3Sn coil fabrication technology based on the wind-and-react method. This work is an important step toward using Nb_3Sn accelerator magnets in real machines. The key issues to be verified and demonstrated by this work are long coil reaction, impregnation and handling, cold mass assembly, and pre-load. Fermilab has developed the appropriate infrastructure to perform this work which includes long coil winding, curing, reaction, impregnation and handling tooling. A 6 m long reaction furnace has been procured and installed recently at Fermilab. This effort complements the Nb_3Sn scale up work being performed at BNL using Nb_3Sn flat racetrack coils in the framework of US LHC Accelerator Research Program (LARP) [3] and will pave the way toward fabrication and testing of LARP 4 m long Nb_3Sn quadrupoles at Fermilab [4].

This paper presents a summary of Fermilab's short model R&D program, including fabrication and tests results for the third dipole model HFDA07 made of PIT strand, conductor choice for the technology scale up, and details on the 2 m and 4 m long two-layer Nb_3Sn dipole mirror magnet design and fabrication, including infrastructure, coil tooling and mechanical structure.

II. SHORT MODEL R&D RESULTS

A. Dipole and Mirror Designs

The dipole model design (HFDA) developed at Fermilab is based on a two-layer shell-type coil with a 43.5 mm bore and cold vertically-split iron yoke. The magnetic mirror configuration (HFDM) uses the same mechanical structure with horizontally split yoke in which one of the two half-coils is replaced with the iron half-cylinder (magnetic mirror). The mirror dipole design allows for substantial cost reduction, shorter fabrication times and extensive instrumentation while preserving almost the same level of magnetic field and Lorentz forces in the coils as in a complete dipole model. The dipole mirror cross-section and end view of a dipole mirror magnet are shown in Fig. 1. Details of the magnet design and technology are described in [5], [6].

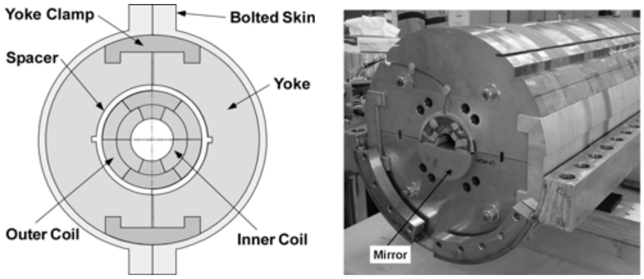

Fig. 1. HFDA dipole and HFDM mirror models with bolted skin.

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Authors are with the Fermi National Accelerator Laboratory (Fermilab), P.O. Box 500, Batavia, IL 60510 USA (phone: 630-840-4271; fax: 630-840-3369; e-mail: nobrega@fnal.gov).

B. *Strand and cable*

The magnet coils are made of a keystoned Rutherford-type cable with 28 Nb_3Sn multi-filament strands, each 1 mm in diameter. During the course of the Nb_3Sn magnet R&D it was established that flux jumps significantly affected magnet performance [1], [7]. The Modified Jelly Roll (MJR) strand used in first models had a rather large effective filament diameter on the order of ~110 μm, and high critical current density Jc(12T,4.2K)~2.0 kA/mm^2. To avoid the instability problem, the strand design in the last models was based on the Powder-in-Tube (PIT) process. The filament diameter in round PIT strands was approximately 50 μm and Jc(12T, 4.2K) was ~1.8 kA/mm^2. The cable insulation system consists of two layers of half lap 0.125 mm thick by 12.7 mm wide ceramic tape.

C. *Coil Fabrication*

Four PIT coils (#12-#15) have been fabricated and tested during 2004-2006. The details of the coil fabrication procedure are reported elsewhere [8].

The coils were wound using a procedure where the inner coil is wound and cured, and then the outer coil is wound over the cured inner coil and inter-layer insulation. Both coil layers are made from one piece of cable without an inter-layer splice. Both layers are then injected with CTD1008x liquid ceramic binder and cured together at 150ºC for half an hour. Coil end parts are made of Al bronze. A thin layer of mica is placed between each wedge surface and the insulation. An identical mica sheet is placed between the pole piece and the inner coil along the straight section.

The coils were cured in the LHC 2 m model outer coil mold cavity shimmed azimuthally to a size ~1 mm smaller than the nominal coil size. This gap is needed to prevent coil over-compression due to Nb_3Sn phase expansion during reaction. The final coil size was achieved during the coil impregnation and was nearly identical for all coils.

Ground insulation, made of 3 layers of 0.125 mm ceramic sheet, was installed before reaction. Each coil was reacted using a one or a three step cycle. The details of coil reaction cycle are reported in [8], [9]. Several witness samples made of round strand and extracted from cable were reacted along with each coil to estimate the coil short sample limit.

Before impregnation the Nb_3Sn coil leads were spliced to flexible NbTi cables. Each coil was impregnated with CTD101K epoxy and cured at 125°C for 21 hours.

D. *Model Assembly and Short Sample Limit*

The first PIT coil was tested first in the mirror configuration and then all four coils were tested in three dipole model magnets. The mirror magnet was assembled with a horizontally split yoke and the dipole model magnets were assembled with a vertically split yoke, as shown in Fig. 1. In both cases, a bolted stainless steel skin with bolted thick end plates was used. Coil transverse prestress in the mirror model was provided by mid-plane radial and azimuthal shims. The coil radial and azimuthal prestress in dipoles was provided by radial shims, which were installed between the coil and coil-yoke spacer. Additional radial shims were installed between the spacer and the iron yoke near the coil mid-plane. The maximum coil pre-stress was limited by ~100 MPa based on two conflicting requirements; one calls for high pre-stress in order to support the turns up to the maximum Lorentz forces, while the other requires a low pre-stress due to high sensitivity of PIT strand critical current to transverse pressure [10].

Magnet configurations, as well as coil and magnet short sample limit (SSL) predictions are reported in Table I. One can see that coils #13 and #15 were tested only one time, coil #14 twice and coil #12 three times. Multiple assembly and re-assembly of coils #12 and #14 in magnets confirm both the coil and structure technology. Short sample limit range is determined by degradation of PIT cable critical current under 100 MPa transverse pressure reported in [10].

TABLE I. MAGNET CONFIGURATION AND SHORT SAMPLE LIMIT

Model	Coil #	Coil SSL @4.5K, kA	Magnet SSL @ 4.5K, kA
HFDM03	12	17.3-20.6	17.3-20.6
HFDA05	12	15.2-17.8	15.2-17.8
	13	16.2-18.7	
HFDA06	14	14.7-17.3	14.3-16.8
	15	14.3-16.8	
HFDA07	12	15.2-17.8	14.7-17.3
	14	14.7-17.3	

E. *Test Results*

Magnetic mirror HFDM03 and dipole models HFDA05-07 were tested in the Vertical Magnet Test Facility at Fermilab in boiling liquid helium. The quench performance studies included training quenches at 4.5 K with the current ramp rate of 20 A/s which were followed by ramp rate studies, magnet training at 2.2 K, temperature dependence measurements, and finally quenching the magnet again at 4.5 K. The standard test program also included magnetic measurements, AC loss measurements and quench heater study.

Fig. 2 summarizes the magnet quench performance during training at 4.5 K. The quench current for each magnet was normalized to its maximum value reached after training at this temperature and current ramp rate of 20 A/s.

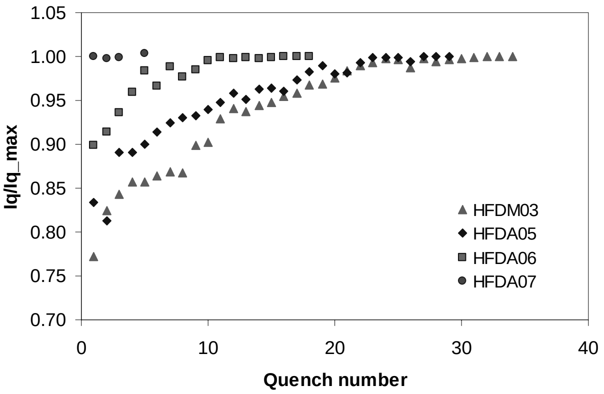

Fig. 2. Magnet training summary at 4.5 K and 20 A/s.

Based on signals from the voltage taps, all quenches in all magnets occurred inside the coil body in the high field region. Coil azimuthal stresses and longitudinal end forces in all models were monitored during fabrication and cold testing in each excitation cycle using resistive and capacitive gauges. Azimuthal coil pre-stress was maintained at 4.5 K from zero current through the maximum current reached. Coil deformation due to the Lorentz force was elastic throughout the test current range.

The dependence of magnet quench current vs. helium bath temperature for dipole models HFDA05-07 is reported in Fig. 3. The data for all models in the temperature range 2.2-4.5 K are consistent within 3%. Measured temperature dependences are in good agreement with Summers parameterization [11] with B_{c2}=28 T and T_c=16 K, confirming that the magnets reached their short sample limit at all temperatures.

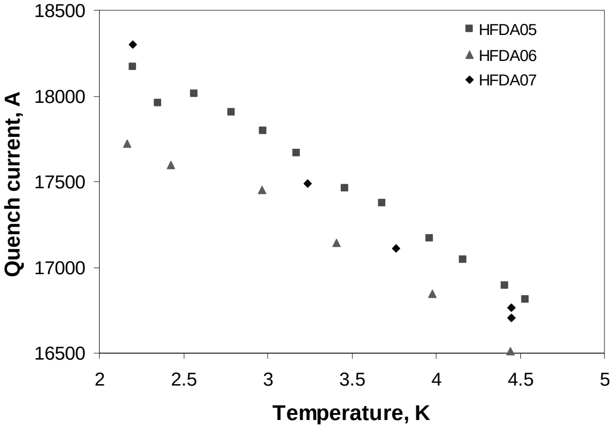

Fig. 3. Temperature dependence of quench current measured at 20 A/s.

The ramp rate dependences at 4.5 K of HFDM03 and HFDA05-07 normalized to their maximum quench current at dI/dt=20 A/s are shown in Fig. 4.

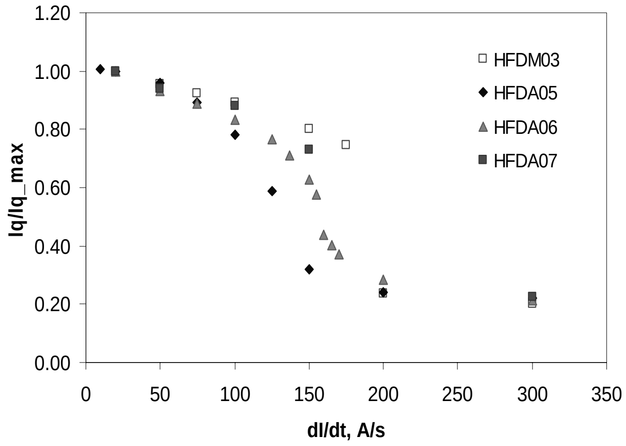

Fig. 4. Ramp rate dependence of magnet quench current at 4.5 K.

Measured ramp rate dependences are similar for all the magnets. The quench current in all magnets decreases with increasing ramp rate following a smooth function confirming that the magnets are at their critical current limits. The shape of ramp rate dependences at low current ramp rates suggests that it is dominated by the eddy current component of AC losses in the cable. According to measurements, the eddy current losses are quite large in these coils. 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 is typical for magnets with high AC losses and limited coil cooling conditions.

Model maximum quench current I_{max}, field in the coil B_{max}, and field in the dipole model bore B_o, reached at 4.5 and 2.2 K are summarized in Table II (ramp rate 20 A/s unless otherwise noted). Comparison of results presented in Tables I and II shows good correlation of predicted SSL and measured magnet maximum quench current.

TABLE II. MAXIMUM QUENCH CURRENT AND FIELD

	T=4.5K			T=2.2K		
	I_{max}, A	B_{max}, T	B_o, T	I_{max}, A	B_{max}, T	B_o, T
HFDM03	21031	9.6	-	21777	10.0	-
HFDA05	16832	9.8	9.4	18169#	10.6	10.1
HFDA06	16414	9.6	9.1	17666	10.3	9.8
HFDA07	17305*	10.1	9.6	19047*	11.1	10.6

* - at the current ramp rate of 1 A/s
\# - 5 A/s

To summarize the R&D results, 4 nearly identical 1 m long shell-type Nb_3Sn coils were fabricated and successfully tested in mirror and dipole configurations. The magnet quench performance, summarized in Fig. 2-4, and field quality measurements in HFDA models [12] show good reproducibility and robustness of the developed magnet design and technology. The mechanical structure developed for these magnets demonstrated reliable performance up to maximum field in the coil of 11 T.

III. TECHNOLOGY SCALE UP

Successful testing of the 1 m long Nb_3Sn coils makes it possible to begin a Nb_3Sn technology scale-up program using cos-theta dipole coils, mirror design and developed Nb_3Sn coil fabrication technology based on the wind-and-react method and using existing long LHC IR quadrupole tooling.

A. *Strand and Cable*

The scale-up will be performed in several steps starting from a 2 m long coil made of PIT strand which has demonstrated good stability and reproducible performance. This will be followed by 4 m long PIT coil. The performance of 1 m long PIT coils reported above will provide the reference for the scale up program evaluation.

It is also planned to perform a Nb_3Sn technology scale up using Re-stack Rod Process (RRP) strand since this strand is considered a baseline conductor for LARP magnet R&D. The work of improving the 1 mm RRP strand performance is in progress, in collaboration with Oxford Superconductor Technologies, Inc. [13].

B. *Long mirror design modifications*

The 2 m and 4 m mirror magnets will have the same cross-section as the 1 m long mirror magnet except for the skin design. The bolted skin design will be replaced by the LHC skin design that is welded using the same press and contact tooling used for the LHC MQXB production quadrupoles [14].

C. Long Coil Fabrication

Long coil fabrication is nearly identical to that used for the 1 m coils as described earlier in this paper. Minor differences include using CTD1202x binder instead of CTD1008x, placing wedges in 2 sections with staggered gaps of 2 mm instead of one long piece with 2 mm gaps at each end, and changing the cable and wedge insulation scheme to half lap S2 glass instead of ceramic tape. Fig. 5 shows a 2 m inner coil with the 6 m long reaction furnace in the background. The winding table shown will be used for both the 2 m and 4 m coils. Coils will be cured using existing LHC IR curing molds.

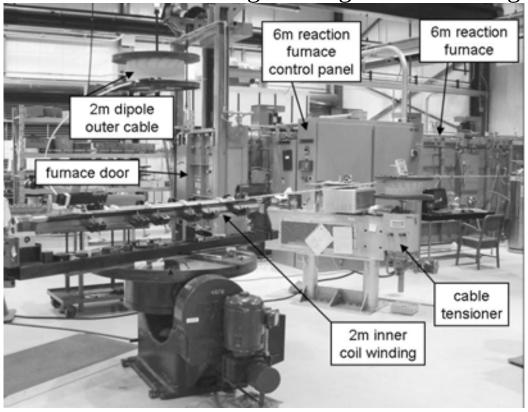

Fig. 5. Inner 2 m coil and 6 m long reaction furnace.

D. Reaction and impregnation

The reaction tooling used is modular and can be used as the impregnation tooling in Fig. 6. The base plate is either 2 m or 4 m long with EDM'ed tooling blocks used to define the coil volume. The reaction furnace, in Fig. 5 & 6, is a gas tight design recently installed at Fermilab. Qualification tests preformed at the vendor site, shown in Fig. 6 just prior to shipment, showed temperature uniformity at both 210° C and 650° C within ±3° C, well within the specified tolerance of ±5°C. The maximum furnace temperature is 1000° C. The coil impregnation vacuum oven at Fermilab has a diameter of 2 m and length of over 6 m. Coils are vacuum epoxy impregnated at 60° C and 30 μm Hg pressure.

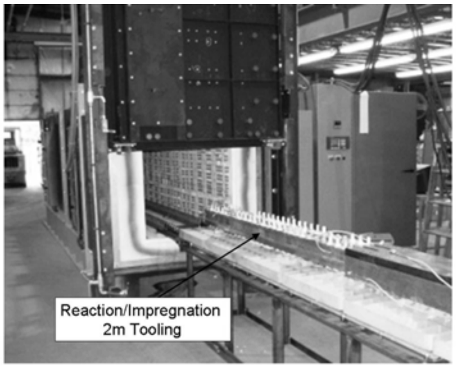

Fig. 6. Reaction/Impregnation 2 m tooling & 6 m furnace qualification.

E. Status and next steps

Two, ~135 m and ~187 m, long pieces of keystoned Cu cable for 2 m and 4 m practice coil winding, reaction and impregnation have been fabricated. A 140 m long piece of keystoned PIT cable for a 2 m long mirror has been fabricated and tested; test results are reported in [15].

The 2 m long coil fabrication is well underway. It will be assembled into a mirror magnet configuration and tested by the end of 2006. Coil winding for the 4 m dipole coils will immediately follow and is expected to begin in late 2006 or early 2007. The long curing press and contact tooling used for LHC's MQXB IR quadrupoles coils will be used for curing 4 m dipole coils.

IV. CONCLUSION

The success of the 1 m PIT model magnets has set the foundation for the length scale up to 2 m and 4 m long mirror magnets. The long magnet tooling used is from proven LHC MQXB quadrupole technology. The mechanical structure was demonstrated to be reliable for coil fields up to 11 T. Quench performance and field quality have good reproducibility.

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