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Nb_3Sn Accelerator Magnet Technology Scale Up Using Cos-Theta Dipole Coils

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***Abstract*— Fermilab is working on the development of Nb_3Sn accelerator magnets using shell-type dipole coils and the wind-and-react method. As a part of the first phase of technology development, Fermilab built and tested six 1 m long dipole model magnets and several dipole mirror configurations. The last three dipoles and two mirrors reached their design fields of 10-11 T. The technology scale up phase has started by building 2 m and 4 m dipole coils and testing them in a mirror configuration in which one of the two coils is replaced by a half-cylinder made of low carbon steel. This approach allows for shorter fabrication times and extensive instrumentation preserving almost the same level of magnetic field and Lorentz forces in the coils as in a complete dipole model magnet. This paper presents details on the 2 m (HFDM07) and 4 m long (HFDM08) Nb_3Sn dipole mirror magnet design and fabrication technology, as well as the magnet test results which are compared with 1 m long models.**

***Index Terms*—Superconducting accelerator magnets, dipole mirror magnet, Nb_3Sn Cos-Theta dipole coils, technology scale up.**

I. INTRODUCTION

ACCELERATOR magnets based on Nb_3Sn superconductor produce magnetic fields above 10 T and drastically increase the coil temperature margin relative to NbTi magnets. Magnets with such parameters are needed for the LHC IR upgrade and critical components of the ILC.

Fermilab is developing Nb_3Sn accelerator magnets using shell-type dipole coils and the wind-and-react method. The R&D program includes the demonstration of main magnet parameters (maximum field, quench performance, field quality) and their reproducibility using a series of short models, followed by the demonstration of technology scale up using relatively long coils. As a part of the first phase of technology development, more than fifteen 1 m long coils were fabricated and tested in six short dipole model magnets and several dipole mirror models. The last three dipole magnets and two mirrors reached their design fields of 10-11 T. All six short dipole model magnets demonstrated good, well-understood and reproducible field quality. The technology scale up phase began by building 2 m and 4 m long dipole coils and testing each in a mirror configuration. The status and results of the Nb_3Sn accelerator magnet R&D at Fermilab are reported within this paper.

II. MAGNET DESIGN

A. *Magnet Design*

The design and parameters of Fermilab's HFDA dipole series are described in [1]. These magnets were designed for a nominal field of 10-12 T at a temperature of 4.5 K. The design is based on a two-layer shell-type coil with 43.5 mm bore and a cold iron yoke.

The coils were wound using keystoned Rutherford-type cable made of 28 (recently 27) Nb_3Sn strands, each 1 mm in diameter.

B. *Dipole Mirror Model*

To reduce the fabrication cost and turnaround time for coil testing, a mirror configuration was used [2], [3]. The cross-sections of the HFDA coil, dipole cold mass, and mirror mechanical structure are shown in Fig. 1.

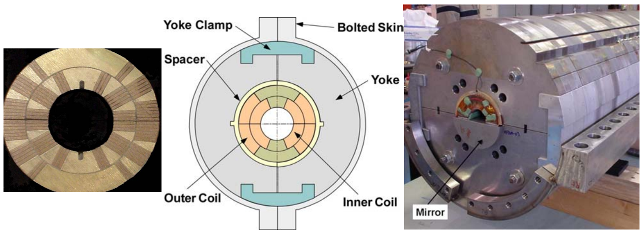

Fig. 1. HFDA coil, dipole cross section, and HFDM mirror .

The mirror structure is similar to the dipole structure except that the iron yoke is split horizontally and one of the two half-coils in the dipole magnet structure configuration is replaced by half-cylinder blocks made of iron. Aluminum-bronze spacers surround the coil inside the yoke. Stainless steel shims placed azimuthally between the mirror and coil midplane and radial Kapton shims between the coil, spacers and yoke are used to control the coil prestress. Azimuthal coil preload is applied by a combination of the aluminum yoke clamps and a thick bolted stainless steel skin for 1 m structures, or welded stainless steel skins for the 2 m and 4 m structures. Axial preload is applied through end preload bolts attached to the thick end plates.

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C. *Strand and Cable*

The scale-up is being performed in two steps starting from a 2 m long coil made of PIT strand, which has demonstrated good stability and reproducible performance. The performance of 1 m long PIT coil magnets will provide the reference for the scale up program evaluation. The 4 m long coil was made using Re-stack Rod Process (RRP) strand since this strand is considered a baseline conductor for the LARP magnet R&D. The work of improving the 1 mm RRP strand performance is in progress in collaboration with Oxford Superconductor Technologies, Inc. [4].

The PIT strand had J_c~1.6-1.8 kA/mm^2 and d_{eff}~50-60 µm [5]. The RRP strand provides the highest J_c (~3 kA/mm^2) and has a larger number of sub-elements with a smaller size (~70 µm). PIT and RRP strands are shown in Fig. 2.

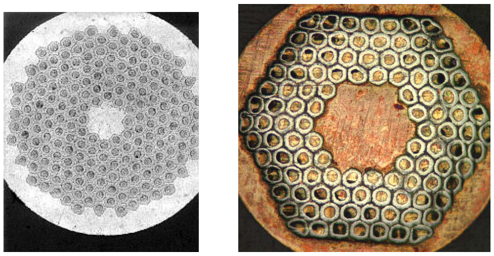

Fig. 2. PIT-196 (left) and RRP-108/127 (right) strand.

III. LONG MAGNET FABRICATION

A. *Long Coil Fabrication*

The coil fabrication technology is based on the wind-and-react method where the superconducting Nb_3Sn phase is formed after winding and during coil high-temperature heat treatment. This technique requires using special high-temperature cable and coil insulation and metallic coil components. A significant improvement of the Nb_3Sn coil fabrication technology was achieved at Fermilab by using a ceramic binder which sets during curing and provides a ridged coil for handling. To improve insulation properties after reaction, the Nb_3Sn coil is vacuum impregnated with epoxy.

The long dipole coil winding and curing is similar to the 1 m dipole coils fabricated at Fermilab [4], [6]. Both the 2 m and 4 m coils were wound without a layer jump splice; one continuous piece of cable. The cable lengths were approximately 90 m and 180 m respectively. A rotating winding table was used with the outer spool of cable suspended above the winding table while the inner coil was being wound as shown in Fig. 3. The 2 m PIT cable insulation was 125 µm thick ceramic cloth with 50% overlap. The 4 m RRP cable insulation consisted of two layers with the first layer being a 50% overlap of 75 µm thick E-glass and the second layer was a butt lap of 75 µm thick S2 glass.

The 2 m coils were cured in a closed cavity mold leftover from the LHC IR R&D quadrupole program, while the 4 m coils were cured in a closed cavity mold from the LHC IR production quadrupole program. A ceramic binder, CTD1202 [7] was applied before curing. Once the outer coil was wound on top of the inner coil, the outer coil was cured resulting in the inner coil being cured twice. End parts were water jet cut and pole pieces were machined, both made of Al bronze.

Fig. 3. LM02, 4 m RRP inner coil being wound with spool of outer cable suspended above the winding table.

The reaction tooling used is modular and doubles as the impregnation tooling. The base plate is either 2 m or 4 m long with EDM tooling blocks used to define the coil volume. The reaction furnace is a gas tight design and has temperature uniformity at 210°C, 400°C, and 650°C within ±3°C, well within the specified tolerance of 5±°C. The maximum furnace temperature is 1000°C.

The reaction cycle for the 2 m PIT and 4 m RRP coils is shown in Table I. Witness samples were placed at each end and in the middle of the reaction tooling using stainless steel and titanium barrels with round and extracted strand from the cables. The witness samples were tested at Fermilab's short sample test facility to estimate the coil short sample limit. The reaction cycle begins by increasing the temperature of the reaction fixture from 20ºC to approximately 210ºC at 25ºC per hour. The temperature is held for some duration depending on the strand material followed by increasing the coil temperature to 400ºC at 50ºC/hr. The third and final temperature plateau is reached by ramping at 75ºC per hour until the maximum temperature of either 660ºC for PIT cable or 646ºC for RRP cable is attained. Type J thermocouples were used to monitor the reaction fixture temperature and type K thermocouples were used to control the gas tight furnace during the reaction cycle.

TABLE I Reaction Cycle Time-Temperature Profile

PIT 2 m dipole coil

Ramp, ºC /hr	Max Temp, ºC	Dwell, hrs
25	210	72
50	400	50
75	660	170

RRP 4 m dipole coil

Ramp, ºC /hr	Max Temp,ºC	Dwell, hrs
25	212	84
50	402	48
75	646	51

The coil impregnation vacuum oven at Fermilab has a diameter of 2 m and length of over 6 m. Coils are epoxy impregnated using CTD101K at 60°C and 30 µm Hg.

Coil width, thickness, and flatness (bow) are measured after impregnation. The 2 m coil width variation was ±50 µm, thickness was ±25 µm, with a bow of 40 µm over the coil length. Inspection data, as shown in Fig. 4, from a coordinate measuring machine was used to determine the midplane shim for the 2 m long coil. The same procedure is planned for the 4 m long coil.

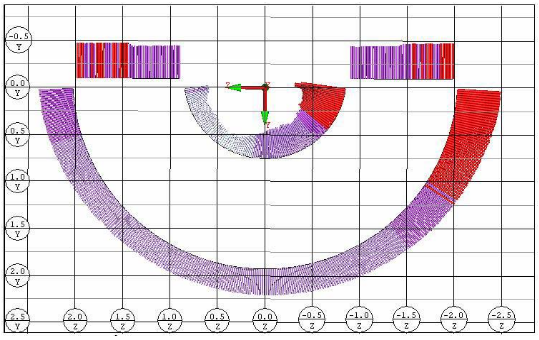

Fig. 4. Coordinate measuring machine inspection of 2 m impregnated coil.

B. *Magnet Assembly and Instrumentation*

HFDM07 used resistive and capacitive gauges to measure the coil azimuthal preload. Resistive gauges measured preload at the inner and outer straight section midplane and splice leads. Capacitive gauges measured preload at the midplane straight section near the same longitudinal position as the resistive gauges in the coil. Resistive gauges were also bounded to the inner radius of the impregnated coil and on the inner surfaces of the inner and outer pole pieces. Additional resistive gauges were mounted on the outer surface of the stainless steel shell. Fig. 5 shows the HFDM07 mirror with instrumentation. The HFDM08 instrumentation system will be based on the one used for HFDM07.

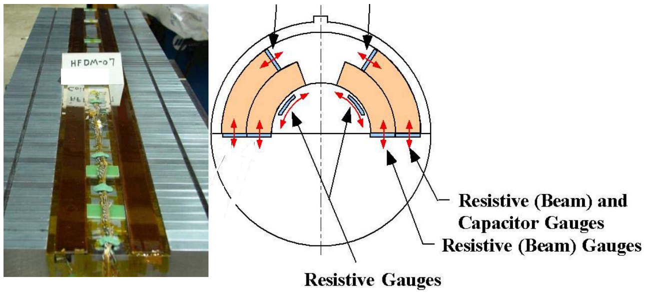

Fig. 5. HFDM07 mirror instrumentation.

The first long mirror magnet assembly HFDM07 began with the installation of iron mirror blocks into the lower yoke. The coil was placed onto the mirror, the upper yoke blocks installed, and the aluminum yoke clamps inserted with hydraulic pressure. The subassembly was placed into the lower half shell as shown in Fig. 6. The upper shell half was installed and the shelled yoked assembly was welded together. Yoke assembly and shell welding was done in several steps while the stresses in the coil and end spacers were monitored by the strain gauges. After the shells were welded together, 50 mm thick end plates were welded to the cold mass ends.

Fig. 6. HFDM01 yoked mirror magnet being placed into the lower shell on the insertion table of the weld press.

C. *Coil Target Prestress*

To determine the coil target prestress, analysis using ANSYS® was performed assuming plastic coil properties [8]. The maximum coil prestress value for the HFDM07 inner coil was 80 MPa. Table II summarizes the results of coil prestress measurements by the coil gauges and calculations for the gauge location. There is good correlation between strain gauge measurements and analysis. The measurement data confirm that the target coil prestress during assembly was achieved. An end load of ~8 kN was used to maintain coil contact at zero current and 4.5 K.

TABLE II HFDM07 coil prestress, measured/predicted.

Gauge Location	Measurements, MPa	FEA-plastic, MPa
Inner mid plane	50	80
Outer mid plane	60	40, 80
Inner pole	80	65
Shell	220	230

IV. HFDM07 TEST RESULTS

The magnet test program started with quench training at 4.5 K with 20 A/s ramp rate and acceleration 10A/s^2. The quench detection threshold was set to 500 mV. Dump delay was set to 1 ms, two strip heaters were set in protection mode at 400 V with delay set to 1ms. The quench history is show in Fig. 6.

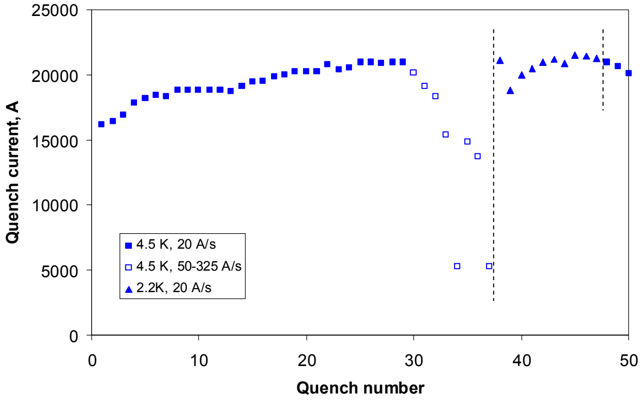

Fig. 6. HFDM07, 2m long mirror magnet quench history.

Training at 4.5 K began with 3 quenches at the Vertical Magnet Test Facility (VMTF) superconducting leads.

Therefore, the first real quench (4th quench) was detected at 17862 A in the pole turn of the inner layer of the coil. One should mention that most voltage taps were mounted on the inner layer only. In addition, voltage tap segments were in the region of splices between NbTi and Nb_3Sn conductors on both inner and outer layers.

The Automatic Quench Detection (AQD) system tripped at the VMTF leads at about 18800 A from quench number 9 through quench number 12. After the AQD circuits were balanced at 5000 A and then at 10000 A, a quench current plateau limited by the conductor critical current was reached. The final quench at 4.5 K was at 20966 A.

After the ramp rate study at 4.5 K the magnet was cooled to 2.2 K and the training started from 21085A followed by a significant step back to 18825A. The quench current then increased to 21500A in 6 quenches. Quenches 42 and 44 most likely originated from the outer layer of the coil where no voltage taps exist to identify quench location.

The quench program was completed with a few more quenches at 4.5 K. The first quench confirmed that the magnet had reached its limit at 4.5 K because the quench current was in the same range as it was before the 2.2 K training. The following 2 ramps resulted again in trips at the VMTF superconducting leads.

Voltage tap segments on the inner-layer pole turn showed most of the quenches during the training and all quenches at the plateau. Several quenches during the training at 4.5 K were detected at the VMTF superconducting leads. Some of them showed a voltage rise in the splice between NbTi and Nb_3Sn conductors on the inner layer. The splice voltages were measured as a function of magnet current to determine their resistance Rin = $3.9\cdot10^{-10}$ Ω and Rout = $4.1\cdot10^{-11}$ Ω.

For comparison, the quench history for the 1 m long mirror magnet HFDM03 is also shown in Figure 7. Strand parameters and coil fabrication technology are the same for both mirror magnets.

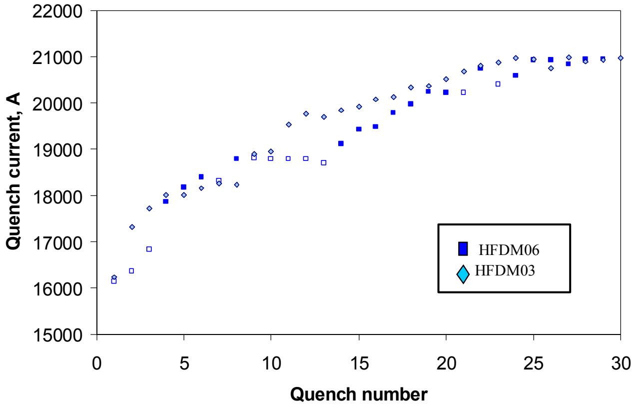

Fig.7. HFDM07 (2m long mirror magnet) training at 4.5K. The training quenches for the 1m long mirror magnet HFDM03 are also shown.

Ramp rate dependence studies were performed at 4.5 K. Results normalized to their maximum quench current at dI/dt=20A/s are shown in Fig.8. Quench current decreases with increasing ramp rate. The RRR in HFDM07 coil segments were made using data captured during the initial cool down of the magnet and estimated to be RRR = 90±10.

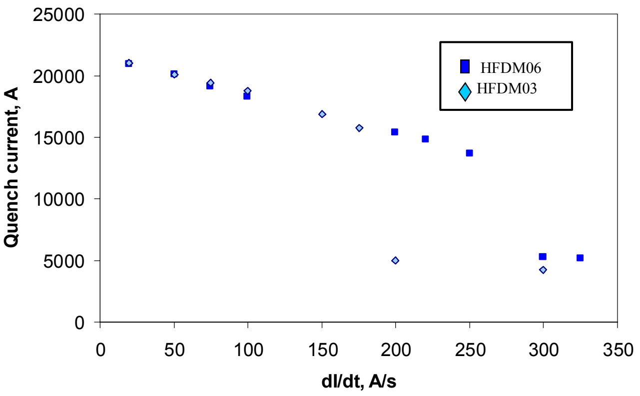

Fig.8. Ramp rate dependence of magnet quench current at 4.5K. The same dependence for the 1m long mirror magnet HFDM03 is also shown.

The PIT mirror models reached their short sample limit and the field level of 10 T. Comparison of HFDM07 and HFDM03 quench performance shows that they are practically identical, demonstrating that the goal of the first step of the scale up program has been achieved.

V. 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 2 m PIT mirror magnet successfully went to the cable's short sample limit. 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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