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Development and Test of Single-Layer Common Coil Dipole Wound with Reacted Nb3Sn Cable

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***Abstract*—The first one-meter long common coil dipole model (HFDC-01) has been fabricated and is being tested at Fermilab. This magnet has several innovative features such as: single-layer racetrack coils, a 22-mm wide 59-strand Rutherford-type cable made of 0.7-mm Nb3Sn strands, and a stainless steel coil-support structure reinforced by horizontal bridges inserted between coil blocks. The model was instrumented with voltage taps, quench heaters, temperature sensors and strain gauges in order to monitor the quench origin and propagation, and to study mechanical and quench protection issues. This paper summarizes the model design parameters, the fabrication procedures and the test results.**

***Index Terms*—common coil dipole, Nb3Sn, superconducting accelerator magnet, manufacturing, tests.**

I. Introduction

A single-layer common coil dipole magnet has been developed at Fermilab for a future Hadron Colliders [1]. The magnet was designed to generate a 10 T nominal field in two 40-mm apertures at operation temperature of 4.5 K. It is based on Nb_3Sn superconductor and react-and-wind fabrication technique [2]. This magnet has several innovative design and technological features such as single-layer racetrack coils, a 22-mm wide 59-strand Rutherford-type cable made of 0.7-mm Nb_3Sn strands, and stainless steel coil support structure reinforced by horizontal bridges inserted between coil blocks [3]. Both left and right coils are wound simultaneously into the collar structure and then impregnated with epoxy. The development of magnet design has been completed. Three simple single-layer racetracks based on the sub-scale cable and react-and-wind technique were fabricated and tested [4, 5], and two short mechanical models and technological model were also assembled prior to the common coil model fabrication. Based on the results obtained necessary corrections in the design and fabrication procedure were introduced. The fabrication of the first common coil dipole model was accomplished this year. The model is being tested at Fermilab's Vertical Magnet Test Facility.

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This paper summaries the magnet design parameters and manufacturing procedures, and report the preliminary test results of the common coil dipole magnet.

II. Magnet Design

The 3D view of the magnet cold mass and magnet mechanical structure laminations are shown in Fig.1 and Fig. 2. The magnet design is based on single-layer flat racetrack coils with shifted blocks, which forms two apertures separated in vertical plane [6]. The nominal magnet parameters are reported in Table 1. The coils are made of rectangular Rutherford-type Nb3Sn cable.

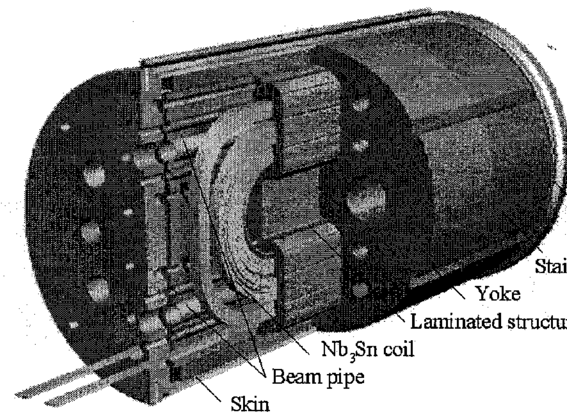

Fig. 1. Common Coil Dipole Cold Mass

Each coil consists of 58 turns grouped into 3 blocks with 18, 22, and 18 conductors respectively. The pole blocks are shifted horizontally towards the apertures by 5 mm with respect to the middle blocks to improve magnetic field quality. The gap between pole blocks of 40 mm determines the magnet horizontal aperture. The design was optimized for the react-and-wind technique. This approach suggests the minimum-bending radius of 90 mm for the chosen cable size and thus restricts the minimum aperture separation by 290 mm. The iron yoke is splitted vertically into two pieces. Special holes correct the iron saturation effects.

The mechanical design developed for this magnet uses an effective stress management strategy to protect brittle Nb_3Sn cable and other structural elements from the over-load [3].

Coil blocks, surrounded by the 0.5 mm thick electrical insulation, placed inside a strong support structure formed by stainless steel collar laminations (see Fig. 2) in straight section and by solid stainless steel parts at both ends.

TABLE I
MAGNET PARAMETERS

Parameter	Design value
Magnetic field, T	10
Current, kA	23.6
Aperture, mm	40
Aperture separation, mm	290
Number of turns per coil	18+22+18
Iron yoke OD, mm	564
Stored energy @ 11 T, kJ/m	2 x 410
Inductance @ 10 T, mH/m	2 x 1.475
Magnet straight section length, m	0.4
Magnet yoke length, m	0.4
Superconductor	Nb_3Sn
Superconducting cable dimensions, mm x mm	22.23 x 1.28
Number of strands	60
Strand diameter, mm	0.7
Filament diameter, μm	100
Strand critical current at 12T, 4.2K	500
Copper : Non-Copper	1

During fabrication the structure provides the required vertical prestress and protects the coil from the horizontal and vertical over-compression while during operation it prevents an accumulation and transfer of the vertical Lorentz forces from the pole blocks to the mid-plane blocks. It also intercepts a significant part of the horizontal Lorentz force components reducing stresses in the yoke and relatively thin skin to the level well below their yield stresses. The calculated stress in the coil at all conditions is less than the degradation limit for the brittle Nb_3Sn cable.

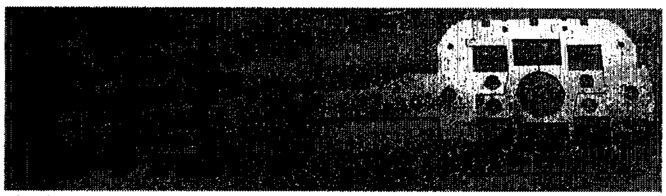

Fig. 2. Common Coil Dipole Cross Section

The described mechanical design requires simultaneous winding of both coils directly into support structure and then coil impregnation with epoxy inside the mechanical structure. The collared coil assembly is surrounded by the iron yoke and a 10 mm thick stainless steel skin. The stainless steel skin via the iron yoke provides the horizontal pre-compression of the collared coil. Thick 50 mm end plates welded to the skin with bullets restrict the longitudinal motion of the coil ends.

III. MAGNET FABRICATION

A. Nb3Sn Cable

The Nb3N cable with 59 strands and slightly reduced width was used to feet the gap in the collar packs. The Nb3Sn cable for react-and-wind technology should be specially prepared. Before reaction it was impregnated with Mobile 1 synthetic oil to avoid strand sintering at high reaction temperature which cause the large cable degradation during winding. Then two ~120-m long pieces of cable one for each coil were wound on two stainless steel reaction spools together with a mica-glass tape (Suritex 0822) 0.1mm thick, 22mm wide in order to prevent turn sintering during the heat treatment. The reaction spools had a diameter of 360 mm, which is by a factor of two larger than the minimum bending diameter in the coiling order to minimize the bending strain of the cable during winding. The heat treatment suggested by the wire manufacturer (OST) performed in argon atmosphere.

B. Winding Internal Splice

Two Nb_3Sn cables were spliced before winding of both coils into the support structure. Two U-shaped copper connectors with Nb3Sn splice cables joined the cable's ends. The 41-strand Nb_3Sn cable was placed into the copper stabilizer using a special fixture and reacted inside of the small oven. The heat treatment cycle was the same as for the main coil conductor.

C. Coil Winding and Instrumentation

The cable insulation consisted of two tapes, 0.16 mm thick pre-preg fiberglass tape and 0.08 mm thick Kapton tape. Both tapes were spooled together on a single bobbin.

Four tensioners were used for coil winding, two for the cables and two for the insulations. The cable and the insulation were wound under the tension directly from the spool into the slots of collar structure. After internal splice installation and instrumentation, the first block of 17 conductors was wound with cable tension of 14 kg and insulation tension of 11 kg. The real thickness of first wound block was larger than specified value because of rather large cable thickness variation. It was decided to wind one turn less than in the design and fill in the extra space with 1.27 mm G10 strip-fillers. The coil blocks were compressed by next sets of laminated packs using a special fixture. The collar packs were locked together with keys and inserted tubes. The stainless steel end parts compressed the coil ends with screws, rods and nuts (see Fig. 4). Then the next block ground insulation was installed into a new structural slot and a transition turn was wound. Each cable in the block transition area was instrumented with voltage taps and temperature sensors. Second and third conductor blocks were wound in the same way as the first one.

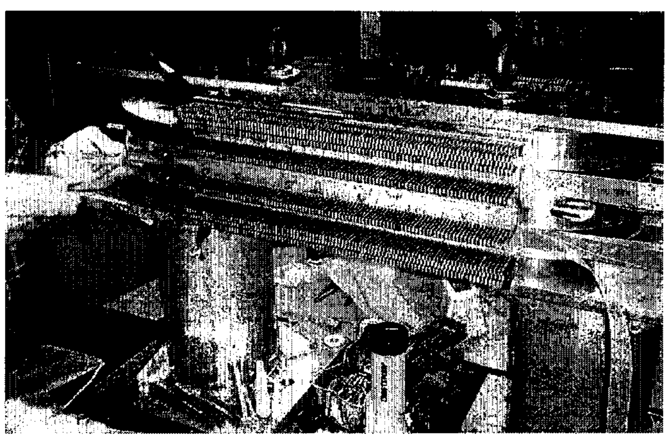

Fig. 4 Coil winding and collaring

The coil winding and instrumentation were performed simultaneously, since there is no access to the coil after each block collaring. The coil ends are the only available location for different instrumentation. There are total of 50 voltage taps, 4 spot heaters and 6 temperature sensors installed on the coils.

D. Lead Splices

Each Nb_3Sn lead cable was spliced with two NbTi cables and two stabilizing copper strips. The splicing procedure was identical to the splicing procedure developed for the racetrack models [5-6]. The 150-mm long splices were placed in the lead end block such that about a half of splice was outside of the collared coil in order to have direct contact with LHe.

E. Impregnation

The winding assembly was vacuum impregnated with epoxy in the close mold. All internal cooling channels were closed by special plugs and sealed with red RTV (see Fig. 5). Entire outside surface of the coil block was mold released. The block placed into an impregnation fixture which (after pumping out) was filled with epoxy CTD 101. Then the impregnation fixture was placed into the oven and cured at 125 C° during 21 hours.

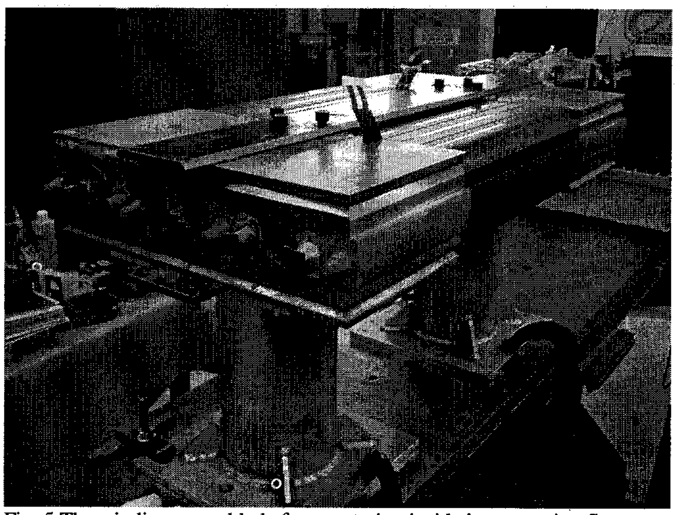

Fig. 5 The winding assembly before mounting inside impregnation fixture

F. Yoking

The impregnated coil block was shimmed and placed into a skin-yoke structure. The length of the iron in the short model is only 0.4 m. Two stainless steel blocks were installed on each magnet end. The gap between two yoke blocks at room temperature was ~1.25 mm at the magnet body and gradually reduced to zero at the magnet ends with stainless steel blocks. Both halves of the skin were partially (50%) hand welded together inside the press using a tack-weld and skip-weld techniques. Final 4 passes were performed outside of the press and after installation of the end plates. The common coil magnet assembly is shown in Fig. 6.

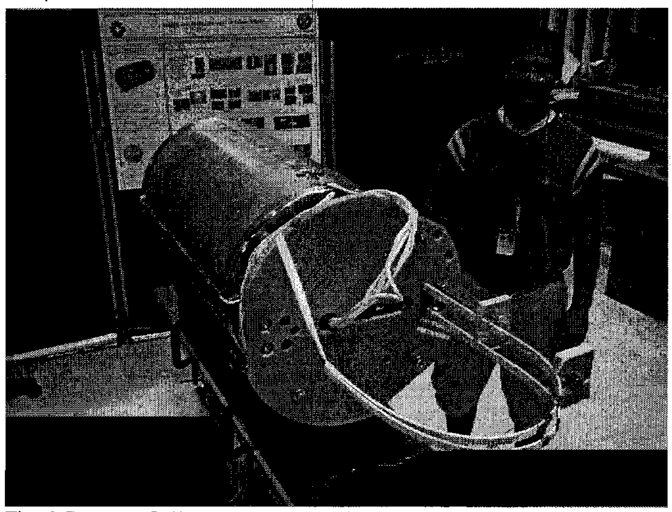

Fig. 6 Common Coil Magnet

IV. MAGNET TEST

A. Magnet Training

The common coil magnet was tested in the vertical magnet test facility [8] at Fermilab. The magnet training history in two thermal cycles is shown in Fig. 7.

Two thermal cycles (magnet warmed up to 200 K only) were performed and the magnet showed rather slow training. The maximum quench current 13.6 kA was reached after 67 quenches. All magnet coils were carefully instrumented with 50 voltage taps, 4 spot heaters and 6 temperature sensors. The information from voltage taps helped to localize the winding blocks where quenches started. The quench sequence in each winding block is shown on Fig. 8. The first 21 quenches took place in inner blocks of both coils others in outer blocks.

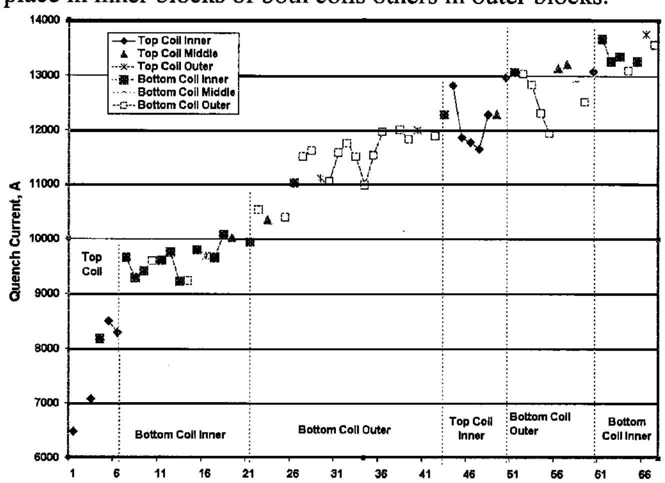

Fig. 7 Magnet training history

Only small number of quenches was in middle blocks. It can be explained the lower magnetic field in middle blocks and as a result lower Lorentz forces and better mechanical stability. Each coil block showed good training efficiency (see Fig. 8).

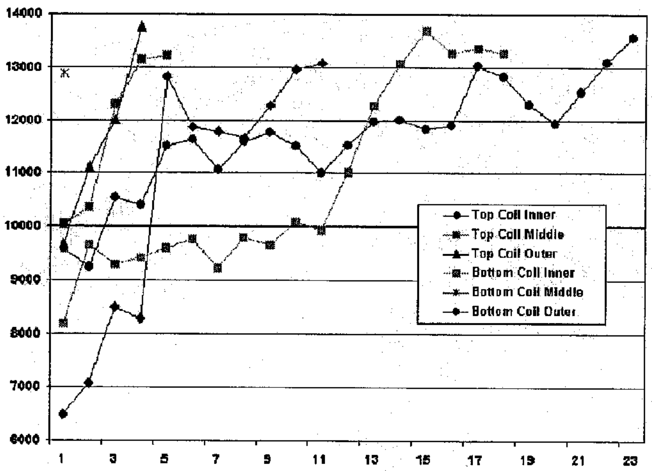

Fig. 8 Coil blocks training history

B. Snapshot – Fast Event Detection System

The Snapshot system was used to capture digital quench detection ADC buffer signals. The system triggered by signals with threshold |Hcoil1 – Hcoil2| > 0.05 or 0.1 V. These signals were digitized at 11520 Hz frequency and stored during 54 msec of time. The system "dead" time was ~ 30 sec after each detected event. Fig. 9 shows the typical voltage spike detected by the snapshot system.

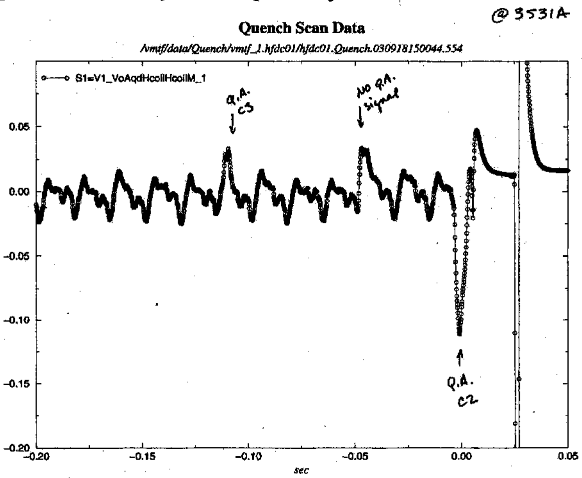

Fig. 9 Voltage spike detected by the snapshot system

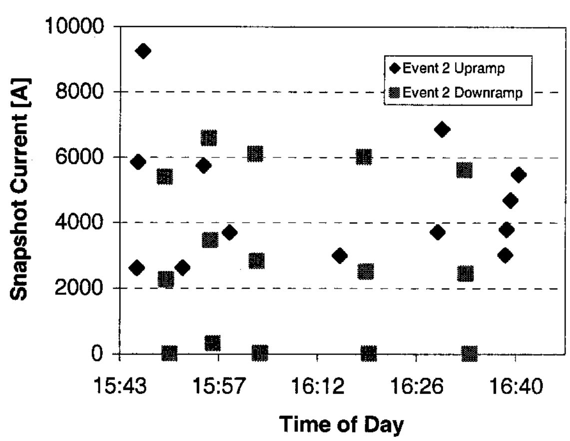

Fig. 10 Voltage spikes detected during one-hour period of magnet test

The quantitative distribution of detected events shown on Fig. 10. The most events were up to current 7 kA and may be correlated with flux jumps and mechanical motions.

C. Mechanical measurements

Magnet ends were preloaded by bullets. All bullets were instrumented with strain gages, which were used for the load control at different stages. The initial 500 kg per bullet load was chosen to provide continuous contact up to LHe temperature and load transfer from magnet ends to 50 mm thick end plates. Strain measurements showed smooth Lorentz forces transfer to magnet ends. Nevertheless at low currents about all longitudinal force was accepted by outer skin because of friction between winding assembly, iron yoke and the outer skin.

V. Conclusion

The manufacturing and tests of a single-layer common coil dipole based on Nb_3Sn conductor was completed at Fermilab. This magnet is the first Nb_3Sn double aperture accelerator magnet with the react-and-wind technology. The magnet showed rather slow training from 6.5 kA to 14 kA, which can be caused by the low, prestress applied to the coil blocks and blocks motion. Nevertheless new mechanical structure successfully intercepts Lorentz forces and no indication of cable degradation were found in spite of large number of quenches during magnet training. The results of magnetic measurements (presented in this conference paper) confirmed the good field quality, which is in an agreement with the previous magnetic field calculations.

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