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Development of a Single-Layer Nb_3Sn Common Coil Dipole Model

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Abstract— **A high-field dipole magnet based on the common coil design was developed at Fermilab for a future Very Large Hadron Collider. A short model of this magnet with a design field of 11 T in two 40-mm apertures is being fabricated using the react-and-wind technique. In order to study and optimize the magnet design two 165-mm long mechanical models were assembled and tested. A technological model consisting of magnet straight section and ends was also fabricated in order to check the tooling and the winding and assembly procedures. This paper describes the design and technology of the common coil dipole magnet and summarizes the status of short model fabrication. The results of the mechanical model tests and comparison with FE mechanical analysis are also presented.**

Index Terms—**common coil dipole, mechanical model, Nb3Sn, superconducting accelerator magnet, technological model.**

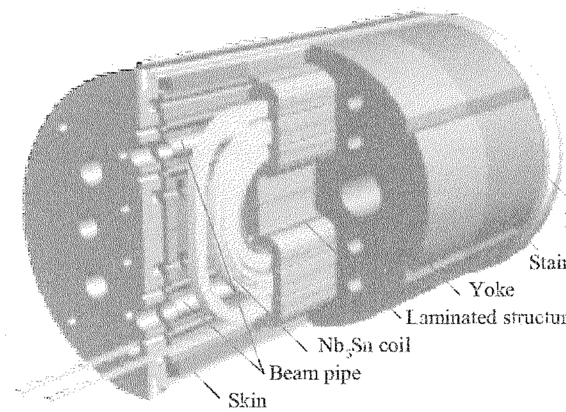

Fig. 1. Common Coil Dipole Cold Mass.

I. Introduction

A single-layer common coil dipole magnet had been developed at Fermilab for a future Very Large Hadron Collider [1]. Magnet was designed to provide a 10 T nominal field in two 40-mm apertures at operation temperature of 4.5 K. It is based on Nb3Sn 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 60-strand Rutherford-type cable made of 0.7-mm Nb3Sn 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 and the short model R&D program to study and optimize the common coil magnet design and react-and-wind technology has been started. This program consists of different steps such as cable development, fabrication and tests of simple racetrack coils as well as common coil mechanical and technological models, and finally fabrication and tests of series of common coil short models. Up to now two racetracks have been fabricated and tested. The results are reported elsewhere [4], [5]. Two short mechanical models and technological model have been also assembled and tested. Based on the results obtained necessary corrections in the design have been introduced and model fabrication has been started. This paper describes the design and technology of the common coil dipole magnet and summarizes the status of short model fabrication.

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II. Magnet Design

The 3D view of the magnet cold mass is shown in Fig.1. The magnet design is based on single-layer flat racetrack coils with shifted pole blocks shared between two apertures [6]. The coils are made of rectangular Rutherford-type cable with the width of 21.09 mm and the thickness of 1.245 mm. The cable consists of 60 strands, each 0.7 mm in diameter. The nominal cable insulation is 0.10 mm thick. 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 minimize geometrical harmonics. The gap between pole blocks of 40 mm determines the magnet 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 split vertically into two pieces. Special holes correct the iron saturation effect.

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, are placed inside a strong support structure formed by stainless steel collar laminations in straight section and by solid stainless steel parts at both ends. 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.

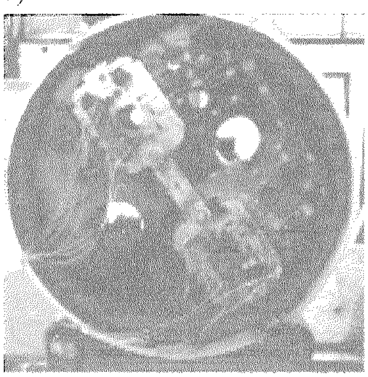
The described mechanical design requires simultaneous winding the both coils directly into the support structure and then impregnating coils with epoxy inside the structure. The collared coil assembly is placed inside the iron yoke surrounded by a 10 mm thick stainless steel skin. The stainless steel 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. Mechanical Models

The magnet mechanical concept, the main components such as the cable, insulation, collars as well as the impregnation, yoking and skinning procedures have been tested using Mechanical Models.

The Common Coil Mechanical Model #1 is a 165mm long slice of the magnet straight section including the collared coil, the iron yoke and the skin (see Fig. 2a). The model design, fabrication procedure and room temperature (300 K) test results are reported in [7].

a) b)



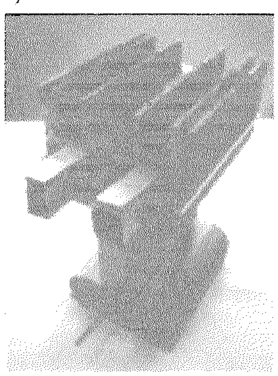


Fig. 2. Instrumented Common Coil Mechanical Model #1 and Model#2.

The Model was cooled down in liquid Nitrogen to 77K and the tests of the electrical insulation were repeated. The lowest coil-to-ground breakdown voltage was >3kV and turn-to-turn voltage was >2.5kV.

The Model was instrumented with resistive gauges installed on the collar, the yoke and the skin as it shown in Fig 2a. The stress measurements were performed at both room and liquid nitrogen temperatures and compared with the updated ANSYS calculations. The measured and calculated data are shown in Tables I. As it can be seen the skin tension increased from 160 MPa to 285 MPa and the yoke gauges showed compression of 70-110 MPa.

TABLE I
Skin, Collar and Yoke Stress Measurements (MPa)
(The Data From Mode And FEA Prediction Are Given In The Parenthesis)

Condition	Skin	Collar	Yoke
Skin welding	160 (130)	-	-
Cool down to 77K	285 (310)	60	72-110 (100)

After skin welding strain gauges were also installed on the coils on several pole (W1, W3) and midplane (W2) blocks. These gauges were used to measure the coil stress change during cooling dawn. The measurements were performed both with and without the iron yoke. The data on cool-down stress reduction in horizontal and vertical directions are summarized in Table II.

TABLE II
Coil Stress Data From Resistive Gauges (MPa)

Condition	Coil stress in X-dir.			Coil in Y direction			
	W2	W1	W2	W2	W1	W2	W3
with yoke	12	17	17	-26	-22	-26	-32
w/o yoke	31	21	30	-18	-19	-18	-17

The calculated final coil block size was smaller than the design geometry due to variations in the insulation scheme and in the cable dimensions. As a result no pre-stress was applied to the coils after collaring. The coil stress loss in vertical direction after cooling down was in the range of 20-30 MPa. The coils were additionally compressed by 12-17 MPa in horizontal direction due to skin shrinkage.

The model predicts the experimental data reasonably well for the yoke and the skin. The coil data need additional verification since the un-reacted cables have been used.

Based on the results of the cable insulation study performed on MM#1 the spacer-type double-layer insulation [7] has been chosen for further studies in the racetrack and in the next mechanical model. The coil size with modified insulation has been checked on the model #2.

In order to determine the optimal block sizes with chosen cable insulation which provide the nominal coil prestress at room temperature, the Mechanical Model #2 was used. Stacks of reacted ITER cable were locked by laminated packs with keys and a central tube as it shown in Fig.2b. Capacitance gauges were used to control the coil stress. Oversized by 0.3 mm stack was compressed to 90 MPa during tube insertion . The stress in the coil block after spring back had reduced to 30 MPa and to zero pressure a day letter. The reduction of stress was a result of creeping of soft B-stage glass tape. Taking into account the complete lost of the pre-stress due to the insulation creep and avoiding dangerous coil over-compression during collaring, the nominal dimensions for all coil blocks in the magnet were chosen as the coil target size.

IV. Technological Model

To test the fabrication tooling and assembly procedures, 800-mm technological model have been recently built using reacted Nb3Sn cable and real magnet components.

A. Superconducting cable

The cable for the technological model was made of 60 Nb3Sn strands with a diameter of 0.7 mm. The strand was produced by Intermagnetics General Corporation (IGC) using Internal Tin Diffusion process developed for ITER conductor. Successful cabling run of 300 m long, 22.22 mm wide, and 1.35 mm thick cable was performed at LBNL using synthetic oil and power turks-head.

For strand reaction two 120-m long pieces of cable were wound on two single-layer metallic spools together with a mica-glass tape in order to prevent turn sintering during heat treatment. The reaction spools had the diameter that is a factor of two larger than the minimum diameter in the coil ends. That allows minimizing the bending strain of the cable during winding.

The cable was reacted in Argon atmosphere inside a retort following the schedule: ramp at 6 C/h up to 215 C, on hold for 175 h; ramp at 15 C/h up to 340 C, on hold for 120 h; ramp at 25 C/h up to 575 C, on hold for 160 h; ramp at 25 C/h up to 700 C, on hold for 30 h.

In order to determine the size of the cable after reaction, two cables made of different strands, IGC used in the technological model and OST to be used in the common coil model, have been measured at free condition before and after heat treatment cycle. The data averaged for 15 points are shown in Table III. The measured increase of cable width for the IGC cable was 0.7% and cable thickness increased by 3%. For the OST cable it is 1.6% for both dimensions.

TABLE III
Cable Expunction After Reaction

Conductor	Width, mm Before reaction and After		Thickness, mm Before reaction and After	
IGC	22.27	22.43	1.28	1.32
OST	22.32	22.68	1.25	1.27

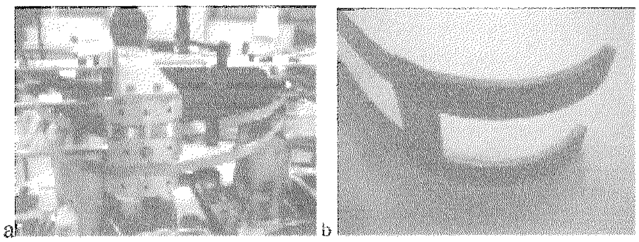
B. Insulation

Turn-to-turn insulation was chosen base on the test results obtained from the mechanical models and the racetrack [5,7]. To minimize a risk of additional cable degradation due to insulation wrapping and additional cable re-spooling during this procedure, a spacer-type insulation was placed between each couple of adjacent turns during coil winding. The insulation consists of two tapes with the same width as the cable: a 6.5 mil average thick pre-impregnated glass tape and a 75-um thick Kapton tape. The glass tape had several splice joints due to short peace length. The 15-mm long overlap junction has the same thickness as the tape after heating and compression in the splicing fixture. Both 110-m long glass and Kapton tapes were wound on the same spool.

Ground insulation was placed around all conductor blocks in the magnet. For a convenience of winding of slightly oversized in width cable the total thickness of the nominal thickness of ground insulation was reduced by 250 um using the combination of 0.5 mm thick G10 sheets and 0.25 mm Kapton film.

C. Splice joint

For simultaneous winding of both coils into support structure the two Nb3Sn cables have to be spliced before the winding. Cable splicing was performed in special fixture after both spools were installed on two tensoiners as shown in Fig.3a. The cables were joined using the U-shaped pre-reacted multistrand Nb3Sn connector and the copper stabilized. The fixture provides the final curved shape of the splice as it shown in Fig.3b.



a b

Fig. 3. Cable Splice Fixture And Cable Splice Ready For Installation

D. Coil winding

One coil consists of 3 blocks. Each block was wound inside the pre-formed windows formed by the collar laminations (see Fig.4), and stainless steel ends, and locked by keys or screws.

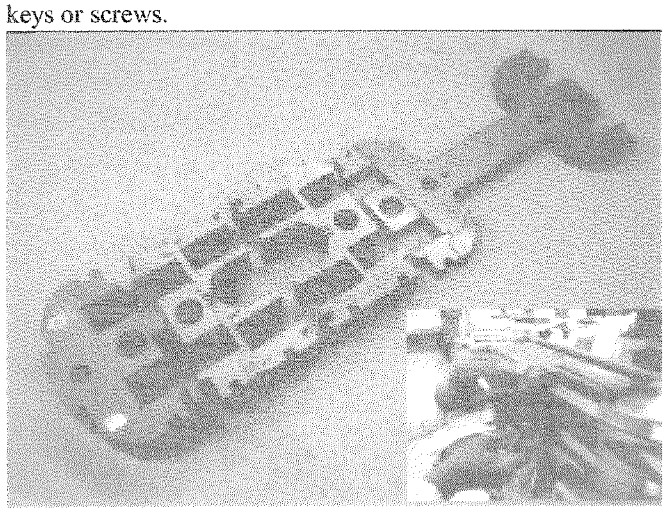


Fig. 4. Collar Lamination Packs And Pack Insertion During Winding.

Both coils were wound and locked simultaneously block-by-block. The insulation strips are wound simultaneously with the bare cable. Four independent tensioners show in Fig. 5, were used to apply a tension of 20 lbs to each cable and 30 lbs to the insulations. The strip is sufficiently strong to be wound under tension larger than cable tension. This approach reduces a risk of cable collapse and strand pop-out, and lower the coil spring back during winding.

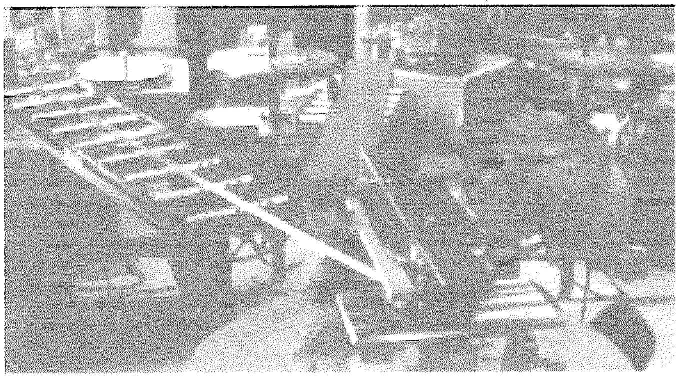


Fig. 5. Coil Winding Setup.

Insulated splice was carefully inserted in the splice slot on the return end of the winding mandrel avoiding extreme cable bending. The structure formed by the collars provides the proper positioning for the insulation tapes and the cables. Side pushers had been used to achieve a dense winding. The entire straight section was compressed from both sides using special collaring fixture to insert the keys. The fixture is then removed to wind the next coil blocks. Alternated laminations were assembled in ~1.5in long (20 lams) packs using two pins as a base. Thin SS washers separate laminations in the pack and provides path for epoxy during impregnation.

E. Magnet Leads

After winding, each Nb_3Sn lead cable was spliced with two NbTi cables and two stabilizing copper strips using special splicing fixture shown in Fig.6. The splicing procedure was identical to the lead splicing procedure developed for the racetracks [4,5]. The 150-mm long splices are placed in the lead end block such that about half of each splice is outside of the collared coil and is being in direct contact with liquid He.

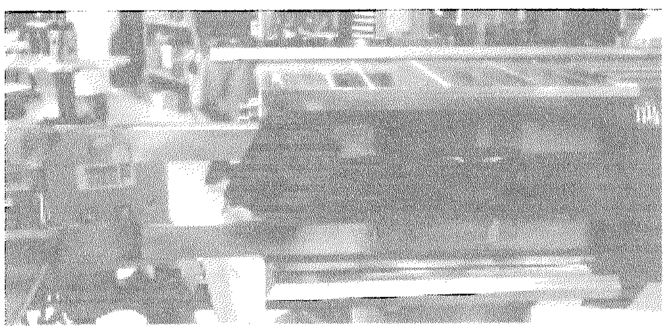


Fig. 6. Cable Lead Splices and Impregnation Fixture

F. Epoxy Impregnation.

The completed collared coil was assembled in the impregnation box, which provides the final alignment. The assembled and prepared for epoxy impregnation common coil collared coil shown in Fig.7.

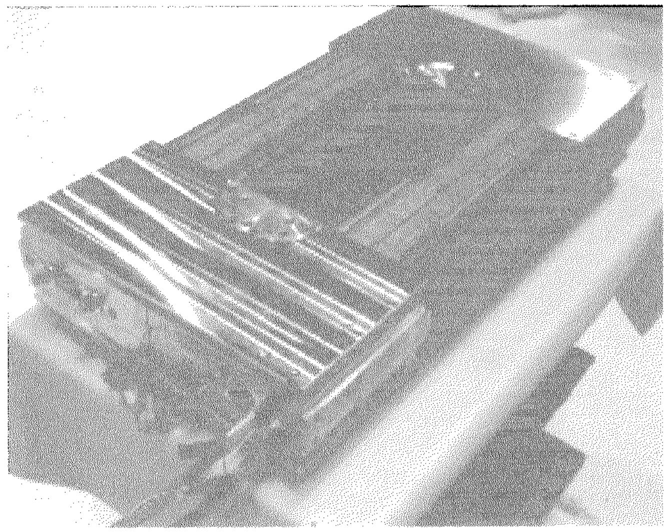


Fig. 4. Common Coil Technological Model

V. Conclusion

The design of a single-layer common coil dipole based on Nb3Sn conductor and the react-and-wind technology was completed at Fermilab. The magnet mechanical concept and the assembly procedures wereified on the mechanical and technological models. The fabrication of 800 mm long Nb3Sn Common Coil Dipole magnets is underway. Te tests of the first common coil model magnet is planned for December 2002.

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