R & D for a Single-Layer Nb_3Sn Common Coil Dipole Using the React-and-Wind Fabrication Technique

G. Ambrosio, N. Andreev, E. Barzi, P. Bauer, D. R. Chichili, K. Ewald, S. Feher, L. Imbasciati, V. V. Kashikhin, P. J. Limon, L. Litvinenko, I. Novitski, J. M. Rey, R. M. Scanlan, S. Yadav, R. Yamada, A. V. Zlobin

***Abstract*-- A dipole magnet based on the common coil design, using prereacted Nb3Sn superconductor, is under development at Fermilab, for a future Very Large Hadron Collider. This magnet has some innovative design and technological features such as single layer coils, a 22 mm wide 60-strand Rutherford type cable and stainless steel collars reinforced by horizontal bridges inserted between coil blocks. Both left and right coils are wound simultaneously into the collar structure and then impregnated with epoxy. In order to optimize the design and fabrication techniques an R&D program is underway. The production of cables with the required characteristics was shown possible. Collar laminations were produced, assembled and tested in order to check the effectiveness of the bridges and the validity of the mechanical design. A mechanical model consisting in a 165 mm long section of the magnet straight section was assembled and tested. This paper summarizes the status of the program, and reports the results of fabrication and test of cable, collars and the mechanical model.**

***Index Terms*—Superconducting magnet, accelerator dipole, mechanical model, common coil magnet.**

I. Introduction

THE final development of a single layer common coil magnet is underway at Fermilab (Figure 1) [1]. This magnet has a maximum nominal field of 11 T, at 4.5 K, in a 40 mm aperture, and is a candidate for a possible VLHC [2]. In order to exploit the low inductance of a single-layer design, a 22.2 mm wide cable is used. The cable, made of 60 strands with 0.7 mm diameter, is reacted before winding. The coils are simultaneously wound inside the collars, made of alternated laminations, in order to allow the insertion of bridges above and below each aperture. These bridges increase significantly the stiffness of the collars against the main component of the magnetic forces. They allow to have small displacements and low stresses in the coils during energization, and a skin not thicker than 10 mm. The magnetic design has been finalized and the main parts of the mechanical design were completed. Cables with the required characteristics have been produced and tested. Other tests have been performed, or are underway, in order to define the insulation scheme and to verify the collars' design and behavior. A mechanical model of the straight section has been assembled and is under test in order to define magnet assembly procedures, practice with and develop all tools, and compare the results of mechanical tests with the prediction of finite element analyses.

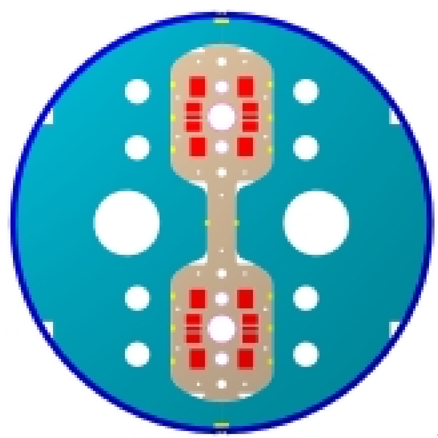

Fig. 1. Cross section of the single-layer common coil dipole magnet.

II. Conductor fabrication and test

The cable design is the result of two conflicting requirements. The react-and-wind technology demands thin strands, because the bending degradation increases with the strand diameter. On the other hand, the need of ampere-turns for the magnetic design, requires a large cable in case of a single-layer magnet.

Two measures of the relative difficulty in fabricating a Rutherford-type cable are the number of strands, and the width to thickness aspect ratio. The production run cable which, at present, has the largest number of strands is the LHC high gradient quadrupole cable, with 48 strands and an

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G. Ambrosio, N. Andreev, E. Barzi, P. Bauer, D. R. Chichili, K. Ewald, S. Feher, L. Imbasciati, V. V. Kashikhin, P. J. Limon, L. Litvinenko, I. Novitski, S. Yadav, R. Yamada, A. V. Zlobin are with the Fermi National accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 (telephone: 630-840-2297, e-mail: giorgioa @fnal.gov).

R. M. Scanlan is with Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720.

J. M. Rey is with DAPNIA CEA, Saclay, France.

aspect ratio of 13.4. The present cable with 60 strands of 0.7 mm diameter wire has an aspect ratio of 17.8. Fabrication of this type of cable requires specialized equipment with a number of important capabilities. Due to the high friction loads associated with a large number of strands, these cables must be fabricated using a powered turkshead so that the tensile load on the cable as it exits the turkshead can be controlled. Another requirement is that the cabling machine be capable of accommodating the number of strands.

A proof of principle cabling run was performed at LBNL in September 2000, using ITER-type Nb_3Sn wires drawn to 0.7 mm diameter. This initial length of wire was 165 m/spool, and the final yield of useful cable was 110 m (105 m are required for each coil). Subsequent evaluation of this cable at FNAL indicated that it could be reacted and wound successfully into racetrack type coils. Also, Ic measurements of extracted strands indicated that the critical current degradation due to cabling damage was small, and that the bending degradation was acceptable [3].

Two subsequent runs have been performed with different strand material in order to establish that this cable can be reproduced and fabricated in long production lengths. The results are shown in Table 1.

TABLE I
LENGTH AND DEGRADATION OF CABLE PRODUCED

Length (m)	Strand source	Comments	Cabling degr. at 12 T
110	IGC B7408, B7410	ITER - 65 % Cu	
457	IGC 7423, 7439	ITER - 65 % Cu	10 %
121	OST 151, 152	High Jc - 48 % Cu	4 – 7 %

III. Mechanical design

The main components of the mechanical design are the collars, consisting of packages of alternated stainless steel laminations, 2 mm thick, reinforced by bridges. Those bridges increase the stiffness of the collars allowing them to withstand large part of the magnetic forces. The remaining part of the forces will be reacted by a 10 mm thick skin. The yoke has a vertical gap. The mechanical design and finite element analyses were presented in [4]. It was shown that this combined action of collars and skin allows to restrain displacements and stresses in the coil within 70 μm and 140 MPa respectively.

The maximum stress in the collars is expected to occur in the bridges where it should reach about 750 MPa. Nitronic 40, which has a yield stress higher than 1100 MPa at cryogenic temperature and a very low magnetization, will be used for all parts of the collars.

IV. Collar laminations

The collar laminations are the center-piece of the single-layer common coil. Coils are wound and impregnated inside these laminations, they provide the centering of the coils respect to apertures, and give the main part of the support against the magnetic forces.

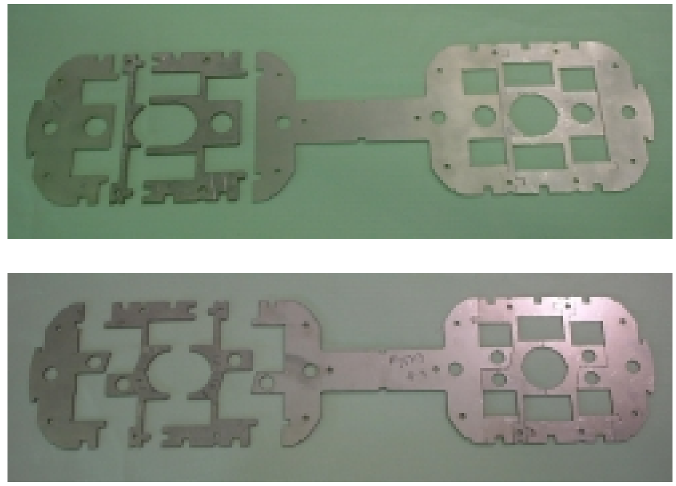

Fig. 2. Two designs of the collar laminations. First design using five different pieces (top), and second design using three different pieces (bottom). The assembled laminations are shown on the right, the parts on the left.

Two designs are presently under study (Figure 2). The first design uses five different types of laminations, the second three types.

A small number of laminations of both designs have been fabricated by laser cutting and wire EDM (electrical discharge machining). They are being used for mechanical tests and for two mechanical models. EDM was necessary to cut the bridges because the heat produced by the laser was source of excessive deformations (the tolerances required were 25 μm). After the fabrication of the first magnet model the design will be finalized and precise stamping technique will be used for further production.

Some lamination packages were tested under side load, in order to verify their capability to withstand the pre-compression, transferred from the skin to the collars through the yoke. The target value of the pre-compression after skin welding is 72 kg/mm per aperture and it should increase to 235 kg/mm during cooldown. In case of excessive shrinkage of the skin the compression on the collars will be limited by yield of the skin to 310 kg/mm. Collar laminations were tested up to 500 kg/mm. Two samples consisted in packages of ten laminations (a sample for each design) assembled with pins and keys. A third sample had the laminations welded together in ten points and impregnated. For comparison tests were performed also on a solid piece with the same shape of the collars after assembly. All samples had empty block windows. The results of the first load test are presented in Figure 3. Both type of laminations and the impregnated laminations show similar stiffness, slightly lower than that of the solid piece, and don’t exhibit signs of instability or plastic deformation even after repeated cycles.

Under the effect of the magnetic forces the pre-compression will be released and most part of the laminations, especially the bridges, will experience high tensile stresses. In order to test the collars under these conditions an Instron 8503 machine was used.

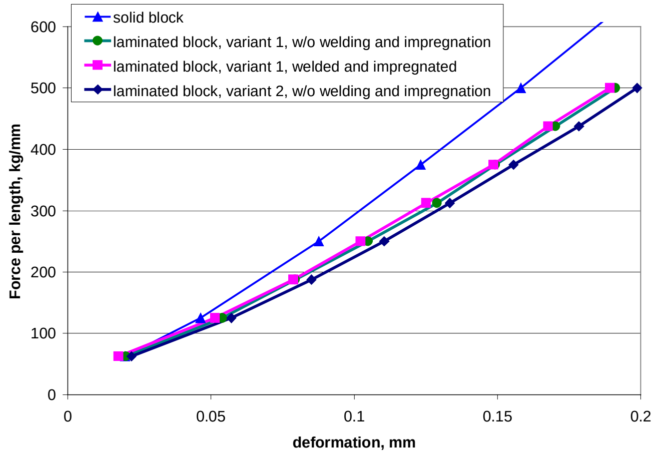

Fig. 3. Test of collar laminations under compression. Samples were made of ten laminations. Load was applied on the side of one aperture.

The samples tested (Figure 4) were similar to those used in the previous test. The tensile load, up to 5000 kg, was applied only to the central block window, so that the greatest part of the load was transferred to the bridges. In the first test series the load was distributed on the whole window surface, giving an average pressure of 65 MPa at maximum load. In the magnet the average pressure at maximum field will be 70 MPa with a peak of about 90 MPa in the center of the window. A second test series was performed applying the load on half the surface (130 MPa at maximum load). In both tests the three packages showed a similar stiffness slightly lower than the stiffness of the bulk sample. In the second test they exhibited a small deformation above 4000 kg during the first load. The first load curve of the second series is shown in Figure 5 for all samples.

Fig. 4. A sample for tensile test during fixture assembly. This sample consists of alternated lamination assembled, welded and impregnated.

It should be noted that the displacements measured in these tests are much larger than the coil displacement expected in the magnet, where collars will be initially under compression and then will share the tensile load with the skin.

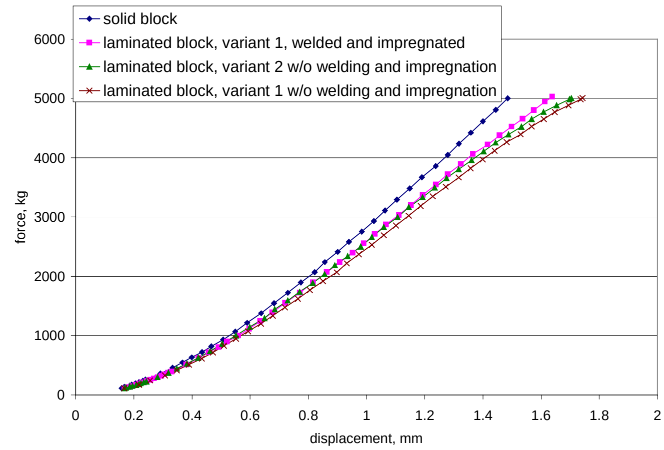

Fig. 5. Test of collar laminations under tensile load. Samples were made of ten laminations each. Load was applied in the center of the central window of one aperture, on half surface.

V. Insulation

Two turn to turn insulation schemes are under consideration. The first foresees the use of a fiberglass tape wrapped on the cable after the heat treatment. To insulate the cable after the heat treatment allows the use of E-glass tape, with two advantages with respect to the tapes required by the wind-and-react technology: cost savings and thinner insulation. A 50 μm thick tape was procured and was used with a 45% overlap to obtain the nominal insulation thickness of 0.1 mm. The second scheme uses a 0.2 mm thick Kapton strip set between each couple of adjacent turns. The strip, as wide as the cable, is wound simultaneously with the bare cable in order to provide a continuous insulation layer. Because of its thickness the strip is sufficiently strong to be wound under tension with two beneficial effects: the winding tension of the cable can be reduced (with a lower risk of cable collapse or strand pop out) and the coil spring back during winding is also reduced. This solution has also the advantage of avoiding the wrapping of the insulation on the reacted cable. The frame formed by the collars provides the proper centering of the Kapton layer on the cables. The Kapton should be carefully cleaned before installation in order to obtain a good bonding with the epoxy during the vacuum impregnation (required to avoid stress concentrations in the Nb_3Sn wires). Scratching its surface is an option that could be adopted in order to further improve the bonding.

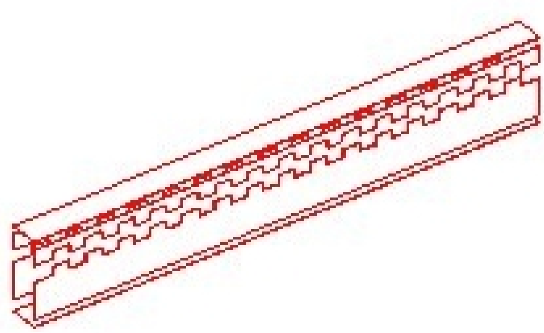

Fig. 6. G10 layers for ground insulation.

Also for the ground insulation two schemes are under study. In the first case 0.5 mm thick G10 spacers are used together with a 75 μm Kapton film. Six G10 spacers (Figure 6) are required around each coil block. The spacers on the coil sides have the shape of matching combs because the top spacers stick out of the collar window during the winding and slide completely inside the window during collaring. This is necessary in order to center the outermost turns of the block that lay out of the window until collaring. The Kapton film set on the coil-block sides, between the G10 spacers and the cables, provide a sliding surface for the top spacer. Both the Kapton film and the G10 spacers are painted with mold-release in order to avoid the bonding of the coil-block to the collar, as required by finite element analyses [4].

The second scheme foresees the use of Kapton films only. The films, with an L or U shape, are set around the coil block in order to give a continuous insulation and to provide paths for epoxy during impregnation. Mold-release is painted on the outermost foils in order to avoid bonding with the collars.

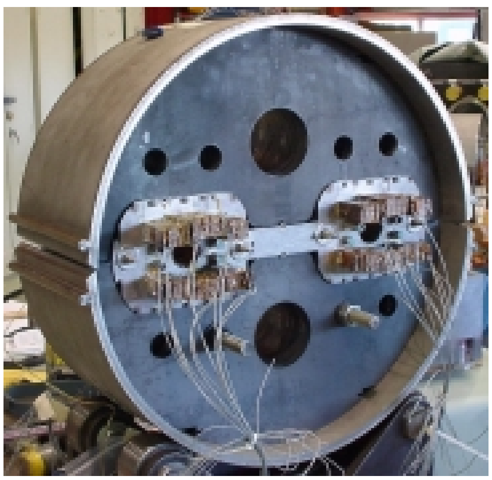

Fig. 7. The mechanical model before skin welding.

VI. Mechanical model

A mechanical model, consisting in a 165 mm long slice of the straight section, was assembled (Figure 7) and is under test. The model comprehends all part of the straight section: coils, collars, yoke and skin. Coil blocks are made of 250 mm long pieces of cable insulated by hand.

The purposes of this mechanical model are: to test different turn-to-turn and coil-to-ground insulation schemes; to practice in coil-collar assembly and simulate the coil winding inside the collars using different insulations; to study the stresses in the skin and in the collars after skin welding and after cooldown.

All cables close to one aperture (blocks 7 to 12 in Table II) where insulated with a 0.05 mm thick E-glass tape with 45% overlap, all other cables had a 0.125 mm Kapton layer as turn-to-turn insulation. Different ground insulation materials were used with both type of cable insulation in order to study all possible combinations. Blocks 6 and 8 had the ground insulation made of G10 layers, in blocks 9 and 10 Kapton was used, in the other blocks mixed solution were experimented. The model was assembled, vacuum impregnated and the insulation tested at room temperature (Table II). The tests were performed on four adjacent cables located at the bottom or at the top of each block. The current leakage at maximum voltage (3 or 4.5 kV) was always lower than 0.01 μA (bottom scale). If a breakdown occurred the measurement was repeated three times and the lowest value is reported.

The assembly of the mechanical model will be completed adding the yoke, consisting of 36 laminations and the skin. The skin will be welded under a press and the stresses in the skin, yoke and collars will be measured and compared with prediction from finite element models.

TABLE II
Electrical insulation test

Turn-to-turn:	**KAPTON**						**E-GLASS TAPE**					
block #	1	2	3	4	5	6	7	8	9	10	11	12
Ground Insulation test												
B V (kV)		S				2.3		3.3		3.3	1.9	3
Max V (kV)	3		3	3	4.5		4.5		4.5			
Turn-to-turn insulation test												
B V (kV)	2.8	1.3	1.5	2.2		1.4	1.4	2.5	1.9		1.6	
Max V (kV)					3					3		3

Insulation test at room temperature. The lowest breakdown voltage (BV) is reported for each coil block, or the maximum voltage (Max V) reached during the test. In block #2 there was a short (S) caused by a shim with wrong dimensions.

VII. Summary and status of the program

The latest test and results of the R&D for a single-layer common coil have been presented. These results show that the main components of this magnet (the 60-strand cable and the collar laminations reinforced by bridges) can be produced and satisfy the design requirements. Tests are underway in order to finalize the insulation scheme and verify the mechanical design after skin welding and cooldown.

The procurement of the parts for the first short model is underway. These parts will be used first for a technological model (assembled but not impregnated) using ITER conductor, and then for the real model using OST conductor.

VIII. Acknowledgment

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IX. References

[1] G. Ambrosio et al., "Design and development of Nb3Sn single-layer common coil dipole magnet for VLHC" to be published in the Proc. of PAC 2001, Chicago, June 2001.
[2] P. Limon et al., "VLHC design study report", Fermilab TM 2149, May 2001.
[3] P. Bauer et al., "Fabrication and Testing of Rutherford-type Cables for React and Wind Accelerator Magnets", *IEEE Trans. on Applied Superconductivity*, vol. 11, no. 1, 2457, March 2001.
[4] I. Novitski et al., "Design and Mechanical Analysis of a Single-Layer Common Coil Dipole for VLHC", *IEEE Trans. on Applied Superconductivity*, vol. 11, no. 1, 2276, March 2001.