Development and Fabrication of Nb_3Sn Rutherford Cable for the 11 T DS Dipole Demonstration Model

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Abstract— **Fermilab and CERN started the development of 11 T 11-m long Nb_3Sn dipoles to replace few regular LHC NbTi dipoles and free space for cold collimators in LHC DS areas. An important step in the design of these magnets is the development of the high aspect ratio Nb_3Sn cable to achieve the nominal field of 11 T at the nominal LHC operating current of 11.85 kA with 20% margin. The keystoned cables 14.7 mm wide with and without a stainless steel core were made out of hard Cu wires and Nb_3Sn RRP strand 0.7 mm nominal diameter. The cable optimization process was aimed at achieving both mechanical stability and minimal damage to the delicate internal architecture of the Restacked-Rod-Process (RRP) Nb_3Sn strands with 127 restack design to be used in the magnet short models. Each cable was characterized electrically for transport properties degradation at high field and for low field stability, and metallographically for internal damage.**

Index Terms— **Rutherford cable, Nb_3Sn, subelement, stability.**

I. INTRODUCTION

THE recent progress in Nb_3Sn accelerator magnet technology by US-LARP and core programs in U.S. national Laboratories make it possible to envision Nb_3Sn magnets with nominal fields up to 12 T (B_{max} up to 15 T) in actual machines, particularly for the LHC upgrades. The second phase of the LHC collimation upgrade will enable beam operation at nominal and ultimate intensities. To improve collimation efficiency, additional collimators are foreseen in the dispersion suppression (DS) regions. To provide a longitudinal space of about 3.5 m for the additional cryo-collimators, a solution based on shorter 11 T dipoles as a replacement for several 8.33 T 15 m long LHC main dipoles (MB) is being considered [1]. These twin-aperture dipoles operating at 1.9 K shall be powered in series with the main dipoles and deliver the same integrated strength of 119 Tm at the nominal current of 11.85 kA.

To demonstrate the feasibility of this approach, CERN and FNAL have started an R&D program with the goal of building by 2014 a 5.5 m long twin-aperture Nb_3Sn dipole cold-mass suitable for the DS region upgrade. The first phase is the design and construction of a single-aperture 2 m long demonstrator dipole magnet, delivering 11 T at 1.9 K in a 60 mm bore with 20% margin on the load line [2, 3]. Then, two twin-aperture 2 m long demonstrator magnets will be fabricated and tested to study and optimize the quench performance, field quality, operation margin, and quench protection of Nb_3Sn collared coils inside the modified LHC iron yoke. The conceptual design studies of the twin-aperture 11 T dipole have been started [4].

An important goal of this phase is cable development. The parameters of the Rutherford-type cable for the demonstrator magnet were selected based on the following considerations:

- The maximum number of strands has to be less than 40 to comply with the capability of CERN cabling machine (FNAL cabling machine allows for 42 strands [5]).
- The strand diameter should be less or equal to 0.7 mm to achieve the required magnet transfer function (11 T or more at 11.85 kA or less) [6].
- The critical current degradation due to cabling has to be 10% or less to provide the required operation margin.

This paper summarizes the optimization process of cable design and fabrication, and presents the cable test results.

II. STRAND DESCRIPTION

The Nb_3Sn technology of the wires to be used in the short models of the 11 T dipoles is that of the Restacked-Rod Process (RRP) by Oxford Superconducting Technology (OST) [7], with a 108/127 design and 0.7 mm in diameter. The cross section of RRP-108/127 strand is shown in and Fig. 1. The strand parameters are summarized in TABLE 1.

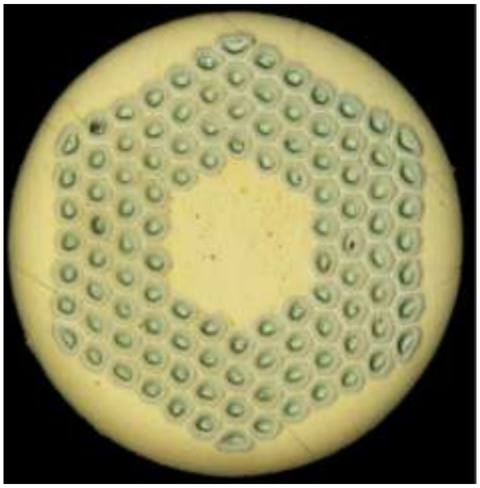

Fig. 1. Strand cross-section.

Manuscript received 12 September 2011. Work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

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TABLE 1. RRP-108/127 Strand Parameters.

Parameter	Value
Strand diameter, mm	0.700±0.003
Cu fraction, %	53±3
Effective sub-element diameter, µm	<60
Critical current I_c(12T, 4.2K), A	>475
Critical current density J_c(12T, 4.2K), A/mm^2	>2650
RRR (after heat treatment)	>60
Twist pitch, mm	14±2

III. CABLE SPECIFICATION DEVELOPMENT

A. Tooling and Instrumentation

The large aspect ratio of the cable and the procedure presently used at FNAL require a two stage cable fabrication: first a rectangular cable with narrower width and lower packing factor, and next a keystoned cable with final cross section. The rectangular cables were made using a 42-spool compact cabling machine [5], and a forming fixture made of two vertical rolls with variable gap and two horizontal rolls 1.2 mm thick. The second, keystoning, cabling step was made using a two-roll die with variable gap, and with fixed keystone angle and cable width. Both these fixtures are shown in FIGURE 2.

Cable quality control included measurements of the strands diameter, visual inspection of the cable during fabrication to check for imperfections (crossovers), measurements of cable thickness and width, microstructural analysis of cable cross sections, and strands electrical characterization (virgin wires and extracted from cables).

The cable size measurements were obtained through Mitutoyo dial indicators with 1 µm resolution placed on the top rollers of the rectangular and keystoned tooling. Such measurements were acquired every 3 cm at 1 m/ min of production speed.

B. Cable Sample Fabrication and Test

The following cables were fabricated during cable development. Four rectangular Cu practice cables with and without stainless steel (SS) core to finalize geometry parameters, two rectangular Nb_3Sn cable short samples with and without SS core (RRP 108/127 strand design) to check the cabling impact on the conductor, a 250 m long Cu cable for the first practice coil, and a 250 m long Nb_3Sn keystoned cable for the second practice coil made of RRP 114/127 wire. The Cu cable and mandrel parameters are shown in TABLE 2.

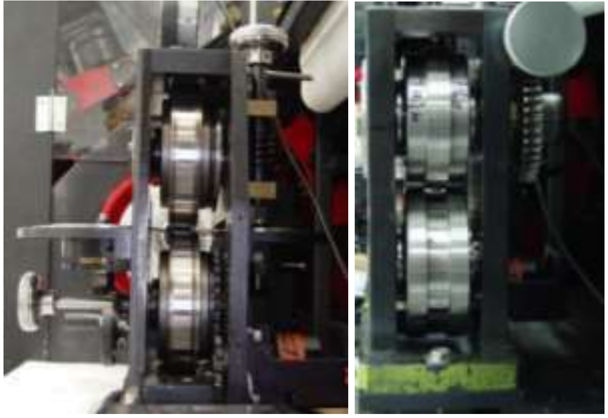

Fig. 2. Cable forming fixture for the rectangular cable geometry (left) and keystoned tooling (right).

TABLE 2. Cu Rectangular Cables Description (strand size=0.697 mm).

No. strands	Mandrel width, mm	Width, mm	Thickness, mm	Lay angle, °	PF, %	SS Core
40	13.93	14.55 ± 0.03	1.302 ± 0.002	15	83.4	N
40	13.95	14.58 ± 0.01	1.312 ± 0.003	15.5	83.8	Y
40	13.95	14.58 ± 0.02	1.306 ± 0.005	17.5	85.1	Y

TABLE 3. RRP-108/127 Rectangular Cables Description (strand size=0.703 mm).

No. strands	Mandrel width, mm	Width, mm	Thickness, mm	Lay angle, °	PF, %	SS Core
40	13.95[a]	14.62 ± 0.02	1.328 ± 0.003	15	82.8	N
40	13.95[a]	14.61 ± 0.02	1.331 ± 0.003	15	83.7	Y

[a] Mandrel had 11.3 mm wide slot.

A 0.025 mm thick and 9.525 mm wide SS tape was used as a core. In such case, a mandrel with an 11.3 mm wide upper slot was used. The rectangular cables formed to produce keystoned cables 14.7 mm with 40 strands were 1% narrower than the final desired widths to account for width expansion when performing the second, keystoning, cabling step.

To verify the impact of the cabling process on the superconducting strand that will be used in the magnet short model, two short samples of rectangular superconducting cable with and without SS core were produced out of 40 RRP-108/127, 0.7 mm strands. Their parameters are shown in TABLE 3. Over six unreacted cross sections that were prepared for microscopy, and analysed for each cable, only one strand showed possible damage to two subelements, which is less than typical cabling damage.

The reaction cycle that was used had three temperature plateaus at 210ºC, 400ºC and 640ºC in an Argon gas atmosphere and a total soak time of 7 days. FIGURE 3 shows the electrical characterization at 4.2 K of strands extracted from the uncored cable as a function of magnetic field compared to the round strand results. In this and subsequent similar plots, for the V-I tests solid markers represent the critical current I_c as obtained from a full transition, whereas empty markers represent the maximum current reached by the sample before quenching with no visible transition. The average I_c cabling degradation was 1% at 14 T and less than 3.5% at 12 T. The maximum J_c(12T, 4.2K) was 2620 A/mm^2. The RRR of the Cu matrix was 232. When tested at 1.9 K, the minimum current obtained through the V-H test was 951 A at 4.9 T, and the I_c(12T, 1.9 K) was 602 A.

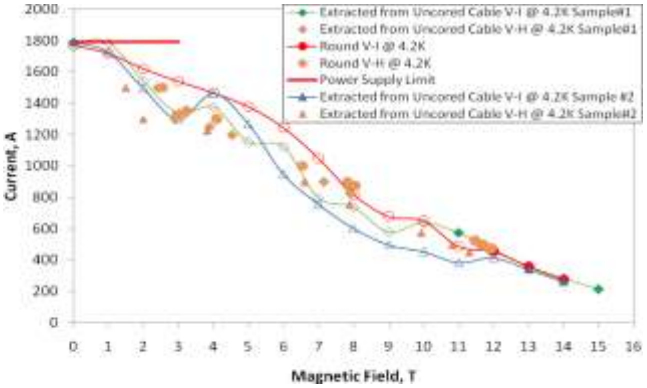

Fig. 3. V-I and V-H tests at 4.2 K of strands extracted from the uncored cable compared to round strand results.

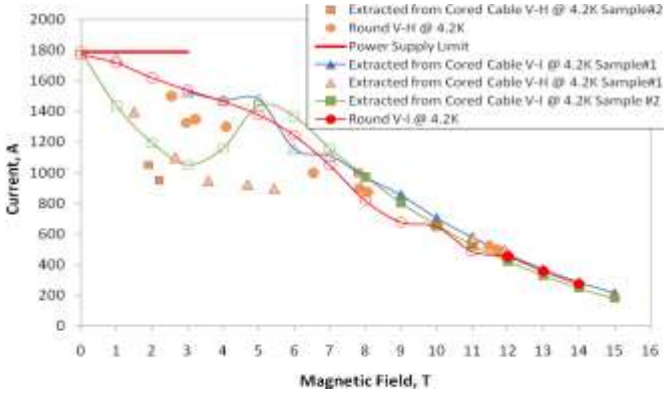

Fig. 4. V-I and V-H tests at 4.2 K of strands extracted from the cored cable compared to round strand results.

FIGURE 4 shows the electrical characterization at 4.2 K of strands extracted from the cored cable as a function of magnetic field compared to the round strand results. The average I_c cabling degradation was 2% at 12 T. The RRR of the copper matrix was 182. The maximum J_c(12T, 4.2K) was 2643 A/mm^2. When tested at 1.9 K, the minimum current obtained through the V-H test was 812 A at 4.6T, and the I_c(12T, 1.9 K) was 592 A.

C. Cable Specifications

Based on the above results, the cable specifications were established as shown in TABLE 4, where the geometrical parameters that were chosen for a cable without stainless steel core and cable insulation before and after reaction are listed.

TABLE 4. Cable Parameters.

Parameter	Value	
	Unreacted	Reacted
Cable unit length, m	210	
Number of strands	40	
Transposition angle, degree	15	
Transposition direction	Left-handed	
Mid-thickness, mm	1.269	1.307
Thin edge, mm	1.167	1.202
Thick edge, mm	1.370	1.411
Width, mm	14.70	14.847
Key-stone angle, degree	0.79	0.81
Insulation thickness, mm	0.150	0.100

During reaction, the Nb_3Sn strands expand due to phase transformation. Experimental data [8] collected for Nb_3Sn cables suggest an expansion factor of ~3% in thickness and ~1% in width. The unreacted cable cross section determines the dimensions of the coil winding and curing tooling, whereas the dimensions of the coil reaction and impregnation tooling, and the coil electromagnetic optimization and analysis are based on the reacted cable dimensions.

IV. KEYSTONED CABLE TECHNOLOGY

The first keystoned cable for the first superconducting practice coil was made using an RRP strand with 114/127 restack design that had been drawn down from 1 mm to 0.7 mm after twisting. About 230 m of cable were keystoned without annealing the rectangular cable, and 15 m were used to study the effect of intermediate annealing before keystoning. TABLE 5 shows the parameters of these various cables.

TABLE 5. RRP-114/127 Cables Description (mandrel 13.92mm, lay angle 15 deg).

Type	Length, m	PF, %	Cable width, mm	Cable mid-thickness, mm
R	248.4	84.0	14.556±0.038	1.316±0.009
K	230	86.3	14.71±0.012	1.265±0.005
R[a]	15	84.1	14.599±0.039	1.309±0.005
K[a]	15	85.8	14.69±0.02	1.274±0.005

[a] Rectangular cable was annealed in Argon at 180 C° for 1 hr.

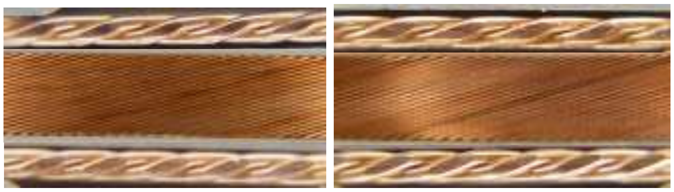

Fig. 5. Three-side views of the superconducting annealed (left) and non-annealed (right) keystone cable.

FIG. 6. Cross section of the rectangular (top) and keystoned (bottom) cross sections of the demonstrator dipole cable.

FIGURE 5 shows three-side views of the annealed and non-annealed keystoned cables, and FIGURE 6 the non-annealed rectangular and keystoned cable.

The results of the cable microstructural study are shown in TABLE 6. The effect of annealing the rectangular cable before the keystoning step can clearly be seen in the substantial difference in internal strand damage between the annealed and non-annealed keystoned cable. It should also be observed, that the merging effect is enhanced by the processes occurring during the Nb_3Sn reaction.

TABLE 6. Strand damage analysis using six cross sections for each cable.

Type	HT	No. of damaged strands/ cross section	No. of broken SE/ cross section	No. of merged SE/cross section	No. of damaged SE/cross section
R	N	0	0	0/0	0
R	Y	0.17	0.33	0	0.33
K	N	0.67	2.5	0.83	2.5
K	Y	1	2.2	2.33	2.67
K[a]	N	-	-	-/ -	-
K[a]	Y	0.33	0.5	0.3	0.5

[a] Rectangular cable was annealed in Argon at 180 C° for 1 hr.

FIGURE 6 shows the electrical characterization at 4.2 K of strands extracted from the annealed and non-annealed keystoned cables as a function of magnetic field compared to the round strand results. The average I_c cabling degradation at 12 T of the non-annealed cable was negligible, and its average RRR was 150. The average I_c at 12 T of the annealed cable was actually 7% larger than that of the round wire, and its average RRR was 213. These results are consistent with the microstructural analysis, and have led to include an intermediate annealing step to the rectangular cable stage in the cabling procedure.

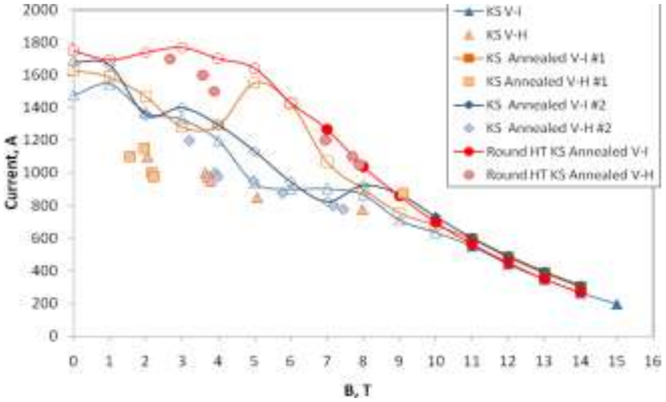

Fig. 6. V-I and V-H tests at 4.2 K of strands extracted from the annealed and non-annealed keystoned cables compared to round strand results.

V. CONCLUSION

The 40 strand Rutherford-type cable based on RRP-108/127 0.7 mm strand and with PF~86% for the 11 T Nb_3Sn demonstrator dipole magnet has been developed at FNAL. The cable fabrication procedure consists of two steps with an intermediate anneal. Cable samples with rectangular and keystone cross sections, and with and without a SS core were fabricated and successfully tested. The I_c cabling degradation was always less than 3.5%. A single 440 m long piece of cable has been fabricated providing two ~200 m long unit lengths for demonstrator dipole coils and ~25 meters of cable for short sample studies.

ACKNOWLEDGMENT

The authors thank M. Bossert and A. Rusy for technical assistance during cable fabrication and tests.

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