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Development of Rutherford-type Cables for High Field Accelerator Magnets at Fermilab

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***Abstract*—Fermilab's cabling facility has been upgraded to a maximum capability of 42 strands. This facility is being used to study the effect of cabling on the performance of the various strands, and for the development and fabrication of cables in support of the ongoing magnet R&D programs. Rutherford cables of various geometries, packing factors, with and without a stainless steel core, were fabricated out of Cu alloys, NbTi, Nb_3Al, and various Nb_3Sn strands. The parameters of the upgraded cabling machine and results of cable R&D efforts at Fermilab are reported.**

***Index Terms*—cabling machine, critical current degradation, superconducting strand, Rutherford cable.**

I. Introduction

RUTHERFORD cable has played a key role in establishing NbTi accelerator magnet technology, widely used in modern high energy accelerators thanks to its excellent mechanical, electrical and thermal properties. Superconducting (SC) dipoles and quadrupoles based on this cable design were successfully used in the Tevatron, HERA, RHIC and LHC. A new generation of accelerator magnets being developed at Fermilab [1], other U.S. Laboratories [2], and in Europe [3] is using Rutherford cables based on Nb_3Sn strands. The work on Rutherford cables based on some other superconductors, such as Nb_3Al and BSCCO-2212, for future accelerator magnets is also in progress [4], [5].

The SC cable R&D program at Fermilab focuses on two important issues: the study of the effect of cabling on the performance of the various strands (design, materials), and the development and characterization of cables in support of the ongoing magnet R&D programs. The availability of a cabling facility is an important part of this effort as it allows a faster turnaround with respect to using cabling facilities in industry, which are more oriented towards large scale cable production. A few years ago Fermilab purchased a compact cabling machine and re-spooler developed and fabricated at IHEP (Protvino) [6]. The capability of these machines was originally limited to a 1 mm strand and a 28-strand cable, which was used in the first Nb_3Sn dipole models [7]. Since then, the machine was significantly upgraded to meet the growing needs of the conductor and magnet R&D programs. This paper reports on the status of the cabling facility and presents the most recent results of cable R&D performed at Fermilab.

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II. Description of Cabling Facility

The cabling facility consists of a compact cabling machine, re-spooler, sets of forming fixtures and measuring devices. Operations include re-spooling of strands from the vendor to the cabling machine spools, transposition of strands into a cable and forming of the cable with a rectangular or keystone cross-section, control of the cross-section size under small compression, and cable spooling onto the pick-up reel.

After purchase, the cabling machine had only one motor, which provided motion to the main 28-spool wheel with its planetary mechanism, to the caterpillar, and to the cable spooler. The synchronization of these various systems was provided by several gear boxes. The gears were designed for a 28-strand cable made of 1 mm strand with a fixed 14 degree transposition angle. The forming fixtures and the measurement devices were also designed for these cable specifications. To expand the range of cable designs the machine kinematics was later upgraded. These upgrades included the development and installation of a new 42-spool wheel, independent motors to move main wheel, caterpillar and cable spooler, new electronics and software for motor synchronization, and a more sophisticated cable size control.

The new 42-spool wheel was developed, fabricated and installed by experts from IHEP (Protvino). The new wheel was designed to fit into the same space occupied by the previous 28-spool wheel. The wheel capacity was increased thanks to using slightly smaller spools and a better compaction of the wheel components. A picture of the new 42-spool wheel after installation on the cabling machine is shown in Fig. 1.

Four motors were used to deliver the motion directly to each system, eliminating the need for mechanical gears and drive trains. Motor synchronization is based on servo motor systems. The speed and position of the various systems is controlled with a PLC controller. The caterpillar motor has a servo driver that is set in an "electronic gearing follower" mode. In such mode, the driver controls the motor position as a function of the signal of an encoder placed next to the main wheel. This signal is multiplied by a gearing ratio parameter that is fed directly into the driver itself. The pickup spool synchronization is controlled by the PLC. The use of the independent synchronized motors instead of gears eliminated the problem of backlash and mechanical wear, resulting in a precise and repeatable control, and reducing machine maintenance. The cabling machine parameters after the upgrades are summarized in Table 1.

TABLE I. CABLING MACHINE PARAMETERS.

Parameter	Value
Number of strands	42
Strand diameter range	0.3-1.5 mm
Planetary ratio	0, +1, -1
Main engine power	1.34 kW
Maximum wheel speed	40 rpm
Maximum strand tension	30 N
Maximum cable pulling force	5000 N
Spool size DxdxH	150x96x105 mm
Cable reel size DxdxH	400x260x175 mm

The re-spooler had been designed to perform strand re-spooling and cutting to length. To reduce the risk of strand breaks during cabling, re-spooling is performed under a tension provided by two driving drums kinematically connected by the magnetic clutches. The main re-spooler parameters are shown in Table 2. The re-spooler was later equipped with a motor and driver to synchronize spool motion and obtain an adjacent turn-to-turn placement for strands in an ample size range.

TABLE II. RE-SPOOLER PARAMETERS.

Parameter	Value
Strand diameter range	0.3-1.5 mm
Re-spooling speed	10-120 m/min
Tension in the controlled section	50-350 N
Take-up and supply tension	20-50 N
Spool weight capacity	32 kg
Drive motor power	0.23 kW

The machine uses ~90 mm long mandrels (Fig. 2), optimized to reduce friction and provide good strand stability during cabling [8]. For fabrication of cables with a core, the mandrels used in this case have grooves machined on the upper flat surface of mandrel [9]. A flexible mandrel connection allows its self-aligning with respect to the cable forming fixture.

The primary forming fixture shown in Fig. 3 forms a cable with a rectangular cross-section and a low packing factor. It consists of two wide vertical rolls with variable gap, and of two thin horizontal rolls. The final precise keystone cross-section of a cable is formed using a two-roll die with variable gap, fixed keystone angle and cable width.

Cable thickness during fabrication is measured under a transverse compression using a device with a PC based data acquisition system for continuous control in the cabling process (Fig. 4). Typical variations of cable width and thickness along the length of a keystoned cable are ±0.011 and ±0.003 mm respectively. Work on a new cable size measurement system based on laser micrometers has been started.

Fig. 1. New 42-spool wheel installed in the cabling machine.

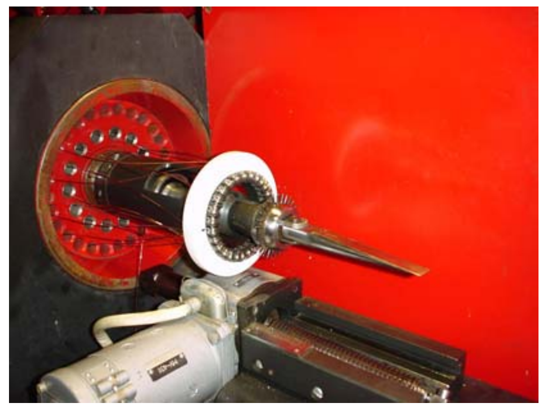

Fig. 2. Cable mandrel.

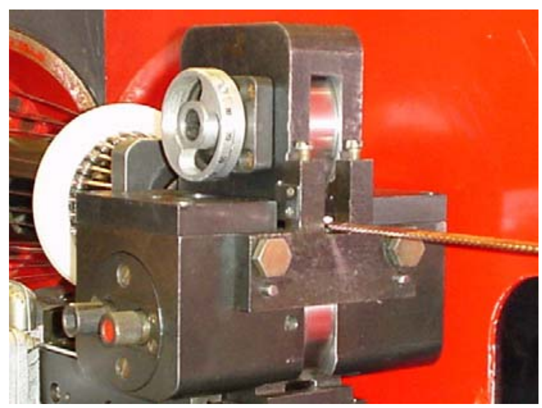

Fig. 3. Rectangular cable forming fixture.

Fig. 4. Cable sizing fixture and automatic measuring device.

III. Cable Fabrication and Studies

A. Pitch Angle Range Study

A study of the possible pitch angle range for Rutherford cables was started using 1 mm hard Cu strand and 28-strand cable design. Optimization of the cable pitch angle provides more mechanically stable cable and possibly lower critical current degradation due to less severe deformation of the wire at the edges of the cable [10]. 100 m of right-handed and left-handed cables with pitch angles between 9 and 19 degrees were fabricated. It was found that below 12 degree the cable shows mechanical instability and that at 16 degree popped strands, sharp edges and crossovers occur. Crossovers appeared and disappeared with a good reproducibility with the pitch angle. This study was performed also using 27 and 39 strand cables made of 0.7 mm Cu Alloy68 strand. In this case the stable range of transposition angles was within 9-16 degrees. A study of the pitch length on the strand critical current degradation will follow.

B. Strand Number Optimization

Two keystoned cables with 27 and 28 strands, using 1 mm NbTi strands were fabricated to study the effect of even and odd number of strands in a cable of same cross-section. Analysis and comparison of these two cables demonstrated that, although the cable with an odd number of strands has a slightly smaller packing factor, it remains mechanically stable and has a smaller value and variation of the minor edge compaction. The analysis of sub-element deformation inside strands at the cable edges demonstrated better results for the cable with odd number of strands.

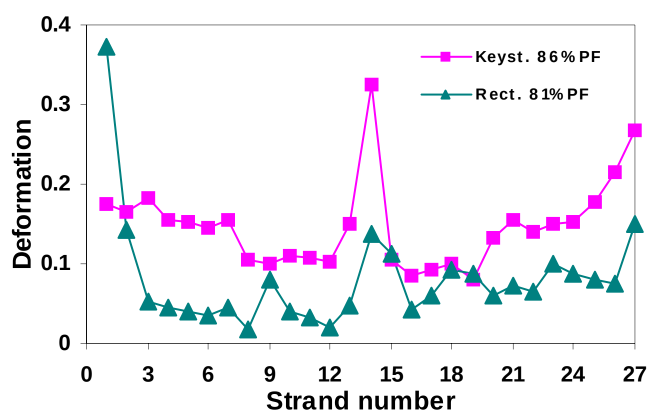

Fig. 5. Strand deformation as a function of position in 27-strand cables.

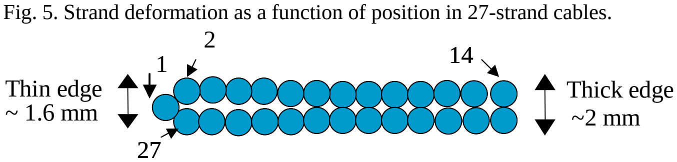

Fig. 6. Scheme of the strand numbering used in a cable.

C. Strand Deformation

Fig. 5 shows the deformation of each strand as a function of its location in the cable (Fig. 6) in a keystoned and rectangular 27-strand cables made of 1 mm Nb_3Sn strands produced using the Restack Rod Process (RRP) (see also *Section III.D*). The definition that was used for strand deformation is:

$$Deformation=(d_{max} - d_{min})/ d_0,$$

where d_{max} and d_{min} are the longest and shortest diameters measured through the strand center, and d_0 is the original round strand size. Within the limited statistics, there is already an indication that in both cables the largest deformation values are found at both cable edges. The average strand deformation is lower in the least compacted cable. However, despite this cable being rectangular, its end strands saw even larger deformation values than their keystoned counterparts. These results are so far consistent with critical current degradation in Nb_3Sn depending on packing factor [11]. Continuing these studies on more cable sizes and geometries will allow determining empirical laws correlating packing factor with average strand deformation in a cable, and to establish an upper limit for the keystone angle.

D. RRP 108/127 Cable Fabrication and Test

Based on the results of strand number optimization, a 70 m piece of keystoned 27-strand cable with 1 mm RRP strands of 108/127 sub-element design was fabricated, and round and extracted strands were tested. A small racetrack and a cos-theta half-coil were fabricated using ~15 m and ~50 m long pieces of this cable. The small racetrack was tested and reached its predicted short sample limit [12]. More recently, a 300 m long piece of this cable was fabricated for a 4-m long cos-theta coil [14].

E. Nb_3Al Cable Development

Feasibility studies of Nb_3Al Rutherford cable based on a strand produced using the Rapid Heating-Quenching Treatment (RHQT) process and stabilized with Cu with the ion deposition method were performed in collaboration with NIMS (Japan). First, a ~60 m long piece of 27-strand Nb_3Al/NbTi hybrid cable, with both rectangular and keystoned cross-sections, was fabricated. Studies of this cable provided feedback to NIMS that helped improving the strand design and coating procedure. Then a ~30 m piece of rectangular 27-strand Nb_3Al cable with 83% to 90% compaction was fabricated (Fig. 7). The round and extracted strands, and cable samples that were tested showed small cabling degradation. A small racetrack based on Nb_3Al cable and the wind-and-react method was fabricated and successfully tested [13].

Fig. 7. Rectangular Nb_3Al cable with 83% packing factor.

F. PIT Cable for Nb_3Sn Magnet Technology Scale Up

The Nb_3Sn accelerator magnet technology scale up program at Fermilab uses 2-m and 4-m cos-theta dipole coils [14] made of cables with Nb_3Sn strands produced by ShapeMetal Innovation (SMI) based on Powder-in-Tube (PIT) technology. The 1 mm strands used for the 2-m long coil include billets 187 to 193 (4.7 km total length) with 192 filaments. A similar strand was used in 1-m long 10 T dipole models developed at

Fermilab [14]. A new PIT strand design (billet 207) with 288 filaments and larger critical current density was proposed by SMI for use in the 4-m long coil. A 50-m long strand sample of this billet was used for round strand test and for fabricating a 27-strand cable together with strands from standard billets 187 to 193. The two different strand designs were tested and compared round, and after cabling. Some of the results including critical current I_c, n-value, instability current I_s and RRR of the round and extracted strand tests are presented in Table III.

The J_c(4.2K,12T) of billets 187 to 193 ranged from 1.8 to 1.9 kA/mm^2. As expected, the J_c(4.2K,12T) of billet 207 was about 10% higher, reaching 2.1 kA/mm^2. However, after reaction, several Sn bursts were found on the extracted strand edges from billet 207. No Sn bursts were found on extracted strands from billets 187 to 193. The critical current degradation of billet 207 ranged between 21% and 31% at 12 T. The I_c degradation at 12 T of billets 187 to 191 ranged between 4.4% and 6.8%, i.e. similar to that of the strands used in the model magnets. The causes of the Sn bursts and larger degradation in the new PIT strand need to be understood before using it for the Nb_3Sn technology scale up.

TABLE III. EXTRACTED STRAND TEST RESULTS AT 4.2 K

Strand ID	Sample	I_c(12T), A	n(12T)	I_s(A), A	RRR
187	Round	715	40	>1775	268
	Extracted	673	-	>1750	255
190	Round	679	40	>1775	344
	Extracted	649	45	> 1775	294
191	Round	708	47	> 1750	363
	Extracted	660	-	-	279
207	Round	823	47	>1775	212
	Extracted	652	-	1400	95
	Extracted	652	-	1350	167

Note: 1800 A is the Power Supply maximum current

G. Cable for LARP Magnet R&D.

Tools to produce the cable used in LARP technology quadrupoles (TQ) and long quadrupoles (LQ) were developed and tested at Fermilab. Cable fabrication and measurement tooling was developed for two cable designs with keystone angles of 0.9 and 1.3 degree. The cable development was performed in two steps. First, for each keystone angle practice cables with 27 and 28-strands were fabricated using 0.7 mm hard Cu to optimize the cable geometry. Then, cables of the same designs were fabricated out of Nb_3Sn RRP and Modified Jelly-Roll (MJR) strands. The MJR strand had been used in the first LARP quadrupole models.

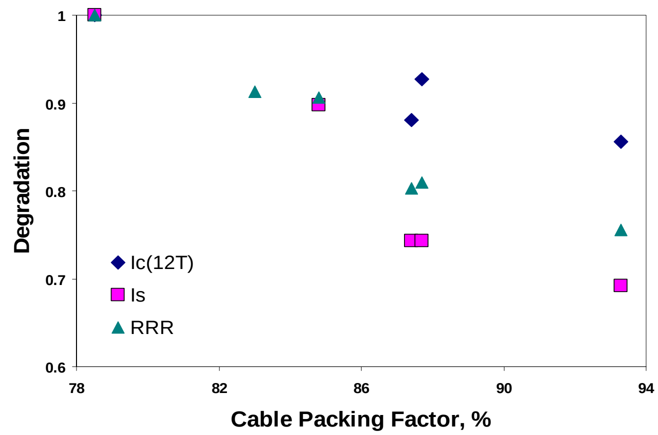

Fig. 9. Cabling degradation at 4.2 K for nominal TQ cable at 12 T and 4.2 K.

The cabling degradation of strand parameters relative to those of the virgin strand is shown in Fig. 9 as a function of the cable packing factor for TQ cables with 27 and 28 MJR strands and keystone angle of 0.9 degree. The measured I_c, I_S and RRR degradation was the same as that of similar cables fabricated at LBNL [15].

IV. CONCLUSIONS

Fermilab's cabling facility has been upgraded and commissioned to a maximum capability of 42 strands. The performance of new RRP and PIT Nb_3Sn strand designs with larger number of sub-elements (filaments), and of Nb_3Al strand was tested with respect to the cabling process. This provided feedback to strand vendors. Production included cables for the Nb_3Sn technology scale up and short model programs at Fermilab. This cabling facility can now be used as a second cable production line for LARP magnet R&D.

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