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Cable R&D for the LHC Accelerator Research Program

Daniel R. Dietderich, Emanuela Barzi, Arup K. Ghosh, Nathan L. Liggins, and Hugh C. Higley

***Abstract*—Future luminosity upgrades for the LHC at CERN will require higher field magnets than those presently being utilized. The US LHC Accelerator Research Program (LARP) is addressing this need with the design and fabrication of prototype quadrupole magnets utilizing Nb_3Sn technology. A part of the R&D effort is the development of suitable cables for the magnet designs being considered by LARP. The cable parameter limits for LARP prototype and production cables are presented. At present the standard strand for LARP is the Restack Rod Processed (RRP) strand being produced by Oxford Superconducting Technologies. The present strand has 54 sub-elements and 53% Cu. An optimal cable for the first generation of LARP quadrupole magnets has a width of 10 mm, thickness of 1.26 mm, and a keystone angle of 1 degree. This work shows that if a strand is properly cabled a nearly degradation-free mechanically-stable cable can be produced.**

***Index Terms*—Accelerator magnets, Nb_3Sn, Rutherford superconducting cables.**

I. Introduction

MAGNETS for High Energy Physics (HEP) applications require the highest critical current densities to obtain the highest magnetic fields. To that end, the Rutherford laboratory in England developed a rectangular cable that bears its name [1]. The "rectangular" geometry of the cable provides both the highest packing density, also called packing or compaction factor, of the strand and provides the flexibility for winding coils of various types, $\cos\theta$, $\cos 2\theta$, and racetracks coils.

For over 15 years the Superconducting Magnet Group of Lawrence Berkeley National Laboratory (LBNL) has been fabricating rectangular and keystone cables. During this time over 900 cables of Nb_3Sn, NbTi, and Bi-2212 have been produced. Some were very long lengths, while others were only short prototypes. This paper summarizes the experience at LBNL, presents guidelines for the fabrication of damage-free cables, and places this experience in context of the LHC Accelerator Research Program (LARP).

II. Cable Design

The development of a cable for a magnet is an iterative process. The magnet designer proposes a cable for a particular magnet design. These initial parameters (i.e. number of strands, strand diameter, cable width, cable thickness and keystone angle) are used as a starting point for prototype cable development. The initial parameters are modified so that a mechanically stable cable is obtained for winding that also has minimal, or no critical current degradation.

The LARP cable design is based on some empirical guidelines developed over the years at the DOE-HEP laboratories. Recently LBNL has established certain guidelines when making Rutherford cables from strand of internal-tin or powder-in-tube wire. Due to the difference in mechanical properties of the wire components, i.e. core materials (i.e. Sn or Sn alloy or Nb-Sn powders) and the Nb-Cu matrix, they cannot be deformed to the same extent as NbTi strand. Cables made of Nb_3Sn strand always (except perhaps for Nb_3Sn bronze-processed wire) need to be made wider than cables made of NbTi strand for the same cable parameters (i.e. number of strands, strand diameter, cable pitch length).

By shearing the strand the Sn cores can leak Sn and contaminate the Cu stabilizer or worse, have a molten Sn leak that shorts several turns of the coil. There is some experimental evidence at FNAL that highly sheared strands can have merged sub-elements after heat treatment and produce strand with larger effective filament diameter (D_{eff}) that are more unstable. This results from the sub-elements coming into contact from excessive deformation and then sintering during heat treatment. To overcome any issue with strand stability, for the present, LARP has elected to heat treat coils at low temperature for short times to limit the Sn diffusion out of the sub-elements into the copper stabilizer that could impact magnet performance.

III. Cable Parameter Determination

LBNL has developed a simple empirical formula for determining an acceptable cable dimensions for the odd strand configuration. This strand configuration in Fig. 1 is the widest section of the cable and it is from this that the ideal "theoretical width" (W_{th}) is calculated in (1). The input for this calculation is the number of strands in the cable (N), the strand diameter (d), and the cable pitch angle (PA) [2]. The Width Parameter (WP) for a cable is defined by (2).

$$W_{th} = d * (N/2) * [\mathrm{Cosine}(PA)]^{-1} \quad (1)$$

$$WP = (w - W_{th})/W_{th} \quad (2)$$

A value of $WP > 0$ means that a cable has been fabricated wider than its theoretical width and the opposite is true for values of WP less than zero.

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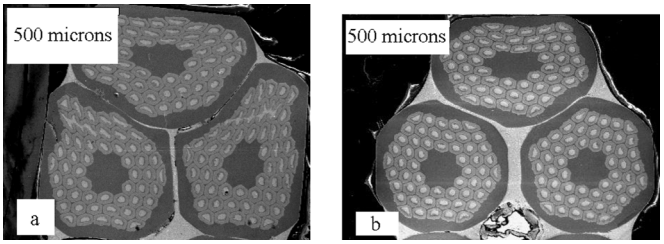

Fig. 1. Cross-sectional image of the 3 strands at the thin (minor) edge of two different cables: (a) Cable 939R with sheared sub-elements observed in at least two of the three strands; (b) cable 946R with no sheared sub-elements.

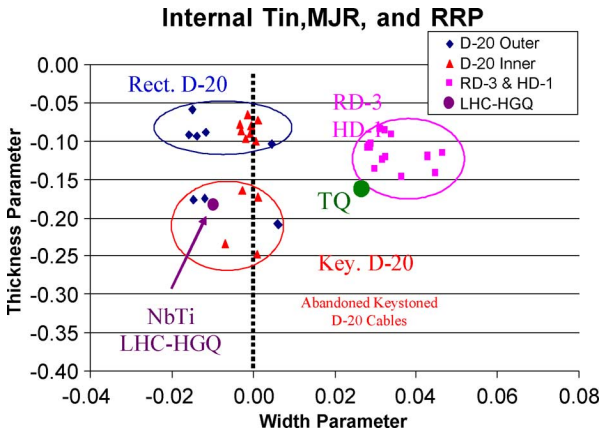

Fig. 2. Plot of the thickness parameter vs. the width parameter of cable fabricated at LBNL.

For NbTi strand, and perhaps a Nb_3Sn bronze-process strand, one can deform the strands more since the strands are more tolerant to deformation. For NbTi strands one is mainly concerned with eliminating, or reducing, the number of broken NbTi filaments during the cabling process. This is still a concern for Nb_3Sn strands but there is the added concern for Nb_3Sn strands produced by internal-tin type processes; one must not shear the sub-elements and rupture the diffusion barriers of the wire. The Sn-rich core gives these types of strands different mechanical properties than NbTi. Therefore, when designing cables for strands with Sn or powder cores, such as the powder-in-tube (PIT), one must use the more conservative, out of phase configuration, shown in Fig. 1. This reduces the edge deformation but may make the cable less mechanically stable for winding coils.

Even within the same strand family (internal-Sn and PIT), variations in mechanical properties occur. This requires that one use these initial cabling parameters as the first iteration in fabricating a cable for a magnet and then finalize the magnet dimensions. For years LBNL, and others, have used the overall compaction of a cable as a guide for its fabrication. However, this does not provide guidance regarding the deformation of the width relative to the thickness. The deformation, i.e. strain, in the two dimensions must be decoupled as it is in Fig. 2. With the early keystone cable R&D runs for magnet D-20, and its final production cable runs, the importance of the deformation at both the major and minor edges of the cable began to be recognized [3]. By making a cable too narrow, strands at both edges of the cable can be highly deformed, and thus severely damaged.

Recently LBNL has been separating the thickness from the width deformation in place of using the overall compaction of a cable in determining the final dimensions of a cable. The overall compaction is still useful in terms of determining how efficiently the cable is packed.

TABLE 1
TQ CABLE PARAMETERS

Parameters	Units	TQ Cable	Tolerance
Strands in cable	No.	27	NA
Strand diameter	mm	0.7	+/- 0.002
Width	mm	10.077	+0.000, -0.100
Thickness	mm	1.26	+/- 0.010
Keystone angle	deg.	1.0	+/- 0.10

If one adds the inner cable of the LHC High Gradient Quadrupole that is made of NbTi to the plot of Fig. 2 one sees that it is in the lower left corner of the graph. The NbTi strands in this cable can undergo more strain without severe damage than the high-J_cNb_3Sn strands.

IV. LARP CABLE SPECIFICATIONS

The early prototype cables for the LARP quadrupole magnets were made with 26, 27 and 28 strands and keystone angles of 1.0 and 1.3 degrees [4]. Based on the results of these earlier cables, we chose to use 27 strands with a keystone of 1.0 degrees. The present cable parameters for the magnets are given in Table I.

V. CABLING PROCEDURES

In order to improve the mechanical characteristics of the cable for magnet winding and to remove part of the contraction that a cable undergoes during heat treatment LBNL has implemented a double rolling procedure for our last several magnets [5]–[7]. The initial cable is fabricated to the desired width but made 50–75 microns oversize in thickness. After the cable has been annealed at 200 C for 4-6h the cable is rolled to the desired thickness. This procedure has two functions: The cable contracts by 0.20–0.25% removing about half of the overall contraction that the cable will undergo during a complete heat treatment cycle due to release of tensile strain in the Nb filaments in the Cu matrix [8], [9]. This reduces the dimensional changes that would take place during coil heat treatment. The second is to give the cable a higher overall compaction (an increase of 2–3%) after a re-rolling step such that the cable critical current density is increased slightly. However, more importantly it provides a more mechanically stable cable for magnet winding due to better interlocking of the strands.

The recent cables made for LARP are listed in Table II. All of the cables were production runs except 933R, it was a short R&D run.

Even though cable 939R (Table II) was made within the specifications listed in Table I the cable had edge damage. After this was observed the re-rolling procedure was modified with the vertical rolls being made 0.050 mm wider. This would ensure that during re-rolling the edge would not be over compacted. Since the cable increases in width and thickness during the annealing step the wider rolls will only deform the cable back to the original rolling width and not more. This is important since friction between the vertical rolls and the strands prevent the edge load from being transferred to the strands in the center of

TABLE II
STRAND AND CABLE PARAMETERS

Cable No.	Billet No.	Strand Dia. (mm)	Thick. (mm)	Width (mm)	P.L. (mm)	K.A. (deg.)
928R	205, 206, & 208	0.703	1.264	10.056	78.0	1.05
933R	8220	0.703	1.267	10.042	78.7	1.09
939R	8220	0.703	1.262	9.993	80.5	1.04
940R	8647	0.704	1.264	10.026	80.5	0.98
946R	8781	0.705	1.266	10.062	79.5	1.00
947R	8857	0.705	1.265	10.061	79.3	1.01

P.L. is pitch length, K.A. is keystone angle

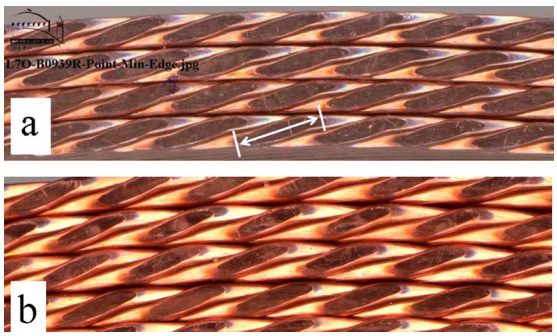

Fig. 3. (a) Facets on the strands at the thin edge of cable 939R. (b) Facets on the strand at the thin edge of cable 946R. The facet size is defined as the length of the long axis of a facet, as shown in (a).

the cable, and as a result, the strain is concentrated to the three strands at the edge of the cable.

VI. LARP TQ CABLE ANALYSES

A. Edge Facet Analyses

During cabling the greatest source of strand damage is at the edge of the cable. Analyses of the size of the edge facet on the strands at the edge of the cable, images in Fig. 3, can quantify the deformation (i.e. strain) of the strand without requiring preparation of a metallographic sample to obtain cross- sectional images like those in Fig. 1. A histogram with the facet size (i.e. length of the long axis of the facet) of several LARP TQ cables is shown in Fig. 4. One can see a direct correlation between the size of the facet on the surface of the cable and the internal deformation of the strands; the larger the facet the greater the shearing deformation.

Fig. 1 shows the cross sections of two of the cables (939R and 946R) shown in the facet size plot of Fig. 4. These two cables are keystone cables made for the LARP technology quadrupole (TQ) magnets. Cable 939R and 946R both met the LARP cable specification in Table I, but cable 939R was excessively deformed at the thin edge and under deformed at the thick edge. The exact cause of this asymmetric deformation has not been determined. However, cable 939R is the narrowest of all of the cables and it was re-rolled to a width 33 microns narrower than it was fabricated. Cables 946R and 947R were fabricated with wider rolls for the second rolling step. This produced some of the smallest facets of the cable set, and the re-rolled cable width was 28 micron larger than it was fabricated.

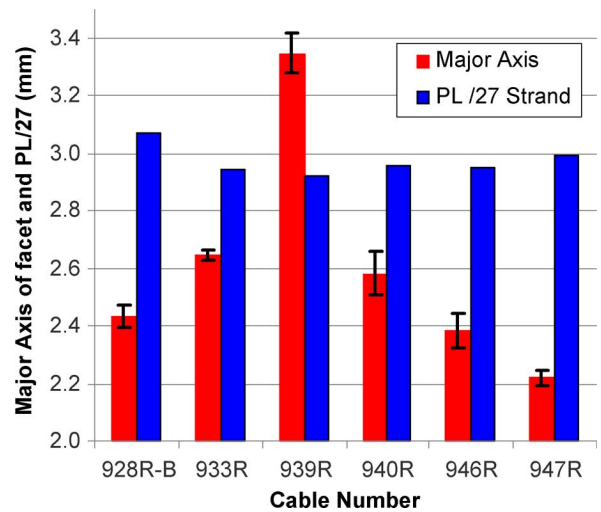

Fig. 4. Histogram for LARP cables showing the length of the major axis of the facet on the thin edge of cables (on the left) along with the pitch length per strand measured between facets (on the right). The bar on each major axis column denotes one standard deviation.

Cable 933R, an R&D run, also showed some evident of sheared sub-elements. It was made within the LARP specification but the keystone angle was near the top of the range at 1.09 degrees. This could introduce damage at the minor edge of the cable. The two cables that showed evidence of damaged sub-elements were 933R and 939R and they were both fabricated from the same billet, 8220.

B. Critical Current and Cabling Deformation

First, we estimate cabling degradation by comparing round strands and strands extracted from cables, both of which are given the same reaction which typically is 210 C for 72 h plus 400 C for 48 h plus 640 C (+/−2 C) for 48 h. Most cables with the exception of 939R show I_c degradation at 12T $\sim$ 0–3%. For 939R, extracted strands were difficult to test with all strands quenching below I_c. Using I_c values extrapolated from the small onset voltages, showed that the strand I_c of the extracted strand was 5% lower than those of round wires. However, for some cables, a determination of the degradation was not possible since the round and extracted strands were not given the same heat treatment. An in depth discussion of the data can be found in the paper by Barzi *et al.* published in these proceedings [10].

Strand from cable 939R was more unstable during I_c testing. The reduced stability of the wire must be due to the rupture of the diffusion barriers of several sub-elements at the minor edge. The barrier damage leads to an increase in the resistivity of the Cu locally with an accompanying loss of dynamic stability. The other possible cause for reduced stability may be the formation of a "super-element" with two or more of the sub-elements sintering forming a large effective sub-element. This will be discussed more in the following section on strand stability.

C. Strand Stability and Cabling Deformation

In prior papers by several of the authors it was shown that a strand stability current (I_s) is a strong function of RRR regardless of the sub-element size [11]–[14]. These showed that

I_s was weakly dependant on the sub-element size. The dynamic stability obtained by decreasing the copper resistivity (i.e. increasing RRR) was 1–2 orders of magnitude larger than the effect of sub-element size. However, there is the risk during cabling that large deformations will shear strands and produce bridged sub-elements with an effective diameter a factor of 2 or 3 larger. Fig. (1a) shows a highly deformed stand that has the potential to produce a "super-element". The severely deformed strand should be avoided during cabling. The cabling parameters should be modified to prevent such a high strand deformation.

The stability current drops significantly with the increase in edge damage of the strand. The I_s of cable 939R dropped by about 50% from the round strand value. This is much larger than all of the other cables which typically decreased by only 10% [10]. The large reduction in I_s suggests that a super-element may have formed or the local RRR was too low, or both aspects could be contributing.

VII. Conclusions

Development of the cabling parameters for LARP has shown that the most important aspect of cabling strands of Nb_3Sn is the width deformation at the edge of a cable. Severe strand damage at the edge of one cable (939R) reduced the critical current by ~5%, while all of the other cables had a negligible I_c reduction of 0–3% which is within the measurement error. Moreover, the damage in cable 939R produces a significant reduction (~50%) in the stability current of the extracted strand relative to the round strand. The facet size on strands at the edge of cable provides a direct measure of the amount of deformation that a strand has undergone and an indicator of the amount of sub-element distortion that has occurred in the interior. This work shows that if a strand is properly cabled a nearly degradation-free mechanically-stable cable can be produced.

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