Nb_3Sn Wire Layout Optimization to Reduce Cabling Degradation

Stefania Farinon, Thierry Boutboul, Arnaud Devred, Daniel Leroy, and Luc Oberli

***Abstract*—The Next European Dipole (NED) activity is aimed at the development of a large-aperture, high-field superconducting magnet relying on high-performances Nb_3Sn conductors. Part of the NED program is devoted to the mechanical study of a new generation of Nb_3Sn wires and to predict and describe their behavior under the severe loading conditions of the cabling process. A Finite Element modelization of Nb_3Sn wires was developed, allowing the wire behavior under simple uni-axial loads to be described. In this paper, the mechanical performances of different strand configurations are compared. The external diameter of the wire being fixed, several parameters are taken into account: the total number of sub-elements, the composition of the sub-elements, the local copper-to-non-copper ratio, the number of copper cells in the central region. The aim is to isolate the influence of each parameter on the Nb_3Sn wire deformations, trying to find an optimum design minimizing cabling damages.**

***Index Terms*—FE analysis, Nb_3Sn wires, NED.**

I. Introduction

THE NED project is one of the Joint Research Activities (JRA) approved by the EU in the framework of the Coordinated Accelerator Research in Europe (CARE) program [1] in view of developing high field accelerator magnets in Europe. The goal of the R&D program to be pursued in collaboration with European industry is to fabricate long lengths of 1.25 mm diameter Nb_3Sn strands having a critical current density of 1500 A/mm^2 at 15 T and 4.2 K in the non-copper part, with sub-elements of 50 μm diameter and an overall copper-to-non-copper ratio of 1.25. This leads to a critical current of 818 A at 15 T and 4.2 K. Two types of technology are being pursued: the Powder In Tube (PIT) and the Internal Tin (IT). In both routes, the Nb_3Sn phases are surrounded by a Nb alloy tube.

To achieve the ambitious goal in current density, a significant volume percentage of the Nb tube, which is also a barrier to Sn diffusion into the copper, must be reacted to produce Nb_3Sn. Then, it is necessary to avoid excessive deformation which could lead to interpenetration or even breaks of the Nb barriers, especially during the cabling process, which occurs before the final Nb_3Sn phase formation. At the edge of the Rutherford-type cable, the local strand deformation, defined as the strand diameter reduction normalized to the initial diameter, has been estimated to be 20–30%. In order to assess the barrier integrity in the various strand designs, a flat deformation of 28% is regularly applied on each manufactured NED strand by passing it through rollers. Micrographs of the deformed strand are then analyzed in a visual way.

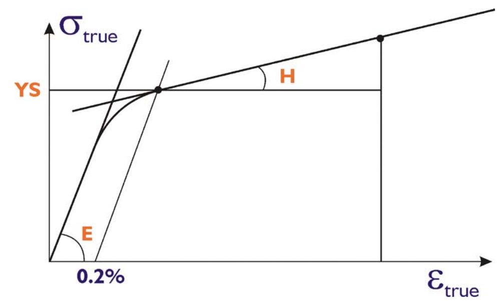

Fig. 1. Bilinear stress-strain curve used to represent the plastic behavior of the materials composing the wires.

In a previous report, a Finite Element (FE) model was developed successfully for PIT strands [2]. In this work, FE calculations, using the same material mechanical properties as for PIT [3], have been undertaken to study the mechanical behavior of various IT strand configurations under deformation, in order to select the most robust design, without manufacturing real wires for each design. In these calculations, the effect of some important parameters, like the total number of sub-elements, the sub-element spacing, the niobium barrier thickness and the amount of copper in the wire core, was investigated.

II. FE Methodology

To study the mechanical behavior of a Nb_3Sn wire subjected to a severe plastic deformation, a general Finite Element (FE) methodology, using the FE code ANSYS [4], was assessed in a previous work [2] related to the PIT conductor as already mentioned. The developed FE methodology uses the following characteristics.

- A suitable representation of the mechanical material properties by a bi-linear stress-strain curve, as shown in Fig. 1. It is the simplest description of a complex plastic behavior in which no Ultimate Stress limit is prescribed.
- A 2D plane strain option, representing infinitely long structure with zero strain in the longitudinal direction, is the best compromise between run time and precision of results. It means that the transverse deformations and the 2D-plane strain components will be slightly overestimated.

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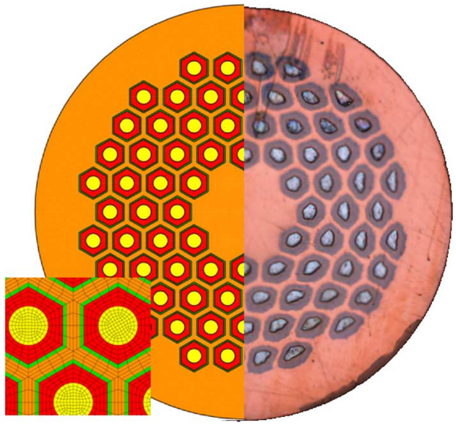

Fig. 2. ALSTOM/NED 085/07 Nb_3Sn internal tin wire shown together with its FE model and a mesh enlargement. White (yellow) represents tin, light grey (orange) is copper, grey (green) is the Nb barrier around each sub-element and dark grey (red) is a homogenized material representing the Nb-7.5wt.%Ta filaments in Cu matrix. The wire diameter is 1.25 mm.

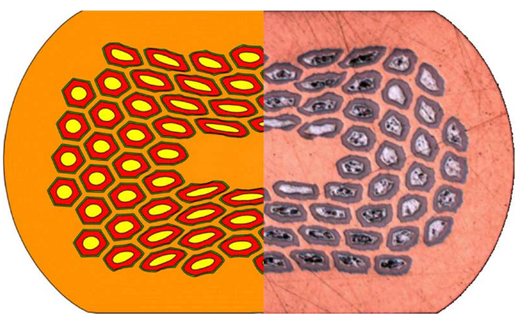

Fig. 3. ALSTOM/NED 085/07 Nb_3Sn internal tin wire after a 28% reduction in diameter. The observed deformation is shown together with the FE analysis result. The FE model was rotated clockwise by 25° with respect to Fig. 2.

- An ANSYS element (PLANE182), which is able to handle plasticity, large displacements and large strain variations, is used.
- Between the different elements used in the simulations, a perfect bonding is assumed, and neither sliding nor separation is allowed.

Finally, the loading of the FE model has been represented by using, in the ANSYS code, two rigid and parallel planes in contact with the external surface of the wire. Whilst one of the planes is kept fixed, the other is gradually lowered, resulting in a uni-axial displacement of the wire in the vertical direction as illustrated in Figs. 2–3.

III. Wire Model

The starting configuration is an IT wire manufactured by Alstom/MSA for NED and shown in Fig. 2. It is made up of 85 hexagonal sub-elements: 7 Cu hexagonal cells in the wire core and 78 superconducting hexagonal sub-elements around. Each sub-element is made up of Nb-7.5wt.%Ta filaments arranged in a pure-Cu matrix (called filamentary zone) around a Sn pool and is surrounded by a Nb diffusion barrier, which protects the stabilizing copper from Sn contamination. The left part of Fig. 2 shows the FE model for this analysis; it is made up of 4 different materials: copper is represented in light grey (orange), the Nb barrier in grey (green), the tin source in white (yellow), and finally dark grey (red) is a homogenized material representing the filamentary zone.

IV. FE Analysis Assessment

In our previous work [2], the adequacy of the FE modeling was demonstrated by simulating an SMI/NED PIT wire and also a 19 sub-element Alstom/CEA Internal Tin wire having a collective Nb/Ta barrier. Before investigating various IT wire configurations, the consistency of the FE model is verified by applying it to the existing 85 sub-element ALSTOM/NED wire described in the previous Section. The result after a 28% reduction in wire diameter is shown in Fig. 3, displaying side by side a cross-section of a deformed wire and the model-calculated deformation. The shapes of the sub-elements are in fair agreement between the model and the real case. Nevertheless, discrepancies can be observed in the non-hexagonal shape of the sub-elements on the left and right sides in Fig. 3, corresponding to the least deformed regions. These discrepancies are already observed in the un-deformed wire Fig. 2. Indeed, the heavy cold drawing process in the wire manufacture induces alteration of the sub-element shape from their original hexagonal one. However, this does not affect significantly the agreement in the most critical regions, i.e. where the sub-elements are more distorted.

V. Results and Discussion

A. Parameters of Comparison

An extensive FE calculation campaign has been launched for IT strands, taking into consideration several geometrical parameters: the number and dimension of the sub-elements in the wire, the copper core size, the niobium barrier thickness and the local copper-to-non-copper ratio.

For the results interpretation, a major difficulty was the identification of significant indicators reflecting the status of the deformed wire. In fact, many parameters, like the aspect ratio of sub-elements, peak or average Von Mises stress, plastic energy density, do not appear very sensitive, to enable a clear distinction of the various configurations. However, parameters related to the thickness of the Nb barriers around the sub-elements were found to be particularly relevant and are used to compare various designs. Indeed, when the Nb barriers are too thin, there can be tin leakage and, eventually, fracture and merging of the sub-elements. The selected indicators, used in Tables I–III, are:

- *Minimum thickness of Nb barrier* (μm), which is the lowest value of the Nb barrier minimal thickness among all the sub-elements;
- *Minimum thickness of Nb barrier (%)*, calculated by dividing the minimum thickness of Nb barrier (μm) by the thickness of the un-deformed barrier;
- *Number of sub-elements with a minimum Nb barrier thickness of less than a particular threshold* (1, 2 or 3 μm);
- *Fraction of sub-elements with a minimum Nb barrier thickness of less than a particular threshold*, calculated by dividing the number of sub-elements with a minimum Nb barrier thickness of less than the threshold by the number of superconducting sub-elements in the wire.

TABLE I
MAIN RESULTS FOR THE REFERENCE CONFIGURATIONS AFTER 28% REDUCTION IN DIAMETER

	085/07	121/07	151/07	253/07	295/07
Undeformed sub-element diameter (μm)	89	74	66	51	47
Undeformed barrier thickness (μm)	3.8	3.2	2.8	2.2	2.0
Number of sub-elements with Nb barrier thinner than 1 μm	0	0	0	31	52
Fraction of sub-elements with Nb barrier thinner than 1 μm (%)	0	0	0	13	18
Min thickness of Nb barrier (μm)	1.6	1.3	1.1	0.8	0.7
Min thickness of Nb barrier (%)	43	40	39	34	34

TABLE II
253 AND 295 SUB-ELEMENTS CONFIGURATIONS WITH DIFFERENT Cu CORE SIZES AFTER 28% REDUCTION IN DIAMETER

	253/01	253/07	253/19	295/07	295/19
Number of sub-elements with Nb barrier thinner than 1 μm	42	31	18	52	42
Fraction of sub-elements with Nb barrier thinner than 1 μm (%)	17	13	8	18	15
Min thickness of Nb barrier (μm)	0.7	0.8	0.9	0.7	0.8
Min thickness of Nb barrier (%)	33	34	39	34	39

TABLE III
MAIN RESULTS FOR THE REFERENCE CONFIGURATIONS WITH DOUBLED/TRIPLED Nb BARRIER THICKNESS AFTER 28% REDUCTION IN DIAMETER

	085/07	121/07	151/07	253/07	295/07
Number of sub-elements with Nb barrier thinner than 2 μm	0 / 0	0 / 0	8 / 0	40 / 10	60 / 24
Fraction of sub-elements with Nb barrier thinner than 2 μm (%)	0 / 0	0 / 0	6 / 0	16 / 4	21 / 8
Number of sub-elements with Nb barrier thinner than 3 μm	8 / 0	25 / 4	42 / 14	127 / 73	172 / 95
Fraction of sub-elements with Nb barrier thinner than 3 μm (%)	10 / 0	22 / 4	29 / 10	52 / 30	60 / 33
Min thickness of Nb barrier (μm)	2.8 / 3.8	2.1 / 2.8	1.8 / 2.4	1.2 / 1.7	1.1 / 1.5
Min thickness of Nb barrier (%)	37 / 33	32 / 29	32 / 28	28 / 25	27 / 25

The first two parameters indicate the location of the most strained sub-element in the wire. The other two parameters can be considered as a sort of factor of merit of the overall behavior of the wire. The threshold has no special physical meaning; it is an arbitrarily fixed value which allows a relevant comparison among the various configurations. The chosen threshold values are 1 μm for the reference Nb barrier thickness, 2 μm for the double barrier thickness and 3 μm for the triple barrier thickness.

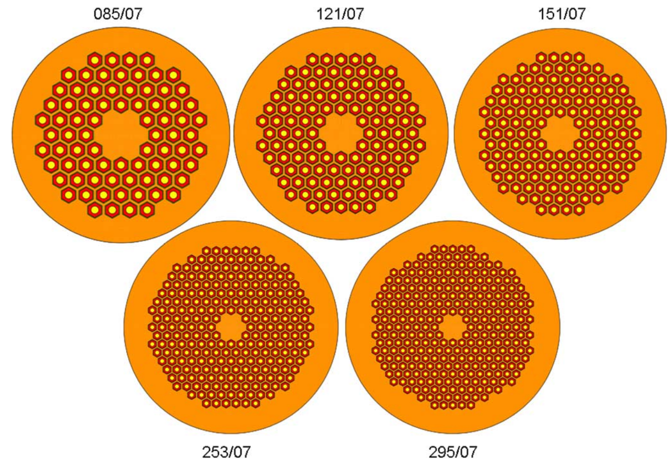

Fig. 4. The five different sub-element distributions, with increasing number of sub-elements, which were investigated and compared by FE analysis.

All the results discussed in the following paragraphs concern a flat deformation of the wires corresponding to a 28% reduction in diameter.

B. *Effect of the Total Number of Sub-Elements*

Fig. 4 displays the five reference configurations which have been investigated. A local Cu-to-non-Cu ratio of 0.4 is assumed for all configurations. Sub-element dimensions are determined in order to keep the total amount of niobium constant in each wire. The sub-elements present the same internal structure, in proportion, in all the designs under consideration.

The configurations are numbered 085/07, 121/07, 151/07, 253/07 and 295/07. The first number indicates the total number of hexagonal sub-elements stacked in the billet; the second number gives the number of Cu hexagonal cells in the core part of the billet.

A first consideration concerns the dimension of the sub-elements. Indeed, to avoid premature quenches at low field, the product $J_C \times d_{eff}$ (critical current density times effective filament diameter) should be kept as small as possible, the effective filament diameter being of the same order of magnitude of the sub-element dimension [5]. Achieving very high critical current density implies that the sub-element size should be as small as possible. In particular, the NED wire specifications require a sub-element diameter of 50 μm or less. From this point of view, the first three configurations (085, 121, 151), which have a sub-element diameter larger than 50 μm, are examined for comparison only. They are fairly equivalent when comparing their Nb barrier deformation behavior, as shown in Table I. In all cases, no sub-element has its barrier thinner than 1 μm, and the minimum barrier thickness is around 40% of its original value. The other two configurations (253 and 295), which have acceptable values of sub-element diameter, have too many sub-elements with Nb barrier thinner than 1 μm. This indicates that the barrier thickness has to be increased. Furthermore, neither 253 nor 295 seems to be especially better than the other.

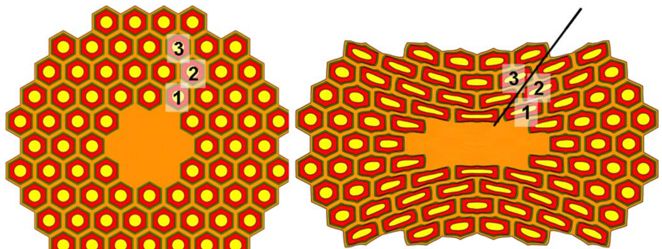

Fig. 5. Locations about the 45° shear plane of the sub-elements exhibiting the minimum Nb barrier thickness.

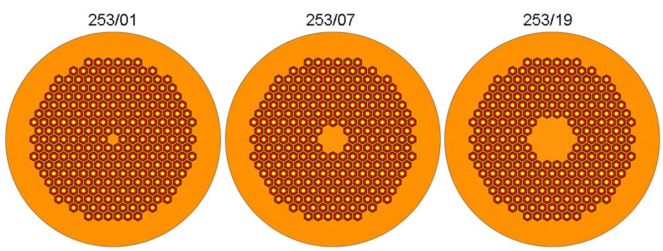

Fig. 6. The 253 sub-element configuration with three different numbers of Cu hexagonal cells in the core: 1, 7 and 19.

Finally, the sub-elements exhibiting the minimum Nb barrier thickness always appear to be located along a 45° shear plane as shown in Fig. 5. Following the numbering in Fig. 5, these sub-elements are number 1 for the 85 configuration, number 2 for the 121 and 151 configurations, and number 3 for the 253 and 295 configurations.

C. *Effect of the Number of Cu Hexagonal Cells in the Core*

Fig. 3 shows that the most distorted filaments are those close to the wire center. Then, it is worthwhile to study the effect of the number of Cu hexagonal cells in the wire core. The calculation results of the 253 sub-elements configuration with 1, 7 and 19 Cu hexagonal cells in the core Fig. 6 together with the 295 sub-elements configuration with 7 and 19 Cu sub-elements in the core are presented in Table II and lead to a few comments. First, it appears that the minimum thickness of Nb barrier is more or less similar for all configurations. This means that the strain status of the most deformed sub-elements (those belonging to the internal rings and located along a 45° shear plane) does not depend on the Cu core dimensions. Second, it appears that there is an overall effect of the Cu core size on the Nb barriers, since the fraction of sub-elements with Nb barrier thinner than 1 μm decreases when the number of Cu elements in the core increases: it goes from 17% in the 253/01 configuration to 8% in the 253/19 configuration. Finally, the 253 sub-element configurations, having slightly bigger sub-elements, appear also mechanically safer than the 295 sub-element configurations.

The conclusion is that there is a real advantage in leaving a larger Cu core. The drawback is that, correspondingly, there is a reduction of the critical current of 4% to 5%, when moving from 7 to 19 Cu sub-elements in the core. However this problem can be overcome, for instance, by distributing the 12 missing sub-elements (or part of them) on the external ring, where the deformation conditions are less critical.

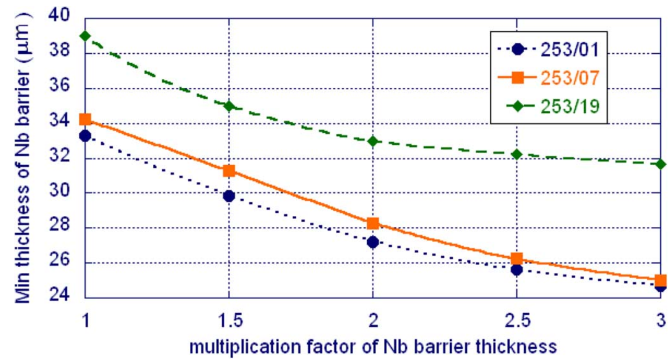

Fig. 7. Minimum thickness of Nb barrier with respect to its nominal value after 28% reduction in diameter of the wire as function of the multiplication factor of the reference Nb barrier thickness (2.2 μm) for the 253 configuration series.

D. *Influence of Nb Barrier Thickness*

Considering that, as previously noted, the Nb barrier in the studied configurations is not thick enough, the possibility of increasing the Nb thickness at least up to three times its reference value has been explored. The Nb thickness has been raised at the expense of the filamentary area, i.e., the sub-element dimension and the spacing between sub-elements are unchanged. In this case, the reduction in the number of Nb filaments in the filamentary area is balanced by the increased barrier thickness. Table III summarizes the main results obtained on the reference configurations after doubling and tripling the Nb barrier thickness. If we compare, for instance for the 253/07 configuration, the percentage of sub-elements with barrier thinner than 1 μm, for the reference case, thinner than 2 μm, for the double Nb barrier thickness, and thinner than 3 μm, for the triple thickness, we find, respectively: 13%, 16% and 30%, corresponding to 31, 40 and 73 sub-elements. There is a net gain in the absolute minimum of barrier thickness which is respectively, 0.8, 1.2 and 1.7 μm, but this gain is lower than the multiplication factor applied to the initial Nb barrier thickness.

Fig. 7 shows the minimum thickness of the Nb barrier with respect to its nominal value as function of the multiplication factor of the reference Nb barrier thickness for the 253 configuration series. The advantage of a larger Cu core, even when increasing the thickness of the Nb barriers is confirmed.

E. *Dependence on the Local Cu-to-Non-Cu Ratio Between Sub-Elements*

The behavior of some selected configurations as function of the local Cu-to-non-Cu ratio has been studied. The local Cu-to-non-Cu ratio between the sub-elements is the ratio of the Cu volume around the sub-elements to the total volume of the sub-element and copper. This parameter is related in fact to the spacing between the sub-elements. Fig. 8 shows the minimum thickness of Nb barrier with respect to its nominal value as function of the local Cu-to-non-Cu ratio for the 253/07 configuration with reference and double Nb barrier thickness and for the 253/19 configuration with reference Nb barrier thickness. The minimum thickness of the Nb barrier appears to increase linearly as function of the local Cu-to-non-Cu ratio with the same slope of $\sim$10% in all the envisaged configurations. The apparent invariability of the slope is explained by the fact that the sub-element showing the most strained Nb barrier is usually one of

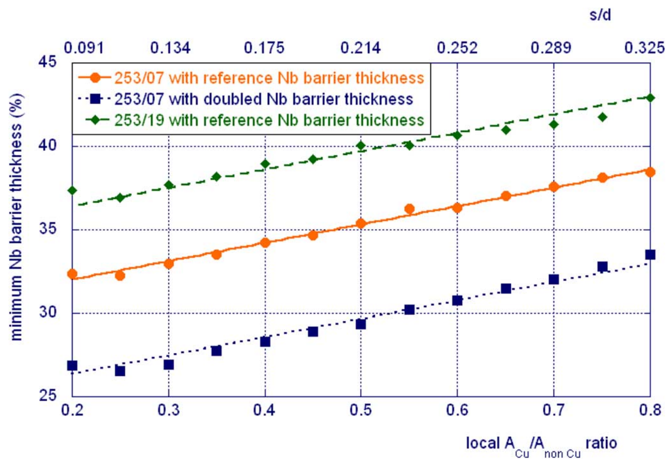

Fig. 8. Minimum thickness of Nb barrier with respect to its nominal value after 28% reduction in diameter of the wire as function of the local-Cu-to-non-Cu ratio for the 253/07 configuration with reference (2.2 μm) and double (4.4 μm) Nb barrier thickness and for the 253/19 configuration with reference Nb barrier thickness (2.2 μm). For completeness, the s/d values (spacing between sub-elements over sub-elements diameter) are also shown.

the innermost laying on a 45° shear plane, as clearly shown in Fig. 5. The corresponding shear stress is shared between the Nb barriers and the Cu separating them, so that more Cu leads to a higher minimum thickness of the barrier. Fig. 8 shows also that the behavior of the 253/19 configuration, which has a larger Cu core, has better performances as compared to the other ones. Furthermore, let us point out that the 253/07 configuration with double Nb barrier has the best performances when considering the absolute minimum thickness of the Nb barrier.

Fig. 9 shows the number of sub-elements with Nb barrier thickness of less than 1 μm as function of the local Cu-to-non-Cu ratio for the 253/07 and 253/19 configurations with reference Nb barrier thickness. It appears that there is a noticeable benefit in the reduction of the total number of barriers under 1 μm when moving the Cu-to-non-Cu ratio from 0.2 to 0.4, followed by a substantial flatness up to 0.7. Then, it is not necessary to increase the local Cu-to-non-Cu ratio more than 0.4 $\div$ 0.45. It should be noticed again that the 253/19 configuration has a lower number of barriers of less than 1 μm than the 253/07 configuration.

VI. Conclusions

We set up a solid and reliable method based on FE mechanical analysis enabling a comparison of different wire configurations based on a few parameters. Moreover, we developed the

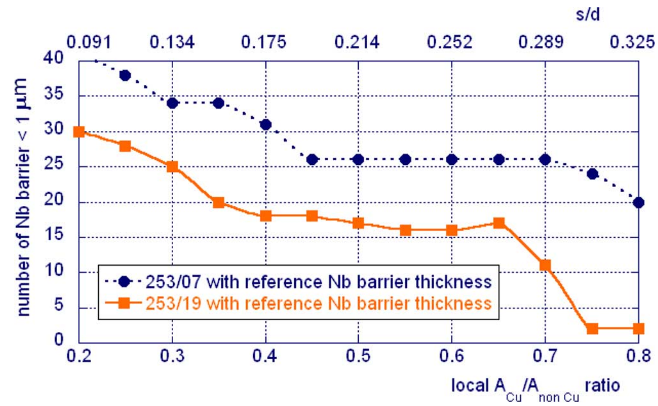

Fig. 9. Number of sub-elements with Nb barrier thickness of less than 1 μm after 28% reduction in diameter of the wire as function of the local Cu-to-non-Cu ratio for the 253/07 and 253/19 configurations with reference Nb barrier thickness (2.2 μm). For completeness, the s/d values (spacing between sub-elements over sub-elements diameter) are also shown.

proper approach to understand the parameters playing a fundamental role in the deformation, with the aim to design an Nb_3Sn internal tin wire as robust as possible with respect to applied deformation.

Main conclusions are that the adequate local copper to non-copper ratio is around 0.4 $\div$ 0.5, as we already found for PIT Nb_3Sn wires, that the increase of the Nb barrier thickness is always beneficial, even if with some saturation, and that a larger copper core of 19 sub-elements ensures an improved mechanical behavior.

It is important to underline that this approach allows comparing different wires but cannot predict when and where Nb barriers eventually loose their integrity, leading to fracture and merging of the sub-elements and possibly to tin leakage. This limit can be explored only experimentally.

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