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Authors

Pong, Ian

Lin, Andy

Kikuchi, Akihiro

et al.

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Fabrication of 8-Strand Rutherford Cables Using Roped Strands Made from Ultrafine Wires

Ian Pong, *Senior Member, IEEE*, Andy Lin, Akihiro Kikuchi, Jean-Francois Croteau, and Nandana Menon

***Abstract*—Conventional Rutherford cables are typically made from solid round wire. While multi-stage cables have been made elsewhere, the purpose was usually to achieve a higher strand count and therefore a higher current carrying capability. In this work, we attempt to use two-stage roped strands made from ultrafine wires to fabricate Rutherford cables. The ultimate goal of this work is to obtain a very flexible cable that can wind accelerator magnet coils with a very tight bend radius in both the "easy way" (along the broad face of the cable) and the "hard way" (along the edge of the cable) in the wind-and-react manner, or wind coils with a radius typically used today but in the react-and-wind manner with a much reduced degradation in critical current. We report our experience fabricating such Rutherford cables at the Lawrence Berkeley National Laboratory, and the initial findings from the analysis of the experimental cables made. We will discuss how the conventional wisdom and some rules of thumb for making Rutherford cables are no longer applicable or relevant, and the new thinking required in designing these cables.**

***Index Terms*—Nb_3Sn, Nb-Ti, Rutherford cables, ultrafine wire**

I. Introduction

THE present state-of-the-art conductor for particle accelerators and similar types of superconducting magnets is a single-stage "Rutherford" cable made of Nb-Ti or Nb_3Sn wires that are typically of diameter between 0.7 mm and 1.1 mm [1] [2] [3]. The dimensions of the Rutherford cables depend on the number and the diameter of strands used, which may vary from 2.35 mm ×1.25 mm (six strands of 0.7 mm) [4] to 26.00 mm × 1.92 mm (44 strands of 1.1 mm) [5] and beyond.

Such cables made from solid round wire are very stiff and difficult to bend. But to make coils for magnets, cables have to be wound against a pole and also clear the beam tube or an equivalent bore, and bent in a combination of the so-called "easy-way" (on its broad face, like bending a strip of paper) and "hard-way" (along its thin edge). When the bend radius is tight and the deformation is unfavourable to holding the geometry, mechanical instability can develop, causing strands to pop out of position [6] in a range of severity (from being easily re-seated under finger pressure to requiring tooling and forceful massaging), or even rope irrecoverably.

While it is possible to mitigate such instabilities by using a large bend radius, it would make the magnet less efficient and it is not always practical to do so. And while there are magnet and coil designs that strive to accommodate a more generous bend radius by incorporating creative features such as [7], they exist mostly as models or non-standard prototypes and have other assembly challenges.

Fundamentally, the root cause of this conductor mechanical limitation is tied to the fact that the solid round wire is a beam in the engineering sense, and the larger its diameter, the stiffer it is.

The idea employed in our project supported by the DOE's US-Japan Science and Technology Cooperation Program in High Energy Physics (henceforth "US-Japan") is to manufacture Rutherford cables with ultrafine wires (about the size of the typical subelements in state-of-the-art, high current density (J_C) distributed-barrier design multi-filamentary Nb_3Sn wire [8]) to increase cable flexibility for accelerator-grade magnets. This concept to build strong and flexible Rutherford cables is analogous to that used in suspension bridge cables which is well established in civil engineering.

The use of ultrafine wires that have a cross-sectional area one to two orders of magnitude smaller to build Rutherford cables of the same original size necessitates a corresponding increase of the number of strands. Thus, a multiple-stage approach is required, which incidentally opens a wide variety of twisting and staging design possibilities. That will be for another time—this present study focuses on our fabrication experience during the final Rutherford cabling stage only.

We are aware of at least two past projects that took a similar (though with some very notable differences) approach: the SULTAN facility insert (Nb_3Sn) split coil [9], which used a round cable of 19 × 7 × 0.125 mm first-stage strands to fabricate a 16-element Rutherford cable for embedding into a Cu stabilizer channel to form a conductor with a cooling channel sandwiched between stainless steel reinforcing strips, and an R&D effort at MIT [10] which tested a range of round cables composed of 3, 7, 21, and 54 × 0.13 mm first-stage strands. Their aims were to make coils using the "react-and-wind" method. By contrast, our project is open to both the

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Ian Pong, Andy Lin, Jean-Francois Croteau, and Nandana Menon are with the Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720-8201, USA.

Akihiro Kikuchi is with the National Institute for Materials Science, Advanced Superconducting Wires Group, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan.

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"react-and-wind" and the more common "wind-and-react" methods for Nb_3Sn, with a goal to offer solutions especially for high-field accelerator magnets.

With flexible and strong cables, it will become possible to design more compact and efficient magnets (such as block coils with much shorter end sections, or canted cosine theta (CCT) coils with a much higher current-to-magnetic field transfer function) as well as magnets with novel and complex geometries (such as combined function elliptical CCT [11]). Some coil designs (such as the aforementioned) will benefit more than others (such as common coil). Where coil fabrication infrastructure is concerned, the prospect of a react-and-wind conductor technology would considerably reduce the capital investment and operation cost required for long furnaces.

In this paper, we will report our experimentation with fabricating an 8-strand US-Japan Rutherford cable design using Cu, Nb-Ti, and Bronze Route (BR) Nb_3Sn. The initial findings suggest some conventional rules of thumb for making Rutherford cables will require re-thinking when using ultrafine wires, regardless of the conductor material.

II. Materials, Roped Strands and Cable Parameters

A range of diameter designs of ultrafine wire and primary and secondary ropes (a.k.a. first and second stage roped strands—"strands" being commonly used to refer to the elements in a cable) were trialed. In Table I below, we only list those variants used in the US-Japan Rutherford cables reported in this paper. Reports of the development of ultrafine wire and similar roped strands can be found in [12][13][14]. Fig. 1 illustrates the size and twist of the first and second stage roped strands. We have made five cable runs with all three materials, and in each run we made multiple units. Altogether we made over 100 m of cables and see no showstoppers for making long continuous lengths appropriate for winding prototype coils. No cable breakages were observed during production.

TABLE I

Materials and Roped Strands Parameters

	Cu-alloy	Nb-Ti	Nb_3Sn
Composition	Cu-Co-P	Nb-47at%Ti in OFC	Pure Nb in Cu-Sn-Ti
Cu:non-Cu ratio	n/a	1.3	1.27
No. of SC filaments	n/a	55	31
SC filament size	n/a	4 µm	5 µm
Ultra-fine wire diameter	0.050 mm	0.050 mm	0.065 mm
Primary (1°) rope diameter	0.33 mm	0.33 mm	0.33 mm
No. of strands in 1° rope	36	36	21
1° rope twist pitch	10 mm	10 mm	10 mm
Twist direction in 1° rope	RHH	RHH	RHH
Secondary (2°) rope diameter	1.0 mm	1.0 mm	1.0 mm
No. of strands in 2° rope	7	7	7
2° rope twist pitch	20 mm	20 mm	20 mm
Twist direction in 2° rope	LHH	LHH	LHH

* LHH and RHH stand for left and right hand helix, respectively.

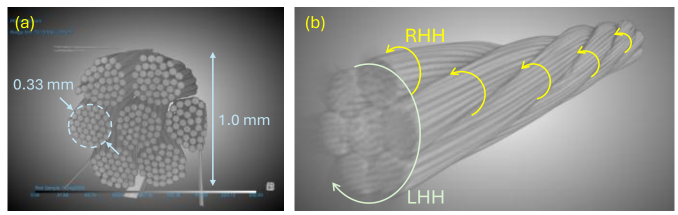

Fig. 1. Tomography reconstruction images illustrating the size and twist of the roped strand construct.

The cable parameters were targeted to be comparable to the USMDP CCT subscale design [15]. But since the diameter of the "final wire" is different—the solid round wire in the USMDP CCT subscale cable is 0.60 mm whereas the secondary rope here is 1.0 mm—the number of strands was adjusted down from 11 in the USMDP CCT subscale cable to 8 here. As a result of using "final wires" of a larger diameter, the cables thus made were thicker. However, given that the cable thickness is an adjustable parameter through the cable forming Turkshead settings, we could use the same cabling hardware such as the rollers and mandrel as what was used for fabricating the USMDP CCT subscale cable reported in [15] without modification. The target thickness of the US-Japan cables was intentionally allowed to be a generous range, left as a tuning parameter for experimentation (see further discussion below). Another notable difference between the two cable designs is the cable twist direction. Following the "reverse lay" convention of using opposite twist direction for every stage up, the US-Japan cables made using roped strands of ultrafine wire all have a right-hand "lay" (i.e. cable twist). Lastly, the cable twist pitch was reduced, and the planetary ratio was modified during experimentation between -2.13, -1 and locked (i.e. zero)—see details in section III. A summary of the cable parameters for comparing the US-Japan 8-strand cable and the USMDP CCT subscale 11-strand cable is provided in Table II. The tension setting per strand spool was the same, ~6 kg.

Fig. 2 shows optical microscopy images of one of the US-

Japan cables (Nb-Ti) and illustrates the challenges with defining some of the conventional cable parameters. The top broad face surface (Fig. 2a) shows the complex rearrangement of individual ultrafine wires and 1st and 2nd stage roped strands. A 2nd stage roped strand was coloured with a blue permanent marker before cabling. Although the marked strand is still distinguishable from adjacent ones after cabling, accurately segmenting ultrafine wires and determining the roped strand they originally belonged to is challenging. Production segmentation is required to use traditional in-line imaging techniques and it is more challenging for a moving cable that is imaged with a lower resolution in-line camera [16]. The definition of a facet, i.e. the plastically deformed flat and oblong surface of an edge wire, is also different due to the ultrafine wires' rearrangement during cabling (Fig. 2b). Research is currently ongoing at LBNL to address these challenges. The cable metallography cross-section (Fig. 2c) shows the complex wire rearrangement and ultrafine wire plastic deformation in this highly compacted cable. Quantitative analyses of the ultrafine wires will appear in a future publication.

TABLE II
CABLE PARAMETERS COMPARISON

	US-Japan	USMDP CCT subscale
No. of "final wire"	8	11
Diameter of "final wire"	1.0 mm	0.6 mm
Twist direction in "final wire"	LHH	RHH
Cable twist direction	RHH	LHH
Cable twist pitch	21.9 mm	27.0 mm
Nominal cable width	4.0 mm	4.0 mm
Target cable thickness	1.2 mm - 1.5 mm	1.1 mm
Nominal keystone angle	0°	0°
Planetary ratio	Experimentation	-0.57:1

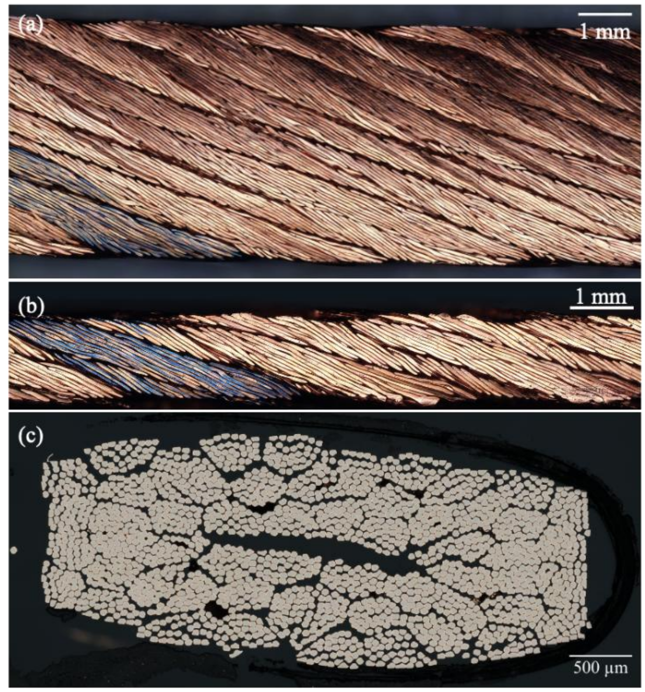

Fig. 2. Optical microscopy images of the Nb-Ti cable (B31KL3701E). (a) Top broad face and (b) major edge images, with a 2nd stage roped strand coloured blue to track the position of the ultrafine wires along the cable. It can be seen that the features from the primary rope interfere with the boundary of the "final wire" in the Rutherford cable. This segmentation challenge will be a topic of a dedicated investigation in a separate future publication. (c) Cross-section metallography showing the high cable compaction, wire rearrangement, and wire plastic deformation.

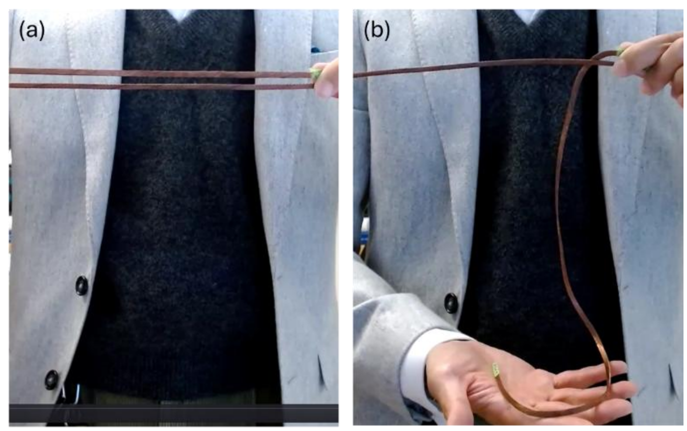

Fig. 3. (a) US-Japan cable (top) and USMDP CCT subscale cable (bottom) held on both ends, with the broad face towards the viewer (i.e. gravity bends them hard-way). (b) The same two cables held only on one end. The US-Japan cable flows down the hard way very smoothly.

III. CABLE MECHANICAL PROPERTIES

The cables made using ultrafine wires are remarkably flexible, even more so than expected. Fig. 3 is a comparison between a US-Japan cable made using Cu-alloy ultrafine wire and a USMDP CCT subscale cable made using 0.6 mm RRP® Nb_3Sn wire. We observed that the natural (gravity-induced) hard-way bend radius of the US-Japan cable is over an order of magnitude smaller than the natural easy-way bend of the USMDP CCT subscale cable.

IV. Implications on Cable Fabrication

A. Wire Handling

The US-Japan secondary ropes made of Cu-alloy, Nb-Ti, and Nb_3Sn all behave very differently compared to solid wires, as one would expect of ropes. They have a tendency to partially untwist and kink during handling. The ends of the ropes also fray or unravel very easily. At LBNL, we use tapes or solder to hold the strands ends of a rope together when sectioning them, for example during respooling for cable fabrication preparation.

While these US-Japan secondary ropes of 1.0 mm diameter, regardless of the materials of which they are made, feel soft and flexible, they are quite elastic (or "springy"). Under our standard spring back test [17], we use a dedicated test fixture (Fig. 4) to wind a 1 m long sample on a 10 mm diameter shaft 10 times under a 2 kg load. Then, after clamping the wire above the load, the spring winder is let free to unwind and the turn degree and the inside diameter of the uncoiled sample are measured. The US-Japan Cu-alloy samples we measured showed a very wide measurement uncertainty: even samples cut adjacent to each other could spring back with a range from 300° to well over 1100°, presumably due to partial untwisting during handling and to a very low spring constant that makes them very sensitive to handling. The spring back diameter is notably high, consistently well over 20 mm. For comparison, the as-received (unannealed) solid Nb_3Sn wires we have measured over the years typically spring back by 460° ± 30° (average ± one standard deviation) while pre-cabling annealed (such as applied in [5]) solid Nb_3Sn wires spring back by 550° ± 40°, with a narrow spread of spring back diameter of only 11.5 mm ± 0.5 mm, regardless of wire diameter.

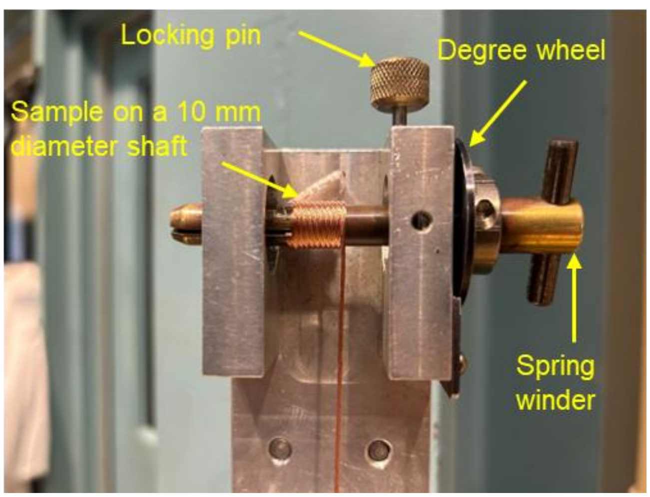

Fig. 4. The LBNL springback test fixture. The sample is attached to a 2 kg weight.

This property of the US-Japan rope makes respooling and setting up the cabling machine considerably challenging. For example, during the machine stringing process, the typically innocuous practice of uncoiling enough length to thread a strand through the next path guide becomes problematic, because these very flexible US-Japan secondary roped strand would be pulled down by gravity, locally coiled, and partially untwisted. When the rope is pulled through and tensioned up, local kinks can easily develop at multiple places with the twist pitch uncontrollably varied along the length. As mitigation, appropriate twist and tension must be maintained during handling at all times wherever possible, and any untangling must be performed with exceptional delicacy and attention.

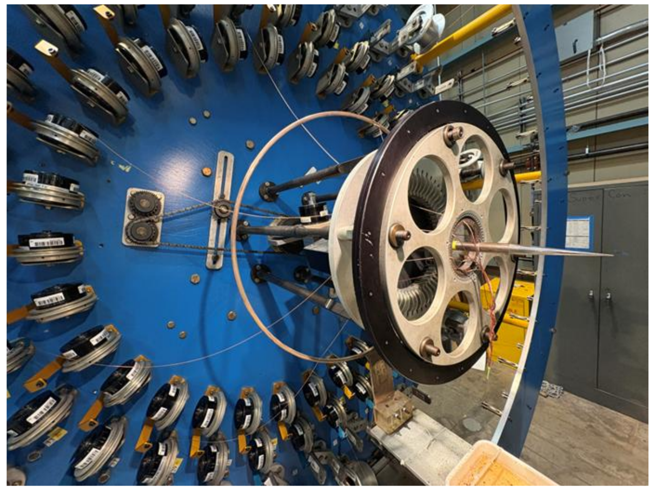

Fig. 5. A photograph of the cabling machine at the end of a run with the secondary roped strands made of ultrafine wire and the cable end, drooping under gravity, showing their extraordinary flexibility.

B. Flaring, Transient and Differential Residual Twist

We encountered two technical control matters with forming the cable during startup that are much more challenging than with forming conventional cables.

First, it is the prevention of "flaring". Local bellowing of the rope (i.e. rope opening up in the transverse direction, usually due to untwisting while longitudinally constrained), frayed ends (typically from broken wires) and loss or excessive buildup of strand wrap on the mandrel (resulting in the strands entering the aperture straight instead of at an angle, or at too high an angle) could push the ultrafine wires outside the prescribed path towards the corners of the Turkshead aperture, where the sharp edges of the vertical rollers meet the walls of the horizontal rollers. Here the ultrafine wires have a much higher tendency to be caught ("flare"). Once caught, it requires a tedious recovery process of opening up the rollers to re-seat the ropes. The two main parameters we control to prevent flares are non-excessive local compaction through startup thickness and pinch point adjustments, and maintaining downstream tension. The latter is the difficult one, as explained below.

The second concerns how to tune and balance the Turkshead rollers and the bay-caterpuller power settings to dial the machine into a steady state of cable production. In this type of cable made using ultrafine wires, a few factors, as described below, are much more sensitive and harder to control than typical solid-wire cables, making it very challenging to proceed from the transient state.

In Rutherford cable fabrication, we define the transient state as the period when the line properties between two fixed points are still largely non-uniform and varying in time. Here are three examples of the sources of a transient state: (1) Upstream of the cable forming, the two fixed points are the strand payout tangent and the Turkshead aperture. If the strand twist direction or twist pitch is changed (such as an intended adjustment of the planetary ratio or an unintended effect, see below), before the modified strand twist propagates through the length and stabilizes, the system is in a transient state. (2) Downstream of the cable forming, the two fixed points are the vertical rollers and the caterpuller belts, to which the broad faces of the cable must align. A cable with uniform residual twist between these two fixed points would be constrained and remain straight. However, if there is an internal change of residual twist within this length, a differential twist would be exhibited on the two sides of that change (i.e. one side has a positive twist, and the other a negative one, they sum to no net twist between the two fixed points), and the system is in a transient state until the point of change enters the caterpuller belt. At the very beginning of the cable start, before any formed cable enters the caterpuller belt, this twist is particular difficult to control. (3) If the vertical rollers are under-powered compared to the torque required to counter the back tension of the strands, the cable would be formed more slowly than the caterpuller belts are moving. During the transient state, the downstream cable tension would increase until the caterpuller delivers the balancing force to equalize the strand back tension.

What is challenging is that these three transient contributions are much more pronounced in this type of cable made from ultrafine wires. During stringing, it is very difficult to maintain a constant roped strand twist pitch along the wire path, meaning the upstream transient varies more markedly and persists for longer with roped strands than when strung with solid wires. Meanwhile, the amount of residual twist in the newly formed cable section is easily affected by the upstream twist as well as the tension balance on the two sides of the Turkshead. It requires not only quick (in time) but also exceptionally fine-tuned (small amplitude, ~0.1%, about an order of magnitude more sensitive than other cables) changes in the vertical roller powers to control. If the power is too high, the cable is made more quickly than the bay can rotate, then the strand wrap on the mandrel can be over-consumed, leading to instability or even flares, and, without tension on the cable, the feedback for adjustment would be lost. Conversely, if the delivered power is too low, the downstream tension quickly increases and the amplitude of residual twist goes up, resetting / restarting and thus prolonging the downstream transient. If the differential twist builds up excessively, flaring can occur also. Effectively, the upstream transient contributes to unpredictable residual twisting and exacerbates the downstream transient, making it much harder to move on to a steady state of cable making.

On the positive side, it appears that it is possible to "massage" the cable (such as counter-twisting by hand with finger pressure) to reduce residual twists locally. This is of course an observation only and would not be implementable or practical as a cable production parameter. The implication, however, is that for coil winding, given this residual twist pliability, the as-fabricated cable residual twist specification is probably less of a priority, which can be helpful for mitigating the issue reported next.

C. Loss of Planetary Controls

The roped strands exhibited a very weak resistance to torsional and shear forces, as expected of a rope construction. A consequence of that, however, is that transverse loading and bending can also affect the twist and twist pitch stability. Notably, on the cabling machine, friction on path guides and pulleys combined with stringing tension is found to be sufficient to effect a significant local change of twist pitch (Fig. 6).

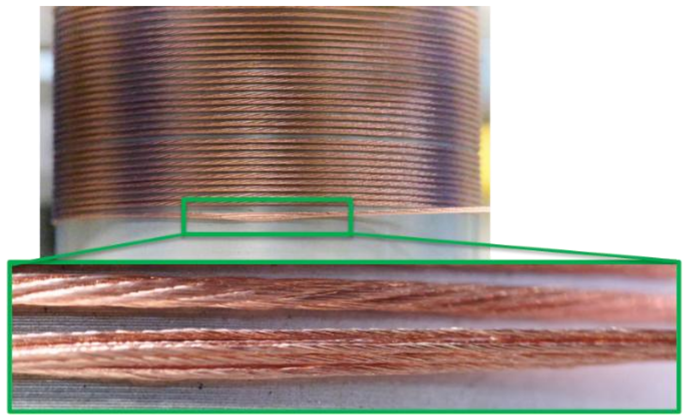

Fig. 6. Photograph of a 1 mm diameter secondary roped strand on an aluminium spool mounted on the cabling machine. The roped strand is strung under tension. The inset zooms in on the roped strand at the payout tangent, showing that the stringing tension translates to a local transverse loading, deforming (flattening) the rope. Further out, the roped strand twist is also affected by interaction between path guide and pulley friction and the running planetary.

What is problematic is that, because of this, our planetary capability is effectively lost, and with that we lose a conventionally key ability to tune the cable residual twist. In our nomenclature, the planetary ratio is defined as the number of rotations made by the wire spool on its fork axis per rotation of the bay. Thus, a planetary ratio = 0 is equivalent to locked spools with no planetary rotation, similar to the moon's movement around the Earth, where the same side of the moon always faces the Earth; whereas a planetary ratio = -1 means a flat tape will be paid out perpetually without twist, or as one can gesture with one's hand (palm facing down and not turning the wrist) in a circular motion. What we observed during our cable fabrication using roped strands was that while the machine components still revolve and rotate according to the planetary ratio settings, and while the cable *integral* twist obeys the mechanical movements, the planetary twist can become partially locked in and accumulate locally at fixed or semi-fixed points, such as guide pulleys and capstan tangents. This was most evident in one of the cable samples where we attempted to use a negative planetary ratio to reduce the residual twist in the Rutherford cable. Instead of finding a reduced secondary rope twist, we found, after some lengths, that the fractional negative twist accumulated locally such that the roped strand became twisted in the opposite direction between the payout tangent and the first pulley! After some transient, that opposite direction twist propagated and eventually reached the cable. At the final semi-fixed point before the mandrel, a fixed planetary (planetary ratio = 0) twist was added back. We believe the planetary eventually would go into quasi-steady state, but it will be dictated by local friction, with the roped strands potentially twisted back and forth along an extended length over the cable.

D. Higher Compaction Needed to Form Stable Cable

Finally, we found that if one takes the nominal “final wire” diameter to determine the target cable width, cable thickness, and twist pitch using the standard formula [18][19], the cable will be too “fluffy” (too loose) and mechanically unsound due to excessive void fraction. One needed to apply a much higher compaction (lower thickness, and a shorter cable twist pitch to adjust for the width when using the same vertical rollers). As an approximate correction, we assumed ~1/3 of the rope volume is void space, and increased the compaction fraction accordingly. The nominal target thickness for a Rutherford cable made from typical 1.0 mm diameter solid round wires would have been ~1.7 mm. In our experiments, we found that a compaction of a further 18% to ~1.4 mm (~33% void volume per unit length translates to an equivalent diameter reduction of 18%) was needed for the cables to achieve good stability. Too high a compaction (<1.3 mm thick) risks rupturing the ultrafine wires due to pinching. The rough approximation presented above can be arrived at by taking the nominal cross-sectional area of all the ultrafine wires multiplied by a factor to account for the fact that they are not orthogonal to the plane transverse to the cable axis. However, contrary to a solid wire Rutherford cable, this factor is more variable for roped strands built up through multiple stages, because the pitch length (and in some cases also the direction), as reported, may exhibit a wider range of change during non-steady-state cable fabrication process.

V. Conclusion

We fabricated Rutherford cables using two-stage roped strands made from ultrafine wires of three materials: Cu-alloy, Nb-Ti, and Nb_3Sn. The fabricability and handling differences between the three materials were minor compared to those between Rutherford cables made using conventional solid wire and using these roped strands built with ultrafine wires.

The cabling of this type of multi-stage ultrafine wires presented appreciable challenges that thrilled the team. While extraordinarily flexible, handling was definitely not easy. The roped strands exhibited a tendency to coil and untwist locally, and a propensity to kink during subsequent straightening. The implication is that, even with a lot of attention, considerable twisting variability and possibly local deformation along the path would inevitably be incorporated during stringing, contributing significantly to cable startup transient instability. This, coupled with the residual twist sensitivity to cable tension, requires exceptionally fine skills of the operator to prevent introducing defects and to move the cable production into a steady state. Once in the steady state, the parameters are expected to become stable.

The important questions are: How much of that matters downstream in the coil and magnet fabrication processes and what features are tolerable. These are unclear at this stage of our project, and feedback from those downstream activities will certainly benefit the cabling process, so that attention can be focused on the parameters that are truly important. There will also be much to learn from future work on coil winding as well as magnet assembly and testing: apart from cabling-relevant lessons, there will be coil and magnet specific questions to be answered that will be relevant to the application of the ultrafine wire designs, such as penetration of impregnation medium and of cryogen given the very large cable internal surface area.

In terms of executing the cable design, we discovered that the roped strands’ limited twist stability rendered our planetary capability ineffectual. Nevertheless, cables made from ultrafine wire tend to be quite pliable, making planetary adjustment a much less critical cabling parameter. We also found that the target cable compaction ought to account for the void fraction in the roped strand in order to achieve mechanical stability.

Despite these challenges, the remarkable flexibility of the Rutherford cable made using ultrafine wires is a most exciting and highly promising development that has the potential to enable more compact and efficient, as well as novel and geometrically complex magnet designs, for both wind-and-react and react-and-wind fabrication routes.

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