Development of Multi-Strand Cables with REBCO CORC® and STAR™ Wires for Very High Field Accelerator Magnets

P. Ferracin, I. Pong, X. Wang

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, pferracin@lbl.gov

Superconducting dipole and quadrupole magnets for particle accelerators are usually designed to generate high magnetic fields with superconducting coils operating at currents in the range of 10 to 20 kA [1]. To achieve such currents, the coils are typically wound with so-called multi-strand cables, composed by about 20 to 50 superconducting round strands, each of them with a diameter in the 0.6-1.2 mm range. The advantages of multi-strand cables are multiple. A superconducting coil with multi-strand cable is characterized by a significantly smaller number of turns compare to a single wire coil: this aspect facilitates the fabrication process and reduced the required strand unit length. Also, a lower number of turns results in a lower magnet inductance, which decreases the voltages during magnet ramping up and down, and, in the case of a transition from the superconducting to the normal conducting state (quench), allows for a faster discharge of the current and a reduction of the peak temperature in the windings. Another important advantage comes from the fact that in a multi-strand cable, the close contact between wires can result in "current-sharing", and local damage or degradation in individual strands can be potentially bypassed. In addition, with the wires twisted in a rope-type configuration, multi-strand cables can minimize the inter-strand eddy currents, and consequently the heat loads during ramping and the perturbations of the magnetic field. Finally, the mechanical stability of these multi-wire cables, coupled with their intrinsic flexibility, makes possible the winding of very compacted coils, with tight bending radii.

The most common multi-strand cable used in superconducting magnets for particle accelerator is the Rutherford cable. With a rectangular or trapezoidal cross-section, two broad faces (top and bottom) and thin side edges (see Fig. 1, left and center), they can be stacked around the coil aperture, in a roman-arc layout called $\cos\vartheta$ design (see Fig. 1, right), or in rectangular blocks, in so-called block or common coil designs, thus maximizing the overall current density in the superconducting coils.

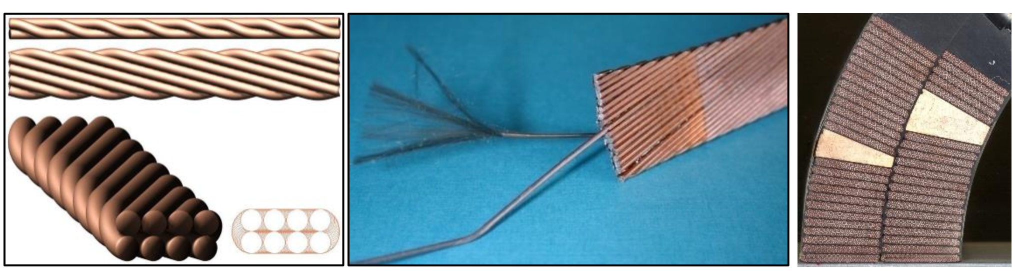

Fig. 1: Schematic view of a Rutherford cable [2] (left), the LHC dipole cable (center), and a cross-sectional cut-out of a superconducting Nb_3Sn coil (right).

Rutherford cables have been used in all superconducting dipole and quadrupole magnets installed to date in particle accelerators, with wires made with both Nb-Ti and Nb_3Sn

superconducting material. Either in accelerator quality or in R&D model magnets, these materials have allowed generating fields up to 10 T for Nb-Ti and 16 T for Nb_3Sn. In order to pass the 16 T field level, considered a limit for Nb_3Sn magnets, and reach fields of 20+ T, a new generation of superconductors, called High Temperature Superconductors (HTS), is required. The two most promising materials currently under development for HEP magnets applications are Bi2212 [3] and REBCO [4]. Economically viable 20 T magnet designs could consist of an HTS insert, located in the high field part of the superconducting coil, powered in series with outsert coils, wound with Nb_3Sn and Nb-Ti cables, in a so-called hybrid configuration. Alternatively, provided a significant cost reduction in HTS conductors, an all-HTS 20 T class dipole magnets could also be possible.

However, to meeting the stringent requirements of particle accelerator application, these hybrid or all-HTS magnets will have to operate with high currents. While Bi2212 can be fabricated in round wires and then combined in "traditional" Rutherford cables [5], fundamentally identical to the ones with Nb-Ti and Nb_3Sn strand and with the same high current capability, REBCO is fabricated in thin tapes consisting of a superconducting layer deposited on a Hastelloy substrate and surrounded by a stabilizer [6]. Therefore, in order to increase the current in REBCO coils, the tapes are then assembled together to form wires or cables. In Fig. 1 (courtesy from [7], [8]) the three most common configurations are depicted: Cable on Round Core (CORC®) or Symmetric Tape Round (STAR™) wires [9]-[12], Roeble cable [13], [14] and Twisted Stack cable [15], [16].

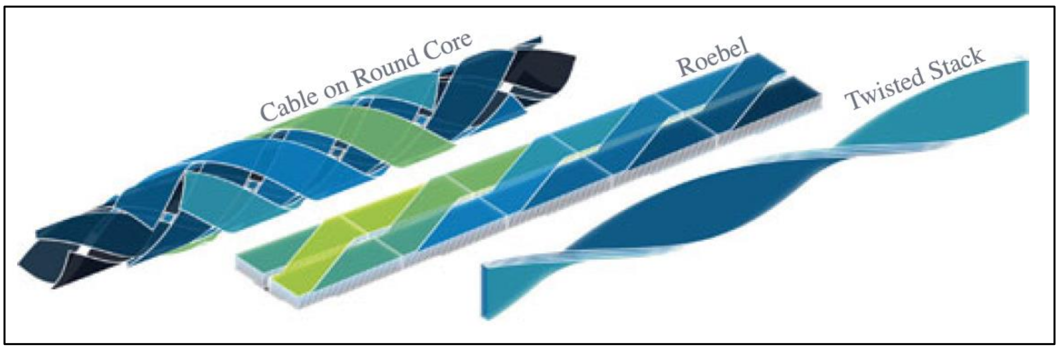

Fig. 2: Schematic view of REBCO wires and cables (courtesy from [6], [7]).

In recent years, the US Magnet Development Program [17] has been carrying out R&D on superconducting magnets with REBCO superconductor, focusing on the fabrication of sub-scale insert coils wound in a canted cos-theta (CCT) design with CORC®/STAR™ wires [18]. As shown in Fig. 2, a CORC®/STAR™ wire is composed of several REBCO tapes wrapped around a central strand (former) made of a stabilizer material. Several wire designs have been explored and tested with former diameter ranging between 1.3 to 4.5 mm, and using about 10 to 50 tapes. In general, with respect to the other REBCO cables, CORC®/STAR™ wires feature a higher Cu/Sc ratio, which helps protect the magnet in case of a quench, and a greater flexibility, which facilitate winding small coils. A minimum bending radius of 15 mm has been routinely demonstrated in STAR™ wires [19] with the possibility of an even smaller bending radius.

With this letter we express our interest in developing a multi-strand cable using CORC®/STAR™ wires. We believe that, in parallel to the development of larger CORC®/STAR™ wires, resulting in larger current, but with the drawback of an increase bending rigidity, the study of a multi-strand cable composed of smaller CORC®/STAR™ wires with augmented flexibility could be extremely advantageous considering the requirements for a 20+ T magnets. Moreover, the flexibility of a Rutherford-type cable composed of multiple small-diameter CORC®/STAR™ wires could allow winding very compacted coils, with small bending radius in the end region, thus potentially reducing the overall size of the magnet. A similar approach, but with Twisted Stack cable, has been investigated in [20]-[22].

Through experiments and advanced modelling techniques, this proposed R&D program should address the following questions. 1) What are the feasible multi-strand cable architectures based on CORC® or STAR™ wires that can meet the 20 T class dipole magnet needs? 2) What are the potential designs of 20 T class dipole magnets that can be enabled by multi-strand cable concepts? 3) Which is the optimal wire diameter and tape size/number for this application? 4) How can we minimize the conductor degradation due to cabling? 5) Which are the cable parameters, such as number of CORC®/STAR™ wire, cross-section dimension, twist pitch? 6) What amount of cable compaction should be chosen to guarantee mechanical stability without decreasing the current carrying capability 7) How do we define the minimum bending radius, in both the perpendicular and parallel direction with respect to the wide surface of the cable? 8) Which are the effects of inter-tape and inter-wire eddy currents in a cable with twisted CORC®/STAR™ conductors?

We believe that such R&D program could potentially define, characterized and qualify a new HTS cable for the next generation of particle accelerator magnets, opening new opportunities for the use of REBCO conductor in hybrid and stand-alone superconducting magnets with a 20 T bore field.

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