Design and Manufacturing of a 45 kA at 10 T REBCO-CORC Cable-in-Conduit Conductor for Large-Scale Magnets

Tim Mulder, Alexey Dudarev, Matthias Mentink, Helder Silva, Danko van der Laan, Marc Dhallé, and Herman ten Kate

***Abstract*—The European Organization for Nuclear Research (CERN) is developing high-current ReBCO-CORC strand-based cables for use in future large-scale detector magnets. A six-around-one, forced flow gas-cooled ReBCO-CORC cable-in-conduit conductor (CICC) is envisioned for application in magnets operating in the 20–40 K temperature range. A CICC, rated for 45 kA at 4.2 K and 10 T, is designed and in production. The CICC comprises a cable of six CORC strands helically wound around a tube. The cable has an expected current density of 105 A/mm^2 at 10 T/4.2 K, which corresponds to an overall current density of 53 A/mm^2. A cable current density of 110 A/mm^2 can be reached when increasing the temperature to 20 K and operating in a magnetic field of 5 T.**

***Index Terms*—Cable-in-conduit conductor, CICC, CORC, ReBCO.**

I. Introduction

IN the past decade, ReBCO (Re = rare earth) tape technology experienced major improvements, which boosted the development of ReBCO cables and other ReBCO based technologies. ReBCO makes it possible to manufacture cables and magnets capable of operating in a higher temperature range, i.e. 20 to 40 K, compared to commonly used NbTi and Nb_3Sn cables. As advantage, this simplifies the cooling equipment requirements and thus significantly reduces operation costs of large stationary magnets. However, gas cooling brings the drawback of inefficient heat removal due to the low density of the coolant. Another benefit of ReBCO is its high T_c, which reduces the possibility of quenches almost totally, thereby excluding training quenches. ReBCO tape has a relatively high electrical and thermal resistivity in normal state, due to the limited amount of copper stabilizer. In the case of a sudden change from superconducting to normal state it is important to have additional material in parallel with the conductor with good thermal and electrical properties to avoid damage. The Cable-In-Conduit Conductor (CICC) provides a solution with increased stability due to added heat capacity of the conduit, reduced thermal/electrical resistance in cable direction and mechanical support. The development of ReBCO cable based CIC-Conductor variants [1], [2], are pursued by several laboratories over the world, mainly for application in the fusion sector, but the ReBCO CICC technology is also interesting for detector magnets. The Twisted Stacked cable [3] is such a ReBCO based strand for CICCs and has been implemented in several short CIC-Conductor samples [2]. CERN is currently developing the ReBCO based six-around-one CIC-Conductor using Conductor On Round Core (CORC) [4] strands for application in detector magnets to benefit from the extended operating temperature range and conductor stability [5], [6]. Large detector magnets commonly have outer dimensions of several meters. This allows a conductor with a large cross-section and bending radius in the meter range. The detector design proposed in [6] uses a conductor with a large cross-section that carries current in the 50 kA to 100 kA range to produce a magnetic field of 8 T. The current state of the design and development process of the CORC based Cable-In-Conduit Conductor is presented here.

II. ReBCO-CORC CICC Concept

The focus mainly is on the development of the CORC six-around-one Cable-In-Conduit Conductors. Obviously other CORC based CICC variants are feasible as well of which two examples are presented.

A. Six-Around-One Configuration

The CIC-Conductor comprises a cable of six CORC strands helically wound around a rod or hollow tube. The CORC strands are relatively flexible and allows straight forward twisting around the central core. The cable is inserted into a square, round or rectangular jacket. The jacket is ideally made of aluminum alloy, which is mechanically strong, while maintaining good electrical en thermal properties. Fig. 1 shows a square-jacket demonstration model manufactured using this configuration and Fig. 2 shows a 3D drawing of the cable inside the jacket. Internal forced flow gas cooling can be established via parallel flow in a perforated tube and the voids between strands.

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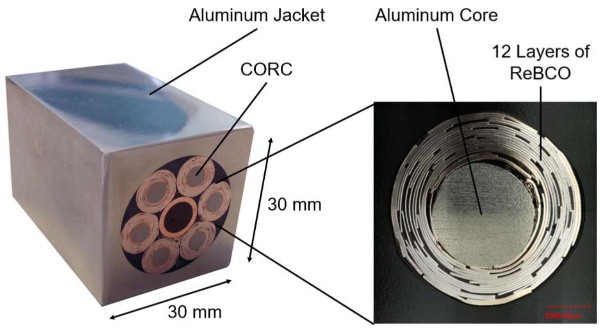


Fig. 1. World's first CORC-based cable-in-conduit conductor with a closeup view of the CORC strand.

Fig. 2. Three-dimensional CAD drawing of the ReBCO-CORC six-around-one CICC.

Direct cooling of the strands is beneficial for the stability of the cable and thus preferred for magnets operating close to I_c or in high ramp-rate conditions. In stationary magnets, i.e. large detector magnets, it is more practical to apply a conduction cooled conductor. In this case, the tube can be replaced by a rod and all voids can be filled with solder material. The solder material adds to the heat capacity of the conductor and reduces the thermal resistance to the cooling channel. The thermal contraction of aluminum is larger than common solder materials. Therefore, if the cable is cooled to operating temperature a tight fit between jacket and cable is assured.

B. Other Variants

Several other variants of the CICC are possible. One example is the triplet; three twisted CORC strands in a rectangular or circular jacket. The cable is smaller and more practical to handle than the six-around-one variant. The lack of the central core implies a current density of this variant higher than of the six-around-one CICC.

Another variant uses many smaller CORC strands, each comprising only a few ReBCO layers, positioned around a larger diameter cooling channel. The advantage of this design is increased heat and current sharing between tapes and strand core. Thereby increasing the stability of the conductor. ReBCO tapes have a minimum bending radius. Therefore it is only possible to make smaller CORC strands with smaller tapes comprising reduced thickness Hastelloy substrate.

III. Fabrication

A. Cable

The cable comprises six CORC strands helically wound around central rod with a twist pitch of 400 mm. The twist pitch length is chosen to fit 1.5 pitches within the high-field region of

Fig. 3. (Left) Photograph of the winding process where the six dummy strands are wrapped with a central copper tube. (Right) Photograph of the twisted strands positioned inside the conduit.

TABLE I
Properties of the CICC

Property	Value	Unit
Number of CORC strands	6	-
Twist pitch	0.4	m
Expected critical current (4.2 K, 10 T)	47	kA
Overall critical current density (4.2 K, 10 T)	53	A/mm^2
Cable critical current density (4.2 K, 10 T)	105	A/mm^2
Jacket outer dimension	30 x 30	mm x mm
Jacket bore diameter	24	mm
Central rod diameter	8.0	mm
CORC strand diameter	7.6	mm
Total cross-sectional area	900	mm^2
Aluminum cross-sectional area	523	mm^2
Copper cross-sectional area	168	mm^2
Void cross-sectional area	134	mm^2

the test setup described in Section IV-C. The cable is wrapped with copper foil to increase current sharing between strands and with the jacket. Optionally, voids between strands can be filled with copper wire for better current sharing and to increase the stability and protection of the cable. However, this is not implemented in the first test sample. A demonstration cable was manufactured from dummy strand. The dummy strand uses 50 μm thick copper tapes and 50 μm thick stainless steel tapes to mimic the stiffness of the ReBCO tapes. Six dummy strands were twisted around a copper tube, as presented in Fig. 3. The twisting was straight forward due to the flexibility of the cable and no issues were encountered. More geometrical properties of the CIC-Conductor are presented in Table I.

B. Conduit

The conduit comes in two halves closed by Electron Beam (EB) welding after insertion of the cable in the 24 mm bore. Both halves interlock due to a step-shaped groove on their edges. This shape also prevents the welding arc to break through the conduit and possibly damage the cable during welding. Long lengths can be welded following this method. Aluminum

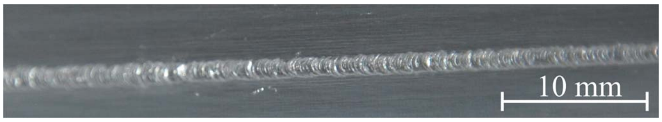


Fig. 4. Closeup photograph of the weld between the two jacket halves.

5083 is used in the first production runs for its good performance for EB-welding. In the future a different, less resistive, Al alloy can be used if there are no welding issues. Three practice runs were carried out on empty jackets or jackets filled with dummy strand to test the welding procedure and to monitor the temperature on the inner surface of the bore of the jacket during welding. The temperature test showed the temperature in and on the jacket did not exceed 160 °C, which is well within the safe temperature limit of the cable [7]. The welding procedure showed good results. The weld between the two halves is very thin as illustrated in Fig. 4.

C. Joint Terminals

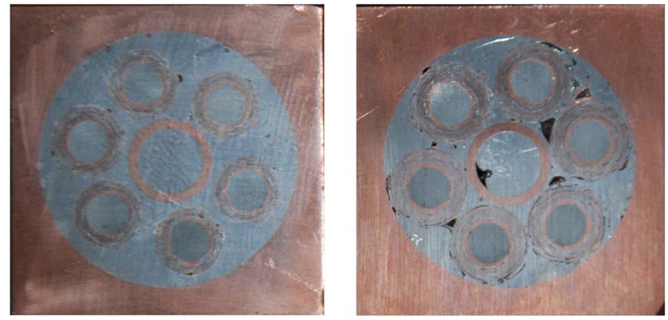
A joint terminal design for the CORC based CICC was proposed earlier this year [5]. The design features an OFHC copper casing, which receives the joint section of the cable and is then filled with solder material. The layers in the joint section of each strand are trimmed into a staircase-like fashion. This allows current to flow directly into the inner layers, without having to pass the high-resistive Hastelloy substrate of the layers above. The resulting joint resistance is lower than without trimming and current is distributed more evenly between layers, as shown in [5], [8].

A demonstration joint terminal was manufactured using six dummy strands. The dummy strands comprises 50 μm thick stainless steel and copper tapes instead of ReBCO tape. The ends are trimmed into five sections of four layers each (thickness equivalent to 2 ReBCO layers). A joint casing is machined from a 30 mm by 30 mm by 400 mm long copper bar. A single stage hole of 350 mm deep is drilled into the bar to receive the cable. The casing and cable are heated over the length of the joint terminal and filled with Sn63Pb37 solder from the top. Cross sectional views of the demonstration joint terminal are presented in Fig. 5. The cross sections show solder filling with minimal formation of gas pockets in the bottom half of the terminal. In the top half, where the strands are inserted in the joint casing, show more gas pockets, but likely not harm the integrity of the joint terminal.

A challenge is how to connect terminal to conduit; joining copper to aluminum is not trivial. A good thermal and electrical connection is required, but it also has to withstand stress caused by thermal shrinkage.

IV. World's First CORC-Based CICC

A 1.5 m long ReBCO-CORC six-around-one CICC and its sample holder is being prepared for a test in the FRESCA cable test facility at CERN.



(a) (b)

Fig. 5. Two cross-sectional views of the solder-filled demonstration joint. Six trimmed dummy strands positioned around a copper tube. (a) and (b) Cross sections from the bottom and top of the joint terminal. Gas pockets are visible as small black spots in the pictures.

A. Strand, Cable, and Conductor

The cable comprises six CORC strands of each 38 Superpower SCS4050 (4 mm wide, 96 μm thick and an I_c of about 130 A at 77 K) tapes, for a total of 228 tapes. The strand contains an aluminum core with an outer diameter of 4 mm. Several extra layers of copper tapes increase the core diameter to 5 mm, followed by 12 ReBCO layers and 2 additional layers of copper tape for mechanical protection and stability. The outer diameter of the strand is 7.6 mm. The strand was characterized in the FRESCA facility at CERN. The measured I_c is 7.9 kA at 4.2 K and 10 T, which corresponds to a current density of 174 A/mm^2. A more detailed description of the strand and its characterization results can be found in [9].

The cable section is 1500 mm long with the six CORC strands helically wound around a central copper tube. The tube has an outer diameter of 8 mm, which makes the total cable diameter 23.2 mm. The cable diameter is increased to 24 mm by winding several layers of wide copper tape around the cable. The jacket is machined out of aluminum with outer dimensions of 35 mm by 45 mm. The dimension are slightly larger than the ones mentioned in Table I, to realize a better fitting on the sample holder for the test in FRESCA. The CICC has a length of 800 mm and at either end a joint terminal is present, with the same outer dimensions as the conduit. The terminals are 450 mm in length and the cable is inserted over a length of 350 mm into the terminals. This makes the total sample length of 1700 mm. Both joints are filled with a solder material, while the voids in the cable section are left empty to facilitate space for instrumentation and wiring.

B. Performance

The expected I_c is derived using single strand characterization results [9] in combination with temperature and magnetic field scaling of Superpower ReBCO tape. The I_c is presented in Fig. 6 as function of magnetic field for various temperatures. A benchmark I_c of the six-around-one CICC at 10 T and 4.2 K is 45 kA, which translates to a cable current density of 105 A/mm^2 and an overall engineering current density of 53 A/mm^2. For a magnetic field of 5 T in large detector magnets, a critical current of 50 kA at 20 K is available, corresponding to in a J_e of 55 A/mm^2.

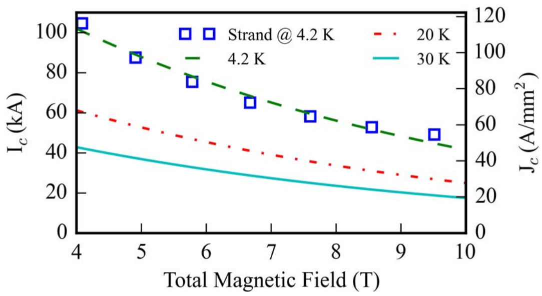


Fig. 6. (Left axis) Expected critical current and (right axis) corresponding current density (external + self-field) as a function of the total magnetic field for the six-around-one CICC using a square conduit of 30 mm × 30 mm (lines). The measured single strand I_c and J_c at 4.2 K [9] are extrapolated to the six-around-one configuration (square markers).

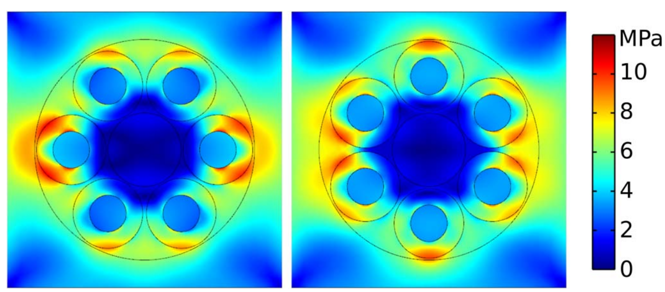


Fig. 7. FEM analysis of the global Von Mises stresses inside a solder-filled conductor operating at 40 kA in a 10 T background magnetic field oriented in the x-direction.

The Von Mises stress inside a solder filled six-around-one CICC are analyzed using Finite Element Modeling. The geometry of the CICC in the simulation is simplified. In the model the ReBCO layers are merged to a single superconducting ring around an aluminum core. All voids in the conductor are filled with Sn63Pb37 and the solder is also connected to the conduit. This means all stresses can be redistributed via the solder material. The stress maps are presented in Fig. 7. The peak stress is about 12 MPa well within the safe transverse pressure limit of the tape [10]. However, it also means that, if gas pockets are still present in the solder filling, there is a chance of delamination of the ReBCO tape. Without solder filling the peak stress in the CORC strands increases by a factor of 4. In this case stress concentrations are primarily located around the contact points between strands and between strand and conduit.

C. Test Setup for Critical Current Measurement

FRESCA features a 10 T dipole magnet producing a homogeneous magnetic field in a region of 600 mm along the sample. FRESCA can provide a current up to 100 kA with a superconducting transformer. A sample holder is designed for a hairpin style characterization of the CICC. The layout of the sample holder is similar to the one used for characterizing single CORC strand [9]. The holder comprises a "go" and "return" leg. The CICC is used as go leg to transport the current over the peak field region and a stack of three Nb_3Sn Rutherford cables returns the current. A 3D representation of the sample on the sample holder is presented in Fig. 8. The sample is cooled in a liquid helium bath as gas cooling is not possible in the FRESCA cable test station.

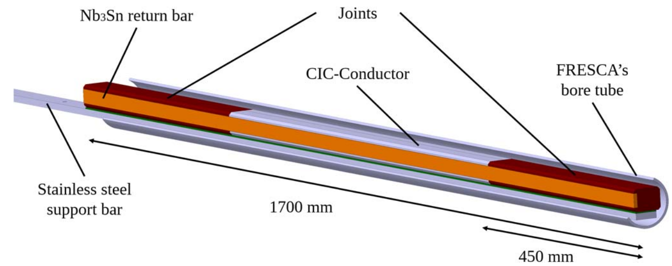


Fig. 8. Three-dimensional representation of the sample holder for the ReBCO-CORC CICC characterization in the FRESCA facility. The CICC has a copper joint at each end and is attached to a stainless steel support bar. The sample is inserted in the bore tube of the magnet and locks into the measurement station to prevent rotation during the test.

V. Outlook

The CORC strand used in this first CIC-Conductor test is already outdated. New CORC strands using thinner tapes are able to achieve much higher current densities. Thinner and more stable strands are expected in future CORC based CICCs. In addition, pre-tinned ReBCO tapes are currently in production. These tapes allow to increase the thermal and electrical stability of CORC cables with minimal heat treatment for solder melting.

VI. Conclusion

The first ReBCO-CORC six-around-one Cable-In-Conduit Conductor is being manufactured by CERN, rated to carry at least 45 kA at 10 T and 4.2 K, which corresponds to a cable current density of 105 A/mm^2 and an overall current density of 53 A/mm^2. Though tested in 4.2 K, the conductor will operate at higher temperature as well featuring a critical current of 50 kA at 20 K and 5 T. The production procedure was successfully tested by manufacturing a demonstration cable, full-size conductor and joints. A full characterization of the CICC is scheduled for early 2016. The development of CORC and CORC based Cable-In-Conduit Conductors is ongoing and many improvements in current density, stability, cabling and joint quality are expected.

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