Performance Test of an 8 kA @ 10-T 4.2-K ReBCO-CORC Cable

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

***Abstract*—CERN is developing high-current ReBCO conductor on round core (CORC) cables for application in future detector and accelerator magnets. A characterization test on a ReBCO-CORC cable sample and its joints is performed in the 10-T FRESCA cable test facility at CERN. The sample is taken from the first 12-m-long CORC production. Key is the characterization of the field- and temperature-dependent critical currents of the CORC cable at 1.9 K and 4.2 K. Secondary objectives include evaluating the response of the CORC cable to quenches and the performance of cylindrical low resistive cable terminals especially designed and manufactured for use on CORC cables. The 7.6-mm CORC cable features 8 kA at 4.2 K and 10 T, and the joint terminals show a $25 \pm 5 - n\Omega$ resistance for 20-cm length.**

***Index Terms*—Cable joints, characterization, CORC, ReBCO.**

I. Introduction

Most detector and other large magnets are manufactured using NbTi superconducting cables, which are robust and relatively inexpensive. In recent years the development of ReBCO (Re = rare earth) tapes and ReBCO based cables is moving forward at a fast pace, allowing ReBCO-based cables implementation in superconducting magnets. Several types of ReBCO cables are being developed including Roebel [1], Twisted Stack [2] and Conductor On Round Core (CORC) [3], [4] cables. ReBCO cables have several benefits over the widely used NbTi and Nb_3Sn cables. ReBCO has a higher B_{c2} and T_c than both NbTi and Nb_3Sn and does not require diffusion heat treatment. ReBCO tape is mechanically strong and is relatively flexible. The high B_{c2} makes ReBCO cables interesting for implementation in high magnetic field inserts for accelerator magnets [5]. The high T_c of ReBCO allows magnets to operate at a higher temperature than 2 to 5 K, i.e. 20 to 40 K, therefore reducing cooling costs. The combination of a high T_c and B_{c2} makes ReBCO cables very stable and almost impossible to quench, which is an important property for future large detector magnets with many gigajoules of stored energy [6], [7]. Clearly, at this moment, the primary issue limiting the use of ReBCO tapes is the too high costs per kAm.

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TABLE I
GEOMETRICAL PROPERTIES OF THE CORC CABLE

Property	Value	Unit
Manufacturer	ACT	-
Tape manufacturer	Superpower	-
Tape type	SCS4050	-
Number of ReBCO tapes	38	-
Number of copper tapes	18	-
Number of layers	12	-
ReBCO tape width	4.0	mm
ReBCO tape thickness	96	μm
Outer diameter (including sleeve)	7.8	mm
Outer diameter (without sleeve)	7.6	mm
Core material	Al 1350	-
Core diameter	4.0	mm
Core diameter with copper tapes	5.2	mm

ReBCO-CORC cable technology is developed by CERN for use in future detector, accelerator magnets and high-energy physics related applications like busbars and high-current links. The CORC cable comprises ReBCO tapes wound in many layers around a round core. The cable is relatively flexible and has good electrical/mechanical properties [8]–[10]. It is important to develop a full understanding of the behavior and limits of the cable and its electrical connections. A characterization test is performed on a 1.8 m long CORC cable in the FRESCA cable test facility at CERN.

II. Sample

A. CORC Strands

The characterized CORC sample is taken from a 12 m long cable produced for CERN by the company Advanced Conductor Technologies (ACT) in Boulder, Colorado. The cable comprises 38 ReBCO Superpower SCS4050 tapes wound in 12 layers around an aluminum core. Each layer is wound in opposite winding direction compared to the layer below. The outer three ReBCO layers comprise 4 tapes each, the next eight layers comprise 3 tapes each and the last layer has 2 tapes. Two extra layers of copper tape and a polyethylene sleeve are added for protection. The tapes have various I_c, which ranges from 100 to 140 A at 77 K. Table I provides more geometrical properties of the CORC sample. Fig. 1 shows a short section of the 7.6 mm diameter cable and its cross-section.

B. Joint Terminals

One of the key challenges in the CORC cable development is the design and production of low-resistance joint terminals.

Fig. 1. (Left) CORC cable side view. (Right) Cross-sectional view of the CORC cable with 12 ReBCO layers.

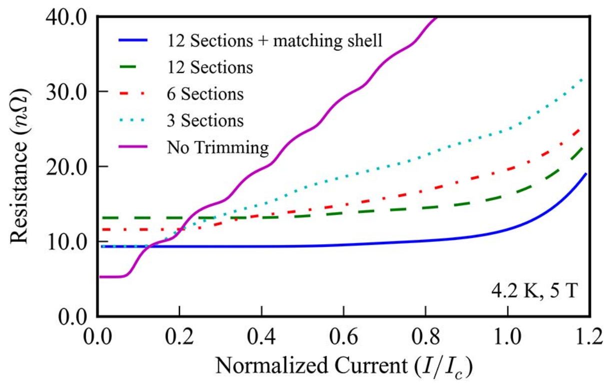

Fig. 2. Simulated joint terminal resistance for various trimming configurations using the geometry of the characterized CORC cable.

Without any processing on the CORC cable, the current injected stays in the outer layer, due to the high resistivity of the Hastelloy substrate within the tapes. This leads to an inhomogeneous current distribution among the tapes in the various layers in the cable and a high joint resistance near its critical current. A new terminal design is proposed [11] where tape layers in the terminal section of the CORC cable are trimmed (also known as staggering) into a staircase-like geometry. The joint resistance is much reduced compared to the non-trimmed joint terminal, as shown in Fig. 2, and the current is distributed more homogeneously over the layers. The joint terminal comprises an OFHC copper casing pushed over the trimmed joint section of the CORC cable. The terminal is then filled with solder.

The twelve ReBCO layers in the CORC sample are trimmed into 12 sections of each 17 mm long. The OFHC copper casing comes in four sections successively pushed over the cable end. The cylinders, with a combined length of 200 mm, each have a different inner diameter that matches the outer dimensions of the trimmed sections and therefore reduces the required amount of solder material. The casing is filled with Sn63Pb37 solder while they are heated to a temperature of 200 °C. A computer model, custom built for evaluating various joint terminal configurations [11], shows that the expected resistance of the joint terminal, described above, is about 13 $n\Omega$. The results of the test in FRESCA are used to validate and fine-tune the model.

III. Experimental

The test of the CORC sample is performed in the FRESCA cable test facility at CERN [12]. FRESCA features a 10 T dipole magnet with a homogeneous magnetic field region extending over 600 mm. The bore tube has an inner diameter of 71 mm in which a sample can be inserted for a test in 1.9 K and

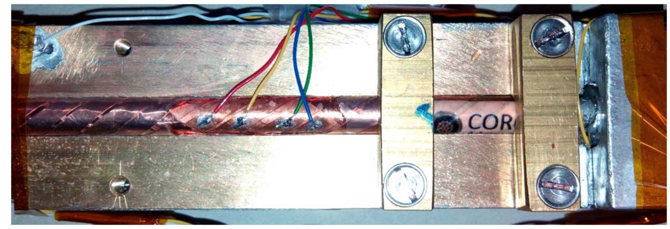

Fig. 3. Voltage taps soldered to the outer layer tapes of the CORC cable.

4.2 K up to 32 kA. The characterization is performed at 4.2 K up to 9 T and at 1.9 K up to 9.6 T. Quench protection is added as a precaution not to severely damage the sample.

A. Sample Holder

The sample holder in FRESCA is of the hairpin type. The sample holder has superconducting "go" and "return" legs that transports the current over the high-field region. The CORC cable is used as the go leg and a stack of three NbTi LHC-type Rutherford cables shape the return leg. The CORC cable is clamped onto the sample holder using several brass brackets positioned about every 150 mm. Voltage taps on the four outer layer tapes allows monitoring of single tape behavior, see Fig. 3. The sample holder is inserted vertically in the bore-tube of the magnet. A stainless steel support structure holds the sample and locks the sample in the bore-tube to prevent sample rotation. The CORC cable and NbTi stack are positioned in the background field to produce force directed towards each other. The CORC joint terminals are soldered into rectangular copper joint block using an In44Sn42Cd14 with a melting temperature of 93 °C. NbTi Rutherford cables are soldered into a groove on the copper joint blocks and are routed back to the power supply connectors. Cross-sectional views of the sample holder are presented in Fig. 4.

B. Quench Protection

The CORC sample is protected in the case of a sudden change to normal state by a brass shunt in electrical contact with the two joint terminals. The current is transferred to the shunt via the joint terminals when the sample quenches. The resistance of the shunt is such that over 98% of the current flows through the CORC sample up to its critical current. Consequently, voltage measurements can still be performed accurately on the CORC cable. Without shunt, the cable temperature is calculated to reach 300 K in 0.4 seconds at a constant current of 10 kA.

C. Heaters

Flexible MINCO heaters are attached on two outer layer tapes in the high magnetic field region, see Fig. 5. An extra insulation layer reduces the heater power needed. The heaters are used to locally decrease the critical current by increasing the temperature of the insulated section and, by increasing the temperature over its critical level, initiate a quench.

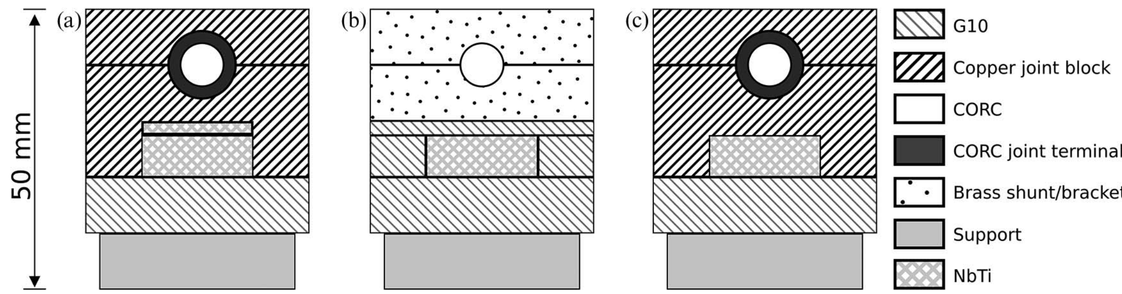

Fig. 4. Cross-sectional views of the three sections of the sample holder with (a) the top joint, (b) the main sections, and (c) the bottom joint.

Fig. 5. Two flexible MINCO heaters are glued to two tapes for heating and introducing a normal zone.

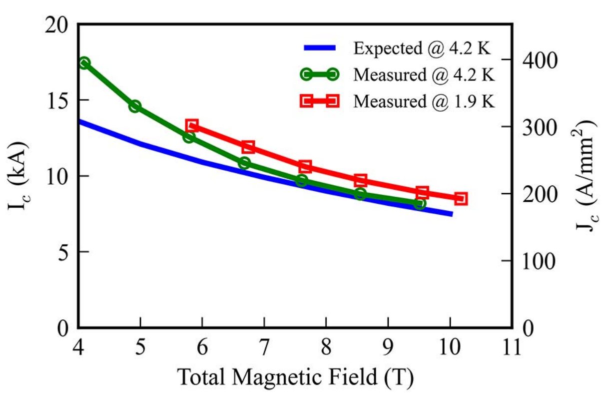

Fig. 6. Measured critical current (left axis) and mean current density (right axis) as function of the total magnetic field (external + self-field) at 1.9 K and 4.2 K with the expected I_c at 4.2 K as reference.

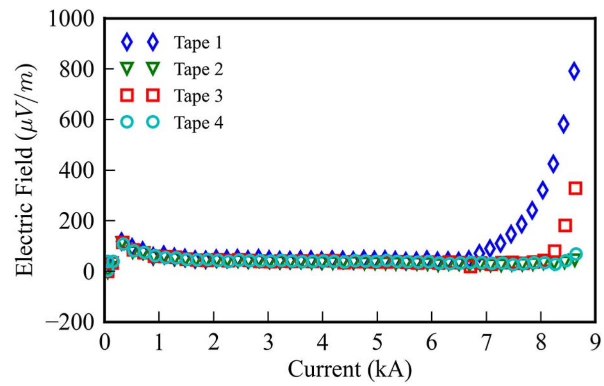

Fig. 7. Electric field of the outer layer tapes as function of current at 4.2 K and 9 T. Tape 1 performs worse than the other tapes, and tape 2 shows no voltage buildup in the measured current range.

IV. Results

A. Critical Current, N-Value and Current Sharing

To monitor the performance of individual outer layer tapes no equipotential voltage taps were used. Therefore, the I_c and n-value are determined by fitting the voltage over the two least performing tapes of the outer layer with a power-law function, the real I_c might be slightly higher. The measured I_c as function of magnetic field is presented in Fig. 6 for 1.9 K and 4.2 K. It includes the self-field correction with the expected I_c as reference. The expected I_c is derived from an I_c measurement of this cable at 4.2 K in self-field in combination with temperature and field scaling for ReBCO tape. The measured I_c is conform expectations in high background magnetic field and even higher in low magnetic field. The measured n-value is 13. A critical current of 8.2 kA is found at 9.6 T, which can be extrapolated to a benchmark critical current at 4.2 K and 10 T of 7.9 kA. The corresponding engineering current density is 174 A/mm^2 at 10 T/4.2 K. Performance is increased by about 5% by reducing the temperature to 1.9 K. The critical current is not dependent on the field-angle, since the CORC cable has an axis-symmetrical tape layout.

Voltage taps on the outer layer tapes show low current sharing between tapes, see Fig. 7. This means the tapes do not couple well, which is clearly indicated when the tapes reach their respective critical current at different currents. Tape nr. 1 builds up voltage first. This means that tape nr. 1 has the lowest contact resistance, also observed in [13], or lowest I_c of the four outer layer tapes. Tape nr. 1 is followed by tape nr. 3 and nr. 4. Tape nr. 2 showed no or minimal voltage when the current approached the cable critical current.

B. Heating and Quench Behavior

Heaters on single outer layer tapes locally reduced the critical current by raising the temperature. By turning on a single heater on a single tape, while the current is close to the I_c of the sample, all outer layer tapes respond immediately. The voltages over all four outer tapes rise evenly, most likely caused by a similar temperature rise in the other tapes than extra current due current redistribution. When both heaters are used at the same time, the same behavior is observed. The cable was quenched 11 times; 7 times using heaters and 4 times by going over the critical current. Quench current of the sample has been probed by increasing the current in small steps. The cable limit was strongly indicated by a voltage rise of the outer layer tapes, without observing thermal runaway. A quench is triggered by increasing the current over the quench current of the cable. A

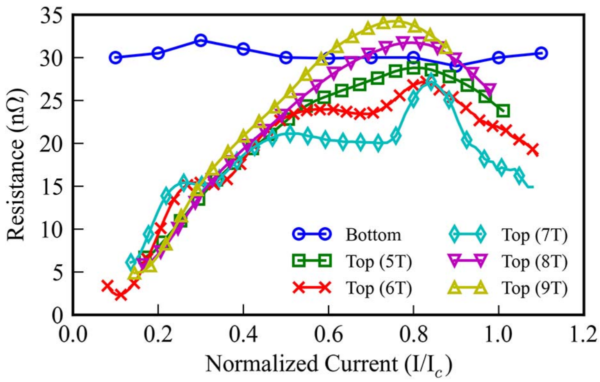

Fig. 8. Resistances of the top and bottom joint terminals as function of the normalized current. The resistance of the bottom terminal is not dependent on the applied magnetic field and current, and the resistance of the top terminal is dependent on the magnetic field and current.

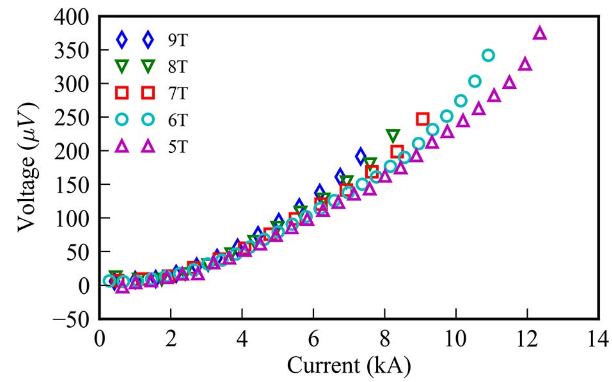

Fig. 9. Voltage over the entire CORC sample (excluding joints) for various applied magnetic fields at 4.2 K. Current redistribution takes place outside the joints, resulting in a clearly visible voltage rise far before the cable I_c is reached.

voltage in the range of 1 V/m is measured within 200 ms after thermal runaway. After the quench is detected, the power supply is turned off and the current is ramped down to zero in 100 ms. In total, a quench event takes about 300 ms. Verification measurements were performed after each quench and which showed no cable degradation due to quenching, as expected since the cable is protected by a shunt.

C. Joint Terminal Resistance

The voltage over both NbTi splices and CORC joint terminals is measured. The NbTi splice resistance of both joints is about 2 nΩ. Both CORC joint terminals were manufactured to be identical, however, they show different behavior. The measured resistances of the joint terminals as function of the normalized current are presented in Fig. 8. The joint terminal at the bottom of the sample has a constant resistance of 30 nΩ, independent of current and magnetic field. On average, the resistance of the top joint terminal is less than the resistance of the bottom terminal with a resistance of 20 to 35 nΩ. The top terminal showed high current and magnetic field dependent behavior, although the joint was positioned outside the peak applied magnetic field region. The non-linear current dependence can be explained by inhomogeneous contact resistance to the ReBCO layers. The resistance decreases when approaching critical current, which is unexpected and unexplained. The large difference between measured (20-35 nΩ) and simulated (13 nΩ) resistance is likely due to a non-perfect solder splice between the copper joint block and the cylindrical CORC joint terminal on both sides of the sample, which was confirmed by visual inspection after the test. Both splices showed similar imperfections with dispersion and local accumulation of solder. The joint resistance is higher than expected and also caused current redistribution outside the joints, clearly visible in Fig. 9. Voltage taps on the cable, located between the joints and the peak-field region, measure a resistance caused by current redistribution of about 13 nΩ on both sides, which is likely caused by the imperfect joints.

V. Outlook

The development of ReBCO-CORC cables is progressing, due improvements in the ReBCO tape technology and developments in the CORC layout and cable winding process. A J_c of 341 A/mm^2 has been reached in a field of 17 T with tapes that have thinner substrate and thinner copper stabilizer [14]. Narrower tapes of 2 mm are in production to make very flexible CORC cables that can bend at small radii. Laser striation of thin filaments into the tapes reduces the already low coupling losses even further [15]. Additional Zr doping will increase tape I_c in perpendicular field and solder coating on the tapes improves current sharing and the stability of the cable [16]. Furthermore, CERN is developing a ReBCO-CORC 6-around-1 Cable-In-Conduit Conductor for possible implementation in future detector magnets [17], [18]. The CICC comprises six CORC strands of the characterized CORC cable and is rated to carry at least 45 kA at 4.2 K and 10 T.

VI. Conclusion

A CORC cable comprising 38 ReBCO tapes was characterized in the FRESCA cable test facility at CERN. A critical current of 7.9 kA is found at 4.2 K in a magnetic field of 10 T, which corresponds to a cable current density of 174 A/mm^2. The critical current is 5% higher at 1.9 K. Eleven quenches were initiated using heaters and by going over the cable I_c. The cable survived all quenches without degradation. Both joint terminals show a resistance between 20 and 35 $n\Omega$ at critical current. These values are larger than expected requiring further investigation.

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