Recent Progress in the Development of CORC Cable-In-Conduit Conductors

Tim Mulder, Jeremy Weiss, Danko van der Laan, Alexey Dudarev, and Herman ten Kate

***Abstract*—In recent years, three unique *Re*BCO-CORC CICC samples with six-around-one cable layout were developed as technology demonstrators at CERN in collaboration with Advanced Conductor Technologies. The tests of these conductors at low temperature in external magnetic field yielded very promising results, but also showed several issues requiring improvement. A new 2.8 m long CORC CICC has been prepared to replace a degraded sample. The voids between CORC strands in the new sample are filled with solder alloy to provide increased mechanical support to the strands, however, this yielded an additional set of new challenges. The conductor has a design critical current of 100 kA at 10 T and 4.5 K and is designed specifically for high-current bus-bars and large detector-type magnets. It therefore features a copper jacket and practical conduction cooling via a cooling line embedded in the jacket.**

***Index Terms*—CORC, cable-in-conduit conductor, ReBCO, HTS.**

I. Introduction

THE in-field performance of *Re*BCO coated conductors underwent substantial improvement in recent years, with a significant rise in current density, as well as an increase of their flexibility due to the option of thinner substrate thickness. Use of *Re*BCO opens up the operating temperature range of 20 to 50 K, not accessible by any other practical superconductor. The tapes also enable a magnetic field in large magnets far beyond 20 T at 4.5 K and a dramatic increase in thermal stability compared to NbTi or Nb_3Sn based superconductors. Still, many magnet applications have current requirements that exceed the capacity of a single *Re*BCO tape. CORC, Roebel and TSTC cables [1]–[3] offer a solution by combining many *Re*BCO tapes in to a high-current cable. Still, some applications require currents greatly exceeding the capacity of a single *Re*BCO cable and therefore a next step is to combine several of these *Re*BCO cables in to a larger (often internally cooled) multi-strand conductor. CERN and Advanced Conductor Technologies are working on the development of the *Re*BCO-CORC Cable-In-Conduit Conductor (CICC). The CORC CICC is a high-current multi-strand conductor aimed for application in large-scale magnets, for example in magnets for particle detectors and fusion experiments; but also for use in bus lines feeding high currents to magnets or other devices. It features several CORC strands that are helically wound around a central rod and the most recent samples are designed to carry over 80 kA at 10 T and 4.5 K.

In 2015 a first short trial sample was produced and successfully tested at CERN [4]–[6]. In the years 2017 and 2019, three new CORC CICCs with higher current rating were prepared at CERN and ACT [7] and tested in the SULTAN test facility at the Paul Scherrer Institut in Villigen, Switzerland. One of the three samples showed promising results with near-expected critical current at elevated temperatures in the range of 40 to 60 K. The other two under-performed, but provided valuable information of the present limitations and directions for further improvement of the CORC CICCs. The measurement results of the latest three samples are presented and discussed in this paper.

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II. Conductor Properties and Test Setup

A. Properties

All CORC CICCs that have been prepared at CERN have the six-around-one cable layout with a twist pitch of 400 mm. The fusion type sample has a stainless steel jacket and internal forced flow cooling via the voids between CORC strands to cope with the relatively high heat loads and mechanical loads common to magnets in fusion reactors. The CORC strands in this CICC have a solid copper core of 5 mm and contain 42 *Re*BCO tapes. The first detector/bus-bar sample, *CICC-Cu1*, has a copper jacket and has optional internal forced-flow cooling and/or conduction cooling via a cooling line embedded in its jacket. Copper is chosen as jacket material for this CICC to give it a thermal contraction coefficient similar to the CICC with stainless steel jacket, since both the samples are measured in the same setup at the same time. The conductor is therefore primarily designed for the purpose of bus-bar instead of conductor for a detector magnet. The solid core of the CORC strands has an outer diameter of 4 mm, which is extended to 5 mm by five layers of copper tape. The preparation of the trial CICC and the first fusion and detector/bus-bar samples are described in references [4]–[7]. One new CICC has been prepared last year that has an improved mechanical design compared to the previous samples and is further described in Section IV. Properties of the three latest CICC samples and the trial sample from 2015, for reference, are presented in Table I and an overview of their layouts is shown in Fig. 1.

TABLE I
PROPERTIES OF THE FOUR CORC CICC SAMPLES

Property	Trial (2015)	Fusion Sample (2017)	Detector Sample 1 (2017)	Detector Sample 2 (2019)	Unit
Sample Name	CICC-Al1	CICC-SS1	CICC-Cu1	CICC-Cu2	
Length	1.7	2.8	2.8	2.8	m
Number of tapes	38	42	42	42	-
Number of layers	12	14	14	14	-
Tape Type	SCS4050	SCS4050	SCS4050	SCS4050	-
Copper plating	40	10	10	10	µm
Jacket material	Al-5058	Stainless Steel	Copper	Copper	-
Core material	Aluminium	Copper	Copper	Copper	
Core diameter	4	5	4	5	mm
Strand outer diameter	7.6	7.7	7.7	7.7	mm
Expected I_c (4K, 10T)	48	90	90	100	kA

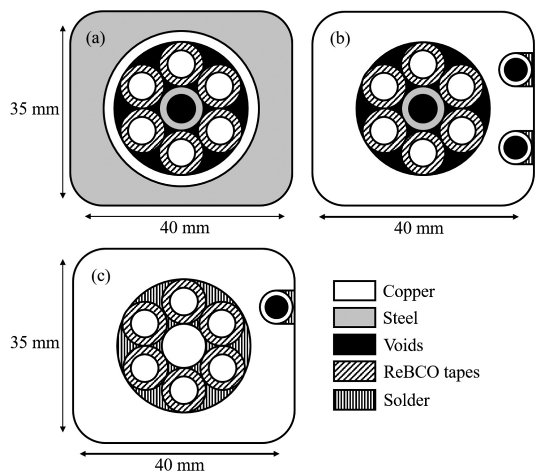

Fig. 1. (a) Layout of the *CICC-SS1* sample with a stainless steel jacket and cooling via the voids between CORC strands. A copper tube is placed around the CORC strands to increase the amount of stabilizer material in the conductor. (b) Layout of the *CICC-Cu1* sample with a copper jacket and the possibility of internal forced-flow cooling and/or conduction cooling of the CORC strands via the cooling line embedded in its jacket. (c) Layout of the *CICC-Cu2* sample. Here the voids are filled with solder and cooling is only supplied by conduction via the cooling channel in its jacket.

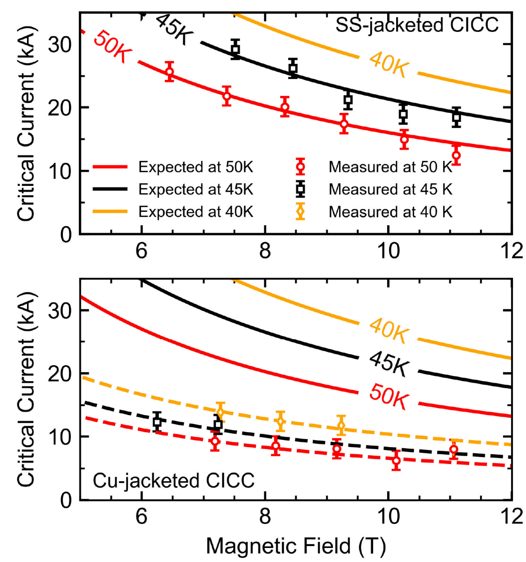

Fig. 2. Measured critical current of the SS-jacketed CICC (*CICC-SS1*) (top) and the Cu-jacketed CICC (*CICC-Cu1*) (bottom) as function of magnetic field between 40 and 50 K.

B. Test Setup

The test setup includes two samples that are electrically connected in series and are tested simultaneously. One conductor carries current through the high-field region of the split-pair magnet in one direction, and the other one carries it back. The samples are joined on the 'bottom' side of the sample holder with a praying-hands type joint and the samples are connected to the facility's power supply on the 'top' side of the sample holder with a shaking-hands type joint. The samples are measured in an external magnetic field up to 10.9 T and at an operating temperature up to 60 K.

III. RESULTS OF FUSION AND DETECTOR TYPE CICCS (CICC-SS1 AND CICC-CU1)

A. Critical Current and N-Value

The measured critical currents of both samples are presented in Fig. 2 as function of temperature and total magnetic field (external + self-field). The measured I_c of the CICC with the stainless steel jacket (*CICC-SS1*) falls within the range of expectation in the temperature interval of 40 to 60 K. The n-value of this CICC is 14 ± 3, a value very similar to the n-value of the aluminium-alloy jacketed trial sample [6]. The I_c of sample *CICC-Cu1* is much lower than expected with a critical current retention of only 30 to 40% and a n-value of 5 ± 1, shown in Fig. 3. I_c measurements on the SS-jacketed CICC could not be performed below 45 K because the samples were connected in series and the Cu-jacketed CICC already demonstrated fast thermal runaway before the SS-jacketed one showed signs of a superconducting to normal transition. The CICC with stainless steel jacket has been thermally cycled three times over all measurement runs and showed no signs of degradation due to these cycles. Also, both cooling methods, internal forced-flow cooling and conduction cooling, were demonstrated to be feasible methods of cooling for such conductor type.

B. Degradation of Sample CICC-Cu1

Individual strands of sample *CICC-Cu1* were tested post-mortem at 77 K in self-field. The critical current of the strands

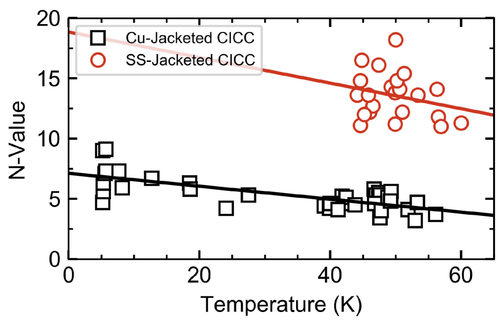

Fig. 3. Measured n-values of both the *CICC-SS1* and *CICC-Cu1* samples as function of temperature. The n-value of the stainless steel jacketed CICC (14 ± 4) is substantially higher than the n-value of the copper jacketed CICC (5 ± 1) and comparable to the n-value of the trial Al-alloy jacketed CICC.

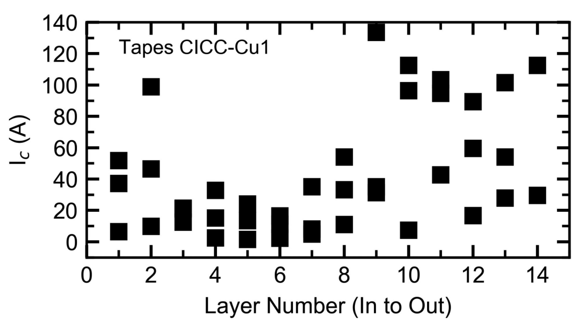

Fig. 4. Critical current of the 42 tapes that were located in the degraded region of the worst-performing CORC strand of the *CICC-Cu1* sample measured at 77 K measured at ACT. A major decrease of I_c is observed compared to the average original I_c of 135 A. The most degraded tapes are layers 3 to 7.

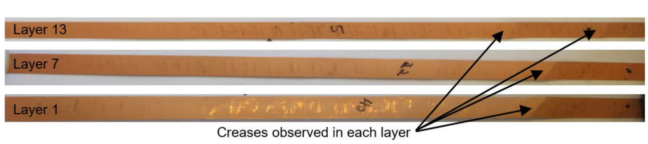

Fig. 5. Observed creases in the recovered *Re*BCO tapes from the most-degraded CORC strand. The creases are more pronounced in the tapes that were located closer to the strand's core, which indicate local kinking due to insufficient mechanical support.

ranged from 20 to 60% of their original I_c [8]. The location of the degradation is pinpointed to several specific regions that were located in the high-magnetic-field zone of the facility's test setup. Single tapes from the degraded regions were analyzed and showed substantial degradation of their critical current, presented in Fig. 4. Visible creases on the tapes, shown in Fig. 5, indicate that the tapes did not have sufficient mechanical support during the test. Similar degradation has been observed in CORC wires that were pushed to their limits. Such degradation was as well traced back to mechanical strain in the *Re*BCO tapes [9]. Although CORC strands/cables are able to withstand high transverse loads applied on their central axis [10], it is likely that in this case the combination of off-axial forces on the CORC strands in the six-around-one configuration, non-optimal cabling parameters and the thinner and softer copper core facilitated a destructive pinching effect on the tapes, as illustrated in Fig. 6.

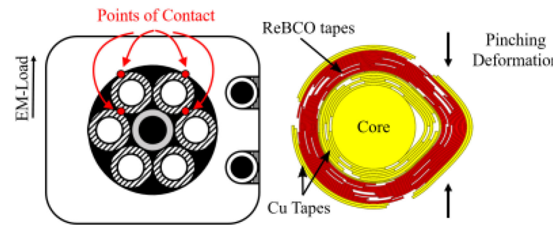

Fig. 6. Illustration of the destructive pinching effect on the tapes of the CORC strands due to a too thin core and not-optimal tape tension when the CICC is operated in an external magnetic field.

The pinching pushes the strain within the tapes over the critical limit and causes permanent degradation. The degradation only occurred in the CORC strands of the *CICC-Cu1* sample, as these strands have different winding parameters, e.g., the thinner solid core that is supplemented with Cu-tapes, compared to the ones in the *CICC-SS1* sample, and thus offer less mechanical support to the tapes.

IV. Second Detector CICC (CICC-Cu2)

A. Conductor Improvements

A new six-around-one CORC CICC was prepared to replace the degraded one. Each strand contains 42 ReBCO tapes with a slightly higher performance rating compared to the tapes in the previous samples. The solid core diameter is increased from 4 to 5 mm to improve handling of the large electro-magnetic loads. In contrast to its predecessor, the voids between the CORC strands are fully filled with a solder alloy (BiSnPb). The solder filling is present for additional mechanical support of the CORC strands. Its joint terminals are filled with indium for a very low resistance connection of about 1 nΩ at 4.2 K and 12 T. Cooling is only supplied via conduction through a cooling line soldered in the conductor's jacket, as shown in Fig. 1.

B. Performance of Sample CICC-Cu2

The second Cu-jacketed CORC CICC was tested in series with the stainless-steel jacketed one and demonstrated a much lower performance than expected with a critical current of about half of the expected value. The stainless-steel jacketed CICC, however, did not show a decrease in performance compared to the previous test. The low performance of the *CICC-Cu2* sample likely has a different origin than the degradation in the *CICC-Cu1* sample. It appears to have originated from inhomogeneous current distribution between CORC strands, which in turn can be traced back to the joint terminals. The likely cause of this behavior is unexpectedly fast alloying between the indium in the joints and the filler BiSnPb metal in the central part of the CICC while filling the voids between CORC strands. The alloying may have occurred over a large section of the joint terminal, instead of a small alloying region at the interface of the jacket and the terminal, because the resulting intermetallics within the InBiSnPb phase diagram can have melting temperatures as low as 58 °C. These intermetallics also tend to have much

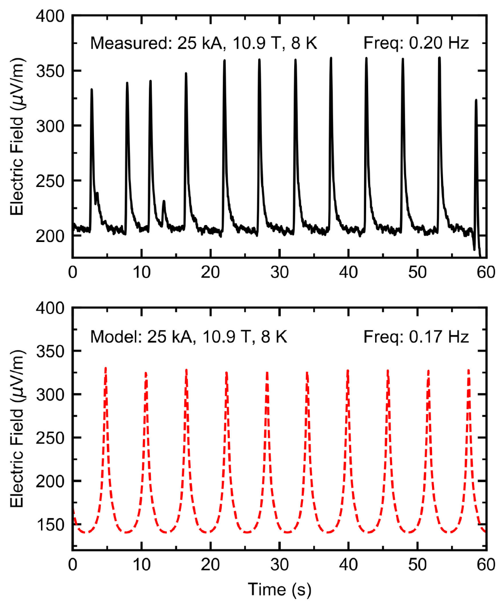

Fig. 7. Measured oscillations of the electric field (top) at a current of 25 kA, an external magnetic field of 10.9 T and a temperature of 8 K. At this current, the frequency of the voltage oscillation is 0.20 Hz. At a current of 24 kA, the frequency is reduced to 0.10 Hz. The calculated voltage oscillations have a similar frequency and amplitude as the measured ones.

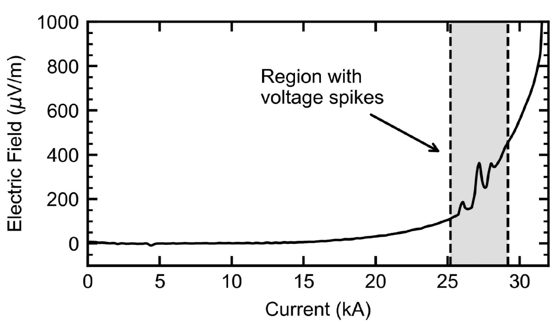

Fig. 8. Voltage over the CICC-Cu2 sample as function of current during a ramp to quench with 400 A/s at 15 K and 10.9 T. Voltage and temperature oscillations occur in a very narrow region that is highly depended on operating current and temperature. Below this region no oscillations are present. Within the region, there are oscillations, but the conductor recovers as cooling is sufficient. Above the region, a quench is imminent.

higher resistances than pure indium and likely resulted in a large variation in the strand contact resistance.

During the measurements, a peculiar phenomenon appeared in the voltage across- and the temperature of the *CICC-Cu2* sample. Highly repetitive voltage and temperature oscillations were measured. The oscillations in the electric field are shown in Fig. 7. Their frequency, amplitude and presence are dependent on temperature and sample current, and an example is given in Fig. 8. This phenomenon can be explained by one (or a few) of the CORC strands carrying a much higher current than the other strands, due to the large variation in contact resistance. At a certain current, thermal runaway occurs within these strands. Induction prevents current from immediately redistributing to the other strands, and therefore causing a sudden spike in voltage and consequently in temperature. Over time, the current eventually redistributes, which allows the quenched strands to cool down and thus to recover. This is followed by current distributing back in to the recovered strand and restarting the same loop of events. Very similar values for the voltage and temperature oscillations can be obtained by simulation, as shown in Fig. 7. The model solves a one-dimensional nodal network that combines the electrical LR-circuit of the CICC geometry with the corresponding thermal equations. It assumes that one CORC strand has a much lower contact resistance than the others, forcing most current in to this strand until thermal runaway occurs. Although the model is fairly simple, its resulting values are in close resemblance with the measured ones and it offers a likely explanation of what occurred without having to open the sample, as that is currently not possible. The model also showed that such oscillation can only occur with a very specific combination of inductance values, cooling, current distribution and the relatively large transition-temperature range of HTS materials. This makes this a phenomenon very specific to HTS multi-strand conductors.

C. Refilling of the Sample

The joint terminals of the *CICC-Cu2* sample were emptied after the tests and the solder was analyzed. The solder in both terminals was confirmed to be a mixture of the original indium solder and the BiSnPb filler metal, with a highly non-eutectic melting temperature of 60 to 80 degree Celsius. The solder in the CICC and its joint terminals has been drained and the CICC and terminals were subsequently refilled with indium to restore the electrical connection to the CORC strands.

At the time of writing, it is uncertain if the CORC strands in the CICC actually sustained degradation or if refilling allows recovery of the full expected performance of the sample. Further tests are scheduled for the first half of 2020.

V. Conclusion

In recent years, three CORC Cable-In-Conduit Conductors were prepared and tested. One was designed for magnets for fusion experiments and two were designed for detector type magnets and bus-bars. The 'fusion' CICC has a measured critical current that follows expectations in the measurement range of 40 to 50 K. It has an n-value of 14 $\pm$ 3, which is similar to the n-value of the first CICC trial sample. It underwent three thermal cycles and showed no straightforward signs of degradation due to the cycling. The first 'detector/bus-bar' CICC shows an I_c retention of only 30 to 40% and a low n-value of 5 $\pm$ 1 in the temperature range of 40 to 60 K. The degradation is likely caused by a mechanical pinching effect in high electro-magnetic load operation due to a too thin and soft strand core and not-optimal cabling parameters. A second 'detector/bus-bar' CICC was prepared to replace the first one. This one has improved mechanical support for the CORC strands that allow better performance in high magnetic field and high current operation. This conductor unfortunately encountered a current sharing issue which prevented accurate I_c measurements. This issue is currently being resolved and new measurements results are expected early 2020.

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