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Design and Preparation of Two ReBCO-CORC® Cable-In-Conduit Conductors for Fusion and Detector Magnets

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Abstract. Two new ReBCO-CORC® based cable-in-conduit conductors (CICC) are developed by CERN in collaboration with ACT-Boulder. Both conductors feature a critical current of about 80 kA at 4.5 K and 12 T. One conductor is designed for operation in large detector magnets, while the other is aimed for application in fusion type magnets. The conductors use a six-around-one cable geometry with six flexible ReBCO CORC® strands twisted around a central tube. The fusion CICC is designed to be cooled by the internal forced flow of either helium gas or supercritical helium to cope with high heat loads in superconducting magnets in large fusion experimental reactors. In addition, the cable is enclosed by a stainless steel jacket to accommodate with the high level of Lorentz forces present in such magnets. Detector type magnets require stable, high-current conductors. Therefore, the detector CORC® CICC comprises an OFHC copper jacket with external conduction cooling, which is advantageous due to its simplicity. A 2.8 m long sample of each conductor is manufactured and prepared for testing in the Sultan facility at PSI Villigen. In the paper, the conductor design and assembly steps for both CORC® CICCs are highlighted.

1. Introduction

Magnets for large scale particle detectors, magnets for fusion experiments, and their bus lines require high currents in high magnetic fields at a wide range of operating temperatures. The operating limits of NbTi and Nb_3Sn conductors in terms of magnetic field, current density and temperature warrant the development of cables made from high temperature superconductors (HTS).

HTS materials such as ReBCO (Re = Rare Earth), BSCCO or MgB_2 greatly broaden the operating spectrum of temperature, current and magnetic field ranges compared to cables using traditional Nb-based low temperature superconductors. CERN is exploring several HTS options, including the use of MgB_2 for superconducting links that power parts of the Large Hadron Collider [1], as well as ReBCO based conductors using either Roebel [2] or Conductor On Round Core (CORC)® cable variants [3].

The CORC® cable is a round conductor that offers isotropic flexibility in combination with high current densities, ranging from 100 to 600 A/mm^2 at 4 K and 10 T, and high electrical

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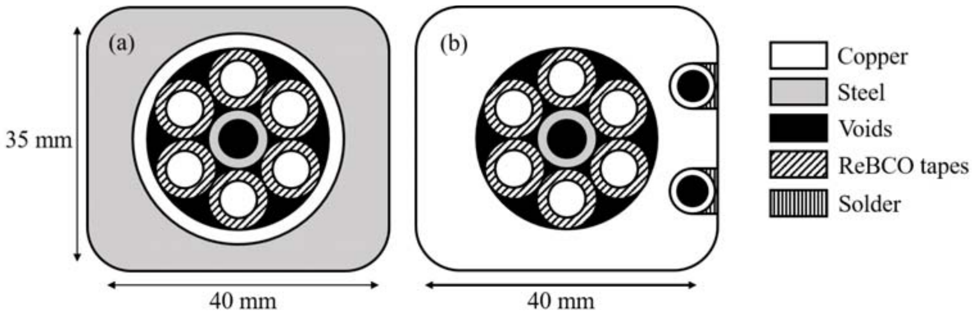

Figure 1. CORC® Cable-In-Conduit Conductor cross-sections with (a) stainless steel jacket for fusion magnets and (b) copper jacket for detector magnets and bus bars, comprising two additional cooling channels for conduction cooling.

and thermal stability. Several CORC® strands can be combined within a jacket to make a Cable-In-Conduit Conductor (CICC) designed for carrying high currents up to 100 kA at 4 K and 10 T, which are required for the next generation of magnets for particle detectors and their bus bars.

The first of its kind CORC® six-around-one CICC was manufactured and successfully tested in 2016 [3]. This demonstration conductor comprised 6 CORC® strands in the six-around-one configuration in combination with an aluminium alloy jacket. Two tests were performed: first in liquid helium in an external magnetic field of 9 T, and second in liquid nitrogen in self-field.

Two new and much improved CORC® CICCs are presented here, featuring a higher current rating and internal forced-flow cooling combined with external conduction cooling for one of the samples, as presented in Figure 1. One new conductor is especially designed for use in high magnetic field- and high heat load environments found in tokamak type fusion magnets. The other conductor is designed for high thermal- and electrical stability, as required in detector magnets and superconducting bus bars. Two 2.8 m long conductors were manufactured at CERN in collaboration with Advanced Conductor Technologies (ACT). Both conductors are to be tested in the SULTAN cable test facility at PSI, Villigen, Switzerland in the second half of 2017.

2. New CORC® Cable-In-Conduct Conductors

The two new CORC® CICC conductors are similar in terms of general design, cable configuration, performance and joint terminals. They differ in method of cooling and jacket material.

2.1. ReBCO CORC® Six-Around-One Cable

Both conductors use the six-around-one cabling layout where the cable comprises six CORC® strands, helically twisted around a stainless steel center tube. Each strand contains 42 SCS 4050 ReBCO tapes from Superpower Inc., for a total of 252 tapes in the CICC. The tapes have 5 μm of copper plating on each side which greatly increases the strand current density compared to the tapes in the previous CORC® CICC that had 20 μm of copper plating on each side.

The CORC® strands for each CICC are slightly different in design. The core of the CORC® strands for the fusion-type CICC is a solid copper former approximately 5 mm in diameter while the strands for the detector-type CICC has a solid copper former of 4 mm in diameter that is extended to 5 mm diameter using 5 layers of copper tapes. The thinner solid copper core makes the second type of strands easier to twist. The disadvantage is that after twisting, these strands tend to spring out a bit more than the strands with the thicker, more rigid core.

The CORC strands consist of 14 layers of ReBCO tape that are wound around the 5 mm copper core followed by two additional layers of copper tapes and a layer of polyester insulation. The outer diameter of each strand is 7.6 mm. The twisting from CORC® strand to six-around-one CORC® conductor was done manually. The twist starts around 150 mm distance from the joint section. The strand pitch length is 400 mm allowing a full pitch in the high magnetic field region of the SULTAN facility. There are 4.5 cable pitches between the joint terminals.

The polyester insulation around the CORC® strands protects the tapes during twisting. This insulation was removed after twisting to allow firstly direct contact between gas/liquid and the tapes, and secondly, electrical contact between CORC® strands. Each six-around-one bundle is wrapped in a layer of 50 μm thick and 40 mm wide copper foil for mechanical protection inside the jacket.

A detailed overview on the conductor properties is presented in Table 1. In addition the table provides details on the conductor that was tested in 2016 at CERN to show the evolution in size and performance of the CORC CICCs.

Table 1. Properties of the new (2017) and old (2016) CORC® Cable-In-Conduit Conductors.

	2016 CICC Test Sample	2017 CICC Fusion Sample	2017 CICC Detector Sample
Layout	Six-Around-One	Six-Around-One	Six-Around-One
Cooling Method	Liquid Bath	Int. Forced-Flow	Int. Forced-Flow + Ext. Conduction
Jacket Material	Aluminium Alloy	Stainless Steel	OFHC Copper
Jacket Dimensions [mm x mm]	30 x 30	40 x 35	40 x 35
Number of Strands	6	6	6
Strand Diameter [mm]	7.6	7.6	7.6
ReBCO Tapes per Strand	38	42	42
ReBCO Layers per Strand	12	14	14
Length [mm]	1700	2777	2777
Cable Pitch Length [mm]	400	400	400
Cable Pitches	1.5	4.5	4.5
Calc. I_c at 4K/12T [kA]	42	80	80
$J_{Stabilizer}$ at 80 kA [A/mm^2]	133	79	232

2.2. Cable Performance

The cable is rated for 80 kA at 12 T and 4 K. The CORC® strands are twisted to form a cable of 23.6 mm in diameter. The outer layers of copper foil increase the diameter to 24.0 mm before jacketing for a total area of 452 mm^2. The cable current density is rated for 176 A/mm^2 at 12 T and 4 K.The critical current is calculated using single tape I_c(B, T) scaling data, in combination with the corresponding length and angle dependence after being wound to a CORC® strand.

The calculated engineering current density of the entire conductor including the jacket sized 35 mm x 40 mm, is 57 A/mm^2. Measurements are scheduled at temperatures ranging from 4 K up to 50 K. The calculated I_c(B) curve of the CICCs for various temperatures is presented in Figure 2.

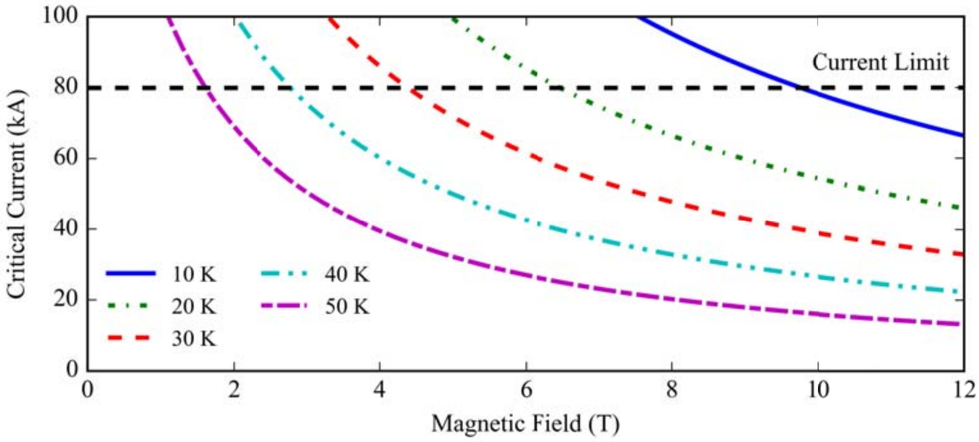

Figure 2. Projected cable critical current versus magnetic field, I_c(B), for various operating temperatures. The measurement station has a current supply limit of 80 kA and therefore it is not possible to measure I_c(B) at low applied magnetic field and low temperatures.

2.3. Conductor Jackets and Cooling layout

The fusion-type CORC® CICC has a stainless steel jacket and internal force flow cooling. High strength materials, such as stainless steel, are needed in modern tokamak magnets for taking up and transferring the enormous accumulated Lorentz forces acting on the superconducting cables during operation. The high heat load from fusion heating on the conductor requires internal flow cooling, as conduction cooling is not effective via the stainless steel jacket. The bore of the stainless steel jacket is 28 mm in diameter. The six-around-one CORC® cable is enclosed by an OFHC copper tube with a wall thickness of 2 mm for a total cable outer diameter of 28 mm. The copper tube is soldered in to the copper joint terminals to provide a parallel path for the current if necessary. The CICC and the six-around-one cable during assembly are shown in Figure 3.

The forces acting on the conductors of detector magnets and their bus lines are much lower compared to the forces in fusion magnets. Therefore, a material with lower strength and higher thermal and electrical conductivity can be used to jacket the six-around-one CORC® cable. In practice, high purity aluminium is commonly used in conductors for detector magnets due to their high radiation transparency. OFHC copper stabilizer is not uncommon in conductors for detector magnets, but better suited for their bus bars. The high thermal conductivity of these materials opens the possibility of a conduction cooled conductor and greatly improves its thermal and electrical stability. Conduction cooling is preferred for its simplicity and practical implementation. The detector-type CORC® CICC sample has an OFHC copper jacket with two helium lines integrated in the jacket for conduction cooling, as well as the option of internal forced-flow cooling via an additional helium line entering the jacket near the joint terminals. The cooling schematic for the CORC® CICC samples is presented in Figure 4.

Copper was chosen over aluminium in the detector-type CICC sample because it more closely matches the thermal expansion of the stainless steel jacket of the fusion-type CICC, since both sample are measured in series in the same sample holder. The copper material of the jacket is cold worked, high tensile strength OFHC copper, since stresses up to 200 MPa are expected in the jacket during the test in Sultan that would exceed the yield strength of fully annealed OFHC copper. In practice, the copper jacket can be fully annealed if this conductor is used in a lower stress environment such as in detector magnets and their bus lines. The peak stress in

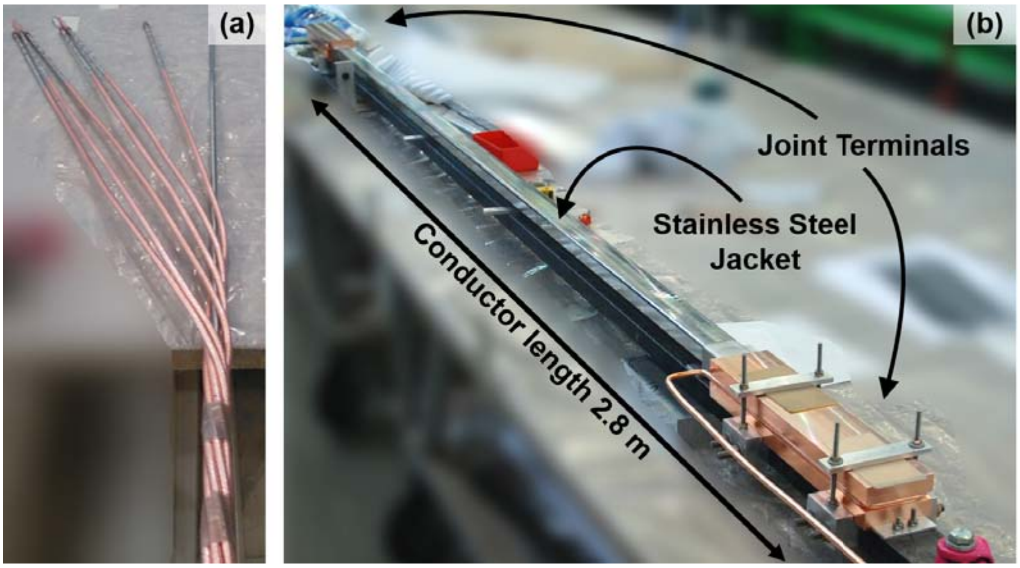

Figure 3. (a) Winding of the six-around-one CORC® cable performed manually around a stainless steel tube. (b) The CORC® CICC with the two joint terminals and the stainless steel jacket during assembly. The conductor is mounted on a stainless steel bar during assembly to ensure that both joint terminals are mounted exactly parallel.

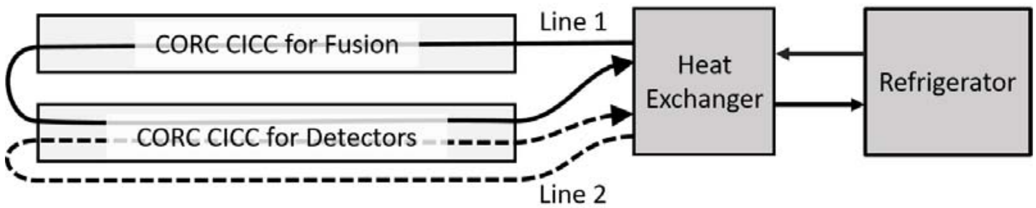

Figure 4. Schematic of the two cooling channels including the heat exchanger. The temperature of the helium gas in each channel is individually regulated by heaters and the heat exchanger. The heat exchanger is not present if the sample is cooled with liquid helium. The mass-flow in each channel can be regulated. Line 1 (solid line) applies internal forced flow cooling to the CORC® CICC within the stainless steel jacket and returns as a conduction cooling line for the CORC® CICC with copper jacket. Line 2 (dashed line) supplies additional forced-flow cooling to the CORC® CICC with copper jacket if necessary.

the stainless steel jacket is well below its yield strength.

Each jacket is divided in two halves lengthwise. The halves of the jackets are mounted and welded using electron beam welding for both the stainless steel jacket and the copper jacket. A bimetallic connection between copper joint terminals and stainless steel jacket is created by brazing a 50 mm long stainless steel adaptor piece to the joint terminals. The adaptors are shown in Figure 5.

The six-around-one CORC® cable was inserted via the adaptor to the terminal. Access to the terminal for soldering was possible via the small gaps between CORC® strands. The CORC® CICC with the copper jacket has the same adaptor pieces to provide symmetry between the two conductors. The adaptor pieces also serve as inlet and outlet points for the internal gas flow cooling.

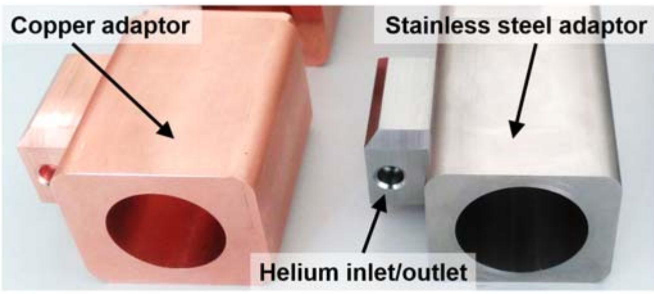

Figure 5. The picture shows the copper and stainless steel adaptor pieces before assembly in the conductor. The adaptor pieces are later brazed to the copper joint terminals and form the link between terminal and jacket. The jackets are welded to the adaptor pieces using electron beam welding. These adaptors also serve as inlet and outlet points for the internal forced-flow cooling.

3. Joint Terminal Layout and Optimization

The joint terminals are designed for a low resistance connection that distributes current equally between CORC® stands. The expected joint terminal resistance is about 2 nΩ per joint terminal at 4 K for a total loop resistance of 8 nΩ. At 50 K, the expected resistance is approximately 6 nΩ per terminal for a total loop resistance of 24 nΩ. The copper joint terminals are 305 mm in length, in which the CORC® strands are inserted over a length of 285 mm.

The connection from CORC® strands to terminals is made in a similar fashion as in the previous (2016) CORC® CICC sample [5]. The entire terminal is heated to about 196±2 °C and filled with eutectic Sn63Pb37 solder. The ends of the CORC® strands are tapered to a staircase like geometry and solder coated. That means several upper layers of the CORC® strands are cut short to facilitate direct, low resistive current injection to the inner ReBCO layers. This termination method has been successfully applied in terminals for single CORC® cables [4] and is explained in more detail in reference [5]. Twisting of the strands within the terminal is hardly possible due to the solder coating on the strand ends, therefore they remain straight in the terminals. The cooling tubes are soldered in a groove on the surface of the joint terminals in the last step of the CICC assembly. Soldering of the cooling tubes is performed with low temperature solder (Sn44In42Cd14), such that the solder in the terminals is not affected.

3.1. Current Distribution in the Cables

The samples are relatively short with 2777 mm end-to-end distance. Current is mainly distributed in the joint terminals, since there is only a relatively low pressure contact between strands. The CORC® strands are twisted such that half a cable pitch difference remains between joint terminals. The half pitch difference ensures a specific strand layout within the terminals, as shown in Figure 6. This layout purposely avoids that one or two strands have a much lower contact resistance compared to the other strands and instead forces a very similar contact resistance to each strand, thereby greatly improving current distribution between strands.

Calculations show that by using this shifted layout, the current distribution between strands differs up to 5% at temperatures around 40 to 50 K compared to 35% in case of a full cable pitch difference [6]. The current distribution in the 5 to 15 K range improves as well by applying this strand layout, however the effect is less pronounced due to the lower resistivity of the copper. The difference in current distribution is reduced from 20% to about 3% in this case.

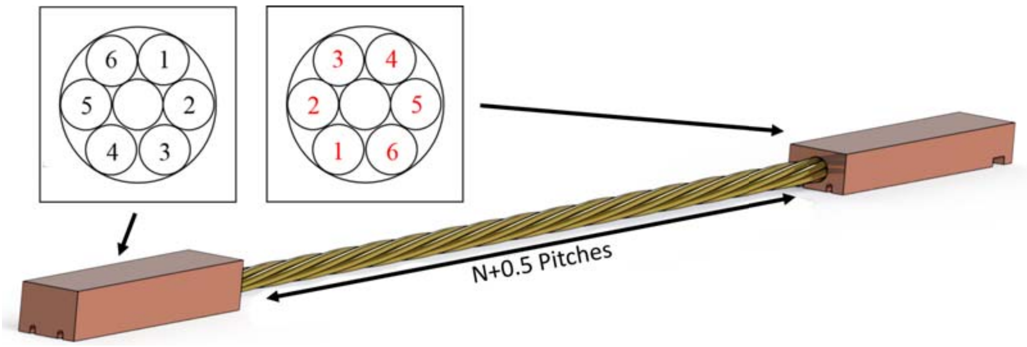

Figure 6. The CORC® six-around-one cable with a terminal connected on each end, including the strand layout inside the two terminals. Current is injected/extracted from the bottom of the terminals. There is half a cable pitch difference between terminals. This shift in cable pitch equalizes the total contact resistance per strand and forces a more homogeneous current distribution in the cable.

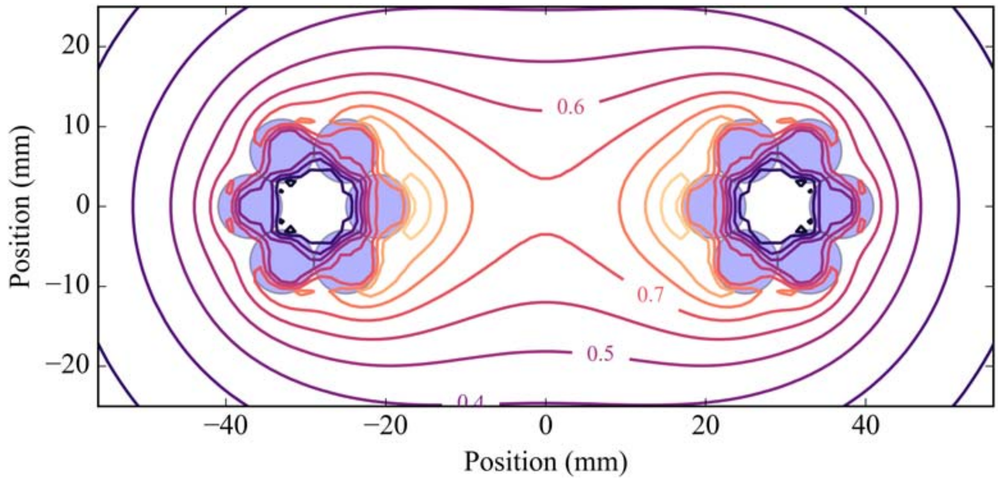

Figure 7. The contour-lines of the self-field of the CORC® CICC conductors in the sample holder for the test at PSI. Both conductors combined produce approximately 1 T per 50 kA peak field on the cable. Since the 6-around-1 cable is twisted, all six strands will experience this peak field at some point within a full cable pitch.

4. Full Sample and Measurement Facility

The SULTAN cable test facility features a 10.8 T split pair solenoid providing the test magnetic field with 2% uniformity over a section of 400 mm [7]. The self-field on the sample is about 1 T per 50 kA in all cable orientations as presented in Figure 7. That results in a maximum magnetic field on the conductor of 12.4 T in the peak field region of the SULTAN magnet system at full background field.

The Sultan test facility offers the possibility to cool the sample with 10 g/s helium gas in the range of 5 to 50 K or with liquid helium at 4.5 K. In case when the sample is cooled by gas, the temperature is regulated with the combination of a heat exchanger and heaters. Both straight sections of CORC® conductors are combined in series to a hairpin test sample with one leg carrying the feed current and the other carrying the returning current through the high field region of the facility.

The forces in the samples are directed outwards. An aluminium alloy clamping structure

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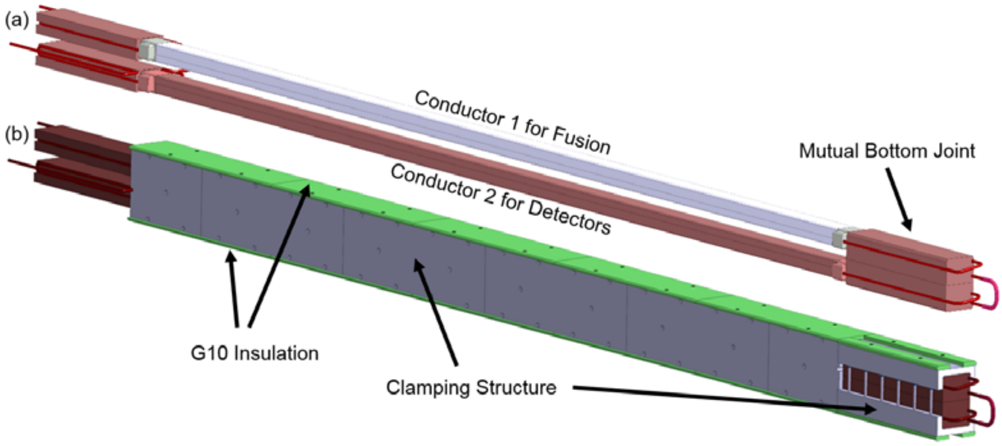

Figure 8. (a) The two bare CICCs jointed together on one side without any of the clamping structure. (b) Both CICCs including the clamping structure and insulation/guiding plates.

keeps both conductors together. G10 plates on the surface of the aluminium alloy clamps serve as a guiding system for inserting the sample into the station and also provide insulation between the cryostat and the sample. The joint terminals of the sample make a clamping contact to the terminals of the facility using squeezed indium wires as the interface to minimize the contact resistance. The terminals on the bottom side of the sample where the current returns feature a soldered contact using indium as soldering material. A schematic drawing of the two conductors in combination with the clamping system in presented in Figure 8.

5. Conclusion and Outlook

Two new ReBCO CORC® Cable-In-Conduit Conductors were manufactured at CERN. One has a stainless steel jacket aimed for use in magnets for fusion experiments and the other CICC has a copper jacket for implementation in detector magnets and superconducting bus bars. Both conductors are rated for 80 kA at 12T/4K.

The joint terminals were produced using a proven method that was developed and tested with the previous CORC® CIC-Conductor [3]. The joint terminal resistance is expected to be about 2 nΩ at 4 K and 6 nΩ at 50 K.

The performance test of both conductors and their joint terminals at various temperatures will take place in the SULTAN cable test facility in August and October of 2017.

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