Journal of Physics: Conference Series

PAPER • OPEN ACCESS

# Development and test of a 35 kA - HTS CroCo cable demonstrator

To cite this article: K-P Weiss *et al* 2020 *J. Phys.: Conf. Ser.* **1559** 012082



Journal of Physics: Conference Series **1559** (2020) 012082 doi:10.1088/1742-6596/1559/1/012082

# Development and test of a 35 kA - HTS CroCo cable demonstrator

**K-P Weiss, W H Fietz, M Heiduk, C Lange, A Preuß, M J Wolf**

Karlsruhe Institute of Technology, Institute for Technical Physics, Hermann von Helmholtz Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

klaus.weiss@kit.edu

**Abstract.** The answer to energy-efficient electric power transfer of high currents in the range of several tens of kA can be given by high temperature superconducting (HTS) cables. BSCCO and $MgB_2$ have been used widely for such cables, reaching maximum currents of about 20 kA. REBCO coated conductors are promising for future HTS cables beyond 20 kA and allow the operation based on subcooled liquid nitrogen. Several cabling concepts based on REBCO tapes were developed world-wide to realize such cables. Using the stacked-tape concept, a scalable semi-industrial process was developed by KIT, called HTS CrossConductor (HTS CroCo). Key aspects of the conceptual design of high-current HTS cables are discussed and the design of a 35 kA DC cable demonstrator made from HTS CroCo strands is presented. Aspects regarding joints, current redistribution between individual strands and electrical stabilization are highlighted. The performance of this demonstrator cable was tested, reaching the envisaged current.

## 1. Introduction

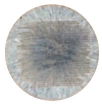
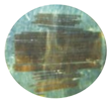
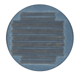
Technical superconductors in the shape of round wires or tapes are facilitated for various technology fields. Beside of magnet technology several superconducting applications enter the market within the field of power technology, e.g. rotating machines, transformers, fault current limiters or power transmission [1-3].

One specific area of application can be found within high power consumption industry as steel, paper, glass, chemicals and metals production [4, 5]. For direct current (DC) cables, superconducting characteristics are of interest operating at high currents with zero loss. Especially high temperature superconducting (HTS) cables can give an answer to energy-efficient electric power transfer of high currents in the range of several tens of kA. Projects based on *BSCCO* and $MgB_2$ reached maximum currents of about 20 kA. With the *REBCO* coated conductors HTS cables beyond 20 kA are now feasible operating at a temperature of 77 K or below. Typical electrical currents for such applications range from about 10 kA up to 100 kA [6-11].

Starting from a single HTS tape provided by commercial suppliers several cable concepts were developed to bundle tapes into larger strands to reach high currents [12]. At KIT a stacked-tape cable concept, called HTS CrossConductor (HTS CroCo) was developed. The scalable semi-industrial process allows to produce in a continuous mode strand length in the range of several meter. The strands are used for the various projects based on this technology, like fusion magnets or power applications [12-14]. To adapt these HTS CroCo strands to the specific needs, it is possible to obtain strands with different size and performance depending on the used width and number of tapes within these strands as shown in table 1 [15].

Developing towards a 100kA cable prototype the test of a 35kA demonstrator as described in this work will prove the feasibility of this technology. In section 2 the design of a 35kA demonstrator is shown to allow the characterization of the superconducting performance. In section 3 the HTS CroCo production is described and the performance of the obtained strands presented. The test results of the demonstrator are given in section 4. Finally, in section 5 the results are discussed in the context of optimization and the next steps foreseen.

**Table 1.** Example of HTS CroCo strands produced in various sizes

| | **6/4 CroCo** | **4/3 CroCo** | **4/2 CroCo** | **3/2 CroCo** |
|---|---|---|---|---|
| |  |  |  |  |
| Number of REBCO tapes | 22 x 6 mm<br>10 x 4 mm | 28 x 4 mm<br>10 x 3 mm | 18 x 4 mm<br>18 x 2 mm | 18 x 3 mm<br>10 x 2 mm |
| Diagonal of the cross | 7.2 mm | 5 mm | 4.5 mm | 3.6 mm |
| $I_c$ (T=77K, s.f.) [a] | 3,100 A | 2,090 A | 2,000 A | 1,460 A |
| $I_c$ (T=4.2 K, B=12 T ǁ c) [a] | > 10 kA | ~ 9.5 kA | ~ 6.5 kA | 6.0 kA |
| Bending radius $R_{min}$ | 60 cm | 45 cm | 40 cm | 30 cm |

[a] max. critical current $I_c$ depends on used tape.

## 2. Design of 35kA Cable Demonstrator

Common aspects of superconducting cables as shown in figure 2 are the superconductor itself for current transport together with an electrical stabilizer for protection in case of a fault, then coolant area to maintain a cryogenic temperature, a thermal insulation to reduce the heat input during operation, and finally an electrical insulation to separate the cable from ground potential [6, 16]. Summarizing all these components the typical sizes of a cable should be below 200 mm, e.g. to allow sufficient length of cable to be stored on a standard drum.

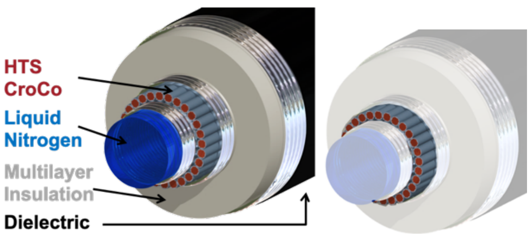



**Figure 1.** A typical cable layout is shown on the left hand side with all integral parts. On the right hand side only the superconducting core investigated in this work is highlighted.

In this work the focus is on the superconducting performance of such a cable made with HTS CroCo strands. Aiming towards a 100kA-class cable it was decided to use 6/4 CroCos to balance maximum current and the diameter to arrange the strands. This consideration led to a core diameter of about 130 mm to fit 36 strands. As stated already, a 35 kA cable demonstrator will be the first step in this qualification process of such a cable. The number of strands as an integer fraction of a 360° circumference allows a symmetric design and downscaling to a 35 kA cable demonstrator. Using one third of the 36 strands, results in a 12 strand cable. In this study the operational current is equal to the critical current of the cable defined by a 1 $\mu$V/cm criterion,

To reach the envisaged current, 6/4 CroCos need to produced using commercial tapes with a specified minimum critical current of about 30 A/mm-width at a temperature of 77 Kelvin and self-field conditions. In total 22 tapes with 6 mm width and 10 tapes with 4 mm width are used. The total copper cross section per CroCo is about 17.2 mm². In figure 2 self-field calculations are shown for the 36- and the 12-strand configuration on the 130 mm core circumference to predict the total critical current to be achieved. The calculations were performed with the FEM software tool COMSOL. The tapes within the strand are arranged to minimize the influence of the magnetic field. The magnetic field should be parallel tape surface, due to the critical current anisotropy regarding magnetic field orientation to the tape. As to symmetry reasons it is sufficient to analyze single CroCo strands to reduce calculation time.

The 36-strand configuration will achieve about 104 kA, while the 12-strand configuration should allow 37 kA at 77 K, self-field. For the 36-strand cable the close in view in figure 2 of the strand cross section shows a significant increase of the magnetic field up to 0.44 T from the inner to the outer side, but with the magnetic field *B* oriented almost parallel to the tape surface. In the 12-strand cable the impact of adjacent strands is significantly smaller and an almost circular field orientation around the strand as in a single-strand configuration is maintained. The maximum field of about 0.28 T is observed at the outermost 4-mm wide tapes of the HTS CroCo strands.

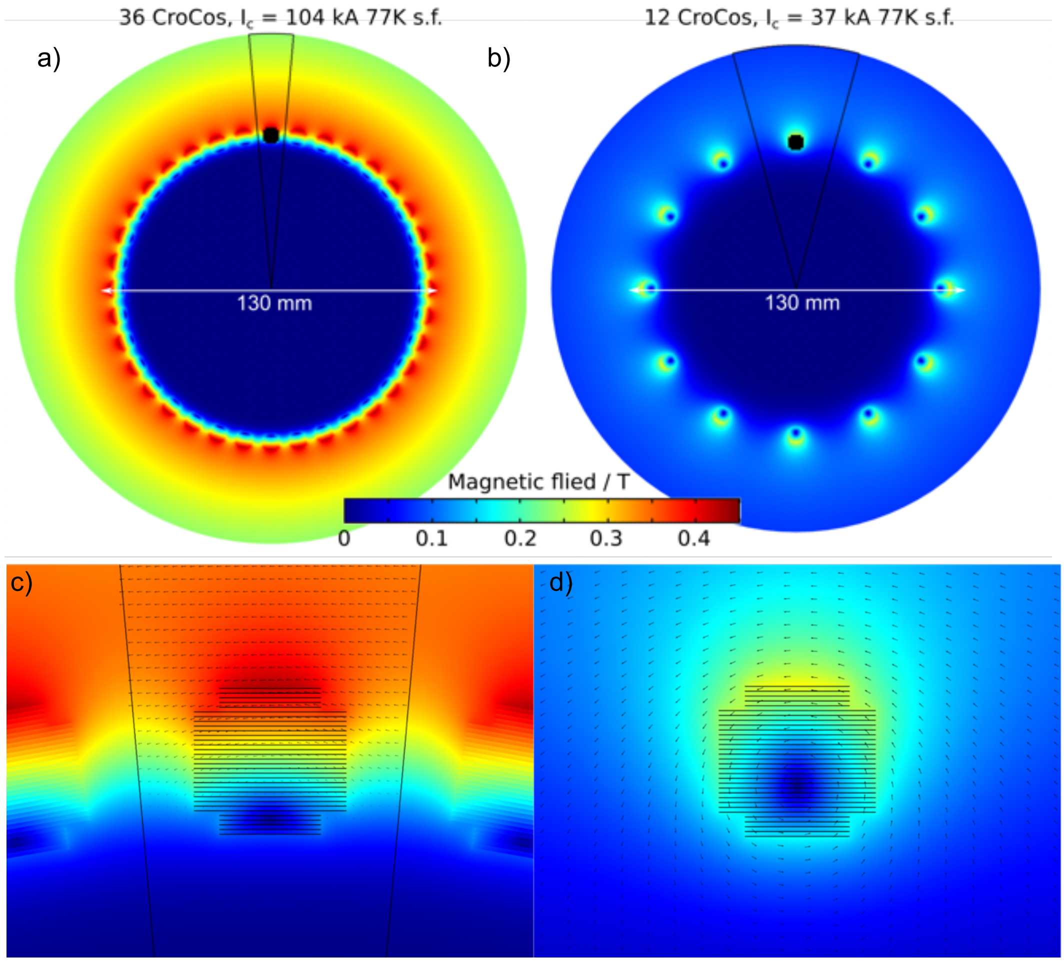



**Figure 2.** Finite element analysis to determine the maximum current for strands arranged around a 130 mm circumference. In a) 36 strand configuration at a maximum of 104 kA and in b) the 12 strand configuration at 37 kA is given. Below in c) and d) the corresponding detail of a single strand is given. Arrows indicate the field orientation.

The difference in the field profiles has a direct impact on the achieved critical current per CroCo strand. Despite the significantly higher absolute values of the magnetic field at the positions of the HTS CroCo strands, only reduction of about 7% per strand from the 12-strand to the 36-strand configuration is seen due to the more favorable field orientation.

In table 2 details of the cable demonstrator specifications can be found. The overall length of the superconducting cable was set to be at least 3 m, operated at 77 K in liquid nitrogen at atmospheric pressure. The maximum voltage should not exceed 50 V due to safety reasons, while the fault current of 50 kA was given by the maximum current of the power supply. The design reaction time to switch of the current is assumed to be 1 s, although the quench protection system is able to react within milliseconds.

**Table 2.** Specification of the cable demonstrator

| Description | Value |
|---|---|
| Operational current | 35 kA |
| Operational voltage | < 50V |
| Cable length | 3 m |
| Fault current | 50 kA |
| Fault duration | 1 s |
| Operational temperature | 77 K |
| Maximum outer diameter | 130 mm |

To characterize the superconducting performance of the cable demonstrator, a controlled environment is necessary. Therefore, the strands are mounted around a central former and connected separately by flexible copper leads to allow a test of each single strand to detect any failure and allow adjustment due to shrinkage during cool down. Temperature sensors (Pt100) are put to both sides and into the middle of the demonstrator to monitor the temperature during cooling. Voltage taps allowed a detailed monitoring of the voltage drop during current ramp up using a 12 pulse thyristor converter from ABB as current source. The possible maximum current is 50 kA DC and 30 V. A Fiber Optic Current Sensor from ABB based on the Faraday effect allows to determine the total cable current. The sampling rate is about 4 kHz. A possible quench can be detected by using a dedicated quench detection system that monitored the voltages over each of the twelve superconducting strands with individual threshold voltages adjustable between 1 mV and 10 mV. An emergency shut down is triggered to shut down the current source with about 1 kA/ms ramp rate [17].

The voltage measurements were performed using a multichannel NI SCXI 1125 conditioning module together with a NI PCI analog-digital converter using a sampling rate of 100 Hz.

The cooling of the whole cable system was done with a liquid nitrogen bath in a cryostat build for this purpose. The inner cryostat dimensions are 5870 mm x 870 mm x 485 mm (length x width x height). In figure 3 the design of the demonstrator together with pictures of the assembled test setup is given. The cryostat is closed by five lids to allow a controlled cool down and warm up of the cable demonstrator. Liquid nitrogen enters through a lid in the middle and exits at both ends of the cryostat.

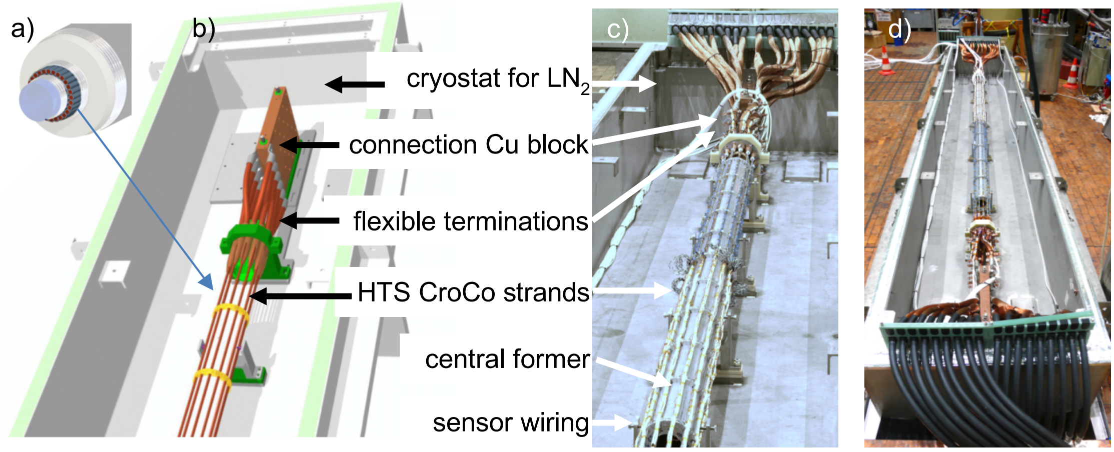



**Figure 3.** Design of the cable demonstrator derived from the circumferential arrangement of a cable as shown in the upper far-left corner a). A detailed plot of the test arrangement is shown in b) with the corresponding setup in c). Picture d) on the far-right hand side gives an overview of the full 6 m long test arrangement.

## 3. Performance of HTS CroCo Strands

As described 12 HTS CroCo strands with a minimum length of 3 m were assembled. Therefore, about 50 m of strands were produced, cut into 3.6 m and characterized to qualify them to be used in the 35 kA demonstrator setup. Each single strand length was measured using a smaller version of the demonstrator cryostat. The critical current was determined by the 1 $\mu$V/cm criterion with voltage-taps in 2 m and 2.8 m distance along the strand. The results are summarized in table 3. After a typical learning curve, 8 m HTS CroCo strands were produced with no tape degradation. The process is qualified to allow lengths well above 8 m. Further details can be found in [18].

The critical currents of the twelve strands were qualified as sufficient to proceed to the assembly and test of the 35kA demonstrator.

**Table 3.** Measured critical current performance of the twelve strands

| HTS CroCo strand | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_c$ (2 m) / A | 3080 | 3210 | 3398 | 3437 | 3680 | 3482 | 3597 | 3618 | 3621 | 3607 | 2890 | 2928 |
| n (2 m) | 18 | 18.3 | 20.6 | 18.5 | 13.5 | 24.5 | 18.5 | 18.2 | 11 | 18.1 | 24 | 24.9 |
| $I_c$ (2.8 m) / A | 3060 | 3193 | 3410 | 3320 | 3699 | 3485 | 3596 | 3632 | 3607 | 3615 | 2890 | 2926 |
| n (2.8 m) | 19.4 | 16.4 | 17.4 | 15.4 | 12.4 | 22.4 | 19 | 18.2 | 11 | 18.3 | 24 | 24.9 |

## 4. Test of 35kA Cable Demonstrator

The 35kA demonstrator was assembled within the cryostat according to the in section 2 described design. After functional test of all systems and sensors the cool down was started. In figure 4 the assembled test configuration is shown indicating the placement of the temperature sensors (west, center and east).

Journal of Physics: Conference Series **1559** (2020) 012082 doi:10.1088/1742-6596/1559/1/012082

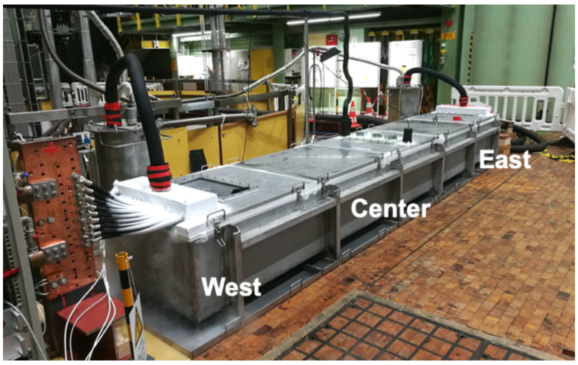



**Figure 4.** The test assembly with closed lids during testing at 77 K. Liquid nitrogen enters in the center part and exits at both ends on the west and east side.

In figure 5 the temperature profile of the complete measurement campaign is summarized showing the temperature readouts for the Pt100 sensors over time. The cool down took about 30h as overnight operation was avoided due to safety reasons. The test sequence to characterize the 35kA cable took about 6h starting after the 30h cool down. Clearly visible are several spikes in the temperature sensor readout that correspond to the current ramping during test. Warm up of the demonstrator lasted more than 60h to reach ambient temperature. The warm up process was only driven by the heat conduction of the external copper leads into the cryostat. A nitrogen atmosphere was maintained to avoid freezing oxygen or condensed water until opening of the cryostat.

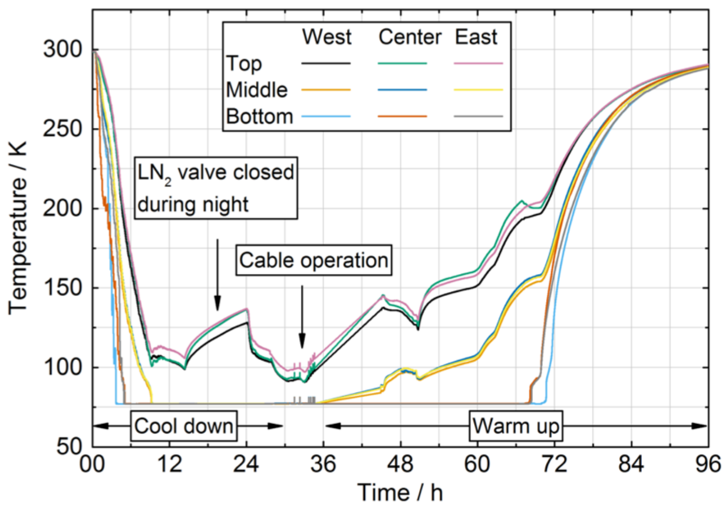



**Figure 5.** Temperature profile during the test campaign of all nine Pt100 sensors. Cool down takes about 30h, warm up after cable operation lasts more than 60h.

Electrical tests were performed by ramp and hold method. The current was increased with a ramp rate of about 5 kA/min and kept constant at defined levels. In figure 6 on the left axis the electric field measured over a length of 2.8 m on each strand is given versus time to determine the transition from superconducting to resistive state. In addition, the overall current is given on the right axis side.

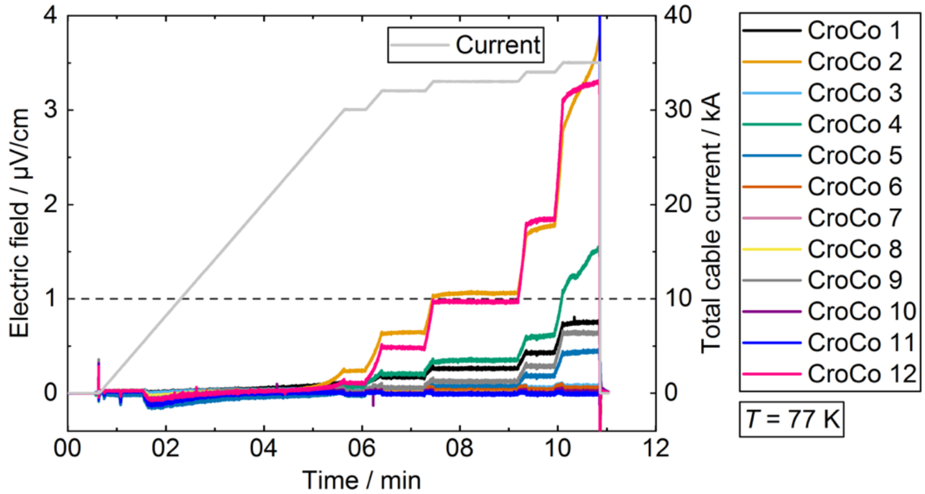



**Figure 6.** Electric field (left axis) measured on single strands versus time and increasing current (right axis).

First, the current was ramped up to 30 kA. Here the first two strands (#2, #12) show initial transition onset. The other strands do not exhibit any onset. Keeping the current constant at this level the electric field remains also constant. Further, the current is increased up to 32 kA adding two more strands showing a transition onset (#1, #4). Again, the electric fields measured stay constant while keeping the current constant. The current was then increased in 1 kA steps. At 33 kA strands #5 and #9 start to show an onset. Reaching 34 kA the electric field for these six strands (#1, #2, #4, #5, #9, #12) increases. However, the remaining six strands (#3, #6, #7, #8, #10, #11) do not show any transition onset at all. Nevertheless, it can be stated that up to this current a stable operation is achieved. Finally, the current was increased up to 35kA. Still, only the six initial strands show further increase in the electric field. But strands #2 & #4 clearly experience a runaway with constant current, leading to a quench triggered due to strand #2.

The 35 kA could be reached in this cable configuration. However, the imbalance between the twelve strands visible in the electric field needs to be investigated.

## 5. Discussion of Results

To understand the cause of the imbalance of the strand behavior within the cable demonstrator, the effective current distribution among the strands has to be considered. The HTS CroCos together with the terminations determine the electric performance of the cable. The maximum current carrying capacity is set by the critical currents of the HTS CroCos. However, the current distribution is controlled by the resistive terminations and leads. The individual resistances of the terminations and leads are with one exception in the range between 7.8 and 9.0 $\mu\Omega$ as discussed in detail in [18]. Knowledge of these two parameters help to understand the behavior shown in figure 6.

Using the known electrical resistance of the flexible copper leads of each HTS CroCo strand the current flowing in each strand was determined by the measured voltage drop. In figure 7 the compact lines show the current carried by each single strand while increasing the overall cable current up to 35 kA. The strands follow an almost linear behavior. As expected, strand #2 and #12 exhibit a smaller slope at high currents, as they are limited by the developing electrical field in the superconductor. From this plot the current imbalance is clearly visible, ranging at maximum cable current from below 2 kA for strand #11 up to almost 3.5 kA for strand #9.

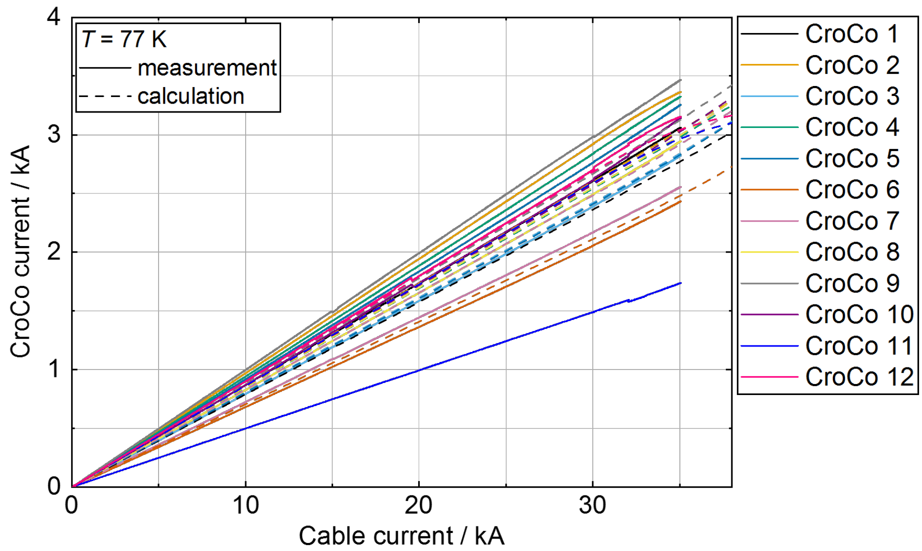



**Figure 7.** The individual strand current versus the total cable current up to 35 kA is plotted, The measurement of the cable demonstrator is given by the compact lines, while the dashed lines represents the behavior considering only the resistance of the single strand with the flexible terminations as expected from the single-strand characterization.

The expected current distribution considering the superconducting strands together with their flexible copper terminations can be calculated from the single strand voltage-versus-current performance adding the specific resistance of the flexible termination of each strand that were performed individually for each strand prior to the assembly of the demonstrator. Again, details to this procedure can be found in [18]. In figure 7 the dashed lines correspond to this expected current distribution. Obviously, the expected behaviour does not match the experimental result. The only cold connection that could not be tested in the individual-stand pre-tests is the clamped connection to the common copper block.

Assuming additional individual contact resistances at the flexible termination of each strand to the common copper block on both sides of the cable demonstrator (see figure 3) it is possible to simulate the experimental results. The calculated additional resistances are summarized in table 4. Now, the adapted theoretical behaviour matches very well the experimental results represented in figure 8 by the dashed lines. The majority of the necessary additional resistive values are within the range of 0.5 $\mu\Omega$ up to 3.18 $\mu\Omega$. A significant higher value is obtained for strand #11 with 9.06 $\mu\Omega$. Effectively, this additional contact resistance more than doubles the total resistance of this strand # 11, which leads to pronounced reduction of the current in this strand compared to the other strands. This high value might be attributed to a poor connection due to condensed water during a prior cool down test reducing the effective connecting area.

These results underline the sensitivity of the design to additional resistive elements and needs to be optimized in further tests.

**Table 4.** Calculated contact resistance based on the cable measurements

| HTS CroCo strand | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Resistance / $\mu\Omega$ | 1 | 0.64 | 2.05 | 0.89 | 0.88 | 0.5 | 3.18 | 2.72 | 0.82 | 1.96 | 9.06 | 1.86 |

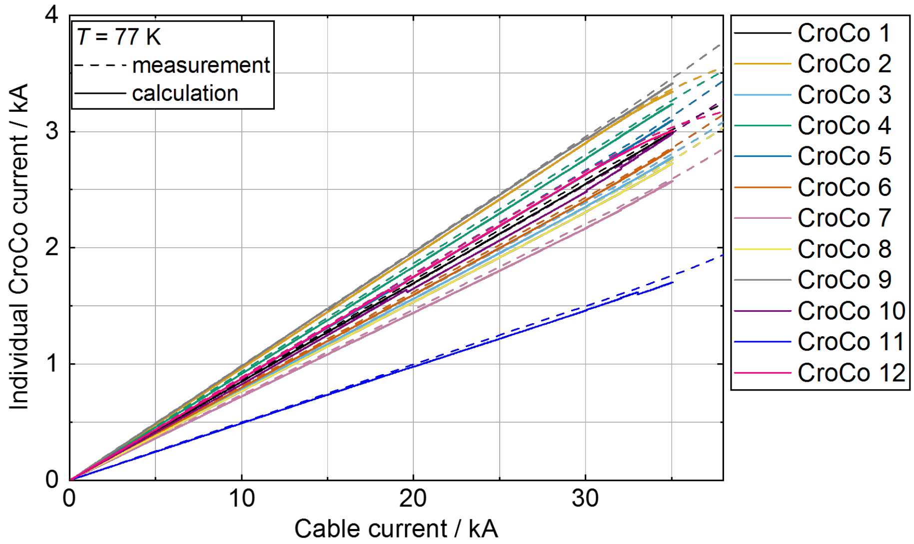



**Figure 8.** The individual strand current versus the total cable current up to 35 kA is plotted. As in figure 7 the measurement of the cable demonstrator is given by the compact lines. The dashed lines represent the adapted theoretical behavior considering in addition an additional resistive part due to the connection of the flexible termination to the copper block (see figure 3).

## 6. Summary and outlook

The results confirm the potential use of the HTS CroCo design for cable application well above 20 kA. Still some improvements need to be implemented to reach a 100 kA class cable.

After adaption of the HTS CroCo production twelve strands were successfully qualified for the 35 kA cable demonstrator test

Assembly and first test of the cable demonstrator was carried out successfully. The results revealed an imbalanced current distribution due to not well controlled connection of the flexible termination to the common copper block. Adapting the theoretical calculation by an additional resistive element in the termination contacts the experimental results were matched. Therefore, an improvement of the setup is necessary. Using shared copper connection directly to the HTS CroCo strands will allow a significantly reduced lead resistance and therefore an efficient current sharing between CroCo strands.

Further a reassembly of the demonstrator into a more compact cable design is foreseen to allow a small diameter design of a 35 kA cable. Finally, a full equipped 100 kA cable with 36 strands is to be envisaged.

## References

[1] Haran K S *et al*. 2017 *Supercond. Sci. Technol.* **30** 123002
[2] Badel A *et al*. 2016 *IEEE Trans. Appl. Supercond.* **26**(3) 4803908
[3] Schlachter S I, Goldacker W, Holzapfel B, Kudymow A, Wu H 2017 *CEC-ICMC conference* Design Aspects for DC-HTS Cables in Hybrid-Electric Propulsion Systems for Aircraft https://indico.cern.ch/event/578092/contributions/2537822/attachments/1491653/2345743/M2OrE-04_Schlachter.pdf (11.07.2017)
[4] Duval C, Renaudier S, Bardet B, Martin O and Wang Tang Kuan S 2014 Aluminum smelter comprising electrical conductors made from a superconducting material *patent* WO2013007893A3
[5] Zhang D, Dai S, Zhang F, Zhu Z, Xu X, Zhou W, Teng Y and Lin L 2015 *IEEE Trans. Appl. Supercond.* **25** (3) DOI 10.1109/TASC.2014.2374691
[6] Morandi A 2015 *Supercond. Sci. Technol.* **28**(12) 123001
[7] Xiao L *et al*. 2012 *IEEE Trans. Appl. Supercond.* **22**(3) 5800404

Journal of Physics: Conference Series **1559** (2020) 012082 doi:10.1088/1742-6596/1559/1/012082

[8] Tomita M, Muralidhar M, Suzuki K, Fukumoto Y and Ishiara A 2012 *J. Appl. Phys.* **111**(6) 063910
[9] Michael P C, Bromberg L, Dietz A J, Cragin K J and Gold C 2015 *IEEE Trans. Appl. Supercond.* **25**(3) 5401005
[10] Pratt A, Kumar P and Aldridge T V 2007 *INTELEC 07–29th Int. Telecommun. Energy Conf.*, http://dx.doi.org/10.1109/INTLEC.2007.4448733
[11] Ballarino A and Flükiger R 2017 *J. Phys.: Conf. Series* **871**(1) 012098
[12] Fietz W H , Wolf M J, Preuss A, Heller R and Weiss K-P 2016 *IEEE Trans. Appl. Supercond.* **26**(4) 4800705
[13] Heller R, Blanchier P, Fietz W H and Wolf M 2019 *IEEE Trans. Appl. Supercond.* **29** (7) 4703111
[14] Wolf M J, Bagrets N, Fietz W H, Lange C and Weiss K-P 2018 *IEEE Trans. Appl. Supercond.* **28**(4) 4802404
[15] Wolf M J, Fietz W H, Bayer C M, Schlachter S I, Heller R and Weiss K-P 2016 *IEEE Trans. Appl. Supercond.* **26**(2) 6400106
[16] Stemmle M, Marzahn E, West E, Schmidt F and Schippl K 2012 Superconducting HVDC Power Cables for Voltage Source Converter Systems *Cigre* B1-302_2012
[17] Hollik M, Fietz W H, Fink S, Gehrlein M, Heller R, Lange C and Möhring T 2013 *Fus. Eng. Des.* **88**(6-8) 1445
[18] Preuss A, Wolf M J, Heiduk M, Lange C and Fietz W H 2012 *IEEE Trans. Appl. Supercond.* **29**(5) 8685127