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A turnkey gaseous helium-cooled superconducting CORC® dc power cable with integrated current leads

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Abstract

High-temperature superconducting (HTS) direct current (dc) power cable systems, capable of delivering power exceeding 10 MW while being cooled with cryogenic helium gas, have been developed for applications on naval electric ships, electric aircraft and in data centers. Current injection from room temperature into the superconducting power cable causes by far the greatest heat load to the cryogenic system. Efficient current leads with integrated helium gas heat exchangers were developed to inject a current exceeding 1 kA from room temperature into a superconducting Conductor on Round Core (CORC®) power cable, without the need for liquid nitrogen pre-cooling. A 2 m long single-pole CORC® power cable system that included current leads was cooled using a Stirling cryocooler with a closed-loop helium gas circulation system. The turnkey power cable system allowed cool down from room temperature to its operating temperature of 60 K–70 K within 5 h, after which continuous operation at 1.2 kA was demonstrated. The successful development and demonstration of a CORC® power cable with current leads containing integrated helium gas heat exchangers enables widespread implementation of HTS MW-class, high current density superconducting dc power cables in many applications with constrained space that require a power dense solution.

Keywords: superconducting power cable, helium gas cooling, CORC® power cable

(Some figures may appear in color only in the online journal)

1. Introduction

The need for high current density direct current (dc) power cables based on high-temperature superconductors, such as RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) coated conductors, has been growing rapidly in recent years. Several applications that require delivery of 1–10 MW of electric power in confined spaces using dc power cables are naval ships [1, 2], electric aircraft [3, 4] and potentially within datacenters [5, 6]. These applications often require cooling with high-pressure cryogenic helium gas instead of liquid cryogens to avoid asphyxiation hazards, reduce weight and to allow for reduced operating temperatures in the range of 20 K–60 K. Helium gas cooling also avoids the risks associated with distributed liquid hydrogen cooling in future electric aircraft, in which liquid hydrogen is envisioned as a fuel [7].

Advanced Conductor Technologies (ACT) is pioneering the development of flexible high-current Conductor on Round Core (CORC®) power cables [8–12]. ACT, in collaboration with the Center for Advanced Power Systems (CAPS) at Florida State University, has recently demonstrated the successful operation of a 10 m long two-pole dc CORC® power cable

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at a current exceeding 4 kA that was cooled with pressurized helium gas and operated at 65 K–70 K [13]. Although the test was successful, it clearly identified the technological limits of the cable system that required liquid nitrogen pre-cooling of its current leads, which makes the solution unsuitable for many future applications.

Practical high-temperature superconducting (HTS) power cables require efficient and compact current leads with integrated heat exchangers, in which the combination of conductive and resistive heat load from room temperature is removed by helium gas that also cools the cable. A closed-loop cooling system based on a single cryogenic medium would allow turnkey continuous operation. Here, we report on the development and testing of a short single-pole CORC® dc power cable system with current leads containing integrated helium gas heat exchangers. Several prototype current leads, rated between 800 and 2000 A, were designed, characterized and utilized in a short CORC® power cable system. Continuous operation over an extended period using a Stirling cryocooler with an integrated closed-loop helium gas circulation system has been demonstrated.

2. Experimental

2.1. Conduction-cooled current leads containing helium gas heat exchangers

Three pairs of current leads with current ratings between 800 and 2000 A were developed, in which the McFee optimization [14] was performed that resulted in no heat flow into or out of the warm end of the current leads at their rated current. This was achieved by selecting a current lead material with favorable thermal and electrical conductivity, followed by optimization of the current lead dimensions for operation between 50 K and 300 K. Current leads CL-1, rated at 800 A, were made from brass, while current leads CL-2, rated at 2000 A, were made from copper (table 1). Current leads CL-3 were made by reducing the diameter of leads CL-2 from 12.7 to 9.2 mm, to achieve a current rating of 1050 A. Table 1 lists the calculated heat load through conduction per lead with no current flowing and the ohmic and total heat at the rated current.

Although the optimization assumed the current leads had a constant diameter, in reality the diameters of the current leads vary along their length. A larger diameter is required at their warm end that protrudes from the cryostat to allow the copper cables that inject current into the cable to be mounted. The current path through the copper center of the heat exchanger is also much larger than the optimized diameter listed in table 1. The effective current rating and heat load of the leads therefore likely deviate from the target values. A more precise optimization through detailed modeling that considers the actual dimensions and composition of the current leads falls outside the scope of this work.

2.2. Helium gas cooled CORC® power cable

A CORC® cable, 2.9 m in length, was fabricated by winding 12 REBCO tapes (SuperPower Inc.) in four layers onto a 5.3 mm diameter copper former. The tapes used were 4 mm wide and contained a substrate of 50 μm thickness and a surround plated copper layer of 5 μm thickness. The 6 mm diameter CORC® cable contained an insulating layer formed by polyester heat shrink tubing of 50 μm thickness and a copper braided shield layer. Although the insulation would likely allow operation of at least 300–500 V, the highest voltage the cable would experience in the experiments was 10 V, which was the voltage limit of the high current power supplies. Cable terminations were installed on both ends of the cable by trimming each tape layer, after which a copper tube of 8 mm outer diameter and 170 mm in length was placed over the exposed tapes and filled with indium solder. The CORC® cable was then installed into a flexible Technifab cryostat (type B150), 2 m in length, with a 38 mm inner diameter and a 1 m long flexible section between the two female bayonets (figure 1). Two custom enclosures were manufactured from off-the-shelf components to house the current leads and the electrical joint between the current leads and the cable terminations.

The power cable was connected to the cryogenic helium circulation loop of the one cylinder two-stage Stirling cryocooler SPC-1 at ACT (figure 2(a)). Cold helium gas was injected into the helium line of one of the vacuum enclosures, where it ran through the heat exchanger of the current lead before being injected into the flexible cryostat housing the CORC® cable. The helium gas exited the flexible cryostat at the opposite end, where it was channeled into a helium line that would cool the second current lead before returning to the cryocooler. Copper cables, size 4/0, were bolted to the current leads at each end of the power cable (figure 2(b)) to inject current from a high current source formed by connecting in parallel several Sorensen 1200 A power supplies.

Table 1. Optimized parameters and heat loads per current lead developed for this study.

	CL-1	CL-2	CL-3
Material	Brass	Copper	Copper
Optimized length	260 mm	300 mm	300 mm
Optimized diameter	18 mm	12.7 mm	9.2 mm
Design current rating	800 A	2000 A	1050 A
Conductive heat at no current	16.1 W	43.7 W	22.9 W
Ohmic heating at rated current	32.3 W	87.4 W	45.7 W
Total dissipation at rated current	32.3 W	87.4 W	45.7 W

2.3. Instrumentation layout

Characterization of the current leads containing helium gas heat exchangers was performed within a vacuum vessel at CAPS. A pair of current leads was mounted within the top flange of the vessel (figure 3(a)), while the current leads were connected in series within the vacuum vessel using a 1 m long CORC® cable containing 30 REBCO tapes of 4 mm width.

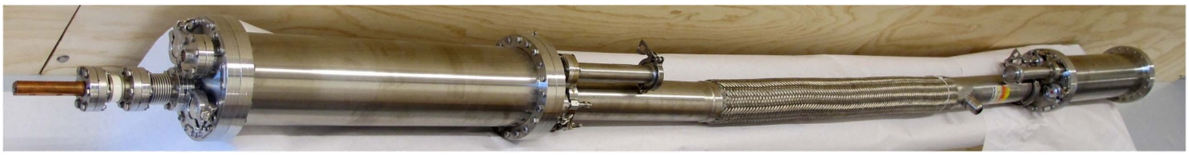

Figure 1. The single-pole CORC® cable located in a flexible cryostat containing a pair of terminations.

Figure 2. (a) The CORC® power cable being tested with the Stirling cryocooler with the closed-loop helium gas flow system. (b) A closeup of one of the current leads connected to four copper cables.

Helium gas from a Stirling cryocooler (SPC-1) was injected into the helium line from the bayonet connection on the top flange of the vacuum vessel and contained a fitting that split the helium flow into two directions to cool the two heat exchangers in parallel. The CORC® cable was cooled through conduction from the cold end of the heat exchangers and by thermally anchoring the cable directly to the helium lines. The current leads with heat exchangers, the CORC® cable and the connectors between the CORC® cable and current leads were instrumented with a total of eight voltage wire pairs to allow detailed electrical characterization of the current leads. The temperatures of the helium gas entering and exiting both heat exchangers, as well as the temperatures of the connectors to the CORC® cable, were measured. The helium circulation system at CAPS allowed measurement of the helium gas mass flow rate, and thereby provided the option to calculate the cooling power of the helium gas delivered to the components within the vacuum vessel. A similar instrumentation layout was used during operation of the CORC® power cable at ACT, except the number of temperature sensors and voltage pairs was each reduced to five (figure 3(b)) and the system did not offer the capability to measure the mass flow rate of the helium gas.

3. Results

3.1. Characterization of current leads rated 2 kA

3.1.1. Current ramp to 3 kA. Copper current leads CL-2, rated 2 kA, were outfitted with heat exchangers and mounted in the vacuum vessel for characterization (figure 3(a)), while helium gas with a flow rate of about 6.9 g s^{-1} cooled the current leads (about 3.5 g s^{-1} per lead). The current through the current leads and the CORC® cable was increased stepwise, while the voltage over the system components was measured. Most of the voltage developed over the current leads (figure 4). The current lead voltage stabilized after a short time once the current was increased. The time taken for the voltage to stabilize increased once the current exceeded 1.5 kA, because the ohmic heating in the current leads raised their temperature. The voltage over the CORC® cable increased once the current reached 3 kA, which indicated that the critical current of the CORC® cable had been exceeded.

Figure 5 shows the temperatures of the helium gas entering and exiting the heat exchanger mounted onto one of the current leads (left current lead in figure 3(a)) and that of the CORC®

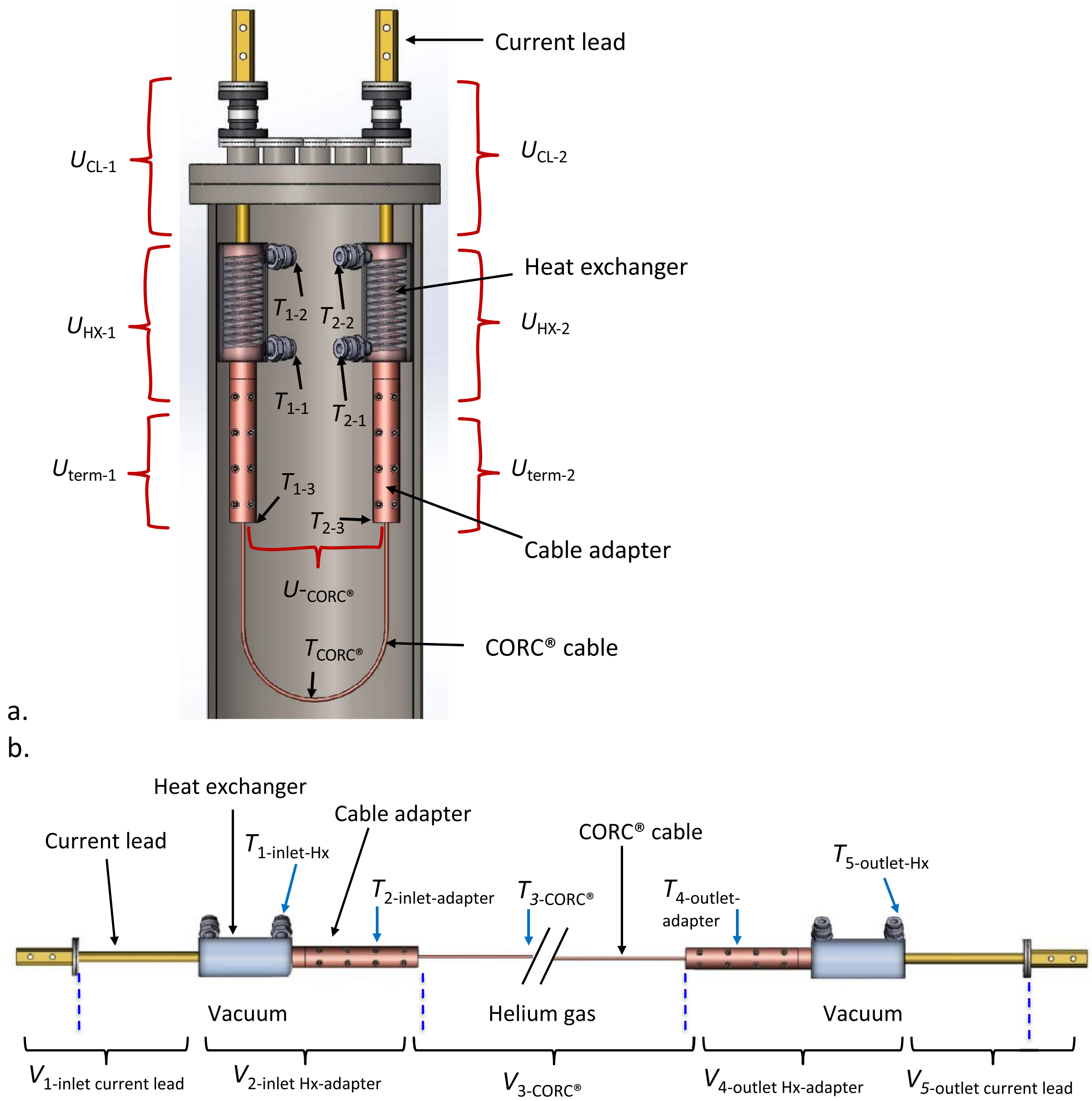

Figure 3. An overview of the location of the voltage wires and temperature sensors (a) during the characterization of the heat exchangers within the vacuum vessel at CAPS, and (b) in the CORC® power cable system at ACT.

cable. The temperature of the incoming helium gas started to rise once the operating current reached 2 kA, which indicates that the heat load had exceeded the cooling capacity of the Stirling cryocooler. The temperature of the CORC® cable also increased and reached 81.5 K at a current of 3 kA. The lowest temperature was measured on the current adapter (T_{1-3}) and not at the inlet of the heat exchanger (T_{1-1}) because the incoming helium line was in direct contact with the CORC® cable.

Figure 6 shows the electric power generated in the current leads and CORC® cable, which was calculated by multiplying the current by the overall voltage measured over the components. It also shows the cooling power provided by the Stirling cryocooler, which was calculated from the helium gas flow rate of 6.9 g s^{-1}, the heat capacity of helium gas of 5.124 J g^{-1} *K and the difference in the helium gas inlet and outlet temperatures. The cooling power provided to the cable system by the Stirling cryocooler was about 146 W before current was applied, which was required mainly to overcome the heat load through conduction of both current leads and, to a lesser extent, to overcome the heat load through the walls of the vacuum vessel. The cooling and electric power increased over time at a constant current, indicating an increase in temperature of the current leads before the system would reach an equilibrium state. Figure 6 also shows that there was a delay in heat load into the helium gas after each increase in current, because it took time for the system to reach its new equilibrium state. An equilibrium state could be reached within a short period during which the current was kept constant during the experiment for currents up to 1 kA.

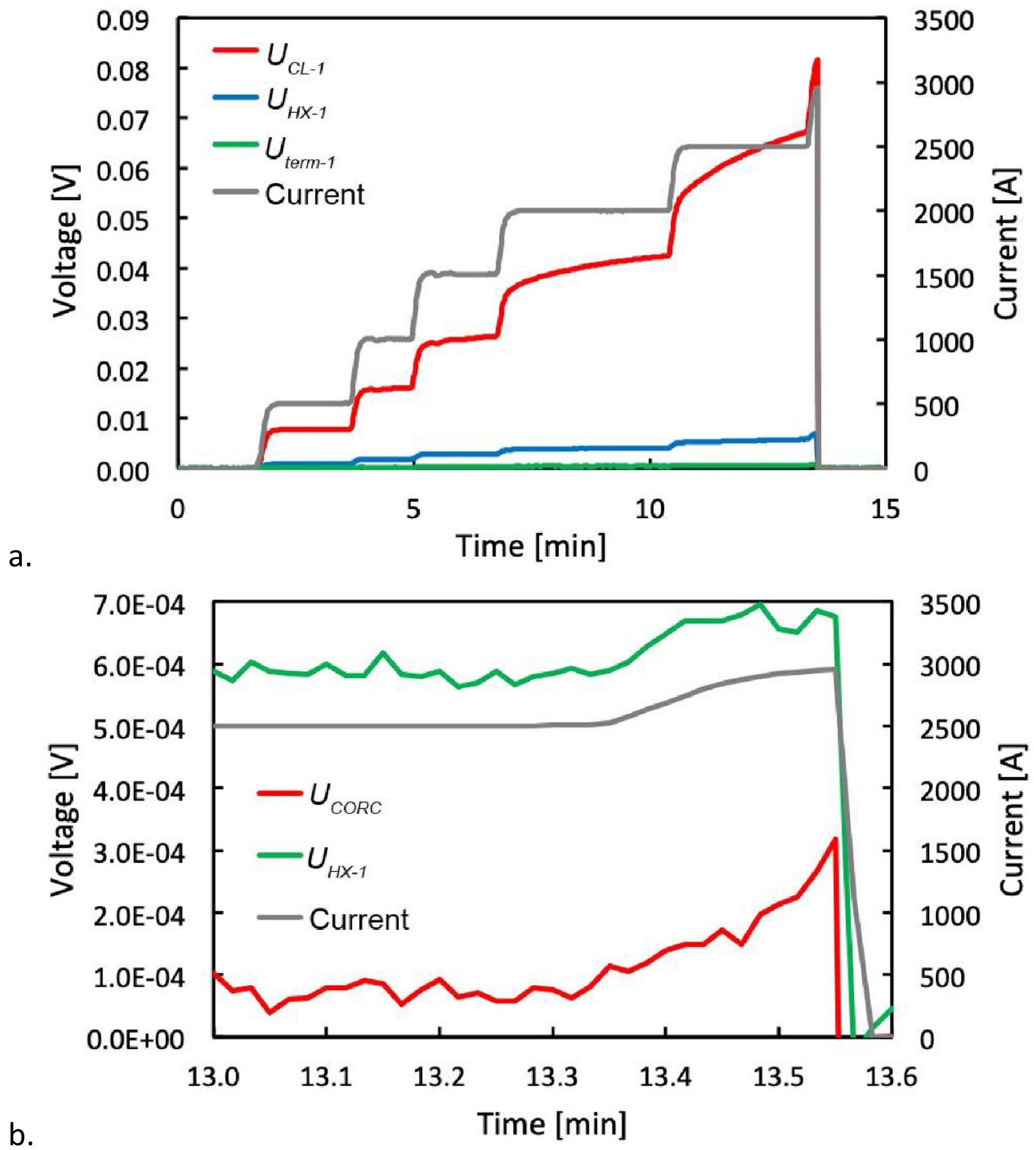

Figure 4. (a) Voltages measured over one of the heat exchangers and current leads CL-2 as a function of time while the current was increased stepwise. (b) Detailed voltages measured when the current was increased to 3 kA.

3.1.2. Continuous operation of the current leads at 1.5 and 2 kA. Current leads CL-2 were also characterized at a constant current of 1.5 and 2 kA to allow the system to reach equilibrium. At a constant current of 1.5 kA, the temperature of the incoming and outgoing helium gas increased by about 3 K–6 K over 1 h, after which time it stabilized (figure 7). The temperature of the conduction-cooled CORC® cable increased from about 77 K to 82 K. The total electric power dissipated at 1.5 kA was constant at about 98 W, while the heat removed by the helium gas in its equilibrium state was 248 W (figure 8).

The temperature of the helium gas and CORC® cable increased gradually over time at a current of 2 kA (figure 9). The current was switched off after 17 min. Both the ohmic heating and cooling power increased over time and did not reach an equilibrium state. The maximum power removed from the system by the helium gas was 319 W (figure 10), which exceeded the cooling power of the Stirling cryocooler. This is evident from the increase in temperature over time of the helium gas returning from the Stirling cryocooler to the heat exchangers, as indicated by temperature sensors T_{1-1} and T_{2-1}. The total ohmic heating in the current leads also increased over time from about 155 W to about 208 W just before the current was switched off, indicating gradual heating of the leads.

3.2. Operation of the CORC® power cable system

The current leads with built-in heat exchangers were mounted within compact enclosures connected to a 2 m long cryostat at ACT that housed a single-pole CORC® cable. This configuration allowed direct cooling of the CORC® cable with flowing helium gas, instead of cooling from conduction that resulted in a relatively high temperature of the CORC® cable during

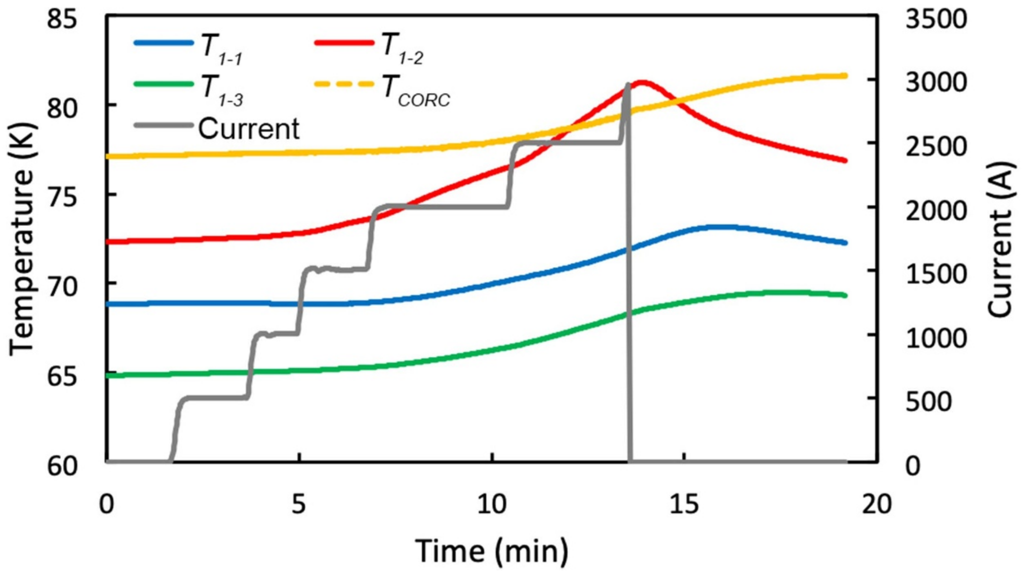

Figure 5. The temperature of one of current leads CL-2 (T_{1-2}), its heat exchanger (T_{1-1}), one of the CORC® cable terminals (T_{1-3}) and the center of the cable ($T_{CORC®}$) as a function of time while the current was increased to 3 kA.

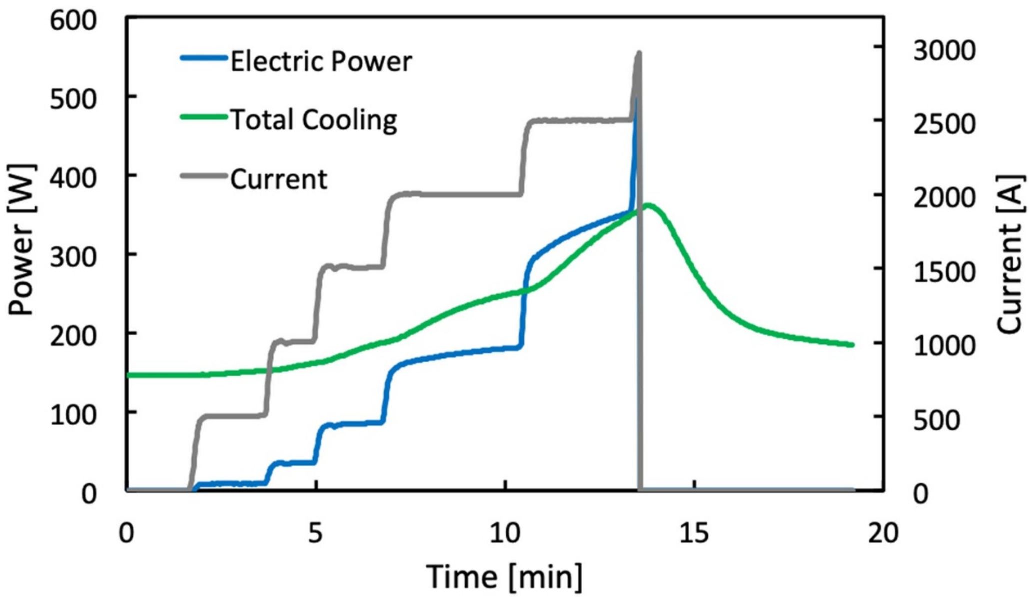

Figure 6. Electric dissipation and helium gas cooling power as a function of time, measured at different operating currents for current leads CL-2.

testing in the vacuum vessel at CAPS, because of the relatively high heat load from the vacuum vessel wall (figures 7 and 9). The system was designed to mimic a typical application, where helium gas enters the cable system on one side and exits on the other side. As a result, the current leads operated at different temperatures because the helium gas warms as it moves through the cable system from one side to the other.

3.2.1. Operation with current leads optimized for 800 A. The CORC® power cable with compact enclosures containing brass current leads CL-1 was connected to the helium gas lines of the Stirling cryocooler at ACT (figure 2). The system needed about 6 h to cool the cable from room temperature to 45 K. The helium gas pressure was 12 bar and the total pressure drop over the cable system was 14 mbar. The lowest temperature was measured at the center of the power cable, about 1 m away from both current leads, where the flowing helium gas had direct contact with the cable. The connection between the CORC® cable and the heat exchanger at the helium inlet was only 1 K–2 K higher than that of the CORC® cable. The temperature of the helium gas entering the heat exchangers at the outlet of the cryostat was 53 K.

The temperature of the system was still decreasing when a current of 1 kA was applied at a time of 393 s. The applied current exceeds the 800 A expected current rating of the brass

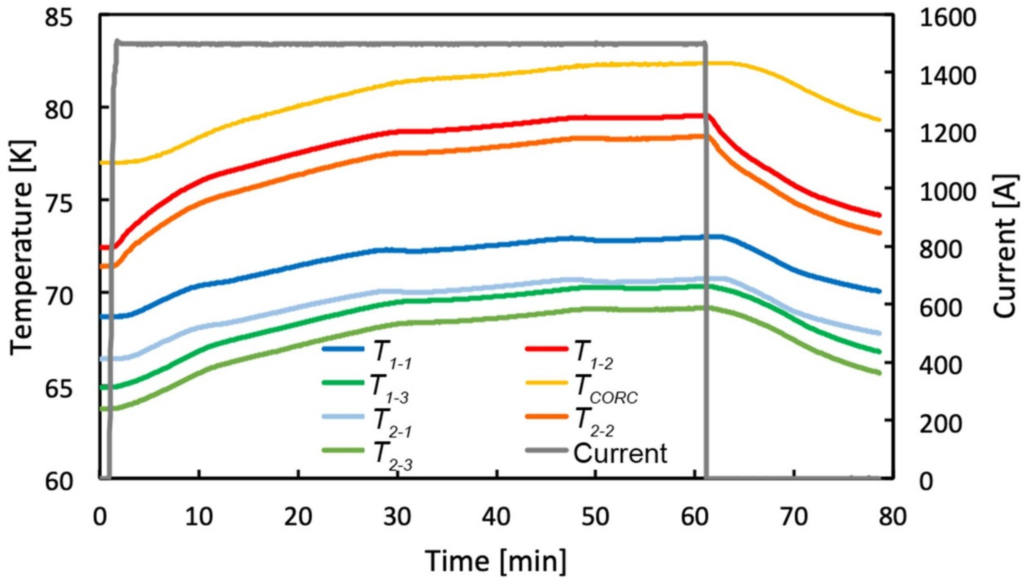

Figure 7. The temperature of current leads CL-2 ($T_{1\text{–}2}$, $T_{2\text{–}2}$) and heat exchangers ($T_{1\text{–}1}$, $T_{2\text{–}1}$), as well as both of the CORC® cable terminals ($T_{1\text{–}3}$, $T_{2\text{–}3}$) and the center of the cable ($T_{\mathrm{CORC®}}$) as a function of time at a constant current of 1.5 kA.

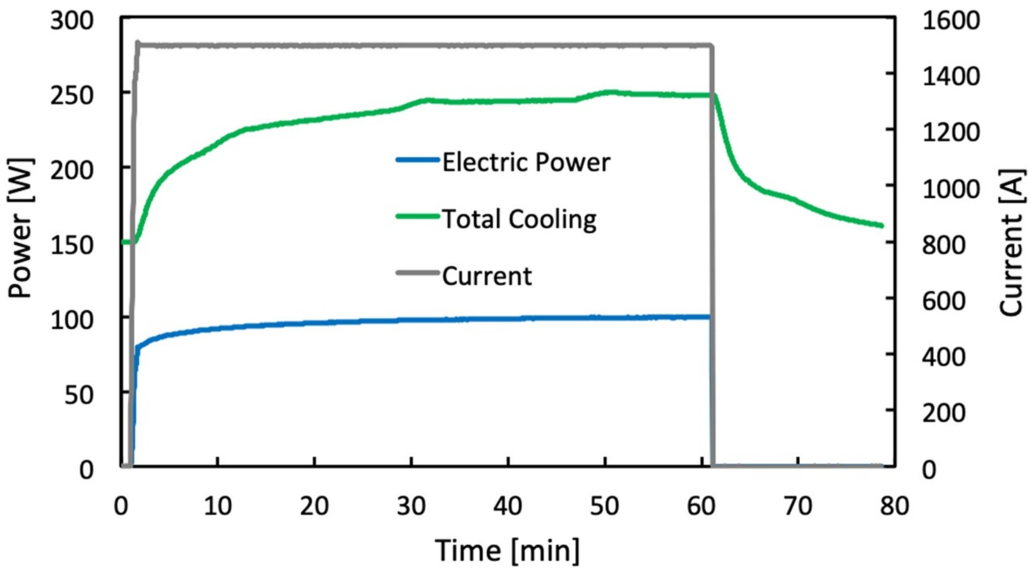

Figure 8. Electric dissipation and helium gas cooling power of current leads CL-2 as a function of time at 1.5 kA.

current leads, which caused the system temperature to increase slowly over time (figure 11). The temperature of all the components increased by about 10 K during the 30 min after which the current was switched off. The excessive ohmic heat generated by operating the current leads above their rated current exceeded the cooling power of the Stirling cryocooler at the relatively low temperature of 48 K–58 K at which the helium gas entered the power cable.

The system was able to recover soon after the current was switched off. The system was then operated at 1 kA for almost 1 h at which time the temperature of the cable reached 65 K and that of the current adapter on the outlet side exceeded 75 K. At that time the current was reduced to the rated current of 800 A. Temperatures continued to decrease by about 1 K–2 K while operating at 800 A for 30 min, indicating that continuous operation at 800 A would be possible. Table 2 lists the temperatures and voltages of the cable system at 495 min under 1 kA after the start of the initial cool down, and at 524 min under 800 A after the initial cool down. Ohmic heating in each current lead was 75.7 W at 1 kA and 47.4 W at 800 A, as determined from the respective voltages measured across the leads.

3.2.2. Operation with current leads optimized for 1050 A.

The brass current leads (CL-1) were replaced by the copper current leads CL-3 rated at about 1050 A (the cooling power of the Stirling cryocooler at ACT is insufficient to operate current leads CL-2 at their rated current of 2 kA).

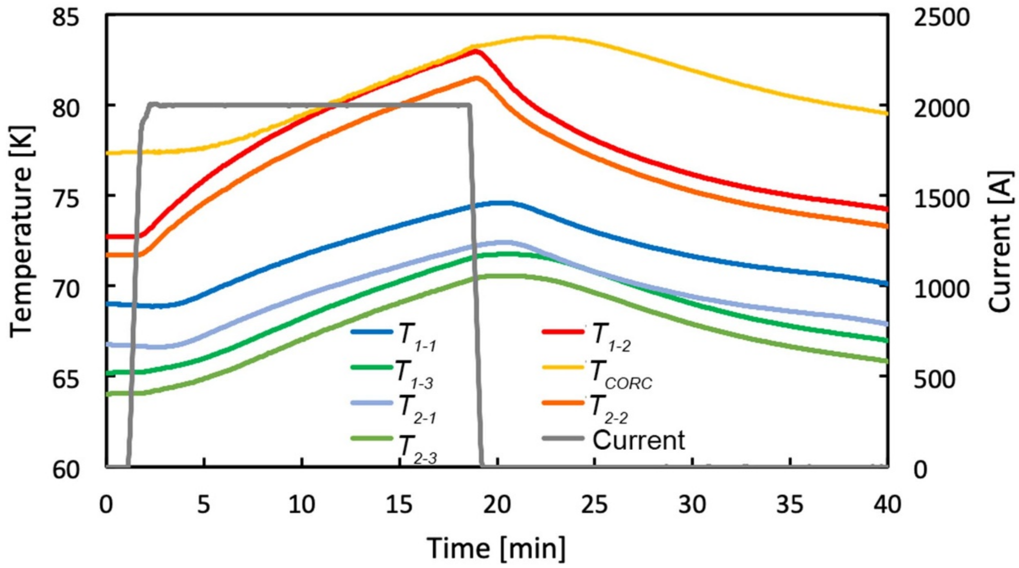

Figure 9. The temperature of current leads CL-2 ($T_{1\text{–}2}$, $T_{2\text{–}2}$) and heat exchangers ($T_{1\text{–}1}$, $T_{2\text{–}1}$), as well as both of the CORC® cable terminals ($T_{1\text{–}3}$, $T_{3\text{–}3}$) and the center of the cable as a function of time at a constant current of 2 kA.

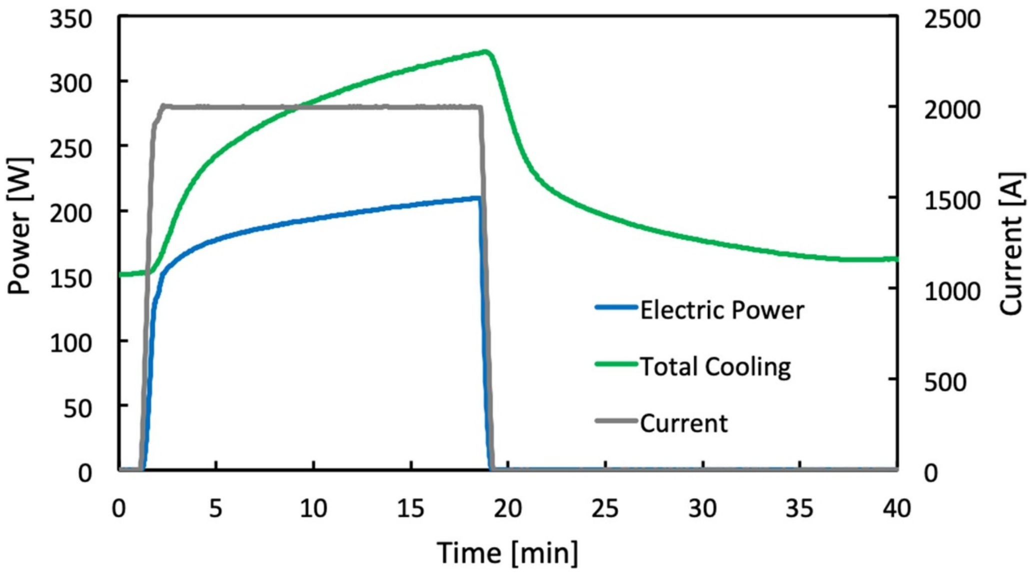

Figure 10. Electric dissipation and helium gas cooling power as a function of time of current leads CL-2 at a constant current of 2 kA.

The cable system was cooled down from room temperature to 47 K, measured at the cold end of the current lead of the helium gas inlet side of the cryostat, in less than 5 h at a helium gas pressure of 12–14 bar. The cable was energized at a current of 1 kA for 2 h, during which time the temperature of the heat exchanger on the helium outlet continued to decrease from 70 K to about 66 K (figure 12). The temperature of the warm end of the current leads to which the copper cables were mounted was 298 K, or close to room temperature.

The current was subsequently increased to 1270 A, which caused a rise in temperature of the system components. The temperature stabilized after more than 2 h of operation, at which time the current leads protruding from the cryostat reached a temperature of about 350 K. This is a clear indication that the current leads were operated above their rated current, resulting in excessive ohmic heating. The current was reduced to 1210 A, at which time the temperature of the system components decreased. The decrease in temperature indicated that the cable system could be operated indefinitely at a current of 1210 A. Table 3 lists the temperatures and voltages of the power cable system after the system was operated for a longer time duration at 1000, 1270 and 1210 A. The ohmic heating per current lead was 35.2 W at 1000 A, 64.9 W at 1210 A and 76.8 W at 1270 A, respectively.

The current was ramped to over 3 kA at the end of the experiment, while the voltage over the CORC® cable and its terminations was measured to determine its critical current (figure 13). The temperature of the adapter between the CORC® cable and heat exchanger ($T_{\text{2-inlet-adapter}}$) on the helium gas inlet side was about 61.2 K, while that on the outlet side

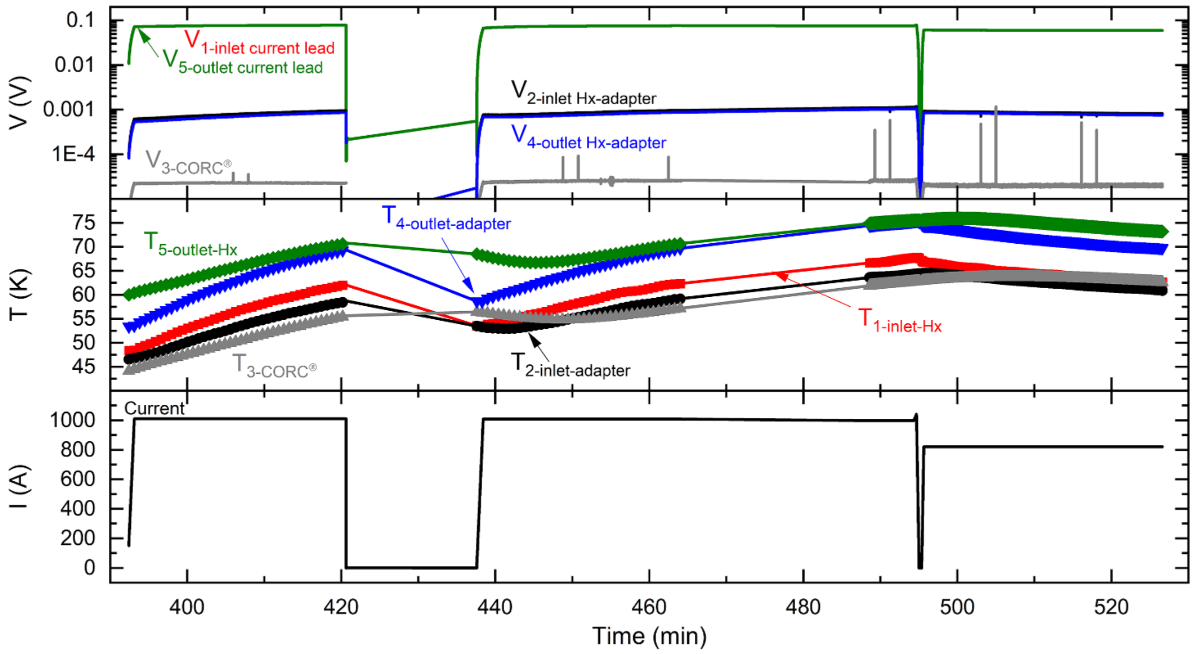

Figure 11. Voltages, temperatures and current as a function of time of the CORC® power cable system when equipped with the brass current leads CL-1 rated at 800 A.

Table 2. The performance of the cable system containing brass current leads CL-1.

	Location	524 min 800 A	495 min 1000 A
Voltage (mV)	$V_{\text{1-inlet current lead}}$	59.250	75.700
	$V_{\text{2-inlet Hx-adaptor}}$	0.815	1.130
	$V_{\text{3-CORC®}}$	0.0019	0.026
	$V_{\text{4-outlet Hx-adaptor}}$	0.754	1.040
	$V_{\text{5-outlet current lead}}$	60.000	76.600
Temperature (K)	$T_{\text{1-inlet-Hx}}$	62.7	67.7
	$T_{\text{2-inlet-adapter}}$	60.9	64.3
	$T_{\text{3-CORC®}}$	62.6	62.7
	$T_{\text{4-outlet-adapter}}$	69.7	75.4
	$T_{\text{5-outlet-Hx}}$	73.2	75.5
Expected ohmic heat load (W)	Per lead	32.3	50.1
Actual ohmic heat load (W)	Per lead	47.4	75.7

($T_{\text{4-outlet-adapter}}$) was 72.3 K. The critical current of the cable could not be determined accurately because the temperature gradient over the cable of about 10 K makes it difficult to estimate the cable length over which the voltage is generated. It can, however, be concluded that the critical current of the CORC® cable was above 3 kA at 72.3 K, while the contact resistance between the cable and its terminations was 27 nΩ.

4. Discussion

The vacuum vessel at CAPS and the possibility to measure the cooling power of the helium gas delivered to the components within the vacuum vessel allows relatively accurate characterization of current leads. The purpose of this work was not to fully optimize the conduction-cooled current leads, and therefore only limited data were collected during the characterization of current leads CL-2. The measurements still allowed a comparison of the relative performance of the current lead designs and their actual performance. The cooling power of the helium gas to cool the conductive heat into the vacuum vessel with current leads CL-2 mounted was about 147 W (figures 6–10), after the system reached an equilibrium state just before current was applied. The calculated heat load of 43.7 W per lead (87.4 W in total) (table 1) suggests that the additional conductive heat load into the vacuum vessel was over 60 W, which seems excessive. Unfortunately, no measurement of the baseline heat load without any current leads mounted was performed. Another reason for the higher heat load on the helium gas is that some of the system components

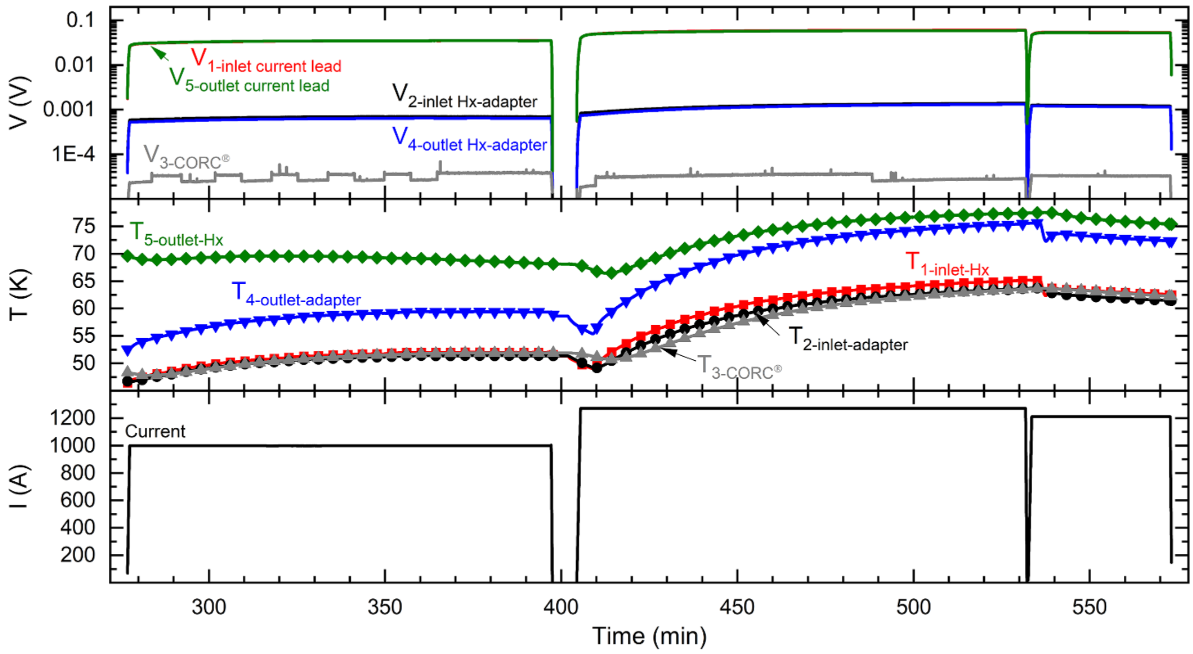

Figure 12. Voltages, temperatures and current as a function of time of the CORC® power cable system and copper current leads CL-3, rated at 1050 A.

Table 3. Performance of the cable system with current leads CL-3.

	Location	398 min 1000 A	530 min 1270 A	522 min 1210 A
Voltage (mV)	$V_{1\text{-inlet current lead}}$	35.220	60.450	53.640
	$V_{2\text{-inlet Hx-adaptor}}$	0.694	1.390	1.220
	$V_{3\text{-CORC®}}$	0.038	0.028	0.033
	$V_{4\text{-outlet Hx-adaptor}}$	0.640	1.320	1.150
	$V_{5\text{-outlet current lead}}$	35.110	59.220	52.730
Temperature (K)	$T_{1\text{-inlet-Hx}}$	52.0	65.2	62.5
	$T_{2\text{-inlet-adapter}}$	51.4	63.7	61.5
	$T_{3\text{-CORC®}}$	51.9	63.5	62.3
	$T_{4\text{-outlet-adapter}}$	59.3	75.5	72.3
	$T_{5\text{-outlet-Hx}}$	68.2	77.4	75.4
Expected ohmic heat load (W)	Per lead	41.1	66.2	60.1
Actual ohmic heat load (W)	Per lead	35.2	76.8	64.9

had not reached an equilibrium state and were still coming down in temperature, which resulted in additional heating of the helium gas.

The ohmic heating of current leads CL-2 of 49 W each at an operating current of 1.5 kA (figure 8) was comparable to their design value of 48.5 W. At that current, the conductive heat load cooled by the helium gas, defined as the total cooling power of the gas minus the ohmic heating in the current leads, remained at about 147 W. The ohmic heating of the current leads when initially operated at 2 kA of 77.2 W each was below their design value of 87.4 W (table 1). Besides a deviation in current lead dimensions, the current leads not having reached their design temperature with their warm end operating at 300 K could explain the difference. Although the temperature of the warm end of the current leads was not measured, except for two instances, it was assumed that it was significantly below 300 K at the start of the measurement. The ohmic heating in each current lead reached 104 W after 19 min at 2 kA, indicating a significant increase in current lead temperature. Calculations suggest the warm end of the current lead reached a temperature of 340 K.

Tables 2 and 3 list the expected and actual ohmic heat loads per current lead at different operating currents of CL-1 and CL-3 mounted within the CORC® power cable system at ACT. The actual ohmic heat load of the brass current leads (CL-1) was about 50% higher than expected. On the other hand, the actual ohmic heat load of current leads CL-3 was lower than expected at 1 kA, slightly higher than expected at 1270 A, and comparable to the expected heat load at 1210 A. The difference between the actual and expected ohmic heat load of the brass current leads (CL-1) is most likely caused by a deviation in actual current lead dimensions and possibly by a deviation in material properties. On the other hand, the deviation between the expected and actual ohmic heating in the

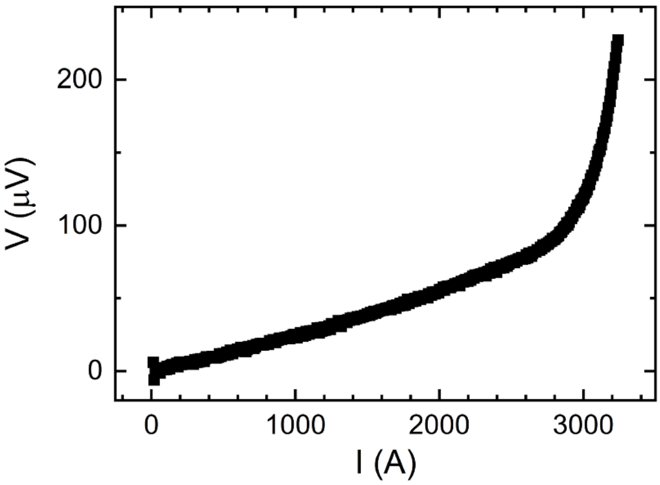

Figure 13. Voltage as a function of current measured over the CORC® cable at a starting temperature of the cable connector on the helium outlet side of 72.3 K.

copper current leads (CL-3) is most likely due to the actual temperature gradient over the leads. The warm end of the leads is most likely below the design value of 300 K at 1 kA (not measured), while it was about 350 K at 1270 A. The warm end of the current lead was about 300 K at 1210 A.

The results presented here show that the optimization of conduction-cooled current leads that are cooled with helium gas heat exchangers requires careful design and characterization. Deviations in actual dimensions, material properties and temperature gradient have a major impact on their current rating. Still, even the limited characterization of the current leads allowed development of a helium gas cooled CORC® power cable system that could be operated continuously close to its design current.

5. Conclusions

Several conduction-cooled current leads with helium gas heat exchangers, designed for operation from 800 A to 2 kA, were developed and characterized using a Stirling cryocooler with a closed-loop helium gas flow loop. The results show that precise optimization and characterization of the current leads are required to reach their target current rating. Current leads were integrated into a single-pole CORC® power cable to form a turnkey power cable system that could be operated continuously at a current exceeding 1 kA without the need for liquid nitrogen pre-cooling of the current leads. This accomplishment removes one of the remaining technical hurdles that prevented widespread applications of high current density superconducting power cables in naval ships, electric aircraft and data center application.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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