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First Electrical Characterization of Prototype 600 A HTS Twisted-pair Cables at Different Temperatures

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Abstract

Following the development of twisted-pair cables prepared with High Temperature Superconducting (HTS) tapes and their initial tests at 4.2 K in liquid helium at CERN, the cable samples of 2 m lengths were subsequently tested in flowing helium gas at temperatures between 10 K and 77 K at University of Southampton. A cryostat with optimized hybrid HTS current leads was purposely built for the tests up to 2.5 kA. The cryostat has two separate helium flow conduits, each accommodating a twisted pair and allowing independent temperature control. With the completion of the tests on the twisted-pair cables, a 5 m long semi-flexible Nexans cryostat was also set up for the testing of prototype HTS links assembled at CERN. The link, which is optimized for application to the remote powering of LHC 600 A electrical circuits, consists of a compact multi-cable assembly with up to 25 twisted-pair 600 A HTS tapes. The cables are cooled by a forced-flow of helium gas the inlet temperature of which can be changed in order to compare the electrical performance over a range of temperatures. The paper reports on the results of powering tests performed on the individual cables and the integration process for the forthcoming tests of the prototype links.

Keywords: HTS; Cables; MgB_2; Bi-2223; YBCO

1. Introduction

With the purpose of developing HTS cables optimized for electrical transfer in accelerator systems, several cable geometries have been studied [1]. In particular, a concept of 600 A twisted-pair cables made from HTS tapes has been proposed, together with an associated multi-cable assembly suitable for use in superconducting links of the type being studied for the LHC machine (Fig. 4 in [1]). Prototype 600 A twisted-pair cables were assembled at CERN for tests at the University of Southampton in a purpose-built

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test station that enables the electrical characterization of up to 2 m long cables in a variable temperature range. The cables were cooled by forced flow of helium gas at different temperatures, as envisaged for the application to the remote powering of LHC 600 A electrical circuits. In parallel, the same types of cables were measured at CERN at liquid helium and liquid nitrogen temperature [2]. A 5 m long link containing a multi-cable assembly was also prepared for test. A cable assembly was made at CERN and it is ready to be tested with cooling by flowing helium gas at the University of Southampton in an adapted test station.

2. Conductors and Methods

2.1. Characteristics of twisted-pair cables of HTS superconducting tapes

Tapes from five different HTS manufacturers were used for the twisted-pair cables. These cables are referred herein as: *Type-1* with Bi-2223 from Bruker HTS, *Type-2* with Bi-2223 from Sumitomo, *Type-3* with YBCO from SuperPower, *Type-4* with YBCO from AMSC, and *Type-5* with MgB_2 from Columbus. The HTS tapes used were in unit length in excess of 100 m and the detailed manufacturers' specifications can be found in [2].

The twisted-pair assemblies, hereafter referred to as cable units, incorporate about 3.2 mm^2 of copper stabilizer for protection requirements [1], implemented either by copper alloy laminations soldered onto the two sides of each tape (Type-2 and Type-4) or by four copper strips (4×0.2 mm^2) interleaved between the tapes during the preparation of the stacks. The electrical insulation of each stack is provided by Kapton® tape (6 mm by 50 µm), wrapped with 50 % overlapping back and forth around the conductor and the final assembly. The twist pitch of all assemblies is 0.4 m and the total length of the cable unit is 2 m.

2.2. Setup for twisted pair measurements

A cryostat, as illustrated in Fig. 1, was purposely built for the test of twisted-pair cables of 2 m length at different temperatures. The cryostat is equipped with a pair of hybrid HTS leads capable of 2.5 kA refrigerated by effluent of the cooling helium gas for the cables. The cryostat consists of two vessels (translucent in Fig. 1), each houses a twisted-pair cable and forms an independent helium flow conduit connected to the flow heat exchanger of a current lead. One of the two strands of the cable is connected to the respective current lead at one end and the two strands connected to the current leads are joined together at the opposite ends to form a continuous circuit for electrical tests. With independent

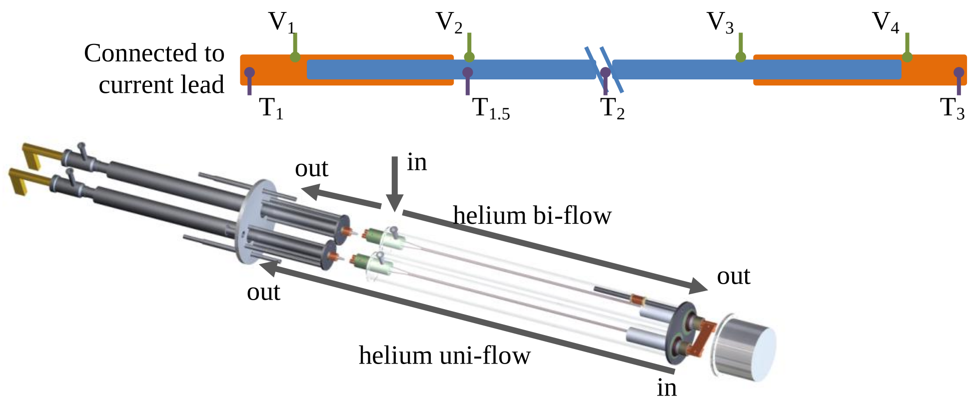

Fig. 1. An illustration of the cryostat for the electric tests of twisted-pair HTS cables. The uni- and bi-flow configurations for the cooling helium gas and the layout of the instrumentations are shown as indicated.

adjustments to the temperatures and flow rates in the two vessels, better flexibility can be obtained to accommodate uneven performances in the strands than using a single vessel.

The cryostat has been designed for two different flow arrangements: (i) uni-flow where the cold helium gas enters from the end opposite to the current leads, flows along the vessel, and exits via the current lead; (ii) bi-flow where the helium gas is injected at the middle of the vessel then split into two streams towards the two ends of the vessel. The uni-flow configuration results in a positive temperature gradient (2.5 K/m at ~0.2 g/s He flow, equivalent to 2.5 W/m heat load) along the vessel and the cable strand in the flow direction towards the current lead, a situation found in the typical cable/bus-bar applications. In contrast the bi-flow configuration can be used to give a near uniform temperature profile along the cable by adjusting the mass flow ratio between the two split streams, as < 0.5 K was obtained in tests. The entry port for the bi-flow configuration is placed asymmetrically (Fig. 1) nearer to the terminals between the cable and the current lead to offset the conduction heat load from the lead. It is also possible to combine uni- and bi-flows with dual helium inlets to increase the cooling for the current leads in order to exceed their design capacity. The cooling helium gas is generated in a liquid vessel and adjusted to a set temperature before entering the cable vessels.

The instrumentation for the electrical tests of the cables consists of (i) four voltage taps (V_1, V_2, V_3 and V_4) which are combined to give three recorded voltages: V_{12} and V_{34} for the cable terminations and V_{23} for the cable strand; and (ii) three thermometers: T_1 and T_3 on the two cable terminals respectively and T_2 in the middle of the cable strand. The overall voltage V_{14} of a cable strand can be obtained by summing up the three voltages. For some tests a further thermometer $T_{1.5}$ was added to indicate the cable temperature just outside the terminal to the current lead.

2.3. Setup for HTS link measurements

A 5 meter long semi-flexible Nexans cryostat (Fig. 2) was used for the test of HTS links in forced flow helium. The cryostat has a single inner vessel to house a HTS link consisting of up to 50 twisted-pair cables. A helium gas cooled current lead unit (Fig. 2 inset) is coupled to the cryostat for the electrical tests. There are two independent ports for helium entry/exit, located respectively at the two ends of the inner vessel. It is possible to configure the uni- and bi-flow for the helium as described above. The

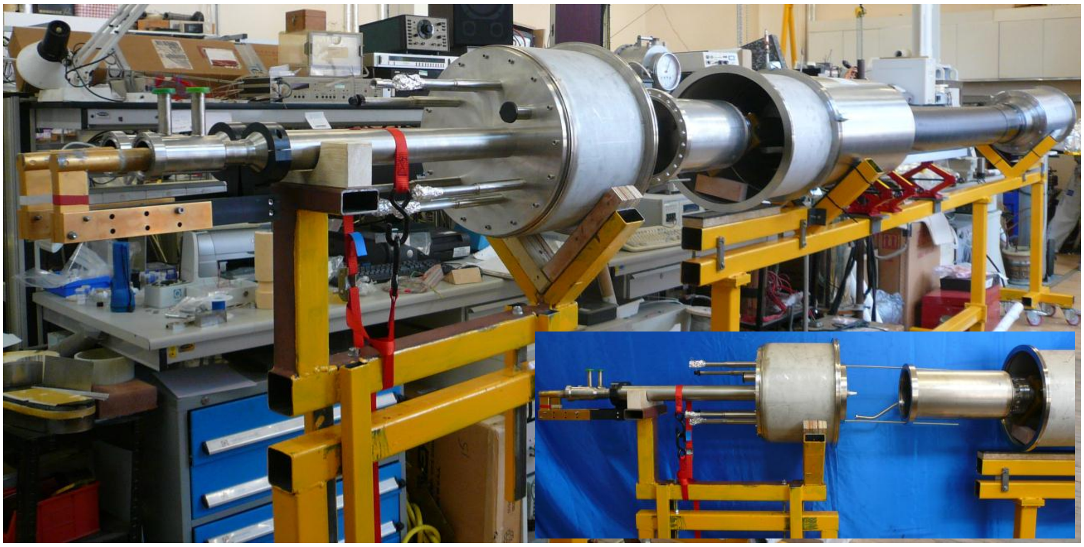

Fig. 2. A 5 m semi-flexible cryostat commissioned at University of Southampton for the test of HTS links. The inset shows the interface between the cable vessel and the current-lead unit.

twisted pairs of each cable are shorted together at one end and connected to strands of two different adjacent cables on the other end so that the all the strands in the link are joined together in series for electrical tests with one pair of current leads. The flow and temperature control are similar for the cable test cryostat.

2.4. Electrical measurements of superconducting cables in flowing He gas

The main aims of the electrical tests are to ascertain the critical current of twisted pair cables at different temperatures and assess their stability in a gas cooled environment when carrying a transport current at near critical values. It should be noted that the critical current measurement on long length conductors/cables in a gas cooled environment cannot be performed with a slow current ramp as often used in measurements with pool cooling in cryogenic liquids. To ensure a near stationary isothermal or defined temperature profile along the cables, short square current pulses with a plateau duration of 1-10 s were injected into the cables and the time traces of the electrical voltages were recorded simultaneously. A low noise data acquisition system was used to give a voltage resolution less than 5 μV. This semi-transient protocol not only allowed the successful determination of critical current I_C for the twisted –pair cables but also yielded *V-I* characteristics over a voltage range of more than three decades.

The temperatures of the cables were monitored throughout the measurements to ensure the thermal condition remained stationary.

Once the critical current is determined at a given temperature, the thermal stability of the cable at near critical current was tested by setting the cable to carry 80%-95% of I_C for more than 5 minutes. The voltages and temperatures of the cable were recorded during the period.

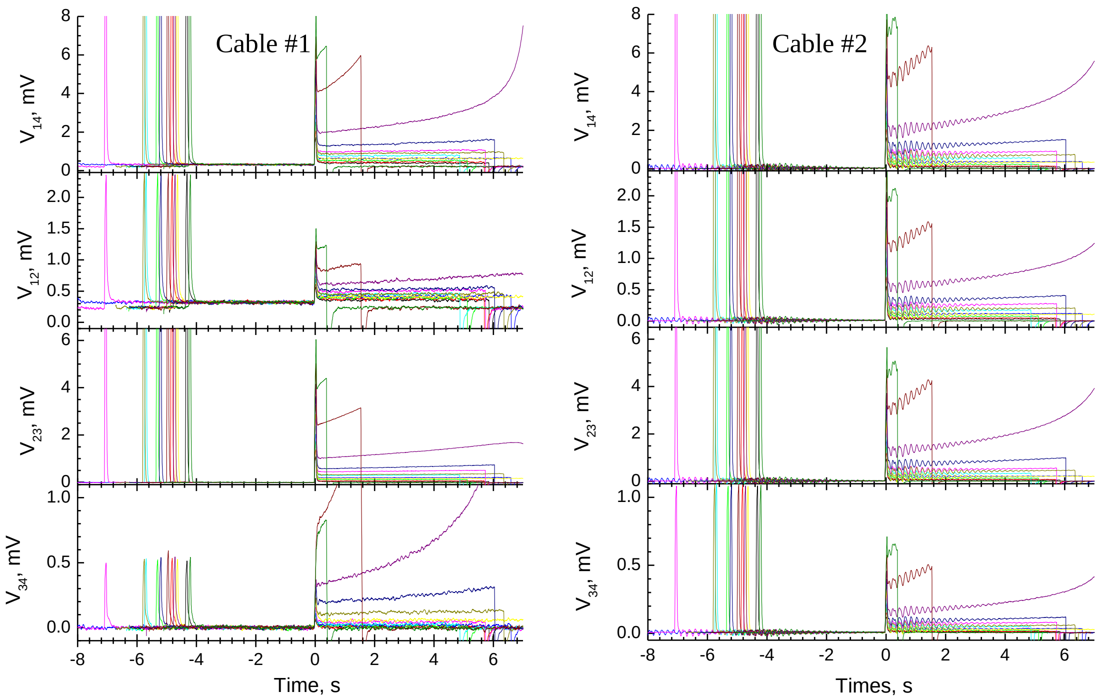

Fig. 3. Voltage traces along two strands of Type-3 cables at 50 K in a uni-flow configuration upon the injection of current pulses. Each colour corresponds to a current value ranging from 880 A to 1100 A in 20A intervals. Thermal runaway occurred at 1160 A.

3. Results

3.1. Determination of critical current of gas cooled long length superconducting cables using a semi-transient protocol

Strictly speaking it not possible to define the critical current of a cable in a uni-flow of cooling helium gas as there is always a temperature gradient along the cable. Instead the critical current obtained is only associated with the warmest part of the conductor which is at the termination connected to the current lead. In order to obtain the I_C of the cable strands, it is important that the temperature gradient is sufficiently small so that a significant stretch of the cable strand is almost at the same temperature. Together with a moderate $dI_C(T)/dT$, voltages should be detected simultaneously in V_{12} and V_{23}. The magnitude of V_{23} is direct indication of the strand section whose critical current has been exceeded. Another practical purpose for the electrical test is to determine whether inhomogeneous degradation has incurred to the twisted pair, as indicated by an earlier onset of voltage in V_{23} ahead of V_{12}.

An example of a typical voltage sequences for a set of current pulses at different amperage is shown in Fig. 3, corresponding to Type-3 cable at 57 K with current injected in two-step square pulses, a first plateau of 800 A and rising to a second plateau up to 1100A. The spikes in the traces are the inductive pickup corresponding to the onset of the current pulses. A two-step current pulse gives a smaller inductive pickup in the second pulse when the resistive voltage is sought after. The voltages of the two cable strands located respectively in the two helium flow vessels are shown side by side for comparison. The overall voltages V_{14} for the two cable strands remarkably similar, confirming the overall reproducibility of the Type-3 cable strands. A closer examination shows that cable #2 (right pane in Fig. 3) has a higher V_{12} and V_{23}, suggesting its terminal to the current lead is slightly warmer. The ratio between V_{12} and V_{23} was found to be roughly 1:2.5 for both cables. Since V_{12} covers a length of 160 mm superconducting strand in the termination and beyond, the portion of the strands within V_{23} which has been exceeded in critical current was approximately 400 mm. At higher current above I_C, the terminations became unstable and thermal runaway ensued. It appeared the terminal of cable #1 at the end opposite to the current lead connection (V_{34}) had a faster voltage increase, possibly due to a slightly poorer cooling.

With a bi-flow arrangement, the temperature gradient was significantly reduced along the whole cable lengths. In this case it was found that the voltage onset along the cable was uniform and isothermal V-I characteristics were obtained, as shown in Fig. 4 for Type-2 at several temperatures. In Fig. 4, the termination voltageV_{12} exhibited a resistive voltage below I_C as the result of the contact resistance

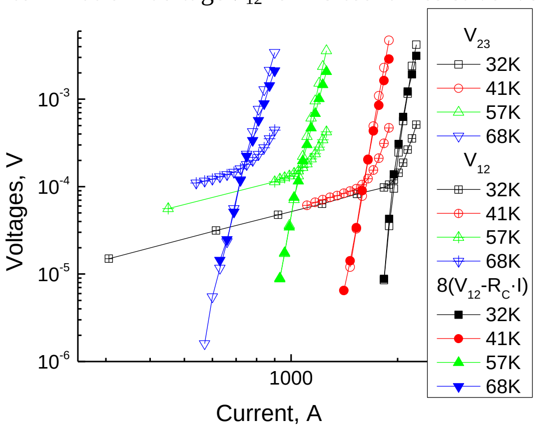

Fig. 4. V-I characteristics of a terminal (V_{12}) and the complete strand (V_{23}) for Type-2 at different temperatures.

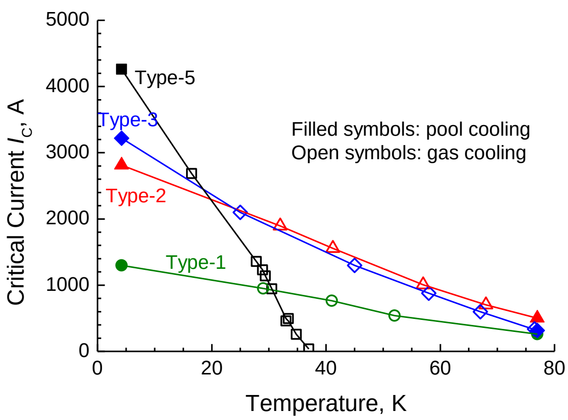

Fig. 5. Critical current I_C as a function of temperatures for different cable types.

between the strand and the copper in the joint, while the whole strand voltage V_{23} showed typical power-law like behavior. With the contribution of the contact resistance R_C removed, the residual voltage (V_{12}-$I \cdot R_C$) was found to be $V_{23}/8$, in agreement with the length ratio between V_{12} and V_{23}. This is a convincing confirmation of the strand homogeneity in performance as well as that of the strand temperature during the test. The contact resistance of the terminal (~ 800 mm^2) was 50 nΩ at 32 K, rising to 200 nΩ at 77 K.

The critical currents of different cable types as a function of temperature are shown in Fig. 5, where the open symbols represent results for measurements with gas cooling at University of Southampton and the filled symbols with pool cooling in liquid nitrogen or helium at CERN. The results are consistent with expectations.

3.2. Stability near the critical current

The stability of the twisted pair cables at the vicinity of the critical current has been successfully demonstrated for all types of cables. An example for Type-2 at 32 K and 58 K is shown in Fig. 6, where the temperature traces are those within the vertical bar and both voltage and temperature traces are identified by the color correspondence to the axis labels. With an overall voltage of 0.1-0.4 mV, the cable was stable for more than 5 min even with an appreciable temperature rise on the cable (~1.5 K at 32 K 1860 A).

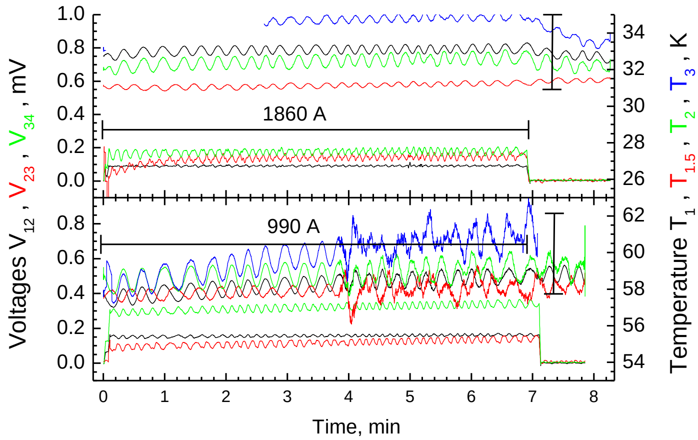

Fig. 6. Time series of voltage and temperature for Type-2 cable at near critical currents at 32K and 67K, showing stability for over 5minutes.

4. Conclusions

The first electrical tests on the twisted-pair HTS cables were successful and confirmed the uniformity as well as stability for their operation in a gas cooled environment. A cryostat for the test of a prototype 5 m long link has been assembled and tests on HTS links to follow soon.

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