Development and Test of High-Temperature Superconductor Harness for Cryogenic Instruments on Satellites

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***Abstract*—Extremely sensitive x-ray or infrared detectors that have to be cooled to temperatures well below 1 Kelvin will be used in a number of future satellite missions within ESA's Cosmic Vision and Voyage 2050 program, e.g. ATHENA. To provide sufficient cooling power at different temperature levels, complex cryogenic chains are being developed with different types of coolers. Adiabatic demagnetization refrigerators (ADRs) can be used to reach the lowest temperatures in the range of 50 mK – 100 mK. Due to the limited electrical power available on satellites and other space constraints, superconducting ADR magnets are usually operated with dc currents of only a few Amps. Despite the low currents, the current leads connecting the power supply at a higher temperature stage to the magnet at the cold stage contribute with a high heat load to the limited thermal budget.**

In this paper we present the design, manufacturing and first tests of a high-temperature superconducting current lead harness which is designed to operate up to a temperature as high as 85 K with a nominal current of 2 A and a maximum current of 5 A.

Design choices based on characterization of laser-cut *RE*BCO tapes from different suppliers, characterization of structure materials and on thermal and mechanical simulations are presented. First test results for the assembled harness are discussed. They include current and bending tests, as well as insulation resistance tests.

***Index Terms*— HTS current leads, jacket, mechanical behavior, satellite, thermal performance**

I. Introduction

SPACE Science missions such as SPICA with the SAFARI and B-BOP instruments and the X-ray telescope ATHENA with the X-IFU instrument require a complex cryogenic chain to ensure temperatures in the order of 50 mK at the level of their respective detectors [1], [2]. The last cooling stage in these complex chains includes Adiabatic Demagnetization Refrigerators (ADRs) which use the magnetic disorder entropy of the electronic magnetic moments in paramagnetic salts. The ADR requires the ability to generate a variable magnetic field that can be used to cyclically align the electronic magnetic moments in a paramagnetic salt pill, while thermally insulating it from its surroundings so that the change in entropy in adiabatic conditions can be used to cool the system. A variable magnetic field with a maximum of around 3 T is generated by a coil that requires an electric current in the order of 2 A. Routing such high currents to the low temperature stages of the cryostat is a challenging endeavor and a big contributor to the parasitic heat loads in the cryogenic chain. We are dealing with conflicting requirements; ideally, the harness should have high electrical conductivity (low electrical resistance and therefore low Joule losses) and low thermal conductivity. This is not possible with normal metallic materials, where the thermal and electrical conductance are correlated by the Wiedemann-Franz Law. Superconductors (SC) on the contrary have a low/zero electrical resistance and a low thermal conductance and are therefore used as a lead-in wire for superconducting magnets. For the XRS-2 instrument of the Astro-E2/Suzaku mission, MgB_2 wires have been developed as lead-in wires for valves and an ADR magnet cooled by superfluid helium at a temperature $T = 1.3$ K. The warm end temperature of the current lead wires was 17 K [3], [4]. Similar MgB_2 wires have been prepared for the Engineering Model (EM) of a combined sorption/ADR cooler for the SpicA FAR infrared (SAFARI) instrument [6]. For the x-ray instruments SXS onboard the Astro-H/Hitomi mission and the RESOLVE instrument onboard XRISM current lead assemblies with high-temperature superconducting (HTS) *RE*-Ba-Cu-O (*RE*BCO, *RE* = Rare Earth) tapes have been developed at NASA GSFC [7], [8]. Due to the higher warm end temperature up to 62 K, MgB_2 with a critical temperature (T_c) of 39 K could not be used as current leads for the multi stage ADR cooler and was therefore replaced by *RE*BCO tapes with $T_c \sim 90$ K.

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In this paper, the development of an EM HTS-harness for future science missions of the European Space Agency (ESA) is described and first test results are presented.

II. Harness design

A. Technical Requirements Baseline

A number of technical requirements for the HTS harness (Fig. 1) have been set by ESA: The harness, which connects Phosphorbronze (PhBr) leads on the warm side to a NbTi ADR magnet at the cold end needs to consist of 1-m-long outward and return conductors with a jacket. Interface (I/F) brackets at 85 K and 4 K serve as electrical contacts to PhBr and NbTi wires, respectively. Mechanical supports fix the harness at temperature levels of 80 K and 30 K to the cryostat. The harness shall bring a total heat load not higher than 1 mW to its 4 K I/F, while conducting a current of 2 A DC in the superconductive state with the ohmic to SC I/F at 85 K. Furthermore, the harness shall be able to conduct a current of 5 A in its superconductive state without any degradation. The ohmic to SC I/F (85 K) shall be able to dissipate a total heat load of 800 mW while the heat load dissipation at the 30 K I/F shall not exceed 20 mW.

Besides the high warm end temperature of 85 K, the most challenging requirements are the flexible design with the possibility of bending with a minimum radius of 5 cm in all spatial directions and the requirement that the harness needs to withstand high mechanical loads despite the long distance of 25 cm between I/F brackets and/or mechanical supports. Further requirements include, but are not limited to the use of low magnetic and low outgassing materials, an insulation resistance > 100 MΩ at 200 V_{DC}, the ability to conduct a current of 100 mA in its non-superconducting state, and a long-term stability in air to meet storage requirements of 5 years in air and 15 years in space.

The design of the harness is presented in the next sections.

B. Selection of Superconducting Wire

After a survey about the availability of *RE*BCO conductors from different suppliers, two different 12-mm-wide *RE*BCO coated conductors from two different suppliers were chosen: a silver (Ag) coated tape from SuperOx and a siver/gold (AgAu(5%)) coated tape with reduced thermal conductance from SuperPower. The two tapes have a similar total thickness of approximately 0.05 mm with a total Ag or AgAu(5%) cover layer thickness of approximately 3 - 3.6 µm. Due to the different chemical nature of the cover layer, the thermal conductivity of the SuperPower tape with AgAu(5%)-coating is much lower than that of the Ag coated SuperOx tape – almost one order of magnitude at temperatures below 10 K as shown in Fig. 2a. The lower thermal conductivity leads to strongly reduced heat loads at the cold end in current lead applications. The current carrying capability at high temperatures, however, is much higher for the Ag-coated SuperOx tape (Fig. 2b). The SuperOx tape has a GdBCO superconducting layer with a high T_c of 93 K. The SuperPower tape is an advanced pinning (AP) conductor optimized for high-field applications. Due to the inclusion of artificial pinning centers, the critical temperature is reduced to 89 K.

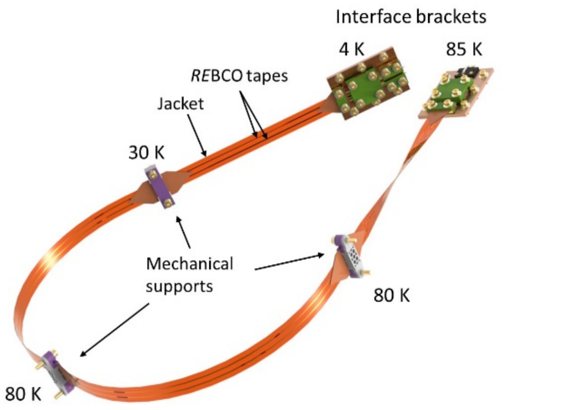

Fig. 1. ESA HTS harness with outward and return conductor, jacket, I/F brackets at 85 K and 4 K and mechanical supports at 80 K and 30 K.

Both conductors are able to carry the required current of 5 A at 85 K for a 1-mm-wide tape, however, the critical current (I_c) of the Ag coated SuperOx tape is a factor of 2 higher at this temperature than I_c of the AgAu(5%) coated SuperPower tape. For this reason and due to the wider availability of conductors with standard Ag coating, ESA decided to use the SuperOx tape for the EM harness. As the current carrying capability of a 1-mm-wide section of the SuperOx tape is high enough to transport the required 5 A at 85 K, five neighboring 1-mm-wide and 1250-mm-long tapes were cut out of the center of the original 12-mm-wide tape with a pico-second laser to reduce the thermal conductance. 125 mm sections at each end of the tape were then Cu plated and the I_c of each 1-mm-wide tape was measured in liquid nitrogen (LN_2). A total number of 17 tapes passed the I_c-threshold of 25 A with an electric-field (E) criterion $E_c = E(I_c) = 0.01$ µV/cm and were used for further production steps.

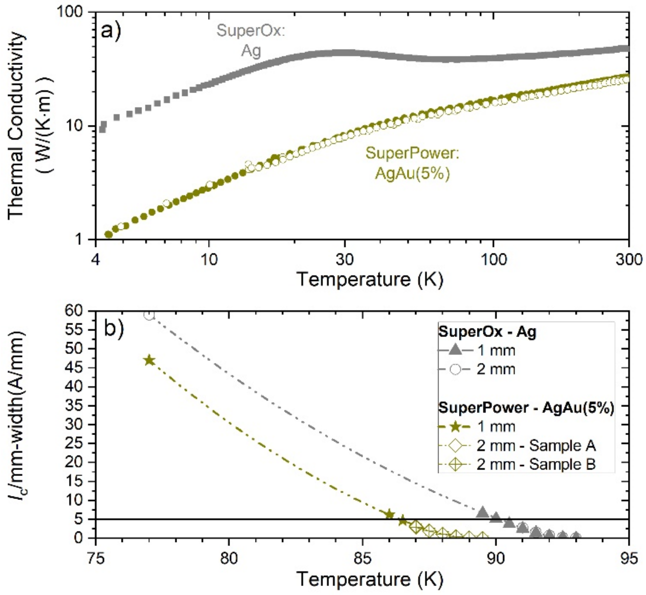

Fig. 2. a) Temperature dependence of longitudinal thermal conductivity of Ag-coated *RE*BCO tape from SuperOx and of AgAu(5%)-coated *RE*BCO tape from SuperPower measured with the Thermal Transport Option of a Quantum Design Physical Property Measurement System. b) Temperature dependence of critical current per mm width of 1-mm and 2-mm-wide Ag-coated *RE*BCO tapes from SuperOx and AgAu(5%)-coated *RE*BCO tapes from SuperPower.

C. HTS Cable Jacket

The jacket of the cable is required as humidity protection, electrical insulation and mechanical reinforcement. It needs to be flexible to allow bending to install the harness in a cryostat. In order to protect the *RE*BCO tapes with their open laser-cut sides from humidity, an approx. 30 µm thick coating with Parylene C was applied in the 1-m-long non-Cu-plated sections of the *RE*BCO tapes by Plasma Parylene Systems, Germany [9][9]. Parylene is an inert, water-repelling, chemically resistant and electrically insulating polymeric coating material that has been used in aerospace applications. After the Parylene coating process, the critical currents of all *RE*BCO tapes were measured again in LN_2 and no degradation was observed.

In a next step, two parallel Parylene C coated *RE*BCO tapes (outward and return conductor) were hot laminated between two 1-m-long, 14-mm-wide and 125-µm-thick Kapton tapes. The Cu plated ends were not covered by the Kapton laminate. The exact position of *RE*BCO and Kapton tapes was ensured by using 3D-printed lamination aids through which the *RE*BCO and Kapton tapes were pulled before entering the lamination machine. The distance between the two *RE*BCO tapes is 4 mm. After the hot lamination process, a “health check” was performed by applying a current ramp up to 20 A to each of the *RE*BCO tapes to see if a voltage rise occurs. No voltage increase or degradation was observed for the laminated tapes of a first test harness and the qualification EM.

D. I/F Brackets at 4 K and 85 K

I/F brackets as shown in Fig. 3, which will be attached to 85 K and 4 K I/Fs of a cryostat, serve as connectors to PhBr wires and the NbTi magnet, respectively. Both I/F brackets consist of gold-plated Cu-parts to which the *RE*BCO tapes are soldered with InAg3 solder. These Cu parts are connected with Cu wires to a Glenair® series 171 MicroStrip™ socket connector to which PhBr current lead wires can easily be connected with a pin connector. In order to allow dissipation of heat coming through the PhBr wires from a higher temperature stage, the Cu-*RE*BCO connectors are thermally connected to a gold-plated Cu base plate that can be fixed with screws at the cryostat. Electrical insulation between the current carrying Cu-*RE*BCO connectors and the base plate is achieved with AlN plates, which have a high thermal conductivity despite being electrically insulating. InAg3 foil between the Cu parts and the AlN plates is used to reduce the thermal contact resistance. G10 holders press the Cu-*RE*BCO connector to the base plate and serve as strain relief. The 4 K I/F bracket that connects the *RE*BCO tapes to the NbTi magnet leads has a similar design, however, the NbTi wires are soldered to gold-plated Cu blocks, that can directly be fixed with screws at the Cu-*RE*BCO connectors. A sensitivity analysis has been performed to check if the I/F brackets are able to dissipate a major part of the incoming heat to the cryostat. A thermal contact resistance of 2000 W/(K·m^2) at the 85 K I/F bracket and of 500 W/(K·m^2) at the 4 K I/F bracket results in a heat load of 0.57 mW at the 4 K stage. A major part of the incoming heat of 800 mW can be dissipated to the thermal bath at 85 K.

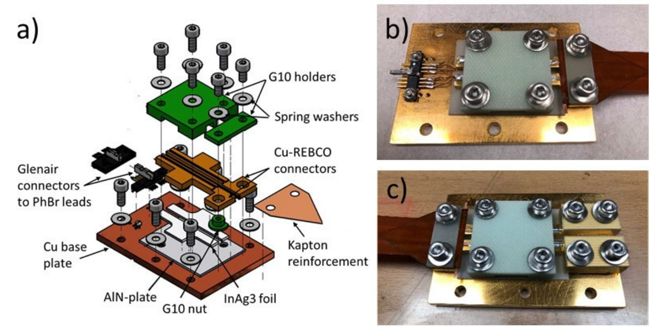

Fig. 3. a) Exploded view of 85 K I/F bracket. b) Photo of 85 K I/F bracket. c) 4 K I/F bracket.

E. Mechanical Supports

According to ESA requirements, two mechanical supports will be used to fix the harness at an 80 K I/F and one mechanical support to fix it at a 30 K I/F. The distance between mechanical supports and/or between mechanical supports and I/F brackets is 0.25 m. The 80 K mechanical supports are made of 3D-printed PEEK and have a low thermal conductance, while the 30 K mechanical support is made of conductive aluminium to act as a heat sink. In order to prevent sharp bending over the edges of the mechanical supports, the Kapton-laminated *RE*BCO tapes are reinforced with triangular-shaped Kapton foil as shown in Fig. 4. The double arrow shape of the Kapton reinforcement results in a gradual change of the stiffness of the laminated *RE*BCO tapes.

III. Harness testing

After assembly of the qualification EM, a health check with a maximum current of 20 A was performed. For this health check, a short connection was applied at the 85 K I/F bracket while the current leads were connected at the 4 K I/F bracket. The voltage was measured at both *RE*BCO tapes. A slight voltage increase was observed for one of the *RE*BCO tapes. It turned out that this slight voltage increase was caused by the close position of the short connection at the 85 K I/F bracket and the voltage taps. No indication of degradation due to the assembly process could be observed. After the first health test of the assembly, the test campaigns with mechanical, electrical and thermal tests started at KIT and CEA.

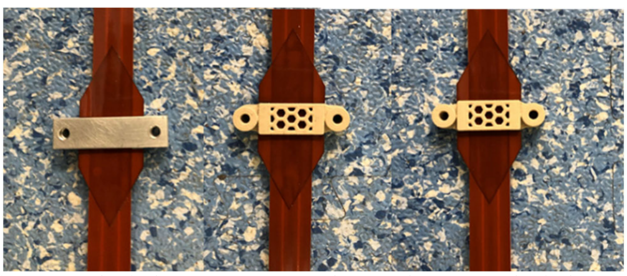

Fig. 4. Mechanical supports at 30 K and 80 K. The 30 K mechanical support (left) is made of aluminium and acts as a heat sink, while the 80 K mechanical supports (middle and right) are made of 3D-printed PEEK with a low thermal conductance.

A. Harness Bending Test

A bending test was performed according to the ESA requirements that the harness shall be designed to withstand dynamic bending of at least 1000 bends without any degradation and that the cable shall allow for a minimum bending radius of 5 cm in all spatial directions. For the bending test, two G10 cylinders with an outer diameter of 10 cm were mounted on top of each other with their axes aligned parallel in horizontal direction. The straight harness was placed perpendicular to the cylinder axes between the two cylinders. The section between the 30 K mechanical support and the 80 K support in the middle of the harness was then manually bent 1000 times around the cylinder above and the cylinder below, so that the harness touched the cylinders on a half circumference, i.e. on a length of 15.7 cm during each bending step. After bending no damage or delamination could be observed in the bent section. A health check with a current of 20 A in LN_2 did also not show any indication of a damage.

B. Insulation Resistance Test

In a next step, the insulation resistance was checked with an insulation tester (Danbridge JP30A). Three different cases were tested by applying a voltage of 200 V_{DC} between different parts of the harness and measuring the leakage currents.

- Case 1: 200 V: Tape 1, Tape 2; Ground: Base Plates
- Case 2: 200 V: Tape 1; Ground: Tape 2, Base Plates
- Case 3: 200 V: Tape 2; Ground: Tape 1, Base Plates

Leakage currents were measured after 1, 3 and 5 minutes to observe also changes caused by capacitive current contributions. A minimum insulation resistance value of 0.87 GΩ was determined during these tests exceeding the minimum required value of $R > 100$ MΩ. A further health test did not give any indication of degradation.

C. Structural Analysis and Shaker Test

In order to evaluate if the HTS harness is able to withstand the mechanical environment during the launch of the satellite without degradation, a structural analysis has been performed. A structural model with a free cable length of 25 cm was created in Hypermesh/Optistruct and calculations were performed with a non-linear solver for quasi-static loads (QSL) and random loads as given in Table I. Margins of Safety (MoS) were calculated as $MoS = (AL/(DL \cdot FoS) - 1)$, where AL is the allowable load under specified conditions, DL is the design load and FoS is a factor of safety. For quasi-static loads and a free cable length of 25 cm, MoS values of 504 and 81 were calculated for the *RE*BCO tapes and Kapton jacket, respectively. For random loads, the MoS values for the *RE*BCO tapes and Kapton jacket are 38 and 9, respectively. Positive MoS indicated that the materials will stay within the loads they can cope with.

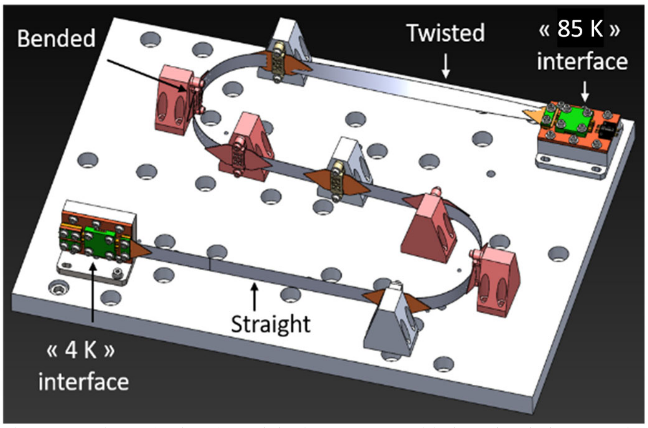

Fig. 5. Schematic drawing of the harness assembled on the shaker test plate with straight, twisted and bent sections.

In order to verify the simulation results, a shaker test was performed with the qualification harness with quasi-static, sine, random and shock excitations as shown in Table I. During the tests the harness was mounted on the shaker plate with straight, bent and twisted sections as sketched in Fig. 5. The free lengths of the straight and twisted sections was 25 cm, approximately 10 cm longer than the maximum distance between mechanical supports in conventional ESA harnesses and therefore a worst-case scenario. The measurement results have not been fully analyzed at the time of writing this paper and will be published later. However, in a visual inspection and in a health check following the shaker test, no indication of degradation could be observed.

TABLE I
MECHANICAL TESTING

Excitation	Frequency	Levels (all axes)
Quasi-static		25 g in all axes
Sine	5 - 25 Hz	±10 mm
	25 - 100 Hz	25 g
	Sweep rate	2 Oct/min
Random	20 - 100 Hz	+3 dB/Oct
	100 - 300 Hz	0.3 g^2/Hz
	300 - 2 000 Hz	-5 dB/Oct
	Global	13.1 g_{rms}
	Duration	2 min /axis
Shock	10 Hz	20 g
	1 000 Hz	2 000 g
	10 000 Hz	2 000 g

IV. CONCLUSION AND OUTLOOK

A high temperature superconducting EM harness for future ESA missions with ADR sub-Kelvin coolers has been designed and manufactured. First electrical and mechanical tests did not show any signs of degradation of the flexible current lead harness. Thermal cycling tests and thermal tests will be performed as next steps. The harness will be fixed at appropriate temperature stages in a cryostat at CEA and the performance will be tested with heat loads of 800 mW at the 85 K I/F bracket while conducting the nominal current of 2 A. Heat loads at the low temperature stages will be measured and a current test with the maximum design current of 5 A will be performed. After the thermal test, the harness will be shipped back to KIT where further insulation resistance tests and a destructive test will be performed.

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