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M7.5.1: Final design report HTS link

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Geneva, 20 April 2012

Design report of Task 7.5, High-Tc Link

Reported for the Task 7.5 members by A. Ballarino (Task Leader) and M. Sitko (CERN fellow financially supported by the FP7 collaboration).

1. Introduction

The proposal of developing High Temperature Superconducting (HTS) cables derives from the potential of the application of HTS in the powering system of the LHC accelerator [1]. The powering of the LHC magnets is today performed via power converters located in tunnel alcoves. Warm cables connect the power converters to the leads integrated in cryostats in line with the beam. The use of superconducting links allows the removal of the powering equipment from the radiation areas in the tunnel to remote radiation-free locations. As a result, one can ensure safer long-term operation of the equipment as well as easier access - in non radiation zones - of personnel to power converters, current leads and related control apparatus for the maintenance, repair, diagnostic and other interventions. The FP7 activity performed within the Task 7.5 aims at the development of a superconducting link of the type that could be applied in the LHC at P3 or P7. It consists of 48 cables, rated at 600 A – DC, and developed for the powering of the LHC corrector magnet circuits. The deliverable of the Task 7.5 is a 20 m long prototype link, consisting of a cryostat and of the HTS multi-cable (24 pairs) assembly.

The candidate superconducting materials considered for this application are:

- first generation conductor (**Bi-2223**) in the form of multi-filamentary composite in a silver alloy matrix;
- second generation conductor (**Y-123**) based on technology of thin layers deposited on metallic substrates;
- **MgB_2** – recently developed low-cost material produced via the powder-in-tube technology.

The use of high temperature superconductors provides not only increased temperature margin with respect to conventional Nb-Ti, but also capability of adsorbing higher heat load and possibility of gas cooling at different temperatures over long lengths. This brings to a simplified cryogenic scheme of the entire cold powering system (link, current leads and associated cryostat). The critical temperatures of LTS and HTS superconductors are reported in Figure 1.

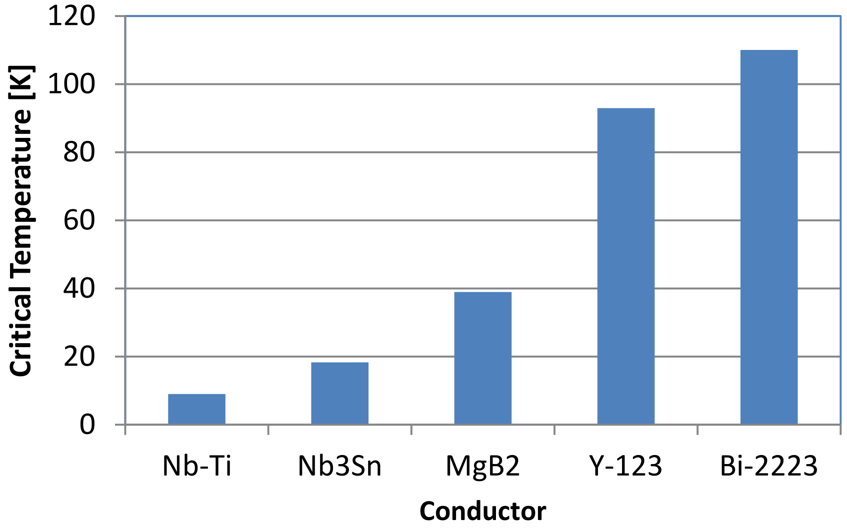


Figure 1: Critical temperatures of superconductors.

2. Design parameters

For the development of the HTS link, the following design parameters have been defined:

- **Nominal current:** according to the LHC magnet design, each HTS cable shall operate at a maximum current of 600 A in DC mode.
- **Operating temperature:** the operating temperature should provide a sufficient margin with respect to the critical temperature of the superconductor. In addition, for first and second generation superconductors, there is an interest in operating them at lower temperatures in view of their higher current critical current. On the basis of these considerations, maximum operating temperatures of 25 K for MgB_2 and 35 K Bi-2223 and Y-123 were selected.
- **Copper stabilizer:** at least 3.2 mm^2 per cable.
- **Cooling:** helium gas entering at variable temperatures in the range from 5 K to 20 K and at a pressure of about 1.5 bar.
- **Mechanical constraints:** the design shall be flexible and compact in order to enable integration in the LHC tunnel at P3 and P7.

3. Superconducting materials

All HTS superconductors described in section 1 (Y-123, Bi-2223 and MgB_2) are produced in the form of thin tapes. However, they have very different electrical and mechanical properties.

Several types of superconductors delivered by five different manufacturers were investigated at CERN. Conductors were procured and delivered to CERN in lengths exceeding 100 m. In this section a brief overview of the HTS tapes considered for the HTS link application is presented. All critical current (Ic) values given below are measured at 77 K and in self-field by the direct current transfer method and according to the electric filed criterion of 1 µV/cm, with the exception of MgB_2, for which the value 30 K is reported.

3.1. BSCCO

Bi-2223 tape delivered by Bruker HTS, referred in this document as Type-1 conductor, is 3.95 mm wide and 0.21 mm thick (Figure 2). The minimum critical current guaranteed by the supplier is 85 A. The Ic values measured at CERN on several 1 m long samples range from 93 A to 95 A, which provides an engineering critical current density of the order of 11 kA/cm^2. The critical tensile stress is 210 MPa at 77 K, and the minimum bending radius that can be applied at room temperature is 30 mm [2].

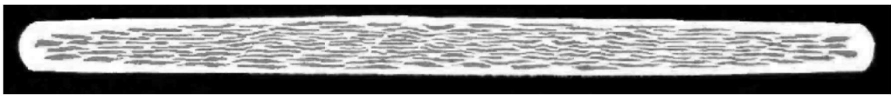


Figure 2: Cross section of BSCCO Bruker HTS tape.

Bi-2223 tape supplied by Sumitomo Electric, referred in this document as Type-2 conductor, is a high current density superconductor that incorporates 50 µm thick copper alloy laminations soldered on both sides of the silver alloy matrix (Figure 3). The conductor is 4.5 mm wide and 0.36 mm thick. The minimum critical current value guaranteed by the supplier is 180 A [3], whereas the Ic values measured at CERN vary from 194 A to 196 A, which gives an engineering critical current density of the order of 12 kA/cm^2. Copper alloy reinforcement provides not only a by-pass in normal state but also improves the mechanical properties of the tape. The tensile stress that the tape can reach without degradation of superconducting properties is 250 MPa at 77 K, and the minimum double bending diameter (double bending applied at room temperature) is 60 mm [4].

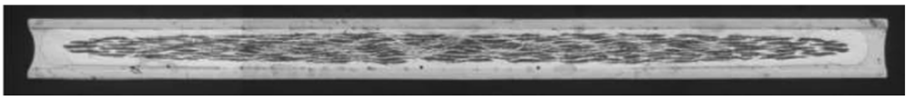


Figure 3: Cross section of BSCCO Sumitomo reinforced tape (4).

3.2. YBCO

YBCO SuperPower tape, referred in this document as Type-3 superconductor, is 4.1 mm wide and 0.095 mm thick. The sandwiched structure of the conductor consists of YBCO layer of about 1 µm thickness which is deposited onto a 50 µm Hastelloy®C-276 substrate. It is surrounded by 20 µm thick copper stabilizer (Figure 4). Thanks to excellent mechanical properties of the Hastelloy®, the superconducting tape is characterised by very high critical tensile stress (> 550 MPa at room temperature) and a minimum bending diameter of 11 mm [5]. The minimum critical current guaranteed by supplier is 90 A and the Ic values measurements at CERN vary from 105 A to 110 A, giving an engineering critical current density of about 28 kA/cm^2.

Figure 4: Cross section of YBCO SuperPower tape.

YBCO tape delivered by American Superconductor, referred in this document as Type-4 conductor, incorporates on both sides soldered copper alloy laminations. The tape is 4.4 mm wide and 0.44 mm thick. The Ic guaranteed by the supplier is 90 A whereas the Ic values measured at CERN vary from 105 A to 110 A. The critical tensile stress at room temperature is 200 MPa and the minimum double bend diameter is 35 mm.

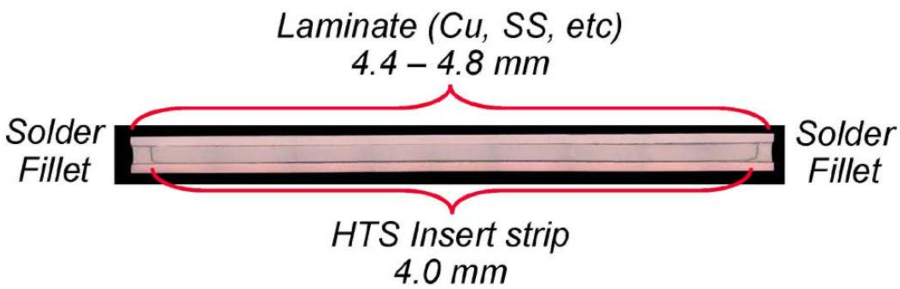


Figure 5: Cross section of YBCO American Superconductor tape.

3.3. MgB_2

MgB_2 is the most recently developed superconducting material. Thanks to low production costs and wide availability, it is a very promising superconductor for the superconducting link project. The superconducting tape produced by Columbus, referred in this document as Type-5 superconductor, is 3.6 mm wide and 0.67 mm thick. The supplier guaranties a minimum Ic of 330 A at 30 K and in self-field, what provides a minimum engineering critical current density at 30 K of 13 kA/cm^2.

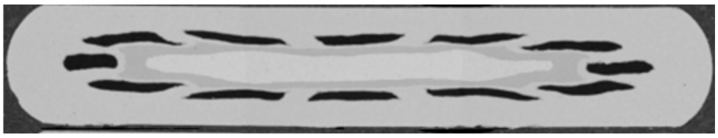


Figure 6: Cross section of Columbus MgB_2 tape.

A summary of the main characteristics of the superconducting tapes considered for the HTS cable in the link is reported in Table 1. A comparison of critical current values guaranteed by supplier and of the results of measurements carried out at CERN is given in Table 2, where also the index of transition (*n*-value) is reported.

Table 1: Basic characteristics of superconducting tapes procured for the HTS link project.

Conductor	**Superconducting material**	**Supplier**	**Width [mm]**	**Thickness [mm]**	**Copper alloy lamination**
Type-1	BSCCO	Bruker HTS	3.95	0.21	No
Type-2	BSCCO	Sumitomo	4.5	0.36	Yes
Type-3	YBCO	SuperPower	4.1	0.095	No
Type-4	YBCO	AMSC	4.4	0.44	Yes
Type-5	MgB2	Columbus	3.6	0.67	No

Table 2: Electrical properties of superconducting tapes: values guaranteed by the suppliers and measured at CERN.

Conductor	**I_c guaranteed [A]**	**Min. I_c measured [A]**	**Max. I_c measured [A]**	***n*-value**	**Average J_e [kA/cm^2]**
Type-1	85	93	95	21	11.3
Type-2	180	194	196	19	12.0
Type-3	90	114	119	29	29.9
Type-4	90	105	110	36	5.5
Type-5	≥ 330 @ 30 K	> 1360 @ 4.2 K	> 1360 @ 4.2 K	not measured	> 13.7 @ 30 K

4. High current HTS cables: twisted pair and multi-cable assembly

The HTS cable developed for electrical transfer over long lengths is a novel concept that we call "**Twisted Pair Cable**" [1]. The twisted pair consists of two cables transferring the same current in opposite direction. A single cable is made of an the assembly of three HTS tapes with the required copper stabilizer, which is either already incorporated in the tape (this is the case for Type-2 and Type-4 conductors with have laminations soldered onto the conductor) or added via parallel copper strips, four in total, interleaved between the superconducting tapes. The assembly is electrically insulated by Kapton® tape, wrapped with 50 % overlapping twice around the conductors. The final cable unit is then composed of two single cables, the insulated stacks of conductors, which are twisted together to form the twisted pair (see Figure 7). The two cables of the twisted pair feed the same magnet circuit. The twisted-pair assembly is again insulated by Kapton® tape. The size of the insulated twisted-pair assembly, depends on the geometry of the superconducting tapes used (see Table 1), and varies from 5.2 mm in case of Type-3 conductor to 7.2 mm for Type-5 conductor. The advantages of the twisted-pair design are [6]: cancelation of cross talk - EMI effects among cables – the link contains in total 48 cables powering different electrical circuits; reduction of perpendicular self-field component on the conductor; possibility of using tape conductor in a compact cable assembly while taking into account the mechanical characteristics specific for each type of conductor; incorporation of some flexibility for compensation of longitudinal thermal contraction over long lengths.

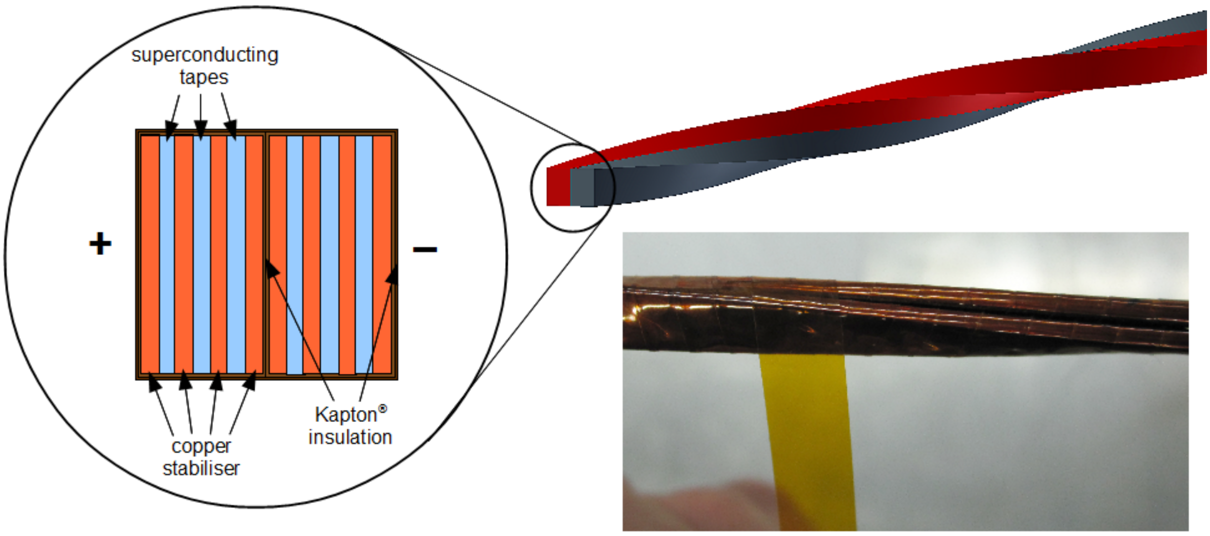


Figure 7: Assembly of twisted-pair cable unit.

Table 3: Geometric characteristics of twisted-pair cables made from different HTS materials.

Conductor	Copper tapes added	Width [mm]	Thickness [mm]	Diameter of envelope [mm]
Type-1	Yes	4.36	3.26	5.44
Type-2	No	4.9	2.56	5.52
Type-3	Yes	4.5	2.57	5.22
Type-4	No	4.8	3.04	5.68
Type-5	Yes	4.0	6.02	7.23

In the twisted pair cable, the perpendicular component of the self-field ($B\perp$) is significantly reduced with respect to the case where a single cable of the assembly is powered at the same current [6]. As an example, the finite element analysis performed for a single 600 A cable and for a twisted $\pm$ 600 A pair made of Type-3 conductors is reported in Figure 8. Thanks to the use of a twisted pair assembly, the peak value of perpendicular field component is decreased from ± 0.1 T to ± 0.06 T. This is particularly interesting in view of the anisotropy of the HTS conductors, which are sensitive to the perpendicular field component.

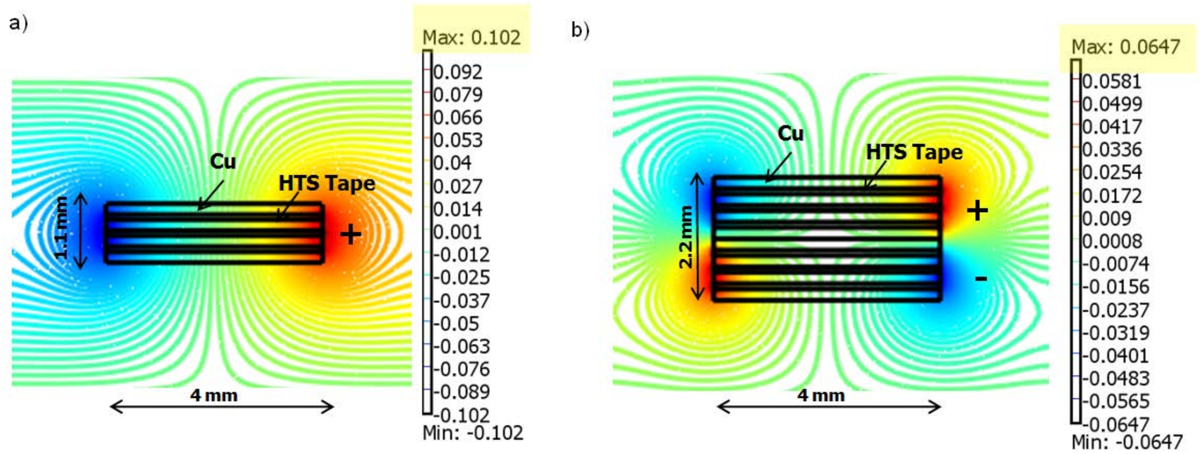


Figure 8: Perpendicular self-field component in one 600 A cable (left) and in a twisted pair of 600 A cables (rigth). Colour scale: Max: red, Min: light blue.

Twenty-four twisted pair cables are then assembled together, to form the multi-cable assembly, twisted again and electrically insulated. The resulting cable is finally integrated inside a cryostat to form the superconducting link (see Figure 9).

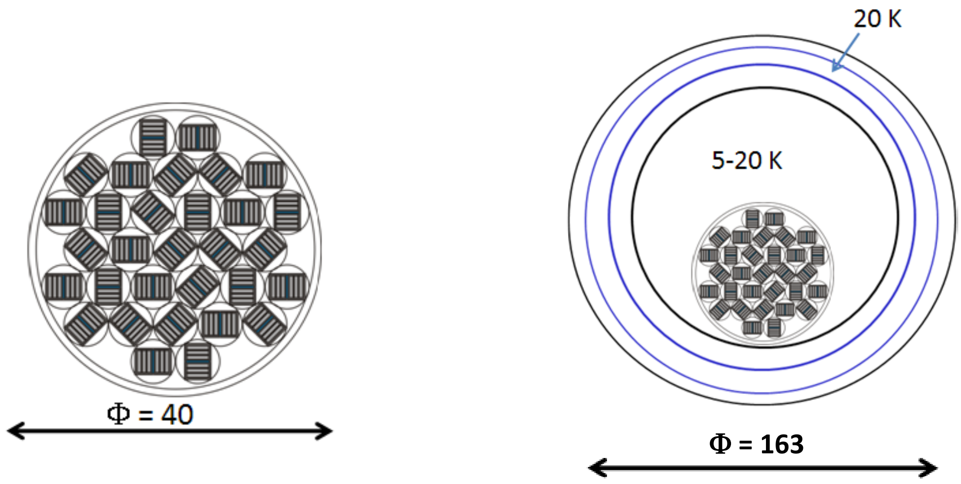


Figure 9: multi-cables assembly of 24 twisted-pair cables (left) and cryostat with the cable (right).

5. Assembly and test of prototype HTS cables

In order to validate the cable concept, several prototype twisted-pair cables were assembled at CERN and tested in liquid helium at 4.2 K and liquid nitrogen at 77 K [7].

The prototype cables have a total length of 2.5 m and a twist pitch of 0.4 m (see Figure 10). The tested twisted-pair assemblies were made from tapes from the same manufacturer.

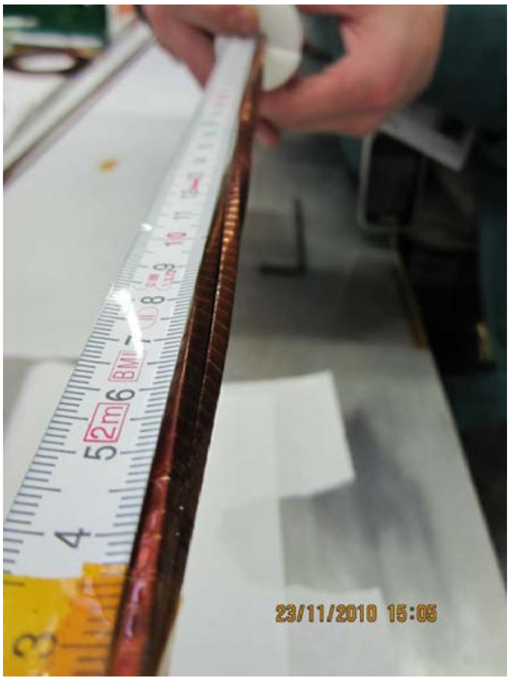
A specific sample holder, consisting of a flat stainless steel plate, was used as supporting structure of the cables during test. The measurements were performed in the CERN FRESCA test station at 4.2 K both in self-field and in external magnetic fields. A homogeneous field of up to 10 T ($\Delta B/B$=0.03) was applied perpendicular to the sample holder over a length of 0.6 m. The insulated cables of the twisted-pair unit were soldered together at one end, while at the other end they were connected to a Nb-Ti Rutherford cable transferring the current from/to the bottom end of the two current leads [7].

For the liquid nitrogen tests, the cables were placed in a round cryostat of 0.6 m diameter, which imposed a bending radius of 0.3 m. The two cables of each unit were soldered together at one end, while current was fed in and out from the other two terminations. A voltage drop signal, measured across 0.6 m length of each cable, was used to derive the critical current. For cables made from Type 1 and Type 4 conductors, three voltage taps soldered on individual tapes were extracted via a common voltage signal. For cables made from Type 2 and Type 3 conductors, the voltage drop across each tape of a cable was measured. The Ic measurements in self-field are summarized in

Table 4. As an example, Figure 11 reports the E-I curve (electric filed as a function of current) measured at 4.2 K on each of the three Bi-2223 Sumitomo tapes in a single cable of a twisted pair. Figure 12 shows the critical currents measured at 4.2 K in perpendicular magnetic fields. The Ic values reported in Figure 12 refer to one single cable of the twisted pair unit -– for the total current of the twisted pair, the Ic value shall be multiplied by two.

Table 4: Critical current measured on each cable of the twisted-pair unit made from different superconducting materials (6).

Conductor	HTS material	Cable +/ Cable – Ic at 77 K [A]	Cable +/ Cable – Ic at 4.2 K [A]
Type-1	Bi-2223	257 / 263	1220 / 1320
Type-2	Bi-2223	490 /496	2880 / 2890
Type-3	YBCO	291 / 299	4410 / >4410
Type-4	YBCO	304 / 315	3220 / >3220
Type-5	MgB_2	-	4260 / 4170



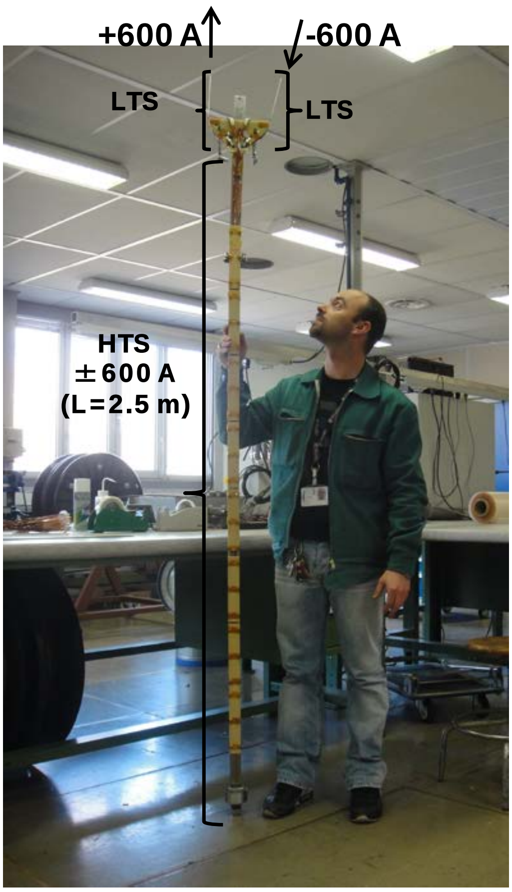


Figure 10: Twisted pair cable (left) and sample holder used for the critical current measurements at 4.2 K (right).

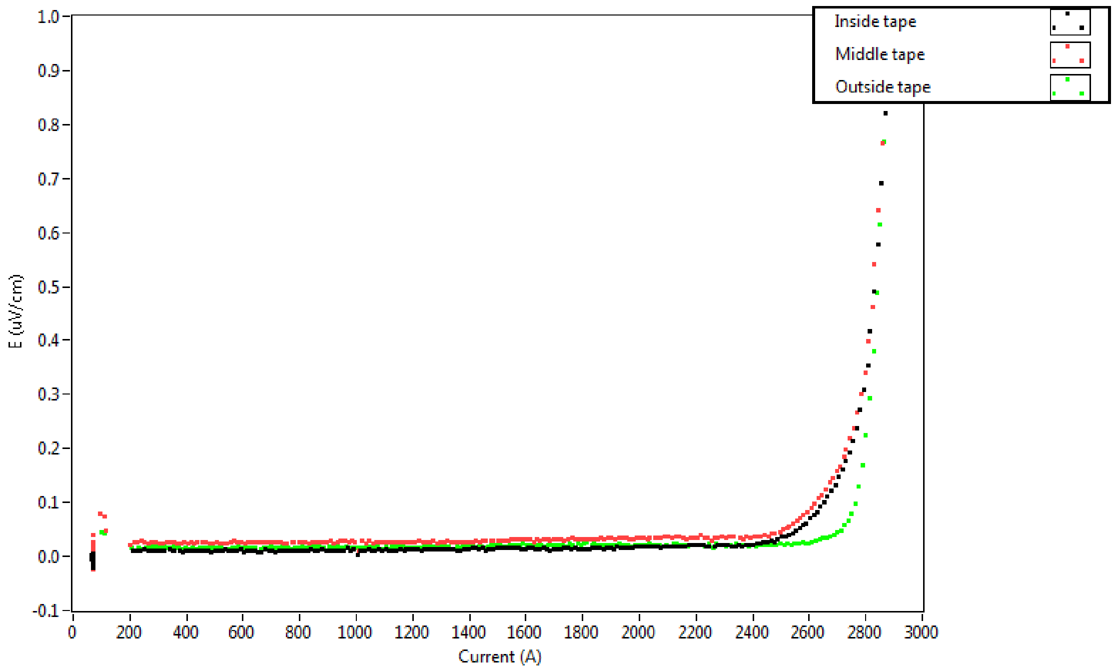


Figure 11: E-I curve measured at 4.2 K and in self-field on each of the 3 tapes in a single cable of a Bi-2223 (Sumitomo) twisted pair unit.

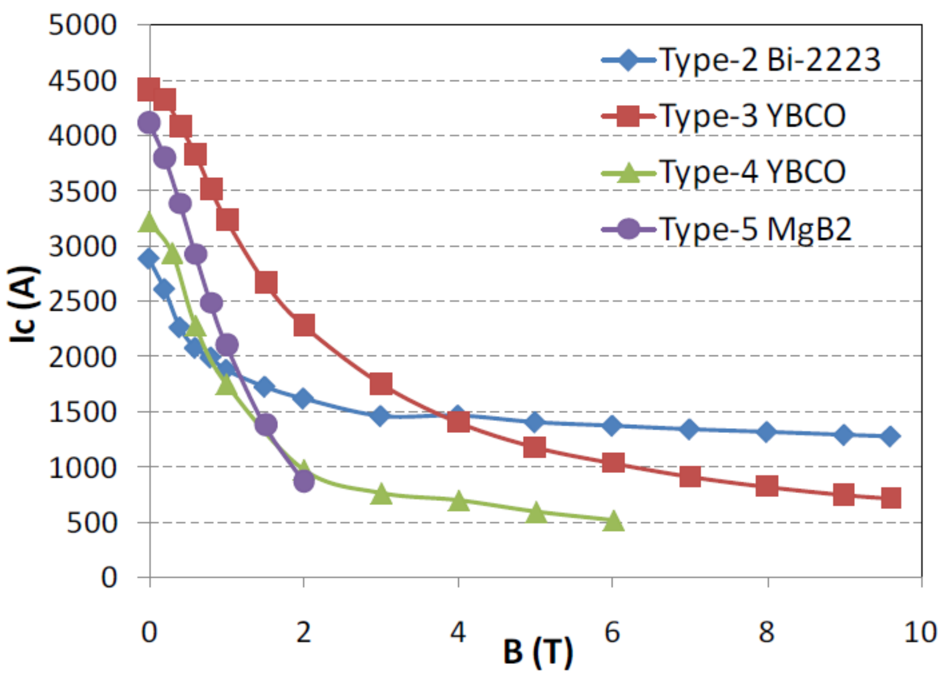


Figure 12: Ic of one single cable of the twisted pair unit as a function of perpendicular magnetic field at 4.2 K.

The distribution of the current among the superconducting tapes in the same cable has been studied, and we report here the analysis made on cables containing Type 2 conductors [7]. When a twisted-pair cable operates at 77 K, the calculated peak $B\perp$ value is ± 10 mT. According to data provided by the tape manufacturer, the corresponding local reduction in Ic is 20 %, i.e. Ic($B\perp$=20 mT,77 K)/ *Ic*(self-field,77 K) = 0.8. The model shows that because of the different self-field experienced by the tapes, when the twisted pair unit transfers the currents indicated in Table 4, the central tape of each cable carries about 6 % less current than the two external tapes. When the same twisted-pair assembly is operated in self-field at 4.2 K, the peak value of perpendicular field at the edges of the central tape is ± 125 mT. The corresponding local reduction in Ic is 22 %, i.e. Ic($B\perp$=125 mT,4.2 K)/Ic(self-field,4.2 K) = 0.78 and the difference in current between the central and the two external tapes of each cable is calculated to be less than 3 %. The Ic of the Type-2 tape measured at CERN at 4.2 K and in self-field is 1059 A.

The Ic at 77 K of the two cables in the same twisted-pair unit differs by less than 3.5 %, a value which is well within the variation in Ic measured on individual tapes. Tapes and cables from Type-2 conductor showed a remarkable uniformity in Ic both at 77 K and at 4.2 K.

Electrical tests of HTS twisted-pair cables in a variable temperature range were performed at the University of Southampton. These tests were done to:

1) characterize the cables operated in helium gas environment;

2) measure the critical current at different temperatures;

3) investigate the thermal stability of the cables in gas at various temperatures [8].

For these measurements, the University of Southampton has built a new test station for characterizing the designed cables - with a length of up to 2 m. The test station is equipped with a pair of HTS current leads rated at 2000 A (see Figure 13). The cables were cooled by forced flow of helium gas with temperatures in the range from 5 K to 70 K. A full characterization was made, and results of the measurements are reported in Figure 14. Additionally, the thermal stability of the cables at near critical current was successfully tested by setting the cable to carry 80 %-95 % of Ic for more than 5 minutes. The Ic values reported in Figure 14 refer to one single cable of the twisted pair unit – for the total current of the twisted pair, the Ic should be multiplied by two.

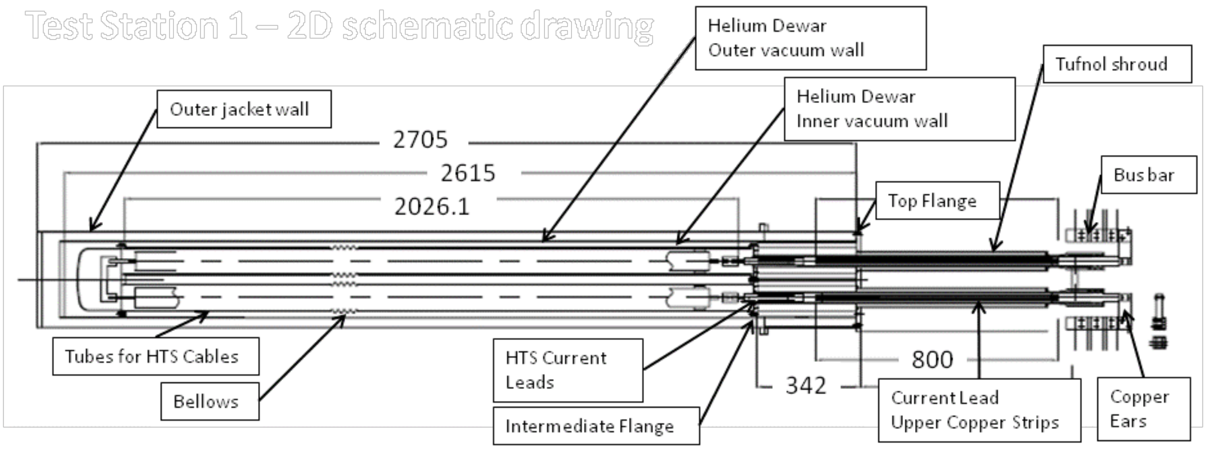


Figure 13: Cryostat built for the measurement of the twisted pair cables in He gas in a variable temperature range.

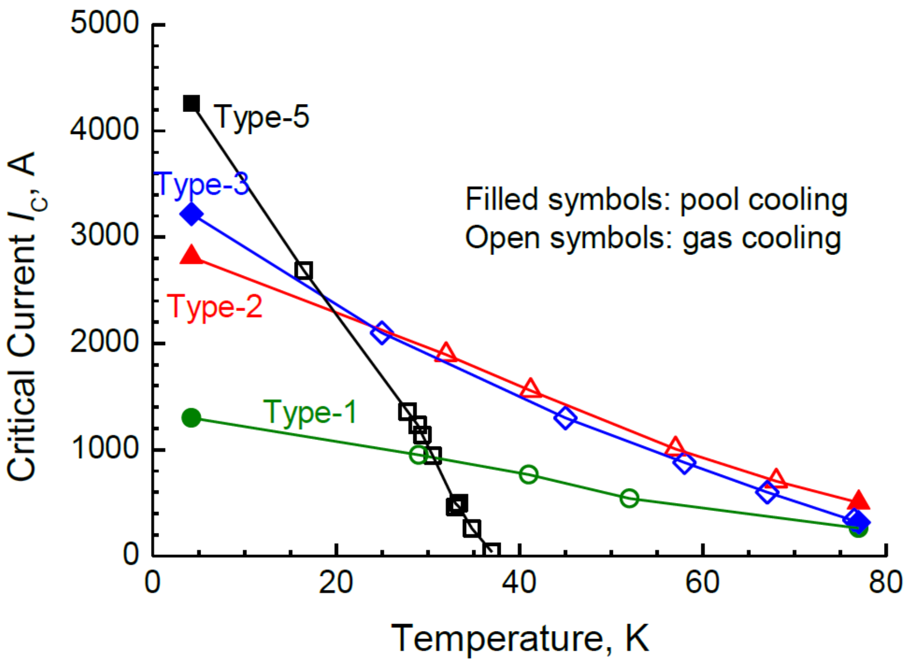


Figure 14: Critical current as a function of temperature measured on one cable of the twisted-pair unit [8]. The correspondence between the Type-n cable and the type of conductor is reported in Table 1.

6. Assembly of long cables

A cabling machine for the controlled assembly and twisting of the twisted pair cables has been designed at CERN.

The machine consists of two units:

1) the first unit, hereafter referred to as the static machine (see Figure 15), performs the assembly of stacks of up to eight tape conductors (HTS or copper stabilizer), makes their electrical insulation, and finally assemble the electrically insulated unit onto a spool;
2) the second unit, hereafter referred to as the rotating machine (see Figure 16), performs the twisting of two insulated stacks of conductors, provides an additional electrical insulation, and finally assembles the final twisted-pair cable onto a spool.

In the static machine, the eight spools rotate simultaneously at a constant speed. Each of them is equipped with an electro-magnetic brake and a tension gauge, and the tension on the HTS tape during cabling is maintained to below a pre-defined value, which varies depending on type of conductor used. The size of the spools and the path followed by the tape during cabling are such that the bending radius is always above the critical one of the HTS conductor.

The rotating machine enables the twisting of the cables with a twist pitch that can be varied from a minimum of 100 mm to a maximum of 500 mm. Permanent magnet brakes and tension gauges with Bluetooth connections are used to control the maximum tension applied to the conductor to a pre-defined value below the critical one.

The static machine is completely assembled and it is being commissioned at CERN. The rotating machine is being assembled at CERN, and it is planned to be commissioned in summer 2012. These machines will be used for the assembly of the 20 m long superconducting cables, which are the deliverable of Task 7.5.

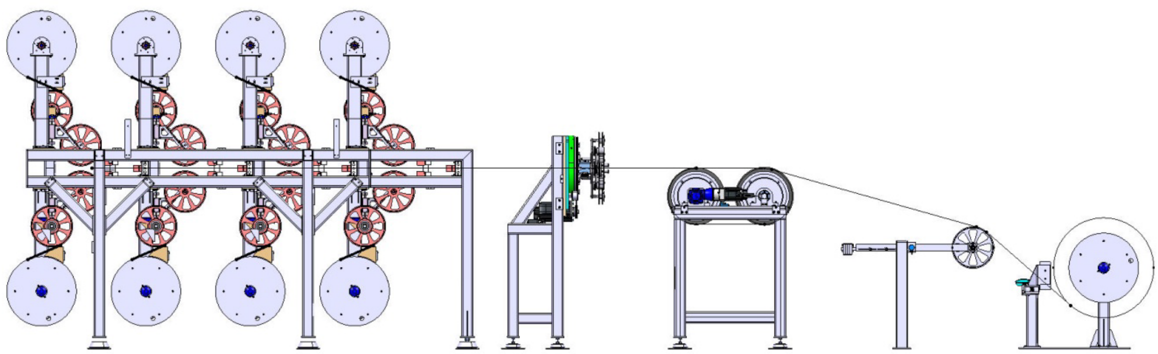


Figure 15: Static machine for the assembly of insulated stacks of tape conductors.

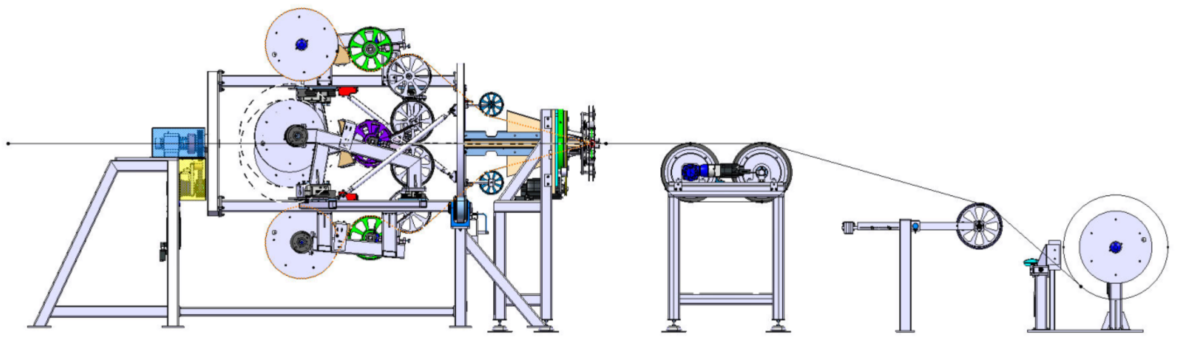


Figure 16: Rotating machine for the twisting of the insulated stacks of the conductor – assembly of twisted-pair cables.

7. Cryostat of superconducting link

The cryostat of the superconducting link is a 20 m long Nexans Cryoflex® line. It consists of four concentric corrugated pipes (see Figure 9, right), and it contains: 1) the cold mass, with the He gas environment where the cables are operated, 2) a thermal shield actively cooled by He gas entering at about 20 K, and 3) the thermal insulating vacuum environment. The 20 m long line has been specified and procured by CERN. A picture of the cryostat installed in the SM-18 CERN laboratory is shown in Figure 17.

Figure 17: Twenty meter long cryostat of the link (Nexans Cryoflex® line) installed in the SM-18.

8. Test of superconducting link

CERN will test the 20 m long superconducting link in nominal operating conditions. For this purpose, a cryostat has been built, and specific electrical and mechanical interfaces to be connected at the two terminations of the link have been designed. The test station will enable the test of cables and of the complete superconducting link in a variable temperature range (5 K to 70 K). Forced flow of He gas will assure the cooling of the cables and of the thermal shield inside the Cryoflex® cryostat. Several tests will be performed, included the study of the thermo-electrical performance of the HTS cables during resistive transition. The test station will be operated in the CERN SM-18 laboratory. A layout of the SM-18 indicating the location where the test station with the 20 m long cryostat will be operated is reported in Figure 18.

Figure 19 reports the drawing of the 20 m long superconducting link connected to the cryostat equipped with a pair of current leads rated at 20 kA. The cryostat with the leads contains a liquid He bath at 4.2 K, while the cold mass of the superconducting link contains helium gas delivered in the link at variable temperatures. A mechanical structure supporting the cryostat of the link has been designed and assembled at CERN. This structure enables an easy removal of the link cryostat and of its terminations, in view of the need of extracting, integrating and testing different types of cables.

The superconducting link will be equipped with all instrumentation required for its operation and protection (temperature sensors and voltage taps). Dedicated DAQ and protection systems have been designed and prepared.

9. Conclusions

A novel concept of cable, the twisted-pair HTS tape cable, to be used in electrical transfer lines has been proposed. Several prototype cables, about 2 m long, have been assembled and tested. These prototypes were made from MgB_2, Y-123 and Bi-2223 tape produced by different manufacturers. Successful tests were performed both at liquid nitrogen (Y-123 and Bi-2223) and at liquid helium temperatures, and in a variable temperature range produced via forced flow of helium gas. The tests show that no degradation in Ic in introduced on the tapes during cabling. At 4.2 K, twisted pair cables made from three MgB_2 or Y-123 tapes were able to transport currents above 9 kA (± 4.5 kA) in self-field. In the same configuration and conditions, the Bi-2223 twisted-pair cable was able to transport about 6 kA (± 3 kA). Following successful validation of the design concept, dedicated cabling machines have been designed and are being assembled for the cabling of the 20 m long HTS twisted pairs in the link. A 20 m long cryostat has been specified and procured from Nexans. The progress of the activity is such that the FP7 Task 7.5 deliverable - superconducting link 20 m long – is presently expected to be available according to the original plan.

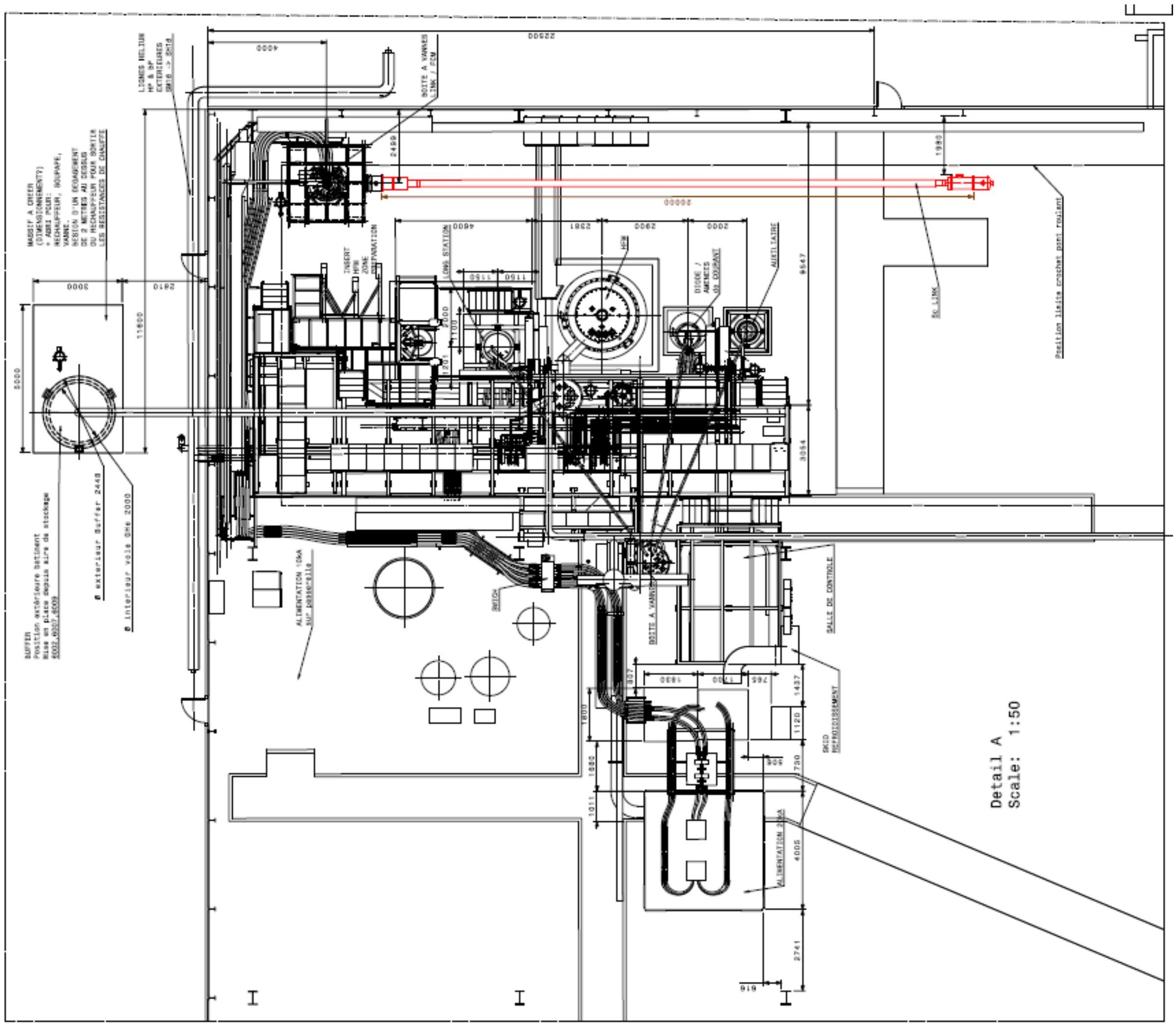


Figure 18: Layout of the SM-18 laboratory and location of the test station of the 20 m long link (red cryostat).

Figure 19: Test station: cryostat with current leads and superconducting link.

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