IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044024, (2014).

Development of Superconducting Links for the LHC Machine

Amalia Ballarino

CERN, European Organization for Nuclear Research, 1211 Geneva 23, Switzerland

Email: amalia.ballarino@cern.ch

Abstract. In the framework of the upgrade of the LHC machine, new superconducting lines are being developed for the feeding of the LHC magnets. The proposed electrical layout envisages the location of the power converters in surface buildings, and the transfer of the current from the surface to the LHC tunnel, where the magnets are located, via superconducting links containing tens of cables feeding different circuits and transferring all together more than 150 kA. Depending on the location, the links will have a length ranging from 300 m to 500 m, and they will span a vertical distance of about 80 m. An overview of the R&D program that has been launched by CERN is presented, with a special attention to the development of novel types of cables made from MgB_2 and High Temperature Superconductors (Bi-2223 and REBCO) and to the results of the tests performed on prototype links. Plans for future activities are presented, together with a timeline for a potential future integration in the LHC machine.

1. Introduction

The electrical feeding of the about 1700 LHC superconducting circuits requires the transfer of more than 3 MA of current from the power converters to the magnets. This is done via the use of conventional copper cables for the room temperature path between power converters and current leads, HTS or resistive currents leads for the transfer to the 4.5 K liquid helium bath, and Nb-Ti bus-bars operated in liquid helium at 4.5 K or 1.9 K and making the connection to the magnets. In the present LHC configuration, power converters and current leads are both located in underground areas, the first mainly in alcoves, parallel to the machine tunnel, and the second in cryostats which are near the LHC interaction points and in line with the superconducting magnets. All equipment in the tunnel is exposed to significant levels of radiation.

For the Hi-Luminosity upgrade of the LHC machine [1] [2], novel superconducting lines are being developed for feeding the LHC magnets from remote distance [3]. The new electrical layout envisages the location of the power converters and of the current leads either in surface buildings or in underground areas over five hundred meters away from the tunnel, and the transfer of the current to the magnets is performed via superconducting links containing tens of cables feeding different circuits and transferring all together up to about 150 kA. The benefits of this remote powering via superconducting lines are several and can be summarized as follows:

1) Location of the LHC power converters in radiation free areas with a definitive solution to the problem associated with the radiation damage of these devices. As already experienced during the first years of operation of the accelerator, events that result stochastically from single interactions between energetic ionizing particles and electronic components – single event effects – at some locations in the tunnel affect the performance of the power converters and induce failures that impact on beam availability for physics;
2) Access of personnel for maintenance, tests and interventions on power converters and current leads in radiation free areas, in accordance with the CERN ALARA principle of radiation

protection that optimizes doses to personnel exposed to radiation by keeping them As Low As Reasonably Achievable;

3) Removal of the current leads and associated cryostats from the accelerator ring, thus making available space for other accelerator components.

At LHC interaction points P1 and P5, where the high-luminosity experiments ATLAS and CMS are located, the proposed electrical layout envisages the installation of the power converters and current leads in surface buildings. This calls for development of superconducting lines (hereafter called "links"), about 300 m long, spanning across a vertical distance of 80 m and transferring a total DC current of about 150 kA. The powering of the new insertion magnets developed in the framework of the LHC Hi-Luminosity upgrade requires two such links per point, i.e. four in total. Also at P1 and P5, four additional links are being studied for the powering of magnets in the LHC matching sections and arcs. At LHC P7 power converters and current leads are planned to be moved in an underground radiation-free gallery, which serves as access to the LHC ring. At P7, two superconducting links are needed. Each of them is about 500 m long and transfer a total DC current of about 30 kA. This paper reports on the status of the development of the superconducting links needed for the Hi-Luminosity upgrade of the LHC Triplets and for LHC P7.

2. Superconducting Links for the LHC machine

2.1. Electrical and cryogenic configuration

In contrast with superconducting transmission lines developed for electrical power distribution, where one or a maximum of three cables are contained in the same cryogenic envelope, the links for the LHC contain tens of cables rated at different DC currents ranging from a minimum of 120 A up to a maximum of 20 kA. For LHC P1 and P5, each of the four links contains six cables rated at 20 kA, fourteen cables rated at 3 kA, four cables rated at 0.4 kA, and eighteen cables rated at 0.12 kA. The total current transferred by the assembly of these forty-two cables is ~ 150 kA. The 20 kA cables are required for powering the low-beta insertion Nb_3Sn quadrupole magnets together with one Nb-Ti dipole, while the other cables feed corrector and trim circuits. The link at P7 contains fifty cables rated at 600 A, all connected to correction magnet circuits.

The cable assemblies are incorporated in semi-flexible cryostats of the CRYOFLEX® type. The present baseline, which is to be confirmed through on-going integration studies, envisages integration in the LHC tunnel of the cryostat with the cable assemblies already pulled in at the surface. The cryogenic envelope consists of four corrugated pipes and it includes an actively cooled thermal shield. The cooling of the superconducting link is provided by helium gas entering at a temperature of about 5 K and warming up along the line while absorbing the static load of the cryostat. The maximum operating temperature of the superconducting cables is defined to be 25 K for links containing MgB_2 cables and 35 K for links with REBCO or Bi-2223 cables. After having cooled the superconducting line, the helium is used for the cooling of the current leads and of the corresponding cryostat, and it is finally recuperated at the surface at room temperature. The whole system, i.e. the link and current leads, relies on cooling with helium gas.

2.2. Superconductors: MgB_2, REBCO and Bi-2223

The superconductors which are investigated for application to the Superconducting Link project are MgB_2, REBCO and Bi-2223. Today commercially available REBCO and Bi-2223 tapes meet the electrical requirements specified for the project, i.e. a critical current (I_c), at 35 K and in a field of 0.5 T, of at least 400 A. Tapes of about 4 mm width are considered for this application. The mechanical characteristics of these conductors are above the minimum specified performance, which asks for a minimum bending radius of 100 mm and critical tensile strain of 0.3 %. To avoid risks associated with high-current resistive joints operated in helium gas environment, the cables are planned to be assembled in one single unit length with no internal splices. For this reason, the conductor must be produced in unit lengths of greater than 500 m. The availability of helium at low temperature enables the use of MgB_2 conductor. MgB_2 round wire is proposed for the links at P1 and P5. The specified mechanical characteristics of the MgB_2 conductor are the same as those required for the REBCO and Bi-2223 tapes for this application. Also required current capability is the same but operation is at lower temperature, i.e. the I_c of a MgB_2 wire with a diameter of less than 1 mm is specified to be at least 400 A at 25 K and in a field of 0.5 T.

Long lengths of commercially available REBCO, Bi-2223 and MgB_2 tapes have been procured for production of cables at CERN. However, from the very beginning of the project it appeared that long-lengths of round MgB_2 wire with the specified characteristics were not yet available. In 2008 CERN and Columbus Superconductors entered into a collaborative R&D activity aimed at the development of suitable MgB_2 round wire. Different types of MgB_2 wires with improved characteristics were studied and produced at Columbus Superconductors [4]. This activity was accompanied by an intensive characterization program performed at CERN with the purpose of qualifying the conductor and providing feedback on performance. High-current cables produced recently at CERN use an optimized wire (S3 in Fig. 1) that successfully went through qualification measurements.

The first attempts at Columbus to make MgB_2 wires for the Superconducting Link project led to the production of a conductor (S1, Fig. 1) with a quasi-square cross section and a width of initially 1.6 mm, and later 1.1 mm [5]. The composition of this wire was the same as that of the tape commercialized by Columbus, i.e. 12 quasi-rectangular superconducting filaments (130 μm -170 μm width) were embedded in a Ni matrix, and the stabilizer was provided by a central Cu core surrounded by a Fe barrier. The filling factor of this wire was about 14 %. The engineering current density measured on short samples was up to 300 A/mm^2 at 20 K and 0.5 T, but homogeneity of critical current as measured on short samples at 4.2 K had to be improved.

With the purpose of enhancing uniformity of the wire cross section, reducing the filament-size, and increasing the filling factor, a new wire (S2, Fig. 1) with Monel matrix and quasi-trapezoidal or hexagonal superconducting filaments was produced. The filaments were surrounded by a Ni barrier, of which different thicknesses were tried. Several quasi-square wires with 12, 19, 36 or 37, 61 and 91 MgB_2 filaments were manufactured, and filling factors of about 24 % were achieved. First round wires with 1.1 mm diameter and 37 superconducting filaments were produced and engineering critical current densities of up to about 550 A/mm^2 were measured at 20 K and 0.5 T. With this first generation of wire, homogeneity of I_c, as verified on critical current measurements at 4.2 K of hundreds of short-length conductor, was not yet achieved, and premature quenches were observed on some samples. SEM and EDS analysis [6] identified in the two porous and brittle MgB_2-Ni reaction layers - each about 7-10 μm thick - generated during heat treatment by chemical reaction of the wire at the interface between the superconductor and the Ni barrier (Fig. 1), as the cause for a non-uniform current distribution among the superconducting filaments. In particular, thermo-electrical stability of some samples was found to be compromised by porosity and voids generated at the interface between the two reaction layers. Inhomogeneous current distribution among superconducting filaments at the joints and increased current-transfer length in the resistive Monel matrix were generating premature quenches in some wires. Because of their brittle structure, the MgB_2-Ni reaction layers were also found to be critical for the achievement of the required mechanical properties of the wire.

In the third generation of wire (S3, Fig.1) the nickel was replaced with niobium as barrier around the superconducting filaments. Round wires of 0.98 mm diameter with Monel matrix, a Nb barrier around each MgB_2 filament, a Ni barrier around the Nb and a central Cu core were produced [6]. This wire has 30 superconducting filaments and a filling factor of about 10.4 %. SEM analysis of several cross sections showed no merging of filaments, intact barriers and formation of a thin and uniform Nb-Ni reaction layer in between the Ni and the Nb barriers. Hundreds of short samples measured at CERN at 4.2 K showed reproducible critical current densities of about 500 A/mm^2 at 4.2 K and 1 T [7]. The J_c at 20 K and 0.5 T measured at Columbus on short samples was 380 A/mm^2. The minimum bending radius of reacted wires was found to meet the specified requirements [8].

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044024, (2014).

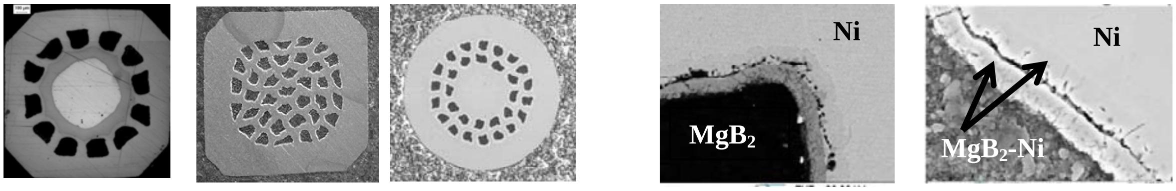

Fig. 1. Left: Different generations of MgB_2 Columbus round wires. S1: octagonal wire with nickel matrix and central copper stabilizer surrounded by iron barrier, S2: quasi-square wire with Monel matrix and nickel barrier around the filaments, S3: round wire with Monel matrix and niobium barrier around the filaments. Right: SEM cross section imaging of wire S2 [6], porosity and detachment in between the two MgB_2-Ni reaction layers

A new generation of wires (S4) with 0.85 mm diameter, having the same composition of S3, but the central Cu core suppressed and an increased number of superconducting filaments - 37- is now being produced at Columbus. In this this last generation of wires, the stabilizer is introduced by plating the external surface of the conductor with a thin layer of Cu. Plating is followed by tinning of the Cu surface, with the purpose of producing a final 0.85 mm diameter strand suitable for integration in a cable having a controlled inter-stand resistance.

2.3. Superconducting cables

Concepts of cables and prototypes made from wire and from tape superconductors were developed and validated at CERN.

For the links to be integrated at LHC P7, where cables rated at 600 A are needed, a new concept of cable optimized for electrical transmission, and conceived for enabling the use of tape conductor in cables, has been developed [3]. The cable, hereafter referred to as a Twisted-Pair, consists of two cable units that transfer the same current in opposite directions. A unit is a stack of three tapes of superconductors, interleaved with copper strips, which are electrically insulated by wrapped Polyimide tape and then twisted together with a second such stack to form the Twisted-Pair assembly (Fig. 2, left). This type of cable has been assembled at CERN using commercial MgB_2 (3.6 mm width, 0.67 mm thickness), REBCO (4.1 mm width, 0.095 mm thickness) and Bi-2223 (4.5 mm width, 0.36 mm thickness) tapes. The final Twisted-Pair assembly has an equivalent diameter varying from 5.6 mm to 7.2 mm and a typical twist pitch of 400 mm. The measured current capability is 1 kA per unit of the Twisted Pair assembly at about 30 K for MgB_2 and 60 K for REBCO and Bi-2223 [9] [10]. Two cabling machines, a static machine for assembling stacks of insulated tapes and a rotating machine for the twisting the two insulated stacks, were designed and built at CERN. These machines enable the production of long - kilometer - lengths of Twisted-Pair cables.

For the superconducting links to be integrated at LHC P1 and P5, where cables rated at up to 20 kA at 25 K are needed, the effort has up to now been concentrated on development and test of prototype cables demonstrating of the possibility of transferring high-current with MgB_2 conductor [11]. The 20 kA cable consists of six sub-cable units, each made of eighteen MgB_2 round wires twisted around a flexible multi-strand copper core (Fig. 2, right). After the successful development of MgB_2 round wires, a sub-cable unit about 2 m long was assembled using the third generation of MgB_2 wires (S3 in Fig. 1) described in section 2.3. This cable was electrically characterized in liquid helium at 4.2 K and it reached a critical current of 10.507 kA (1 μV/cm criterion, self-field conditions) [12]. A two meter long 20 kA cable at 25 K, consisting of six sub-cable units, was also measured in liquid helium at 4.2 K and it reached the expected critical current of 30.4 kA (1 μV/cm criterion, self-field conditions) [12]. In addition, two 10 m long sub-cable units were tested at CERN in a purpose-built test station where cooling of the cables is provided by flow of helium gas entering at temperatures that can be varied from 5 K to 70 K. Homogeneity of the temperature across the 10 m length is maintained to within 1 K. The critical current of these 10 m long MgB_2 cables at 27.5 K was measured to be 3541 A, in accordance with that calculated from the strand performance [13]. Several quenches were performed with no degradation of electrical properties. The same cables were successfully operated in DC mode at 20 K and 5000 A – the maximum current at which the test station could be operated. At 20 K, the estimated critical current of the cables is 5800 A. These tests represent the first reported measurements of long high-current cables assembled with reacted MgB_2 wires. Presently an upgrade of the test station is taking place with the objective of qualifying 20 m long cables at currents of up to 20000 A at 20 K.

2.4. Superconducting Links

Cables of the type described in section 2.3 are grouped together to form the cable assemblies required for the superconducting link.

Twenty-five Twisted-Pair cables form the cable assembly of the link required at LHC P7. This assembly has a diameter ranging from 40 mm (REBCO tape) to 50 mm (MgB_2 tape). A 20 m long MgB_2 prototype has recently been assembled at CERN and qualification in nominal operating conditions will follow. In addition, tests have already been performed on 5 m long assembly, which was fully validated and operated at nominal current [14]. The external diameter of the complete cryogenic envelope is about 163 mm.

The link at LHC P1 and P5 contains six cables rated at 20 kA, fourteen cables rated at 3 kA, four cables rated at 0.4 kA, and eighteen cables rated at 0.12 kA for a total current capacity of 150 kA (Fig. 2). In addition to the 20 kA cables described in section 2.3, the link contains concentric and electrically insulated 3 kA cables, each made of 18 MgB_2 wires, and 400 A and 120 A cables made of twisted copper and MgB_2 strands. The complete multi cable assembly has an external diameter of about 65 mm and a mass of about 11 kg/m. The external diameter of the cryogenic envelope is 220 mm. This link will cover 80 m of vertical distance for transferring the current from the surface down to the LHC underground areas.

Fig. 2. Left: MgB_2 Twisted-pair cable, Φ=5.6 mm and Twisted-Pair assembly of 2×25×600 A cables for LHC P7, Φ=40 mm. Right: 20 kA MgB_2 cable, Φ=6.5 mm (top), 2×3 kA MgB_2 concentric cables, Φ=8.2 mm (bottom), 150 kA cable assembly for LHC P1 and P5 (6×20 kA, 2×7×3 kA, 4×0.4 kA, 18×0.12 kA), Φ=65 mm

3. Plans and schedule

The total quantity of superconductor required for the Superconducting Link project for LHC exceeds 1000 km. Today plans envisage integration in the LHC accelerator during the foreseen machine shut-downs, i.e. in 2018 for the link at P7 and in 2022 for the links at P1 and P5. The integration of the links requires the removal of existing equipment and the design and integration of purpose-built interfaces to the machine. With the present schedule, procurement of conductor for series production shall start in early 2015, for the system at P7, and it will continue until 2020 with completion of the procurement for P1 and P5.

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044024, (2014).

4. Conclusions

Important milestones have been achieved in the development of the superconducting links for the LHC machine. In particular, system requirements from the Hi-Luminosity upgrade project have been defined, cables rated at above 600 A at 25 K and made from REBCO, Bi-2223 and MgB_2 commercial tape conductor have been developed and validated, and a prototype superconducting link 5 m long made from 25 Twisted Pairs MgB_2 cables has been successfully tested in nominal operating conditions. Thanks to a collaborative effort between CERN and Columbus Superconductors, round MgB_2 wires with uniform current density and optimized for use in high current cables have been developed and produced at Columbus. First cables made with MgB_2 reacted round wires were successfully assembled and measured at CERN, and currents of up to 30.4 kA at 4.2 K and up to 5 kA at 20 K were measured. A test station for the measurement of 20 m long cables at any temperature in the range from 5 K to 70 K and at currents of up to 20 kA was developed and commissioned at CERN. Future efforts will be focused on final development of high current cables and multi-cable assemblies, on the system design and on integration studies in the accelerator. The quantity of superconductor required for the Superconducting Link project - more than 1000 km - is such as to represent a medium-sized application of high temperature superconductors to accelerator technology.

Acknowledgments

This work could be done thanks to: the collaboration with G. Grasso and the team at Columbus Superconductors for the development of the MgB_2 wire and Y. Yang and the team at the University of Southampton for the qualification of prototype links, the contribution at CERN of B. Bordini, J. Fleiter, S. Giannelli and G. Willering for analysis and measurements and A. Gharib, A. Jacquemod and J. Hurte for the technical activity.

References

[1] Rossi L 2011 LHC Upgrade Plans: Options and Strategy *Proc. IPAC11* http://www.jacow.org/

[2] Rossi L 2012 http://cds.cern.ch/record/1515013/files/CERN-ACC-SLIDE-2013-003.pdf

[2] Ballarino A 2011 *IEEE Trans. Appl. Supercond.* **21** 980-984

[3] Cubeda V, Tropeano A, Nardelli D, Piccardo R, Bordini B, Ballarino A, Grasso G 2013 Development of ex-situ MgB_2 round wires for the LHC Superconducting Link project *Presented at EUCAS 2013*

[4] Berta S, Brisigotti S, Tumino A, Pietranera D, Grasso G, Ballarino A 2008 Development of MgB_2 conductors for application to superconducting bus *CERN EDMS no. 965302*

[5] Scheubel M 2012 SEM observations of MgB_2 conductors *CERN EDMS no. 1216393*

[6] Bordini B, Ballarino A, Richter D, Cubeda V, Grasso G, Piccardo R, Tropeano M 2013 Electro-mechanical characterization of the MgB_2 wire developed for the LHC Superconducting Link Project *Presented at EUCAS 2013, Proc.SuST*

[7] Piccardo R, Barberis F, Capurro M, Cirillo P, Zattera E, Ballarino A, Bordini B, Cubeda V, Nardelli D, Tropeano M, Grasso G 2013 Room temperature stress-strain curve and its correlation to the superconducting transport properties of MgB_2 ex-situ wires developed for the LHC Superconducting Link project *Presented at EUCAS 2013*

[8] Ballarino A, Fleiter J, Hurte J, Sitko M, Willering G 2012 *Physics Procedia* **36** 855 – 858

[9] Yang Y, Young E, Bailey W, Beduz C and Ballarino A 2012 *Physics Procedia* **36** 1337 – 1342

[10] Ballarino A 2010 *J. Phys. Conf. Series* **234** 032003

[11] Fleiter J, Ballarino A, Bordini B, Hurte J and Peiro G 2013 Electrical characterization at 4.2 K of MgB_2 cables *Internal Note, CERN Document Server*

[12] Giannelli S, Ballarino A, Bordini B, Feuvrier J, Hurte J and Jacquemod A 2013 First measurement of MgB_2 cables operated in helium gas at up to 30 K *Internal Note, CERN Document Server*

[13] Spurrell J, Bailey W, Young E A, Ballarino A and Yang Y 2013 Cryogenic Stability and quench characteristics of twisted-pair cables assemblies of MgB_2 tapes *presented at EUCAS 2013*