Design of an MgB_2 feeder system to connect groups of superconducting magnets to remote power converters

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Abstract. Following the successful adoption of high temperature superconductors (HTS) in current leads for the Large Hadron Collider (LHC), it is now being investigated if it may be possible to use HTS to link superconducting magnet system feed-boxes, located in zones liable to receive large doses of radiation, to safe locations near the power converters. In the LHC supercritical helium at 5 K / 3 bar is available, and the use of MgB_2 can be envisaged for this purpose, rather than the more expensive YBCO and BSCCO materials. The design concept of a multi-conductor link to carry a total of up to about 115 kA of quasi-DC current has been elaborated, and tests to validate the principle are presently under way. The advantages afforded by such a link as compared to one based on low temperature superconductor are an increase in the margin of temperature stability, and a simplification of the feed-box, cooled with helium gas. Whereas the initial application requires links of about 100 m in length and 10 m in elevation, if the technology is shown to be viable there could be other applications in the CERN LHC complex for links of up to 500 m in length and up to 150 m in elevation. The conceptual design is presented, together with the plan for its validation and a report of progress with the associated testing.

1. Introduction

High temperature superconductor (HTS) technology has been widely applied to the assembly of prototype HTS power transmission cables for electrical utilities made using YBCO or BSCCO tape. The possibility of using liquid nitrogen for cooling is particularly enticing – both from the point of view of cooling cost and high voltage insulation. However, even at the temperature of sub-cooled nitrogen the critical current density of these materials is low, and their use would be more efficient at lower temperatures. The boundary conditions are not the same for the application of HTS to high current bus links for superconducting particle accelerator systems [1]. These systems rely on the use of liquid helium technology, so associated devices can be designed to run at lower temperatures. Presently the transfer of current over horizontal distances of the order of 100 m is achieved using cables of low-temperature superconductors (LTS), mainly Nb-Ti [2], cooled using liquid helium, but the temperature margin is small and it can be difficult to ensure that there are no warm regions that may interfere with operation. Moreover, vertical transfer is limited due to temperature differences associated with pressure head. The purpose of this study is to address the possibility of using HTS for such an application.

2. Application to the LHC machine

The final focusing of the intersecting beams at the LHC is achieved by means of the so-called "Inner Triplet" of quadrupole magnets located on either side of the experiments. In fact there are four quadrupoles - the centre magnet consisting of two units - and the whole system includes in addition beam orbit correction dipoles, multipole correctors, and a large dipole for separating the counter-rotating beams of particles. It is foreseen to replace the present triplets on either side of the two major experiments (ATLAS and CMS) with larger aperture systems of magnets in order to increase the luminosity of the beam interactions [3]. The interactions give rise to intense radiation in the forward directions, and the new inner triplet systems (NIT) will become increasingly irradiated, complicating interventions. With this in mind it has been decided to install the electrical feed boxes with the current leads for each new triplet system, which are presently in the tunnel, near to the power converters in places that are relatively well shielded. This implies connection between the magnet system and feedbox via superconducting links, four in total, with a length ranging from 30 m to 100 m depending on the location. The LHC is situated in a system of caverns and tunnels between 80 m and 130 m underground: the paths that the links will have to take around the already installed equipment are tortuous.

If the link is based on the use of standard LTS (Nb-Ti) conductor, the entire system has to be kept below about 5.5 K, and in particular the bottom of the current leads must not overheat (quench) the bus. These constraints are relaxed with a bus system based on the use of HTS. The YBCO and BSCCO tapes used for commercial prototype cables were considered. However, the low temperature of supercritical helium available for this application (about 5 K) and low field provide a suitable environment for using currently available MgB_2 material [4]. Use of this material would allow running the feedbox at the end of the link at up to 20 K – a temperature well-adapted for cooling the current leads. This study therefore considers the variant using MgB_2; variants based on the other HTS materials are addressed in parallel ongoing studies.

It should be noted that the interest in this technology is not confined to the links for the new inner triplet systems. So-called “single particle events” due to radiation leaking into the parallel tunnels and alcoves become increasingly likely as the luminosity of the accelerator is increased, causing problems with the power converters that feed the magnets. In addition, access to this equipment for maintenance is difficult and time-consuming and can lead to poor duty factors in machine operation. There is therefore an interest in relocating this sensitive equipment to the surface, away from the radiation and rapidly accessible in case of failures. Links of a type similar to that being presently studied for the triplet could make this possible.

2.1. System description

The cold-powering system for the NIT consists of a feed-box, which is the cryostat supporting the current leads and within which the connection to the link is made, and the link itself, contained in a long cryostat enclosure, through which all the currents are transferred via a system of superconducting cables [4]. The feed-box is located at up to about 100 m distance from the tunnel, in caverns which are in a relatively radiation free area. The connection between the link and the Nb-Ti bus, which then brings the current to the (Nb-Ti) magnets, is done in a cold connection cryostat on the side of the magnets.

The cooling of the link is made via supercritical helium available at about 5 K. The gas is collected at about 20 K in the feed-box at the bottom end of the current leads, where it is used for their cooling and finally recovered at room temperature. In this configuration, the current lead cryostat does not require a liquid helium bath - as do the present LHC feed-boxes for the operation of the Nb-Ti bus connecting the leads to the magnets. The cryogenic envelope of the link is a flexible cryostat with a thermal screen at about 50 K. The heat load on the link cold-mass is estimated to be of the order of 0.3 W/m. In the present configuration of the system, the flow through the link is determined by that required for the cooling of the current leads in the different operating modes: all the gas for cooling the leads passes through the bus. A complete description of the layout is given elsewhere [1], [3].

The electrical insulation between cables powering different circuits is designed for nominal use up to about 1 kV in nominal cryogenic conditions. The link is designed to have the stabilization required to safeguard its integrity in case of resistive transition of a magnet. The time constant of the circuits is of the order of a second. The stabilizer is provided by the copper in the superconducting wire, and by additional copper strands that are added in the cables.

2.1.1. *Link design.* The link contains the cables required for the powering of the NIT magnets. It is cooled with supercritical helium that is supplied at about 5 K and 3 bar on the magnet side, and is recovered at about 20 K at the feed-box end. The cables are assembled in a semi-flexible Nexans-type Cryoflex 4-tube transfer line, which incorporates a thermal screen actively cooled by helium gas supplied at about 50 K. The overall external diameter of the transfer line is 220 mm. The conductors are to be incorporated in the cryogenic envelope at the surface, where the system is tested before final integration in the tunnel as a complete unit. In order to fit in the confined space in the tunnel, the minimum bending radius of the link is specified to be 1.5 m. The total length depends on the location in the tunnel and varies from a minimum of 30 m to a maximum of about 100 m.

2.1.2. *Cable design.* The link for the present configuration of the NIT will require four cables rated at 14 kA for the insertion quadrupoles, two cables rated at 8 kA for the beam separation dipole, two cables rated at 3 kA for the trim currents for the quadrupole circuits, and a number of 3 kA and 0.6 kA cables for the corrector magnets. The electrical layout is still being optimized, and the correction coils may be required to run at 0.12 kA instead of 0.6 kA. The maximum total current to be transferred, in quasi-dc mode and at temperatures of up to 20 K, is of the order of 115 kA.

The cables are assembled from MgB_2 strands. The models made at CERN use MgB_2 multi-filamentary wires purposely developed by Columbus Superconductors. The wires, produced with the *ex-situ* process, are delivered pre-reacted on spools of 1 km unit length. The conductor has a square cross section of 1.1 mm width – with chamfered corners. The project aims to use round wires of 1.1 mm diameter, and such conductor geometry is presently being optimized by Columbus Superconductors. The electrical and thermal properties measured on short-samples are presented elsewhere [5]. The critical current of the wire at 20 K and in an external field of 0.8 T is 370 A, and the minimum guaranteed critical current at 30 K and in self-field is 300 A. The conductor, which has a filling factor of 14 %, is composed of a nickel matrix with embedded 12 superconducting filaments, an iron barrier, and a central core of copper stabilizer (15 %). The superconducting filaments are twisted with a twist pitch of 0.3 m. The minimum bending radius corresponding to zero degradation of critical current is specified to be 100 times the diameter of the wire.

The dipole and quadrupole magnets will be ramped at rates of up to 10 A/s. At this rate the AC and magnetization losses are neglible with respact to the steady thermal losses.

The radiation resistance of MgB_2 was found to be similar to that of A15 conductors [6] and not critical for the purposes of this project – the equivalent does of the most exposed section of the link was estimated to be of the order of 0.5 MGy [7].

The high-current cables (> 0.6 kA) are assembled from a sub-cable element consisting of 12 fully transposed superconducting wires wound around a multi-strand copper core acting as mechanical support and stabilizer (Figure 1 (a)). The wires have a twist pitch of 0.3 m. One sub-cable element is used for the 3 kA cable, while a 14 kA cable consists of 6-on-1 sub-cables wound around an open helical core, of about 5 mm diameter, with a twist pitch of about 0.5 m (Figure 1 (b)). The 0.6 kA cable consists of 3 superconducting wires wound with 3 copper strands on a central copper stabilizer (Figure 1 (c)). Each cable is electrically insulated with four layers of half-overlapped polyimide. In order to validate the concept, a multi-cable design consisting of 7 cables rated at 14 kA, 7 cables rated at 3 kA and 8 cables rated at 0.6 kA has been developed. In this configuration the high-current elements are disposed around the 0.6 kA units (Figure 1 (d)), and one 14 kA cable and one 3 kA cable are included as spare elements. The external diameter of the whole assembly, electrically insulated, is about 62 mm. The peak field, calculated when all cables are powered at maximum current and taking into account the polarities of the cables powering the various electrical circuits, is of the order of 1 T.

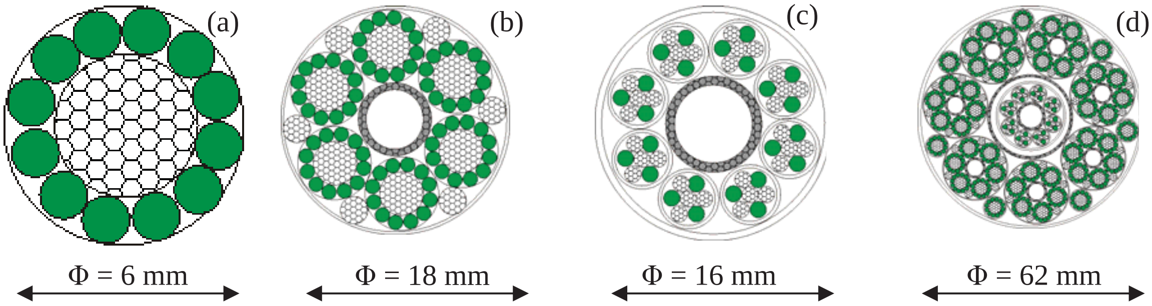

Figure 1. Layout of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The MgB_2 is shown solid, the copper is shown hatched.

Other cable configurations are being studied. These configurations, which have different cable arrangements suited to the latest version of the NIT electrical layout, use the same 3 kA sub-cable element.

2.1.3. *Assembly and tests.* Assemblies of cables of the type described in section 2.1.2 were initially made using copper wires of 1.1 mm diameter. These cables, about 3 m long, were used to validate the geometry and assembly procedures, and to perform a number of preliminary warm tests, among which tests on the electrical insulation, mechanical rigidity and thermo-hydraulic behaviour. A corrugated stainless steel pipe of 84 mm inner diameter was purchased from Nexans, and electrical insulation, void fraction and pressure drop measurements are now being performed on the complete cable integrated inside the pipe. This cable, shown in Figure 2 (d), was used to verify the system flexibility and the handling characteristics. The mass of the cable – suitable for conducting about 115 kA @ 20 K - is of the order of 4 kg/m. Cross sections of the different cables made are reported in Figure 2.

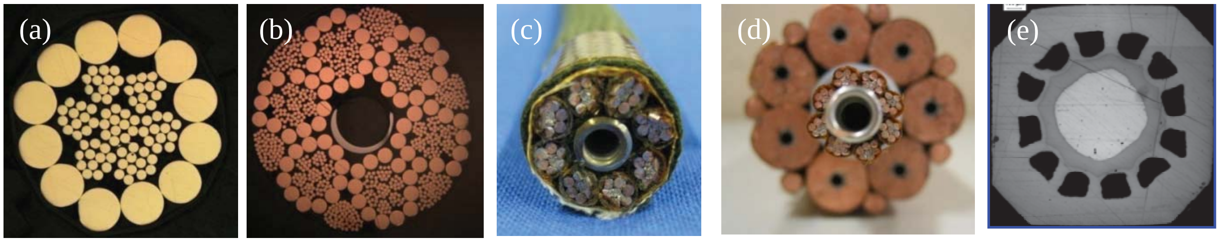

Figure 2. Mock-up made with copper wires of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The external diameter of each assembly is reported in Figure 1. Cross section of MgB_2 wire (e).

A campaign of tests was launched to optimize the soldering procedures between MgB_2 and Nb-Ti wires or cables. Eutectic Sn-Ag solder was used. A first series of tests underlined the difficulty in performing repetitively low resistance joints by soldering directly onto the nickel matrix without using high activity flux. It was therefore decided to electroplate with a thin layer of copper (~ 10 μm) the MgB_2 wire or cable terminations. To verify the strength of the copper-plated joints, short samples of joints in a “praying- hands” configuration made between MgB_2 and MgB_2 wires and between MgB_2 and Nb-Ti wires were subjected to mechanical cycling tests. Six hundred cycles were performed on each joint with a force of 50 kg pulling apart, at 90° angle, each wire of the joint. No degradation of the joint quality was observed. It should be noted that this configuration was only used as an expedient to make the mechanical test – “praying-hands” joints will not be used in the final system.

Splice measurements were performed at 4.2 K using the inductive method, according to which a current is induced in a superconducting loop with the wire under test, and from the time of decay of the current the joint resistance is calculated [8]. The measurements were performed in the CERN Cryolab with Nb-Ti loops used for the LHC splice qualification measurements, where a straight part of Nb-Ti was replaced with MgB_2 wires or cables. Because of limitations imposed by the existing set-up, the length of the joint was limited to 30 mm. Eight measurements of splices between one 0.6 kA MgB_2 cable and four 0.8 mm diameter Nb-Ti wires gave joint resistances of 7 ± 0.5 nΩ. Six measurements of splices between a 3 kA MgB_2 cable and a Nb-Ti Rutherford cable gave joint resistances of 11 ± 1 nΩ. For both types of cable, currents up to 2.2 kA were induced in the superconducting loop.

Direct current measurements were performed on a 3 kA sub-cable unit (Figure 1 (a) and Figure 2 (a)). A 3 kA cable was assembled with MgB_2 wires taken from a 1 km unit length. The 12 wires were wound around the multi-strand copper stabilizer to provide a cable with a total length of 0.6 m, with a twist pitch that was sufficient to provide mechanical stability (about 300 mm). In the final cable design it will be avoided the use of the same, or simple of multiples of, twist pitch of the filaments in the wire. The external diameter of the insulated cable was about 6 mm. The cable was soldered at each extremity to a Nb-Ti Rutherford cable, and tested in a straight configuration in liquid helium at 4.5 K and in self-field conditions. The cable operated in DC mode at currents of up to 11.2 kA, when a quench occurred in the LTS part of the circuit external to the MgB_2 cable. Each of the two joint resistances between the MgB_2 and the Rutherford cable were lower than 3.5 nΩ.

Measurements of MgB_2 short samples extracted from a 1 km unit length were performed by Columbus Superconductors at different temperatures (16 K - 24 K) and fields (0.6 T - 1.8 T) (see Figure 3). Data at each temperature (T) were fitted with the equation: $J_E(B)=C1\cdot(1-(B/C2)^n)$ to obtain the dependence of the engineering critical current density (J_E) on the magnetic field (B). The curve for the engineering critical current density at 4.5 K passing through the point measured in self-field and in liquid helium was then extrapolated from these curves. The parameters C1, C2 and n used for the fitting are reported in Table 1. The fit will be refined as further measurement data is accumulated (and at which point a single fit for both B and T dependence will be constructed).

Table 1. Fitting parameters for $J_E(B)$ curves of MgB_2 wires in Figure 3

	T=4.5 K	T=16 K	T=20 K	T=24 K
C1	440937	7845	1914	534.4
C2	6.038	2.99	2.460	1.808
n	0.000957	0.04	0.1582	0.6466

The sub-cable (Figure 1 (a) and Figure 2 (a)) unit was able to transfer > 11.2 kA @ 4.5 K in self-field conditions (peak field of about 0.85 T). From Figure 3, the engineering critical current density at 4.5 K is estimated to be about 2.8 times the value at 20 K, which means that the cable would be able to transfer in self-field and at 20 K a current > 4000 A. In a field of 1 T, the expected critical current at 20 K is estimated to be > 3.4 kA. The 0.6 kA cable, which was operated in the set-up for the measurement of the splices at > 2.2 kA at 4.5 K, is expected to transport a current > 680 A at 20 K and in a field of 1 T.

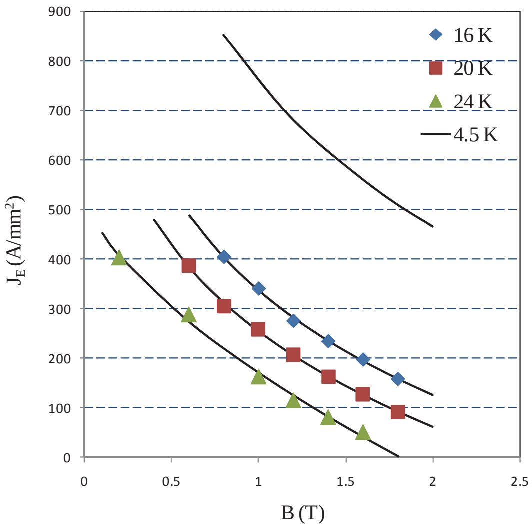

Figure 3. Dependence of the engineering critical current density of MgB_2 wires (1.1 × 1.1 mm^2 cross section) on magnetic field and temperature. Markers are measurements (Columbus Superconductors); curves are fitted and extrapolated from data.

3. Conclusion

A composite multi-conductor MgB_2 cable, having a total current capacity of over 100 kA at 20 K, has been designed for linking a superconducting magnet system to its feed box located up to 100 m distant. A full-size mock-up has been assembled for tests of flexibility, electrical insulation and thermo-hydraulic characteristics. Techniques have been developed for making reliable low-resistance joints. The large current conductors are based on a common element consisting of 12 strands of twisted multi-filamentary MgB_2 cabled around a stabilizing core of multi-strand copper. A short length of such an element has been assembled and tested in liquid helium: it carried a current > 11 kA in self-field at 4.5 K. The cable is expected to transfer a current of above 3.4 kA at 20 K and in field of 1 T. A cable layout taking account of the results obtained to date and corresponding to the final powering scheme for the new LHC inner triplet magnet systems is currently under optimization. A test station is being prepared for performing measurements on a prototype cable in nominal cryogenic and electrical conditions. In the future, BSCCO and YBCO conductors will also be considered as potential candidates for links operating at higher temperatures.

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References

[1] Ballarino A, Meß K H and Taylor T 2008 *IEEE Trans. Appl. Supercond.* **18** 1455-58
[2] Goiffon T, Perin A, Van Weelderen R, Darve C, Doohan R S , Sharma R S 2009 *Proceedings of CEC/ICMC*
[3] Ostojic R *et al*. 2008 *CERN Document Server LHC Project Report 1163*
[4] Ballarino A and Taylor T 2008 *CERN Document Server EDMS N. 965303*
[5] Ballarino A, Berta S, Brisigotti S, Grasso G, Tumino A, Pietranera D *CERN Document Server EDMS N. 965302*
[6] Putti M, Vaglio R, Rowell J 2008 *Journal of Physics Conference* Series **97** 012327
[7] Cerutti F and Mereghetti A 2009 *CERN Document Server EDMS N. 1002480*
[8] Hagedorn D and Herzog R 1998 *Proceedings of ICEC17* **12** 495-498