Chapter 8

Powering the High-Luminosity Triplets

A. Ballarino and J. P. Burnet
CERN, TE Department, Genève 23, CH-1211, Switzerland

The powering of the magnets in the LHC High-Luminosity Triplets requires production and transfer of more than 150 kA of DC current. High precision power converters will be adopted, and novel High Temperature Superconducting (HTS) current leads and MgB₂ based transfer lines will provide the electrical link between the power converters and the magnets. This chapter gives an overview of the systems conceived in the framework of the LHC High-Luminosity upgrade for feeding the superconducting magnet circuits. The focus is on requirements, challenges and novel developments.

1. Introduction

The powering of the High-Luminosity Triplets requires production and supply of about 160 kA DC current for feeding twenty electrical circuits. The triplet system comprises three quadrupole optical elements made of four Nb₃Sn magnets (Q1, Q2a, Q2b and Q3), a Nb-Ti separation dipole (D1) and several Nb-Ti corrector magnets. The low-beta quadrupoles are fed via two circuits with trims and all other magnets are individually powered.

Two main features distinguish the powering system of the High-Luminosity Triplets from that of the present LHC triplet configuration:

- (1) A significant higher current has to be generated and transported (about 160 kA to be compared with the present need of 40 kA), because of the high operating current of the low-beta quadrupoles and of the superconducting separation dipoles — the latter replaces the currently resistive low-field dipole modules;
- (2) The cold powering relies on the use of hundreds of meters long high temperature superconducting (HTS) lines (hereafter called “links”) providing the electrical connection between the current leads and the magnets.

In the LHC, power converters and current leads are both located in underground areas, the first either in galleries parallel to the main tunnel (UA zones) or directly in the tunnel (RR and UJ alcoves and below the dipole magnets) and the second in cryostats, which are at each end of the LHC sectors and in line with the superconducting magnets. Conventional copper cables connect the power converters to the current leads.

The cold powering system for the High-Luminosity upgrade incorporates novel superconducting lines that enable feeding the magnets from power converters and current leads located at a remote distance, i.e. either in surface buildings, located above ground near the LHC access shafts, or underground in radiation free access areas [1].

The use of superconducting links brings a number of benefits to the system that can be summarized as follows:

- (1) Location of the power converters in areas with no radiation to avoid the problem associated with the SEU (Single Event Upset), i.e. events that result stochastically from single interactions between energetic ionizing particles and electronic components and that can affect the performance of the power converters;
- (2) Easier access of personnel for maintenance, tests and interventions on equipment like current leads and power converters in radiation free areas, in accordance with the CERN principle of radiation protection that optimizes doses to personnel exposed to radiation by keeping them As Low As Reasonably Achievable (ALARA);
- (3) Removal of the current leads and associated cryostats from the accelerator ring, thus making space available for other accelerator components. The LHC Points 1 and 5, where the High-Luminosity insertions will be located, are among the most critical areas of the LHC machine, and removal of some large components will make easier integration of new equipment.

According to the present baseline, for the powering of the High-Luminosity Triplets at P1 and P5, power converters are planned to be located in surface buildings and connected to the magnet circuits via superconducting links containing tens of cables transferring all together about 160 kA. One link per triplet is needed. Each superconducting link is about 300 m long and has to span a vertical distance of about 80 m.

A solution similar to that of the High-Luminosity Inner Triplets is being studied also for the powering of the magnets in the LHC matching sections and in arc at LHC P1 and P5. Each of these systems requires two additional links per

point. The links provide the electrical connection from the surface to the underground areas.

A solution for remote powering is proposed also for LHC P7 [2, 3]. In this case, power converters and current leads are located in an underground radiation-free gallery, which serves as access to the LHC ring (TZ76). At P7, two superconducting links are needed. Each of them is about 500 m long and transfers a total DC current of about 30 kA.

The superconducting links for the LHC upgrade are under development at CERN. They represent a challenging and unprecedented development of compact and high-current superconducting transfer lines meeting all requirements needed for use as integral part of a cold powering system for the LHC accelerator.

A program has been launched at CERN for developing radiation hard electronics for power converters that could be operated in the LHC tunnel in zones exposed to radiation. This program, which started in 2010, aims at making available power converters that can withstand doses of up to about 100 Gy/year when exposed to neutron (1 MeV) and hadron (20 MeV) fluences of respectively $1.5 \cdot 10^{11} \text{ n/(cm}^2 \cdot \text{year)}$ and $5 \cdot 10^{10} \text{ p/(cm}^2 \cdot \text{year)}$.

2. Powering the High-Luminosity Triplets

The present LHC Inner Triplets have a complex powering scheme based on the use of nested circuits [4, 5]. Stability in current reaches the required performance of one per million of maximum current. However, during operation of the machine it was found that the MTTR (Mean Time To Repair) in case of faults in the power converters is much longer than for the other LHC circuits [6]. This is a drawback of the complexity of the powering layout which makes debugging the circuit more difficult to handle.

The powering scheme proposed for the High-Luminosity Inner Triplets [7] tries to simplify the electrical circuits with the purpose of improving availability of the machine while providing full flexibility for beam optics. The quadrupoles of the High-Luminosity Triplet (Q1, Q2 and Q3) are powered via two main circuits, each one equipped with a trim power converter (see Fig. 1). The two Q2a units are powered in series with a 200 A trim converter on Q2a. Q1 and Q3 are powered in series with a 2 kA trim converter on Q3. The separation dipole (D1) and the corrector magnets (the nonlinear correctors and the dipole correctors) are individually powered.

The current rating of the powering equipment is reported in Table 1. The new power converters will be based on the same principle of the present LHC modular switch-mode power converters [8]. All the converters will have redundant

modules to maximize the availability of the machine. The 2.4 kA units, working in 4-quadrant, require a dedicated development. In the LHC, 4-quadrant power converters were required only for corrector circuits operated at currents of up to 600 A.

Fig. 1. High-Luminosity Inner Triplet powering scheme.

Table 1. Current rating of magnets [9] and of powering equipment and number of power converters (PC), superconducting (SC) cables and current leads per triplet.

Circuit	Magnet current (kA)	PC rating (kA)	Cold powering system rating (kA)	Number of PC/SC cables/leads
Quadrupole	17.3	20	20	2/4/4
Trim on Q3	± 2	± 2.4	3	1/1/1
Trim on Q2b	± 0.3	± 0.4	0.4	1/1/1
Corrector dipole	2.4	3	3	6/12/12
Nonlinear corrector	± 0.1 A	± 0.12	0.12	9/18/18
Separation dipole	11.8	14	20	1/2/2

3. Cold Powering System

The cold powering system [10] consists of HTS current leads integrated in a distribution feed-box cryostat, of a superconducting link, which is a long cryostat enclosure containing an assembly of HTS cables, and of two interconnection boxes connecting the link at its colder side to the magnet cryostat in the tunnel and at its warmer side to the distribution feed-box cryostat. Electrical connections

between superconducting cables take place in the interconnection boxes, which house also the cryogenic instrumentation needed for control and operation. The cold powering system relies on cooling with helium gas supplied from the tunnel [11]. The gas warms up while absorbing the static load of the link cryostat and it is recuperated at the surface after cooling of the link and of the current leads. The superconducting cables in the link are designed for operation at a maximum temperature of 25 K — with nominal operation at about 20 K. The availability of helium gas at about 5 K in the cryogenic system enables the use of MgB_2 superconductor.

Novel cables made from different types of high temperature superconducting materials are being developed at CERN for use in the LHC superconducting links [2, 10]. For the links powering the High-Luminosity Triplets, an extensive program aiming at the development of both MgB_2 round wires and cables was carried out during the last three years. Thanks to a development program between CERN and the company Columbus Superconductors, MgB_2 round wires with the mechanical properties required for cabling were produced and extensively characterized [12, 13]. The first ever made high-current superconducting (20 kA at 24 K) cables assembled from reacted MgB_2 round wires were then assembled and successfully measured at CERN in a system-like configuration [10, 14]. A dedicated test station was built for measuring up to 20 m long superconducting cables operated in helium gas at any temperature in the range from 5 K to 70 K.

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 the powering of the High-Luminosity Triplets, each of the four links to be integrated 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 (see Fig. 2). The total current transferred by the assembly of these forty-two cables is 165 kA DC.

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 cables already pulled in at the surface. To limit the 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 splices between cables inside the link. This is possible thanks to the availability of unit lengths of MgB_2 wire in excess of 1 km. The cryostat consists of four corrugated pipes and it includes an actively cooled thermal shield.

The forty-two multi cable assembly has an external diameter of about 65 mm and a mass of about 11 kg/m. The external diameter of the CRYOFLEX® semi-flexible cryostat containing the cable assembly 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 (see Fig. 3).

Fig. 2. Cables made with MgB₂ round wire. (a) One of the six sub-units making a 20 kA cable, $\Phi \sim 6.5$ mm; (b) 20 kA cable, $\Phi \sim 19.5$ mm; (c) concentric 2 $\times$ 3 kA cable, $\Phi \sim 8.5$ mm; (d) 0.4 kA cable (top) and 0.12 kA cable (bottom), $\Phi \sim 3$ mm; (e) 165 kA cable assembly (6 $\times$ 20 kA, 7 $\times$ 3 kA, 4 $\times$ 0.4 kA, 18 $\times$ 0.12 kA), $\Phi \sim 65$ mm. MgB₂ wire is in green, copper stabilizer is in red.

Fig. 3. From left: schematic layout at LHC P1 and P5, with superconducting links spanning across a vertical distance of 80 m and connecting the current leads, located in cryostat in surface buildings, to the LHC magnets in the tunnel; integration at LHC P5, with two superconducting links powering the insertion magnets developed in the framework of the LHC High-Luminosity upgrade.

4. Conclusions

A new powering scheme for the High-Luminosity Triplets is proposed with the goal of maximizing the availability of the machine and freeing precious space in the underground areas. The powering system will require the transfer of about 160 kA DC current for feeding twenty electrical circuits. Novel superconducting transfer lines are under development to enable the feeding of the magnets from power converters and current leads located in surface buildings. The type of LHC power converters with high current stability will be extended to cover the upgrade requirements. The powering layout proposed for the High-Luminosity Triplets will be reviewed in a more advanced phase of the project, when additional input from the magnet system is available.

A powering system is being studied for the High-Luminosity matching section magnets in IR1 and IR5, with superconducting links to remove onto the surface the cryogenic feedboxes and the power converters. The technical challenges are similar to those of the system feeding the Inner Triplets.

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