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Chapter 10

Cold Powering of the Superconducting Circuits

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This chapter describes the cold powering, i.e. the transfer of current from room temperature to the liquid helium environment, of the High-Luminosity LHC (HL-LHC) [1] magnets. Target R&D was done to develop novel systems relying on long superconducting transfer lines, with up to |120| kA current capability, called Superconducting Links, based on MgB_2 superconductor. The Superconducting Links are part of the so-called Cold Powering Systems that include complex terminations at the two extremities for interfacing with the magnets and the power converters. High Temperature Superconducting REBCO based current leads, housed in a cryostat of novel concept, make the electrical transition between room temperature and 17 K. Two types of system were conceived and designed for the powering of the HL-LHC magnets in the Triplets and the D2 separation dipole in the Matching Sections. Following the successful completion of a staged and focused R&D, which included qualification of prototype systems, series production has been launched. Aspects associated with the integration and operation of the systems in the final LHC configuration were also studied in-depth and optimized.

1. Introduction

The powering of the High-Luminosity magnets requires the transfer of large quasi-DC currents from the power converters, located in the new UR technical galleries, to the LHC machine tunnel [2]. Two different types of Cold Powering System will provide this functionality: the system for the HL-LHC Triplets, which will feed the low-beta quadrupoles, the D1 beam separation dipoles and the corrector magnets, and that for the HL-LHC Matching Sections, which will feed the D2 beam recombination dipoles and the corrector magnets. In total, eight systems are needed for integration in the LHC at Point 1 (P1) and Point 5 (P5): two systems, one of each type, right and left of each Interaction Point. They will ensure the electrical transfer from room temperature to the liquid helium environment, and they will span in the LHC underground areas over a physical distance of up to about 120 m.

Two main features distinguishes how the High-Luminosity magnets are powered compared to that in the present LHC configuration:

(1) A significantly higher current has to be transported (up to a total of around 120kA for the Triplets, compared to the currently required 40 kA), because of the high operating current of the low-beta quadrupoles and separation dipoles (in the case of D1, the present resistive low field dipoles will be replaced by superconducting magnets).

(2) The use of hundreds of meters long superconducting MgB_2 lines (hereafter called "SC links") needed for providing the electrical connection between the current leads, in the UR galleries, and the magnets in the LHC machine tunnel. The need for high-current superconducting power transmission was due to the location of the power converters in the radiation-free UR galleries.

The above requirements called for the development of complex and novel superconducting systems.

2. Cryogenic and Electrical Functionalities

The Cold Powering Systems for HL-LHC provide the electrical connection between the current leads, near the power converters, and the magnets, in the LHC main tunnel. They span the temperature range from 4.5 K to room temperature and rely on cooling via forced flow of helium gas generated, in the coldest part of the system (DF in Figure 1), by liquid helium boil off. Helium gas at low pressure – about 1.3 bara – enters the SC Links in the LHC tunnel and exits, at room temperature (RT), in the UR galleries after having cooled the SC Links and the current leads. The system is designed such that it minimizes the helium mass flow rate and the global cryogenic cost of the refrigeration.

Each Cold Powering System comprises of (see Figure 1):

- a SC Link, i.e. a flexible cryostat with MgB_2 cable assemblies inside;
- at the cold termination of the SC Link (4.5 K), a DF cryostat, which contains the splices between the MgB_2 cables of the SC Link and the Nb-Ti cables passing though the λ-plate and reaching the magnets' cold mass;
- at the warm termination of the SC Link (17 K), a DFH cryostat, which contains the splices between the MgB_2 cables and the REBCO termination of the High Temperature Superconducting (HTS) current leads;
- current leads, incorporating a section made from REBCO HTS material;
- the electrical and cryogenic instrumentation required for operation and protection.

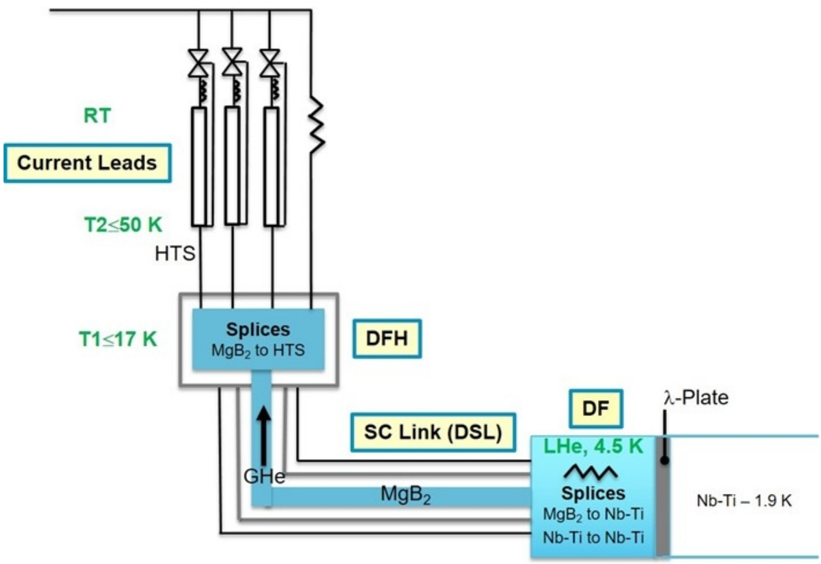

Fig. 1. Schematic of a Cold Powering System and operating temperature range. Helium gas is generated from liquid helium boil off inside the DF cryostat, in the LHC tunnel. It is recuperated at room temperature (RT) at the exit of the current leads.

2.1. *SC Links*

A SC Link consists of a flexible cryostat housing the MgB_2 cables required for feeding the SC magnet circuits. The cables are made from MgB_2 reacted wire [2-5], developed at an early stage of the project in a collaboration between

CERN and industry. The cables were also initially developed and qualified at CERN, and then industrialized for the final prototypes and series production.

In contrast with superconducting transmission lines developed for electric power distribution, where one (single phase) or a maximum of three (three-phase) cables are contained in the same cryogenic envelope, the SC Links for HL-LHC contain tens of cables rated at different DC currents ranging from a minimum of 0.6 kA up to a maximum of 18 kA. For the powering of the High-Luminosity Triplets, each of the four SC Links to be integrated at LHC P1 and P5 contains four cables rated at 18 kA, three cables rated at 7 kA, and twelve cables rated at 3 kA (see Figure 2) [6]. These cables are twisted together to form a final assembly that has an external diameter of about 90 mm. The 3 kA cables are concentric, i.e. the two polarities of a circuit are part of the same cable and are separated by polyimide insulation. The peak magnetic field experienced by the cables is about 0.8 T. The total current transferred by the assembly of these nineteen cables is about |120| kA DC - 60 kA per polarity. For the powering of the magnets in the Matching Sections, each of the four SC Links to be integrated at LHC P1 and P5 contains three cables rated at 18 kA and eight cables rated at 0.6 kA. The external diameter of the cable assembly is about 60 mm.

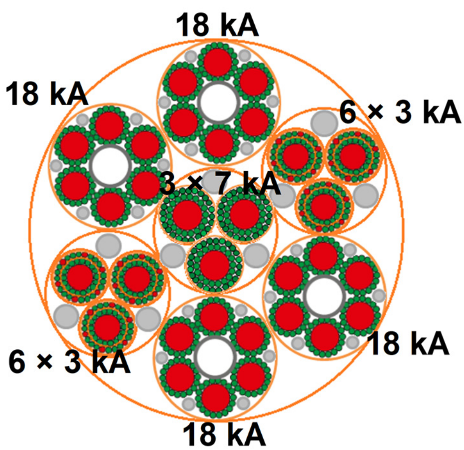

Fig. 2. Schematic of the MgB_2 cable assembly conceived for the powering of the HL-LHC Triplets. Green are MgB_2 wires, red is copper stabilizer, gray are fillers, and orange is electrical insulation. The external diameter of the cable assembly is about 90 mm. To minimize the peak field in the cable assembly, the two 18 kA cables nearby have opposite polarity.

The MgB_2 cables are designed to transfer the maximum design current at a temperature of at least 25 K. The maximum temperature experienced in nominal operating conditions is 17 K.

The cryostat of the SC Links consists of two concentric corrugated pipes. Despite operation at temperatures well below that of liquid nitrogen, it does not include an active thermal shield. The optimization of the Cold Powering System is such that the static heat load of the cryostat, which is about 1.5 W/m, is absorbed by the helium mass flow required for the cooling of the current leads: the cooling of the SC Link itself is therefore fully transparent to the system, in that it uses the enthalpy of the gas, needed for the operation of the current leads, to warm up from 4.5 K to 17 K. A specific development was done with industry to verify the possibility of achieving the desired low static heat load. The advantages of the passive cryostat, which does not have an actively cooled thermal shield and uses two, instead of four, corrugated pipes are: more flexible, and simplifies the global system, e.g. no need of controlling the helium mass flow cooling the shield, and lower cost.

The MgB_2 cable assemblies are pulled inside the cryostats at the surface. They are assembled in one single unit length with no splices inside the SC Link. At one termination, the MgB_2 cables are connected at the surface to Nb-Ti cables: this termination of the SC Link is housed inside the DF cryostats. The Nb-Ti cables operate in a bath of saturated liquid helium. They will be spliced, in the tunnel, to the Nb-Ti busbar passing through the λ-plate (see Figure 1) and connecting to HL-LHC magnets.

2.2. *DF Cryostats*

The DF cryostats are connected to the colder termination of the SC Links [7,8]. They contain the splices between MgB_2 and Nb-Ti cables (see Figure 1). Their main functionalities are:

- ensuring that the Nb-Ti cables and splices are submerged in liquid helium;
- to generate the gaseous helium required to cool the full length of the SC Link and HTS current leads at the DFH extremities.

These two functions are achieved by maintaining a helium bath, in a fountain configuration, equipped with heaters to create the boil-off. Level gauges are used to monitor and control the helium in-flow from the cryogenic distribution line (QXL). The design is such that, in case of interruption of the cryogenic supply with the system at full current, all conductors and splices are sufficiently cooled during the current ramp down and do not undergo a resistive transition; the helium vessel and fountain configuration are designed with buffer volumes to ensure adequate autonomy.

Two types of DF cryostats are required: the DFX as part of the Cold Powering System powering the Triplets and the DFM for the Cold Powering System powering the Matching Sections. Eight DF units are needed in total for installation in the LHC underground.

2.3. *Current Leads*

The current leads are the same type as was used in the LHC machine [9]. They consist of a HTS part, operated between 17 K and 50 K, and a resistive part making the electrical connection in the temperature range between 50 K and room temperature. However, they differ from the HTS current leads in the LHC machine in that:

- The HTS material in the HL-LHC current leads is REBCO tape. In the LHC, BSCCO 2223 tapes, with a silver-gold matrix, were used in the form of vacuum soldered stacks [9].
- The HL-LHC current leads are cooled by the helium gas entering the HTS part of the current leads at about 17 K. The gas is generated at 4.5 K in the DF cryostat and warmed-up, while absorbing the static and dynamic heat loads of the system, to about 17 K, at the inlet of HTS part of the current lead, and to room temperature at the exit of the resistive part of the current leads. In the LHC current leads, the cold termination of the HTS dips into a saturated liquid helium bath and the HTS section is self-cooled, while the resistive part is cooled by forced flow of helium gas made available at about 20 K by the LHC cryogenic system.

Each Cold Powering System requires either nineteen current leads, for the Triplets, or twelve current leads, for the Matching Sections. In total, one hundred and twenty-four HTS current leads are needed to power the HL-LHC magnets.

2.4. *DFH Cryostats*

The DFH cryostats house the HTS gas cooled current leads. The SC Link cable assembly enters the DFH by means of a shuffling module where the individual cables are separated and guided to the so-called splice box, where the MgB_2 cables are connected to the HTS part of the current leads (see Figure 1). Helium gas at about 17 K, flowing from the SC Link, is channeled over each splice and then through the associated current lead from where it is recovered at room temperature. Regulation of gas flow at each current lead is achieved by control valves. In stand-by conditions, with no powering of the circuits, excess helium flow from the SC Link is diverted through a by-pass channel within the DFH (see Figure 1).

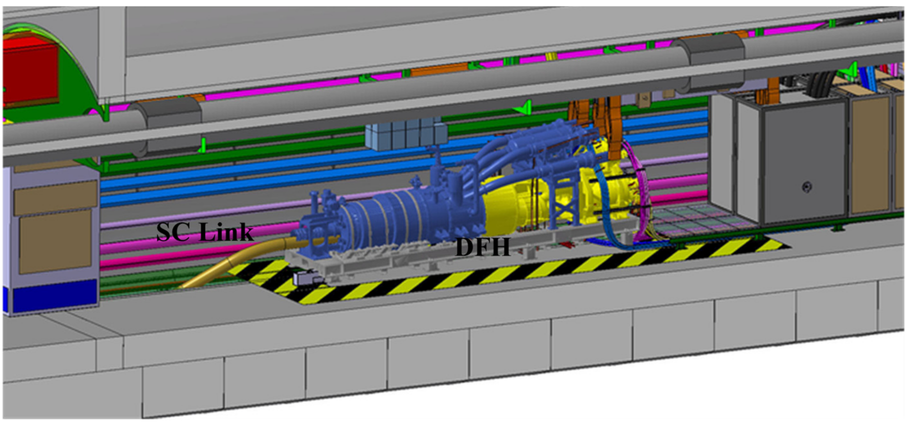

Fig. 3. DFH Cryostat with current leads in the LHC underground. The DFH incorporate nineteen HTS current leads and the corresponding REBCO to MgB_2 splices. It has a total length of about 4.5 meters.

The innovative design of the DFH allows its full assembly with the associated SC Link prior to installation in the underground areas. There are multiple benefits of this concepts, such as: allowing the combined cryogenic testing in nominal operating conditions of superconducting cables, splices, current leads, and instrumentation. This will be achieved via a dedicated system test in the CERN SM18 test facility, with no decoupling of the SC Link required for underground installation. During transportation, the SC Link is spooled so that the combined assembly can be handled in a common support frame.

Two types of DFH cryostats are required: the DFHX as part of the Cold Powering System for the Triplets, and the DFHM, a rescaled smaller version for the powering of the Matching Sections. Eight DFH units are needed in total are needed to power the four high luminosity insertions for ATLAS and CMS.

2.5. *Instrumentation*

Each Cold Powering System incorporates the instrumentation required for its operation. This includes voltage taps, needed for protection – in case of resistive transition of the superconducting parts of circuits or over-heating of the resistive part of the current leads – and monitoring of the splices, and temperature sensors used for helium gas flow control. A large number of voltage tap signals are part of the MgB_2 cable assembly, cabled in bundles.

2.6. *Prototype Cold Powering Systems*

During the R&D phase, demonstration systems were developed and tested at CERN. The most complete ones were the so-called Demo 2 and Demo 3 systems. Demo 2 was a demonstrator system for the Triplets. It consisted of:

- a 62.5 m long SC Link, i.e. a double wall cryostat, produced in industry, with inside a full cross section MgB_2 cable assembly, cabled in industry with industrial cabling machines;
- a demonstrator DF;
- a demonstrator DFH including two prototype 18 kA REBCO Current Leads designed and constructed at CERN.

Demo 3 was a demonstrator system for the Matching Sections. It used the same components as Demo 2, but the SC Link contained inside the cryostat a full cross section MgB_2 cable assembly for the Matching Sections.

To enable simultaneous powering of several circuits, the SC Links of Demo 2 and Demo 3 could be fed with current from both terminations. In addition to the prototype REBCO current leads in the DFH, a pair of conventional current leads were connected also at the DF side. The extensive campaign of tests performed enabled successful qualification of Demo 2 and Demo 3 systems [10-12]. This included validation of cryogenic, electrical and mechanical performance both in nominal and transient conditions, as well as realization of complex handling and installation that confirmed feasibility of

Fig. 4. View of a demonstration Cold Powering System – Demo 2 – tested at CERN for cryogenic and electrical qualification. The SC Link is 62.5 m long and it contains a full cross section MgB_2 cable assembly of the type needed for the powering of the HL-LHC Triplets.

procedures proposed for final integration of the systems in the LHC underground areas. Attaining world record currents for MgB_2, Demo 2 and Demo 3 are the first ever power transmission lines made with MgB_2 superconductor and were operated at temperatures of up to 31 K.

3. Integration

The use of the SC Links in the HL-LHC Cold Powering Systems enables the removal of radiation sensitive power converters from high exposure areas of the LHC tunnel and facilitates integration challenges in the densely populated LHC tunnel upstream of the high-luminosity interaction points. The power converters are displaced to the so-called UR underground technical galleries, which are radiation free, and are located near the current leads housed on the DFH cryostats. The SC Links connect the DFH, in the UR technical gallery, to the DF in the LHC tunnel via a sixty-meter-long horizontal UL gallery followed by an eight-meter vertical shaft of about one meter diameter (see Figure 5). In all there are four UL galleries, each with two SC Links routed side by side, one SC Link feeding the Triplets and the other the Matching Sections. To facilitate logistics in the UR galleries and the first meters of the adjoining UL gallery and for safety aspects, the SC Links are placed in covered trenches.

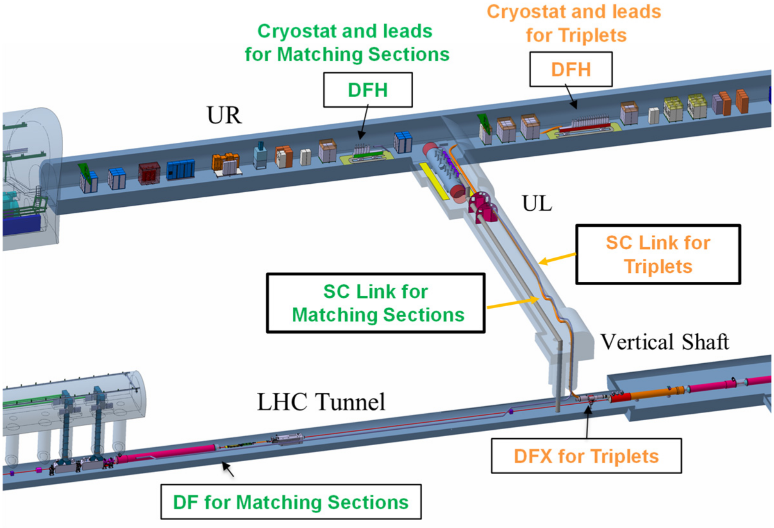

Fig. 5. Schematic view of a Cold Powering System installed in the LHC underground areas.

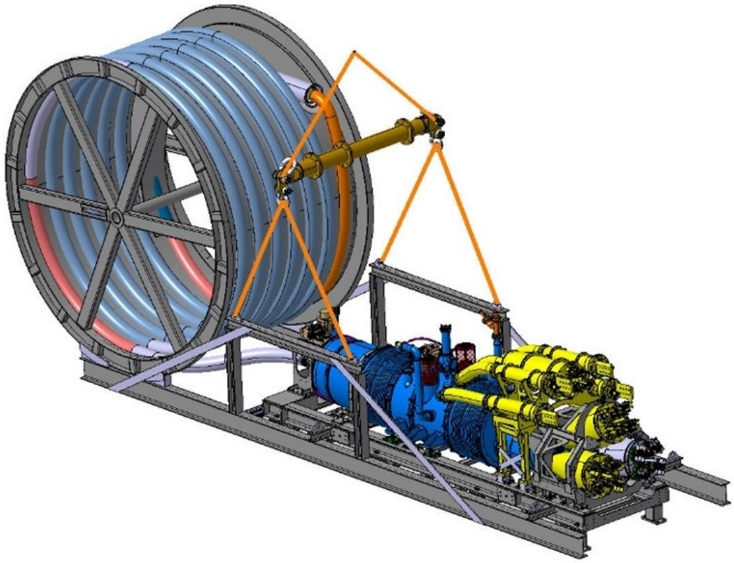

Fig. 6. Configuration of the SC Link after connection to the DFH and ready for being transported in the LHC underground areas. The diameter of the drum onto which the SC Link is spooled is about four meters. The total weight of the system is about 5 tons.

Each SC Link will be lowered into the HL-LHC underground areas spooled onto a drum with a diameter of about four meters and already connected to its DFH. The system as it will be transported is represented in Figure 6. It will be tested at the surface in nominal operating conditions prior to installation.

To cope with thermal contraction of the SC Link cable assembly, each SC Link will be installed with a snaking path having a nominal wavelength of 4 meters and minimum 0.25 m peak-to-peak amplitude of the cryostat axis. Furthermore, to mitigate execution tolerances of the civil engineering infrastructure and link manufacturing, the lateral space allocation is enhanced to allow larger peak-to-peak amplitudes as required.

For the Triplets, the DFX in the LHC tunnel receives the SC Link through its upper flange directly below the eight meters vertical core. The DFM is located above the D2 beam recombination dipole magnet, approximately forty meters from the vertical core; after emerging from the core, its superconducting link is routed about forty meters horizontally in the LHC above the helium transfer line (QXL), again with a snaking path.

4. Safety Aspects

Unlike the existing underground areas of the LHC, the UR underground technical galleries remain accessible during accelerator operation. HL-LHC Cold Powering failure modes leading to cryogenic or electrical hazards in the UR have been identified and analysed [13]. Mitigation by design, safety devices and procedures have been presented and documented [14]. Failure modes leading to helium release and/or electrical arcs are considered up to the Worst Case Incident (WCI) – the extremely rare scenario of a short circuit with electrical arc not detected by the protection system. The analysis demonstrates that access to the UR underground areas remains acceptable in conjunction with technical mitigation, e.g. Oxygen Deficiency Hazard detectors, and organizational measures, e.g. identification of no-stay areas when circuits are powered at nominal current. Mitigation of hazards includes staging of safety valve opening pressures such that helium is preferentially released to the LHC tunnel rather than the UR. Helium and vacuum envelopes, and sensitive instrumentation feedthroughs are protected from accidental damage. Perhaps of most significance, each SC Link with its splices and current leads will be fully tested under operational conditions before its installation in the underground areas.

5. IT String

The so-called Inner Triplets (IT) String will be built and operated prior to the installation of HL-LHC series components in the underground areas during the Long Shutdown 3, which is presently foreseen to start by beginning 2025. Its configuration is that of an insertion region with the Nb_3Sn quadrupole triplets, the corrector magnets and the D1 separation dipole, with all technical systems required for powering to nominal conditions. The IT String will be equipped with a Cold Powering System comprising the pre-series units of DFH, DF and a 73 meters long SC Link. While the main goal will be to learn about collective behavior of technical systems, significant learning will also come from the installation and commissioning phases as the Cold Powering interfaces to many other HL-LHC systems. Following its exploitation in the IT String, the Cold Powering System will be demounted and stored as spare for the HL-LHC accelerator.

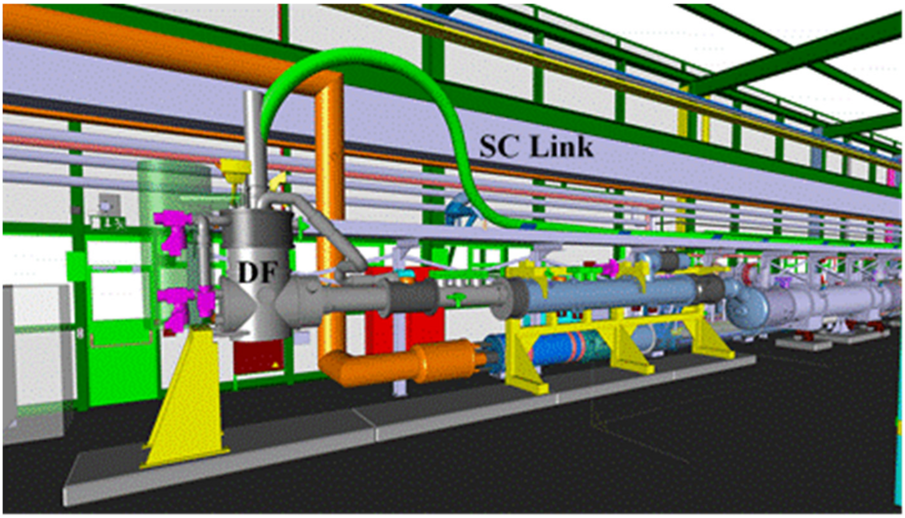

Fig. 7. Configuration of the SC Link after installation in the CERN SM18 cryogenic test facility for the powering of the IT String. After a long horizontal path, the SC Link enters vertically inside the DF, which interfaces with the magnets' cold mass.

6. Conclusions

The Cold Powering Systems for the HL-LHC magnets are based on innovative technologies that include helium gas-cooled MgB_2 electrical transfer lines transporting currents of up to |120| kA over a distance of more than a hundred meters in the LHC underground areas and HTS REBCO based current leads incorporated in compact cryostats of novel concept. The extensive development campaign carried out at CERN was completed in 2020 with the successful qualification of demonstrator systems. Construction of series components has now been launched. The challenging aspects associated with the handling and installation at the surface and in the LHC underground areas have been studied and give confidence in the possibility of integrating the flexible transfer lines in the accelerator environment. Thanks to the compact design, the systems of SC Link, DFH and HTS current leads will be tested at the surface in nominal cryogenic conditions and brought down in the LHC underground areas, after full qualification, already connected.

The novel Cold Powering Systems for HL-LHC attracted the attention of the electrical power transmission community. This included the European BEST PATHS ("BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems") project that studied the potential of MgB_2 SC Links for high power transmission – gigawatt range – in replacement of convention lines in a grid network [15].

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