Chapter 6A

Cold powering of the superconducting circuits

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6A. Cold powering the superconducting circuits

6A.1 Overview

For the HL-LHC project, a novel concept for the cold powering of superconducting magnets has been developed. It is based on a new type of superconducting lines (hereafter referred to as Superconducting (SC) Links) that have been developed to transfer the current to the new HL-LHC insertion region magnets from remote distances [1]. Power converters and current leads will in fact be located in the new underground areas (UR) excavated for the HL-LHC (technical galleries running aside the LHC tunnel), and the SC Links will provide the electrical connection between the current leads and the magnets – the latter being located in the LHC main tunnel [2]. Each SC Link has a length of more than 100 m and transfers a total current of up to about |120| kA.

The benefits of the remote powering of the HL-LHC magnets via SC links are several and can be summarized as follows:

- Access of personnel for maintenance, routine tests and specific interventions on power converters, current leads and associated cryogenic/electrical equipment can be located in areas far away from the LHC ring and therefore radiation free, in accordance with the principle of radiation protection that optimizes doses to personnel exposed to radiation by keeping them As Low As Reasonably Achievable (ALARA);
- Current leads and associated cryostats (in LHC called Distribution Feedboxes, DFBs) are removed from the accelerator ring, thus leaving space in the main tunnel for other equipment. In the HL-LHC Interaction Regions (IR) around P1 and P5, no space has been reserved for DFB-type cryostats with current leads, which are now located in the new UR galleries. Connection to the magnets' bus-bar is made at 4.2 K via short connection cryostats.;
- The new technical galleries are areas with less restrictive access for personnel. Access to these galleries may be granted under certain conditions even during operation of the accelerator with beam, with the advantage of reduced time for interventions on the equipment which is located there.

The HL-LHC Cold Powering work-package (WP) conceived, developed, and is producing:

- High Temperature Superconducting (HTS) current leads (DFLH), based on High Temperature Superconducting (HTS) REBCO technology;
- SC Links (DSH) based on MgB_2 technology;
- Cryostats in the LHC main tunnel (DF) containing the Nb-Ti cables from/to the magnets and the electrical splices to the SC Links;

- Cryostats (DFH) in the new technical galleries containing the splices between MgB_2 and the HTS;
- Technologies specific to the HL-LHC Cold Powering Systems, e.g. electrical splices between HTS and MgB_2, MgB_2 and Nb-Ti, Nb-Ti and Nb-Ti;
- Cryogenic and electrical instrumentation;
- Definition of operating parameters (cryogenic flow and related control) and protection requirements (interlocks, protection strategy and thresholds of resistive and superconducting components).

The Cold Powering Systems for the HL-LHC includes: a system for the Inner Triplets, one for the Matching section magnets and finally the upgrade of the DLS in order to power the Q4, Q5 and Q6.

6A.2 Cold powering systems

The Cold Powering Systems for the HL-LHC Triplets and for the Matching sections have different layouts, lengths, and routing in the LHC underground areas. The number and type of superconducting cables and current leads required for each system type are summarized in Chapter 6.

The SC Links connect the current leads, placed in the technical galleries, to the Nb-Ti bus-bar located inside the DF cryostats (DFX for the Triplets and DFM for the Matching sections) which are placed in the LHC main tunnel. Their routing – through the UL galleries – respects a specified minimum bending radius of 1.5 m and includes a vertical height change of about 8 m.

The SC Links for the Triplet magnets transfer the current from/to the technical galleries to feed the following magnets: Q1, Q2 and Q3 (i.e. the main low-β quadrupole circuit along with the 2 kA trim circuits), D1 and the associated orbit correctors. The higher order multiple correctors operating at currents $\leq$ 200 A and the k-modulation circuit on Q1 are not fed via the SC Links. Their cold powering is instead provided by conduction-cooled resistive current leads located directly in the magnets' cryostats [3]. Their design is based on the development done for the LHC dipole orbit corrector current leads [5], and it takes into account the specific boundary conditions including routing and cooling possibilities. Differently from the LHC corrector current leads, which rely on two thermalization points, only one thermalization, provided by the HL-LHC beam screen cryogenic circuit, is available.

The SC Links for the Matching Sections transfer from/to the technical galleries the current feeding D2 and its orbit correctors.

The DFX and DFM cryostats interface with the cryostats of the D1 and D2 magnets, respectively. A schematic of the layout of a Cold Powering System in the underground areas of LHC Point 1 is shown in Figure 6A-1.

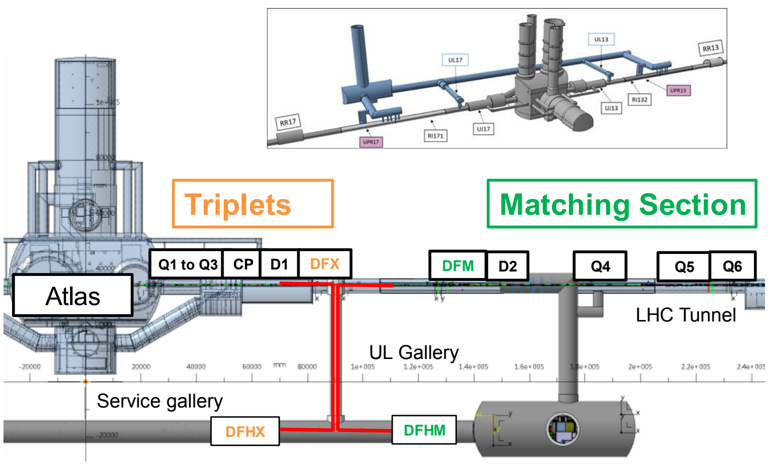


Figure 6A-1: Schematic routing of the SC Links (red lines) at LHC Point 1

The cryogenic cooling of the Cold Powering Systems relies on a forced-flow of helium gas generated by boil-off of liquid helium in the DF cryostats [6]. The amount of helium flowing through a SC Link is defined by the cooling needs of the current leads: the SC Links are not only electrical lines, but also cryogenic lines that transfer the helium required for the cooling of the current leads from the LHC main tunnel to the technical galleries. The He gas absorbs the static heat load of the SC Link cryostat and consequently warms-up over the length of the link up to the maximum operating temperature of the MgB_2 (17 K, T1 in Figure 6A-2). From the DFH, it is then distributed among the installed current leads. The maximum operating temperature of the HTS (T2 in Figure 6A-2) is 50 K. After having cooled the current leads, the helium gas is recovered at room temperature in the technical galleries.

Superconductors used throughout in the HL-LHC Cold Powering Systems are: Nb-Ti inside the DF cryostats, MgB_2 in the SC Links and HTS REBCO material in the current leads. In nominal operating conditions, the superconducting part of the system spans the temperature range from 4.5 K up to 50 K – with Nb-Ti at 4.5 K, MgB_2 at up to 17 K, and HTS at up to 50 K. However, the MgB_2 system is designed for operating at up to 25 K, and the REBCO at up to 60 K. The generous temperature margin ($\geq$ 7 K) and the operating temperature much higher than in previous cold powering system working at 4.5 K, made possible by the use of MgB_2 and HTS superconducting components, renders the HL-LHC Cold Powering Systems very robust against thermal disturbances and transients to ensure reliable operation in the LHC machine.

The HL-LHC Cold Powering System consists of several HTS current leads optimized for different current ratings, a DFH cryostat, a SC Link, and a DF cryostat. It contains cryogenic equipment (helium valves, level gauges) and all cryogenic and electrical instrumentation needed for operation of the system and for protection of the superconducting and resistive components. The protection strategy of the HTS REBCO material relies on the development and experience gained from operation of the HTS BSCCO 2223 in the LHC current leads [7].

By design choice, the Nb-Ti cables and the MgB_2 to Nb-Ti splices in the DF cryostats are submerged in liquid helium (LHe) and operated in pool-boiling conditions.

Figure 6A-2 shows a schematic of a Cold Powering System with the respective nominal operating temperatures. Interfaces with the HL-LHC Work Packages are also indicated. Main interfaces with the other HL-LHC systems are at the level of the λ-plate, which is part of the magnets WP, of the He gas recovery lines with the valves controlling the flow through the current leads, which are part of the cryogenics WP, and of the room temperature power cables, which are part of warm powering and technical infrastructures WPs. The electronics for the protection of all superconducting components and current leads is the responsibility of the Machine protection Work package, based on performance specification and electrical instrumentation installed by the Cold powering Work package.

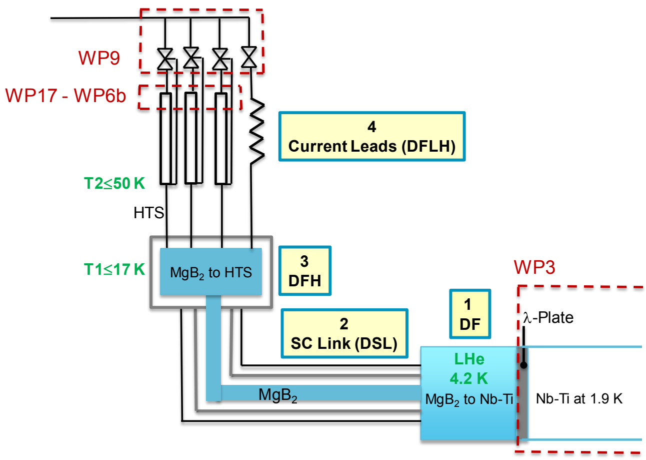


Figure 6A-2: Components of a Cold Powering System and naming conventions. Operating temperatures are indicated, as well as interfaces with other HL-LHC Work Packages

6A.2.1 Superconducting links (DSH)

The SC link is an electrical transfer line that consists of a long, semi-flexible cryostat and MgB_2 cables. The latter are housed inside the cold mass of the flexible cryostat.

The cryostat consists of two corrugated concentric pipes (2-wall configuration, see Figure 6A-3): the inner pipe houses the superconducting cables, while the outer pipe is the vacuum insulation envelope. Initially, the SC Link cryostat incorporated a He- gas cooled thermal shield (4-wall configuration). Following the evolution of the HL-LHC project and the reduction of length of the SC Links, the possibility of simplifying the cryostat design was identified, and the development of 2-wall cryostats with high thermal performance was launched with industry. As a result of this effort, low static heat load 2-wall flexible cryostats of the size required for the Cold Powering Systems of the HL-LHC Triplets were extensively and very successfully qualified at CERN. The challenging project specification (static heat load in nominal cryogenic conditions - 4.5 K to 17 K - of the order of 1.5 W/m) was met by each of the three industrial partners that produced a 60 m long prototype. The achievement of the target performance on the three prototypes enabled the adoption of the 2-wall design. The benefits of the 2-wall cryostat are: a global simplification of the Cold Powering System at the level of DFH design and system operation, a lower weight and higher flexibility of the SC Links. The latter facilitate spooling and routing operations.

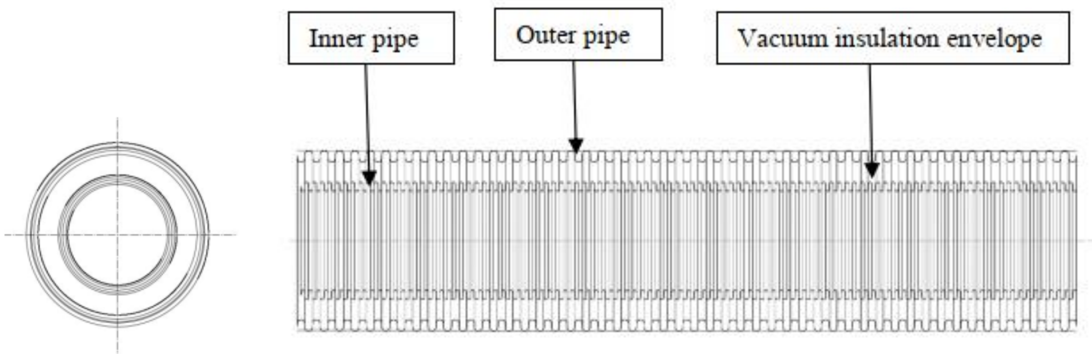


Figure 6A-3: Schematic cross-section (left) and longitudinal section (right) of the flexible cryostat for the SC Links. The diameter of the outer pipe, for the Triplets, is about 170 mm. The minimum bending radius is 1.5 m. The weight of the cryostat is of the order of 10 kg/m.

The MgB_2 cables inside the flexible cryostats are complex assemblies made from different cable types. Each cable type is optimized for the current rating of the corresponding circuit. There are two different cable assemblies: one for Triplets and one for the Matching sections. Their total current capability is about |120| kA and |61| kA respectively.

The cables are made from round ex-situ Powder-In-Tube (PIT) MgB_2 wire specifically developed for this project in collaboration between CERN and ASG Superconductors. The development aimed at producing long lengths (> 500 m) of MgB_2 wire with mechanical properties enabling cabling after reaction. Different wire layouts were produced in industry and characterized in-depth at CERN. The layout retained is a 1 mm diameter multi-filamentary wire, with Monel matrix and copper stabilizer that is electro-chemically deposited around the external surface. Superconducting filaments in the wire have an equivalent diameter of less than 60 µm, and are twisted with a pitch of 100 mm.

At the end of the development, unit lengths of wire exceeding 2 km were produced. The minimum specified critical current is 480 A at 20 K and 0.5 T, and 320 A at 25 K and 0.5 T. The main characteristics of the adopted wire design are summarized in Table 6A-1. The total production of MgB_2 wire for the project is about 1130 km.

Table 6A-1: Main characteristics of the MgB_2 wire. Mechanical properties refer to a reacted wire. Ic is the critical current of the wire, whereas RRR is the Residual Resistivity Ratio of the copper stabilizer in the MgB_2 wire.

Wire diameter	**mm**	**1±0.2**
Wire ovality	mm	≤ 0.15
Copper fraction in the wire	%	> 12
Filaments equivalent diameter	µm	≤ 60
Filaments twist pitch	mm	100±5
Tensile stress at room temperature	%	≥ 0.26
Bending radius	mm	≤ 100
Unit length	m	≥ 500
RRR of copper	-	> 100
Ic (25 K, 0.9 T)	A	≥ 186
Ic (25 K, 0.5 T)	A	≥ 320
Ic (20 K, 0.5 T)	A	≥ 480
n-value at 25 K and 0.9 T	-	> 20

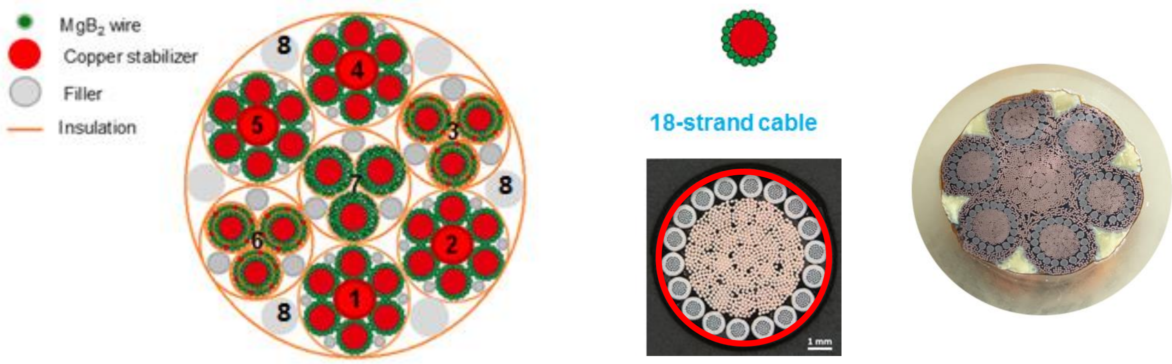


Figure 6A-4: Left: Schematic of MgB_2 cable assembly for the HL-LHC Triplet string [4]. 1,2,4 and 5: 18 kA cables; 3 and 6: triplets of concentric 3- kA cables; 7: triplet of 7- kA cables. 8: bundles of instrumentation wires. The external diameter of the cable assembly is ~ 90 mm. Current capability is specified at 25 K and in an external field of 0.9 T. Center: schematic (top) and cross-section (bottom) of a base cable made from 18 MgB_2 wires. The core of the cable is made from copper strands. The external diameter of the base cable is about 8 mm. Right: cross-section of 18- kA cable. The external diameter of the cable is 27.6 mm.

The MgB_2 cables have a round geometry. The layout of the cable assemblies was conceived in such a way that it could be produced in the final required lengths using industrial large industrial cabling equipment [4]. Cable development and characterization were done at CERN. The high-current cables are derived from a base cable layout. The base cable is made from eighteen MgB_2 wires twisted around a central multi-strand copper core (see Figure 6A-4, left). Six base cables twisted around a central multi-strand copper core form a 18- kA cable; a base cable with an additional second layer of MgB_2 wire forms a 7- kA cable; a base cable electrically insulated and with an additional second layer of MgB_2 wires around the electrical insulation forms a co-axial 3- kA cable (see Figure 6A-4). The 7- kA cables and the 3- kA cables are twisted together to form triplets. The 18- kA cables, the triplets of 7- kA cables and the triplets of 3- kA cables are twisted together to form the final cable assembly for the Triplets (see Figure 6A-4 left). Electrical insulation is provided by polyimide tape wrapped around each cable type with appropriate overlapping that enables achieving the high-voltage electrical insulation requirements. Each cable type contains sufficient copper to limit heating in case of resistive transitions to temperatures not exceeding 50 K.

Each MgB_2 cable assembly is cabled in its final length and then pulled inside the long flexible cryostat to produce a SC Link. MgB_2 cable assemblies, SC Link cryostats and final SC Links are transported spooled on drums of from about 1.5 m to 3.5 m internal diameter, and an external diameter of less than 4 m. In particular, the SC links are conceived for being lowered into the LHC underground areas spooled on drums with dimensions and weight compatible with a descent from the surface through the HL-LHC PM shafts. The new and compact design of the DFH enables lowering the SC Links after connection to the DFH cryostats. Integration studies in this direction are being performed. Unspooling and routing of the SC Links to the final location is done in the underground galleries. The minimum bending radius of the SC Links is 1.5 m. The weight of the 120- kA SC Link for the Triplets – cryostat with cable assembly – is about 40 kg/m.

At one termination, each MgB_2 cable type is soldered to a Nb-Ti cable with an equivalent current capacity at 4.5 K. This connection is done at the surface, after having pulled the MgB_2 cable assemblies into their flexible cryostats. This is the termination of the SC Link that is destined to be located in a DF cryostat (see Figure 6A-2). The Nb-Ti cables are connected, in the tunnel, to the Nb-Ti bus coming from the 1.9- K magnet cold mass after passing through the λ-plate.

The SC Links incorporate all instrumentation required for the protection of the superconducting cables as well as for the monitoring of all electrical splices within the systems. The instrumentation wires are first cabled together to form round cables, and then twisted with the MgB_2 cables in order to be an integral part of the final cable assembly – instrumentation signals occupy three of the six locations of the most external fillers in Figure 6A-4.

6A.2.2 Current leads and DFH

The HTS current leads rely to a large extend on the technologies developed for the LHC HTS leads [8]. The main difference is the use, for the superconducting part, of REBCO tape superconductor instead of BSCCO 2223 Ag-Au tape, and the HTS part is a flexible cable instead of an assembly of stacks of superconducting tapes vacuum soldered onto a metallic structure. Also, the cryogenic cooling is different. The LHC HTS section terminates with its Nb-Ti extension in a saturated liquid helium bath at 4.5 K and is self-cooled up to a temperature of about 50 K. The resistive copper section receives helium gas at about 20 K from an independent LHC cryogenic line [8]. The cryogenic cooling of the HL-LHC Cold Powering Systems relies entirely on forced flow of helium gas: the HL-LHC HTS current leads receive gas from the SC Link at about 17 K and return it at room temperature at the level of the UR after the cooling of the resistive section. As in the LHC, the helium flow through each current lead is controlled by the temperature of the HTS warm-end termination, which should never exceed 50 K.

The electrical connection between each MgB_2 cable type and the corresponding HTS current lead is done inside the DFH cryostat (see Figure 6A-2). The cryostat houses the electrical splices between the MgB_2 cables in the SC Link and the HTS cold-end termination of the current leads. The design of the DFH assures a reliable and secure routing of the superconducting cables. The development of low-resistance splices between MgB_2 and REBCO has successfully been done at CERN. For the 18- kA splices, contact resistances of a few nΩ have been measured in nominal operating conditions , in line with the specified electrical resistance of not more than 2.5 nΩ for the high current (18 kA and 13 kA) circuits [9]. Electrical resistances of not more than 15 nΩ are specified for 3- kA circuits. The design of the DFH cryostat assures effective cooling of the splices via the helium gas delivered by the SC Link.

6A.2.3 Cryostats interfacing to the LHC machine

The DF cryostats are located in the LHC main tunnel between the SC Links and the magnet cold masses (see Figure 6A-2). Two types of DF cryostats are required: the DFX for the Triplets – for the connection of the SC Link to the D1 - and the DFM for the Matching sections – for the connection of the SC Link to the D2. The main functionalities of these cryostats consist in: a) receiving and routing the Nb-Ti termination of the SC Link; b) host the splices between the Nb-Ti terminations of the SC Link and the Nb-Ti bus-bar coming from the magnets via the λ-plate; c) maintaining an appropriate volume and level of liquid helium in order to cover emerge the Nb-Ti cables and splices; d) producing, via liquid helium boil-off, the mass flow rate passing through the SC Link and cooling the current leads; e) extracting the instrumentation (voltage taps and temperature sensors) required for operation and protection aspects. Table 6A-2 summarizes the main design parameters of the two types of cryostats.

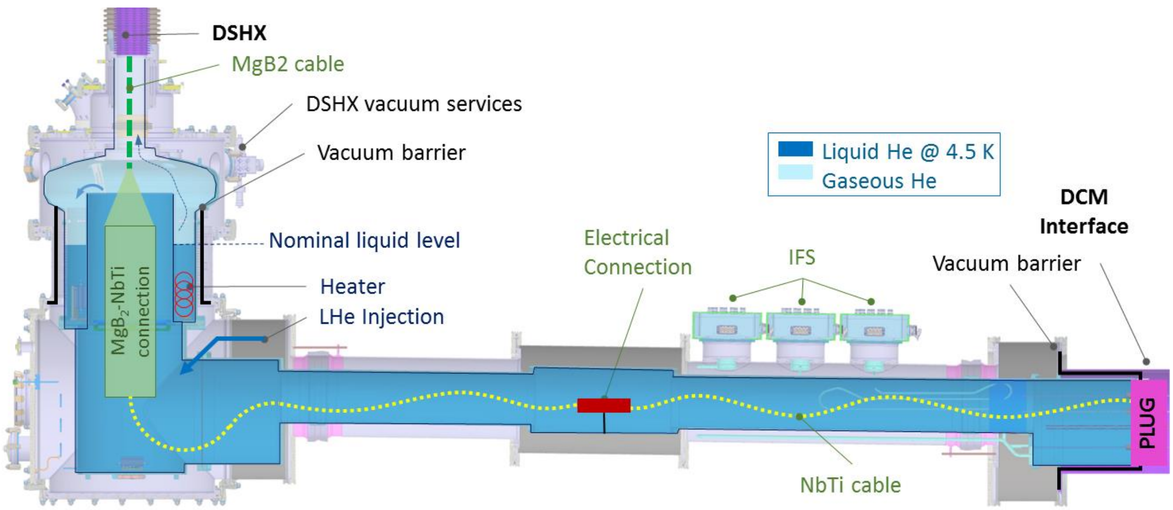
Table 6A-2: Design parameters of the DFX and DFM cryostats.

Helium volume	**Unit**	**DFX**	**DFM**
Approximate volume	litres	650	360
Nominal temperature	K	4.5	4.5
Design pressure	bara	3.5	3.5
Nominal He mass flow rate produced	$g.s^{-1}$	5	2
Maximum heat loads to the helium volume	W	30	20
Insulation Vacuum volume	**Unit**	**DFX**	**DFM**
Nominal pressure level	mbar	10^{-5}	10^{-5}

The DF cryostats and the SC Link share common helium volumes and are hydraulically separated from the superfluid helium volume of the magnets via a λ-plate (plug in Figure 6A-5). The controlled gaseous mass flow is produced by vaporising liquid helium via electrical heaters and/or a heat exchanger integrated inside the DF cryostat. The liquid helium level, measured by superconducting level gauges, is controlled through an inlet cryogenic valve. In case of unforeseen interruption in the supply of liquid helium, the helium inventory in the DF ensures a cooling autonomy for a period of about ten minutes, sufficient to enable re-establishment of nominal cryogenic conditions without impacting operation of the LHC machine. Since the DF cryostats are not constrained by stringent thermal heat loads, a thermal shield is not incorporated, permitting a simple, compact, and economic design. Cold surfaces are covered by 30-layers of Multi-Layers-Insulation (MLI) blankets to limit the radiation heat load and reduce heat inleak in the case of accidental venting.

Following the study of different layouts, the vertical integration option has been retained as the most appropriate design concept: the SC Link (DSHX in Figure 6A-5) terminates in the HL-LHC vertical shaft cores. The DFX receives the Nb-Ti termination of the SC Link in its vertical section, and routes it into the horizontal section. The MgB_2 cables and the MgB_2 to Nb-Ti splices are located in the vertical section. A schematic of the DFX cryostat is shown in Figure 6A-5 [9].

The DFX cryostats are located under the UL vertical cores, at about 90 m distance from the Interaction Points. The DFM cryostats are installed in the LHC tunnel at about 45 meters distance from the PM shaft.



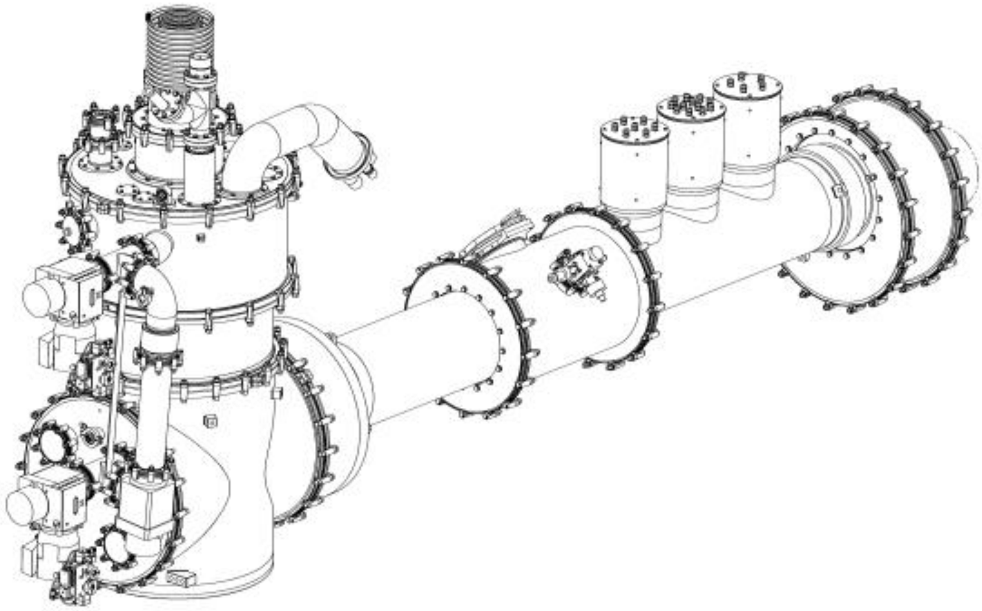


Figure 6A-5. Schematic (top) and 3D drawing (bottom) of DFX cryostat. The SC Link (DSHX) terminates in the vertical section of the cryostat, where the MgB_2 to Nb-Ti splices are located. The instrumentation signals are routed out from electrical connectors (IFS) located in the horizontal section of the DFX. The electrical connection between the Nb-Ti extension of the SC Link and the Nb-Ti cables coming from the magnets and passing through the λ-plate (plug) is also indicated. The horizontal length of the DFX, flange to flange, is about 4 m.

6A.3 Control, protection and electrical insulation

Operation of the Cold Powering System relies on maintaining two nominal temperatures, i.e. not more than 17 K at the location, in the SC Link, of the splices between MgB_2 and REBCO in the SC Link (T1 in Figure 6A-2) and not more than 50 K at the warm end of the REBCO section (T2 in Figure 6A-2) [4]. These two operating conditions define the amount of helium mass flow rate that is needs to be produced in the DF cryostat for the cooling of the system. Appropriate override of the two controllers is devised in order to have them working correctly in tandem. In nominal operating conditions, the total amount of helium flow circulating in the system is imposed by the requirements of the current leads and of the bypass valve. The helium gas is recovered, at room temperature, in the technical galleries from the current leads and the DFH.

A quench in the superconducting part of the system or a thermal run-away of the resistive heat exchanger of a current lead is detected by the quench detection system and will result in the firing of the corresponding magnet protection system (CLIQ, quench heaters and energy extraction systems as a function of the protected circuit). Each MgB_2 cable, REBCO cable and Nb-Ti cable is independently protected in case of resistive transition. The protection threshold of the REBCO cables is in the order of a few mV and relies on the experience gained from operation of the HTS current leads in the LHC machine [7] as well as the DEMO2 tests. The MgB_2 cables are protected at a voltage threshold of about 100 mV [10]. The amount of copper stabilizer in the MgB_2 and in the Nb-Ti cables is such that in case of a resistive transition the peak temperature never exceeds 50 K. Each MgB_2 to Nb-Ti splice and MgB_2 to REBCO splice is monitored and their protection is incorporated in the corresponding overall protection scheme of the corresponding circuits. Each resistive section of a current lead is independently protected at voltages of the order of 100 mV.

The Cold Powering Systems are designed in order to withstand the high voltage requirements imposed by the magnets' circuits [4]. In view of the operation in helium gas, the high voltage test levels, which are specified for the magnets in liquid helium, are performed in helium gas environment at room temperature and atmospheric pressure.

6A.4 References

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