Conceptual study of the cryostats for the cold powering system for the triplets of the High Luminosity LHC

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Abstract. The High Luminosity LHC (HL-LHC) is a project aiming to upgrade the Large Hadron Collider (LHC) after 2020-2025 in order to increase the integrated luminosity by about one order of magnitude and extend the operational capabilities until 2035. The upgrade of the focusing triplet insertions for the Atlas and CMS experiments foresees using superconducting magnets operating in a pressurised superfluid helium bath at 1.9 K. The increased radiation levels from the particle debris produced by particle collisions in the experiments require that the power converters are placed in radiation shielded zones located in a service gallery adjacent to the main tunnel. The powering of the magnets from the gallery is achieved by means of MgB2 superconducting cables in a 100-m long flexible cryostat transfer line, actively cooled by 4.5 K to 20 K gaseous helium generated close to the magnets. At the highest temperature end, the helium flow cools the High Temperature Superconducting (HTS) current leads before being recovered at room temperature. At the magnet connection side, a dedicated connection box allows connection to the magnets and a controlled boil-off production of helium for the cooling needs of the powering system. This paper presents the overall concept of the cryostat system from the magnet connection boxes, through the flexible cryostat transfer line, to the connection box of the current leads.

1. Introduction
The principal part of the High Luminosity Large Hadron Collider (HL-LHC) project [1] requires the installation of new triplet insertions focusing the beams at each side of the Atlas and CMS interaction points. Due to increasing intensity and luminosity, the higher levels of radiation require shielding of the power converters by installing them in a newly dug parallel gallery. The powering of the triplet insertion magnets is performed via a flexible superconducting line (hereafter called “SC link”) about 100 meters long, connected to the magnets on one end and to the power converters on the other end through dedicated connection cryostats referred respectively in the LHC naming convention as DFX and DFH, see figure 1. The High Luminosity HL-LHC project [1] will include four of these SC links with DFH-DFX connection cryostats and will be installed in the LHC tunnel in 2024-2025.

In this paper the main functions of the flexible line and the two connection cryostats are presented, the main challenge being to design a cooling scheme ensuring the superconducting state of the conductors with high reliability. Technical requirements requiring further detailed studies are listed and identified.

The conceptual designs of the electrical, vacuum, cryogenic and mechanical layouts are described taking into account the specificities of maintainability and operation in an activated area. A specific
chapter is dedicated to a more detailed description of the DFX cryostat. Finally, the integration and the installation constraints are discussed.

![Illustration of the chain of cryostats from the triplet magnets to the power converters.](image)

**Figure 1.** Illustration of the chain of cryostats from the triplet magnets to the power converters.

2. Conceptual design of the cryostats of the cold powering system

2.1. Overall design
The cold powering system is distributed between the two parallel tunnels on each side of the Atlas and CMS interaction points. The electrical power converters (PC) dedicated to the triplet magnets are installed in the new tunnels about 400 meters long, excavated parallel to the LHC main tunnel. In these galleries, the PC are electrically connected to the current leads of the DFH cryostats installed close by. A SC link, about 100 meters long routed through a transverse tunnel about 50 meters long connects the DFH cryostat to the DFX cryostat in the main LHC tunnel. The DFX cryostat, situated 80 meters away from the interaction point, ensures the electrical continuity with the triplet continuous cryostat [2], see figure 1.

The main function of the DFH cryostat is to ensure the transition of the electrical conductors between ambient and cryogenic temperatures. The SC Link routes the cables from one tunnel to the other ensuring their superconducting states. The DFX cryostat performs the electrical connections to the magnets bus-bars and supply the cold powering system chain in cryogenic fluids.

2.2. Electrical layout
The insertion magnets are connected to the power converters with up to 44 conductors rated from 120 A to 18 kA nominal current. Niobium-titanium (Nb-Ti) cables connect the magnets to the Nb-Ti cables of the DFX leak tight interface (hereafter referred as “plug”), see figure 2. The superconducting cables in the SC link are made of magnesium diboride (MgB2) presenting a soldered interface to the Nb-Ti cables at the DFX end. In order to optimise the installation sequence in the tunnel and maximise reliability of the assembled equipment, electrical connections in situ are limited to well proven and reliable Nb-Ti to Nb-Ti soldered or ultrasonically welded connections. The MgB2 cables to Nb-Ti soldered connections are foreseen to be performed and validated at the surface before installation in the LHC tunnel.
In the DFX helium volume, the Nb-Ti cables routed through the plug are soldered to the Nb-Ti cables ends of the superconducting MgB$_2$ cables. The design of the 100 meters long set of MgB$_2$ cables is presented in [3] and the MgB$_2$ to Nb-Ti soldering in [4].

At the other end of the superconducting link, in the service gallery, the MgB$_2$ cables are soldered to High Temperature Superconducting (HTS) leads in situ, the latter being connected to the lower cold termination of the actively cooled current leads. At the room temperature end of the current leads, conventional water-cooled cables complete the electrical path to the power converters.

For the DFX-SC Link-DFH chain of cryostats, up to about 220 electrical connections operating at cryogenic temperatures have to be installed, tested and properly cooled. To offer reliable and maintainable technical solutions, the development of soldering techniques and procedures require specific in-depth studies.

2.3. Conceptual design of the cryogenic scheme
The helium volumes of the cold powering cryostats and the triplet cryostat are separated. However, the chain of cryostats comprised of the DFX, the SC Link and the DFH present a common cryogenic layout.

2.3.1. Specifications. In the DFX to DFH cryostats, cryogenic fluids are used to ensure the superconducting state of the conductors. Along this electrical path, the maximum allowed temperature of the conductor in nominal operation evolves. In this configuration, the specified cables maximum temperature for the Nb-Ti material is about 5.5 K, about 20 K for the MgB$_2$ cables in the SC link, and 50 K for the HTS cables in the DFH cryostat. In addition, the inlet temperature of the gas through the current leads is 30 K for a total designed mass flow of gaseous helium of 5 g/s.

2.3.2. Conceptual design approach. To limit the static heat loads to the vessels containing the superconducting conductors, the three cryostats, DFX, SC Link and DFH contain an insulation vacuum specified below $1.10^{-5}$ mbar [1], which significantly reduces the heat transfer by convection from the ambient temperature vacuum vessels walls. The DFX cryostat shares its insulation vacuum with the triplet cryostat. Studies are under way to provide sufficient conductance between the two volumes to benefit from the pumping capacity of the triplet cryostat and save additional pumping equipment. The superconducting link insulation vacuum is independent and presents a vacuum barrier at each end. The DFH cryostat, located in the adjacent tunnel where constraints are less restrictive will have its own dedicated vacuum pumping system. Insulation vacuum interfaces will be sealed with elastomer seals compatible with the environment.

The radiative heat loads to the helium vessels are minimized with the integration of thermal shielding in each of the three cryostats. The superconducting link comprises an actively cooled thermal shield with an inlet gas temperature of 20 K. Heat loads due to conduction will be studied and minimized during the detailed design phase.

![Conceptual electrical layout of the cold powering cryostats](image-url)
2.3.3. **Cryogenics scheme.** The triplet and corrector magnets as well as their Nb-Ti bus-bars are under nominal conditions completely immersed in pressurized superfluid helium at 1.9 K [2]. The cryogenic layout of the cold powering system presents a continuous helium volume from injection into the DFX up to the DFH where the fluids are returned to the cryogenics lines. The design pressure is about 3.5 bara and the temperature ranges from 4.5 K in the DFX to 20 K at the cold end of the current leads in the DFH.

The leak tight interface between the superfluid volume of the triplet magnets and the DFX helium volume requires the development of a specific thermal and electrical insulating plug containing the Nb-Ti cables. The study is based on the knowledge acquired from the design of similar plugs currently used at CERN [5] [6]. This key component shall withstand differential pressures up to 20 bar combined with thermal cycles during the whole life time of the HL-LHC machine.

The DFX helium vessel is filled in nominal operation with LHe at 4.5 K. The level of the saturated helium bath is controlled to guarantee a permanent immersion of the electrical connections and the superconducting cables. A return helium gas line from the DFX is foreseen for transient phases. Heaters are located in the liquid phase of the DFX and produce, by vaporisation, the required mass flow of gas flowing through the SC link. At the DFH end of the SC link, the temperature of the gas shall remain below 20 K in order to cool by convection the electrical connections between the MgB$_2$ and the HTS cables connected to the bottom of the current leads. The current leads are gas cooled with a temperature gradient of the gas between 20 K and ambient, see figure 3. The outlet of the thermal shield circuit may be brought to contribute, with additional mass flow, to cool the current leads.

![Cryogenic and vacuum layouts of the DFX, SC Link and DFH cryostats in nominal operation](image)

**Figure 3.** Cryogenic and vacuum layouts of the DFX, SC Link and DFH cryostats in nominal operation.

To optimise the integration, the accessibility and the manoeuvrability of components during installation and maintenance, the thermal shield of the DFX cryostat is conduction cooled using the thermal shield of the triplets cryostat as the cold source. The resulting additional heat loads to the 4.5 K saturated bath has been evaluated to be below 1 Watt and is considered acceptable. This solution allows an inlet temperature of the thermal shield circuit of the superconducting link to be close to 20 K. Thermal shields and helium vessels are externally surrounded by multi-layer insulation (MLI) for respectively reducing the static radiative heat loads and to limit the transient heat deposition to the cold fluid in case of air in leak to the vacuum vessels. The common helium volume is protected by safety relief devices located on both DFX and DFH cryostats.

2.3.4. **Heat loads.** First estimations of the static heat loads for the three cryostats give an order of magnitude for the previously presented conceptual designs. Radiative heat loads to the thermal shield...
are estimated at about 30 W for the DFX and DFH and about 250 W for the Superconducting link. Static heat transfer by conduction to the 4.5 K-20 K volume in nominal operation is estimated below 20 W for each cryostat as a first estimation.

Sources of dynamic heat loads are various. Electrical connections between superconductors are resistive and dissipate heat locally to the cryogenic fluid. The study of the resistivity of the electrical connections is identified as a key topic and parameter for the detailed design. The cryogenic configuration shall ensure the reliability and performance of the electrical connections.

2.3.5. Transient phases. During transient phases, the heat loads distribution varies and the cryostats shall be properly instrumented to monitor the pressure profiles and the temperature distribution.

From a mechanical point of view, the most critical phases occur during cool-down and warm-up transients. The helium vessels of the three cryostats are connected with flexible bellows to cope with thermal contractions. The SC link is made of four corrugated and concentric pipes fixed together at each end. The outer corrugated tube is the vacuum vessel envelope, the two middle pipes form the thermal shield circuit and the inner one contains the 4.5 K to 20 K helium volume. This corrugated configuration allows local compensation of the thermal contractions of these vessels. The thermal contractions of the conductors presents a key challenge for the detailed design phase. As for the vessels, it is intended to defined fixed points for the conductors at each end of the SC link. Consequently, an integrated extra length or a specific design shall ensure the safe control of thermal contractions over the transient cycles. In the DFX and DFH cryostats, local integration of extra length of Nb-Ti cables is foreseen.

3. Detailed conceptual design of the DFX cryostat

The detailed study of the DFH cryostats is still at a conceptual stage. Additional information about the SC Link cryostat can be found in [3]. The DFX cryostat, source of the cryogenic layout of the cold powering system is presented in more details and illustrates the key challenges for the design of the other cryostats.

3.1. Design of the DFX cryostat

The two main functions of the DFX cryostat are to transfer current from the triplet cryostat to the SC link conductors and to supply the superconducting link with cryogenic fluids.

For the conceptual design, two strong boundary conditions are taken into account: a) maintenance operations to be carried out in an activated zone must be limited and optimised and b) the interferences with the beam pipe must be minimised.

Different basic concepts have been studied and have converged on a design with a DFX cryostat and SC link independently located above the beam tube without any mechanical links, see figure 4. Advantages are numerous, not only this ensures that the mechanical loads from vacuum, thermal contractions, SC link stresses and pressure fluctuations of the cryogenic circuits do not affect the beam tube alignment but it also leads to lighter components, easier to transport, manufacture, control and maintain, that can be installed independently without the tight specifications inherent to the beam tube.

3.2. Specificities of the DFX cryostat

Figure 4 shows a three dimensional illustrative view of the DFX cryostat and its interfaces with the triplet cryostat on one side and a representation of the SC link on the other.

The DFX cryostat main components consist of a ≈ Ø 0.8 m x 1.5 m vacuum vessel, a thermal shield made from rolled aluminum sheets thermally attached to the actively cooled thermal shield of the triplet cryostat at 40 K-60 K via aluminum braids, and a stainless steel helium vessel containing the conductors, electrical connections and heaters.

In order to minimize the operations in situ, the electrical connections of the cables from the triplet magnets to the plug ends shall be performed and qualified on the surface.

For maintainability purposes, it is required that the plug be replaceable in case of a leak between the two volumes.
The heaters producing the gas flow through the SC Link are designed to be easily accessible for maintenance. They are located in a semi-separated vessel above the immersed electrical connection to optimize the quality of the liquid and therefore the heat exchange at the conductors’ and connections level.

One specificity of the DFX cryostat is the heat load by conduction from the 4.5 K saturated bath to the 1.9 K volume through the cables of the plug and contribute to the cooling of the conductors and the liquid bath. The design of the conductors is not yet advanced enough to quantify this heat flux.

As outcome from the conceptual design, instrumentation for pressure monitoring in both vessels is foreseen as well as wires routing to feedthroughs for temperature sensors and voltage taps. Locations for safety relief pressure devices are reserved. The quantification of spares and redundancies is a key topic for the detailed design phase.

![Figure 4. Illustrative representation of the DFX cryostat](image)

4. Introduction to integration and operational challenges
The DFX, SC Link and DFH cryostats are independently positioned and fixed to the ground. Their interfaces are mechanically assembled with flexible elements such as hydro-formed bellows. This choice brings high flexibility in the installation sequence with more adjustment margins for the assembly and fixing options. The study of the integration and the installation sequence of the superconducting link and the two connection cryostats is under way. A specific system is foreseen in the transverse tunnel to adjust the length of the superconducting link to cope with civil engineering tolerances.

Due to the increased level of radiation in the main LHC tunnel, restrictions apply to the future maintenance and must be taken into account at the conceptual design level. Consequently, the design aims at limiting or optimizing future interventions by reducing the number of components requiring maintenance, facilitating access and manipulation, and identifying needs for integrated spares and redundancies in the activated areas.

5. Conclusion
A conceptual design of the DFX, superconducting link and DFH cryostats for the cold powering of the triplet magnets of the HL-LHC project is presented. The electrical paths and electrical connections from
the power converters to the triplet magnet cryostat are identified. The sources of heat and temperature limits are defined and a conceptual cryogenic scheme is presented.

The key challenges are now under study starting with particular attention paid to the installation sequence, the maintainability in activated areas, the development of the leak tight plug, the study of the resistivity of the electrical connections and the study of the thermal contractions of the conductors. The detailed design of the connection cryostats has started. The development of the superconducting links is well advanced and the first demonstrators of the cryostats have been manufactured and hydraulic tests shall be performed at CERN in the coming months.

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