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Conceptual design of the cryostat for the new high luminosity (HL-LHC) triplet magnets

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Abstract. The High Luminosity LHC (HL-LHC) is a project to upgrade the LHC collider after 2020-2025 to increase the integrated luminosity by about one order of magnitude and extend the physics production until 2035. An upgrade of the focusing triplets insertion system for the ATLAS and CMS experiments is foreseen using superconducting magnets operating in a pressurised superfluid helium bath at 1.9 K. This will require the design and construction of four continuous cryostats, each about sixty meters in length and one meter in diameter, for the final beam focusing quadrupoles, corrector magnets and beam separation dipoles. The design is constrained by the dimensions of the existing tunnel and accessibility restrictions imposing the integration of cryogenic piping inside the cryostat, thus resulting in a very compact integration. As the alignment and position stability of the magnets is crucial for the luminosity performance of the machine, the magnet support system must be carefully designed in order to cope with parasitic forces and thermo-mechanical load cycles. In this paper, we present the conceptual design of the cryostat and discuss the approach to address the stringent and often conflicting requirements of alignment, integration and thermal aspects.

1. Introduction

The Large Hadron Collider (LHC) is the flagship accelerator at CERN. It was successfully commissioned in 2010 and since then accelerates and collides proton beams and heavier ions up to lead. It is installed in a 27 km circumference tunnel, about 100 m underground. To extend its discovery potential, the LHC will need a major upgrade after 2020-2025 to increase its luminosity by a factor of five and extend the physics production until 2035. The integrated luminosity goal becoming a factor of ten higher than the LHC nominal design value. The resulting machine configuration, the High Luminosity LHC (HL-LHC), will comprise a new generation of Nb₃Sn superconducting magnets, superconducting crab cavities for particles' bunch rotation, new technology for beam collimation and new MgB₂ superconducting electrical powering lines for the magnets; among others [1].

The cornerstone of the HL-LHC will be the replacement of the insertion regions, on either side of the experiments Atlas and CMS. By 2023 it is expected that the LHC will reach an integrated luminosity sufficiently high to induce radiation damage in some components of the insertion region magnets, resulting in potential failure. Their replacement will be an opportunity to increase the aperture in the insertion region main quadrupoles and allow for an increase in luminosity through a lower β^* . The solution for aperture maximization relies on the recent advances in Nb₃Sn superconductor magnet technology, which will be used in the 24 quadrupoles needed for the triplet assemblies [2]. A new and very compact cryostat will be required since the cold mass diameter increases from 570 mm to 630 mm



due to larger aperture, but still has to be integrated in the constrained space of the LHC tunnel. Moreover, cooling at 1.9 K in presence of high heat loads, resulting from particle debris from the experiments, implies large pumping lines to be integrated. Hereafter we present a concept for this cryostat and the design features aiming at stringent requirements in terms of cooling, alignment stability, reliability and maintainability of the system.

2. The continuous cryostat

The layout of a typical string of insertion magnets on either side of the experiments ATLAS and CMS is presented schematically in figure 1. This string of magnets, operating at 1.9 K and comprising the main quadrupoles Q1 to Q3, correctors and beam separation dipole D1 [3], is enclosed in one 60 m long continuous cryostat spanning from about 20 m to 80 m from the interaction point (IP). Stainless steel shells of 630 mm outer diameter perform as helium vessels and form a stiff cylindrical structure, usually referred to as cold masses, to contain the main magnets either individually, such as D1, or paired with correctors such as Q2a and Q2b. Q1 and Q3 magnets are split in two parts due to manufacturing limitations but enclosed in a single cold mass. Lengths of cold masses vary from 6 m to 10 m and require either two or three supports to limit the sag induced by a distributed weight of about 2 ton per meter, within acceptable values both for alignment reasons and to not overstrain the brittle Nb3Sn coils.

The continuous cryostat is divided in 6 cryo-assemblies, each comprising one cold mass with its supports inside a cryostat vacuum vessel and thermal shield. Thanks to flexible interconnects between cryo-assemblies, it is possible to align the cryo-assemblies independently from each other and compensate for longitudinal thermal contractions.

It was decided to place the connections to the cryogenic distribution line as far away as possible from the interaction point (IP) to minimize the radiation dose in case of intervention. The first connection to the distribution line is located between Q3 and the corrector package (CP). At the D1 extremity, a second connection to the distribution line completes the magnet cooling circuit and feeds helium to a superconducting link, through which the magnets are powered from converters located in a different gallery 90 m away.

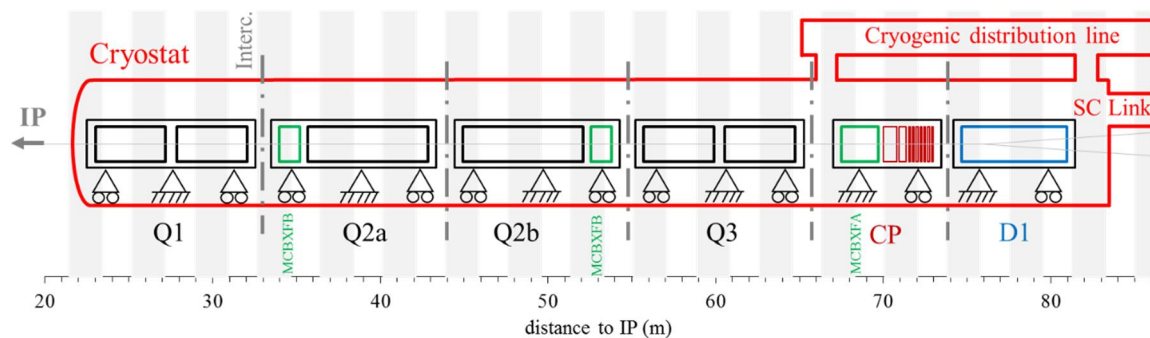


Figure 1. Schematic layout of a continuous cryostat at the right hand side of the interaction point, comprising the insertion region quadrupoles Q1-3, corrector package CP and separation dipole D1. Two connections to the cryogenic distribution line are foreseen. A superconducting link connects the magnets to the power converters located in another gallery. Dashed lines indicate interconnect locations and each section between them represents one independent cryo-assembly.

3. Cooling

Cooling of the magnet coils at 1.9 K is achieved by full immersion in a static superfluid helium bath at 1.3 bar. Heat is then extracted from this bath through two-phase heat exchangers in which saturated helium is evaporated by pumping at 15 mbar [4]. Figure 2 presents a schematic diagram of the cryogenic system for a string of magnets on one side of the IP.

High dynamic heat loads exceeding 800 W at 1.9 K require large pumping capacity and therefore high conductance pumping lines from the heat exchangers to the cold compressors. Diameters up to 100

mm are required to limit pressure losses and ensure a stable temperature of the coils. Moreover, given the high heat load and limitations to the diameter of the linear heat exchanger imposed by magnet design, it was necessary to split the system longitudinally in three sections, each with independent pumping, as shown in figure 2.

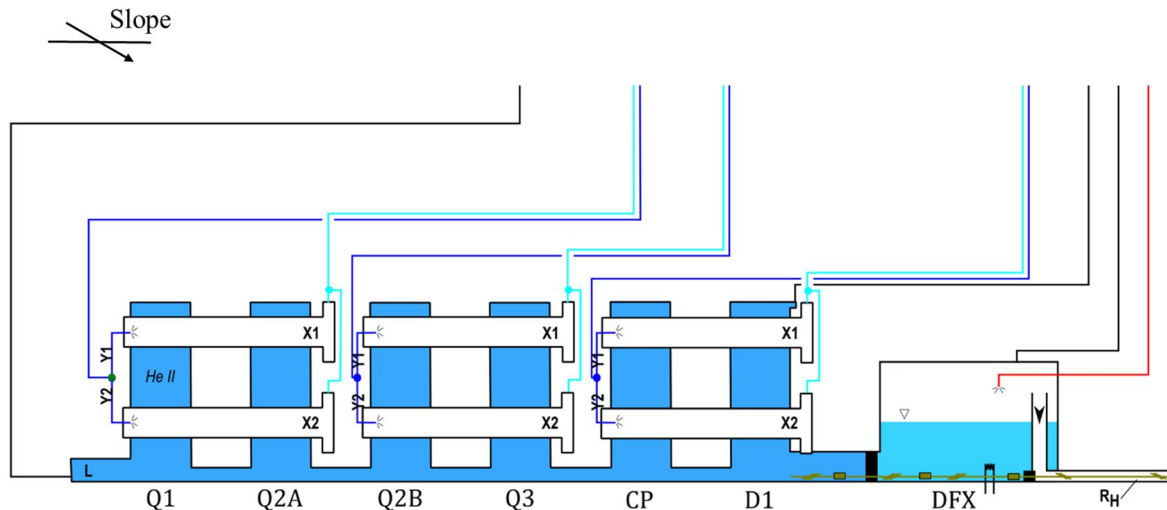


Figure 2. Example of cryogenic flow scheme for a location with negative slope.

Liquid helium is injected at the end of each heat exchanger section and flows towards the opposite end as it evaporates. Any remaining liquid is then collected at a phase separator volume. Pumping lines connect to the upper part of the phase separator volume to pump the helium gas. This type of heat exchanger has been successfully implemented in the LHC and was also found to be the most adequate solution for cooling the HL-LHC insertion regions at 1.9 K. One important integration aspect is that, when installed on a slope, the direction of flow and locations of inlets and outlets must be chosen accordingly. Although not an issue per se, this implies more variants of cryostats, as explained later.

In addition to the 1.9 K for the magnets, there is an intermediate temperature level at 40 to 60 K for cooling of the beam screen, which thanks to tungsten absorbers allow extraction of over 1000 W at a thermodynamically more efficient temperature. This temperature level is determined by beam vacuum operation constraints relating to beam induced gas desorption, and it is subject to change to 60 to 80 K depending on results from on-going studies. Nevertheless, it is also useful in the thermal shield of the cryostat, intercepting radiative heat loads from surfaces at room temperature and in the intermediate temperature thermalisation of cold mass supports.

4. Conceptual design of the cryostat

The excellent return of experience from the LHC arc cryostats both in terms of performance, construction and installation justify using identical design principles as a starting point [5]. It was therefore chosen to stay with the alignment approach consisting of moving the complete cryo-assembly on support jacks. The assembly of the magnet inside the cryostat is done without any adjustment of its position with respect to the vacuum vessel and the relative position of the various components relies only on manufacturing tolerances.

It was therefore chosen to stay with the alignment approach consisting in the assembly of the magnet inside the cryostat without adjustment of its position with respect to the vacuum vessel, other than that resulting from manufacturing tolerances, but an alignment in the tunnel by displacements of the complete cryo-assembly on support jacks. As once installed and interconnected, the magnet interfaces are no longer accessible, the alignment procedure relies on a previous measurement of the magnet position with respect to fiducials placed outside the cryostat. This alignment principle has the advantage

of avoiding adjusting mechanisms inside the cryostat and allows for the design of support structures with maximum stiffness. On the other hand, the support system must also be stiff enough to handle reaction loads from interconnect expansion joints between magnet cold masses and from connection to the cryogenic distribution line and the superconducting link. Since there is still a risk that the cold mass moves during handling, thermal cycles or by creep in the supports over time, a monitoring system is being developed for continuous check of the position inside the vessel at all times. This system is based on frequency scanning interferometry and designed to be radiation hard [6].

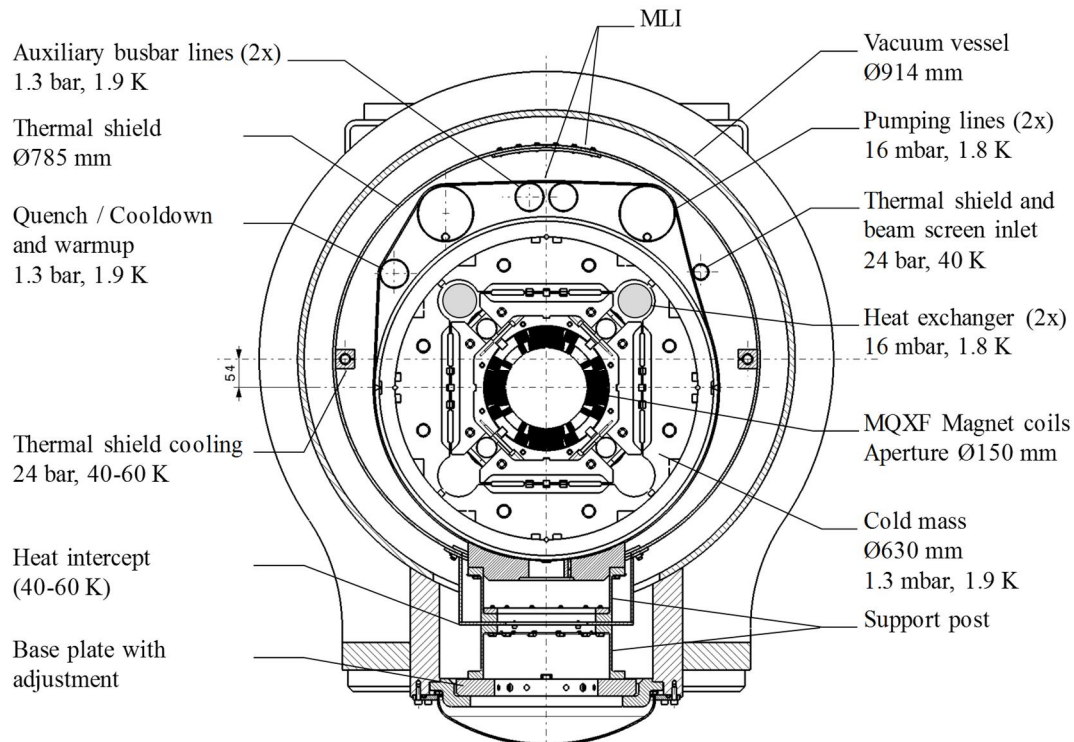


Figure 3. Cross section of the cryostat for the HL-LHC insertion regions.

With the cold mass diameter increasing from 570 mm, in the present LHC configuration, to 630 mm and additional cryogenic piping routed inside the magnet cryostat, it would have been convenient to increase the vacuum vessel diameter. A study to evaluate the maximum allowable dimensions of the new cryostat was then carried out taking into account not only the space available at the location of installation but also the complete transport route through the tunnel. Unfortunately, several points along the way limit the maximum width of the cryo-assembly. The maximum diameter increase was limited to a couple of centimeters. The feasibility of an elliptical shape cryostat with the standard width, but higher, was studied as a solution to accommodate the large cold mass and all cryogenic piping. Despite being a promising solution, it was left as second choice, given a preference for a more cost effective circular shape of cryostat even if it imposed significant challenges in terms of integration. The diameter of the straight parts of the cryostat was then set at the present 914 mm outer diameter of the LHC to use a standard industrial pipe dimension and benefit from cost savings. The main challenge was how to accommodate a 630 mm cold mass, an actively cooled thermal shield, column type support posts, two 100 mm pumping lines plus several other cryogenic pipes inside a 914 mm cryostat.

After considering several options for the support of the cold mass inside the vacuum vessel such as spider supports in the existing insertions regions [7]; tie-rods as found in other machines [8]; and compression columns as in the LHC arcs [9], preference went to column support posts as the most advantageous when precise and stable positioning is required under loads from various directions. Column type posts take up space in the transverse plane that cannot then be used to route piping. The

solution was to vertically offset the centre of the cryostat with that of the cold mass, opening up a space above the cold mass to route the pumping lines, powering busbars and other cryogenic lines as presented in figure 3. The figure shows a typical cross section of the cryostat through a fixed support post and a main quadrupole MQXF magnet.

The concept for the HL-LHC insertion region cryostats is a cylindrical cryostat and column support posts, closer to the one adopted for the LHC arcs than the one of the current insertion regions, but with a significant difference as the support posts protrude through the lower part of the cryostat, adding some complexity to the assembly procedure. Glass fibre reinforced epoxy posts are bolted to the cold mass on the upper part and are either sliding on a ring bolted to the vacuum vessel for a moveable support or bolted to the same ring if a fixed support configuration. For reasons of accessibility to the bolts, each column is split in two parts. A heat intercept with a thermal bridge to the thermal shield is stacked between the two parts.

Since the LHC tunnel has a slope that changes along the ring, the beam line has an inclination that changes from positive to negative between ATLAS and CMS. This implies that at some locations along the continuous cryostat, two pumping lines are required, as shown in the cross section of figure 3, but only one or none at other locations. Above the cold mass there are also two 53 mm diameter pipes for routing of corrector and trim busbars in superfluid helium. All these lines are supported on the cold mass and wrapped with a 10 layer insulation blanket (MLI), except for the gas inlet to the thermal shield and beam screen which is supported on the thermal shield.

The thermal shield is a 786 mm diameter aluminium cylinder cooled by two parallel cooling pipes. Two MLI blankets of 15 layers each are placed around the thermal shield to lower the heat load from room temperature to about 1.5 W/m^2 , a value successfully achieved in the LHC thanks to careful design and assembly of all seams. By supporting the thermal shield directly on the heat intercepts of the cold mass support posts, no additional heat is transferred by conduction to the 40-60 K temperature level.

The vacuum vessel is specified in normalized fine grain low carbon steel for pressure applications with impact tests at $-50 \text{ }^\circ\text{C}$. Given the standardized diameter, the series production vessels can be made from pipe, either welded in spiral or longitudinally, with significant cost savings. Reinforcement rings at the location of the support posts prevent ovalisation. Interconnect flanges are machined from austenitic stainless steel in the form of forged rings. To ensure the correct shape and geometrical position of the interfaces for the cold mass supports with respect to the interconnecting flanges, the vessels shall be stress relieved after welding and then finished by machining. This requires a milling machine capable of working parts in excess of 10 m length, but such machines are readily available to manufacturers in the large pressure vessel industry.

5. Assembly

Long magnets made of brittle Nb_3Sn must be handled carefully to prevent excessive strain in the coils. Consequently, finished cold masses for main quadrupoles must be supported on at least three points along the length at all times. The insertion of the cold mass into the cryostat relies on temporary rails placed inside the vacuum vessel, and sledges with low friction sliding material to support the cold mass as it is pulled by a winch into the vacuum vessel.

The cold mass is first equipped with support saddles welded to the shell and then placed on a bench for assembly of the cryogenic piping, thermal shield and MLI, whilst standing already on the insertion sledges. The thermal shield is manufactured in segments to be fastened together around the cold mass and form a rigid cylinder. Welded seams provide the thermal conductance between cooling pipes and thermal shield shell.

As the cold mass and thermal shield assembly is pulled into the vacuum vessel, temporary filling rings are placed under the sections of rail as they go over the opening for the support posts (see figure 4). When the cold mass arrives to its final position, the rails and sledges are unloaded through jacks which lift the cold mass from within the support openings. The filling rings, all split in at least two parts, are then taken out from below as well as part of the sledges. Subsequently, the rails and sledges can be pulled out. The cold mass support post components and thermalisation plate, which were waiting on the

lifting jacks, are then bolted to the cold mass and thermal shield (figure 5). Finally the load is transferred to the support posts by lowering the jacks and the vacuum vessel sealed with a leak tight flange and elastomer seal.

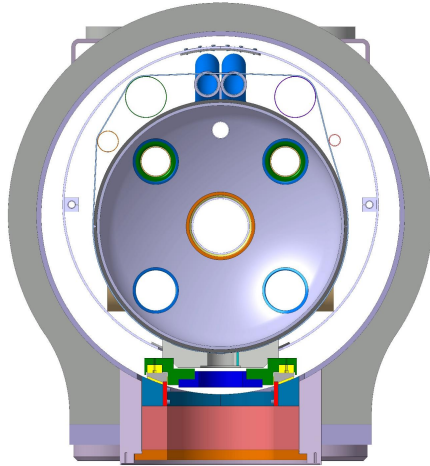


Figure 4. Cold mass and thermal shield sub-assembly sitting on sledges and rails as it is pulled into the vacuum vessel.

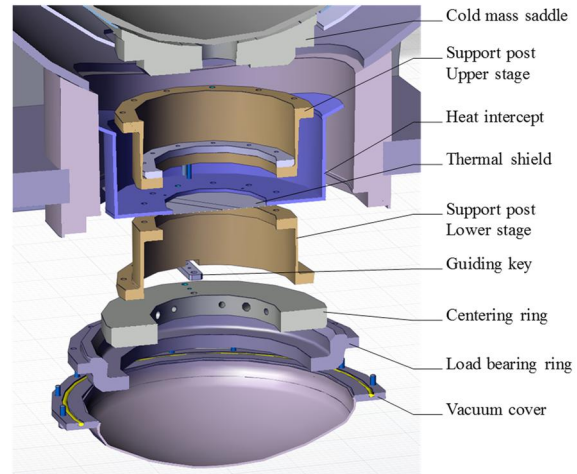


Figure 5. Sliding support post assembly. Installed after cold mass insertion.

The alignment of the cold mass inside the vacuum vessel is determined by precise machining of interfaces in the cold mass itself, the support posts and vacuum vessel. Nevertheless, should either the cold mass or the vacuum vessel machined interfaces for the supports be out of straightness tolerance, it is still possible to make some corrections thanks to radial screws on the base of the sliding supports, if the defect is in the horizontal plane, or by shimming, if the defect is in the vertical plane.

Instrumentation feedthroughs are then assembled and the cryo-assembly prepared for cold test. After cold test, the position of the magnets with respect to the external fiducials mounted on the outside of the vacuum vessel are measured and recorded in a database. The beam screens and beam instrumentation are usually installed as a last step before installation in the tunnel.

6. Cryo-assembly external supports and anchoring

The stringent alignment requirements for the HL-LHC insertion regions call for continuous position measurement and remote alignment of the cryo-assemblies in order to compensate any deviations that may result from tunnel movements, parasitic loads or other effects. It is therefore planned to use motorised jacks with capacity for movements within a range of ± 2 mm at high resolution as supports for the cryo-assemblies.

At the extremities of the continuous cryostat, the support system for cryo-assemblies Q1 and D1 must handle the loads resulting from atmospheric pressure on the order of 8 ton once the insulation vacuum is pumped down. Forces of the same order of magnitude are also possible in the opposite direction resulting from cold mass internal pressure, for example, when the cryostat is pressure tested whilst vented to atmosphere. It is crucial that these loads do not interfere with the alignment jack mechanisms and driving motors, for example through slip-stick effects from friction on highly loaded surfaces, when moving the magnets in the horizontal plane. The proposed solution is to use jacks that restrain vertical and radial movements but not longitudinal. Longitudinal forces acting at the extremity cryo-assemblies are reacted by 0.5 m long tie rods, parallel to the direction of the load, with spherical joints attached at one end to the vacuum vessel and at the other end to a support bracket that spreads the load over a large area of the concrete slab in the tunnel floor. In such configuration the motorised jacks allow for adjustment of all degrees of freedom, except for longitudinal displacements, whilst all the vacuum or internal pressure loads are taken by the tie-rods. It is straightforward to show that such a short tie rod is enough to decouple any transverse displacements of few millimetres from longitudinal

movement, but it can also be made robust enough to sustain tensile forces as well as compression forces without buckling. Nonetheless, the vacuum vessels shall be designed with enough stiffness to prevent any deformations resulting in internal displacements of the magnet with respect to the cryostat.

7. Interconnects

Interconnects between cryo-assemblies are a critical element of the design as they will have a direct impact on the alignment precision and maintainability over the lifetime of the machine. Ideally, interconnects should have no stiffness and would give ample space for work when connecting and disconnecting a magnet. Figure 6 shows a conceptual representation of a typical interconnect being developed.

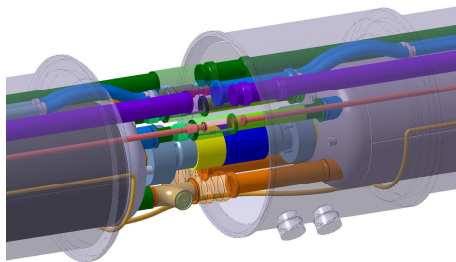


Figure 6. View of a typical interconnect.

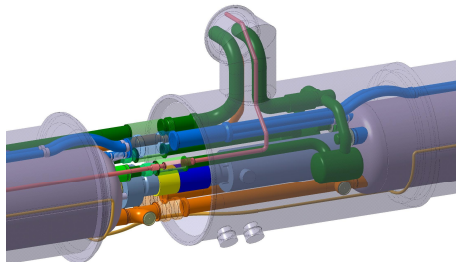


Figure 7. Conceptual design of the interconnect between Q3 and CP. The phase separator volumes are connected either to the Q3 or CP heat exchangers depending on slope.

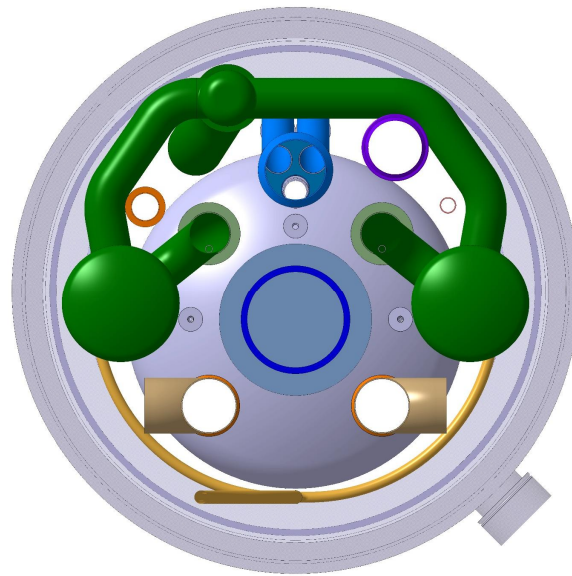


Figure 8. Cross-section of an interconnect with phase separators and pumping manifold.

Expansion joints made of corrugated metal bellows are the flexible elements allowing for position adjustment of each cryo-assembly independently. Their flexibility is limited by design as they must withstand high internal pressure when a magnet quenches. Pressure can rise up to 20 bar, the value at which pressure release valves located in the cryogenic distribution line will open. This implies thick corrugations and consequent transverse stiffness even with multiple plies. The approach to overcome this excessive stiffness is to use universal expansion joints, i.e. two bellows with a length of straight pipe separating them. Such an expansion joint design minimizes transverse stiffness thanks to a lever arm effect that transforms the shear deformations into bending of the bellows.

Four out of the five interconnects are 1 m long (figure 6), the interconnect between Q3 and CP being 1.8 m to allow for the jumper connection to the cryogenic distribution line (figure 7). This length, which from the machine optics perspective should be as short as possible, is a compromise between a compact system and a minimum allowance for integration of all interconnect elements, especially along the beam line where beam position monitors must be installed.

As explained in section 3, phase separators must be installed at locations that depend on slope. These must be integrated as part of the interconnect, as well as their inherent pipe manifolds, and still give way to other piping running straight along the continuous cryostat. The proposed solution consists of locally enlarging the vacuum vessel at the interaction point side of each cryo-assembly and design a pumping

line manifold connecting two phase separator volumes as shown in figure 8. This local enlargement still complies with the maximum allowed width in the tunnel but requires the vacuum vessel interconnect sleeve to access the interconnect only opens towards the interaction point.

All joints are welded to minimize leaks but thanks to a lip welded flange design widely used in the LHC, joints can be cut and re-welded up to three times with the same flanges. Finally, welding work in-situ is minimized by design with only two welds required per line. The bulk of the welding work being done as part of the cryostat assembly work done in a workshop environment.

The result is a concept of interconnect which, although compact and still challenging from the point of view of accessibility for repairs, does make the best of the very limited space available for integration. Special tooling will be developed for work in the tunnel in order to minimize radiation dose during interventions.

8. Conclusion

A concept of cryostat for the insertion region magnets around ATLAS and CMS experiments for HL-LHC has been presented. The cryostat incorporates design principles that have proven successful in the LHC but has also new features to answer to stringent integration requirements. The main issue is how to integrate a larger cold mass and the additional cryogenic lines, needed to cope with high heat loads, into a cryostat that must not be wider than existing ones. This requirement led to the development of a support system that opens up space inside the cryostat but still provides for a stable positioning of the magnets. An assembly procedure was developed as part of the concept development and validation. Interconnects that minimize the work in the tunnel make optimum use of available space for accessibility in case of intervention in a radiation environment.

The project is now entering the detailed design phase. The first prototype of cryo-assembly with a machine configuration is planned for 2019 and the beginning of series assembly is due to start in 2020. Meanwhile, several mockups and subassemblies will be constructed to validate key concepts such as interconnects, support posts and cryo-assembly anchoring.

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Acknowledgments

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