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The design of the new LHC connection cryostats

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The design of the new LHC connection cryostats

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Abstract. In the frame of the High Luminosity upgrade of the LHC, improved collimation schemes are needed to cope with the superconducting magnet quench limitations due to the increasing beam intensities and particle debris produced in the collision points. Two new TCLD collimators have to be installed on either side of the ALICE experiment to intercept heavy-ion particle debris. Beam optics solutions were found to place these collimators in the continuous cryostat of the machine, in the locations where connection cryostats, bridging a gap of about 13 m between adjacent magnets, are already present. It is therefore planned to replace these connection cryostats with two new shorter ones separated by a bypass cryostat allowing the collimators to be placed close to the beam pipes. The connection cryostats, of a new design when compared to the existing ones, will still have to ensure the continuity of the technical systems of the machine cryostat (i.e. beam lines, cryogenic and electrical circuits, insulation vacuum). This paper describes the functionalities and the design solutions implemented, as well as the plans for their construction.

1. Introduction

The Large Hadron Collider (LHC), currently in operation at CERN, relies on a collimation system in order to safely intercept and absorb beam losses, which otherwise would cause magnets to quench because of excessive amounts of heat energy deposited in the Nb-Ti superconducting coils [1], [2]. With the planned increase of beam intensities foreseen from the High-Luminosity LHC (HL-LHC) Project [3] came the need to develop a solution for installation of additional collimators in the Dispersion Suppressor (DS) regions. The present collimation upgrade baseline comprises DS collimation around the betatron cleaning insertion in IR 1 and 7 and around the ALICE experiment in IR 2. In the current LHC layout the arc and DS magnets are grouped in eight long sectors, each consisting of a continuous cylindrical cryostat of more than 3.3 km in length. Over this length, the only sections that are not occupied by magnets and their interconnections are the so-called connection cryostats [4]. In IR 7, beam loss studies indicated that such a position is not suitable, here instead, the collimator is installed on a bypass cryostat in combination with two 11 T dipole magnets together replacing a standard LHC cryo-dipole. In IR 2, studies showed the installation of the collimator is feasible in the connection cryostat area in combination with a beam bump. In the solution described hereafter the required space is obtained by replacing a single connection cryostat by two shorter ones in combination with the bypass cryostat designed for use in IR 7 [5]. The design of the new connection cryostat is presented and design solutions to ensure the continuity of the cryogenic, vacuum and powering systems, without impacting either LHC performance or its reliability, are proposed.

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2. Main requirements

In addition to the standard LHC cryogenic and vacuum requirements, the continuity of the magnet powering circuits shall be preserved. The 13 kA busbars powering the main dipoles and quadrupoles are stabilized with copper in the form of extruded bars [6]. As the busbars are rigid, differential thermal contractions are accommodated by lyra-shaped flexible sections made from stacked copper foils. All LHC cold mass busbars have built-in flexibility at one end and at the opposite end are fixed. This scheme of fixed and moving extremities must be reproduced in the new connection cryostat design to remain compatible with the neighbouring magnets on either side of the connection cryostat being replaced.

Interconnection flange interfaces shall be identical to those of the adjacent magnets [7], [8].

3. Layout

Both to the left and right of IR 2 of LHC, the 12.7 m long existing connection cryostats will be replaced by two 5.3 m long new connection cryostats separated by a short bypass cryostat (Figure 1). To limit design work and procurement costs the bypass cryostats designed for use in combination with 11 T dipoles in IR 7 will again be used in point 2 [5].

Since the busbars lines in the bypass cryostat are situated radially further outward with respect to their position in a standard interconnection, the new connection cryostats have to be equipped with radially enlarged end covers at their extremities for connection to the bypass cryostat.

The helium circuit of the connection cryostat is composed of straight tubes disposed conforming to the standard LHC interconnect layout (main busbars lines, heat exchanger line, beam line) connected to a closed volume termed “shuffling module” composed of two dished ends welded back to back. The shuffling module houses a copper bayonet heat exchanger, for sub-cooling helium in the connection cryostat to 1.9 K, and the lyres of the main busbars, it also allows the transition between the standard LHC interconnect layout and the bypass cryostat layout.

The new connection cryostat cryo-assemblies sit on three alignment jacks each, providing fully adjustable isostatic support to the LHC tunnel floor.

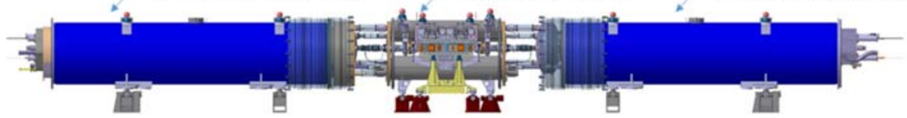

Figure 1. 12.7 m long string of three cryo-assemblies comprising two LEP connection cryostats and a LEN bypass cryostat for replacement of an LHC connection cryostat. The collimator is installed in a room temperature beam vacuum sector created by the bypass cryostat.

4. Vacuum vessel

For standardisation, the 4.1 m long vacuum vessels for the new connection cryostats follow a very similar concept and specification to that of the existing LHC magnet cryostats. A pressure relief valve of 200 mm inner diameter located on top of the vessel protects the insulation vacuum volume against overpressure in case of major helium leak.

The supporting system uses standard LHC jacks [9] at three support points. The longitudinal distance between supports is determined by the space needed at both inner extremities for sideways opening of the interconnection sleeves.

5. Thermal shield

As in the LHC continuous cryostat, an actively cooled thermal shield operating in the 50 to 65 K temperature range intercepts thermal radiation emitted from the vacuum vessel inner surface. It is made from 2.5 mm thick AW1050 aluminium sheets supported on a standard LHC AW 6061 thermal shield extrusion. The thermal shield is actively cooled by gaseous helium flowing inside a duct of the extrusion, providing a distributed heat extraction along the full length. On the extremity facing the bypass cryostat, the thermal shield diameter is enlarged and the extrusion cut short to provide space for the shuffling module of the cold mass.

Forming part of the LHC continuous cryostat, the thermal shield is wrapped with 30 layers of MLI interleaved with polyester net and assembled into blankets. While the cold mass of the connection cryostat is wrapped with 10 layer MLI blankets to achieve thermal insulation performance conforming to LHC specifications.

6. Cold mass

All cryogenic, beam vacuum and powering systems are assembled to a mechanical structure to form the so-called cold mass (Figure 2).

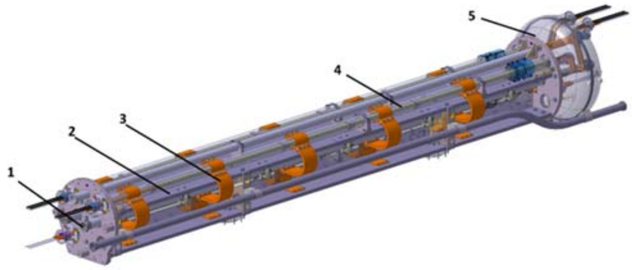

Figure 2. Cold mass assembly (without MLI): beam lines (1), support structure (2), thermalizations (3), busbars lines (4) and shuffling module (5).

6.1. Beam lines

To fulfil the beam vacuum requirements of the HL-LHC, the maximum temperature at any point along the beam lines shall be below 2.7 K. To respect this temperature requirement, the cold bores (53 mm external diameter) are installed inside a 65 mm internal diameter concentric tube (V' line). The radial interspace is filled with superfluid helium cooled by conduction to the shuffling module. A design calculation shows that with this configuration (Figure 3) the maximum temperature of the beam line at the extremity of the cold mass is 1.901 K with an ultimate static and dynamic heat load of 0.65 W/m and a temperature of 1.9 K in the shuffling module.

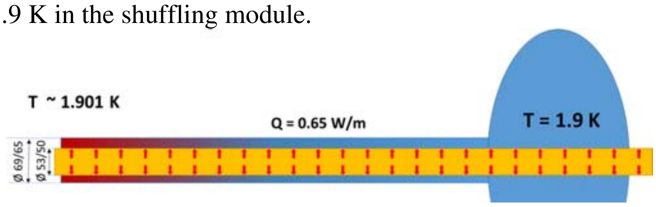

Figure 3. Overview of the calculated maximum temperature of the beam line in operation.

Being installed in the DS region, the connection cryostats have to respect the so-called LHC Golden Class requirements for beam line positioning (i.e. tolerance on horizontal position: +/- 0.8 mm, vertical: +/- 0.5 mm over the full length). To respect these tight alignment tolerances of the beam lines, the relative movement between the chain of components supporting the beam-lines, composed of the V' line and its alignment system, shall be minimised.

To limit the radial play between the V' line and the cold bore while preserving the cooling section and allowing insertion of the cold bore inside the cooling tube, the external tube is plastically deformed locally by precise indenting in three positions around the circumference spaced at 120 degree intervals (Figure 4). Indentation tooling and procedures were developed to limit the radial gap between tubes to less than 0.1 mm with no deformation of the cold bore. This group of deformations is repeated every 750 mm over the length of the cold mass.

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Figure 4. Local plastic indentation of the external cooling tube.

To reduce radial play between the alignment system and the V' tube, the latter is equipped, at the position of the alignement system, with a tight toleranced machined sleeve. The adjustment system for precise alignment of the beam lines has been developed specifically for this application. Based on the X-Y table principle with push-pull screws, it is designed to withstand the forces resulting from the alignment of the beam lines and allows longitudinal movement of the V' tube to compensate differential thermal contractions.

The alignment of the beam lines is performed after completion of the cold mass and before its insertion into the cryostat.

6.2. Support structure
To limit weight and to simplify the assembly, a support structure composed of bolted 304L stainless steel plates has been chosen. The support structure is composed of a 40 mm thick web and two 25 mm thick flanges, stiffeners are positioned close to the support posts to add torsional rigidity. The support structure is equipped with end plates and reinforcements at both extremities (Figure 5).

As the support structure is the reference for alignment of the beam lines, its geometrical stability during and after cooldown and over time is of prime importance. As part of the effort to ensure the dimensional stability requirements are met, all the plates composing the structure will be stress relieved by heat treatment before final machining.

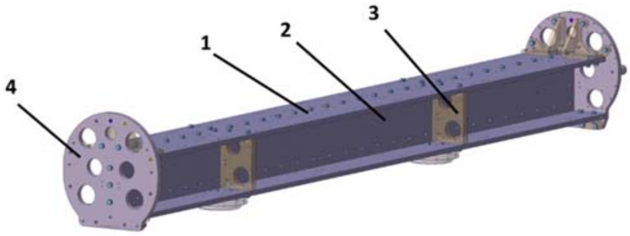

Figure 5. Overview of the cold mass support structure: 25 mm flange (1), 40 mm web (2), stiffeners (3) and end flanges (4).

6.3. Thermalization system
As an integral part of the LHC the connection cryostat cold mass operates at a temperature of 1.9 K. The large mass of the support structure has to be cooled down in a time equivalent to that of its adjacent magnets without generating damaging deformation and thermally induced internal stress in the structure. Heat is extracted from the cold mass through 1200 mm^2 copper braids placed at 833 mm intervals and connecting the support structure to the two upper busbars lines, from which it is planned to provide both the cooling with a forced flow of gaseous helium to 4.5 K and the filling of the beam-line helium volumes.

6.4. Flexible busbars lines
In the LHC, the interconnections rely on flexible bellows at expansion joints for compensation of thermal contractions and mechanical offsets. Design pressures up to 20 bar and adequate resistance to

buckling define the base material thickness the number of concentric walls and the number of convolutions. The resulting compensating bellows are rigid enough to generate reaction forces to transverse and longitudinal displacements of respectively 455 N/mm and 200 N/mm. In the case of a maximum transverse offset, the reaction forces may reach values (up to 2920 N) resulting in deformations of the connection cryostat supporting structure and leading to unacceptable displacement of the beam lines. The solution proposed (Figure 6) to minimize such deformations to acceptable limits is to use the cryogenic lines as universal expansion joints and consists of a standard LHC interconnection bellows compensating the longitudinal displacement and a 2.5 m length of cryogenic pipe compensating the transverse displacement. This design reduces the stiffness to transverse displacement to 18 N/mm, reducing the maximum transverse forces appearing in the interconnect to 300 N and resulting in maximum deformation of the cold mass of 0.01 mm, negligible with respect to the alignment tolerance of the beam line. The standard bellows expansion joints used in the LHC interconnection are not designed for this application and may be subjected to instabilities due to internal pressure as one of their extremities is not properly supported in transverse direction. The solution proposed is to move the bellows used for longitudinal displacements inside the cold mass and guide it according to the requirements of the EJMA expansion joint construction code to withstand the operational internal pressure.

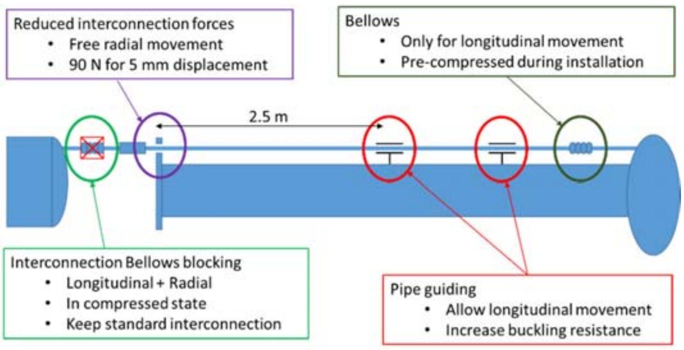

Figure 6. Description of the implemented layout for the busbars lines.

7. Structural studies

A finite element method (FEM) model of the connection cryostat cold mass was analysed in order to evaluate its mechanical behaviour under all external loads.

Two different loading conditions have to be considered: case A operational conditions with the application of the nominal pressure of 1.3 bar in the helium circuit and case B the quench conditions with the pressure arising up to the design value of 20 bar in the helium circuit. In both cases the cold mass self-weight and the force induced by the extension of the busbars lines bellows during cool-down (3 x 4000 N) are applied.

In case A, the main functional requirement is the preservation of the alignment of the beam pipes. Therefore, the monitored parameter is the radial displacement of the beam pipes. The maximum calculated value of this parameter shall be below 0.1 mm to respect the alignment requirements of the beam line. Calculations show that the cold mass has an adequately stiff behaviour with a negligible bending excursion due to self-weight. The maximum radial displacement of the beam line is situated at the magnet side end plate and is limited to 0.08 mm (Figure 7).

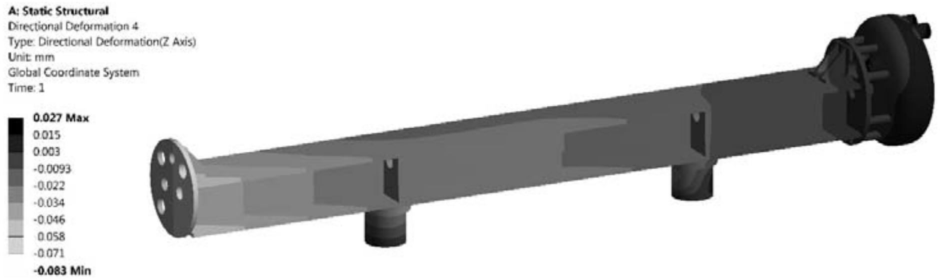

Figure 7. Vertical displacement of the connection cryostat cold mass in Case A.

In Case B, attention is focused on the shuffling module which expands and where the stresses may reach critical values. The stress field in the helium circuit has been assessed using the Annex C of EN 13445-3. According to this annex, stresses shall be classified depending of their origin and region in the pressure vessel. Calculations of the whole pressure vessel showed that the most critical part is the shuffling module and particularly its knuckle region (transition region between the dish and cylinder). After exclusion of the stress concentration points that are not significant for the check, the analysis showed a safety margin of 2.2 and 4.6 with respect to the minimum requirements of the standard respectively on the maximum allowable membrane stress (Figure 8a) and on the membrane plus bending stress (Figure 8b).

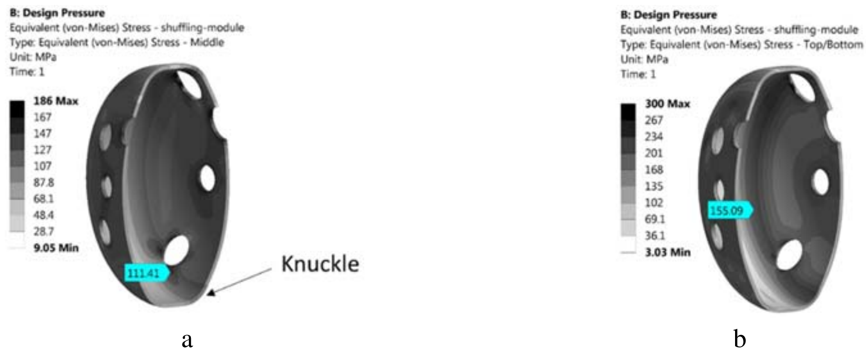

Figure 8. Membrane stress (a) and membrane plus bending stress (b) in the shuffling module.

8. Thermal studies

The performance of the thermalization system was evaluated by performing a transient thermo-structural analysis of the cooldown. A simplified finite element model including both the cold mass structure and the thermalization system was built. The thermal and mechanical properties of the stainless steel AISI 304L are used for the cold mass parts and those of a copper with RRR equal to 30 for the thermalization system. Regarding the thermal contact conductance (TCC) at the stainless steel – stainless steel interfaces and at the copper – stainless steel ones, very conservative values are taken (respectively 725 and 1000 W/m^{2}K) from the literature [10], [11] after calculating the expected contact pressures (respectively 8 and 6 MPa). A sensitivity analysis showed that the temperature field and heat transfer is mainly driven by the bulk conduction, whilst the influence of the TCC is very small.

Two simulations have been carried out: (1) 50 K applied at the end of the copper braids (case A) and (2) real temperature profile of the helium flow inside the busbars lines (case B).

Case A is considered to be the worst condition from the mechanical point of view as it produces the highest stresses due to thermal contractions. Thanks to the symmetry of the thermalization system, large global deformations do not occur during the transient. After excluding singularities, the maximum stress

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(100 MPa) occurs after a cool-down time of 4 hours and is below the yield strength of AISI 304L (240 MPa) resulting in a safety factor of 2.4 (Figure 9).

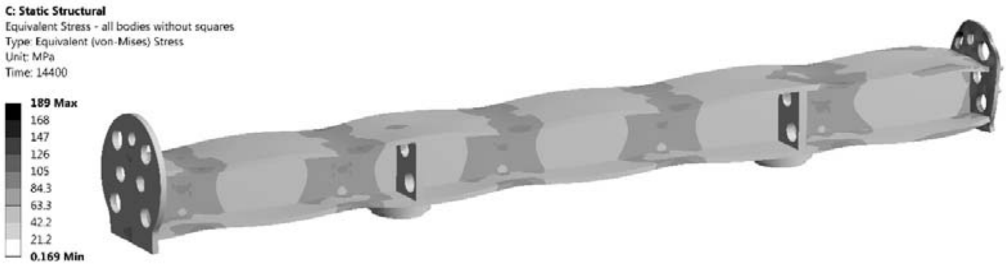
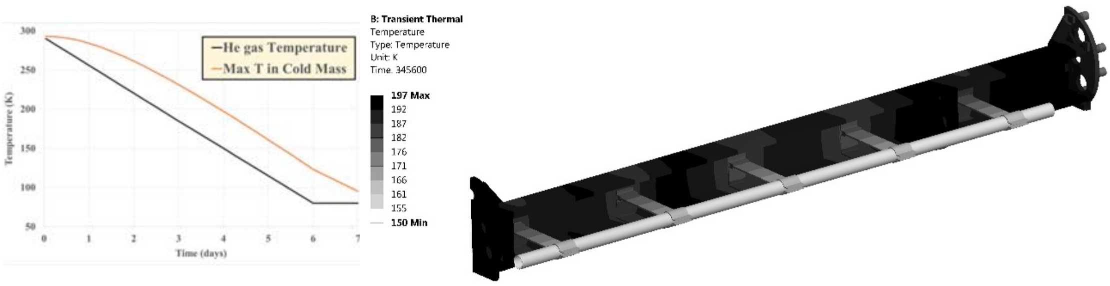


Figure 9. Maximum thermal stress in the support structure (after 4 hours of cooldown).

Case B calculation is helpful to assess the thermal efficiency of the thermalization system and the cooldown speed of the structure. In particular, only the first step of the cooldown from room temperature to 80 K was analysed, since the most potentially damaging part of the thermal shrinkage takes place in this temperature range. The cooling process is done by injection of gaseous helium (up to 20 g/s) inside the busbars lines with a linear temperature/time gradient from 300 K to 80 K. The normal cooldown time allocated to this first step is three weeks, but it could be required to reduce this time to one week in case of need. In order not to retard the cooldown of the cryogenic sector, the connection cryostat structure is required to be cooled down with a maximum delay of one day with respect to the gas temperature. For the calculations, the heat transfer coefficient between the gaseous helium and the busbars line inner wall is considered. This parameter is calculated form the Dittus-Boelter equation [12] and varies from 88 W/m^2K for the helium at 300 K to 72 W/m^2K at 80 K. The simulation shows that the thermal resistance due to the thermalization system adds a time lag between the maximum cold mass temperature and the fluid temperature (Figure 10a). Once the gas reaches 80 K, the structure needs one additional day to achieve uniform stable conditions. The simulation shows also the absence of large thermal gradient in the structure over short distances (Figure 10b), which means that the resulting stresses induced by the cooldown stay within acceptable limits. From the calculations, the performance of the thermalization system appears adequate in regard to requirements but they will be confirmed by a cold test simulating real cooldown conditions.



a b

Figure 10. Maximum temperature in the cold mass as a function of the cooldown time compared with the applied helium gas temperature (a) and temperature field in the cold mass after 4 days of cooldown showing the absence of high structural thermal gradients (b).

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9. Construction and test plan

The detailed design of the connection cryostat assembly is nearing completion, the procurement process for the 3 A and 3 B type connection cryostats has started in preparation for the assembly of the first type A connection cryostat at the end of 2017.

The assembly of the new connection cryostats will be carried out at CERN on dedicated assembly benches. They will then be assembled together with the bypass cryostat for a complete performance test of the full string (LEP-A + LEN + LEP-B) in spring 2018.

10. Conclusion

The design of the new connection cryostats for HL-LHC was presented. The chosen solutions respond to the strict LHC operational specifications with no adverse impact on the reliability of the LHC machine.

The use of both computer simulation and physical mock-ups, has allowed development of new supporting and thermalization solutions in addition to reduction of interconnection forces. These new concepts in combination with use of proven equipment, procedures and existing tooling whenever possible lead to a cost efficient solution answering all requirements. A dedicated cold test of a full assembly is planned in 2018 to assess the thermal performances of the new design.

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