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CONNECTION CRYOSTATS FOR LHC DISPERSION SUPPRESSORS

S. Marque, T. Colombet, M. Genet, B. Skoczen

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The lattice of the Large Hadron Collider (LHC) being built at CERN is based on 8 standard arcs of 2.5 km length. Each arc is bounded on either side by Dispersion Suppressors connected to the arc by connection cryostats providing 15m long drift spaces. As for a dipole magnet, the connection cryostat provides a continuity of beam and insulation vacuum, electrical powering, cryogenic circuits, thermal and radiation shielding. In total 16 modules will be constructed. The stringent functional specification has led to various design options. Among them, a light mechanical structure has been developed with a stiffness comparable to that of a dipole magnet, for alignment purpose. Thermal studies, including lambda front propagation, have been performed to ensure a cooling down time to 1.9 K within the time budget. A special cooling scheme around the beam tubes has been chosen to cope with heat loads produced during operation. We report on the general design of these modules and on the adopted manufacturing process which guarantees the tight alignment of the beam tubes once the module is installed in the machine. Special emphasis is given on thermo-mechanical analysis, lambda front propagation and on the beam-tube cooling scheme.

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The lattice of the Large Hadron Collider (LHC) being built at CERN is based on 8 standard arcs of 2.5 km length. Each arc is bounded on either side by Dispersion Suppressors connected to the arc by connection cryostats providing 15m long drift spaces. As for a dipole magnet, the connection cryostat provides a continuity of beam and insulation vacuum, electrical powering, cryogenic circuits, thermal and radiation shielding. In total 16 modules will be constructed. The stringent functional specification has led to various design options. Among them, a light mechanical structure has been developed with a stiffness comparable to that of a dipole magnet, for alignment purpose. Thermal studies, including lambda front propagation, have been performed to ensure a cooling down time to 1.9 K within the time budget. A special cooling scheme around the beam tubes has been chosen to cope with heat loads produced during operation. We report on the general design of these modules and on the adopted manufacturing process which guarantees the tight alignment of the beam tubes once the module is installed in the machine. Special emphasis is given on thermo-mechanical analysis, lambda front propagation and on the beam-tube cooling scheme.

INTRODUCTION

In the LHC machine, being presently built at CERN, the optical layout requires field free drift spaces located at the boundary between the standard and the so-called Dispersion Suppressors (DS). As the DS zone also contains superconducting elements, the modules in these drift spaces have to provide continuity for the so-called continuous cryostat and for all circuits (cryogenic, electrical) and beam tubes. After recalling the requirements, the overall design is presented, followed by the outcome of structural and thermal studies.

FUNCTIONAL SPECIFICATION

The LHC ring is based on 8 standard arcs and 16 DS zones. In total 16 connection cryostats (hereafter called CC) have to be built. The global design of such units relies on various parameters listed in [1] and 11 different cold mass types were identified.

OVERALL DESIGN

All components located outside of the so-called cold mass (inner tube of ∅570 mm, Fig. 1) are the same as for a cryodipole, length or position being adjusted if needed, i.e. jacks, vacuum vessel and alignment devices, cold mass supports, thermal shield, MLI blankets, thermalisation of cold support posts. Only the cold mass has been redesigned to cope with the functional requirements.

The alignment of cold bore tubes is performed after completion of the cold mass, i.e. the beam tubes are independent of the cold mass geometry. Special supporting plates have been designed to allow angular and transversal geometrical tuning.

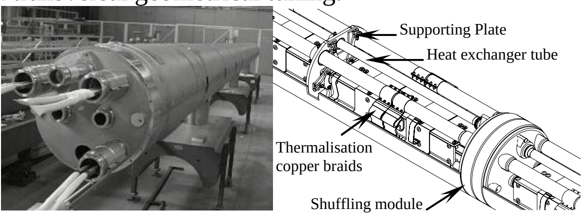


Figure 1: Entire cold mass and detail on central section.

Cold mass shell thickness

For the overall stability of the module, together with the interconnections, as well as for alignment purpose, the same cold mass shell thickness as for cryodipole cold mass has been adopted (10 mm). As the cold mass cylinder is the main contributor to the overall stiffness [2], CC cold mass is nearly as stiff as a cryodipole cold mass.

Superconducting bus bars lyres

The standard dipole design has been adopted for this item. Their fixed point has to be kept on the upstream side of the cryostat. Cooling being a key issue, the detailed analysis led to the choice of a “shuffling module” which groups all 3 lyres in a common He volume and ensures temperature stability. Tubes (80 mm inner diameter), originating from the “shuffling module”, provide sufficient cross-section of He II around the bus bars for their cooling.

Compensators

As the compensators needed to absorb the thermal contraction between a CC and a cryomagnet are the same as for interconnection between cryodipoles [3], a study has been performed to locate properly the fixed points of each line in order to minimize the difference in elongation of the corresponding compensator with respect to a standard dipole-dipole interconnection. The fixed points for all the lines are located in the shuffling module. The shuffling module is centred in the cold mass (longitudinal position) and located above a longitudinally fixed cold support (3 cold support posts are needed).

Owing to this arrangement, all the compensators except the one for the line X, will have the same elongation. The line X compensator on the upstream side of the cold mass (in the neighbouring magnet) will be overloaded by 10 %, which is still in its working range.

External supports: Jacks

The 2+1+1 points supporting configuration of the LHC dipole is also adopted for the CC, as it is the most favourable arrangement from the deflection point of view [4]. The length of the outer sleeve imposes the jacks to be spaced by 3800 mm, as for a quadrupole, otherwise it would obstruct the interconnection working zone in the tunnel.

Shielding against radiation

An absorption factor of 30, reducing the dose rate from 1000 Gy/y to 30 Gy/y is expected with a common 15mm thick lead shielding box around both beam tubes.

Cold mass extremities

For the sake of standardization of interconnection operations in the tunnel, the CC is equipped with standard end covers at its cold mass extremities.

STRUCTURAL STUDIES

Supports of cold bore tubes (V)

Due to the precise alignment requirement for beam tubes, one has to ensure that no relative movement with respect to the cooling tubes is possible when subjected to the interconnection forces. Furthermore, the annular cooling section has to be preserved and the insertion of the V tubes into the cooling tubes should be feasible.

Special elastic supports have been developed to cope with this stringent requirement. Elasticity eases the assembly process and ensures sufficient pressure between both tubes. A calculated stiffness of 100 kN/m has been adopted and reached owing to a special design and the use of an AISI 316LN type stainless steel (Fig. 2).

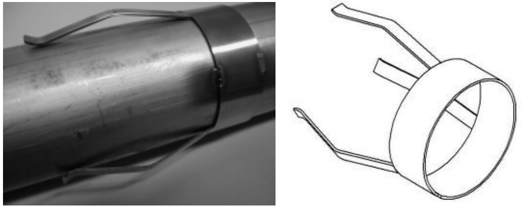


Figure 2: Cold bore elastic supports.

Cooling line (V') guiding supports

As the outside cooling tube V' concentric with the beam tube is of standard make to ensure a precise adjustment of the V tube, one has to cope with the clearance between the V' tube and its adjusting plate. Thus, the adjusting plate is equipped with a machined sleeve (∅80 mm) while the V' tube is equipped with a special guidance tack welded onto it and whose external diameter is machined to fit into the sleeve.

Superconducting bus bars supports

Superconducting bus bars have to be centred in their enclosing tube over their whole length for cooling purposes. As they are not uniformly supported, possible buckling (transverse instability) when interconnection operations are performed (compression of lyres through 6 m long bus bar) might occur. A study performed to define stiffness with a trade-off between ease of installation and amplitude of movement and the quantity/location of the supports to prevent buckling showed that 5 supports equally spaced on each bus bar half length, providing a stiffness of 3 kN/mm, are sufficient.

THERMAL STUDIES

Cooling of beam tubes in operation

We assume that the ultimate static and dynamic heat loads of P=8.2 W [5] dissipated at 1.9 K in the CC are totally intercepted by the cold bores cooling circuits. Figure 3 shows a sketch of the CC cooling scheme. The annular cooling section (S2) around the cold bores, which is defined by the maximum allowable external diameter compatible with a standard end cover beam pipe outlet (70 mm), is linked to 2 superfluid helium volumes kept at constant temperature of 1.9 K, namely the central "shuffling module" and an M line (one of the 3 tubes used to house the SC BB) through a flexible hose of section S1 which acts as a thermal link. The M line is supposed to be at constant temperature as it is linked directly to the adjacent cryomagnets. The shuffling module is kept at constant temperature owing to the copper heat exchanger tube (line X) running through it.

Calculations have been done to evaluate the location and value of the maximum temperature in the annular section around the beam tube. Due to space constraints, the maximum S1 section of the thermal link (flexible hose) is 3.9 cm^2 (∅22.3 mm) and the length (l) is 50 cm, leading to a maximum temperature of 1.901 K located at 165 cm from the hose extremity.

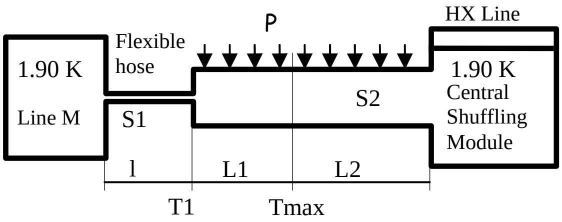


Figure 3: CC cooling scheme (S2 for the cold bores).

Cooling from 300 K to 4.5 K

Cooling is performed via a forced flow of gaseous helium. The general design of the cryogenic lines yields the following figures: total helium free cross section 97 cm^2 and frictional pressure drop 468 Pa at 293 K and 5.6 Pa at 4.5 K. These values are well in the allowable limits [6] for the nominal flow rate.

As shells and supporting plates are not directly cooled by the helium flow, the heat has to be transported by conduction through the cold mass shells to the "shuffling module" inner surface in contact with helium flow. An estimate of the total energy to be removed is 120 MJ. Without any additional device, the estimated time needed to cool down the structure to 80 K is 150 days, much larger than the allocated time (6 days). Therefore, a thermalisation system has been studied and implemented.

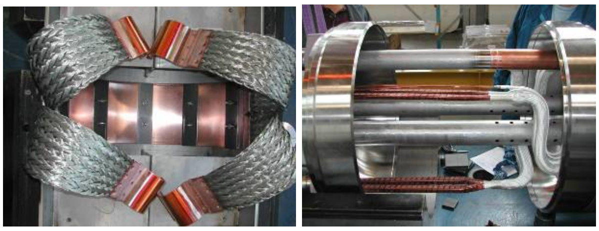
Thermalisation of cold mass shells

Thermal bridges have been installed between stable temperature sinks (M lines) and the cold mass shells and supporting plates. 10 transversal copper strips (Fig. 4) have been attached to the cold mass shells and linked to M lines through copper braids, providing 10x400 mm^2 copper links along the cold mass. The resulting average cooling power is around 800 W compared to 230 W needed to cool the cold mass down to 80 K in 6 days. Detailed numerical calculations have confirmed this design (see the next sections).

Cooling from 4.5 K to 1.9 K: λ front propagation

The so-called sub-cooling from 4.5 K to 1.9 K is achieved in the cryoassemblies by activating the heat exchanger (line X). This copper tube conveys superfluid helium which absorbs, through conduction across the tube copper walls, the heat from the pressurized helium bath contained in the "shuffling module" and the adjacent cryogenic tubes. The heat exchanger tube installed in the CC cold mass is made of 2 stainless steel parts (6.5 m) and one central part (0.35 m) made of high conductivity copper (Fig. 5). The central part is located inside the "shuffling module" (in contact with the pressurized liquid helium) while the stainless steel parts stay in the insulation vacuum. The thermal efficiency of the central part of the heat exchanger is around 80 W which leads to 13 minutes for sub-cooling the entire "shuffling module" volume (65 l).

The sub-cooling of the whole cryostat has been studied [7] using a realistic scenario of heat transfer through the λ front (flux density of 0.5 W/cm^2). The result of the analysis shows that the sub-cooling time of the CC is around 36 minutes (comparable to a cryomagnet). This proves also the usefulness of having in each CC a heat exchanger allowing the reduction of the sub-cooling time from around 73 minutes (without heat exchanger) to around 36 minutes.



Figures 4 and 5: Copper thermalisation bridges and heat exchanger tube.

Thermo-mechanical Finite Element (FE) studies

To assess the global behaviour of the structure, the whole CC has been modelled by using ANSYS® 6.1 software (http://www.ansys.com). The detailed analyses are reported in [8]. The maximum computed deviation of the cold bores with respect to the cold mass centreline is 0.25 mm (compared to the 1.6 mm allowed), the maximum stresses being 120 MPa.

The global thermo-mechanical behaviour of the structure under external loads, pressure, temperature and gravity has also been studied. The detailed analyses are reported in [9]. The results show that the thermal performance of the CC cold mass, equipped with copper thermalisation shells and braids, is correct: a steady state temperature (4.5 K) is reached in 5.2 days. The maximum Von Mises stresses during the cooling process are within acceptable values (350 MPa on AISI 316LN type at 250 K).

CONCLUSION

Extensive studies have been performed to ensure that all functional requirements set for the CC are satisfied. The actual design reflects the results of these studies leading to a numerically validated thermo-mechanical behaviour. Cold tests will be performed in order to experimentally validate the CC design.

ACKNOWLEDGEMENT

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