MECHANICAL DESIGN AND LAYOUT OF THE LHC STANDARD HALF-CELL

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Abstract

The LHC Conceptual Design Report issued on 20th October 1995 [1] introduced significant changes to some fundamental features of the LHC standard half-cell, composed of one quadrupole, 3 dipoles and a set of corrector magnets. A separate cryogenic distribution line has been adopted containing most of the distribution lines previously installed inside the main cryostat. The dipole length has been increased from 10 to 15 m and independent powering of the focusing and defocusing quadrupole magnets has been chosen. Individual quench protection diodes were introduced in magnet interconnects and many auxiliary bus bars were added to feed in series the various families of superconducting corrector magnets. The various highly intricate basic systems such as: cryostats and cryogenics feeders, superconducting magnets and their electrical powering and protection, vacuum beam screen and its cooling, support and alignment devices have been redesigned, taking into account the very tight space available. These space constraints are imposed by the desire to have maximum integral bending field strength for maximum LHC energy, in the existing LEP tunnel. Finally, cryogenic and vacuum sectorisation have been introduced to reduce downtimes and facilitate commissioning.

1 INTRODUCTION

The Large Hadron Collider (LHC) to be installed in the LEP tunnel at CERN will produce two proton beams of 7 TeV energy for head on collisions in 4 points around the circumference. The machine is subdivided into 8 octants, each one comprising a standard arc composed of 54 optical half-cells housed in a common cryostat (Arc cryostat), flanked on each side by specific insertion optics for the various experimental areas and functions of the machine (injection, ejection, cleaning, RF, etc.).

The standard 914 mm diameter arc cryostat, of an octant 2.7 km long, is bounded at each extremity by electrical current feedboxes (DFB) allowing the numerous families of superconducting magnets to be powered in series. The cryogenic distribution line (QRL) housing various headers servicing the main stream of cryomagnets runs parallel to the arc cryostat, and as for the main electrical supplies is fed at the 4 even points of the machine from cryoplants installed at ground level. The basic repetitive segment of the arc is the half-cell of 53.4 m length providing 90° phase advance for the beams. It is composed of 3 two-in-one 8.3 T dipoles of 15 m length,

one two-in-one quadrupole and various sets of correcting magnets. The so-called Short Straight Section (SSS) housing the quadrupole, sextupole, octupole, dipole orbit correctors, and beam position monitors (BPM) is flanked by a cryogenic service module housing service piping for quench discharge into the QRL, phase separation for 1.9 K heat exchanger cooling, etc.

The half-cell length occupancy has been optimised to provide maximum bending field length, taking into account the various functions and elements of the machine.

2 CRYOSTAT

The string of superconducting magnets operates in a static 1.9 K superfluid helium bath pressurised at 1 bar absolute [2]. The heat load budget to 1.9 K is composed of static heat losses through cryostat components (radiation, conduction through support posts, vacuum barriers, etc.) and dynamic loads resulting from resistive heating in splices between cables, beam losses into the 1.9 K bath and synchrotron radiation and RF image current power deposited on the beam screen. To minimise the static heat load to the 1.9 K level at which the cost of refrigeration is 3 to 4 times higher than at 4.5 K, two actively cooled aluminium screens operating at 5-10 K (radiative shield) and 50-75 K (thermal shield) are interposed between the 293 K and 1.9 K levels. These shields are made of polished aluminum sheets welded onto 15 m long structures, extruded together with the cooling channels.
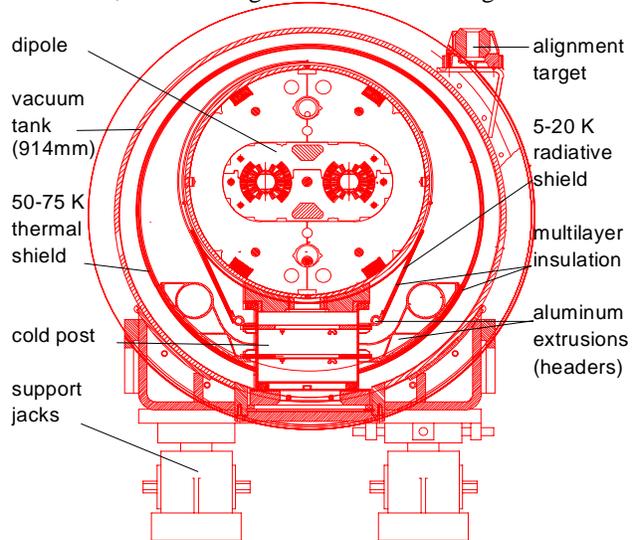

Figure 1: LHC Dipole Cryostat

The radiative shield carries 10 layers of MLI to thermally protect the system in case of degraded vacuum.

The thermal shield is covered by 30 layers of MLI pre-fabricated blankets to reduce thermal radiation load.

The calculated static thermal loads are given in Table 1.

The transverse dimensions of magnet cold masses with their shields have been minimised to fit in an insulating vacuum vessel of diameter 914 mm (36" standard pipe dimension).

3 SHORT STRAIGHT SECTION CRYOGENIC MODULE AND JUMPER CONNECTION

The Short Straight Section which houses the quadrupole, chromatic correction elements, a set of orbit correctors and beam position monitors, also incorporates a cryogenic service module which connects the cryogenic distribution line to the main cryostat out every cell [3].

An intricate set of components finds its place in a reduced volume: the phase separator of the 1.9 K heat exchanger cooling a full cell, the connecting pipes housing the bus bars with manifolds tubes to the QRL allowing filling and discharge of a stretch of cells, the beam position monitors, beam pipes, sectorisation valves, and quadrupole protection diodes, accessible for repair via the interconnect. A set of 50 A current leads installed in the cryogenic module feeds the closed orbit dipole corrector magnets. Low heat in-leak insulating vacuum separation barriers are installed between the quadrupole cold mass and the vacuum enclosure every two cells. This facilitates vacuum pump down, leak testing by confining leaks. The vacuum hardware is attached to the SSS.

To permit an easy and precise alignment of the SSS, it must be mechanically decoupled from the QRL. For this purpose, a set of interconnecting bellows in the jumper connection gives the necessary flexibility and compensation for forces due to atmospheric pressure.

4 ELECTRICAL DISTRIBUTION

Apart from the orbit correctors, all superconducting magnets of the Arc are powered in series from the main electrical feed box installed at the even points. The focusing and defocusing quadrupole pairs of 12.5 kA bus bars run through the two upper slots in the magnet yokes. The main dipole 12.5 kA circuit occupies a third slot, and dipoles have two different types of electrical connections built into the cold masses, lodging alternatively (every half-cell) the magnet inductance on the go and return bus bars in order to limit voltages to ground during a discharge. 40 to 80 auxiliary superconducting cables rated at 600 A run through the magnet cold masses and are electrically connected at each magnet intergap. This represents a total of more than 80'000 electrical connections for the whole machine, which must be carried out within a tight electrical specification concerning insulation breakdown voltage (5 kV) and connection resistance (10^{-8} Ohms).

To minimise erroneous connections and to reduce manpower costs at installation, special multichannel connectors and distributors are envisaged and developed. Furthermore, the electrical connection of auxiliary magnets in the interconnect gap is being studied, as this would specialise SSS only at the installation stage.

Alternative designs currently being studied consider the routing of uninterrupted cable bundles through the cold masses of a half-cell to feed the chromatic magnet correctors installed in the SSS.

Bus bars are routed through 4 slots and 4 interconnecting tubes in and between the cryomagnets.

5 MAGNET SUPPORT AND ALIGNMENT

The superconducting magnets of the arc are positioned by column-type supports. The stringent positioning precision for magnet alignment and the high thermal performance for cryogenic efficiency are the main conflicting requirements which have lead to a trade-off design. An additional function requested of the support system is the suspension of the thermal and radiative screens in the cryostat.

A three point support is chosen for the 15 m long, 30 ton dipoles, where the support spacing limits the maximum vertical sagitta to 0.25 mm; only two support points are needed for the shorter (6 m) and lighter (6 ton) cold mass of the SSS to keep the maximum vertical sagitta below 0.23 mm.

The support is made of a main composite column bolted to stainless steel pads previously welded on the magnet cold masses. The fixations on the vacuum vessels allow sliding of the supports to free the thermal contractions and to leave free the required degrees of freedom.

The thermal performance of the supports is improved by intercepting most of the residual heat conduction at two intermediate temperature levels (one in the 50-75 K and the other in the 4.5-20 K range). These intercepts consist of aluminum plates, glued to the composite column and welded to the thermal and radiative shields via flexible aluminium straps.

The heat loads reported in table 1 are estimated from measurements made on previous supports.

Watts	Temperature level		
	1.9 K	4.5-20 K	50-75 K
Cryomagnet support posts	0.5	9	44
Vacuum barrier Instrumentation capillaries, BPM	3.1	0.2	18.6
Cryostat	0.3	3.2	165.4
Total for LHC standard half-cell	3.9	12.4	228

Table 1: Estimated half-cell static heat loads (Watts)

The composite column of the support is made of a 4 mm thick tube with integrated top and bottom flanges. A glass fibber/epoxy composite system was chosen for its high stiffness-to-thermal-conduction ratio, allowing minimisation of the cross section and, as a consequence, of conduction heat loads. A long-fiber, woven fabric lay-up technology is chosen to achieve the highest stiffness.

The initial positioning precision of the magnet cold masses is ±0.5 mm with respect to the cryostat axis and ±1 mm in the longitudinal direction. This precision is achieved by a tight chain of mechanical tolerances. Under the worst hypothesis of residual mechanical loads, the present design of the support system for magnets gives a stability of ±0.2 mm in the radial and vertical plane.

6 INTERCONNECTIONS

The interconnections between cryomagnets contain a number of structural components which are designed to assure a continuity and provide maximum security to different systems integrated within the accelerator : vacuum systems [4], cryogenics , and electrical distribution. In order to extend the magnetic length of the LHC magnets as much as possible the interconnection space is reduced to a strict minimum. This requirement imposes longitudinal and radial limitations on the interconnect components and implies a compact design compatible with the existing tunnel as well as the established transport and installation procedures [5].

The combination of a relatively high pressure of 20 bar (which may develop during the cool-down procedure or a quench) with a necessity of assuring leak tightness for all the superfluid helium transfer systems leads to a choice of all welded assemblies.

In order to keep up with the LHC project requirements in terms of system reliability, automatic welding, cutting and control procedures were proposed. The stringent space requirements for the welding and cutting tools was restricted to 50 mm. To reduce the helium consumption at 1.9 K the electrical connections will be brazed and the ohmic resistance limited to some 10^{-8} . The large number of bus bar connections (80,000) imposes a high level of reliability as well as strict procedures for manufacture, installation and control.

The interconnect space is determined to a large extent by the superconducting cable overlap length of 120 mm and the necessary length of the bellows expansion joints which compensate for the thermal contraction of the magnets (around 50 mm). In order to reduce the length of the expansion joints and their axial stiffness a special optimisation program has been developed. It aims at reducing the global forces between the magnets (transmitted to the support posts) in the installation phase and during the LHC operation.

Protection diodes constitute some of the critical components of the LHC machine. The present design provides an easy access to the diodes in case they need to be replaced. The access to the box containing the diodes will be possible through the interconnection space, after the removal of the large diameter bayonet sleeve of the vacuum vessel and of the thermal shields.

7 SECTORISATION OF SUB-SYSTEMS

The 2.7 km LHC arc cryostat has a cold mass weight of more than 6000 tons. One cryoplant at the corresponding even point will be able to cool-down and warm-up such a mass via the QRL in about 44 days.

Taking advantage of a separate parallel cryoline naturally decoupling the feeding of cryogens from the main stream of magnets, the arc is cut in four sub-sectors. Insulating vacuum barriers separate the QRL from the main cryostat at each jumper connection and sectorise the main cryostat every two cells [6]. High vacuum valves and cryogenic separation valves are installed at each sector boundary and additional cryogenic valves complete the separation of the QRL from the main cryostat at each jumper connection. Finally, so-called bus bar plugs are installed every two cells in magnet gap interconnects to sectorise the 1.9 K cold mass cryogenic volume. This sectorisation allows the partial and independent warm-up and cool-down of small stretches of a few cells. This will yield a factor 2 reduction in the time required for most interventions for repair.

8 ACKNOWLEDGEMENTS

A large design, development and testing effort is being actively pursued to integrate all LHC intricate systems in the LHC arc cryostat. Technical choices are regularly tested on the LHC prototype test String [7].

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