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LAYOUT AND DESIGN OF THE AUXILIARY BUS-BAR LINE FOR THE LHC ARC MAIN CRYOSTAT

P. Kowalczyk, A. Poncet and B. Skoczen

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The superconducting multipole magnets housed in the cold mass of the LHC arc short straight sections, together with the arc dispersion suppressor and matching section quadrupole magnets, will be electrically fed along the 3 km arcs via 600 A and 6 kA superconducting flexible cables. These will be routed into a tube running parallel to the cold masses, placed inside their cryostat [1], from power converters located at each of the 16 arc extremities.

The superconducting 53.5 m cable segments will be inserted in the pipeline at machine installation time in the tunnel, thus limiting the number of useless electrical interconnections to the minimum necessary.

Cryogenically connected to the 1.9 K superfluid helium vessel of the cold masses at each main quadrupole location, this so-called auxiliary bus-bar tube (EAB) will be thermally and mechanically separated from the magnet main stream.

The general layout of the pipeline, its thermo mechanical functional specification and the tight cryogenic, mechanical, electrical, interface and geometrical constraints imposed by the LHC arc cryostat are presented, together with its detailed design.

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The superconducting multipole magnets housed in the cold mass of the LHC arc short straight sections, together with the arc dispersion suppressor and matching section quadrupole magnets, will be electrically fed along the 3 km arcs via 600 A and 6 kA superconducting flexible cables. These will be routed into a tube running parallel to the cold masses, placed inside their cryostat [1], from power converters located at each of the 16 arc extremities.

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1 INTRODUCTION

The LHC machine is subdivided into 8 octants, each one comprising a standard arc layout composed of 54 optical cells, flanked on each side by dispersion suppressors and experimental and machine insertions. The standard arc and dispersion suppressors are housed in a common cryostat of diameter 914 mm (Fig. 1), together with some adjacent insertion devices, depending on the octant. The cryostat length of an octant varies between 2.7 km and 3 km, and is bounded at each extremity by electrical current feedboxes allowing the numerous families of superconducting magnets to be powered in series.

The basic repetitive magnetic segment of the arc is the half-cell of 53.4 m length providing 45° phase advance for the beams. It is composed of 3 two-in-one 9 T dipoles of 15 m length (MB), a two-in-one quadrupole (MQ) and various sets of correcting magnets. The main dipole has sextupole and decapole correctors (spool pieces) housed in the same cold mass. The Short Straight Section (SSS) comprises the main quadrupole and sextupole, octupole and dipole orbit correctors.

To reduce the number of useless electrical connections and thus limit the parasitic ohmic heat load dumped into the 1.9 K helium bath, the individually powered quadrupoles and the array of corrector circuits associated with the SSS need to by-pass the dipoles and a link is provided along the 53.4 m of the half cell. For the 600 A circuits a flexible multi-wire cable is used containing 42 superconducting wires with a diameter of 1.6 mm and a Cu/Sc ratio of 9.5:1. The outer diameter of the complete cable is 15.5 mm. A similar cable is used for the 6 kA circuits containing 18 conductors and having an external diameter of 23 mm. The number and type of cables vary around the machine according to the local needs.

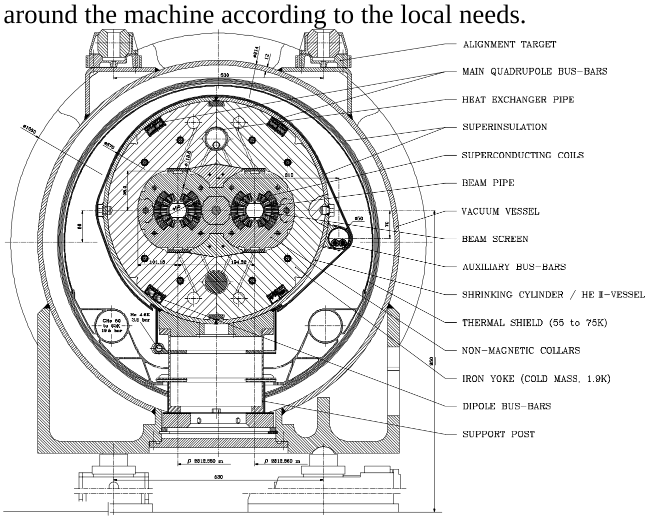

Figure 1: Transverse section of the LHC arc cryostat showing the auxiliary bus-bar tube attached to the side of the magnet cold mass

2 CONCEPTUAL DESIGN

The external auxiliary bus bars (EAB) feeding the lattice correctors are inserted in a 50 mm I.D. stainless steel tube, fixed to the cold masses by metallic supports [2]. The EAB is connected every half-cell to the corresponding SSS (Fig. 2). The tube will carry up to 2 superconducting cables along the arc of the LHC and plastic filler pieces in order to reduce the helium inventory. Equipped with expansion joints, the tube provides a leak-tight cryogenic channel from DFB to the arc SSS. The tube dimensions ∅ 50/53 minimise the number of supports and provide sufficient mechanical stability. It is mechanically decoupled from the cold mass (1 fixed support and sliding guides) so that no axial forces are transmitted to the magnets due to differential thermal gradient.

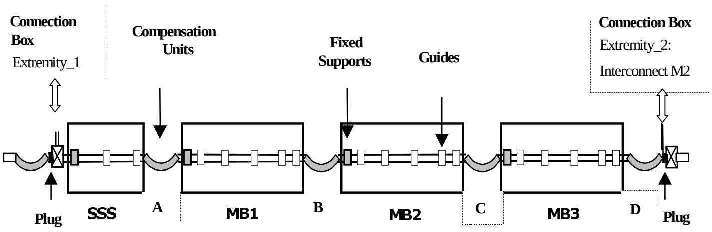

Figure 2: Conceptual layout of the externally routed auxiliary bus bars

The spacing of supports on the dipole cold mass (fixed and sliding guides) is not uniform for reasons of mechanical stability of the tube subjected to inner pressure.

Each tube is locally welded to the cold mass by means of a fixed support situated next to the magnet upstream extremity. The continuous 53.5 m long segments of the superconducting cable, equipped with plugs, will be inserted into the tube in the tunnel, after installation of each half-cell portion of the LHC Arc.

2.1 EAB extremities of a half-cell segment

The inlet/outlet designs of the half-cell segment of the EAB are governed by the layout of the cold mass sectorisation and the cryogenic scheme of the regular arc. Therefore, the notation used with respect to the half-cell portion of the EAB is as follows (Fig. 2): Extremity_1 (link main quadrupole (MQ) – EAB), Extremity_2 (link EAB – interconnect M2).

Extremity_1 provides a direct link between the half-cell portion of the EAB and the quadrupole cold mass. The superconducting wires powering the corrector magnets in the SSS are routed via this link. Extremity_2 has a cryogenic link with the M2 channel in the MB-SSS interconnections, thus completing the cryogenic by-pass of the magnet cold masses by the half-cell segment of the EAB. This link throttles the mass flow of helium in the EAB to a small fraction of the main stream in the magnet cold masses. The design of the Extremity_2 is shown in Fig. 3.

2.2 Mechanical compensation system

In the zone of interconnections (between the LHC magnets), the EAB tube will be equipped with expansion joints in order to compensate for the thermal contraction/ expansion of the magnets and the EAB pipes during the cool-down and warm-up transients. The expansion joints have to sustain all relative displacements between magnets.

The compensation system is based on stainless steel (316L) braided metal hoses, pre-bent at warm (see Fig. 3) and nearly straight at cold. They are designed for an internal pressure of 2 MPa (as for the LHC cold mass).

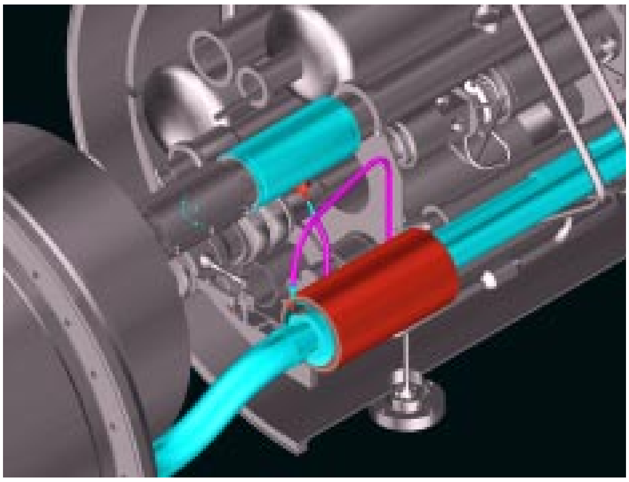
Figure 3: Extremity_2 of the EAB half-cell portion (MB-SSS interconnect)

2.3 The plug

A plug separates every half-cell portion of the EAB from the subsequent segment to satisfy the machine sectorisation requirements. It provides also a mechanical fixation of the superconducting cable and prevents it from moving when cooling down the EAB. Furthermore, the plug protects the connector and the ultrasonically welded bus bars against mechanical damage. The half-cell segment of the EAB cable already equipped with its plug will be inserted at machine installation time.

The plug, fixed on the Extremity_2, is bolted onto the main flange of the connection box with a metallic seal. The required leak-tightness of the plug is 5 x 10^{-2} mbar l/s measured at 293 K under the pressure of 1 bar.

3 HYDRAULIC AND THERMAL DESIGN

The EAB is an integral part of the cryogenic system of the LHC machine and will be cooled down together with the superconducting magnets, using common helium gas/bath. The cables are statically cooled at 1.9 K (±0.05 K) under a pressure of 0.13 MPa by conduction to the SSS cold mass through superfluid helium. This sets a minimum He II free section of 82 mm^2 in the tube for a transverse static and distributed heat load of 7 mW/m. The EAB must withstand temperature variations between 293 K and 1.9 K under a maximum inner pressure of 2 MPa and respect normal and quench cool-down/warm-up times of the LHC half-cell.

3.1 He inventory and flow during transients

In line with the basic cryogenic flow scheme of the arc, whereby cool-down/warm-up of basic half-cell magnet strings is ensured by helium gas flow of up to 0.1 kg/sec, 0.5 to 0.7 % of the main gas stream must be tapped through the EAB tube.

This gas flow, ensured by a fixed hydraulic impedance, is deemed to be sufficient to maintain the EAB temperature within sufficiently narrow intervals with respect to the cold masses, without the need of an active control of the by-pass flow. This fixed hydraulic impedance is provided by the cryogenic link in Extremity_2 of the EAB segment, made of a ∅ 4 mm channel and a ∅ 5 mm capillary metal hose, representing 99 % of the complete EAB segment hydraulic impedance.

3.2 EAB thermal behaviour

The EAB is only partially coupled thermally with the cold mass by means of the fixed supports and extremities [3]. The efficient cool-down is ensured by means of the forced convection of the helium gas flow in the EAB.

Transient phases:

The time required for cool-down of the auxiliary bus bars to the temperature of 4.5 K by forced convection is assumed to be the same or shorter than the time needed to cool-down the cold-mass to 4.5 K.

The final cool-down time from 4.5 K to the operational temperature of 1.9 K in these conditions is roughly identical for the cold masses and the EAB.

The cool-down process with a helium flow was studied with a simple one-dimensional finite element model developed in ANSYS™. The model consisted of two lines of elements, one representing the tube and the cable, the other one helium. The cold mass temperatures given by the cool-down baseline scenario were imposed on the tube at the appropriate locations to simulate the supports, one per cold mass. The temperature evolution of the EAB inlet and outlet during the 6-day cool-down when compared to the evolution of temperature of magnets (over the length of the LHC half-cell) is shown in Fig. 4. Here, the mass flow of helium in the EAB (0.3 g/s) has been assumed to be 0.5 % of the mass flow in the LHC magnets (60 g/s). The temperature of the EAB is always lower or equal to the corresponding half-cell cold masses.

Steady state:

Normal operation conditions assume a temperature of 1.9 K and a pressure of 0.13 MPa. The steady state allowable temperature variations associated with heat inleaks from super-insulation are specified at ±0.05 K. The design heat load associated with the superinsulation is 60 mW/m^2. A safety factor covering the enhanced conductivity in the superinsulation due to the geometrical singularity provoked by the EAB is 1.5. A peak flux of 90 mW/m^2 was therefore taken into account over the portion of the tube being in direct contact with the super-insulation. The resulting distributed heat load apportioned to the EAB amounts to 7 mW/m. This leads to a minimum cross-section of the He-II column of 82 mm^2 to ensure the temperature stabilisation at the required level. Weak thermal coupling to the cold mass (fixed supports + extremities) ensures minimisation of the heat flux to the EAB in case of a magnet quench.

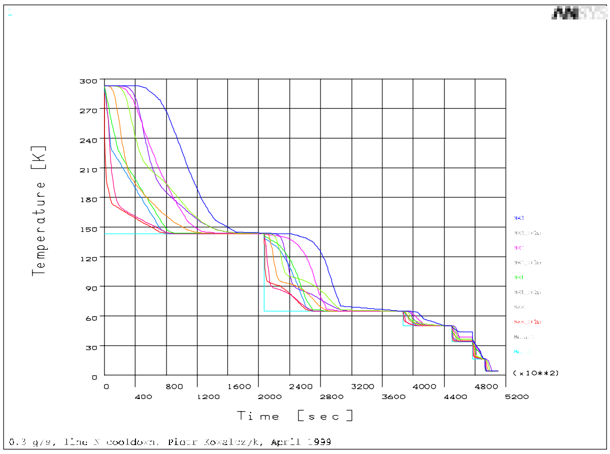

Figure 4: Fast cool-down of the EAB when compared to the cool-down of the LHC half-cell

4 SUMMARY

- The auxiliary bus bars powering the LHC corrector magnets will be routed inside a channel called EAB, running parallel to the cold masses.
- The EAB is mechanically decoupled with respect to the cold-mass, thus not affecting the cold mass curvature in case of transverse thermal gradient between the EAB and the cold mass.
- The EAB is actively cooled by a small fraction (around 0.5 %) of the mass flow defined for the LHC magnets. There is no active control of the cooling flow rate. A passive control is ensured by means of a capillary/metal hose hydraulic impedance installed in the MB-SSS interconnect.
- The cool-down of the EAB develops in the shadow of the cool-down of the LHC magnets. The EAB does not slow down the main cooling process. Given their current density, the bus bars are operational already at 4.5 K.
- The helium inventory has been minimised by using special plastic insertions. Simultaneously, a sufficient section of He II was left in order to ensure the temperature stabilisation in the operational conditions.

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