THE DESIGN OF COLD TO WARM TRANSITIONS OF THE LHC

J. Knaster*, B. Jenninger, D. Ramos, G. Ratcliffe and R. Veness CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC), the next accelerator being constructed on the CERN site, will accelerate and collide 7 TeV protons and heavier ions up to lead. More than 1700 cryomagnets working at 1.9 or 4.5 k will form part of the magnetic lattice of the LHC. The beam pipe passage from cryogenic temperatures to room temperature zones will be achieved by 200 cold to warm transitions (CWTs). The CWTs will compensate for longitudinal and transversal displacements between beam screens and cold bores, ensuring vacuum continuity without limiting the aperture for the beam. The transverse impedance contribution is kept below the assigned total budget of 1 MΩ/m by means of a 4 μm thick Cu coating that also minimises the dynamic heat load through image currents. Tests have been performed that confirm that the static heat load per CWT to the cryomagnets remains below 2.5 W, hence validating the design.

INTRODUCTION

The Large Hadron Collider (LHC) is a 7 TeV proton-proton collider currently under construction at CERN. Each of the 8 arcs of the machine will consist of a 2.5 km long continuous cryostat, operating at 1.9 K. The cryostat contains repeating half-cells comprising three twin-aperture dipole magnets and a 'short-straight section' (SSS) with lattice quadrupole and corrector magnets.

Between arcs there is an insertion region consisting of two dispersion suppressors and a 'Long Straight Section' (LSS), some 570 m long. This region contains a number of magnetic elements, some at 1.9 K, some at 4.2 K and some at room temperature that serve to steer and focus the beams. At the end of each continuous arc cryostat and between many of the cryogenic insertion region magnets the beams pass to a room temperature region. This is either to allow the installation of room temperature equipment, such as magnets or beam instrumentation, or for economic reasons, due to a large separation between elements. Therefore, at the end of a cryostat, the beam line must exit the cryostat and connect to the room temperature vacuum system. A number of these 'Cold to Warm Transitions' (CWTs) have been designed for the LHC beam vacuum system.

FUNCTIONAL REQUIREMENTS

The CWTs will connect the cryogenic-cooled beam pipes to the room temperature region. Each circulating beam will pass 108 CWTs in its journey around the ring. They have to ensure the ultra-high vacuum in the beam line, the beam stability and protect the cryomagnets by limiting the heat flow from the room temperature side.

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*Email: juan.ramon.knaster@cern.ch
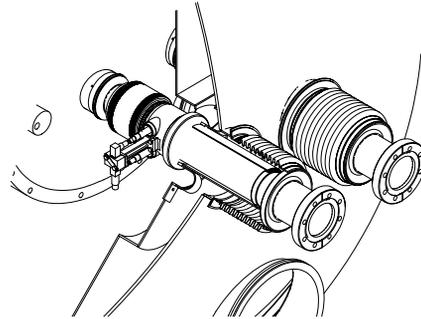
Figure 1: CWT for a twin aperture cryoassembly

The assembled CWT shall have no leak rate higher than 10^{-11} Pa $m^3 s^{-1}$ and shall guarantee the beam aperture. In addition, a good electrical conductance is required to keep the transverse impedance (origin of the main beam instability to be faced by the LHC [1]) below a global budget of 1 MΩ/m [2]. The CWTs shall also compensate for the longitudinal and transverse thermal displacements of the cryomagnet cold bores and beam screens with respect to the insulation vacuum end cover. In addition, a flexible and good thermal conductive connection to the active cooled thermal shield has to be in place to absorb the differential movement between the thermal shield and the CWT without hampering the thermal performance.

CALCULATIONS

Static heat loads

Table 1 - Symbols used in formulas and their values as used in the calculations.

σ	*Stephan Bolzmann Constant (5.67 10^{-8} W.m^{-2}.T^{-4})*
A_{BS}	*Area of beam screen aperture*
ε_{eff}	*effective emissivity between room temperature and beam screen*
F_v	*View factor between room temperature and beam screen*
T_{RT}	*Room temperature (293 K)*
T_{BS}	*Beam screen temperature (20 K)*
T_A	*Temperature of thermal anchor on CWT drift tube (100K)*
T_{TS}	*Temperature of thermal shield of the cryo-assembly (90 K)*
$P_{Rad.BS}$	*Thermal radiative heat load onto the beam screen*
$P_{Cond.BS}$	*Thermal conductive heat load on the beam screen*
D_{CWT}	*Diameter drift tube of cold warm transition*
L_{TA-BS}	*Length of CWT between thermal anchor and beam screen*
L_{RT-TA}	*Length of CWT between room temperature connection and thermal anchor*
e_{ss}	*Thickness of stainless steel tube*
e_{Cu}	*Thickness of copper layer*
λ_{SS}	*Thermal conductivity of stainless steel (temperature dependent)*
λ_{cu}	*Thermal conductivity of copper (temperature dependent)*

The static heat loads at a cold-warm transition (CWT) comprise heat load by thermal radiation from room to cryogenic temperature through the vacuum chamber aperture and thermal conduction through the chamber wall. Figure 2 shows the simplified thermal flow scheme of the CWT. The radiative heat load onto the beam screen is calculated with Equation 1 where the wall emissivity of the CWT drift tube is very low.

$$P_{Rad.BS} = \sigma \cdot A_{BS} \cdot \varepsilon_{eff} \cdot F_V \left(T_{RT}^4 - T_{BS}^4 \right) \quad (1)$$

For the CWT drift tubes, both the effective emissivity and view factor between beam screen bore and room temperature bore becomes ~1 and the radiative heat load is, to a first approximation, independent of the CWT length.
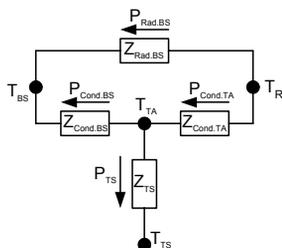
Figure 2: Thermal flow scheme of the CWT. Zi are the thermal impedances and Pi are the heat flows due to these impedances.
The conductive heat load on the beam screen and thermal anchor are calculated with Equations 2 and 3.

$$P_{Cond.BS} = \pi D_{CWT} \cdot L_{TA-BS} \cdot \left(e_{Cu} \int_{T_{BS}}^{T_A} \lambda_{Cu} dT + e_{ss} \int_{T_{Bs}}^{T_A} \lambda_{SS} dT \right) \quad (2)$$

$$P_{Cond.TA} = \pi D_{CWT} \cdot L_{RT-TA} \cdot \left(e_{Cu} \int_{T_A}^{T_{RT}} \lambda_{Cu} dT + e_{ss} \int_{T_A}^{T_{RT}} \lambda_{SS} dT \right) \quad (3)$$

The temperature of the He gas cooling the thermal shield of the cryoassembly may vary between 50 K and 65 K. The thermal resistance Z_{TS} of the Cu braids connected to the thermal shield has been designed such that for a temperature T_A of about 100 K the temperature gradient along Z_{TS} is about 10 K.

Dynamic heat loads

The two main sources of dynamic heat loads are beam image current and the electron cloud activity. The position of the thermal anchor on the CWT drift tube minimises the total heat load onto the beam screen including the dynamic heat loads. The heat load caused by the electron cloud activity has been estimated to be about 1.9 W.m^{-1} [2]. A Cu coating of at least 3 µm ensures that the image current is carried by the Cu layer and reduces the transverse impedance to the required 1 MΩ^{-1} for the total of all CWT in the LHC [3]. The total static heat load on the beam screen from the CWT is estimated to be about 2.5 W (Figure 3). The length of the CWT drift tube between room temperature and the thermal anchor has been chosen such that the heat load will be less than 6 W on the 100 K level. Figure 2 shows that this heat load is divided such that part is absorbed on the thermal shield (≈ 4.5 W) and part continues to the 20 K level (≈ 1.2 W)
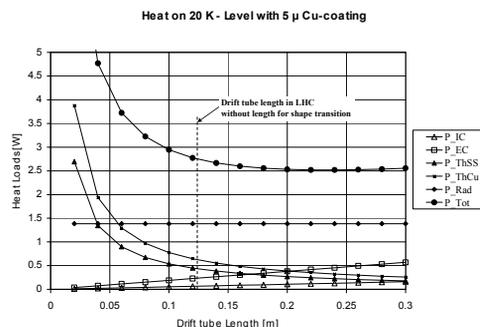
Figure 3: Total heat load *(P_Tot)* to 20 K as function of drift tube length (ID63, 1 mm thick with 5 µm Cu coating) between beam screen and thermal anchor. Stainless steel thermal conduction *(P_ThSS)*; Copper thermal conduction *(P_ThCu)*; beam induced heat load by image current *(P_IC)*; thermal radiative heat load from room temperature *(P_Rad)*; heat load by electron cloud activity *(P_EC)* [4].

DESIGN DESCRIPTION

The CWT will be TIG welded to the interconnect components (Figure 4). Electrical contact with the Au coated beamscreen end is ensured by Au coated vacuum brazed Cu-Be C17200 RF strips.
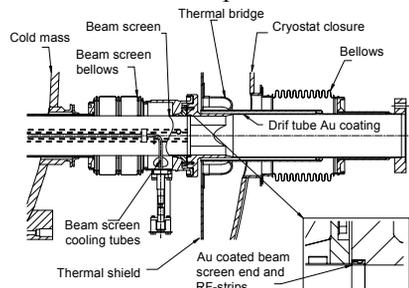
Figure 4: Cross section view of a CWT mounted on a movable beam screen extremity.

A Cu coating 4 ±1 µm thick fulfils the compromise between a low thermal and high electrical conductivity. The thermal bridge consists of two Cu half-shells electron beam welded to a Cu shim, which in turn is vacuum brazed on the stainless steel body. The Cu half-shells are connected to the thermal shield with 4 Cu braids by TIG welding to ensure a good thermal conductivity. In addition, the braids are e-beam welded to a Cu-Al explosion bonded bimetallic piece [5] welded onto the Al thermal shield. The differential thermal expansions during cooling and warming between cold bore and beam screens is absorbed by a nested bellows integrated in the beam line interconnect design [6]; and that between the beamscreen and the cryostat is absorbed by a bellows welded to a special flange integrated in the CWT, which will also absorb the vertical displacement due to the shrinking of the supports and cold masses at operating temperature.

LAYOUT

The 200 CWT's to be installed in the machine LSS will be divided in 14 design variants depending on specific

cryoassembly interfaces. Cold bores of several inner diameters (ID) (Table 2), impose three different drift tube dimensions to cope with the aperture requirements.

Table 2: Cold bore diameters and correspondent CWT drift tubes and UHV flanges.

Cold bore ID (mm)	Number of design variants	Drift tube ID (mm)	UHV flange type
50	3	63	DN63
53	1		
63	4		
69	3	66	
74	2	80	DN100

Attempts were made to standardize the dimension 66 mm to 80 mm, but bolted UHV standard flanges larger than DN63 do not fit the CWT assembly into the cryostat in twin aperture magnets. In the twin aperture quadrupoles (Q4, Q5 and Q6), with cold bore diameters of either ID50 or ID63 mm, different design variants are necessary within each cold bore dimension. CWTs with drift tubes of ID66 mm were designed for installation in the beam separation dipoles D2, D3 and D4. The beam separation dipoles D1 and the distribution feedback DFBX are single aperture cryoassemblies with cold bore of ID80 mm with different interfaces with the cryostat and thermal shield. Particular space constraints in the inner triplet quadruple Q1 imposed the execution of a special design. The drift tube flange is welded directly to the cryostat end cover. The compensation for thermal displacements is performed by a cold interconnect plug-in module [7]. Two more variants are required for the undulator cryoassembly.

TESTING

The static heat load to the cold mass of the cryomagnets was measured at the CERN CRYOLAB under similar conditions to those of the LHC, using heat meter techniques. Figure 5 shows the prototype CWT mounted in the test cryostat, where liquid He is transferred to a phase separator, permitting the cooling of the heat meter with two-phase flow of saturated fluid, and the cooling of the intermediate heat sink by gas flow. Thermometers were mounted as shown by the figure, and a heater was used for the control of the temperature of the hot end. The thermal losses at the cold end using the heat meter were determined, while maintaining the CWT under the expected operation conditions. In the LHC the beam screen temperature varies between 4.2 K and 20 K, and the temperature of the thermal shield between 60 K and 90 K. The CF 63 flange at the hot end is attached onto a Cu bell maintained at 300 K, measured with the thermometer T_{10}, using feedback to the heater strip H_1. The intermediate thermalization of the transition is maintained at the temperature T_{13}, adjusted between 60 K and 90 K by controlling the flow of the cold vapour out of the phase separator. The measurement of the total thermal losses is made with a calibrated heat meter, whose cold end is controlled at 6 K. The resulting total thermal losses to the beam screen by conduction and radiation through

the CWT are shown in Table 3, for two temperatures T_{13} of the thermal screen.
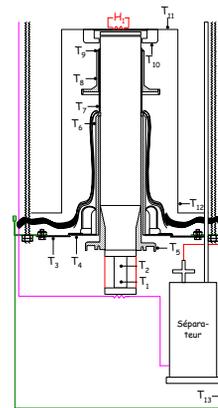
Figure 5: Layout of the test setup, showing the locations where the thermometers and the heater were mounted during the heat load measurements.

Table 3: The heat load measured at two screen temperatures.

T_{13} (K)	Total heat load (W)
62.61	0.722
90.13	1.038

CONCLUSIONS

The fabrication of the 200 units of CWTs will be done in Budker Institute of Nuclear Physics at Novosibirsk. An effort to simplify the design has been deployed, and the challenging task of isolating the cryomagnets from atmospheric conditions in 30 cm space though not easy was achieved. The cryo tests performed with a CWT prototype have validated the design. In addition, the first prototypes from the supplier showed a good fabrication quality. The first series components are expected to be delivered in December 2004.

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