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NUMERICAL AND EXPERIMENTAL EVALUATION OF THE DQW CRAB CAVITY CRYOMODULE THERMAL BUDGET*

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Abstract

One of the key devices of the HL-LHC project are SRF Crab Cavities. A cryomodule with two Double Quarter Wave (DQW) crab cavities has been fabricated at CERN in 2017 and successfully tested with beam in the Super Proton Synchrotron (SPS) in 2018. The aim of this study is to present and compare the estimation of the thermal budget for the different components of the cryomodule, performed with numerical and semi-analytical methods, with the experimental measurements carried out on the cryomodule before its installation in the SPS.

INTRODUCTION AND HEAT BUDGET

Superconducting crab cavities are part of the HL-LHC upgrade, a project that aims at achieving instantaneous luminosities a factor of five larger than the LHC nominal value. The crab cavities provide a deflecting kick on the proton beam, maximizing the overlap at the collision points [1]. During 2018, a prototype two-cavity cryomodule (Figure 1) was successfully tested with beam in the SPS accelerator [2].

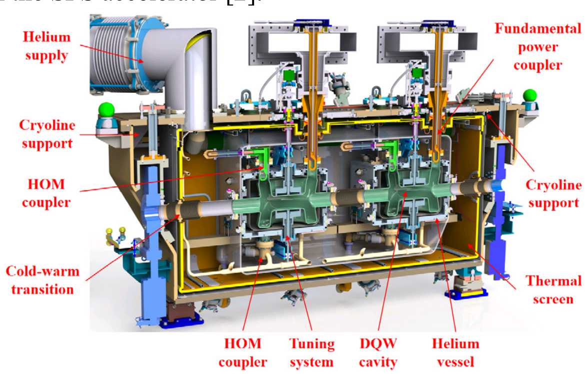

Figure 1: DQW crab cavity cryomodule.

The cavities are placed in a cryomodule and are cooled down to 2 K with superfluid helium. A secondary circuit with helium gas at a temperature of 50 to 70 K is used to cool down the cryomodule. To limit the heat loss to the 2 K bath, and thus the consumption of superfluid helium, several of the main components are connected to the thermal shield, which is directly cooled with the secondary circuit via copper braids that act as heat interceptors. This connection was assumed to be at 80 K in the initial estimation of the heat budget [3], which presented detailed calculations to evaluate the thermal losses in the different components of the cryomodule. The thermal losses in [3] resulted in 16.8 W to the cold bath and 240 W to the thermal shield. During the cool-down of the cryomodule at CERN in December 2017, temperature measurements were taken in the different cryomodule components and He cryogenic lines. The present contribution makes use of these experimental measurements to:

- Update the static heat load balance of the cryomodule accounting for actual temperature measurements.
- Compare the overall static heat load in the cryomodule, obtained after the evacuation of the liquid He, with the heat load balance obtained component by component of the cryomodule.

Table 1 is a summary of the re-evaluated static heat loads to the cold bath (2 K) and the thermal shield (Int.) for each considered part based on measured temperatures.

Table 1: Calculated Static Heat Load Balance (in W) for the Cryomodule

	2 K	**Int.**
Cold/Warm transitions	0.1	28
Supporting system	2.1	21
Tuning system	1.4	15
Radiation	3.3	16
Instrumentation	2.4	8
FPC	5.3	72
HOM/Pickup	5.5	15
Total static	**20.1**	**175**

EXPERIMENTAL MEASUREMENTS

The DQW cryomodule was cooled down at the end of 2017. Temperature probes were placed in specific points in the cryomodule and its components. The locations of these temperature probes comprise the helium vessel walls, the two Cold-Warm Transitions (CWT1 and CWT2), the two Fundamental Power Couplers (FPC1 and FPC2) and the High Order Modes couplers (HOMs), including probes at the thermal intercept level. Table 2 presents some relevant temperature measurements for the calculations presented in the current contribution. At the moment chosen for the cavity static load heat balance calculation, the helium vessel was operated at 2 K, whereas the thermal screen presented a temperature of around 70 K.

Table 2: Relevant Temperature Measurements for the Calculations. Values in Bold are Measured at the Thermal Intercept Level

Component/Location	**T [K]**
Cavity	2.2
CWT1-CWT2	**70.4-77**
FPC1-FPC2	12/56.4/**92.9** – 62.5
HOM1	108.3/**120.3**/191.7

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The overall static heat load to the 2 K bath in the cryomodule was measured by means of the natural evaporation of the liquid helium during warm up. Figure 2 shows the helium level curve during this process. From the values of this curve and the physical properties of helium, the heat load to the 2 K bath is estimated at 18 W.

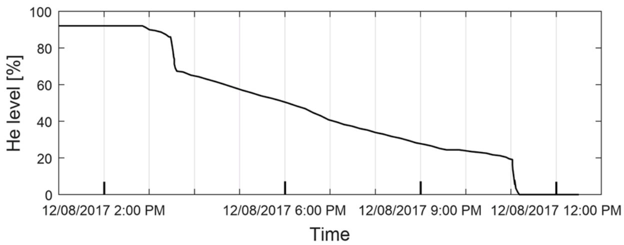

Figure 2: Helium level curve during natural evaporation.

EVALUATION OF THE THERMAL LOADS IN THE CRYOMODULE

Cold/Warm Transitions (CWT)

The CWT directly connect the cavity with the warm beam line by a stainless steel tube and a system of thermally intercepted bellows. A temperature probe is located right next to this intercept (Figure 3). The heat loss by conduction is analytically calculated assuming a system of resistances in series and using Eq. (1). This equation integrates Fourier's law between the cold bath (at 2 K), the temperature of the intercepts (Tint, measured as 70 K and 77 K for the two transitions, see Table 2) and the room temperature (300 K) assuming a temperature dependent conductivity:

$$Q_{2K} = \frac{A}{L_{int}} \int_{2K}^{Tint} k(T)dT$$
$$Q_{int} = \frac{A}{L - L_{int}} \int_{Tint}^{300K} k(T)dT \qquad (1)$$

Note that the heat loss contribution through the CWT, 0.1 W, is very low due to the extremely reduced thickness of the bellows (0.15 mm) and its corresponding high thermal resistance.

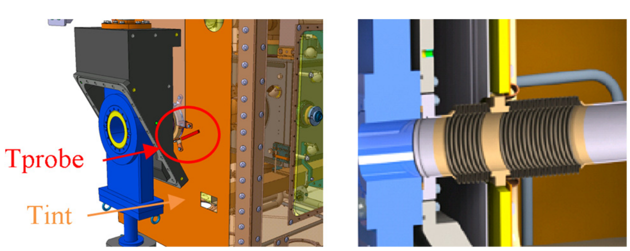

Figure 3: Cold/warm transitions.

Supporting System

The cavities are vertically supported by two blades and the FPC system, as indicated in Figure 4, whereas the cryogenic lines are supported by the cryomodule walls by two different kinds of supports. All these three supporting systems directly connect the cold mass to the cryomodule walls at room temperature. To reduce the heat loss by conduction, these components are thermally intercepted by the helium gas circuit. The heat loss on the blades and cryogenic supports was calculated by means of FEA. Due to the unavailability of a temperature measure at the intercepts in the blades and the supports, the temperature at the intercepts was conservatively assumed as an intermediate temperature between the available intercept temperature measurements and the temperatures at the cold-warm transitions: 90.15 K.

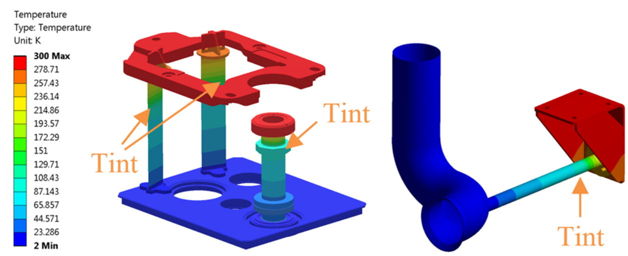

Figure 4: Left: cavity supports. Right: Cryoline support.

Tuning System

The tuner provides a quasi-symmetric elastic deformation to the cavity capacitive plates that shifts the cavity frequency [4]. Figure 5 shows a 3D view of the tuning system. The heat load to the 2 K bath was numerically calculated by FEA and accounts for the heat losses through the four flexures of the tuning frame, which were designed to maximize its thermal resistance and to provide structural support. The tuning system is thermally intercepted on top of its titanium rod. As in the supporting system, a temperature of the intercepts of 90.15 K was assumed.

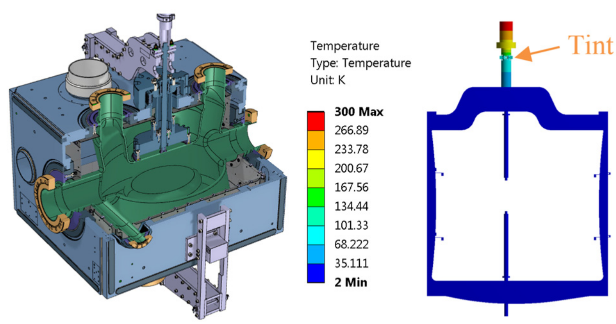

Figure 5: Left: tuning system. Right: temperature distribution of the tuning frame.

Radiation - Thermal Screen

Figure 6 shows a 3D view of the thermal screen, which consists of a copper structure wrapped with Multilayer Insulation (MLI) and directly thermalized by the helium gas circuit through copper cooling pipes [5]. The heat loss of the 2 K bath considers the contribution of the surface-to-surface radiation from the thermal shield, taking into consideration the presence of MLI [6], and the radiation losses through the openings required by the alignment instrumentation. The calculation of the heat loss from radiation to the cold mass was done by FEA, using a mean temperature of the thermal screen obtained from the

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available experimental measurements at the cold-warm transition levels, *i.e.* 73.7 K (see Table 2).

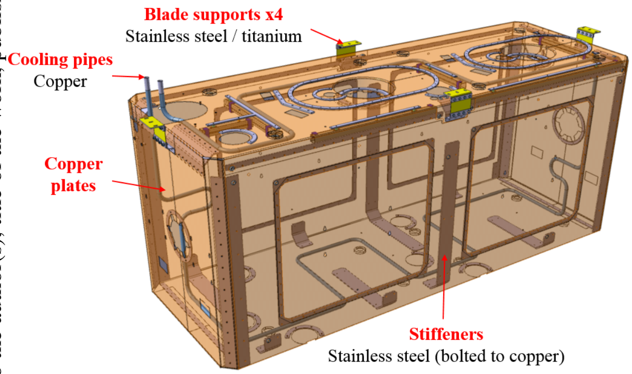

Figure 6: 3D view of the thermal screen.

Instrumentation

The cryomodule is extensively instrumented with temperature probes, magnetic flux sensors and heaters at the end of each cold/warm line. The wires for the powering of these systems conduct heat in static conditions and can be modelled as thermal resistances in parallel. The heat loss of the overall wiring system was analytically calculated following Eq. (1), where the thermal insulation temperature was again assumed as the average temperature at the intercepts level: 90.15 K.

Fundamental Power Coupler (FPC)

The RF components (FPC, HOMs and pickups) are one of the main contributors to the losses on the cold mass, both in static and dynamic conditions. The FPC is made of a copper-coated 316LN tube and a warm copper internal antenna (see Figure 7). The stainless steel tube is subjected mostly to conduction heat transfer. In this case, despite Eq. (1) could be used to describe the losses in static conditions, a semi-analytical approach was adopted, discretizing the system in several nodes and applying to each node the energy conservation law. This allows the calculation of the radiation heat loss and provides the possibility of calculating the heat loss in dynamic conditions. Details of the calculation procedure can be found in [3]. Due to the availability of temperature measurements in the intercept of one of the FPCs (FPC1), real temperature values were included for the estimation of its heat loss. The value of the temperature of FPC2 at the intercept level was obtained by extrapolation of the temperature at the intercept of FPC1 and the values of FPC1 and FPC2 at a height below the intercept (56.4 and 62.5 K, respectively, as indicated in Table 2).

HOM Couplers and Pickup

The cryomodule at SPS contains 6 HOMs and 2 pickups. The design of these components consists of thin coaxial copper-coated stainless steel tubes, which are connected to the cavity through commercial coaxial cables (see Figure 7) [7]. The calculation of the heat load to the cold mass was performed following an analytical procedure, see Eq. (1), along the coaxial line up to the measured temperature at the intercept. Smaller additional thermal resistances, such as massive components at the extremities of the lines and thermal contact interfaces, were not considered in the analytic calculation for the sake of simplicity. The temperature at one of the HOM lines was measured at several points of its external surface (Figure 7). This same temperature distribution was used for the calculation of the heat loss in all the HOM lines. Due to the unavailability of temperature measurements at the pickup, the temperature at the thermalization level was assumed as 90.15 K, as previously indicated for the supports and the tuning system.

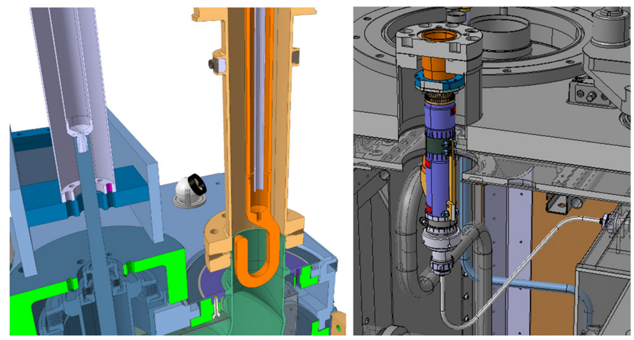

Figure 7: Left: FPC can and antenna. Right: HOM coaxial lines.

CONCLUSIONS

The heat budget of the DQW cryomodule was re-calculated, analytically and numerically, after the experimental measurements performed during its cool-down in December 2017 at CERN, with a more precise knowledge of the values of the temperatures at the intercepts. The refined analysis resulted in an estimated static heat load of 20.1 W to the 2 K bath and 175 W to the thermal intercept. In this framework, the actual heat loss to the 2 K bath, measured by evaporation of the helium, was estimated to be 18 W. This value is in very good agreement between the two methods, with an error in the order of 10 %, confirming the applicability of the adopted approach and the validity of the simplifications done. It is noteworthy to add that the measured heat losses are also quite close to the initial estimations done in the early design phase, in 2016, with a similar error of less than 10 %, in spite of the several uncertainties present in the models at that time.

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