Cryogenic design of the crab cavity modules for the High Luminosity LHC at CERN

K Brodzinski[1], O Capatina[1], T Capelli[1], S Claudet[1], L Delprat[1]

CERN, 1211 Geneva 23, Switzerland

Krzysztof.Brodzinski@cern.ch,

Abstract. The High Luminosity Large Hadron Collider (HL-LHC) upgrade is planned to take place during next long shut down of the LHC, starting in 2025. During this period the matching sections of both ATLAS and CMS experiments will be upgraded to allow for increasing collisions rate and more efficient luminosity production. One of the new element which will be introduced to the layout is the beam deflecting RF system so-called as crab cavities. Eight crab cavities modules, operating in superfluid helium, will be installed in this new machine layout. This paper will focus on the cryogenic design solutions adopted and integrated in the crab cavities cryogenic modules. The concept of the cryogenic modules was created in 2012 and evolved over the years with introduced optimizations of the cryogenic local cooling loops and related safety system. Design aspects of the chosen solutions for the first prototype and LHC compatible solution will be discussed. The thermal behavior results from operation on SPS proton beam from the first prototype module will be developed.

1. Introduction

The first proton-proton collisions in the LHC were performed in March 2010. Since then, the LHC has operated successfully for the physics production braking frontiers of the human knowledge about the particle interaction physics. The announcement of the Higgs Boson experimental discovery in 2012 was the most exciting event coming from utilisation of the LHC and related detectors. According to the exploitation program, the LHC will be upgraded for more efficient luminosity production during its Long Shutdown starting from 2025. The planned upgrade will affect the LHC machine matching sections close to the interaction points of ATLAS and CMS experiments [1, 2]. The major upgraded part of the focusing system is related to replacement of the Inner Triplets using newly developed low temperature superconductor based on Nb_3Sn alloy. In the chain of the HL-LHC matching section elements we will also find new cold powering system consisting in HTS part as well as newly developed RF system so-called crab cavities. In total, there will be eight cryogenic modules installed in HL-LHC, each of them containing two crab cavities. The layout of upgraded part of the LHC and its main components is presented in Figure 1.

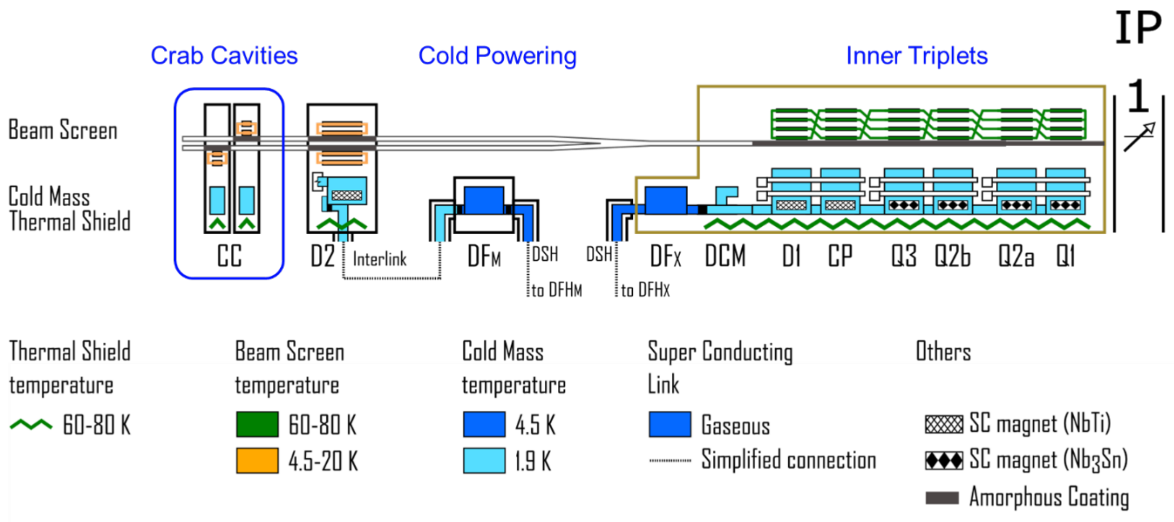

Figure 1. Layout of new HL-LHC matching section for left side of interaction point 1 (ATLAS).

The principle of the crab cavities operation consists in generating the transversal electric field allowing for rotation of each interacting bunch before collision – see Figure 2. In consequence the collision crossing angle is reduced and effective cross section area is increased resulting in more efficient luminosity production [3].

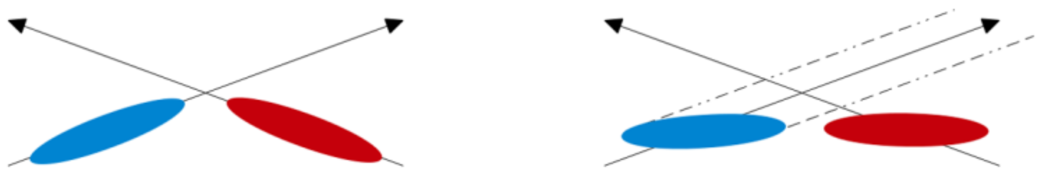

Figure 2. Bunches colliding with a crossing angle without crabbing (left) and with the crab crossing (right) [3].

Following validation process, two types of the crab cavity prototypes were selected for implementation in the HL-LHC: "Double Quarter Wave" (DQW) and "RF Dipole" (RFD) – see Figure 3.

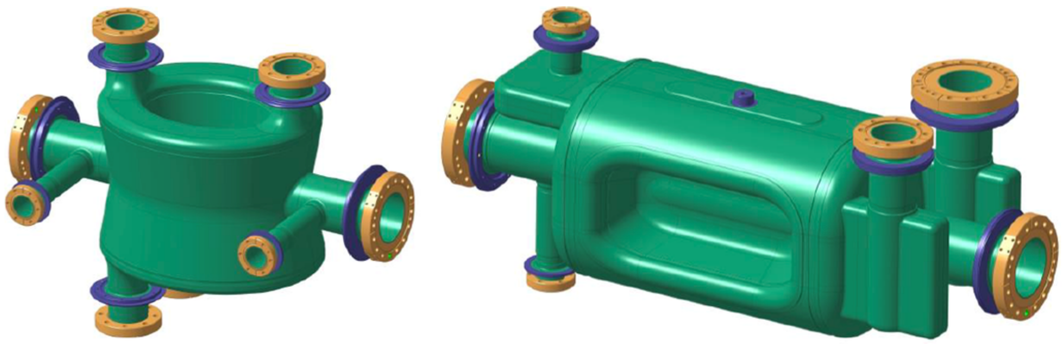

Figure 3. RF crab cavities selected for the HL-LHC (DQW – left and RFD – right).

2. Cryogenic design of the crab cavity cryo-module – cryogenic circuits and instrumentation

The concept design of the crab cavities cryogenic module started in 2012 and was developed over the years. The adopted strategy was to build first the cryomodule to confirm assumed operational principles. Construction of the first prototype module housing two DQW cavities was completed in 2018.
This module was tested at CERN in experimental zone SM18 and also with proton beam in SPS accelerator complex. Basing on the experience from the first prototype the next defined step was to proceed with production of prototypes compatible with HL-LHC environment, housing two DQW and two RFD cavities. This work is currently ongoing. The first HL-LHC compatible prototype housing two RFD cavities should be delivered at CERN in spring 2022. Because of the cavities specific geometry, the DWQ HL-LHC modules will have a length of about 3 m and RFD of about 3.3 m.

2.1. 2 K cryogenic circuit

The RF crab cavities requires operation with superfluid helium. Operational temperature was defined for the design as 2 K. Because of mechanical behaviour of proposed cavities design the adopted solution for the main cryogenic circuit was considered as superfluid saturated helium bath. For both modules, first DQW prototype and HL-LHC compatible solution, the design principles of this 2 K circuit are the same. Two helium tanks house the cavities and are individually connected with double phase horizontal pumping collector using short vertical pipes. The 2 K cryogenic cooling loop consists of two supply circuits. The first one is connected to the bottom of two helium tanks and is used for cool down phase. The second one is connected to bi-phase line at opposite extremity with relation to the pumping outlet and is used for normal operation. Figure 4a shows 2 K cryogenic circuit for DWQ solution and Figure 4b for RFD. The design of this circuit is thermally sized to compensate for the heat load up to the level of 100 W (factor of ~2 vs heat load estimated for nominal operation case).

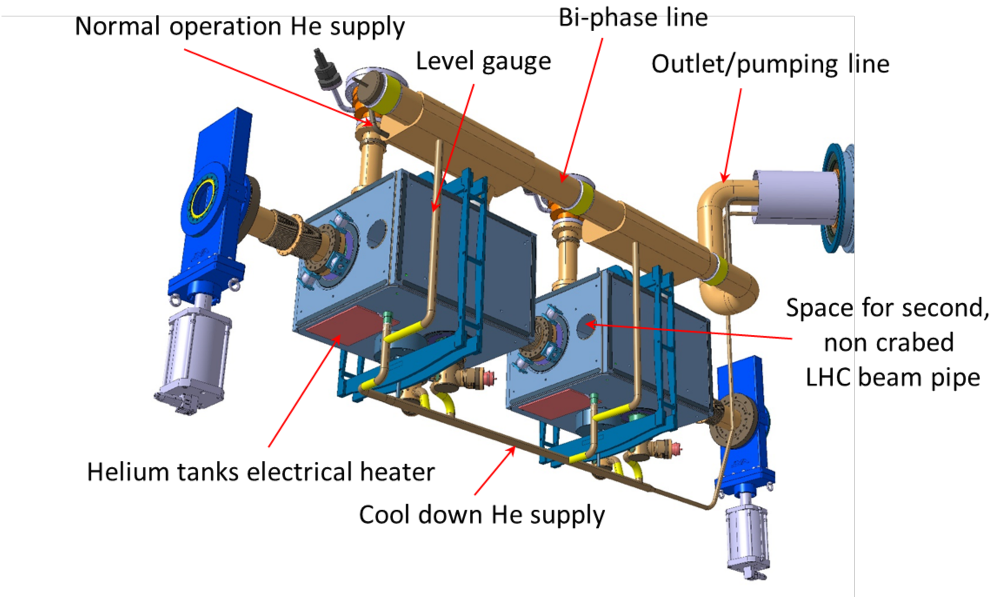

Figure 4a. DQW first prototype – 2 K cryogenic circuit with main components.

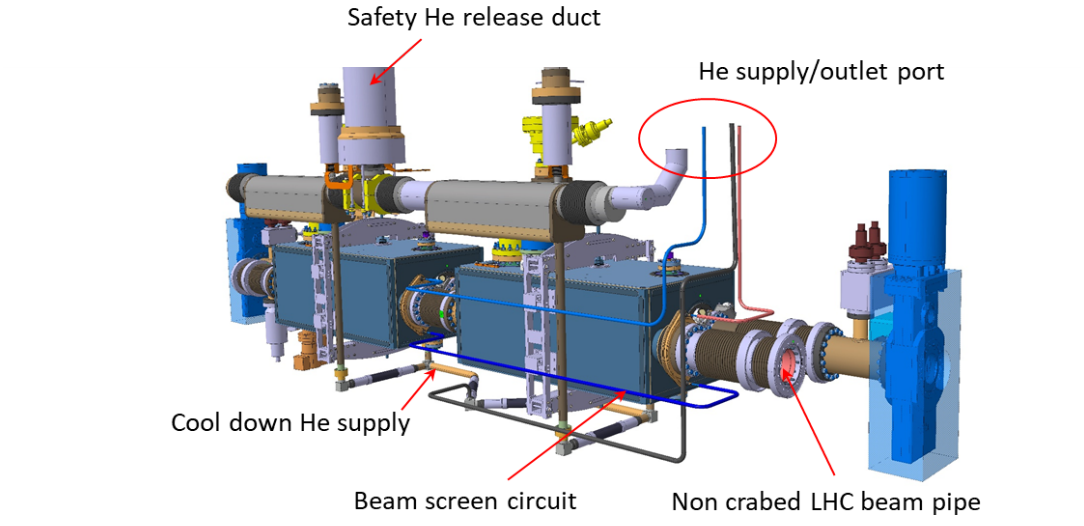

Figure 4b. RFD HL-LHC compatible prototype – 2 K and BS circuits.

The operational principles consider to use the pumping collector as the helium phase separator and operate controlling the superfluid helium level at half height of its cross section. The inlet and outlet lines were placed on opposite extremities of the collector for efficient phase separation. The size of the collector was designed in such a way allowing for damping of unexpected process oscillations (considered ~8 min of autonomy in case of complete supply interruption with the heat load corresponding to nominal operation case) and in parallel to allow for effective evacuation of the gaseous phase to the pumping line well below maximum allowed gas speed of 7 m/s (limit to avoid liquid droplets evacuation to the pumping line).

2.2. Thermal screen circuit

The cryo-module is equipped with actively cooled thermal screen circuit covering whole part of 2 K system. It is supplied with a flow of 60 K helium gas up to 4 g/s, allowing heat load compensation up to 400 W (factor of ~1.8 vs heat load estimated for nominal operation case). It is worth to mention that the main contribution of heat load on the screen circuit comes from thermalization of different equipment such as: Fundamental Power Couplers (FPC), Tuners, Cold-Warm transition (CWT) of the beam pipes, HOM antennas and safety release system). The helium flow in the circuit will be adjusted with a control valve installed on the outlet pipe of the distribution system. Figure 5 shows the design principles of the circuit routing and the thermal shield shape.

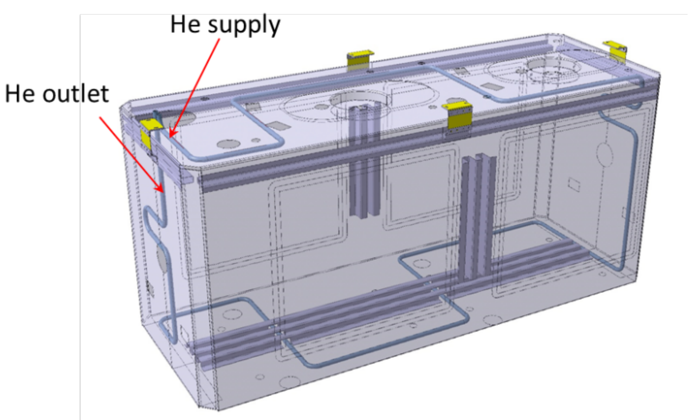

Figure 5. DQW first prototype thermal screen and related cooling loop.

2.3. Beam screen circuit

The beam screen (BS) circuit concerns the second (non-crabed) LHC beam pipe which by integration and design reasons crosses the 2 K helium tank. This circuit is operated as non-isothermal cooling circuit between 4.5 K and 20 K like in standard LHC arc dipoles and quadruples. The aim of this circuit is to protect 2 K helium bath from dynamic heating beam effects and also to provide thermalization for FPCs, HOMs and CWTs to optimize for global thermal performance of the cryo-module. The BS circuit diagram is presented in Figure 6, the principle of its integration is visible in Figure 4b.
Remarks:

- this circuit was not installed in first DQW prototype being tested in SPS as not necessary to confirm principles of cryogenic operation of the crab cavity modules,
- the electrical heater (EH) is used to stabilize helium inlet temperature at required level to avoid thermal induced oscillations in the circuit.

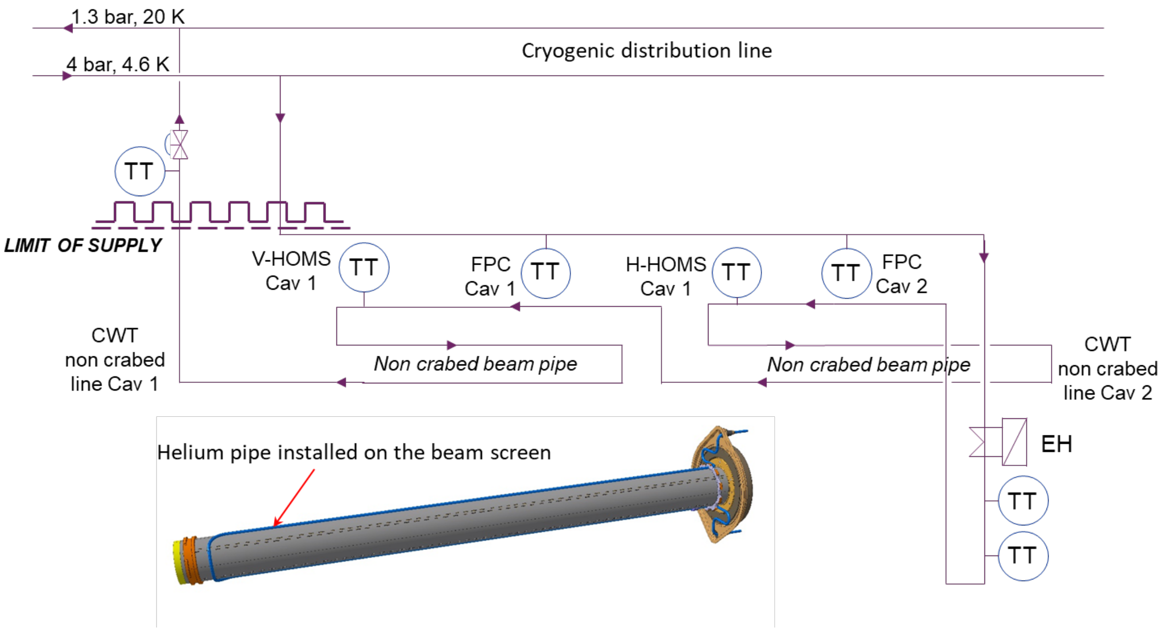

Figure 6. Beam screen flow scheme for HL-LHC crab cavity modules.

2.4. Safety release system

There is the standard system containing the safety valves and the rupture disc to protect internal helium volume from overpressure. Dedicated safety device is installed to the cryostat vacuum envelope. Protection of 2 K helium system is designed using two safety valves in series where the first one is installed is dedicated helium guard. The safety valves system opening pressure is set as 0.7 barg and is designed to fully compensate for the static heat load as well as for some operational instabilities e.g. during cool down. The ultimate protection system is provided with rupture disc sized for identified maximum credible incident as a break of the beam vacuum. Its opening pressure is set to 1.1 barg. The 2 K volume protection system is presented in Figure 7. The related pressure drop in evacuation path for a release case are considered in the design of the system. Thermal shield and beam screen circuits are protected with safety system of the main distribution line of the LHC. The external envelope safety flap protects the envelope from pressurization above 0.5 barg.

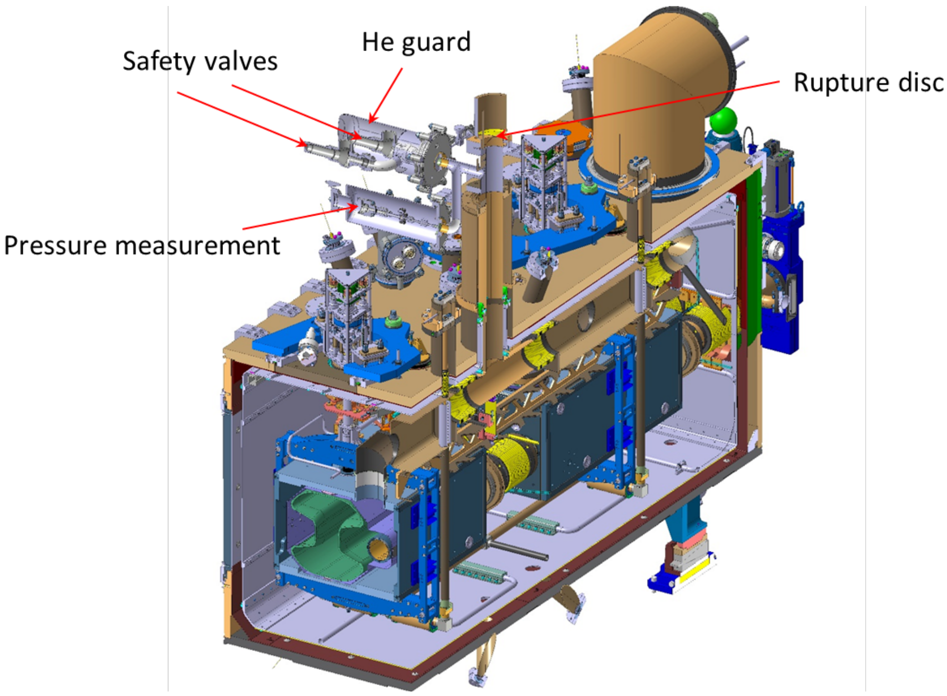

Figure 7. Helium release safety system for RFD HL-LHC compatible prototype.

2.5. Main cryogenic instrumentation

The following cryogenic instrumentation will be installed in the cryo-modules:

- Two electrical heaters, each of 100 W, will be installed on the bottom part of the helium tanks,
- Two level gauges covering whole depth of the superfluid helium,
- Two CERNOX® type thermometers immersed in the superfluid helium,
- Beam screen heater and related thermometers,
- Helium bath pressure sensors covering the ranges from 10 mbar to 4 bara,
- Multiple CERNOX® and PT100 thermometers for monitoring of thermal behavior of different components e.g. FPC, tuners, HOMs, CWT etc.

3. Test results of the first DQW prototype module operation

The first prototype cryo-module containing two DQW cavities was built at CERN and tested for thermal performance, cryogenic stability and RF system operation. One of the most important points for the designers was to confirm about the thermal performance of the system and check heat load to 2 K helium bath. During the test performed in experimental hall SM18 at CERN, the empting time by means of natural boil off could be measured. Knowing exact volumes of the system, evaporation time and using equation (1) the static heat load was recalculated as 18 W, what was in very good agreement with considered design value of 17 W and brought high confidence for applied design solutions [4].

$$Q_{HL} = \frac{L}{t} \cdot m_{He} \tag{1}$$

where L is helium latent heat, t is the measured emptying time and m_{He} is the helium evaporated mass.

The dynamic heat load with operated proton beam was not yet precisely measured and investigation on this value should give first results by end of 2021.

The cryogenic system stability was rated as very good. During steady state operation the pressure in the helium bath stays stable within tolerance of +/- 1 mbar, what is fully compatible with RF requirements.

4. Conclusions and perspectives

For nearly 10 years, the development work to produce the final design of the crab cavity cryogenic modules involves several design teams, specialized in different technical domains such as: RF physicists, vacuum engineers, mechanical designers, experts for different type of instrumentation, precise alignments and cryogenic engineers. This long common effort resulted in finalization of the design and partial testing of the first prototype of the cryo-module with very good results for thermal static heat load and also for first crabbing of the proton beam in the SPS. In Figure 8 we can see the images taken during the SPS test. The left one shows non crabbed beam (voltage = 0), the second one synchronous crabbing with two cavities (voltage of 1 MV from each cavity) and the right one the image of the beam with cavities run in the counter phase [3].

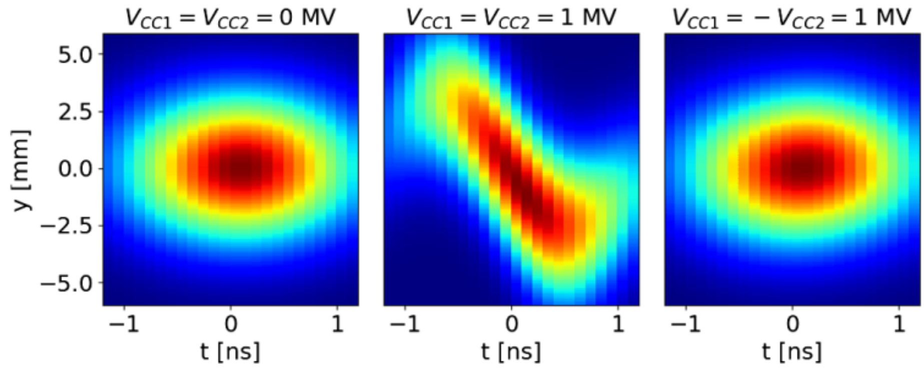

Figure 8. Beam images for crab cavities operation during SPS test [3].

The current development work is focused on extensive testing of the first DQW prototype installed in the SPS and production of two prototype cryo-modules (one with DQW and the second with RFD cavities) with geometry and interfaces compatible for the LHC. After proving of these new prototypes functionalities, the final series production of 10 modules will be launched (total series quantity will include: DQW – 4 modules to be installed in HL-LHC + 1 spare module and RFD – 4 modules to be installed in the HL-LHC + 1 spare module as well). The design of the modules is provided by CERN while the assembly will be performed through collaborations with STFC Daresbury laboratory in Warrington in UK (DQW) and with TRIUMF particle accelerator centre in Vancouver in Canada (RFD). The final installation work of the HL-LHC components is planned to be done during LS3 starting in 2025.

References

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