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DESIGN OF CRAB CAVITY CRYOMODULE FOR HL-LHC*

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Abstract

HL-LHC crab cavities are hosted in a cryomodule to provide optimal conditions for their operation at 2 K while minimizing the external thermal loads and stray magnetic fields. One crab cryomodule contains more than thirteen thousand components and the assembly procedure for the first DQW prototype was carefully planned and executed. It was installed in the SPS accelerator at CERN in 2018 and successfully tested with proton beams. A review has thus been performed right after completion of the assembly in order to gather all the experience acquired and improve accordingly the design of the next generation of crab cryomodules. A second cryomodule with two RFD cavities is currently under production.

INTRODUCTION

The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) will be implemented in 2024-2025. The upgrade aims at increasing the LHC integrated luminosity [1]. One of the key components that contribute to this increase are the RF compact crab cavities that will be placed on both sides of Interaction Points (IP) 1 (ATLAS) and 5 (CMS). Each cavity will apply a transverse kick of 3.4 MV at 400.79 MHz in order to tilt the particle bunches (i.e. crabbing), increasing their overlap when crossing at the IP and resulting in a higher number of collisions [2].There are two types of cavities in the HL-LHC crab cavity project: the Double Quarter Wave (DQW), which will be installed around IP 5 for vertical crabbing, and the Radiofrequency Dipole (RFD) which will be installed around IP 1 for horizontal crabbing.

The cavities are placed in a cryomodule that contains all the components and equipment needed for the operation of the cavities. A section of the RFD prototype of the crab cryomodule can be seen in Fig. 1. Several technologies are used for its manufacturing and operation. The design of the cryomodule was conceived not only to optimize its performance but also the assembly process [3]. The design was driven also by the need for allowing access to the internal components of the cryomodule until a very late stage of the assembly. The assembly of the cryomodule is divided in steps, which consider the different activities that need to be carried out. Each step was planned and detailed in an assembly procedure. Many different tools were required for the handling and positioning of the cryomodule subassemblies. Their interfaces have to be properly defined and integrated in the study of the cryomodule. A preview of the assembly sequence of the cryomodule is shown in Fig. 2.

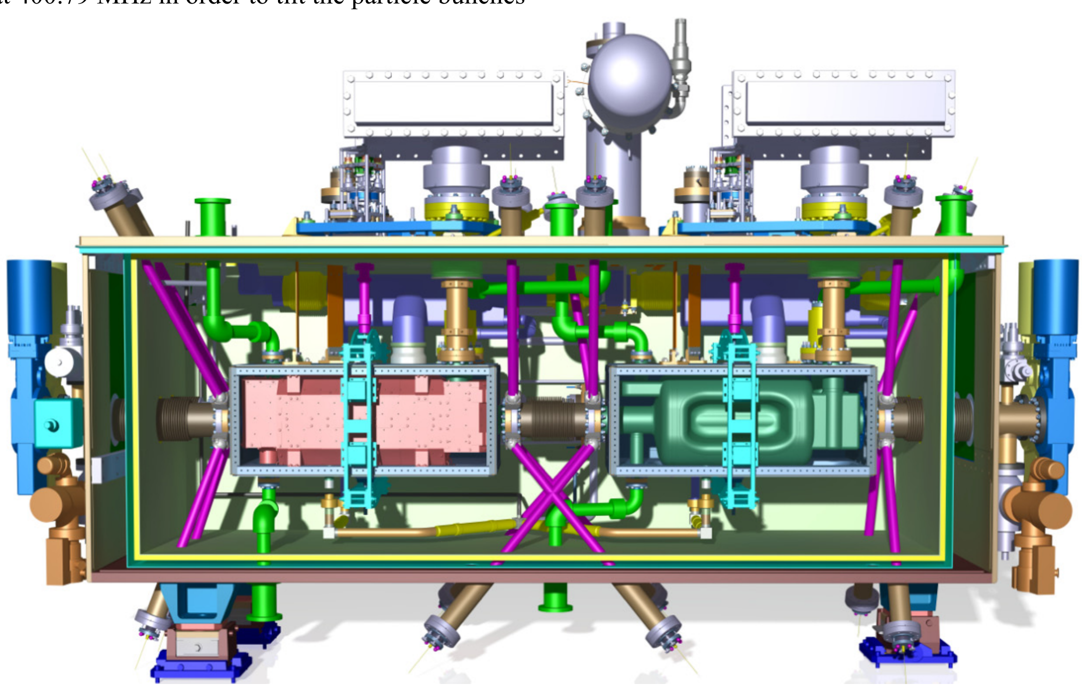

Figure 1: Section of the RFD crab cavity cryomodule prototype.

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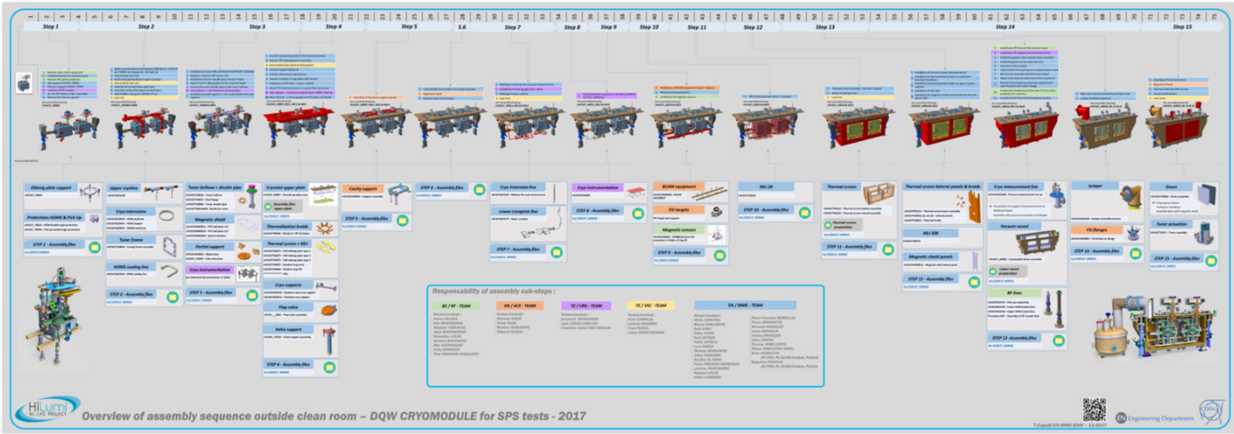

Figure 2: Preview of the assembly sequence of the first crab cryomodule (activities outside the clean room) [3].

CRAB CRYOMODULE DESCRIPTION

Each cryomodule contains two crab cavities, as depicted in Fig. 1. A short description of the main components of the cryomodule is shown in the subsequent subsections.

Dressed Cavity

One dressed crab cavity is composed of the cavity itself in bulk niobium, the helium tank in titanium gr. 2, the cold magnetic shield in Cryophy®, three High Order Modes Suppressors (HOM) for DQW (two for RFD) in bulk niobium, two pick up antennas (one for RFD) in copper or copper with electron beam welded niobium and one Fundamental Power Coupler (FPC) in copper [4].

Cavity String

The cavity string is a closed assembly composed of the two dressed cavities, one inter-cavity bellow (in stainless steel 316LN), two cold/warm beam vacuum chambers and two extremity valves, as shown in Fig. 3. These extremities ensure that the cryomodule components stay under clean air until the final installation in the machine. The string has to be placed in ISO class 5 clean room for preparation, cleaning and conditioning and ISO class 4 clean room for assembly [5].

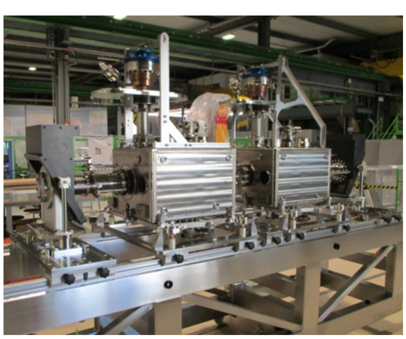

Figure 3: Cavity string assembly for DQW prototype.

Cryogenic Lines

The cryomodule uses helium to cool its inner components at different temperatures using three different lines. One line is used for the cool down of cavities from 300 K to 4.5 K. A second line is used to keep the thermal screen at 50 K. A third line is used during operation to fill the cavity titanium vessels with 2 K superfluid liquid helium.

All the lines are made of non-magnetic stainless steel (relative permeability < 1.005) compatible with the use of cryogenic superfluid helium.

Cavity Support and Alignment

The position of the cavities needs to be adjustable from the outside of the cryomodule. The FPC outer pipe is used as a fixed point for their support, which is also provided by two additional deformable stainless steel blades oriented towards the fixed point (see Fig. 4) [6]. The blades and the FPC outer pipes are thermally intercepted to reduce the heat load to the 2 K cold bath. The support system design is conceived to be stiff enough and, at the same time, to be able to follow the thermal contraction of the cavity.

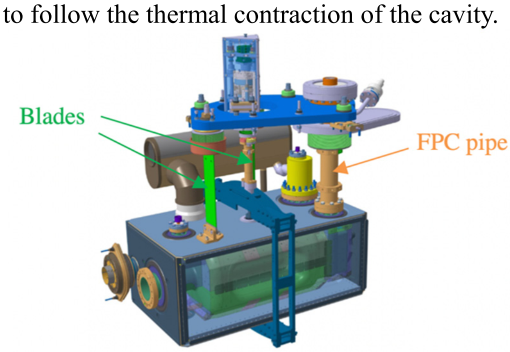

Figure 4: Cavity support for RFD prototype.

Thermal Screen and Super-insulation

The thermal screen consist of a copper structure that is wrapped with Multi-Layer Insulation (MLI). Both the thermal screen and the MLI have the role of reducing the heat load on the 2 K volume. To do so, the thermal screen is actively cooled with a circuit of gaseous helium at 50 K that flows through copper pipes that are brazed to its walls. To reduce the heat loss coming from the 300 K external surfaces, the critical equipment is thermally intercepted through the thermal screen by the use of copper braids [7, 8].

There are two levels of super-insulation in the cryomodule. The first level reduces the radiative heat load from external surfaces at 300 K to the thermal screen at 50 K. The

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second level reduces the radiative heat load from the thermal screen at 50 K to the cold surfaces at 2 K.

Tuner

The tuner has the role of adjusting the cavity to the right frequency (400.79 MHz). The working principle foresees a symmetric mechanical local deformation of the cavity body in the vertical direction. The tuner motor is placed on top of the cryomodule vacuum vessel. For more information about the tuning system and instrumentation see [9].

Coaxial Radio Frequency Lines

The coaxial radiofrequency lines (Fig. 5) are transporting the extracted power at unwanted frequencies from the cavity in operation. The lines are made of a copper-coated 316LN tube that is connected to a commercial coaxial cable. The coaxial lines are connected to the HOM couplers at one extremity and to the outer vacuum chamber at the other extremity. The lines must be designed to provide the best thermal efficiency without compromising RF performance. In fact, the lines are directly linking the cold dressed cavity at 2 K to the 300 K outer vacuum chamber. To reduce the heat loss to the 2 K bath, the coaxial lines are thermally intercepted with the thermal screen at the 316LN tube and present a ceramic insert at the thermalization level [7, 8].

Figure 5: Radiofrequency coaxial line.

Magnetic Shields (Cold and Warm)

There are two levels of magnetic shielding to protect the cavities from stray magnetic fields. The first one, *viz.* cold magnetic shield, is positioned directly around each cavity inside helium tank while the warm magnetic shield is attached like a second skin to the inner surface of the outer vacuum chamber [5].

Position Measurement System (FSI)

The position of cavities inside the cryomodule is measured using Frequency Scanning Interferometry (FSI). Each cavity is equipped with eight targets fixed on its beam flange in insulation vacuum. FSI measuring heads are installed on the outer vacuum chamber. Each head has an optical fiber feedthrough used for the measurement. The deformations must be anticipated (thermal contraction, vacuum forces, etc.) and shall be included in the measurements to know the exact position of the cavity.

The experience on the first prototype showed that the accuracy of the abovementioned system is below 50 µm [10].

Mechanical and Cryogenic Instrumentation

The cryomodule is equipped with thermal sensors (CERNOX and PT100), level gauges, a pressure transmitter, heaters (installed below dressed cavities for warming up), and heating cartridges that are installed on the outer surface of the cryomodule in order to warm-up cold spots and prevent icing. Several strain gauges are also installed on the support system of both cavities in order to monitor the level of stress during transport, installation and operation of the cryomodule. The material and the number of wires are included in the thermal balance study of the cryomodule [11].

Outer Vacuum Chamber (Cryomodule External Envelope)

The outer vacuum chamber is made out of bulk stainless steel and ensures the leak tightness between the outer atmosphere and the insulation vacuum (see Fig. 6) [5]. The general idea for the vacuum chamber assembly consisted in a fully equipped top plate that is lowered on the cryostat (see Fig. 2) [3]. The vessel is equipped with ports for instrumentation and radiofrequency line outlets, in addition to the ports for the FSI positioning system. Three manual supporting jacks are installed on the lower face of the outer vessel in order to adjust its position during installation. The vacuum chamber design was conceived with bolted connection so that it could be reopened in case of need.

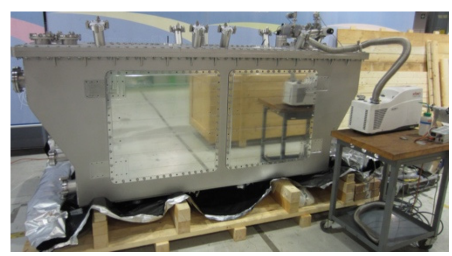

Figure 6: DQW prototype outer vacuum chamber.

Jumper

The jumper connects the cryomodule to the cryogenics services of the machine (SPS/LHC cryogenic plant). It encloses all the cryogenics lines needed for the operation of the cryomodule.

SPS TEST RESULTS

The first tests carried in SPS during 2018 showed the first effect of crabbing on a proton beam, validating the studies carried out for many years [12]. These tests also validated many of the choices made on the design of the cryomodule, such as the radiofrequency coaxial lines and the tuning system (among others). The thermal loads measured during the test were remarkably close to the numerical estimations made during the design phase of the cryomodule [7, 8].

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LESSONS LEARNT AND IMPROVEMENT FOR LHC

Lessons Learnt from the First Prototype Assembly

The design of the components and the assembly strategy of the cryomodule provided satisfactory results. In particular, the idea of lowering the top plate to the cryostat allowed an easy assembly without inserting huge complications in the design and shall be kept for the next generation of cryomodules. However, some changes in the design could improve the design and assembly processes:

Cavity support

The stiffness of the three adjusting rods was not high enough, partially due to the thickness of the base plate (see Fig. 7). In addition to that, a layer of bronze needs to be added below these sliding plates to smooth their displacement in order to remove the stick/slide effect.

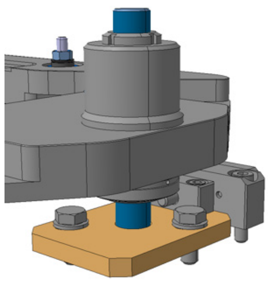

Figure 7: First design of the cavity adjustment. Sliding plate in orange.

Thermal screen

The previously mentioned copper design of the thermal screen was selected due to the familiarity of the CERN team with it, as it was based on the HIE- ISOLDE experience [13]. However, this design is expensive and difficult to manufacture. It is foreseen to reduce the cost of the future generation of cryomodules by using aluminium panels with clamped stainless steel pipes. This new design will provide a reduced (but sufficient) thermal performance with regard to the copper thermal screen.

The support of the thermal screen must also be redesigned so that its vertical position could be adjusted.

Super-insulation (MLI)

Large blankets are complicated to manipulate and to adjust. It would be recommended to divide the blankets in smaller pieces and to add adjustment parts that can be cut. This would also provide a better fitting of the insulation to complex shapes.

The supports and fixations must be improved to prevent excessive sagging, especially in the lower face of the thermal screen.

The Velcro used to attach the MLI was too strong, it was almost impossible to separate two pieces of MLI without damaging them.

Fundamental power coupler outer pipe

The copper coating procedure tested (sputtering) did not provide good results on the final parts. The adhesion of copper on the stainless steel was not good enough and defects on the coating were observable (see Fig. 8). The copper coating has been replaced with a more standard galvanic deposition procedure (under-layer of gold 1-2 µm and copper coating 10-15 µm).

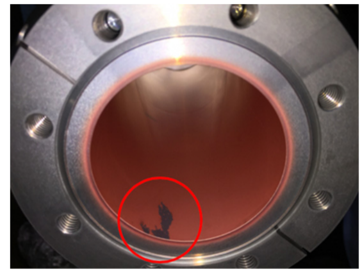

Figure 8: Example of a defect after a test on the first FPC outer pipe coating.

Warm magnetic shield

Contact fingers (see Fig. 9) have proven to be too stiff when welded at both extremities and they buckle once in contact with the shield counterpart, instead of providing an elastic contact force. As an improvement, it has been proposed to weld only one extremity, keeping the other free.

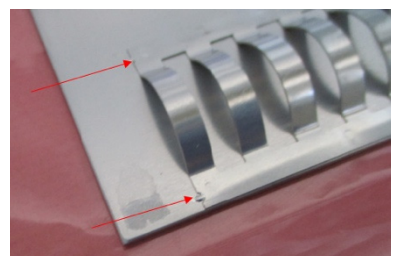

Figure 9: Flexible contact of first DQW prototype welded at both extremities.

Position measurement and adjustment

The integration team responsible for the installation in the tunnel was asked to make some intermediate measurement and position adjustment for this first assembly. No tolerances were fixed, as achievable values were still not known. A best effort campaign was launched, in which a lot of time was spent making the best possible alignment. Thanks to this experience, optimized and realistic tolerances will be provided for the future cryomodules.

Instrumentation

The instrumentation cables (i.e. sensors, gauges, power, etc.) must be categorized by their owner so they can be grouped, separated or shielded if needed.

The SPS test results showed that some glued sensors were lost after a few thermal cycles, while all of the bolted sensors are still working. Hence, bolted connexion are preferred in the future.

Outer vacuum vessel

Surface finishing should avoid any surface blasting techniques, which have demonstrated to be difficult to be cleaned by hand.

During the first assembly, some of the O-ring gaskets were really hard to install (the gasket was falling from the

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groove). Trapezoidal grooves (or any other shape that may hold the gasket) must be used where required.

Jumper

The 3 mm thick centering part in G10 (see Fig. 10) on the service module side was not strong enough and was partially broken during transport. This part has to sustain the forces coming from the thermal contraction of the pipe and the compensators. A thicker support using the same material has been designed for the cryomodule.

Figure 10: Jumper centering part on cryomodule.

Additional requirements for LHC

Radiation level

The radiation dose in LHC in the area of the crab cavities is under calculation. The first estimate shows that the integrated dose close to the beam is in the order of 10 MGy on 12 years when at 50 cm the dose is around 100 kGy. All the material used in the construction of the cryomodule shall be able to sustain such dose without damage for the duration of the operation.

Second beam pipe

A second beam pipe must pass close to the crab cavities in the LHC cryomodules, as shown in Fig. 11. Thus, the corresponding vacuum chambers shall be included.

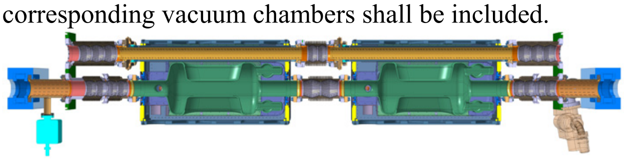

Figure 11: Horizontal section of both beam lines and their corresponding vacuum chamber (LHC cryomodule).

Beam screen with active cooling

The abovementioned second beam pipe passes really close from the active crab line and is subjected to the 2 K helium bath. It is required that the beam pipe passing though the cold sections must be shielded and cooled down at a temperature of around 20 K. This temperature will be guaranteed by an active cooling line welded on the beam screen.

Shielding of vacuum bellows

The radiofrequency impedance of the LHC shall remain below an acceptable threshold. To do so, the beam must be shielded from any abrupt change on the vacuum chamber geometry. The vacuum bellows are one of the most complicated elements to shield as they need to keep their flexibility. A new concept of deformable shield (see Fig. 12) has been developed at CERN and will be used in the crab cryomodules [14].

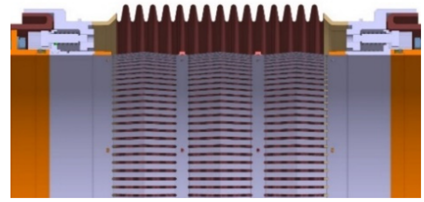

Figure 12: Example of deformable screen in bellows [12].

Cryogenics safety valve

In the SPS accelerator the safety valve for the cryogenic 2 K circuit is installed on the service module side, as the cryogenic plant is dedicated to the crab cavity test stand. In the LHC, the cryogenic plant is supplying helium to many equipment. Therefore, the crab cavity cryomodules need to be individually protected with a safety valve, dimensioned specifically for each type of cryomodule. This valve is positioned on the outer surface of the cryomodule and is directly linked to the 2 K cryogenic line, so that it represents an additional thermal load on the cavity.

Transport of the cryomodule

The assembly of the RFD and DQW series cryomodules will be done in two external institutes. RFD cryomodules will be assembled in Triumf (Canada) and DQW cryomodules in STFC (United Kingdom). Some design improvement (e.g. specific protections or stiffeners) shall be introduced to protect the cryomodule during transport. At this moment a study of the different component behaviour is ongoing and should be integrated soon.

Outer vacuum chamber

The overall shape of the outer vacuum chamber is changed in order to be able to integrate additional beam vacuum equipment. The radiation level increases the risk of damage on rubber O-rings, so it has been decided to replace some gaskets by welded connections with the possibility to cut them to open the cryomodule.

CONCLUSIONS

The crab cryomodule embeds many technologies and a lot of studies must be carried out. Every change on the design must be carefully investigated in order to avoid any unwanted impact on the operation, manufacturing or assembly of the cryomodule. The information that oriented the design must be documented and shared among all the involved actors. This work and the review of the first assembly allowed to improve the next generation of cryomodules.

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