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OPERATION EXPERIENCE WITH THE LHC ACS RF SYSTEM

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Abstract

The LHC accelerating RF system consists of two cryomodules per beam, each containing four single-cell niobium sputtered 400.8 MHz superconducting cavities working at 4.5 K and an average accelerating voltage of 2 MV per cavity. The paper summarises the experience, availability and evolution of the system within 10 years of operation. The lessons learned from the successful replacement and re-commissioning of one cryomodule with a spare module, and the recent re-test of the originally installed module on the test stand are also included. Finally, a review of the spare cavity production and long-term developments are presented.

RF SYSTEM OVERVIEW

The RF system in the LHC machine accelerates the beam during the ramp, compensates small energy losses and provides the longitudinal focusing. The RF section of the machine with a length of approximately 30 m consists of two cryomodules per beam each containing four single-cell superconducting cavities, see Fig. 1, 2.

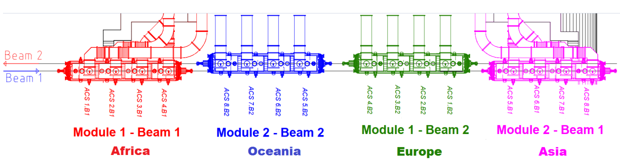

Figure 1: Layout and naming convention of the RF section in the LHC machine as at 14 June 2019.

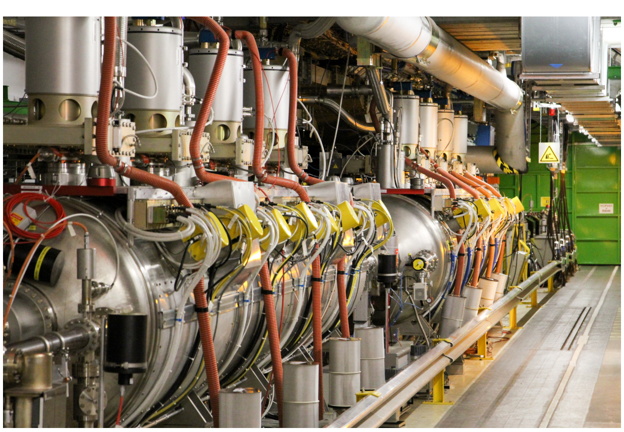

Figure 2: Two out of four RF cryomodules at point 4 of the LHC tunnel.

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Each cavity has four Higher Orders Mode (HOM) couplers of two different types. The narrow-band coupler covers the first two dipoles modes at 500 and 536 MHz and the broad-band coupler covers the range from 700 MHz to 1300 MHz. Inside the cryomodule the cavities are connected by large diameter (ϕ = 300 mm) beam tubes and unshielded bellows. Each cavity has a variable high-power coupler to optimize settings from injection to top energy and is powered by a 300 kW klystron. Mechanical tuner activated by a stepper motor with a 100 kHz range. The Low Level RF (LLRF) system consists of the klystron polar loop and the impedance control feedback system [1, 2].

The nominal RF parameters are listed in Table 1. These parameters were modified during operation in Run I (2009-2012) and Run II (2015-2018). Most of the time the total RF voltage at injection was 6 MV and the total voltage at flat top was 12 MV. At injection the half-detuning beam-loading compensation scheme was used and at flat top the full-detuning beam-loading compensation scheme was used operationally since 2017 [3].

Table 1: Overview of the Nominal RF Parameters.

	Injection	**Collision**
Revolution frequency [kHz]	11.245	11.245
RF frequency [MHz]	400.8	400.8
Total RF voltage [MV]	8	16
Loaded Q_L	20 000	60 000
Klystron forward power [kW]	80-110	80-120

RF SYSTEM AVAILABILITY AND PERFORMANCE

In 2011, cavity 3 in module Americas did not work reliably above 1.2 MV. Consequently, the cavity was operated with lower voltage in 2012, leading to a significant reduction in faults. During the 1st Long Shutdown (LS 1) (2013-2014) cryomodule Americas with this cavity has been replaced.

During Run II, the total downtime of the RF system was about 50 hours per year, as shown in Table 2. The observed increasing number of hardware faults may indicate the ageing of equipment. A noticeable number of controls faults is associated with evolving software in order to cope with the operational requirements that change over time. Nevertheless, a significant number of vulnerabilities were diagnosed and repaired remotely; access to the machine was needed mainly in the case of hardware faults [4].

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Table 2: Distribution of LHC RF System Faults During Run II.

Year	2018	2017	2016	2015
Nb of faults	48	32	32	54
Hardware faults	27	19	16	23
Controls faults	18	10	16	31
Other faults	3	3	0	0

RF System Re-commissioning

The restart of the RF system after annual technical stops can be divided into five phases. The first four are performed before the first beam and consist of the following steps:

- General maintenance, software and control updates.
- Re-commissioning of high-voltage and high-power systems. This includes the calibration of klystron DC power against collector thermal power, and the validation and adjustment of the circulators, arc detectors, interlock levels, etc.
- Re-commissioning of the RF cryomodules. During this step, the high-power couplers are conditioned up to full power and all cavities are conditioned up to nominal field.
- Calibration and staged closing of the LLRF loops at different working points.

The fifth step is the setting up of the LLRF beam control during the first capture of the pilot beam, as well as the first nominal bunch. Furthermore, the beam-loading compensation schemes require fine-tuning when the first batches are injected in the machine [5].

Module Replacement

One of the most important interventions during the 10 years of operation was the aforementioned replacement of cryomodule Americas. One of the cavities in this cryomodule had an unpredictable behaviour above 1.2 MV: long stability periods were interrupted by sudden He pressure spikes and temperature increases of one of the four HOM antennas. To provide 12 MV per beam, uneven cavity voltage settings were used: 1.2 MV for the 3B2 cavity and 1.54 MV for the others. This situation was not optimal as uneven voltages cause an uneven phase shift due to transient beam loading. Hence, it was decided to replace the defective cryomodule with a spare one during LS 1 [6] .

Shortly before the installation of the spare cryomodule Europe in the tunnel, a vacuum leak in one of the pumping manifold of the spare RF cryomodule Europe was detected. A corrosion process caused by residues of the stainless steel cleaning procedure was identified as a likely source of the problem. These pumping manifolds had been designed for the Large Electron-Positron Collider (LEP), without copper coating and they were recycled and copper plated for the needs of the LHC. The cleaning process required after copper plating caused the risk of trapping chlorine residues. The leaky pumping manifold was replaced by spare and cryomodule Europe was installed in the LHC machine.

The defective cryomodule America was tested in the SRF test facility at CERN (SM18). There one LHC type klystron allows testing of one cavity at a time at 4.5 K. Three waveguide switches can send 300 kW of RF power to the individual cavities. RF conditioning with short pulses and high power was effective to recover cavity performance. This resulted in a significant reduction in radiation, and the cavities were able to work stably for several hours at 2.5 MV.

A new set of pumping crosses was designed and fabricated in 2017 by the CERN vacuum group, eliminating the risk of trapping chemicals during copper plating process. To verify the new design and to allow for further investigation of the internal surfaces of the old units, a pair of new units was installed on the spare cryomodule America. During the subsequent high power RF test, each cavity reached stable operation at the required accelerating voltage: 2.5 MV at $Q_x = 60k$ (flat top) and 1.5 MV at $Q_x = 20k$ (injection position), where Q_x is the external quality factor of the cavity [7].

Cavity Field Antenna Investigation

During the ongoing 2nd Long Shutdown (LS 2) (2019-2020) major renovations at the machine are taking place.

At the beginning of RF conditioning in 2017, it has been noticed that for the cavity 1B1, the field level was lower than expected for a given power and coupler position. Out of three possible causes, which are: being off-tune, having wrong coupler position readings, and having wrong field measurements, we could exclude all but the last. Measuring the transmission between the two identical antennas (the operational and the spare antenna, mounted on the same flange) on cavity 1B1, in comparison to the antennas of the other cavities of that module, showed a difference of 10 dB. Since April 2017, the cavity was operated using the spare antenna. As the cause of the problem was not fully understood, it was necessary to open the cryomodule insulation vacuum in situ and check the internal cabling. During the inspection in May 2019, it was noticed that the cable connected to the faulty antenna feedthrough was not completely tightened. Furthermore, the connector nut was badly damaged by improper mounting. The connector was very likely overtorqued, as the outer conductor fingers were significantly deformed, see Fig. 3. In addition to the replacement of the cable, a leak check of the antenna feedthrough was done to rule out problems with the ceramic and no leakage was detected.

SPARE CAVITY PROGRAM

Currently, there is one functional spare cryomodule and one spare dressed cavity available.

The most likely and studied module failure scenario is a break of the ceramic window in a power coupler. In the case of pollution or mechanical damage to a cavity, the entire module would need to be removed. Disassembly of the mod-

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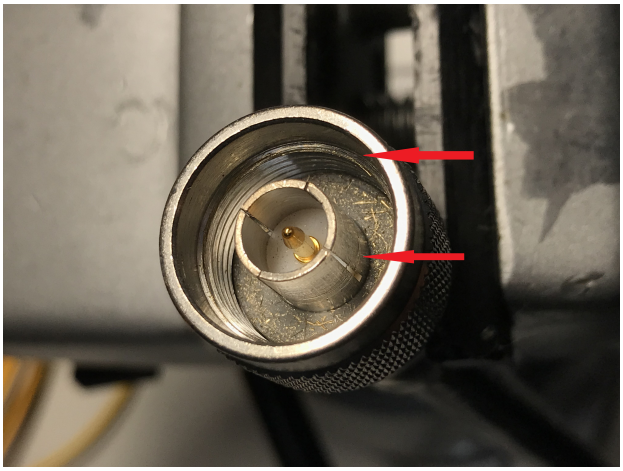

Figure 3: Cable connector showing signs of damage on the thread and RF fingers.

ule, cavity rinsing and eventually re-coating will be needed. After re-testing the cavities in a vertical cryostat, clean room re-assembly of the cavity or cavities in the module with all the ancillary components would follow. Then RF conditioning of the module would need to be done in the horizontal bunker before installation into the machine. All these steps would take 40 weeks.

In order to shorten the downtime due to a potential module failure, it has been decided to produce spare cavities. The goal is to have four dressed spare cavities and one 1/4 test cryomodule available for Run III (2021-2023). With a pre-assembled cavity train, a complete cavity exchange and re-commissioning of a LHC module will take around 23 weeks. The 1/4 cryomodule can then be used as test object in the horizontal test stand in SM18.

Prototype cavities were produced and their results are very encouraging. The first model cavity (MC01) was manufactured and was tested in the vertical cryostat at the beginning of 2019 reaching nominal performance, see Fig. 4.

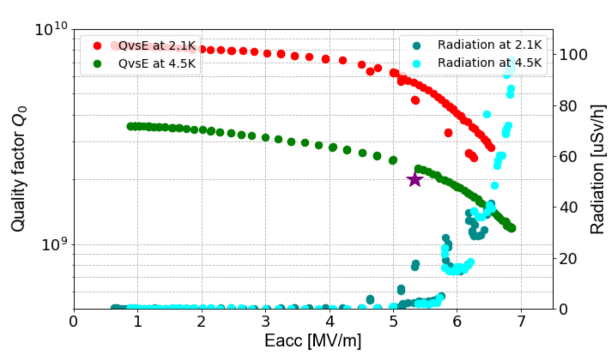

Figure 4: Model cavity performance (purple star represents the specification point).

Another motivation of the spare cavity program is to have a team of trained experts who are familiar with design, manufacturing, and assembly of the LHC modules, to ensure the most efficient response in case of any technical problems. In recent years, significant efforts were made to restore the complete engineering and manufacturing folder. Work has also begun to improve the LHC main coupler design to prepare for the case where spare couplers in stock are affected by ageing [8].

FORTHCOMING

In recent years, many machine development studies have been performed, along with simulation and measurement studies related to longitudinal beam stability, controlled longitudinal emittance blow-up, and RF power limitations at injection. These studies allowed for a better understanding of the longitudinal beam dynamics in the machine [9]. The gradual increase in the beam intensity towards the target value of 1.8e11 ppb for Run III, and 2.3e11 ppb respectively for the High-Luminosity LHC (HL-LHC) may potentially call for an upgrade of the RF system. At the moment, several studies on this subject are ongoing encompassing the high- and low-power RF systems. Dynamic adjustment of the circulator and Switch and Protect module (preventing overdrive of the klystron) to overcome power limitations during injection transients are under study. The possible benefits of high-efficiency klystrons and additional cavities are also taken into account [10]. Numerous upgrades and maintenance of the RF controls and high-power system are also envisaged.

CONCLUSIONS

The RF system has performed very reliably since the start-up. In operation, hardware-related faults were dominating and the ageing effect is expected to reduce the system performance in the long run. This highlights the importance of having operational spares for both high and low power devices, such as LLRF modules, power supplies, high-voltage tanks, cavities, etc, as well as the continuous improvement of the system.

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