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DEGRADATION AND RECOVERY OF THE LHC RF CRYOMODULE PERFORMANCE USING THE HELIUM PROCESSING TECHNIQUE

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Abstract

The LHC RF cryomodule "Asia" suffered an accidental influx of about 0.5 l of tunnel air during the leak checks of the pumping manifolds. The resulting risk of particle contamination was difficult to assess, and could not be excluded with certainty. If one or more cavities were contaminated, a severe impact on beam operations in the LHC machine was to be expected. In order to minimize the risks, the Asia cryomodule has been replaced with a spare unit. Subsequently, the cryomodule was tested in the SM18 test facility without intermediate venting, and showed high levels of radiation due to field emission above 1.8 MV in one of the cavities. The other cavities were less strongly affected, but clear signs of contamination were observed. The helium processing technique was used to improve the performance of the SRF cavity with respect to field emission. This paper will discuss the results of the above-mentioned test.

INTRODUCTION

The RF section of the machine with a length of approximately 30 m consists of two cryomodules per beam, see Fig. 1.

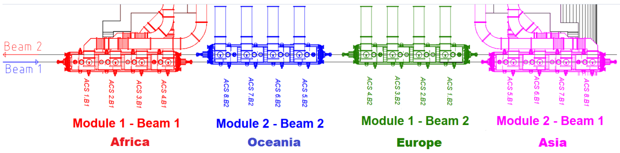

Figure 1: Layout and naming convention of the RF section in the LHC machine as at 31 August 2019.

Each cryomodule contains 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. Each cavity is driven by a 300 kW klystron via a variable power coupler, according to the different requirements at injection and at top energy, together with a heavy beam loading. For damping of higher-order-modes (HOMs), four couplers of two different types are used. The narrow-band coupler covers the first two dipole modes at 500 and 536 MHz and the broad-band coupler covers the range from 700 MHz to 1300 MHz. The LHC niobium-coated cavities are almost insensitive to the Earth's magnetic field, therefore no magnetic shielding is installed inside the cryomodules. The cryomodule has three different and independent vacuum systems: for cavity, secondary beam and cryostat insulation. The cavity vacuum is pumped at room temperature by two 60 l/s ion pumps mounted at each extremity of the cryomodule. The cavity vacuum can be isolated by the gate valves at the ends of each module, to maintain a vacuum during transportation and installation. Due to the size of the beam separation, the second beam tube must pass through the insulation vacuum of the cryostat to allow the beam to pass in the opposite direction [1, 2].

The inner structure of the LHC RF cryomodule is shown in Fig. 2.

LONG SHUTDOWN 2

The currently ongoing long shutdown, LS2, is dedicated to preparations for Run III of the LHC machine, which will achieve an integrated luminosity equal to the two previous runs combined [3]. During this technical break, the LHC RF cryomodules also underwent consolidation works, one of which was to carry out leak checks of the pumping manifolds. These pumping manifolds had been designed for the Large Electron-Positron Collider (LEP) and they were recycled for the needs of the LHC. Since in previous years a corrosion process was observed on one of the pumping manifolds, which caused a vacuum leak, it was decided to visually inspect and leak check all pumping crosses in the LHC tunnel [4].

During the aforementioned leak checks in the LHC, the RF cryomodule M2B1 (Asia) suffered an accidental influx of about 0.5 l of tunnel air, giving a pressure spike of 0.65 mbar. The situation was carefully analysed and it was decided that, in order to minimise the risks, the cryomodule had to be replaced with the operational spare unit (America). It should be noted that the aforementioned accidental venting took place on the pumping cross near the cavity A [5].

Replacement of the Cryomodule

Removal of the possibly defective Asia cryomodule and installation of the spare America cryomodule was agreed and planned in accordance with the LS2 master plan. The operation started in October 2019 and it was completed 10 weeks later. The transportation is associated with a significant risk: any damage to the coupler ceramics can lead to a vacuum failure and, consequently, catastrophic dust contamination of the niobium surface of the cavities. This would require complete disassembly of the module in order to rinse and retest the cavities, and that could delay the restart of the LHC machine for several months [4]. Therefore, the America cromodule was safely transported to the LHC machine prior to start of Asia cryomodule removal. After disconnecting the

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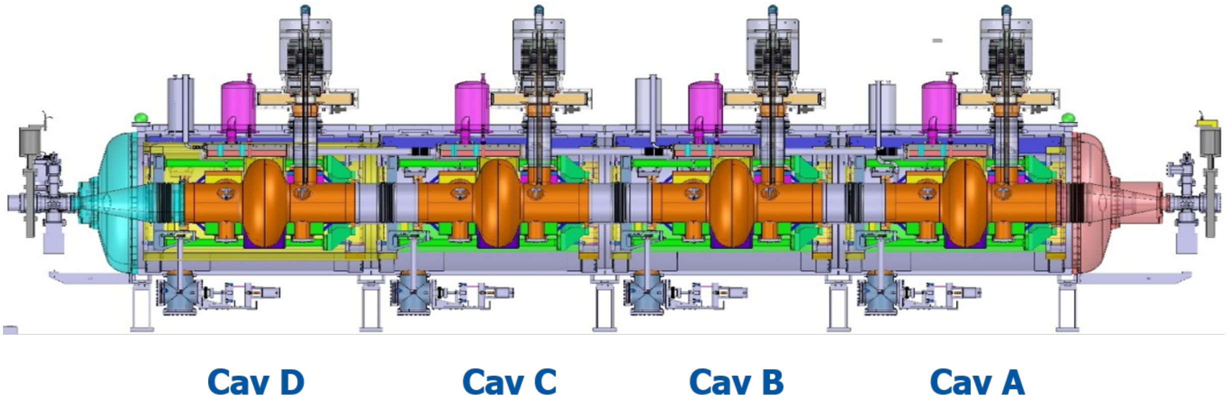

Figure 2: LHC RF cryomodule interior and cavity naming convention. Four cavities each equipped with a helium tank, tuner, HOM couplers and power coupler are grouped together in a single cryomodule. The accelerated beam enters the module through cavity D (courtesy CERN EN-MME).

Asia cryomodule from the beam line, the module remained in the UX45 cavern next to the tunnel until the connection work of the America cryomodule was completed. The transport of both cryomodules was carried out at a maximum speed of 10 km/h, with cavities under vacuum and tri-axial accelerometers mounted on the cryomodules. Registered vibration levels did not exceed 0.1 g at 200 Hz. In the frequency domain, the highest amplitudes were recorded for frequencies below 20 Hz, which are related to the movement of the vehicle on the road. Vacuum measurements taken after the transport also confirmed that the operation was carried out correctly [5].

After the America cryomodule was installed in the corresponding slot, it was pre-aligned and then all systems were connected and progressively validated, including RF waveguides, cabling, vacuum and cryogenic connections. Cooling down and the first cold measurements of this module will be performed in summer 2021 [5]. The installation of the America cryomodule in the LHC tunnel is shown in Fig. 3.

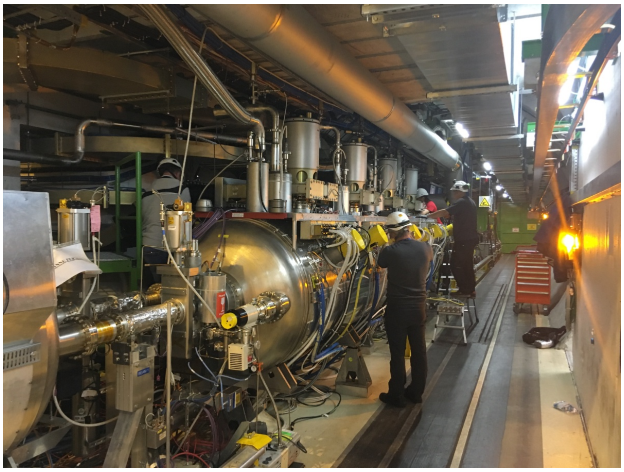

Figure 3: The installation of the America cryomodule in LHC machine, November 2019.

RF TEST PREPARATION AND RESULTS

The Asia cryomodule was transported under vacuum to CERN's SM18 test facility and prepared for the cold test [6].

Horizontal Test Stand

The M9 horizontal test stand is designed to perform the test at 4.5 K and 300 kW CW RF power (LHC machine conditions). Only one 400 MHz klystron is available in the test facility, so cavities have to be tested one by one, and no simultaneous powering of the four cavities is possible. The configuration of RF waveguides is able to distribute RF power to each individual cavity using three waveguide switches [7].

The following diagnostics were available during the test to monitor the cryomodule environment: cavity and coupler vacuum, insulating vacuum, temperature sensors, liquid helium level, helium bath pressure. Several arc detectors were installed to detect a visible light when an RF arc occurs. Two sensors used for monitoring of field-emission induced radiation (WS05C Graetz monitors) were installed at the two extremities to measure the instantaneous radiation dose during the RF tests; their position was adjusted during the test to mimic the position of the radiation monitor in the LHC tunnel [6].

Vacuum

The vacuum pumping conditions during the cryomodule test were as follows:

- The cavity vacuum was pumped by two ion pumps connected to each pumping manifold.
- The insulation vacuum was pumped by a primary pump and a turbo-molecular pump.
- Electron stoppers were installed, and they were actively pumped with the dry pumping units.
- The sector valves remained closed at the beginning of the test.

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- An additional dry pumping unit, consisting of a pre-pump and a turbomolecular pump with helium inlet, was connected to the pumping cross near cavity A.

Cryogenics

The LHC RF cryomodule consists of four single-cell cavities, each with its own 80-liter helium tank. The cryomodule has one inlet for liquid helium (Cavity A) and one outlet (Cavity D) for helium evaporated by static and dynamic losses. Inside, the four helium tanks are connected to each other at the liquid and gas level in such a way that a joint helium feed and a joint gas return are sufficient. The static heat load at 4.5 K is about 150 W per module and, at nominal field (2 MV per cavity) the total RF losses amount to 100 W.

Cooldown from room temperature to 4.5 K was achieved over 36 hours in a controlled manner. While the cryomodule is being cooled, the pressure and liquid helium levels are controlled. Temperature gradients, instead, are not controlled. The nominal operating pressure is 1350 mbar.

RF Conditioning

The RF conditioning of the fundamental power coupler (done at cold) and of the cavity at high field takes approximately one week per cavity. The process consists of pulsed RF conditioning, with a gradual increase of the pulse length (from 200 μs to CW) and amplitude ramping (from 20 kW to 300 kW) using an automatic control process. It is based on a fast loop using the analogue vacuum measurement, with an upper threshold set to $3{\times}10^{-9}$ mbar on the power coupler Penning gauge. If this threshold is reached, a variable attenuator reduces the drive power of the klystron and the forward power is decreased. Frequency modulation with a span of 100 kHz around the center frequency of 400.8 MHz is also applied. As the fundamental power coupler is variable, the RF conditioning procedure has to be repeated at different coupler positions, with a particular attention to the injection and flat top energy position. Maximum cavity field is obtained with the coupler set for a minimum coupling, the cavity conditioning therefore takes place predominantly at this position [6, 7].

RF conditioning of the Asia cryomodule was started according to the above-explained procedure. During the measurements of the D cavity, a high level of radiation, not seen before, was observed, up to 1 Sv/hr at 2.4 MV CW, with the exponential field emission onset around 1.8 MV. There was no quenching. Likely local heat generated by surface defects or contaminants was quickly dissipated by the copper substrate. The temperature sensors on the tank and on the HOM couplers cups showed no temperature increase. There was also no substantial increased of the helium consumption, but due to the very high field emission, the Asia cryomodule could not be operated at 2.5 MV as this was causing the saturation of the radiation sensor. In the long run, such high radiation levels may also damage the surrounding electronics. Therefore, also taking into account the risk of further deterioration of the cavity performance and the possible impact on the performance of the remaining cavities, the cryomodule was not considered qualified for operation.

High power pulsed (HPP) RF conditioning was applied in order to suppress field emission and reduce the x-ray radiation levels. Unfortunately, after several hours of HPP processing with following settings: 270 kW forward power, 3.2 MV and pulses of 500 μs up to 2 ms with a duty cycle of 2.4-10 %, the field emission remained high. Figure 4 shows the radiation measurements as a function of the accelerating voltage for all cavities (cw). It should also be noted that the measured level of X-rays in the remaining cavities was higher than that observed in the LHC tunnel in 2018.

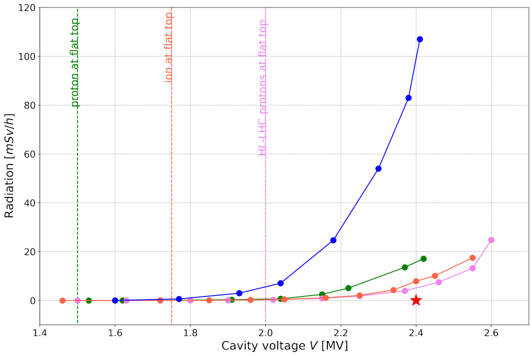

Figure 4: Radiation versus accelerating voltage measurements for all cavities in Asia module. The radiation sensor mimics the position of the radiation monitor in the tunnel (in green - cavity A, in violet - cavity B, in orange - cavity C,in blue - cavity D, the red star shows the results from the LHC tunnel).

Due to the unsuccessful attempts to suppress the field emissions and reduce the X-ray level with HPP, it was decided to apply helium processing.

Helium Processing

The helium processing technique has been used at CERN for many years [8]. It is applied to improve the performance of SRF cavities with respect to field emission, although the exact mechanism by which it causes changes remains unclear [9]. This technique, however, was not frequently used for fully equipped modules due to the risk of damaging the power couplers and the ceramic window by possible glow discharges, which can lead to a permanent damage. Particular attention should be paid to the fact that the cavity vacuum level during He processing is much higher than the vacuum interlock level normally set during RF conditioning, so the procedure has to be applied with virtually bypassed interlocks. Another point that requires attention is the risk of human error, especially with regard to an installation and operation of vacuum devices and gases in the cold environment. During the process, gaseous helium is introduced into the cavity to a pressure just below that which is suitable for an RF discharge. It has been suggested that the field emis-

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sion current locally ionizes the helium gas, creating a local plasma that heats and melts the emission source, provides a microscopic bombardment of the source with helium ions, or amplifies the local field to the point where the current density is enough to detonate the emitter [10]. The injection of a gas into the beam vacuum of an RF cryomodule filled with liquid He is a critical operation and a detailed procedure has been established [6]. The main steps of this procedure concern the clean connection of the vacuum pumping unit to the cavity vacuum, the slow injection of the He gas, the set-up of the vacuum and RF interlocks including a newly developed breakdown detector and the pumping of the He gas after the processing followed by a thermal cycle. An important step is a clean connection to the cryomodule followed by the leak detection and RGA (residual gas analyser) and the bake-out needed to reach the pressure limit of the pumping station ($\approx 1\times10^{-9}$ mbar). Figure 5 shows the He injection pumping unit connected to the pumping manifold of Asia cryomodule. The injection of the gas into the cavity vacuum of a cold module is the most critical operation of the whole procedure: after saturation of the cold inner surface of the cavities, the pressure increases quickly with the quantity of gas injected. The injection must be done very slowly and stopped when the total pressure reaches 1×10^{-5} mbar at the pressure probes mounted on pumping cross on the other side of the cryomodule and the main power couplers that are at room temperature. Several vacuum parameters, which are used as safety interlocks during a normal operation, were modified which has the effect of disabling the protections. In addition, a newly developed breakdown detection that looks at the difference between forward and reflected power during the pulse was implemented.

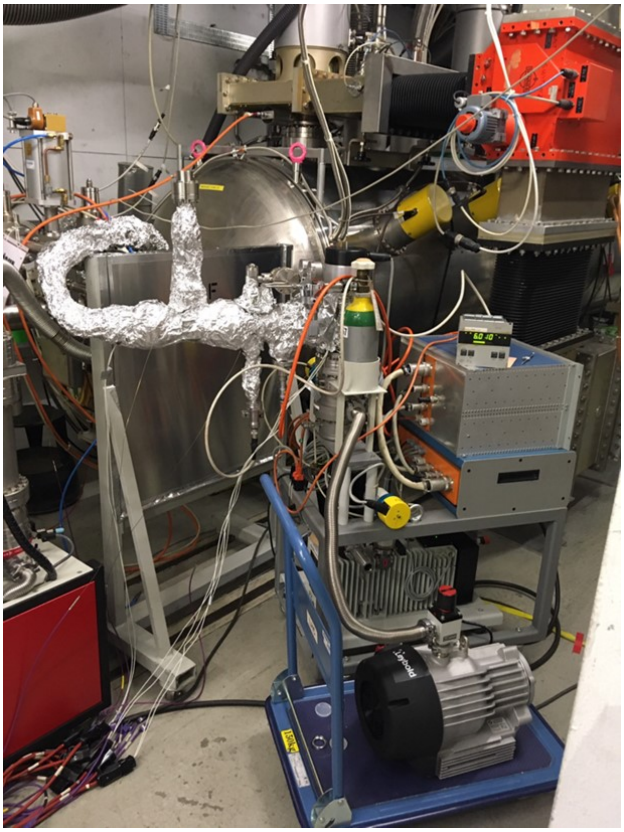

Figure 5: The He injection pumping unit connected to the pumping manifold of Asia cryomodule.

Results of the Helium Processing Progress against the field emission was observed by the reduction of X-rays. After 1 hour of He processing with 10 ms pulse length and 50% duty cycle at 2.5 MV and the pressure of 1.4×10^{-5} mbar, the level of radiation at 2.4 MV was reduced by 85% (from 1 Sv/h to 144 mSv/h), and the onset of field emission was moved around 2 MV. The radiation measured at nominal fieldwas reduced from 80 mSv/h to 10 mSv/h, see Fig. 6. It should also be noted that these results were confirmed after a thermal cycle above the superconducting critical temperature of niobium. In addition, a heat run of 8 hours at 2 MV was carried out and the D cavity was able to work stably with no increase of radiation, temperature, nor quenches observed.

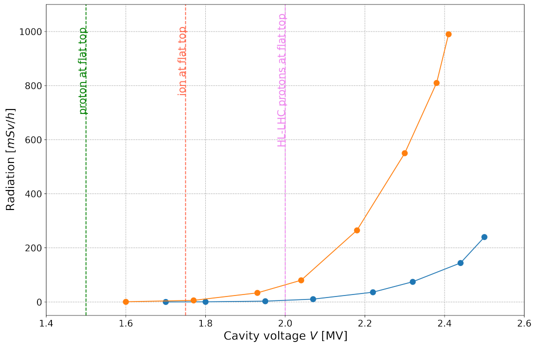

Figure 6: Final measurement for cavity D (in orange - before the helium processing, in blue- after the helium processing).

Measurements of the remaining cavities in this module were also made and no deterioration of their results was observed. Moreover, passive radiation sensors were installed in the bunker to reproduce the array used to design the shielding in the RF zone of the LHC tunnel [11]. The dosimeters' readings were below the minimum readable dose, which allows to state that the dose rates are below the ones considered for the design of the shielding in the LHC machine. Considering the above, the Asia cryomodule was considered to be qualified as an operational spare.

CONCLUSION

Clear signs of contamination were observed in one LHC RF cryomodule, after an accidental venting occurred in the LHC tunnel. The performance of the most severely affected cavity, the D cavity, could not be restored by RF pulse processing. Therefore, the helium processing technique has been used, which successfully improved the performance of the cavity with respect to field emission, and allowed to requalify the cryomodule as a valid spare.

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