RF SYSTEM AVAILABILITY AND PERFORMANCE DURING RUN 2

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Abstract

The Run 2 operation and availability for the LHC RF system are presented, including year-to-year performance comparisons. In addition, the evolution of the present RF system is discussed, with improvements in diagnostics, operation, and software being highlighted. Lessons learned from the Run 2 RF performance are reviewed, with a focus both on limitations that were addressed during Run 2 and limitations that may have implications for Run 3 and beyond. Finally, an overview of operational parameters, spares management, and long-term developments is presented.

RF SYSTEM AVAILABILITY

The RF system remained reliable throughout the years. During Run 2, the duration of the RF root cause faults, which corrects for parallel errors and fault dependencies never exceeded 6 % [1]. The distribution of the different types of RF faults is shown in Table 1. The table takes into account the 'production period' of proton physics, as well as special physics runs as defined in [1].

Table 1: Breakdown of LHC RF system faults during the proton runs of Run 2.

Year	2018	2017	2016	2015
Availability %	98.8	98.7	99.1	-
Nb of faults	59	32	36	59
Hardware faults	27	19	16	23
Controls faults	18	10	16	31
Other faults	3	3	0	0
Child faults	11	0	4	5

As 2015 was a re-commissioning year, the RF system was causing more downtime than in other years. The number of faults in 2018 was large, as in 2015, which was partly caused by a larger number of so-called child faults, mainly due to electrical disturbance. However, the total downtime of the RF system was about 50 hours each year. The increasing number of hardware faults may indicate the ageing of the equipment. This shows how important the spare management program is, for both high and low power devices, such as LLRF modules, power supplies, high-voltage tanks, cavities, etc. A noticeable number of controls faults is associated with evolving software in order to cope with the operational requirements that change over time; these changes inevitably lead to some faults. Nevertheless, a significant number of vulnerabilities have been diagnosed and repaired remotely; access was needed mainly in the case of hardware faults.

In the proton physics period in 2018 (weeks 13 through 44, fill numbers 6488 to 7395), 48 faults caused by the RF system were reported, resulting in a total of 49.2 h (4.9 %) of root-cause downtime. The breakdown of the RF faults into three main categories is shown in Fig. 1.

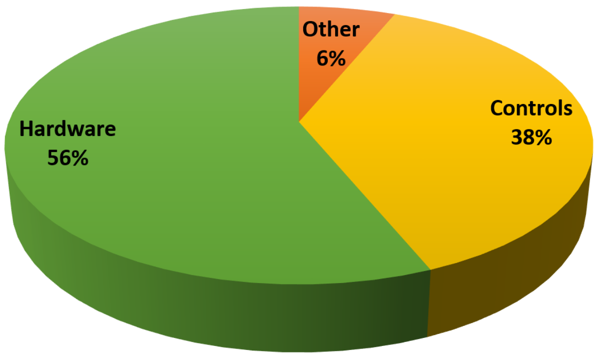

Figure 1: Breakdown of RF faults in 2018 operation by category.

RF Hardware Faults

Most of the faults were concentrated in short periods, since they were often related, see Fig. 2. For example, three faults in week 16 were related to the low-level RF (LLRF) controls (problems with Switch and Protect module and the RF feedback loop being off). An accumulation of faults has been also observed in the weeks 25–29. During this period, a number of klystron arc interlocks have been detected, due to a problem related to the new cavity feedback Set Point firmware that enables the full-detuning beam-loading compensation scheme. Nearly 8.5 hours of downtime came from a beam interlock (BIC) caused by a FESA class migration, which in fact could be interpreted as a control fault as well. In addition, during RF machine development studies, where the klystrons were working close to saturation, six klystron trips have occurred. The total duration of the hardware faults was 38.8 hours. Outside these periods, there were several weeks with no faults at all.

RF Controls Faults

Similarly, the controls related faults have clustered in the weeks 26-32, due to the problem with the new firmware, see Fig. 3. Other issues were related to the malfunctioning of FESA classes and communication issues with the hardware. Problems related to lost communication, server and sequencing, as well as the electrical glitches, caused several spurious faults. The total duration of the controls

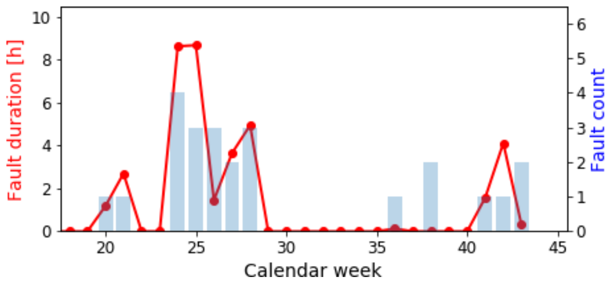

Figure 2: RF hardware faults in 2018 operation.

faults was 9.5 hours. The time needed to solve them was four times shorter than in the case of hardware faults, which is attributed to fast remote problem solving.

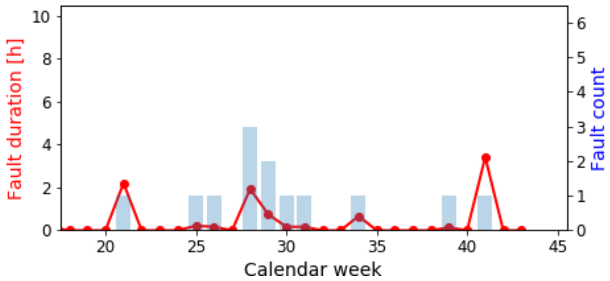

Figure 3: RF controls faults in 2018 operation.

Other RF Faults

This group contains three interlocks caused by the longitudinal instabilities due to dephased RF cavity, and an incorrect parameter configuration during the MD studies. The total duration of faults was 1.5 hours, see Fig. 4.

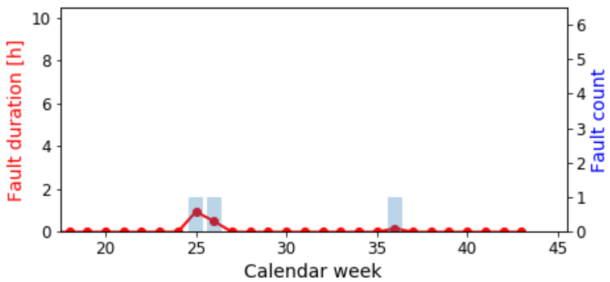

Figure 4: Other RF faults in 2018 operation.

SOFTWARE AND DIAGNOSTICS

Considerable amounts of software and diagnostic improvements have been implemented during Run 2. The LLRF commissioning software has been successfully migrated from MATLAB to Python [2]. The new software was used during the re-commissioning in 2018, providing many improvements, e.g. better data processing, new algorithms, as well as back-up and restore functionalities.

Better control and configuration of the RF conditioning process has also been provided through new Inspector interfaces. The Inspector panels have replaced the interfaces made previously in LabVIEW, with extended functionality. Improvements were made to existing monitoring systems for crowbar and arc detection, and additional monitoring systems have been added for power supplies, interlocks, temperature monitoring, radiation etc.

RF System Re-commissioning

Although the LHC RF system has been working reliably for years, it will approach the design limits in Run 3 and HL-LHC, which calls for sufficient time devoted to the conditioning of the cavities and the main couplers as well as LLRF configuration setup. The restart of the RF System can be divided into five periods. 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 ACS cryomodules after the Departmental Safety Officer (DSO) test. During this step, the high-power couplers are conditioned up to full power and all cavities are conditioned up to full field.
- Calibration and staged closing of the LLRF loops at different working points.

The LLRF beam control is set up during the first capturing of the pilot beam, as well as the first nominal bunch, and during the ion beam setup. Furthermore, the beam-loading compensation schemes require fine-tuning when the first batches are injected in the machine.

Many activities are carried out one after another and depending on the previous results. Planning should be done with some contingency, so that potential delays in the recommissioning without beam do not shorten the setting-up time and beam commissioning can be started as scheduled.

SYSTEM PERFORMANCE

In recent years, many machine development studies have been carried out, along with simulation and measurement studies related to longitudinal beam stability, controlled longitudinal emittance blow-up, and RF power limitations at injection [3]. These studies allowed for a better understanding of the longitudinal beam dynamics in the machine. A gradual increase in the beam intensity towards the target value of 1.8e11 ppb is expected during Run 3. A reduced injection voltage is therefore desirable to reduce the power consumption [4]. However, operational experience suggests that the present RF system is more limited in power than previously assumed. The maximum achievable RF klystron power for two working points can be found in the Table 2. The maximum measured forward power in saturation is lower than the calculated value and varies depending on the lines. For calculation, the efficiency of 60 % has been assumed but it can degrade with ageing. Dedicated MD studies

Table 2: Present LHC klystron working points from the latest measurements.

Klystron HV	Cathode current	DC power	RF power	Measured saturation
50 kV	7.8 A	390 kW	230 kW	190 - 220 kW
58 kV	8.6 A	500 kW	300 kW	250 - 280 kW

has been performed to estimate the RF system performance at injection during Run 3 [5]. To precisely quantify the RF power reach with beam, various studies are being pursued, including the high- and low-power RF systems, new hardware options such as high-efficiency klystrons, and various operational scenarios. These studies will be crucial to perform during the Long Shutdown 2 (LS 2) in order to prepare for future machine conditions.

FORTHCOMING ACTIONS

Cavity Field Antenna Investigation

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 rule out 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 the aforementioned 10 dB. Since April 2017, the cavity was operated using the spare antenna. Because the cause of the problem is not fully understood, it is required to open the cryomodule insulation vacuum in-situ and check the internal cabling, followed by a leak check on the pick-up feedthrough. If replacing the antenna turns out to be necessary, this operation would almost certainly have to take place in a clean room and then it will be necessary to replace the module during LS 2.

Spare Cavity Program

To reduce the downtime due to a potential module failure, it has been decided to launch the LHC spare cavity program as part of CERN's consolidation project. The goal is to produce four dressed spare cavities and one 1/4 test cryomodule (CM) to be available for Run 3. The 1/4 CM can then be used as test object in the ACS test stand in SM18 [6].

Prototype cavities have been produced and their results are very encouraging. The first model cavity has been manufactured and was tested in the vertical cryostat at the beginning of 2019 showing very good results. An important aspect of the spare cavity program is having 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, considerable efforts have been made to restore the complete engineering and manufacturing folder with updated drawings. Work has also begun on improving the LHC main coupler design to prepare for the case where spare couplers in stock are affected by ageing.

Currently, there is one functional spare cryomodule and one spare dressed cavity available. A successful test of the spare cryomodule has been done in October 2018. The objective of the tests was to validate the HCASCGA000-CR000002 CM performances after changing the two pumping crosses at the two beam pipe extremities.

A vacuum leak in one of the VKSDR manifolds [7] of the LHC RF CM HCASCGA000-CR000005, currently in the LHC machine, was detected in 2013. A corrosion process caused by residues of the stainless steel cleaning procedure was identified as a possible source of the problem [8]. To eliminate the risk of beam vacuum contamination, it was decided to design new pumping manifolds, which will facilitate the cleaning process and thus reduce the risk of corrosion. A small series of manifolds was produced according to the new design [9] at the end of 2017.

To verify the new design and to allow for further investigation of the internal surfaces of the old units, it was proposed to install and test a pair of new units on the LHC HCASCGA000-CR000002 spare cryomodule and re-qualify the cryomodule in the SM18 horizontal testing facility. Each cavity was tested and its stable operation at the nominal accelerating voltage was confirmed: 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.

Various additional studies and measurements have been performed also in SM18. A significant number of software updates and improvements have been introduced following the user interface adaptation, too. Works related to the modernization of the testing infrastructure in SM18 will be continued during LS 2 [10].

Software and Hardware Developments

RF system improvements for the post-LS 2 era are currently underway. The production of additional spare crowbars (solid-state thyristors) and the development of the replacement system for the MAC10 modulators (tetrode) are foreseen. Several upgrades to the RF controls will also be performed. It is planned to replace and maintain a large number of PLC processors, interlock cards, and power supplies. The production of spare LLRF modules will be continued. The remaining FESA2 classes will be migrated to FESA3, among others, the beam control classes that are difficult to test on a test bench without a beam.

The future high-intensity beams may potentially call for an RF setting-up that takes into account the beam loading. At the moment several studies on this topic are ongoing. The dynamic adjustment of the circulator and Switch and Protect module to overcome power limitations during injection transients are underway. The possible benefits of high-efficiency klystrons and additional cavities are also taken into account.

CONCLUSIONS

The RF system performed very reliably during the LHC Run 2, and its flexibility has been proven during the MD studies and special runs. In operation, hardware-related faults were dominating and the ageing effect is expected to reduce the system performance in the long run. Therefore, the production of spare parts began, as well as continuous improvement of the system. Many diagnostic and software tools are continuously being developed to ensure smooth operation.

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