LHC RF SYSTEM PERFORMANCE IN 2017

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Abstract

The availability of the LHC ADT and RF systems in 2017 is presented in details, including high- and low-power RF and RF controls. A comparison with 2016 availability is performed. The full-detuning scheme, commissioned early this year, has been operational throughout the year and the first experience with this scheme is summarised. New operational diagnostics, implemented in 2017, are shown as well. Finally, the latest findings from beam dynamics studies and measurements, which have implications for the operation today and in the near future, are highlighted.

RF AVAILABILITY

Globally, the RF system availability was 99.0 % over the reference period for the 2017 LHC proton run, which spans from 28/04/2017 18:00 to 10/11/2017 15:00. In total, there were 32 faults resulting in 47.3 h downtime that was blocking the operation. The distribution of faults and their downtime over the calendar weeks 18–45 is shown in Fig. 1a. The faults can in addition be categorised into hardware, controls, and 'other' faults. Sometimes, however, this categorisation is somewhat arbitrary. Their contributions to the total figures are shown in Table 1.

Table 1: LHC RF faults in 2017, broken down into three categories.

Fault category	Number of faults	Total downtime	Average duration
Hardware	19	36.3 h	1.9 h
Controls	10	9.1 h	0.9 h
Other	3	1.9 h	0.6 h

The full-detuning beam-loading compensation was commissioned in the beginning of 2017, and thus the klystrons were working mostly around 100 kW throughout the year. No visible effect was seen on the RF availability. Globally, most faults were related to klystrons, power supplies, or the unavailability of crates or FESA processes. The antenna of cavity 1B1 gave a weak signal at some point during the run and an intervention was required to switch to the spare antenna. During the YETS, a measurement campaign was performed to verify all antennas and there is no visible trace of this seemingly intermittent problem. For 2018, it was decided to remain connected to the spare antenna.

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RF Hardware Faults

The hardware faults were mainly concentrated around weeks 23–33, see Fig. 1b. In week 26, there were three events due to the same root cause, which was a loose connection on the interlock crate; as it was hard to diagnose, it took three interventions to pin down the problem. This fault caused in total 14.0 h of downtime, and most of it was lost during an RF MD. Another loose cable on the main coupler bias of cavity 4B2 led to another three faults with 4.8 h downtime in week 28.

In more detail, there were four faults on klystrons, related to klystron cooling, vacuum level, thyristor oil level, and too high cathode current. Three power supplies had to be exchanged and twice some crates shut down. On one occurrence, a FESA process was missing. Spurious power trips caused two faults.

RF Controls Faults

Similarly, the controls-related faults were concentrated around weeks 25–34, see Fig. 1c. These faults, however were half as rare as hardware faults and twice as fast to resolve. In about half of the cases, the OP crew was able to solve the issue themselves by a reboot or a restart.

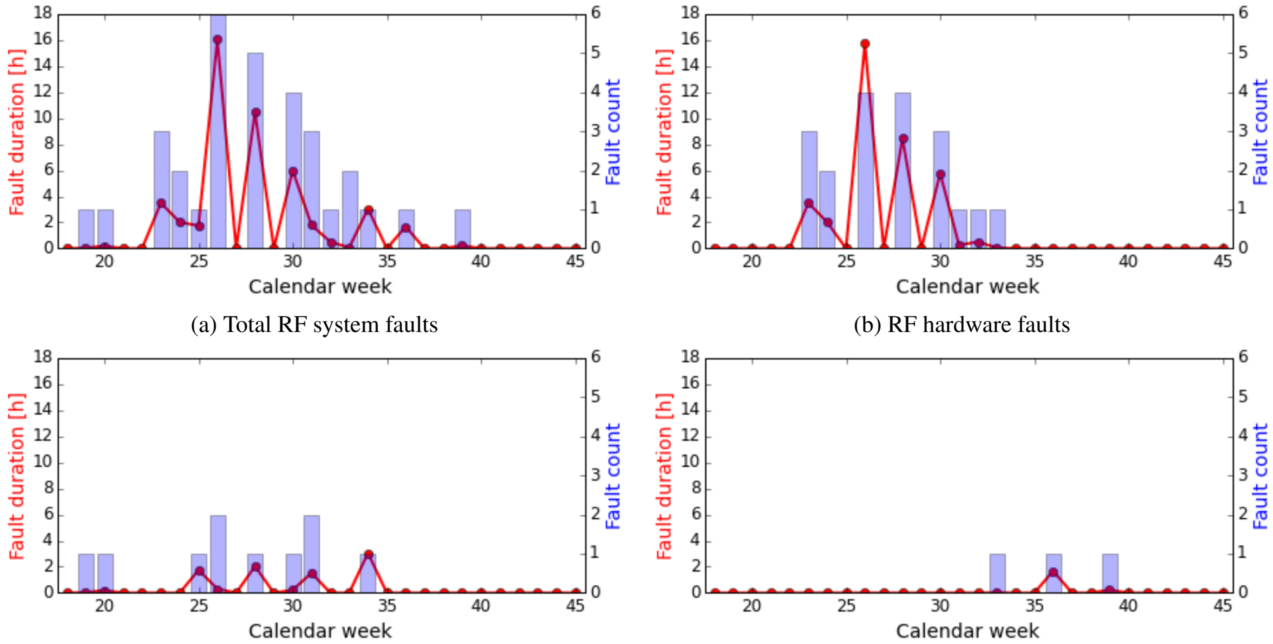
In this category, two FESA processes had to be restarted, once a FEC required a reboot. Spurious trips, arcs, and interlocks caused three failures. RDA communication errors between different FESA classes led to another three faults. On one occasion, a LLRF module had to be replaced, which could be counted as a hardware fault.

Other RF Faults

'Other' RF faults contain three spurious interlocks on vacuum level, main coupler temperature, and an arc in a circulator, see Fig. 1d. These faults were typically diagnosed and reset within about half an hour.

Availability Comparison

During the 2016 proton run reference period (from 25/03/2016 09:00 to 31/10/2016 06:00), there were overall 36 faults, but with only 40.1 h total downtime. Thus, in terms of fault count, the RF system performed slightly more reliably in 2017. The longer downtime in 2017 can be explained with the difficult interventions in week 26, where it took 14.0 h to diagnose the root cause, despite several experts being present. Such interventions are rare and can hardly be avoided. Apart from this one fault, the RF system performed just as reliably as last year.



(a) Total RF system faults

(b) RF hardware faults

(c) RF controls faults

(d) Other RF faults

Figure 1: LHC RF system fault durations (red) and fault counts (blue) in 2017.

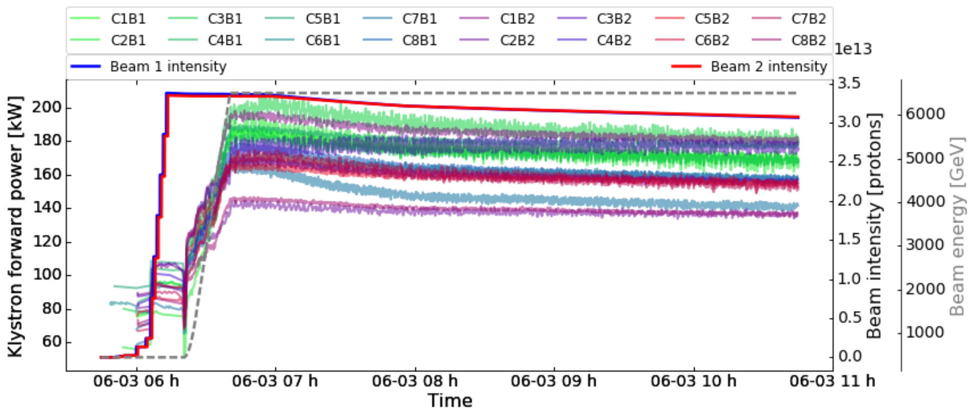


Figure 2: Typical klystron forward power in the half-detuning scheme in 2017; measured on 03/06/2017.

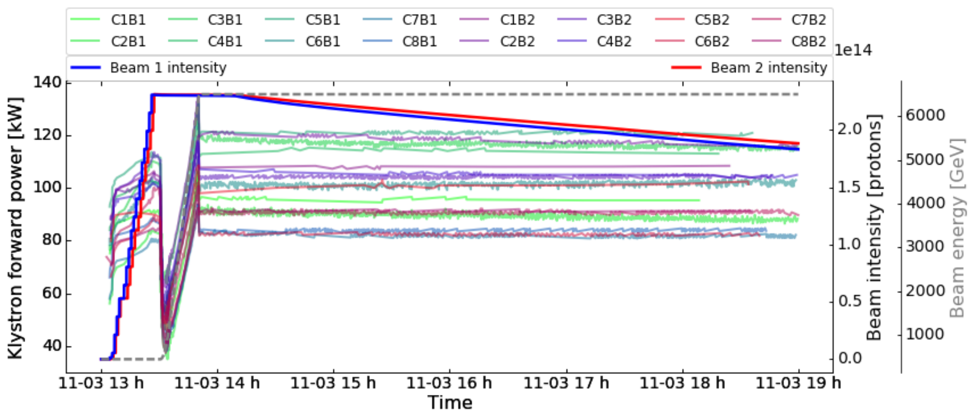


Figure 3: Typical klystron forward power in the full-detuning scheme in 2017; measured on 03/11/2017.

ADT Availability

With only four faults and 3.8 h total downtime, the availability of the ADT was excellent over the entire proton run. One fault was due to a trip of the module V1B1 load, another due to a trip of the module itself, with a timeout upon resetting. Once a reboot of the crates for both modules of B1H was necessary. On another occasion, the abort gap cleaning was not working for module B1V.

Experience with Full Detuning

The full-detuning scheme was commissioned rapidly and smoothly during the intensity ramp-up in 2017, and was used operationally since. Prior to this, the half-detuning scheme was used throughout the cycle, which requires a klystron forward power P (see [1]) of

$$P = \frac{V I_{\text{pk}}}{8}, \tag{1}$$

where V is the voltage per cavity and I_{pk} is the peak RF beam current. With a bunch intensity of about 1.15×10^{11} ppb and batches of 72 bunches or more, the typical power consumption at flat top (1.5 MV/cavity) in the half-detuning scheme is around 190 kW. With the estimated accuracy of about ± 20 % on the power measurement, the measured klystron forward power is in the range 160 kW to 210 kW (with a few outliers), see Fig. 2.

In the full-detuning scheme, the power consumption is independent of the beam current [2],

$$P = \frac{V^2}{8 \frac{R}{Q} Q_L}, \tag{2}$$

where $\frac{R}{Q} = 45\ \Omega$ is the shunt-impedance-to-quality-factor ratio of the cavities and Q_L the loaded quality factor. In 2017, the full-detuning was switched on adiabatically after filling, before the start of the ramp. The expected power consumption for 2017 beam parameters with 1.5 MV/cavity and a loaded Q of 60,000 is 104 kW. This agrees well with the observed 80 kW to 120 kW, see Fig. 3.

During the year, no faults were detected related to the full-detuning algorithm.

SOFTWARE AND DIAGNOSTICS

Longitudinal ObsBox

On the software and diagnostics side, several improvements and new tools have been implemented in 2017. Various bunch-by-bunch (bucket-by-bucket) signals acquired with the longitudinal ObsBox are now available in the logging data base, thanks to a new FESA class that processes and logs on-line data. The signals include:

- Cavity sum amplitude and phase, for full-detuning observations,
- Beam pick-up amplitude and phase, including oscillation amplitudes, for beam stability observations,
- Stable phase shift data, for e-cloud observations.

The e-cloud-related phase shift data requires careful post-processing and regular re-calibration.

The cavity voltage phase data was used regularly by the experiments in order to predict the shifts in collision time and position in the different IPs for different filling schemes. This data is therefore forwarded also to the DIP data base. The shifts for a given filling scheme, see Fig. 4, can be viewed on the LPC website [3].

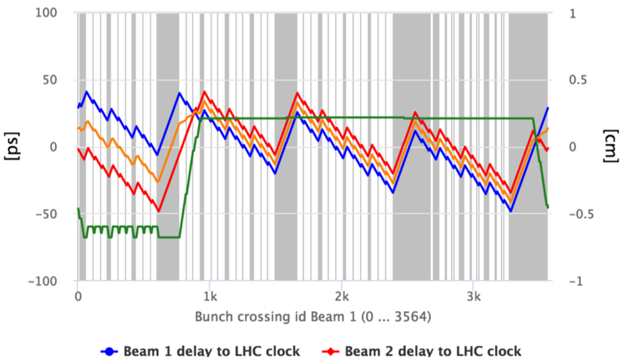


Figure 4: The effect of full detuning in a given IP for a given filling scheme: bunch-by-bunch delay of collision (orange), phase delay of B1 (blue), phase delay of B2 (red), shift of the collision point (green). In the grey-shaded areas, the beam is absent.

ADT

A real-time, transverse instability detection and online monitor has been put into operation in 2017. The bunch-by-bunch transverse activity is published every 4000 turns by the ADT ObsBox. When coherent activity is detected (Fig. 5), it triggers the LHC Instability Trigger network LIST, and freezes the observation buffers of different instruments to obtain synchronous data. The online monitor also provides the tune and the damping time of the bunches at injection and has proven to be an important diagnostics tool for operation in 2017.

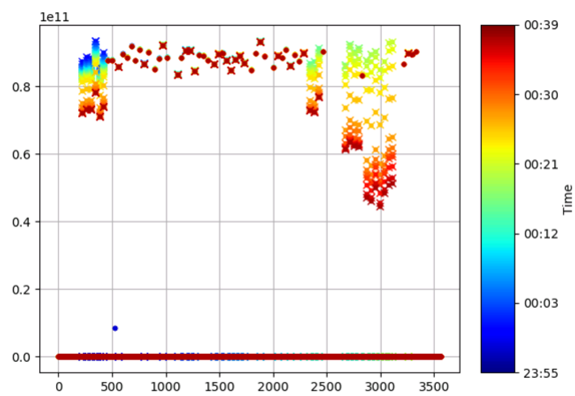


Figure 5: Losses along the ring; bunches marked with a cross are detected by the ADT as unstable.

Further tools that were put in place during the year include (i) the transverse oscillation frequency spectrum, in view of HL-LHC civil engineering studies, (ii) the logging of bunch-by-bunch injection data, to observe drifts, and (iii) the ADT-AC dipole excitation, for automatic coupling measurement and correction. The latter is to be extended in 2018 to on-demand bunch-by-bunch tune measurements for operation and MD users.

High-Resolution Profiles

The high-resolution, 40 GS/s scopes installed in UA43 give more accurate information about the longitudinal profiles than the scopes connected to the CCC display and the BQM, which have only an 8 GS/s sampling rate. The scope for B1 has been replaced with a new one in 2017. A logging FESA class and expert acquisition tools are being worked on. It is foreseen to log both the raw and the transfer-function corrected bunch profiles, and add a high-level application in the CCM for on-line measurements.

Using this profile data, first attempts of the tomoscopic reconstruction of the longitudinal phase space have been performed [4], see Fig. 6. The reconstruction was done using the software that is operational in the PS [5]. For the coming year, it is planned to create a tomoscope user interface.

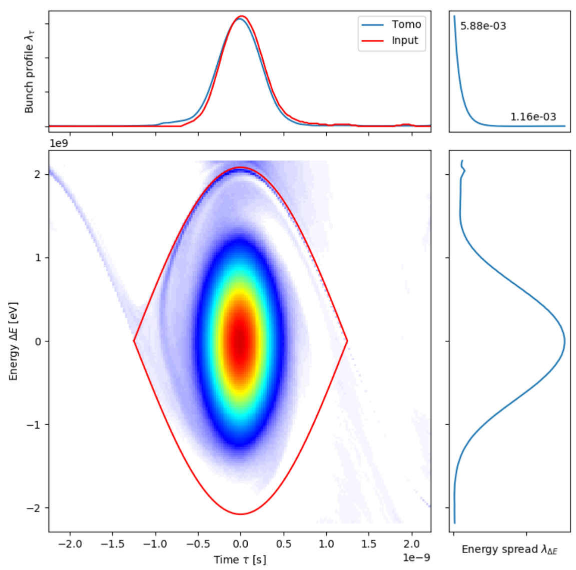


Figure 6: Tomographic reconstruction of longitudinal phase space after 15 h in Stable Beams; B2, 23/11/2017.

Expert Tools

Over the past year, the commissioning software for the LLRF system has been migrated from MATLAB to Python [6]. The new software suite has various advantages:

- No MATLAB license will be needed anymore,
- Communication with FESA classes will happen over PyJapc rather than the JavaCoInterface,
- An automatic back-up and restore function saves the state of the system,
- Improved data processing and new algorithms will be available,

The back-up and restore functionality will also be run on a daily basis on the operational LLRF crates to make sure all FESA properties are restored correctly after a power cut, which was not the case until now. Exhaustive testing has already been performed on the LHC LLRF test stand and on 4–5th December 2017 on the operational crates. The new software suite shall be used for the re-commissioning in 2018.

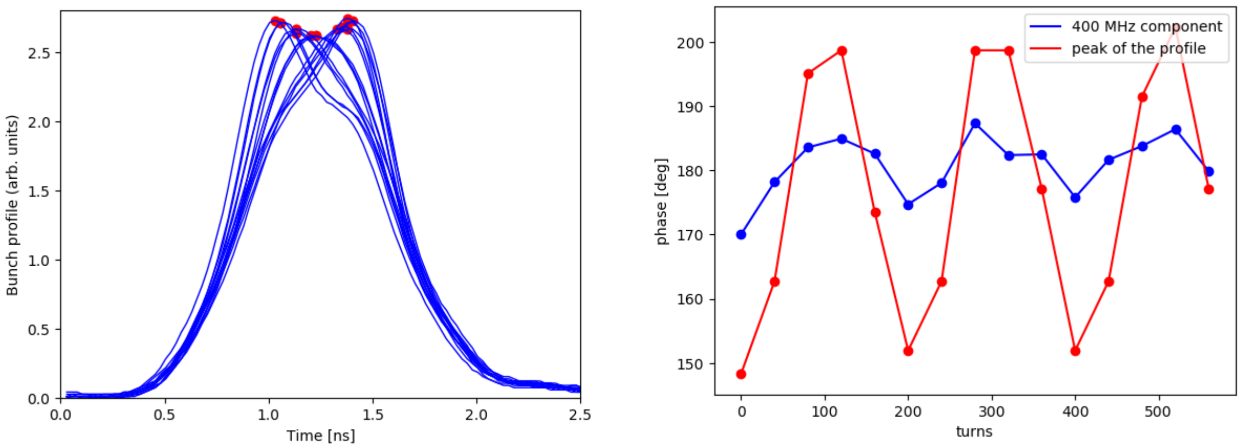
Previously used Labview expert interfaces to the LLRF beam and cavity controllers are tedious to maintain with the FESA2 to FESA3 migration. The interfaces are gradually being replaced by Inspector panels that can be found in the CCM under "LHC Equipment Control" → "RF" → "Expert". Mainly used by RF experts, they also contain some useful tools for the operation crew, e.g. the status of power supplies. In 2018, further tools, such as expert acquistion interfaces for bunch profiles and tomoscope are planned to be added. Concerning FESA migration, 22 out of 50 classes are still to be migrated. Also, all the front-ends have to be migrated from 32-bit to 64-bit. It is foreseen to migrate a large portion of these before the restart in 2018.

BEAM DYNAMICS STUDIES

Long-lasting injection oscillations were observed to survive even the acceleration ramp [7], where phase noise is injected for controlled emittance blow-up. In 2017, two MD sessions were performed to study these injection oscillations [8]. Due to the mismatch between the momentum spread of the injected bunch and the LHC bucket height at injection, and depending on the bunch length and intensity, the filamentation process can lead to island formation close to the bunch core. In such cases, strong, non-rigid dipole oscillations can be observed on the bunch profile, see Fig. 7a.

Looking only at the data from the longitudinal ObsBox, that measures the 400 MHz component of the bunch phase, the oscillations remain typically around $\pm 5°$. Looking at the bunch profiles, however, it turns out that the oscillations can be quite violent, and the bunch peak can move by up to $\pm$ 30°; one example is shown in Fig. 7b. For single bunches around 1.8–1.9×10^{11} ppb, during 20 minutes of oscillations, $\sim$ 10 % bunch lengthening was observed, while IBS can explain only 3 %. In addition, $\sim$ 5 % particle losses were observed during this period, see Fig. 8. It is therefore essential to study the phenomenon more in view of HL-LHC.

First simulation studies were able to reproduce the non-rigid dipole oscillations below a certain injected bunch length. For the time being, the measured decay time of oscillations cannot be reproduced in simulations and is longer than expected. Measurement and simulation studies will have to be continued in 2018. In principle, a lower injection voltage would reduce the mismatch and therefore the os-



(a) Bunch profile

(b) Bunch phase measured with two different methods

Figure 7: Non-rigid dipole oscillations about 1 min. after injection into the LHC. Although the phase oscillations seen on the 400 MHz component remain within ±5°, the peak of the bunch profile oscillates by ±25°.

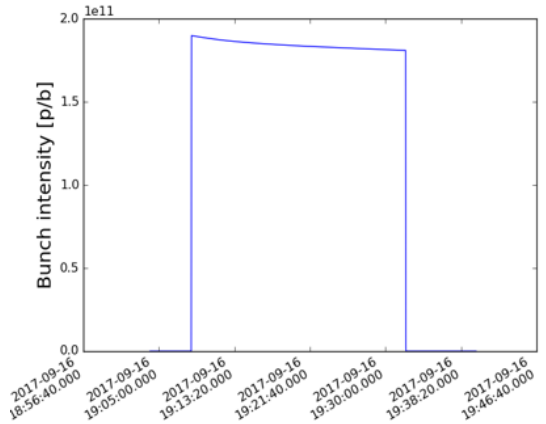


Figure 8: Particle losses of a single bunch with less than 2×10^{11} ppb, during a 20 minutes oscillation period flat bottom, just after injection into the LHC.

cillations, however, it could also lead to increased capture and flat-bottom losses, due to phase and energy errors at injection. Additional measurements are therefore planned as well to find the optimum injection voltage.

CONCLUSIONS

The LHC RF and ADT systems were working reliably and with high availability throught 2017. The full-detuning beam-loading compensation scheme was commissioned and used operationally, without any faults associated to it. Maintaining a high availability requires a continuous, significant effort to migrate, update, and improve software and tools for operation and expert use. The migrated LLRF commissioning software will be used at the next restart. Inspector panels are being created for system diagnostics, and FESA classes are being migrated.

Beam studies in 2017 showed that undamped injection oscillations are present in the LHC. These occur for a certain mismatch between the momentum spread of the injected bunch and the bucket height at injection. Thus, during the filamentation process, an instability can occur. The amplitude of oscillations is larger than previously assumed and can lead to losses for single bunches at intensities below the HL-LHC baseline.

Beam studies and software migration efforts will continue in 2018.

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