OPERATIONAL AND BEAM DYNAMICS ASPECTS OF THE RF SYSTEM IN 2016

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Abstract

The operation of the LHC RF system and beam dynamics studies in 2016 are presented. A fault summary is given, showing a reliable operation. Power consumption and promising studies of the full-detuning scheme are discussed. Diagnostics and software improvements done or to be done are detailed. As for beam dynamics, important advancement has been achieved concerning loss of Landau damping and bunch flattening in 2016. Open questions related to controlled emittance blow-up and how PS-SPS-LHC bunch-to-bucket transfer studies helped to improve LHC injection losses are shown as well. Finally, future improvements and studies are presented.

OPERATIONAL ASPECTS

RF faults

The RF system was very reliable in 2016. Only 31.5 h of downtime, that is about 0.6 % of the LHC operation time, was associated to the system over the whole year. In total, 39 faults and 10 beam dumps in different machine modes occurred.

The distribution of the different types of RF faults is shown in Fig. 1. Hardware-related faults were dominated by issues with the 24 V power supplies and hardware controls (50 %), as well as klystron crowbar events (30 %) that occurred mostly after klystron restart; the remaining issues being related to tetrodes and various other things. In the low-power level RF (LLRF) category, the operational delays were caused by re-synchronisation problems and adjustment time needed for LLRF settings. Child faults were typically electrical glitches or cryogenic failures. Controls issues were related to malfunctioning of FESA classes, blocked front-ends, wrong PLC measurements, or communication issues with the hardware.

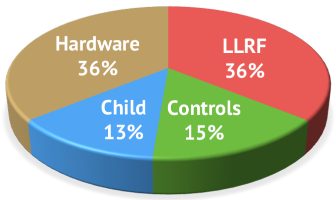

Figure 1: Distribution of RF faults in 2016 operation.

Power consumption

Originally, it was planned to recommission the klystrons to 300 kW, which is their design specification value. Most klystrons, however, saturated around 270 kW, and some even below this value. On the other hand, the klystron forward power is calibrated based on thermal measurements in the heat load, so the power is known with a limited accuracy of about 20 %.

Due to issues with the SPS beam dump, the 48-gap-48 bunches batch pattern was used in 2016. With this batch pattern, beam-loading effects were relatively weak and the average klystron forward power remained well below saturation in 2016, see Fig.2. Yet, the heating of the cavity main couplers was a recurrent issue, especially on cavity 7B1.

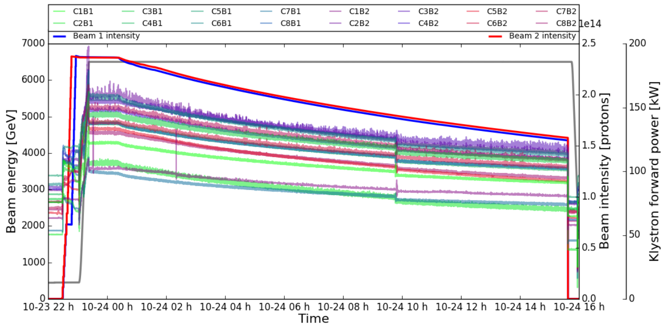

Figure 2: Typical average klystron forward power in 2016 operation with full beam. Data taken on 23rd October 2016.

Despite the limited power demanded, the peak power had still some transients of up to 250 kW. Based on 2015 operational experience with 144 bunches, the klystron power could be insufficient with batches of 288 bunches in the future, at least with the present beam-loading compensation scheme.

An alternative scheme to the presently operational ‘half-detuning’ scheme is the cavity voltage phase modulation or ‘full-detuning’ scheme, which is also the baseline for HL-LHC. Full detuning has been successfully demonstrated in MDs in 2016 [1], showing a power reduction from 160-180 kW to only 60-70 kW at flat top, see Fig. 3. A first test is Physics machine mode [2] showed a modulation of the collision time w.r.t. the bunch clock (in all IPs) and a modulation of z-vertex (in IPs 2&8, see Fig. 4), in agreement with predicted values.

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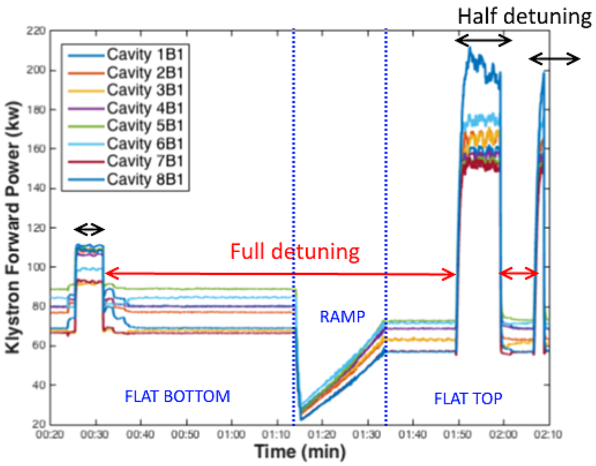


Figure 3: Klystron forward power reduction in MD due to cavity voltage phase modulation ('full detuning') w.r.t. the operational half-detuning scheme.

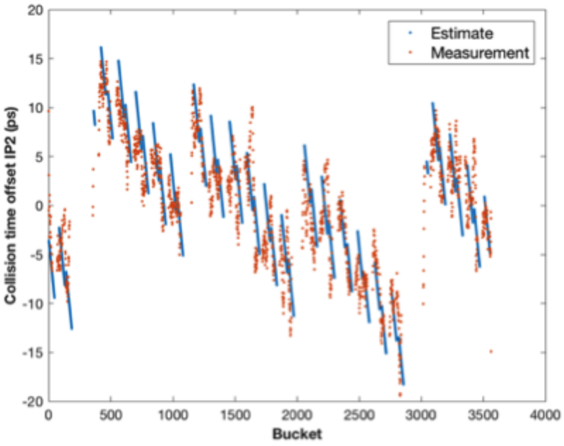


Figure 4: Modulation of the z-vertex in ALICE during full-detuning test in Physics machine mode [2].

Ion run

The ion run went very smoothly from the RF system point of view. The RF parameters for the 4 TeV and 6.5 TeV runs had been prepared beforehand and the commissioning of the p-Pb and Pb-p injection and cogging was unproblematic. At 6.5 TeV, the difference in frequencies between the two beams was increased (by -20 Hz for Pb and +20 Hz for p) to make the cogging faster. At both energies, the beams were moved to the mean frequency orbit for physics. The mean orbit offset was only -0.1 mm for Pb and +0.1 mm for p at 6.5 TeV and three times larger at 4 TeV.

Diagnostics and software improvements

Several improvements to the RF system have been realised in 2016. The expert fixed display for monitoring the power transients was upgraded with new features and its memory leak has been fixed. New FESA classes have been created to log high-resolution profiles and stable phase oscillations from the longitudinal ObsBox; these classes will be available for the start-up in 2017. The RF phase noise on Beam 1 has been reduced as well by exchanging its VCXO crystal oscillator module.

Several developments are yet to be made in the future. A fixed display for the high-resolution beam profiles is planned and the FESA3-migration of FESA classes will have to be completed. Commissioning tools are planned to be migrated from Matlab to python as well. The documentation of the peak-detected Schottky system is still to be done. Interruptions of the beam spectrum logging due to communication issues with the instrument are under investigation. Also, for a smoother recovery of the LLRF system after a power cut or a power cycle, tests in the laboratory will have to be performed.

In order to ensure the continued functioning of commissioning and expert tools that are indispensable for RF operation, CO support for pyjapc and java libraries (maintained in the past by BI and CTF3, respectively) is of vital importance.

BEAM DYNAMICS ASPECTS

Loss of Landau damping

Measurements in 2016 showed that the coupled-bunch stability threshold for a full machine is higher than the single-bunch one [3], at least for the current operational parameters. Therefore single-bunch loss of Landau damping dominated in long fills, and it occurred in physics with beam parameters according to predicted threshold [4]. With the operational bunch intensity of about (1.1-1.15)$\times 10^{11}$ ppb, bunch length oscillations around 0.9 ns have been observed with time constants of several hours, see Fig. 5.

Long-lasting, undamped injection oscillations have also been observed at arrival to flat top [3]. Analysing different cases, it was shown that the bunch phase oscillations at arrival to flat top depend on the time spent at flat bottom, see Fig. 6. The damping time of oscillations is about an hour on flat bottom. It is still unclear how undamped oscillations survive the noise injection of the controlled emittance blow-up during the ramp and make it to flat top.

Bunch flattening

With the positive polarity of the LHCb magnet, the vertex reconstruction is not accurate enough for bunch lengths below 0.9 ns [5]. Bunch flattening using sinusoidal RF phase modulation was used operationally to regulate the bunch length [6]. With the operational modulation settings that target the very core of the bunch, the bunch length typically increased by 150-200 ps, see Fig. 7a. The corresponding estimated loss in integrated luminosity after the bunch flattening was in the range of about 2.5-4.5 % in IPs 1&5, see Fig. 7b. The mechanism of bunch flattening proved to be completely loss-free under the operational conditions.

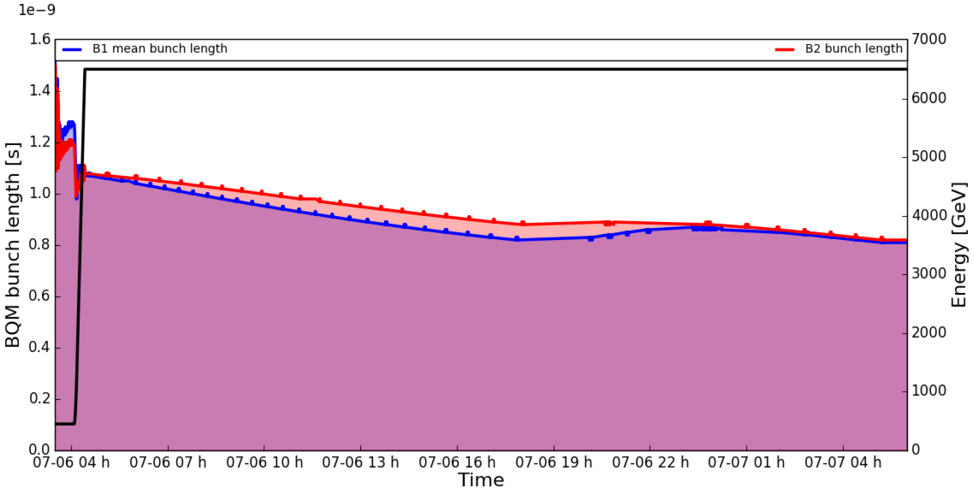


Figure 5: Bunch length oscillations in Physics machine mode due to loss of Landau damping.

Controlled emittance blow-up

In 2016, the controlled emittance blow-up applied during the ramp was close to the limit of stability (leading to large bunch length spread), as the target bunch length was decreased from 1.25 ns to 1.1 ns [7]. For better convergence of the bunch lengths along the machine, the target bunch length was kept at 1.25 ns during the first two-thirds of the ramp, and decreased to 1.1 ns only during the last third. This reduced the bunch length spread from 410-450 ps to 120-160 ps, see Fig. 8.

Latest beam dynamics simulations on controlled emittance blow-up show that the operational procedure is closer to resonant excitation than to diffusion and has island creation in longitudinal phase-space as a consequence. In line with this observation, peak-detected Schottky spectra show a depleted region close to the centre of the bunch after the blow-up, see Fig. 9. This cannot be detected on the beam profile and shows how powerful this diagnostics is to measure the synchrotron frequency distribution.

PS-SPS-LHC bunch-to-bucket transfer

2016 brought also repeated satellite investigations in the SPS and the LHC, as LHC injection losses were recurrently close to the BLM dump threshold. The SPS-LHC transfer losses, however, are on the per mille level and it is hard to improve this performance. The main origin of the LHC satellites is actually the ‘S-shaped’ bunches injected into SPS after the PS bunch rotation, see Fig. 10. ‘S-shaped’ bunches lead to particles being captured in nearby buckets that extend beyond the extraction kicker flat top and thus lead to losses at LHC injection.

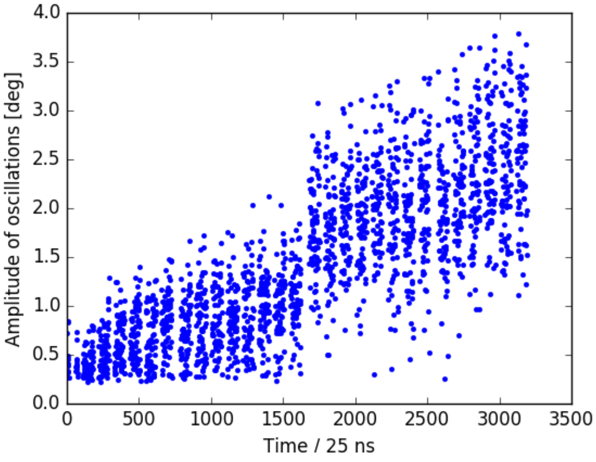
Switching on the spare 40 MHz PS cavity with the optimised settings proposed in 2012 [9] reduced the PS-SPS transfer losses from 5 % to 2.5 %, as predicted. In the LHC, the satellite population reduced by a factor 5-10 as a consequence [10]. An operational use of the spare cavity requires some consolidation of the PS 40 MHz system and an additional power converter for the LIU-era [11].

Forthcoming and continued studies

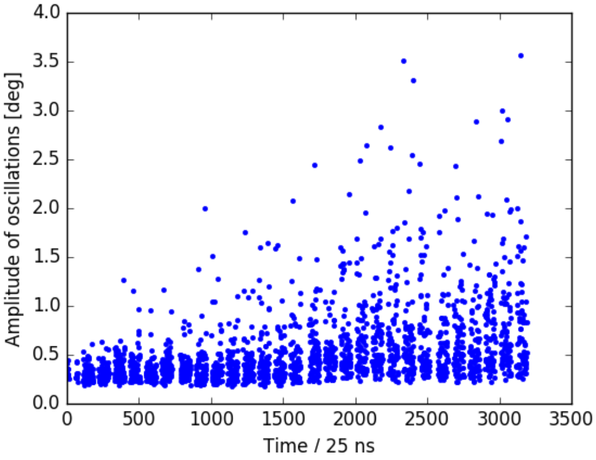
Several open questions remain that require further research. Full detuning, if not becoming operational in 2017, will have to be studied in MDs. The limitations and possibly the optimisation of the controlled emittance blow-up remain to be investigated. Concerning coupled-bunch instabilities, the studies of 2016 need to be continued also for the nominal LHC beam, as well as coupled-bunch instabilities due to the fundamental cavity impedance. Studies on using band-limited RF phase noise for bunch flattening and to counteract synchrotron radiation damping are planned, as well as studies on the longevity of injection oscillations. Measurements of the 400 MHz cavity HOMs are intended, too.

CONCLUSIONS

The operation of the RF system was smooth in 2016. Many studies have been performed and there were several highlights during the year. The full-detuning scheme for beam-loading compensation has been successfully tested to lower klystron forward power compared to the operational half-detuning scheme. Loss of Landau damping has been observed in long physics fills in agreement of previous measurements of the LHC machine impedance. Bunch flattening has been implemented to control the bunch length in physics and has been used operationally when the LHCb magnet had positive polarity to prevent the bunch length from dropping below 0.9 ns. The controlled emittance blow-up has been operated at the limit of convergence in 2016 and studies are required to improved the present blow-up method. Beam satellites causing large injection losses in the LHC have been reduced significantly by applying the optimised PS bunch rotation according to earlier studies. Diagnostics and software improvements continue to be performed. Also, open questions will be addressed in continued studies in the coming year.



(a) End of flat bottom.



(b) Start of flat top.

Figure 6: Amplitude of dipole oscillations in B1 along the ring with a full machine.

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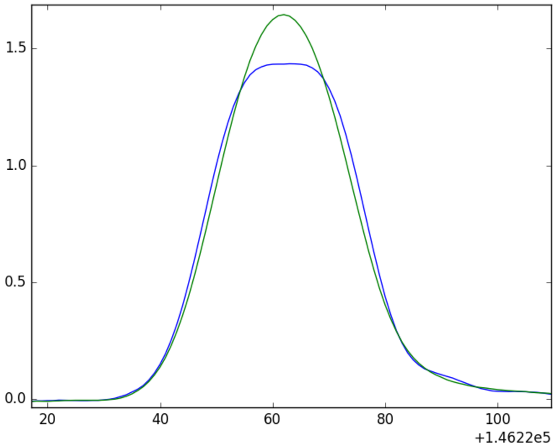
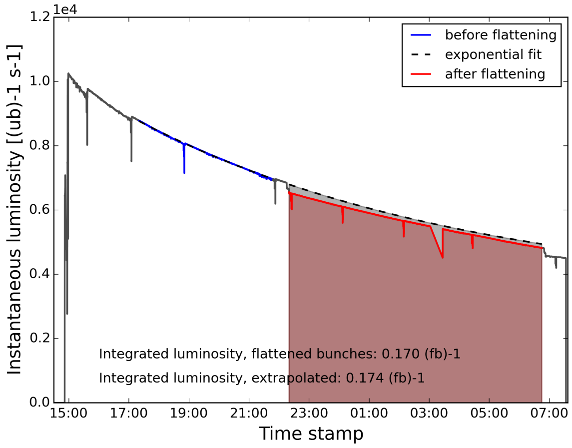
[4] J. Esteban Müller et al., “LHC Longitudinal Single-Bunch Stability Threshold”, CERN-ACC-NOTE-2016-0001, (2016).



(a) Change of bunch profiles, Beam 2. MD on 17th June 2016.



(b) Luminosity drop in ATLAS, 6th August 2016.

Figure 7: Bunch flattening using sinusoidal RF phase modulation.

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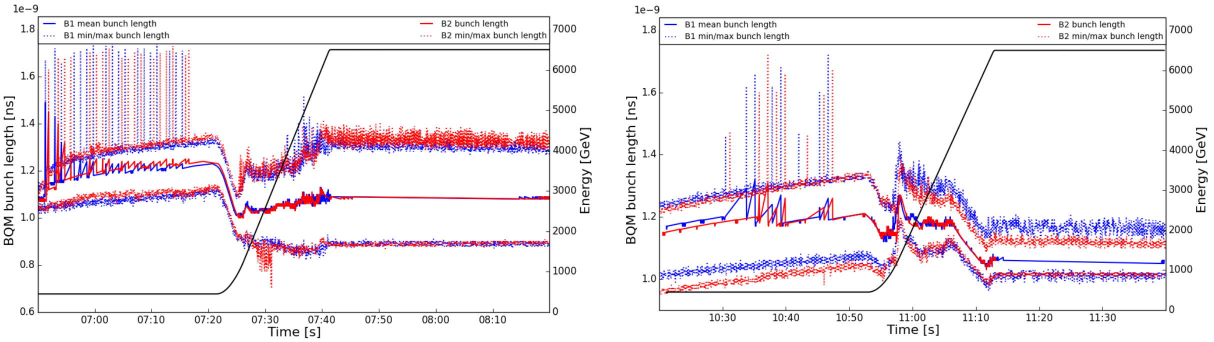
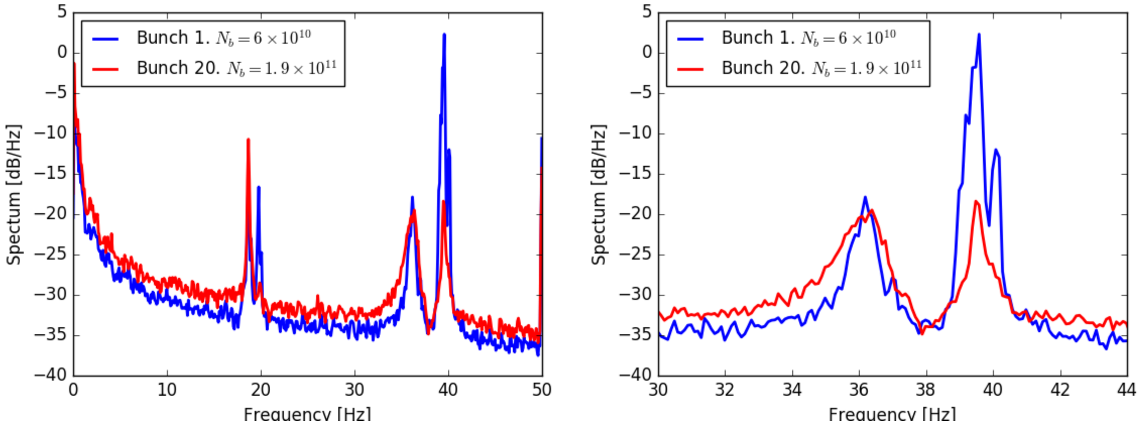


(a) Constant target bunch length of 1.1 ns.

(b) Target of 1.25 ns during the first two-thirds of the ramp, followed by a target of 1.1 ns.

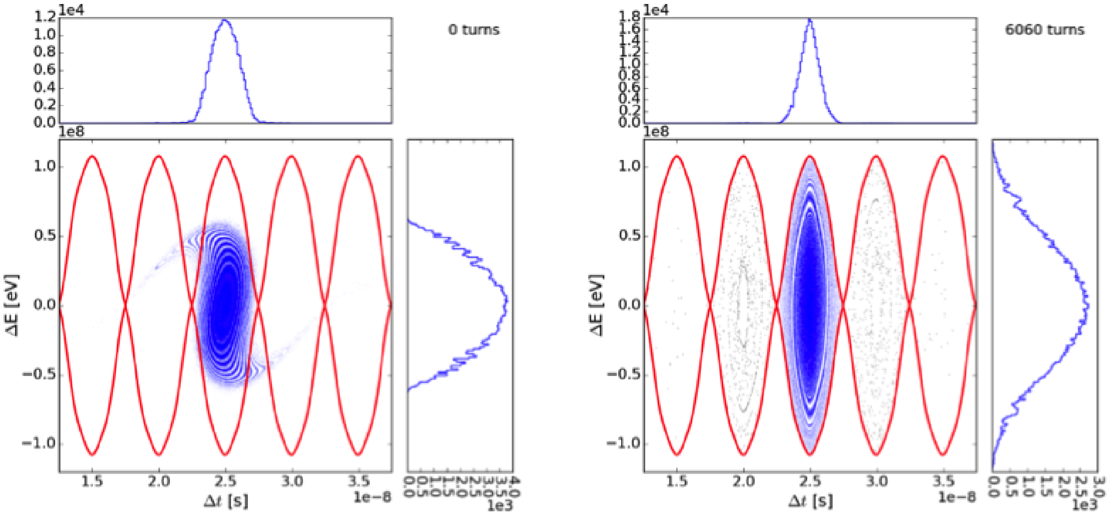
Figure 8: Bunch length spread caused by controlled emittance blow-up during the ramp with decreased target bunch length.



(a) Dipolar and quadrupolar lines.

(b) Zoom on quadrupolar line.

Figure 9: Peak-detected Schottky spectrum of bunches after controlled emittance blow-up and arrival to flat top.



(a) Injection of rotated bunch into the SPS bucket.

(b) Main bunch and satellites at the end of SPS flat bottom.

Figure 10: PS-SPS bunch-to-bucket transfer (simulation with BLonD [8]).