LHC LONGITUDINAL BEAM DYNAMICS DURING RUN 2

H. Timko*, T. Argyropoulos, P. Baudrenghien, R. Calaga, D. Długosz, J. F. Esteban Müller,
I. Karpov, L. E. Medina Medrano, M. Palm, B. Salvachua, E. Shaposhnikova, J. Wenninger
CERN, Geneva, Switzerland

Abstract

During the LHC Run 2, many advances have been made on the beam dynamics in the longitudinal plane. The controlled longitudinal emittance blow-up used in the acceleration ramp was improved and bunch flattening was implemented for bunch length control during collisions. In order to minimise RF power consumption, the capture voltage was optimised and the full-detuning beam-loading compensation scheme was made operational for the ramp and at top energy. Various experimental and simulation studies have helped to improve operation and prepare for the future runs at increased intensities.

INTRODUCTION

The knowledge of the longitudinal beam dynamics in the LHC has been much refined in preparation of and during Run 2, with the help of experimental and simulation studies. Single- and multi-bunch stability thresholds have been measured. Various remedies to limitations encountered in operation have been implemented, too. The full-detuning beam-loading compensation scheme, which is baseline for the High-Luminosity LHC (HL-LHC) era, has been made operational in advance, and has been used throughout the ramp and flat top. The improved and extended bunch shaping methods are discussed as well. Concerning the LHC injection plateau, undamped bunch oscillations, RF power requirements, and the SPS-LHC energy mismatch were studied and are described in detail. Injection voltage requirements and limitations have been estimated for Run 3 and beyond. Finally, diagnostics improvements and RF operational configurations during Run 2 have been summarised, followed by an outlook on upcoming studies for the Long Shutdown 2 (LS2).

The Run 2 operational configurations for protons and ions are summarised in Tables 1 and 2, respectively.

BEAM STABILITY

Completing Run 1 measurements with additional measurements in the beginning of Run 2 [1] at different energies, an accurate threshold $\xi_{\rm th}$ of the single-bunch loss of Landau damping has been established [2, 3] for the stability parameter ξ,

$$\xi \equiv \frac{\tau^5 V}{N_b} > \xi_{\rm th} = (5.0 \pm 0.5) \times 10^{-5} (\mathrm{ns})^5 \mathrm{V}, \qquad (1)$$

where τ is the four-sigma equivalent $(2/\sqrt{2\ln 2})$ FWHM bunch length, V the RF voltage, and N_b the number of protons per bunch. In long physics fills, loss of Landau damping manifested in a gentle longitudinal emittance blow-up over a couple of hours [4], see Fig. 1.

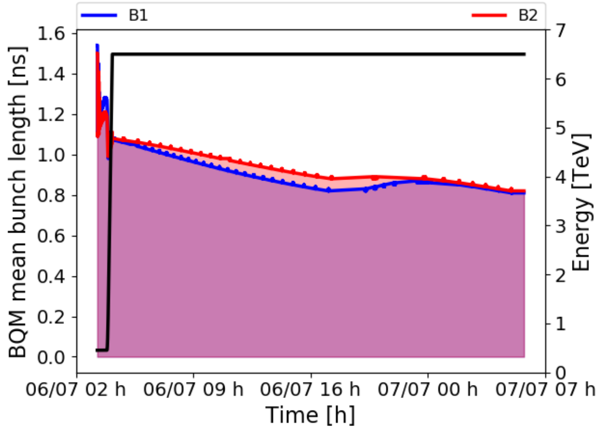

Figure 1: Bunch length evolution in a long physics fill, 6th July 2016. With the intensity burn-off due to collisions and the beam parameters in this fill, gentle bunch oscillations start about 14 h after start of physics, in agreement with the threshold of single-bunch loss of Landau damping measured previously.

Multi-bunch instabilities were studied for the HL-LHC era by probing small emittances and approaching the single-bunch threshold from above (in terms of bunch length) [5]. As no multi-bunch instabilities were observed, see Fig. 2, it was concluded that the LHC is limited by the single-bunch threshold. The HL-LHC stability margins of the RF cavity feedback were probed with batched beam by reducing the feedback gain and thus increasing the effective impedance at the cavity fundamental frequency [6]. Measurements in the LHC showed that sufficient margins for future intensities exist [7].

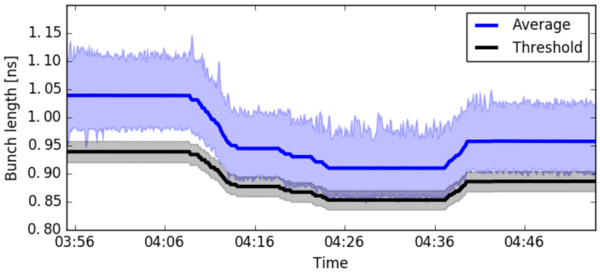

Figure 2: Bunch length evolution of a batch (blue, average and spread) at flat top with different RF voltages probing the single-bunch threshold of loss of Landau damping (black) from above. No coupled-bunch oscillations were observed.

---

* helga.timko@cern.ch

Table 1: LHC RF Run 2 operational parameters for protons. Bunch flattening was applied only in LHCb positive polarity.

Year	**RF capture voltage**	**RF flat top voltage**	**Bunch length, arrival to flat top**	**Bunch flattening available**	**Full detuning after injection**	**10 dB higher RF noise in B1 vs B2**
2015	6 MV	10 MV	1.25 ns	no	no	yes
2016	6 MV	10 MV	1.2 ns, 1.1 ns	yes	no	no
2017	6 MV	12 MV	1.1 ns	yes	yes	no
2018	6 MV, 4 MV	12 MV	1.1 ns	yes	yes	no

Table 2: LHC RF Run 2 operational parameters for ions.

Year	**RF capture voltage**	**RF flat top voltage**	**Bunch length, arrival to flat top**	**Proton-ion cogging**
2015	6 MV	14 MV	1.25 ns	no
2016	6 MV (p), 8 MV (Pb)	12 MV (p), 14 MV (Pb)	1.25 ns	yes
2017	8 MV	12 MV	1.1 ns	no
2018	8 MV	12 MV	1.1 ns	no

In the peak-detected Schottky spectra, a depleted area in the particle distribution was regularly observed at arrival to flat top [8], see Fig. 3. This narrow region cannot be detected on the bunch profiles, but could have an impact on beam stability at top energy. It was observed for multi and single bunches, both with and without crossing the 50 Hz line during the ramp. Its origin remains yet to be studied, and could be related to the controlled emittance blow-up performed in the ramp.

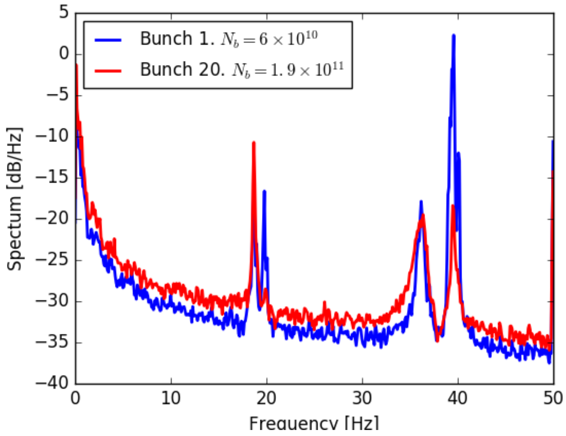

Figure 3: Peak-detected Schottky spectra of single bunches at arrival to flat top for different bunch intensities. A depleted area somewhat below the quadrupolar central synchrotron frequency (2×20.64 Hz) is seen around ~38 Hz.

REMEDIES

In 2016, repeated dumps at injection were encountered, triggering an investigation across the PS-SPS-LHC RF teams. In the end, the satellite population at injection was significantly reduced by switching on the second 40 MHz cavity in the PS for the bunch rotation prior to extraction, which optimises the bunch-to-bucket transfer [9]; this setup was used operationally thereafter. The importance of a good quality bunch rotation in the PS was seen also during the voltage reduction campaign in 2018 on the Longitudinal Beam Synchrotron Radiation Telescope (BSRL) data that shows a significant satellite population of > 1 % in physics, see Fig. 4, whenever the second 40 MHz cavity was off in the PS [10].

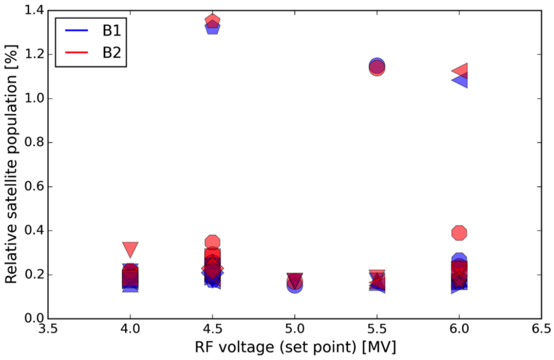

Figure 4: Relative satellite population at arrival to flat top in the injection voltage reduction period, August 2018. The satellites are little affected by the LHC capture voltage, but are dominated by the PS bunch rotation quality instead: the population exceeds 1 % whenever the second 40 MHz cavity was off in the PS.

The full-detuning beam-loading compensation scheme was commissioned in mid-2017 and used operationally till the end of Run 2, during the energy ramp and throughout the flat top. It reduces the RF power consumption by allowing the RF phase to change along a batch and thus placing the RF buckets according to the bunch-by-bunch phase shift along a batch created by beam-loading effects. In the half-detuning scheme, used in the past for the entire cycle and still used for injection, the klystron forward power P (see [11]) can

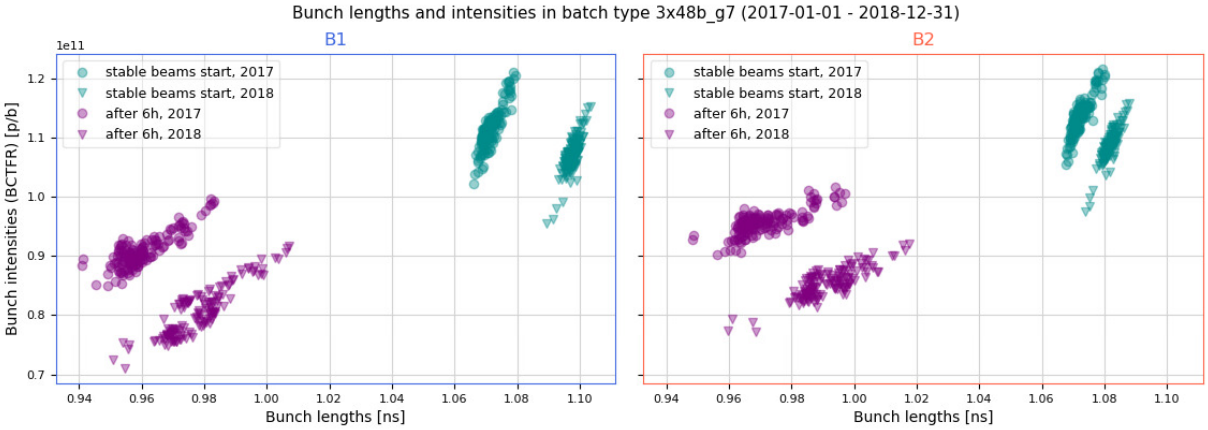

Figure 5: Bunch lengths vs bunch intensities in a batch of 3×48 bunches, at start of stable beams (green) and after 6 h in physics (violet). Average of 2017 fills (circles) and 2018 fills (triangles).

be approximated as

$$P = \frac{V I_{\mathrm{pk}}}{8}, \tag{2}$$

where V is the voltage per cavity and I_{pk} is the peak RF beam current. In the full-detuning scheme, the power consumption becomes independent of the beam current [12],

$$P = \frac{V^2}{8 \frac{R}{Q} Q_L}, \tag{3}$$

where $\frac{R}{Q} = 45\ \Omega$ is the shunt-impedance-to-quality-factor ratio of the cavities and Q_L the loaded quality factor. With 2017 beam parameters, the average power consumption at flat top was reduced from 190 kW to 100 kW [13].

In 2015, a systematically larger abort gap population was observed in B1 than in B2, without having any impact on the operational performance. This was due to the about 10 dB higher RF noise level in B1 than in B2, which was mitigated by the exchange of the Voltage Controlled Crystal Oscillator (VCXO) generating the 400 MHz reference for B1 in the YETS 2015 [14]. During 2016-2018, the noise level was therefore about the same in both beams.

Throughout the entire Run 2, the bunch length at arrival to flat top was regulated within about 50 ps to the bunch length targeted by the controlled emittance blow-up in the ramp, with both beams having the same bunch lengths. For the BCMS batches of 3×48 bunches, it was observed that both the bunch length and bunch intensity of B1 shrinks faster than those of B2, and that this effect was somewhat more pronounced in 2018 than in 2017, see Fig. 5. Investigations are ongoing to understand the reason for this difference between the two beams.

BUNCH SHAPING

Two methods are used operationally in the LHC for bunch shaping: injection of RF phase noise and RF phase modulation. The controlled injection of RF phase noise into the beam control loop leads to diffusion in the phase space of the bunches [15–17]. In the LHC, band-limited phase noise is generated [18] to target the core region of the bunch, in a bandwidth according to the targeted bunch length [19]. The shape of the noise spectrum also determines the resulting bunch profile. The continuous diffusion leads to gradual emittance growth, and in the ramp a bunch length feedback regulates the noise amplitude to achieve the desired length [20].

Single-frequency RF phase modulation, on the other hand, results in the resonant excitation of the bunch [21]. It is a loss-free mechanism to shape the bunch profile. It can furthermore help to reduce heat load and pile-up density, as well as to improve beam stability [22, 23]. The amplitude has to be above a critical value for the resonant excitation to occur, and above this value, the final bunch length is determined by the modulation frequency only and is independent of the amplitude [22].

In the LHC at flat top, the critical amplitude was found to be 0.6° at $0.98 f_{s,0}$ [24], where $f_{s,0}$ is the central synchrotron frequency. Bunch flattening using single-frequency modulation has been operational in physics since 2016, whenever the LHCb polarity was positive, see Fig. 6. This was to

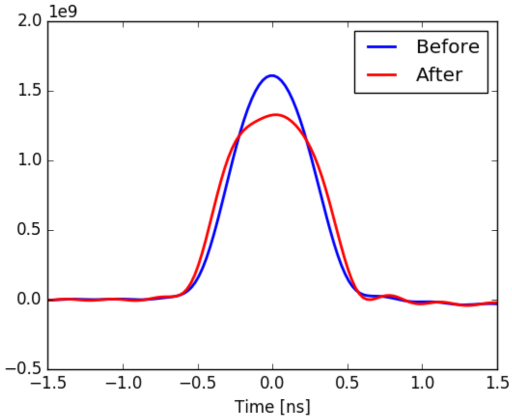

Figure 6: Bunch profile in physics before (blue) and after (red) flattening; measured with an oscilloscope at 40 MS/s.

ensure sufficient vertex resolution in this polarity [25] by keeping the bunch length above 0.9 ns. Operationally, a modulation frequency of $0.9875 f_{s,0}$ was used to limit the bunch lengthening and the decrease in instantaneous luminosity associated with it. The flattening was triggered manually by the operators through the Sequencer application, whenever the bunch length was reaching ~0.95 ns. During the RF phase modulation, the beam phase loop is open.

Controlled longitudinal emittance blow-up is indispensable for beam stability in the LHC during the energy ramp [2, 26]. In operation, an effectively band-limited noise spectrum is desired to target the bunch core. However, the phase noise is injected into the beam phase loop, and the phase loop significantly damps the noise around the central synchrotron frequency [20, 27]. After LS1, a pre-distortion of the noise spectrum has been used to compensate for the response of the beam phase loop for a bunch length of about 1.1 ns.

In early 2016, the target bunch length was reduced from 1.25 ns to 1.1 ns, in steps of 50 ps, upon request from the LHC experiments. Keeping a constant target length throughout the entire ramp, the bunch-by-bunch bunch length spread was kept under control for the target lengths of 1.15-1.25 ns, but was increasing in the ramp for 1.1 ns [8], see Fig. 7. In operation, this was simply mitigated by keeping the target bunch length at 1.25 ns during the first 800 s of the ramp and then decreasing it to 1.1 ns. This results in an adiabatic decrease in the last 400 s, with the blow-up occasionally switching on again just before arrival to flat top.

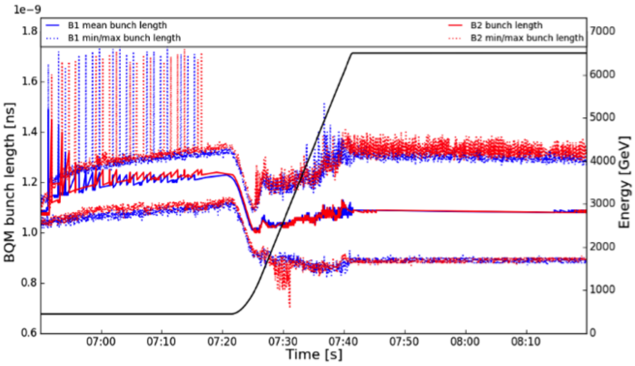

Figure 7: Bunch length evolution during controlled emittance blow-up with 1.1 ns constant target bunch length during the ramp results in increased bunch length spread. B1 (blue) and B2 (red) mean (solid lines) and minimum/maximum (dotted lines) bunch lengths are shown.

In Machine Development (MD) studies, even smaller target bunch lengths of 0.85-1.0 ns were tried and resulted in a divergence of bunch length [1, 14], with some bunches shrinking adiabatically and not being blown up at all, and some bunches blowing up too much, see Fig. 8. Studies are underway during LS2 to understand the mechanism of this divergence and to find a mitigation for future high intensities, where the effect is expected to be enhanced and can potentially become a major concern for HL-LHC.

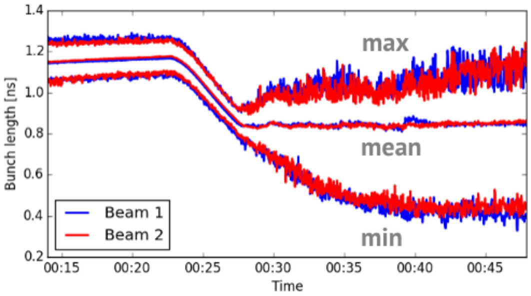

Figure 8: Bunch length divergence during the controlled emittance blow-up in MD with a small target bunch length.

Operationally, the Parabolic-Exponential-Linear-Parabolic (PELP) momentum ramp of 1210 s length was used throughout the entire Run 2. For time-saving purposes, the Parabolic-Parabolic-Linear-Parabolic (PPLP) ramp of 1100 s length was prepared in MD studies [28]. In operation, it was attempted to use the PPLP ramp with controlled emittance blow-up for pilots and nominals on 8th April 2018.

For beam stability, the controlled emittance blow-up is not required for pilot intensities and was only set up for nominals. With the pre-distortion of the blow-up spectrum depending on the bunch length, it is furthermore not expected that the blow-up would work for the generally shorter pilot bunches. In practise, however, it was used for pilots during the verification of the operational cycles, before injecting nominal bunches. With the slower PELP ramp, the pilot bunch length happened to be well controlled. With the faster PPLP ramp and the nominal noise spectrum, neither pilots nor nominals could be controlled.

In the operational PELP ramp, a linear voltage increase can be used and the resulting bucket area is increasing monotonically. Using a linear voltage ramp in the PPLP ramp would result in a decreased bucket area in the beginning of the ramp and therefore increased losses. To keep the bucket area at least constant in the first 50 s, a fast increase of the RF voltage was programmed, see Fig. 9. By keeping the bunch length constant in the ramp, the emittance should be

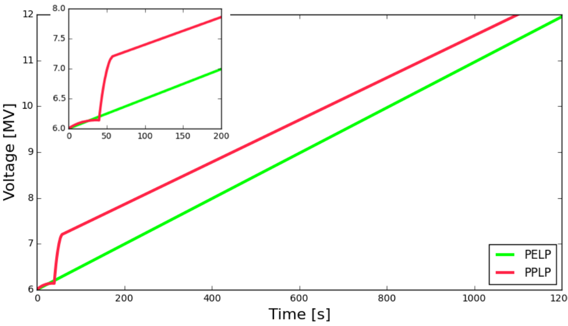

Figure 9: Voltage programmes in the PELP (green) and PPLP (red) ramps. The inset shows the first 200 s of the ramp.

blown-up as the bucket area increases, ensuring also sufficient beam stability. As a result of the voltage programme, in the subsequent 150 s of the ramp, the bucket area increases by almost a factor two in the PPLP case, while in the PELP case it increases only by ~30 %, see Fig. 10.

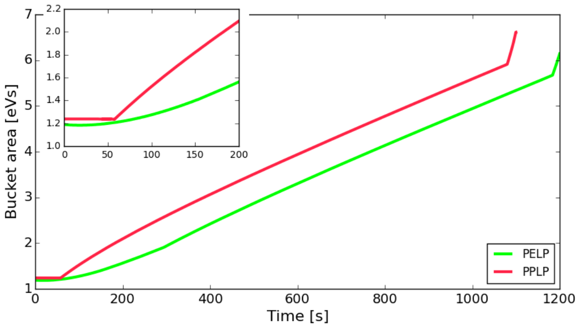

Figure 10: Bucket area in the PELP (green) and PPLP (red) ramps. The inset shows the first 200 s of the ramp.

Consequently, a stronger emittance blow-up has to be applied in the low-energy part of the ramp, where the tail population is still significant and losses are to be avoided. With a narrowed blow-up spectrum, nominals were successfully accelerated, but it was still not possible to regulate the shorter pilots. Studies are planned to better adapt the blow-up for the PPLP ramp.

DYNAMICS AT INJECTION

Persistent bunch oscillations at injection have been observed since the first start-up with beam [29]. On occasion, damping times of up to 1 h have been observed, and the oscillations can even survive the controlled emittance blow-up in the ramp [5], potentially impacting the beam stability at arrival to flat top. In measurements, non-rigid oscillations can be seen on the bunch profiles, see Fig. 11, with peak-to-peak oscillation amplitudes of up to 60° [30]. Furthermore, with single bunches of $1.9{\times}10^{11}$ p/b injected into 6 MV, ~5 % of losses were observed over 20 min at flat bottom, which needs to be mitigated for future high-intensity beams.

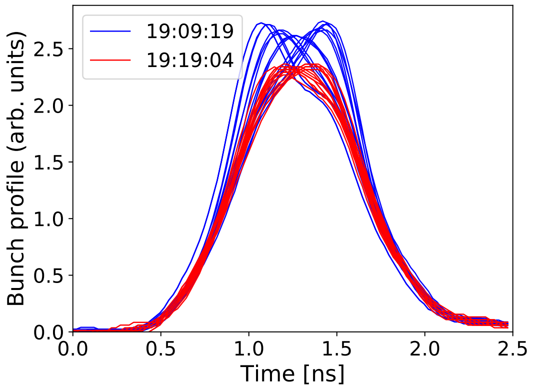

Figure 11: Non-rigid bunch profile oscillations observed in an MD with a single bunch of $1.9{\times}10^{11}$ p/b captured with 6 MV total voltage.

The effect of long-lasting oscillations has been reproduced in particle simulations and can be attributed to the large mismatch between the LHC capturing bucket height and the momentum spread of the arriving bunch [31]. Intensity effects and injection errors in phase and energy can further amplify the oscillations.

The injection voltage has been reduced from 6 MV to 4 MV, in steps of 0.5 MV during August 2018. The 'matched' voltage for the 2018 beam parameters would be closer to about 2 MV, but this is not possible to use as it results in too high capture losses. Then again, the previously operational 6 MV was optimised at the time for the beam produced in the SPS Q26 optics. For Run 2 beam parameters, 4 MV was found to be a good compromise between reduced RF voltage, which is beneficial for beam stability and RF power consumption, and increased RF voltage, which is reducing the capture losses.

The sum of capture and flat bottom losses is detected on the Beam Loss Monitoring (BLM) system at the start of the momentum ramp; the losses increase as the voltage is reduced, see Fig. 12. Whenever the energy mismatch between the SPS and the LHC is large, a large blow-up due to filamentation is observed. In addition, the losses are significantly increased, approaching the dump threshold [10]. This points to a large fraction of the losses being due to flat bottom losses. A longitudinal damper is being (re-)studied to damp energy errors between the two machines. Also the cause and other mitigation methods of the SPS-LHC energy mismatch are to be investigated.

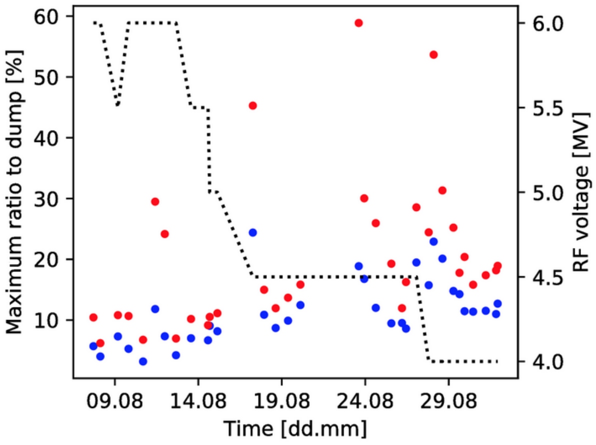

Figure 12: Fill-by-fill maximum ratio to dump among all BLMIs during the voltage reduction period; B1 (blue) and B2 (red).

The full-detuning scheme ensures that the presently available RF power will be sufficient also in the HL-LHC era during the ramp and in physics. However, it cannot be used at injection, because the capturing LHC RF buckets must be aligned with the corresponding SPS bunch spacing at transfer. Also for the HL-LHC era, it is thus intended to keep the half-detuning scheme at injection and switch on the full detuning only after the injection, as was done already in Run 2.

Therefore, RF power limitations at injection using the half-detuning beam-loading compensation scheme have been studied for Run 3 and beyond. Two MD studies with beam have been performed on the topic and a detailed analysis needs yet to be done. In the first MD, with operational margins and presently operational conditions, a total voltage of 10.4 MV could be safely maintained with the maximum klystron forward power and a bunch intensity of 1.15×10^{11} p/b. The second MD showed that possibly higher voltages can be maintained with voltage partitioning and a pre-detuning of the cavities. As is, without a damping of energy errors, a minimum voltage of 4 MV is required for the same intensity, as otherwise start-of-ramp losses could start to impact machine availability.

Without further improvements to the RF system, and scaling the maximum available voltage obtained in the first MD, one expects in the half-detuning scheme to be able to maintain 6.6 MV at 1.8×10^{11} p/b and 5.2 MV at 2.3×10^{11} p/b. With the beam parameters at SPS extraction expected for the future, and assuming that the maximum SPS voltage will be used both for 1.8×10^{11} p/b and 2.3×10^{11} p/b, the minimum LHC voltage required to capture this beam would be 6.4 MV and 7.9 MV [32], assuming SPS Q20 and Q22 optics, respectively. The Run 3 target intensity of 1.8×10^{11} p/b is therefore at the limit of what can be done with the RF system at present, assuming the Q20 optics in the SPS. Various studies to understand the exact voltage limitation at injection including the transients and to mitigate this limitation are underway.

DIAGNOSTICS

In comparison to Run 1, the RF diagnostics has been extended with various tools. The rise time of peak-detected Schottky spectra acquisitions has been shortened in LS1. The measurement of high-resolution bunch profiles has been improved in LS1 by moving the oscilloscopes to UA43 and thus reducing the signal path. For the first time in the LHC, first-turn measurements and tomographic reconstructions of the bunch phase-space distribution have also been performed through expert tools. Especially for the SPS-LHC energy matching, it would be an asset to have these tools operationally available for the restart after LS2. For observations of beam-induced heating, a fixed display and logging of the beam spectra has been made available. A FESA class and logging have been implemented also for the longitudinal ObsBox signals concerning (i) stable phase measurement for e-cloud observations, (ii) bunch-by-bunch oscillation amplitude for beam stability observations, and (iii) full-detuning cavity phase shifts, also available through DIP and the LPC filling-scheme viewer [33].

OUTLOOK

To overcome the power limitations at injection, various studies are ongoing in LS2. These include, among others, the evaluation of alternative beam-loading compensation schemes, pre-detuning of cavities prior to injection, and studies on the feasibility and improvements expected with a longitudinal damper. RF phase modulation, whether applied in the SPS before extraction or in the LHC at injection, does not seem to reduce the RF power consumption during injection. Investigations are being launched to better understand the behaviour of the RF power chain in response to the beam injection transients.

Several aspects of the controlled emittance blow-up need to be studied as well, to prevent bunch length divergence at increased intensities and to enable compatibility with the PPLP ramp. On the high-power side, dynamic circulator adjustment, line-by-line differences, and operational margins are being studied. On the hardware side, the gain from high-efficiency klystrons and additional cavities could be evaluated. Depending on the outcome of these studies, a sequential implementation of the potential RF system improvements can be envisaged during Run 3 and beyond.

CONCLUSIONS

In conclusion, the present LHC RF system performed well with up to 1.3×10^{11} p/b throughout Run 2. A vast range of studies has been performed in Run 2, to better understand the LHC RF system and the longitudinal dynamics in the machine. Today, we have a good understanding of longitudinal stability in the LHC, which is determined by the single-bunch loss of Landau damping, even for batched beam. The controlled emittance blow-up used in the ramp has been improved and bunch flattening has been implemented in physics for bunch length regulation. The RF power consumption at injection appears to be a limiting factor for bunch intensities beyond Run 3, at least with the presently operational features of the RF system. To this end, studies concerning for instance a longitudinal damper and the behaviour of the RF power chain during injection transients are presently ongoing.

ACKNOWLEDGEMENTS

We gratefully acknowledge the kind help of MD Coordinators and the LHC, SPS, PS, and PSB operators, without whom our machine studies would not have been possible. We also thank for the continuous support of our RF colleagues in the various machines, S. Albright, B. Bielawski, T. Bohl, Y. Brischetto, O. Brunner, A. Butterworth, H. Damerau, J. Galindo, A. Lasheen, T. Mastoridis, J. Molendijk, M. Ojeda, G. Papotti, F. Peauger, J. Repond, M. Schwarz, M. Therasse, and K. Turaj,U. Wehrle, who have helped us enormously to prepare machine studies and improve the diagnostics in the LHC.

REFERENCES

[1] J. F. Esteban Müller, P. Baudrenghien, A. Lasheen, T. Roggen, E. Shaposhnikova, H. Timko, ‘LHC Longitudinal Single-Bunch Stability Threshold’, Rep. CERN-ACC-NOTE-2016-0001, CERN, Geneva, Switzerland, 2016.

[2] E. Shaposhnikova, ‘Longitudinal beam parameters during acceleration in the LHC’, LHC-Project-Note-242, Geneva, Switzerland, 2000.

[3] J. F. Esteban Müller, ‘Longitudinal intensity effects in the CERN Large Hadron Collider’, PhD Thesis, EPFL, Lausanne, Switzerland, 2016.

[4] H. Timko, P. Baudrenghien, J. Esteban Müller, E. Shaposhnikova, ‘Operational and beam dynamics aspects of the RF system in 2016’, Proc. 7th Evian workshop, Evian, France, 2017.

[5] J. F. Esteban Müller, E. Shaposhnikova, H. Timko, ‘LHC MD 652: coupled-bunch instability with smaller emittance (all HOMs)’, Rep. CERN-ACC-NOTE-2017-0017, CERN, Geneva, Switzerland, 2017.

[6] T. Mastoridis, P. Baudrenghien, J. Esteban Müller, J. Molendijk, E. Shaposhnikova, H. Timko, ‘Coupled-bunch instabilities due to fundamental cavity impedance’, Rep. CERN-ACC-NOTE-2017-0009, CERN, Geneva, Switzerland, 2017.

[7] P. Baudrenghien and T. Mastoridis, ‘Fundamental cavity impedance and longitudinal coupled-bunch instabilities at the High Luminosity Large Hadron Collider’, Phys. Rev. Accel. Beams, vol. 20, p. 011004, 2017.

[8] J. F. Esteban Müller, P. Baudrenghien, E. Shaposhnikova, H. Timko, ‘LHC MD 232: Longitudinal Impedance Evaluation’, Rep. CERN-ACC-NOTE-2017-0016, CERN, Geneva, Switzerland, 2017.

[9] H. Timko *et al.*, ‘Longitudinal transfer of rotated bunches in the CERN injectors’, Phys. Rev. ST Accel. Beams, vol. 16, p. 051004, 2013.

[10] H. Timko *et al.*, ‘Optimal Injection Voltage in the LHC’, to be submitted, 2019.

[11] D. Boussard, ‘RF power requirements for a high intensity proton collider - Part I’, Proc. PAC‘91, San Francisco, USA, 1991.

[12] P. Baudrenghien, T. Mastoridis,‘Proposal for an RF roadmap towards ultimate intensity in the LHC", Proc. IPAC‘12, New Orleans, USA, 2012.

[13] H. Timko *et al.*, ‘LHC RF system performance in 2017’, Proc. 8th Evian workshop, Evian, France, 2018.

[14] H. Timko *et al.*, ‘Operational and beam dynamics aspects of the RF system in 2015’, Proc. 6th Evian workshop, Evian, France, 2016.

[15] S. Krinsky, J. M. Wang, ‘Bunch diffusion due to RF noise’, Part. Accel. 12, 107–117, 1982.

[16] G. Dôme, ‘Diffusion due to RF noise’, Proc. CERN Accelerator School ‘85, Oxford, UK, 370–401, 1985.

[17] T. Toyama, ‘Uniform bunch formation by RF voltage modulation with a band-limited white signal’, Nucl. Instrum. Meth. A 447, 317-327, 2000.

[18] J. Tückmantel, ‘Digital generation of noise-signals with arbitrary constant or time-varying spectra (A noise generation software package and its application)’, LHC-PROJECT-Report-1055, Geneva, Switzerland, 2008.

[19] P. Baudrenghien *et al.*, ‘Longitudinal emittance blow-up inthe LHC’, Proc. IPAC‘11, San Sebastian, Spain, 2011.

[20] P. Baudrenghien, T. Mastoridis, ‘Longitudinal emittance blowup in the large hadron collider’, Nucl. Instrum. Meth. A, 726, 181–190, 2013.

[21] S. Y. Lee, ‘Accelerator Physics’, and references therein, Third Edition, World Scientific, 2012.

[22] C. Y. Tan and A. Burov, ‘Phase modulation of the bucket stops bunch oscillations at the Fermilab Tevatron’, Phys. Rev. ST Acc. Beams 15, 044401, 2012.

[23] E. Shaposhnikova *et al.*, ‘Flat Bunches in the LHC’, Proc. IPAC‘14, Dresden, Germany, (2014).

[24] H. Timko, P. Baudrenghien, J. Esteban Müller, E. Shaposhnikova, ‘LHC MD 1279: bunch flattening in physics’, CERN-ACC-NOTE-2017-0019, CERN, Geneva, Switzerland, 2017.

[25] P. Robbe, ‘Requirements on bunch length control by LHCb’, Presentation at the LBOC meeting no. 63, 2016.

[26] O. Brüning *et al.*, ‘LHC Design Report’, CERN, Geneva, Switzerland, 2004.

[27] H. Timko, P. Baudrenghien, T. Mastoridis, E. Shaposhnikova, ‘Studies on Controlled RF Noise for the LHC’, Proc. HB2014, THO4LR03, East Lansing, U.S.A., 2015.

[28] M. Solfaroli, T. Argyropoulos, H. Timko, J. Wenninger, ‘Studies with parabolic parabolic linear parabolic (PPLP) momentum function in the LHC’, Rep. CERN-ACC-NOTE-2018-019, CERN, Geneva, Switzerland, 2018.

[29] P. Baudrenghien *et al.*, ‘Longitudinal oscillations with batch injection in the LHC’, CERN, Geneva, Switzerland, Rep. ATS-Note-2011-031-MD, 2011.

[30] I. Karpov, S. Albright, T. Argyropoulos, P. Baudrenghien, E. Shaposhnikova, H. Timko, ‘LHC MD 2042: persistent injection oscillations’, Rep. CERN-ACC-NOTE-2018-0018, CERN, Geneva, Switzerland, 2018.

[31] H. Timko, T. Argyropoulos, I. Karpov, E. Shaposhnikova, ‘Beam instabilities after injection to the LHC’, Proc. HB2018 workshop, Daejeon, Korea, 2018.

[32] H. Timko, E. Shaposhnikova, K. Turaj, ‘Estimated LHC RF system performance reach at injection during Run 3 and beyond’, Rep. CERN-ACC-NOTE-2019-0005, CERN, Geneva, Switzerland, 2019.

[33] LPC website for filling schemes, `https://lpc.web.cern.ch/SchemeEditor.htm`.