BUNCH LENGTH REGULATION IN THE LHC DURING CONTROLLED EMITTANCE BLOW-UP

N. Gallou*, B. Bielawski, A. Butterworth, M. Hostettler, M. Jaussi, H. Timko,

CERN, Geneva, Switzerland

Abstract

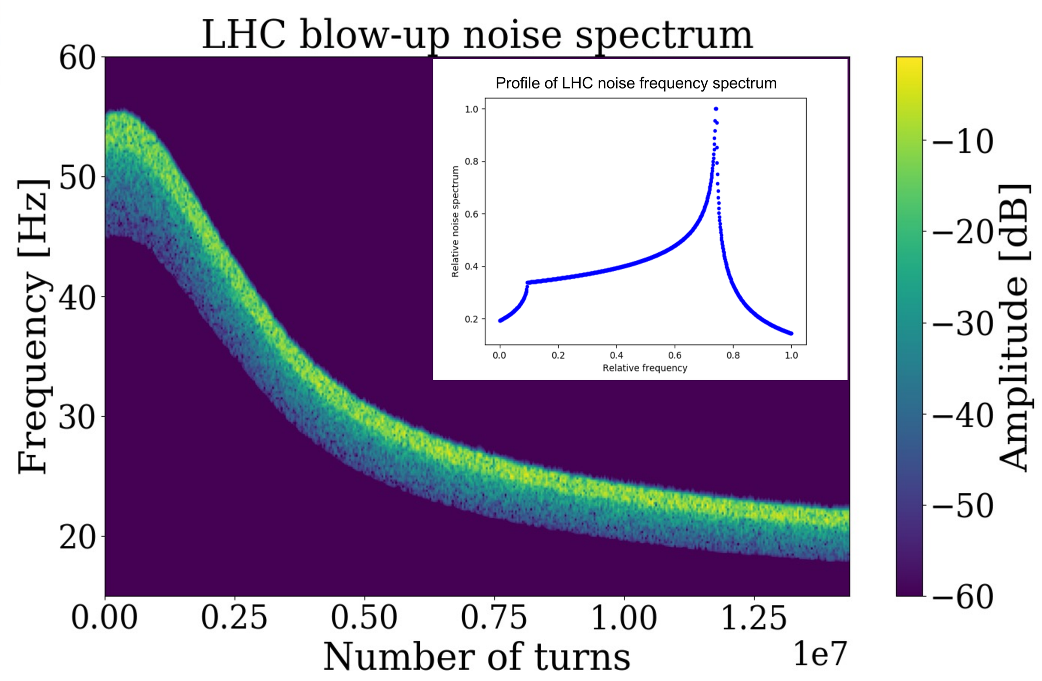
Controlled longitudinal emittance blow-up is indispensable for the operation of the Large Hadron Collider (LHC) to counteract single-bunch loss of Landau damping during the acceleration ramp. The blow-up is performed by injecting RF phase noise in a narrow frequency band into the beam phase loop, with bunch-length feedback regulating the noise amplitude. In 2024, the variation of the bunch length due to imperfect regulation caused unacceptable beam-induced heating of certain accelerator components. In this contribution, we present the results of extensive simulation scans that have been used to optimize the feedback parameters. We show how this optimization, along with a reduction of the feedback delay on the controls side, has been implemented in the LHC and significantly improved the bunch length evolution during acceleration. Finally, we discuss the results of a measurement scan performed during an operational period of five weeks to fine-tune the blow-up feedback settings.

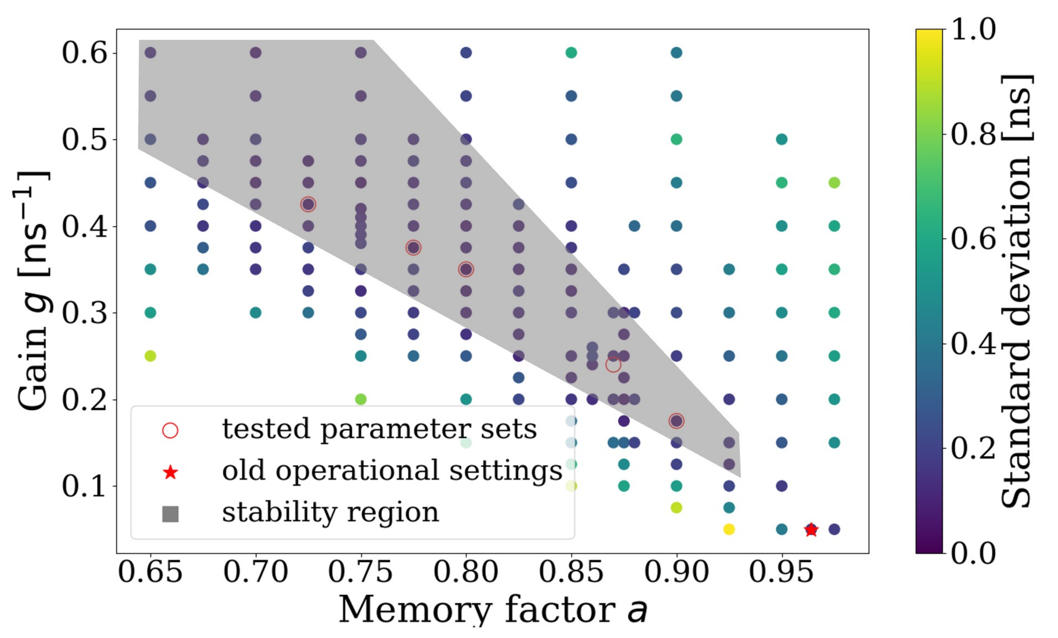
Bunch length regulation

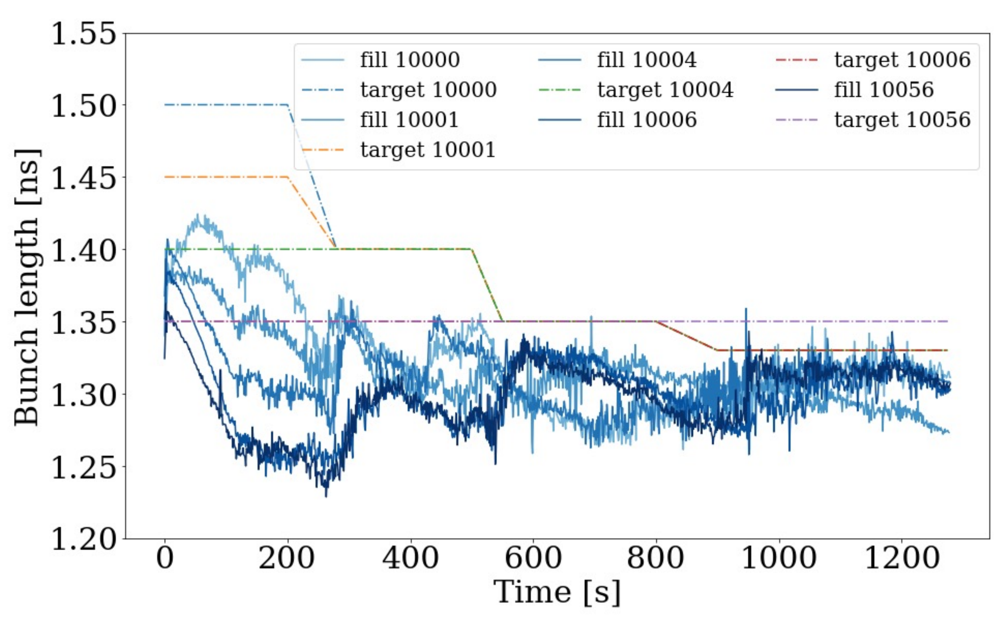
In practice, bunch length regulation is achieved using a feedback mechanism that adjusts the r.m.s. amplitude of the RF phase noise $\varphi_N(t)$ to keep a constant bunch length [2]. The algorithm compares the instantaneous measured bunch length τ_{meas}, average of all bunches in the ring, to the desired target length τ_{targ}, and scales the phase noise excitation amplitude with a dimensionless factor $x_n \in [0,1]$ as follows [3]:

$$x_{n+1} = a x_n + g(\tau_{targ} - \tau_{meas})$$
$$\text{if } x_{n+1} \leq 0, \text{then } x_{n+1} = 0$$
$$\text{if } x_{n+1} \geq 1, \text{then } x_{n+1} = 1$$

where n is the iteration. The recursion represents a low-pass filter (LPF), which suppresses high-frequency noise on the bunch length measurement. The `memory factor' $a \in [0,1]$ is the weight of the previous x_n measurement and determines the time constant of the LPF. The gain g, typically $\mathcal{O}(1)$ ns^{-1}, weighs the bunch length difference.







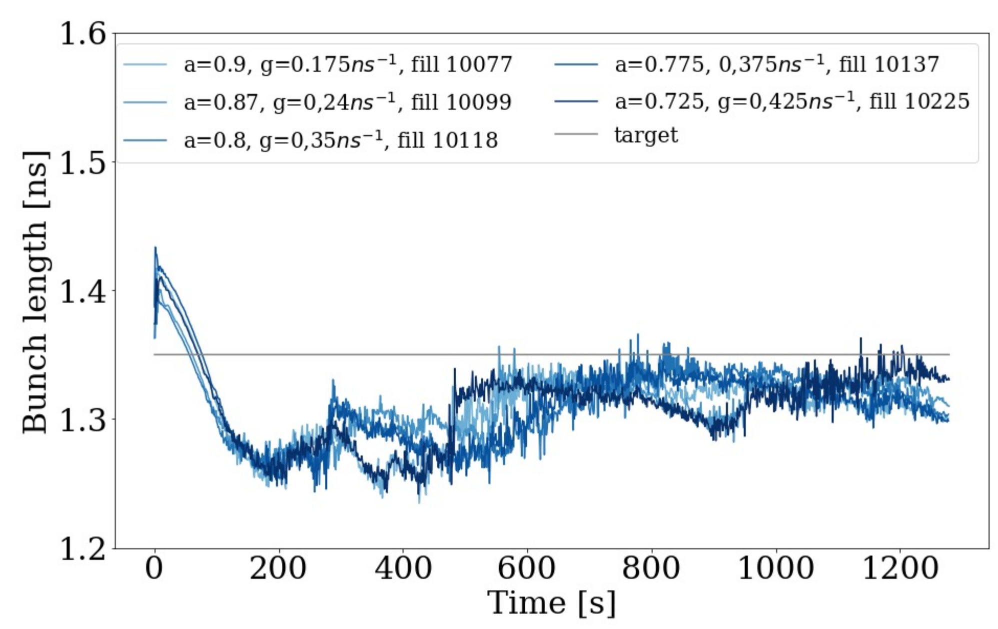
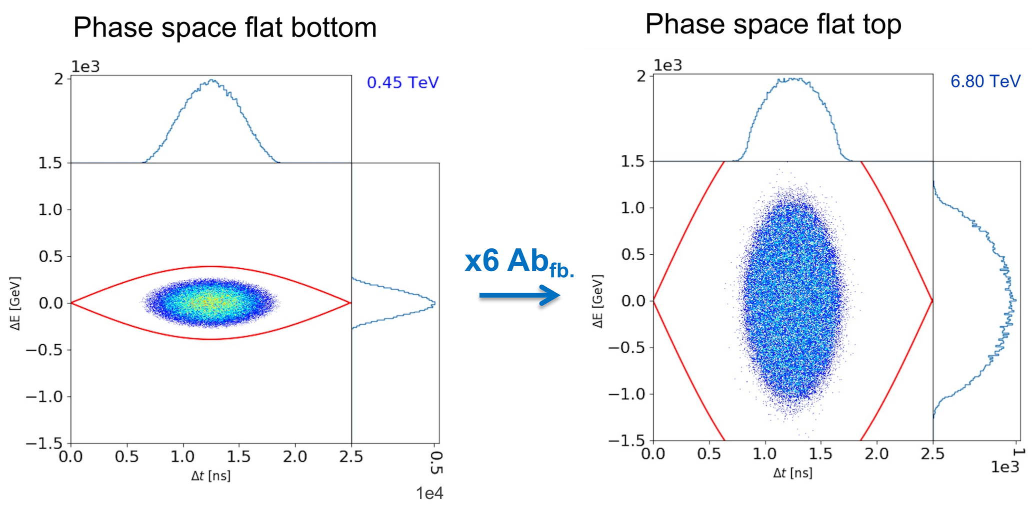
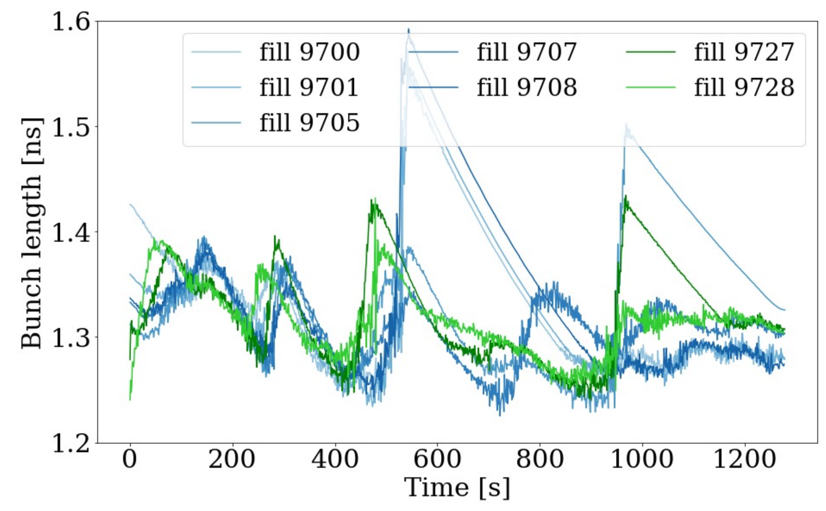


Table 2: LHC acceleration ramp settings 2024

Settings	$E_{fb.}$	$E_{ft.}$	$V_{fb.}$	$V_{ft.}$	$Ab_{fb.}$	$Ab_{ft.}$
value	450 [GeV]	6.8 [TeV]	5 [MV]	12 [MV]	1.09 [eVs]	6.5 [eVs]

In the LHC, a band-limited white noise spectrum is desired, targeting the core of the bunch by tracking the central synchrotron frequency, f_{s0}, along the ramp in the noise band of (0.8571-1.05) $f_{s0}(t)$. In practice, $\varphi_N(t)$ is injected via the beam phase loop (PL) as an additional phase shift in the phase correction between the 400 MHz bunch and cavity phase. However, as the phase loop damps oscillations around f_{s0}, the injected noise spectrum is pre-shaped to compensate the phase loop response.





Simulation: Noise Feedback Parameter Scan

This analysis revealed a region of optimum feedback parameters for a stable bunch length regulation (grey region). The stability region has been selected using only the simulation results that have a standard deviation lower than 2 x 10^{-2} ns.

First tests in the LHC

- To test the blow-up mechanism on multiple beam configurations, we used bunch trains (12b + 3 x 36b) in beam 1 and a single bunch in beam 2.
- Fill 9727: a new software implementation was tested, to decrease the response time of the noise injection mechanism. In this new implementation, the buffer size was reduced to 1 s (from 2 s) and the response time to one buffer (from two buffers). The expected latency between the BQM measurement and the action on the noise buffer is now between 1 s and 2 s (before it was between 4 s to 6 s), which correspond to 1.1 x 10^4 and 2.2 x 10^4 machine turns.
- Fill 9728: a new pair of feedback parameters was tested along with the new software implementation. The parameters a=0.87 and g=0.2 ns^{-1} were chosen based on preliminary simulation results.

Target bunch length changes

- With the improved settings from the MDs, the stepwise target bunch length, that was used as a workaround, had become unnecessary and even seemed to deregulate the bunch length evolution.
- The target was lowered by 0.05 ns per operational ramp, in a total of 4 steps, until it became flat at 1.35ns.
- One can observe that the closer we get to the flat target, the more natural the adiabatic shrinkage is at the beginning of the ramp.

Operational Scan

- The goal of this scan was to validate the stable region and attempt to further fine-adjust the feedback settings. Each parameter set was kept for a week, to investigate also the fill-by-fill variations.
- Finally, it was decided to keep the pair with the higher gain (a=0.725 and g=0.425 ns^{-1}), as it is preferred that the feedback has a faster reaction time according to more recent bunch length measurements.

Table 1: Feedback settings during the LHC parameter scan

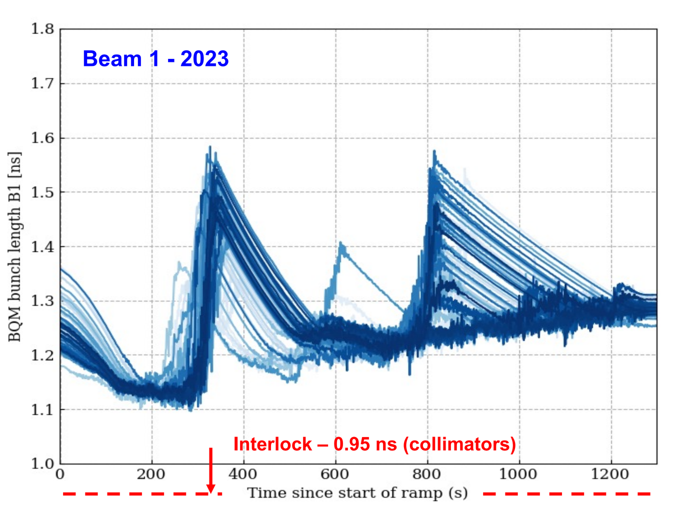
Settings	WK 35	WK 36	WK 37	WK 38	WK 39
a[1]	0.9	0.87	0.8	0.775	0.725
g [ns^{-1}]	0.175	0.24	0.35	0.375	0.425

Conclusions

The bunch length regulation in the LHC was suffering from large excursions with respect to its target value during the acceleration ramp. Thanks to simulations with GPU resources, it was possible to scan a large range of the phase noise feedback parameter pairs and map the stable region. In addition, with improvements in the LHC software implementation of the phase noise injection, the latency between bunch length measurement and noise amplitude regulation was reduced.

After changing the feedback parameters and adopting the new software implementation in the machine, the bunch length control improved significantly. A flat target bunch length function was also restored. Finally, five pairs of feedback parameters were tested in operation, confirming similar regulation quality as predicted. The pair with the highest gain (a=0.725 and g=0.425 ns^{-1}) was kept for operation. This way, local heating on the machine induced by the RF finger modules is no longer an issue for the present operational intensity of 1.6 x 10^{11} p/b.

Before:



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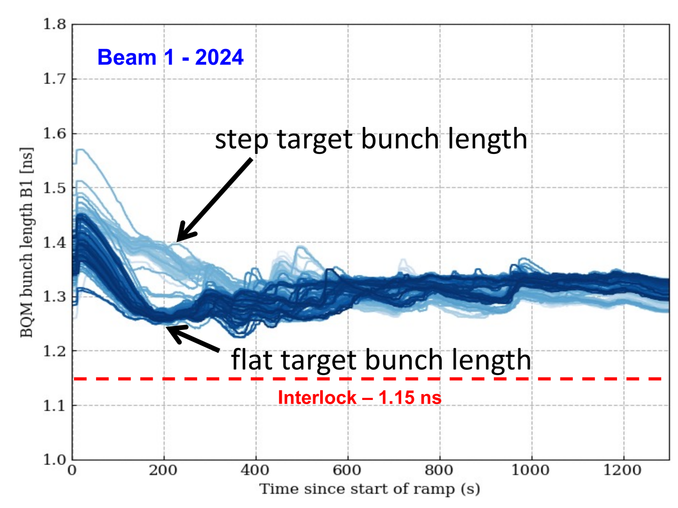

Plots by J. Wenninger [4].

References & Contact

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Contact: niki.gallou@cern.ch