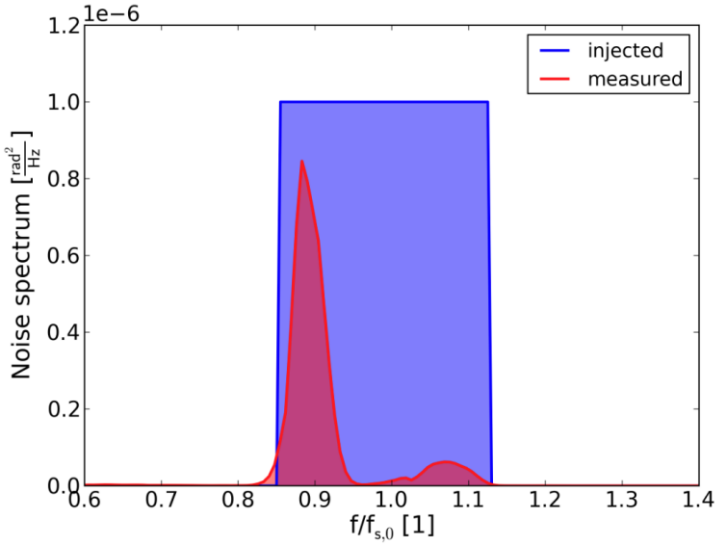
Bunch length regulation in the acceleration ramp

Helga Timko

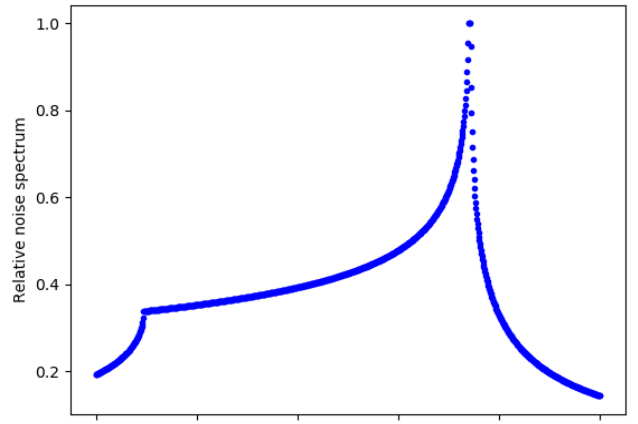
RF fingers expert discussion, 21st March 2024

LHC blow-up implementation (1)

- **Noise is injected through the beam phase loop [1-3]**
- **The beam phase loop counteracts the noise at the central synchrotron frequency**
  - The noise is shaped with the BTF of a parabolic bunch to the beam phase loop
  - The effective noise spectrum seen by the beam is (about) flat
    - The present BTF assumes a bunch length of 1.25 ns (used since 2015)



Action of the beam phase loop



0.857 f_{s0} 1 f_{s0} 1.05 f_{s0}

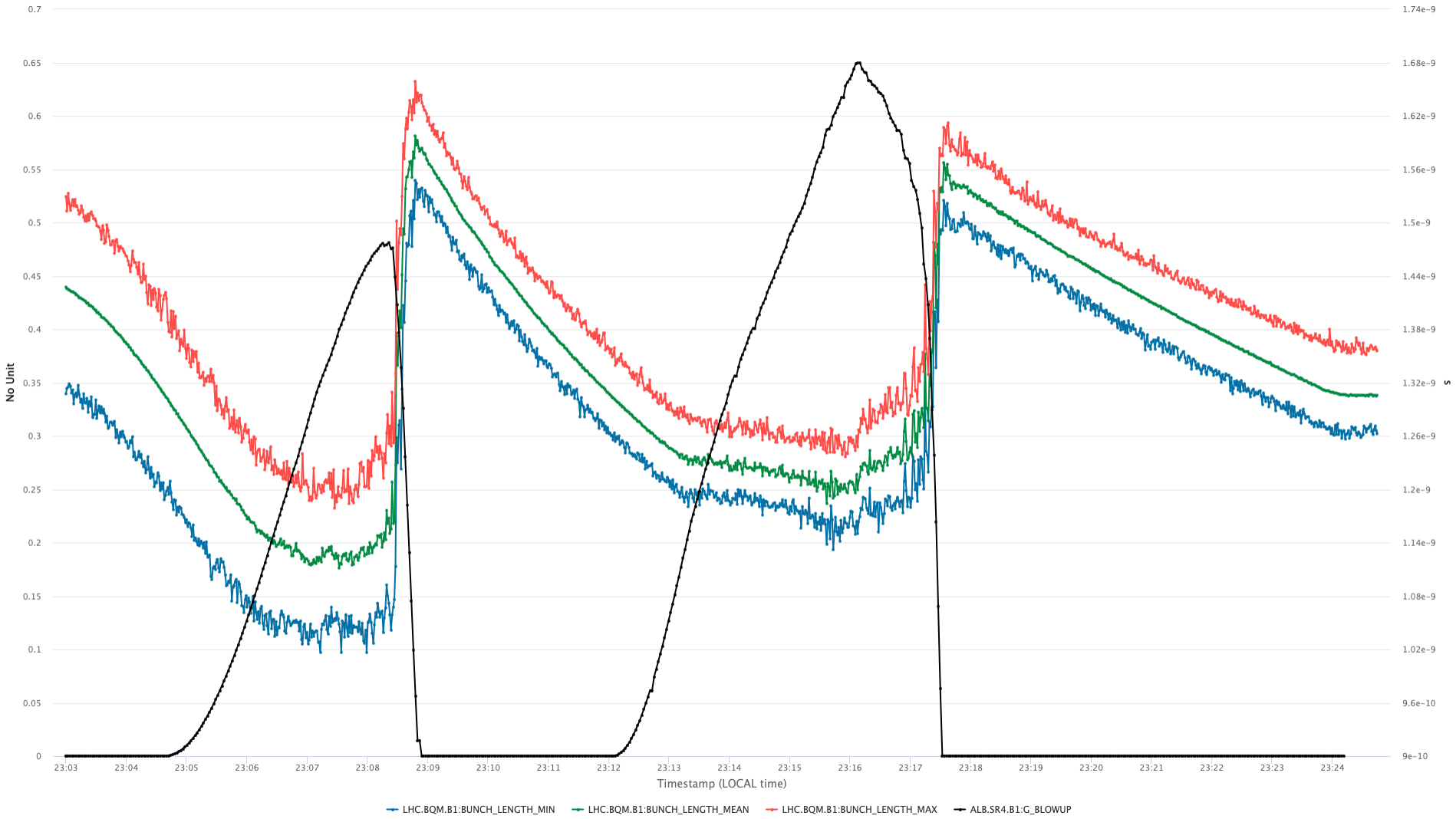
[1] P. Baudrenghien et al.: 'Longitudinal emittance blow-up in the LHC', IPAC'11, San Sebastian, Spain, TUPZ010 (2011).
[2] P. Baudrenghien, T. Mastoridis: 'Longitudinal emittance blowup in the large hadron collider', NIM A, 726, 181–190 (2013).
[3] H. Timko et al.: 'Studies on controlled RF noise for the LHC', HB'14, East Lansing USA, THO4LR03 (2014).

LHC blow-up implementation (2)

- **A bunch length feedback regulates the noise amplitude**
  - Measures the 4-sigma equivalent FWHM bunch length from the BQM every 2 s
  - Acts slowly using a recursive algorithm
  - $x_{n+1} = ax_n + g(\tau_{targ} - \tau_{meas})$
    - Starting amplitude scaling factor: $x_0 = 0$
    - Recursion factor, for noise reduction: $a = 0.964$
    - Gain $g(f_s) = 10^{-9}\left(\frac{f_{s,0}(t=0)}{f_{s,0}(t)}\right)^2$ scaled with the synchrotron frequency to maintain a constant diffusion speed in the bunch core

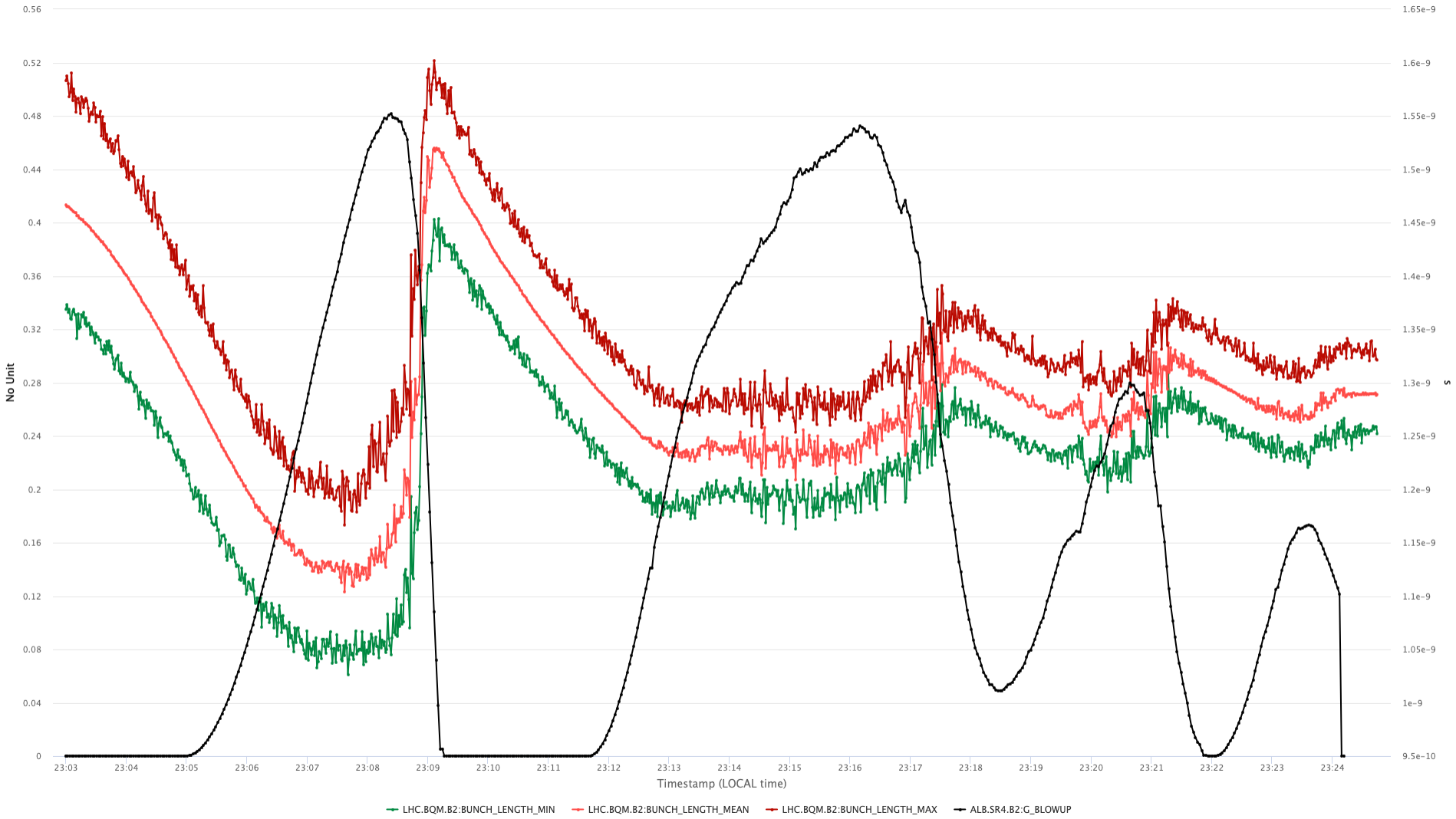
A typical ramp: fill 8675

B1



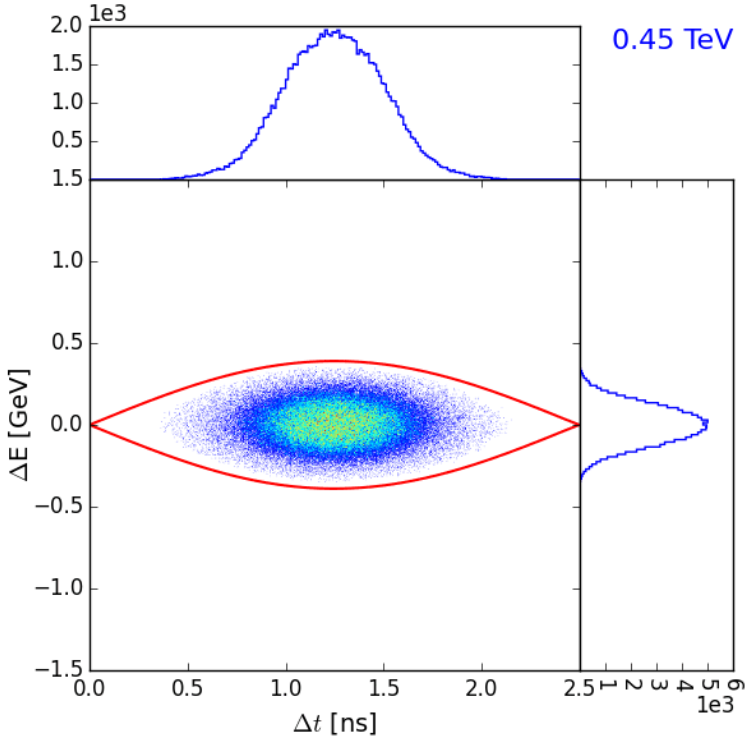
A typical ramp: fill 8675

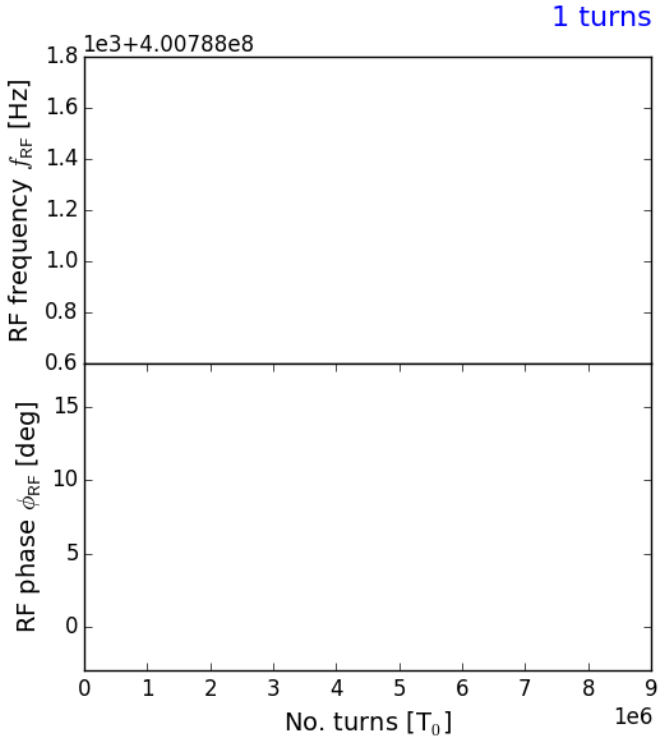
B2



With respect to RF finger heating

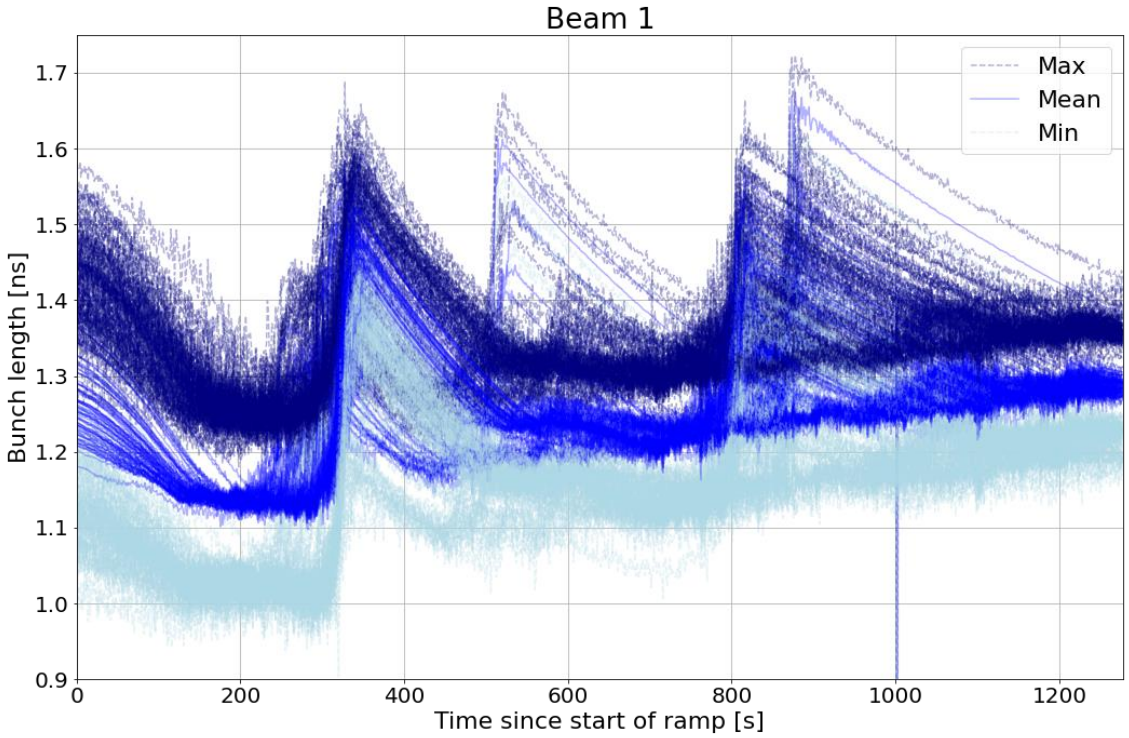
- **During the start of the ramp, the beam profile, spectrum, and bunch length are all drastically changing**
  - There is a large spread among the bunch lengths and the minimum bunch length < 1.0 ns

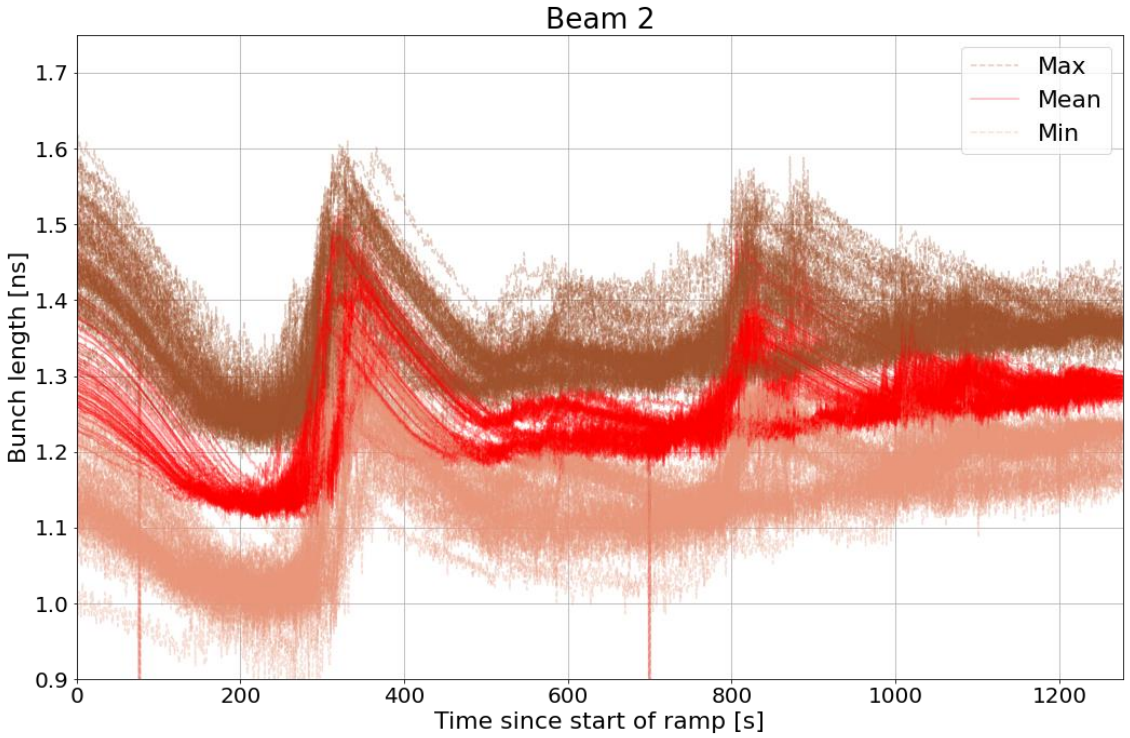




Bunch lengths

- **Minimum, average, and maximum bunch length in 2023 physics fills (> 200 bunches)**

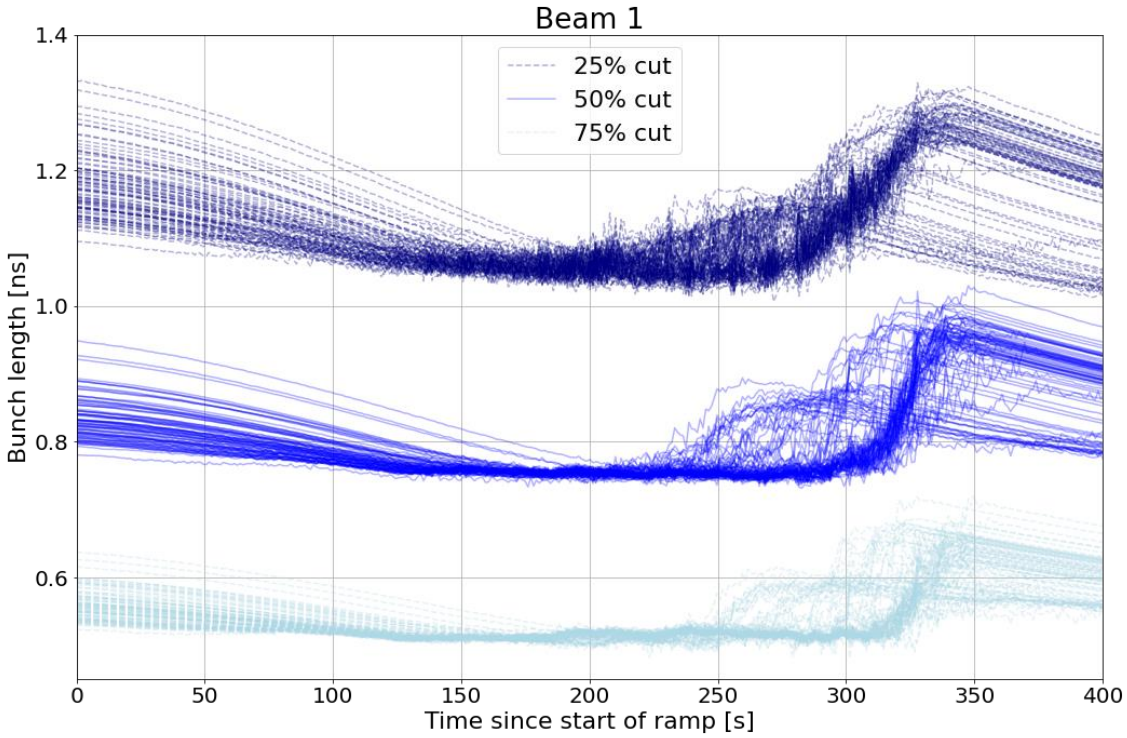


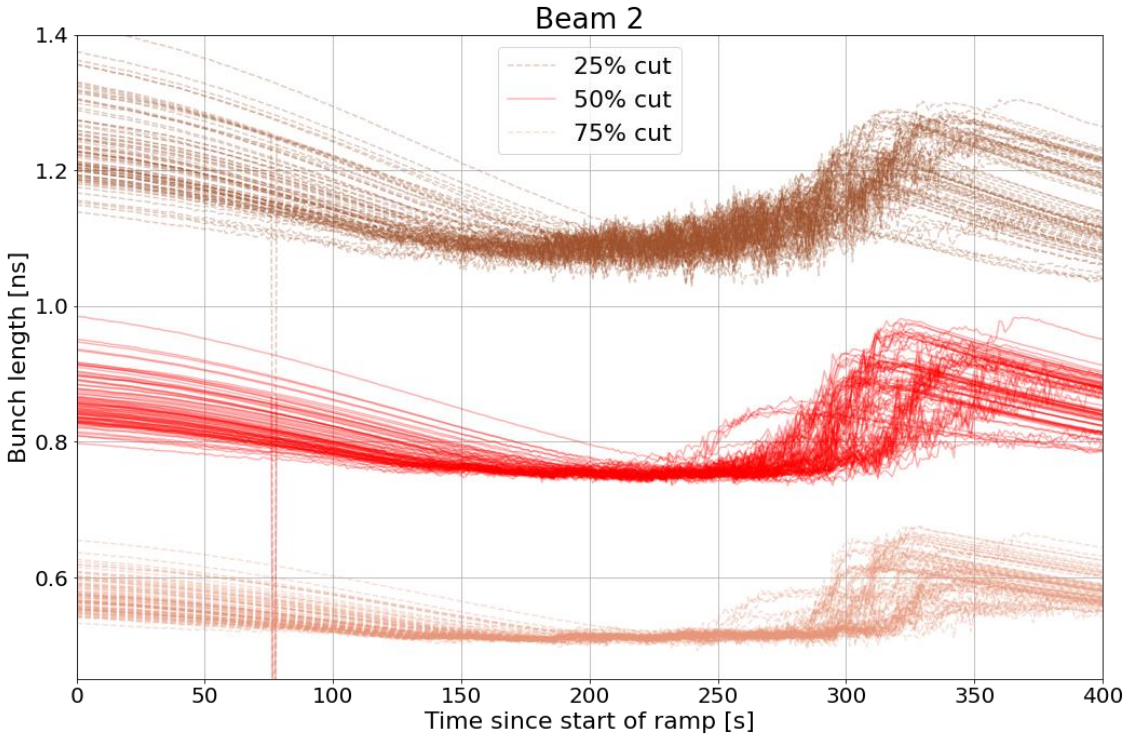


Courtesy of B. Karlsen-Baeck

Bunch lengths

- **25 %, 50 %, and 75 % bunch length in 2023 physics fills (> 200 bunches)**

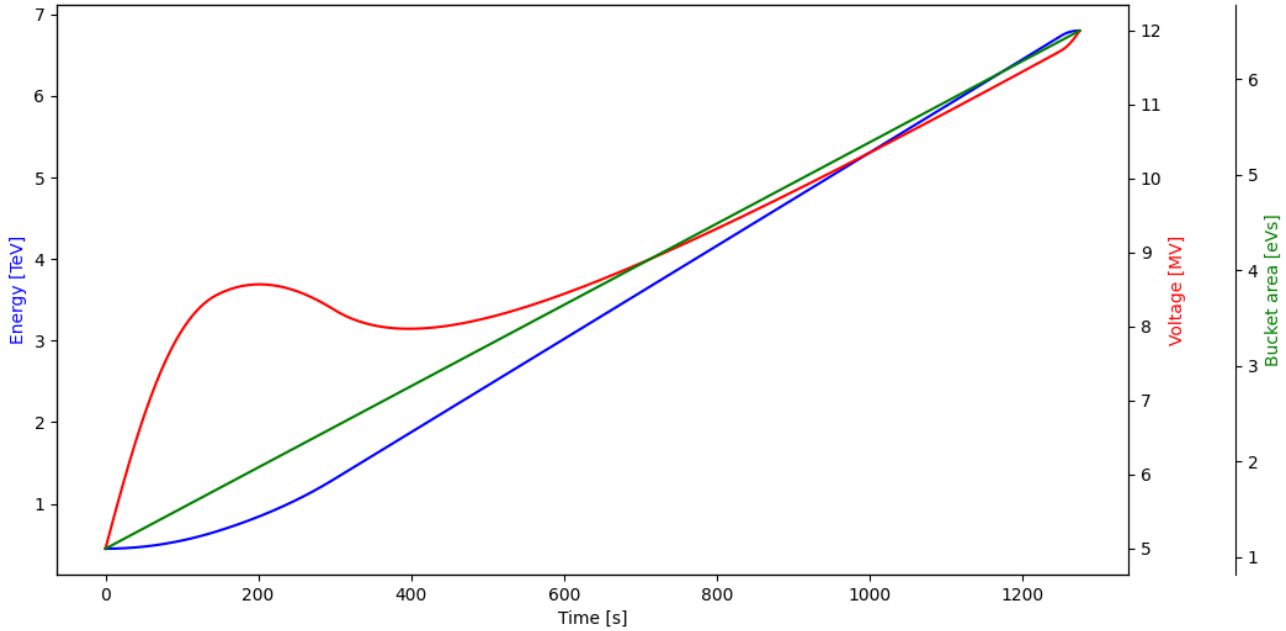




Courtesy of B. Karlsen-Baeck

Bucket area

- **The halo population is large in the start of the ramp**
  - Having too strong blow-up can lead to losses and therefore to a beam dump
  - We have margin to increase the bucket area and with it the target bunch length



Linear bucket area increase

Knobs to turn

- **Increase the bucket area and target bunch length at the start of the ramp**
  - Would need to change QL before the ramp
- **Bunch length feedback: increase the reaction speed**
- **Re-optimize BTF? Will never be perfect…**
- **Investigate the feasibility of the injection of the noise through the cavity controller**
  - First tests in 2012 in MDs
  - Would require the compensation of the noise in the beam phase loop, with turn-by-turn synchronization

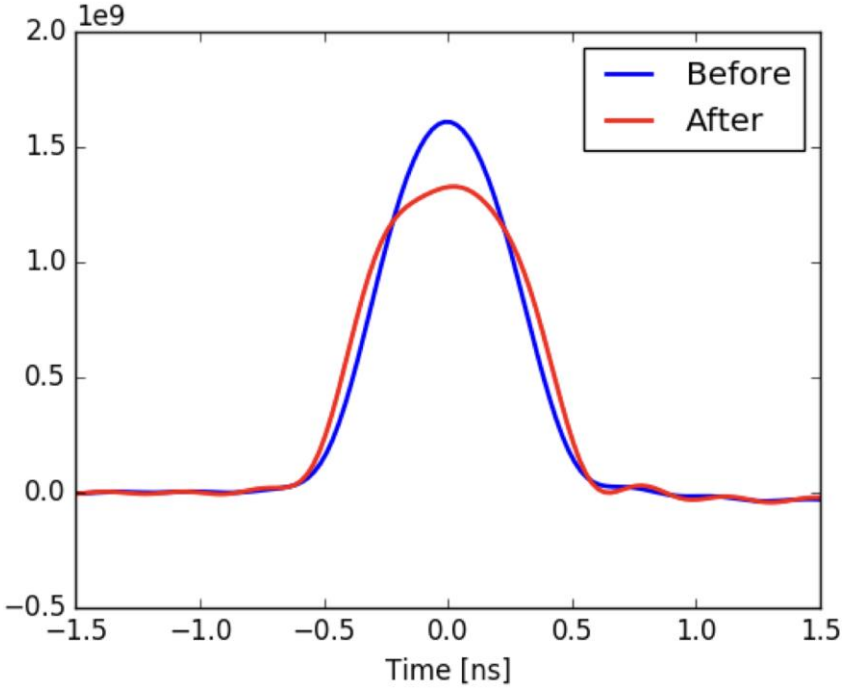
In all cases, testing will require machine time and optimizing the blow-up in the ramp can affect machine availability

Need time to study alternatives in simulations

Backup slides

Sine-wave modulation or bunch flattening

- **Used in physics**
- **Resonant excitation [1-4]: discrete regulation**
  - $\Delta\varphi_{rf,n} = A\sin\left(\sum_{k=0}^{n} 2\pi f_{m,k} T_{rev,k}\right)$
  - LHC flattop parameters are: $f_m = 0.98 f_{s0}$ and $A = 0.6°$
  - *Modulation frequency:* fully determines the final bunch length and shape
  - *Modulation amplitude:* must be above a certain threshold, but does not influence the bunch length

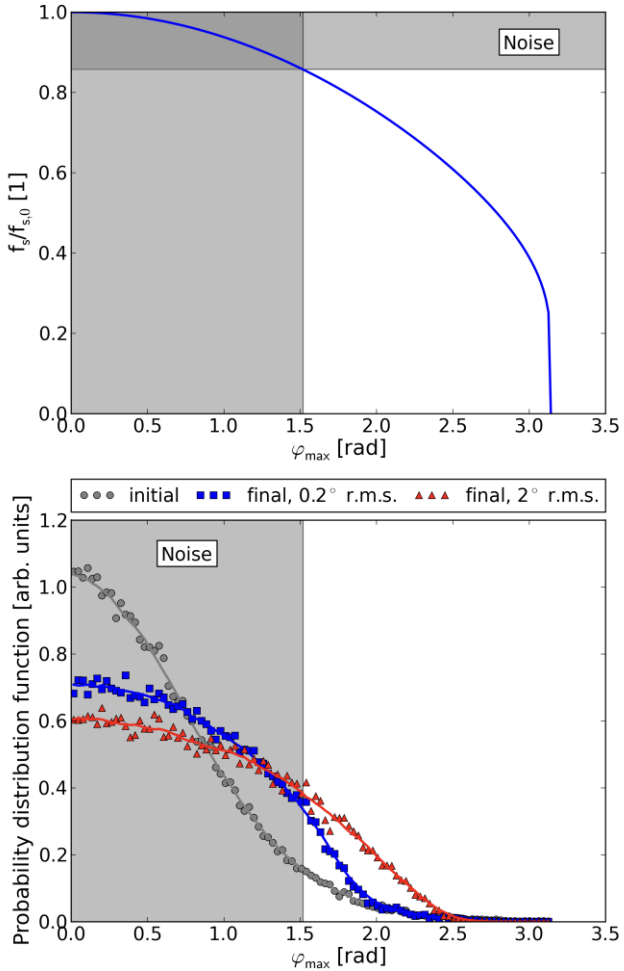


Measured bunch profile in the LHC before and after flattening

[1] S. Y. Lee: 'Accelerator Physics', World Scientific, 3rd Ed., 2012.
[2] C. Y. Tan and A. Burov: 'Phase modulation of the bucket stops bunch oscillations at the Fermilab Tevatron', PRAB 15, 044401, (2012).
[3] E. Shaposhnikova et al.: 'Flat Bunches in the LHC', Proc. IPAC'14, Dresden, Germany, (2014).
[4] S. Albright and D. Quartullo: Journal of Physics: Conference Series 1350, 012144 (2019).

Controlled emittance blow-up or phase noise

- **Used in the ramp, factor six in emittance**
- **Diffusion process [5,6]: continuous regulation**
  - $\Delta\varphi_{rf,n} = \varphi_{noise}(t_n)$
    - LHC: FFT of the noise spectrum
    - Alternative (PSB): as a sum of sine-wave modulations
  - Use band-limited white noise to shape the bunch [7]
    - Target the core region to avoid losses from the tails
    - The average phase noise is: $\langle\varphi_{noise}(t_n)\rangle = 0$
    - The r.m.s. phase noise depends on the double-sided noise spectral density $\varphi_{noise}^{rms} = \sqrt{\int S_\varphi(f)df}$



Diffusion due to band-limited white noise

[5] S. Krinsky, J.M. Wang: 'Bunch diffusion due to RF noise', Part. Accel. 12, 107–117 (1982).
[6] G. Dôme: 'Diffusion due to RF noise', CERN Accelerator School '85, Oxford, UK, 370–401 (1985).
[7] T.Toyama: 'Uniform bunch formation by RF voltage modulation with a band-limited white signal', NIM A, 447, 317–327 (2000).

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