Controlled longitudinal emittance blow-up for high intensity beams in the CERN SPS

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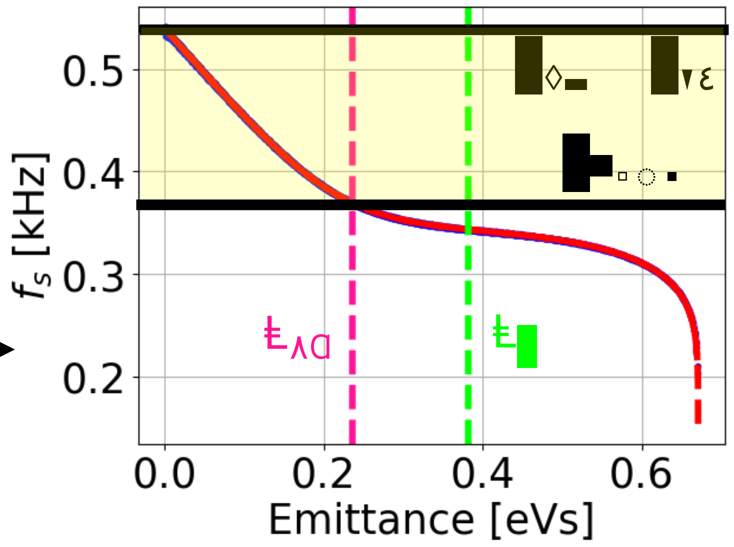
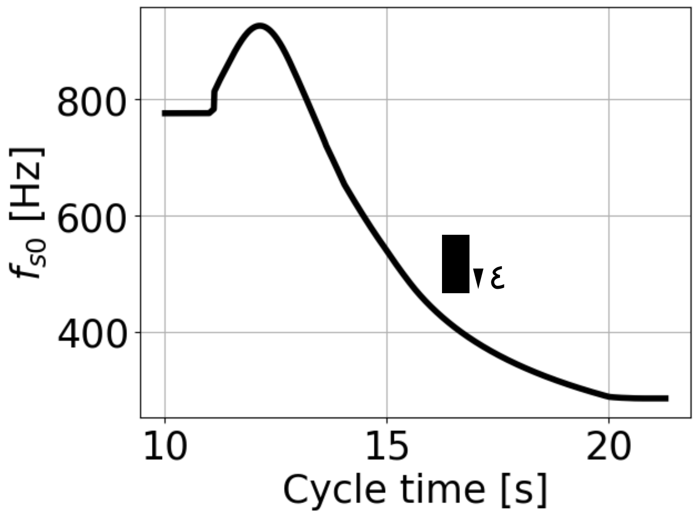
Introduction

- Controlled longitudinal emittance blow-up is needed to stabilize SPS proton beams in the longitudinal plane.
  - Larger emittances increase the intensity threshold for coupled-bunch instabilities.
- Blow up is achieved by injecting bandwidth-limited phase noise into the main RF system (Slide 3).
  - Phase noise should diffuse just the particles inside the bunch core, while tails should not be affected to avoid particle losses.
  - Blow up should occur along the ramp so that particles pushed outside the SPS buckets are not transferred into the LHC.
  - Phase noise should have small leakage outside the frequency-band.
- The determination of the frequency band is challenging.
  - The synchrotron frequency distributions vary along
    - the batch due to collective effects,
    - the cycle due to non-constant machine programs.
  - An algorithm for frequency-band computations has been developed (Slide 4).
- The optimal frequency bands were used in realistic macro-particle simulations of 72 bunches along the SPS cycle (Slide 5).
- Simulations were compared with beam measurements (Slide 6).

Example of synchrotron frequency distribution and noise band at a certain cycle time



Example of [illegible] evolution along the SPS cycle



Implementation of the phase-noise algorithm

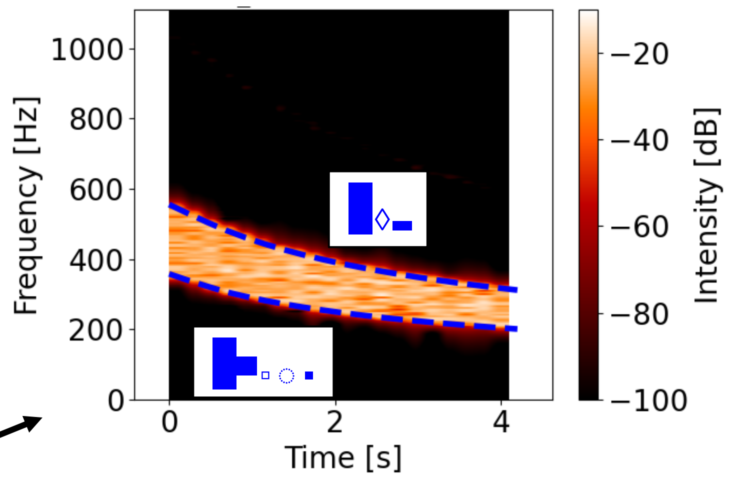
- The LHC Injector Upgrade (LIU) Project included a redesign of the SPS LLRF controls and beam loops.

- Emittance blow-up was already operational in the SPS between 2010 and 2018.
  - It had to be re-implemented in the new digital LLRF system.

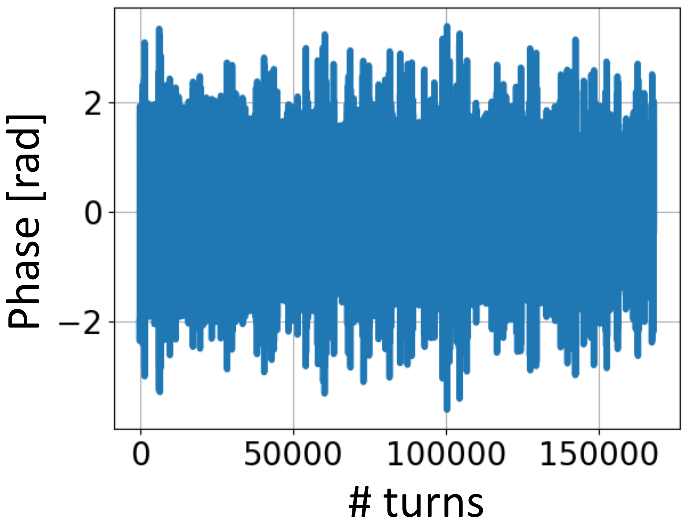
- The algorithm for phase-noise generation remained unchanged during the upgrade.
  - It produces phase noise whose spectral density follows the designed frequency band along the cycle.
  - Very small leakage outside the band.

- The frequency bands are in general computed in the SPS high-level controls by performing very simple computations.
  - ῼي is computed without collective effects.
  - Normalized ῼحخ/ῼي and ῼحدج/ῼي are kept constant along the cycle.

Example of phase noise in frequency domain

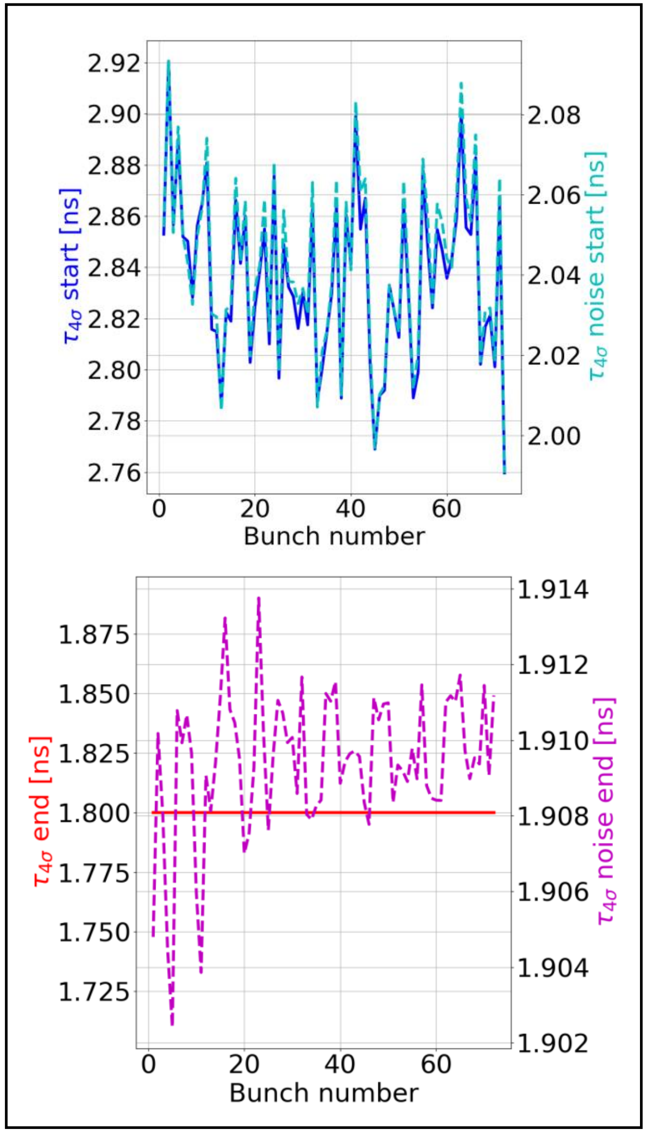


Example of phase noise in time domain



Algorithm for frequency-band determination

Example of inputs and 1st step of the algorithm



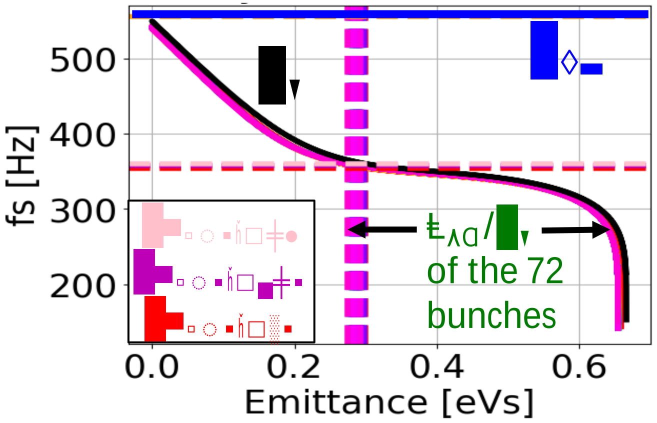
- Inputs:
  - machine parameters,
  - bunch intensities and lengths at flat bottom, desired bunch lengths at flat top,
  - the time interval when phase noise should be applied,

- 1st step: computation of bunch lengths when phase noise starts and ends.
  - Main principles: use of matched bunch-distributions, preservation of the full emittance along the cycle.

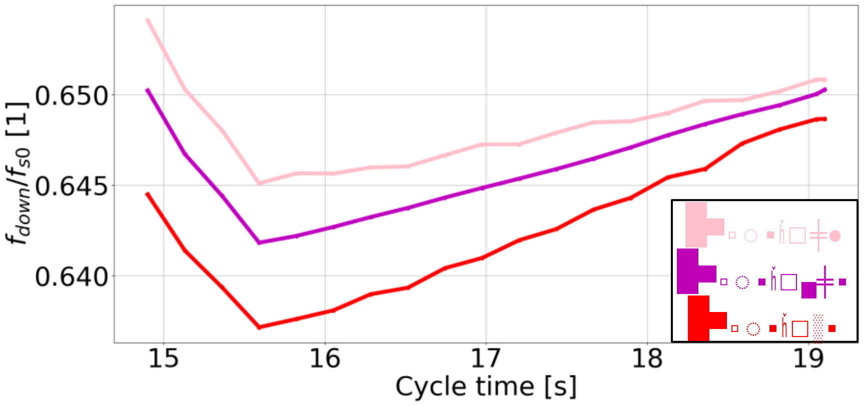
- 2nd step: computation of maximum, mean and minimum [illegible] values during blow-up.
  - Each bunch has a different emittance and [illegible] distribution, so a different [illegible].
  - Emittances are found by matching bunch distributions.

- Outputs of the algorithm: [illegible], [illegible], [illegible], [illegible] and [illegible] during blow-up.

Example of 2nd step of the algorithm at a certain cycle time



Example of outputs of the algorithm: max, mean and min [illegible] during blow up



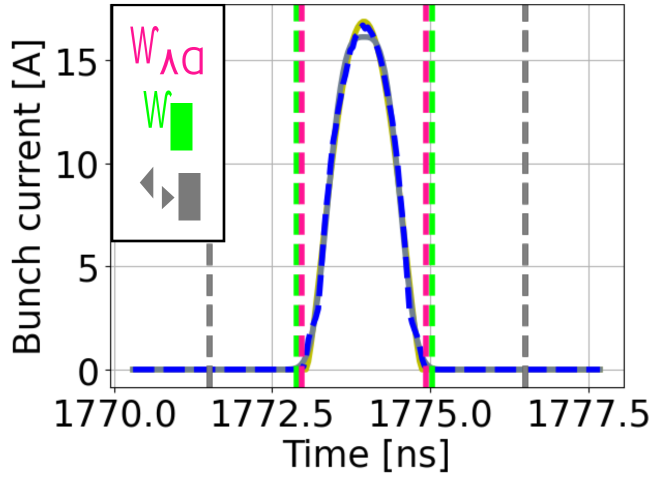
Macro-particle simulations of the SPS cycle

- Realistic longitudinal beam-dynamics simulations of 72 bunches were performed.
  - With collective effects, beam loops, emittance blow up using the computed frequency bands.
  - Starting from realistic bunch distributions at injection, Ŭ> ρ8ς ∉ ρπ°° ppb.

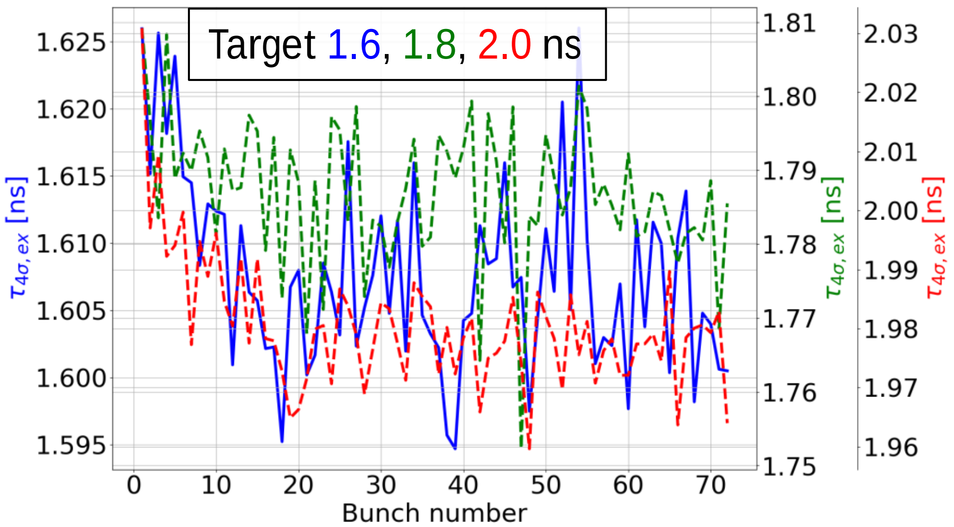
- Selecting properly the phase-noise rms, we obtained the desired bunch lengths at flat top.
  - The spreads in values were at maximum 4%, acceptable if also found for HL-LHC beams.
  - Good bunch quality at extraction (e.g. fully filamented distributions in phase space).

- No losses were observed in simulations, thanks to the fact that the profile tails were not diffused.
  - The full emittance -ٹ remained constant all along the cycle.

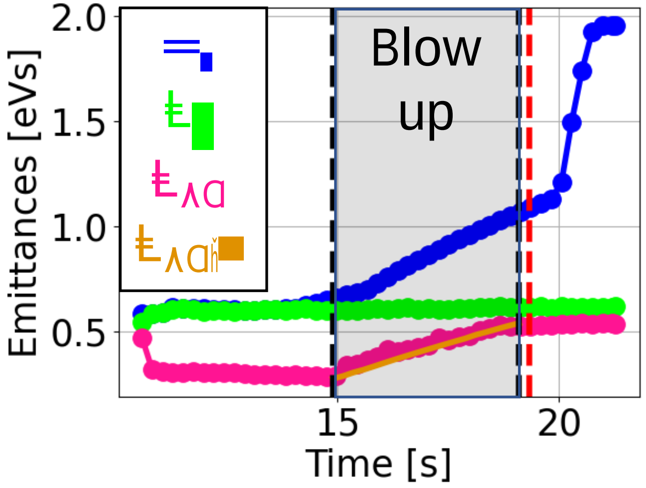
Extracted profile of the bunch 72, target bunch length of 2 ns



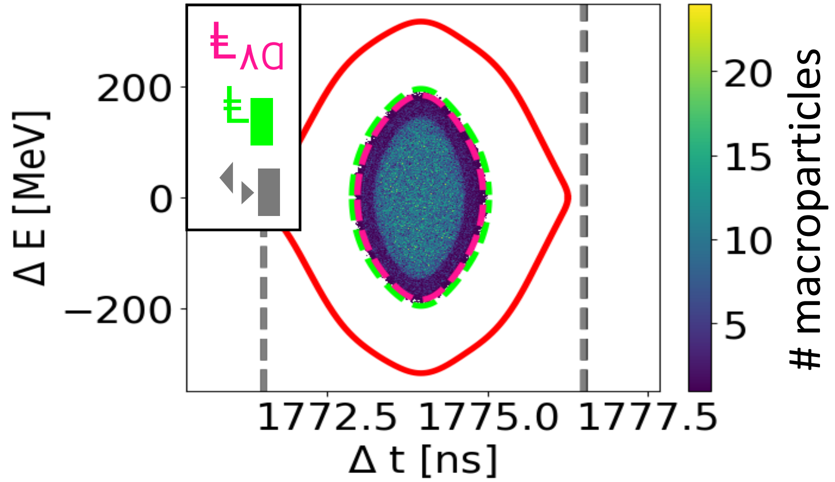
Extracted bunch lengths along the batch for different target bunch lengths



Emittance evolutions for the bunch 72, target bunch length of 2 ns



Extracted distribution of the bunch 72, target bunch length of 2 ns



Comparison to beam measurements

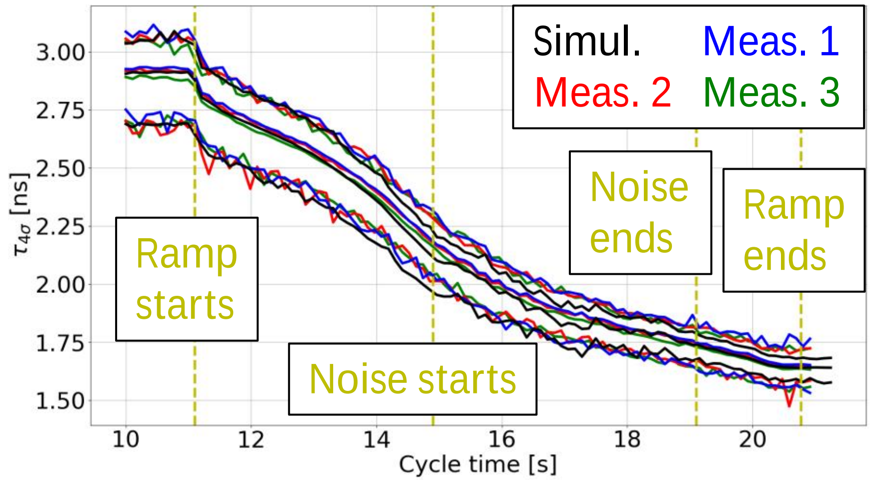
- Comparisons between beam measurements and simulations of one batch of 72 bunches along the cycle including phase noise.

- The optimal [illegible] varied between [illegible] and [illegible].
  - However, we set simply [illegible] along the blow-up time interval, both in measurements and simulations.
  - Can we still obtain stable beams at flat top and the desired extracted bunch length of 1.65 ns?
  - A constant [illegible] would greatly simplify the phase-noise setup in operation.

- Good agreement in bunch lengths between measurements and simulations, both during the ramp and at extraction.
  - The desired average bunch length of 1.65 ns was achieved.
  - The 0.11 ns spread found in measurements would be acceptable for HL-LHC beams.
  - Noise strength adapted to measurements results.

- These comparisons showed that a constant [illegible] can still provide acceptable results in operation.

Max, mean and min bunch-length evolutions in simulation and measurements



Average extracted bunch lengths along the batch in simulation and measurements