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

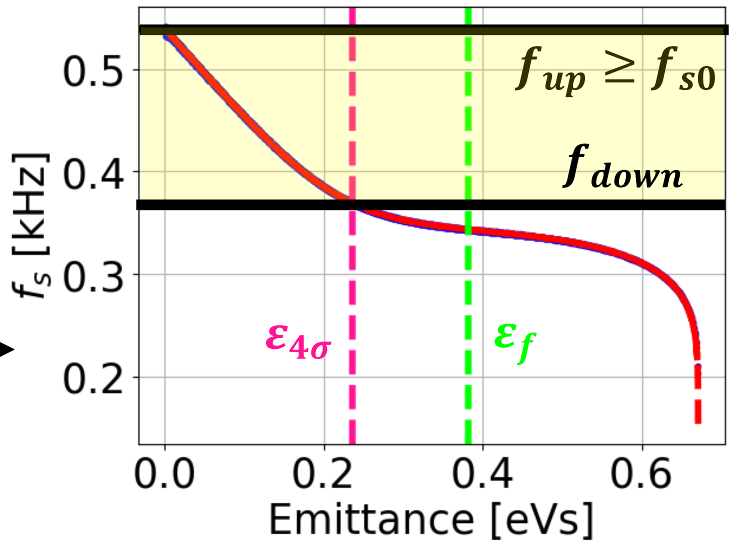
D. Quartullo,

H. Damerau, I. Karpov, G. Papotti, E. Shaposhnikova, C. Zisou

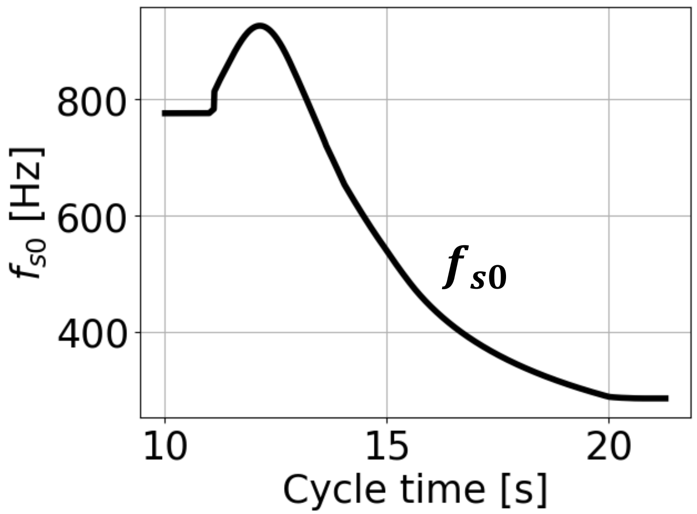
Introduction

- **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 f_{s0} evolution along the SPS cycle



Implementation of the phase-noise algorithm

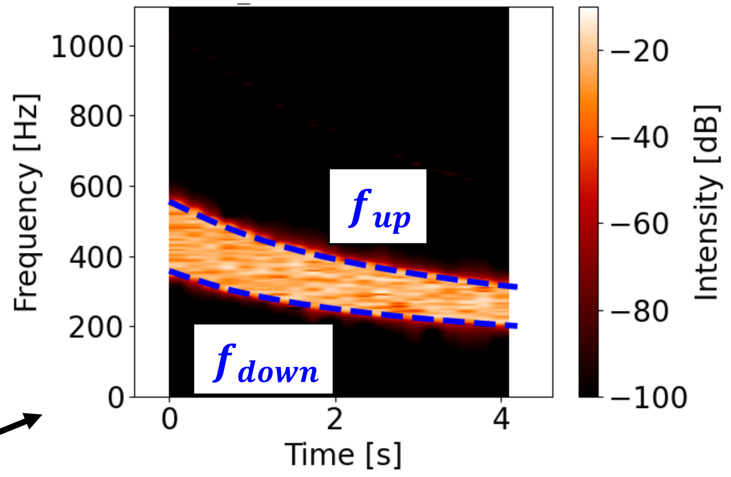
- The LHC Injector Upgrade (LIU) Project included a **redesign of the SPS LLRF controls and beam loops.**

- **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.**

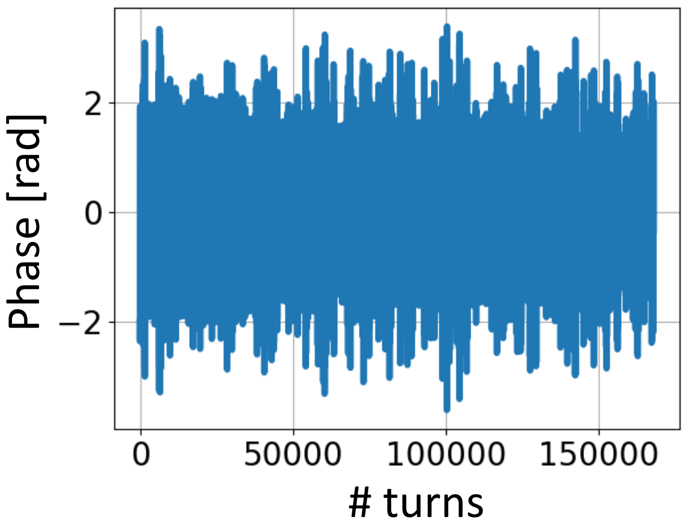
- The algorithm for phase-noise generation remained unchanged during the upgrade.
  - It produces phase noise whose **spectral density follows the designed frequency band along the cycle**.
  - **Very small leakage outside the band.**

- **The frequency bands are in general computed in the SPS high-level controls by performing very simple computations.**
  - f_{s0} is computed without collective effects.
  - Normalized f_{up}/f_{s0} and f_{down}/f_{s0} are kept constant along the cycle.

Example of phase noise in frequency domain

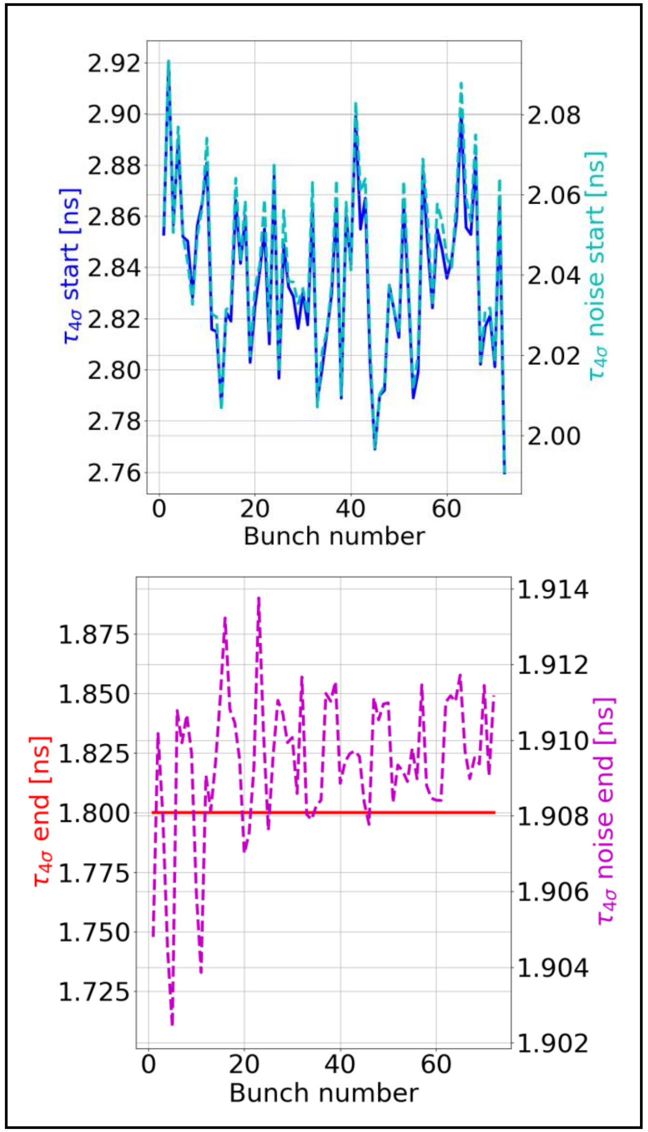


Example of phase noise in time domain



Algorithm for frequency-band determination

Example of inputs and 1st step of the algorithm



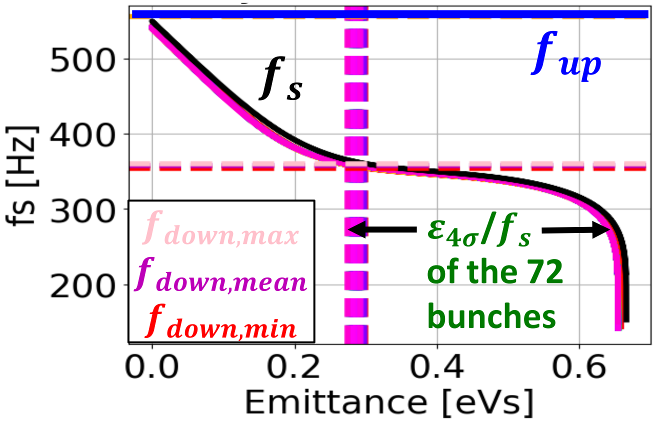
- **Inputs:**
  - machine parameters,
  - bunch intensities and lengths at flat bottom, desired bunch lengths at flat top,
  - the time interval when phase noise should be applied,

- **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.

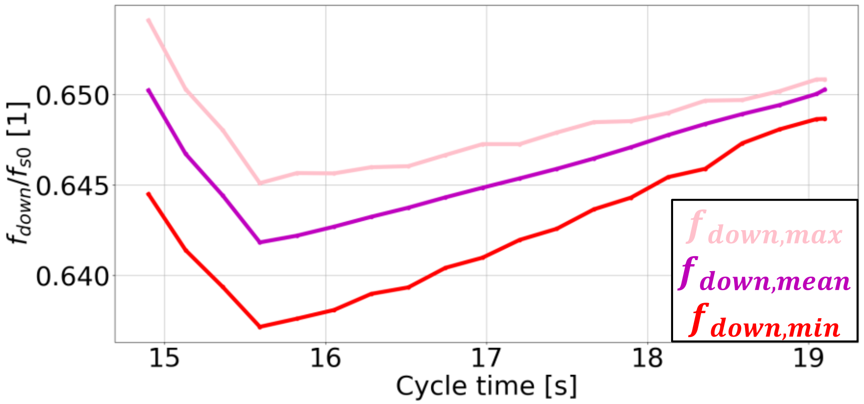
- **2nd step: computation of maximum, mean and minimum f_{down} values during blow-up.**
  - **Each bunch has a different emittance and f_s distribution, so a different f_{down}.**
  - Emittances are found by matching bunch distributions.

- **Outputs of the algorithm**: $f_{up} \geq f_{s0}$, $f_{down,max}$, $f_{down,mean}$ **and** $f_{down,min}$ **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 f_{down} during blow up



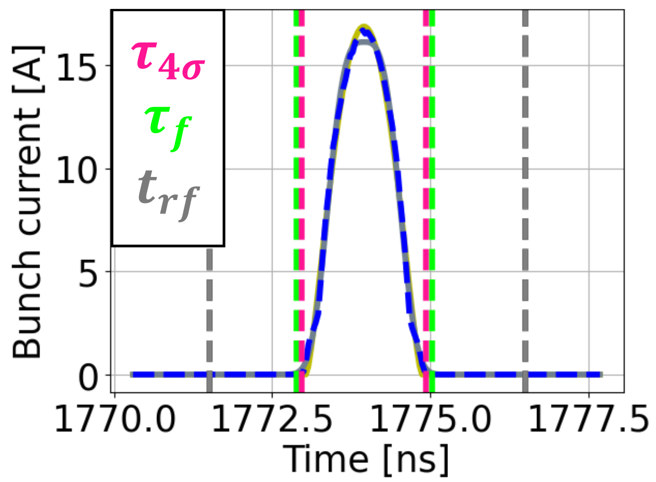
Macro-particle simulations of the SPS cycle

- **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, $N_p = 1.2 \cdot 10^{11}$ ppb.

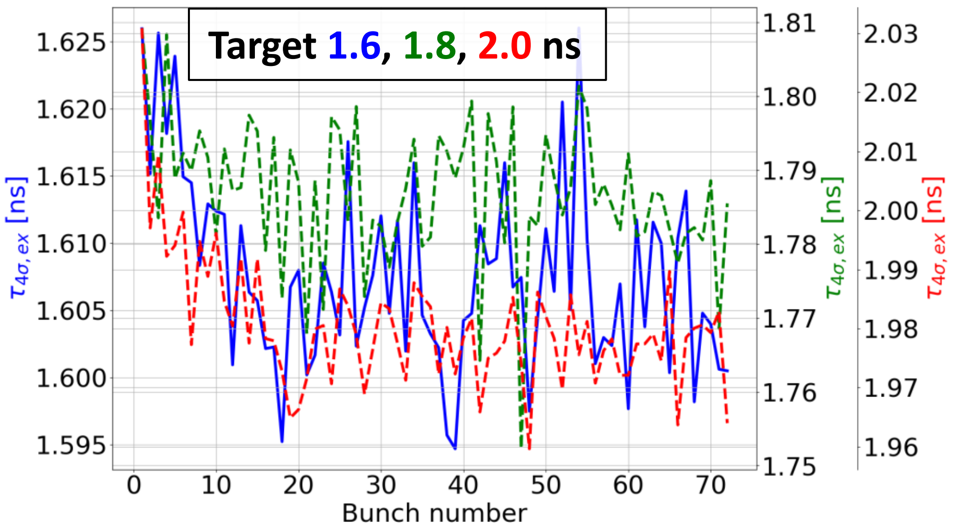
- **Selecting properly the phase-noise rms, we obtained the desired bunch lengths at flat top.**
  - **The spreads in values were at maximum 4%**, acceptable if also found for HL-LHC beams.
  - **Good bunch quality at extraction** (e.g. fully filamented distributions in phase space).

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

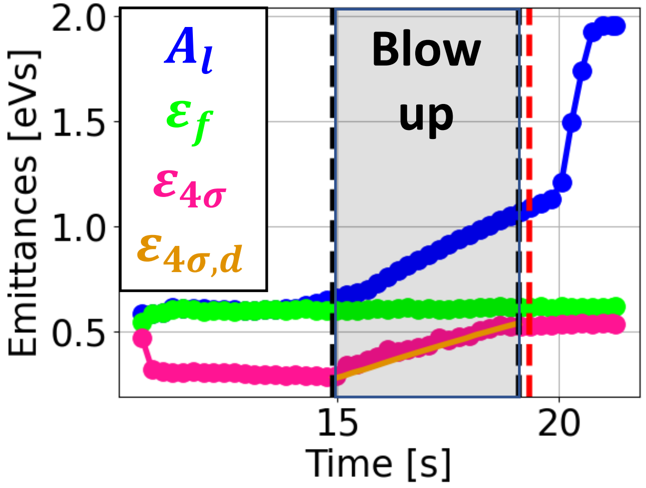
Extracted profile of the bunch 72, target bunch length of 2 ns



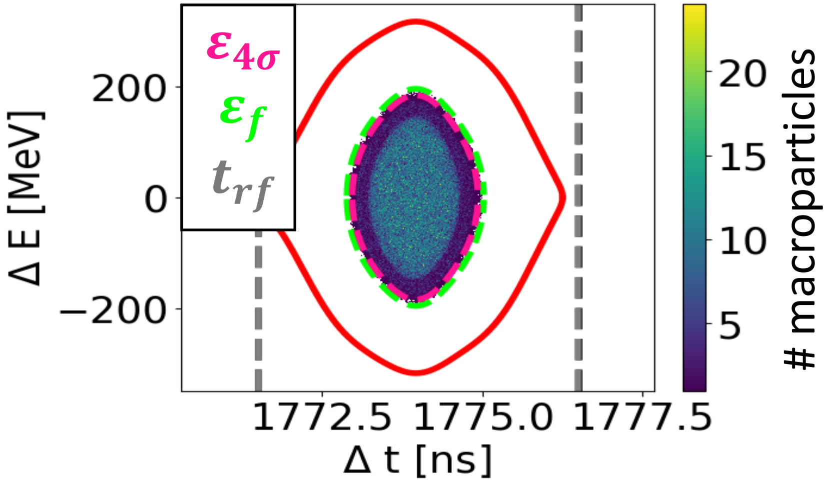
Extracted bunch lengths along the batch for different target bunch lengths



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

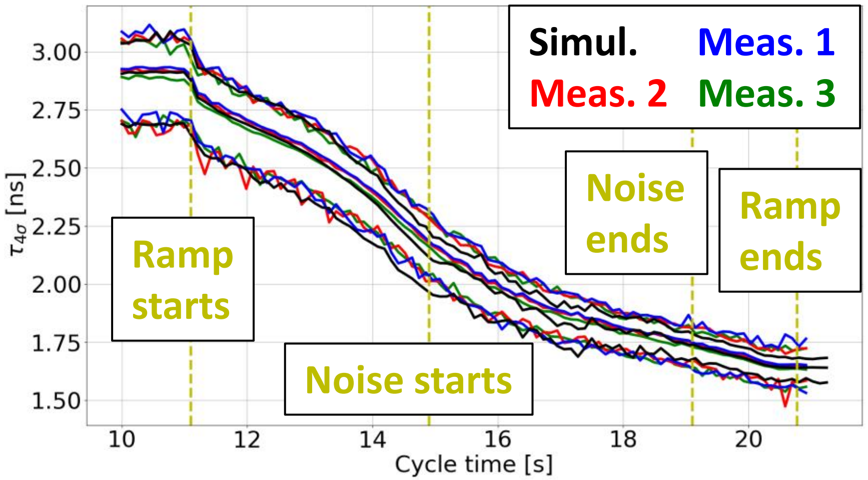
- **Comparisons between beam measurements and simulations** of one batch of 72 bunches along the cycle including phase noise.

- **The optimal f_{down} varied between $0.637f_{s0}$ and $0.653f_{s0}$.**
  - However, **we set simply $f_{down} = 0.64f_{s0}$** 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 f_{down}/f_{s0} 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 f_{down}/f_{s0} 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