LHC Longitudinal Impedance Studies

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Acknowledgements: S. Albright, Y. Brischetto, L. Giacomel, L. Intelisano, A. Lasheen, N. Mounet, B. Salvant, C. Vollinger and CPS/SPS/LHC OP teams

14^{th} HL-LHC Collaboration Meeting, Genoa, Italy, 7-10 October 2024

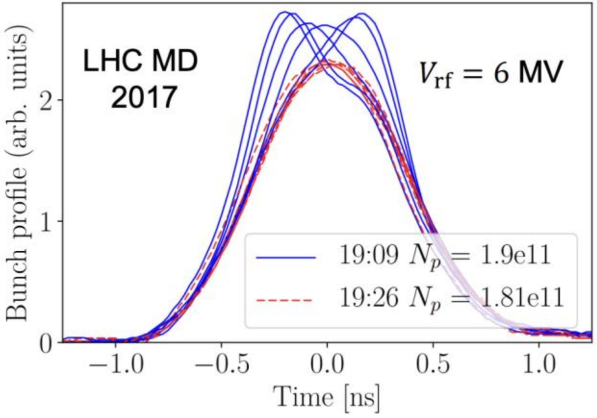
Overview

- Motivation
- (HL-)LHC longitudinal impedance model
  - LHC MD on loss of Landau damping
- Conclusions & Outlook

Motivation

Persistent oscillations after injection

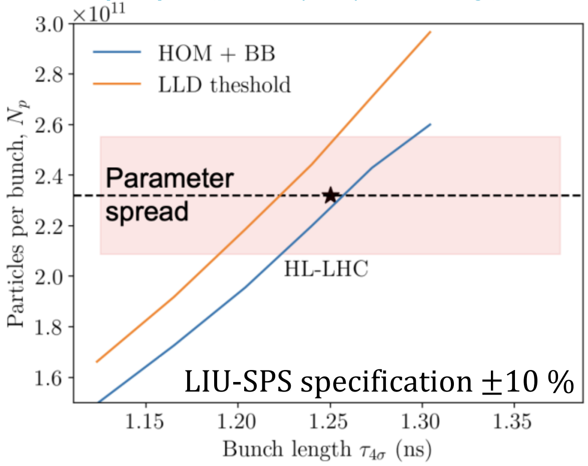
H. Timko et al., "Beam Instabilities after Injection to the LHC", HB2018



Reactive part of the broad-band impedance can lead to the loss of Landau damping (LLD)

Instability thresholds

I. Karpov, Special Joint WP2/WP4/WP7 meeting, June 2024



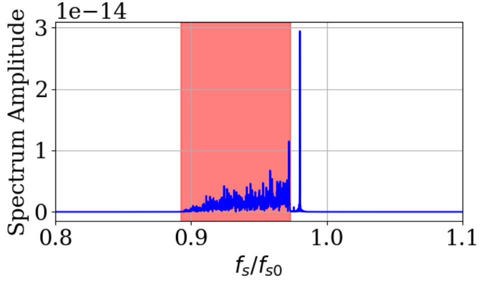
Flat-bottom with $V_{\mathrm{RF}} = 8$ MV,
HOM - $R_{sh} = 4 \times 71$ kΩ, $f_r = 582$ MHz
BB - $(ImZ/n)_{\mathrm{eff}} = 0.075\ \Omega$, $f_r = 5$ GHz

Loss of Landau Damping

Landau damping is an efficient stabilization mechanism

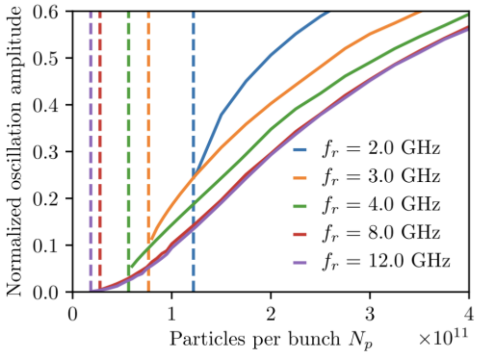
- Damps the coherent oscillations of the bunch
- Caused by the bunch frequency spread
- When the frequency of the coherent bunch oscillations moves outside of the incoherent frequency band of the bunch

⇒ Loss of Landau damping (LLD)



Two important parameters for the LLD[1]:

- The **effective cut-off frequency** of the broad-band impedances and the **effective Im(Z/n)** affect the threshold of the single-bunch LLD mechanism
- The **effective cut-off frequency** affects the amplitude of the persisting bunch oscillations



$$N_p^{\mathrm{th}} = -\frac{\pi V_0 \cos(\varphi_{s0})\varphi_{\max}^5}{32qh^2\omega_0\mu(\mu+1)\chi(y_{\max},\mu)(\mathrm{Im}Z/k)_{\mathrm{eff}}}$$

[1] I. Karpov, T. Argyropoulos, E. Shaposhnikova, *Phys. Rev. Accel. Beams* **24**, 011002, 2021

Increase in the longitudinal impedance budget

- Unshielded bellows P. Krkotić, IWG meeting, March 2024
  - 2x VMZAR (6 conv.) 2x VMLGC (26 conv.)

  ≈ 0.46 %

- Collimators I. Karpov, ColUSM, June 2024 L. Giacomel, IWG meeting, July 2024
  - RF fingers partial shielding

  ≈ 0.20 %

- DRFs ID212.7 bellows
  C. Antuono, P. Krkotić, IWG meeting, February 2024

  ≈ 0.70 %

- …

The LLD threshold further decreases… → *An accurate longitudinal impedance model is needed*

(HL-) LHC Longitudinal Impedance Model

The present longitudinal impedance model of (HL-)LHC is a by-product of the transverse impedance model [N. Mounet, PhD Thesis, *The LHC Transverse Coupled-Bunch Instability*]

Refine the (HL-) LHC Longitudinal Impedance model

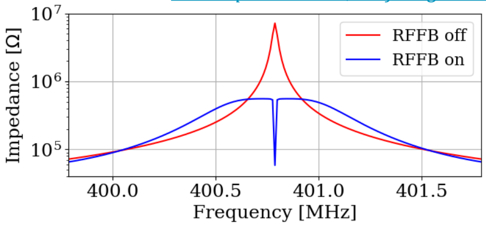
- Impedance measurements / CST simulations
- Beam observations

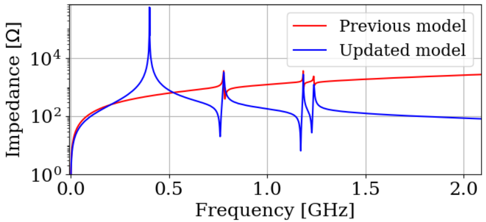
Refining the LHC longitudinal impedance model

- RF Cavities
  - Fundamental mode with RFFB
- Beam screen
  - Stretched-wire and probe measurements
  - Not trivial
- ID212 bellows
  - Attempt to increase simulated frequency range
  - Bellow corrugations can affect the cut-off frequency:

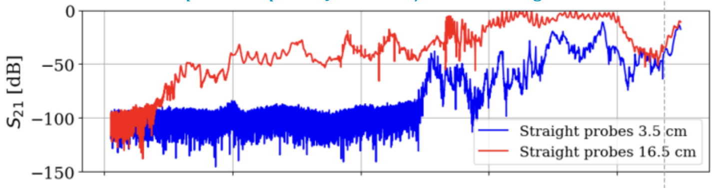
$$f_R \approx \frac{0.218c}{\Delta}\left(\frac{\Delta}{b}\right)^{0.052} \approx 8\ \text{GHz}$$

M. Zampetakis et al., "Refining the LHC Longitudinal Impedance Model", **HB2023**

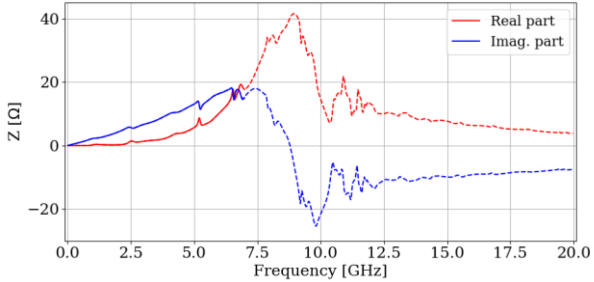




M. Zampetakis, Special Joint WP2/WP4 meeting, March 2024



M. Zampetakis, Special Joint WP2/WP4/WP7 meeting, June 2024



(HL-) LHC Longitudinal Impedance Model

The present longitudinal impedance model of (HL-)LHC is a by-product of the transverse impedance model N. Mounet, PhD Thesis, *The LHC Transverse Coupled-Bunch Instability*

Refine the (HL-) LHC Longitudinal Impedance model

Impedance measurements / CST simulations

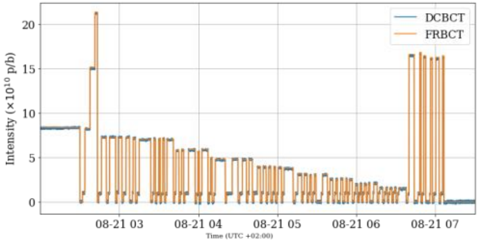
Beam observations

**See also Thursday morning: C. Lannoy, “LHC longitudinal impedance measurement through Schottky spectra”*

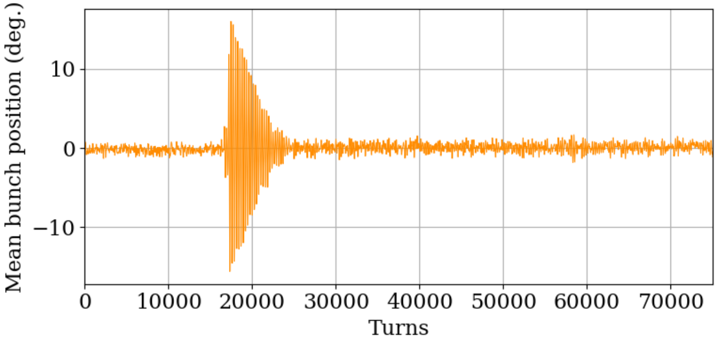
LHC Machine Development Studies

MD #11786: Thresholds of longitudinal loss of Landau damping

- Gain insight on the effective broad-band impedance and cut-off frequency
  - LHC at Flat-bottom, constant RF voltage $V_{\mathrm{RF}} = 3.5$ MV
  - Single bunches with intensities of $5 \cdot 10^9 - 7 \cdot 10^{10}$ p/b
  - Bunch length of ~0.8 ns
  - MD#1, MD#2 and MD#3

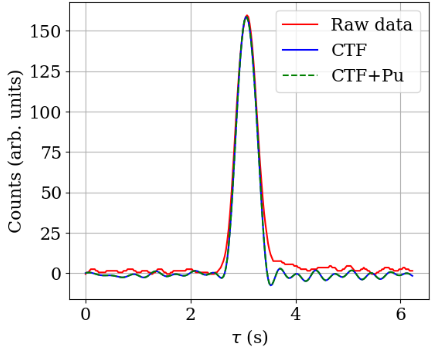


Inject ⟹ filament ⟹ phase kick ⟹ observe ⟹ dump

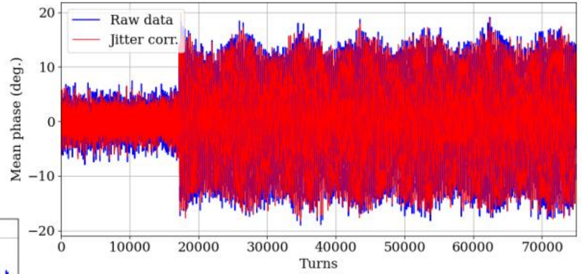


Analysis corrections

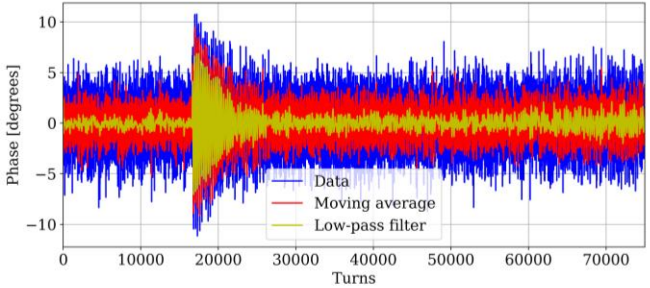
- Profiles corrected with the transfer functions
  - Cable and pick-up



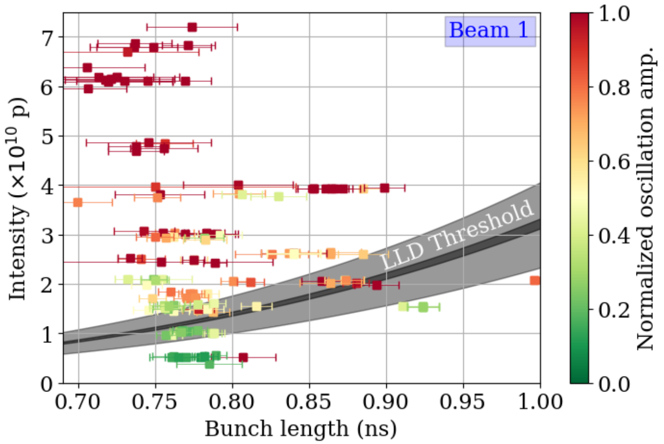
- Jitter from the Scope
  - Acquired and available through the FESA class, to better filter the data

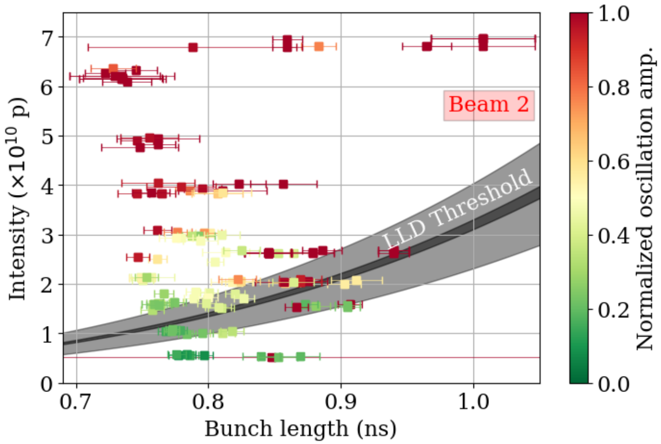


- Low-pass filtering



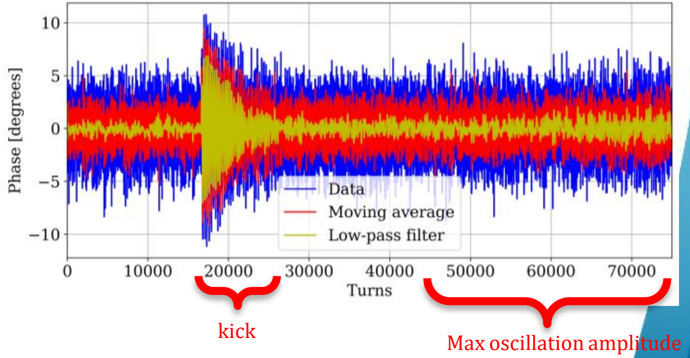
Summarizing the MD results



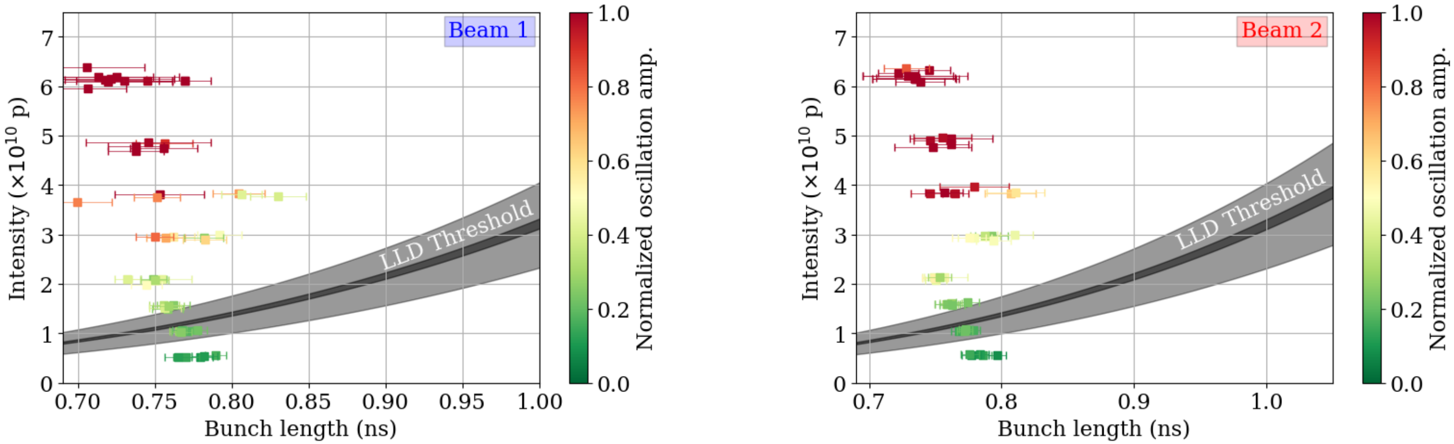


**Expected threshold with the current impedance model and with 30% error*

- Initial bunch length is considered as the average over the first 3000 turns
- Not clear where the LLD threshold is



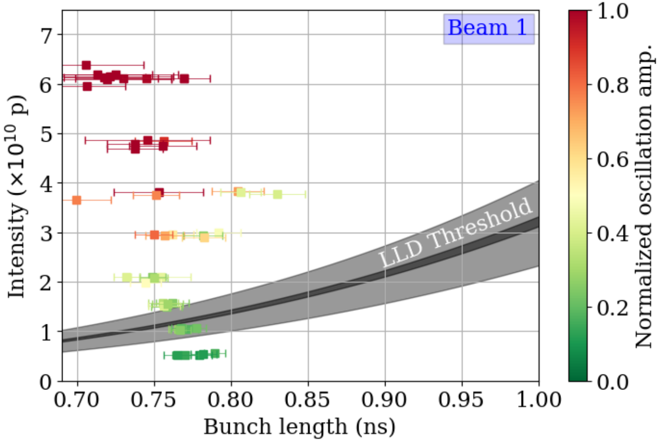
Summarizing the MD#3 results

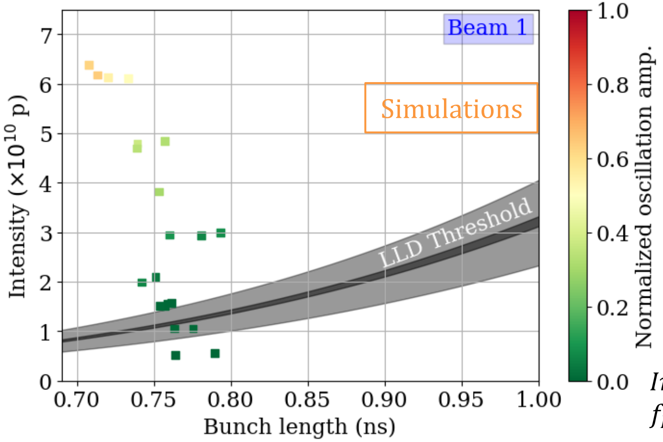


**Expected threshold with the current impedance model and with 30% error*

- Dumping and reinjecting gives more consistent beam behavior
- LLD threshold appears to be close to the expected value from the current impedance model

Comparison with simulations



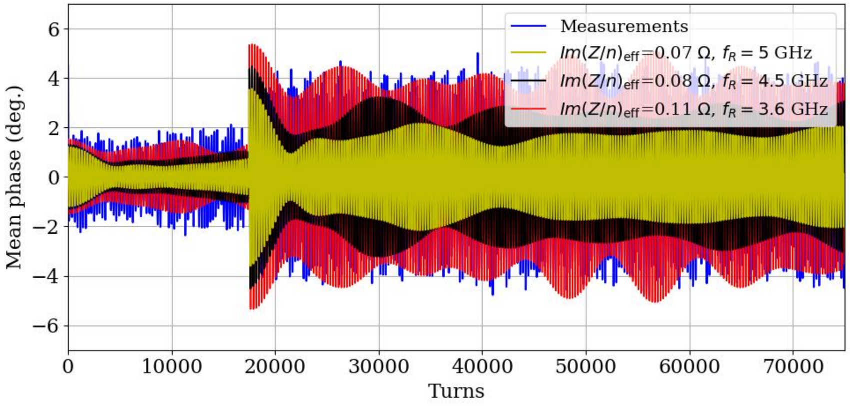


$Im(Z/n)_{\mathrm{eff}} = 0.07\ \Omega$

$f_R = 5$ GHz

- Binomial fit was applied on the measured profiles to generate similar distributions
- Comparison with simulations shows a large discrepancy in the amplitude evolution

Comparison with simulations

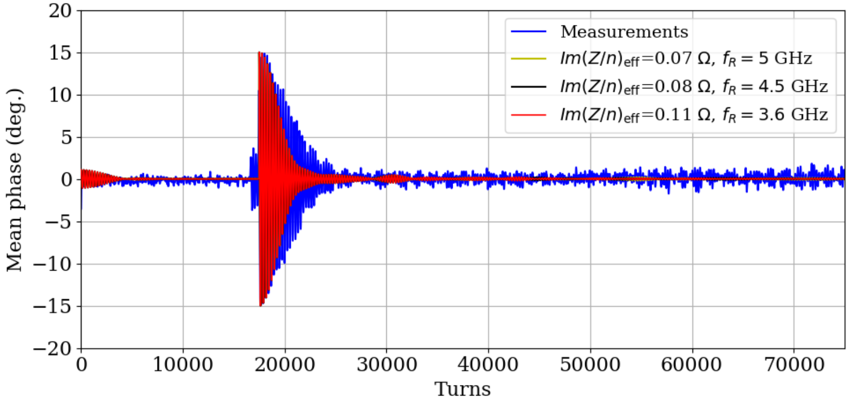


1) Case above the LLD threshold

- $N_b = 6.1 \cdot 10^{10}$ p/b, $\tau_{4\sigma}^{\mathrm{FWHM}} = 0.72$ ns
- Expected impedance does not explain the observed oscillation amplitude
- f_R is expected to be around 4-5 GHz (beam screen cut-off)

2) Case below the LLD threshold

- $N_b = 0.5 \cdot 10^{10}$ p/b, $\tau_{4\sigma}^{\mathrm{FWHM}} = 0.77$ ns
- No significant difference between the cases

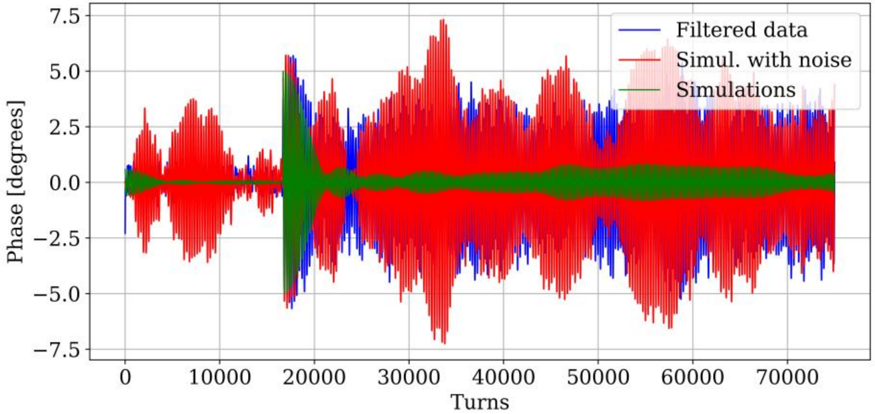


All impedance configurations give the same LLD threshold!

Comparison with simulations

RF noise can contribute to the observed oscillation amplitudes

- Example with more than 100 times stronger RF noise than the measured one



- It might affect the amplitude, but it does not justify the discrepancy between measurements and simulations

Conclusions & Outlook

- The recent increase of the longitudinal impedance budget was summarized; stability predictions are getting tight
- Preliminary results from the MD on longitudinal LLD thresholds were presented
  - Improvements in the acquisition and analysis of the beam profiles
  - LLD threshold appears to be close to the expected regime
  - Further measurements for different emittances and kicks are required
- Discrepancy between the measurements and the simulations was observed
  - Investigation on the validity of the longitudinal impedance model is required
  - Extract the effective cut-off frequency from the oscillation amplitude evolution, in comparison with simulations

Thank you for your attention…