Recent advances in the CERN PS impedance model and instability simulations

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Acknowledgments: D. Cotte, M. Delrieux, A. Huschauer, G. Imesch, A. Lasheen, G. Rumolo, all the PSB and PS operation teams

10/10/2023

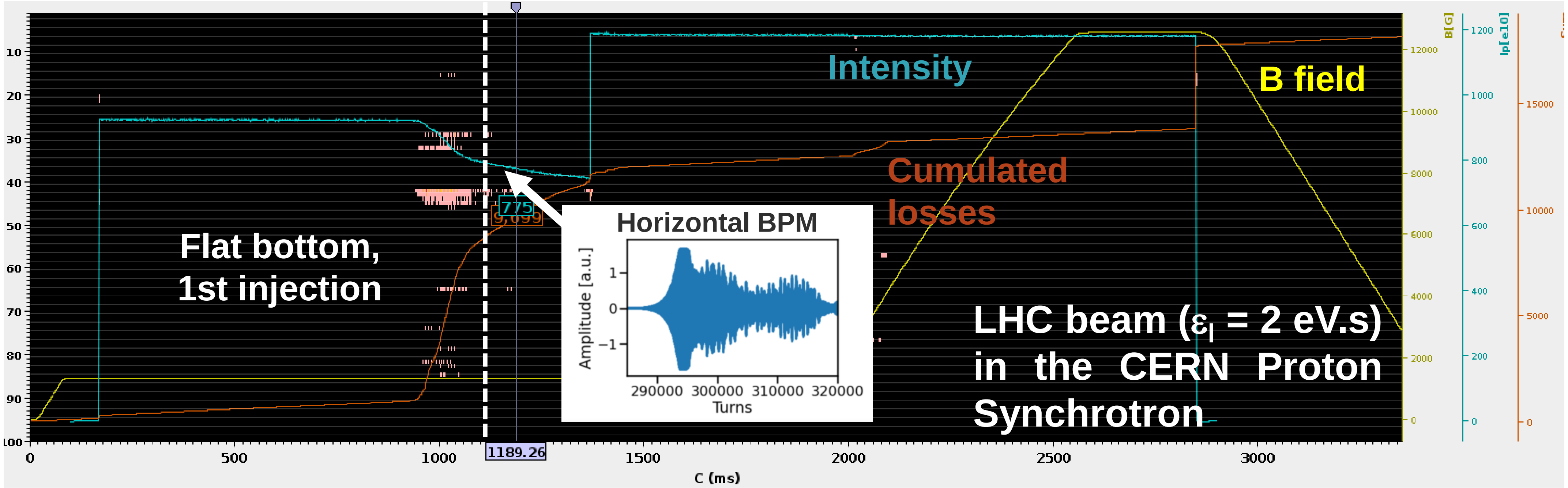
Introduction

- **In preparation of High Luminosity LHC (HL-LHC), its injectors were upgraded during the LHC Injectors Upgrade (LIU)**

  Goal : doubling of beam intensity & transverse emittance preservation

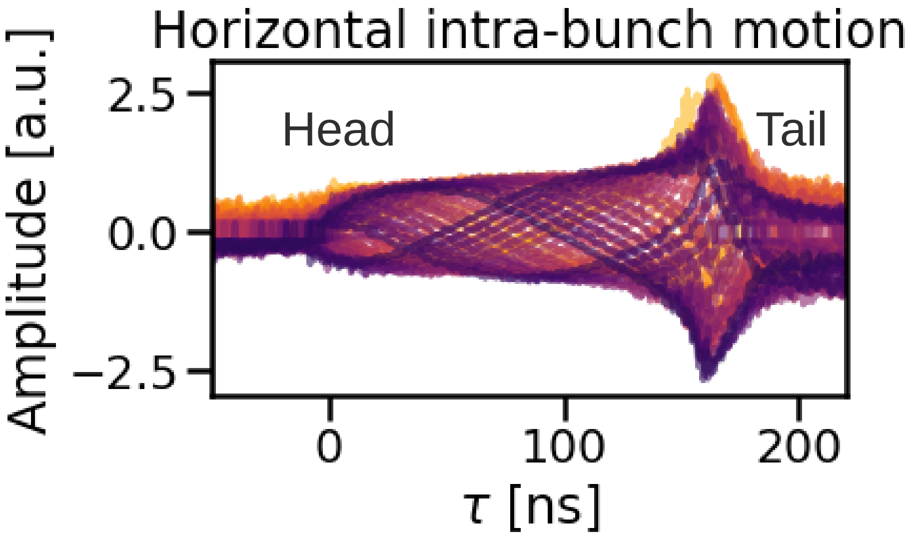
- **Following the PS hardware upgrade → Gradual beam parameters ramp-up**
- **Unforeseen transverse instabilities arising during ramp-up, including a horizontal instability after the first injection**
- **Instability growth rate underestimated by a factor 5~10 in simulations**
- **→ Investigation of this discrepancy**

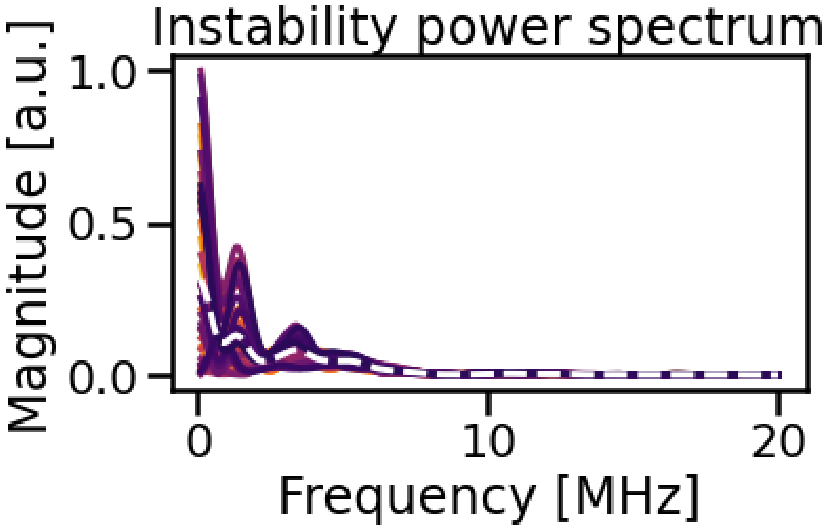
Horizontal instability signature



- End of flat bottom → instability and intensity losses.
- Exponential growth of the horizontal BPM signal.
- Beam intensity could not be pushed to the LIU goal.
- Mitigation strategies (chromaticity trim/RF voltage increase) discussed here.

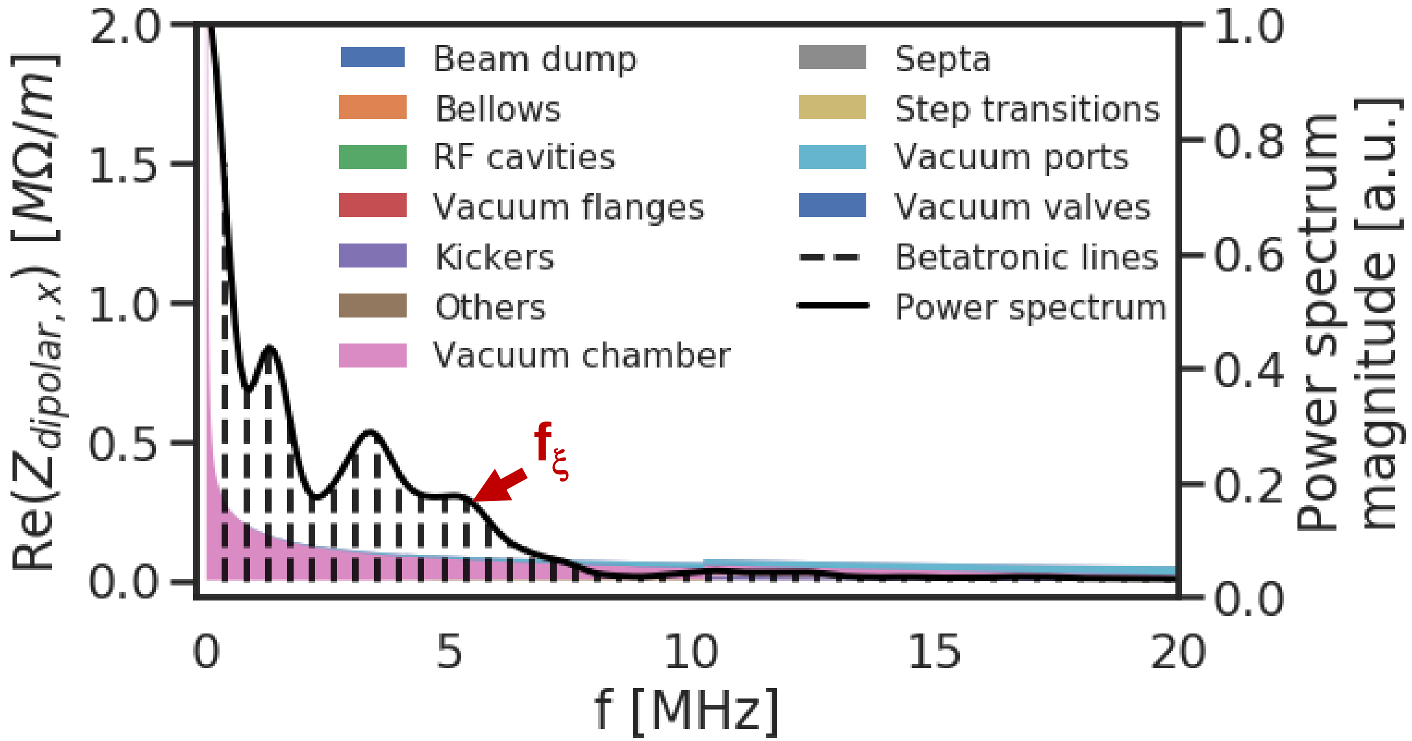
Horizontal instability characterization





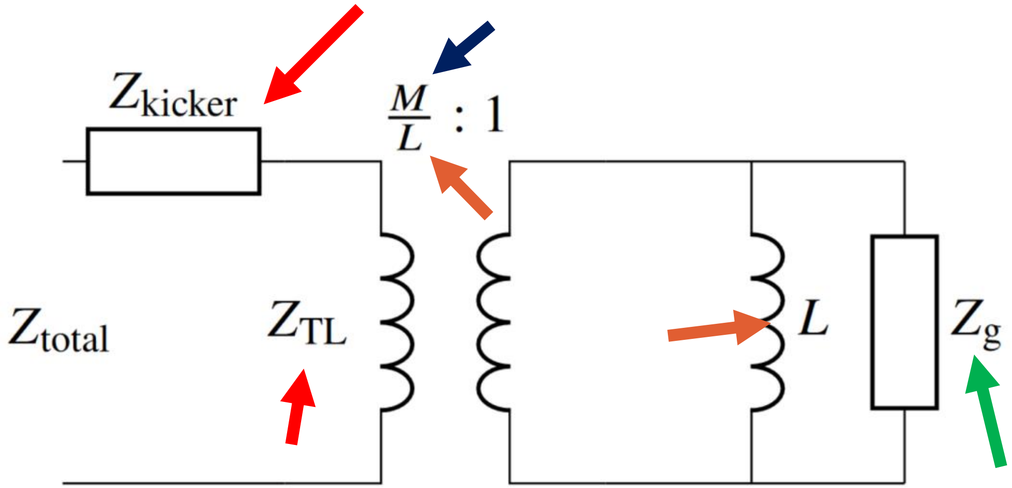
- **Horizontal intra-bunch motion acquired using a wide-band pick-up over 50 acquisitions, each spaced by 3 turns.**
- **Envelope with no node and a head/tail asymmetry.**
- **Equivalent power spectrum ($|\mathcal{F}(\lambda_x)|^2$) exhibits peaks at 0, 1 and 3 MHz.**
- **Link between peaks in the power spectrum and modes in the impedance spectrum ?**

PS transverse impedance model at injection energy



- **Instability originates from sum of the betatronic lines along the overlap of the impedance and unstable mode spectra.**
- **Current model includes only vacuum chamber impedance in power spectrum range.**
- **Missing impedance source between 0 and 10 MHz ?**

Impedance of a kicker magnet connecting cables and external circuits (1/2)



Approximation of the kicker magnet as an ideal transformer

Total impedance of a kicker magnet can be split in two contributions:

- **Geometry and material properties**
- **Coupling with connecting cables and external circuits**

Second contribution depends on the magnet inductance, self-inductance, connecting cables and external circuits.

It can be calculated analytically using the transmission line theory.

Impedance of a kicker magnet connecting cables and external circuits (2/2)

Longitudinal and transverse impedances can be calculated for H and C-shape magnets:

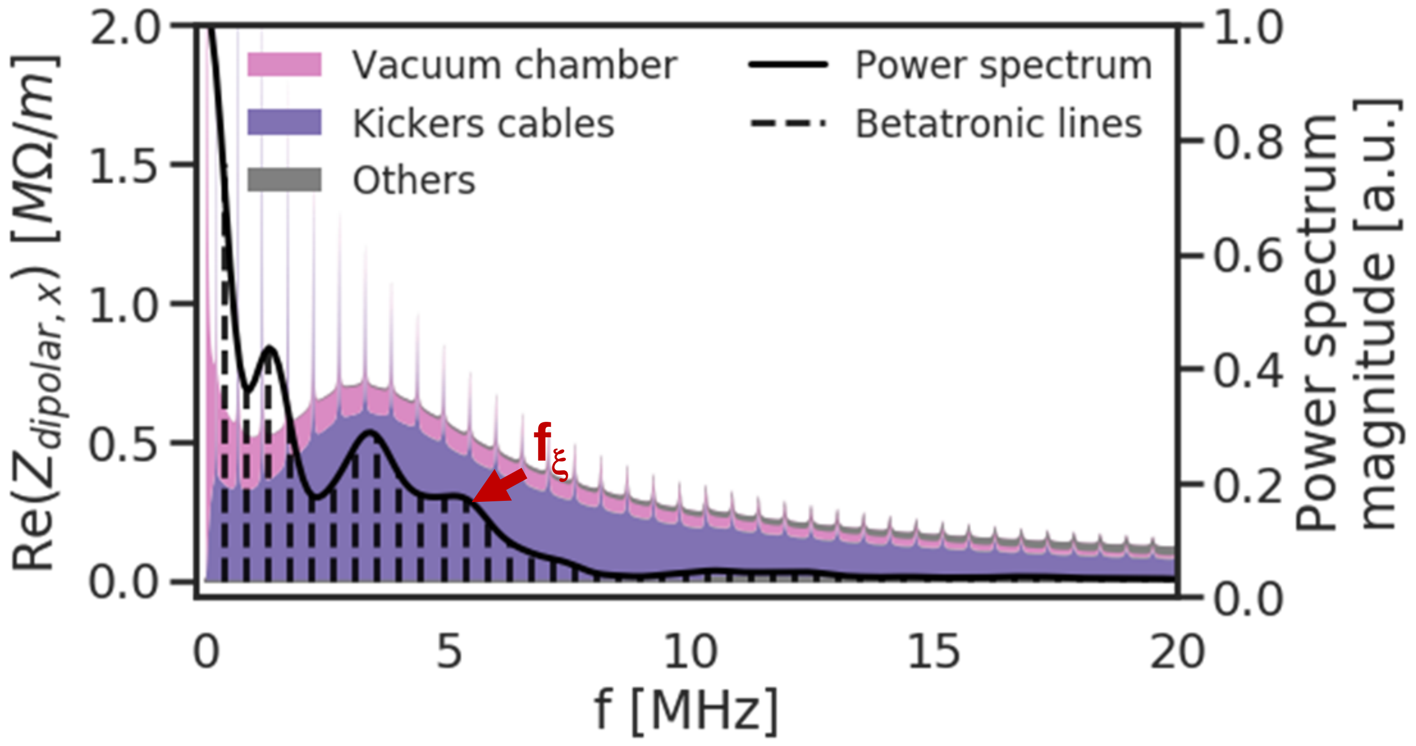
$$Z_l = Z_{TL}|_{x=x_0=0} = \begin{cases} 0 & \text{(H-shape magnet)} \\ \frac{1}{4}\frac{j\omega L Z_g}{j\omega L + Z_g} & \text{(C-shape magnet),} \end{cases}$$

$$Z_x = \frac{c}{\omega}\frac{\partial^2 Z_{TL}}{\partial x \partial x_0}|_{x=x_0} = \frac{c}{4\omega a^2}\frac{j\omega L Z_g}{j\omega L + Z_g}.$$

Horizontal impedance is identical for both magnet geometries. All connecting cables and external circuits information in Z_g.

Different approach presented in M. Neroni talk : *Beam coupling impedance of the main extraction kickers in the CERN PS*, today @ 18:05.

PS updated transverse impedance model at injection energy



New contribution characterized by:

- **Broadband behaviour in MHz range**
- **Sharp peaks caused by the open termination of a kicker magnet cable (BFA09S)**

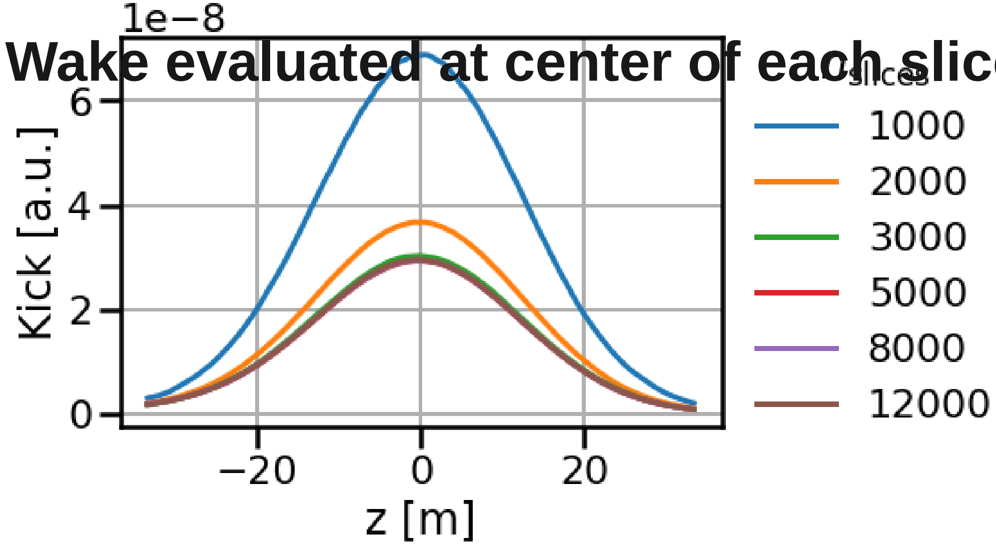
Maximum amplitude frequency coincides with 3 MHz peak of the power spectrum.

Wake kick calculation in tracking codes

Stepwise method (standard method)

$$\Delta p_\mathrm{i} = -\frac{q^2}{m_\mathrm{p}\gamma\beta^2c^2}\sum_{n=i+1}^{N_\mathrm{slices}} N_\mathrm{n}\overline{x}_\mathrm{n} w_\mathrm{n-i}$$

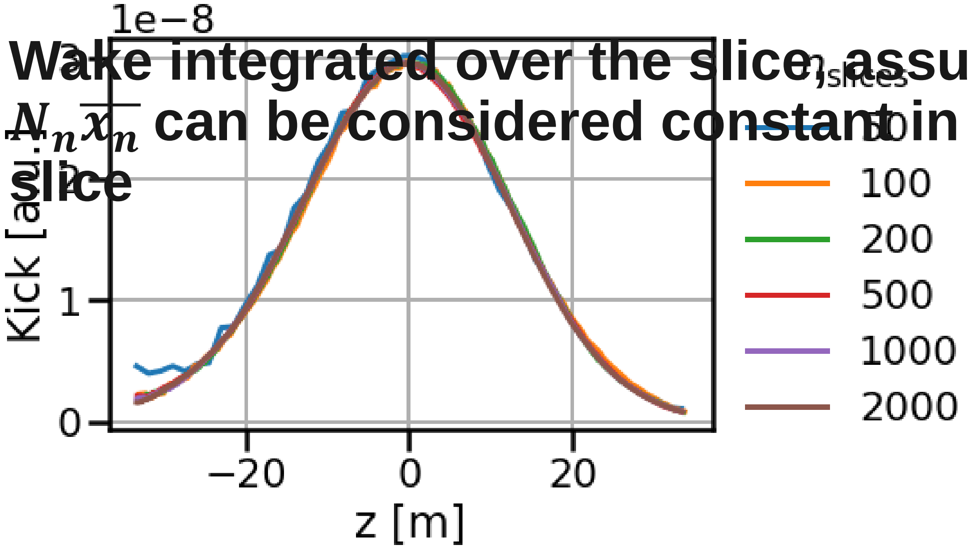
Wake evaluated at center of each slice



Integrated method (alternative method)

$$\Delta p_\mathrm{i} = -\frac{q^2}{m_\mathrm{p}\gamma\beta^2c^2}\sum_{n=i+1}^{N_\mathrm{slices}} N_\mathrm{n}\overline{x}_\mathrm{n}\int_{z'=(n-\frac{1}{2})\Delta z}^{(n+\frac{1}{2})\Delta z}\frac{w(z_\mathrm{i}-z')}{\Delta z}dz'$$

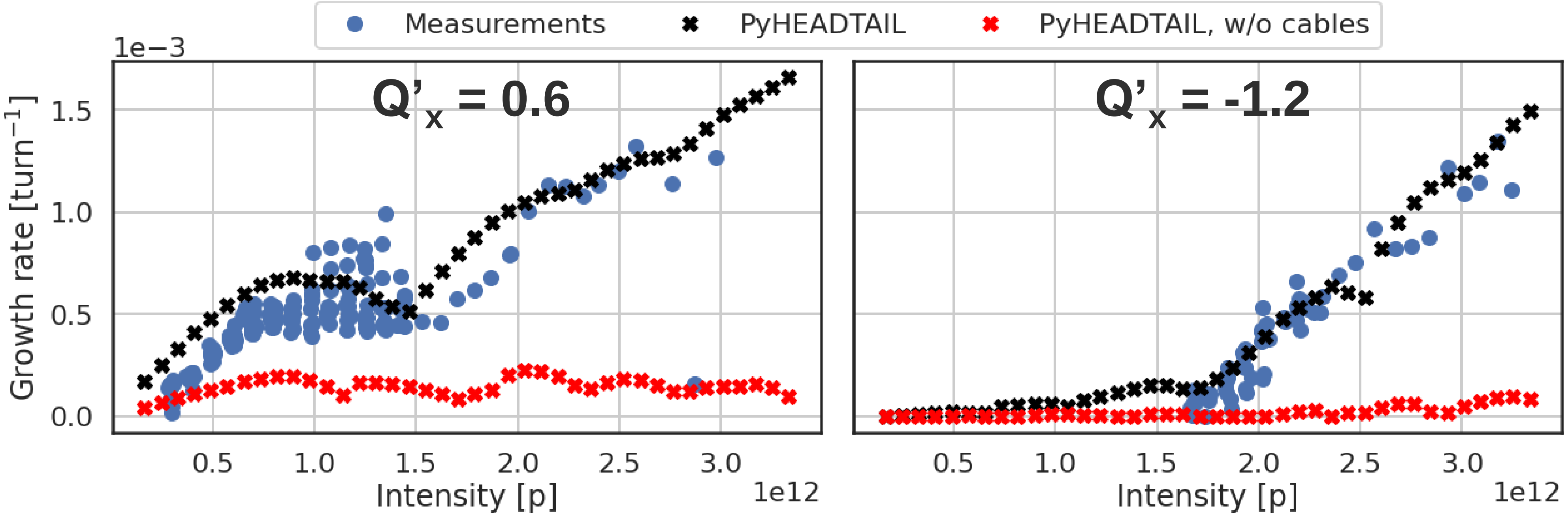
Wake integrated over the slice, assuming $N_n\overline{x_n}$ can be considered constant in each slice



Application to PS wake at injection energy, reduction of required slices by a factor ~10.

→ Simulation time reduced from a week to 8 h.

Comparison between beam-based measurements and simulations



Simulations reproduce the measured growth rates only when the new impedance contribution is included.
→ Confirmation that the instability was driven by an impedance missing from the impedance model in the MHz frequency range. The kickers cables are a good candidate for the missing impedance source.

Conclusions

- **Horizontal instability arising after the LIU intensity increase could be mitigated but not reproduced by simulations.**

- **Instability power spectrum could narrow down the responsible impedance frequency range and hint at a missing impedance source.**

- **PS kicker magnets connecting cables and external circuits impedance calculated with a recently extended analytical formalism.**

- **Using the updated impedance model, measured and simulated growth rates now agree.**

- **New impedance contribution is a good candidate for the missing impedance source.**

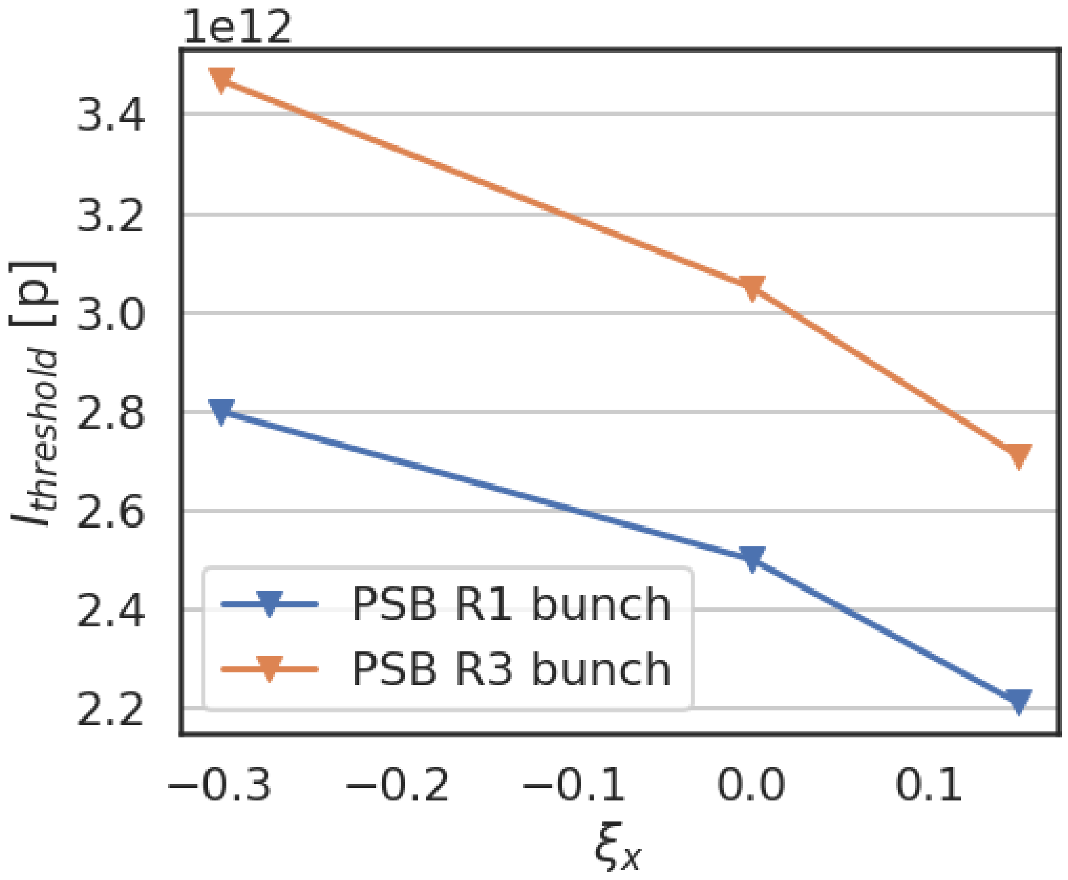
Perspectives

- **Comparison of instability power spectra with space charge simulations.**
- **Use of the instability power spectrum as diagnostic tool for missing impedance source(s) in other machines.**
- **Use of the updated model to predict stability of Physics Beyond Colliders (PBC) beams.**

Thank you for your attention !

Backup slides

Chromaticity as an instability mitigation strategy

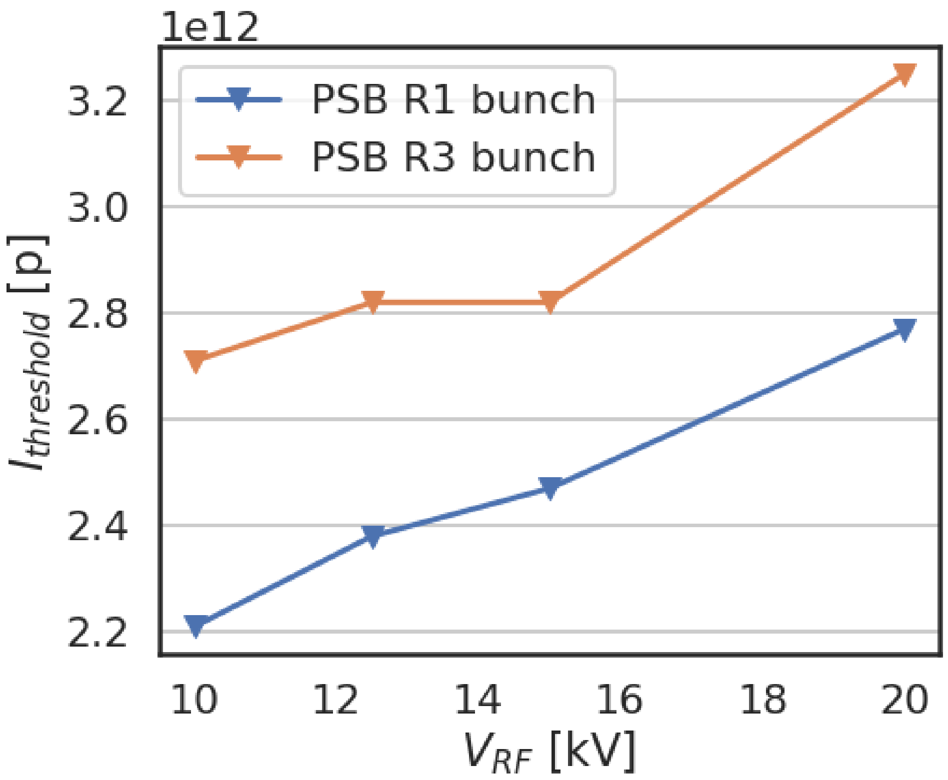


Plot of impedance spectrum with bunch spectrum and show we change chromatic shift frequency with chroma and bunch spectrum span with bunch length

Show plot of measurements with the PS flat bottom instability

Efficient mitigation strategies but chromaticity and bunch length quite often fixed parameters

RF voltage as an instability mitigation strategy



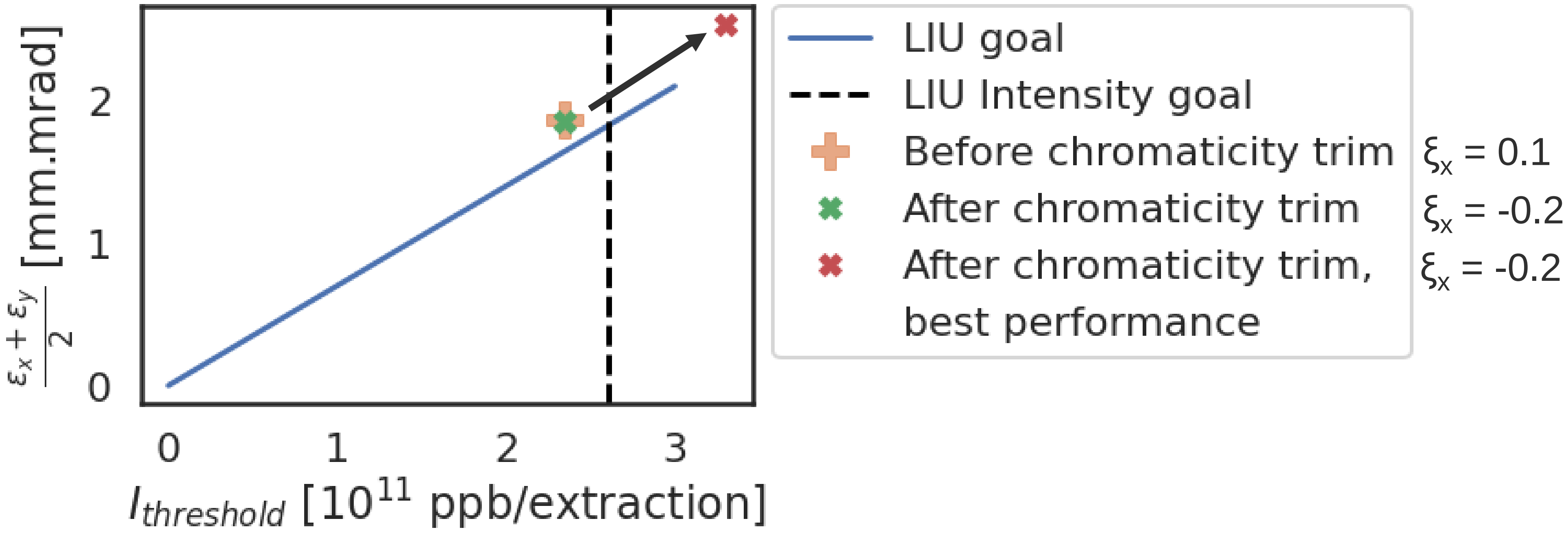
$$\tau_l \propto \varepsilon_{l,0}^{1/2}\, V_{\mathrm{rf}}^{-1/4}\, h^{-1/4}\, E_s^{-1/4}\, \eta^{1/4}$$

The bunch length τ_b scales with $V_{RF}^{-1/4}$, a doubling of the RF voltage decreases τ_b by ~20%

As a result the space charge force thus providing a stabilizing effect and increasing the intensity threshold to higher values

The tradeoff is the increased transverse emittance due to space charge

Brillance measurement after chromaticity trim

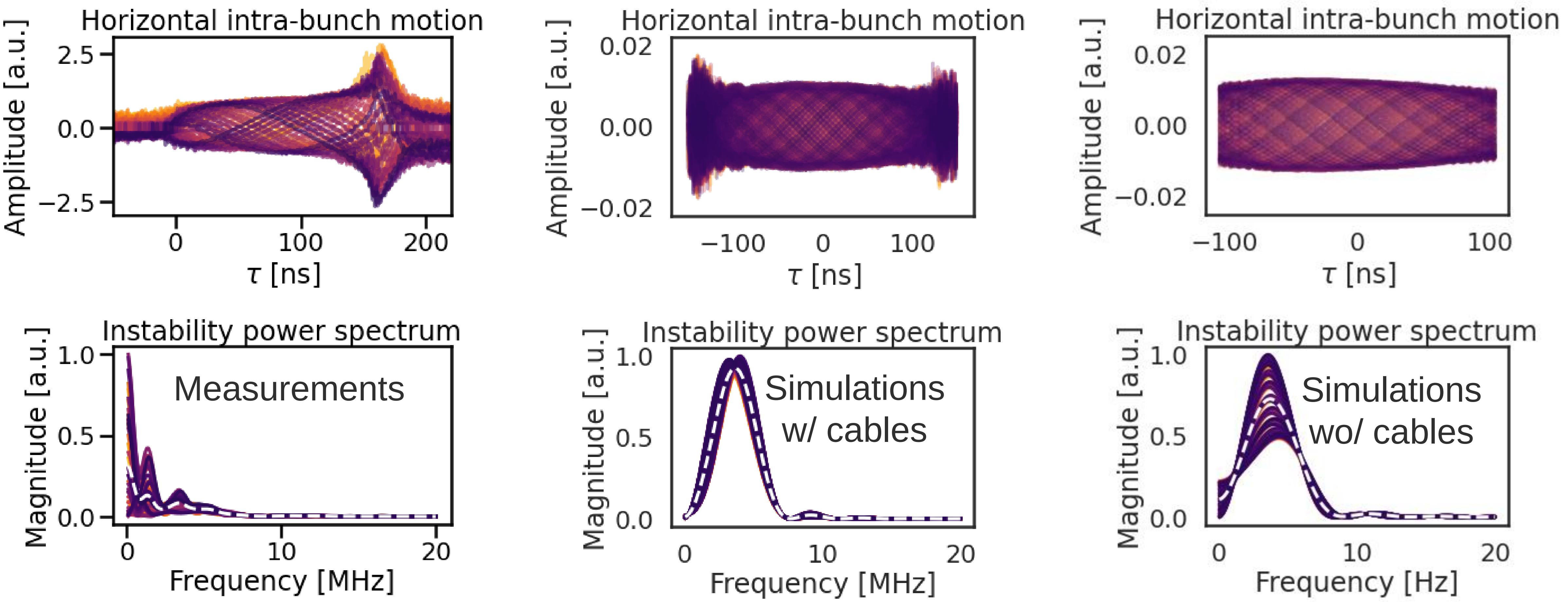


Decreasing the chromaticity (using the PFW) increases the intensity threshold.

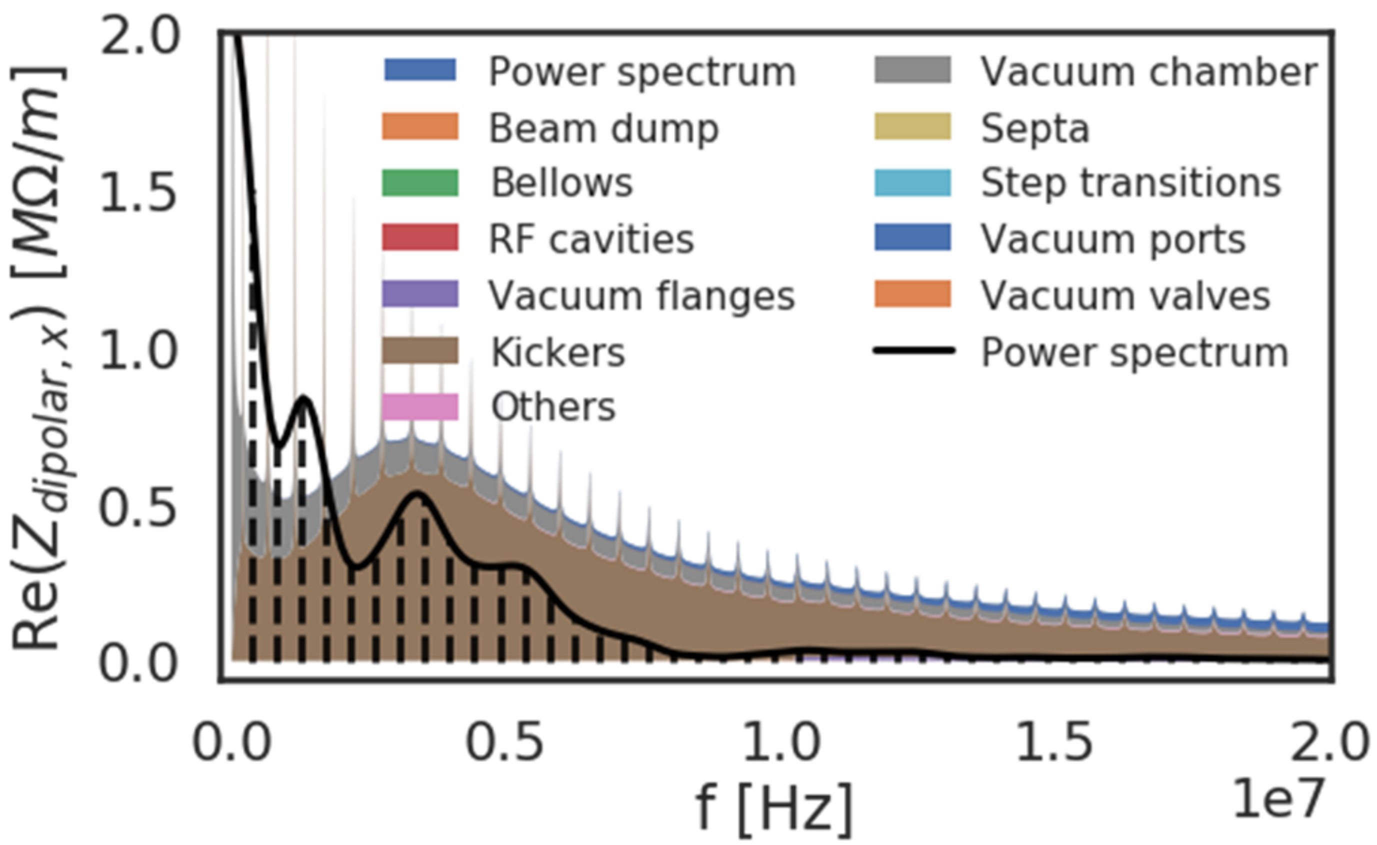
The transverse emittance is preserved even after the chromaticity trim.

Thanks to this trim, the LIU intensity goal could be reached !

Horizontal instability characterization



PS updated transverse impedance model at injection energy



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