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Recent advances in the CERN PS impedance model and instability simulations

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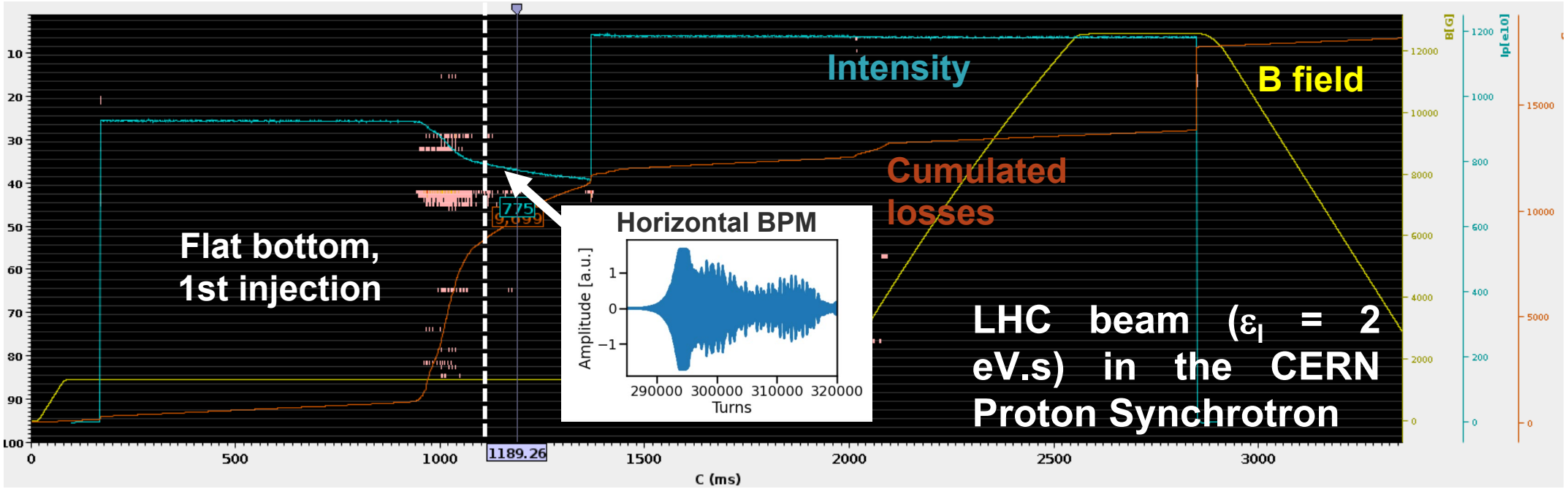
Introduction

- 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

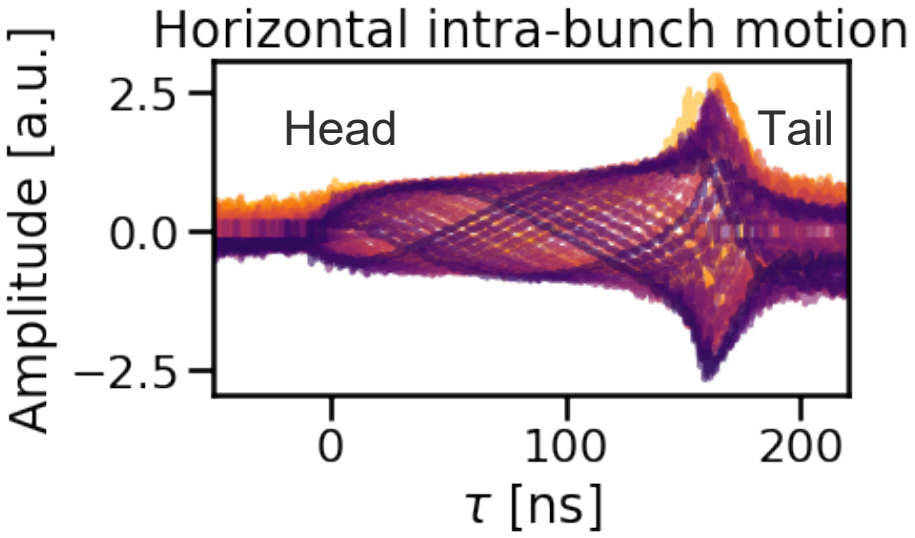
- Following the PS hardware upgrade → Gradual beam parameters ramp-up
- Unforeseen transverse instabilities arising during ramp-up, including a horizontal instability after the first injection
- Instability growth rate underestimated by a factor 5~10 in simulations
- → Investigation of this discrepancy

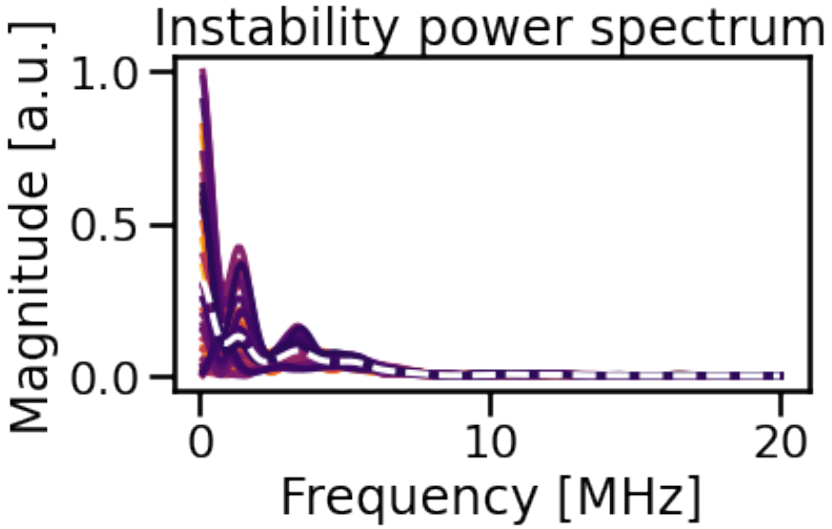
Horizontal instability signature



- 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.

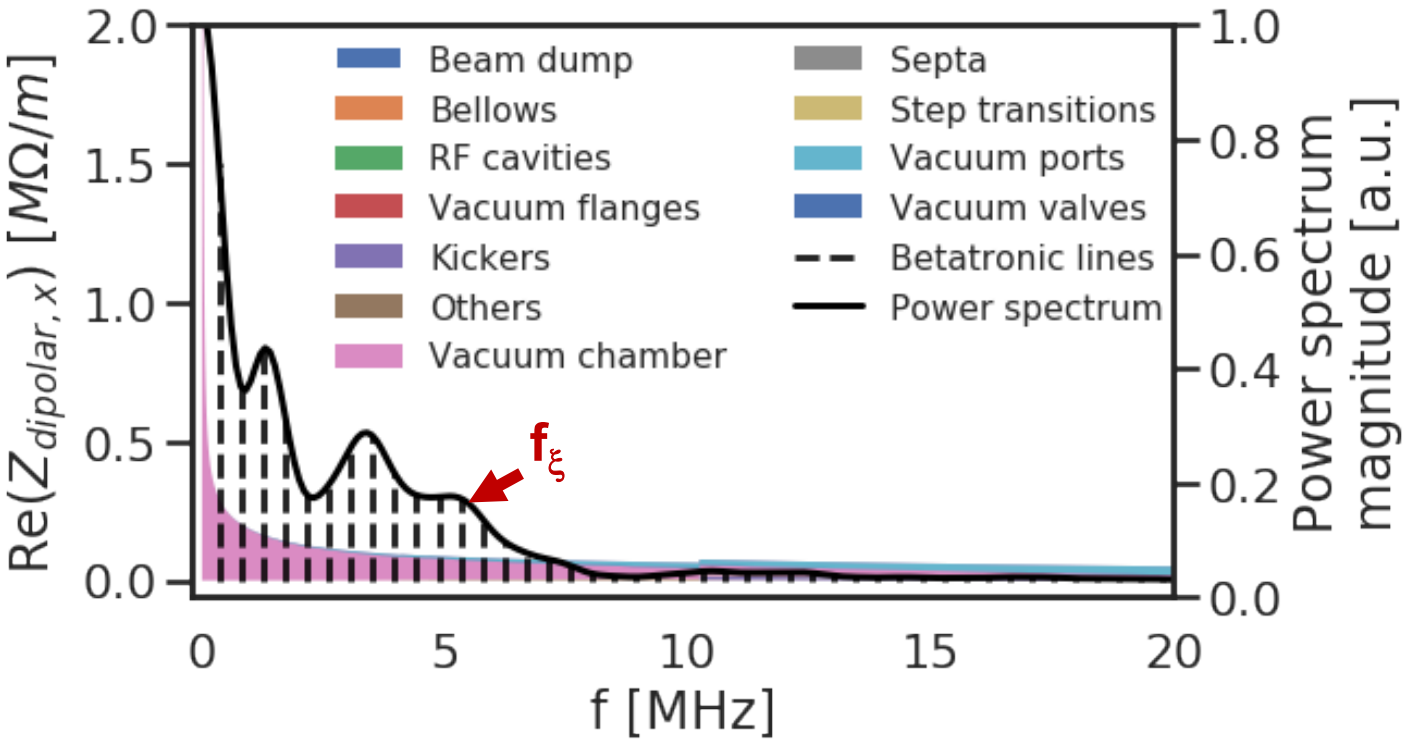
Horizontal instability characterization





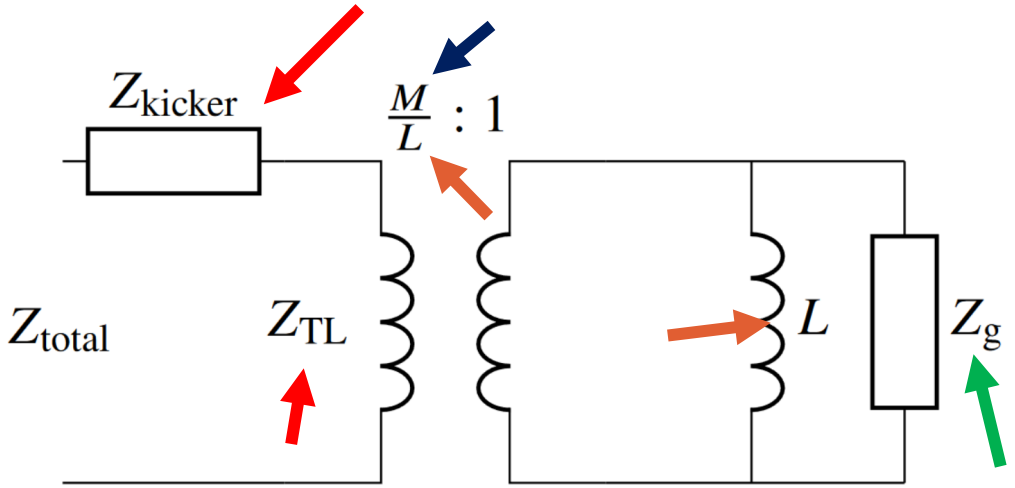
- **Horizontal intra-bunch motion acquired using a wide-band pick-up over 50 acquisitions, each spaced by 3 turns.**
- **Envelope with no node and a head/tail asymmetry.**
- **Equivalent power spectrum ($|\mathcal{F}(\lambda_x)|^2$) exhibits peaks at 0, 1 and 3 MHz.**
- **Link between peaks in the power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

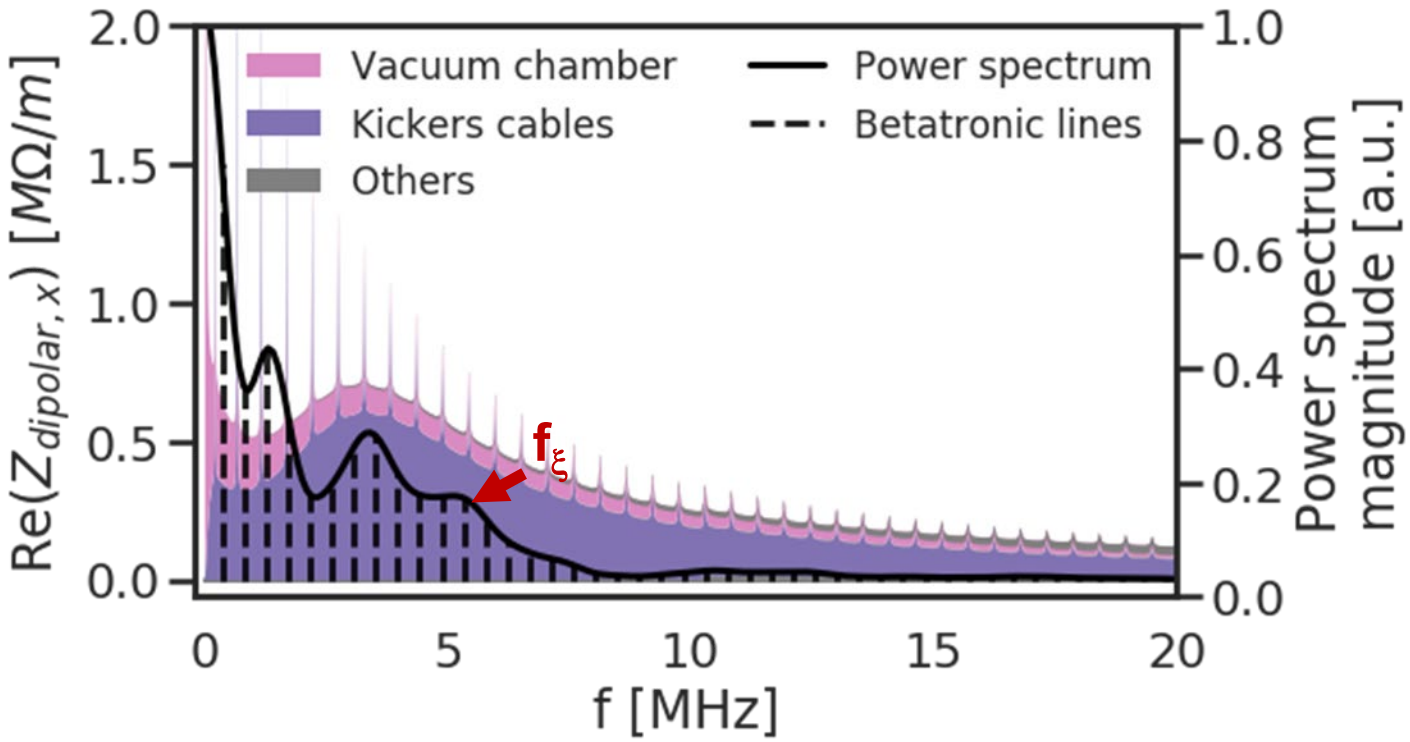
$$Z_{\parallel} = Z_{\mathrm{TL}}|_{x=x_0=0} = \begin{cases} 0 & \text{(H-shape magnet)} \\ \frac{1}{4}\frac{j\omega L Z_g}{j\omega L + Z_g} & \text{(C-shape magnet),} \end{cases}$$

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

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)**

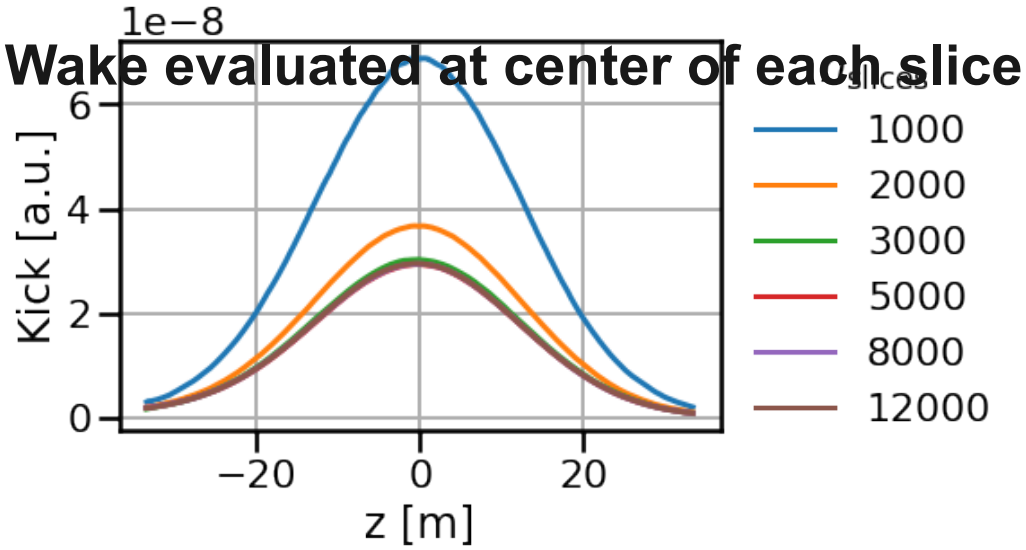
Maximum amplitude frequency coincides with 3 MHz peak of the power spectrum.

Wake kick calculation in tracking codes

Stepwise method (standard method)

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

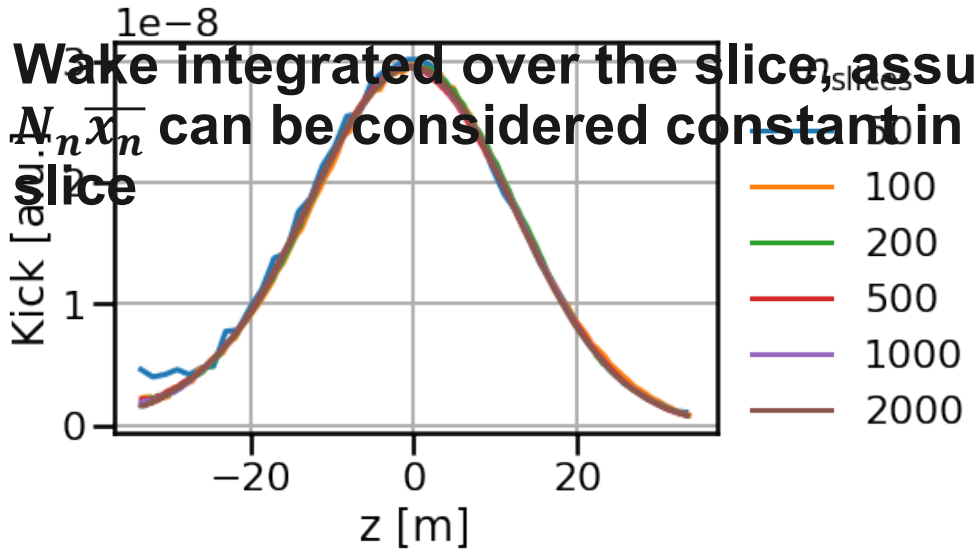
Wake evaluated at center of each slice



Integrated method (alternative method)

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

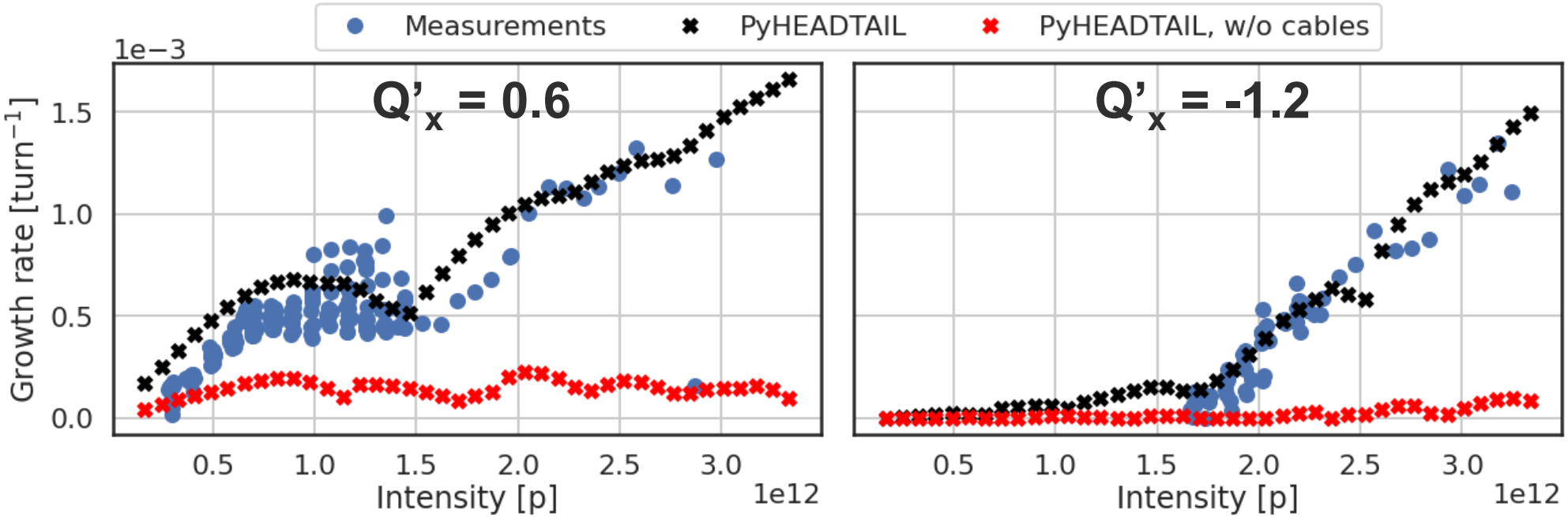
Wake integrated over the slice, assuming $N_n\overline{x_n}$ can be considered constant in each slice



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.

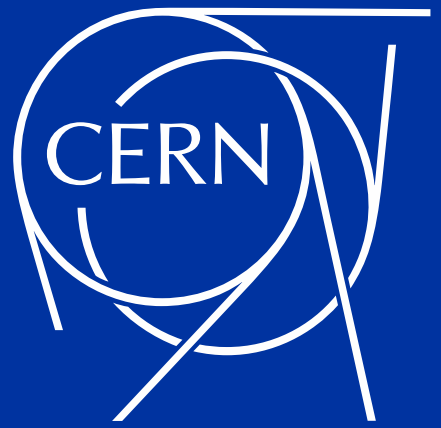
→ Confirmation that the instability was driven by an impedance missing from the impedance model in the MHz frequency range. The kickers cables are a good candidate for the missing impedance source.

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 !