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IPAC22

Suppression of Crab Cavity RF Noise-Induced Emittance Growth by Beam Transverse Impedance

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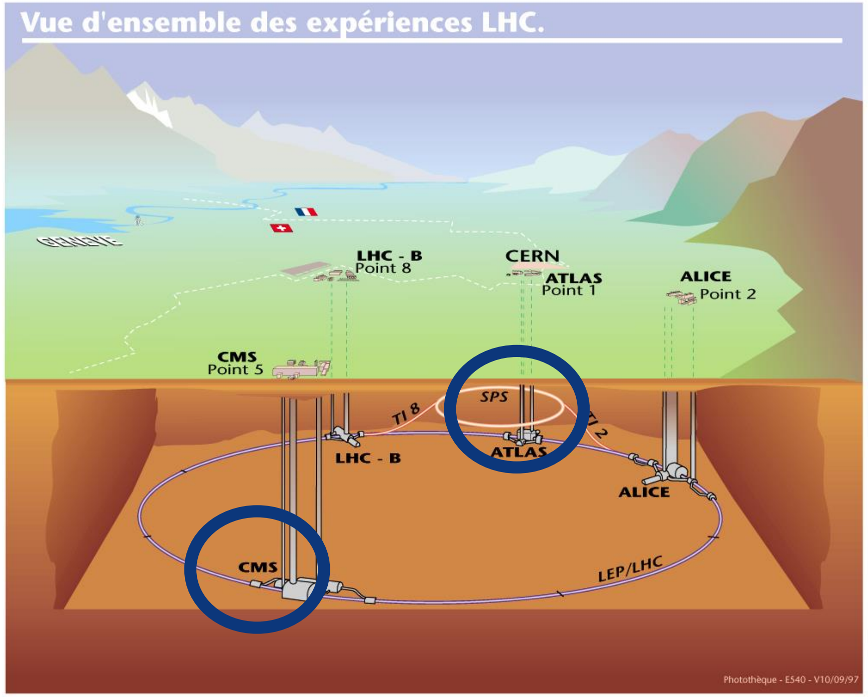
Introduction

Crab Cavities for the HL-LHC

- High Luminosity (**HL-LHC**) project is the **upgrade of the LHC machine**, which aims to increase its integrated luminosity by a factor of 10.
- **Crab Cavities** are a key component for the HL-LHC as they will **restore the luminosity reduction** caused by the crossing angle, in the interaction points of **ATLAS** and **CMS.**



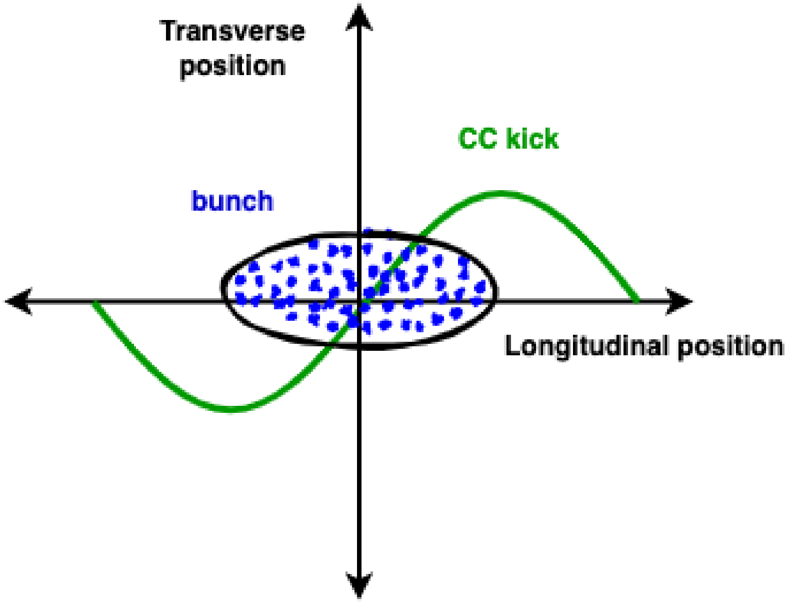
Luminosity in a collider

$$\mathcal{L} = \frac{n_b f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y} \frac{1}{\sqrt{1 + (\frac{\sigma_z}{\sigma_{xing}}\frac{\alpha}{2})^2}}$$

where f_{rev} the revolution freuency of the machine, n_b the number of colliding bunch pairs, $N_{1,2}$ the bunch intensities, $\sigma_{x,y}$ the transverse beam size at the interaction point, σ_z the rms bunch length, σ_{xing} the transverse beam size in the crossing plane and α is the full crossing anlge.

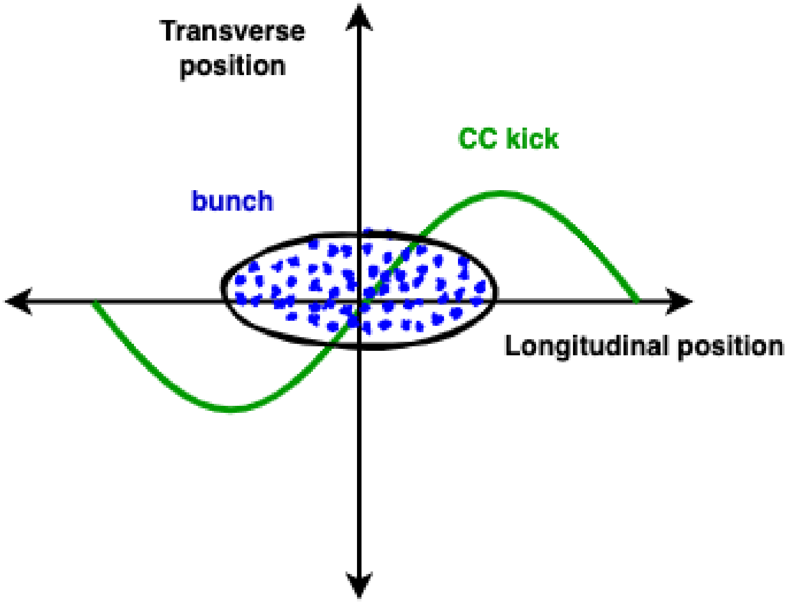
Crab Cavity technology

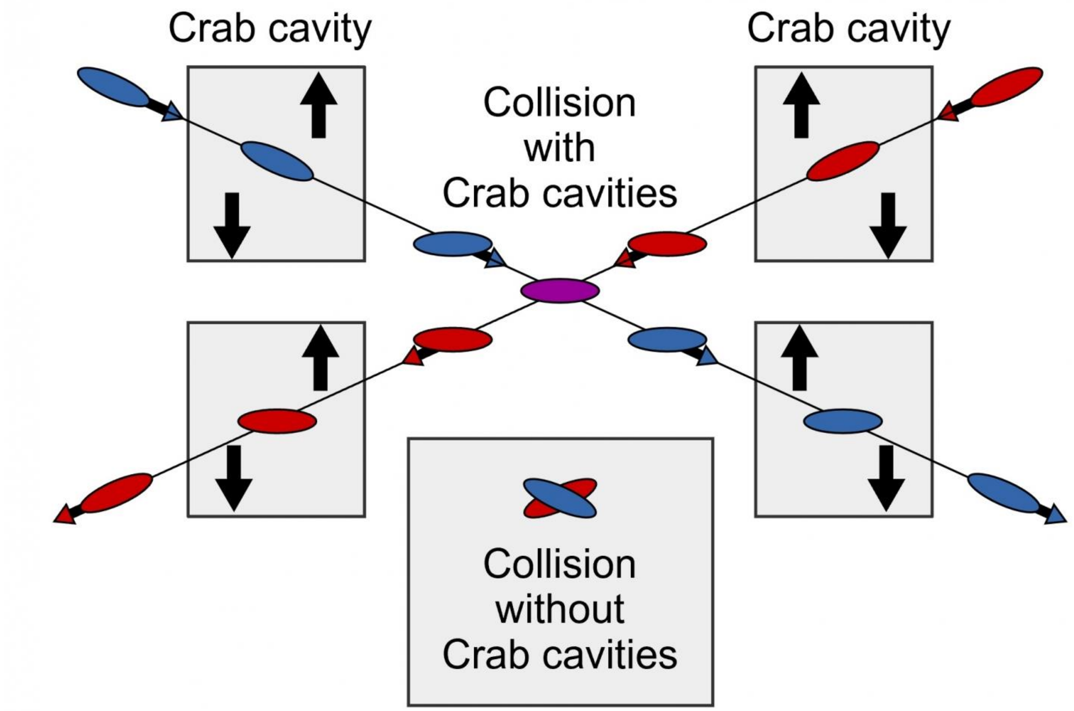
- RF cavity providing **transverse kick** to particles **depending** on their **longitudinal position** within the bunch.
- Head and tail receive opposite deflection while particles at the centre remain unaffected.



Crab Cavity technology

- RF cavity providing **transverse kick** to particles **depending** on their **longitudinal position** within the bunch.
- Head and tail receive opposite deflection while particles at the centre remain unaffected.
- The **bunch rotates,** and the **head-on collision is restored** at the interaction points.



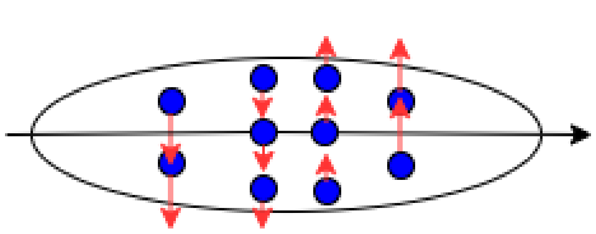


Transverse emittance growth from Crab Cavity RF noise

RF noise in the Crab Cavity

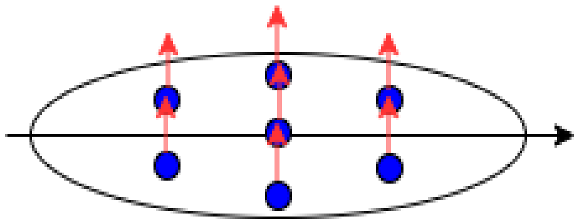
- **Noise** in the Crab Cavity RF system can result in **undesired transverse emittance growth** and therefore **loss of luminosity**.

Amplitude noise



The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

Phase noise



All the particles within the bunch experience kicks that are in phase → centroid shift → dipole / mode 0 motion

Theoretical formalism

- **Need to define limits of Crab Cavity RF noise levels** to achieve acceptable emittance growth.
- A **theoretical model**(*) was derived to **predict the emittance growth** from CC noise.
- The model was validated through numerical simulations (HEADTAIL).
- **Benchmarking with experimental data is necessary → First tests in SPS in 2018.**

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 101001 (2015)

Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities

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(Received 23 June 2015; published 5 October 2015)

The high-luminosity LHC (HiLumi LHC) upgrade with planned operation from 2025 onward has a goal of achieving a tenfold increase in the number of recorded collisions thanks to a doubling of the intensity per bunch (2.2e11 protons) and a reduction of β^* to 15 cm. Such an increase would significantly expedite new discoveries and exploration. To avoid detrimental effects from long-range beam-beam interactions, the half

(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

SPS measurements in 2018

➢ A few important points:

1.	**SPS** was used as a test bed for two **vertical** Crab Cavities **before** their installation in the **LHC**.
2.	**First time** that **proton dynamics with crab cavities** could be studied **experimentally**.
3.	SPS operation as storage ring, possible at highest energy of **270 GeV** → The **results** need to be **scaled for the HL-LHC.**
4.	**Injected artificial noise** **larger than expected in HL-LHC** for better observables. Emittance growth scales with noise power (theory(*)).

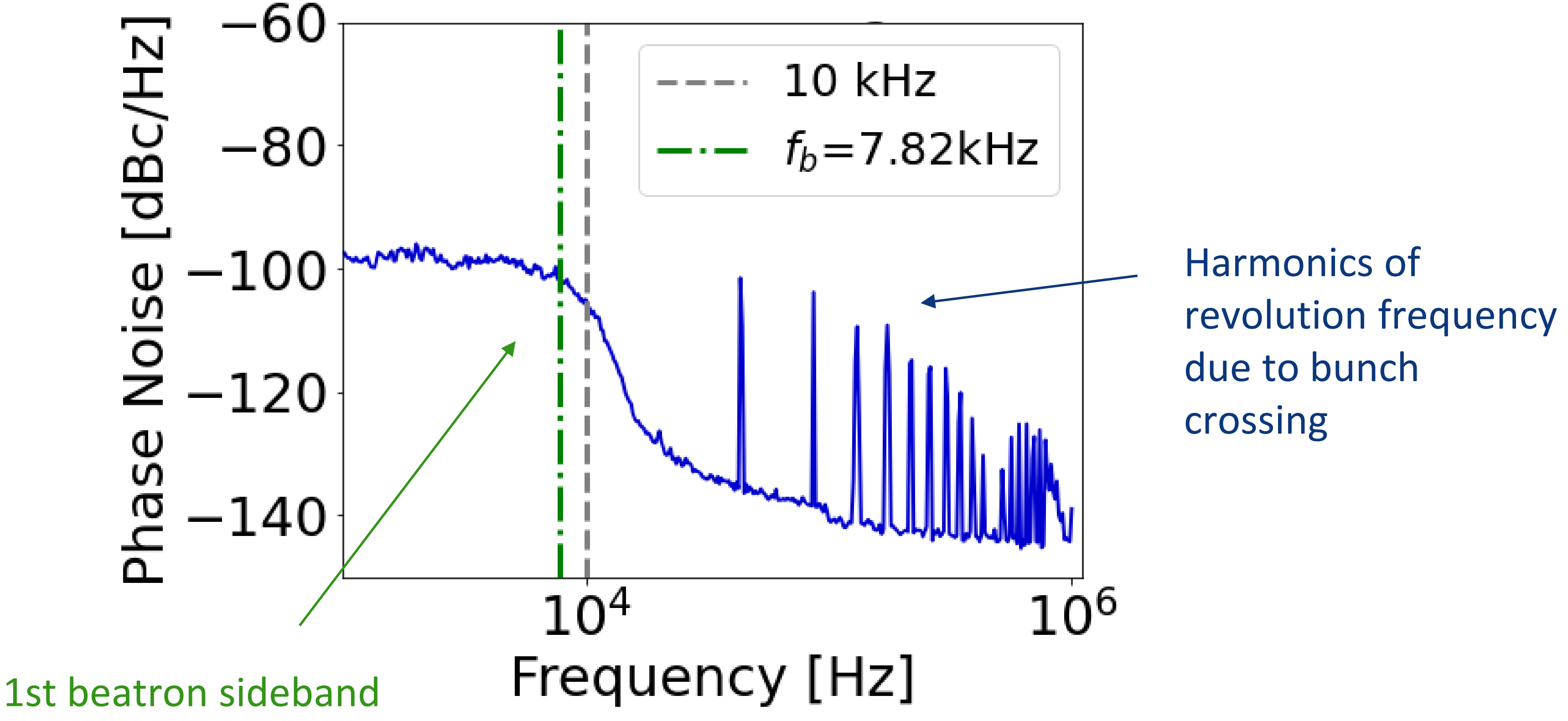
scaling

(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

SPS measurements in 2018 – RF noise

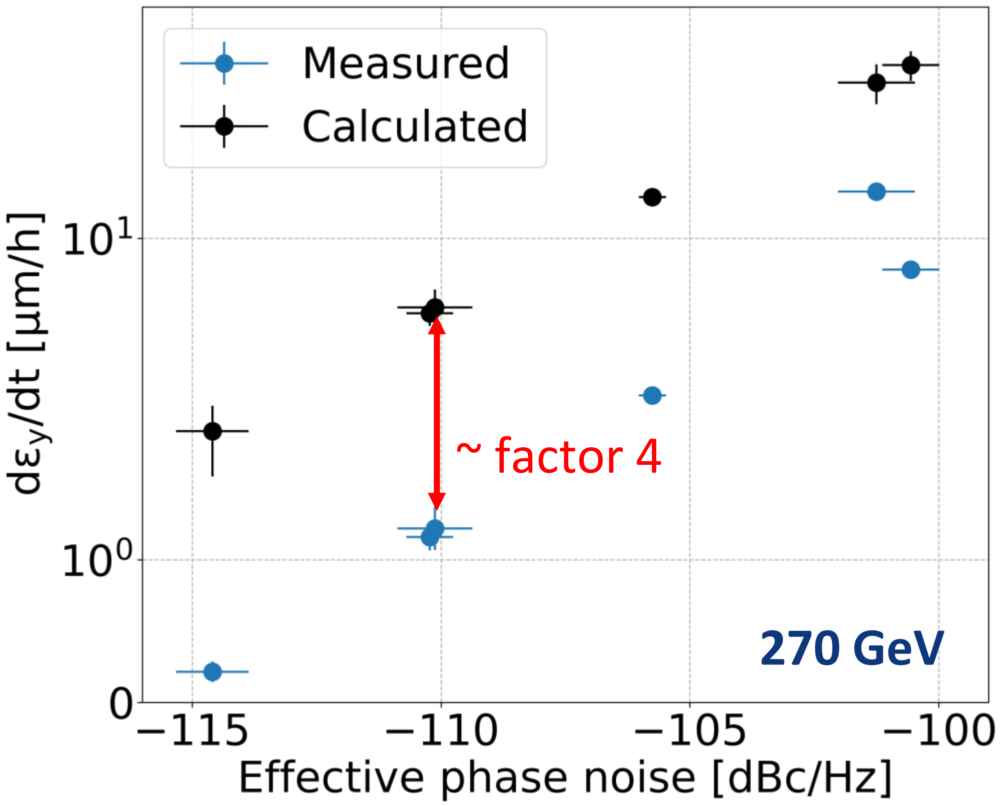
- Mixture of amplitude and phase noise. **Phase noise was always dominant.**

Example noise power measurement in 2018



SPS measurements in 2018 - Results

- Measurements for different (phase) noise levels.
- Observed **scaling** of **measured** emittance growth with **noise power**.
- The **measured emittance growth** was a **factor 4** (on average) **lower** than expected from the **theory** (*).



(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

Investigating possible explanations for the discrepancy

➢ **Points** that were checked but **did not explain the discrepancy**:

1.	Benchmarking of the theory with different simulation codes.
2.	Sensitivity to the non-linearities of the SPS.
3.	Possible errors in the analysis of the experimental data.
4.	Possible errors in the actual noise levels of the Crab Cavities.

2018-2020

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2018-2020

- Only simulations including the SPS **transverse impedance model** (not included in the theory (*)) showed a **significant impact on the emittance growth**.

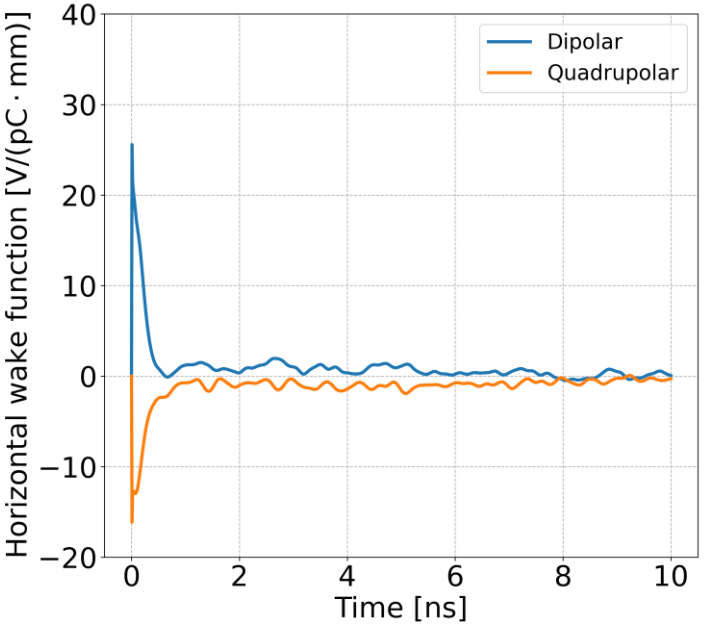
(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

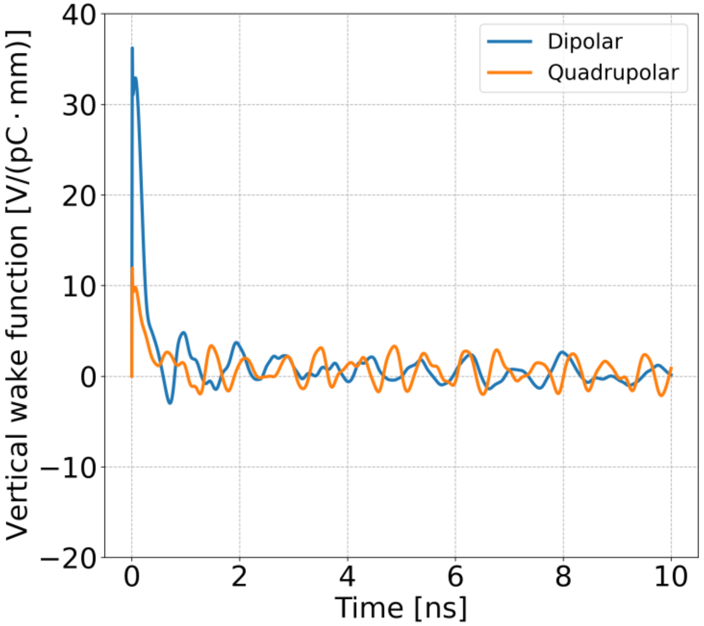
Emittance growth suppression from the beam transverse impedance

SPS transverse impedance model

- The **complete SPS transverse impedance model**(*) provided from detailed electromagnetic simulations is used.
  - Kickers, resistive wall, step transitions, BPMs, RF cavities and indirect space charge etc

SPS wake functions used in the simulations



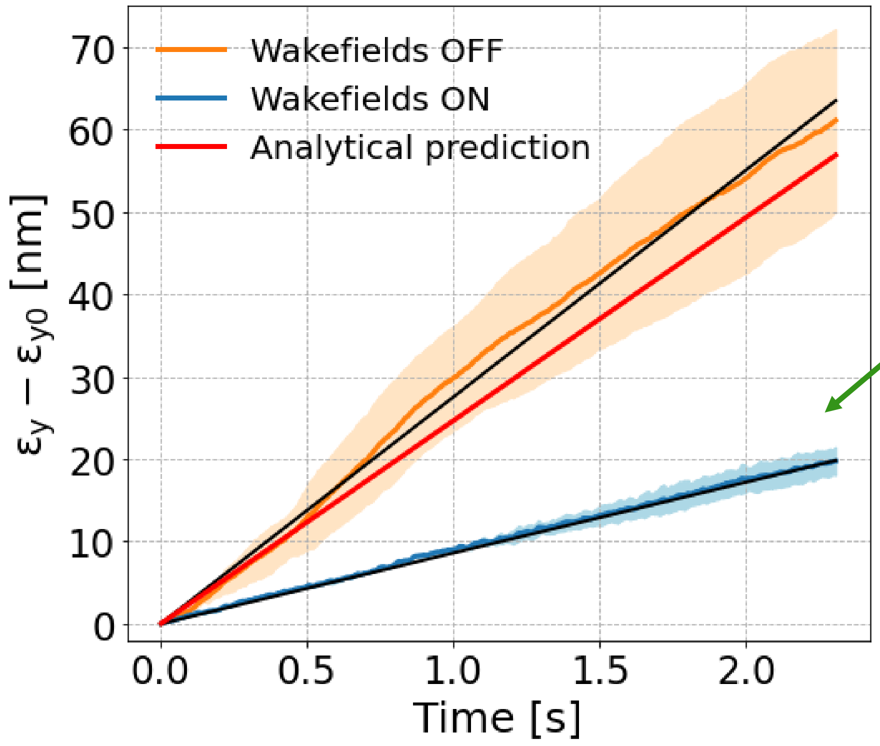


$4\sigma_t$ = 1.85 ns during SPS tests

(*) https://gitlab.cern.ch/IRIS/SPS_IW_model

First simulation results

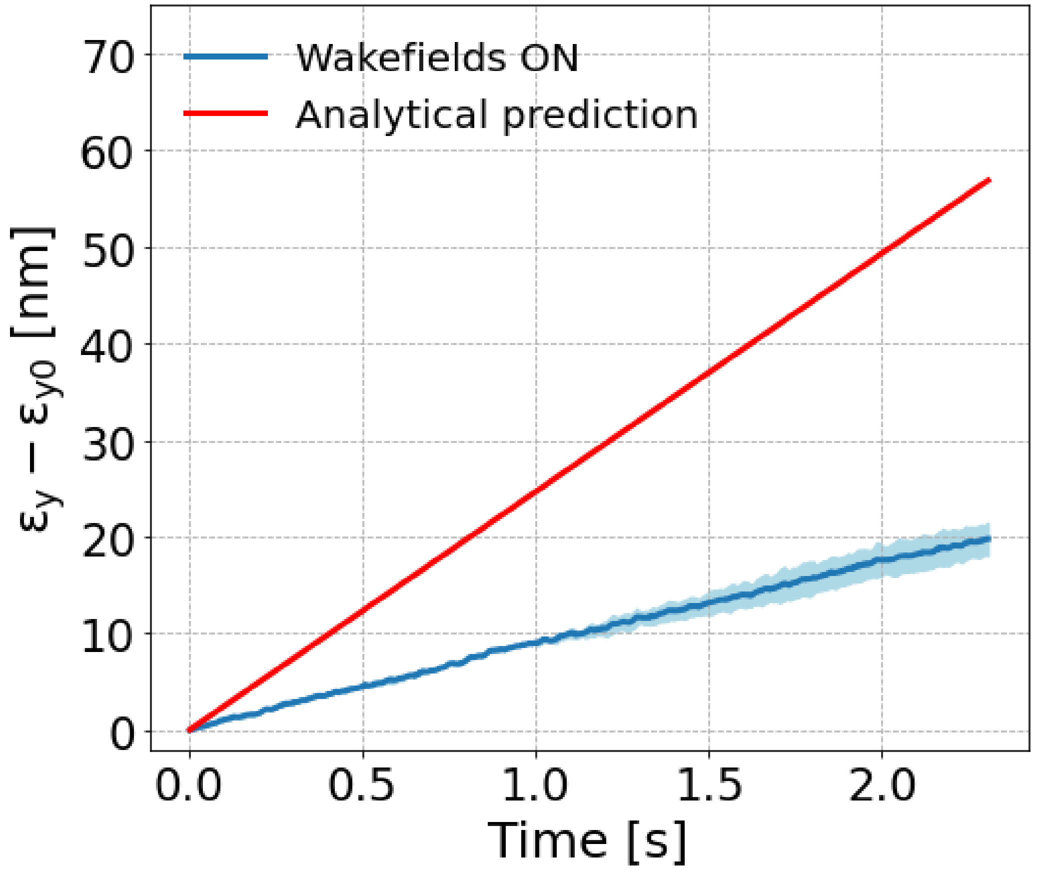
- **Simulations** with **PyHEADTAIL** and the **complete SPS transverse impedance model**.
- Beam and machine conditions as in the 2018 SPS experiment.
- Crab Cavity RF **phase noise** for ~ 25 nm/s
  - Even **stronger than in the SPS experiments**, for observables in the simulation time. **Scaling**.

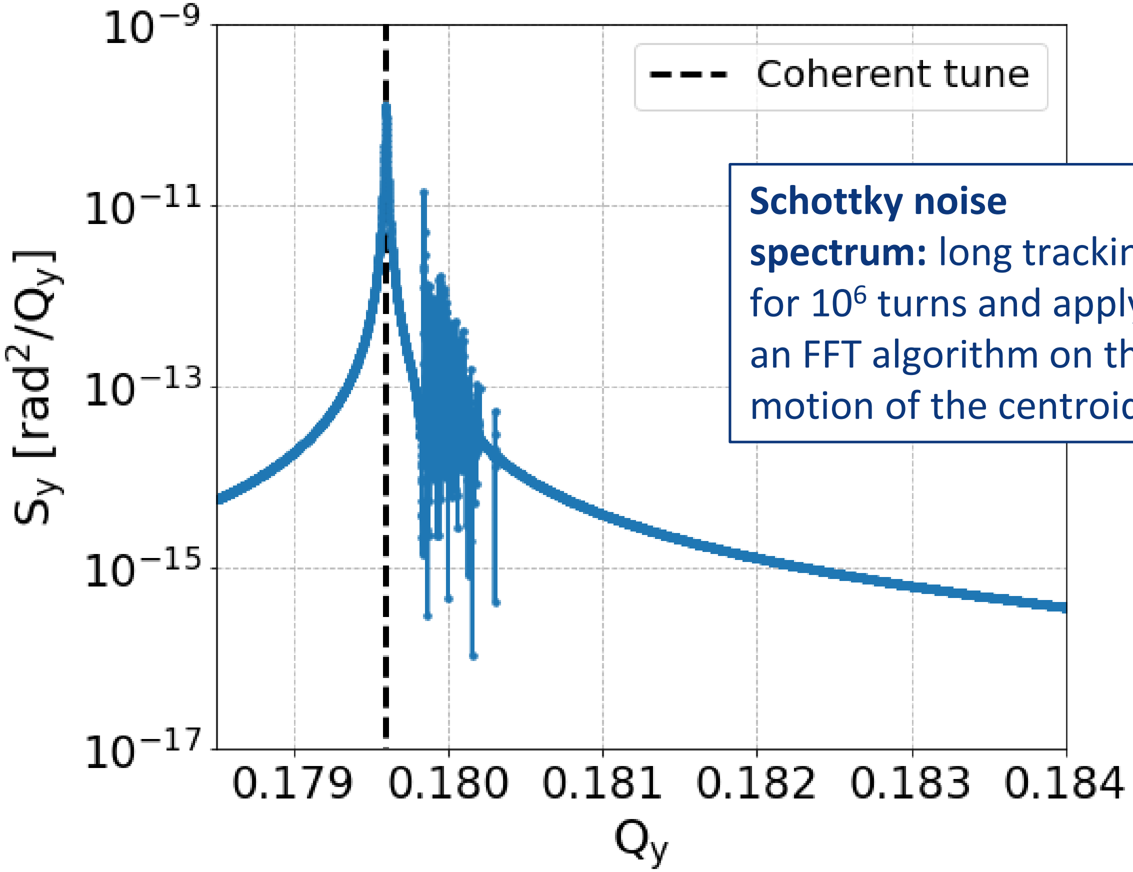


Clear suppression of the **phase noise** induced **emittance growth** in the presence of **wakefields**.

Suppression mechanism - I

The **transverse impedance separates the coherent and incoherent tunes** which leads to an **effective suppression of the Crab Cavity phase noise induced emittance growth**.



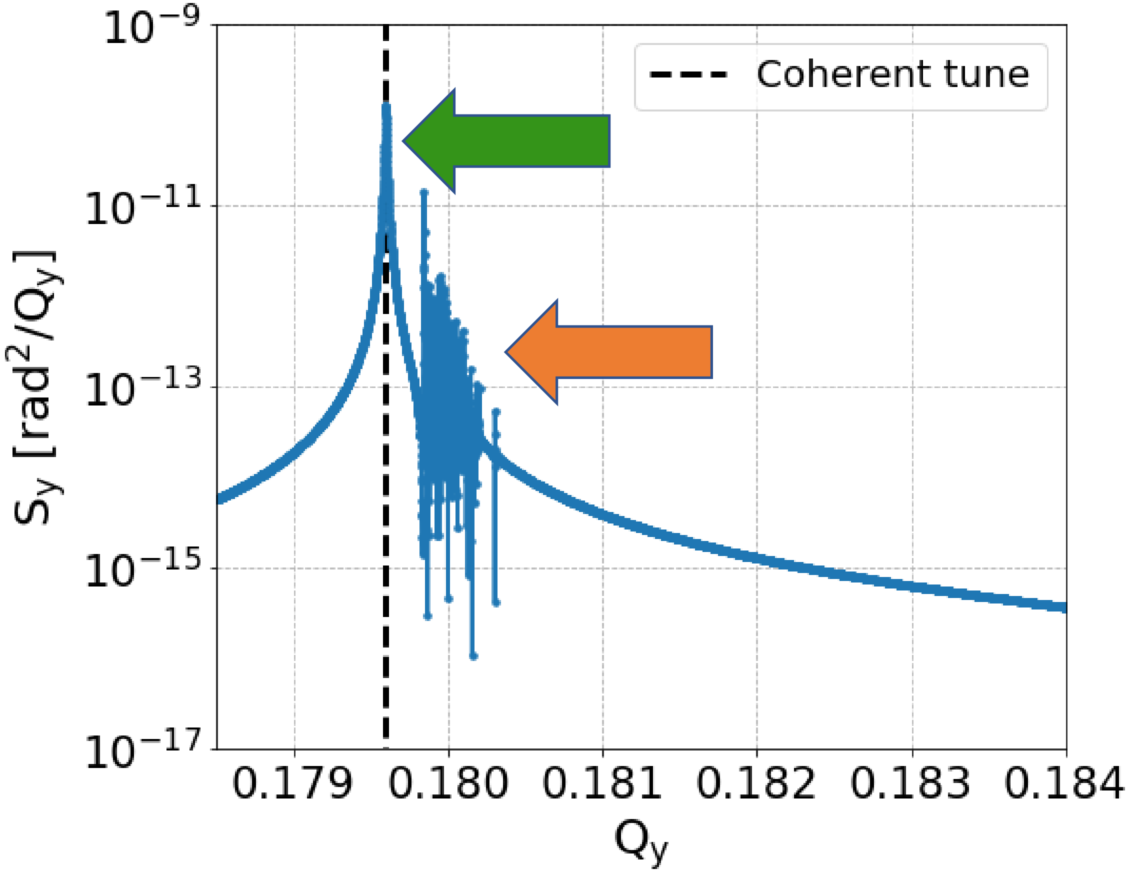


Schottky noise spectrum: long tracking for 10^6 turns and apply an FFT algorithm on the motion of the centroid.

Suppression mechanism - II

The **transverse impedance separates the coherent and incoherent tunes** which leads to an **effective suppression of the Crab Cavity phase noise induced emittance growth**.

- **Only part** of the **energy** from the **noise kicks** drives **incoherent motion** and leads to **irreversible emittance growth.**
- **The rest of the energy** is absorbed by the **coherent mode**, which is **damped** by the **impedance without leading to emittance growth**.



Related studies

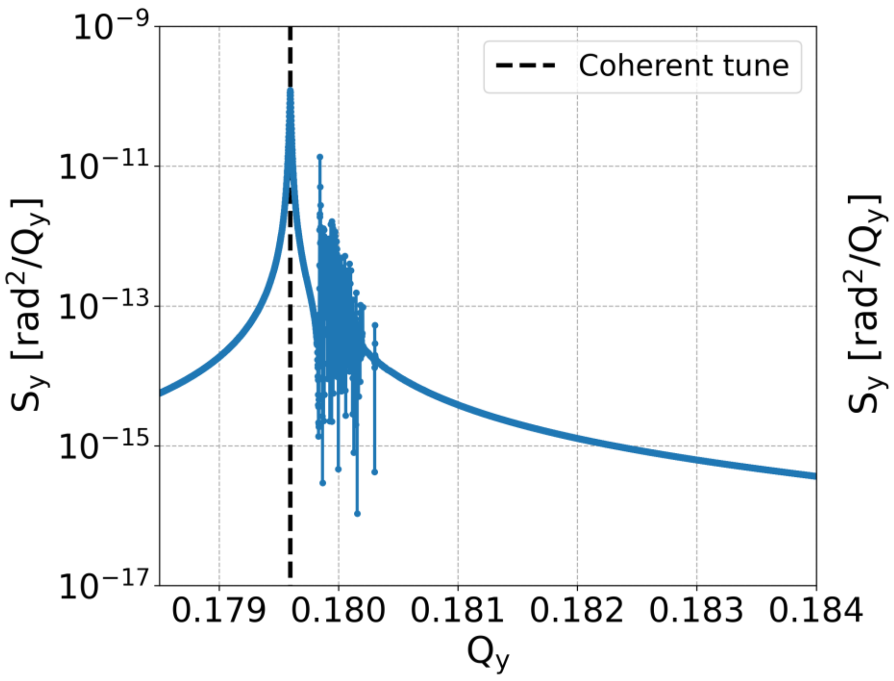
- In the context of the beam-beam modes it has been observed that the **efficiency of a transverse feedback** system at suppressing emittance growth depends on the **overlap between the coherent mode and the incoherent spectrum** in **past** theoretically(*1) and in simulations(*2).

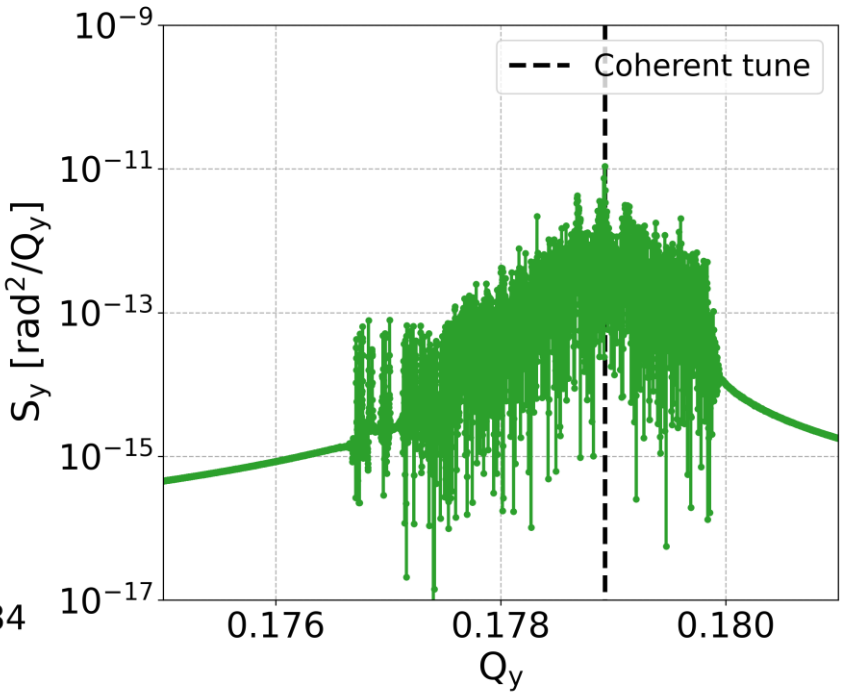
- Recently, this approach was adapted for configurations featuring linear detuning and a complex tune shift from a collective force, supporting the simulation results shown here.
  - **X. Buffat, "Suppression of Emittance Growth by a Collective Force: Van Kampen Approach", IPAC'22: paper WEPOTK059.**

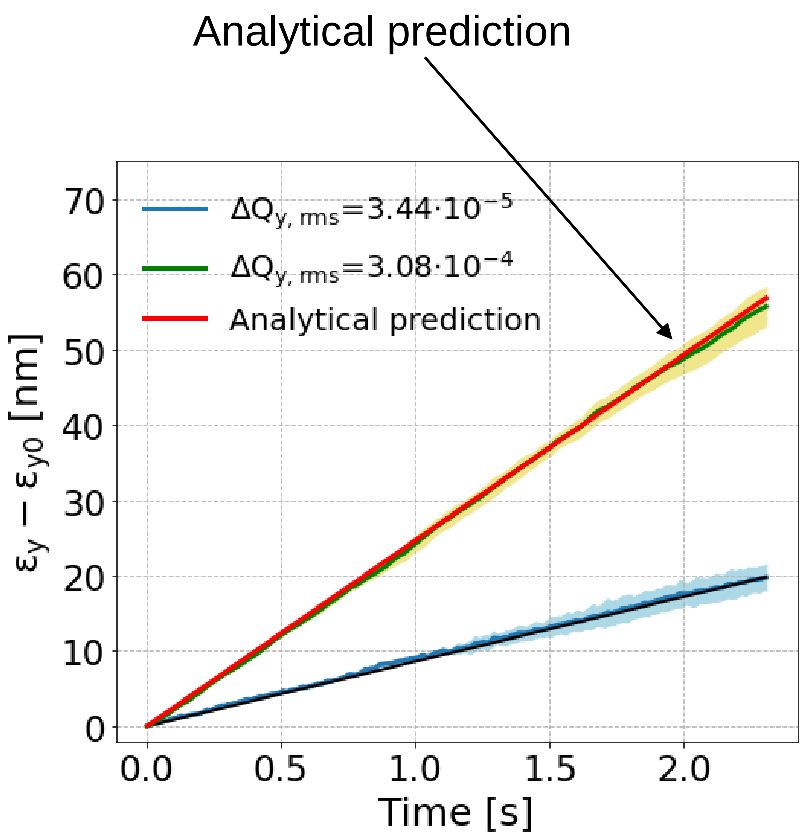
(*1) *Y. Alexahin, "On the Landau Damping and decoherence of transverse dipole oscillations in colliding beams"*
(*2) *X. Buffat, "Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider", Phys. Rev. Accel. Beams 23, 021002 (2020)*

Impact of tune spread

- Simulations studies showed that increasing the tune spread through detuning with amplitude can **bring the coherent mode inside the incoherent spectrum restoring** the emittance growth expected from the theory of T. Mastoridis and P. Baudrenghien (without impedance effects).



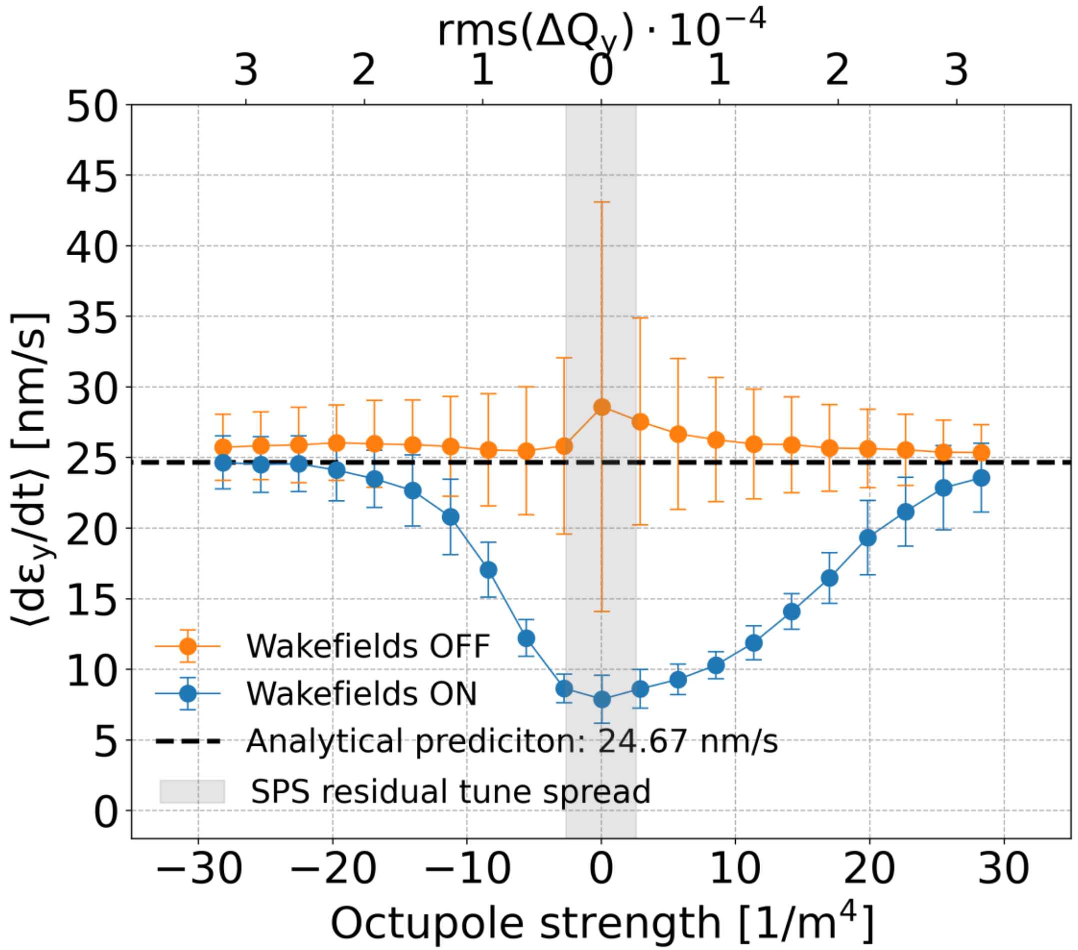




Parameters: 270 GeV, 3e10 protons per bunch, Q’y=0.5

Sensitivity to tune spread

- In the presence of **wakefields**, there is a **clear dependence** of the emittance growth on the **tune spread value** and thus the overlap of the coherent tune and the incoherent spectrum observed in the simulations.



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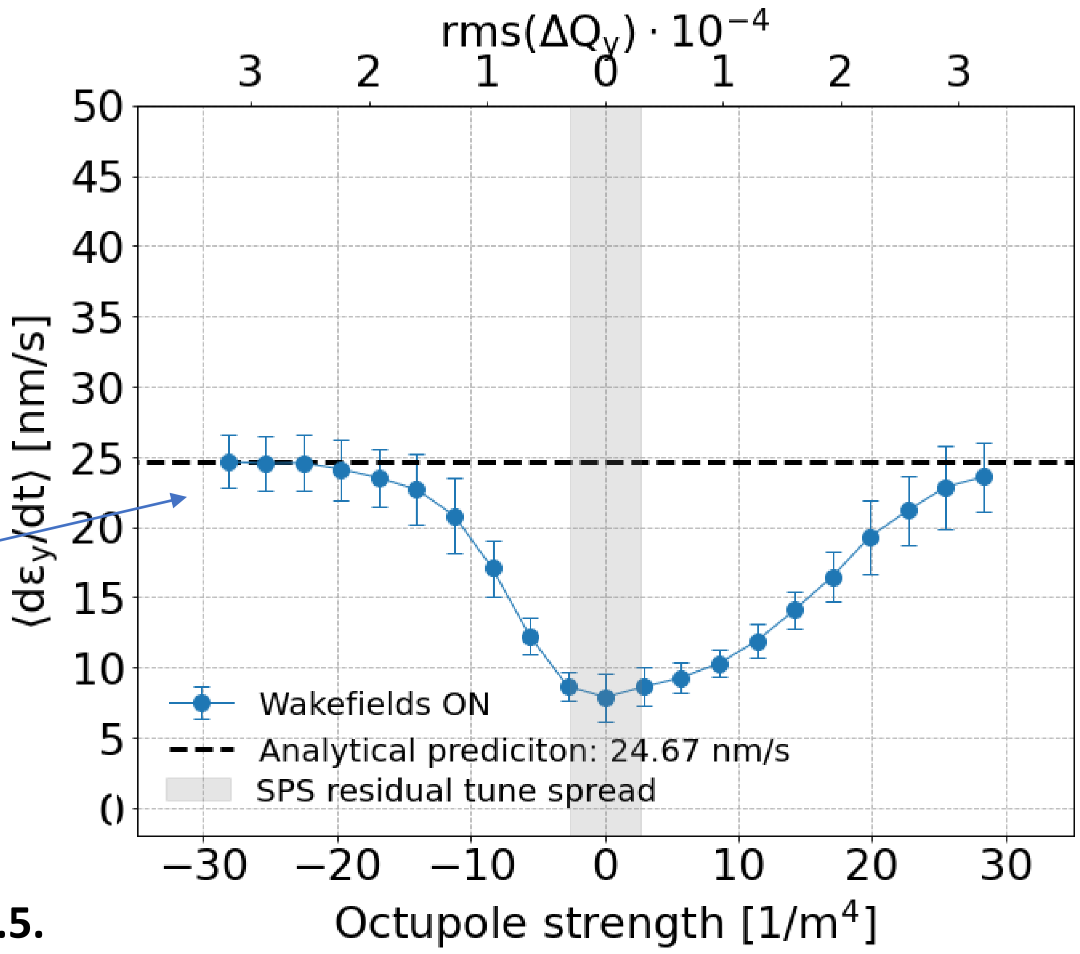
This **behavior** can be **tested experimentally** in the **SPS** → **Tested in 2022.**

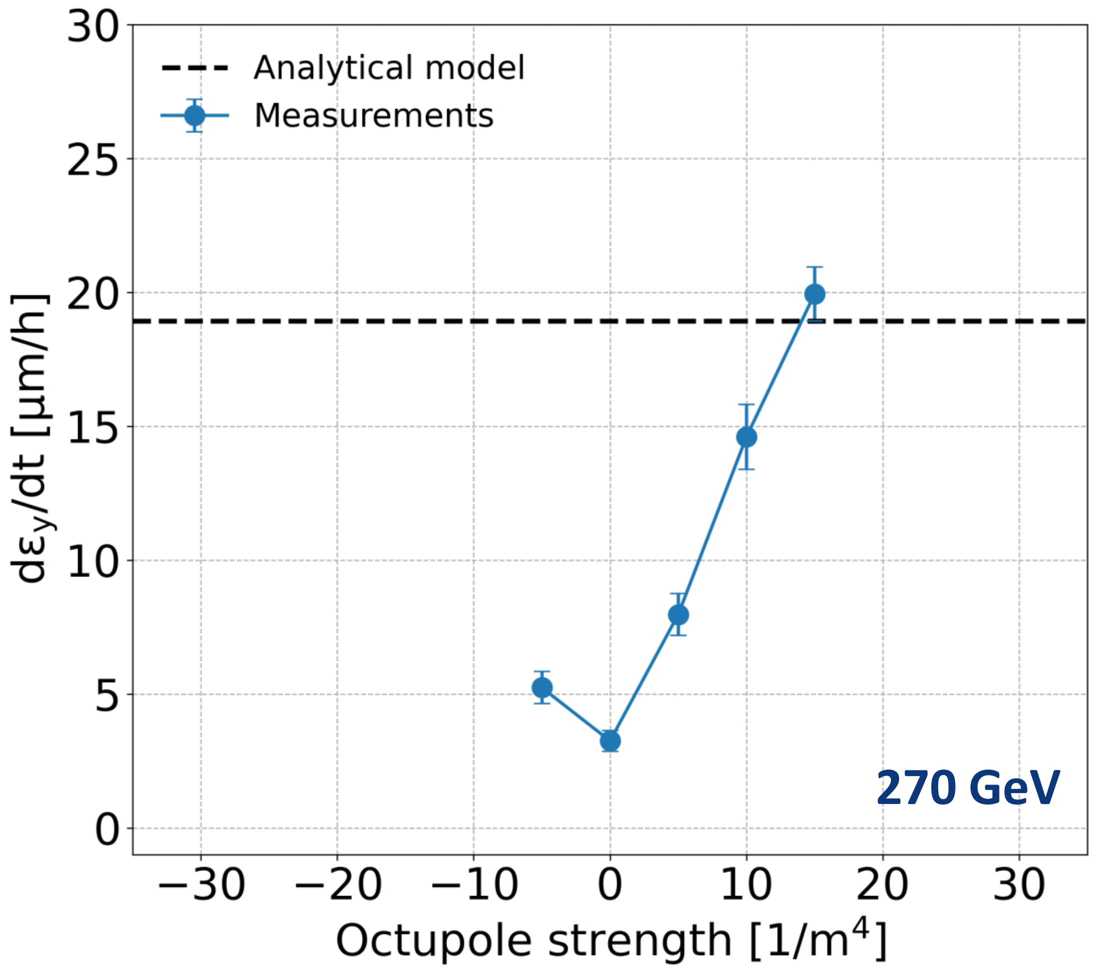
- **Use of SPS octupole families.**
- **Goal: Reproduce the behavior only (due to scaling).**
- **For the residual SPS tune spread: suppression of a factor ~ 3.5.**



SPS measurements in 2022

Experimental results 2022

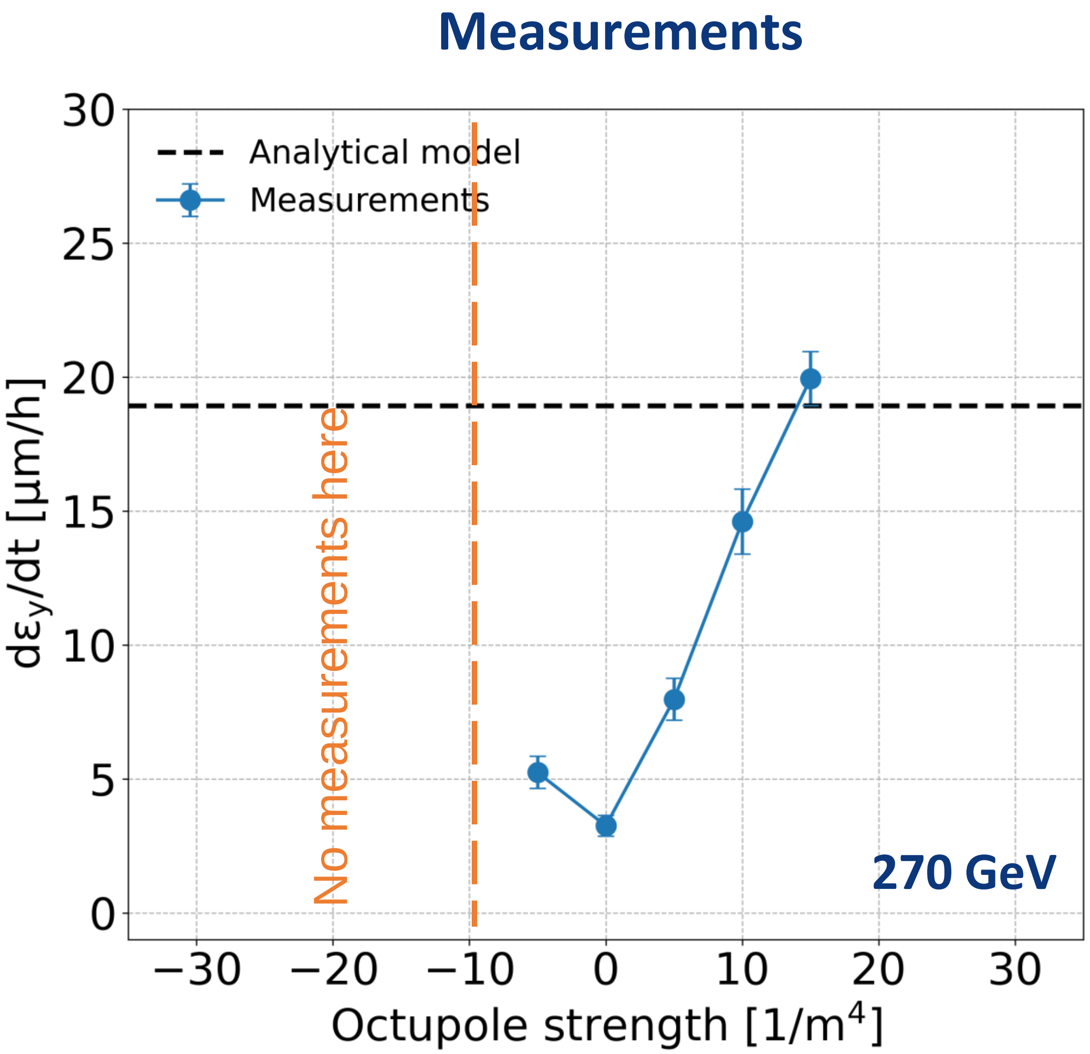
Measurements



- Very **limited machine time** → five data points.

Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.0

Experimental results 2022



- Very **limited machine time** → five data points.
- Vertical instability for negative octupole strengths ($Q'_{y,x} \sim 0$).

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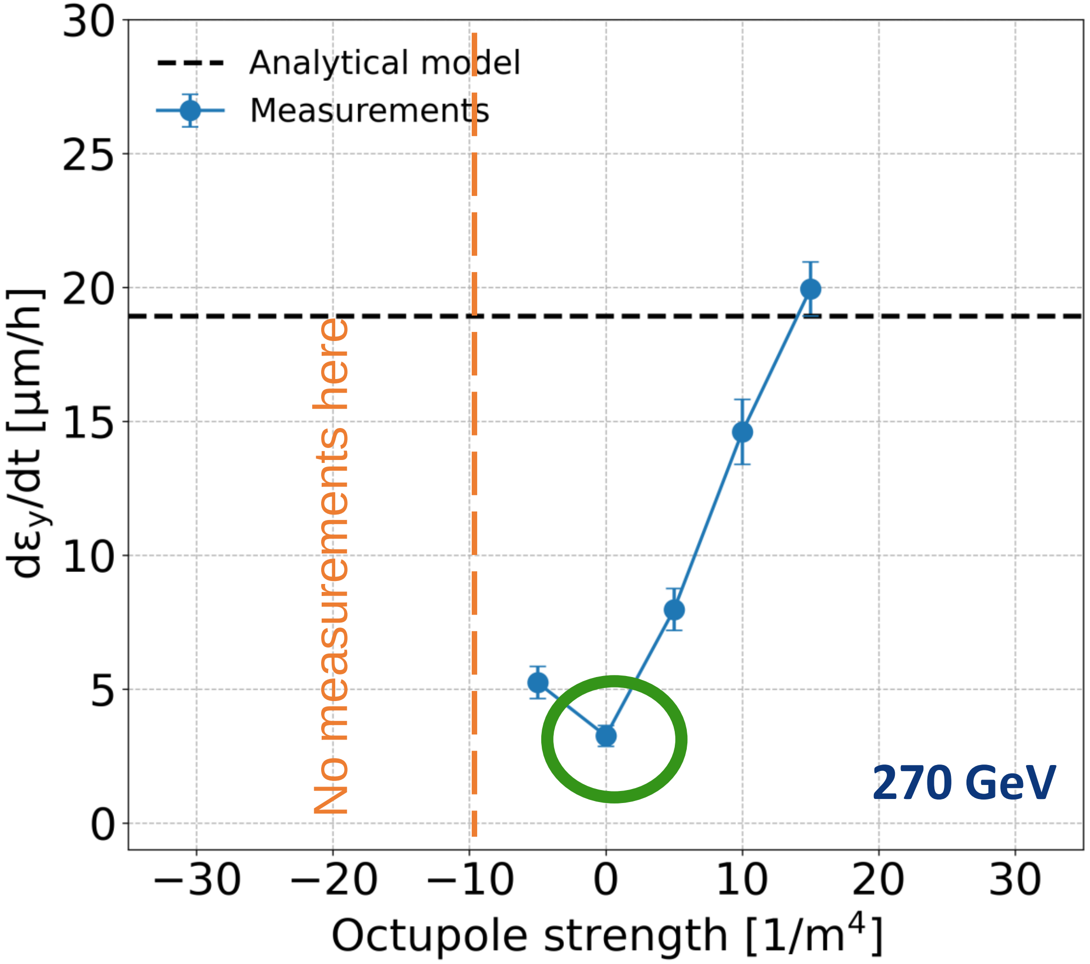
Experimental results 2022

Measurements

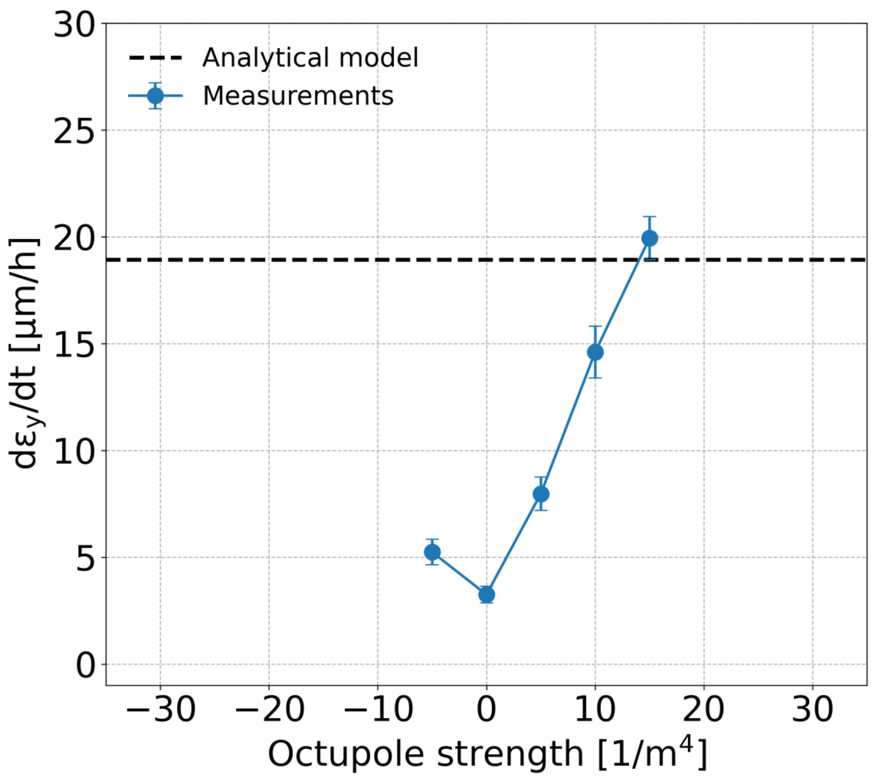


- Very **limited machine time** → five data points.
- Vertical instability for negative octupole strengths ($Q'_{y,x} \sim 0$).
- A suppression of a **factor 4-5** is observed with the residual SPS tune spread (without octupoles). Relatively good agreement with the expectations.

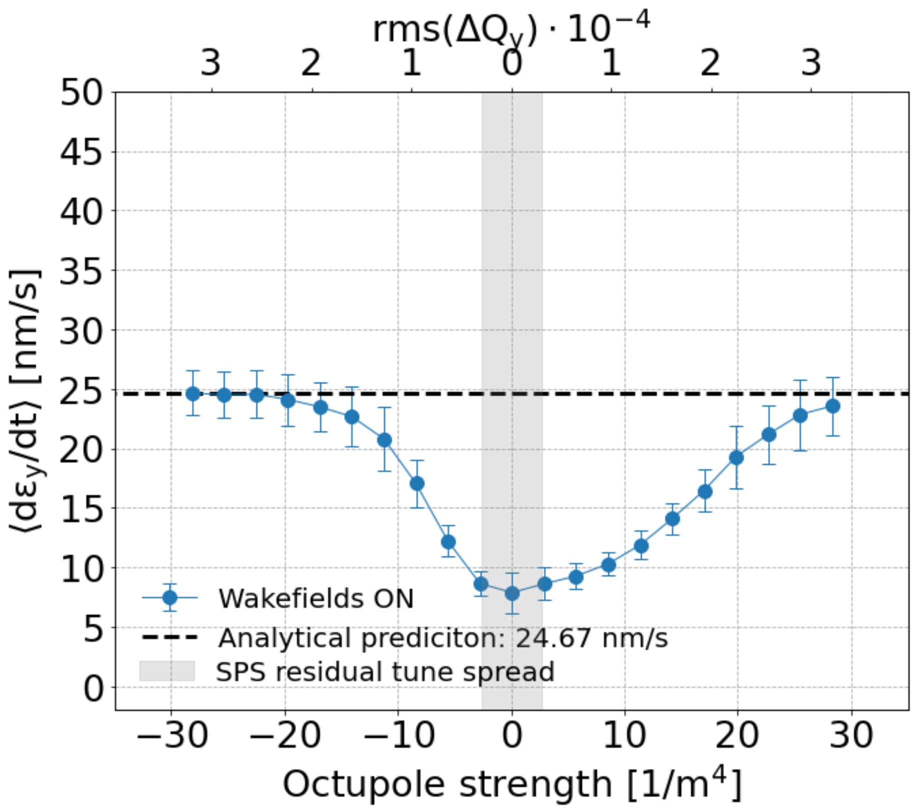
Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.0

Experimental results 2022

Measurements



Simulations



Promising results indicating **qualitative agreement** with the simulations **confirming the damping mechanism from impedance!** Further measurements will be needed to investigate the quantitative agreement.

Summary and future plans

Summary and future plans

- **First experimental demonstration** of **beam dynamic studies** with **Crab Cavities** and **proton beams.**
- **First investigation and experimental validation of the suppression mechanism** of the Crab Cavity RF phase noise induced emittance growth by **transverse impedance**.
- **Further measurements** are planned in the SPS **to refine the experimental observations** and obtain **quantitative agreement** between measurements and simulations.
- Understanding obtained from this studies is **important for the design of the crab cavity HL-LHC Low-Level RF system.**

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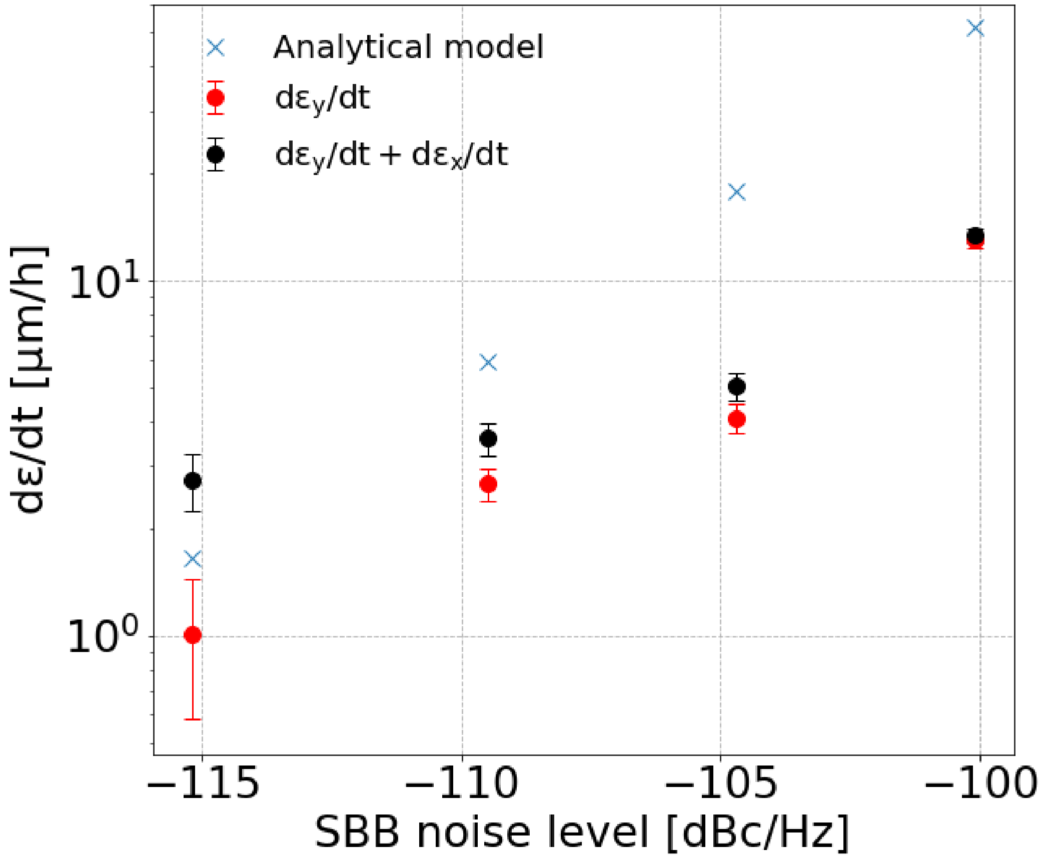
Thank you for your attention!

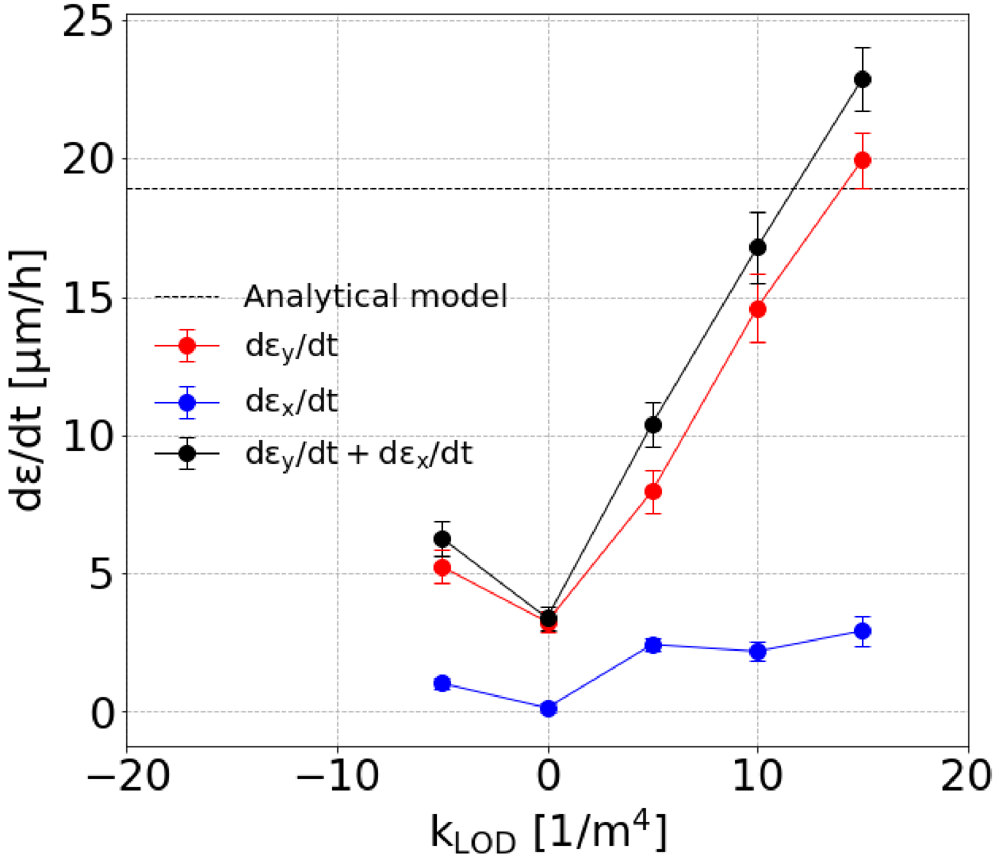
Supporting slides

SPS CC MD – 16 May 2022

Scaling of emittance growth with noise power



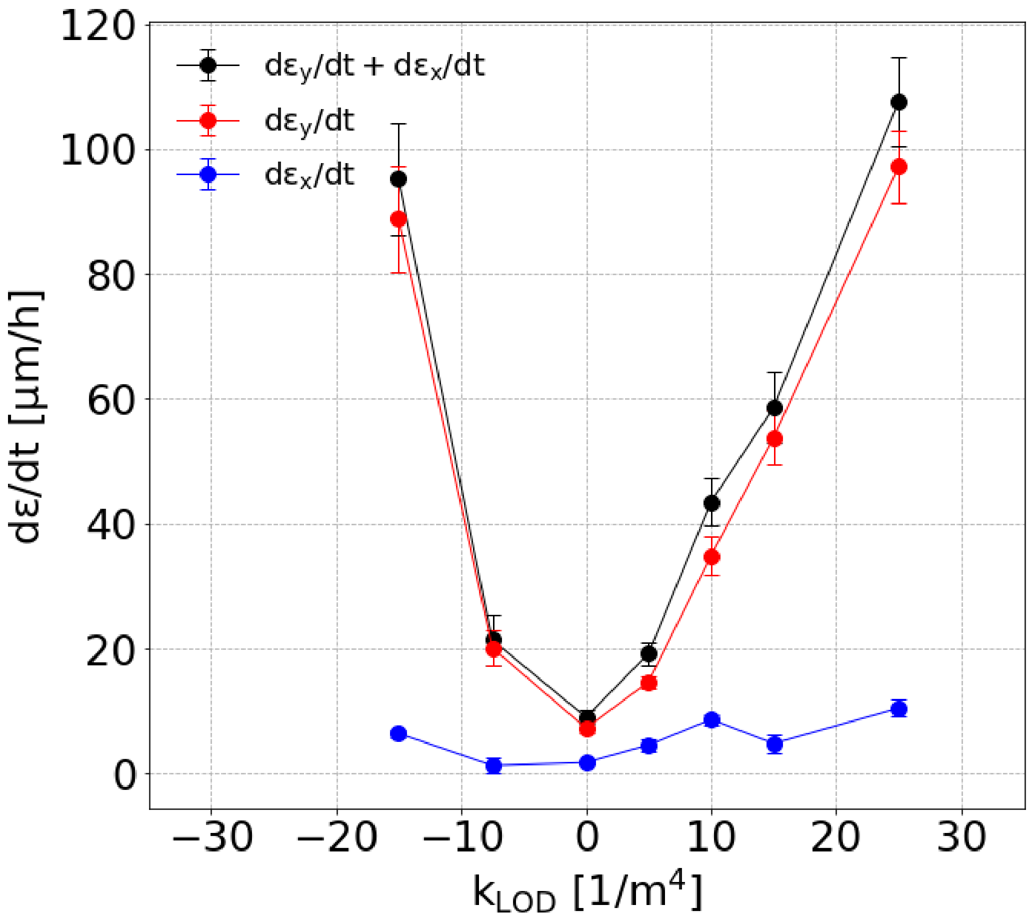
Octupole strength scan



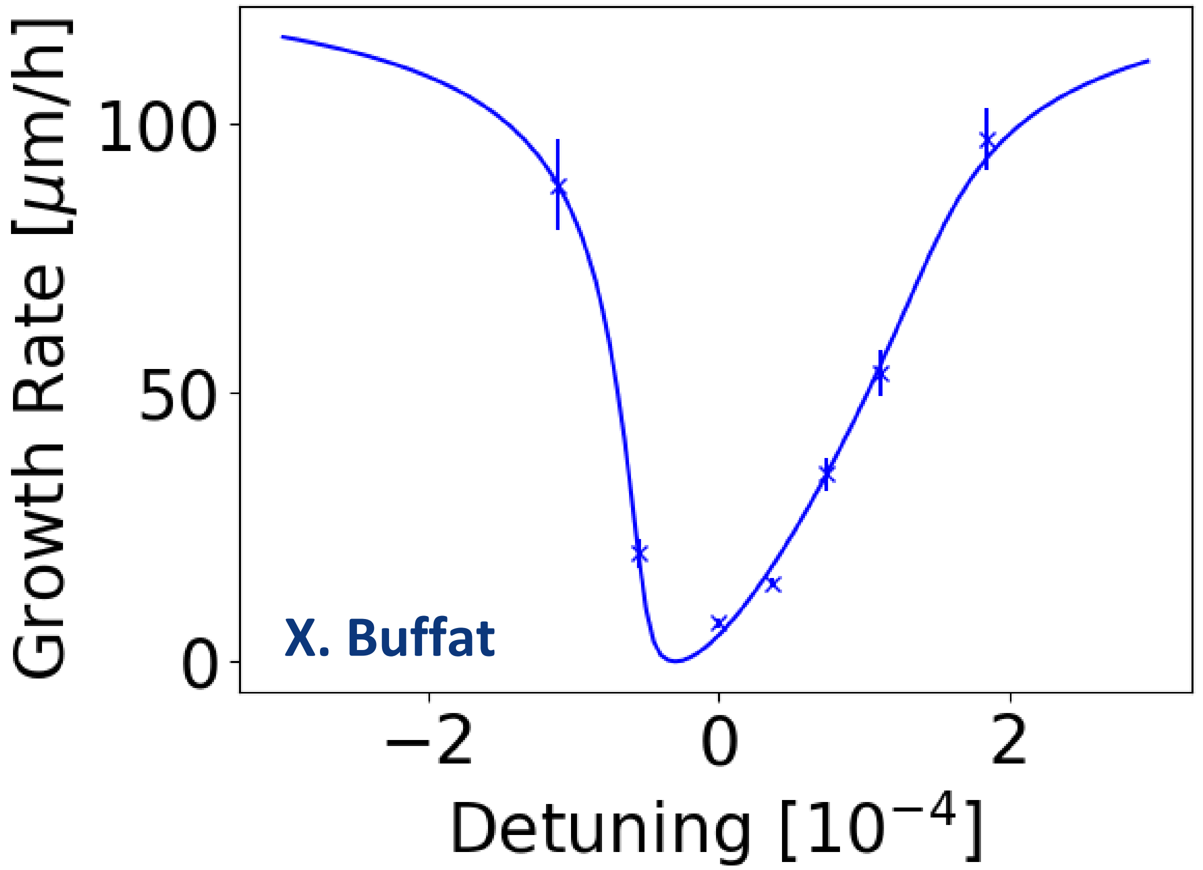
Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.0

MD with damper – 16 May 2022

Measurements



Analytical fit



Parameters: 270 GeV, 3e10 protons per bunch, Q'y~1.3