12th HL-LHC Collaboration Meeting, Uppsala, Sweden, 19-22 September 2022

Crab Cavity Emittance Growth MDs

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Work supported by the HL-LHC project and partially by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC-0019287

Introduction

RF noise in the Crab Cavity

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

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Very tight HL-LHC target values

↓

Maximum luminosity loss from the Crab Cavity RF noise emittance growth → **1%**

↓

Maximum Crab Cavity RF noise induced **emittance growth** → **2%/h**

↓

A good **understanding of the emittance growth** due to Crab Cavity RF noise is **essential**!

RF noise in the Crab Cavity

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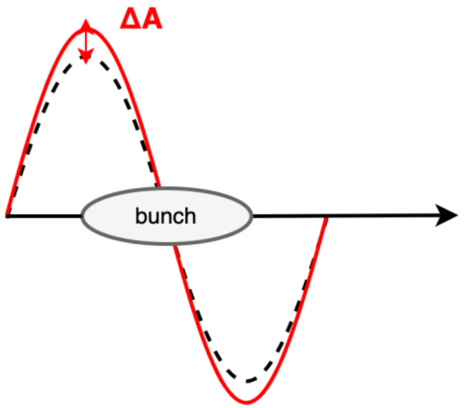
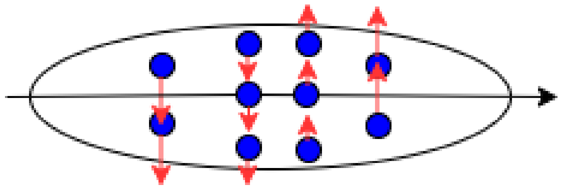
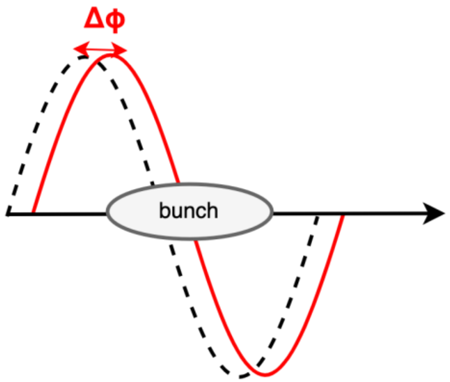
Amplitude noise

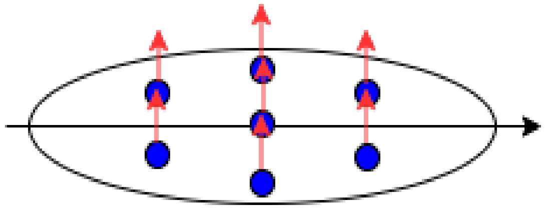




The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

Phase noise





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

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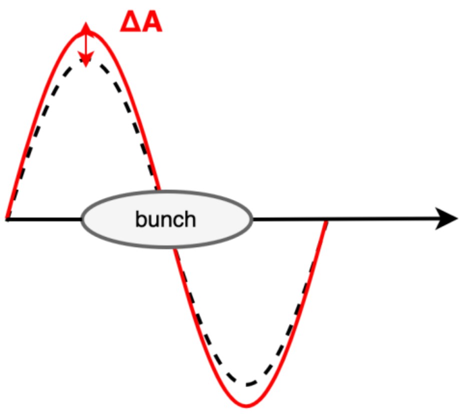
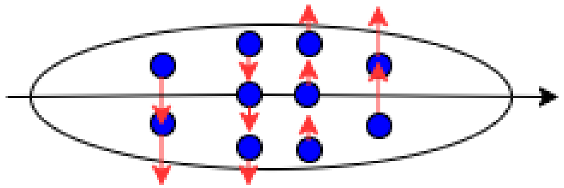
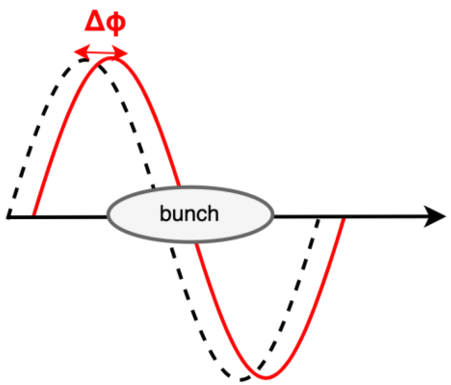


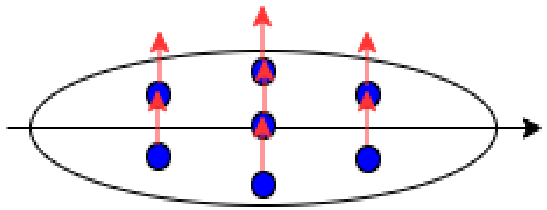


The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

These studies focus on phase noise.

Phase noise





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Theoretical formalism

- The **theoretical model**(*) was derived to **predict the emittance growth** from Crab Cavity noise.

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

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

P. Baudrenghien
CERN, 1211 Geneva, Switzerland

T. Mastoridis
California Polytechnic State University, San Luis Obispo, California 93407, USA
(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

- The model was validated through numerical simulations (HEADTAIL).
- **Benchmarking with experimental data is essential! → Tested in SPS in 2018.**

(*) 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)

Experiment 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.	**Different parameters** in SPS than in HL-LHC i.e. damper, beam-beam, energy, collisions, optics → The **results** need to be **scaled for the HL-LHC.**
4.	**Injected artificial noise** **much larger than targeted for HL-LHC** for better observables.

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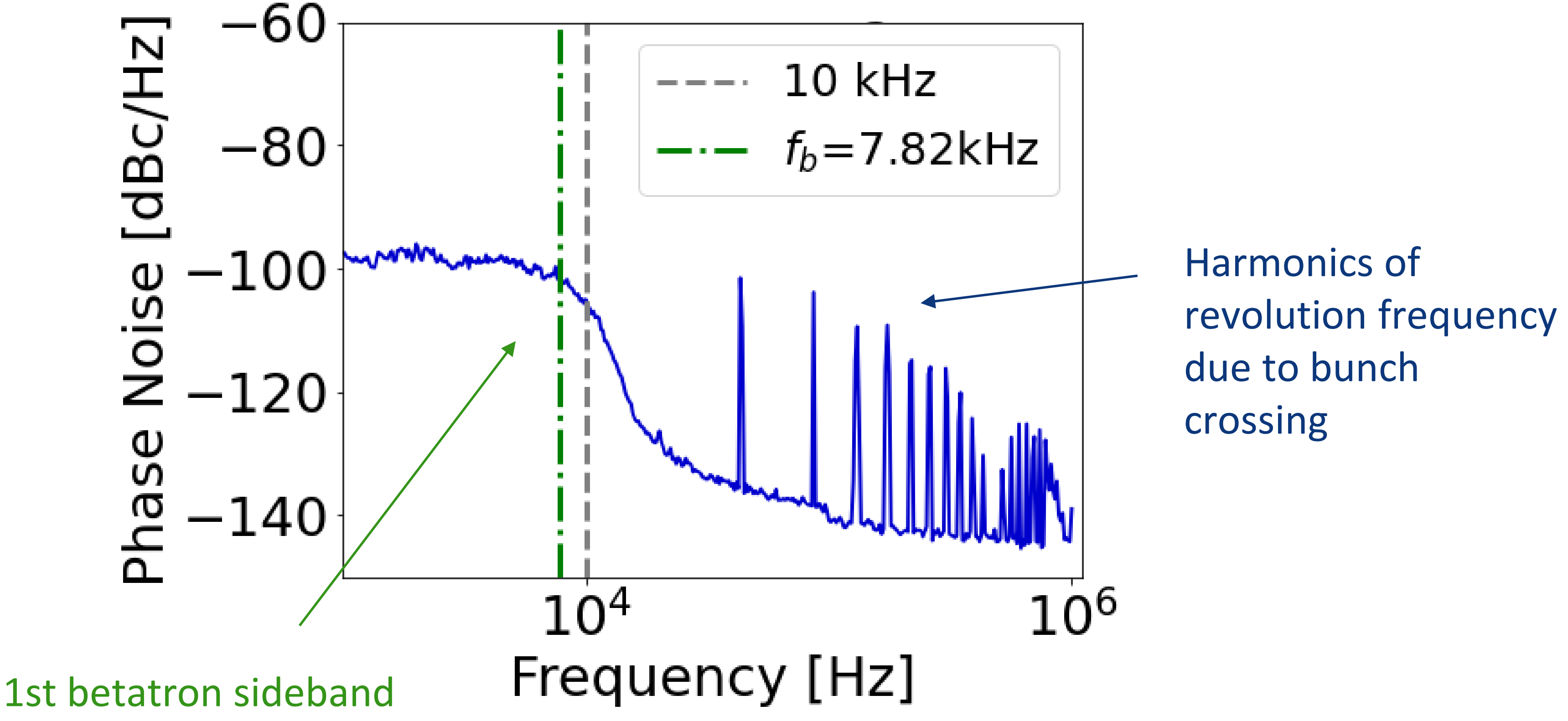
4.	**Injected artificial noise much larger than targeted for HL-LHC** for better observables.
5.	The **goal** is to **validate the predictions** from the **theoretical model. Scaling** will be needed for the **HL-LHC case**.

scaling

Experiment in 2018 – RF noise spectrum

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

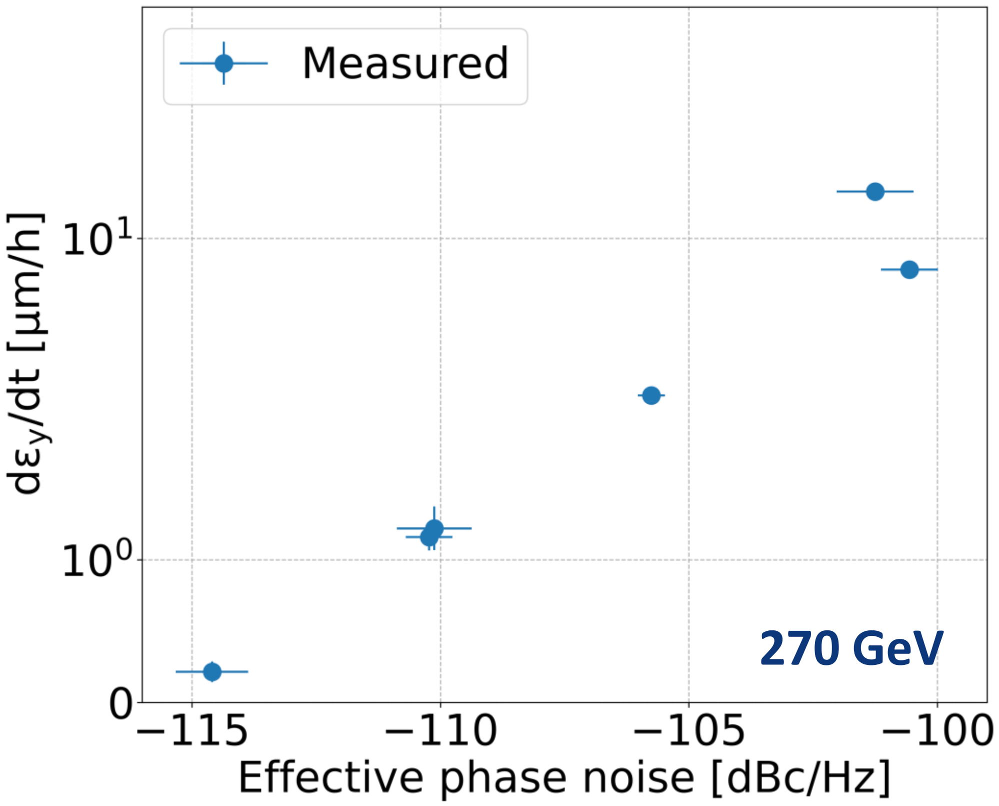
Example noise power measurement in 2018



Experiment in 2018 - Results

- Measurements for different (phase) noise levels.

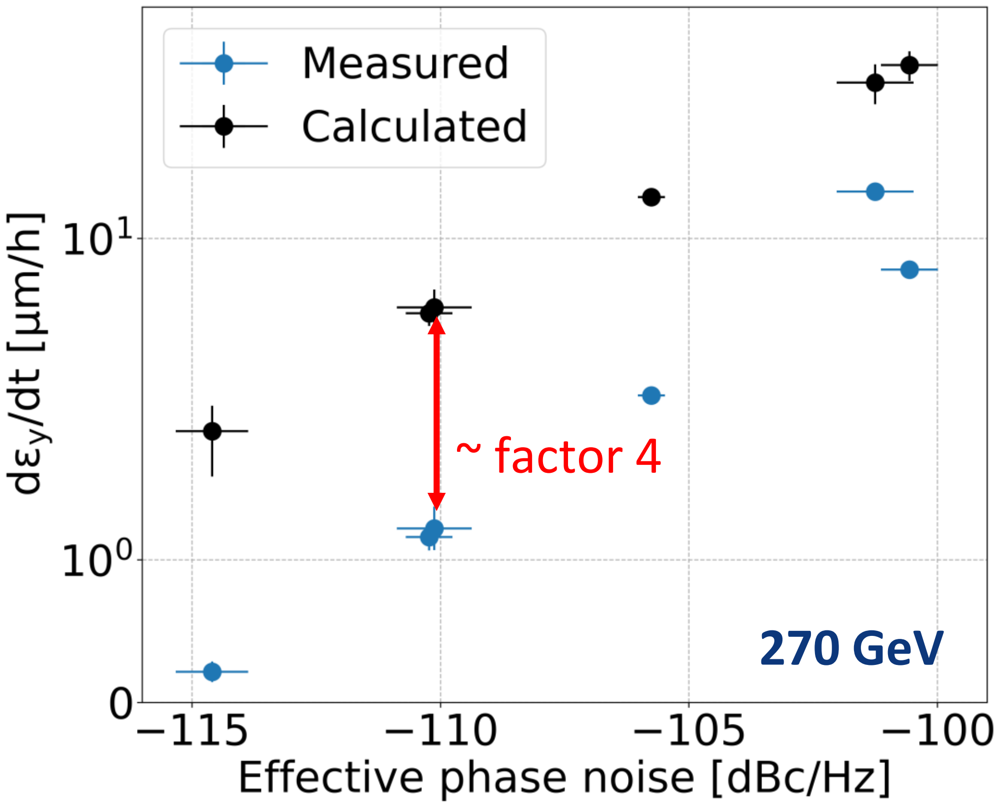
- Observed **scaling** of **measured** emittance growth with **noise power**.



Experiment 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** (*).

Triggered a series of studies!



(*) *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.

Big effort: 2018-2020

Investigating possible explanations for the discrepancy

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Big effort: 2018-2020

- Finally, simulations showed that the **transverse beam impedance** (not included in the theory (*)) has 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)

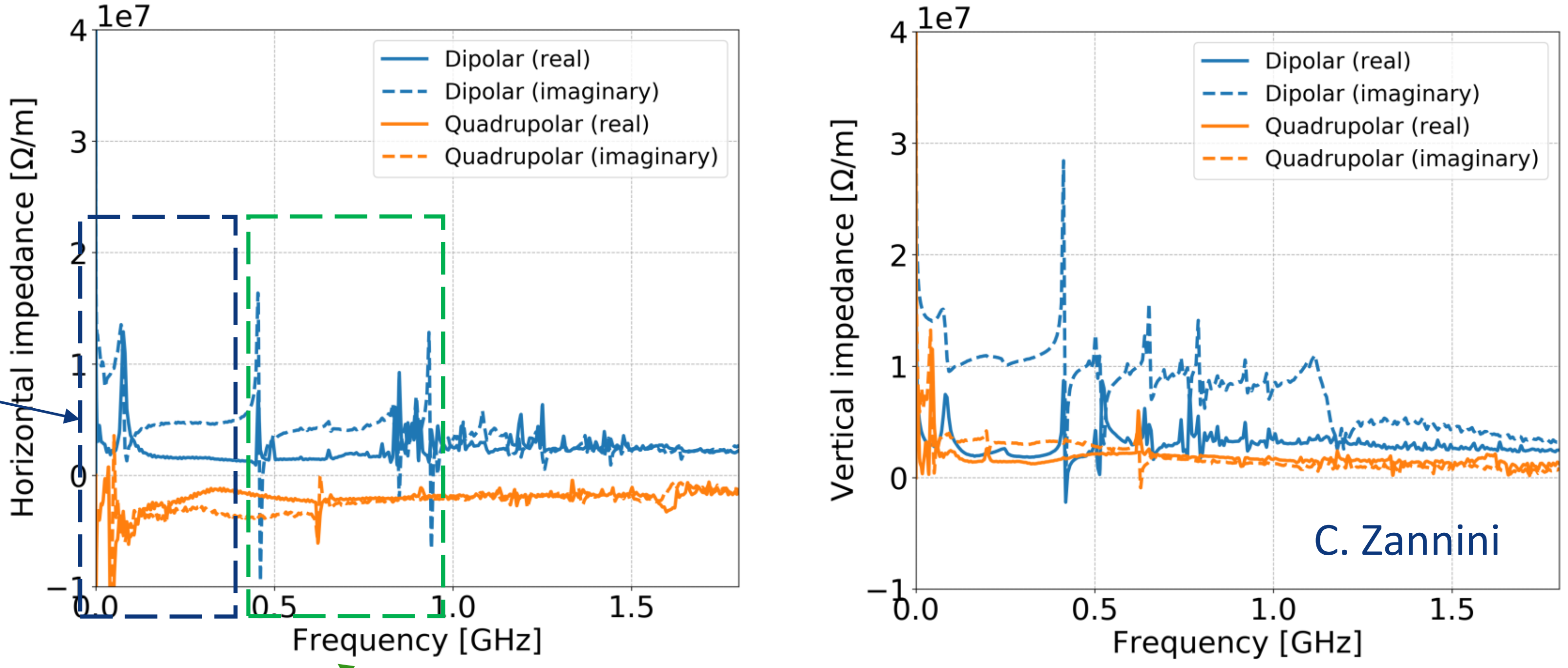
Emittance growth suppression from the beam transverse impedance

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, indirect space charge, etc.

SPS transverse impedance

Kickers, step transitions, wall



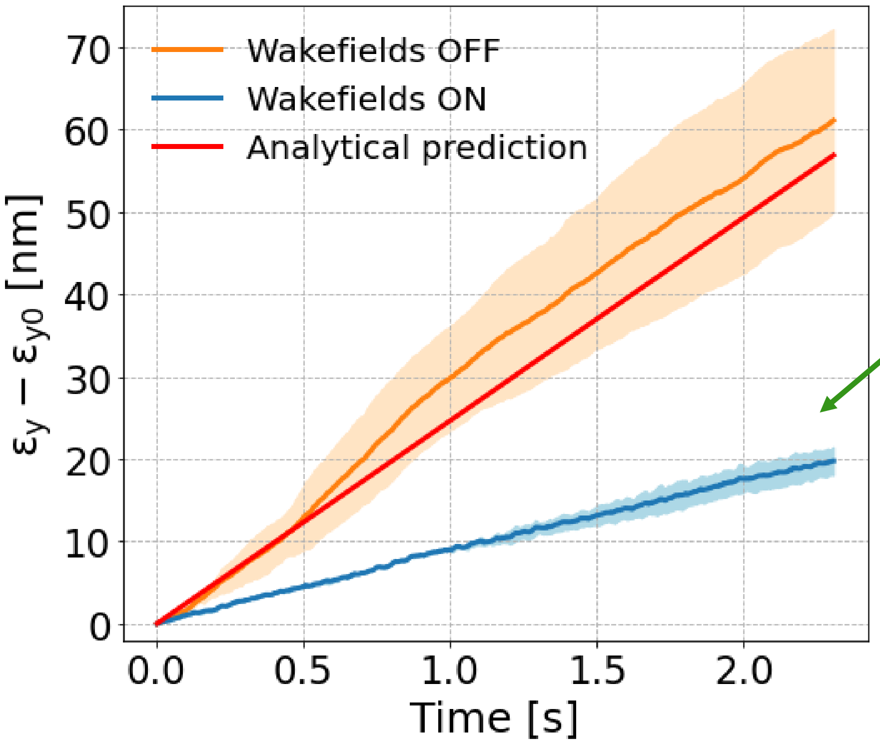
RF system and BPMs

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

First simulation results

Simulations with **PyHEADTAIL** and the **complete SPS transverse impedance model**.

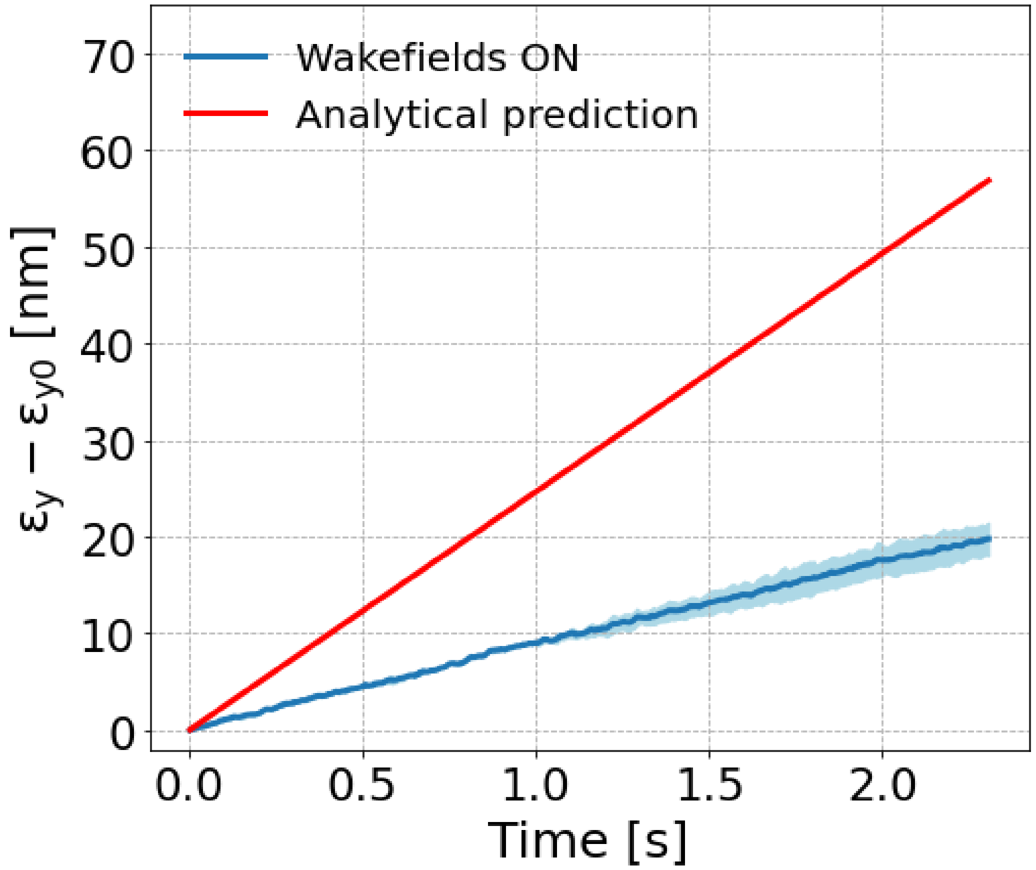
- ➢ Beam and machine conditions as in the 2018 SPS experiment.
- ➢ Crab Cavity RF **phase noise** for ~ 25 nm/s.
  - Even **stronger than in the SPS experiments**, for observables in the simulation time → **Scaling**.

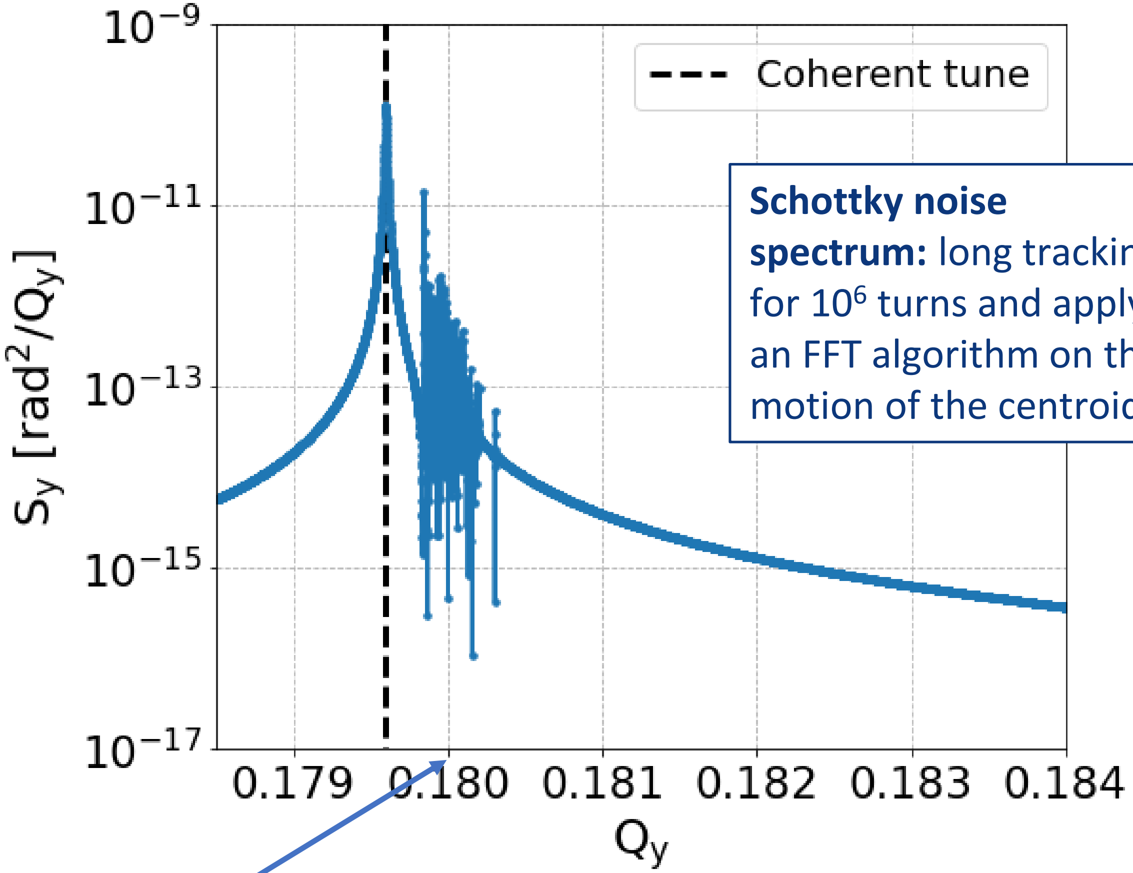


Clear suppression of the **phase noise** induced **emittance growth** in the presence of **wakefields**.

Suppression mechanism - I

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





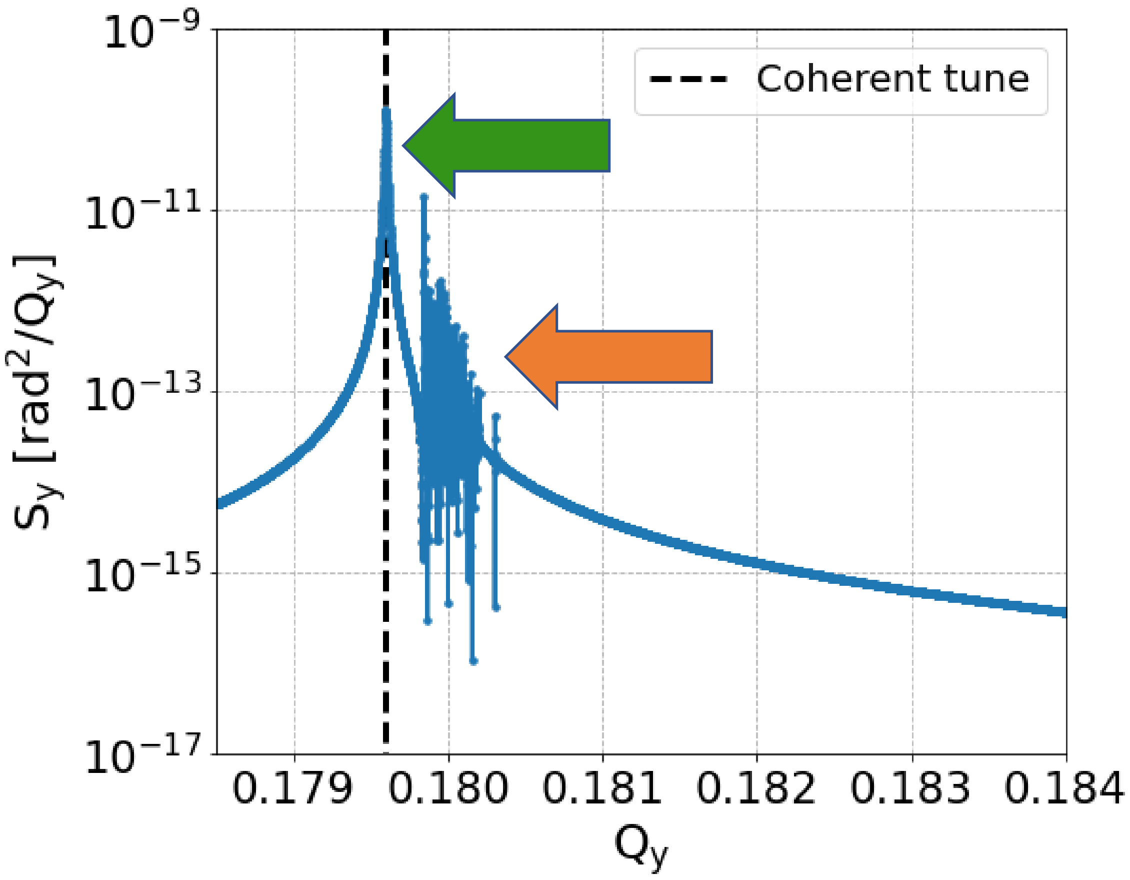
Schottky noise spectrum: long tracking for 10^6 turns and apply an FFT algorithm on the motion of the centroid.

Nominal SPS tune 0.18

Suppression mechanism - II

The **transverse impedance separates the coherent tune from the incoherent spectrum** 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

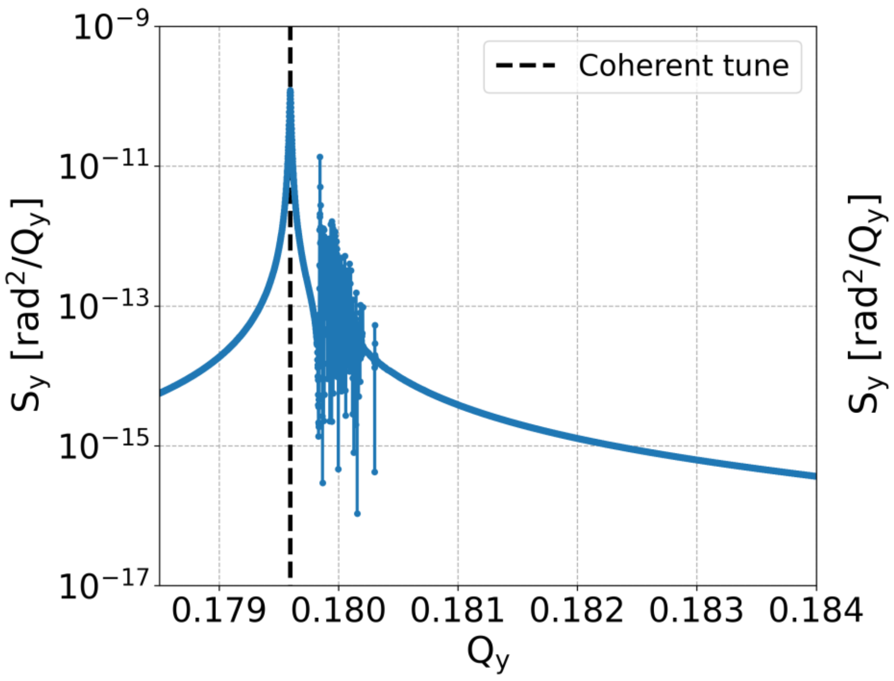
- In the context of the beam-beam modes it has been observed that the **efficiency of a transverse feedback** system at suppressing emittance growth depends on the **overlap between the coherent mode and the incoherent spectrum** in **past** theoretically[(*1)] and in simulations[(*2)].

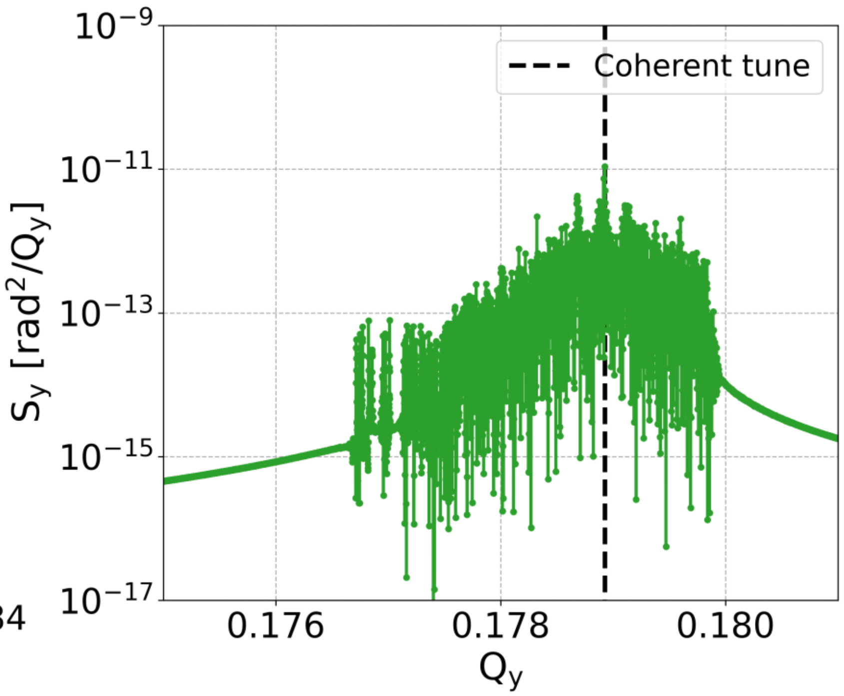
- Recently, this approach was adapted for configurations featuring linear detuning and a complex tune shift from a collective force, supporting the simulation results shown here.
    - **X. Buffat, "Suppression of Emittance Growth by a Collective Force: Van Kampen Approach", IPAC'22 .**

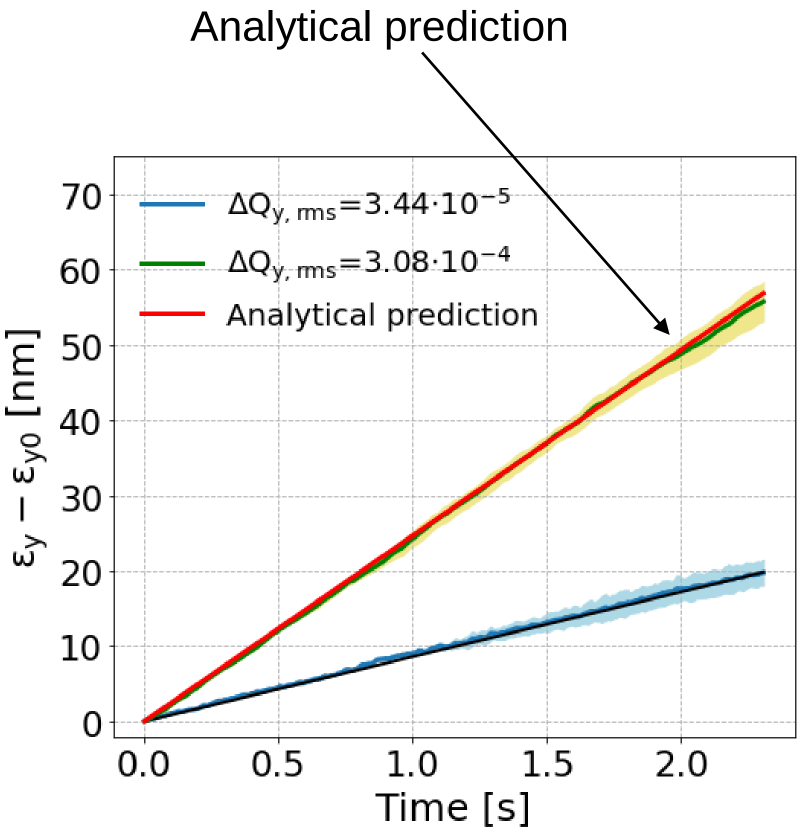
(*1) *Y. Alexahin, "On the Landau Damping and decoherence of transverse dipole oscillations in colliding beams"*
(*2) *X. Buffat, "Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider", Phys. Rev. Accel. Beams 23, 021002 (2020)*

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).



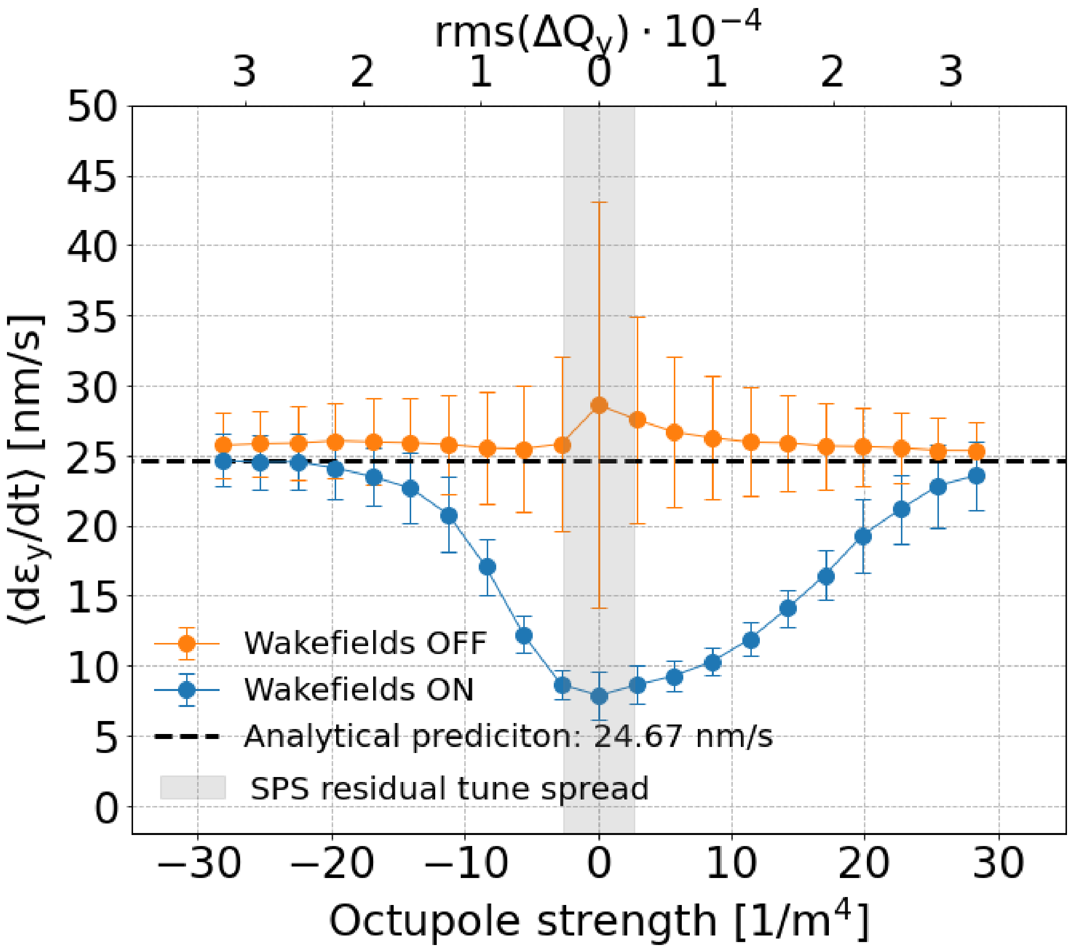




Parameters: 270 GeV, 3e10 protons per bunch, Q’y=0.5

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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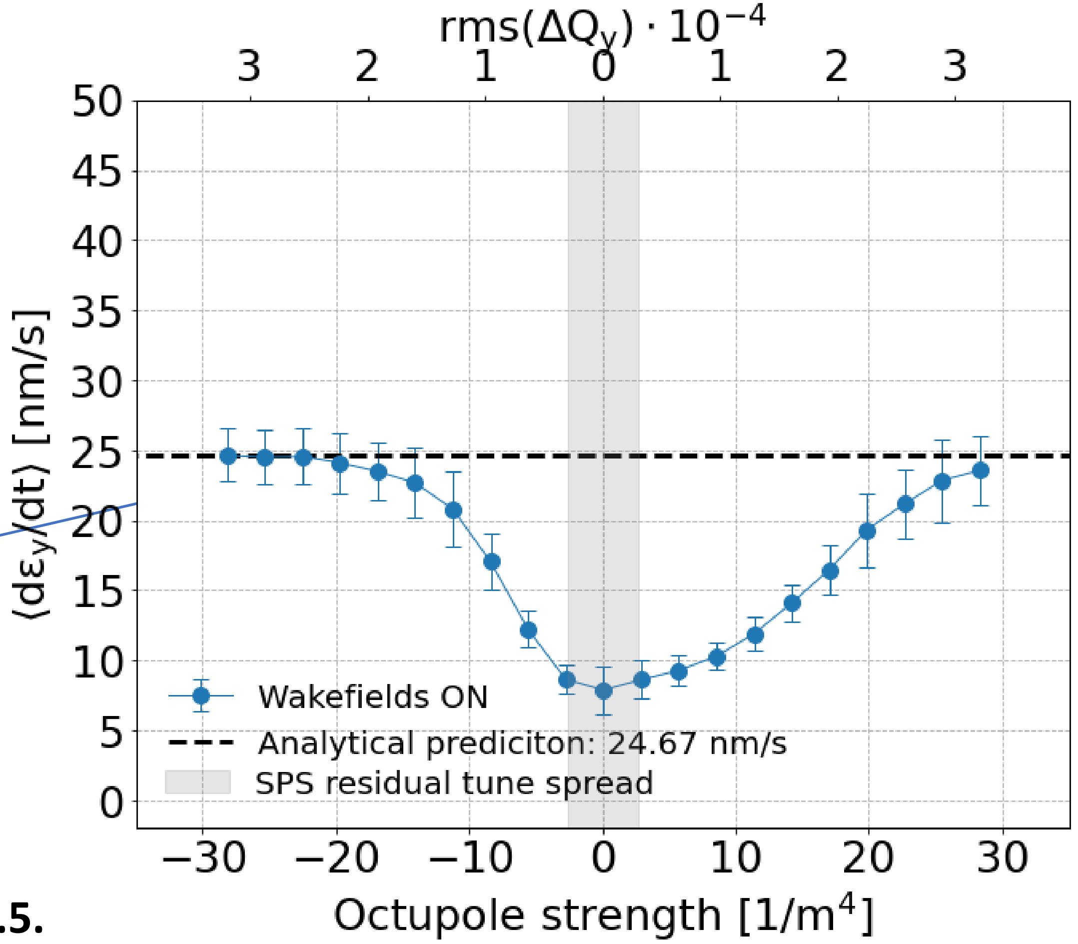
This **behavior** was **tested experimentally** in the **SPS in 2022.**

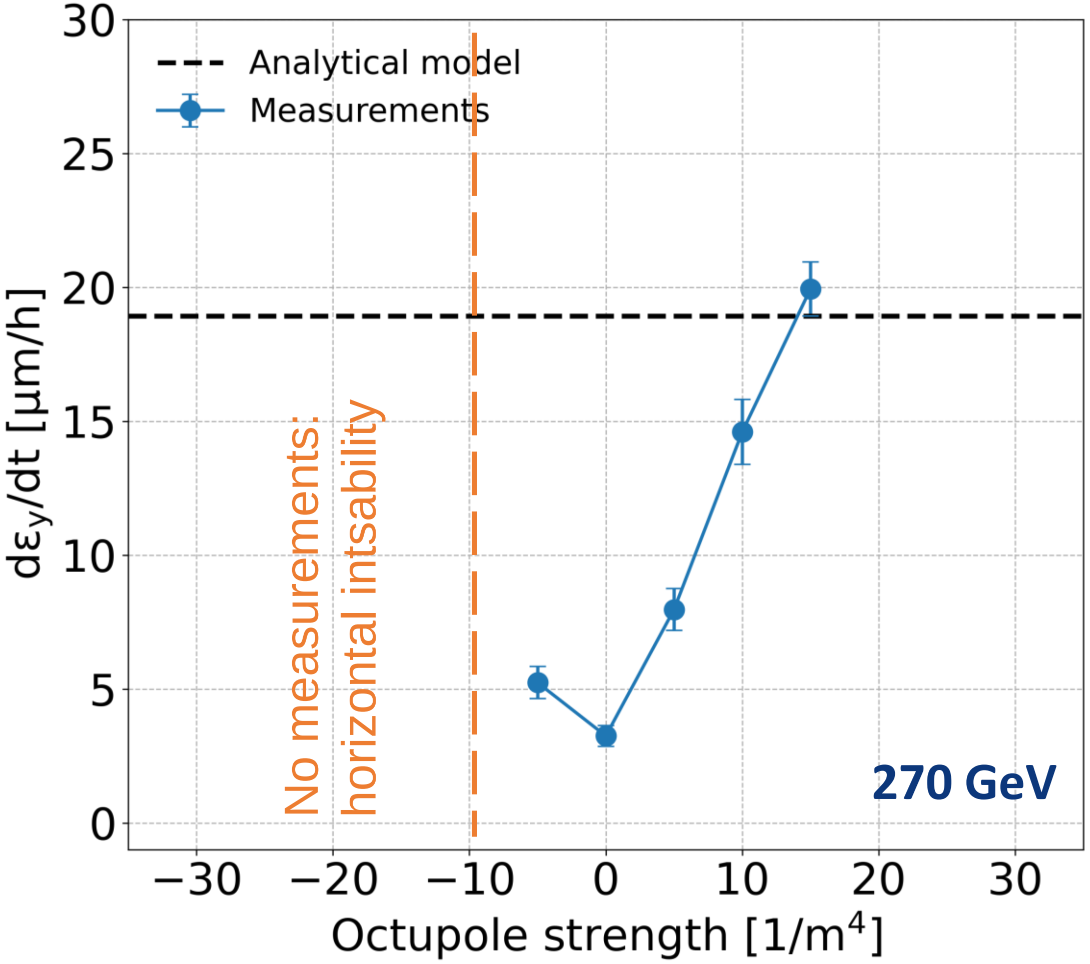
- **Use of SPS octupole families.**
- **Goal: Reproduce the behavior only (due to scaling).**
- **For the residual SPS tune spread: suppression of a factor ~ 3.5.**



SPS measurements in 2022

Experimental results 2022 - I

Measurements



- ➢ Very limited machine time: Full scan not possible.
- ➢ **Clear dependence of the measured emittance growth on the octupole strength.**
  - ➢ Goal of the experiment achieved.

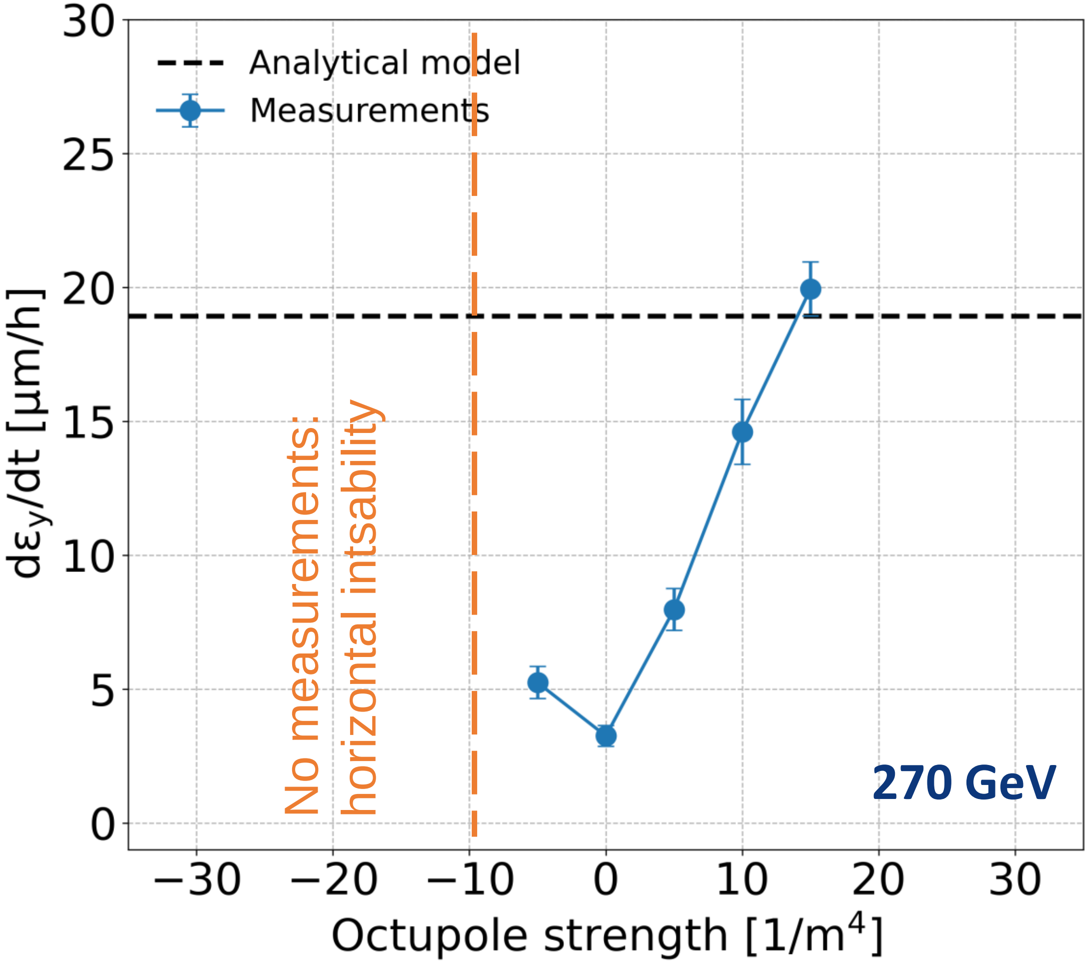
Confirmation of damping mechanism from the impedance!

- ➢ Without octupoles → **suppression factor ~4-5**. **Similar to what is expected from impedance.**

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

Experimental results 2022 - II

Measurements



Very complicated studies

1.	**Limited machine time**

- 5 points are great success

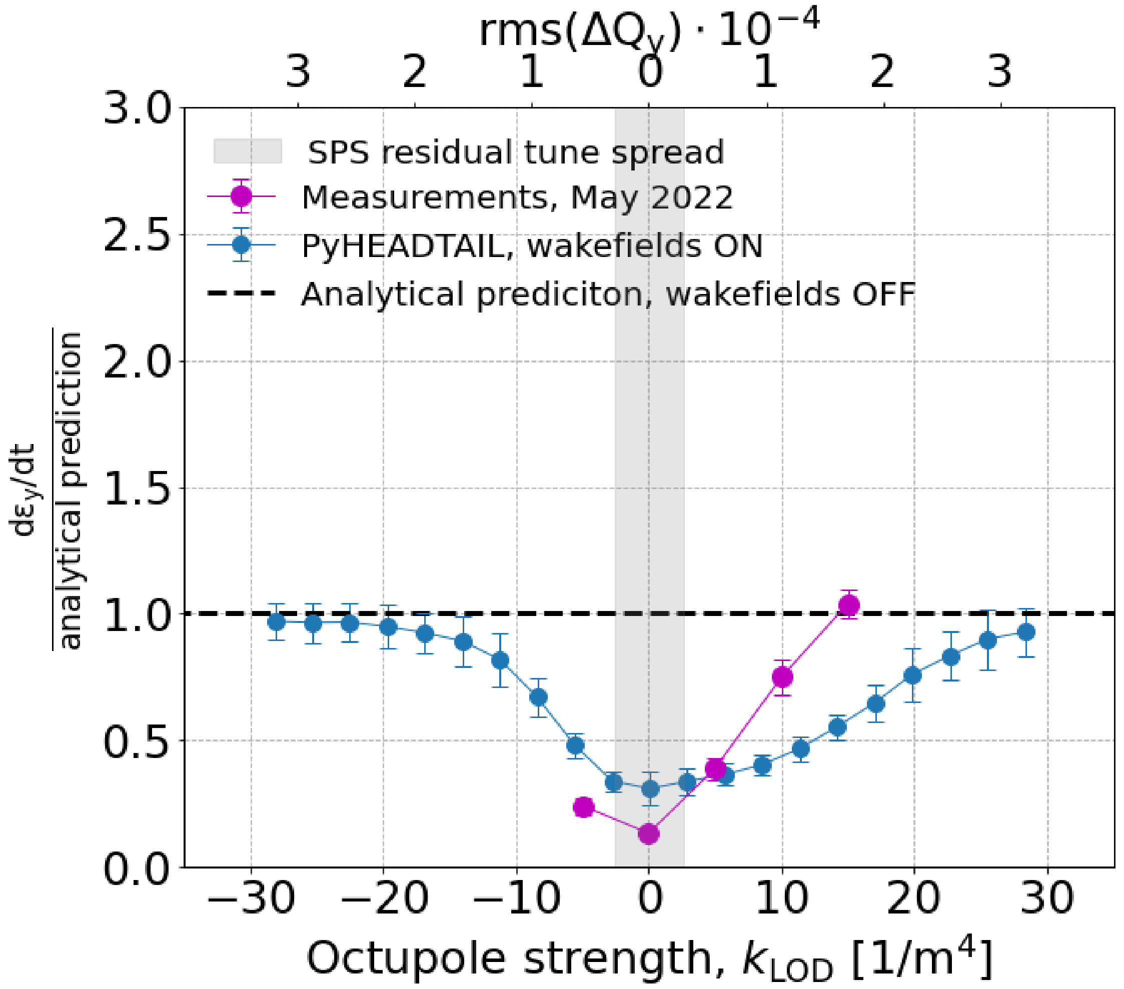
2.	**SPS not in the usual operation mode**

- Crab Cavity operation
- Noise in the Crab Cavity RF
- Stored beam
- Octupoles operation out of the usual regime
- Clear dependence on the octupoles strength is great success

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

Experimental results 2022 - III

Simulations vs measurements



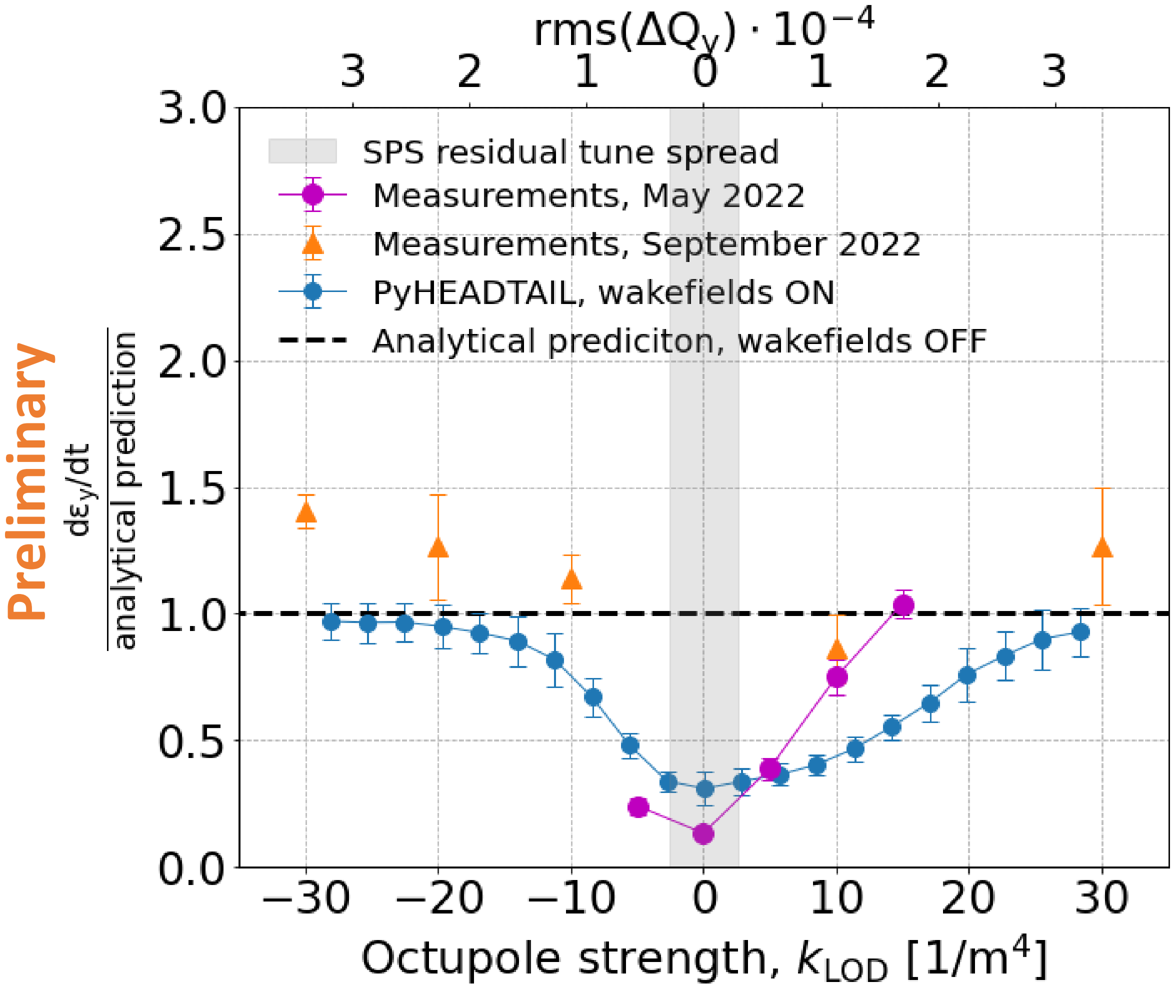
- **Qualitative agreement** with the simulations **confirming the damping mechanism from impedance!**
- Further studies, simulations and measurements are needed to investigate the quantitative agreement.
- Possible factors:

  - Contribution from space charge

  - Significantly larger final emittances in the experiment → larger tune spread

Experimental results 2022 - IV

Simulations vs measurements



- Additional measurements took place last week:

  - **Preliminary analysis:** Measured emittance growths appear slightly larger than expected.

  - The larger growth rates could be explained by e.g. an uncertainty of 0.1 MV in the V_{CC} from the beam-based measurement.

  - Detailed analysis is ongoing.

Summary and future plans

Summary and future plans

- **First experimental 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**.
- **Crucial step forward** on the understanding of the Crab Cavity noise effects which impact the HL-LHC performance:

  - The reason for the discrepancy between measurements and predictions in 2018 is now understood.

- **Additional measurements** took place in the SPS last weak **to refine the experimental observations from May 2022.** Analysis is ongoing to conclude on the **quantitative agreement** between measurements, simulations and theory.
- **Implications for the HL-LHC:**

  - For the HL-LHC operational configuration the coherent modes lie inside the incoherent spectrum. The phenomenon of the suppression will not be observed.

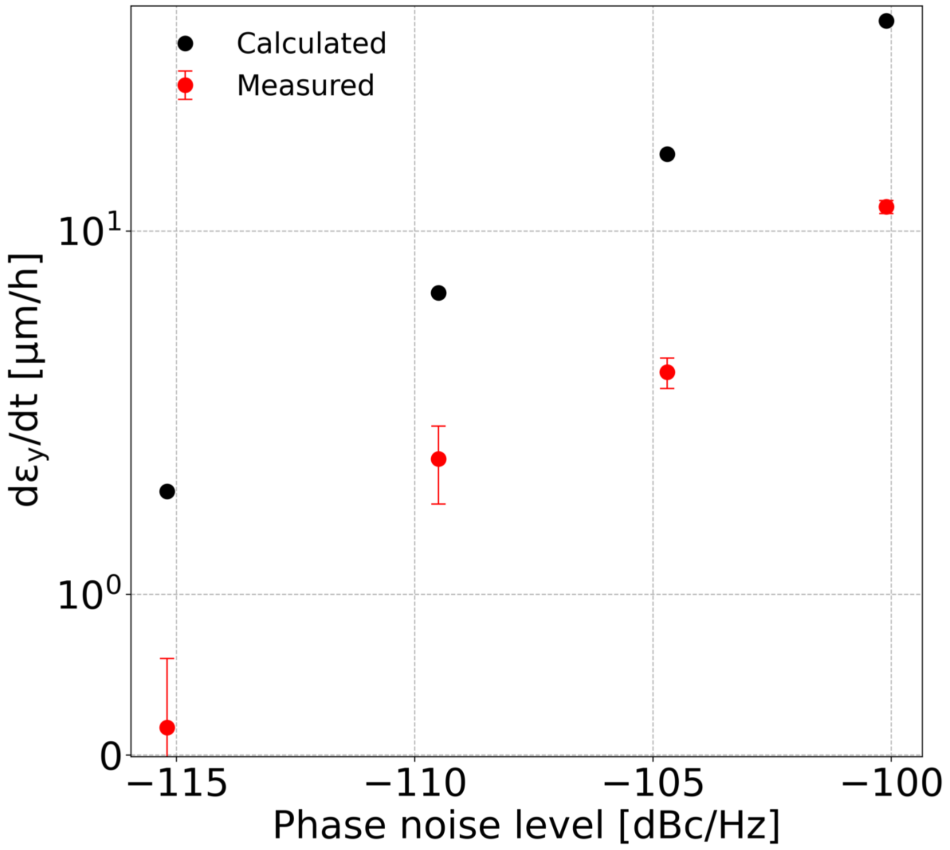
  - The need for the effective feedback on the Crab Cavities is confirmed.

Thank you for your attention!
Questions?

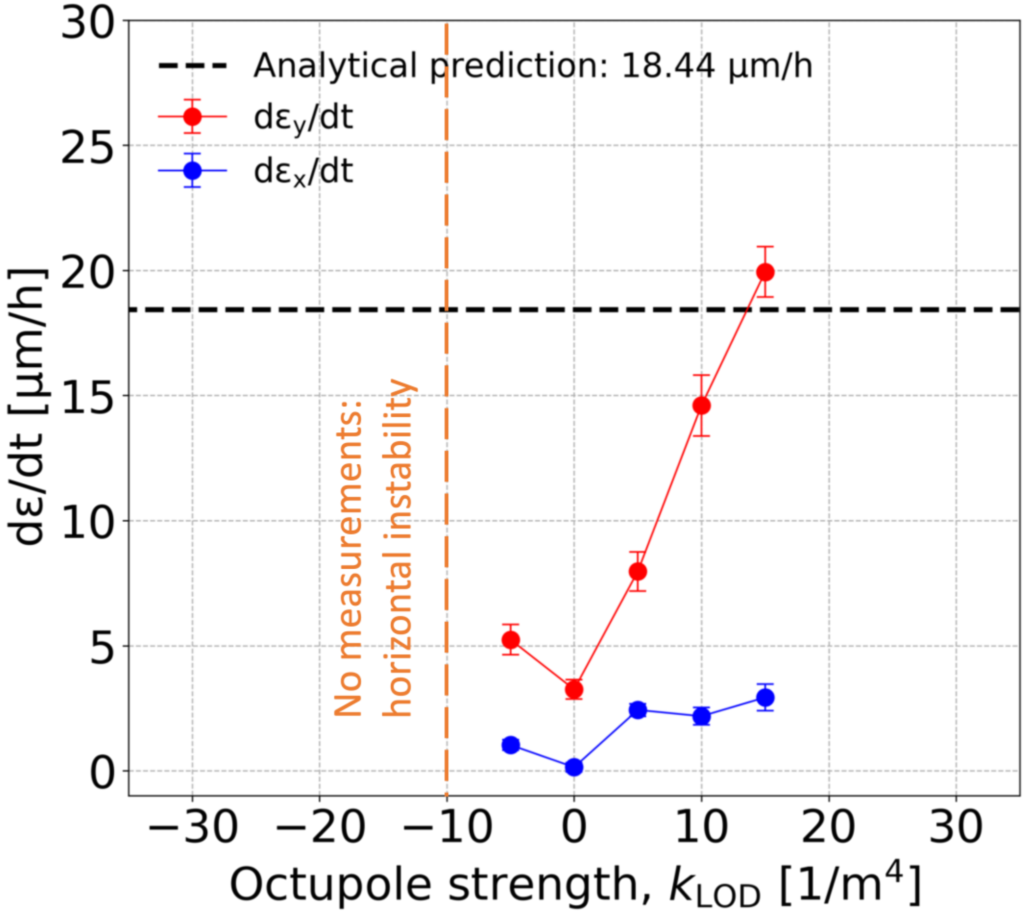
Supporting slides

SPS Crab Cavity MD 16/05/22 - extended

Scaling of emittance growth with noise power



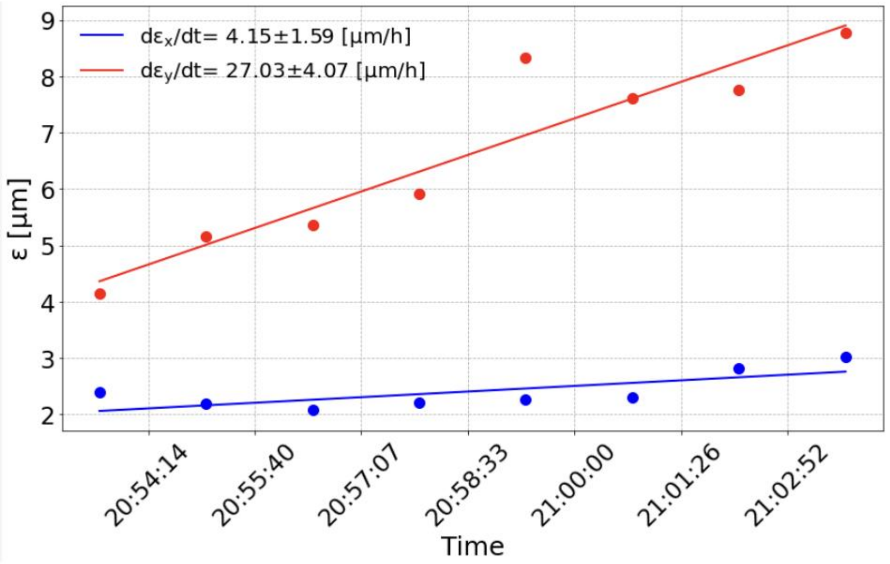
Octupole strength scan



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

SPS Crab Cavity MD 12/09/22

Amplitude noise
PRELIMINARY



- Phase noise: -122 dbc/Hz → expected emittance growth 0.35 μm/h
- **Amplitude noise: -102 dbc/Hz →** expected emittance growth 29.6 μm/h

Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.65