BE seminar – 28 April 2023

Studies of emittance growth due to noise in the Crab Cavity RF systems for the HL-LHC

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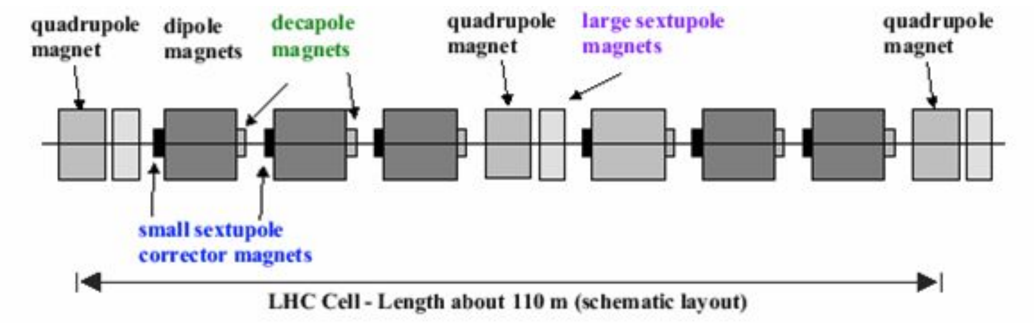
Work supported by the HL-LHC project and partially by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC-0019287

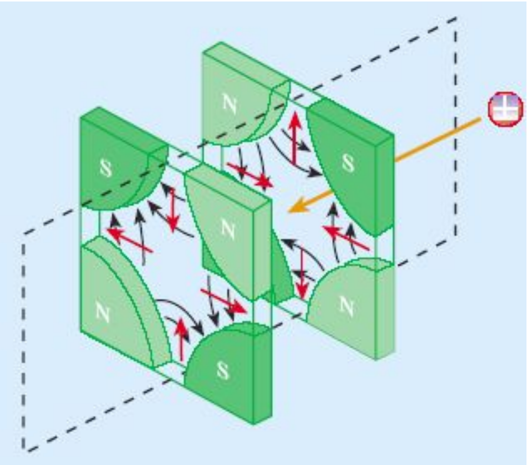
Basic concepts of accelerator beam dynamics

Beam dynamics

➢ Accelerators use **EM fields** to accelerate and steer charged particles
  ○ Magnetic fields for guiding and focusing
  ○ Electric fields for acceleration

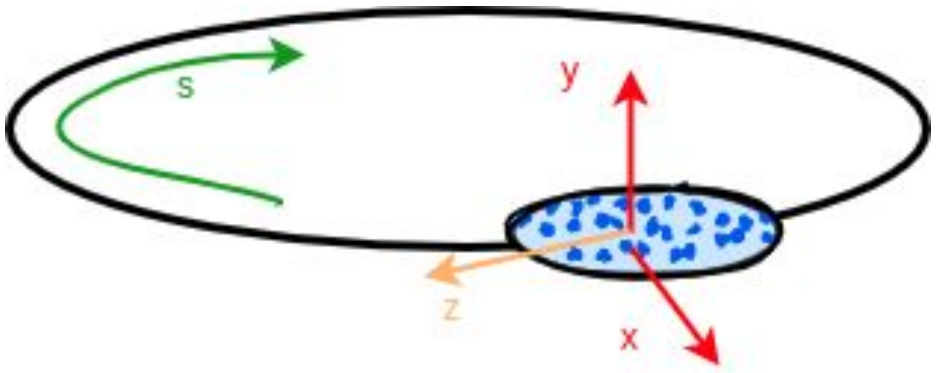


➢ **Beam dynamics** describes the movement of the beam particles through the EM fields of an accelerator



Phase space coordinates

- At every point s along the accelerator each particle can be described with the following 6D phase space coordinates:



$$\left[\begin{pmatrix} x \\ p_x \end{pmatrix}, \begin{pmatrix} y \\ p_y \end{pmatrix}, \begin{pmatrix} z \\ \delta \end{pmatrix}\right]$$

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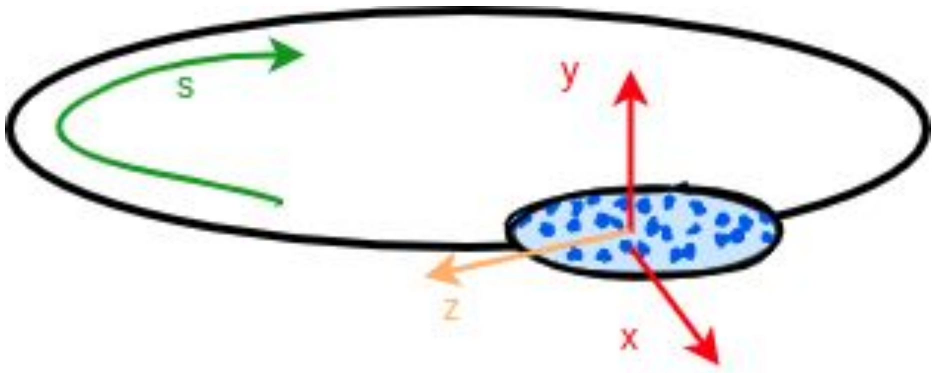
$$\left[\begin{pmatrix} x \\ p_x \end{pmatrix}, \begin{pmatrix} y \\ p_y \end{pmatrix}, \begin{pmatrix} z \\ \delta \end{pmatrix}\right]$$

Transverse plane

Longitudinal plane (along the particle's trajectory)



Beam emittance

- The **distribution of all the particles** in phase space can be described by the Sigma matrix:

$$\Sigma = \begin{pmatrix} \langle u^2 \rangle & \langle up_u \rangle \\ \langle up_u \rangle & \langle p_u^2 \rangle \end{pmatrix}$$

- The square root of the determinant of Sigma matrix defines the emittance:

$$\epsilon_{u,RMS} = \sqrt{det(\Sigma_{u,RMS})} = \sqrt{\langle u^2 \rangle \langle p_u^2 \rangle - \langle up_u \rangle^2}$$

- It is related to the **area of the beam** in phase space

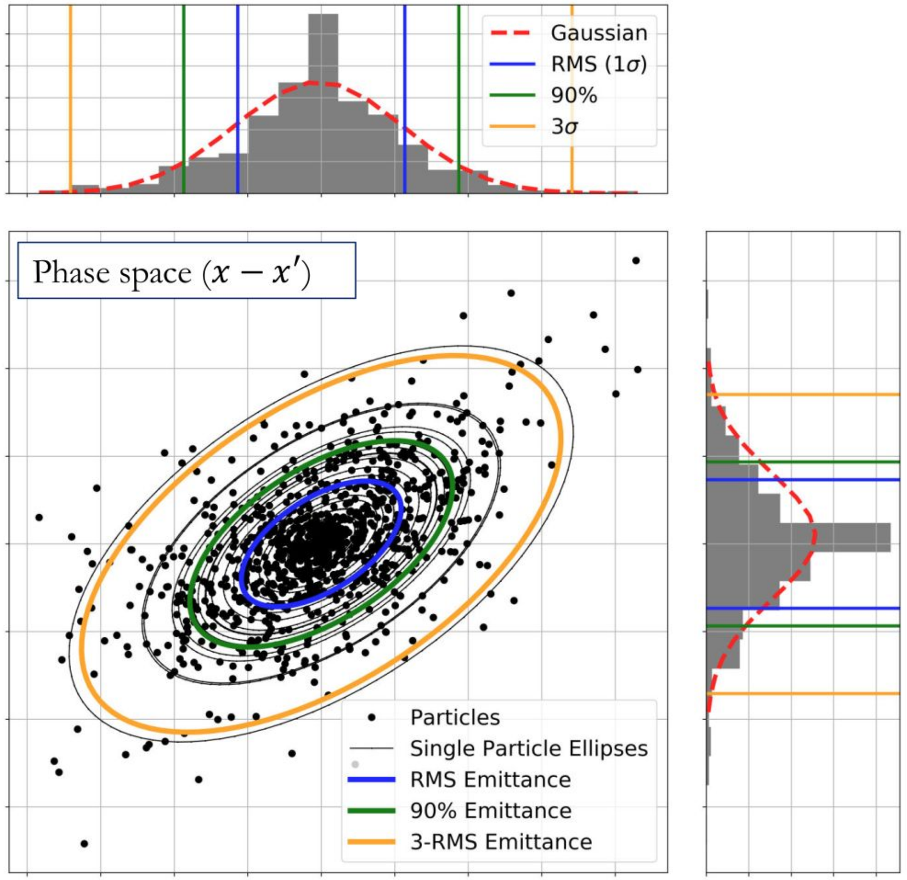


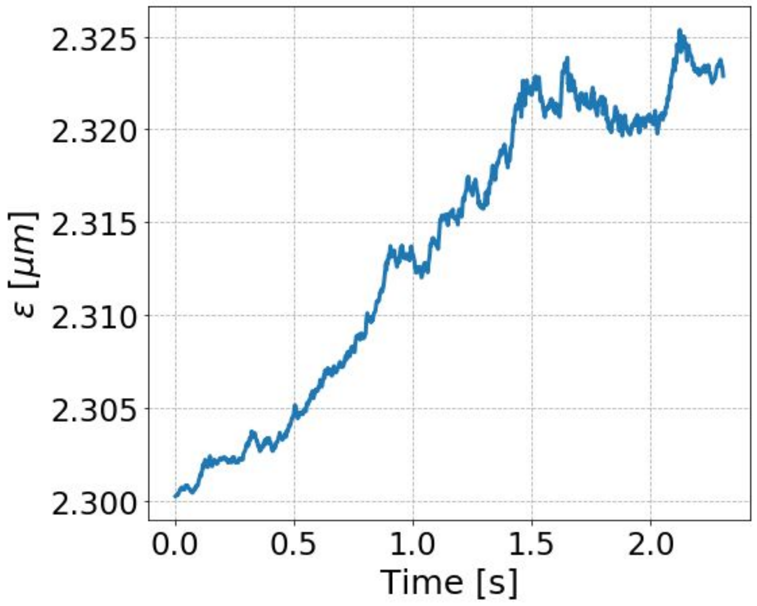
Figure source T. Prebibaj

Noise and emittance

- **Noise**: Random fluctuations in the electric and magnetic fields. Example sources:
  - Ripples in power converters
  - Ground motion
  - Crab Cavities

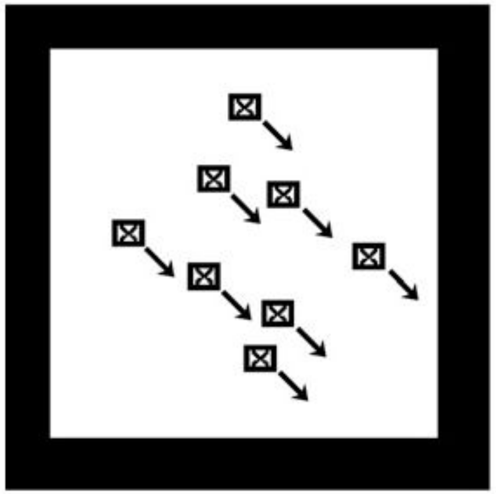
- Noise can affect the beam dynamics, e.g. can lead to **emittance growth**
  - Emittance growth can **limit the performance of accelerators**, therefore we try to characterize the impact of noise on emittance growth and control it

Example of emittance growth due to noise

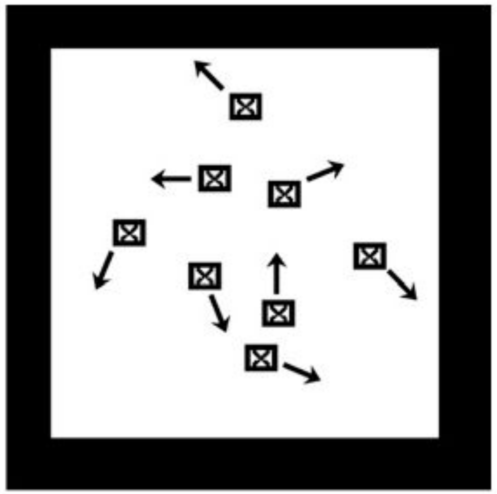


Coherent vs incoherent motion

➢ When we talk about multi-particle systems we differentiate between *coherent* and *incoherent particle motion*
  - **Coherent motion:** Macroscopic view ⟶ we look at the beam as a whole (we refer to its center of mass)
  - **Incoherent motion:** Microscopic view ⟶ we look at each particle individually



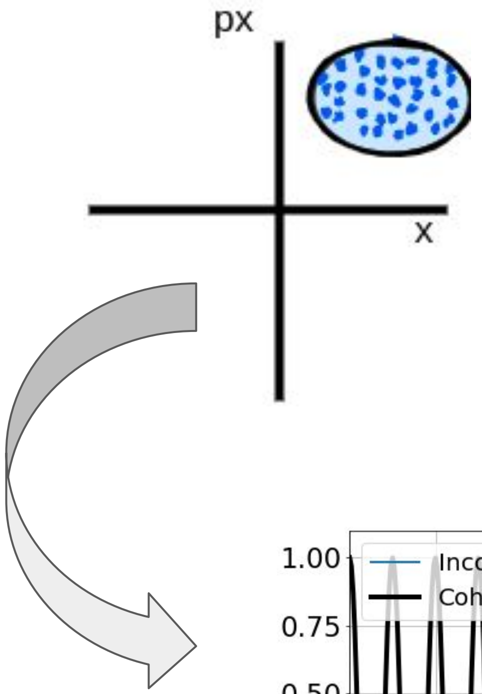
Coherent motion

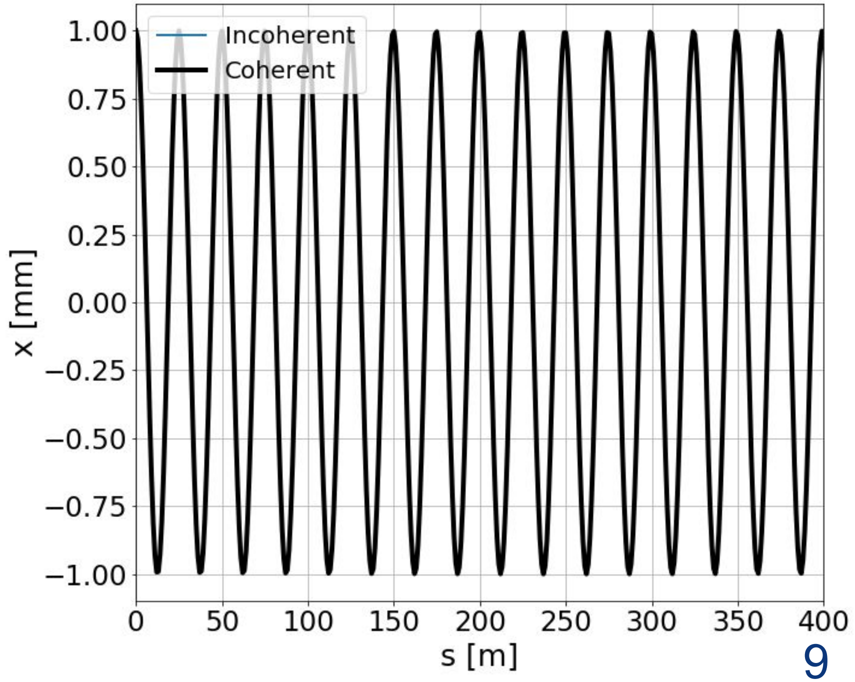


Incoherent motion

Coherent motion

- In order to clearly observe the coherent motion, we give an offset to the bunch and we record its oscillations along the ring

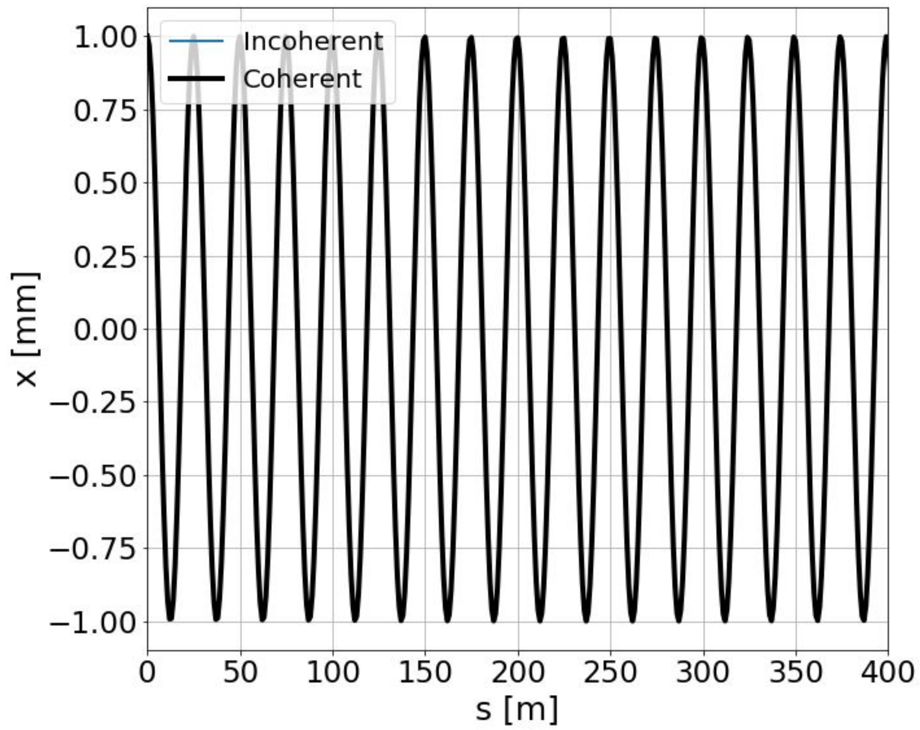




Coherent motion

- ➢ In order to clearly observe the coherent motion, we give an offset to the bunch and we record its oscillations along the ring

- ➢ In the case of an ideal machine without imperfections or non-linearities (e.g. sextupoles, octupoles etc):
  - ○ All the particles and the **center of mass** of the bunch oscillate with the same frequency around the ideal orbit



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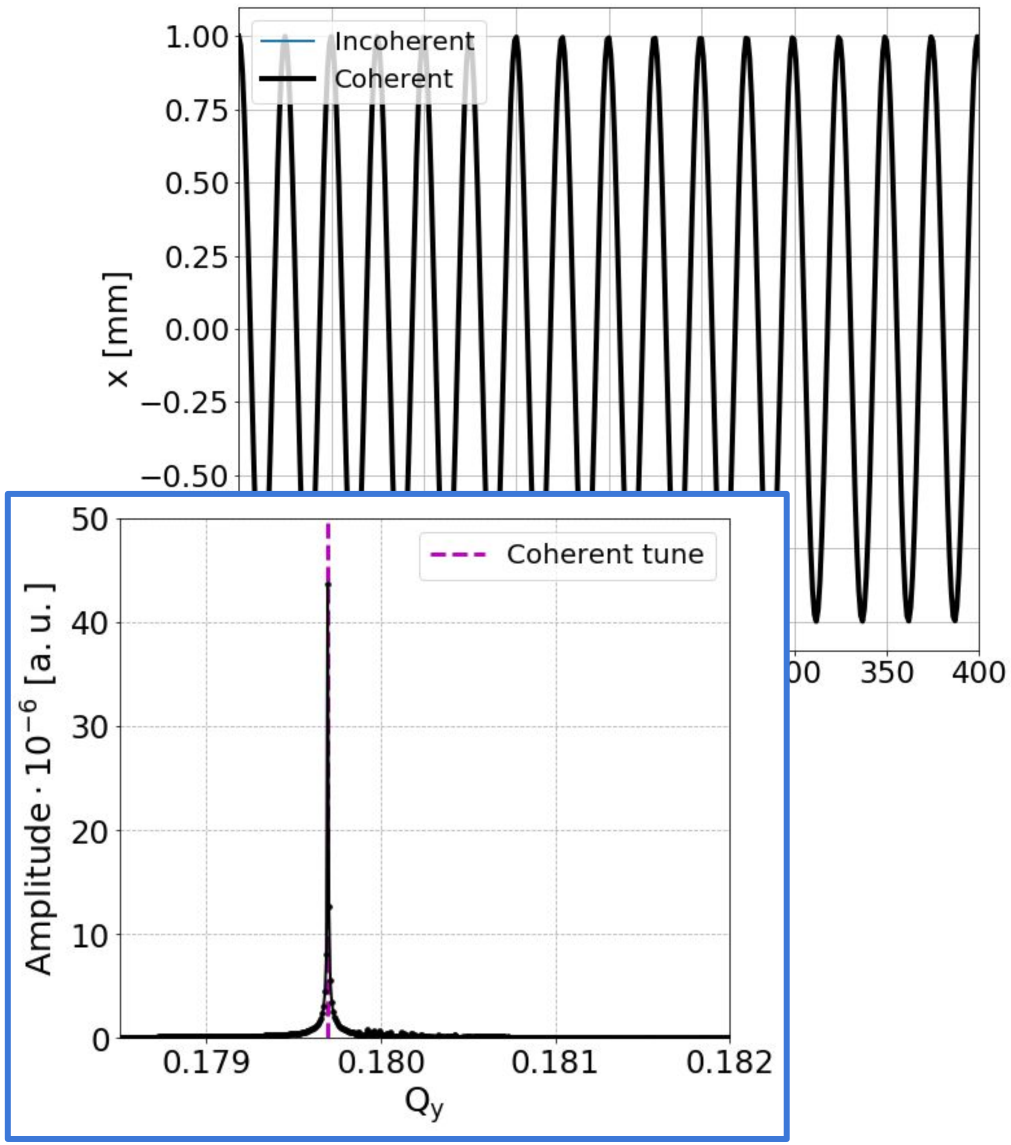
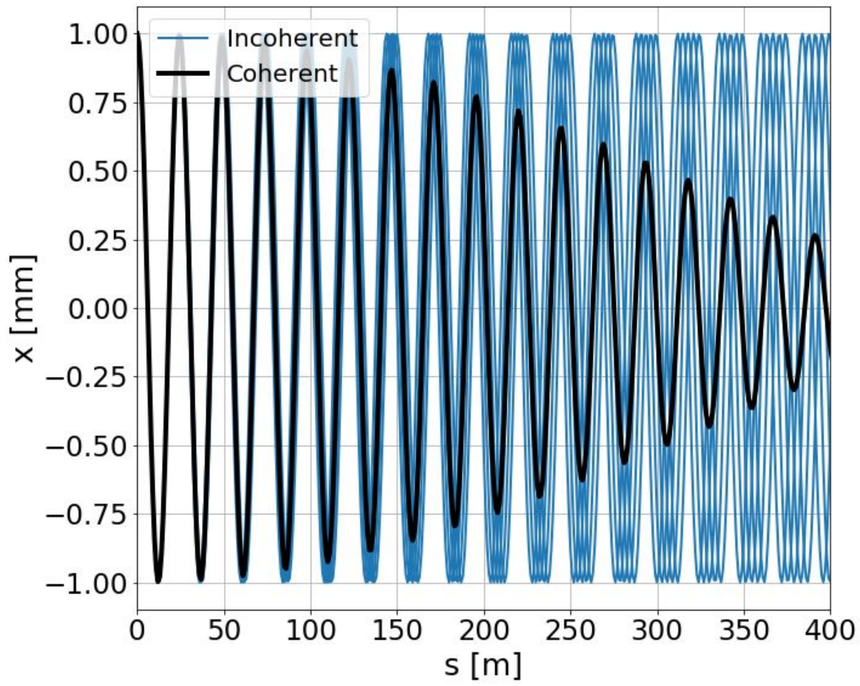
  - All the particles and the **center of mass** of the bunch oscillate with the same frequency around the ideal orbit

- The number of betatron oscillations of the **center of mass** of the bunch in one turn around the ring is called **coherent tune, Q**
  - It can be computed in the frequency domain, by applying a Fast Fourier Transform (FFT) algorithm on the motion of the **center of mass**



Incoherent motion

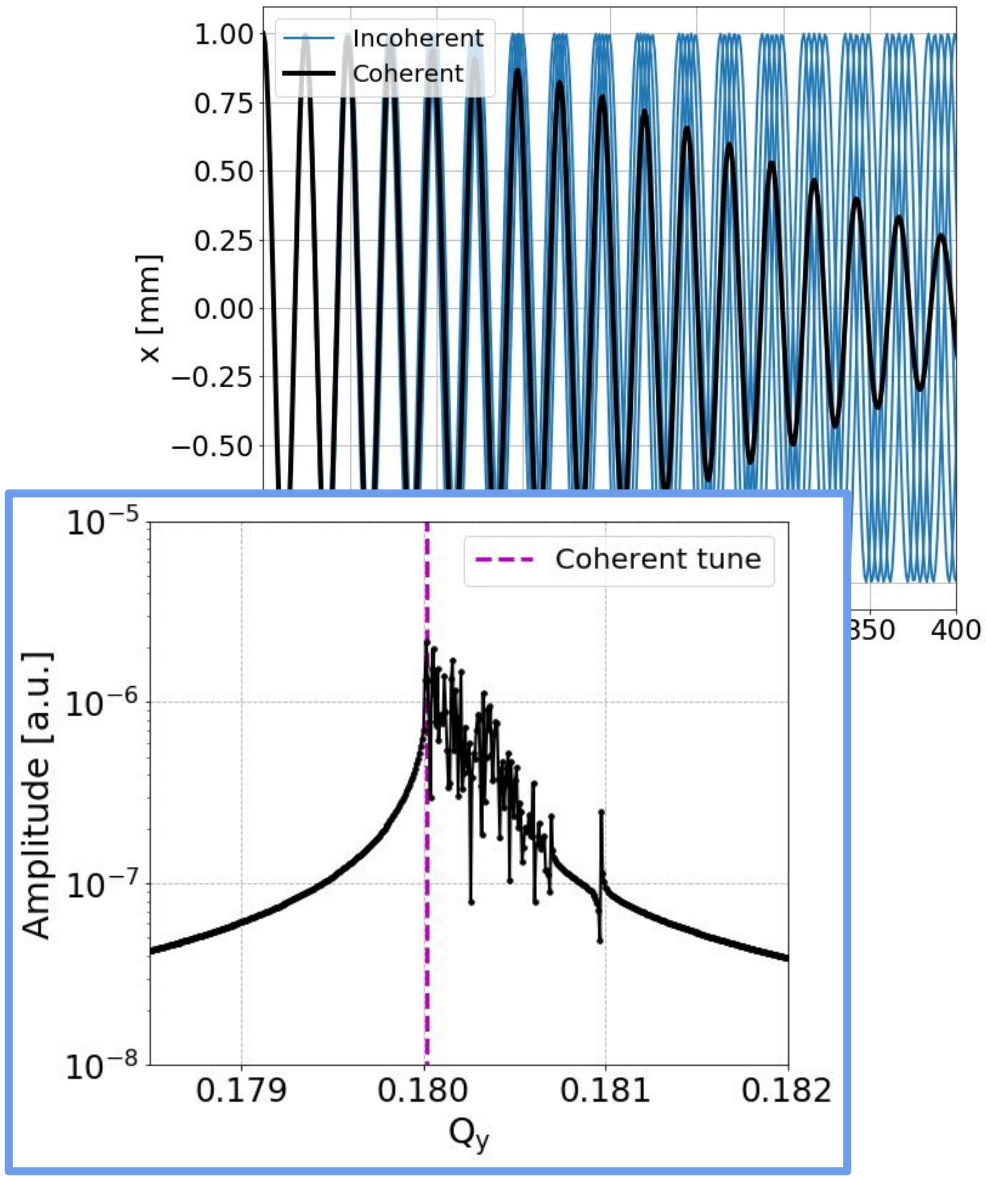
- In a real accelerator, with non-linearities e.g. sextupoles, octupoles etc.
  - Each particle oscillates with a <u>different</u> <u>frequency</u> around the ideal orbit



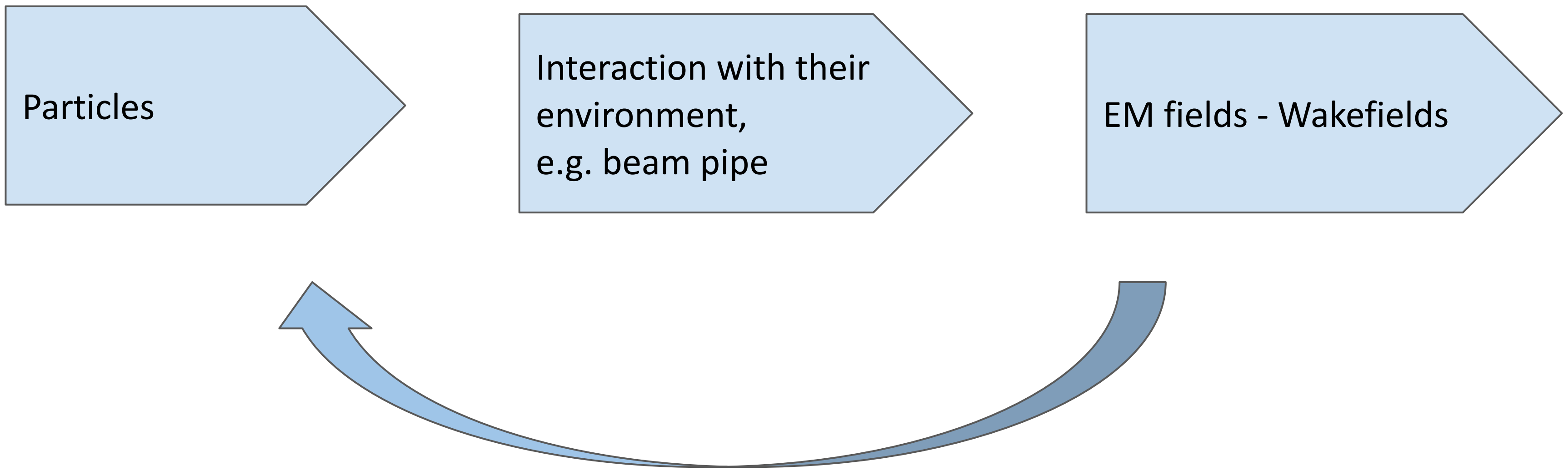
Incoherent motion

- In a real accelerator, with non-linearities e.g. sextupoles, octupoles etc.
  - Each particle oscillates with a <u>different frequency</u> around the ideal orbit

- FFT at the motion of the center of mass of the bunch
  - Many frequencies appear - “tune spread”
  - “Incoherent spectrum”



Impedance and wakefields



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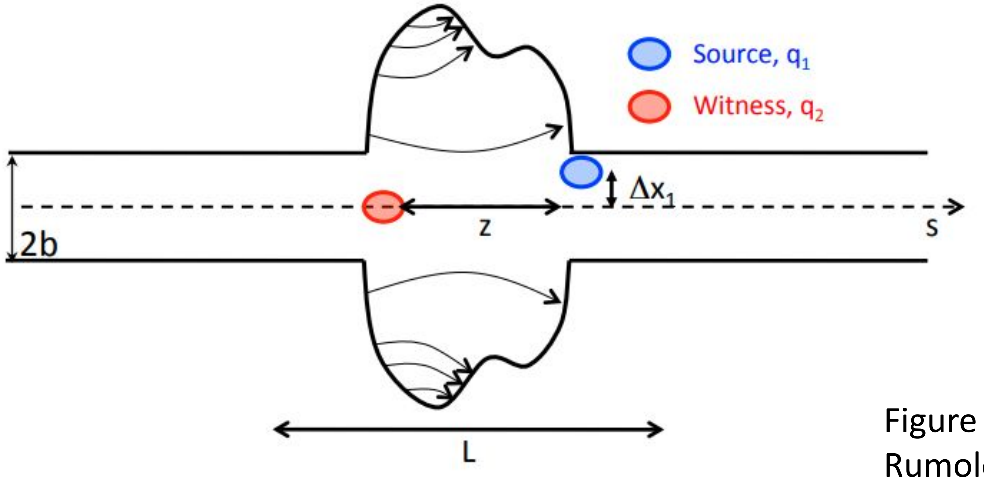


Figure source G. Rumolo, link

Source particle → Discontinuity in the beam pipe → EM fields - wakefields → Witness particle

- **Wakefields:** depend on the position of source and witness particle and their distance
  - They are described with the wake functions e.g.:

$$\Delta x_2'(z) = -\left(\frac{q_1 q_2}{E_0}\right)[W_{Dx}(z)\Delta x_1 + W_{Qx}(z)\Delta x_2]$$

Expressed in frequency domain → **Impedance**

- The wakefields can **affect the coherent motion** of the bunch and hence the coherent tune

Introduction to the HL-LHC project

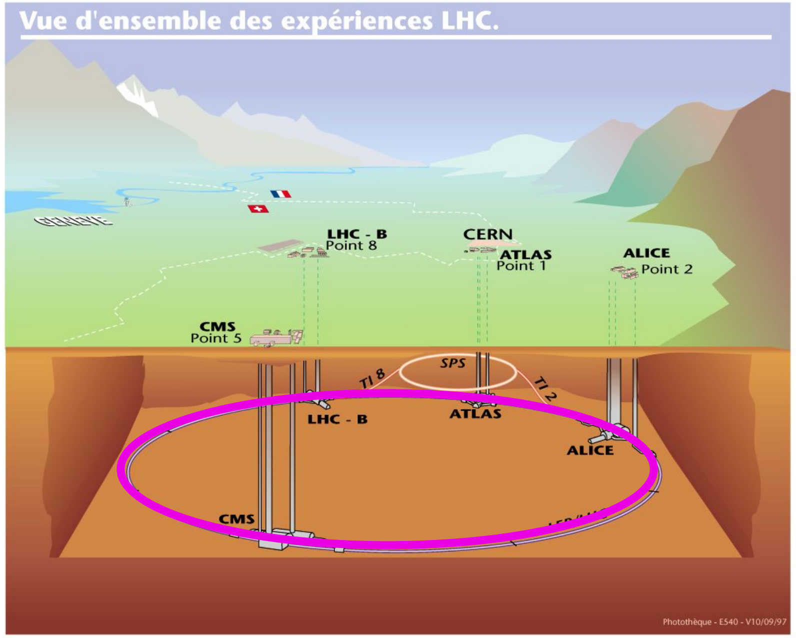
The HL-LHC project

➢ The High Luminosity LHC (**HL-LHC**) project is the **upgrade of the LHC machine**, which will extend its potential for discoveries

- In particular, it aims to **increase** the rate of collisions between particles → **luminosity**

  HL-LHC will:

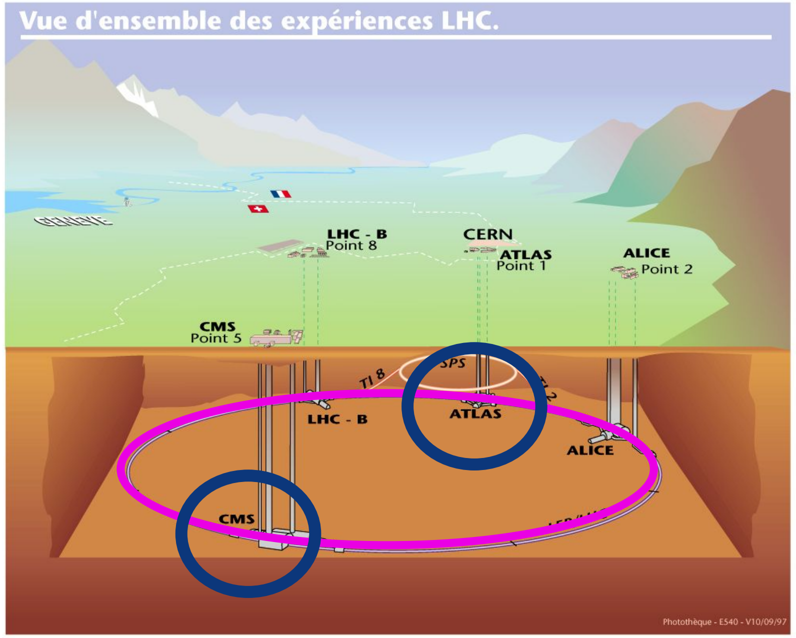
  1. Provide more accurate measurements of already discovered particles
  2. Enable the observations of rare processes



Design target: 10 times increase of the integrated luminosity

Crab cavities for the HL-LHC project

- HL-LHC will rely on many innovative technologies
- **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

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

where f_{rev} the revolution frequency 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 θ_c is the full crossing angle.

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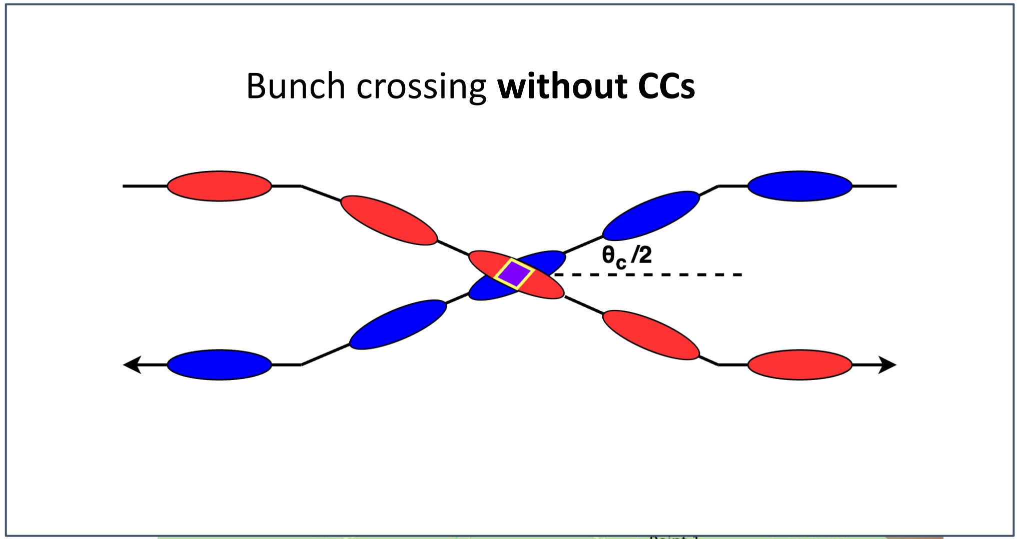

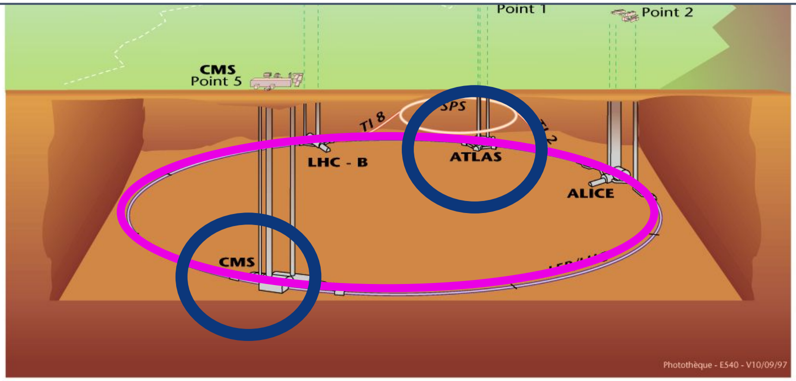

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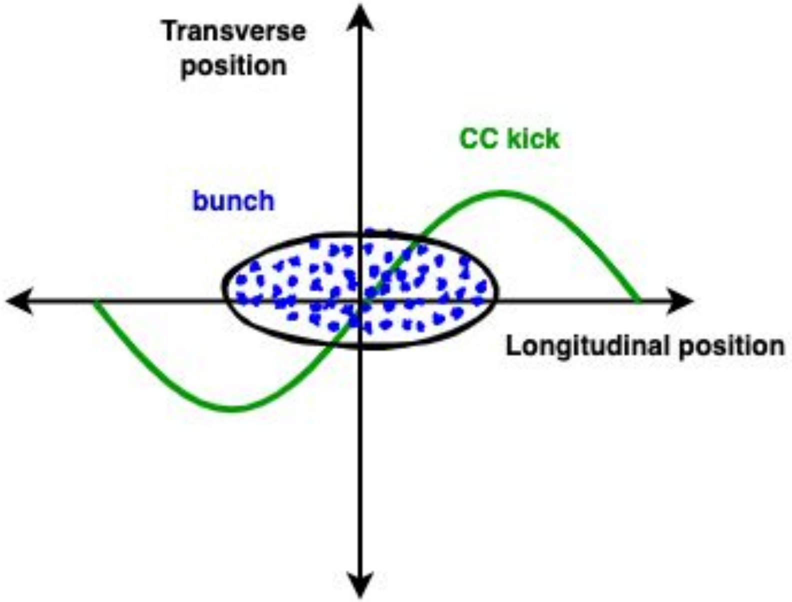
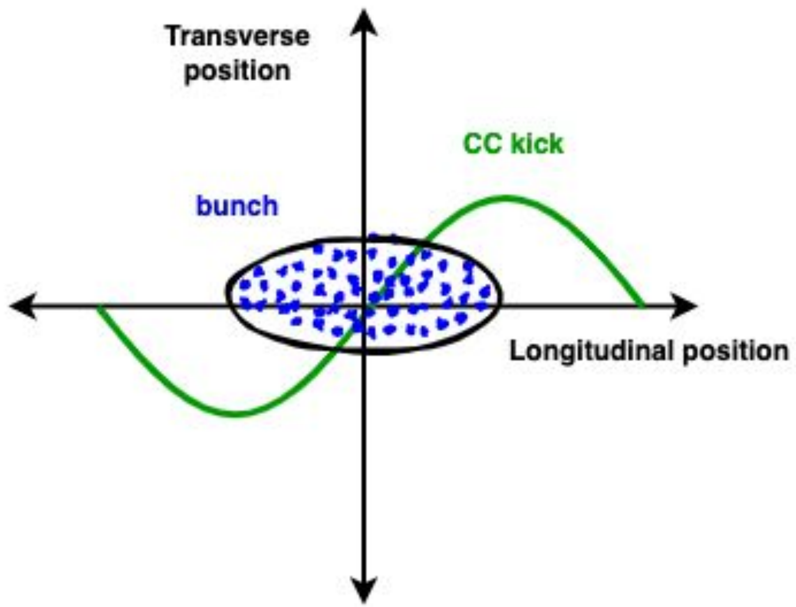
Crab Cavity technology

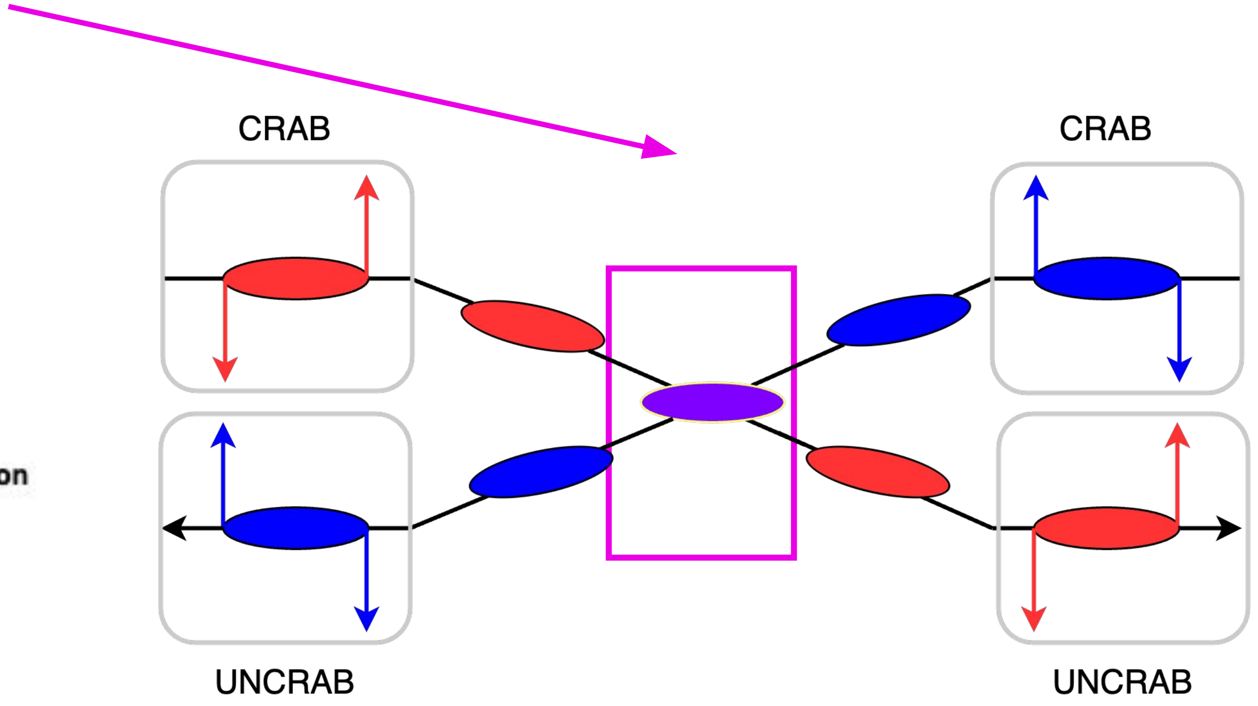
- RF cavity providing **transverse kick** to particles **depending** on their **longitudinal position** within the bunch
- Head and tail receive opposite deflection while particles at the centre remain unaffected



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 point





Transverse emittance growth from Crab Cavity RF noise

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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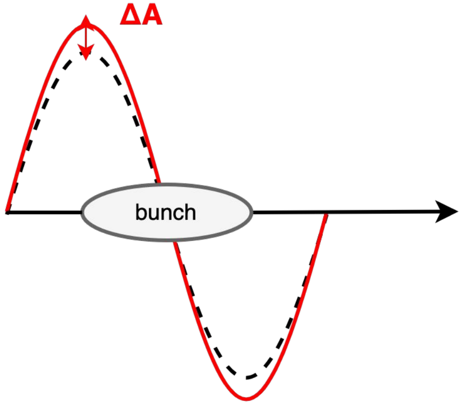
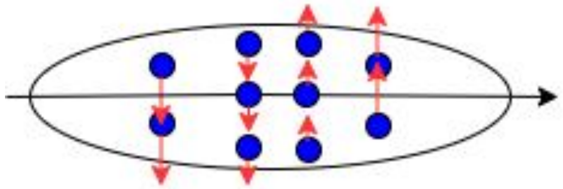
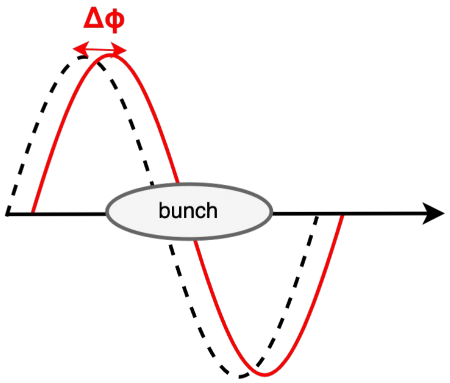
Amplitude noise

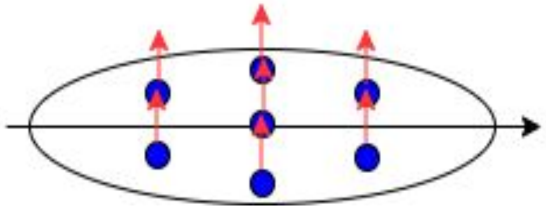




The head and the tail of the bunch are kicked in opposite directions ⟶ **Intra-bunch oscillations**

Phase noise





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

RF noise in the Crab Cavity

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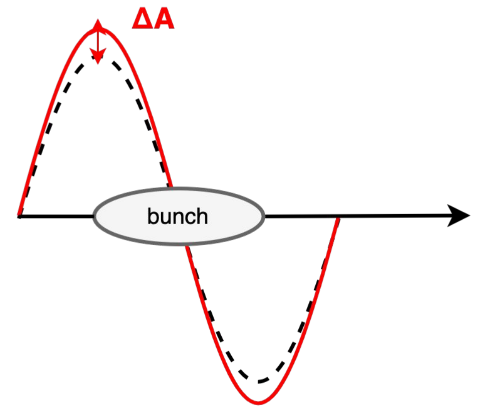
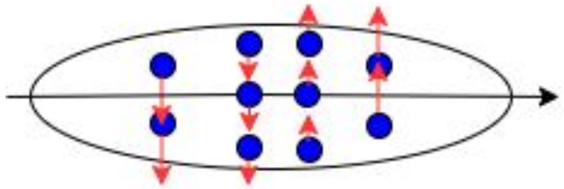
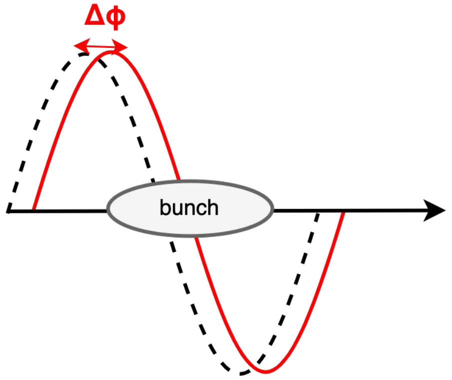


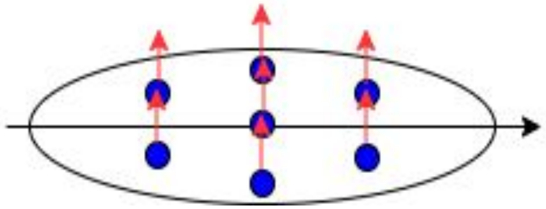


The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

These studies focus on phase noise.

Phase noise





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Theoretical formalism

- Essential to define noise limits and design specifications for the crab cavities
- A **theoretical model**(*) was derived to **predict the emittance growth** from Crab Cavity RF 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

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T. Mastoridis
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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

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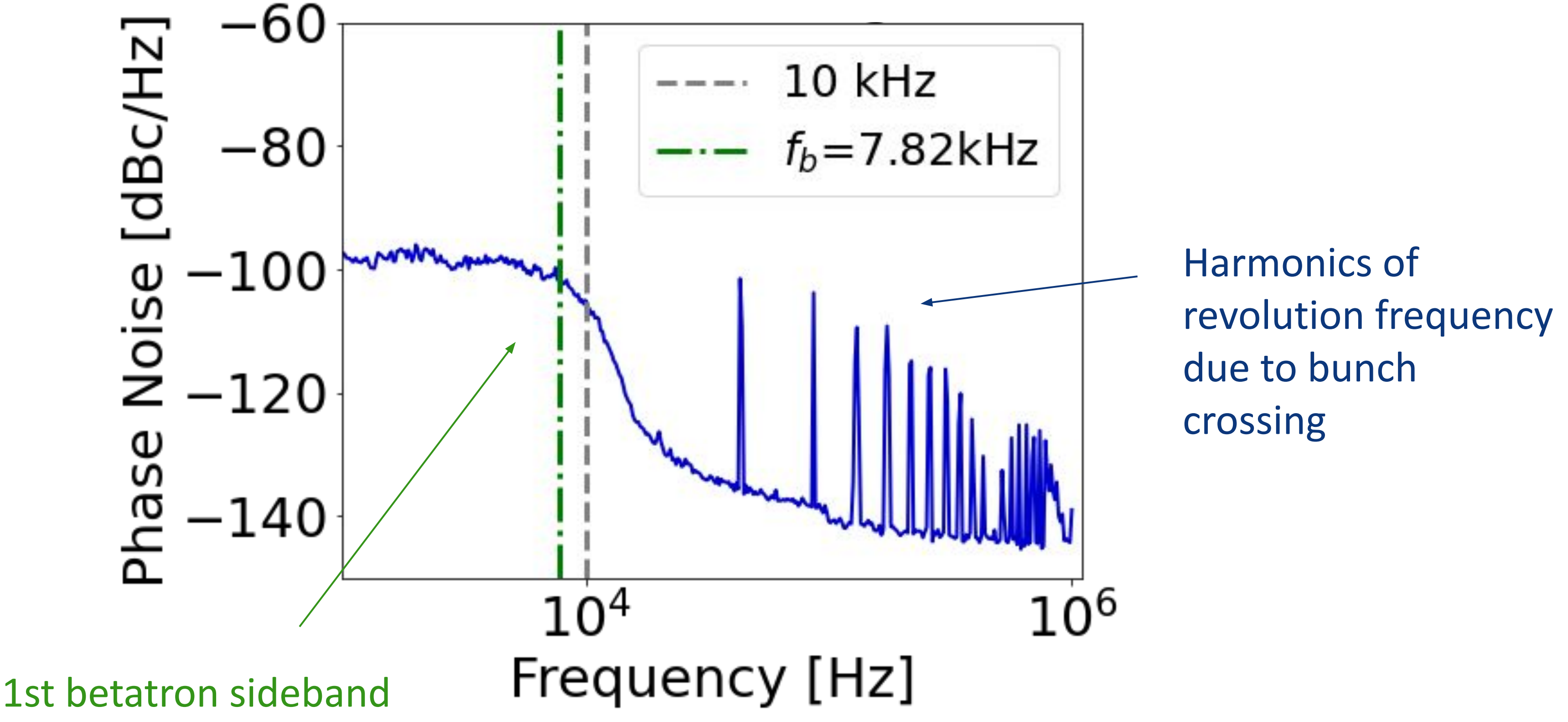
4.	**Injected artificial noise much larger than targeted for HL-LHC** for better observables
5.	The **goal** is to **validate the predictions** from the theoretical model. **Scaling** will be needed for the **HL-LHC case**

scaling (items 3–4)

Experiment in 2018 – RF noise spectrum

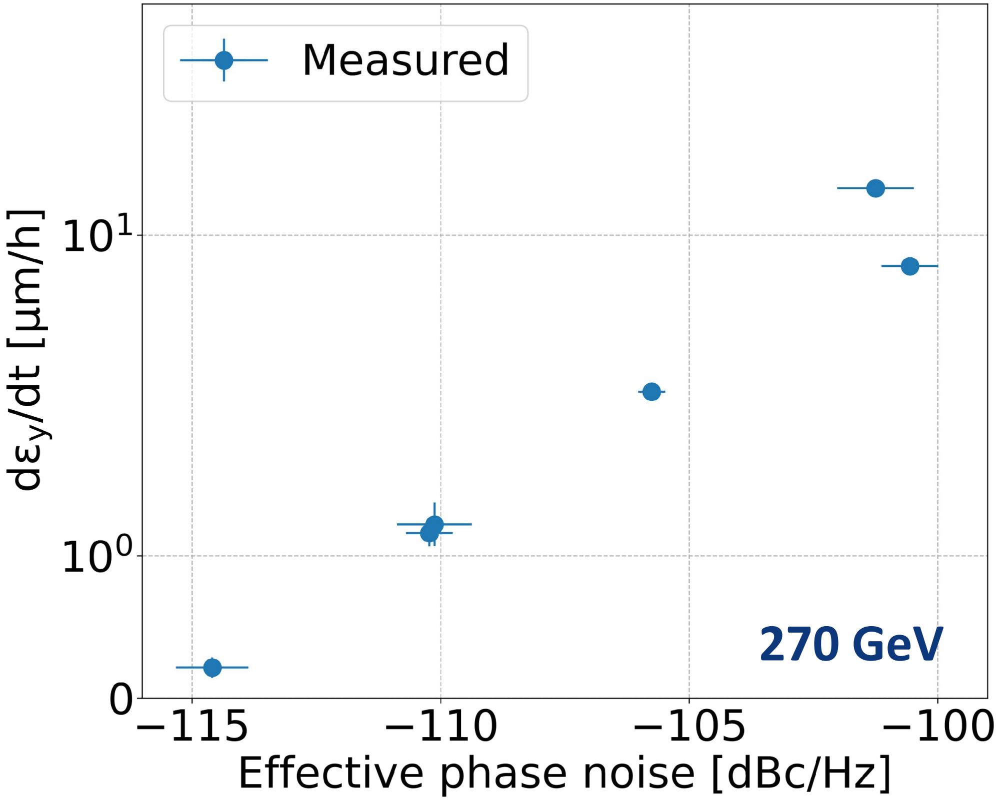
- ➢ Mixture of amplitude and phase noise
- ➢ **Phase noise was always dominant**

Example noise power measurement in 2018



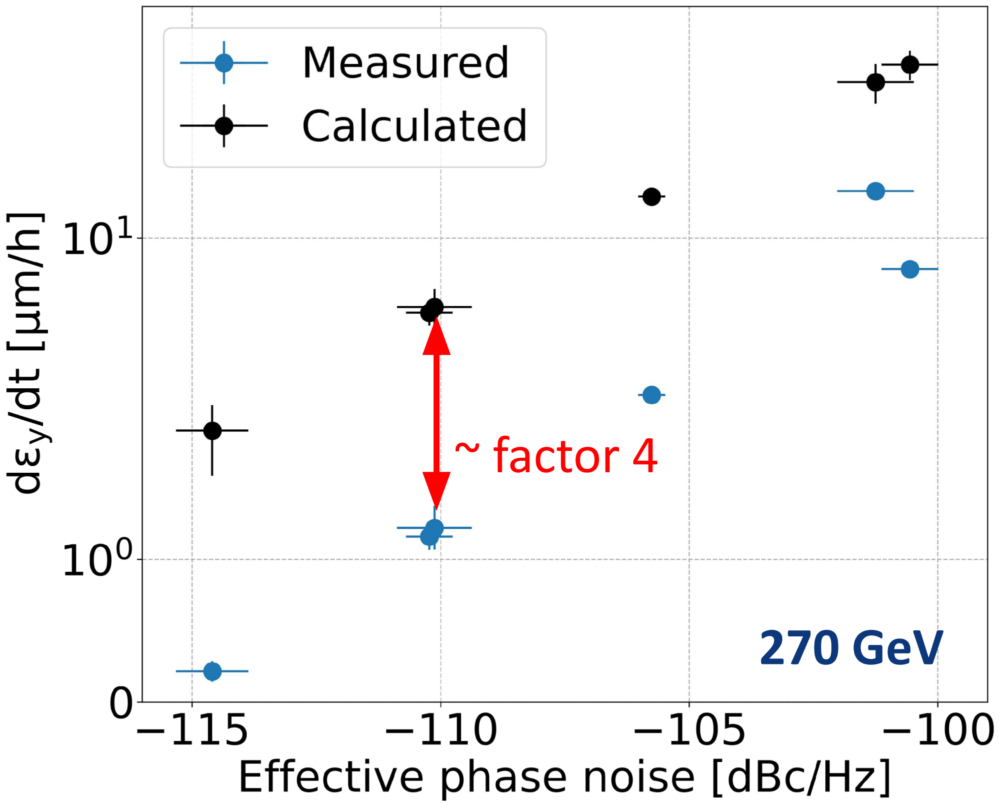
Experiment in 2018 - Results

- 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

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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**

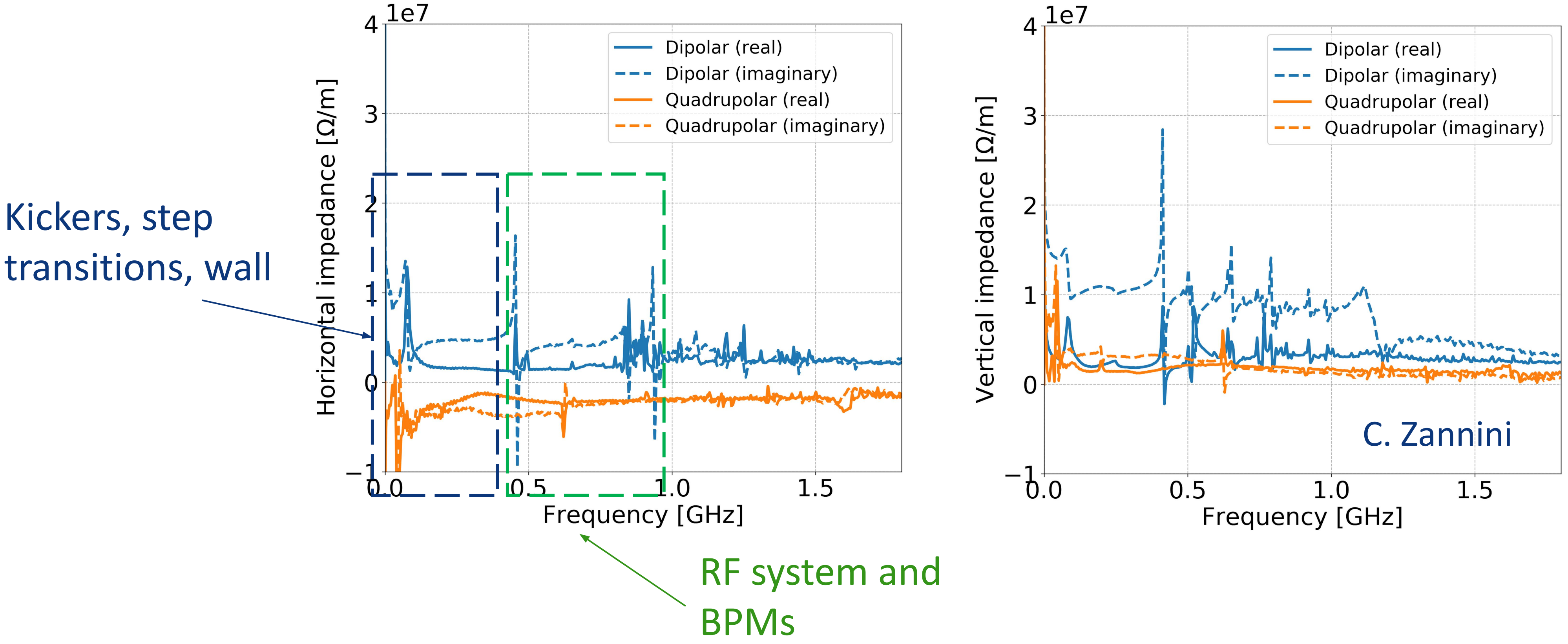
(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

Emittance growth suppression from the beam transverse impedance

SPS transverse impedance model

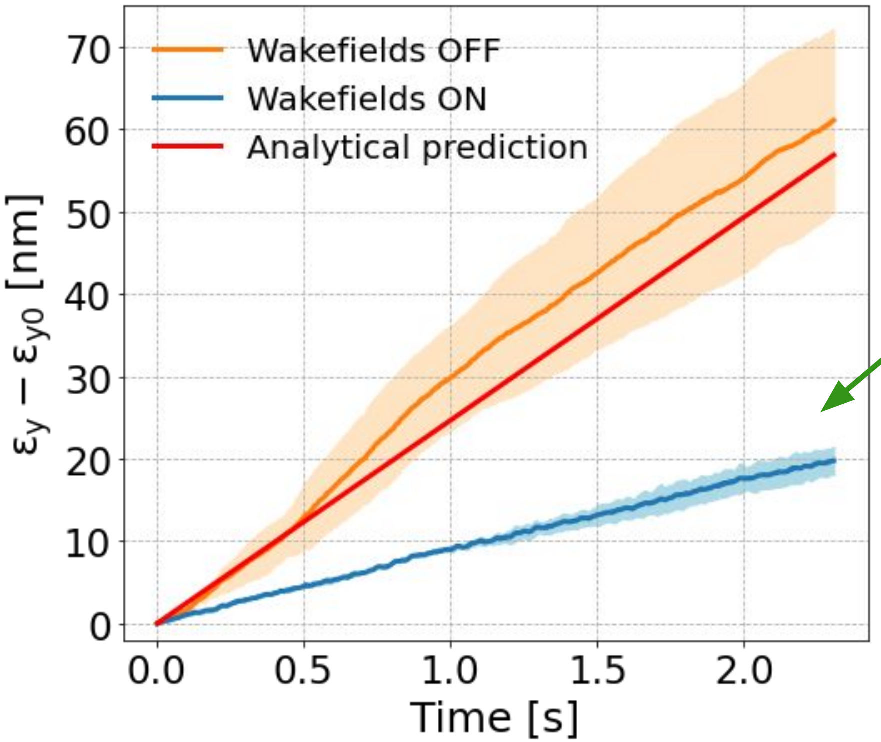
- The **complete SPS transverse impedance model** provided from detailed electromagnetic simulations is used
  - Kickers, resistive wall, step transitions, BPMs, RF cavities, indirect space charge, etc.

SPS transverse impedance



First simulation results

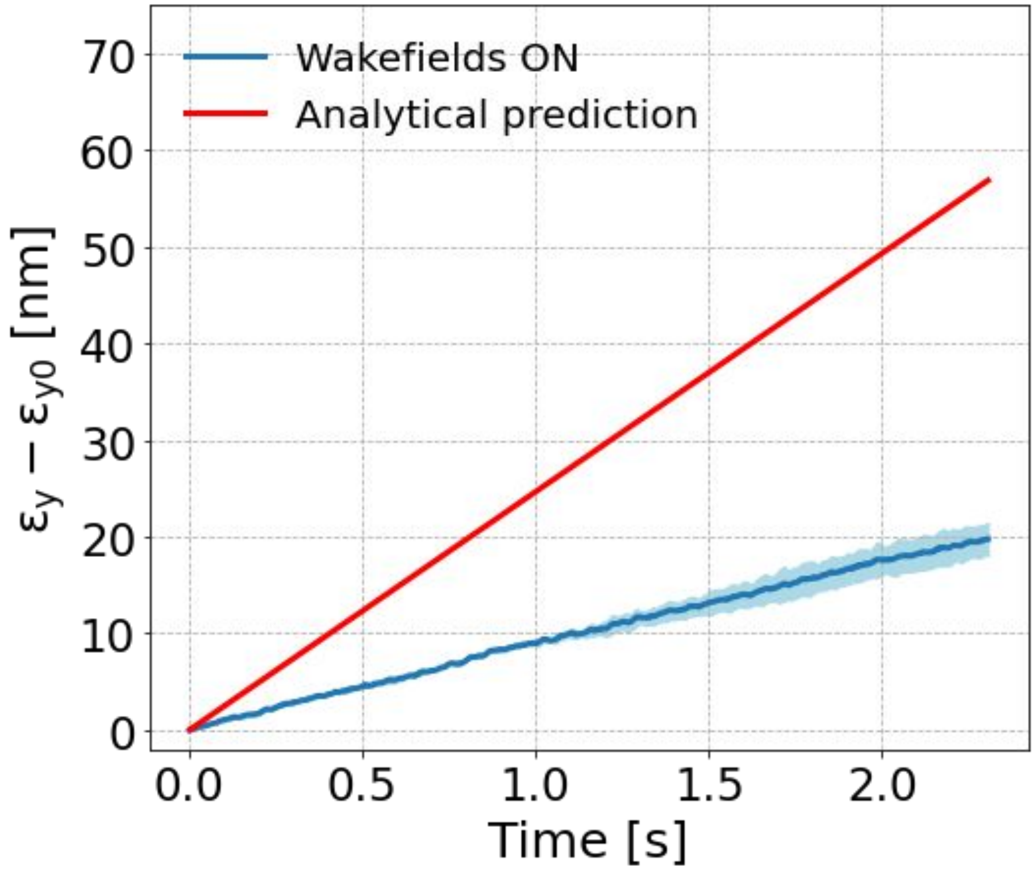
- **Simulations** with **PyHEADTAIL** and the **complete SPS transverse impedance model**
  - Beam and machine conditions as in the 2018 SPS experiment
  - Crab Cavity RF **phase noise** for ~ 25 nm/s
    - Even **stronger than in the SPS experiments**, for sizeable emittance growth in the simulation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

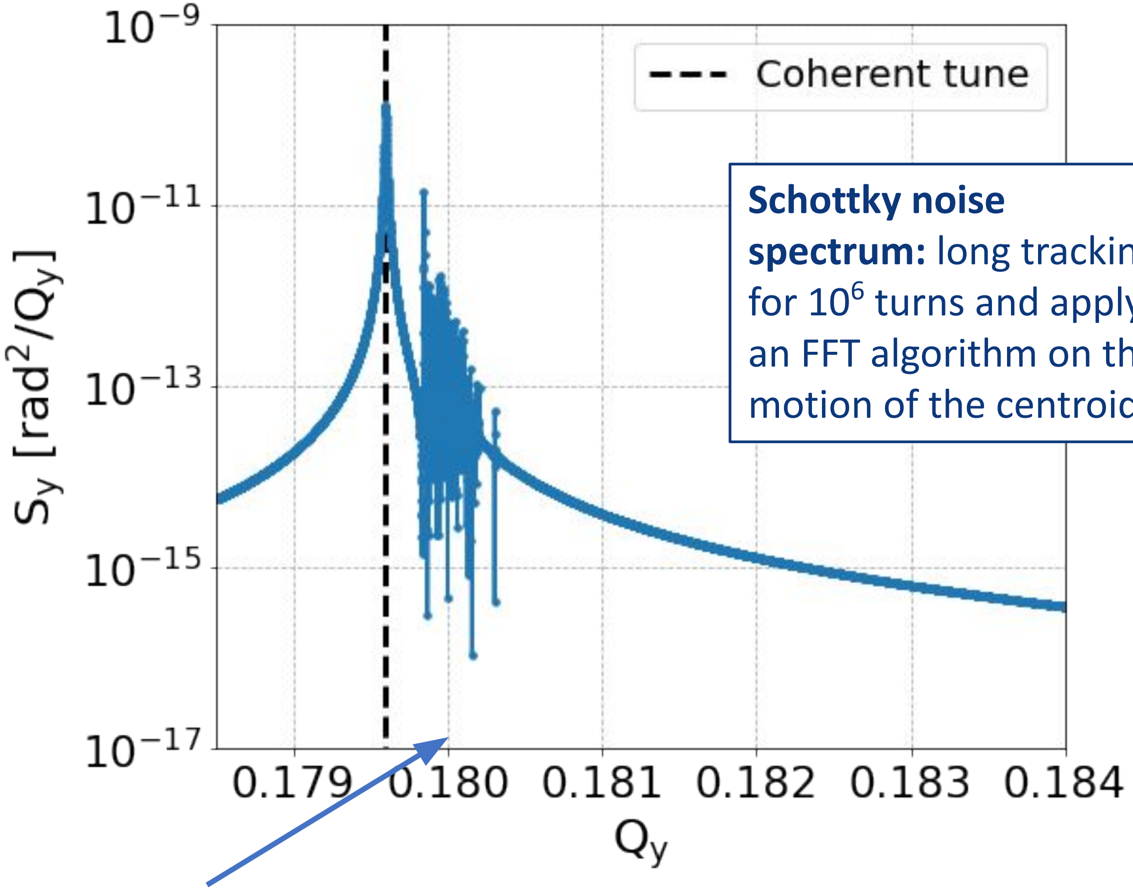


Clear suppression of the **phase noise** induced **emittance growth** in the presence of **wakefields**.

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.

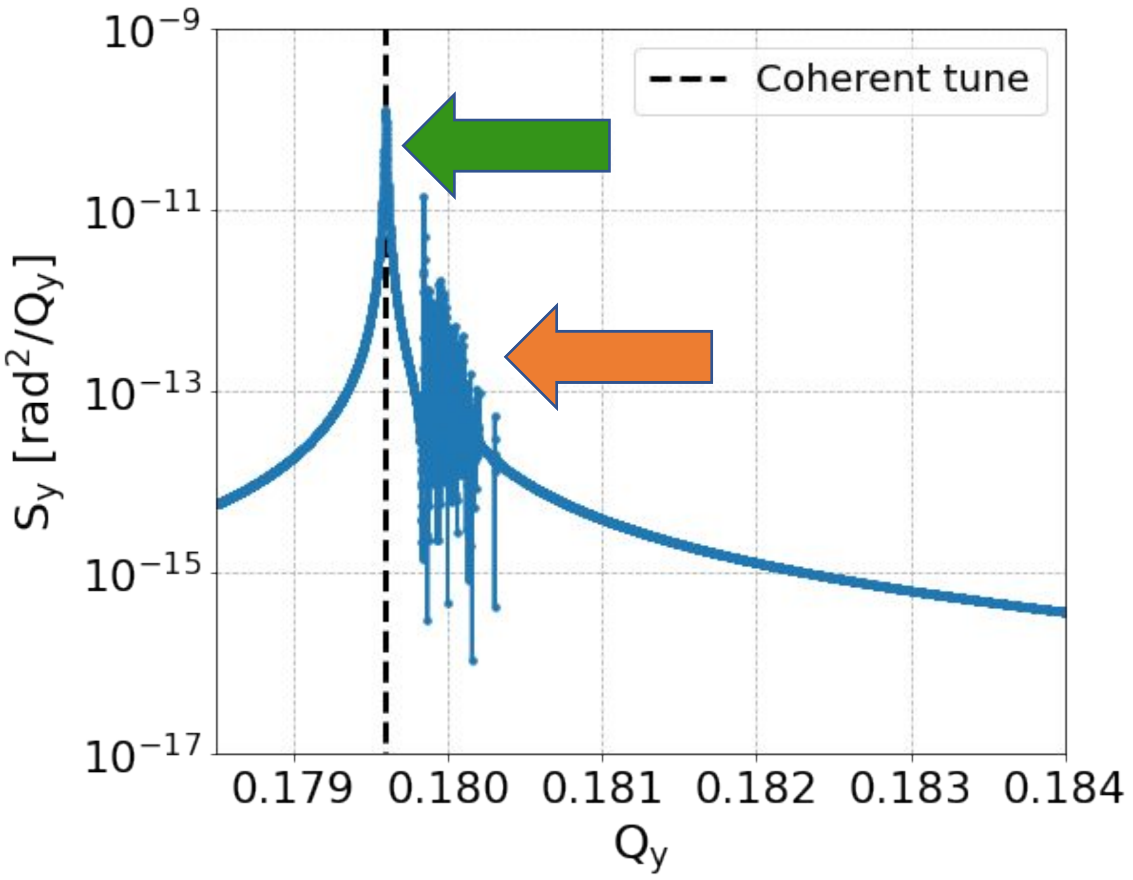
Nominal SPS tune 0.18

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**, the oscillation of 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)

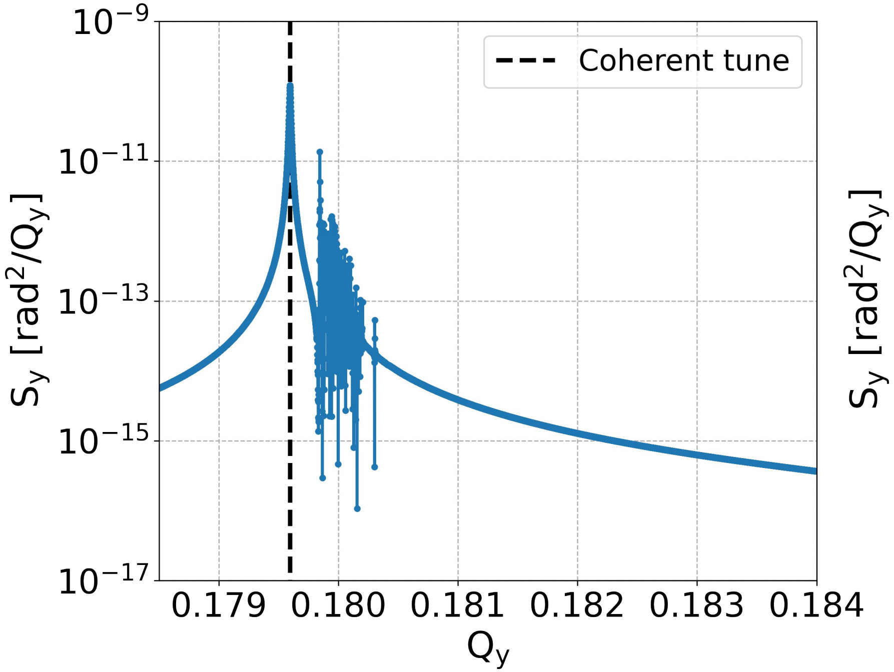
- Recently, this approach was adapted for configurations featuring linear detuning and a complex tune shift from a collective force, supporting the simulation results shown here
  - **X. Buffat, "Suppression of Emittance Growth by a Collective Force: Van Kampen Approach", IPAC'22**

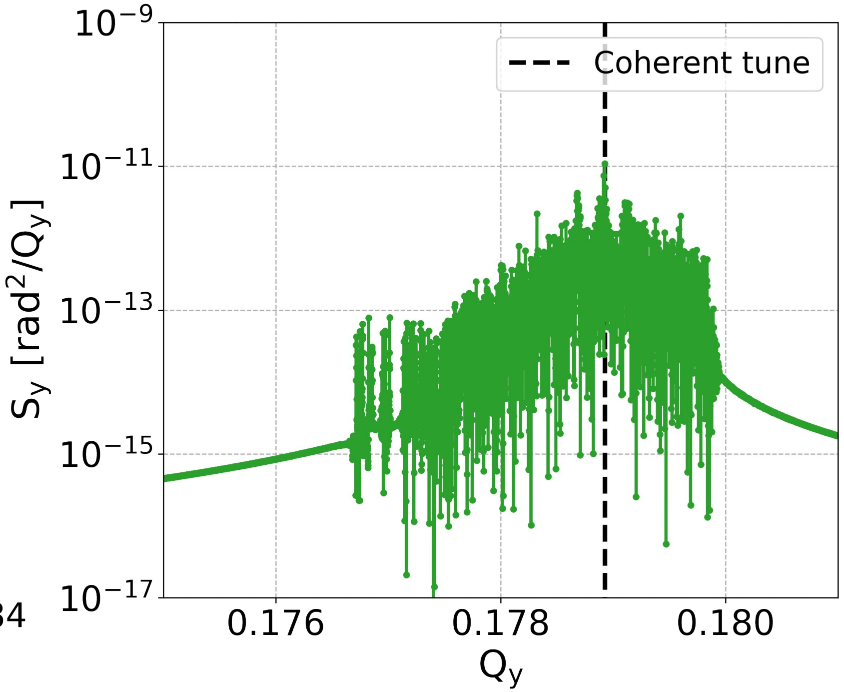
(*1) *Y. Alexahin, "On the Landau Damping and decoherence of transverse dipole oscillations in colliding beams"*

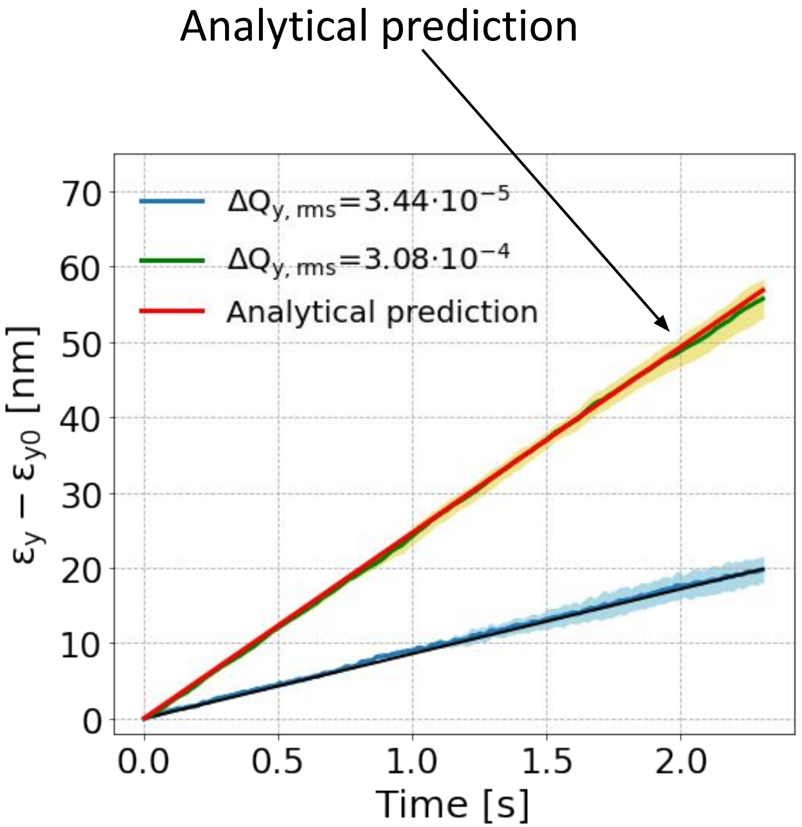
(*2) *X. Buffat, "Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider", Phys. Rev. Accel. Beams 23, 021002 (2020)*

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)



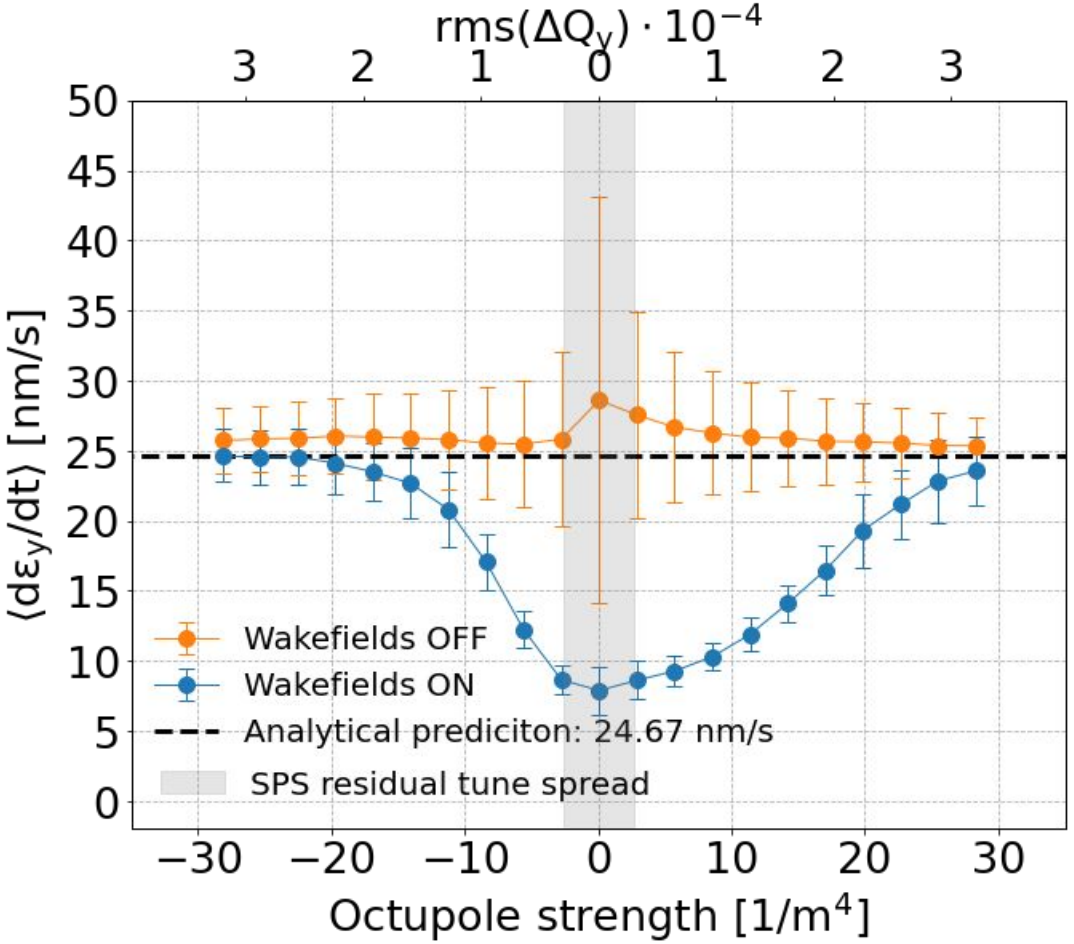




Parameters: 270 GeV, 3e10 protons per bunch, Q'y=0.5

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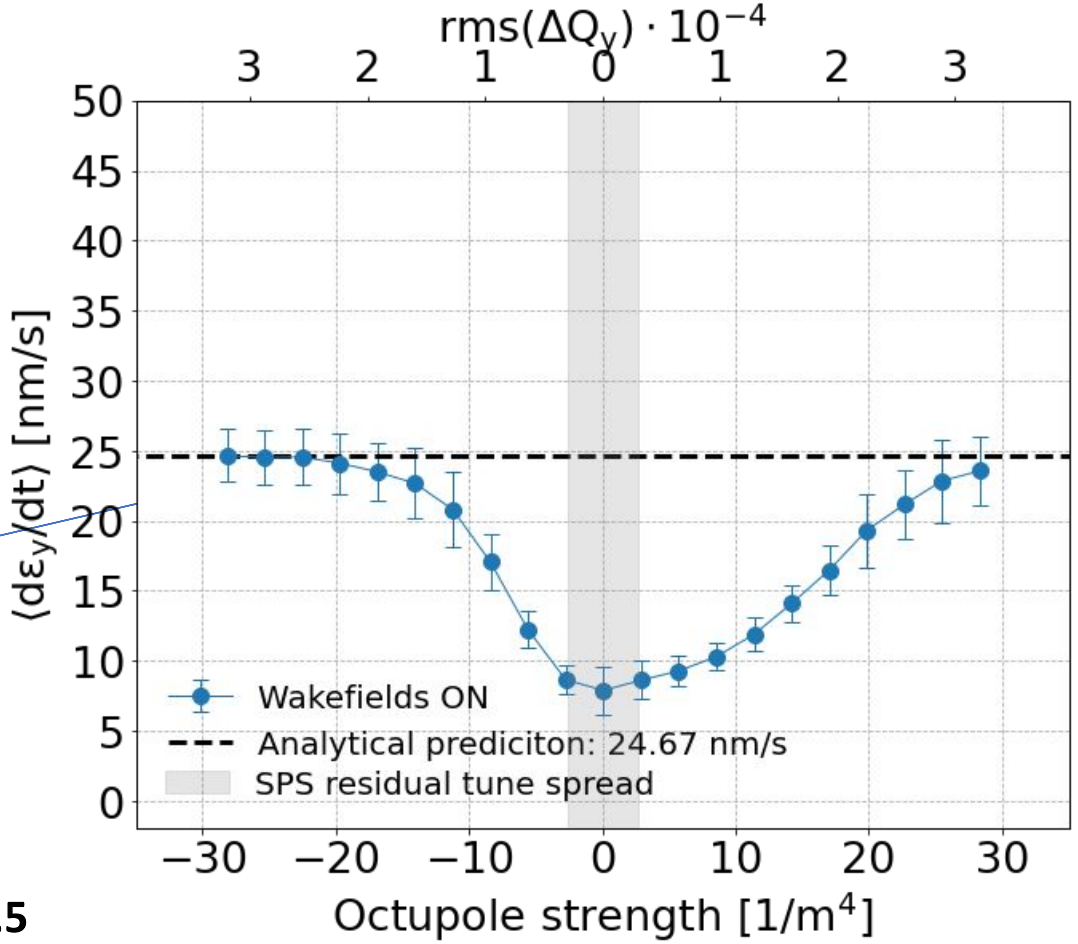
This **behavior** was **tested experimentally** in the **SPS in 2022**

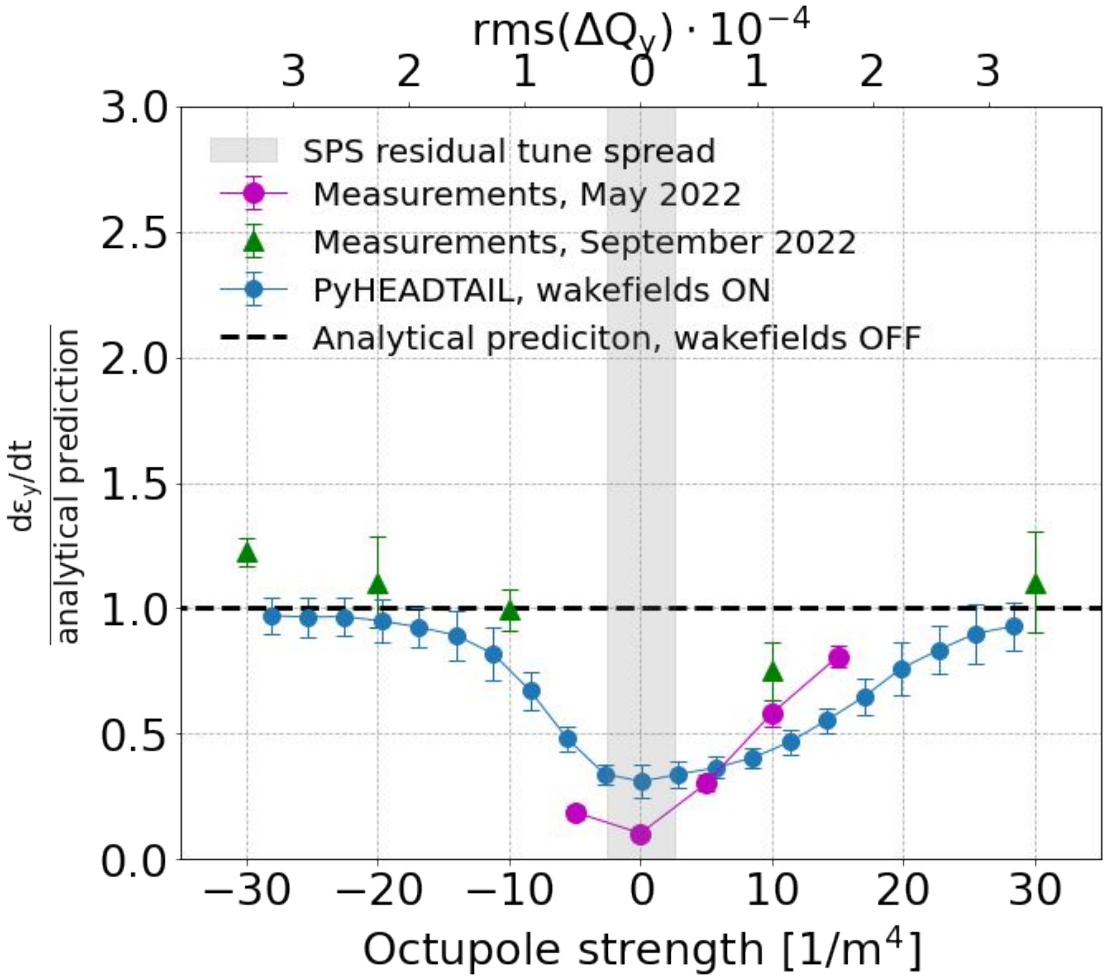


- **Use of SPS octupole families**
- **Goal: Reproduce the behavior only (due to scaling)**
- **For the residual SPS tune spread: suppression of a factor ~ 3.5**

SPS measurements in 2022

Experimental results 2022 - I

Simulations vs measurements

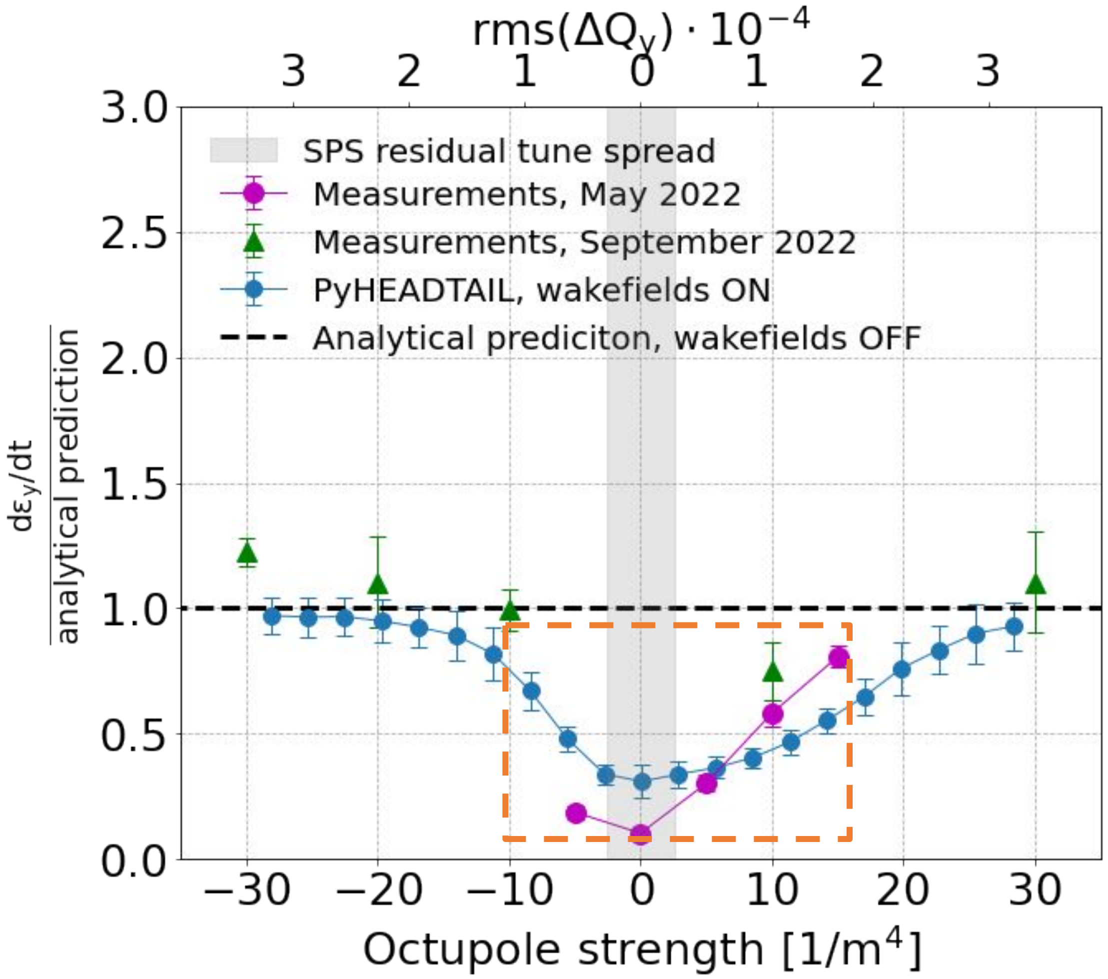


- Two sets of measurements, May and September 2022
- **Clear dependence of the measured emittance growth on the octupole strength**
  - **Qualitative agreement** with the simulations
  - **Goal of the experiment achieved**

Confirmation of the proposed damping mechanism from the impedance!

Experimental results 2022 - II

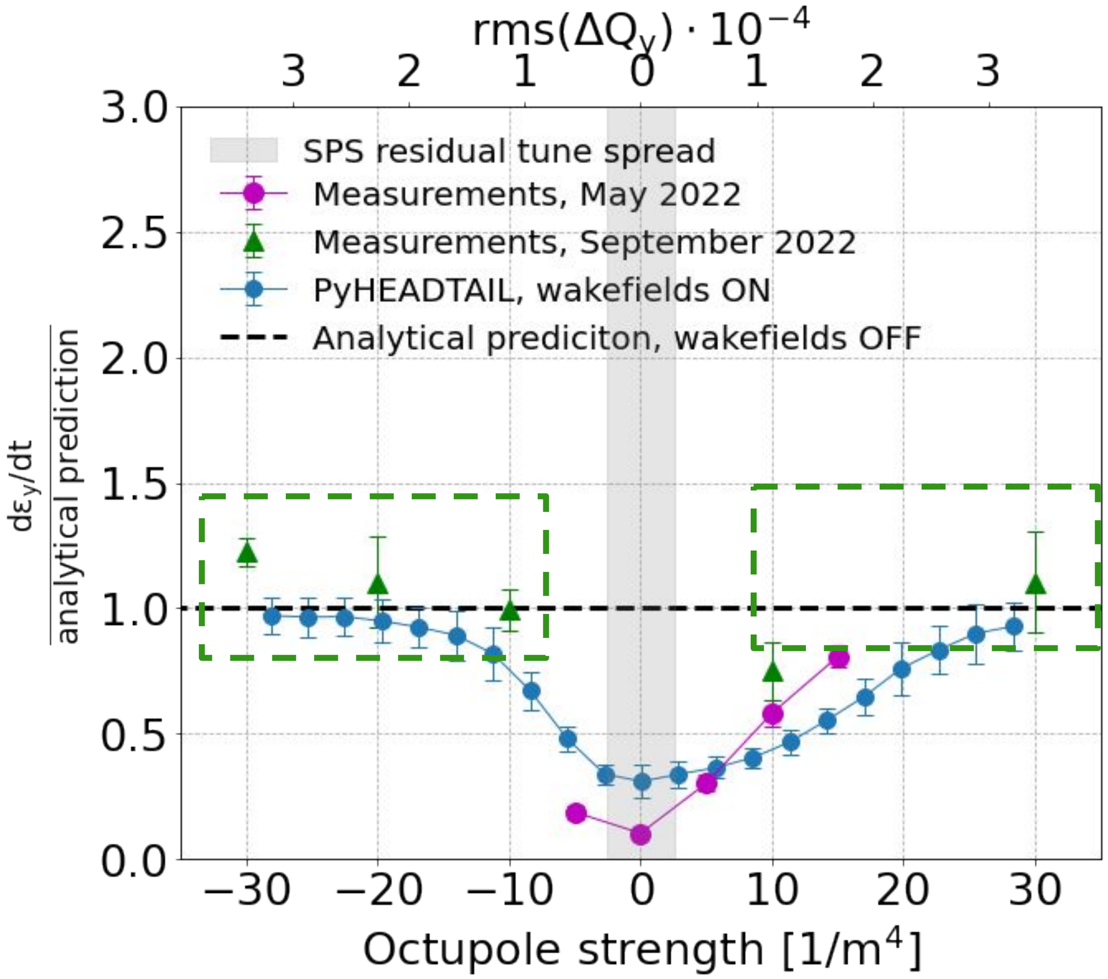
Simulations vs measurements



- Some uncertainty on the level of quantitative agreement for octupole strength < 20 /m^4
  - Possible explanation: contribution from space charge - under investigation

Experimental results 2022 - II

Simulations vs measurements



- ➢ Very good quantitative agreement with analytical model for strong octupoles, **gaining confidence in its predictions**
  - ○ Small discrepancies could possibly be explained by 10% uncertainty on the V_{CC}

Implications for the HL-LHC

- **Regarding the suppression mechanism from the transverse impedance**
  - For the HL-LHC operational configuration the coherent modes lie inside the incoherent spectrum and the phenomenon of the suppression **will not be observed**

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  - The presented work **gained confidence in the predictions** of the model for the operational regime of HL-LHC and it can be used for **defining limits on acceptable noise levels** for the HL-LHC Crab Cavities

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- **Plans for mitigating the expected emittance growth from Crab Cavity RF noise in the HL-LHC**
  - The analytical model predicts ~5%/h emittance growth from Crab Cavity RF noise (link)
  - The reduction to the required 2%/h will come from a **feedback system** which has been proposed since 2019 (link) - The presented work **underline its necessity** for the HL-LHC operation

Summary and outlook

Summary and outlook

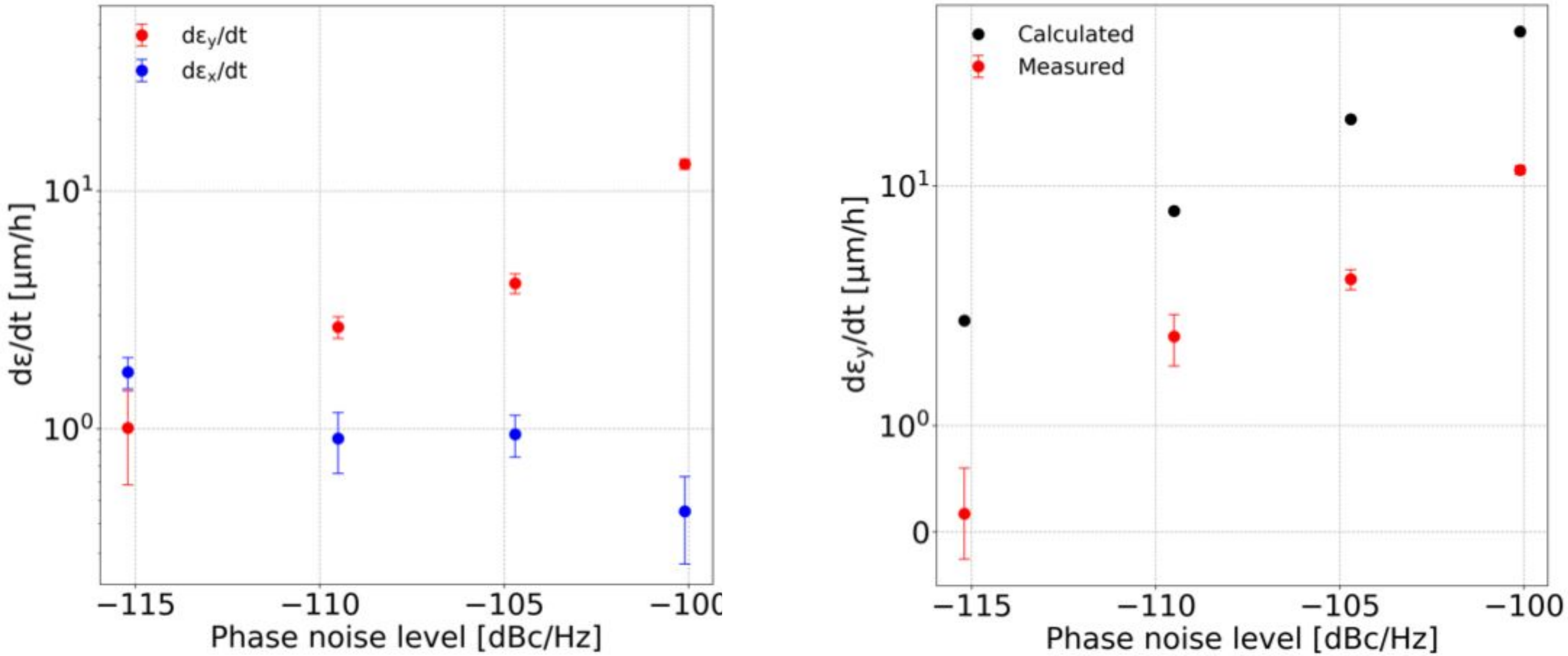
- **First experimental beam dynamic studies** with **Crab Cavities** and **proton beams**
- **First investigation and experimental validation of the suppression mechanism** of the Crab Cavity RF phase noise induced emittance growth by **transverse impedance**
- **Crucial step forward** on the understanding 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
  - The limitations of the theoretical model (without impedance effects) were identified
- **Implications for the HL-LHC:**
  - The phenomenon of the **suppression will not be observed**
  - The analytical model predicts ~5%/h emittance growth from Crab Cavity RF noise
  - **The need for the proposed effective feedback on the Crab Cavities** in order to achieve the HL-LHC target value of ~2%/h **is confirmed**

Thank you for your attention!
Questions?

Supporting slides

SPS Crab Cavity MD 16/05/22 - extended

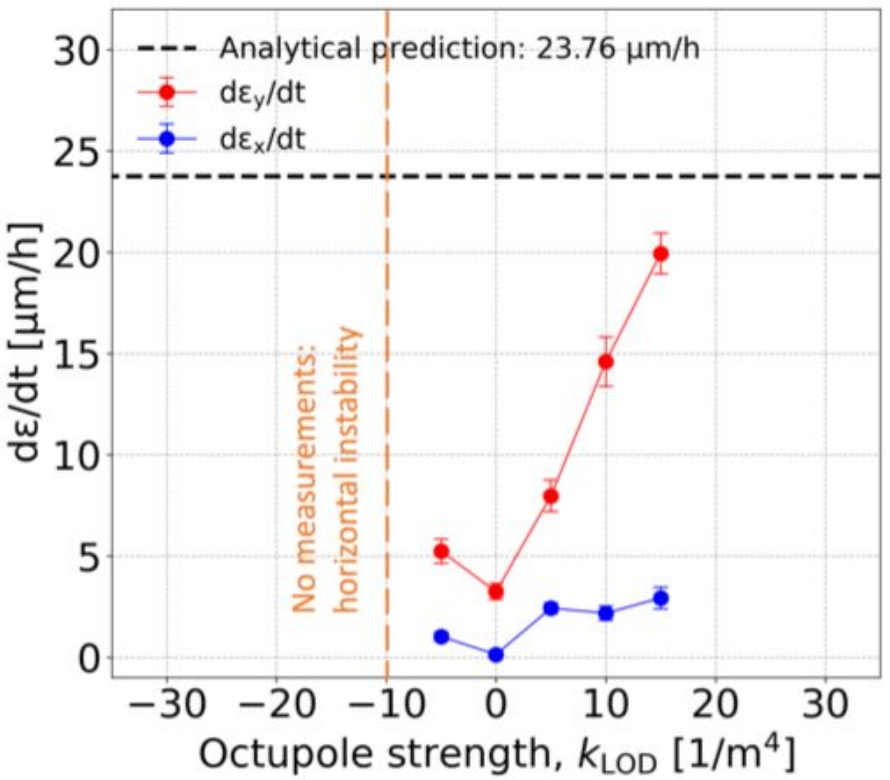
Scaling of emittance growth with noise power



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

SPS Crab Cavity MD 16/05/22 - extended

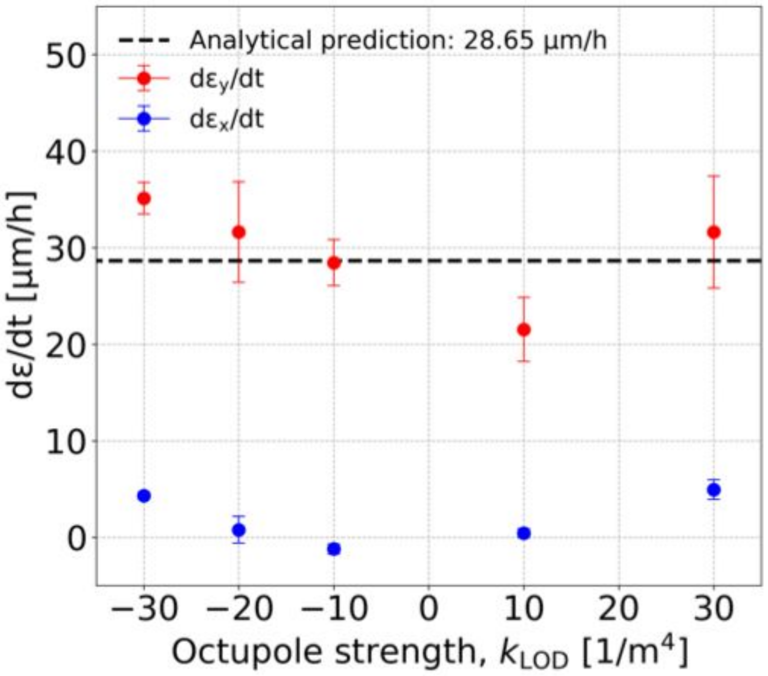
Octupole scan



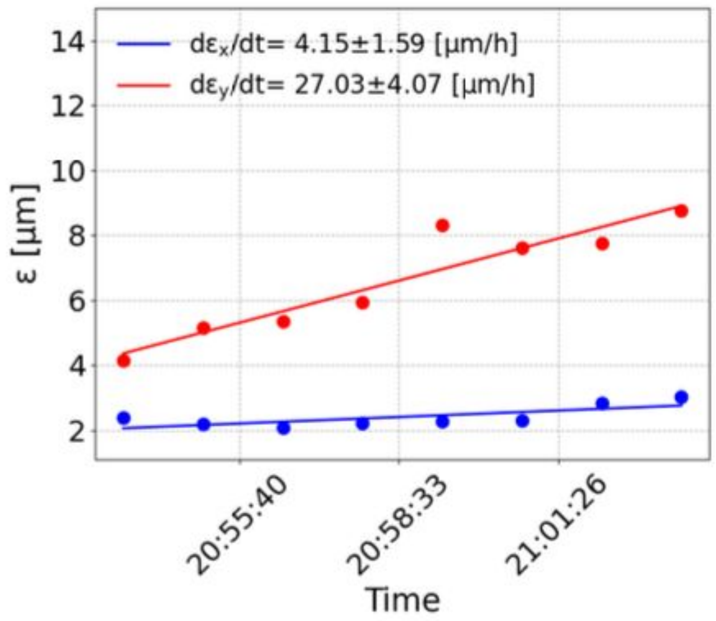
Parameters: 270 GeV, 3e10 protons per bunch, Q’y~0.0

SPS Crab Cavity MD 12/09/22 - extended

Octupole scan



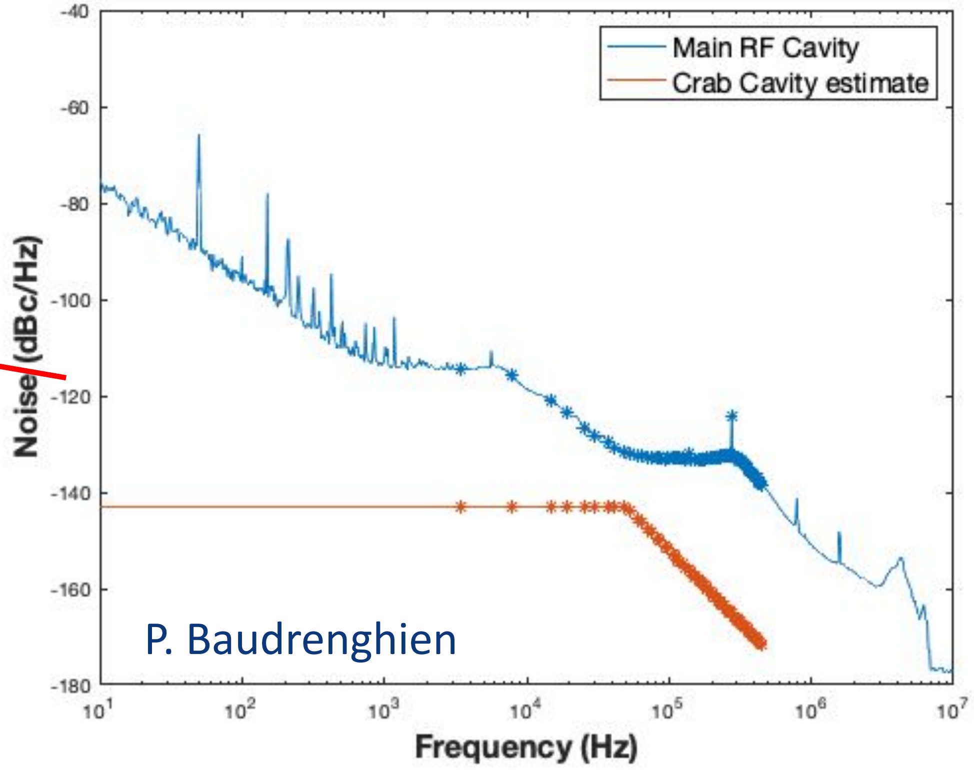
Amplitude noise, k_{LOD}=-30 1/m^4
Expected emittance growth ~ 32 μm/h



Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.7

HL-LHC target values

- **Target value** for the **maximum** luminosity loss from the HL-LHC **Crab Cavity RF noise** □ **1%**
- **Target value** for the **noise-induced** emittance growth □ **2%/h**
- **Expected growth from Crab Cavity RF noise[*]** for the **HL-LHC** □ **~ 5%/h**



- A lot of **<u>challenging</u>** and **<u>critical</u>** work is ongoing to achieve the 2%/h growth rate.

  - Proposed feedback system from transverse beam measurements (<u>link</u>).

(*) 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)