New results of the SPS Crab Cavity noise emittance blow-up analysis

F. Antoniou, H. Bartosik, N.Triantafyllou, A. Wolski
In collaboration with: X. Buffat, P. Baudrenghien, T. Mastoridis,
And input from N. Mounet, Y. Papaphilippou, G. Rumolo, C. Zannini

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187th HiLumi WP2 Meeting

Outline

- Introduction

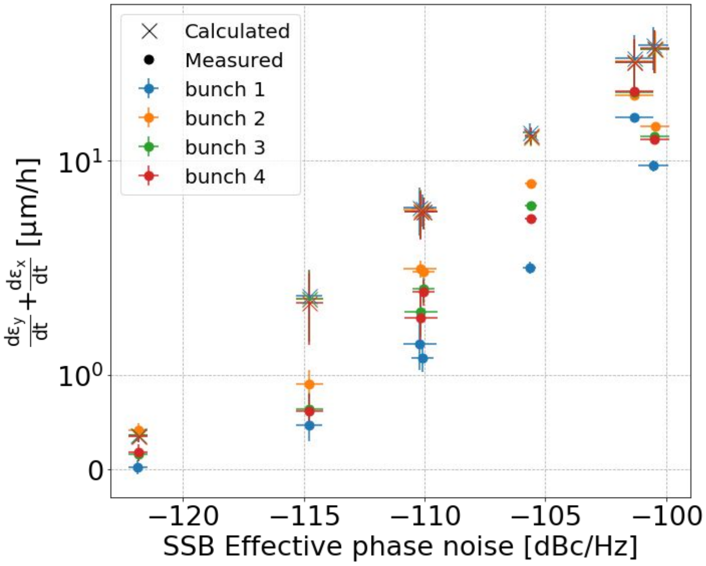
- Suppression of CC noise induced emittance growth from impedance
  - Dependence on amplitude detuning
  - Sensitivity to chromaticity
  - Phase vs Amplitude noise

- What is the mechanism behind these observations?
  - Dipolar vs quadrupolar impedance
  - Pure dipolar noise induced emittance growth
  - CC noise at 200 MHz
  - Coherent tune shift vs incoherent spectrum

- Summary

Motivation

- SPS CC tests in 2018: MD5 → Various levels of **noise** were injected on the crab cavity RF to study the **impact on the emittance growth** at 270 GeV.
    - Measured emittance growth (dots) was found to be:
        - Different bunch by bunch.
        - **Lower** by a **factor 2-3** than the one **predicted** from the available theoretical models * (crosses).
        - A difference **up to a factor of 5** was observed for **bunch 1** (blue), which was the only one found to be **longitudinally stable.**



Measured (Wire Scan) and calculated during coast for different noise levels.

* P.Baudrenghien and T.Mastoridis PhysRevSTAB.18.101001

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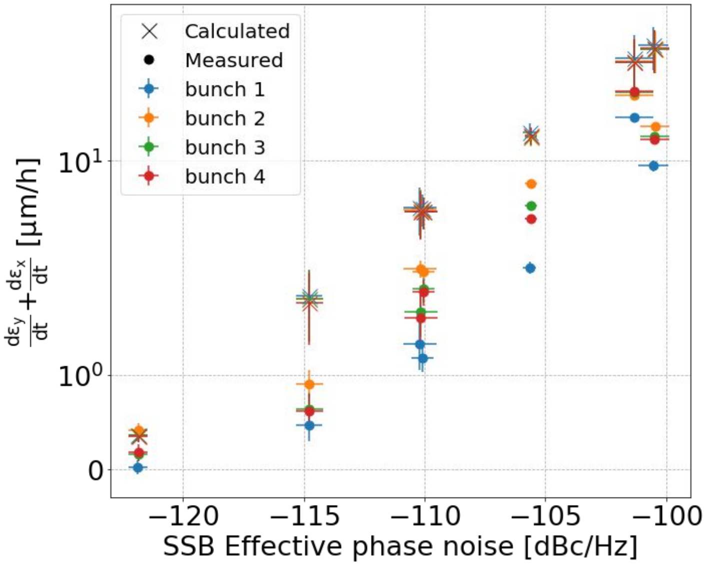


Measured (Wire Scan) and calculated during coast for different noise levels.

- During WP4 meeting (Nov 2020) Yannis proposed to investigate **possible damping mechanisms from impedance.**
  ○ The impedance contribution could also explain the different bunch by bunch growth rate.

- Simulation studies with **PyHEADTAIL** were performed.

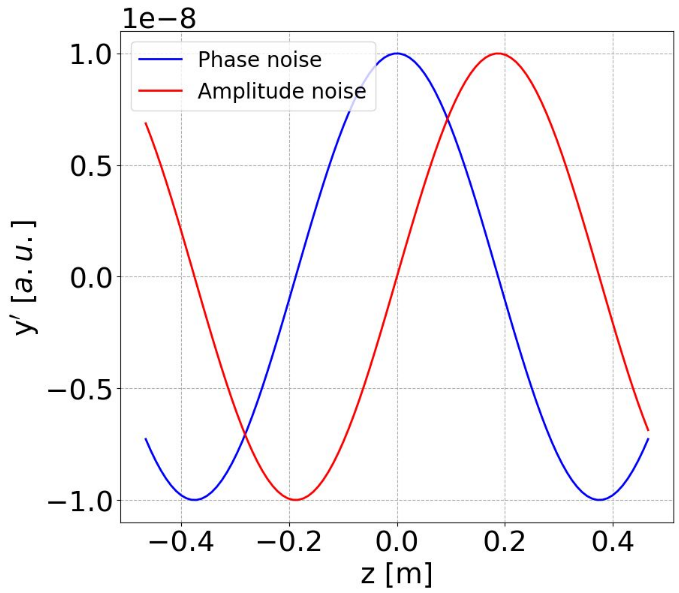
* P.Baudrenghien and T.Mastoridis PhysRevSTAB.18.101001

Crab cavity phase and amplitude noise

- As discussed in PhysRevSTAB.18.101001 the phase and amplitude noise can be:
  - Treated separately for low noise levels.
  - Modeled as the following kicks on the momentum:

Phase noise $$y_1' = y_0' + A\cos\left(\frac{2\pi f_{CC}}{c\beta_{rel}} z\right)$$

Amplitude noise $$y_1' = y_0' + A\sin\left(\frac{2\pi f_{CC}}{c\beta_{rel}} z\right)$$



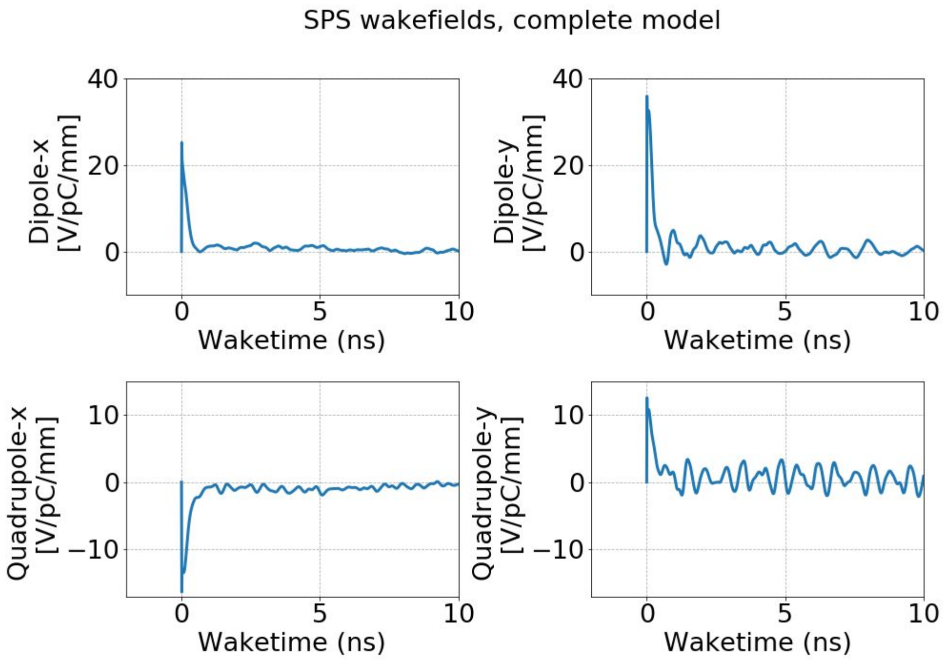
where $y'=p_y/p_0$ is the respective normalised momenta, f_{CC} the crab cavity frequency in Hz, c the speed of light in m/s, β_{rel} the relativistic β and z the longitudinal position in m.

A = Vo/Eb*Δφ(ΔA). Scaling factor

Impedance model

- Used the complete SPS **transverse impedance model** for **Q26** optics as provided by C. Zannini.
  - Kickers, walls, transitions, BPMs, indirect space charge, etc.

- **It is considered that the wakes decay within 1 turn**.



Simulation parameters - PyHEADTAIL

Q26 wakes

- Complete SPS model
- $<\beta_x>$= 42.0941 m
- $<\beta_y>$= 42.0137 m
- 500 longitudinal slices

Single bunch

Local crabbing scheme

Beam energy	**270 GeV**
Horizontal/ Vertical working point, Q_x/Qy	26.13/ 26.18
Synchrotron tune, Q_s	0.0051
Accelerating RF harmonic/voltage	4620/5.088 MV
Normalised horizontal/vertical emittance, ε_x/ ε_y	2 μm/ 2 μm
Vertical beta and alpha function at CC2, β_y/α_y	73.82 m/ 0 m
Horizontal and vertical dispersion, D_x/D_y	0 m/ 0 m
Intensity	**3.5e10**
Macroparticles	5e5
rms bunch length, σ_z	**15.5 cm**
α_{xx}/ α_{xy}	0 m^{-1} / 0 m^{-1}

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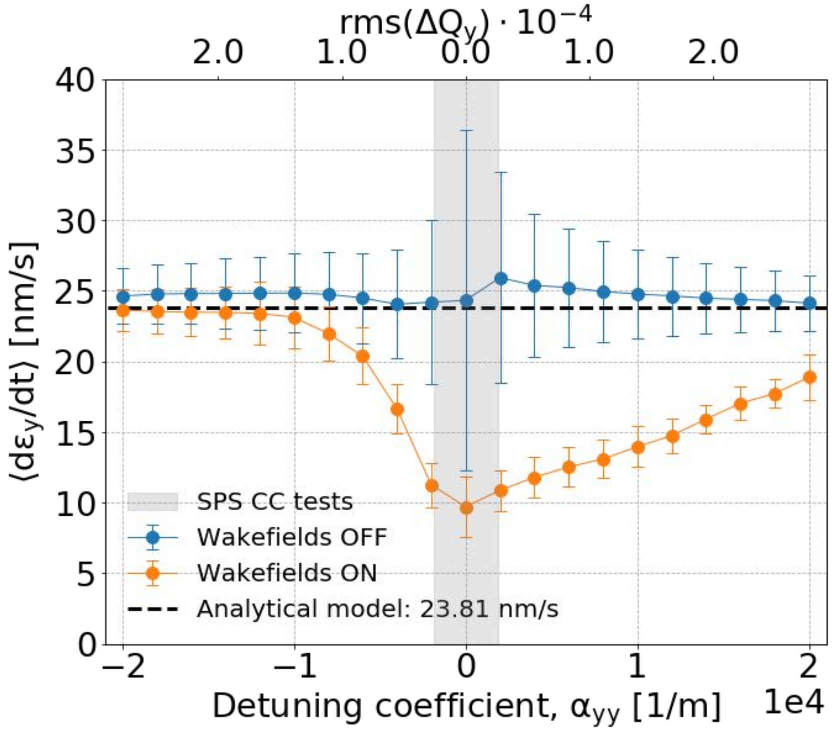
Emittance growth suppression from impedance

- Study with **phase noise** which was dominant in the experiment (here white noise is used).

- The **dependence on α_{yy}** (detuning coefficient) is studied as the machine non-linearities were not clearly characterised during the experiment.



Q'_y=1.0

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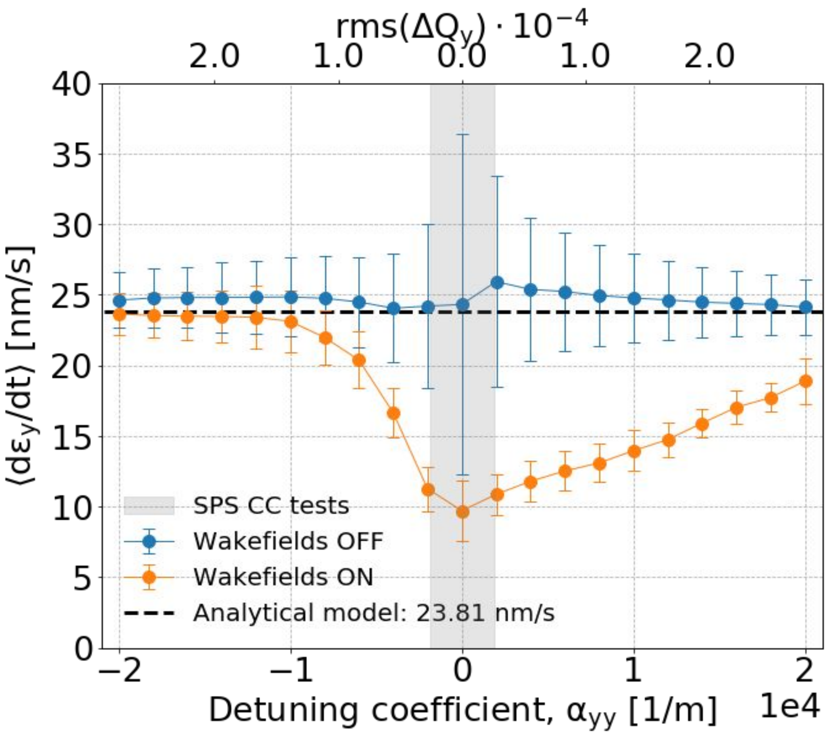
- The **dependence on α_{yy}** (detuning coefficient) is studied as the machine non-linearities were not clearly characterised during the experiment.

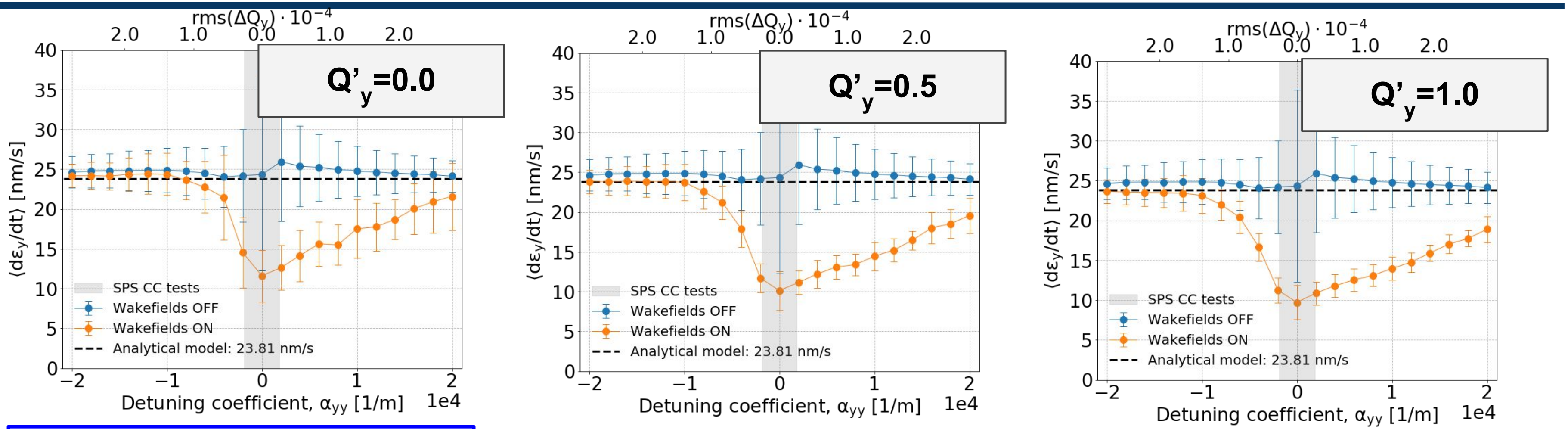
- Clear **suppression** of the emittance growth when the **wakefields are included.**
  - **Up to a factor of 2-2.5** for small values of amplitude detuning (could correspond to the realistic machine conditions).

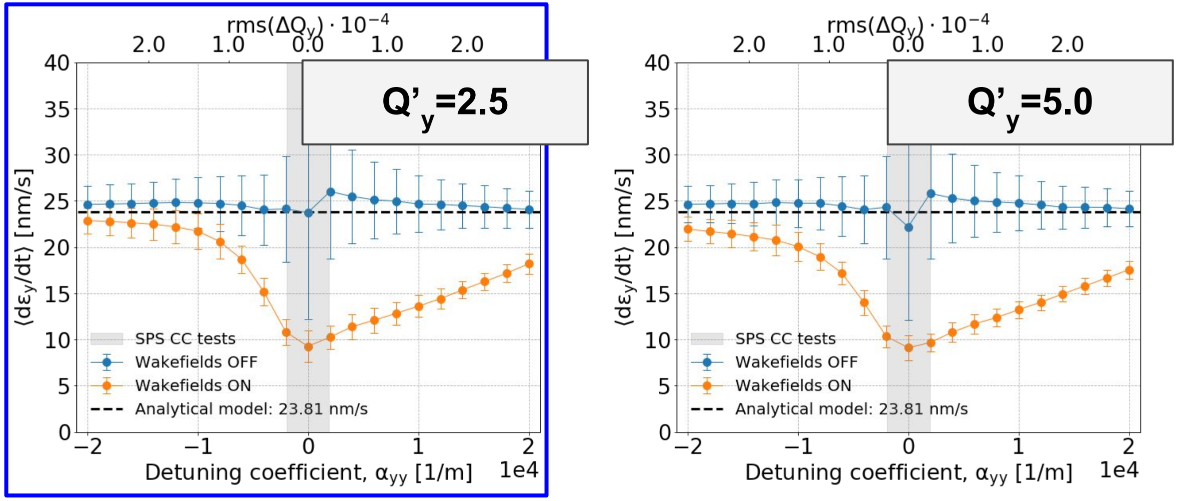
- Clear **asymmetric dependence** on amplitude detuning.
  - Further analysis in the next slides.
  - Detailed mechanism being investigated.



Q'_y=1.0

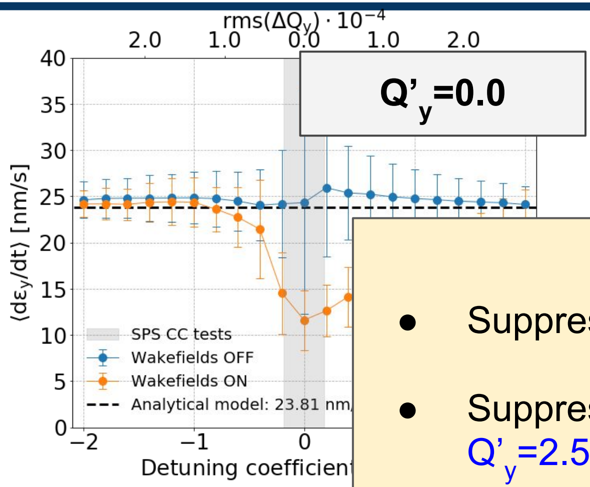
Sensitivity to chromaticity

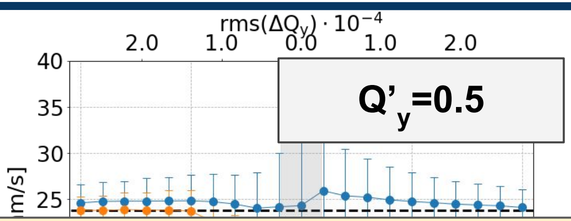


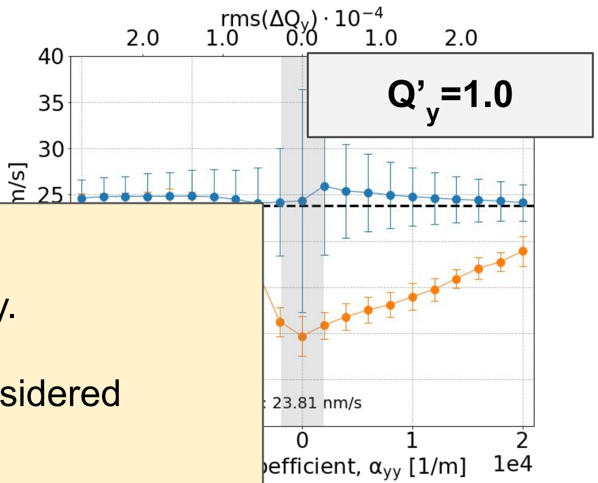


- The sensitivity to *Q'* is studied as the chromaticity during the experiment was not clearly characterised.

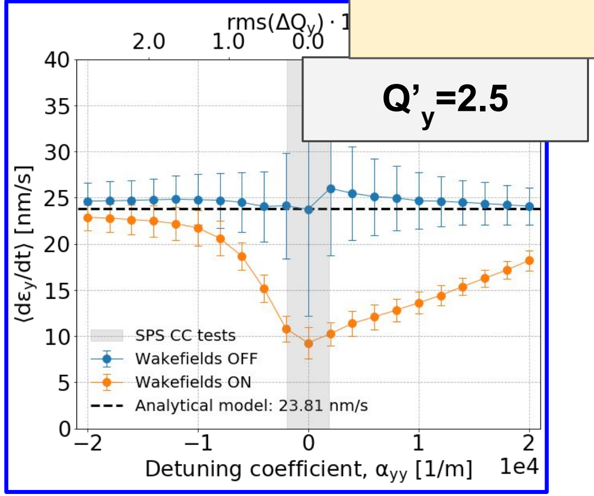
Sensitivity to chromaticity

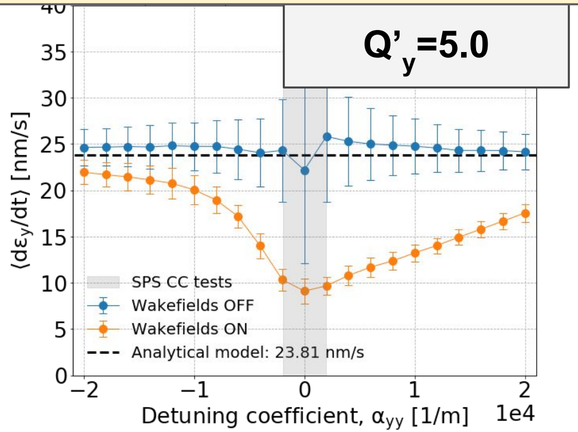






- Suppression even for zero linear chromaticity.
- Suppression up to a factor of **2.5** for the considered $Q'_y=2.5$ during the MD.

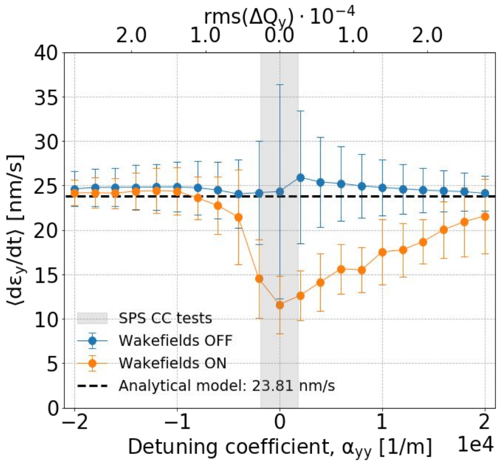


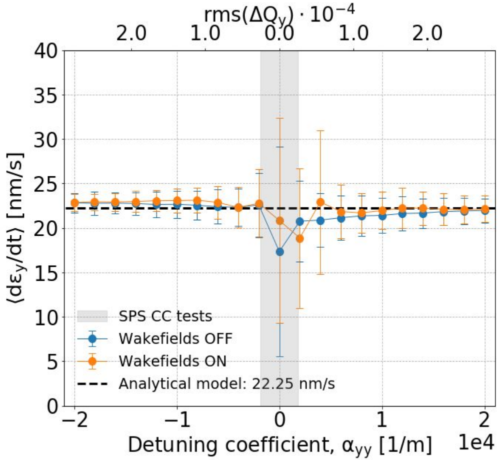


- The sensitivity to *Q'* is studied as the chromaticity during the experiment was not clearly characterised.

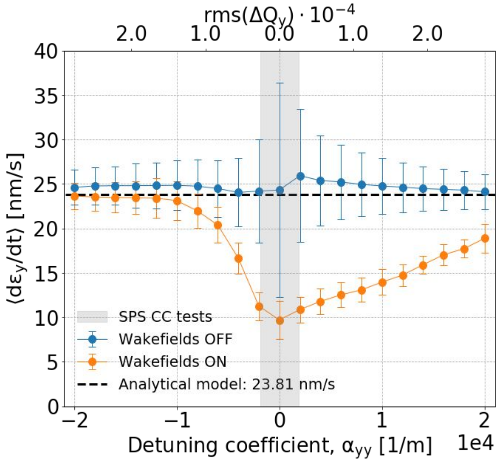
Phase vs amplitude noise induced emittance growth

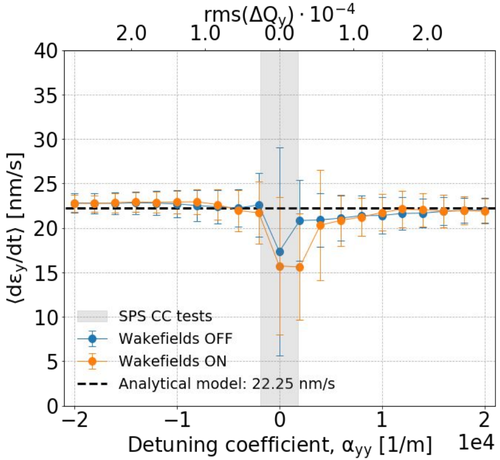
$Q'_y=0$





$Q'_y=1$





Phase noise
Amplitude noise

Suppression of the emittance growth **only** for **phase noise** induced emittance growth.

- Phase noise is **similar** with a **dipole noise kick** but with a high order distortion**.**
- It seems that the observed suppression **is related to the dipole motion**.

f_{CC} = 400 MHz

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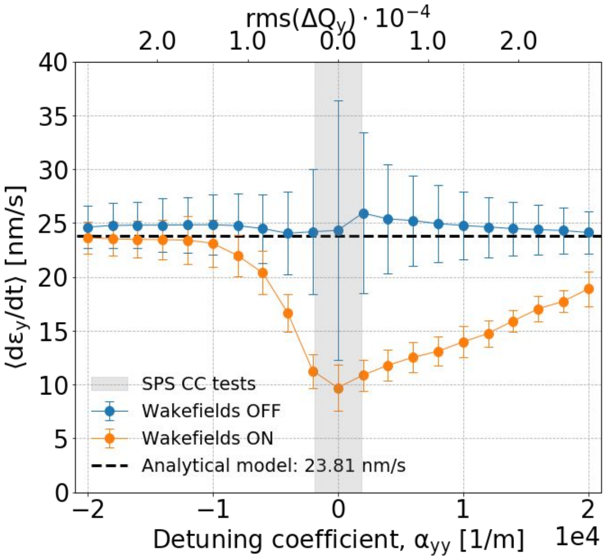
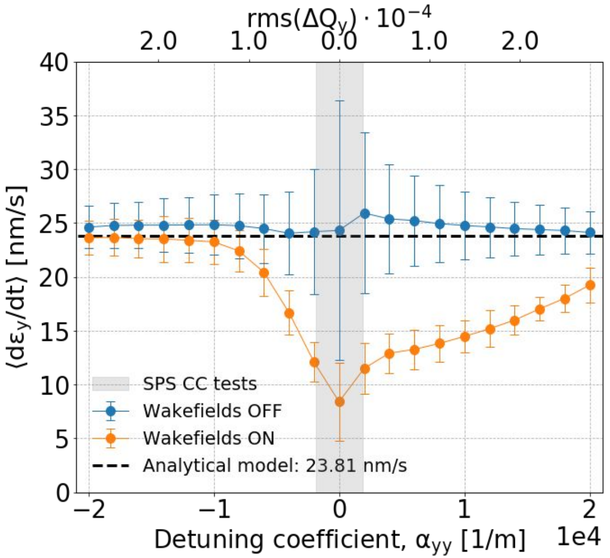
Dipolar and Quadrupolar impedance

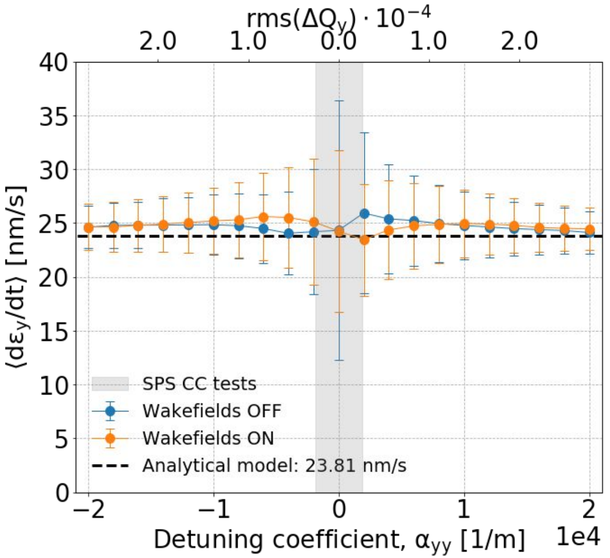
Quadrupolar + dipolar impedance



Only dipolar impedance



Only quadrupolar impedance

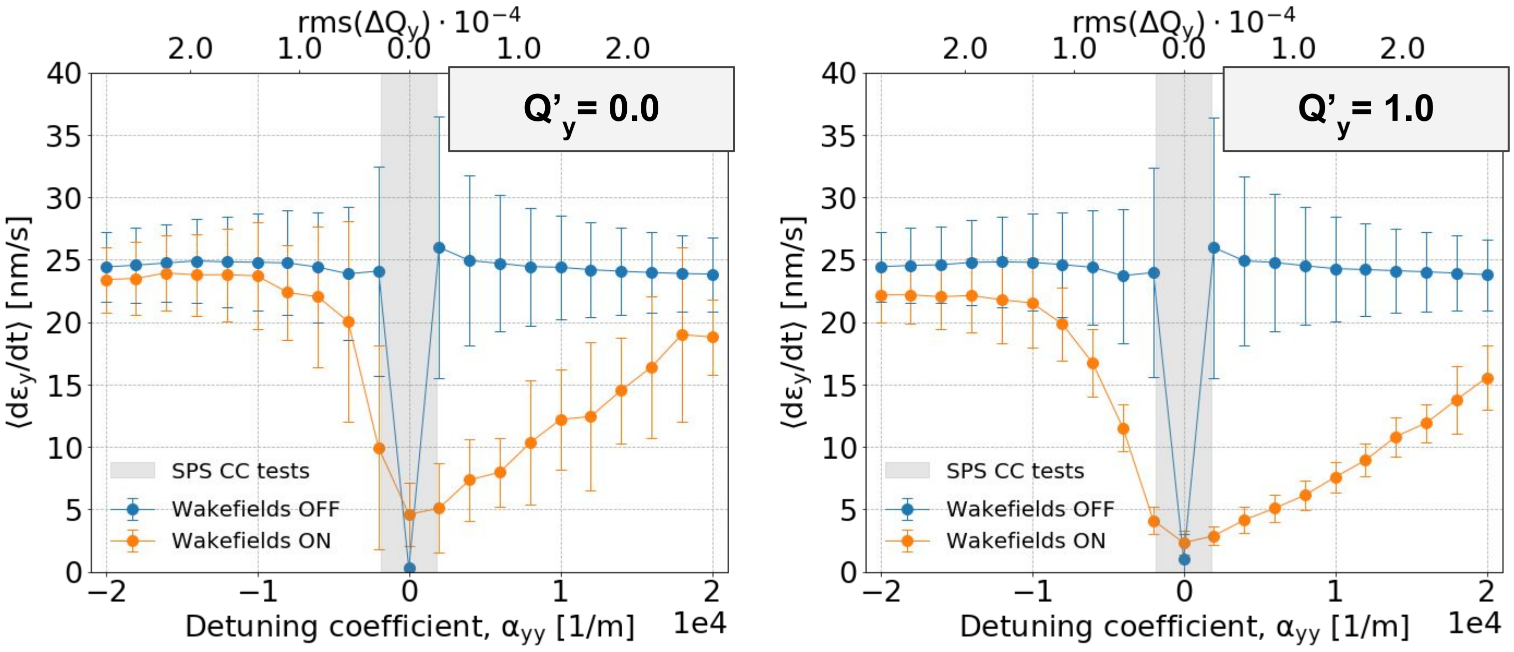


The suppression of the emittance seems to be a result of the **dipolar impedance.**

Q'_y=1.0

Pure dipolar noise kick

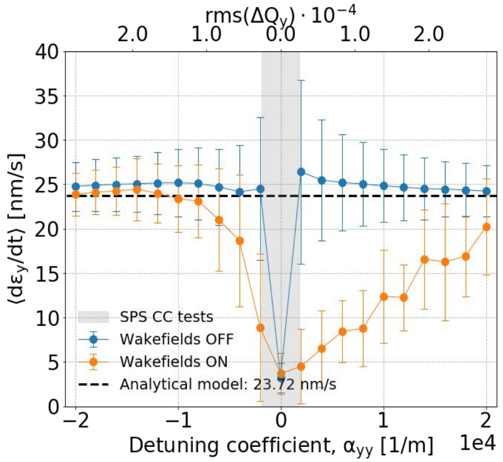
- The suppression of the emittance growth from a pure dipolar noise kick is studied as a test case to better understand the mechanism behind the observations.

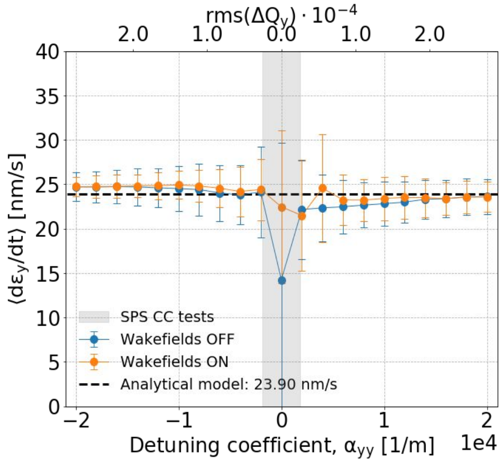


- With a pure dipole noise kick (mode 0) an emittance growth suppression **up to a factor of 10** is observed.
- Without impedance, no emittance growth for zero amplitude detuning as expected

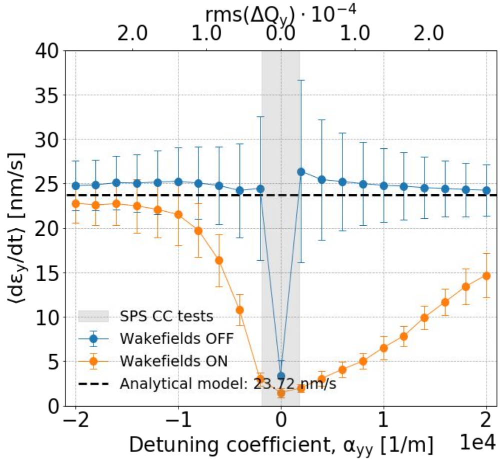
CC noise at 200 MHz

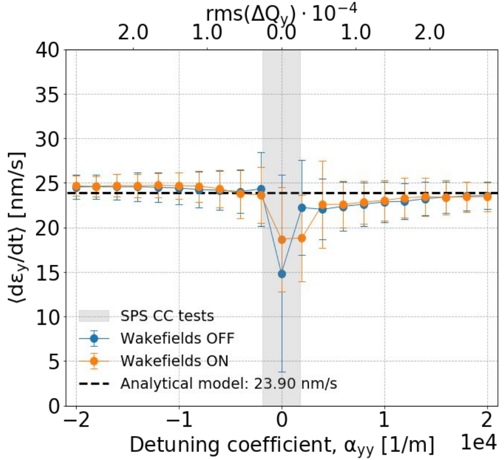
$Q'_y = 0$





$Q'_y = 1$





Phase noise

Amplitude noise

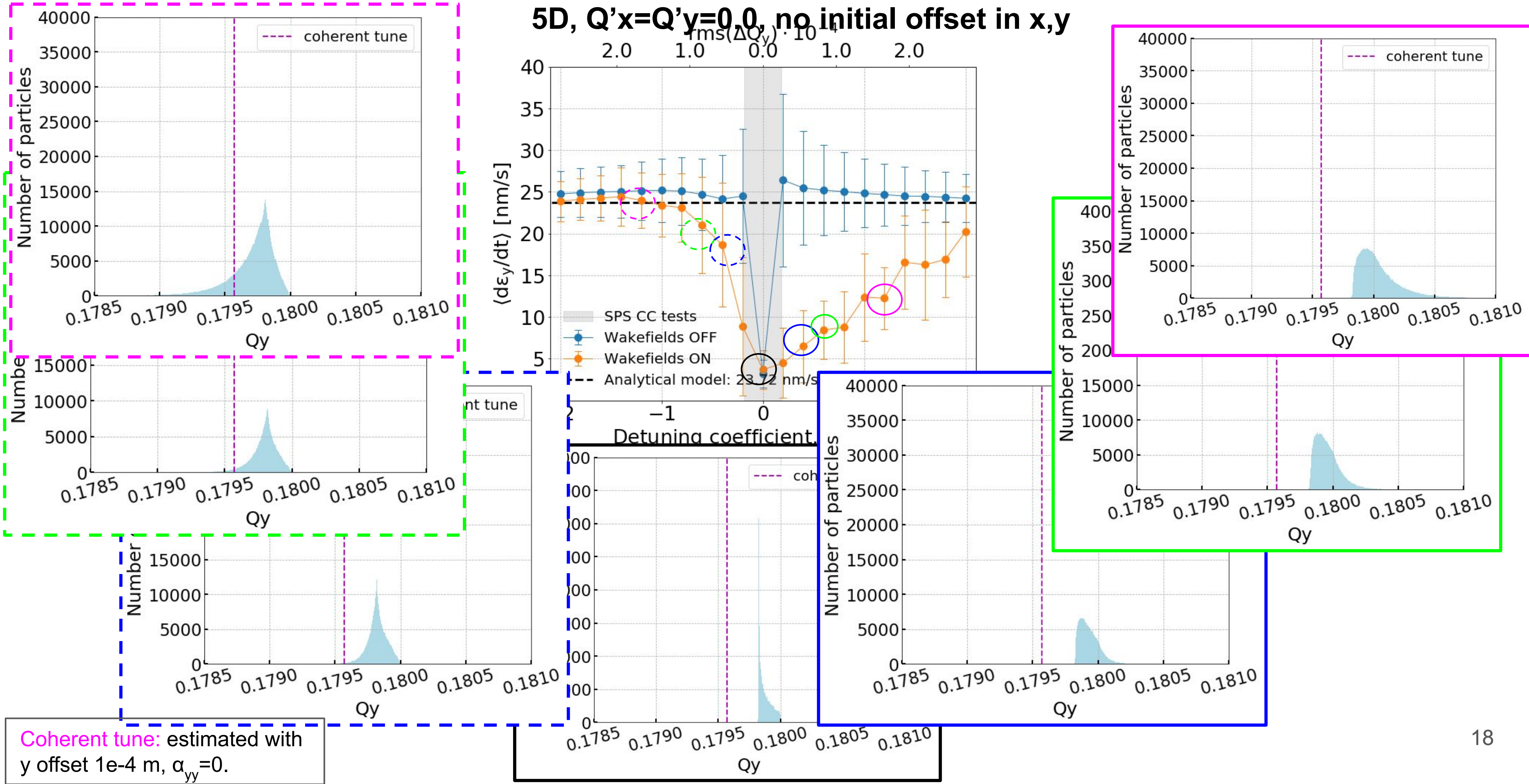
The CC RF has same harmonic as the accelerating RF → The **phase noise** kick is very close to a pure dipolar noise kick and thus **similar strong suppression** is observed.

No impact on the amplitude noise induced emit growth.

f_{CC} **= 200 MHz**

Overlap of the coherent tune and the incoherent spectrum

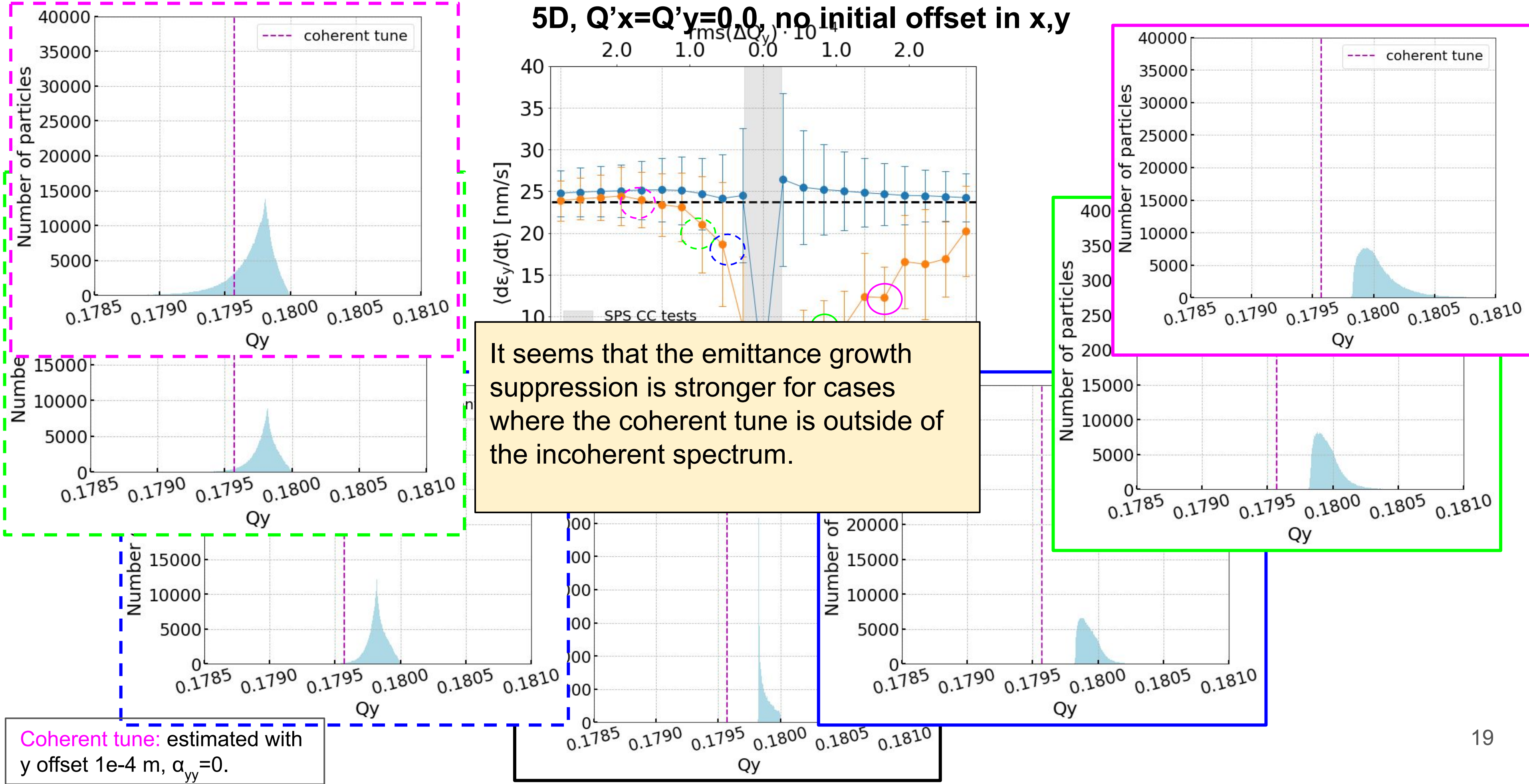
5D, Q'x=Q'y=0.0, no initial offset in x,y



Coherent tune: estimated with y offset 1e-4 m, α_{yy}=0.

Overlap of the coherent tune and the incoherent spectrum

5D, Q'x=Q'y=0.0, no initial offset in x,y



It seems that the emittance growth suppression is stronger for cases where the coherent tune is outside of the incoherent spectrum.

Coherent tune: estimated with y offset 1e-4 m, α_{yy}=0.

Connection to past studies with beam-beam interactions

- As pointed out by Xavier, it seems that the **overlap between the coherent mode and the incoherent spectrum** could explain these observations.
  - Theoretical studies*[1] from Y. Alexahin showed that the **efficiency of the feedback** at suppressing emittance growth depends on the **overlap between the coherent mode and the incoherent spectrum**.
  - Simulations studies*[2] for LHC from X. Buffat et al. show very good agreement with this theory.
  - However, in these studies the coherent mode was shifted by **beam-beam and not by impedance.**
- **Future plans**
  - Explore this mechanism with tracking simulations which are expected to be in good agreement with the theory.
  - Try to adapt Yuri's formalism to impedance in collaboration with Xavier.

*[1] Y. Alexahin, "On the Landau Damping and decoherence of transverse dipole oscillations in colliding beams" (link)
*[2] X. Buffat, "Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider" (PhysRevAccelBeams.23.021002)

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Summary

- PyHEADTAIL simulations show that there is a significant emittance growth suppression from impedance.

- For small values of amplitude detuning (that could correspond to the realistic machine conditions) the suppression (~ a factor of slightly more than 2) seems to explain part of the discrepancy in experimentally observed noise emittance growth compared to the theoretical predictions.

- The suppression is a result of the dipolar wakes, dependant on the amplitude detuning.

- The **overlap between the coherent mode and the incoherent spectrum** could explain these observations.

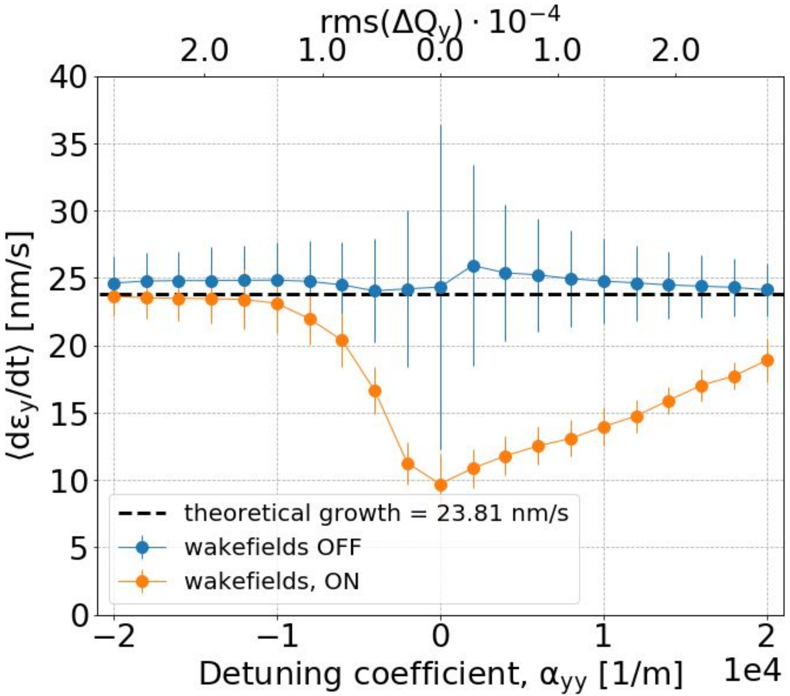
- Studies are ongoing to understand the detailed mechanism in collaboration with colleagues from the CEI section.

Backup slides

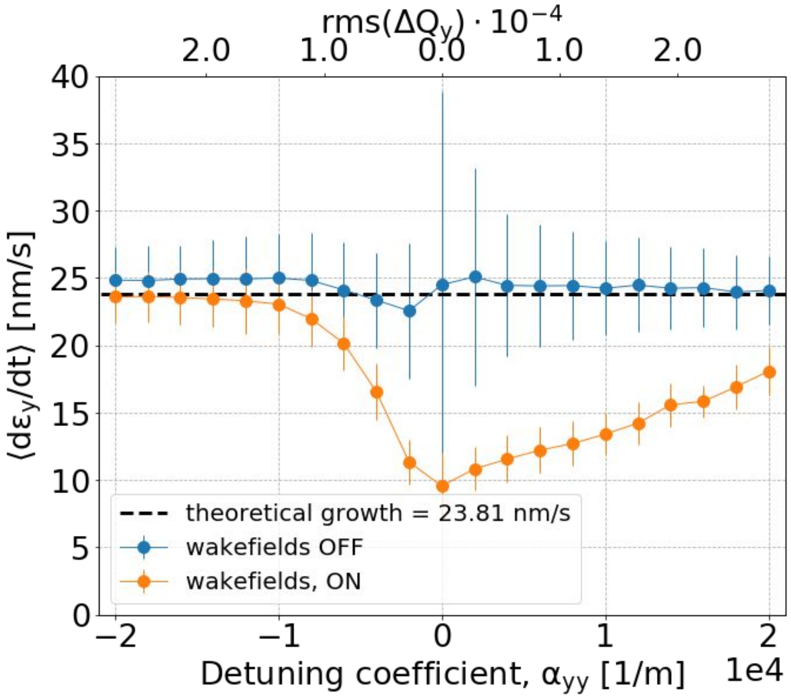
Emittance suppression with a global CC scheme

Q'$_y$=1.0

Local CC scheme



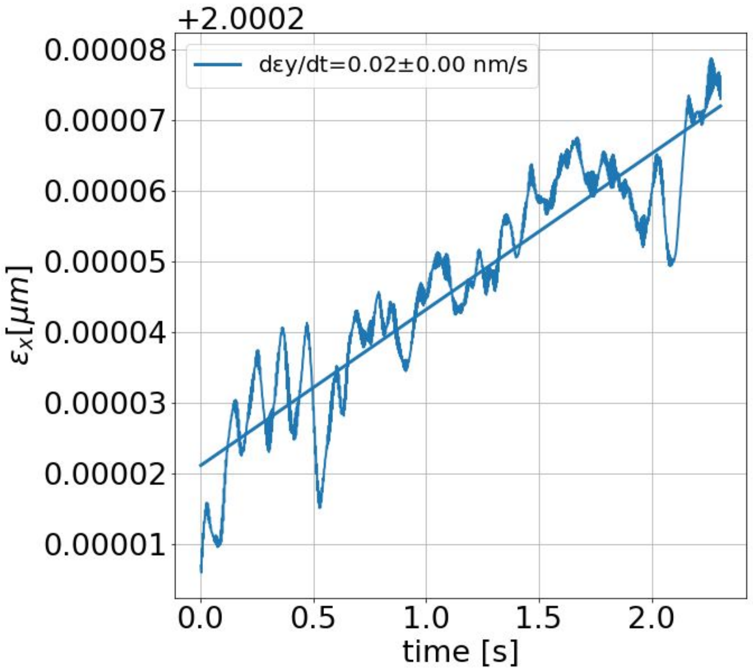
Global CC scheme



* ramping up to 1MV during the first 200 turns

- Phase noise, A=1e-8
- **No sensitivity to the local or global crabbing.**

Emittance growth, only in the presence of Q26 wakes



- The emittance growth in the horizontal plane is about 0.07 μm/h while the natural emittance growth in SPS is about 0.3-0.5 μm/h [reference].
    - We consider this horizontal emittance growth negligible.
- No emittance growth is observed in the vertical plane (link to old studies).