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HL-LHC PROJECT

Emittance growth due to crab cavity noise and expected orbit spread at the crab cavity

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CERN

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- Experimental results
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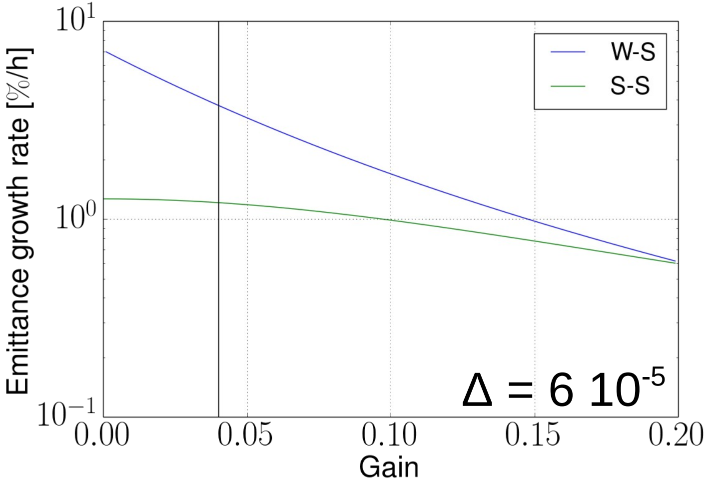
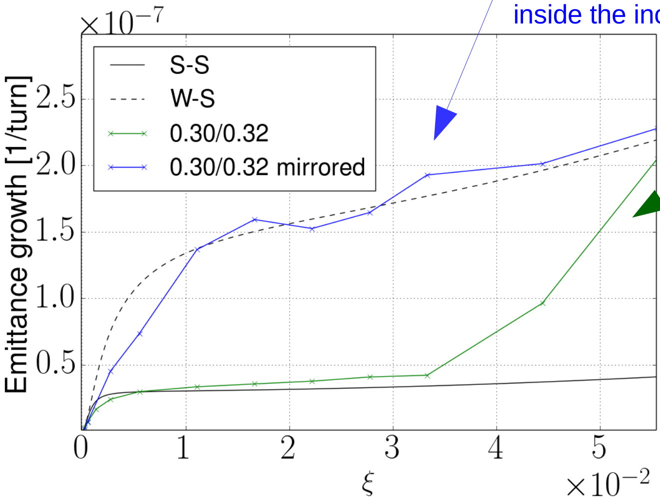
Weak-strong and strong-strong model in theory



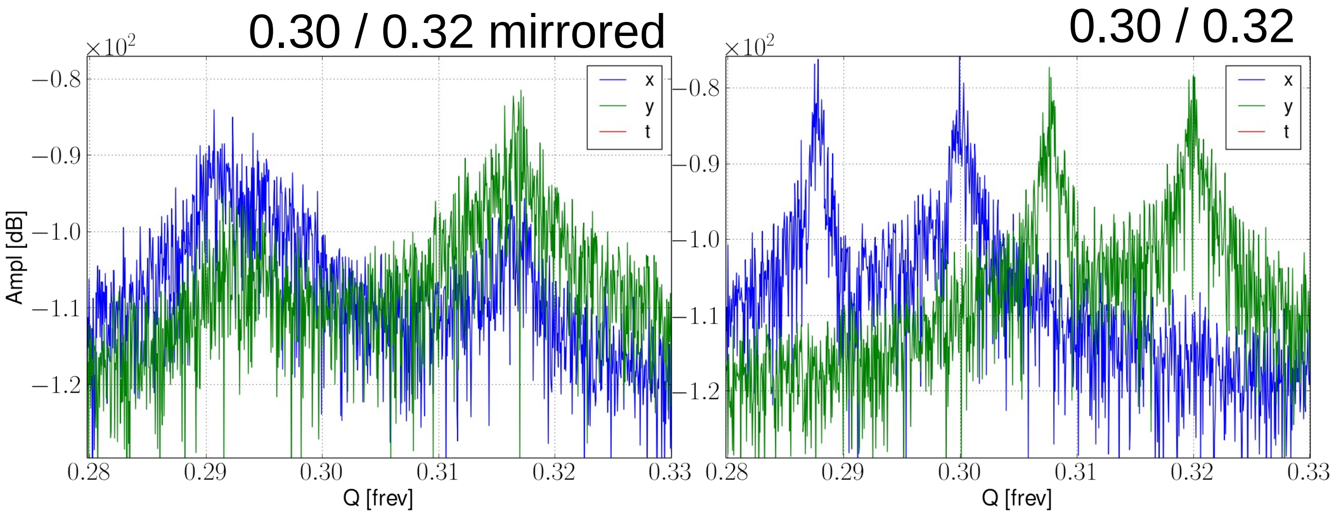


With mirrored tunes for the two beams, the coherent modes are inside the incoherent spectrum

With large beam-beam parameter, the π-mode of the vertical plane is inside the incoherent spectrum of the horizontal plane → similar effect on decoherence due to non-linear coupling (not predicted by first order theory)

- Noise around the betatron frequency leads to emittance growth through decoherence :
- Considering kicks that do not vary on the bunch length and considering the other beam as a fixed lens (weak-strong model) one can derive an analytical formula, taking into account the effect of the feedback acting on the center of mass oscillation (V. Lebedev)
- Taking into account the coherent motion of the other beam (strong-strong) model, the decohrence is different and its effect on the emittance can be reduced w.r.t W-S model predictions (Y. Alexahin)
- This beneficial impact can only be achieved if the coherent modes are outside of the incoherent spectrum (Y. Alexahin)

Example : Mirrored tune

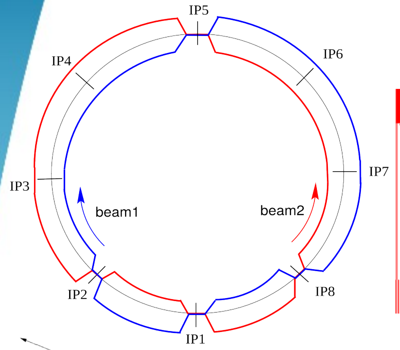


- With mirrored tune, the single particle (incoherent) dynamic is identical for each beam
- The coherent dynamics, and consequently the decoherence is modified

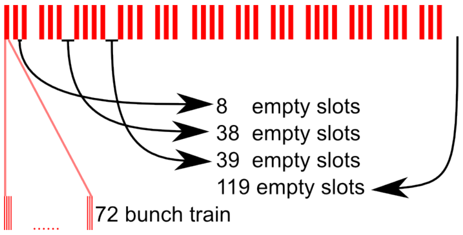
→ For identical tunes, the σ and π mode are visible in both planes

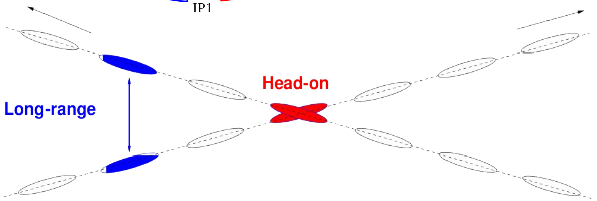
→ For mirrored tunes the coherent beam-beam modes have intermediate frequencies that are in the incoherent spectrum

Weak-strong and strong-strong model in practice

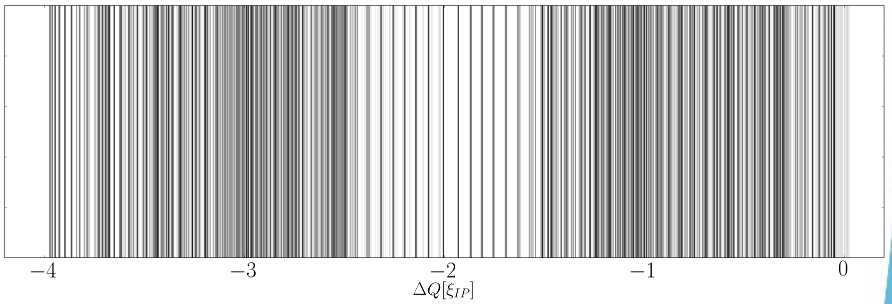


LHC nominal scheme :





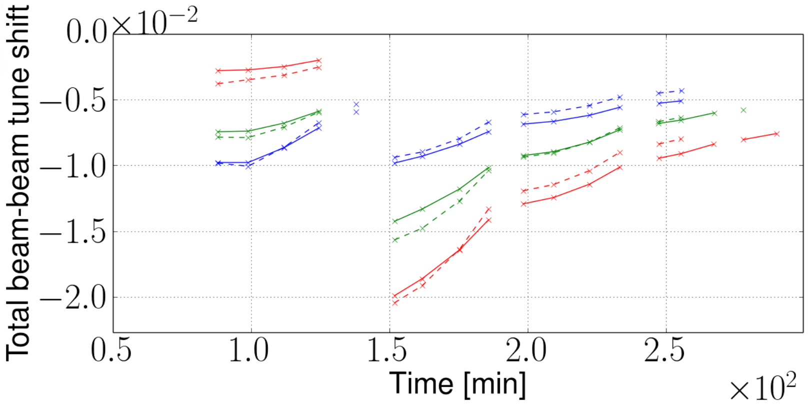
Frequencies of coherent beam-beam modes (Q'=0)

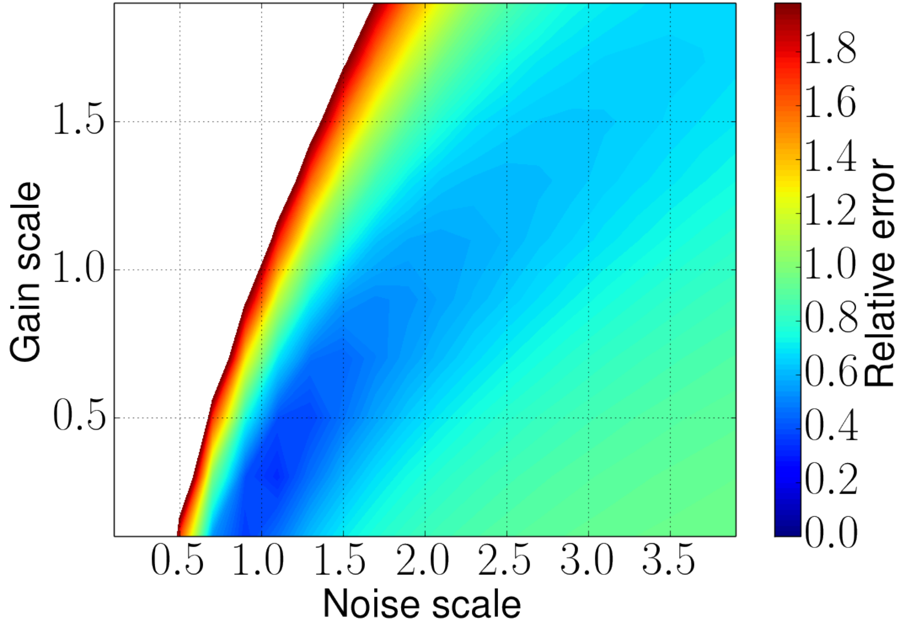


- LHC features a complicated scheme of beam-beam interactions, most coherent modes are inside the incoherent spectrum (T. Pieloni, PhD thesis, EPFL)
- The chromaticity creates an interplay between sidebands, affecting the decoherentce in a similar way even in simple configurations of beam-beam interactions

→ The W-S model is accurate enough for most relevant LHC and HL-LHC configurations

Experimental results





- Past studies at injection energy showed worrying results (interplay with other sources of noise, tune ripple?) (J. Barranco, CERN-ACC-NOTE-2016-0020)

  → Designed an experiment at top energy allowing for a scan of ADT gain / beam-beam tune shift within reasonable amount of time profiting from ADT flexibility (D. Valuch)
- The results indicated a good agreement with the W-S model, assuming a large error on the assumed ADT gain

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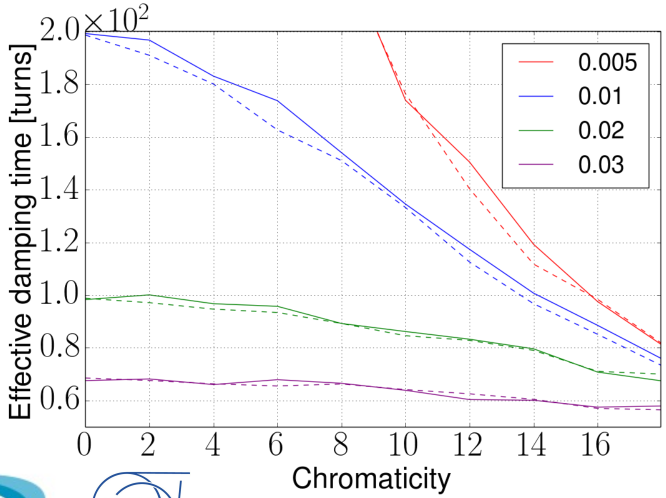
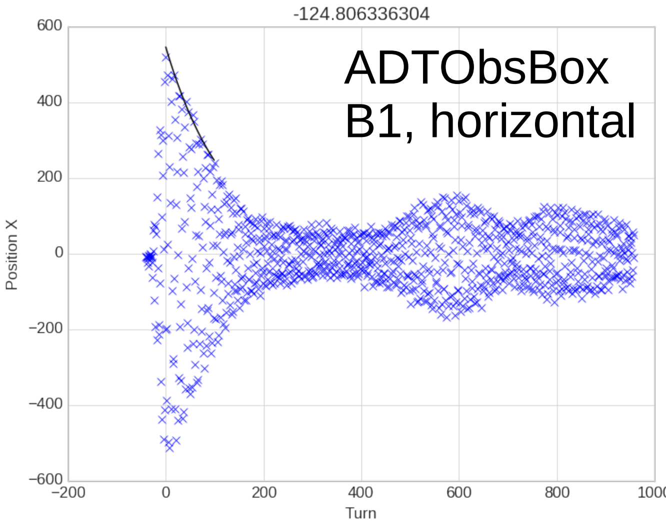
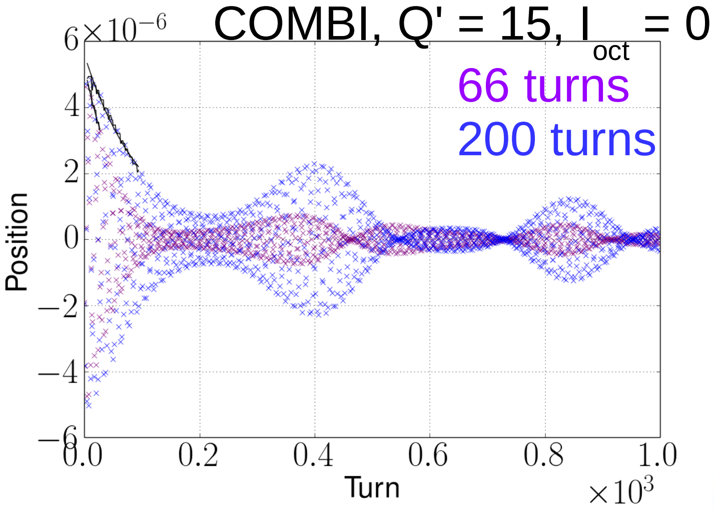
Measurement of the ADT damper gain

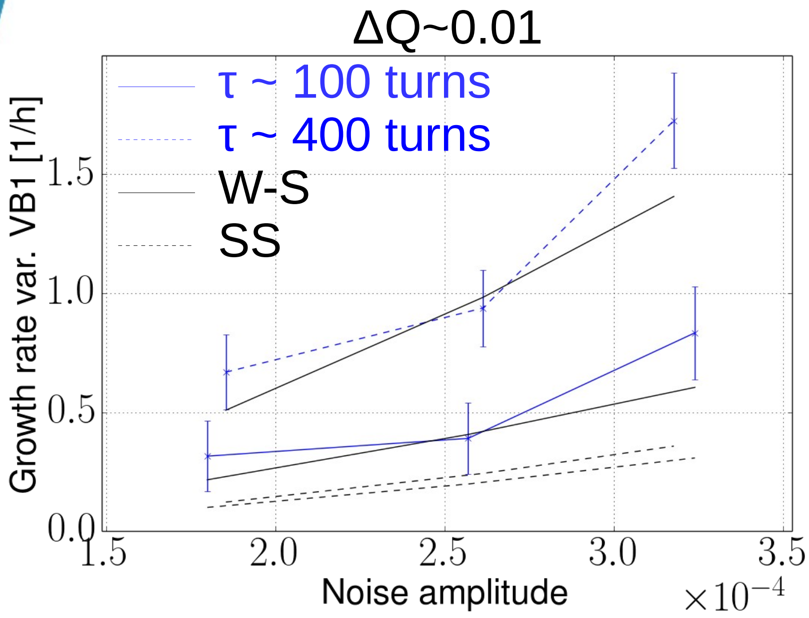
- The reduced gain for single bunches was confirmed by re-analysing another test of single bunch tune measurement at flat top
- The comparison with COMBI simulations suggest that the ADT damping time is shadowed by the chromatic decoherence → the gain is about 4 times smaller than expected

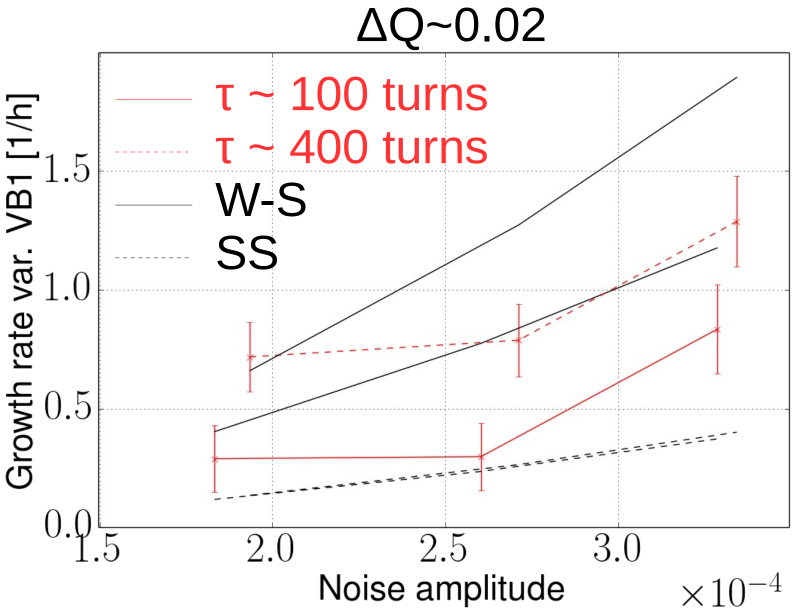






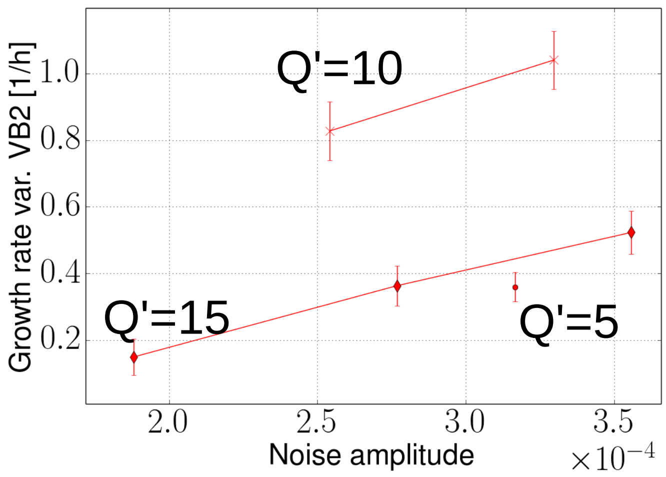
Experimental results



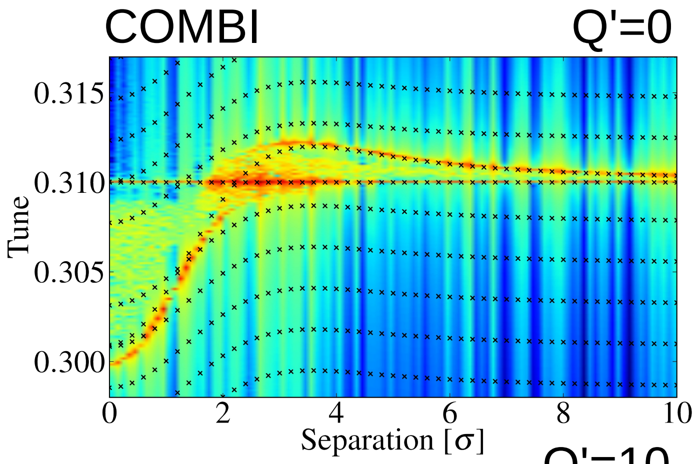


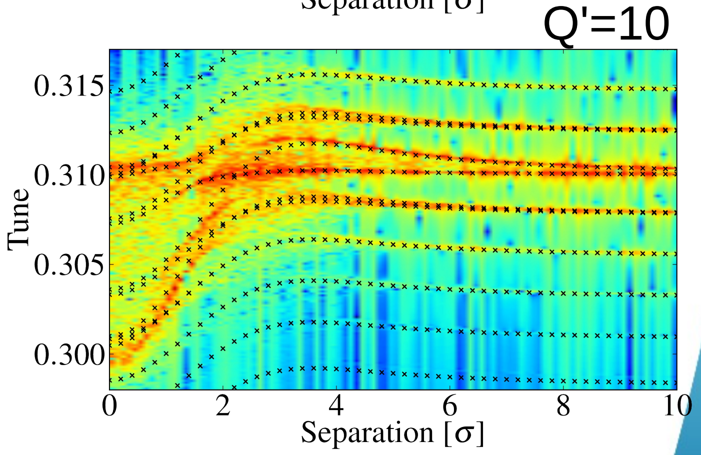
- The variation of the emittance growth rate as a function of the injected noise amplitude follows the W-S model predictions in most cases. In others, the measured variation lies in between the W-S and S-S model, as can be expected depending on phase advance between IPs in the two beams
- Next step : Understand the contribution of the ADT in the measured growth without artificial noise (MD2155)

Experimental results



COMBI





- The impact of chromaticity seemed non-trivial, as expected within S-S model, but not the W-S

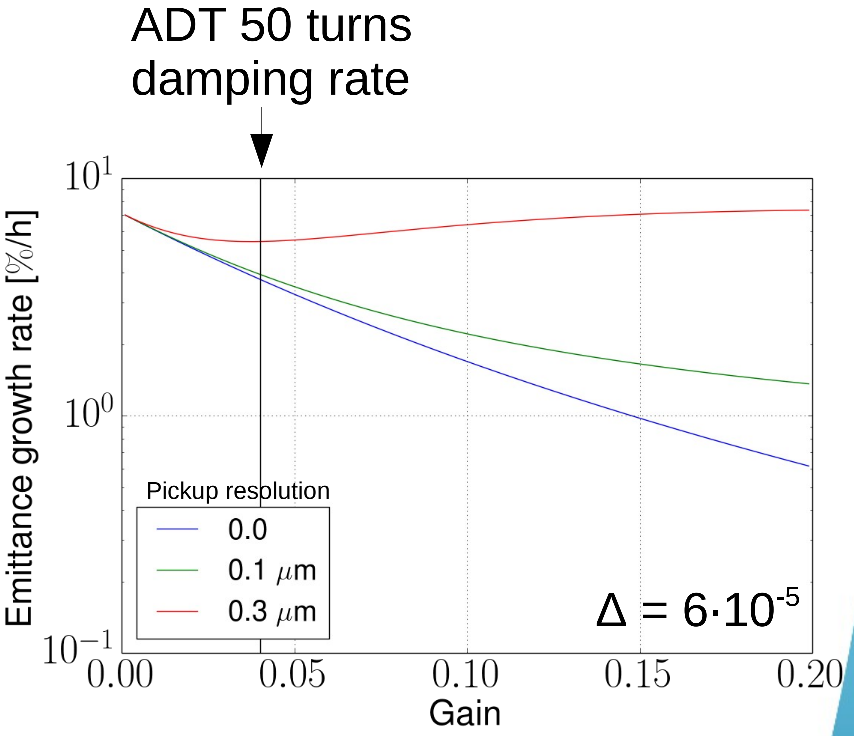
  → This experiment confirms the difficulty to achieve the S-S mechanism for the reduction of the emittance growth, even in the S-S regime

  → HL-LHC design should be based on the W-S model

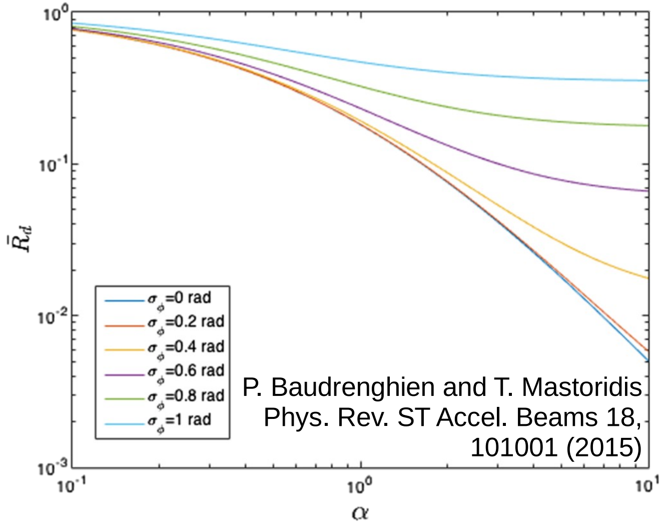
Tolerance for phase noise

- From J. Qiang, et al, BEAM-BEAM SIMULATION OF CRAB CAVITY WHITE NOISE FOR LHC UPGRADE, IPAC 2015 : $\Delta\Phi<10^{-5}$ $\rightarrow$ $1.8\cdot10^{-14}$ rad^2/Hz PSD at Q^*f_{rev} for 2.6 % emittance growth per hour

- New baseline with half the crab cavites (max crab angle 380 μrad) and allowing for 4 %/h $\rightarrow$ $\Delta\Phi<2\cdot10^{-5}$ $\rightarrow$ $6.5\cdot10^{-13}$ rad^2/Hz PSD at Q^*f_{rev}

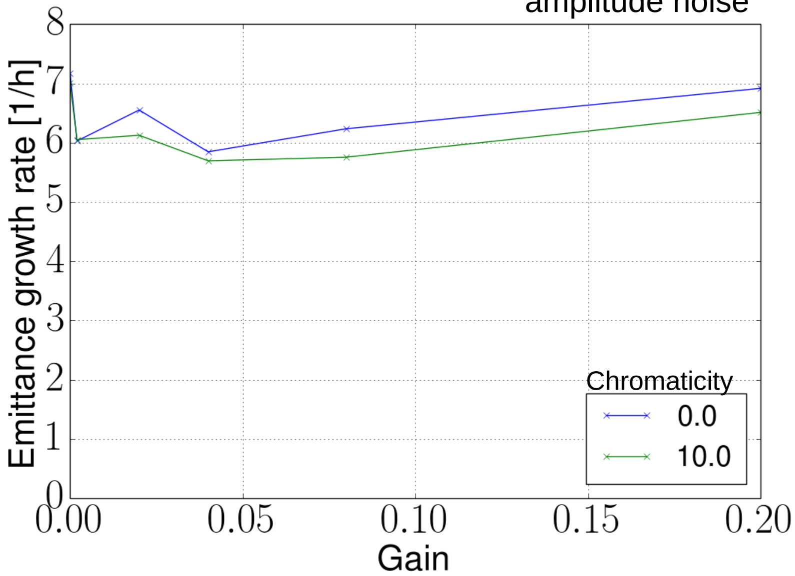


Amplitude and phase noise with RF curvature



P. Baudrenghien and T. Mastoridis Phys. Rev. ST Accel. Beams 18, 101001 (2015)

COMBI in W-S mode with CC amplitude noise

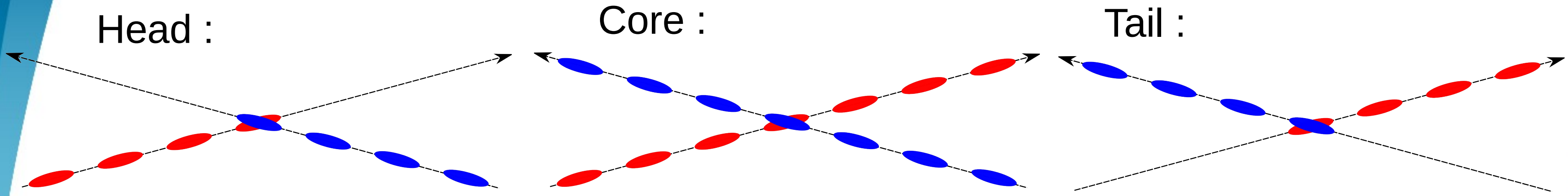


- The feedback based on the centroid motion is inffective in mitigating noise without centroid motion, from the phase noise with RF curvature and the amplitude noise → $5 \cdot 10^{-15}$ rad²/Hz targeting 4 %/h (P. Baudrenghien and T. Mastoridis @ HL-LHC meeting 2015)
- Relaxed settings with the new baseline (factor 1.5 on the noise amplitude) → $1.1 \cdot 10^{-14}$ rad²/Hz PSD at $Q^* f_{rev}$
- In the presence of chromaticity, head-tail modes do have a center of mass oscillation, but it seems too weak to recover the efficiency of the ADT against emittance growth → details to be worked out

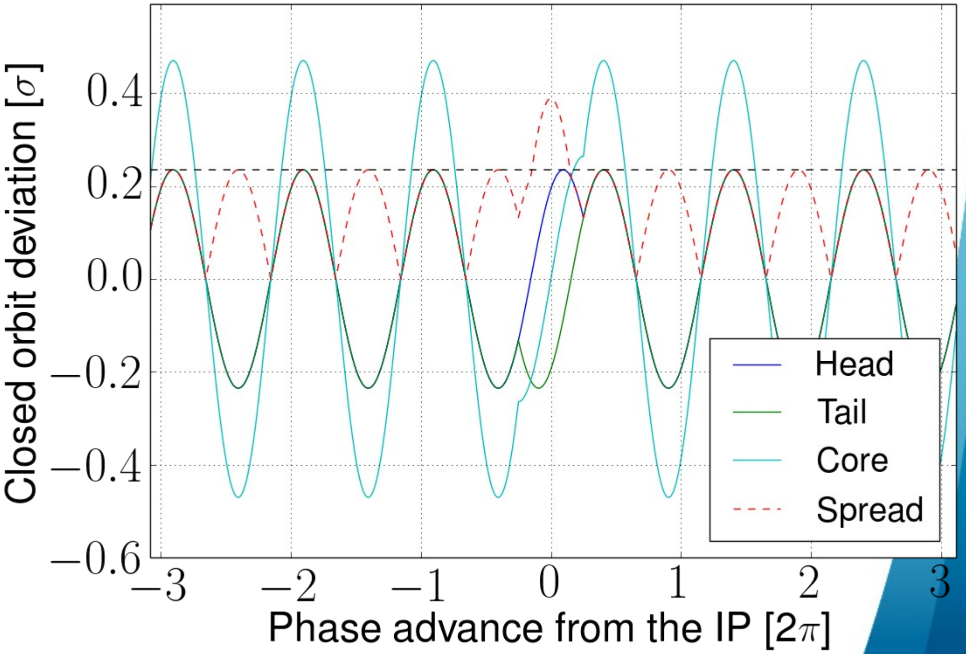
Summary

- The models describing the emittance growth due to external sources of noise were tested experimentally, showing a good agreement with the W-S theory
- Signs of the mitigation predicted by Y. Alexahin in the S-S regime were observed, but are not robust enough to be included in the HL-LHC baseline → further investigations needed
- The feedback is less effective as a mitigation of the emittance growth when the effect of the CC RF curvature is strong or for amplitude noise, even in the presence of chromaticity

Orbit effect



- Long-range beam-beam interactions (or offset interactions) modify the orbit of the two beams due to their dipolar component
- Each bunch experiencing different number of interactions will have different closed orbits (PACMAN effect)
- The average effect can be corrected, but a bunch by bunch spread remains
- The orbit effect depends on 1/d, the normalised separation between the beams, whereas the tune shift and spread depend on $1/d^2$ and $1/d^4$ respectively → The orbit effect is stronger in the HL-LHC w.r.t. LHC



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Orbit effect

- Based on the analytical formula, one expects an orbit spread at the CC in the order of :

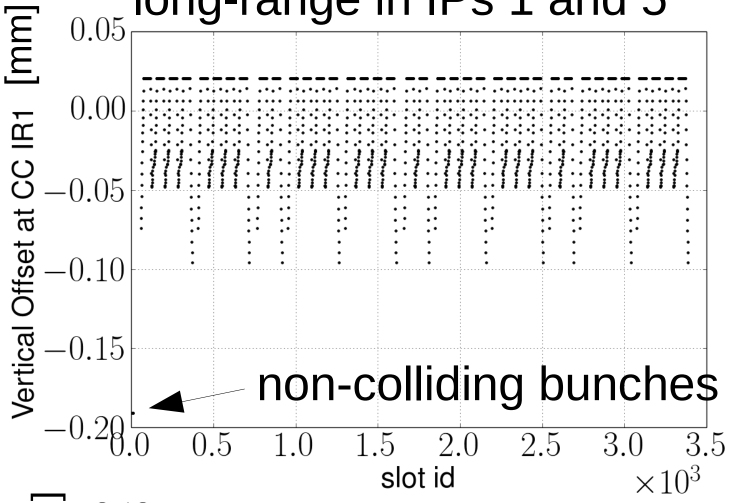
  - 0.2 σ in the two transverse planes due to long-range interaction in IP1 and 5

  - 0.15 σ due to long-range interactions in IP2 and 8

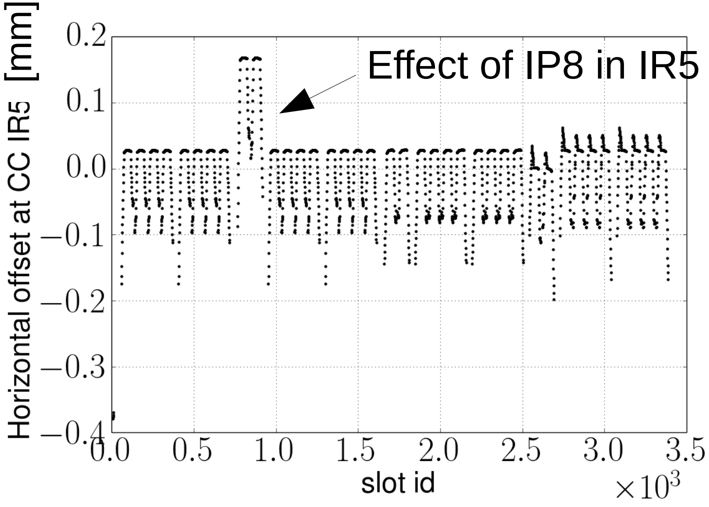
  - 0.1 σ in the two transverse plane due to offset collision in IP2 and 8

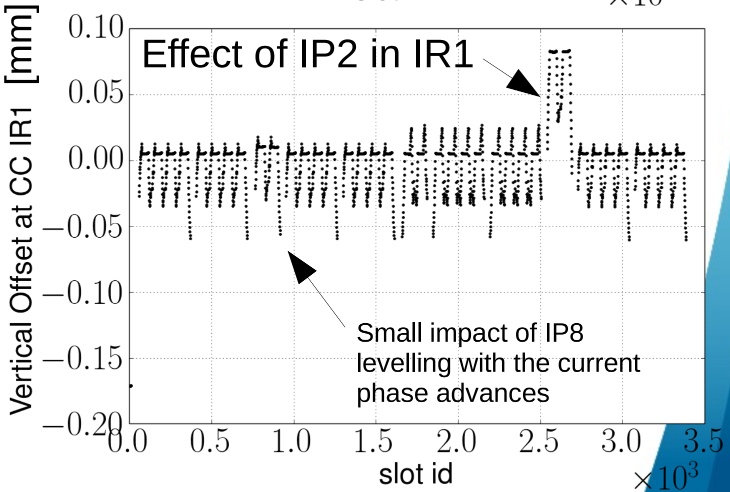
  → Total spread of 0.45 σ in the worst configuration of phase advances

Nominal filling scheme, long-range in IPs 1 and 5



Nominal filling scheme, all beam-beam interactions, including offset levelling in IPs 2 and 8



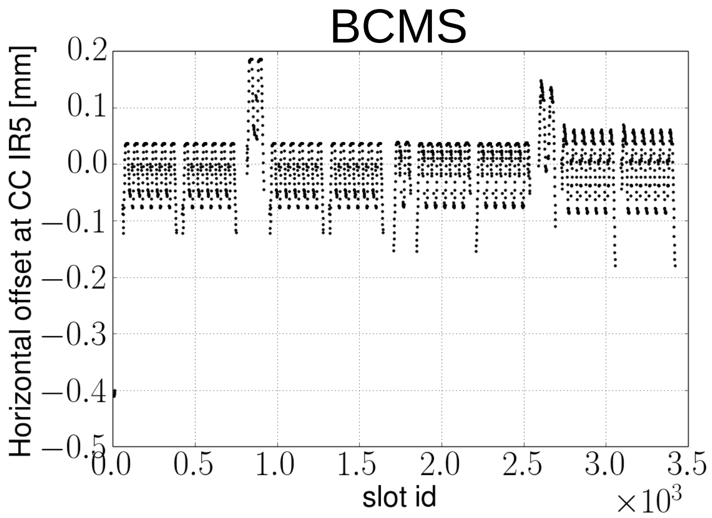


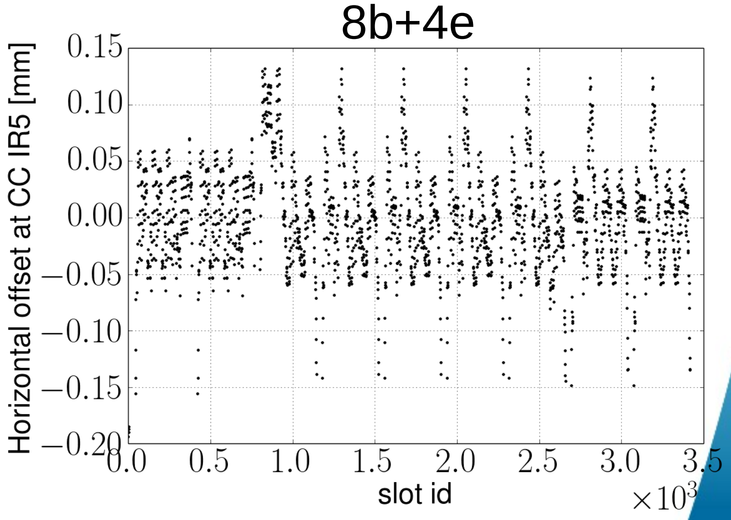
Effect of the filling scheme

- The orbit spread is different for the different scheme, but the RMS remains similar

  → Analysis of the effect on the CC load and on the impact on the orbit tolerance on-going by R. Calaga

	Horizontal RMS orbit at CC in IP5 [mm]	Vertical RMS Orbit at CC in IP1 [mm]
Nominal	0.061	0.025
BCMS	0.062	0.026
8b+4e	0.047	0.023

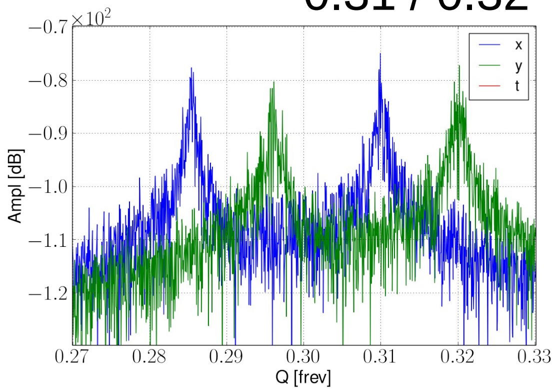


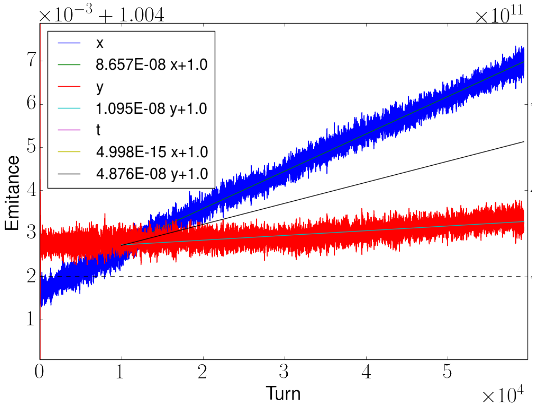


BACKUP : Effect of non-linear coupling

- The presence of the vertical π-mode in the horizontal incoherent spectrum leads to a large growth in the horizontal plane
- The effect is mitigated by increasing the tune split between the planes

0.31 / 0.32





0.30 / 0.32