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

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Weak-strong and strong-strong model in 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 decoherence 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 $\sigma$ and $\pi$ 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 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 decoherence 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
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

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: \( \Delta \Phi < 10^{-5} \)

\[ \rightarrow 1.8 \cdot 10^{-14} \text{rad}^2/\text{Hz PSD at } Q^* f_{\text{rev}} \text{ for 2.6 \% emittance growth per hour} \]

➢ New baseline with half the crab cavites (max crab angle 380 \( \mu \text{rad} \)) and allowing for 4 \%/h \( \rightarrow \Delta \Phi < 2 \cdot 10^{-5} \)

\[ \rightarrow 6.5 \cdot 10^{-13} \text{rad}^2/\text{Hz PSD at } Q^* f_{\text{rev}} \]
Amplitude and phase noise with RF curvature

- The feedback based on the centroid motion is ineffective in mitigating noise without centroid motion, from the phase noise with RF curvature and the amplitude noise $\rightarrow 5 \cdot 10^{-15} \text{rad}^2/\text{Hz}$ targeting $4 \%/\text{h}$ (P. Baudrenghien and T. Mastoridis @ HL-LHC meeting 2015).

- Relaxed settings with the new baseline (factor 1.5 on the noise amplitude) $\rightarrow 1.1 \cdot 10^{-14} \text{rad}^2/\text{Hz PSD at } Q_{\text{rev}}^*$. 

- 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 $\rightarrow$ details to be worked out.

P. Baudrenghien and T. Mastoridis
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

![Diagram showing the orbit effect with Head, Core, and Tail regions.](attachment:orbit_effect_diagram.png)
Orbit effect

- Based on the analytical formula, one expects an orbit spread at the CC in the order of:
  - 0.2 $\sigma$ in the two transverse planes due to long-range interaction in IP1 and 5
  - 0.15 $\sigma$ due to long-range interactions in IP2 and 8
  - 0.1 $\sigma$ in the two transverse plane due to offset collision in IP2 and 8
→ Total spread of 0.45 $\sigma$ in the worst configuration of phase advances

Effect of IP8 in IR5

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

Effect of IP2 in IR1

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

Non-colliding bunches

Small impact of IP8 levelling with the current phase advances
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

<table>
<thead>
<tr>
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<th>Horizontal RMS orbit at CC in IP5 [mm]</th>
<th>Vertical RMS Orbit at CC in IP1 [mm]</th>
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</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.061</td>
<td>0.025</td>
</tr>
<tr>
<td>BCMS</td>
<td>0.062</td>
<td>0.026</td>
</tr>
<tr>
<td>8b+4e</td>
<td>0.047</td>
<td>0.023</td>
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The presence of the vertical $\pi$-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.