Effect of the phase advances between IP1 and IP5 on the coherent beam-beam dynamics

X. Buffat

Acknowledgements : Y. Alexahin, R. De Maria, W. Herr, T. Pieloni

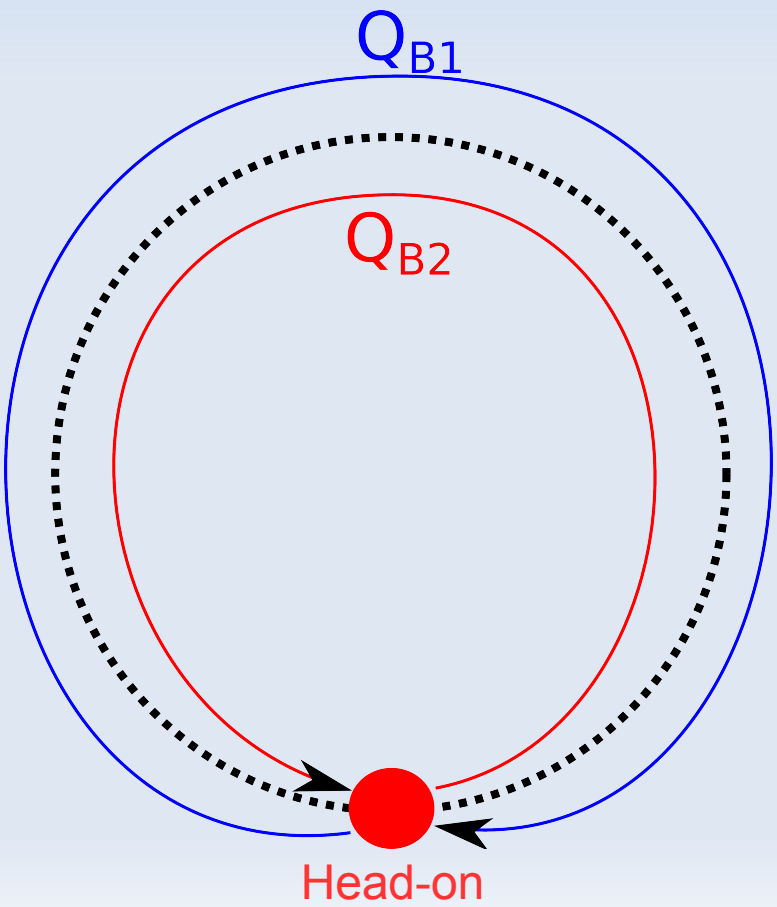
Content

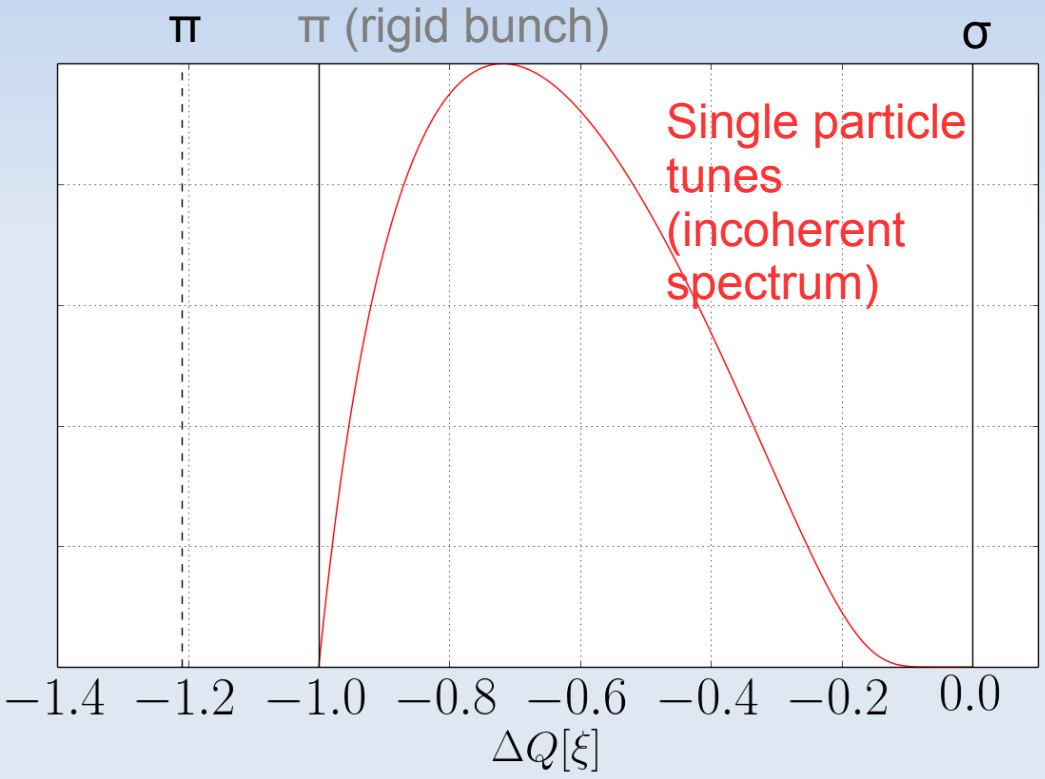
- Head-on interactions
  - Frequency of coherent beam-beam modes
  - Trade-off Landau damping vs. decoherence
  - Landau damping of head-tail modes
- LHC and HL-LHC phase advances
- Long-range interactions
- Orbit effect
- Conclusions

Single head-on interaction

- Two identical beams
- One bunch per beam
- One head-on interaction

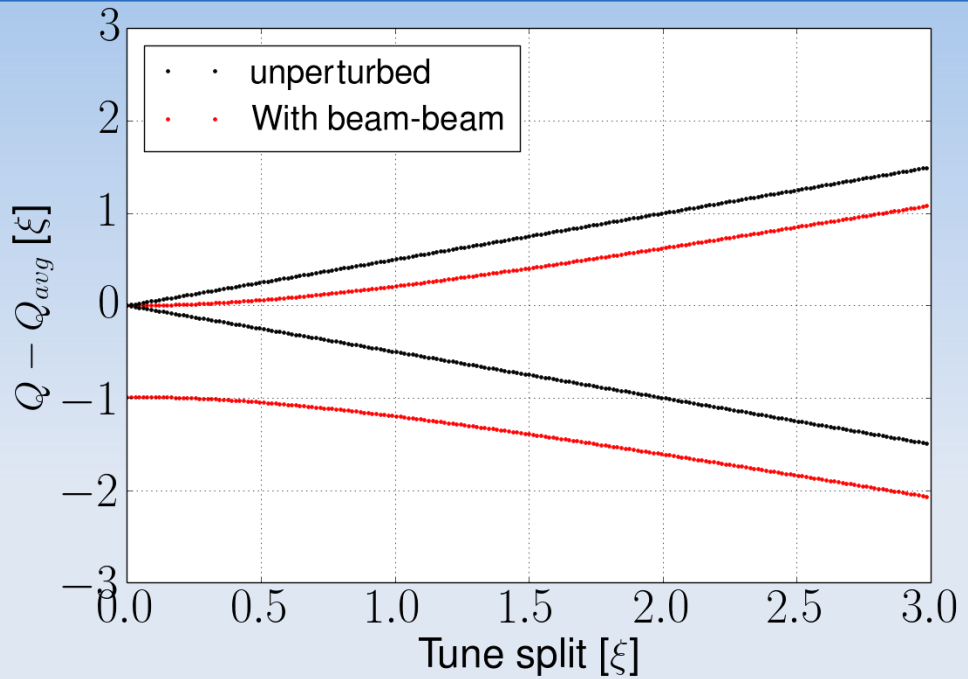
$$Q_{B1} = Q_{B2}$$

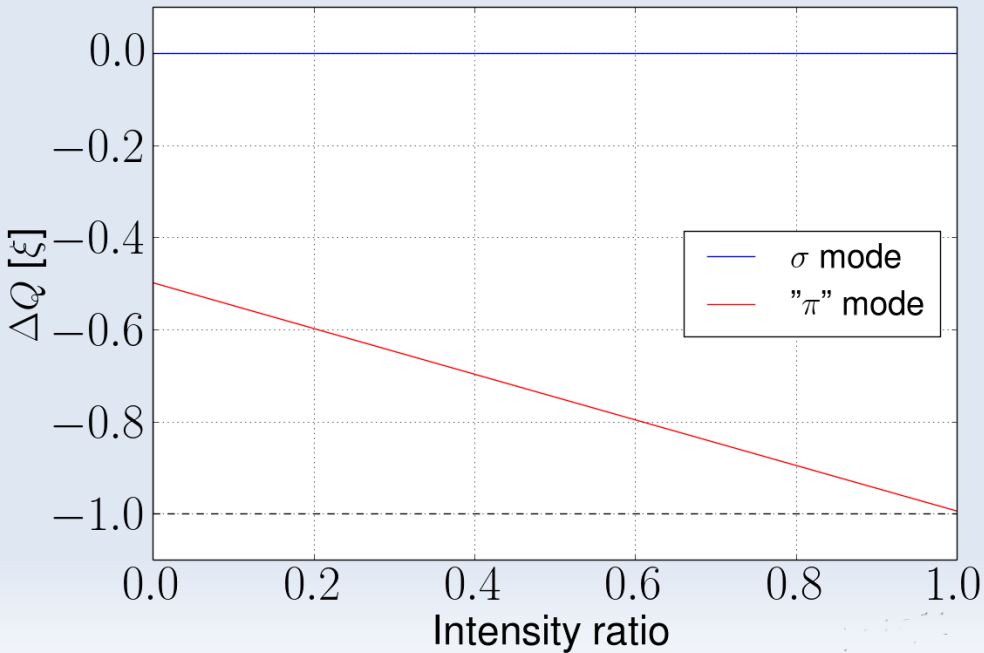




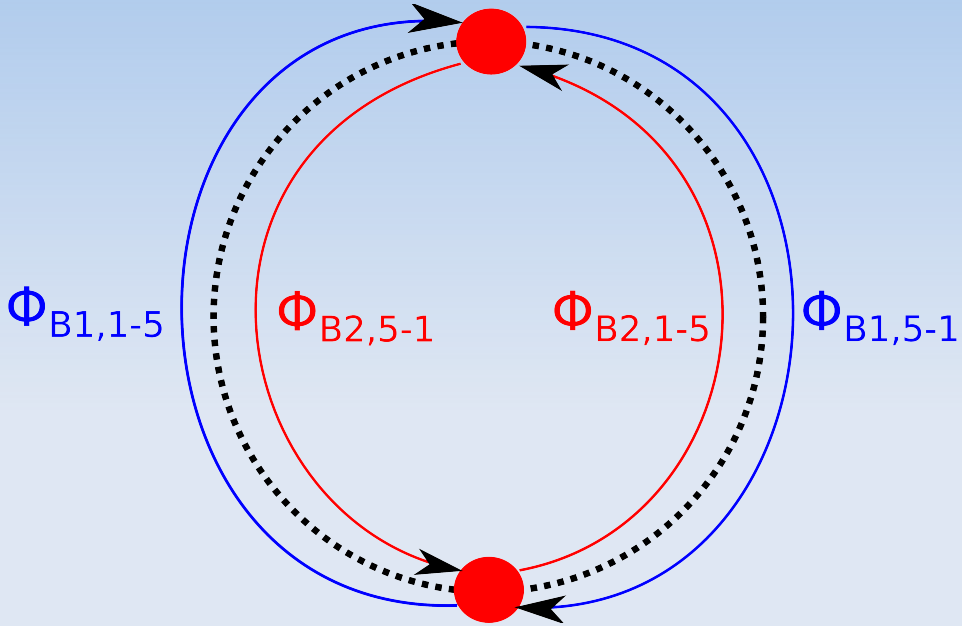
Decoupling mechanisms

- Coupled modes are outside of the incoherent spectrum
- Symmetry breaking tends to decouple the beams (bunch to bunch variations of the intensity/emittance, asymmetric configurations of IPs)
- 'decoupled' modes are inside the incoherent spectrum





2 interaction points



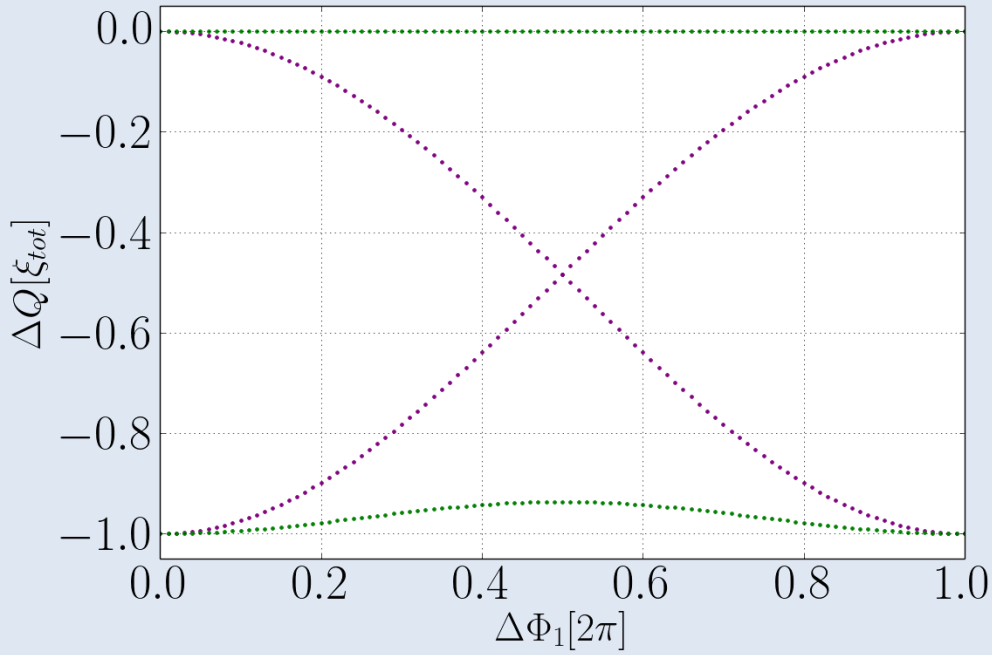
Phase split without global tune change

$\Delta\Phi_{B1} = \Phi_{B1,1-5} - \Phi_{B1,5-1}$

$\Delta\Phi_{B2} = \Phi_{B2,1-5} - \Phi_{B2,5-1}$

Symmetric : $\Delta\Phi_{B1} - \Delta\Phi_{B2} = 2n$

Anti-symmetric : $\Delta\Phi_{B1} - \Delta\Phi_{B2} = 2n + 1$

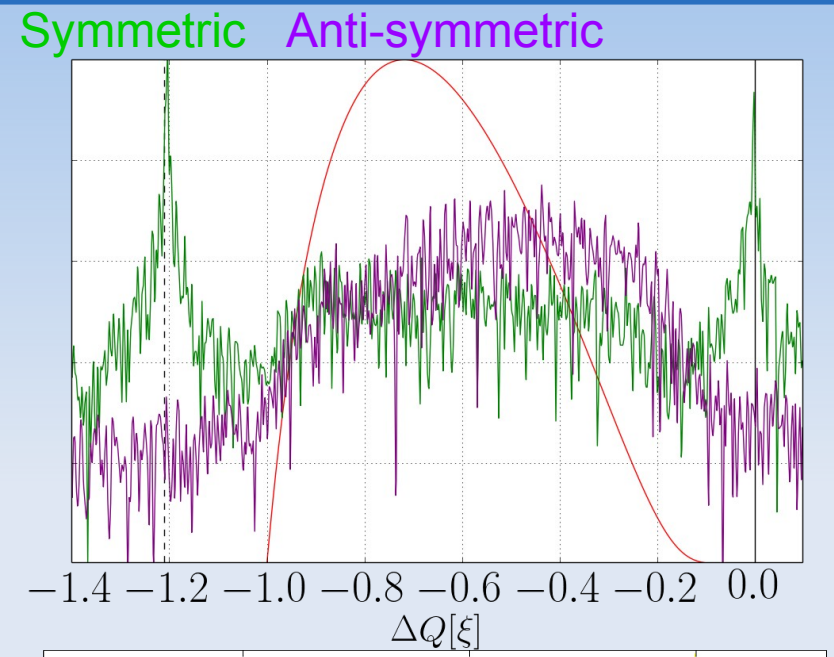


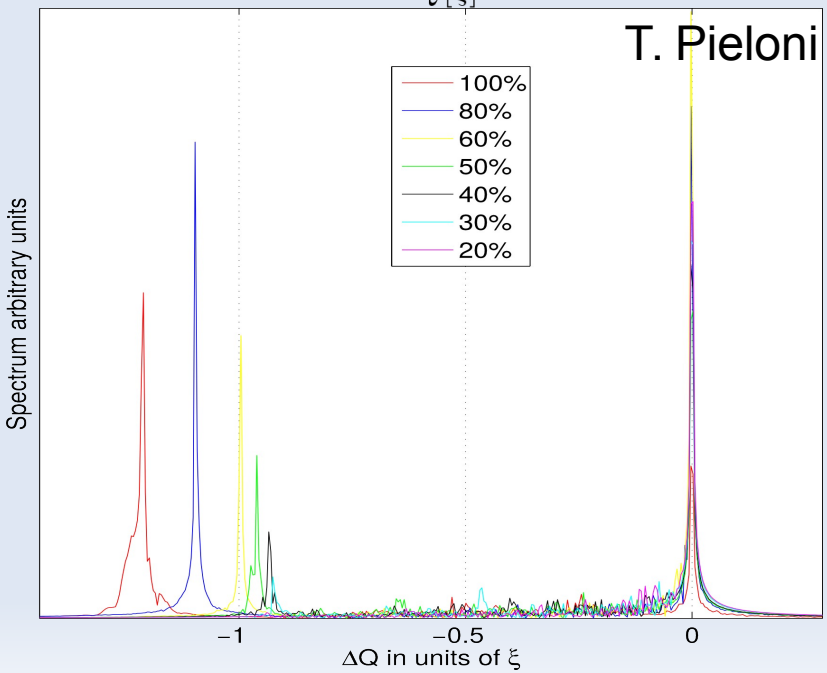
- Anti-symmetric/asymmetric configurations of phases advances between the IPs brings the modes inside the incoherent spectrum

Landau damping

- The presence of an overlap between the coherent mode spectrum and the incoherent spectrum is a necessary condition for Landau damping
- The circulant matrix model (*BimBim*) allows to derive the complex tune of beam-beam-head-tail modes in the presence of impedance
  - No dispersion relation available

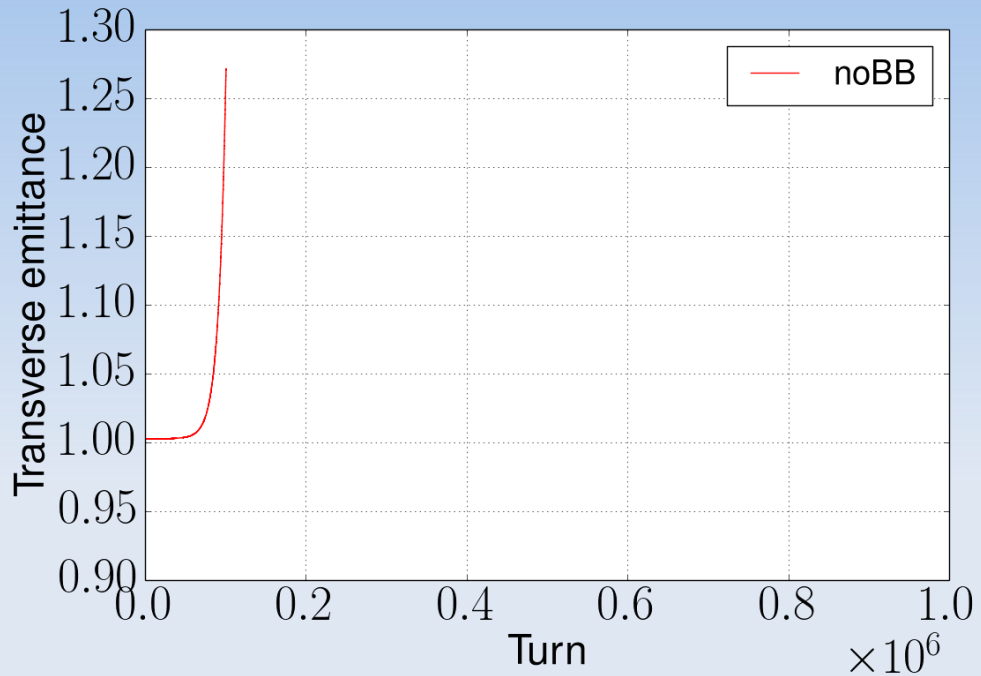
    → Landau damping is quantified with multiparticle tracking simulations (*COMBI*)





Landau damping of head-tail modes

- Fully self-consistent macro-particle simulation (COMBI)
  - HL-LHC beam parameters
  - LHC impedance model
  - Two interaction points with symmetric phase advances
- Loss of landau damping from the octupoles
- Mitigation
  - Transverse feedback
  - Chromaticity
  - Mirrored tune (or other asymmetries)



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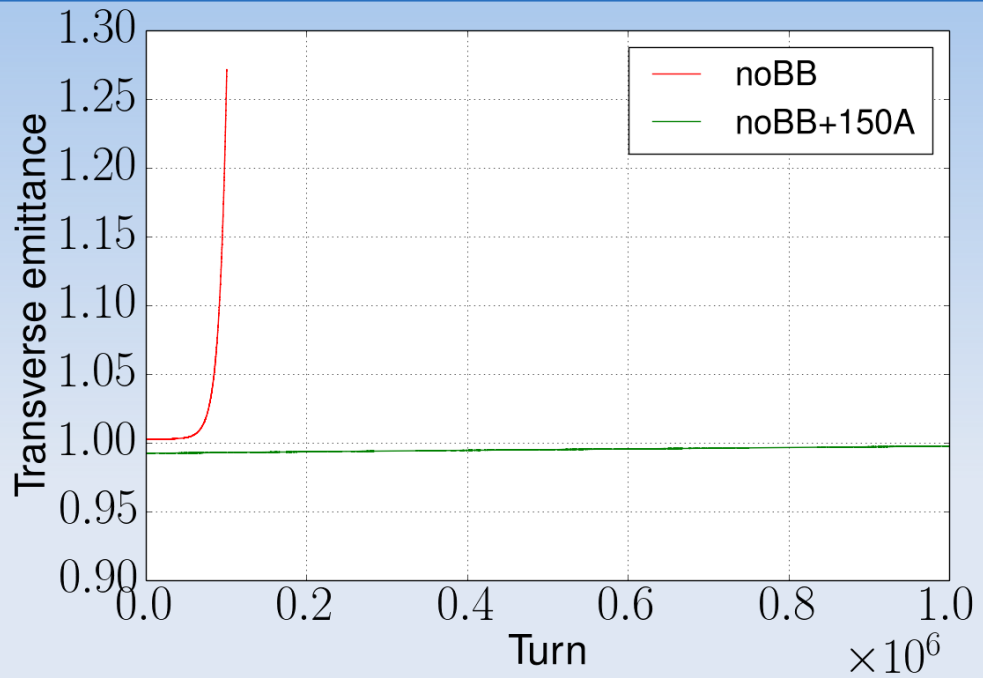

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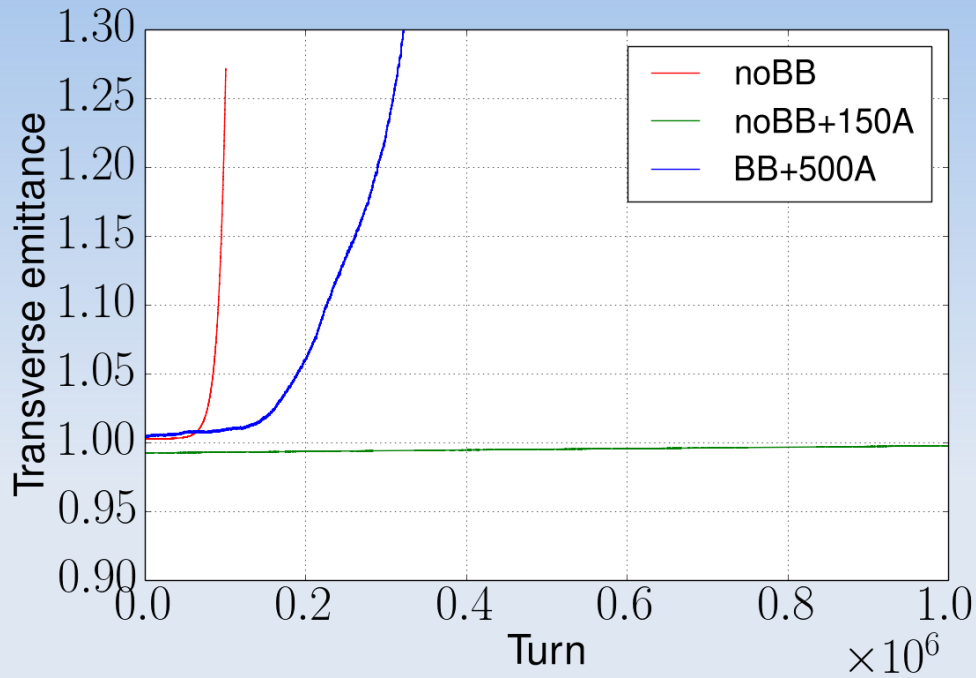

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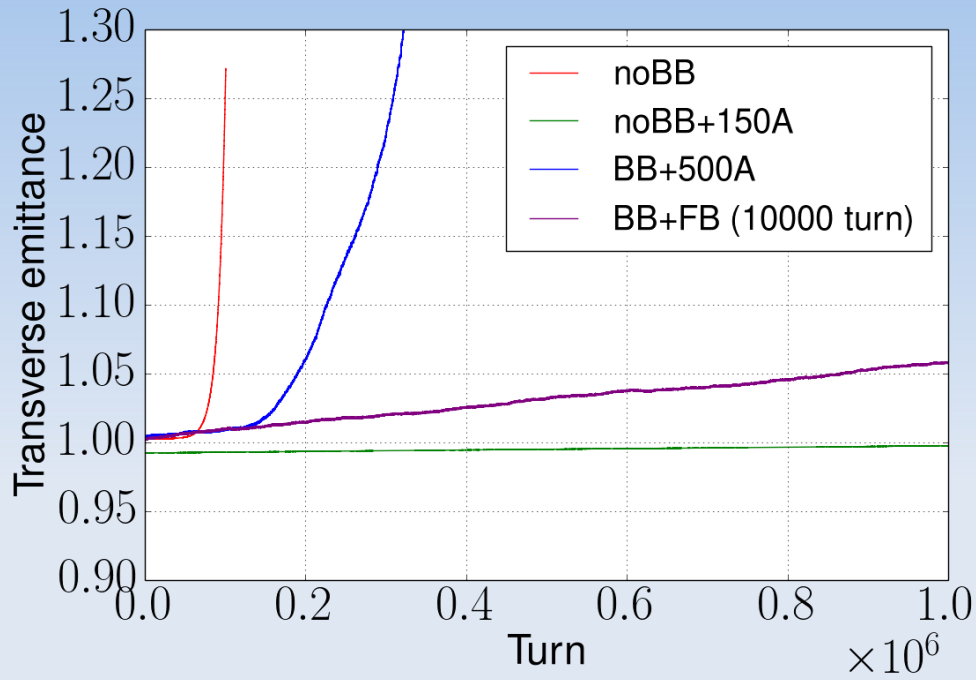

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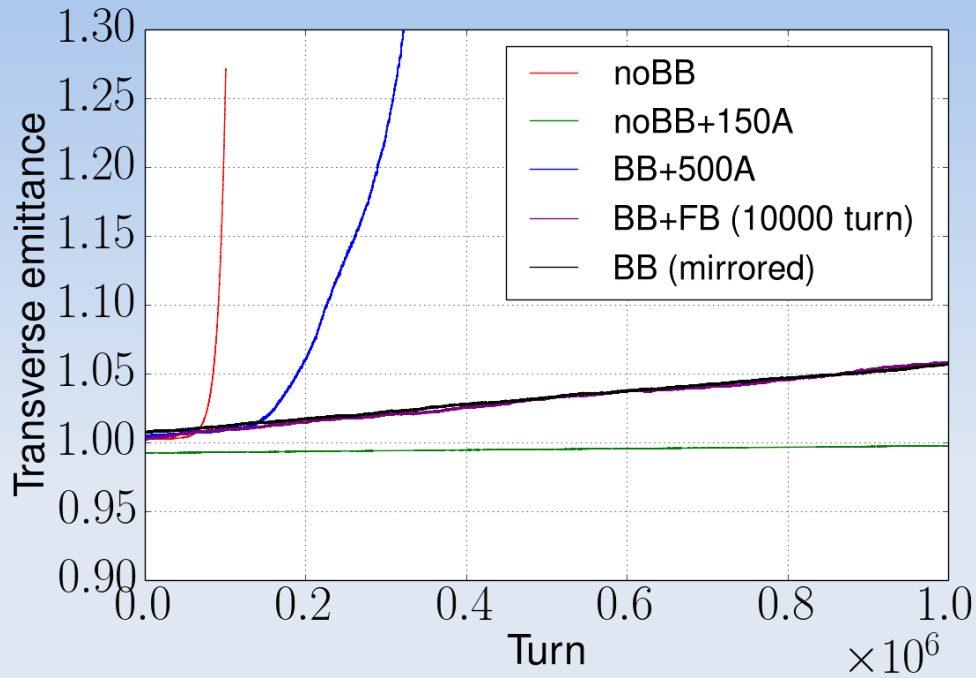

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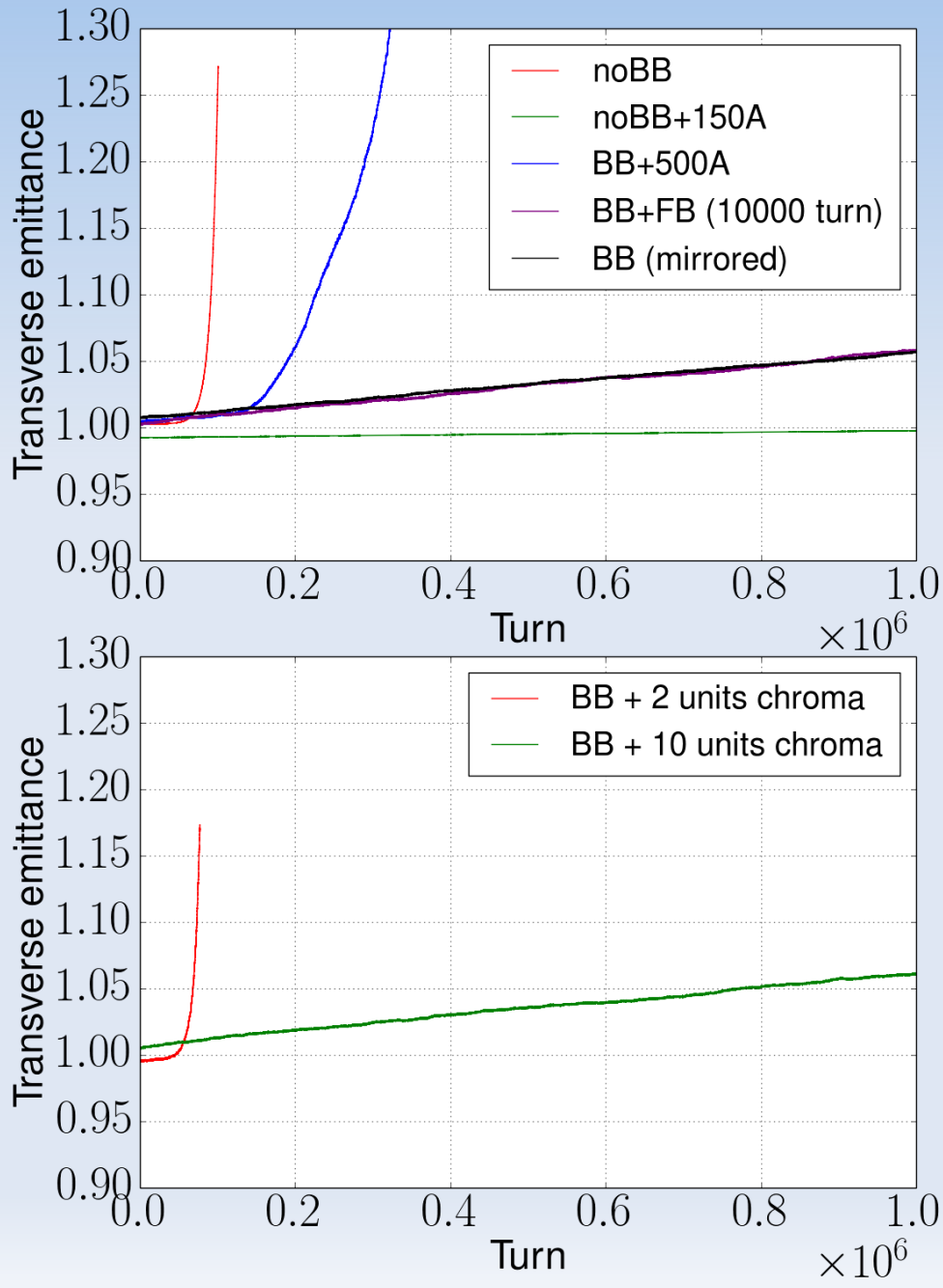
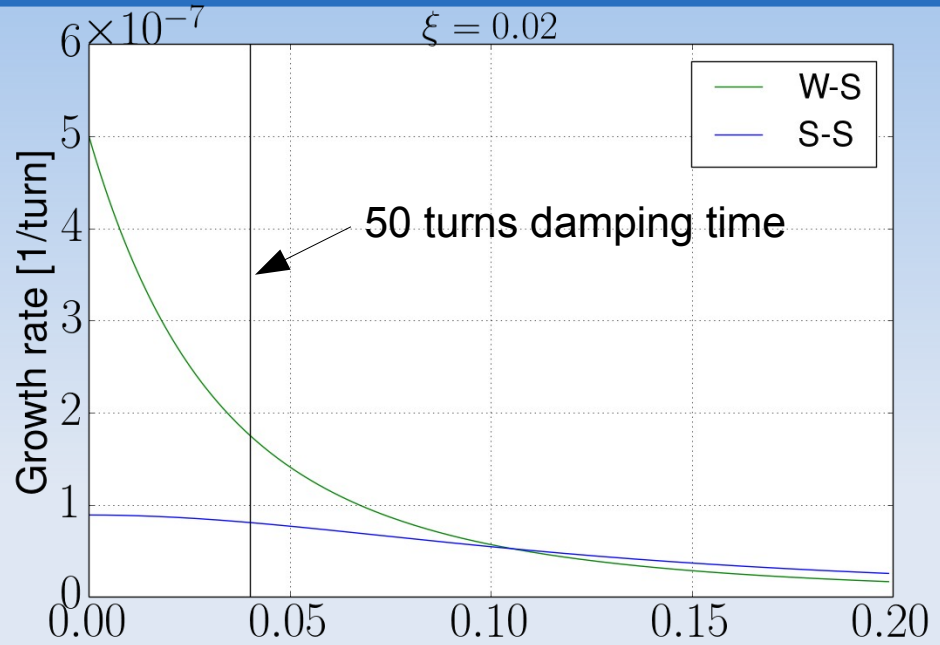
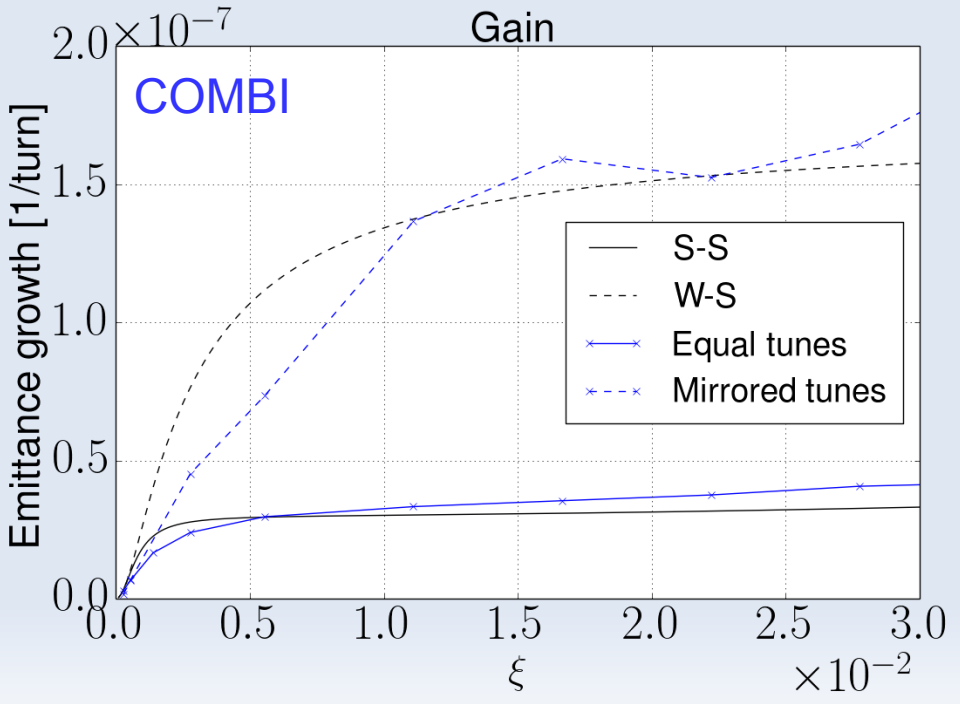


Decoherence

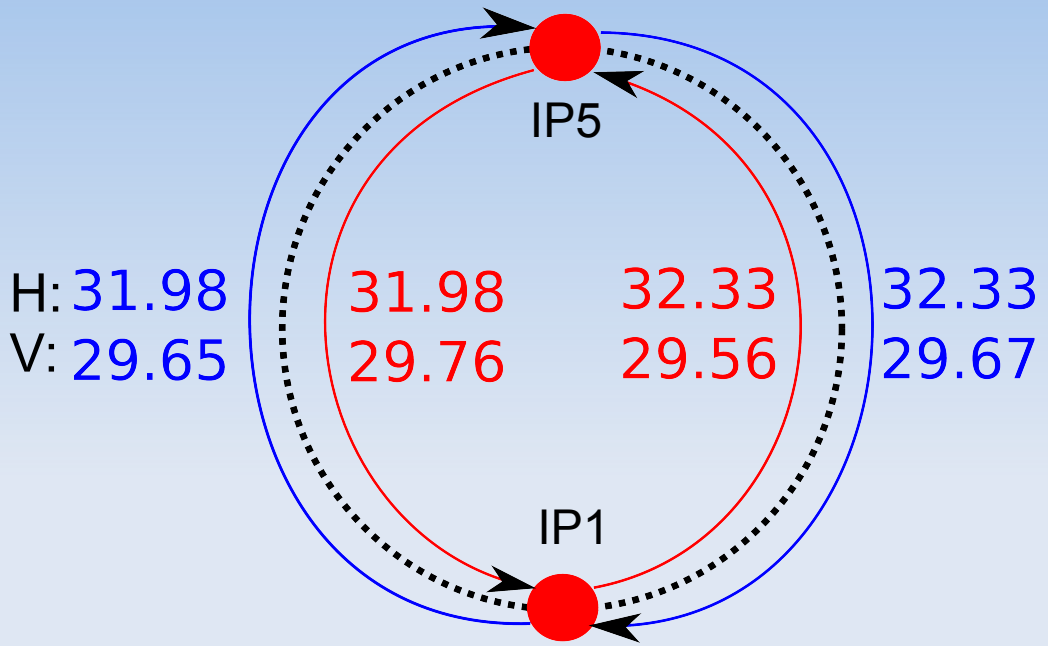
- The decoherence mechanism is different in the weak-strong (V.A. Lebedev) and strong-strong (Y. Alexahin) regime
  - The damper is more efficient to reduce decoherence in the strong-strong regime
  - When the modes are inside the incoherent spectrum, the decoherence is 'weak-strong' like
- Complex configurations have to be addressed with simulations
- Important trade-off :

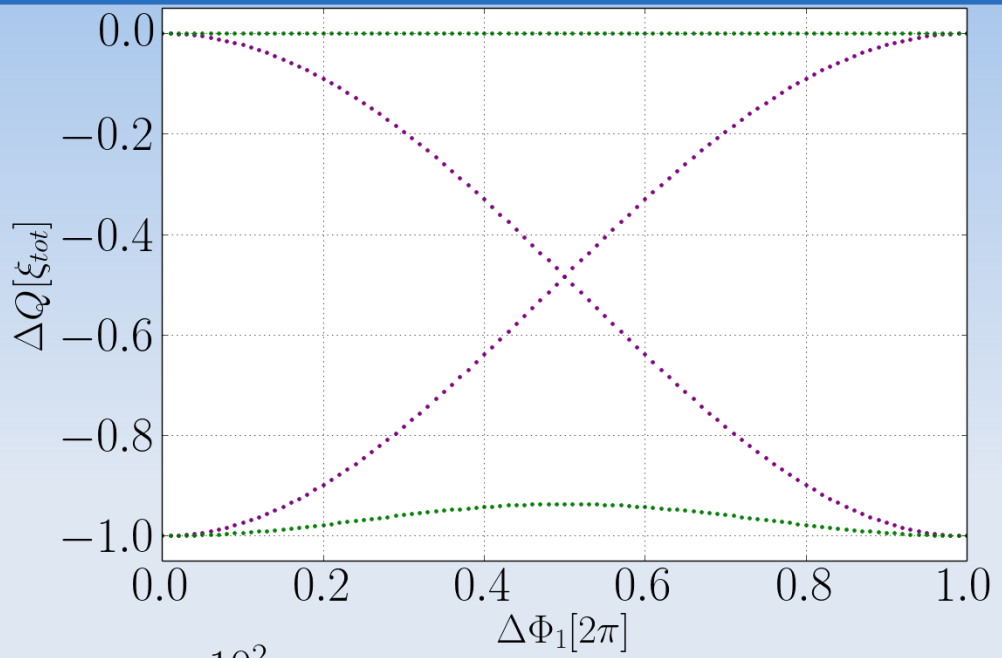
  Landau damping vs. emittance growth due to external noise



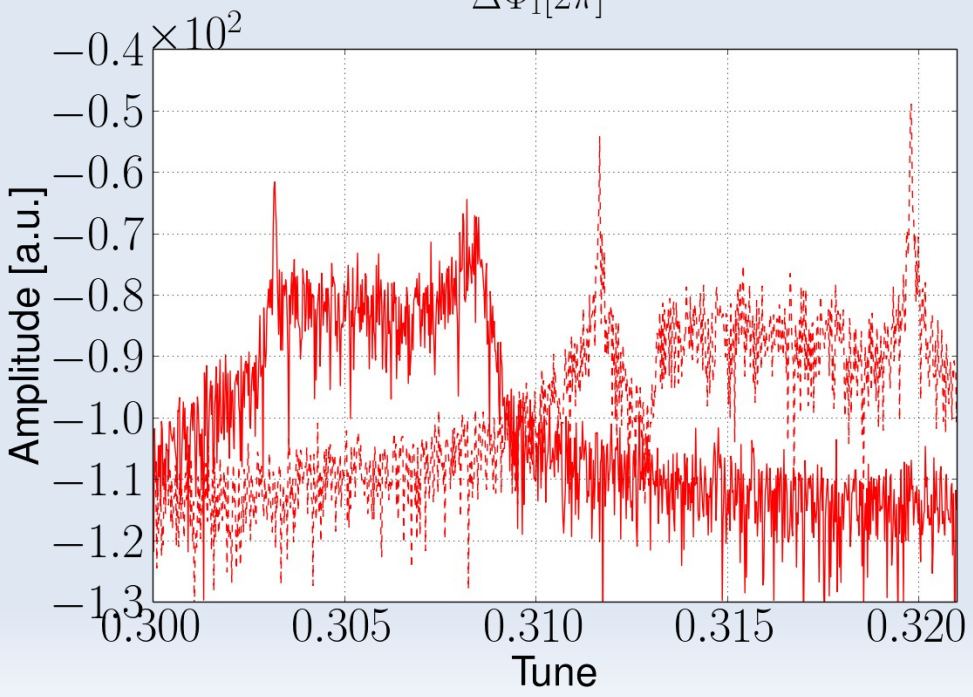


LHC phase advances

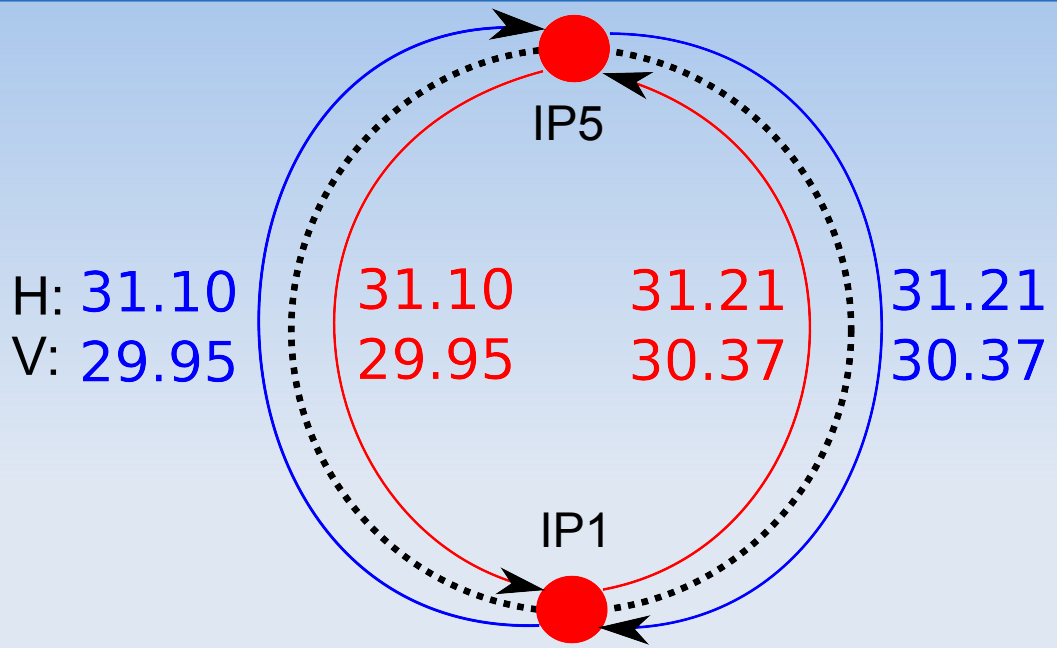


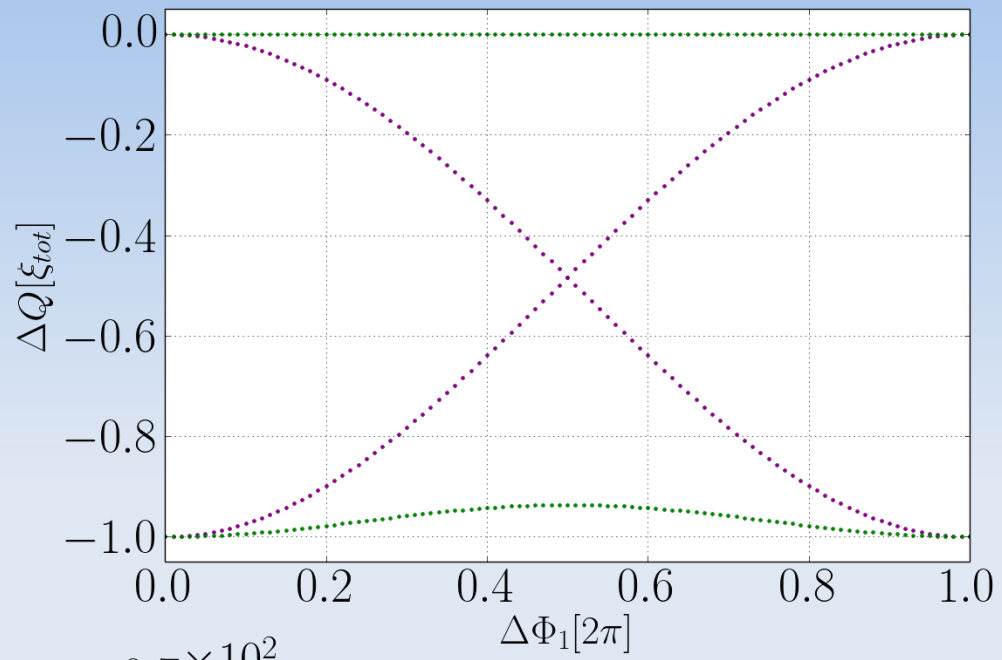


- The LHC phase advances are anti-symmetric in the horizontal plane ($\Delta\Phi_{B1}$ = -$\Delta\Phi_{B2}$=0.35) and close to the symmetric configuration in the vertical ($\Delta\Phi_{B1}$ = 0.02 ,$\Delta\Phi_{B2}$=0.2)
  - Visible in fully self-consistent macro-particle simulation

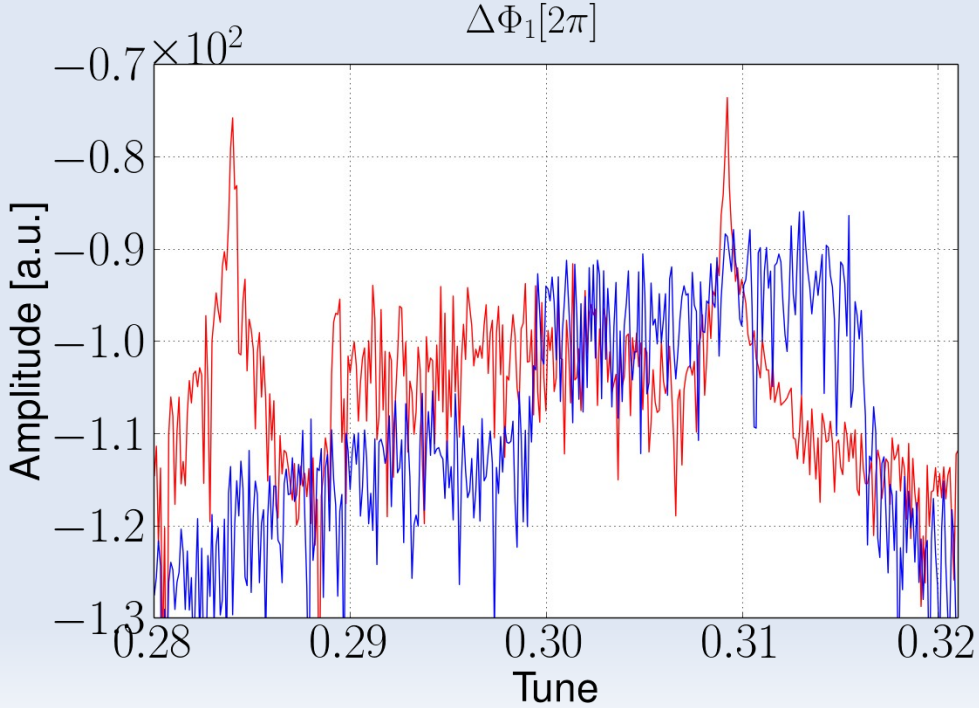


HL-LHC phase advances

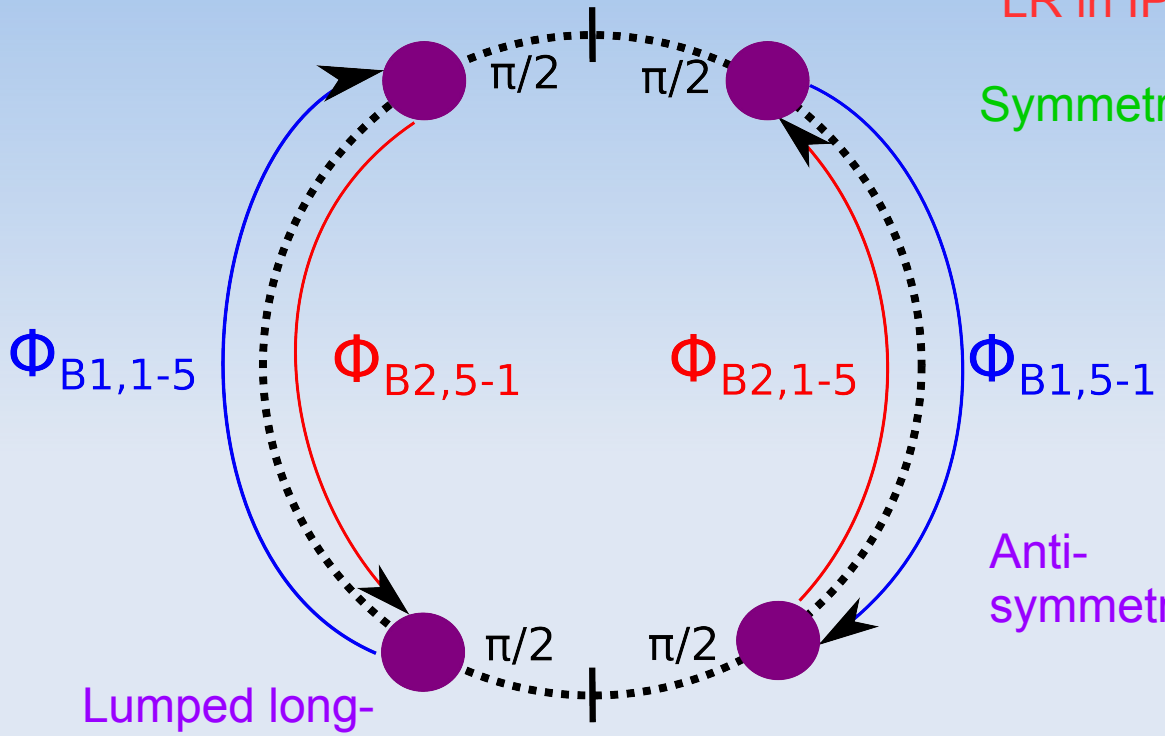


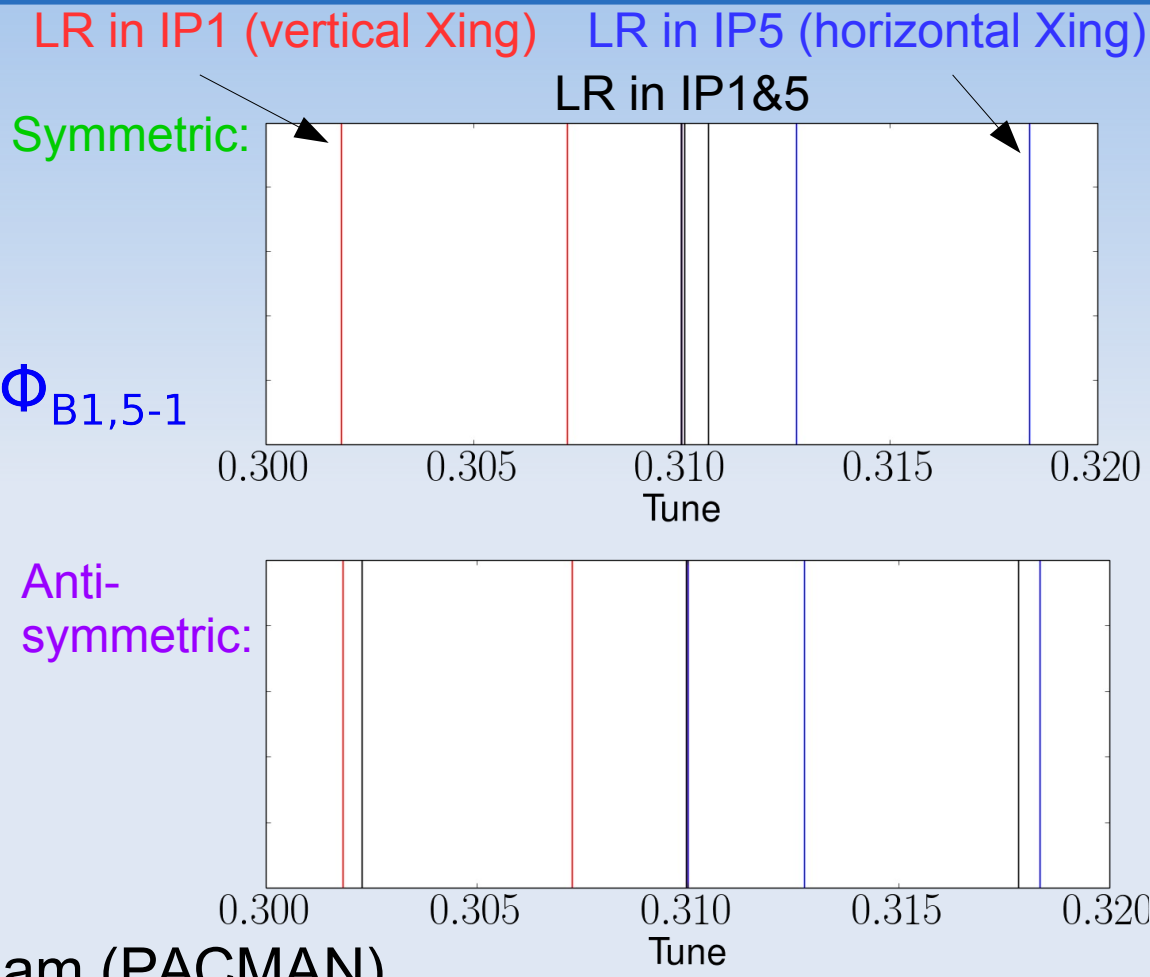


- Symmetry left/right imposed by the ATS optics
- From the point of view of beam-beam interactions the phase advances are anti-symmetric
  - The horizontal phase advances are close to a symmetric condition ($\Delta\Phi_{B1} = -\Delta\Phi_{B2} = 0.11$)
  - The vertical phase advances are very anti-symmetric ($\Delta\Phi_{B1} = -\Delta\Phi_{B2} = 0.42$)



Long-range

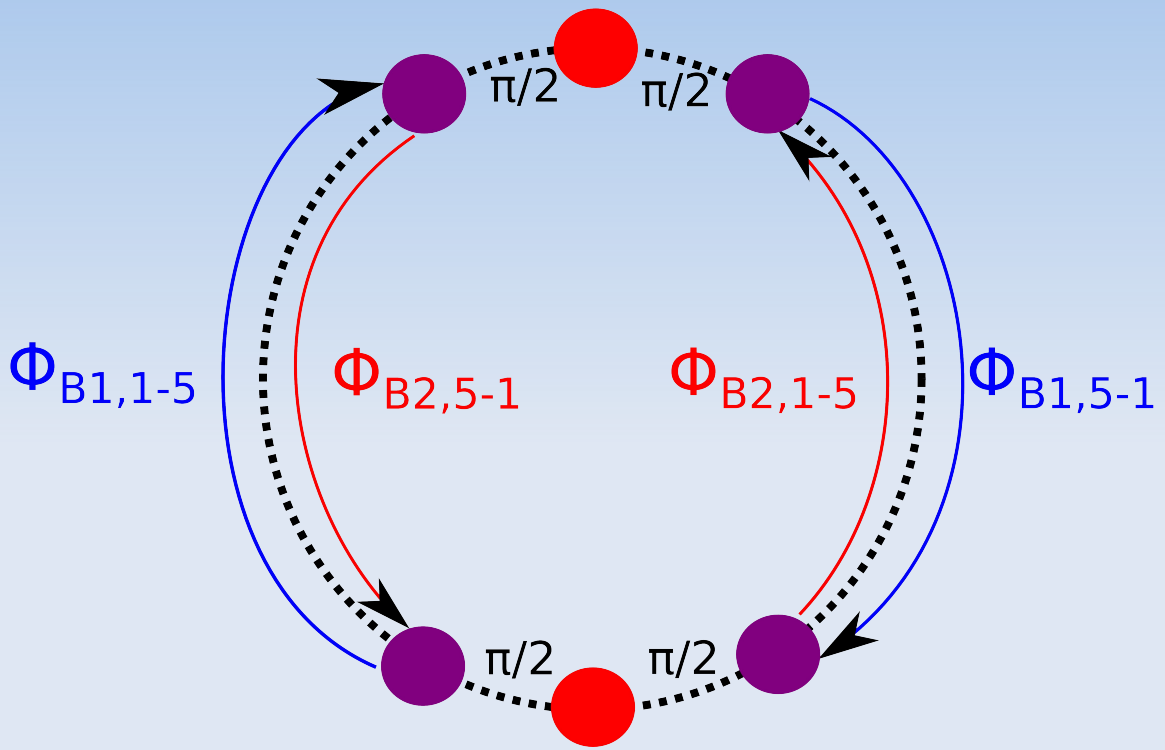


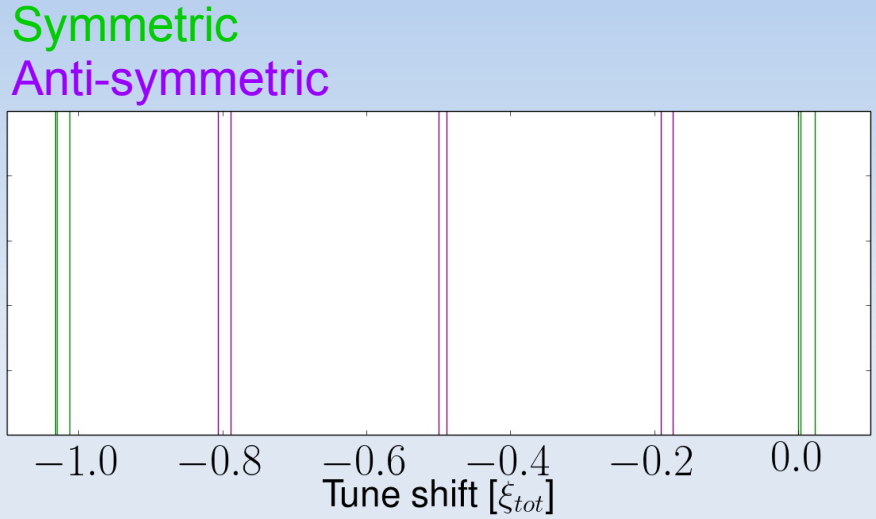


- 1 bunch train of 3 bunches per beam (PACMAN)
- Passive compensation of the tune shift due to long-range interactions for symmetric configuration

  → Broken for the coherent modes in asymmetric configurations, but not for the single particles (i.e. the coherent modes are outside of the incoherent spectrum)

Head-on and long-range

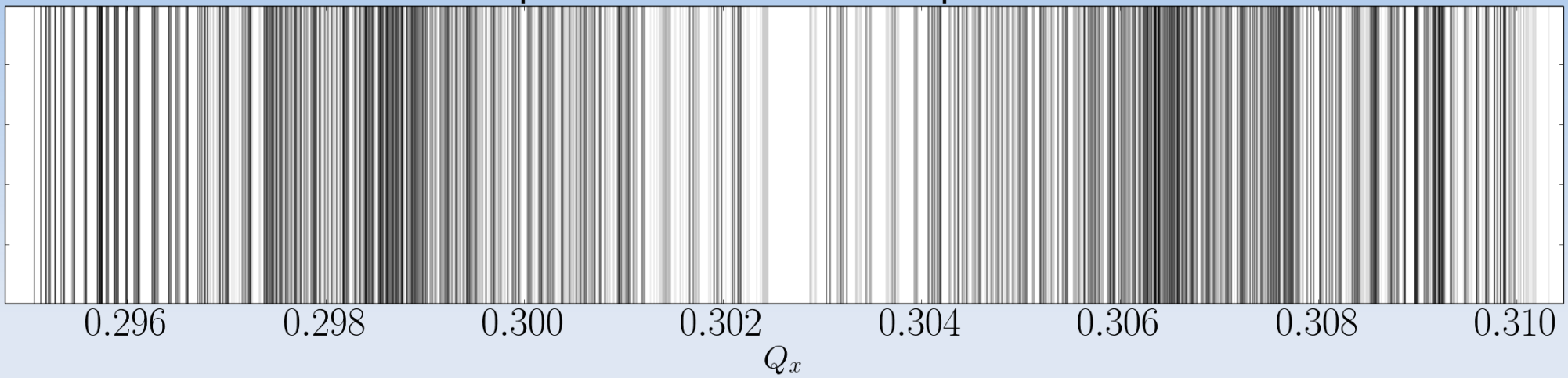




- In symmetric configurations the frequency of the long-range modes are close to the ones driven by head-on
  - No longer the case for asymmetric configurations
- Emittance growth due to decoherence is dominated by head-on interactions

LHC coherent spectrum

Nominal LHC coherent mode spectrum in the horizontal plane

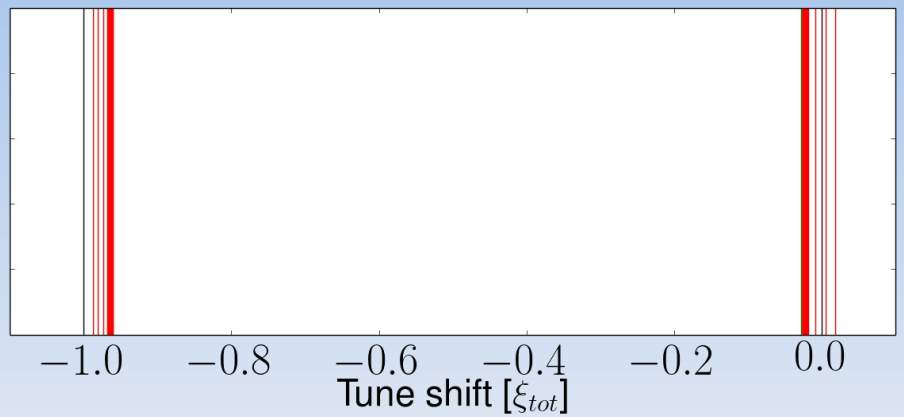


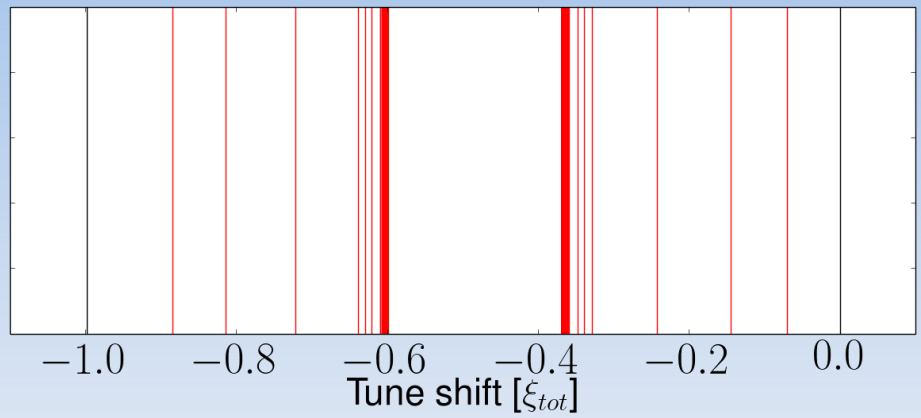
- The coherent mode spectrum of the LHC is complex, mostly due to IP2&8 which, due to their location, breaks the symmetry and couple all bunches together
  - Multibunch coherent beam-beam modes are very sensitive to bunch to bunch variations

    → In operation, all modes are inside the incoherent spectrum regardless of the phase advances

    → Coherent beam-beam modes were only observed in MD with simplified machine configuration

HL-LHC coherent spectrum

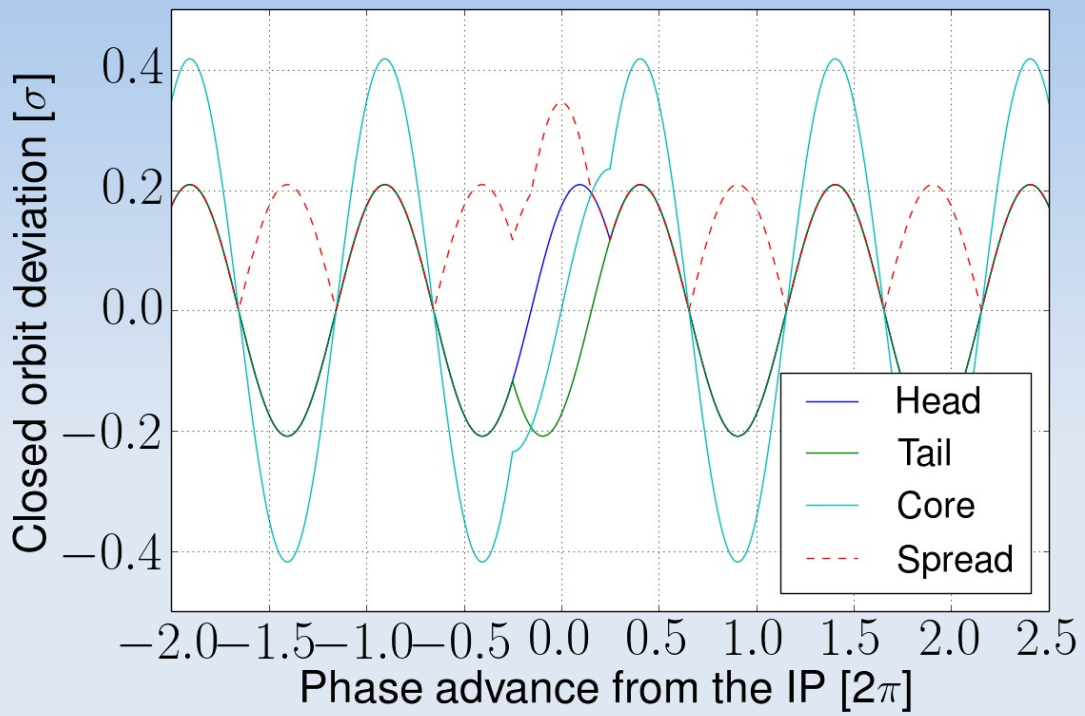




- Discarding IP2&8, the impact of the phase advance becomes relevant
  - If IP2 or 8 beam-beam effects are comparable to IP1&5 (i.e. strong long-range or head with small offset), we fall back into the LHC configuration
- Should we de-symmetrise the horizontal plane or symmetrise the vertical plane (or status quo) ?
  - Beneficial effect of the symmetry on the emittance preservation should be quantified and investigated in MDs
  - Stability limits and mitigation techniques should be quantified and investigated in MDs

Orbit effects

- The orbit effect is symmetric for both beams (i.e. left of one is identical to left of the other)



- The orbit of PACMAN bunches may result in luminosity loss (~5%, less with β* leveling) in the opposite IP
  - With symmetric phase advances, all bunches collide head-on in both experiments (possibly on different orbits)
  - With asymmetric phase advances, this effect cannot be fully mitigated in the opposite IP

Conclusion

- The (anti)symmetry in the phase advances of the two beams imposed by the ATS does not impose constraint on the coherent beam-beam dynamics
- There are fewer symmetry breaking in beam-beam interactions in the HL-LHC with respect to the LHC

  → Potential issue with Landau damping of coherent beam-beam modes

  - Both the transverse feedback and chromaticity are efficient mitigations → The limits needs to be quantified in different configurations (i.e. squeeze / adjust / stable beam)
  - Mirrored tune / asymmetric phase advances could be backup solutions that suppress the coherent modes while keeping the same incoherent dynamics

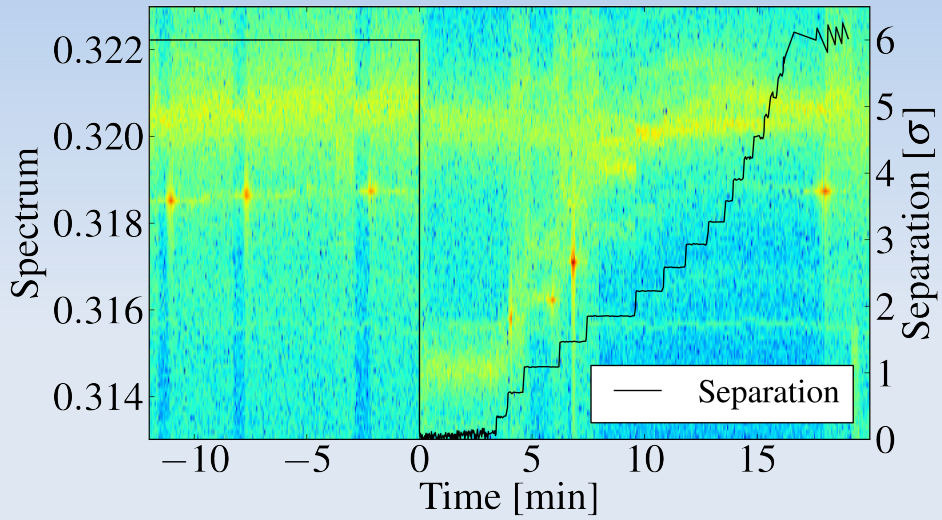
  → Potential reduction of the emittance growth due to external noise

  - Noise studies (J. Barranco, et al) to be continued
  - Experimental tests are needed
- Is there a best choice from the point of view of DA ?

BACKUP Observation of coherent beam-beam instabilities in the LHC

- Vertical plane
- Low chromaticity (~2 units)
- Cured by the transverse feedback

Mode coupling instability MD
(end of fill MD with single bunches colliding in IP1&5 at 4 TeV)



Head-on beam-beam limit MD (2010)
(single bunches colliding in IP1&5 at 450 GeV)