Synchro-Betatron Effects

R. Calaga, R. Miyamoto, S. White
BNL – USLARP

Thanks to S. Fartoukh and R. de Maria for the help with the HL-LHC optics

Model

- Head-on interactions:
  - Self consistent 6D field calculations allowing for arbitrary distributions (BEAMBEAM3D, Ji Qiang)
  - Crossing angle implemented “a la Hirata”

- Long-range interactions:
  - Lumped 4D beam-beam kick at +/-π/2 from the IP (Gaussian approximation)
  - Underestimates the footprint area (constant separation for all interactions)

- Crab Cavities:
  - Thin crab cavity kick at +/-π/2 from the IP
  - Only the local scheme was considered

- Transport is done with a linear 6x6 transfer matrix. Chromaticity kick available

Beam Parameters

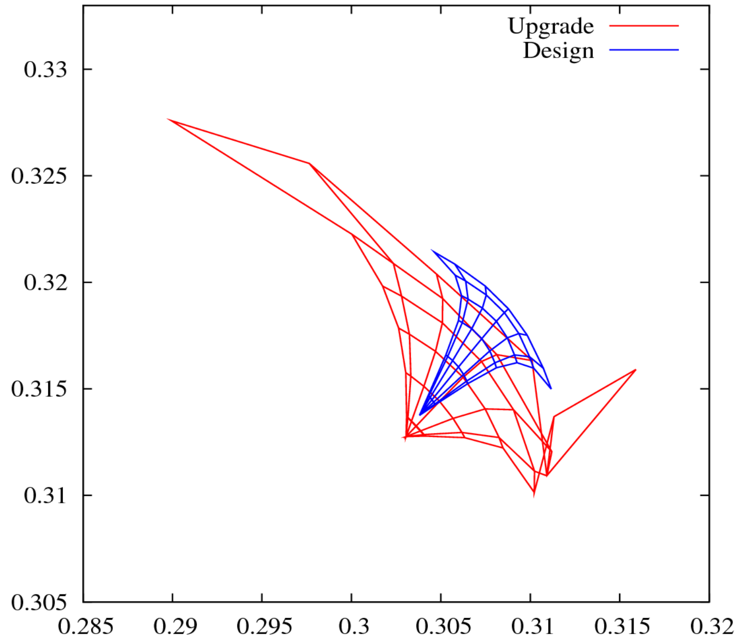
- Beam parameters with 25 ns from O.Bruning's talk in April 2011:

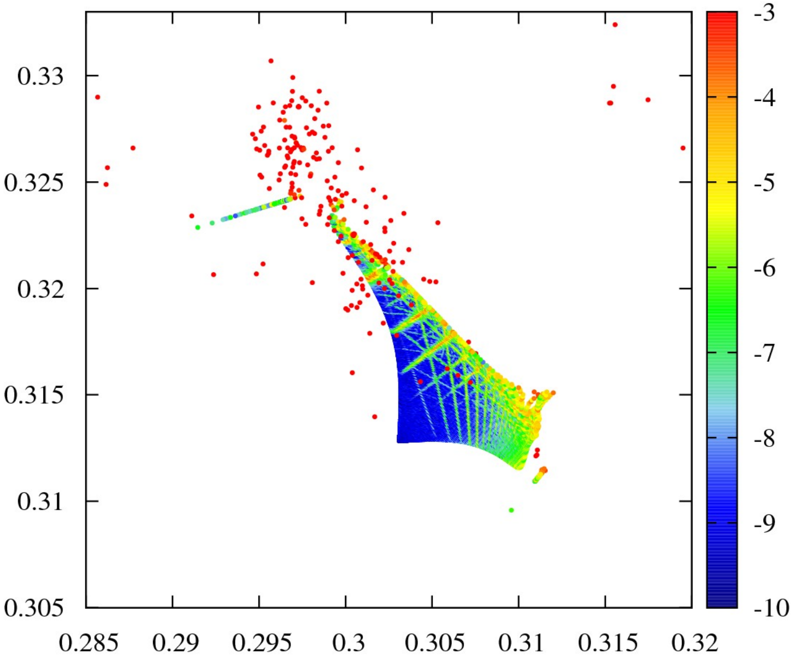
	Design Parameters	Upgrade Parameters
N [p/bunch]	1.15e11	**2.0e11**
ε_N [μm]	3.75	**2.5**
Q_x / Q_y / Q_s	0.31 / 0.32 / 0.002	0.31 / 0.32 / 0.002
β^* [m]	0.55	**0.15**
σ_s [m]	0.075	0.075
dp/p	1.129e-4	1.129e-4
θ [μrad]	285	**475 (~10σ)**
N_{LR}	15	**18-24**
L_{peak} [$cm^{-2}s^{-1}$]	1.0e34	7.4e34 (2.0e35 w. CC)

- Target was at the time 1.0e35 (now 2.0e35) “virtual luminosity” leveled to 5.0e34 → lots of margin w. CC
- Number of long-range depends on the triplets: several options considered
- Crossing angle set to have 10σ separation: still valid for large N_{LR} / bunch intensity?

Footprint

- Take 21 long range interactions as study case (IP1&5 only)

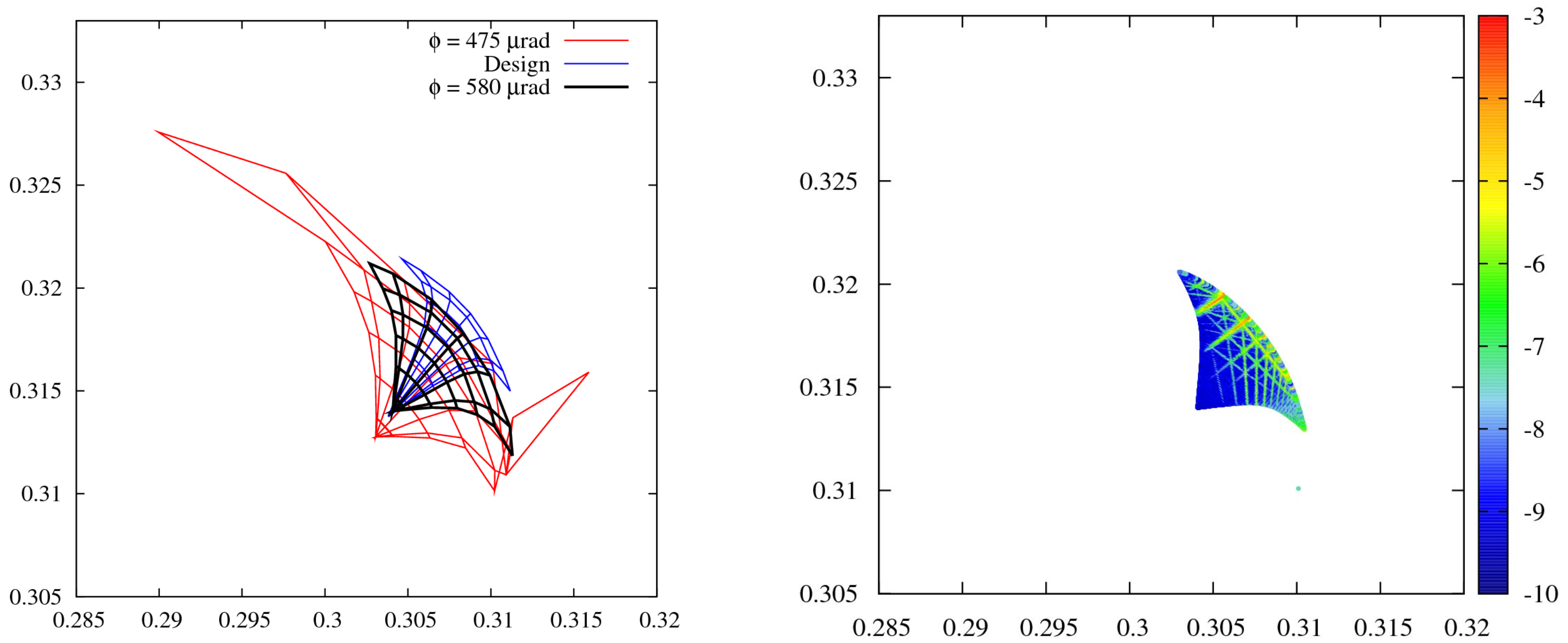




- 10σ separation: footprint strongly distorted (lattice resonances): detrimental effects clearly dominated by LR → poor lifetime / DA (see W. Herr's talk)?
- **Reduce the effect of the long range interactions. Possible mitigations:**
  - Increased β*
  - Increased crossing angle

Increased Crossing Angle

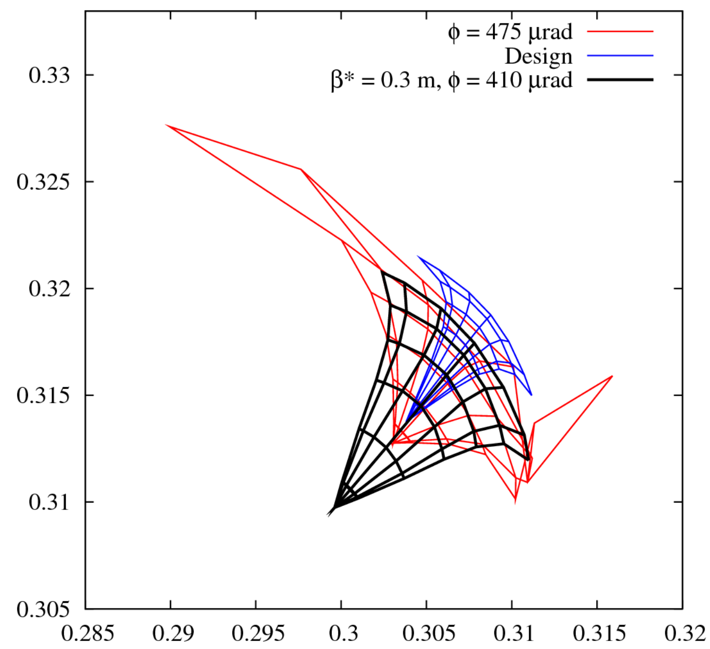
- Increased crossing angle to 580 μrad (~12.2 σ separation)

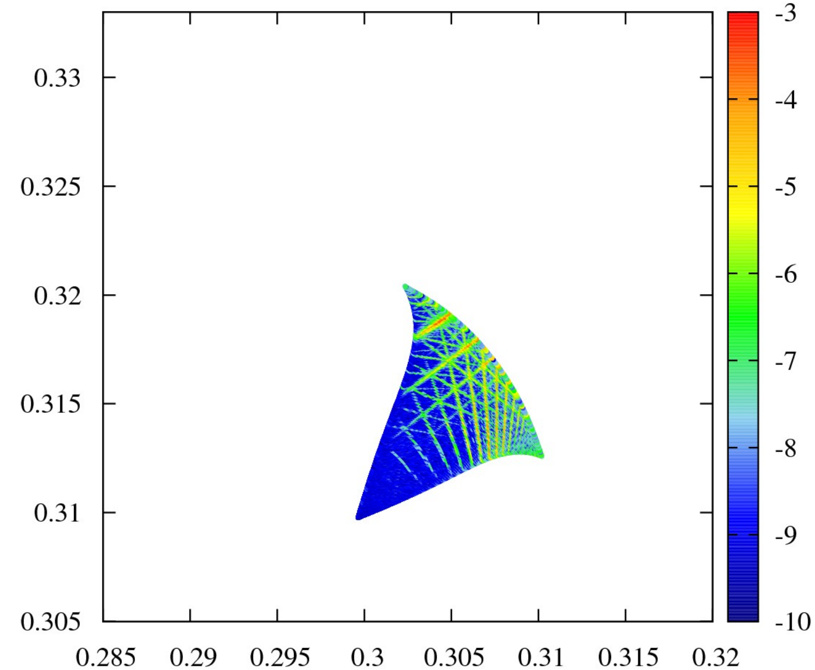


- Still larger than "design" but looks better
- "Virtual luminosity" remains the same assuming we have crab cavities → **plenty of space for leveling with crab cavities**
- Peak luminosity without crabs **$L = 6.2e34\ cm^{-2}s^{-1}$**

Increased β*

- Increased β* to 0.3 m (ATS optics), 410 μrad (rescaled previous angle)

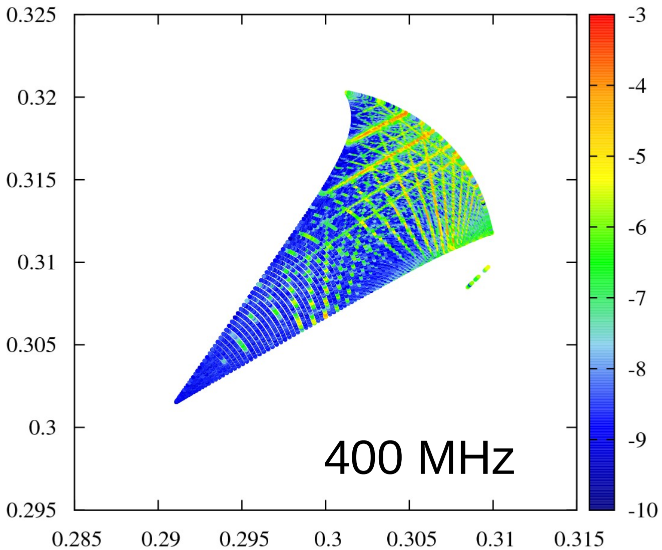


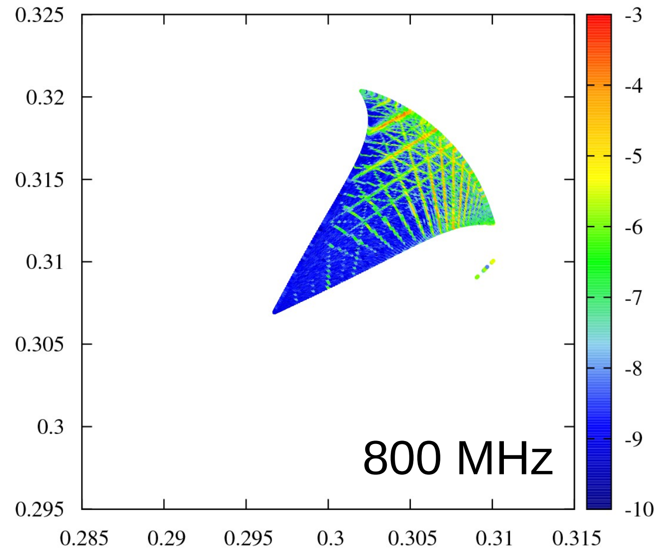


- Same LR as previous slide with larger HD (~1.0e-2)
- “Virtual luminosity” with CC down by a factor ~2 **still reaching 1.0e35**
- Peak luminosity without crabs **$L = 5.4e34\ cm^{-2}s^{-1}$ → leveling with crab cavities required**

With Crab Cavities

- Check whether crabs + LR can degrade the situation





- Large crossing angle:

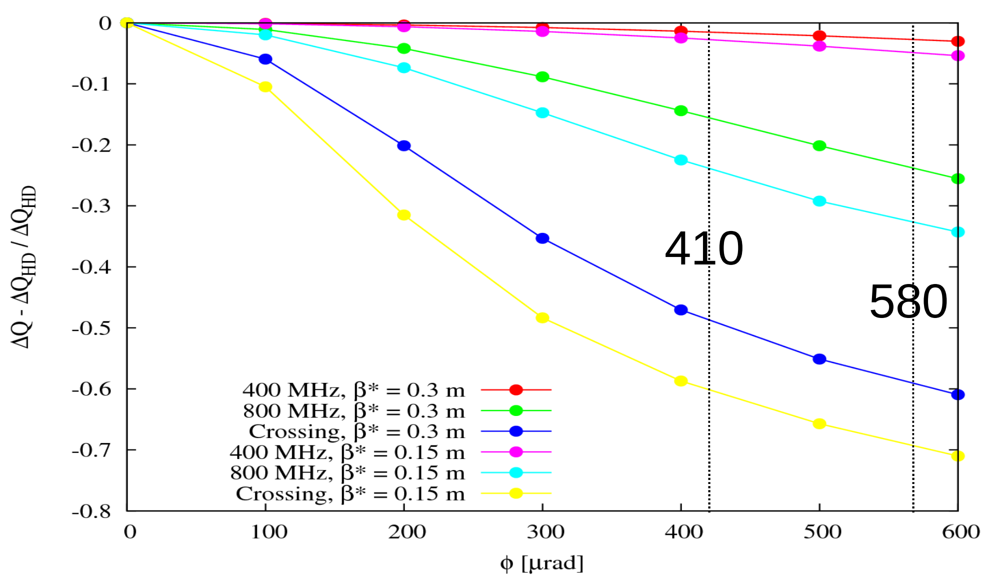
  - No significant differences observed with the case without compensation for either frequencies

  - Large difference in the efficiency of the crossing angle compensation

- Tune shift as a function of the crossing angle:

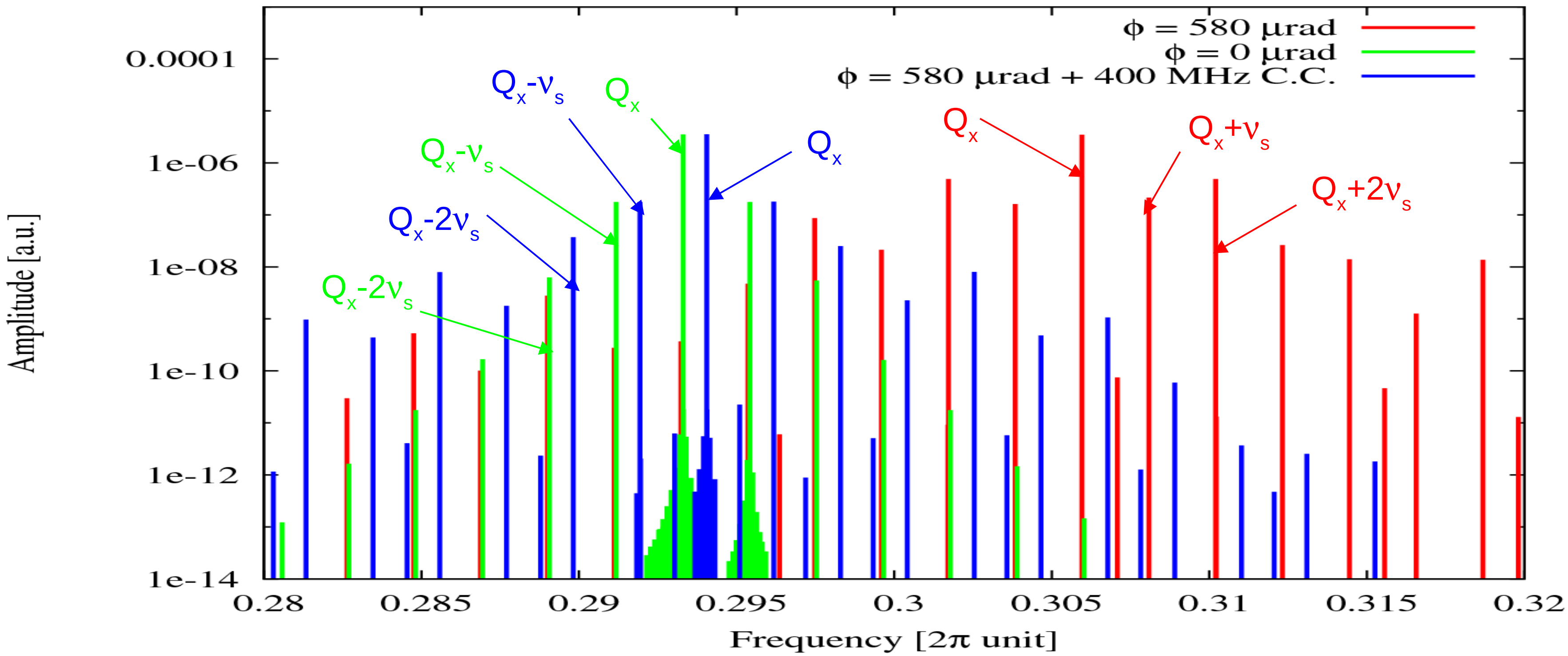
  - compensation works better for larger β*

  - the values of the crossing angle considered clearly favor the 400MHz cavities



Synchro-Betatron Effects

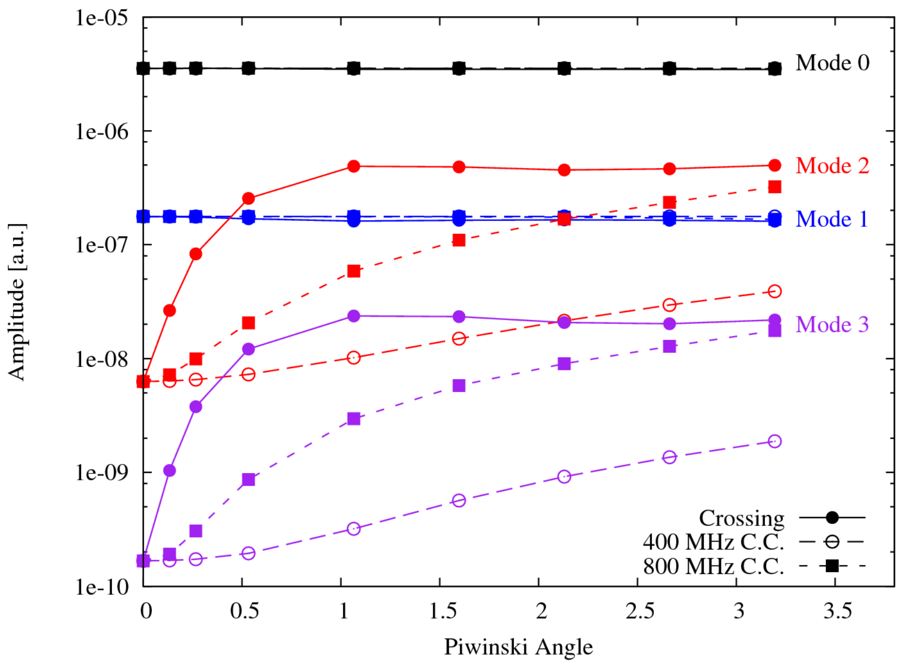
- It was shown by Y. Sun et al. that the crabs could damp the side-bands excited by the crossing angle (sixtrack). Initial amplitude 1 σ_x / 1 σ_s:

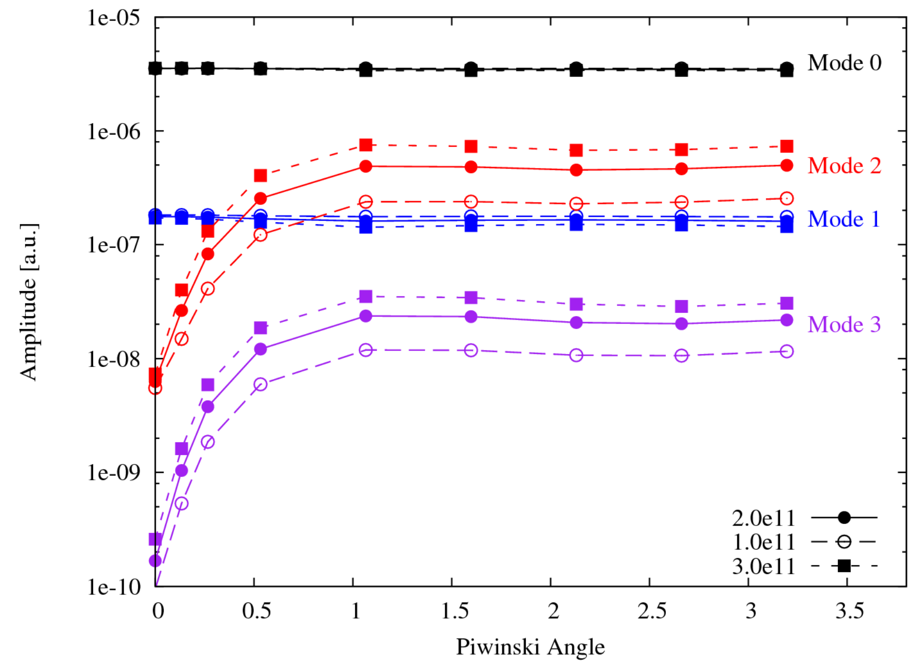


- The results could be well reproduced with BB3D:
  - First side bands not affected
  - Higher order side bands excited by the crossing angle → damped by the crab cavities

Amplitude vs Piwinski Angle

- Modes amplitude with and without crabs as function of the Piwinski angle:

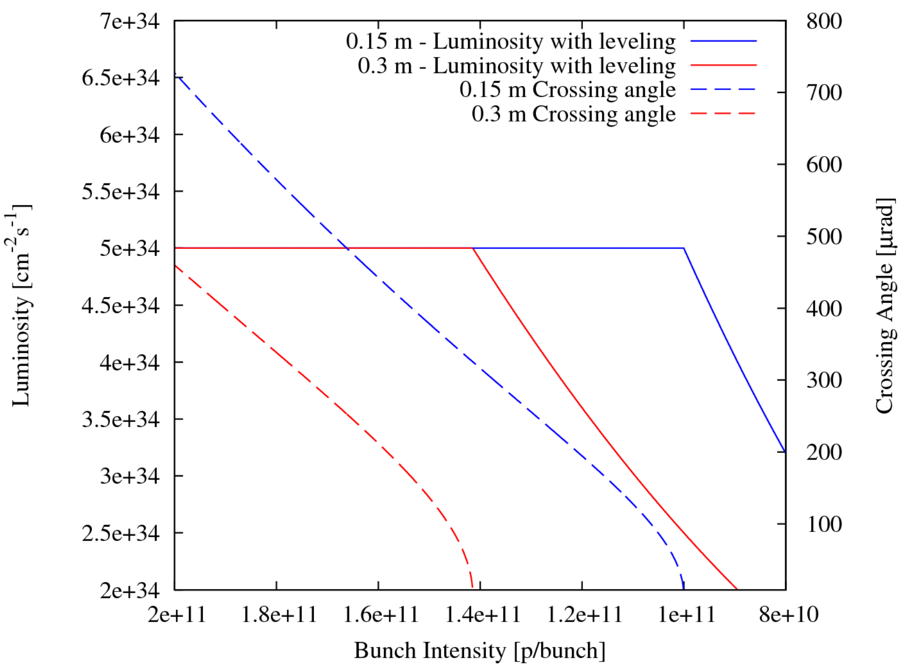


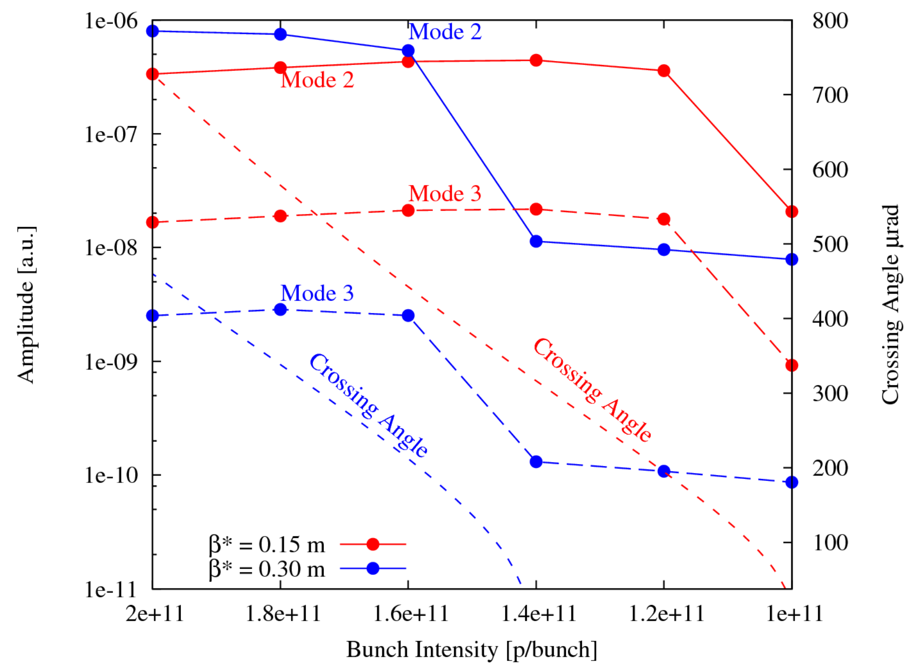


- 2nd side-band and up excited by the crossing angle, peak at Φ~1 → **clear damping effect from the crabs**
- Bunch intensity / ξ has little effect over the range relevant for LHC
- **The HL-LHC regime (Φ~2-3) has not yet been probed by actual operation** (Φ~0.4) but design parameters (Φ~0.7) should provide useful information

Leveling Scenarios

- Consider the simple model where the loss in luminosity comes only from intensity – level to 5e34 using crab cavities until full compensation:

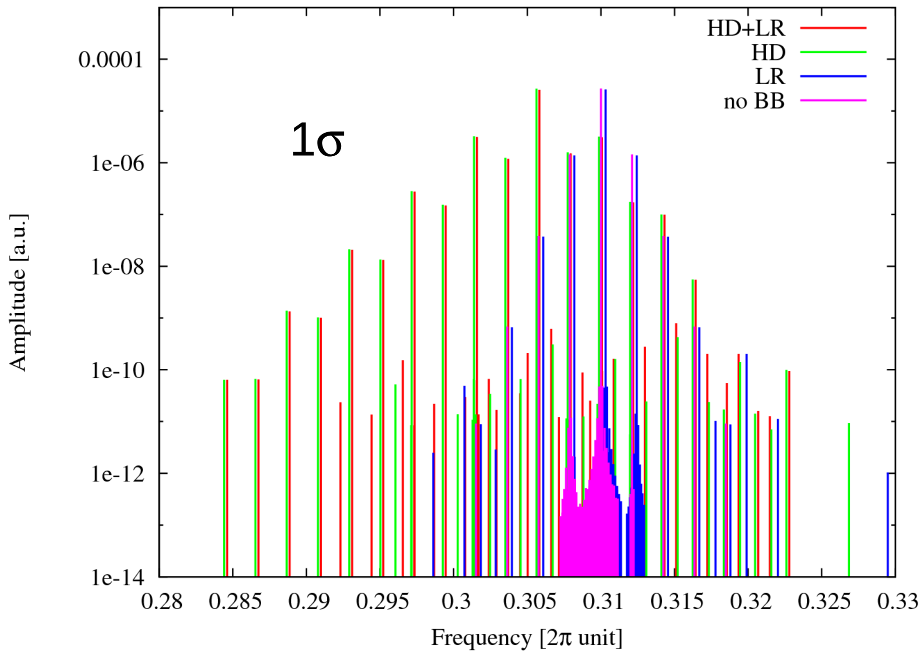


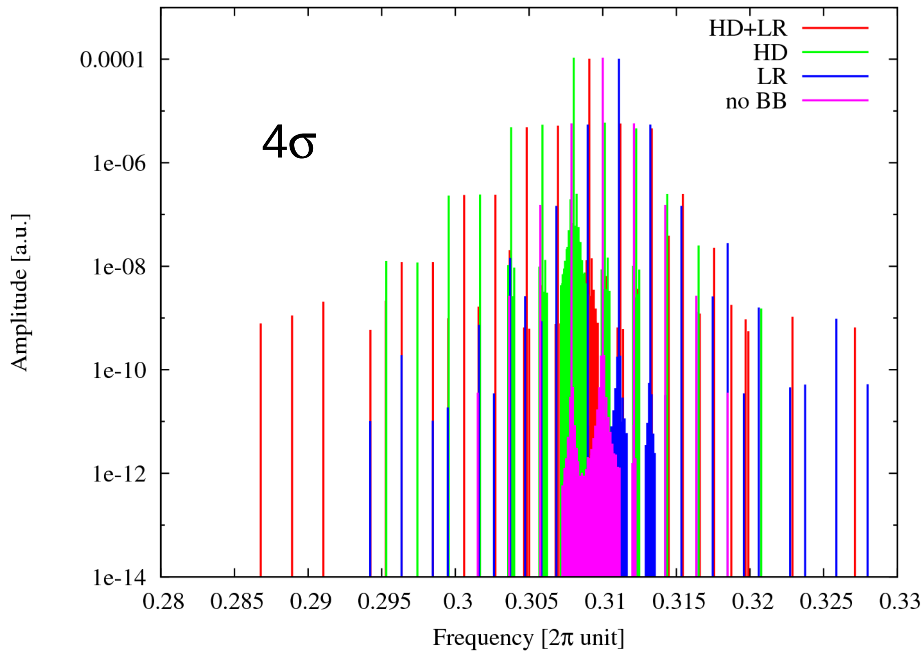


- Start "high" for both options (same regime) slightly better for 0.3m
- Damping comes faster for 0.3m but this option gives less margin for leveling
- Given the requirements in terms of luminosity it seems difficult to use the damping properties of the cavities (in case SBR are a problem) if they are used for leveling

Effect of Long-Range Interactions

- Look at the effect of the long range interactions for a core particle (1σ) and a tail particle (4σ) – in this case LR are modeled with a 6D kick:

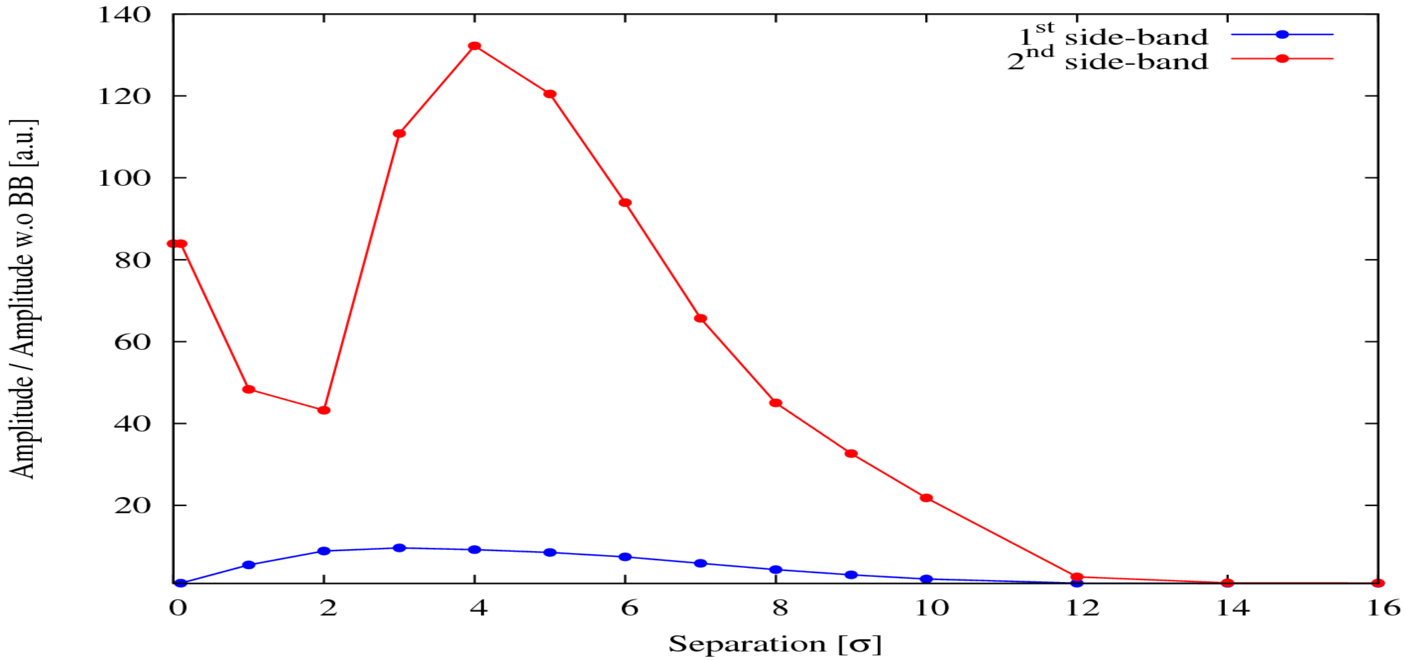




- **Core particles**: not affected by long-range interactions: spectrum with LR only matches the case without beam-beam
- **Tails particles**: no significant difference with respect to the case without beam beam
- **Effect clearly driven by the head-on interactions**

6D Beam-beam Kick with Transverse Offset

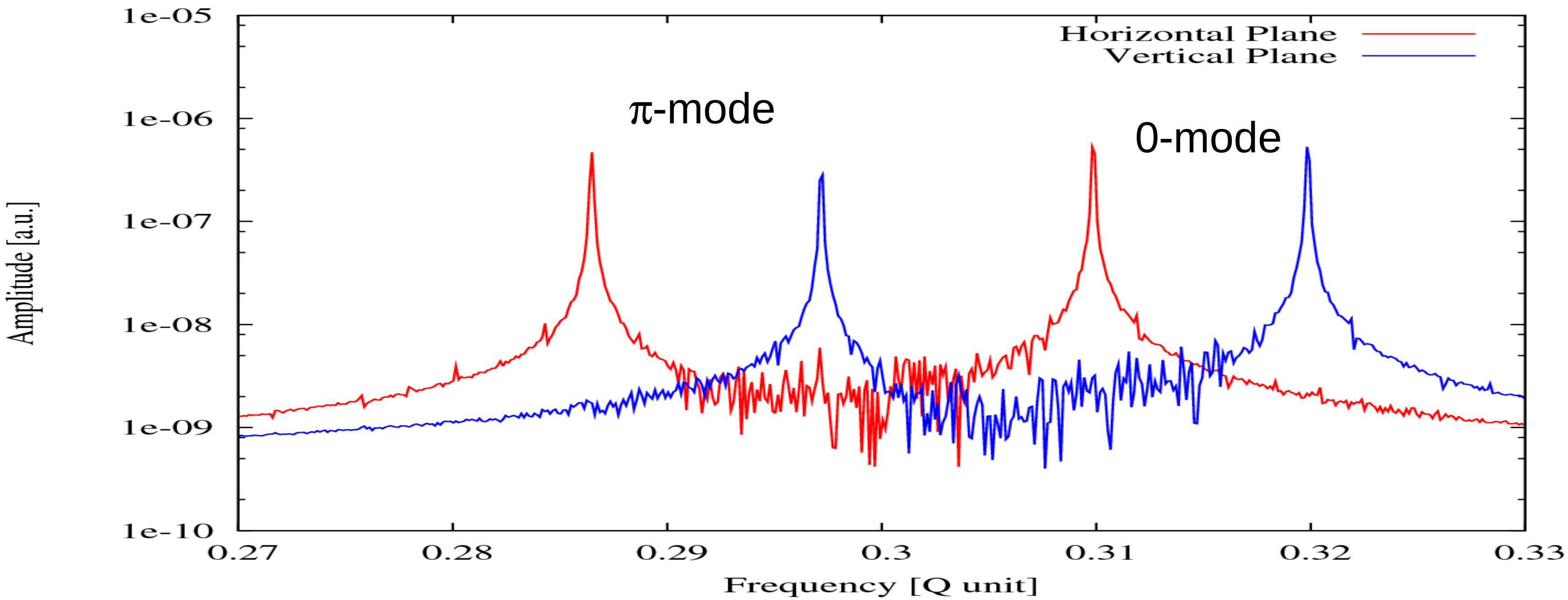
Head beam-beam collision with static offsets. Look at the evolution of the side-bands as a function of separation:



- Done for the 0.15 m option – the separation is applied in the crossing angle plane
- Side bands increase up to ~ 4 σ separation converge to the case without BB for larger separations
- LR separation for 0.15 m ~12-13 σ → **SBR from LR should not significantly contribute to the overall effects**

Coherent Beam-beam Effects

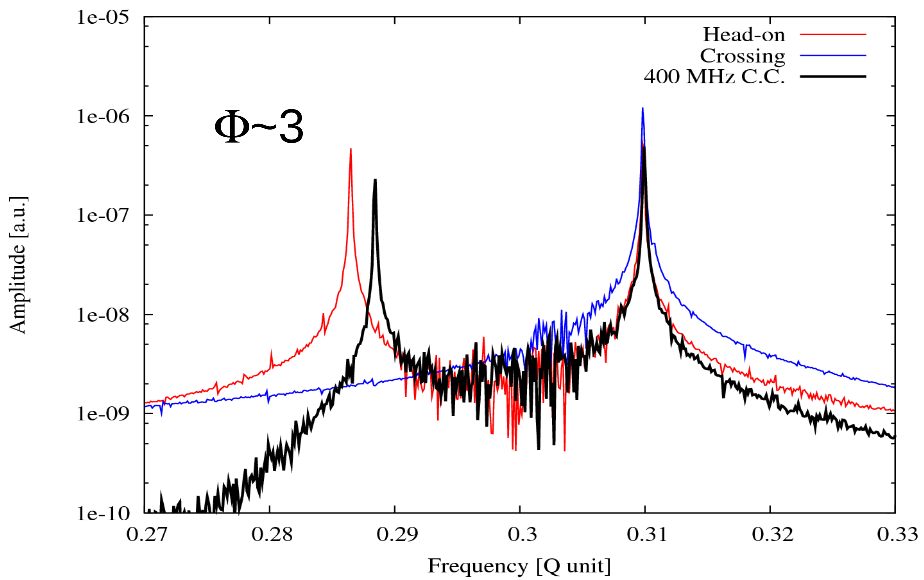
- Previous simulation using the weak-strong approximation. In reality the two beams couple and coherent beam modes develop:

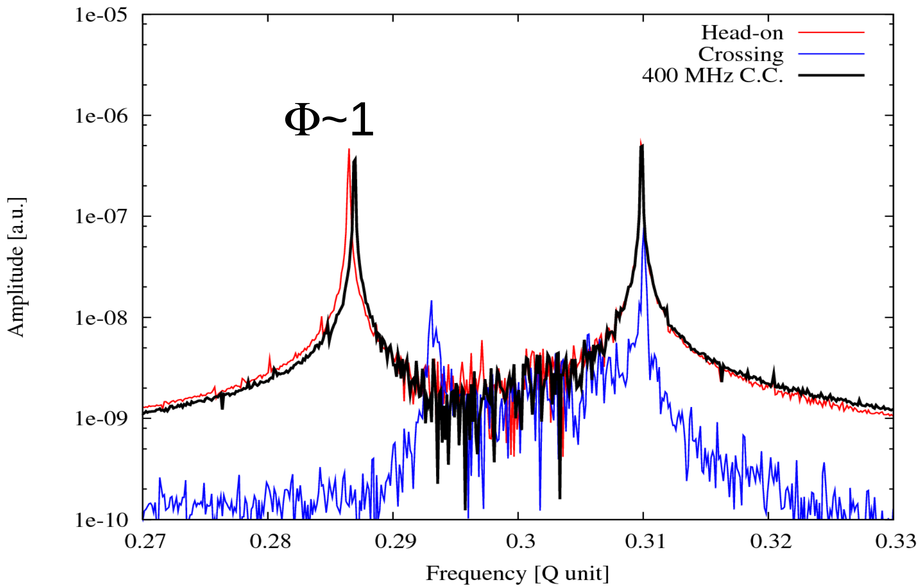


- In the case of the LHC and for collisions in IP1 and IP5 only two modes develop: the 0-mode and the π-mode separated by $Y.\xi$
- This example shows the case of head-on collisions w.o. crossing angle using the 0.15 m beam parameters: what happens with crossing angle and C.C. ?

Damping of the π-mode

- It was shown by Y. Alexahin that for certain ratio of ξ / Q_s the side-bands of the continuum can overlap the π-mode and damp it. This effect should in principle be enhanced by the crossing angle





- **Φ~3:** strong SB coupling + low ξ → π-mode fully damped
- **Φ~1:** weaker SB coupling + higher ξ → π-mode not fully damped
- **Crab cavities restore the π-mode**
- Short term simulations → no information on lifetime/emittance but behavior for short term is very similar in all cases

Conclusions

- Taking the “nominal” HL-LHC beam parameters **the LR interactions seem to be a limitation**. Two mitigation scenarios were considered for this study:
  - **Increased β*:** increased aperture, lower “virtual luminosity”
  - **Increased crossing angle:** enough aperture? High “virtual luminosity”

- Synchro-betatron effects looks similar for both cases:
  - Synchrotron sides-bands excited by the crossing angle
  - Under certain conditions they can damp the π-mode
  - **Removing the crossing angle w. C.C cancels these effects as well**

- **The effect of LR interactions needs to be assessed** to understand limitations
- **Experiments are required** to understand the detrimental/beneficiary effects of running with high synchro-betatron coupling
- C.C. are required to reach design goals for both scenarios considered