Crab cavity RF noise mitigation and transverse tail cleaning

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Introduction

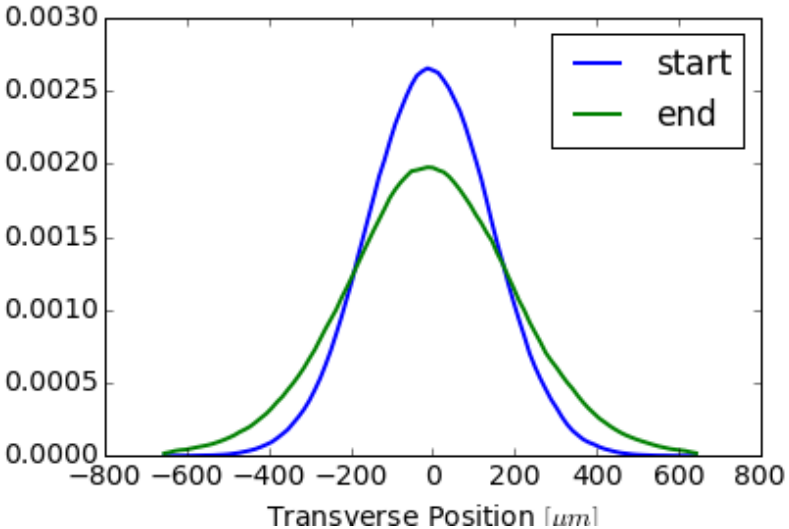
- At the last HiLumi meeting we presented a theoretical formalism and associated simulations relating the expected crab cavity RF noise spectrum with the transverse emittance growth rate [1]
- With this formalism a growth rate of about 4%/hour is anticipated
- Dominated by amplitude noise (ADT can only act on phase noise)
- A mitigation of this effect by a dedicated feedback system acting directly on the crab cavity voltage was investigated
- We also studied the possibility of tail cleaning with selective noise injection through the crab cavity
- Both of these studies conducted with modified versions of HEADTAIL (single-bunch simulations)

Can we use the crab cavity for tail cleaning?

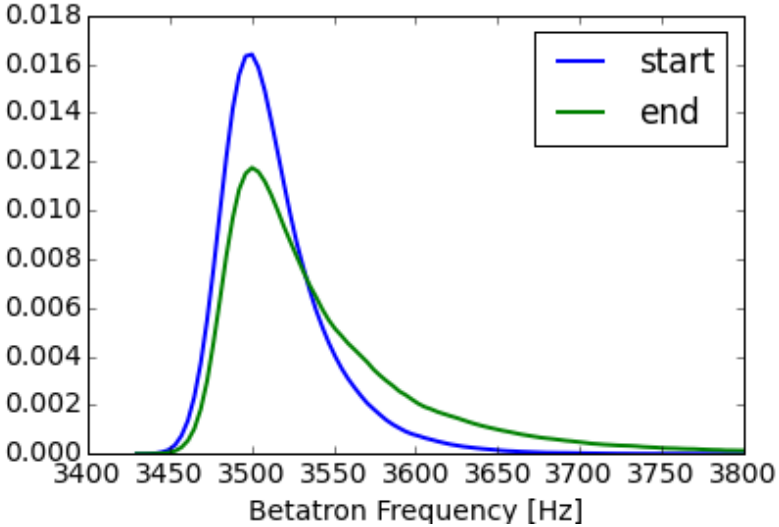
- In the LHC, shaped RF noise in the cavities is injected to blowup the longitudinal emittance during the ramp via longitudinal kicks
- We wanted to investigate what happens when we deliberately inject additional noise in the crab cavities, resulting in transverse kicks
- The final transverse distribution is a function of the tune distribution and the spectrum of the injected noise
- We used the expected HiLumi LHC tune distribution, with a chromaticity (normal distribution) and quadrupole or beam-beam (exponential) contributions
- Motivation: mitigation against large losses following a CC trip.

Distribution evolution for a flat noise spectrum

- Let's start with the "intuitive" case: a flat noise spectrum is injected in the crab cavity
  - This scenario corresponds to the expected baseline RF noise, in the *absence* of the transverse damper
- There was no significant change in the transverse position and tune distribution functional form
- These results agree with the smooth emittance increase theoretically predicted and shown through simulations in [2]



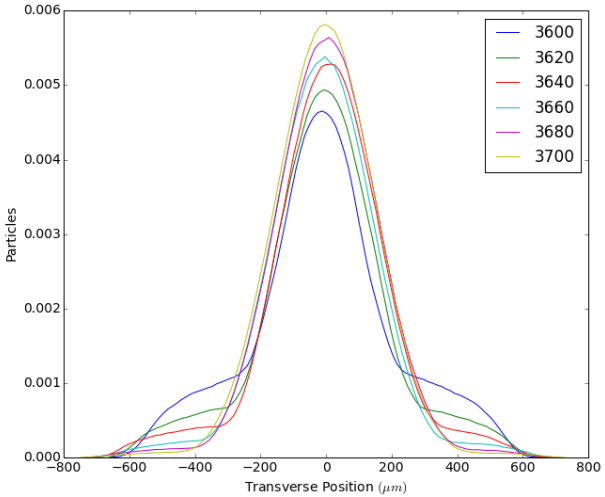
Transverse position distribution at the start and end of a wideband noise run.

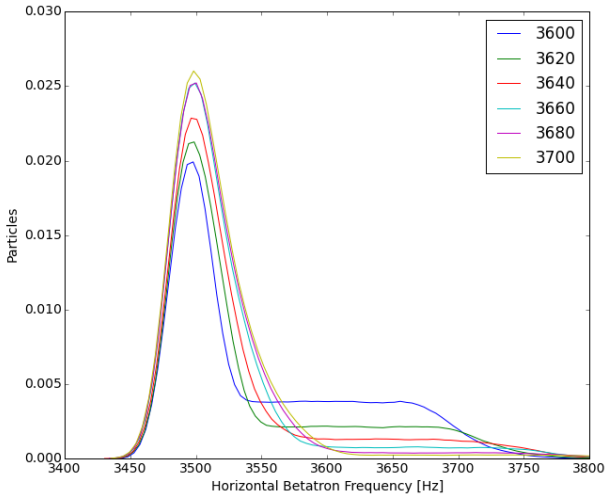


Tune distribution at the start and end of the same run as Figure 5.

Distribution evolution for narrowband noise

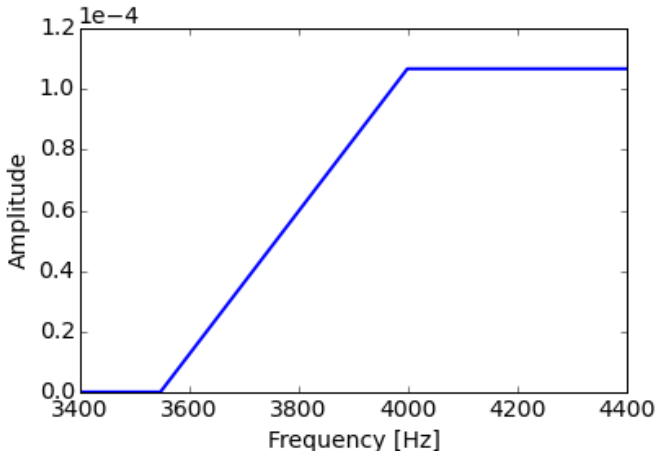
- The flat noise would only populate the tails. We simulated injecting narrowband noise (6 Hz BW) with different center frequencies to achieve tail cleaning
- As expected, the final transverse position distribution of the particles is highly dependent on the noise's center frequency
- This is because the noise only affects the particles whose betatron tune frequency overlaps with that of the noise PSD [2]
- Particles are lost at the core because the noise affects particles on a circle in PHASE SPACE, therefore, affecting particles in all x-positions.
- Why are then particles affected at the core of the TUNE distribution? Mostly because the noise does not roll-off sharply enough and the core is more sensitive





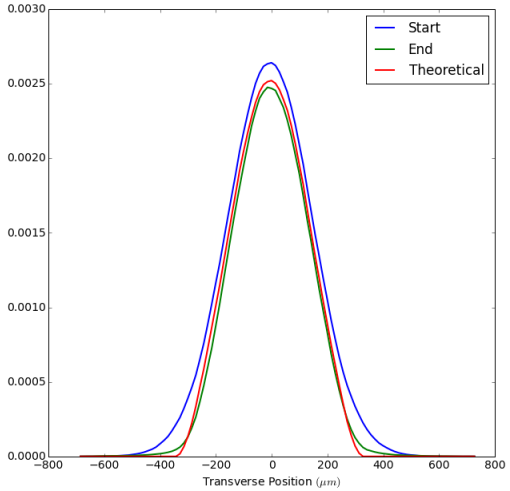
Shaped noise

- To minimize the effects on the core of the bunch and to increase the diffusion rate at the tail, shaped noise should be used that loosely follows the inverse of the tune distribution in the area of interest.
- The noise spectrum below starts at the frequency corresponding to $\approx 2\sigma$ of the transverse distribution

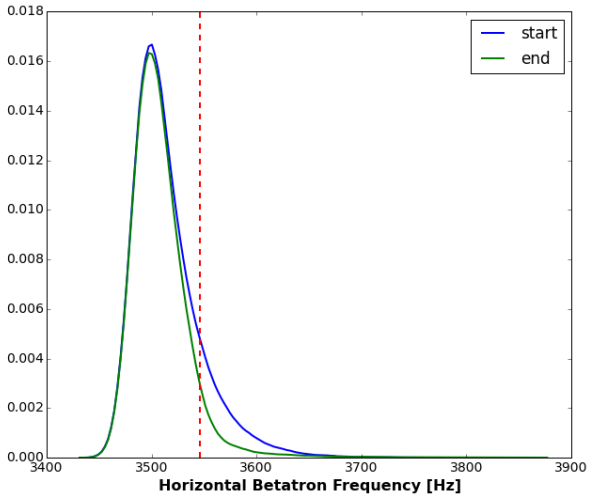


Distribution evolution for shaped noise

- This noise shape works very well
- The final distribution is very close to a the theoretical one (the distribution resulting from removing all particles outside 2σ in phase space)
- The small difference is due to the noise kicks, but also due to the chromaticity induced tune spread $\rightarrow$ longitudinal motion leads to some mixing in the transverse phase space
- This scheme would NOT work as well for high chromaticity



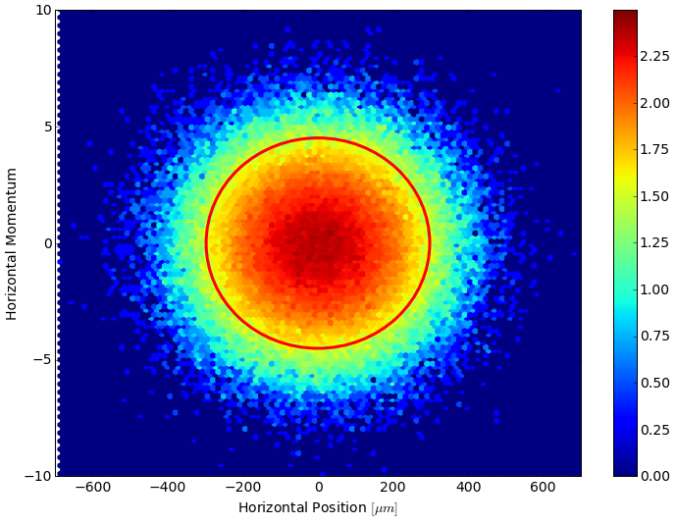
Transverse position distribution with 2σ cleaning



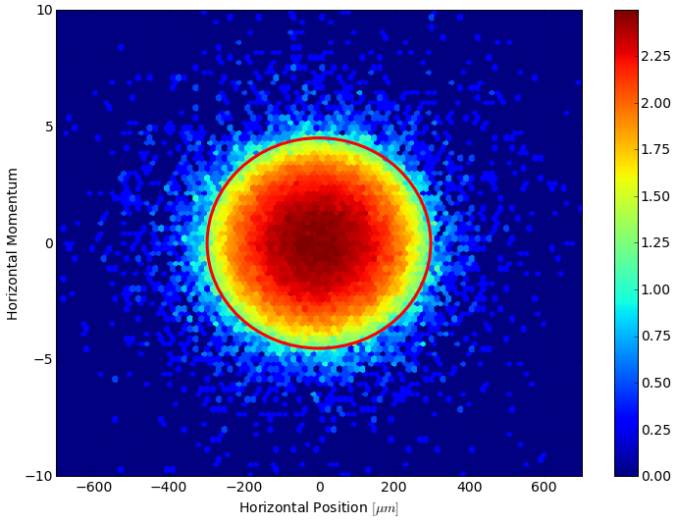
Tune distribution with 2σ cleaning

Phase space evolution for shaped noise

- The results are very promising
- We can also look at the initial and final situation in phase space



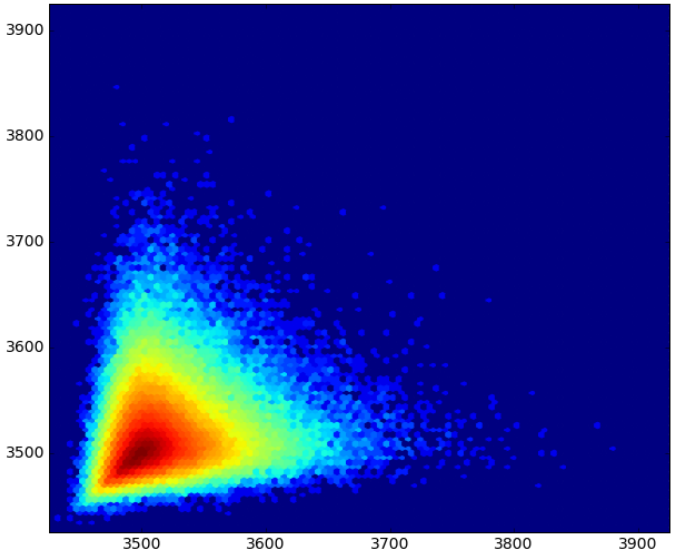
Initial phase space



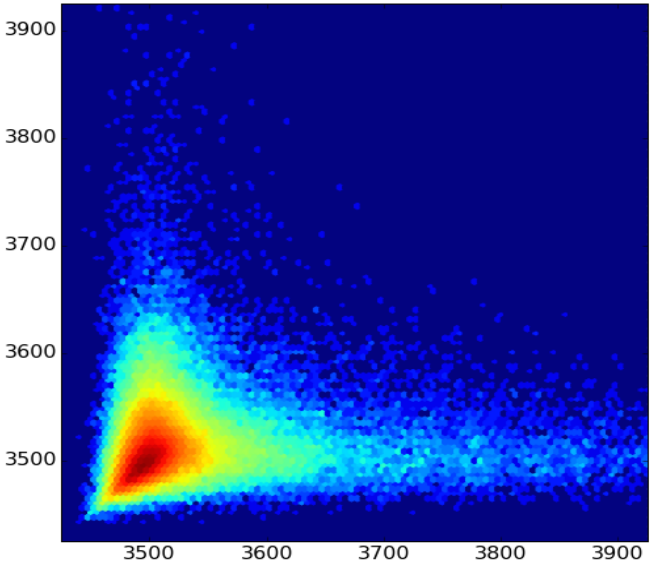
Final phase space

2D Cleaning

- Can we do this in 2D?
- If we just inject noise in x and y independently, we can clean the tails of the corresponding transverse distributions, but this happens along two lines on the tune footprint, not along the diagonal



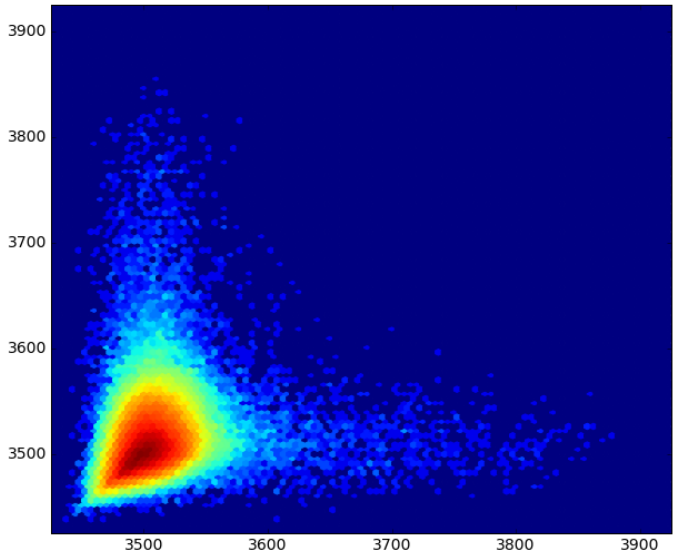
Initial phase space



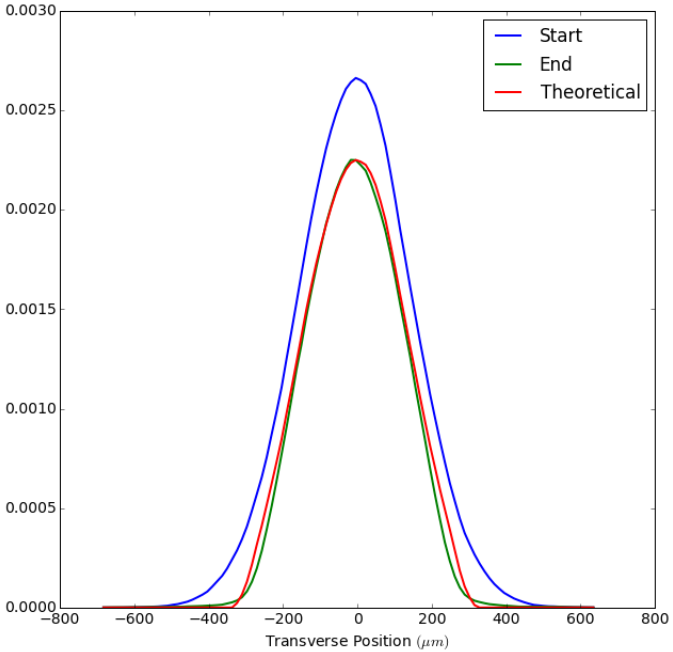
Final phase space

2D Cleaning

- We instead inject **correlated** noise in x, y in a series of steps: clean a small rectangle at a time
- Very promising results
- Single-bunch simulations: the small differences in tune foot-prints among the bunches will lead to slightly different final distributions along the ring, but the result still holds for the beam average



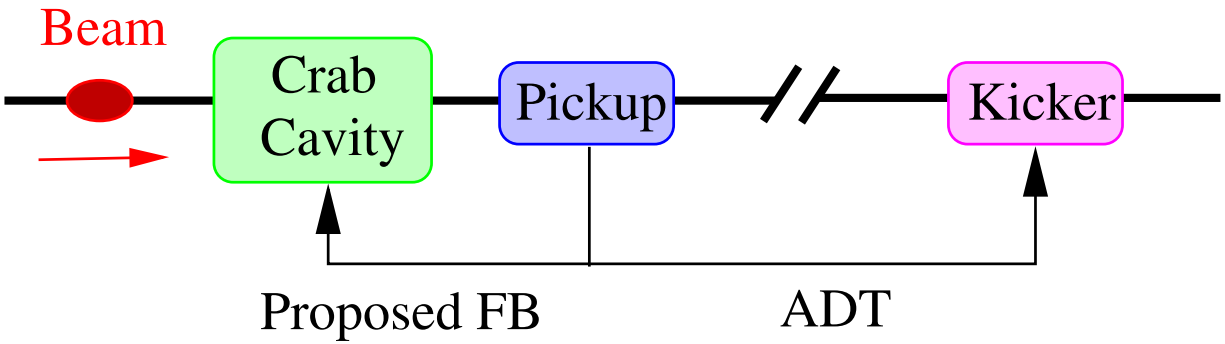
Final phase space



Final Transverse Distribution

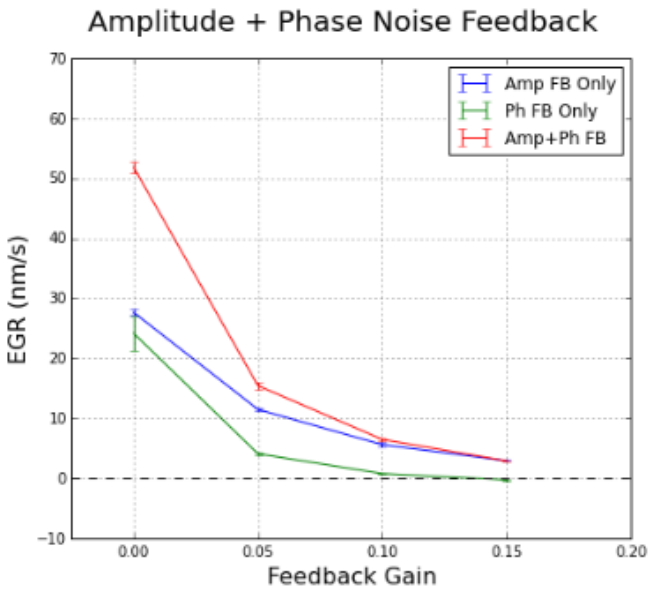
Crab Cavity RF Noise Feedback

- The system would use the same pickup as the damper, but use the information to change the crab cavity amplitude and phase
- It would allow us to act on BOTH phase and amplitude noise; we can act on both dipole and head-tail motion
- Limitation: the achievable bandwidth is the closed loop crab cavity BW (≈100 kHz), BUT this is not an issue, because we are acting on noise injected by the same loop and therefore also limited to the 100 kHz BW. We only need to counteract low-order modes
- We want to evaluate the potential system performance. Also the limitations imposed by the system delay and pickup measurement noise



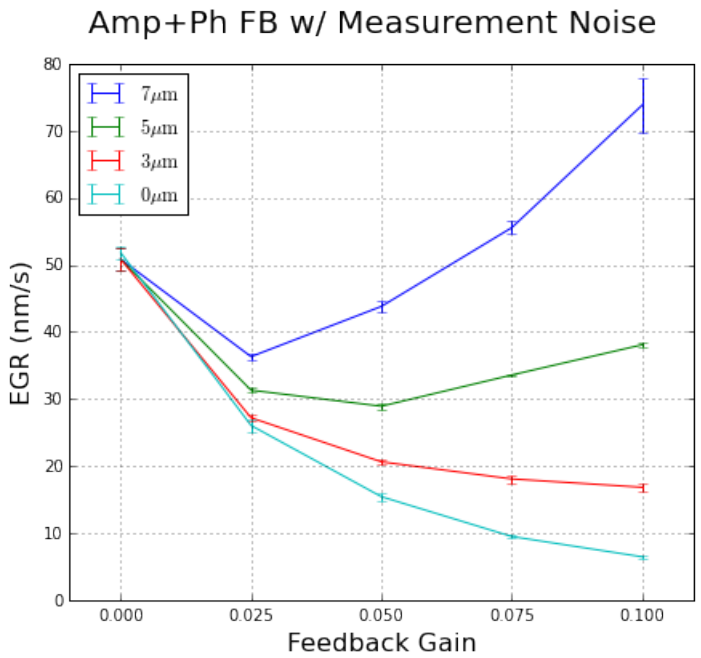
Emittance growth rate reduction

- An ideal system (no delay, no measurement noise) shows the potential for significant emittance noise reduction with this system.
- It also shows that the amplitude and phase feedback systems are independent: the emittance reduction is additive.



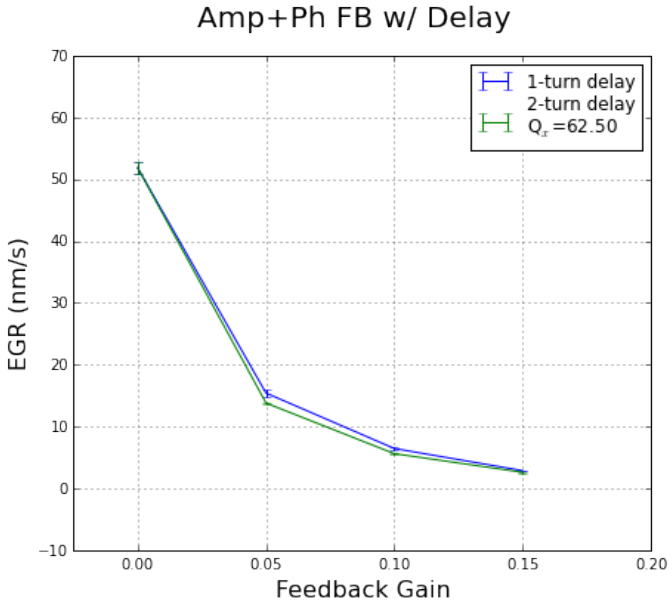
Measurement noise

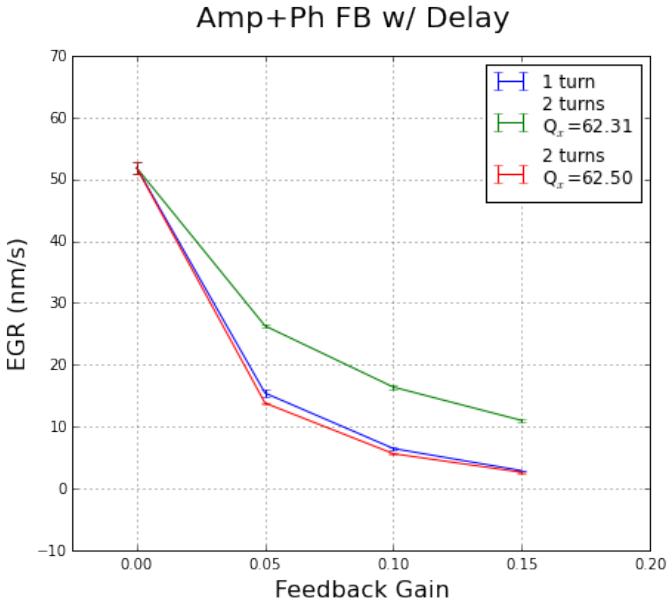
- A more realistic scenario includes measurement noise in the pickup
- The 5 μm level should be what we can achieve with the present pickup, and some smart filtering: the bunches respond to the CC noise on the betatron sidebands only, and, as the CC noise is narrow-band it will excite low-order coupled-bunch modes only. We could filter the measurements to identify these modes out of the noise



Effects of delay

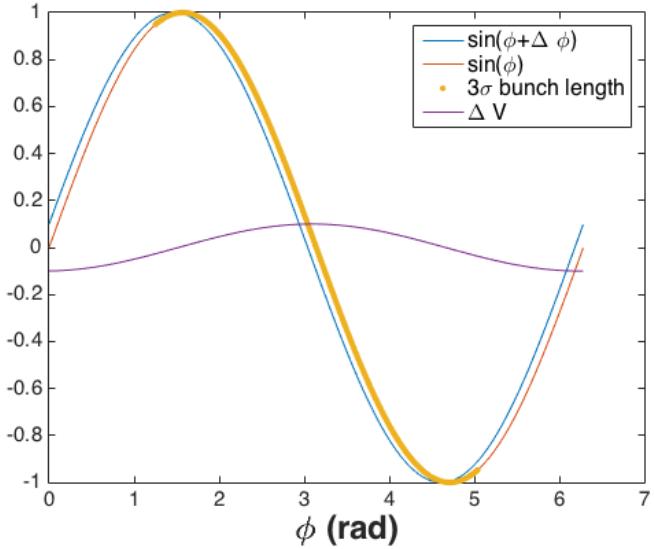
- The system will have a delay of at least 1 (2?) turns. The figure below shows the performance as a function of delay. No significant performance loss is expected due to the low system bandwidth.
- On the other hand, the phase advance between crab cavity and pickup is critical in the presence of delay. Since we can't change the phase advance, we instead changed the tune in the simulations.
- For the actual implementation, 2 pickups at 90° phase difference would be optimal and reduce the sensitivity on location with respect to the CC

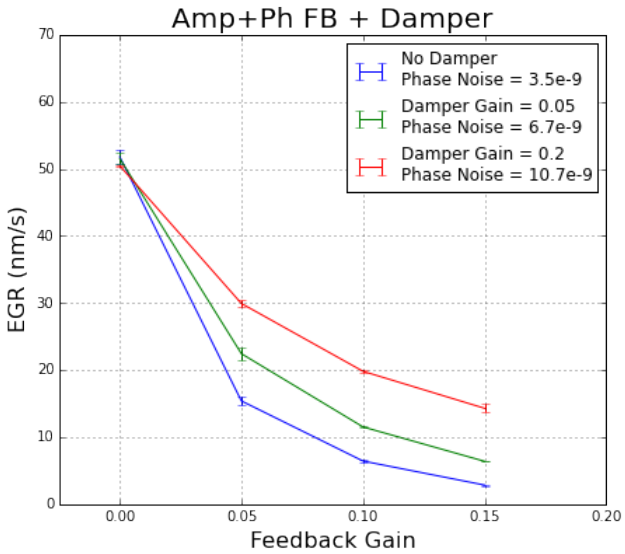




Superposition with Damper

- A voltage phase error leads to a voltage error proportional to a cosine
- Bunch-by-bunch Damper cannot act within a bunch and give a cosine kick to correct this error. It gives a rectangular kick proportional to the average value over the bunch $\rightarrow$ it actually *increases* the noise effect at the tails
- The proposed feedback can perfectly cancel this error
- The results in the presence of damper display this difference: as the damper gain increases, the effectiveness of both systems *together* is slightly reduced.
- The amplitude noise reduction is not affected by the presence of the damper





Conclusions

- Tail cleaning via the crab cavities was investigated with very promising results. The final transverse distribution strongly depends on the noise PSD as expected.
- A noise feedback acting directly on the crab cavities was studied as well. It can significantly reduce the RF noise induced emittance growth rate, if the measurement noise is at reasonable levels.

Thank you for your attention!

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References

- P. Baudrenghien, T. Mastoridis, “Transverse emittance growth due to Crab Cavity RF noise, and requirements for the Crab Cavity RF", HiLumi/LARP meeting, October 26th 2015.
- P. Baudrenghien, T. Mastoridis, “Transverse emittance growth due to RF noise in the High-Luminosity LHC Crab Cavities", Phys. Rev. ST Accel. Beams 18, 101001, October 2015.