# Crab cavities, RF noise and operational aspects (counter-phasing, Full Detuning). An update

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HiLumi WP2 meeting June 13th, 2017

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- Recap of Analytical Derivations
- Expected growth rate and required jitter
- Mitigations: Use CC as transverse kicker
- Making cavities invisible during filling and ramping
- Full detuning scheme
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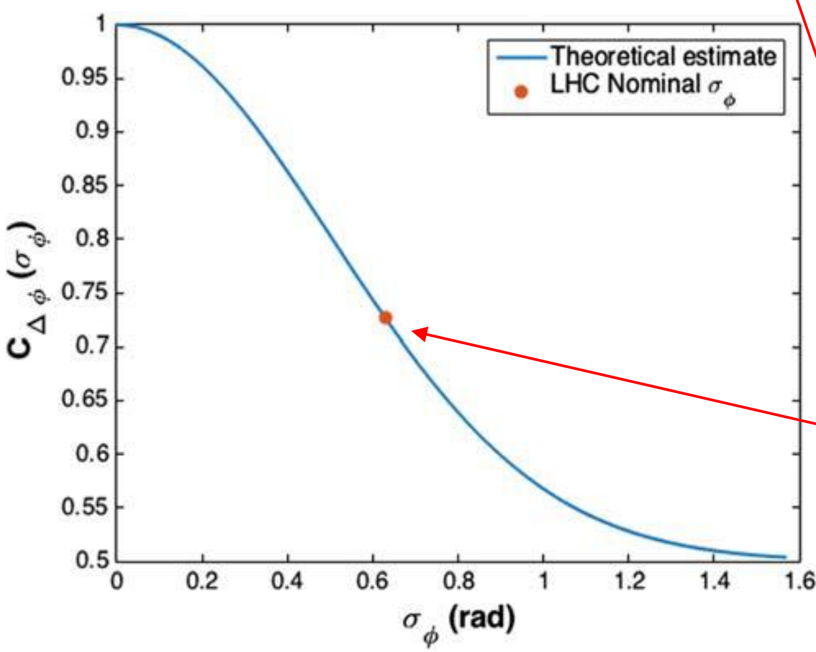
# Recap of Analytical Derivations

- Emittance growth caused by CC phase and amplitude noise

# Phase noise [1]

$$\frac{d\varepsilon_x}{dt} = \beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\sum_{k=-\infty}^{\infty}\int_0^\infty S_{\Delta\phi}\left[(k\pm\nu) f_{rev}\right]\rho(\nu)d\nu$$

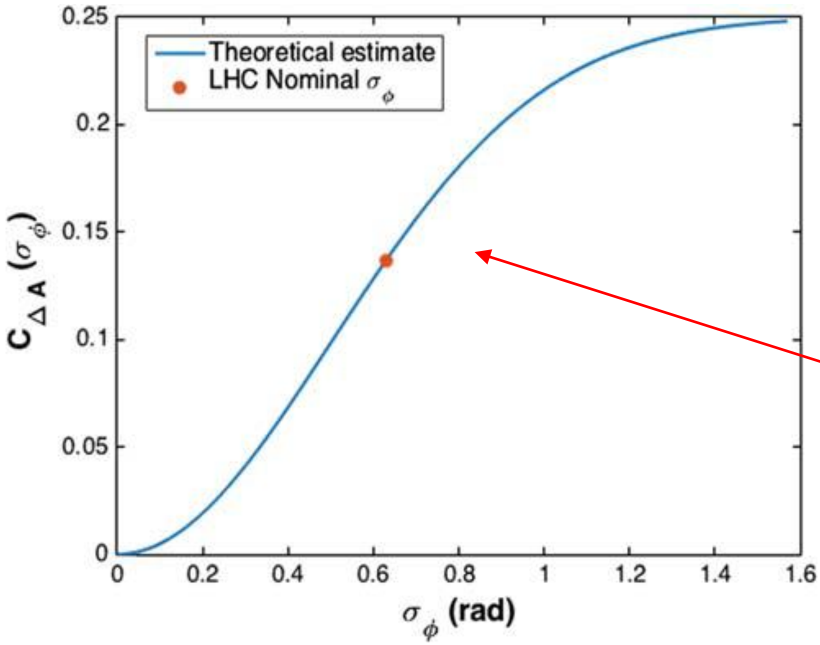



$$C_{\Delta\phi}(\sigma_\phi) = e^{-\sigma_\phi^2}\left[I_0\left[\sigma_\phi^2\right] + 2\sum_{l=1}^{\infty} I_{2l}\left[\sigma_\phi^2\right]\right]$$

- Depends on the overlap between phase noise spectrum and betatron tune distribution
- Phase noise spectrum is aliased at frev
- The “geometric factor” decreases with bunch length

# Amplitude noise

$$\frac{d\varepsilon_x}{dt} = 2\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta A}(\sigma_\phi) \sum_{k=-\infty}^{\infty} \int_0^{\infty} S_{\Delta A}\left[(k \pm \nu) f_{rev}\right] \rho(\nu) d\nu$$




$$C_{\Delta A}(\sigma_\phi) = e^{-\sigma_\phi^2} \sum_{l=0}^{\infty} I_{2l+1}\left[\sigma_\phi^2\right]$$

- Depends on the overlap between phase noise spectrum and betatron tune distribution
- Amplitude noise spectrum is aliased at frev
- The “geometric factor” increases with bunch length

# Transverse damper

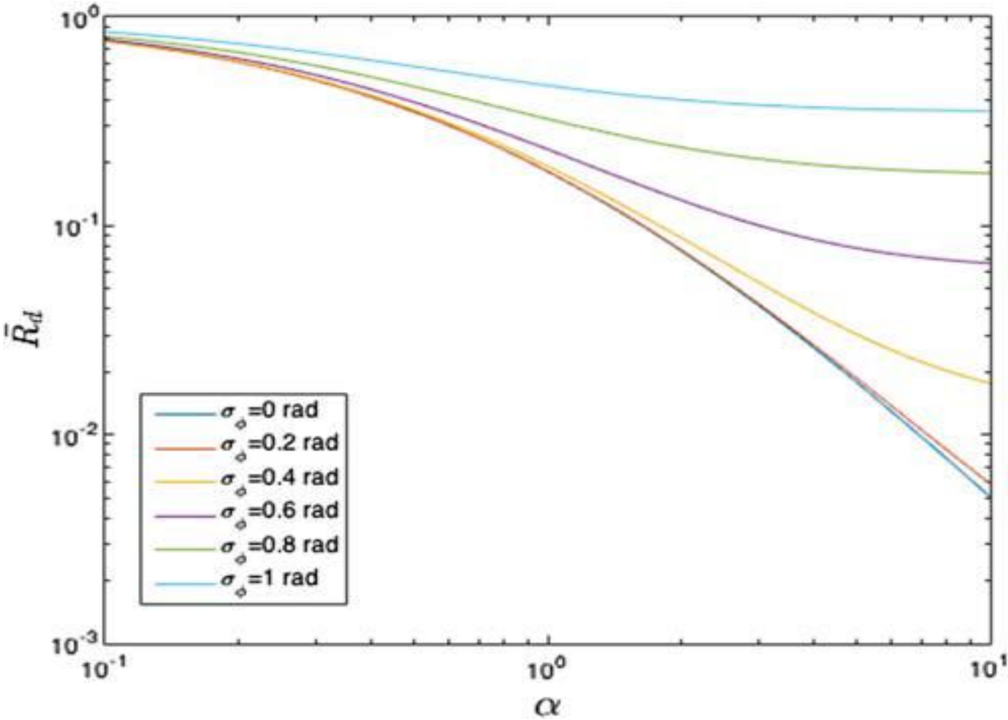
- The LHC transverse damper acts bunch per bunch: it measures the transverse position averaged over all particles in one bunch and generates a correcting kick
- It cannot correct for the effect of CC amplitude noise (as head and tails move in opposite direction)
- It can correct part of the phase noise effect
- Its effectiveness is a race against filamentation. It will depend on the ratio of damping time over filamentation time
- The damper efficiency drops quickly as bunch length increases. The damper kick is uniform along the batch while the effect of phase noise is strong in the core but weak in the tails. Increasing the damper kicks therefore excites the tails

# Damper reduction factor (phase noise)

$$\bar{R}_d\left(\sigma_\phi,\alpha\right)=\frac{1}{\pi}\int_{-\infty}^{\infty} g\left(u\right)\left\{1-\frac{e^{-\sigma_\phi^2}}{C_{\Delta\phi}\left(\sigma_\phi\right)}\frac{\alpha^2\left[g\left(u\right)^2+f\left(u\right)^2\right]+2\alpha g\left(u\right)}{\left[1+\alpha g\left(u\right)\right]^2+\left[\alpha f\left(u\right)\right]^2}\right\}du$$

With $\alpha=\dfrac{G}{2\pi\sigma_v}$ , $g(u)=\pi\,\sigma_v\,\rho(\bar{v}-\sigma_v u)$ , $f(u)=\sigma_v\,\mathrm{PV}\displaystyle\int_{-\infty}^{\infty}\frac{\rho(x)}{x-\bar{v}+\sigma_v u}dx$

- f(u),g(u) are scaled versions of the real and imaginary parts of the Beam Transfer Function.
- The damper efficiency drops quickly as bunch length increases. The damper kick is uniform along the batch while the effect of phase noise is strong in the core but week in the tails. Increasing the damper kicks therefore excites the tails



# Expected growth rate

- Scaling the ACS RF noise
  Bound on RF noise

# Parameters

- Beam

| $F_{rev}$ (Hz) | $\beta_{cc}$ (m) | $\nu_x$ | $\varepsilon_n$ (μm rad) | $E_b$ (TeV) | $\sigma_\phi$ (rad) | $\sigma_{\nu b}$ |
|---|---|---|---|---|---|---|
| 11245 | 4000 | 62.31 | 2.5 | 7 | 0.628 | 0.003 |

- CC

| $V_0$ (MV) | Nbr cavities per beam.plane |
|---|---|
| 3.4 | 4 |

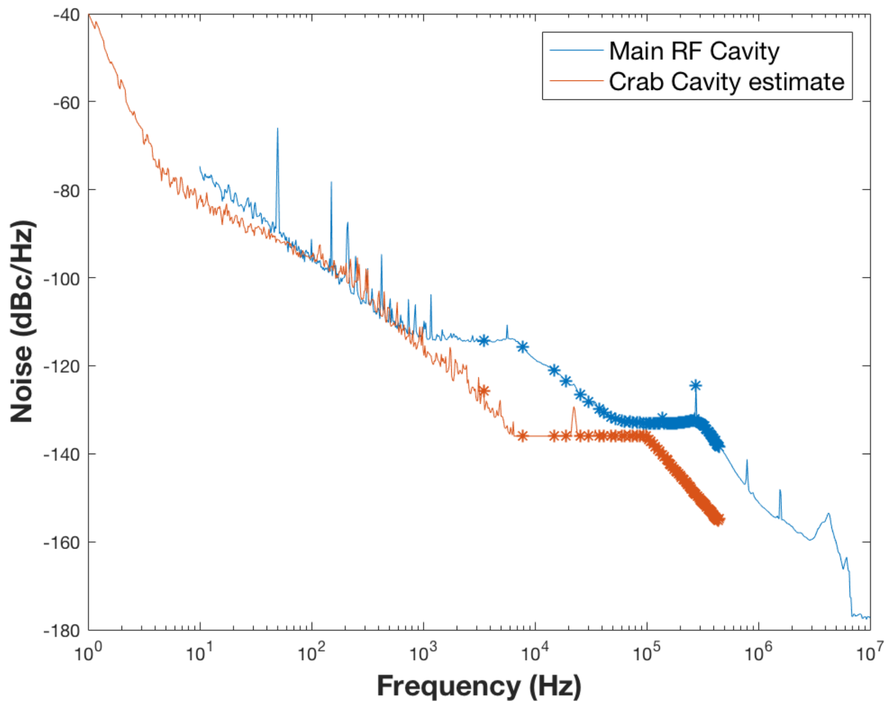
- ADT

| G | $R_d$ |
|---|---|
| 0.04 | 0.097 |

- CC LLRF

| Fdbk Closed-loop BW | TX Polar Loop effectiveness |
|---|---|
| 100 kHz | 40 dB reduction up to 1 kHz |

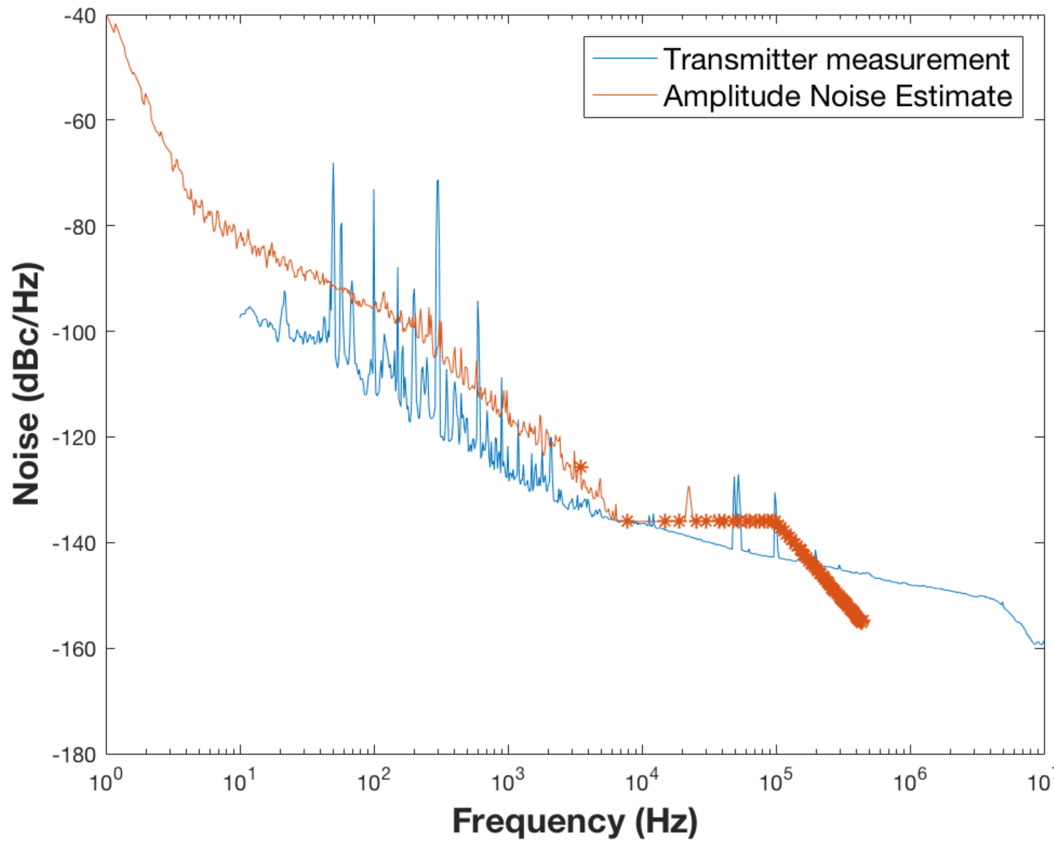
# Scaling the ACS. Phase noise




- Single-Sideband phase noise power spectral density in dBc/Hz. Plateau at –136 dBc/Hz. Total rms phase noise $\sigma = 143\ \mu\text{rad}$
- With reduction of phase noise effect from ADT, the emittance growth rate is 16%/hour

# Scaling the ACS. Amplitude noise

- Single-Sideband amplitude noise power spectral density in dBc/Hz. Plateau at -136 dBc/Hz
- Total rms amplitude noise $\sigma = 685$ V
- The emittance growth rate is 63%/hour



# Summing it up

- The amplitude noise is the limiting factor
- To get reasonable lifetime we must improve the demodulator noise level
- With −147 dBc/Hz (@ 3 kHz offset), plus filtering of the reference RF to reduce the noise level on the first betatron line (3 kHz), we get
  - Phase noise: rms $\sigma = 34\ \mu rad$ resulting in 0.94 %/hour emittance growth rate
  - Amplitude noise: rms $\sigma = 165$ V resulting in 3.7 %/hour emittance growth rate
- Challenging but possible

# Mitigation

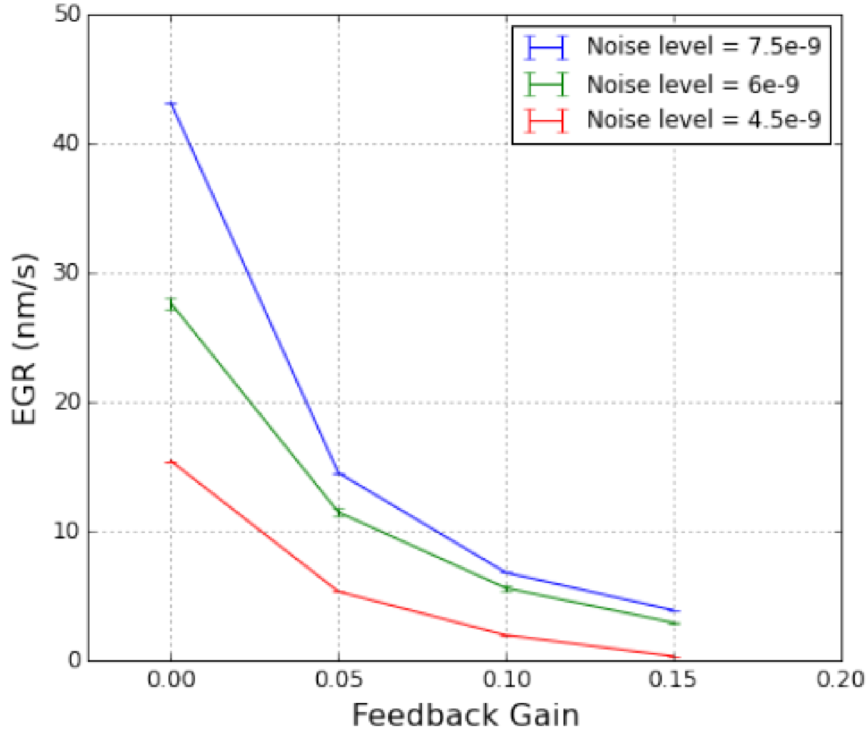
- Transverse feedback using the CC

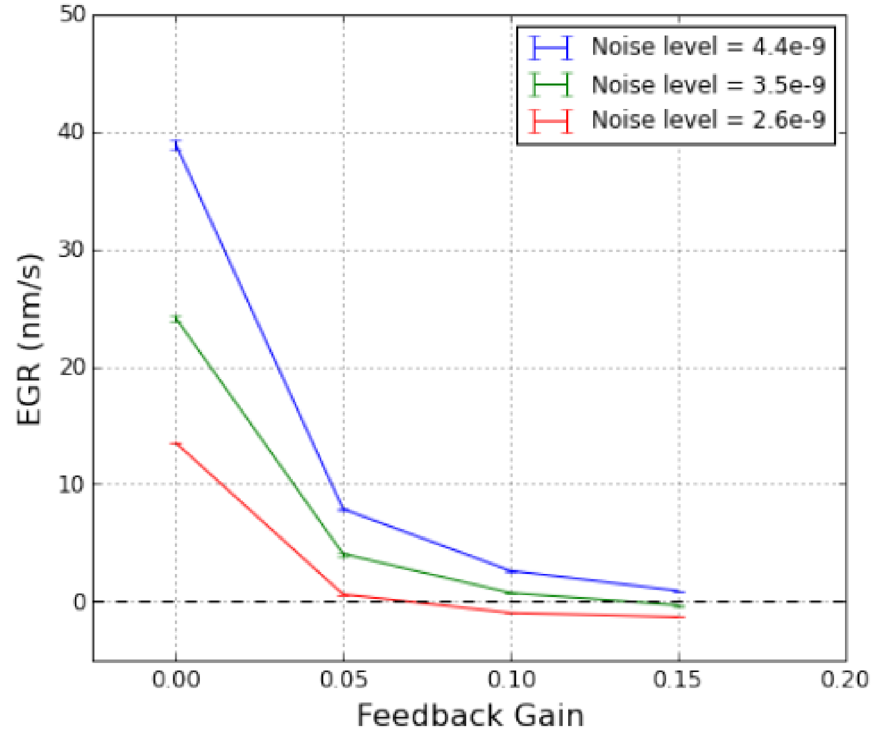
# Idea

- Measure the bunch transverse displacement (head+tail), and the tilt (head−tail)
- Use the Sum signal to feedback on the CC phase
- Use the Difference to feedback on the CC amplitude

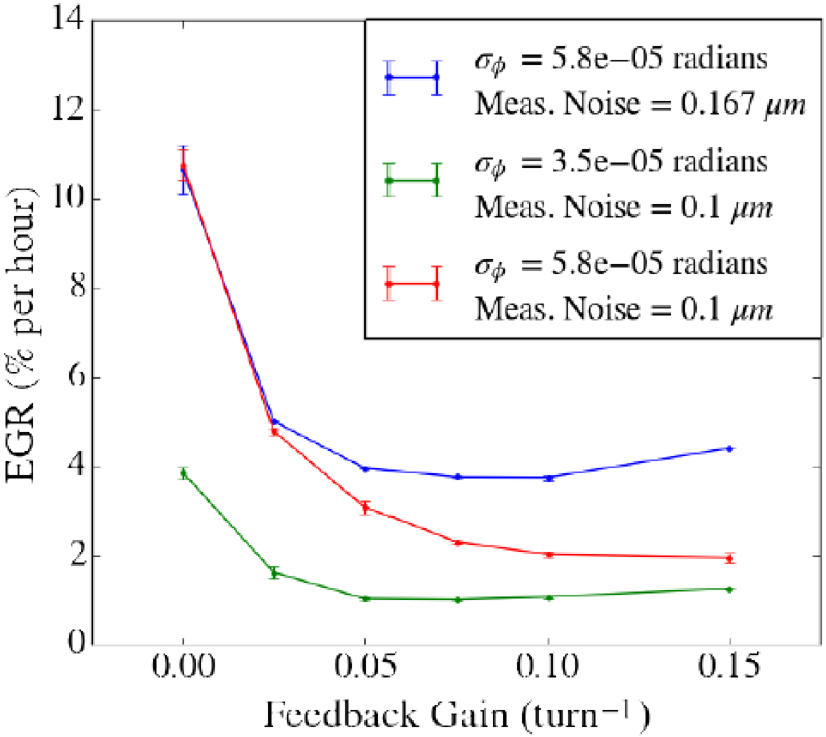
# Very promising in simulations

- Amplitude noise (left) and phase noise



- With measurement noise added




- Synergy with ADT upgrade (reduction of measurement noise)
- The CC excites only low modes (closed-loop BW ~ 100 kHz) so we can average over few bunches -> improves SNR
- Being studied. Collaboration with Cal Poly (T. Mastoridis)
- Paper in preparation.

# Operational scenario

- The RF is ON, with strong RF feedback and tune controls at all time. Cavities are on-tune at all time.
- During filling, ramping or operation with transparent crab cavities:
  - Small cavity field as required for the active Tuning system
  - We use counter-phasing to make the total field invisible to the beam
  - A strong RF feedback keeps the Beam Induced Voltage zero if the beam is off-centred.
- ON flat top:
  - We drive counter-phasing to zero
  - Any adiabatic field manipulation is possible by synchronously changing the voltage or phase in each cavity (luminosity levelling for example).

# Precision

- The RF feedback has measurements of the Antenna of all 4 cavities (per IP.beam) and generate the 4 TX drives
- We can reduce voltage by at least factor 10 (300 kV/cavity)
- Assuming 5 degree (0.09 rad) phase error (between the two counter-phased cavities), the total voltage will be about $3\ 10^5\ 0.09 = 26$ kV

# Emittance growth during filling

- The un-normalized emittance growth scales as $(V/\gamma)^2$
- The normalized emittance growth scales as $V^2/\gamma$
- So, as long as the cavity voltage is reduced by 4 (< 0.75 MV/cavity), the growth rate at injection is lower than in physics
- Strong octopoles and chromaticity increase the betatron tune-spread. That impacts only the phase noise reduction factor that comes from ADT. But recall that the effect of amplitude noise dominates
- Large betatron tune-spread will also reduce the effectiveness of the CC feedback (same mechanism as with ADT). Being studied (Cal Poly collaboration)

# Full detuning

- Consequences of bunch phase modulation

# Bunch phase modulation (1/2)

- The CC field cannot be modulated at Frev (QL=500000)
- The CC RF will therefore slip w.r.t. the bunch core
- Calculations have been done on the effect of longitudinal displacement on Lumi. For symetric bunch 1-2 displacements:
  - A 100 ps displacement of bunch core w.r.t. CC RF zero phase results in 2% reduction in lumi
  - A 200 ps displacement results in 8% loss in lumi
  - We expect 100 ps pk-pk displacement with HiLumi intensity, that is 50 ps max displacement

# Bunch phase modulation (2/2)

- Calculations have also been done for asymetric longitudinal displacements
- An 100 ps shift of one beam only will result in 6 % decrease in Lumi
- We conclude that the CC RF phase must be controlled with a precision better than 5 RF degree @ 400 MHz (35 ps)
- Simulations will follow
- Work done with the HiLumi collaboration (Emi Yamakawa, Lancaster University)
- Results will be presented and published soon

# Conclusions

# Conclusions (1/2)

- Use of the RF receiver designed for the ACS cavities (in 2005) will result in 16 %/hour (phase noise) and 63 %/hour (amplitude noise) emittance growth rate, including ADT reduction
- An upgrade, reducing the noise level by 11 dB and filtering the 400.8 MHz reference would lead to an acceptable 0.94 %/hour (phase noise) and 3.7 %/hour (amplitude noise) emittance growth rate. ACCEPTABLE

# Conclusions (2/2)

- A proposed mitigation is a feedback system acting on the CC phase and amplitude. Promising. Performances limited by the accuracy of transverse measurements. Studies (calculations plus simulations) ongoing (CalPoly collaboration).
- The situation during physics and ramp is more favourable than in physics
- The impact of the Full Detuning scheme is limited. Simulations needed to confirm the calculations (Cockcroft collaboration)
- The accuracy required on the CC cavity phase does not appear too demanding.

# References

[1] P. Baudrenghien, T. Mastoridis, Transverse emittance growth due to RF noise in the high-luminosity LHC Crab Cavities, PRST AB, 18, 101001 (2015)