Update on strong-strong simulations for HL-LHC

3rd Joint HiLumi-LARP Annual meeting

Daresbury, Nov. 2013

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Outline

- Damper (FB) noise
  - Operational parameters
- Crab cavity (CC) noise
  - White
  - Harmonic
- Dipole noise

Numerical Setup

- Strong-strong soft Gaussian collision model
- 1 bunch per beam
- No long range effects
- Linear transfer maps
- 8 million macro particles
- 25 ns bunch spacing HL scenario [1] with β-leveling

[1] O. Brüning et al., MOPPC005, IPAC2012

Default Beam Parameters

Parameter	Value
N_p	2.2×10^{11}
ε_n / µm	2.5
β^* / m	0.49
σ / µm	12.8
Q_x	64.31
Q_y	59.32
θ / mrad	0.295
g_1, g_2	0.05
Damper noise	on
Crab cavities	on
Collisions / turn	1 hor., 1 ver.
ξ	0.022

Damper Model

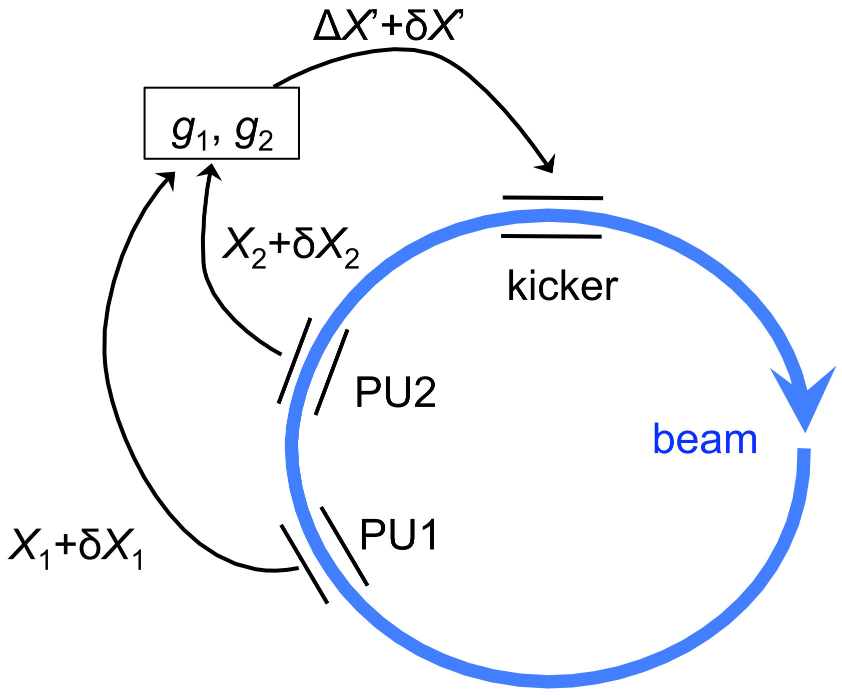
- Hilbert notch filter (equally in *y*):

$$\Delta X' \propto g \sum_m H_m(\varphi_H) \times (X_{n-d+1-m} - X_{n-d-m})$$

- φ_H depends on *Q* and delay *d*
- Pick-up noise (FB)
  Adjusted to match observed emittance growth [1]

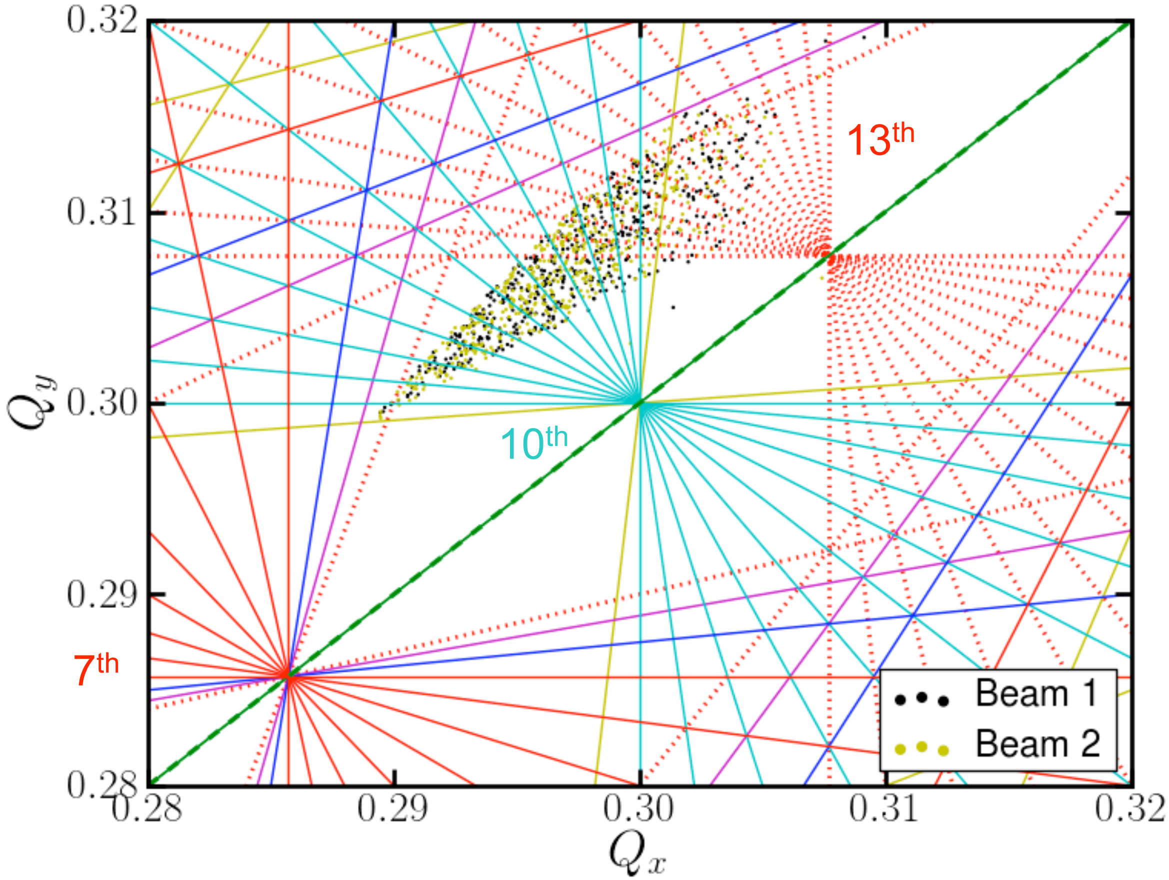
  δX_{rms} = 0.72 µm

  δY_{rms} = 0.50 µm



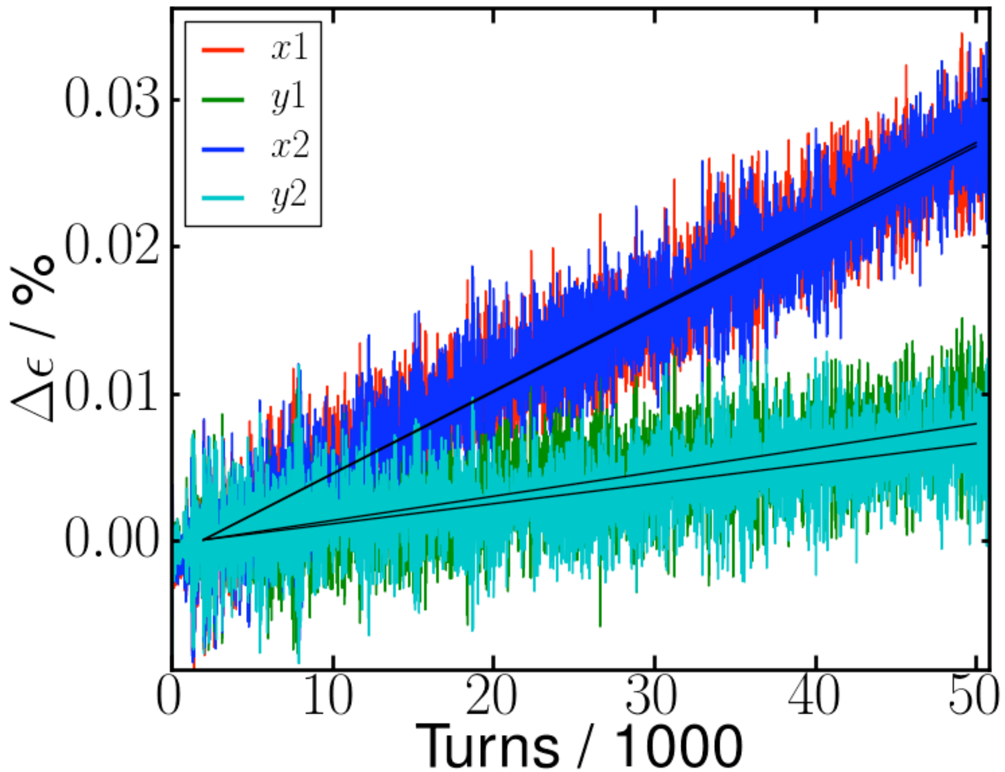
[1] S. Paret et al., TUPME061, IPAC2013

Default Tune Footprint



Default Simulation

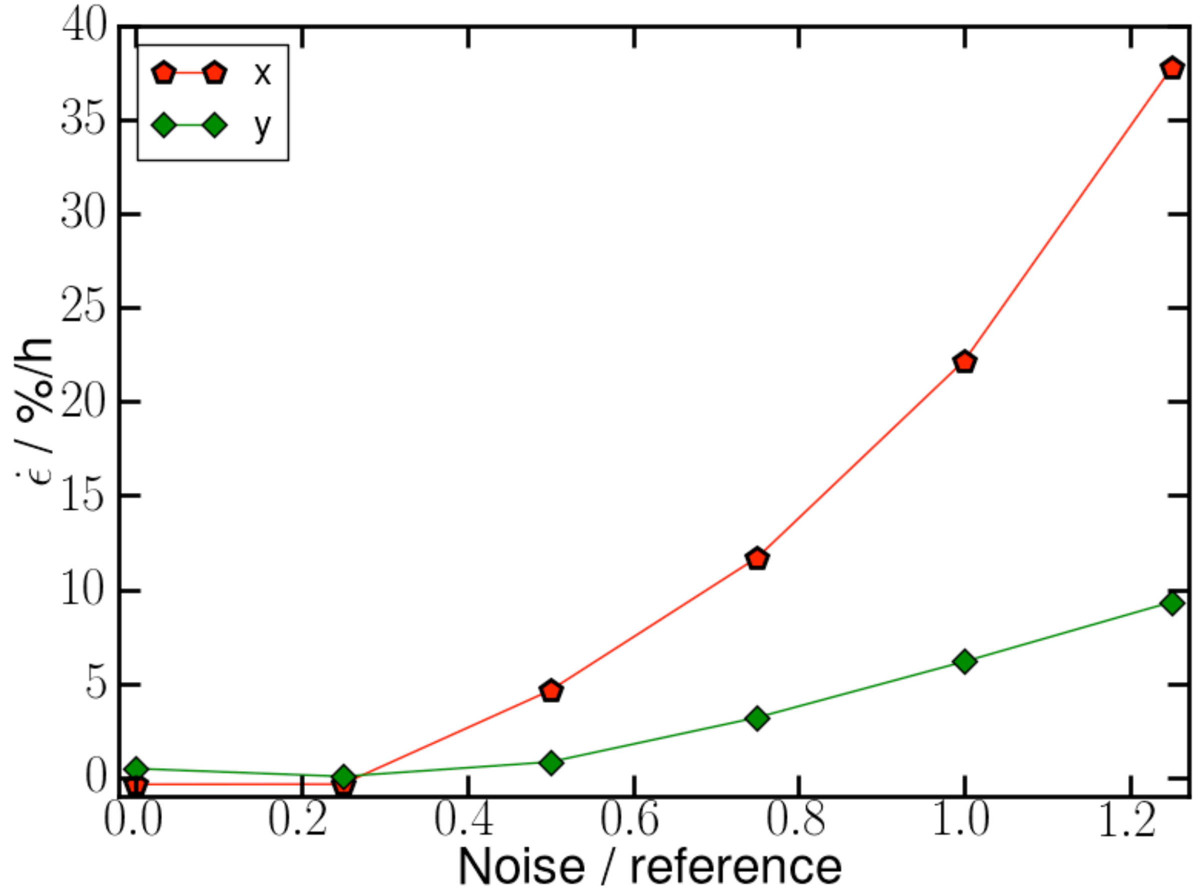
- No CC noise



Average emittance growth rate: 14 %/h

Based on linear extrapolation, average of both beams and planes

Emittance Growth versus Amplitude

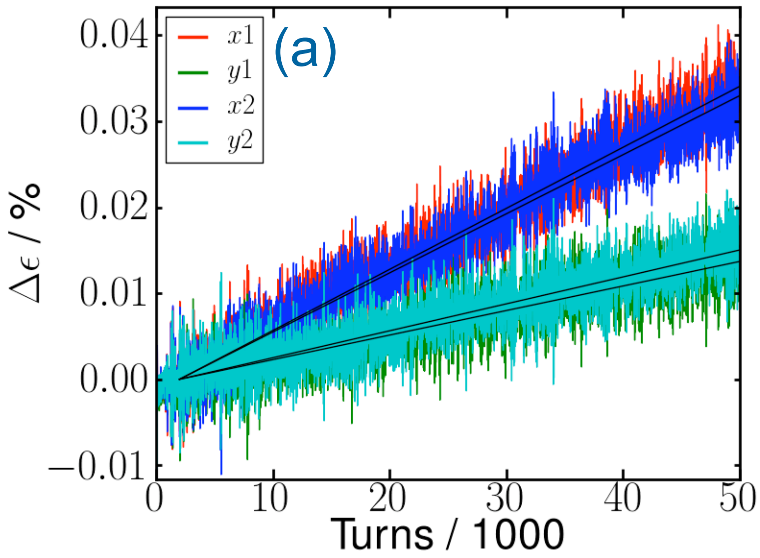


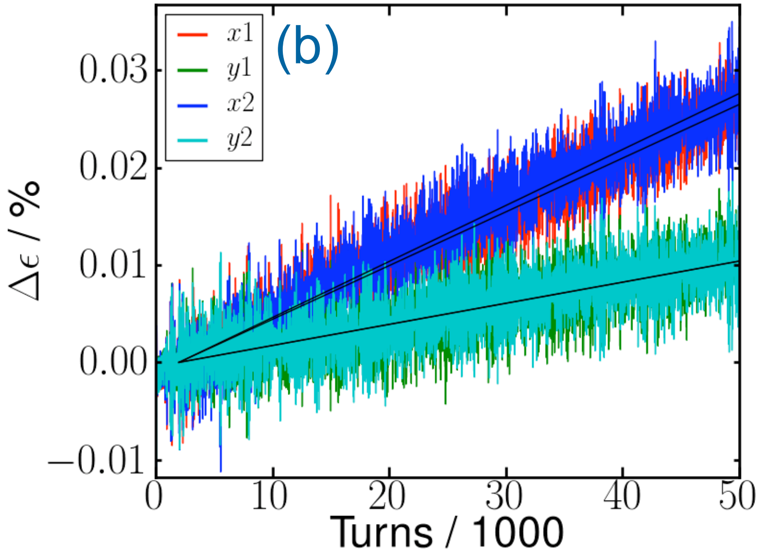
Approximately quadratic scaling

Strong-strong simulations challenging at low noise due to numerical noise

Hilbert Phase with Tune Shift

Calculated phases for Hilbert filter taking into account half (a) and full (b) tune shift



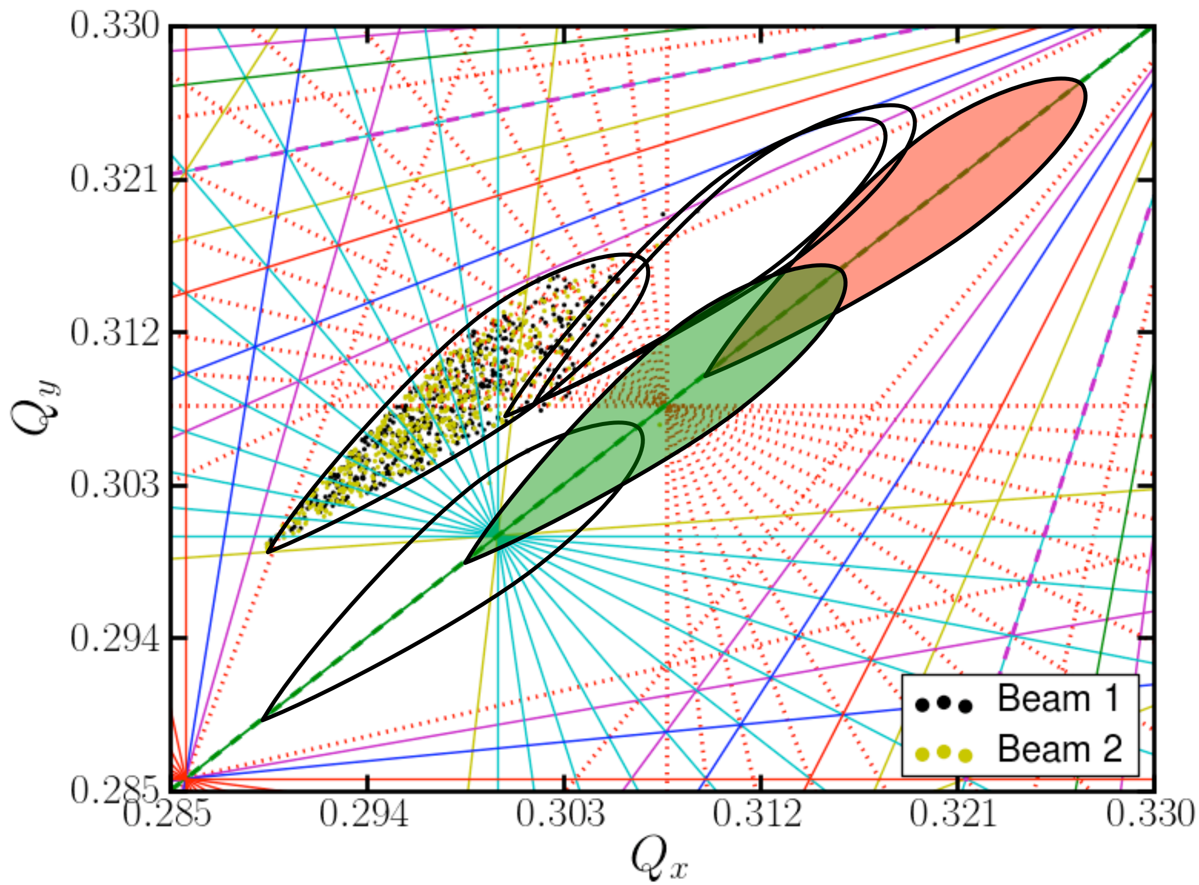


Emittance growth rate: 20 %/h

Emittance growth rate: 16 %/h

➔ No improvement

Improving the Working Point I



Lowest average emittance growth rate: 13 %/h

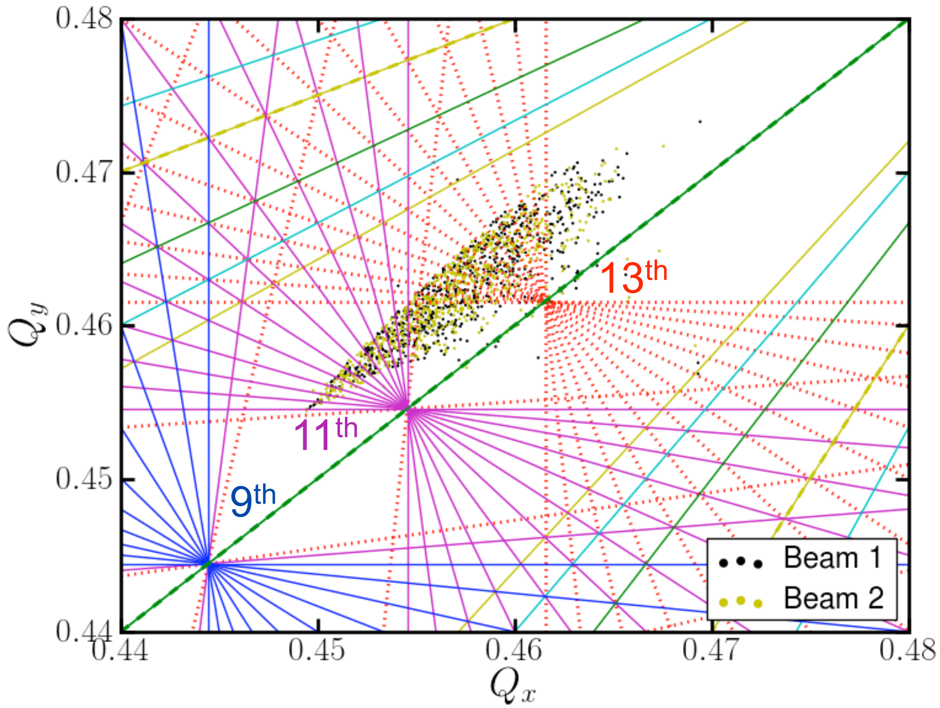
$Q_x = Q_y$ ➔ Symmetry of beams preserved

Working Point II

- Q = (0.47, 0475)

  $g_1 = 0.02$, $g_2 = 0.08$

- Closer to Q = 0.5 damping algorithm fails
  - Alternative damper operating mode required [1]
  - LHC damper needs to be prepared for this mode [1]
  - Can be implemented in BeamBeam3D



Emittance growth rate: 3.4 %/h

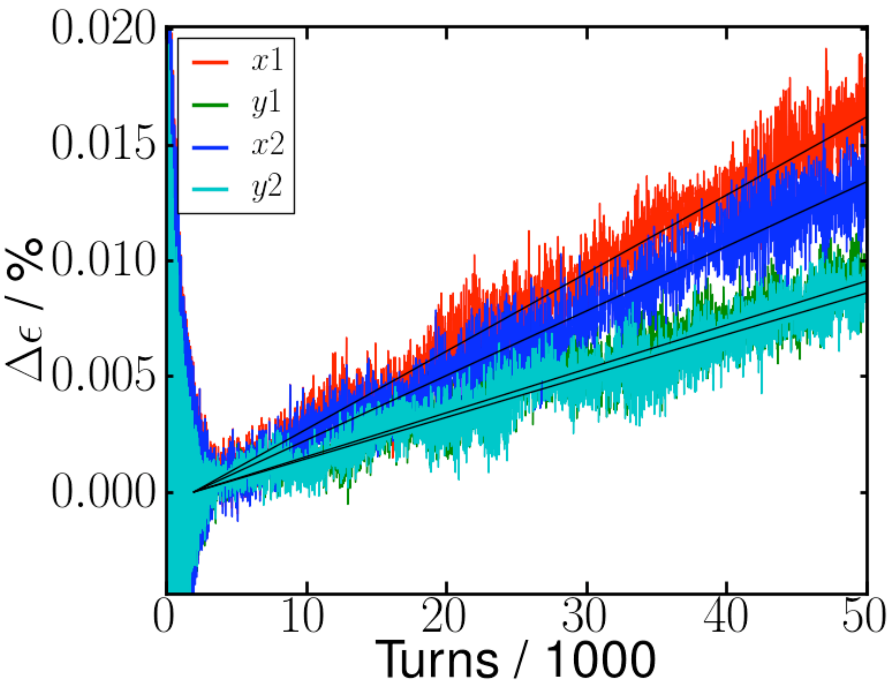
Should this option be investigated?

[1] P. Baudrenghien et al., THPC122, EPAC08; W. Höfle, private communication

Leveling via CCs

- β = 0.15 m
- CCs switched off

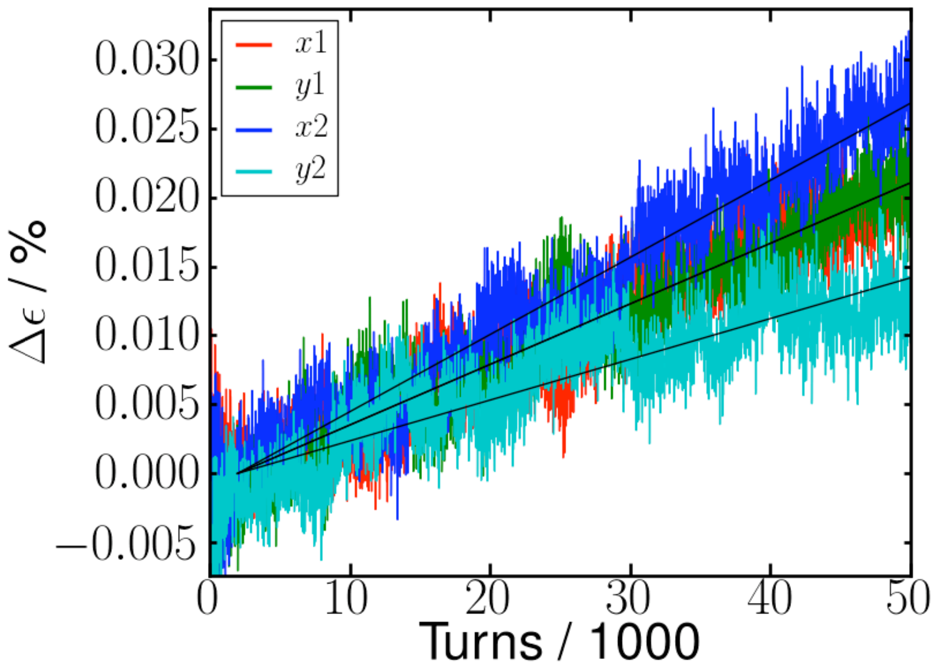
  Approximates leveled luminosity within 10 %



Average emittance growth rate: 10 %/h
More stable than with β leveling
Even more beneficial if CC noise is included

Leveling via Beam Separation

- β = 0.15 m
- Offset: 2.2 σ



Average emittance growth rate: 18 %/h
Less stable than with β leveling

White CC Phase Noise I

- Approximation: Coherent kick yielding offset at IP [1]:

$$\delta X = -\frac{c}{\omega_{cc}} \tan\left(\frac{\theta}{2}\right) \delta\varphi$$

- LHC acceleration cavities: $\delta\varphi$ = 0.2 mrad [2]

  ➔ δX_{rms} = 7nm

- Current model BeamBeam3D

[1] K. Ohmi et al., TUPAN048, PAC07

[2] P. Baudrenghien, LLRF for crab cavities, 2nd Joint HiLumi LHC-LARP Annual Meeting, Nov. 2012

White CC Phase Noise II

- Offset due to noisy CC (equally in *y*):

$$x = -\frac{c}{\omega_{cc}} \tan\left(\frac{\theta}{2}\right) \sin\left(\frac{\omega_{cc} z}{c} + \delta\varphi\right)$$

$$x \approx -\frac{c}{\omega_{cc}} \tan\left(\frac{\theta}{2}\right) \left[\sin\left(\frac{\omega_{cc} z}{c}\right) + \cos\left(\frac{\omega_{cc} z}{c}\right) \delta\varphi\right]$$

tilt (nominal) incoherent perturbation

- Noise term:

  Reduces to coherent offset in first order

  However, poor approximation for HL-LHC (σ_z = 7.5 cm):

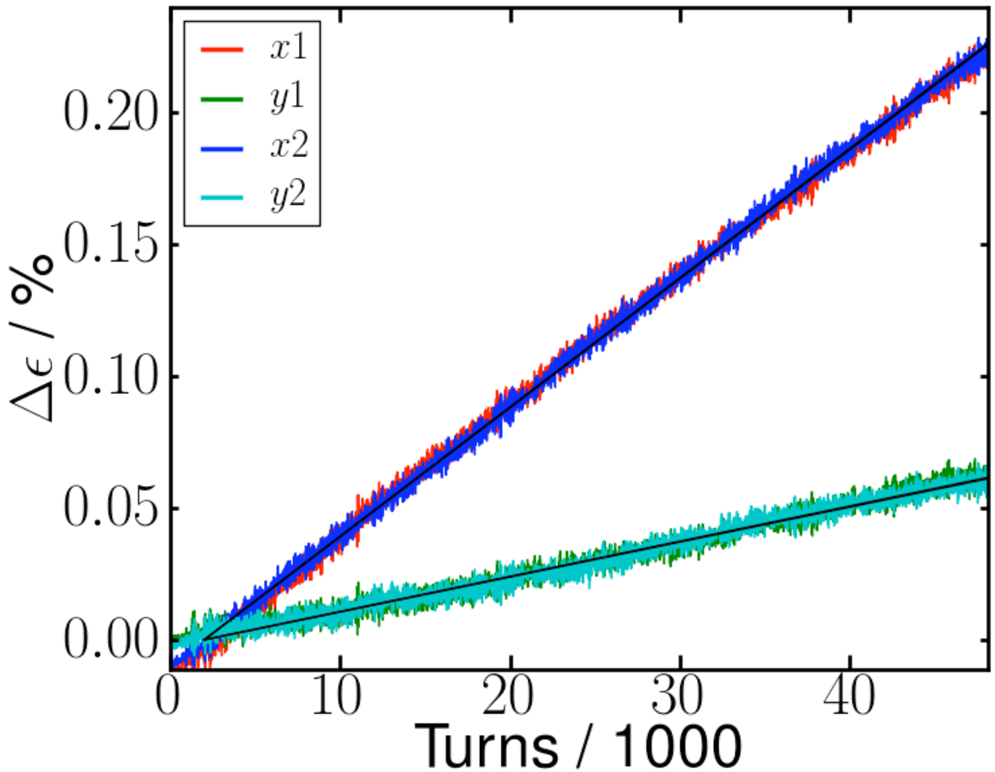
  $z = \sigma_z$ ➔ cos(0.63) = 0.81

  $z = 2\sigma_z$ ➔ cos(1.26) = 0.31

May have impact on emittance

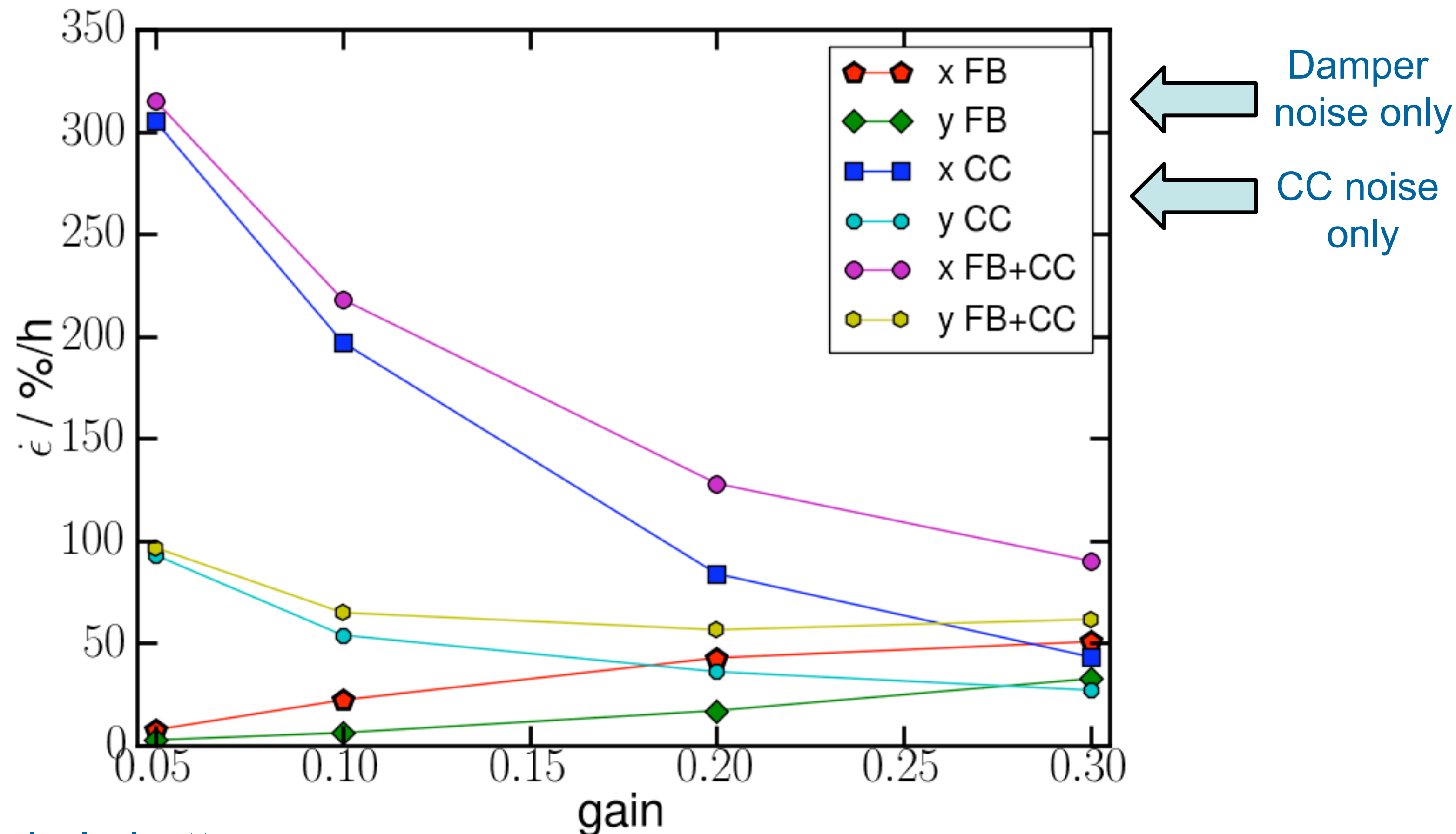
Emittance Growth with White CC Noise

No damper noise



Average emittance growth rate: 126 %/h

Emittance Growth versus Gain



Larger gain is better

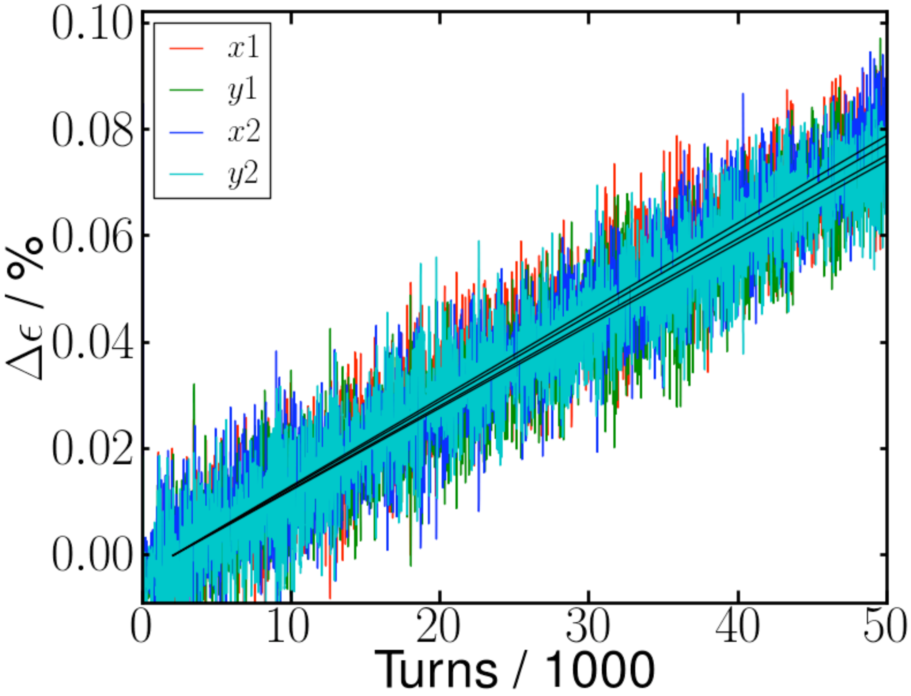
Pick-up noise limits efficiency of damper

Near Half Integer

- $Q = (0.47, 0475)$

  $g_1 = 0.02$, $g_2 = 0.08$

- CC noise + FB noise



Average emittance growth rate: 64 %/h

Improved but still very large

Are assumptions (amplitude, white spectrum) representative?

Harmonic CC Noise I

- Approximated by offset modulation at IP (equally in *y*):

$$\delta X = A_p \cos(\omega_p t + \varphi_p)$$

- Erroneous tilt negligible
- Amplitude, phase and frequency for LHC's CCs unknown
- Observed in KEK: Amplitude about -65 dB [1]
  Applied to HL-LHC parameters
  ➔ $A_p = 2 \times 10^{-8}$ m

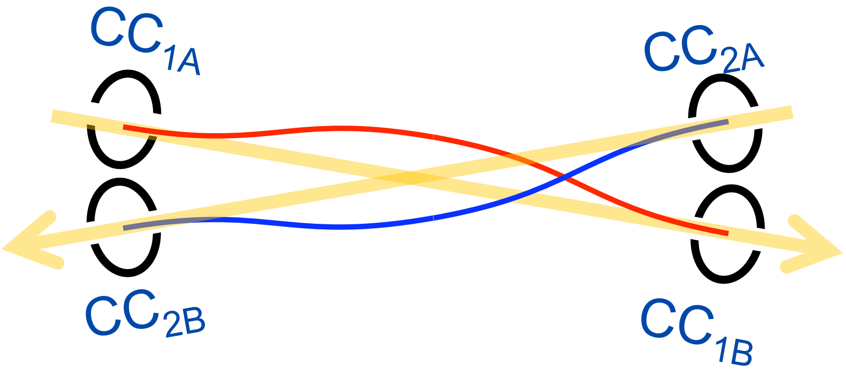
[1] R. Calaga et al., TUPAS089, PAC07

Harmonic CC Noise II

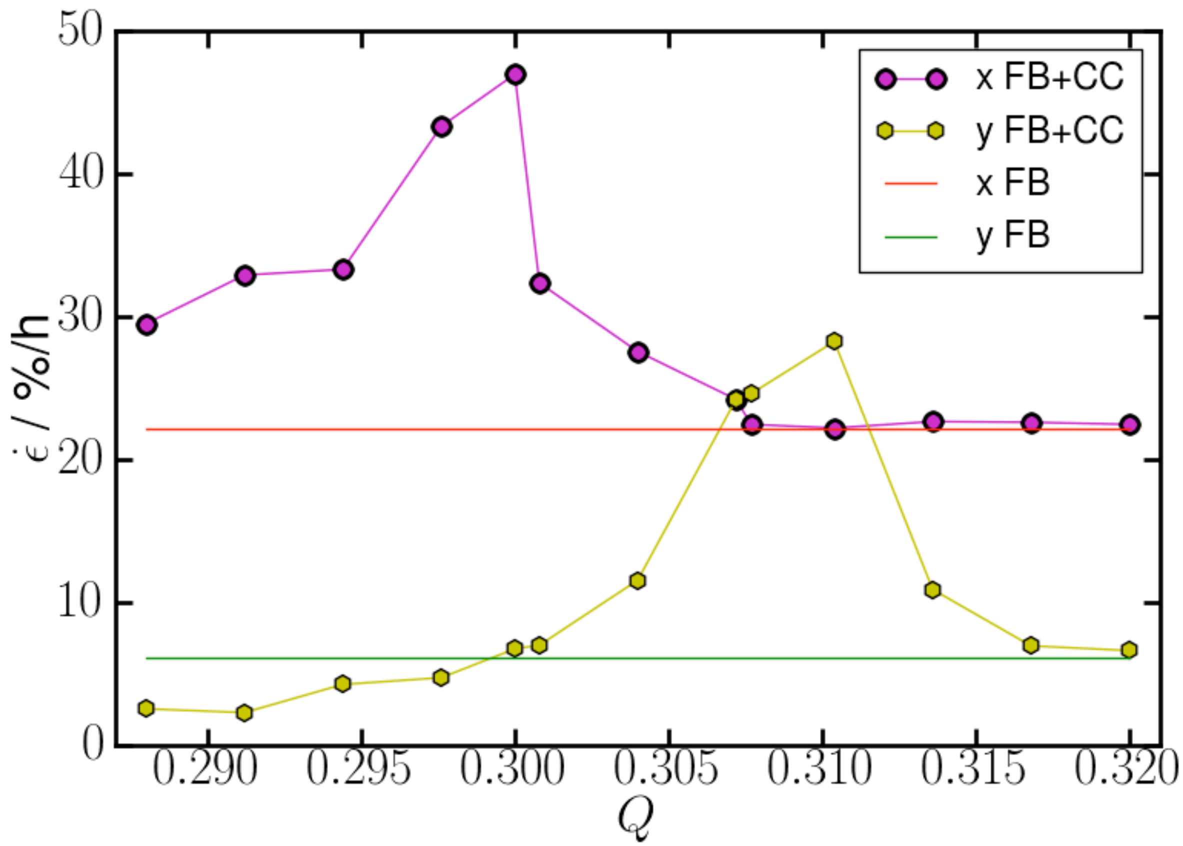
- Assuming $A_p = 2\times10^{-8}$ m in all CCs
- Assuming equal ω_p in all CC
- Assuming

$$\varphi_{1A} = \varphi_{1B} = 0$$

$$\varphi_{2A} = \varphi_{2B} = \pi$$

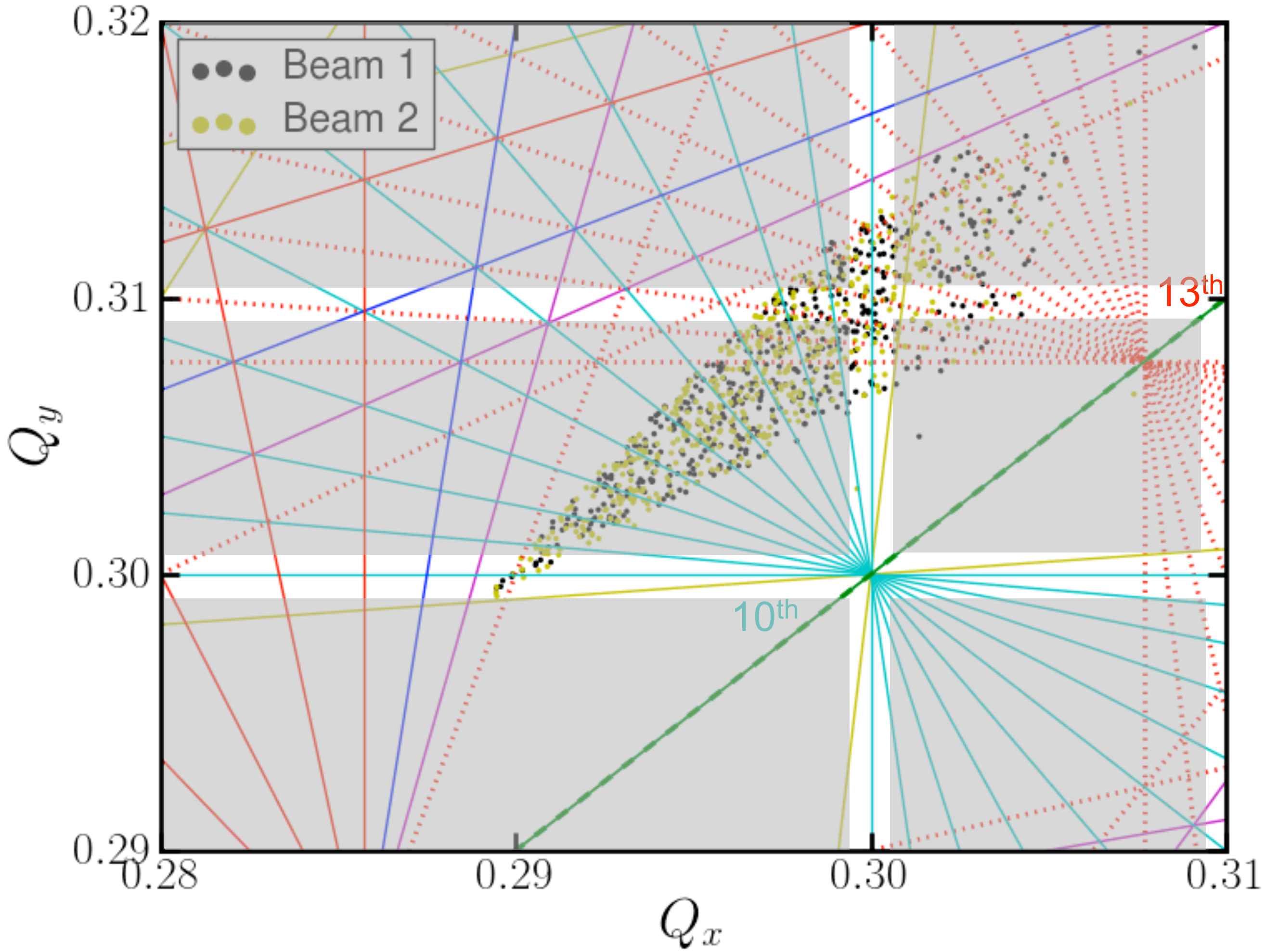


Sinusoidal CC Noise I

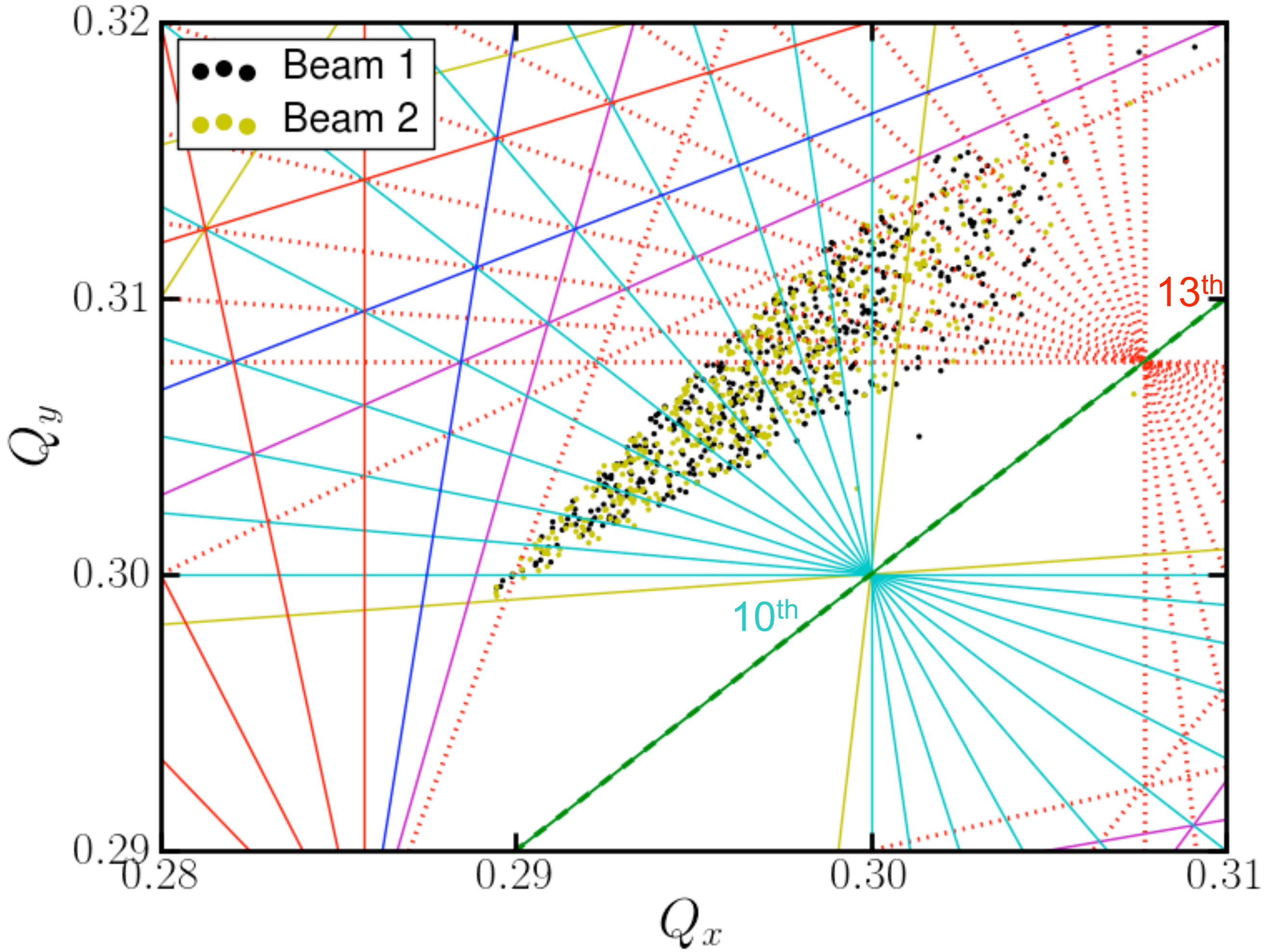


Strong frequency dependence

Sinusoidal CC Noise II



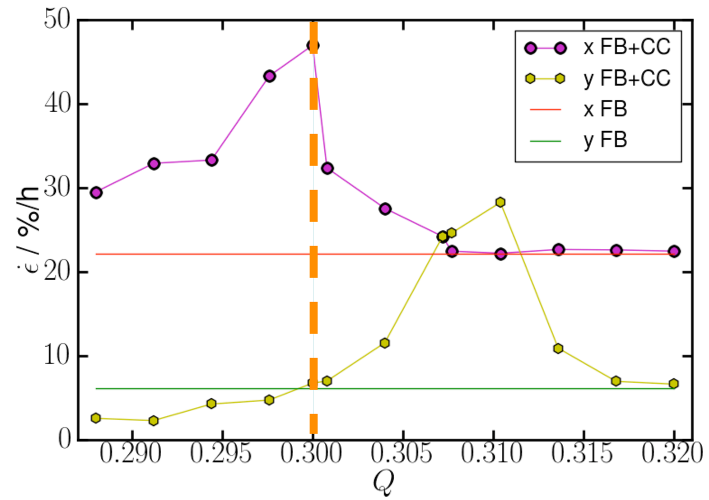
Sinusoidal CC Noise II



Sinusoidal CC Noise III

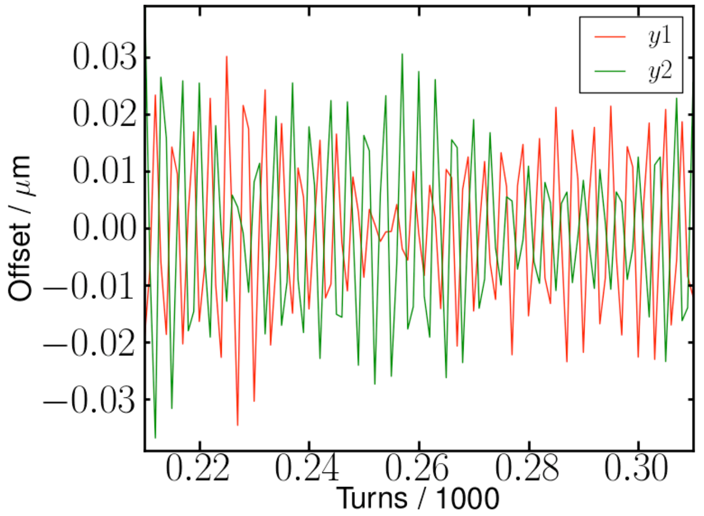
Beam response depends on:

- Size of excited region
- Particle density in excited region
- Non-linearity of beam-beam force
  ➔ emittance growth in tail



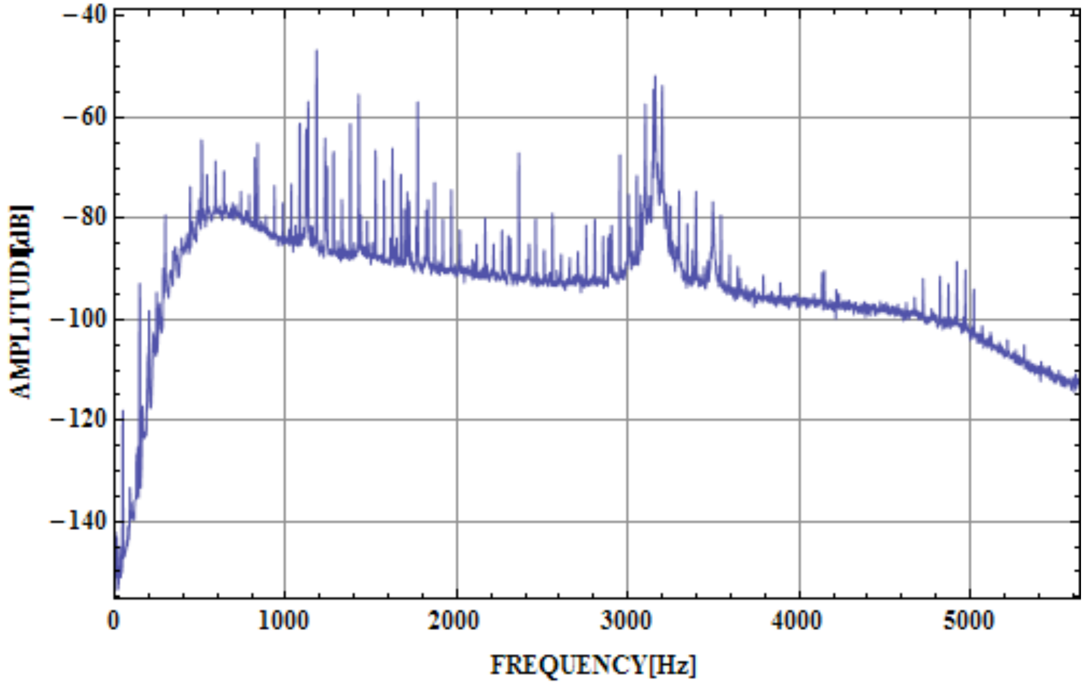
Excitation at $Q = 0.3$:

- Vertical beam oscillation
- No vertical emittance growth



Power Converter Noise

- Notable peaks in horizontal peaks offset spectrum at multiples of 600 Hz [1]
- Independent of tune
  ➔ dipole perturbation



Courtesy G. Arduini

Could this modulation trigger emittance growth in colliding HL beams?

[1] G. Arduini, priv. communication

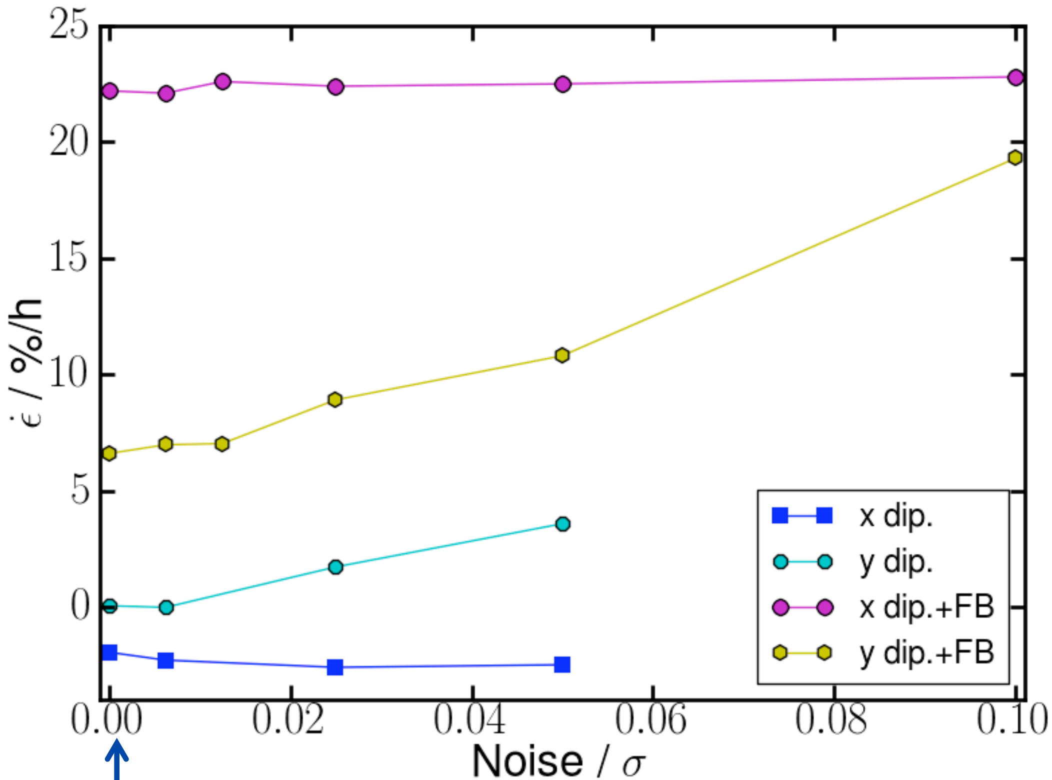
Dipole Noise Model

- Modulation of offset

$$\delta X = \pm A_d \cos(\omega_d t)$$

- $\omega_d = 2\pi \times 600$ rad/s
- Measured amplitude in LHC: ~ 1 µm @ β = 300 m
  ➔ ~ 40 nm @ β = 0.5 m
- One perturbation per turn

Dipole noise



Measured amplitude

Negligible impact at measured amplitude

Conclusions

- Working point close to 0.47 promises little emittance growth
- White CC noise causes large emittance growth
- Harmonic CC noise in tails causes strong emittance growth
- Dipole noise has negligible impact

- Impact of non-linear phase noise to be studied
- New working point should be discussed
- CC noise models should be discussed

Thank you for your attention