Simulation of beam-beam induced emittance growth in the HL-LHC with crab cavities

Joint LARP CM20/HiLumi meeting

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Outline

- Feedback and noise models
- Simulation of LHC in 2012
- Simulation of 50 ns HL-LHC scenario (preliminary)

Feedback Model (FB) I

- Based on LHC's damper *
- Includes
  - Hilbert notch filter ($h_k(\varphi_H)$)
  - Delay (d)
- Kick:

$$\Delta X'_n = \frac{a_0 g}{\sqrt{\beta_{bpm}\beta_{kick}}} \sum_{k=0}^{6} h_k(\varphi_H) \times (X_{n-d-k} - X_{n-d-k-1})$$

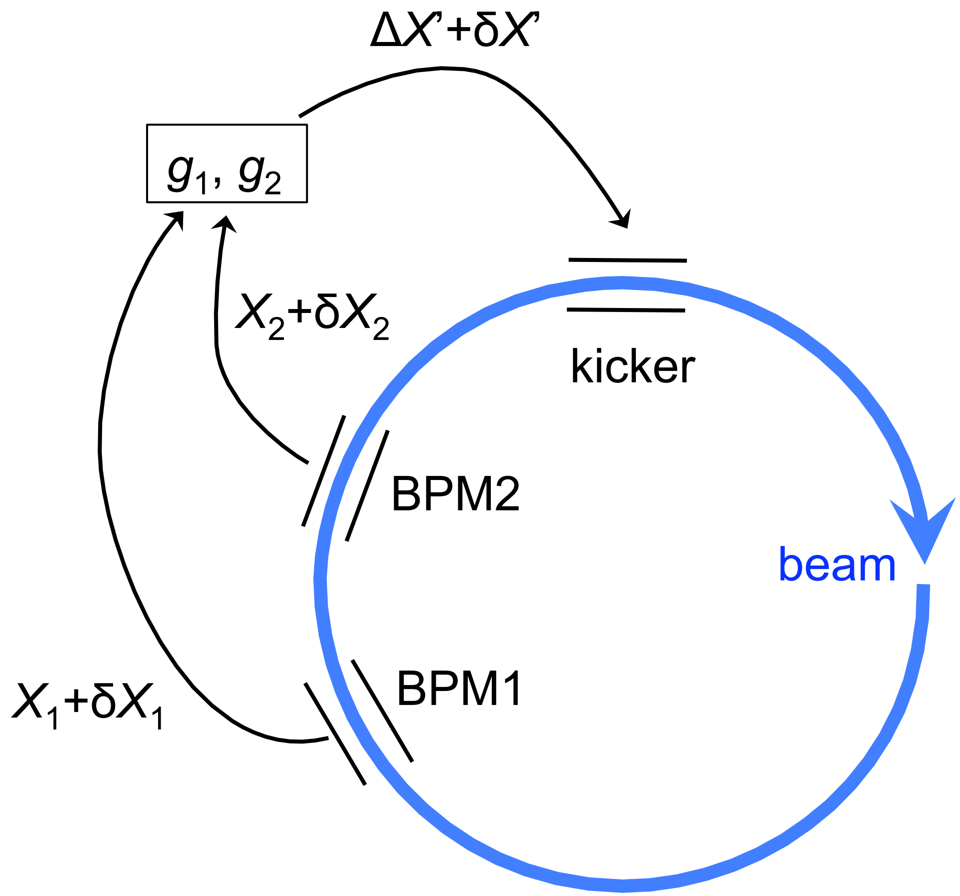
* V.M. Zhabitsky, E9-2011-95, 2011; W. Höfle, priv. communication

FB model II

- 2 Pick-ups (BPMs)
  1 Kicker

$$\Delta X'_n = \Delta X'_{n,1} + \Delta X'_{n,2}$$

- Transfer of centroid via linear map



Crab cavity (CC) noise models

- White noise on phase
  - Offset due to phase perturbation *

$$\delta X = \frac{c}{\omega_{CC}} \tan\frac{\theta}{2} \delta\varphi$$

- Time correlated phase noise *
- Mono frequent perturbation *

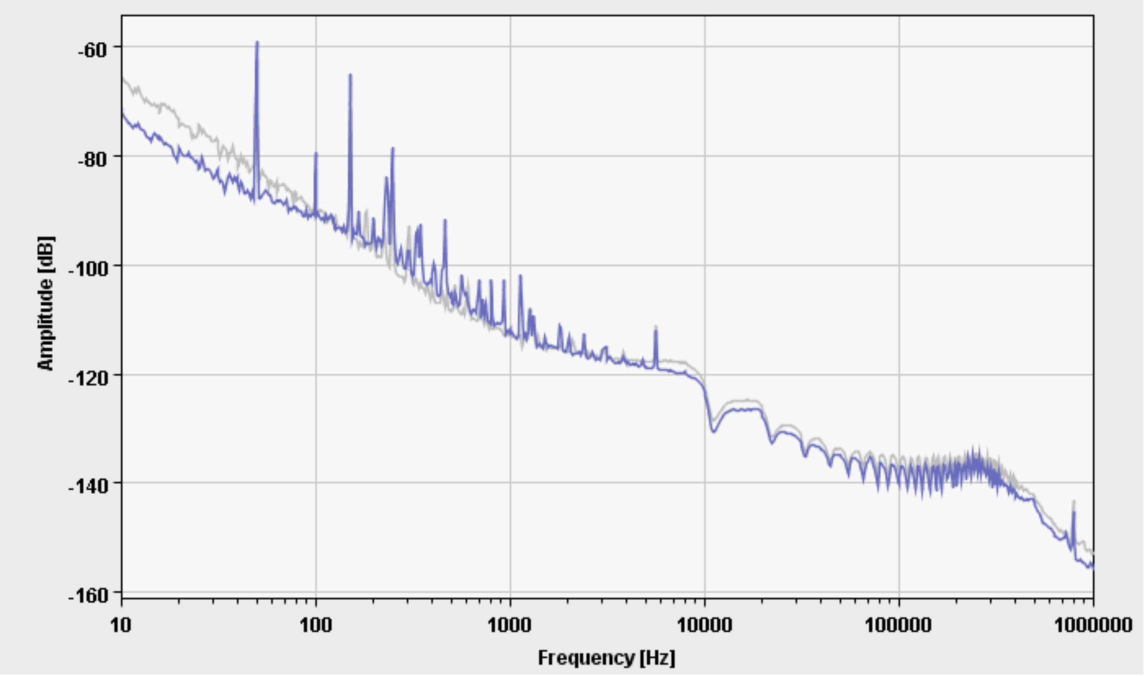
} Not yet applied to HL-LHC

* K. Ohmi et al., TUPAN048, PAC07

RF noise level

- RF noise in LHC's accelerating cavities can be measured
- Estimation of white noise level with equivalent power in all betatron side bands:
  2×10^{-4} rad rms *

ACS phase noise



Courtesy P. Baudrenghien

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

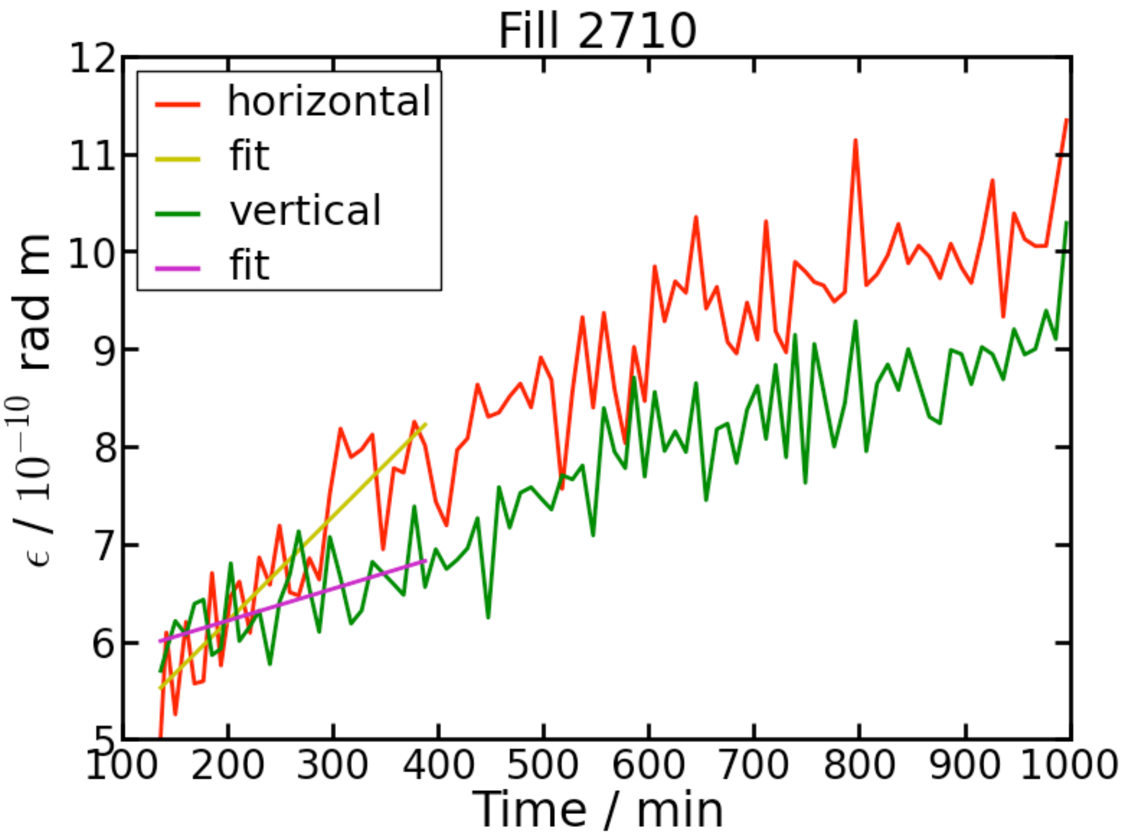
Numerical Setup

- Strong-strong soft Gaussian collision model
- 1 bunch per beam
- Linear transfer maps
- No long range effects
- 8 million macro particles
- 2 cases:
  – LHC parameters from 2012
  – 50 ns bunch spacing HL scenario

Comparison of *BeamBeam3D* simulations with LHC performance

- Goal:
  Verify reliability of code and determine noise level for FB model
- Data from physics run in 2012 (fill 2710) as example
- Measured by operators:
  - Luminous region
  - Intensity
- Emittance calculated from luminous region: $\sigma_x = \sqrt{2}\cos\frac{\theta}{2}\sigma_{Lx}$
- Sampling rate larger than simulation time
  ➔ Interpolation

Emittance growth observed in LHC *



Initial linear growth rate:
12.8 %/h hor.
3.4 %/h ver.

Exclusion of IBS
Horizontally IBS accounts for ≈ 5 %/h **
➔ Max. 8 %/h due to beam-beam effects

* LHC operations data: courtesy G. Trad, CERN
** M. Schaumann, J. Jowett, CERN-ATS-Note-2012-044 PERF

Beam parameters

	2012 operation §	HL 50 ns **
N_p / 10^{11}	1.5	3.5
ε_n / µm	2.3	3.0
β^* / m	0.6	1.02 ***
Q_x	64.31	64.31
Q_y	59.32	59.32
θ / mrad	0.29	0.59
g_1+g_2	0.1	0.1
f_{CC} / MHz	-	400.8
Collisions / turn	1 hor., 1 ver.	1 hor., 1 ver.

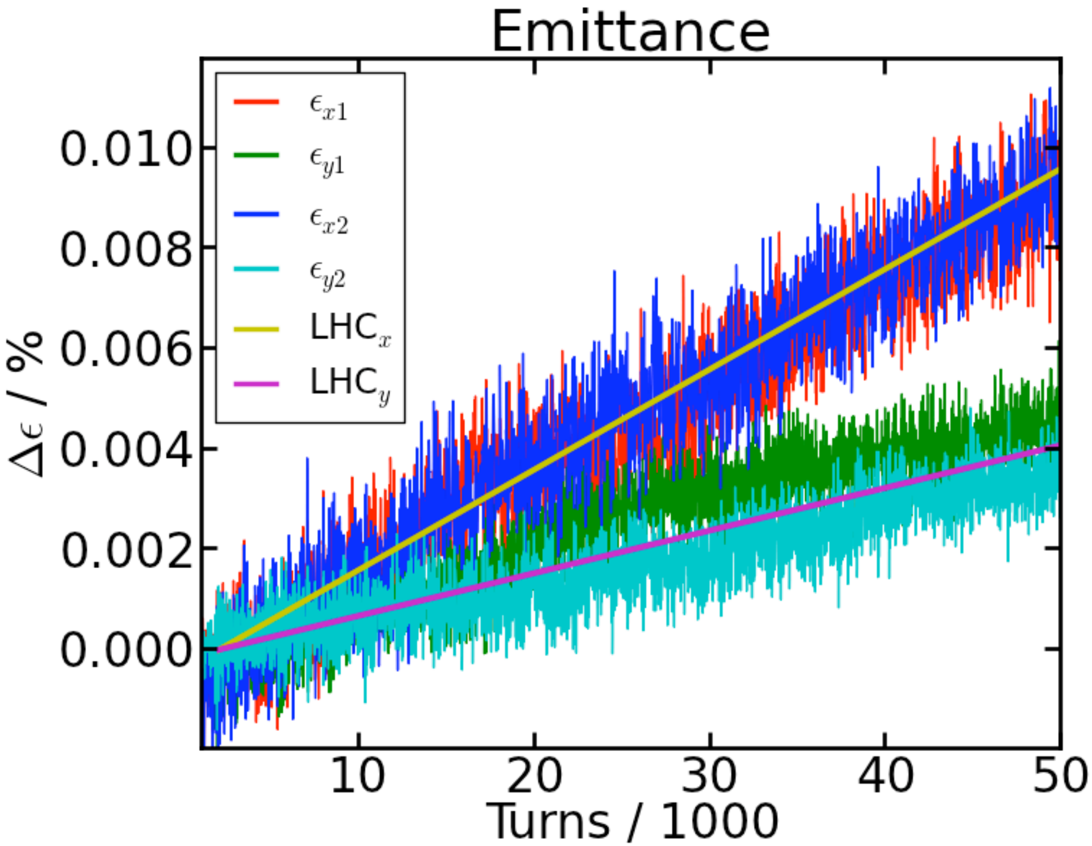
§ G. Trad, private communication

** O. Brüning et al., MOPPC005, IPAC2012

*** assuming *leveling* via beta function

Simulation of LHC in 2012

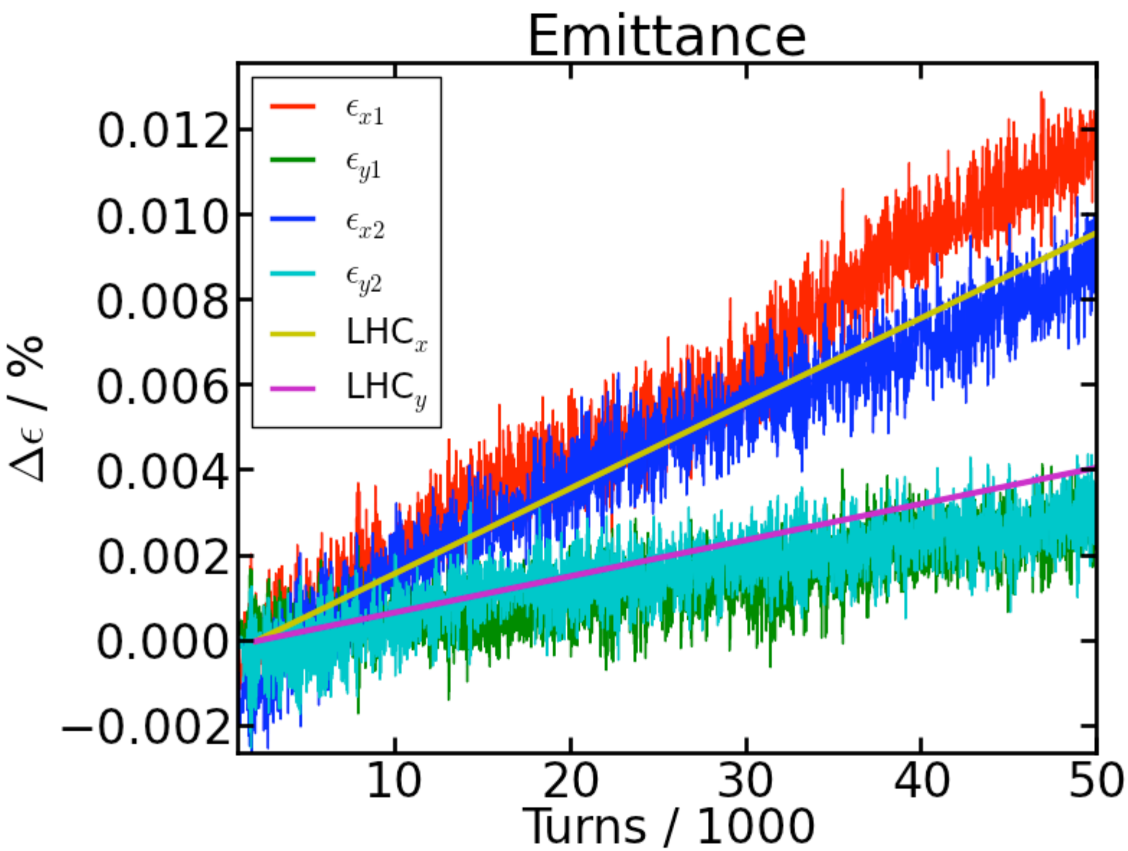
Comparison of measured and simulated emittance growth



rms offset fluctuation
at β^* = 0.6 m
δX = 0.11 μm
δY = 0.09 μm

Validation of emittance simulations provides base for simulations with HiLumi beam parameters and crab cavities

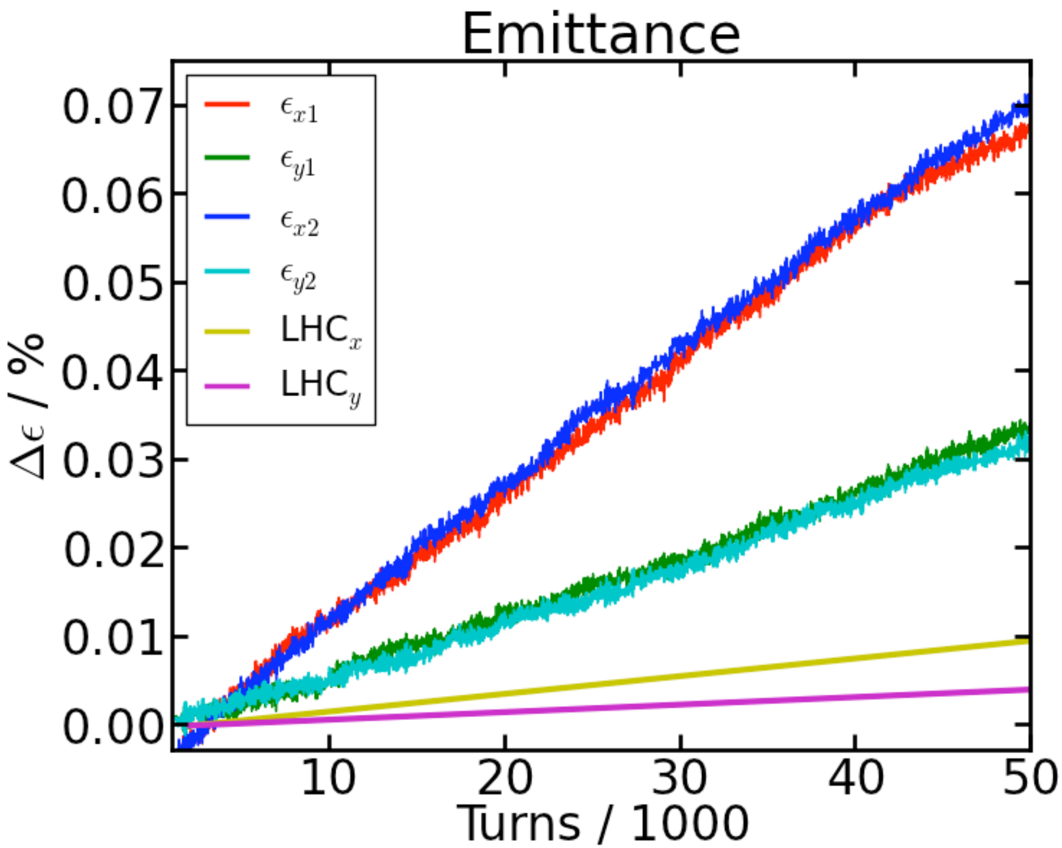
2012 beams – Emittance with FB noise and CCs



No CC noise

Emittance growth is quite the same

2012 beams – Emittance with white CC noise



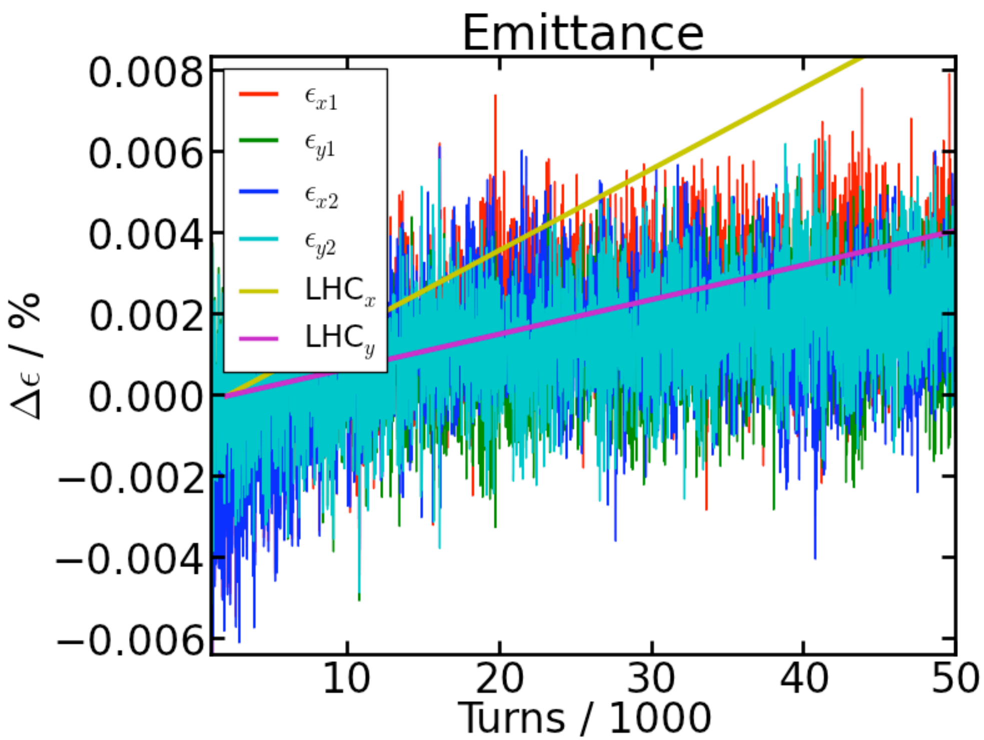
CC noise:
0.2 mrad
(7 nm rms)

No FB noise

White CC noise leads to 60 %/h (hor) and 27 %/h (ver) emittance growth

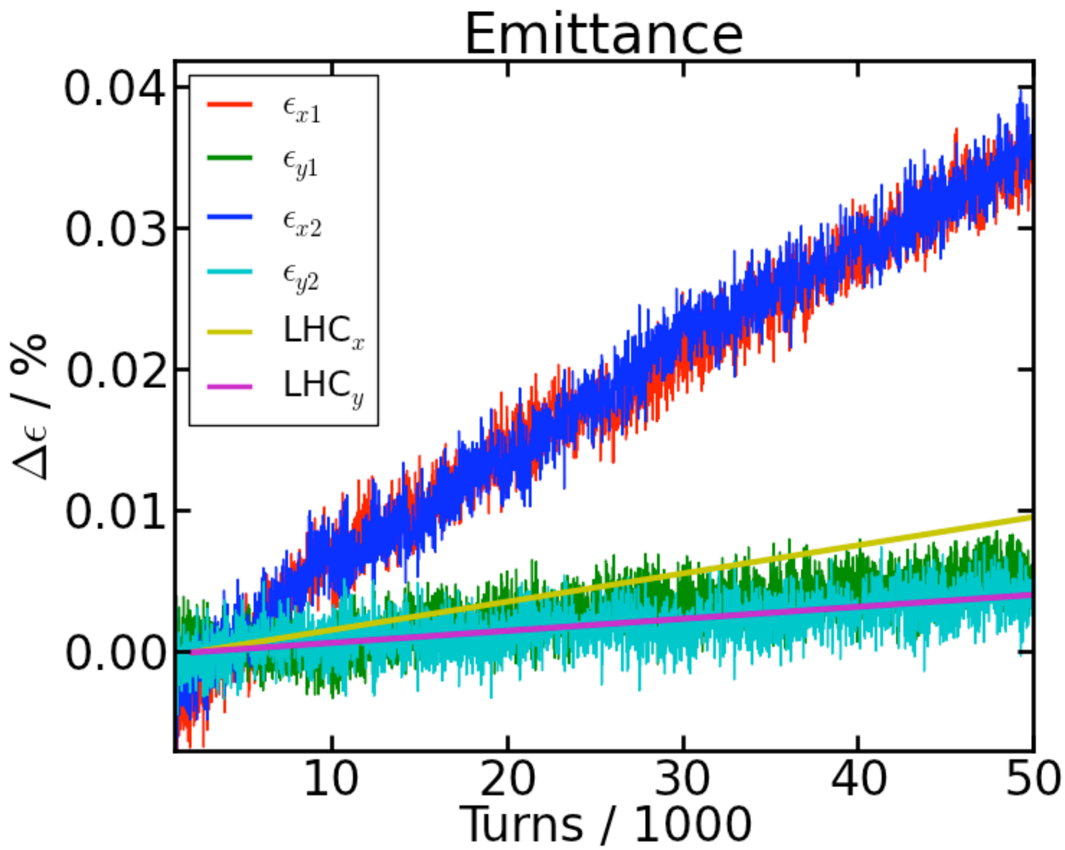
Simulation of HL-LHC
(generally 50 ns scenario)

HL – Emittance without external noise



Emittance growth due to residual noise: 2 %/h

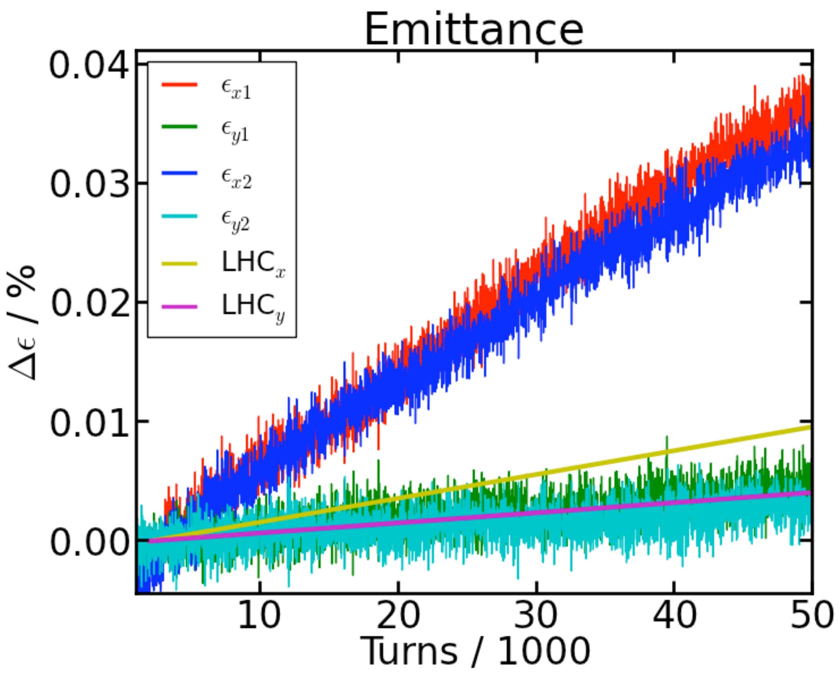
HL – Emittance with FB noise



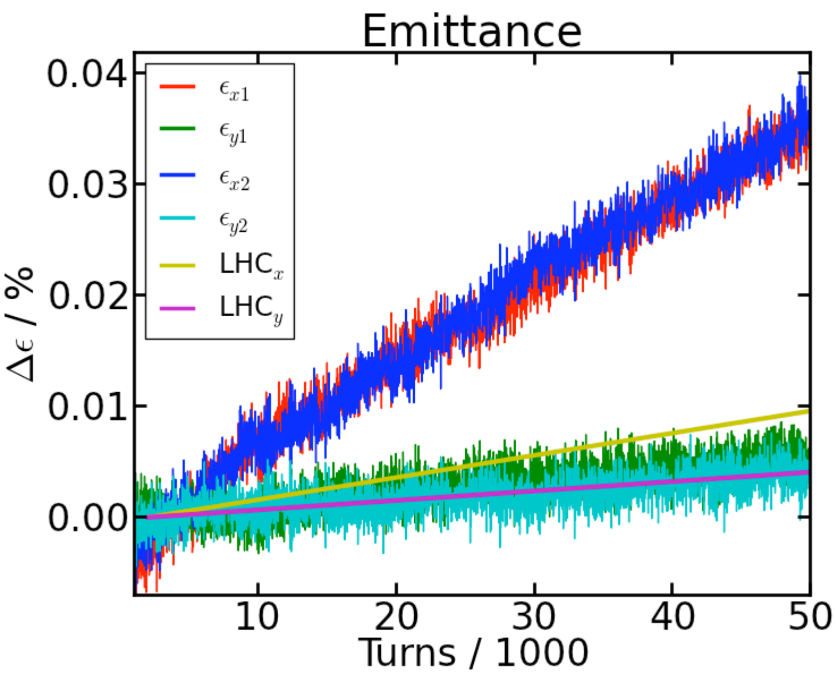
Resulting emittance growth 30 %/h (hor) and 4.0 %/h (ver)

θ = 0 versus CC

θ = 0

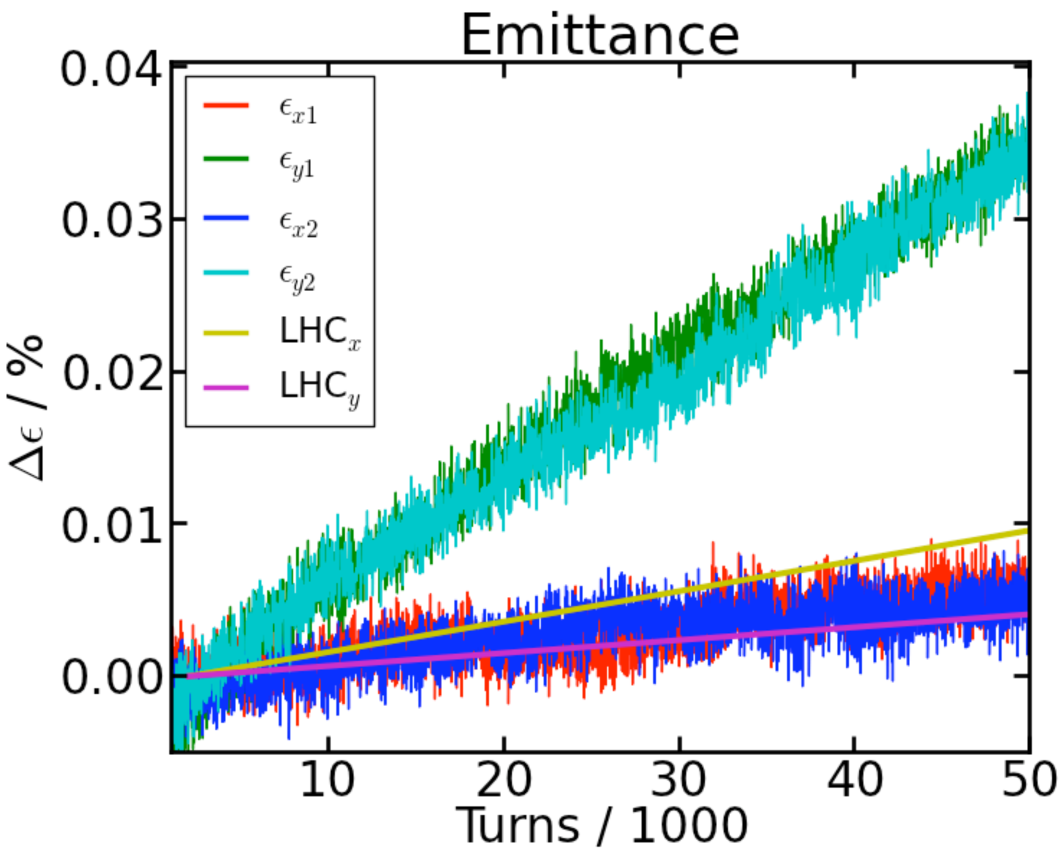


θ = 0.59 mrad, with CC



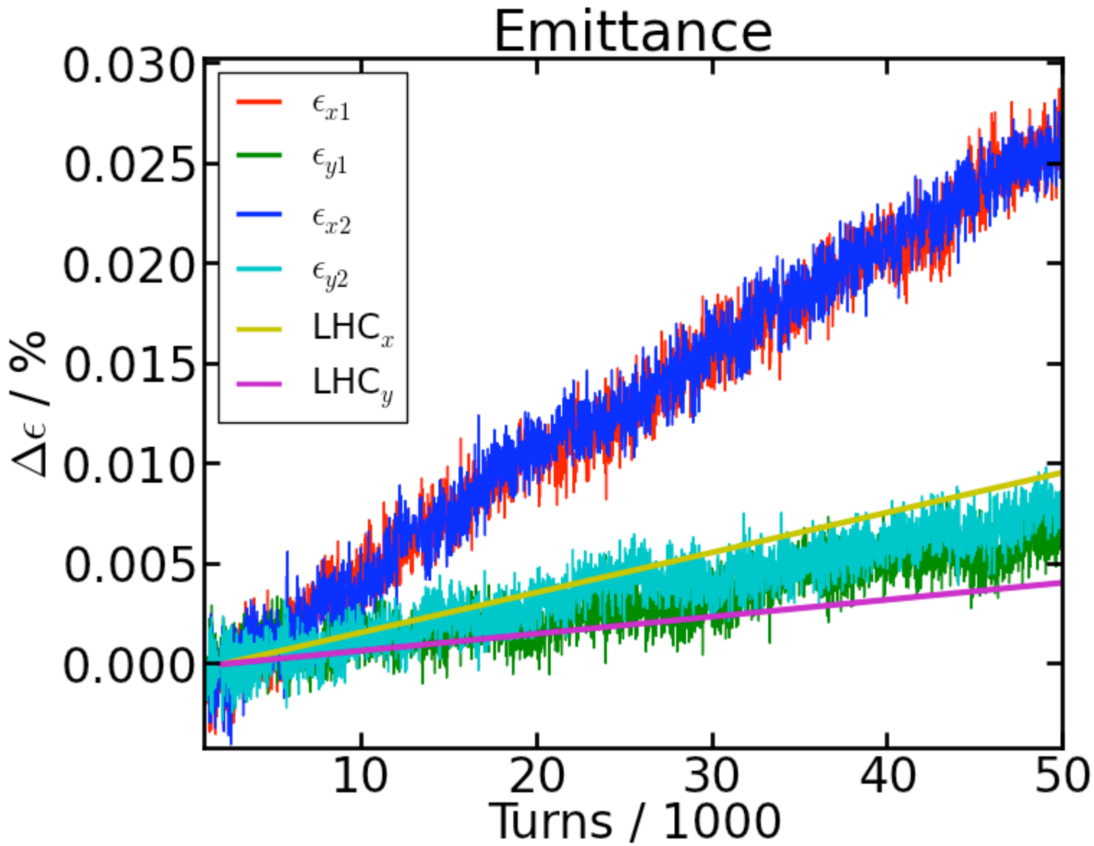
Quite the same emittance growth

Consistency test with exchanged planes



Growth rates change to 4.8 %/h (hor) and 30 %/h (ver)
x-y discrepancy due to working point and FB

25 ns HL* – emittance with FB noise



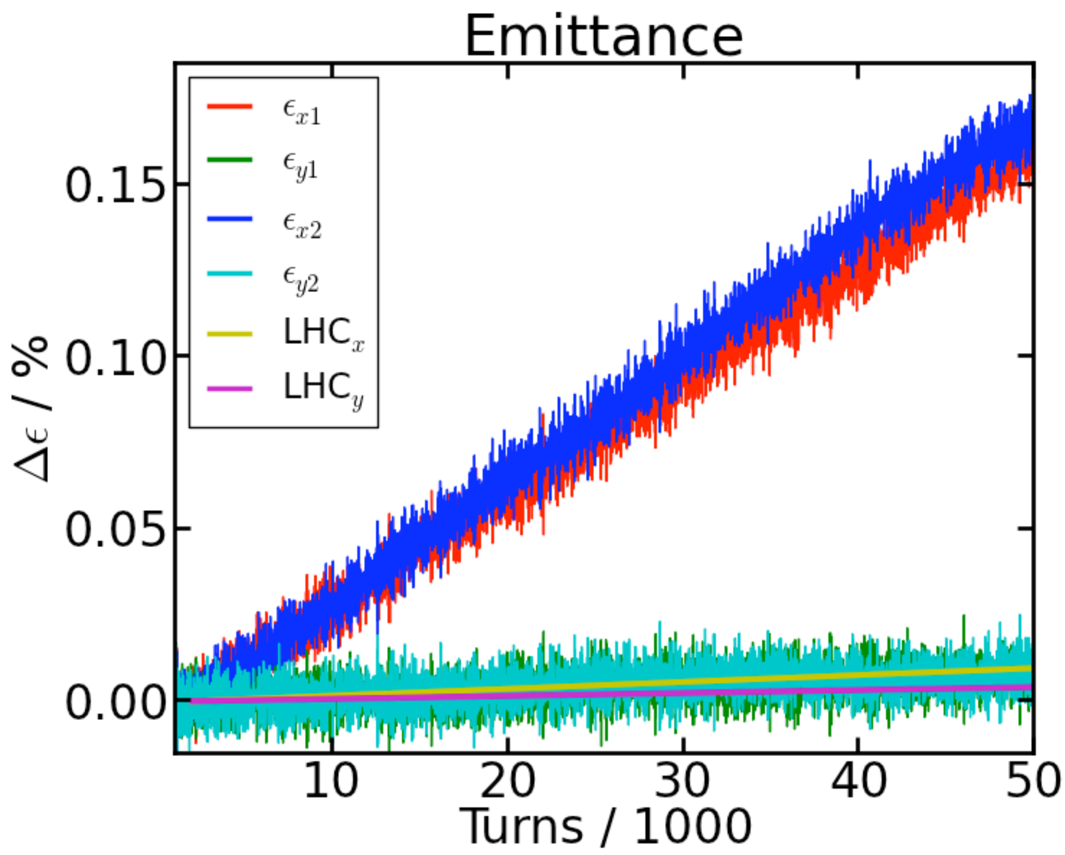
N_p = 2.2×10^{11}
ε_n = 2.5 μm
β^* = 0.49 m

White CC noise causes 22 %/h (hor) and 6 %/h (ver) emittance growth

➔Less sensitive than 50 ns scenario

* O. Brüning et al., MOPPC005, IPAC2012

HL – emittance with white CC noise

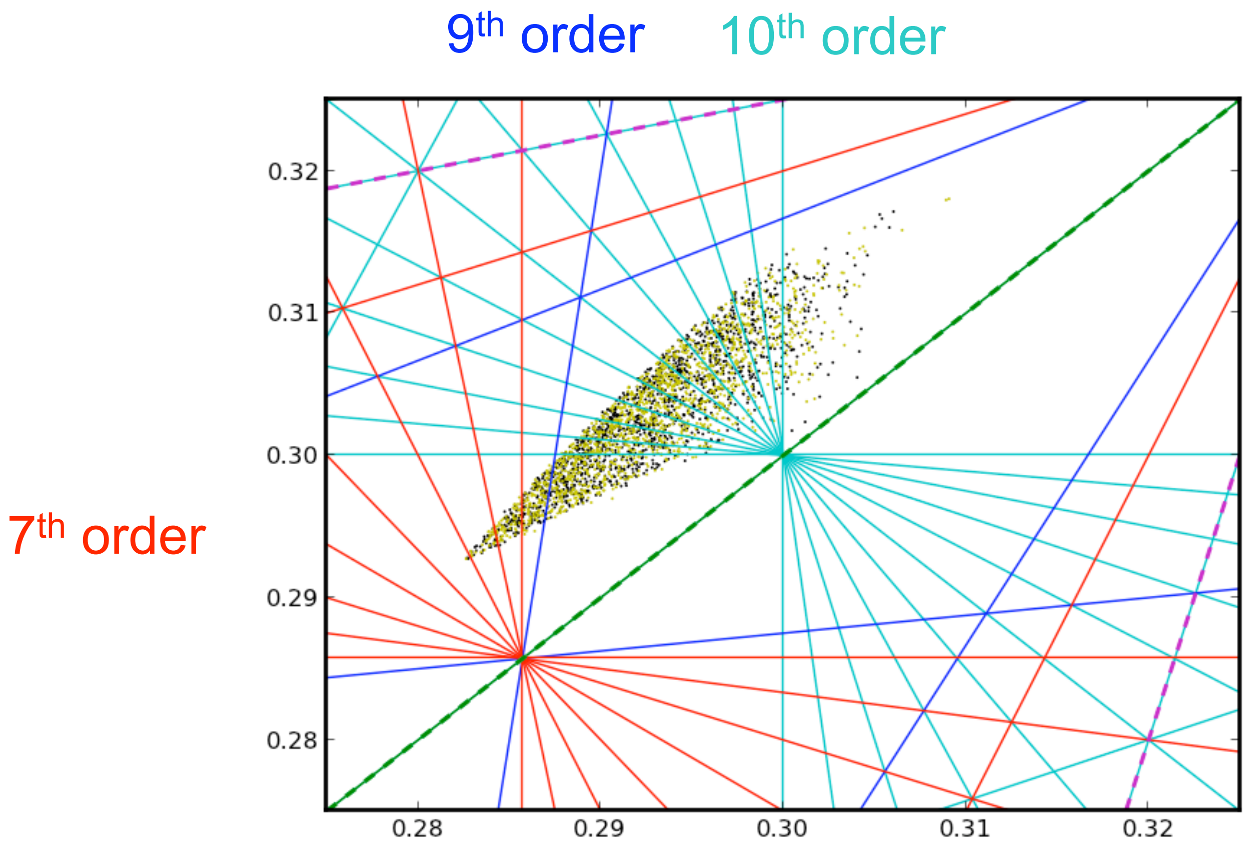


δφ = 0.2 mrad rms

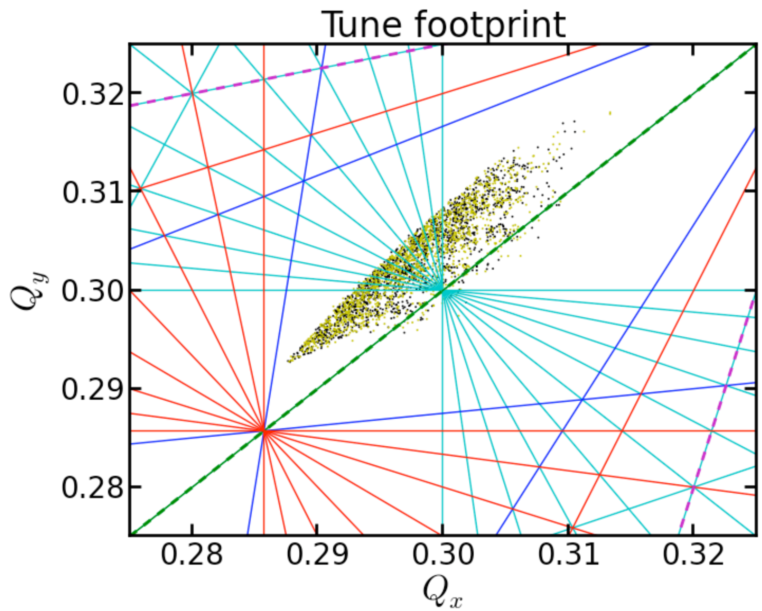
No FB noise

White CC noise causes 140 %/h (hor) and 7 %/h (ver) emittance growth

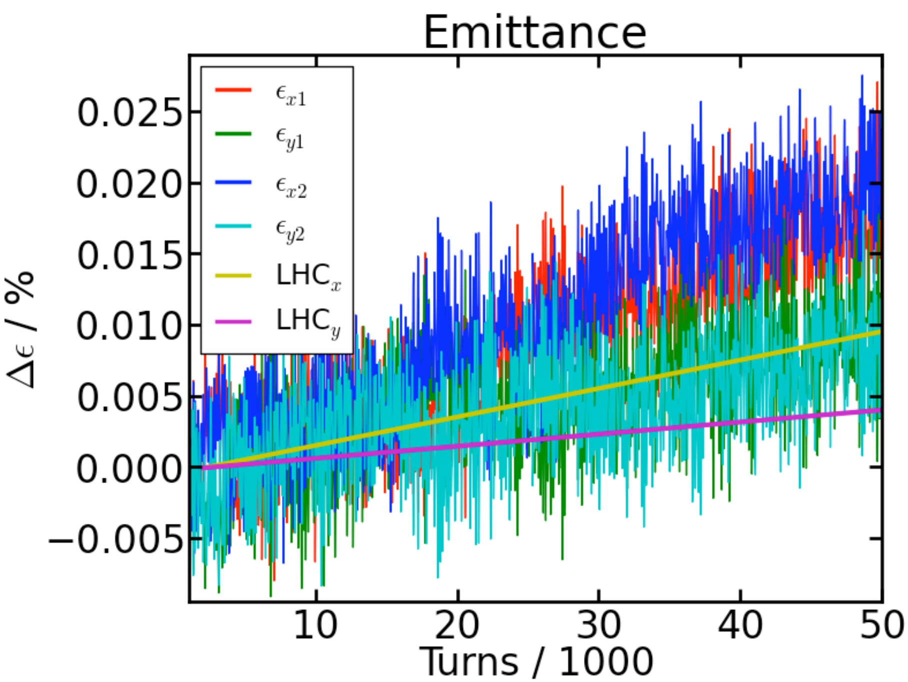
HL – Tune diagram of colliding beams



Change of working point



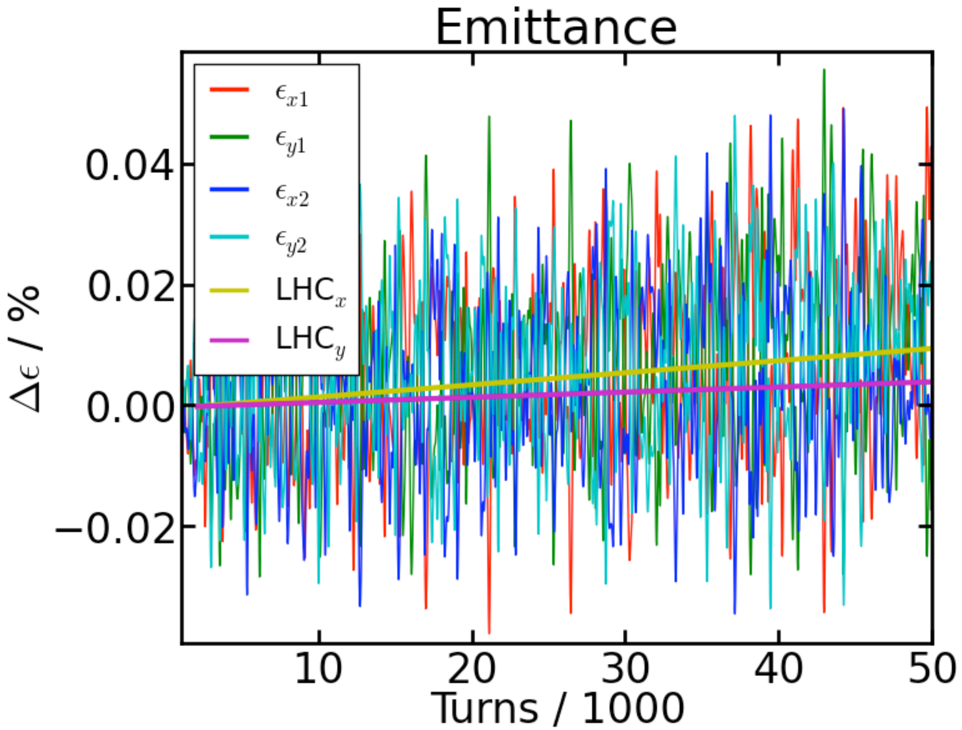
Q_x = 0.315 avoids resonances



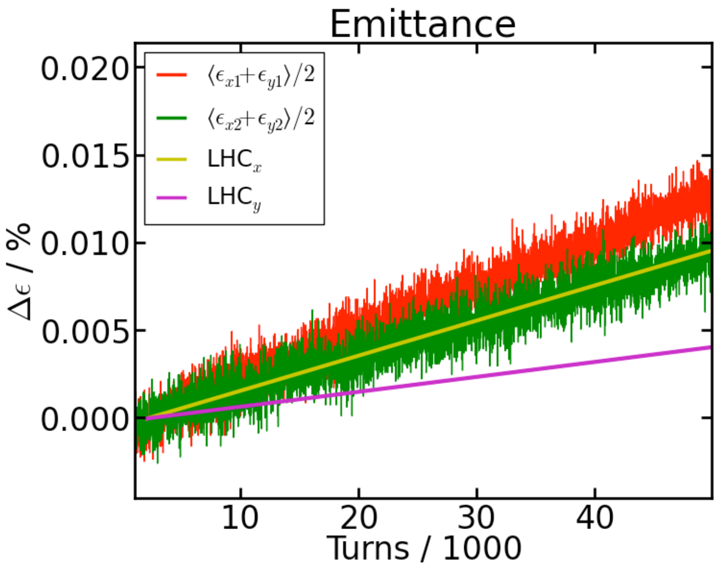
Emittance growth:
17 %/h (hor) and 8 %/h (ver)

Instead of 30 %/h (hor) and 4 %/h (ver)

Change of working point II



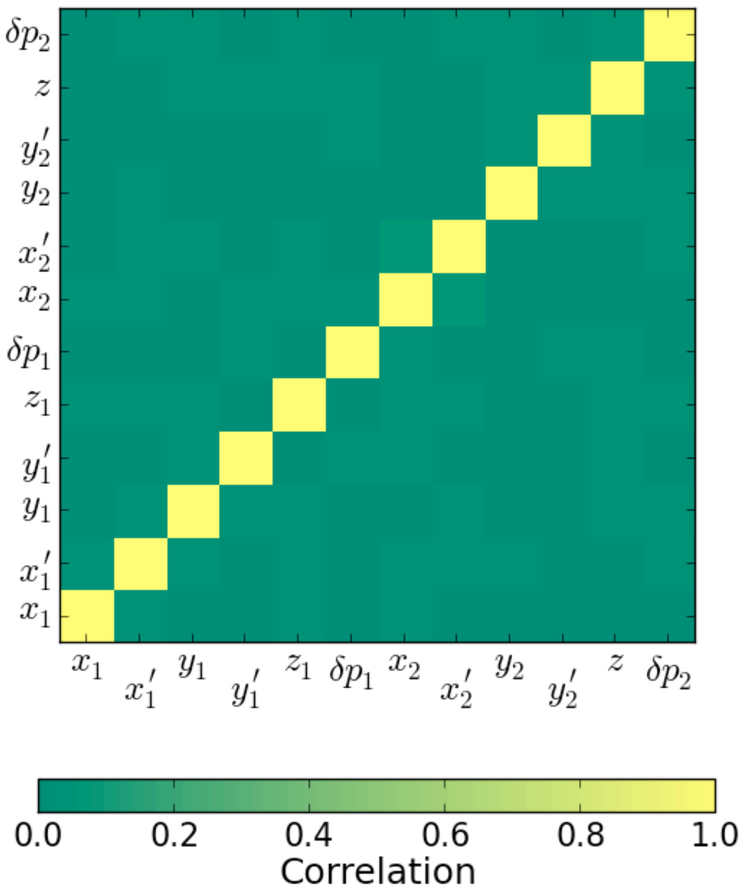
Q_x = 0.32
Strong fluctuation due to coupling



Even less emittance growth:
8 %/h (hor) and 11 %/h (ver)

Instead of 30 %/h (hor) and 4 %/h (ver)

Correlation



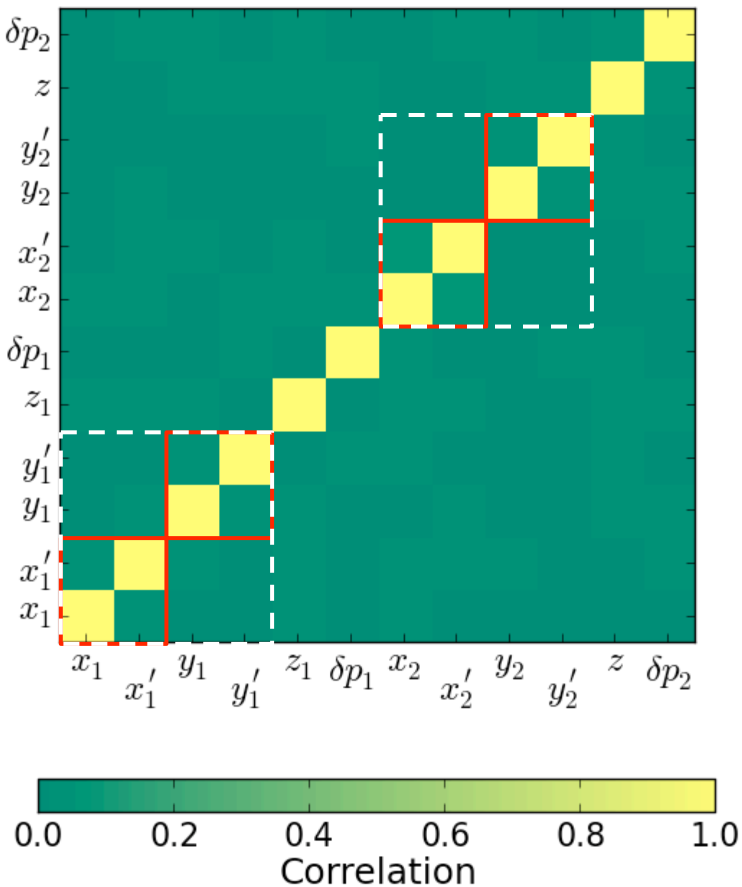
Phase space correlation after 50,000 turns

$$\sigma_{ij} = \langle r_i r_j \rangle$$

$$\Theta_{ij} = \frac{|\sigma_{ij}|}{\sqrt{\sigma_{ii}\sigma_{jj}}}$$

Deviation between 4D emittance and $\varepsilon_x \varepsilon_y$ is about 0.1 %

Correlation



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Deviation between 4D emittance and $\varepsilon_x \varepsilon_y$ is about 0.1 %

Conclusions

- Measured emittance growth was reproduced by simulations with BeamBeam3D
- Simulations with HL parameters started
- Working point needs to be adjusted to tune shift

Outlook

- Find optimal tune
- Employ other
  - Noise models
  - Leveling procedures
  - Beam parameters

to predict emittance growth in HL-LHC

Thank you for your attention

Thanks to G. Trad, W. Höfle and M. Schaumann for useful information