ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Effect of noise on colliding beams. LHC experience and implication to HL-LHC.

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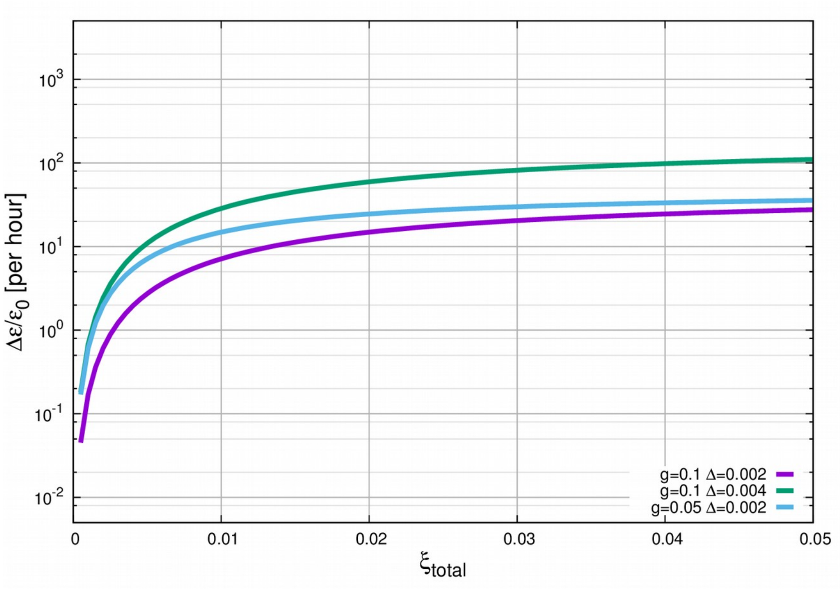
Introduction

- A noise kick gives a coherent betatron amplitude. When a non-linear force like beam-beam appears a decoherence of the the betratron motion is produced giving raise to emittance growth.
- It is therefore necessary to address this *interplay* so the beam is not excessively degraded.
- LHC is a strong-strong machine so self-consistent codes (COMBI) are to be used.
- Analytical estimations exist and are useful but benchmark against measurements and simulations are needed to understand validity and possible limitations.
- In the HL-LHC framework different types of noise are being considered: white noise in the kHz regime, low frequency noise (static orbit effect) and crab cavity noise (longitudinal dependence).

Analytical estimation

- In (1) Y. Alexhin derives an analytical expression to estimate the emittance growth for a given noise amplitude and damper gain.

$$\frac{1}{\epsilon_0}\frac{d\epsilon_x^{1,2}}{dN} = \frac{1-s_0}{4}\left(\Delta^2 + g^2\underbrace{(\Delta_{BPM}^2+\Delta_{ADT}^2)}_{0\ \ \text{(in this presentation)}}\right) S\left(\frac{g}{2\pi|\xi|}\right)]$$



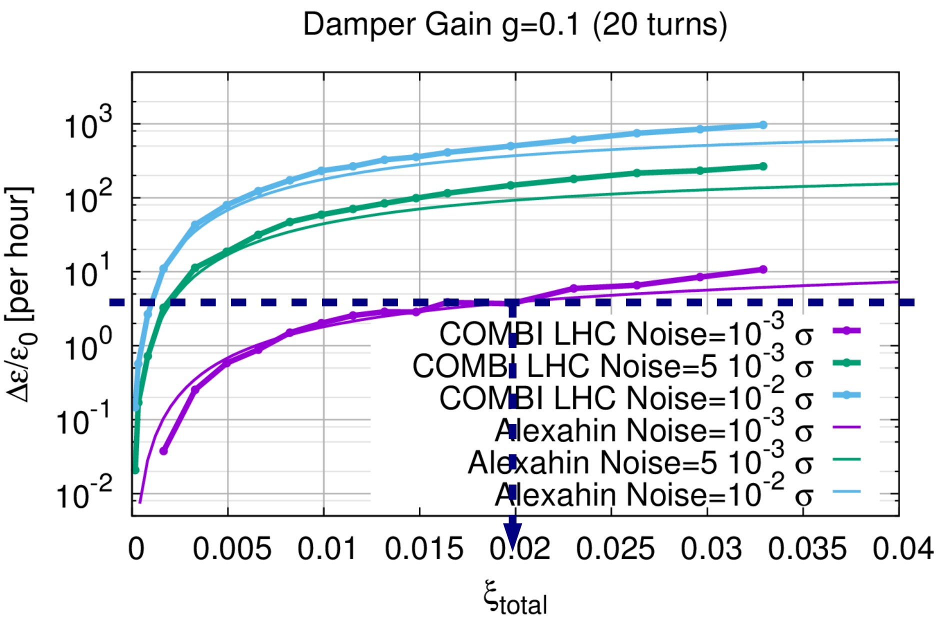
with $$S(x) \approx \frac{1}{(1+x)^2}$$

(1) "On The Landau Damping And Decoherence Of Transverse Dipole Oscillations In Colliding Beams", Y. Alexahin, Particle Accelerators, Vol. 59, pp. 43-74

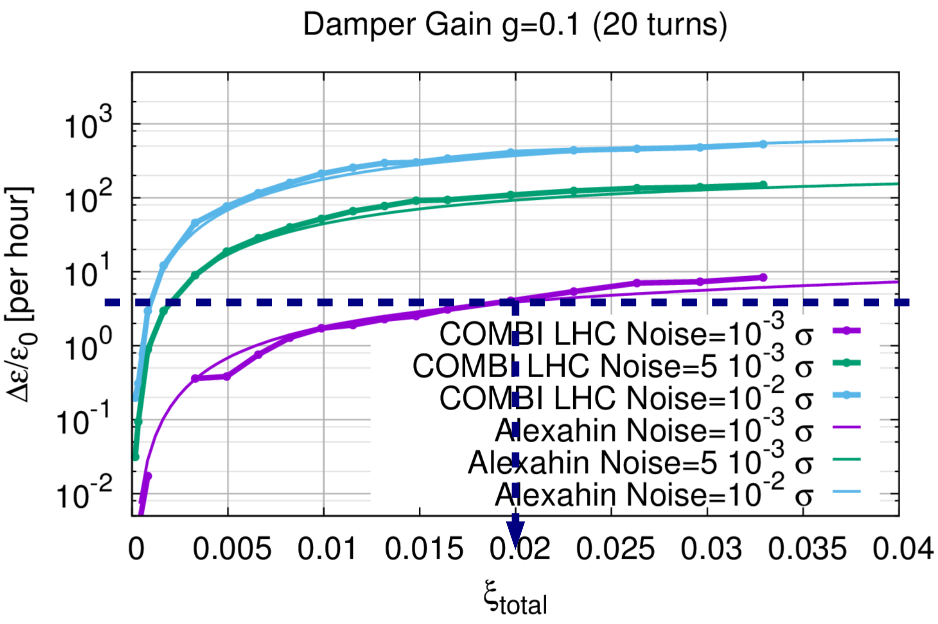
Self-consistent simulations benchmark with analytical estimations

- Since self-consitent simulations are quite time consuming it it is important to check validity of fast analytical estimations.

Horizontal plane



Vertical plane

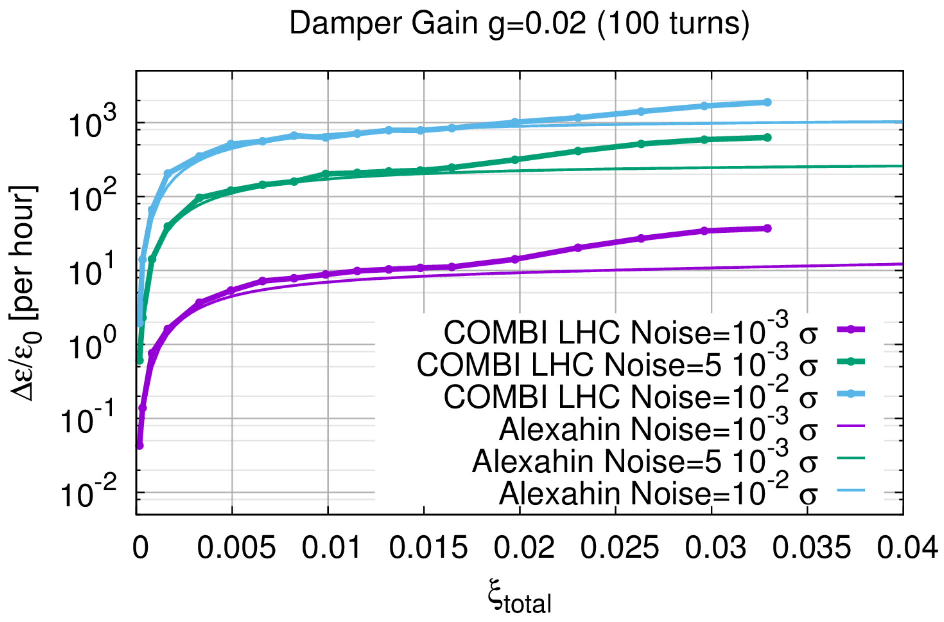


- Assuming the current LHC feedback gain of 20 turns and taking $\xi_{HL\text{-}LHC}=0.02$ in order to keep $\Delta\varepsilon/\varepsilon_0<4\%$/hour then simulations and analitycal model agree on $\Delta_{noise} < 10^{-3}\ \sigma$.

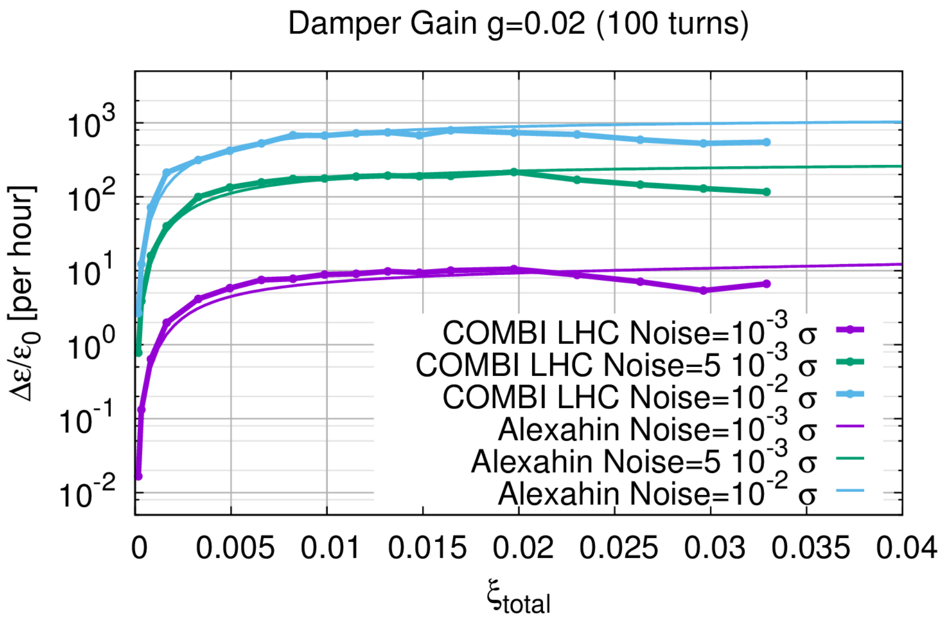
Self-consistent simulations benchmark with analytical estimations

- Interesting *disagreement* for smaller feedback gains. There seems to be a threshold at $\xi_{bb}=0.02$ where the simulation overestimates in the horizontal plane and underestimates in the vertical.

Horizontal plane



Vertical plane

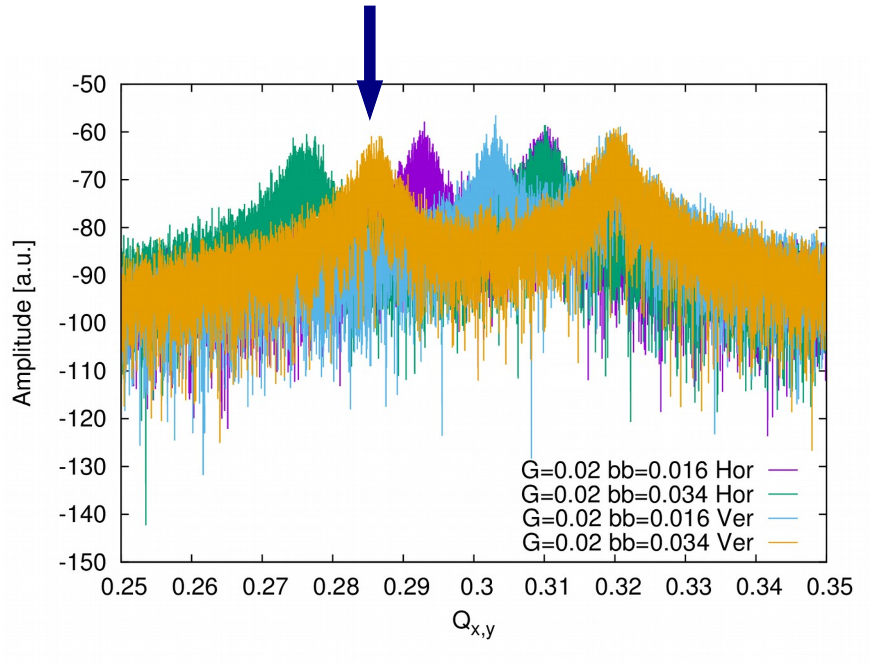


- However considering the combined effect in both planes the agreement is again very good (total energy conserved).

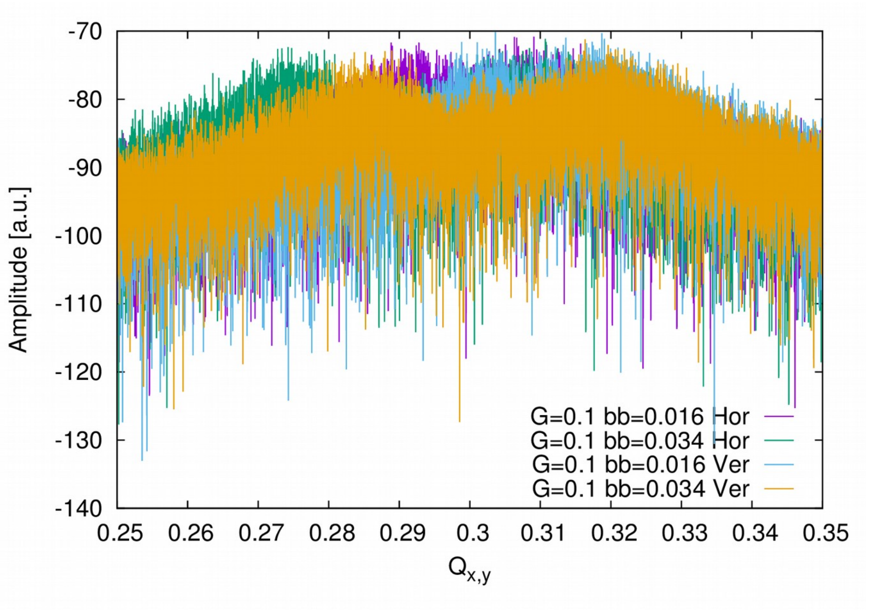
Coherent modes and continuum spectrum interplay

- Possible explanation it is due to an interplay (coupling) between the vertical π-mode and the horizontal incoherent continuum. There could be an energy transfer from the vertical to the horizontal via the vertical π-mode.
- Large feedback gains shave off the coherent modes preventing from this transfer.

Vertical π-mode inside horizontal continuum

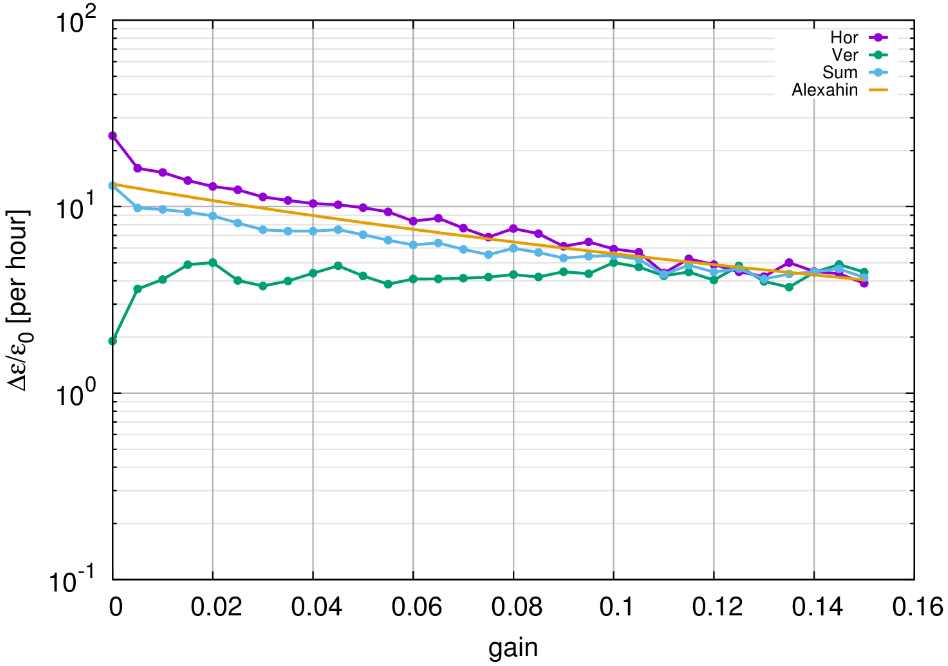


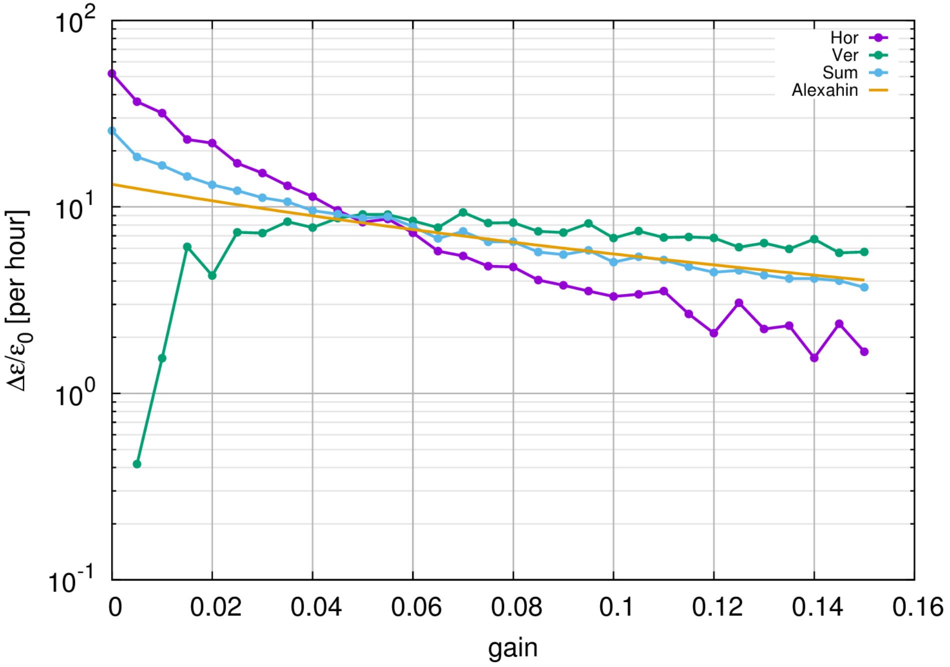
Large damper gains shave off coherent modes



Coherent modes and continuum spectrum interplay

From (1): In a perturbation caused by an external kick the **discrete modes get about 82%** of the delivered energy and only the remaining **18% is imparted into the continuum modes** leading to the irreversible emittance growth due to decoherence of these modes.



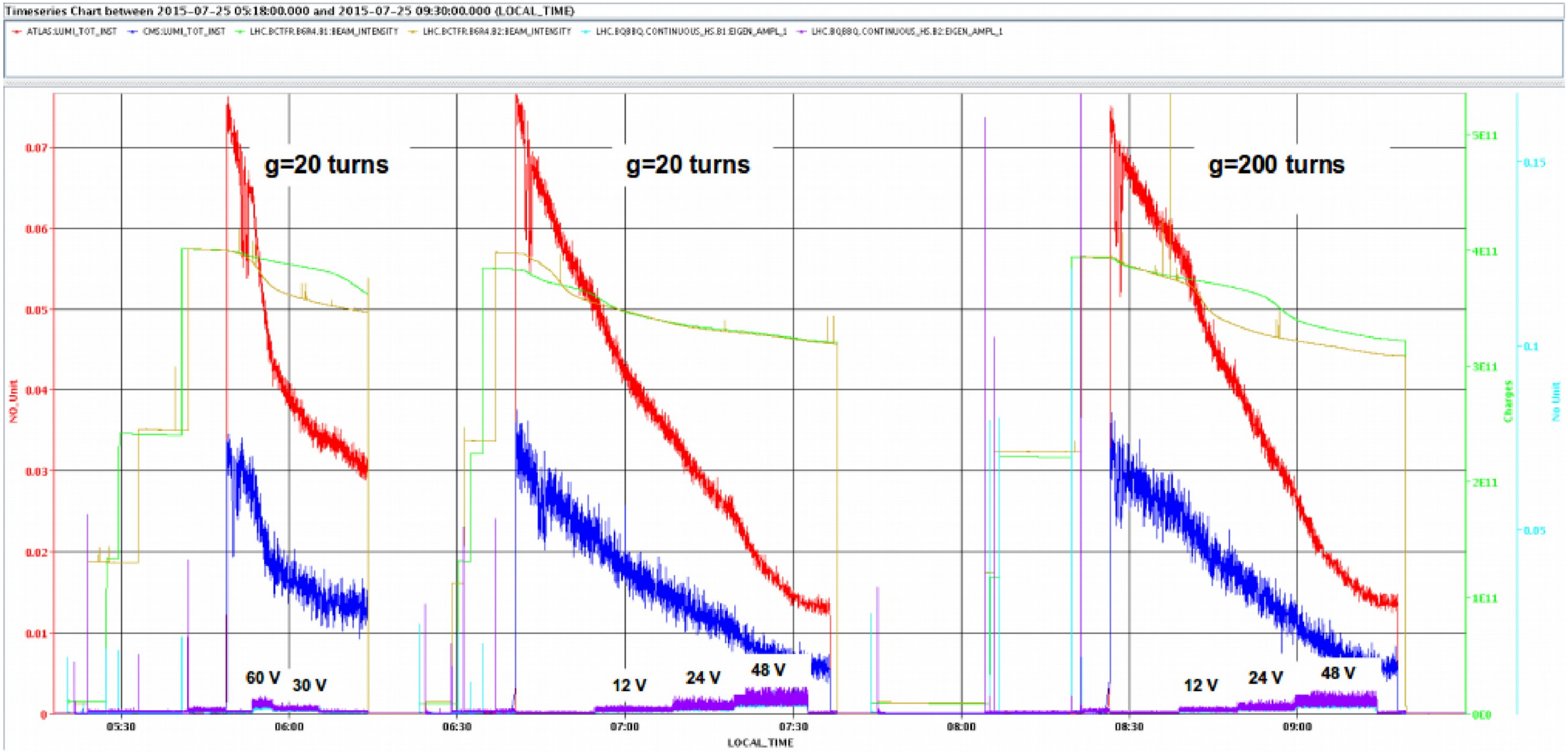


- **Noise and transverse feedback only in the horizontal plane**.
- No energy transfer from the horizontal plane to the vertical is seen.
- Feedback acting on horizontal coherent small horizontal growth independently on the gain.

- **Noise and transverse feedback only in the vertical plane.**
- Energy transfer from the vertical π-mode to the horizontal continuum spectrum.
- Feedback does not act efficiently on the continuum so large emittance growth observed in the horizontal plane for small gains.
- For g>0.04 it seems to be a feedback dominated regime.

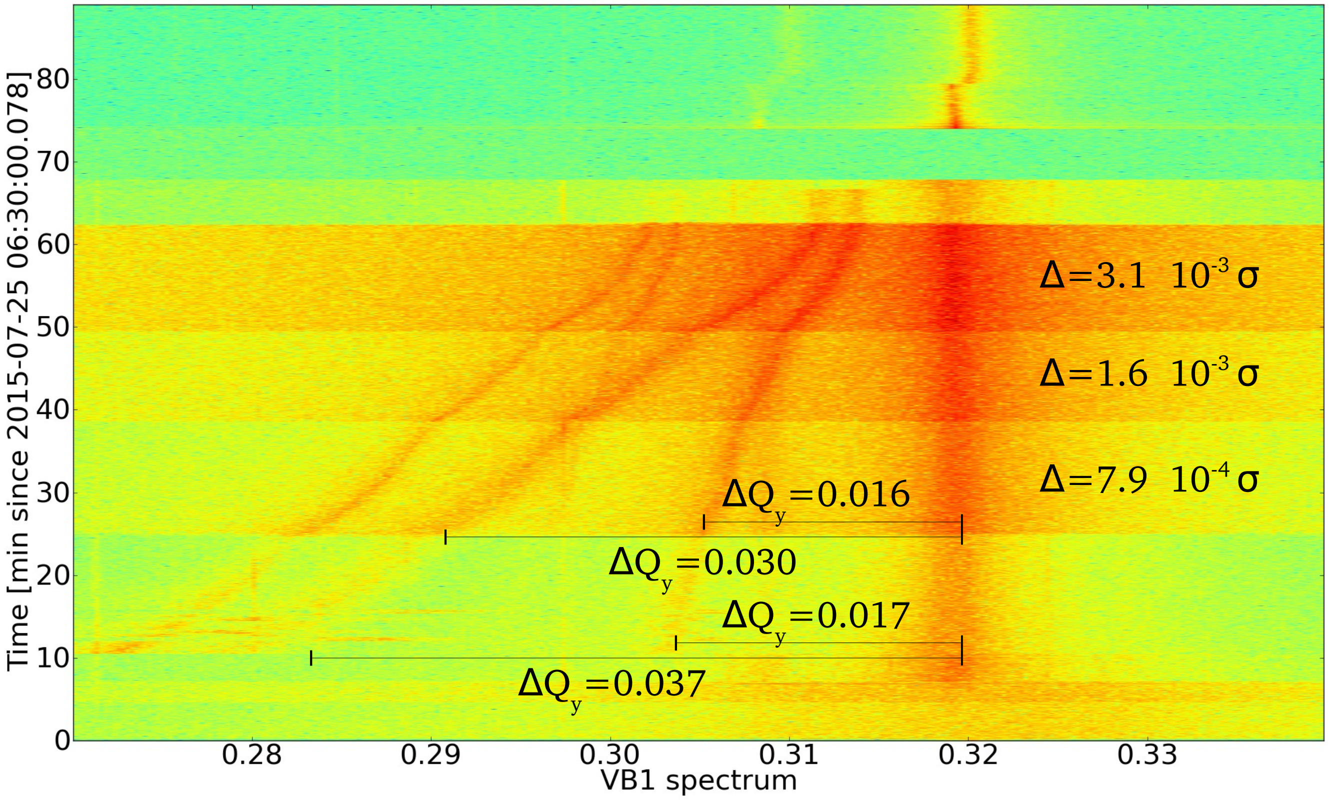
July experiments in a nutshell

- Fairly good agreement between simulations and analytical predictions. Now, how this compares to real LHC data?
- Experiment: 3 fills with head on collisions @IP1 and 5. One high brightness beam ($\xi_{bb,total}$=0.04), one HL-LHC type ($\xi_{bb,total}$=0.02) and one non-colliding for noise reference. Experiment done at injection, E=450 GeV. Transverse feedback used as noise source. The noise amplitude and damper gain was scanned for the two types of beam-beam parameter.


Timeseries Chart between 2015-07-25 05:18:00.000 and 2015-07-25 09:30:00.000 (LOCAL_TIME)

Beam-beam parameter evolution during the experiment

- Beam 1 vertical BBQ signal during the 2nd fill. Beam-beam decreases rapidly due to intensity drop and emittance growth.



$\Delta Q_y = 0.016$

$\Delta Q_y = 0.030$

$\Delta Q_y = 0.017$

$\Delta Q_y = 0.037$

$\Delta = 3.1 \ 10^{-3}\,\sigma$

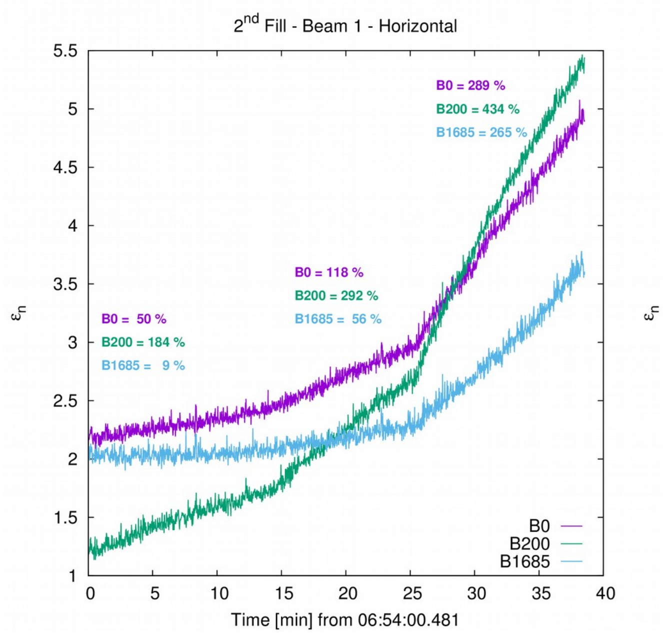
$\Delta = 1.6 \ 10^{-3}\,\sigma$

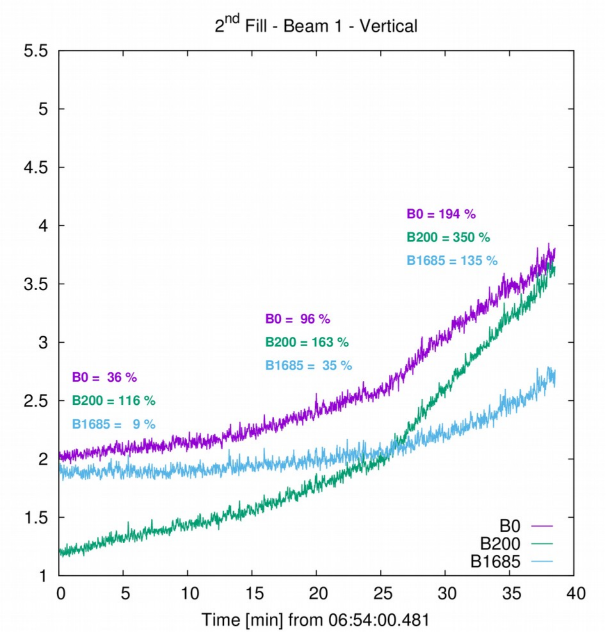
$\Delta = 7.9 \ 10^{-4}\,\sigma$

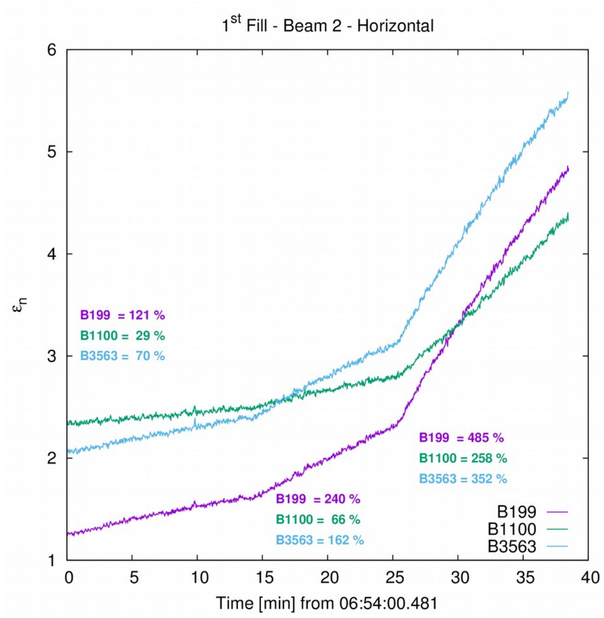
Noise steps

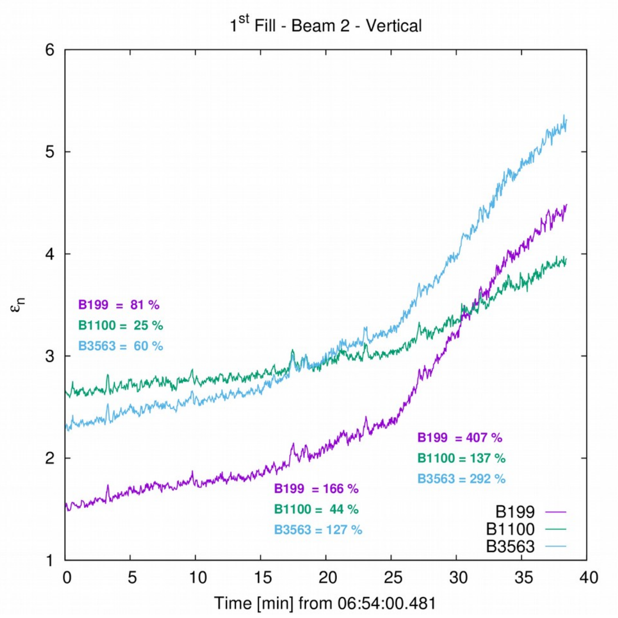
π-mode$_{HB}$ π-mode Σ-mode

Results



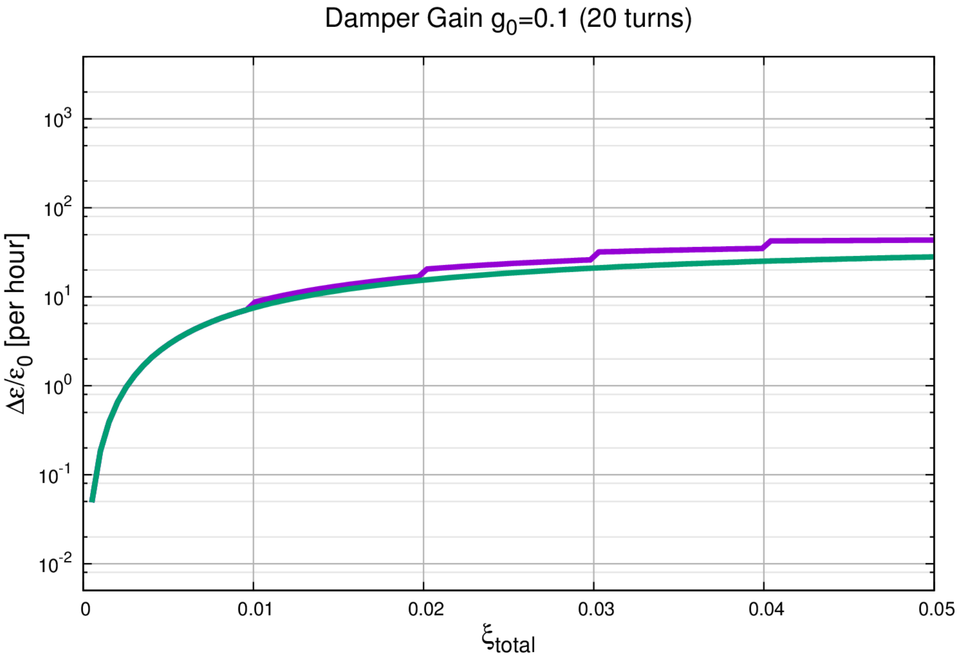






- Emittance growth fit for all 3 bunches.
  - 3 fills, B1/2, H/V
- The non-colliding bunch will be used as reference for the inherent noise levels of the LHC.

Beam-beam parameter and feedback gain

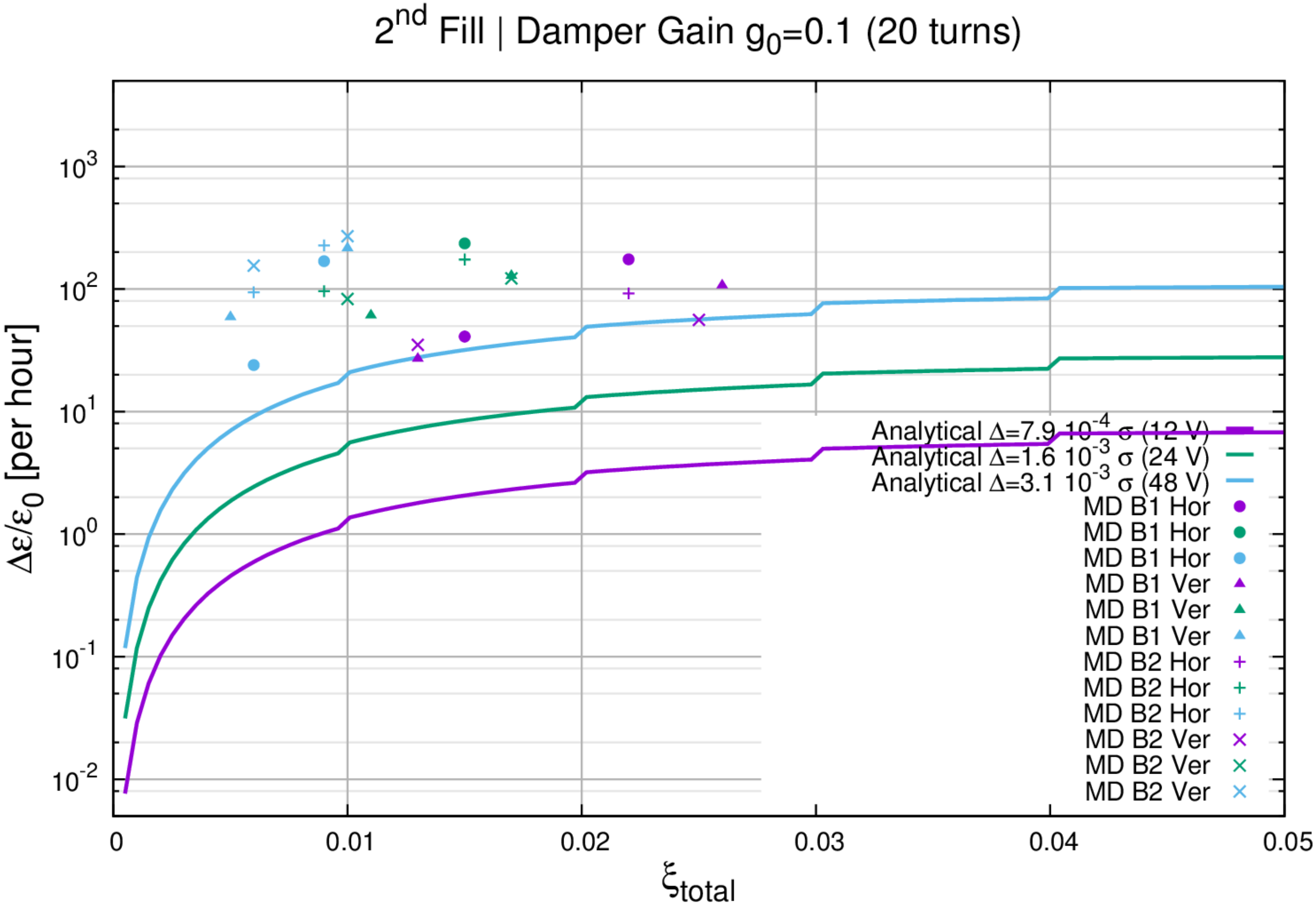


ξ_{bb}	Phase[deg]	Reduction of damping
0.01	16	0.96
0.02	32	0.85
0.03	48	0.67
0.04	65	0.43
0.05	81	0.16
0.06	97	unstable

Courtesy of W. Hofle

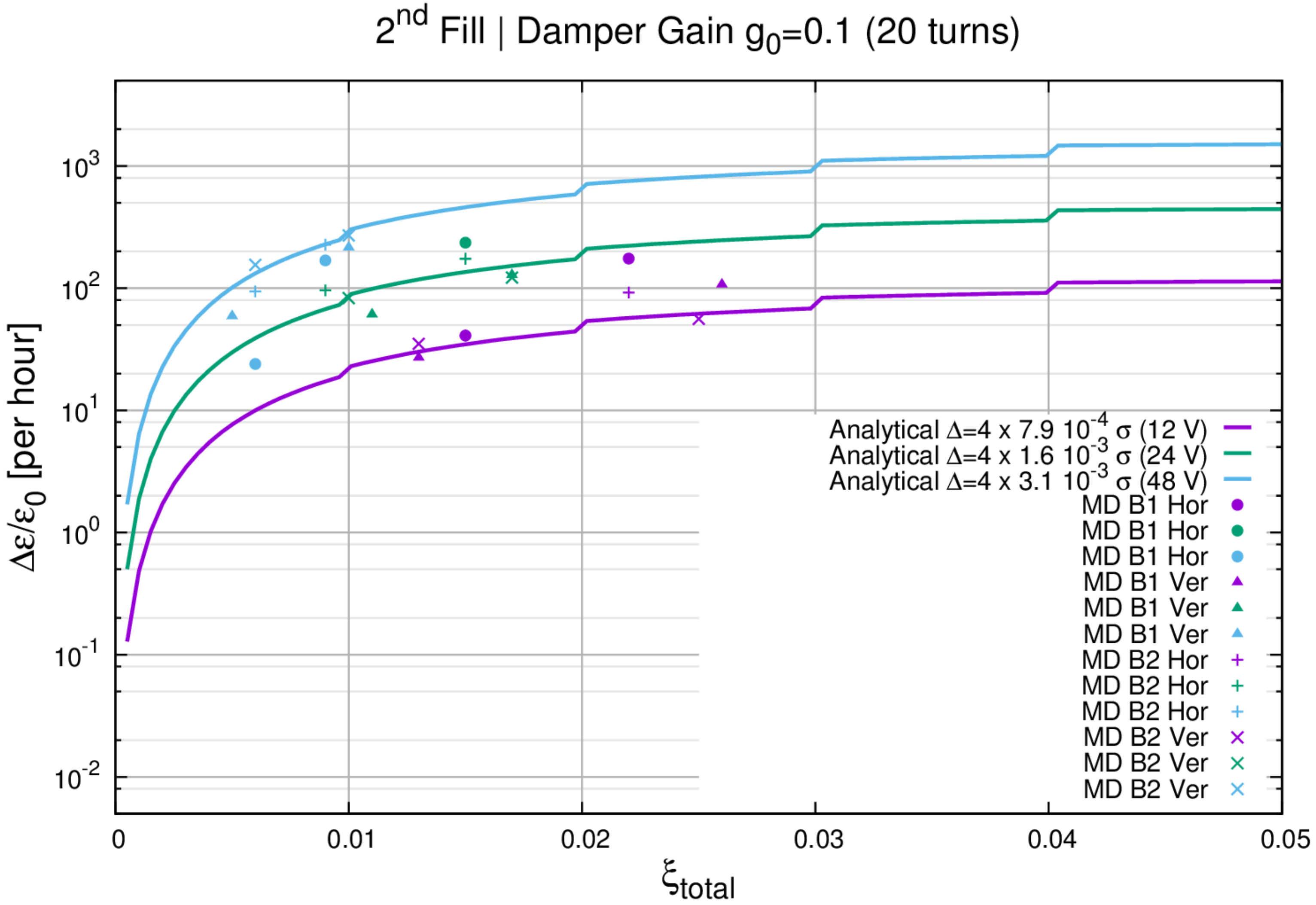
- The damper phase changes with the beam-beam parameter. The damping rate decreases with the cosine of this detuning. The stability limit is at ξ_{bb}=0.0555. The emittance growth is now piecewise in function of the beam-beam parameter.

Results



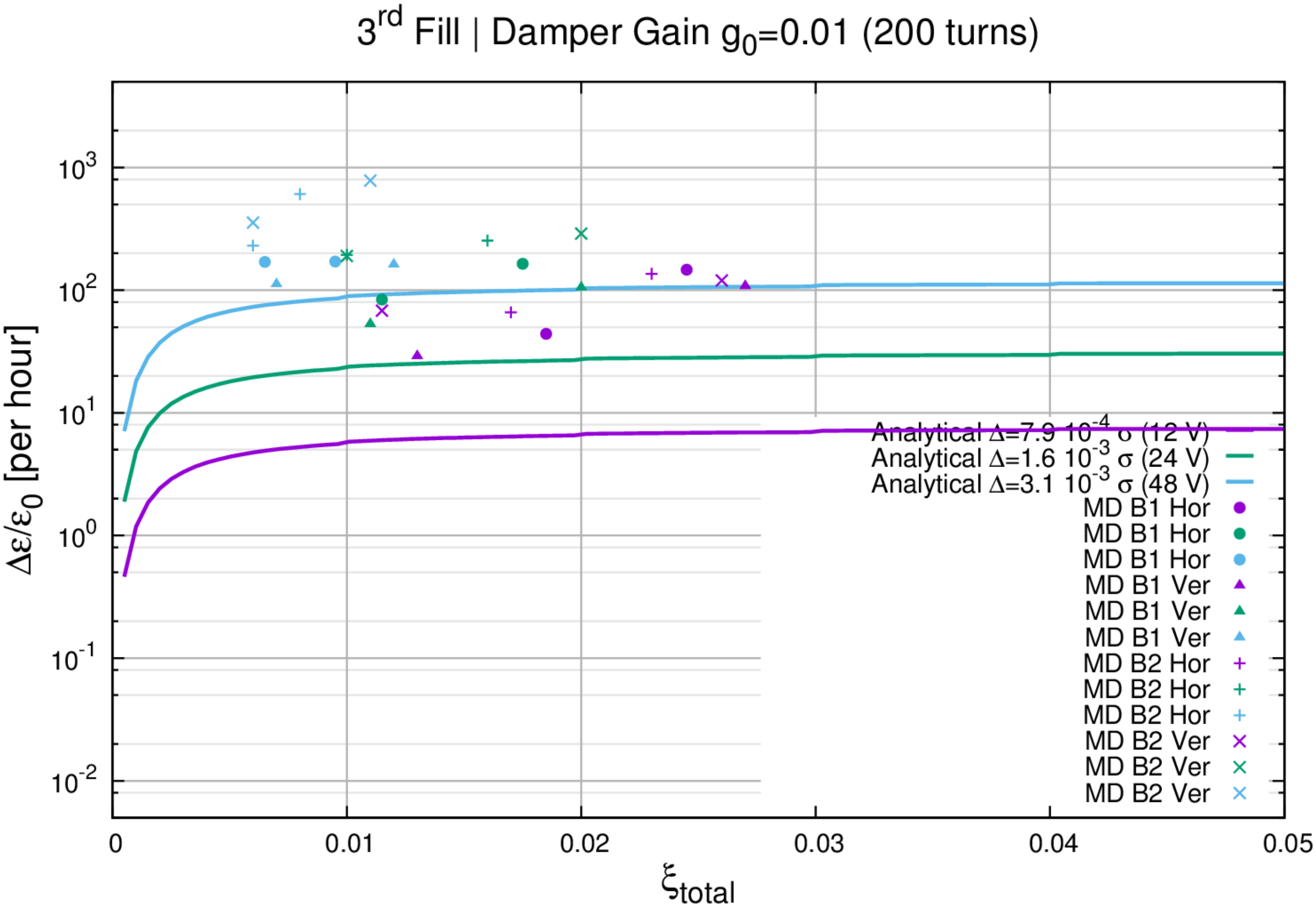
- Measurements shows larger growths for all noise amplitudes.

Results



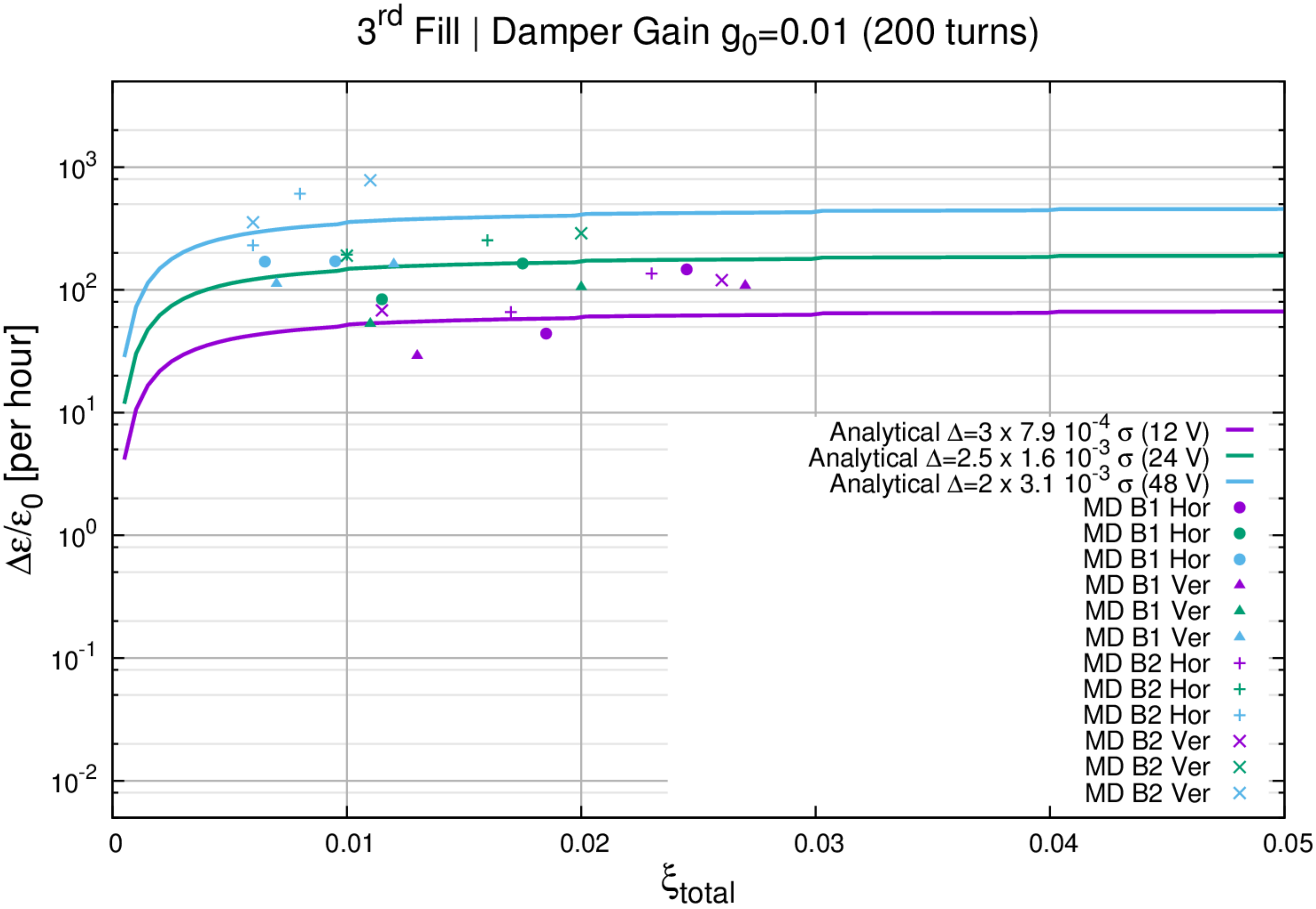
- Measurements shows larger growths for all noise amplitudes. It is possible to improve agreement by scaling up the noise amplitude a **factor 4!**.
- There could be some calibration issues on the ADT noise? To be checked with experts.
- Spread of measurements follows a Δ_{noise} pattern rather a $\Delta_{\text{gain.}}$

Results



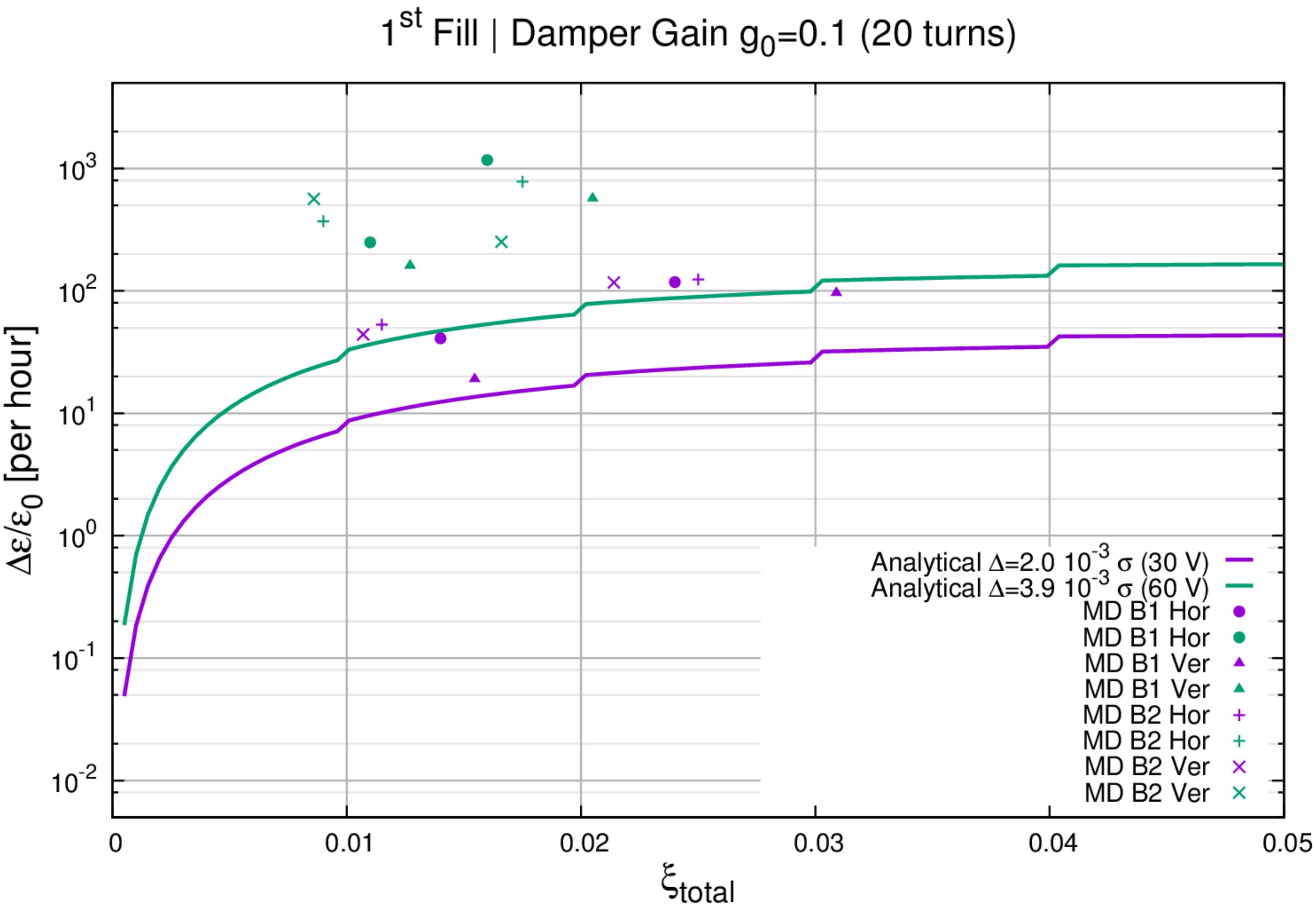
- Measurements shows larger growths for all noise amplitudes.

Results



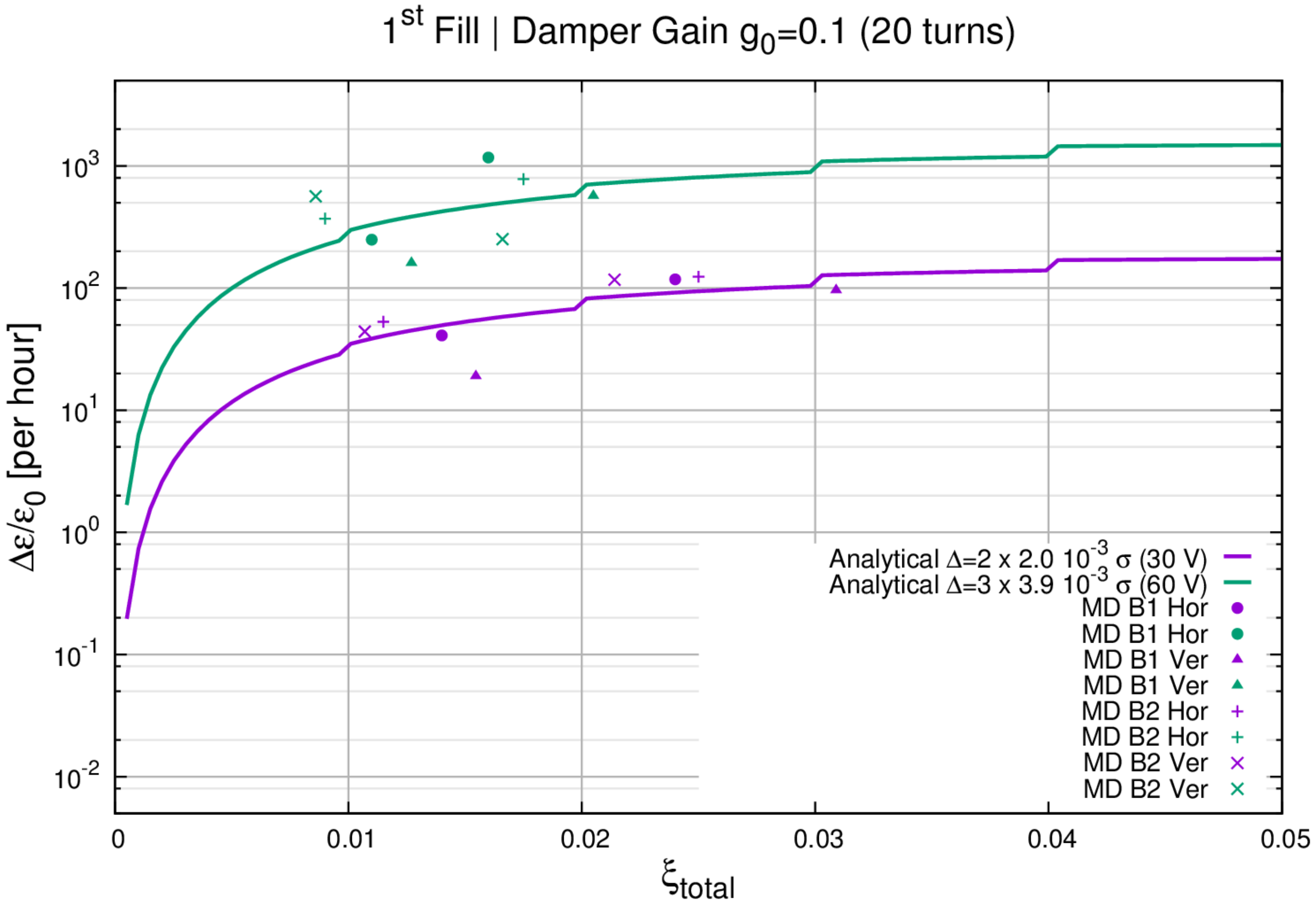
- Measurements shows larger growths for all noise amplitudes. It is possible to improve agreement by scaling up the noise amplitude a **factor 2-3!**.
- How the ADT noise calibration depends on the actual gain. Smaller gain smaller correction factor?

Results



- Measurements shows larger growths for all noise amplitudes.

Results



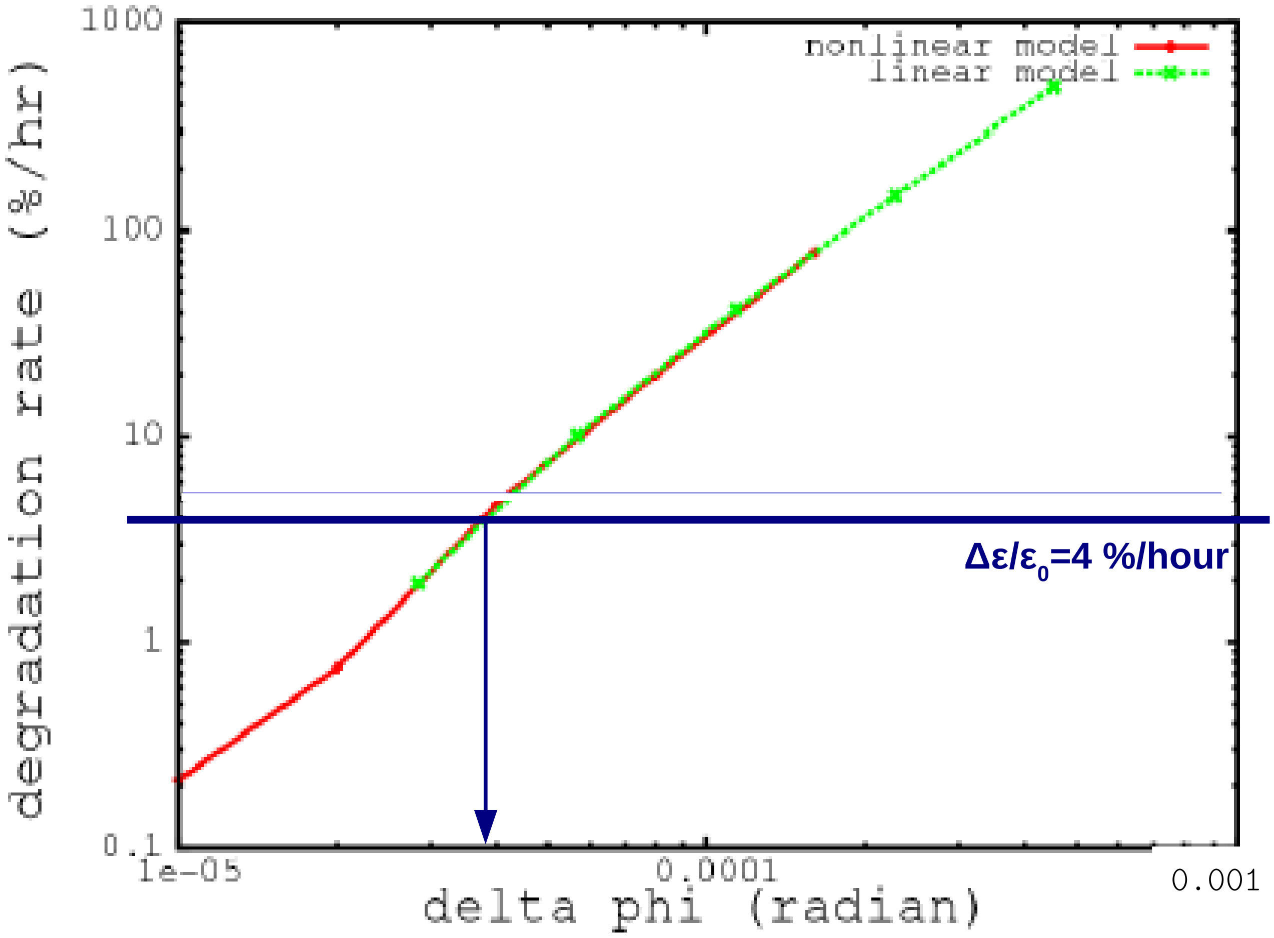
- Measurements shows larger growths for all noise amplitudes. It is possible to improve agreement by scaling up the noise amplitude a **factor 2-3!**.
- In this case g=0.1 but smaller correction factor wrt to fill #2. To be further studied.

Missing ingredients / open questions

- Need better understanding of the effect of feedback detuning with beam-beam parameter. Only reduction of damping or additional source of noise? Include it in COMBI simulations?
- LHC experimental data show considerably larger emittance growth than analytical model and simulations. However the follow and can be fit for an increase noise level.
- Need to check with feedback experts the ADT noise calibration and its dependency on the gain. Can we explain the factor 2-4 needed to improve agreement.
- Measurements seems to agree with a noise error. Other sources of noise not included in the non-colliding beam?
- BPM noise goes with g^2, but depending on the amplitude level could be relevant.
- Intrinsic damper noise, goes as well with g^2, points towards higher noise levels.
- Chromaticity was set to 2 units, so its impact, even if not taken into account by the analytical model should not be significant.
- Need to check with BSRT if large tails observed for high brightness beams could affect the measurement. Preliminary checks show that the fitting should just fine.

CC Noise: Phase noise

- Crab cavities ensure head on collisions at the IP by applying a transverse longitudinal dependent kick.
- Simulations with Beambeam3D.
- Simulations performed with a Crab Cavity at 90° from IP. First an error in phase was introduced. Effect similar to offset at the IP given by,



~4 10^{-4} rad

linear model:

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

Non-linear model (z-dependence):

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

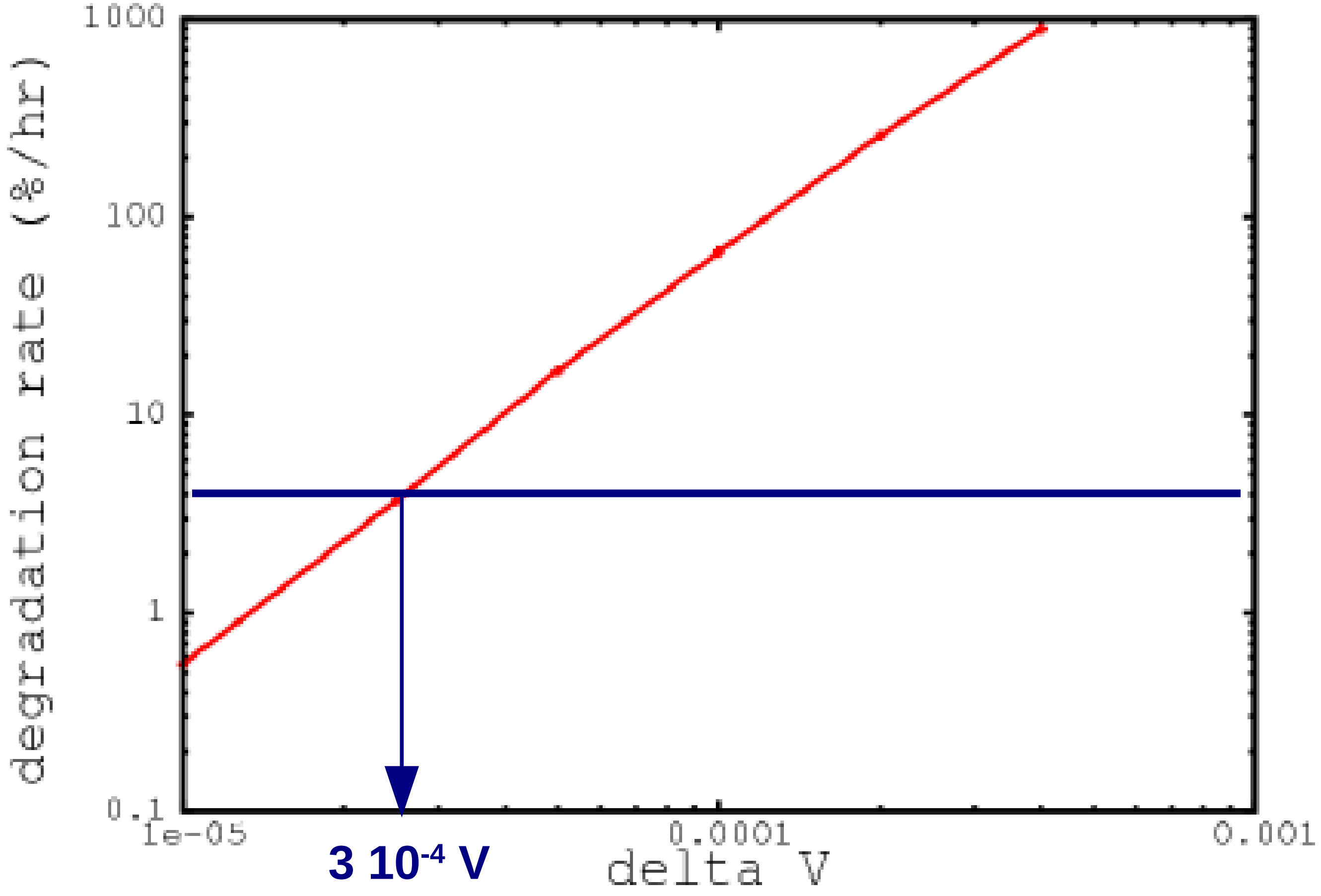
Tolerance for 4%/hour growth

↓

4 10^{-4} rad

Good agreement with P. Baudrenghien and T. Mastoridis analytical predictions.

CC Noise: Voltage noise



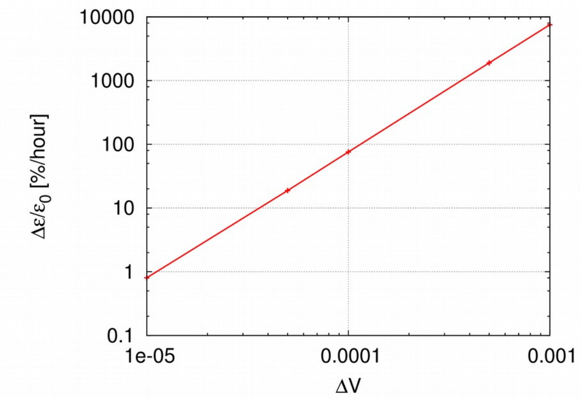
$$\delta x_i \propto \delta V_{cc} k z_i$$

Tolerance for 4%/hour growth

↓

~3 10^{-4} rad

COMBI

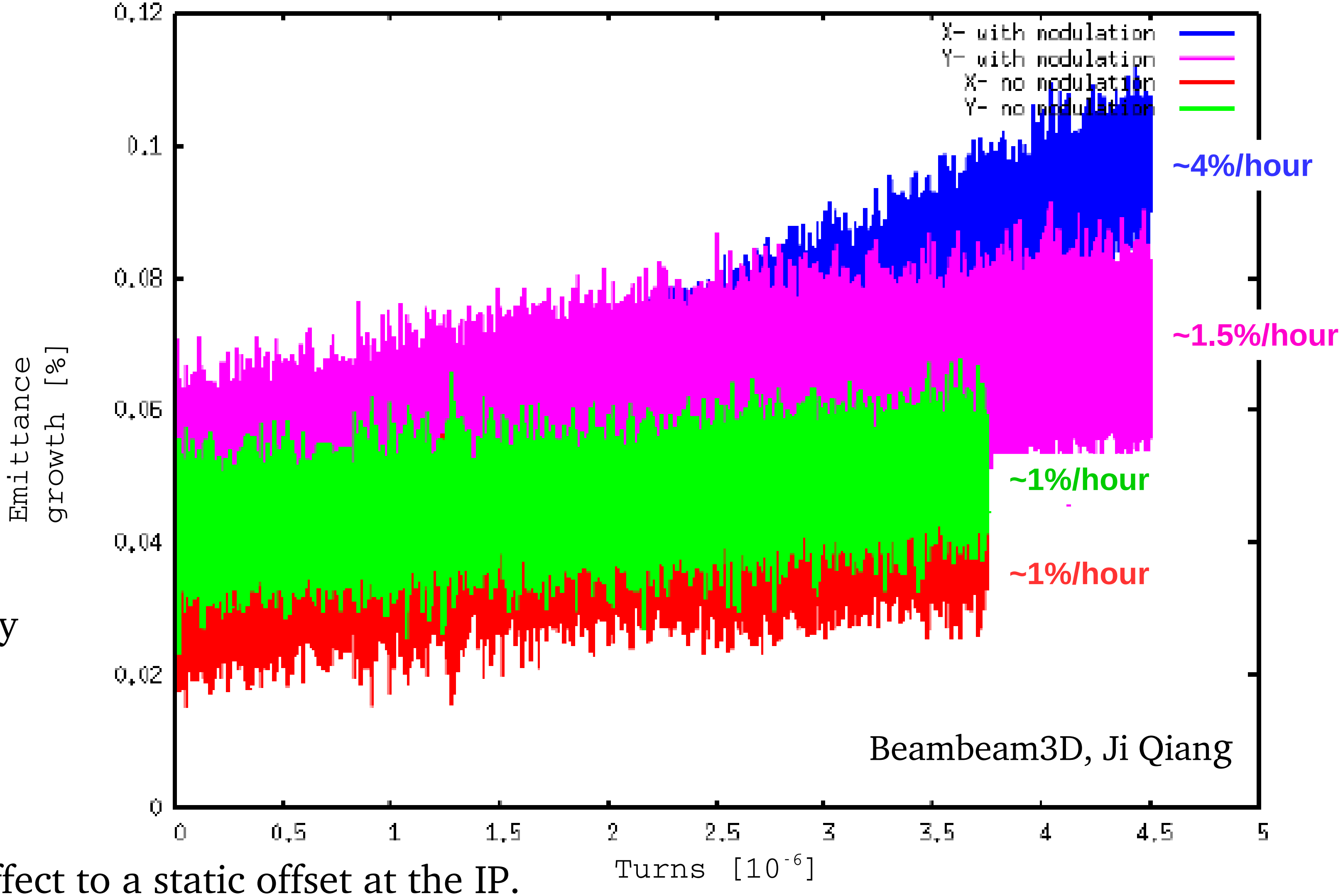


Good agreement with P. Baudrenghien and T. Mastoridis analytical predictions.

Low Frequency Noise Simulations

E=450 GeV
$\varepsilon_{x,y} = 2\ \mu m$
I= 1 10^{11} ppb
No damper

Simulations input by
M. Fitterer.



Beambeam3D, Ji Qiang

- Equivalent effect to a static offset at the IP.
- Emittance growth expected < 4%/hour even with modulation.
- Weak-strength simulations needed to understand the incoherent contribution.
- Available LHC data with noise modulation frequency f < 1 Hz. Analysis ongoing.

Conclusions & Outlooks

- Benchmark between analytical estimations, self-consistent simulations and LHC measurements has been performed.
- LHC measurements show larger growth than predicted but with Δ_{noise} pattern. Improved agreement found for noise amplitude correction factor 2-4.
- Several open questions to further understand. Especially ADT noise calibration.
- Self-consistent codes update with crab cavity elements. Tolerances for crab cavity noises (voltage and phase) are given for a 4%/our emittance growth. Fair agreement found between analytical models and simulation codes.
- Low frequency noise studies show moderate emittance growth from the strong-strong simulations. Consistent with equivalent static offset effect expected emittance growth.
- More complex configurations (with 4 IPs) will study in the future.

BACK UP

Effects of Low Frequency Modulation (preliminary)

beam parameters	Beam 1		Beam 2	
	frequency	amplitude [mum]	frequency	amplitude [mum]
6.5 TeV, 2.1 mum normalized emittance,7.5 cm bunch length, 80 cm beta*, x-angle = 290 urad with damper as well as without damper	H: 11 Hz V: 20.5 Hz	xIP5= 16.86 xIP1 = 9.81 yIP5 =15.45 yIP1 = 14.77	-	-
450 GeV, 1-2.0 mum normalized emittance, 8.25cm bunch length, 11m beta*, w/o x-angle with damper as well as without damper	H: 11 Hz V: 20.5 Hz	xIP5 = 34.44 yIP5 =12.281192 xIP1 = 66.97 yIP1 = 62.88	H: 11 Hz V: 20.5 Hz	xIP5 =0.66 yIP5 = 12.08 xIP1 =62.77 yIP1 = 32.84

Miriam Fitterer et al. for input parameters