The impact of noise on beam stability

X. Buffat, D. Amorim, S. Antipov, L. Carver, N. Biancacci, S.V. Furuseth, T. Levens,
E. Métral, N. Mounet,T. Pieloni*, B. Salvant, M. Soderen, C. Tambasco*, D. Valuch

*ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Many thanks to IT for the effort put in parallel computing resources

Work supported by the Swiss State Secretariat for Education, Research and Innovation (SERI)

8th HL-LHC collaboration meeting – CERN – 11.10.2018

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- Motivation
  - Observations of instability latency in the LHC
- Loss of Landau damping driven by diffusion
  - Simulations
  - Experimental results
- Conclusion

Motivation

Machine impedance
Octupole current
Electron cloud
Landau damping
ADT gain
Chromaticity
Linear coupling
Stability diagram
Tune separation
Offset levelling
Lattice non-linearities
Crab cavity
Transverse tails
Non-linear chromaticity
Head-on beam-beam
Long-range beam-beam
Octupole polarity
ADT bandwidth
Space charge
Longitudinal distribution
Mode coupling instability
Collapse of the separation

Motivation

- We observe that our predictions of stability threshold are usually off by a **factor 2** with respect to measurements

  → In the LHC, this **minimum margin** required to operate reliably is acceptable thanks to the strong octupoles installed

  → In the HL-LHC, mitigations are put in place to maintain this margin (low impedance collimators, enhanced tune spread using the ATS optics)

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  → In the HL-LHC, mitigations are put in place to maintain this margin (low impedance collimators, enhanced tune spread using the ATS optics)

- The direct measurements of the impedance do not show such a discrepancy

  → The scaling is somewhat arbitrary since the cause of the discrepancy is **unknown**

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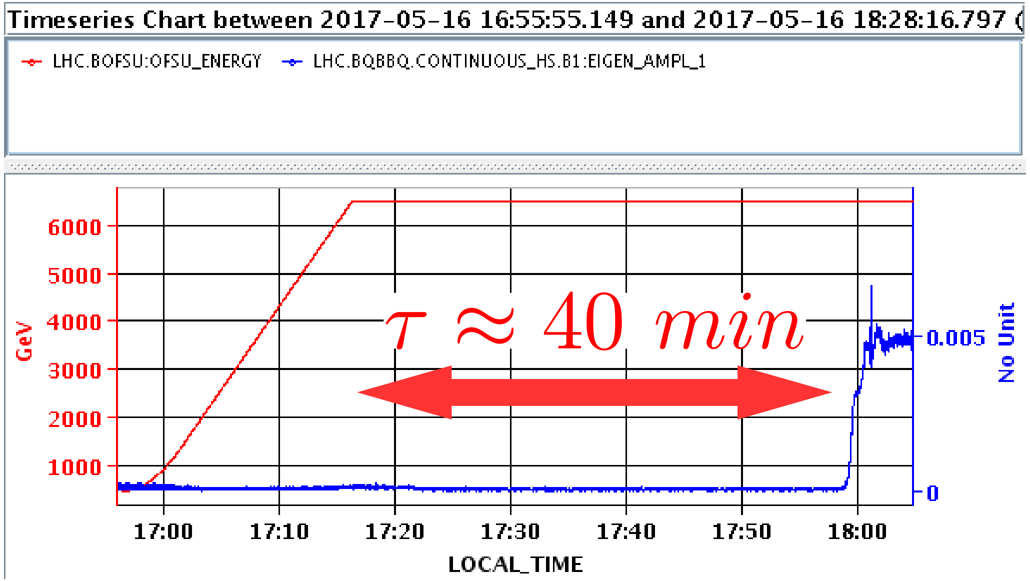
Instability latency

- On few occasions, one of the LHC beam was left steady (non-colliding), leading to an instability after a long latency



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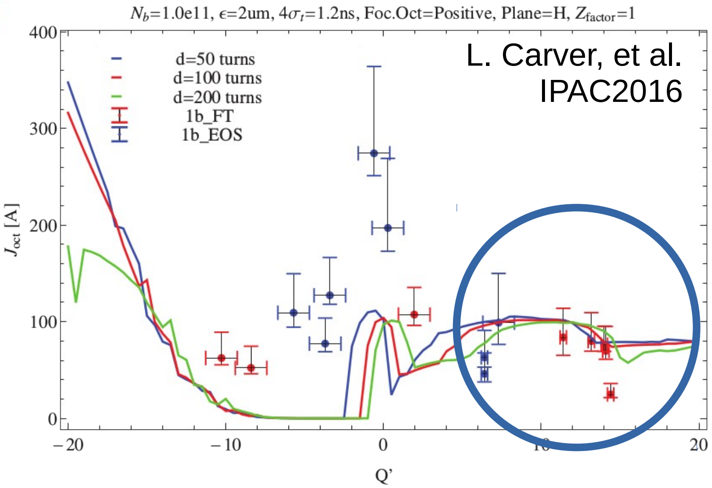
- To our best knowledge, these instability cannot be explained with machine or beam parameter variations

Measured thresold vs. operational threshold



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- Yet during the operation, the required octupole current was >2 times larger !

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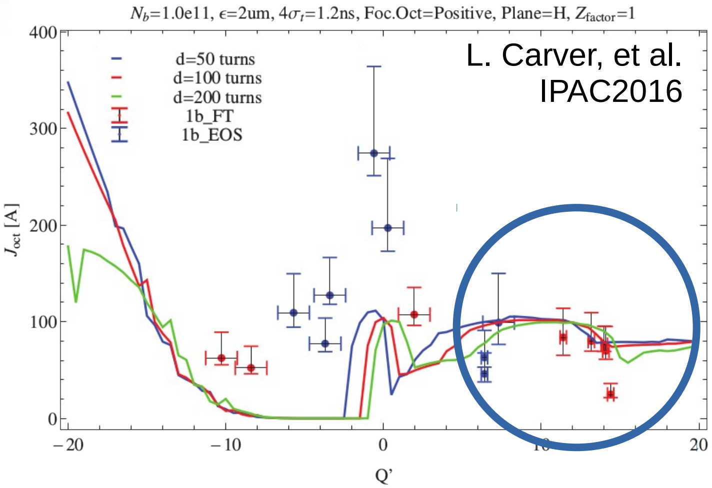

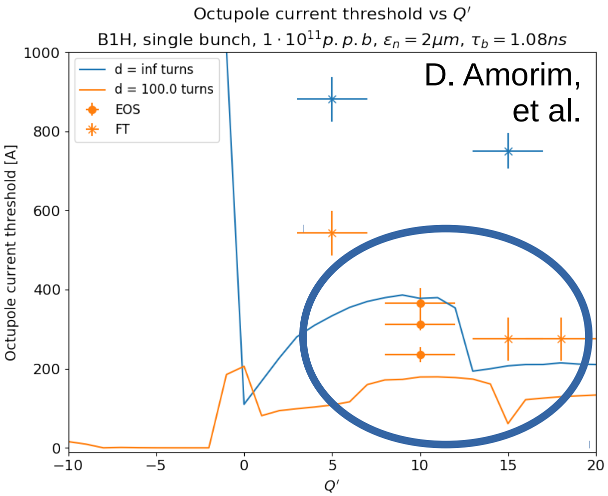

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- Performing slow octupole scans (~10 minutes per step), the threshold were found >2 larger than the prediction
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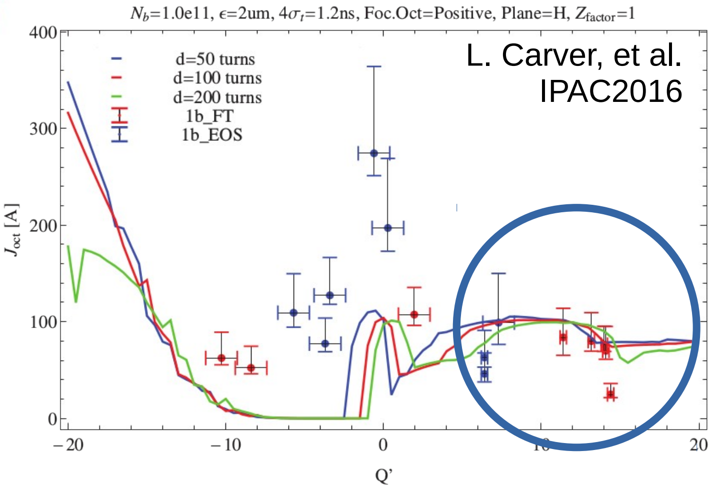

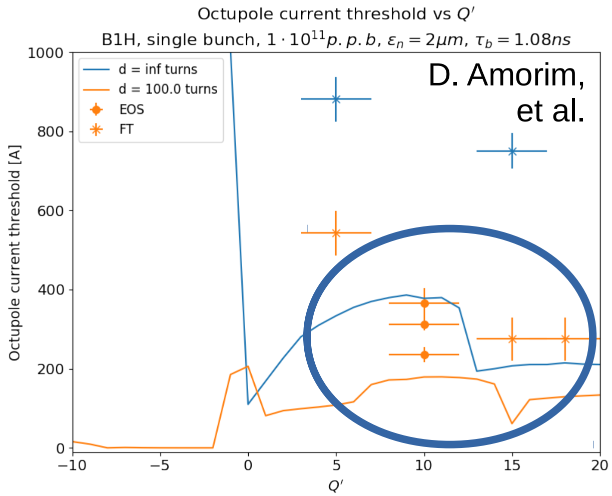

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- Performing slow octupole scans (~10 minutes per step), the threshold were found >2 larger than the prediction
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→ Even without understanding of the mechanism, it is clear that the **latency** plays an important role in the instability threshold

Postulating a mechanism

Steady external excitation
(wide spectrum)

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Beam oscillations → Coherent mode Q_{coh}

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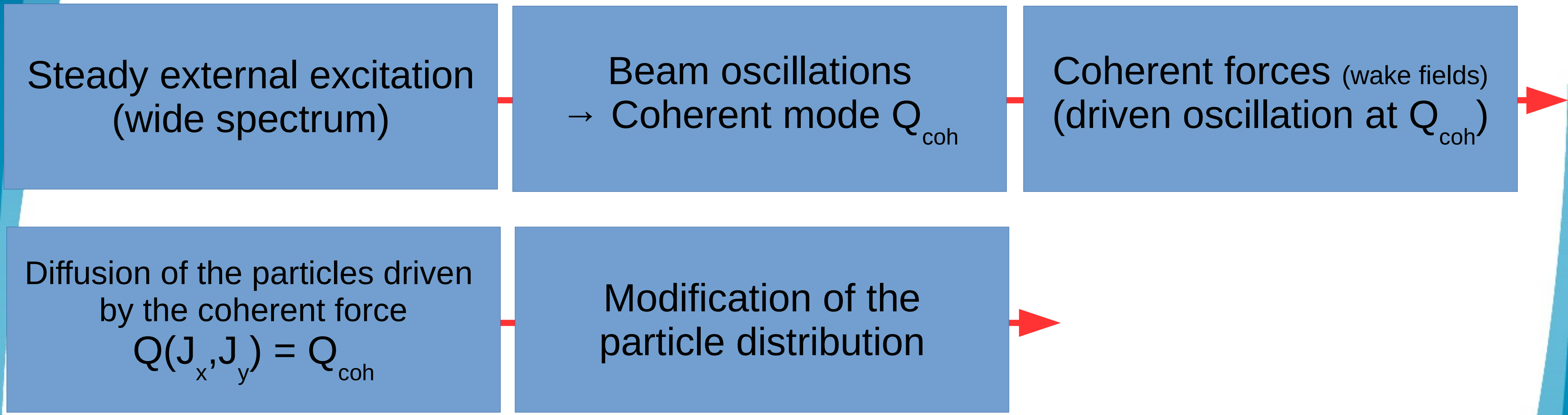

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Loss of Landau damping Driven by Diffusion* (**L2D2**)

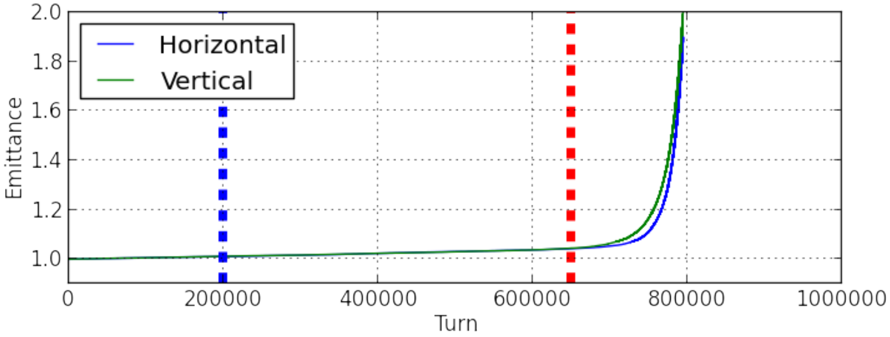
- New analytical models are under development to describe this phenomenon**

  → Today we address this mechanism through multiparticle tracking simulations, including a tune spread and an external noise source

* X. Buffat, PhD thesis, EPFL, 2015

** S.V. Furuseth, HSC meeting, 23.04.2018

Loss of Landau damping driven by diffusion



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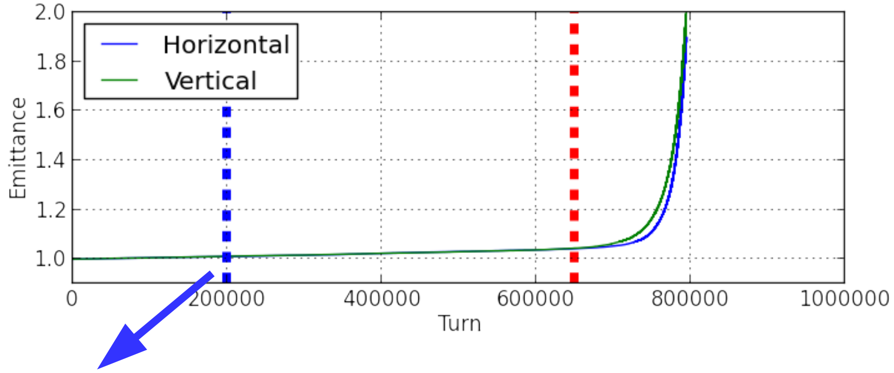

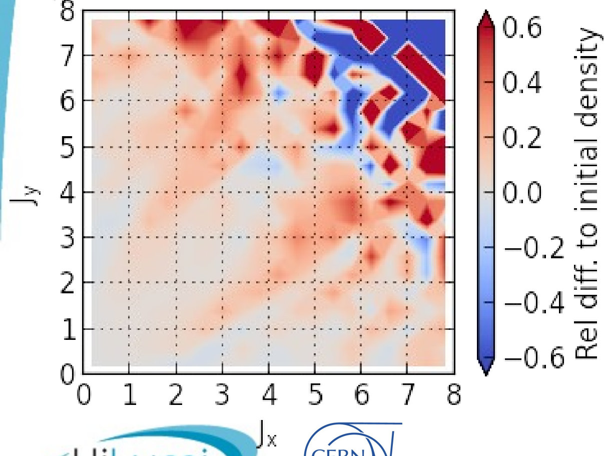

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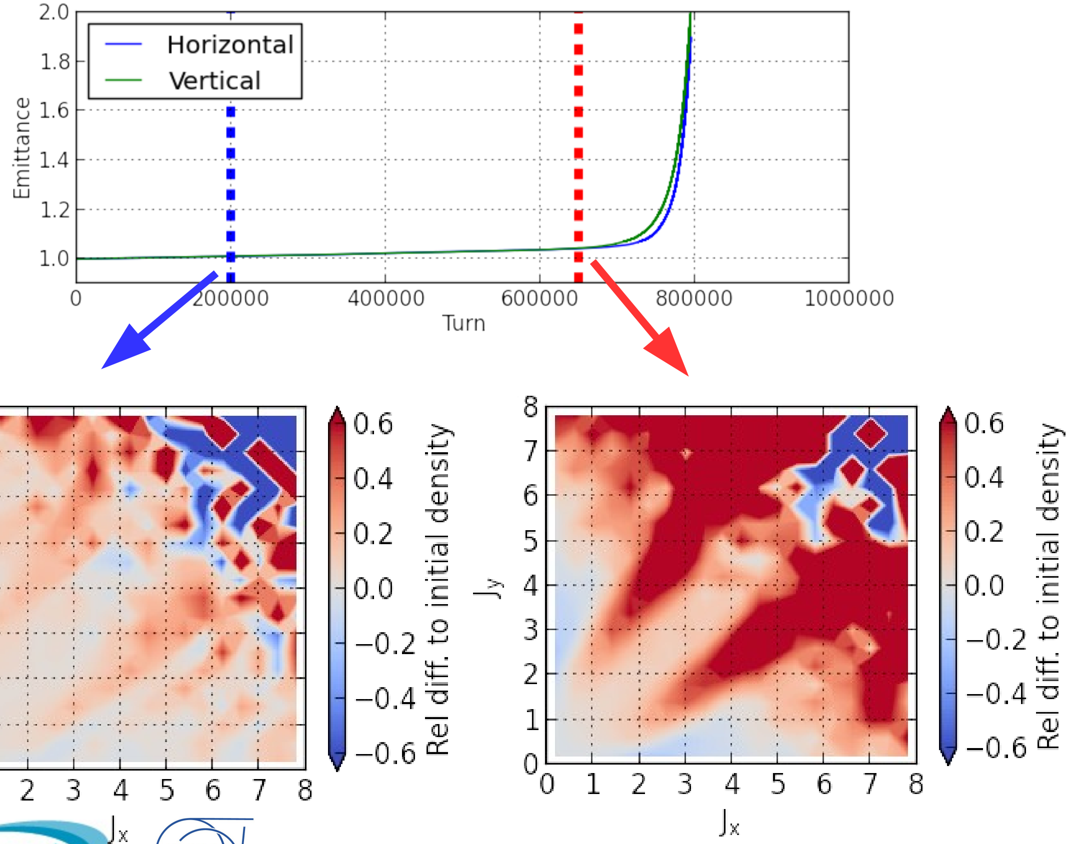

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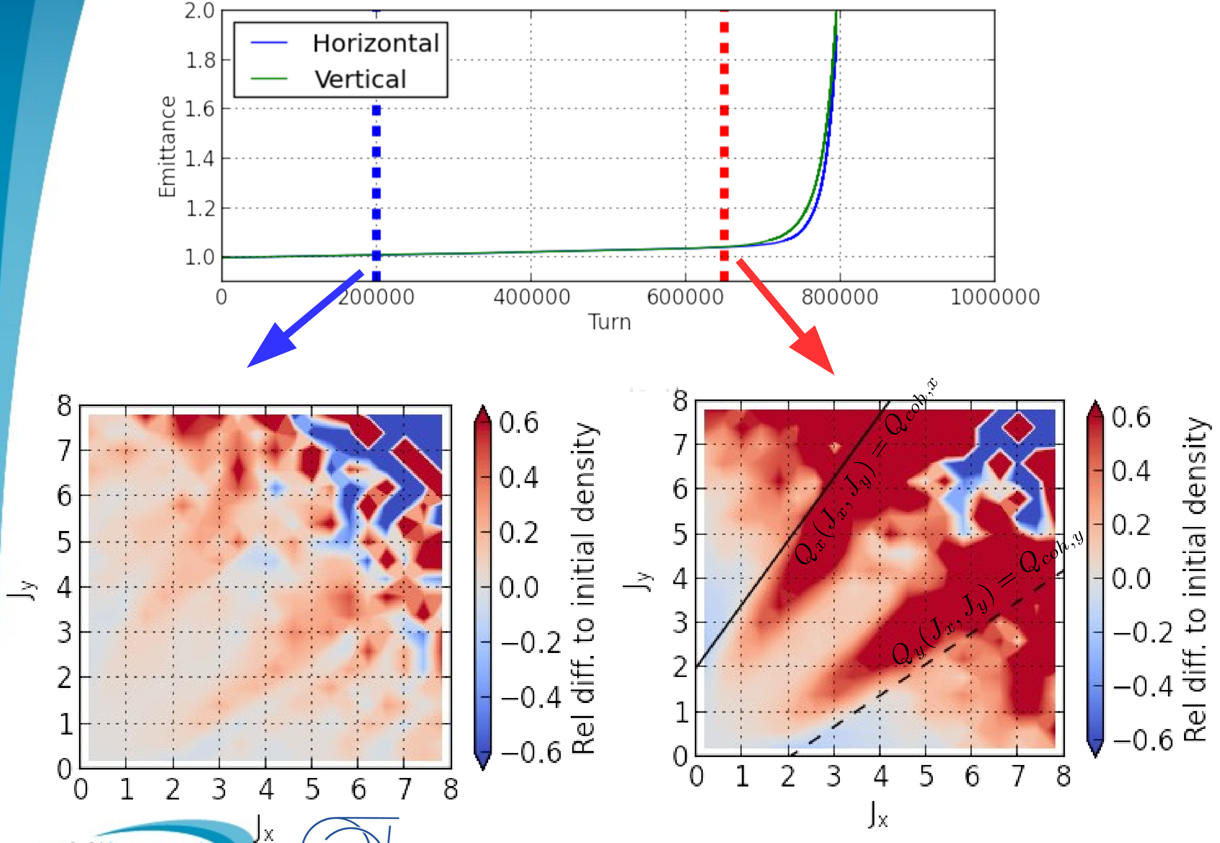

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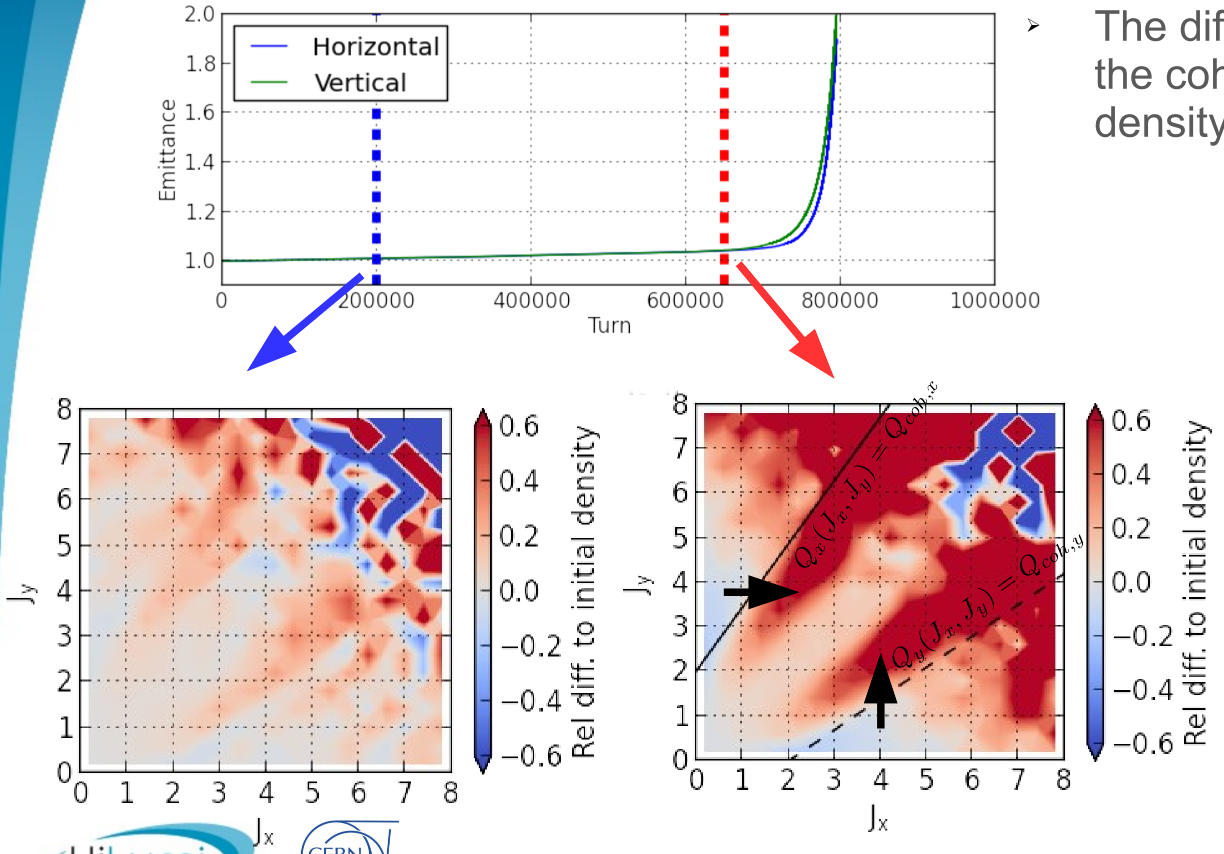

- The diffusion of the particles resonant with the coherent force is visible in the action density profiles

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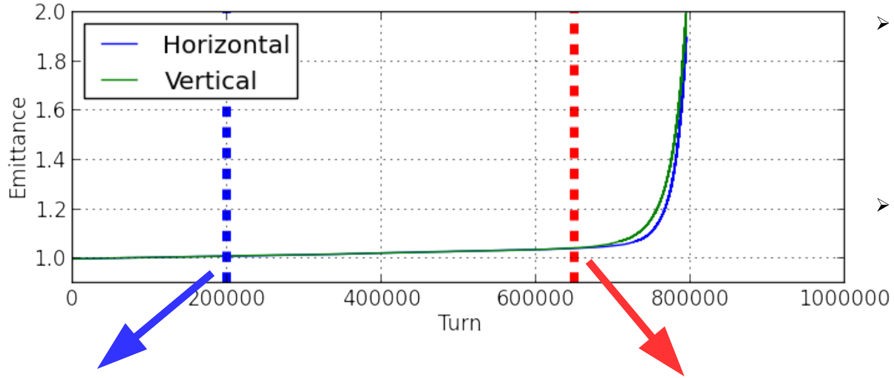
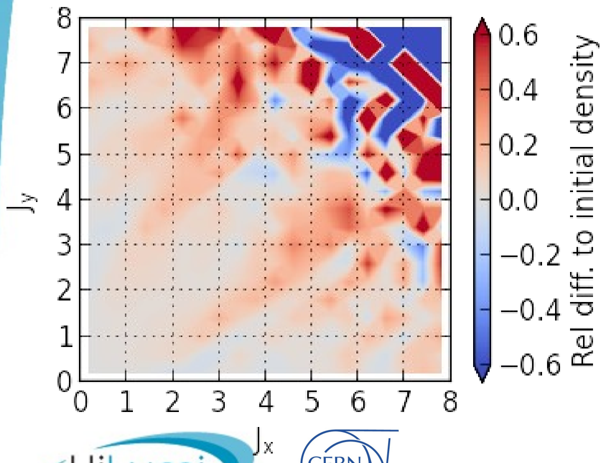
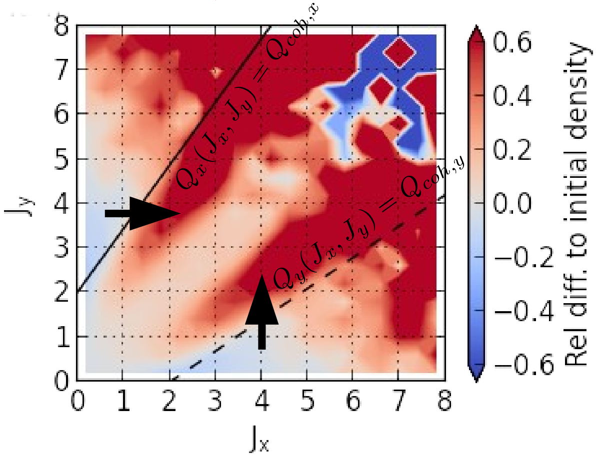
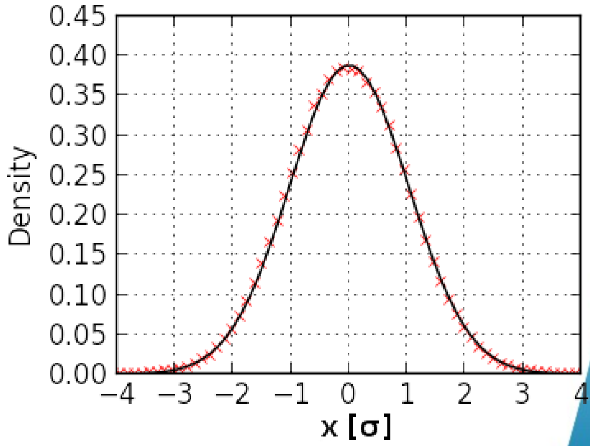


- The diffusion of the particles resonant with the coherent force is visible in the action density profiles
- In physical space, this changes is averaged out → The effect is too weak to be directly measurable in the beam profile







Watch the full diffusion process here!

The *break fade* analogy

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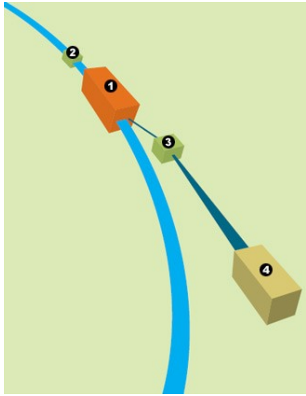
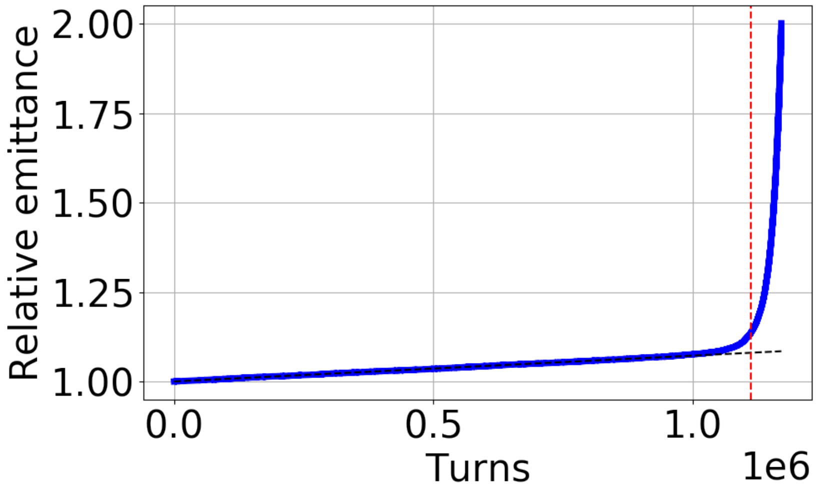


Noise amplitude

- Numerical setup (COMBI) :
  - Linear transfer map with transverse amplitude detuning (octupoles) and chromaticity
  - *Perfect* damper
  - Wake fields
  - Gaussian white (constant over the bunch length) transverse noise with r.m.s. amplitude δ
  - The latency is measured based on the transition from linear to exponential growth of the emittance



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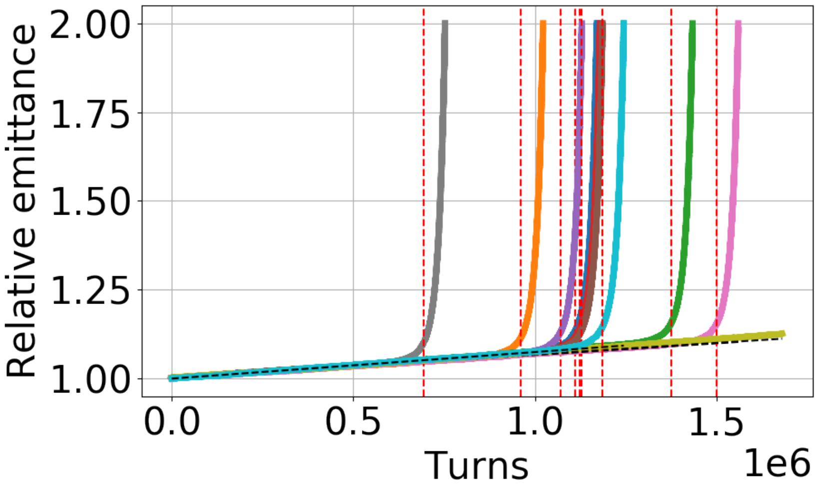
  → Average and error bars based on 10 simulations with different random seeds



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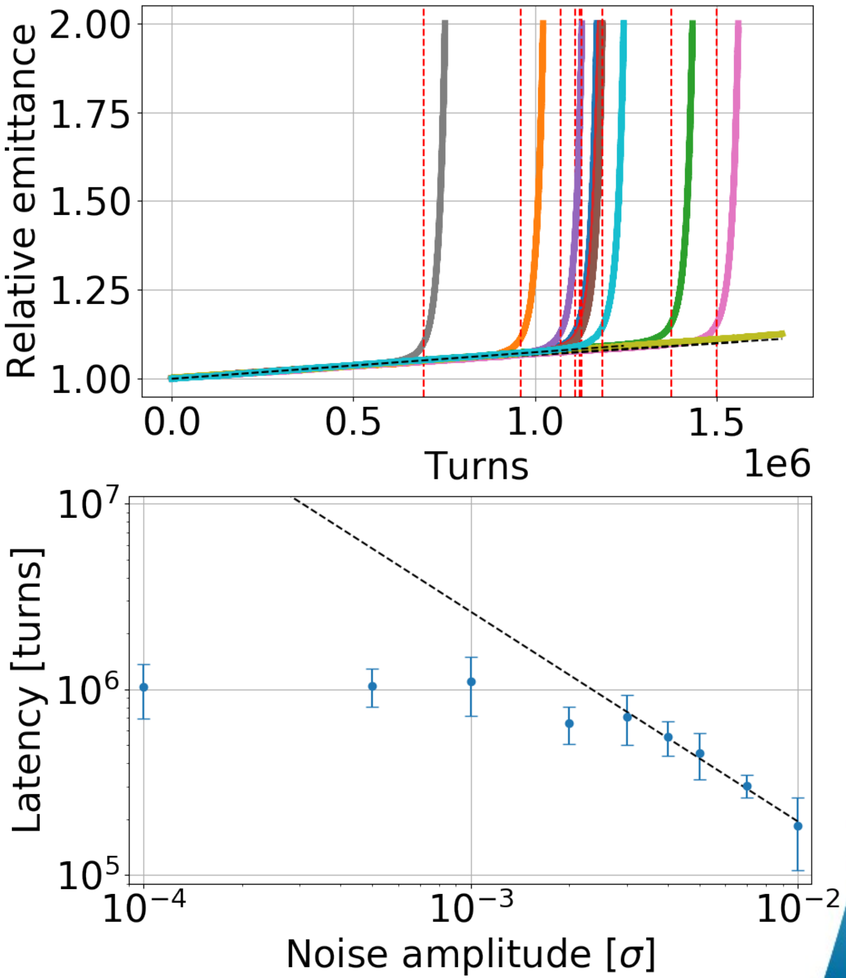

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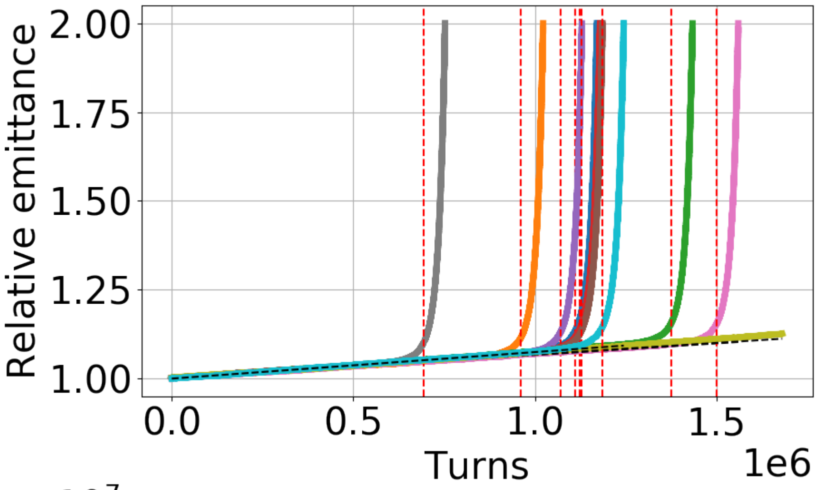

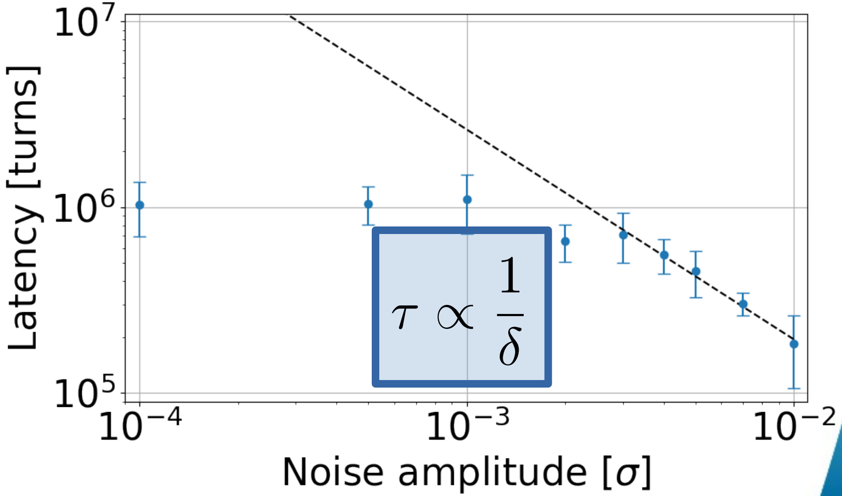

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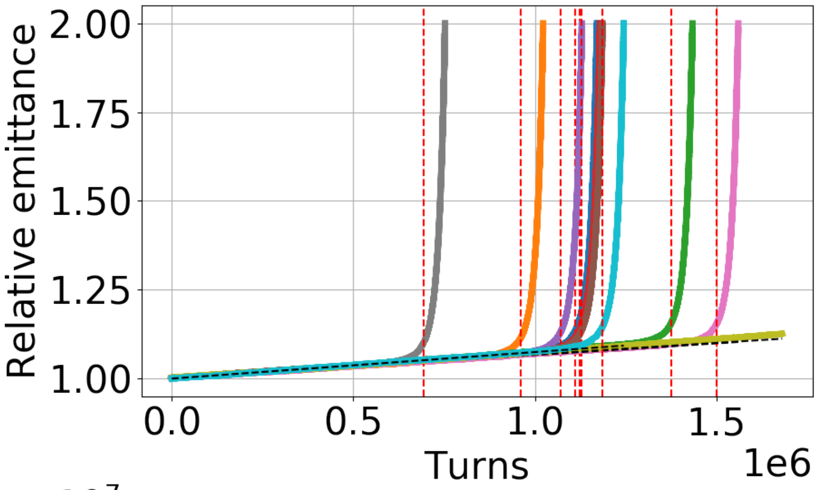
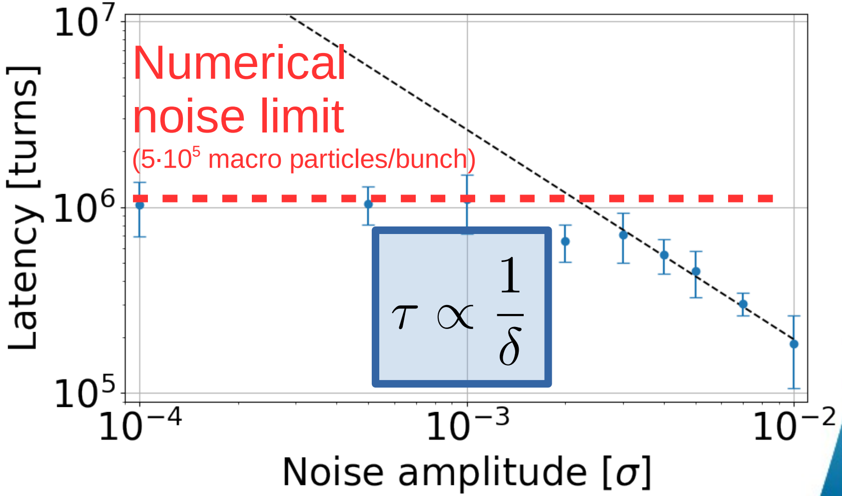
    → Average and error bars based on 10 simulations with different random seeds
- Numerical simulations are limited by there intrinsic noise

  → Realistic latencies (several minutes – millions of turns) are at the limit of the computational power available (on HPC machines)





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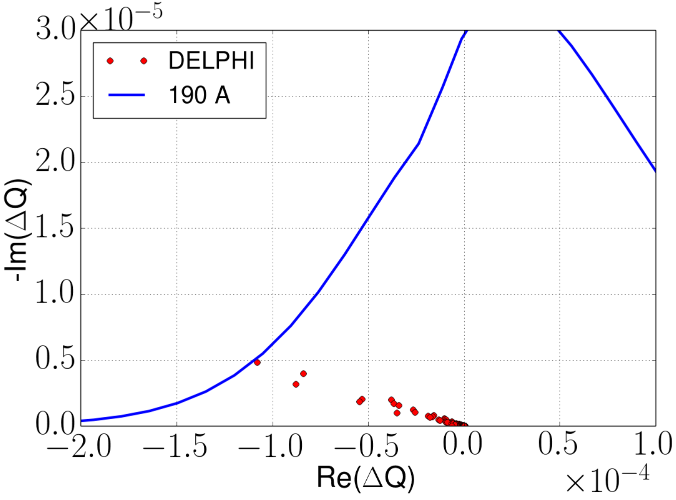
Octupole strength

- With the following parameter set, the expected threshold (w/o noise) is 190 A

Parameter	Value
LHC cycle phase	Flat top (6.5 TeV)
Nb bunches	1
Bunch intensity	$1.2 \cdot 10^{11}$
Emittance	2 µrad
Bunch length	1.05 ns



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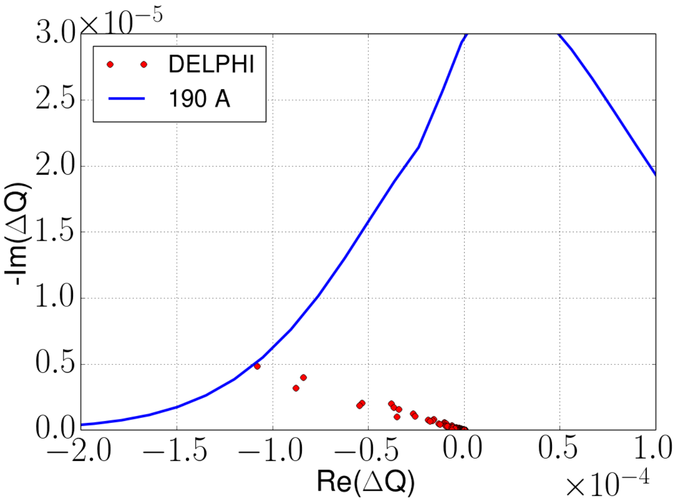
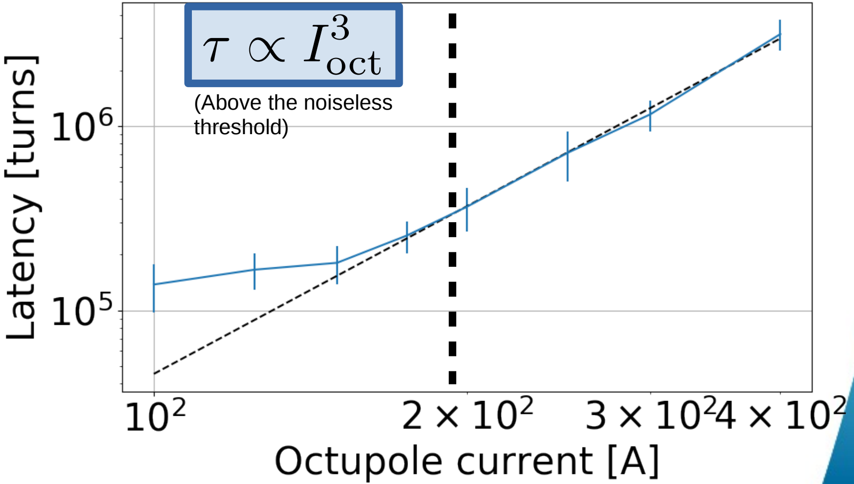
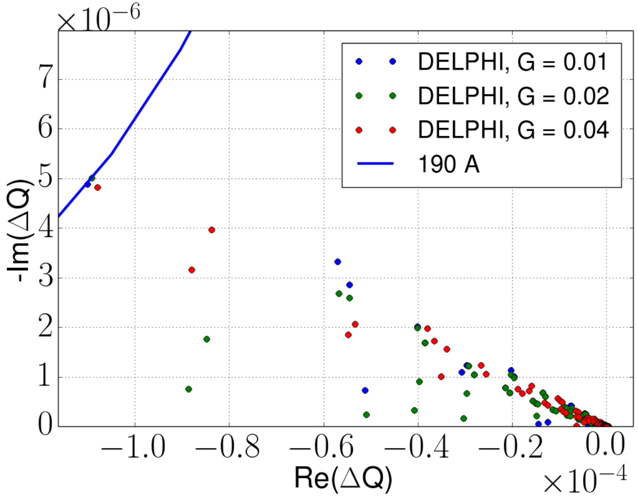
- Even for current a **factor 2** larger than needed without noise, latencies of several minutes are expected





Damper gain

- In the configuration considered, the stability threshold is almost independent of the gain in the *high-gain regime*



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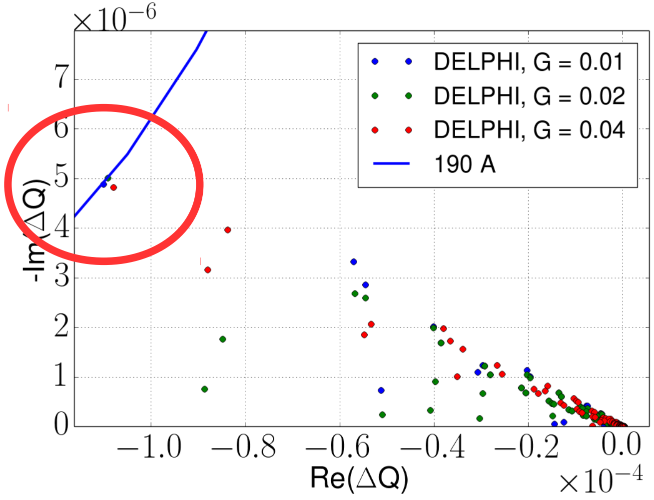

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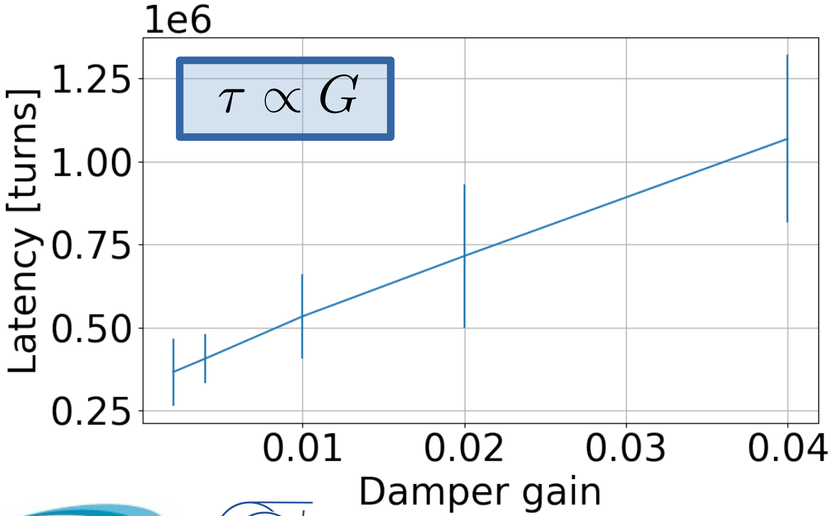

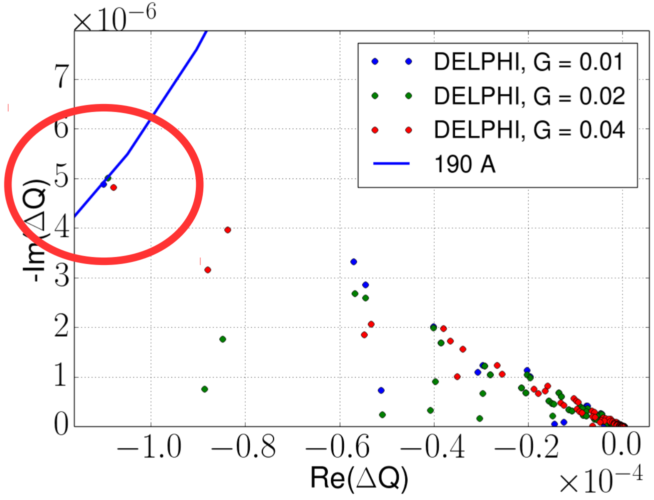

- An *ideal* transverse feedback mitigates the effect of the noise, leading to longer latencies

Extrapolations

	COMBI	LHC flat top (single non-colliding bunch)
I_{oct} [A]	300	**2***190
Gain	0.02	0.005
δ [σ]	$3 \cdot 10^{-3}$	$6 \cdot 10^{-5}$
Latency [min]	1.7	

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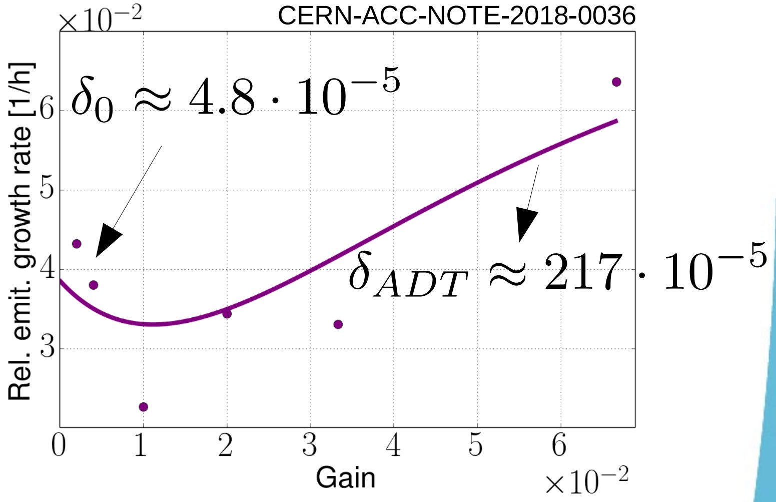

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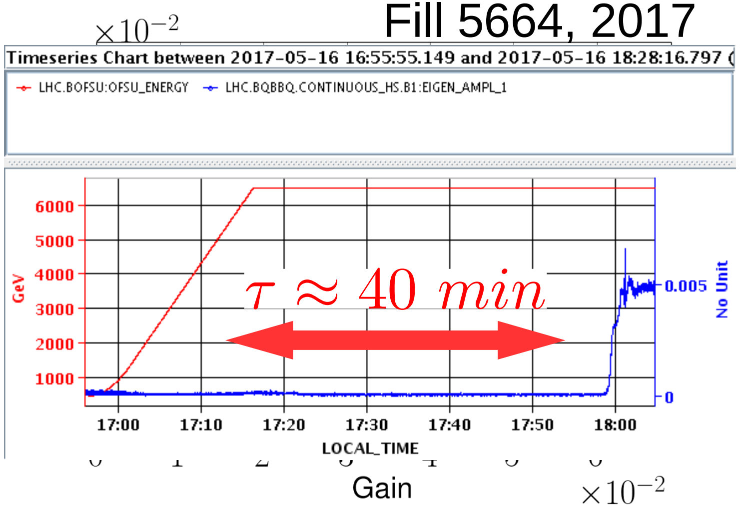

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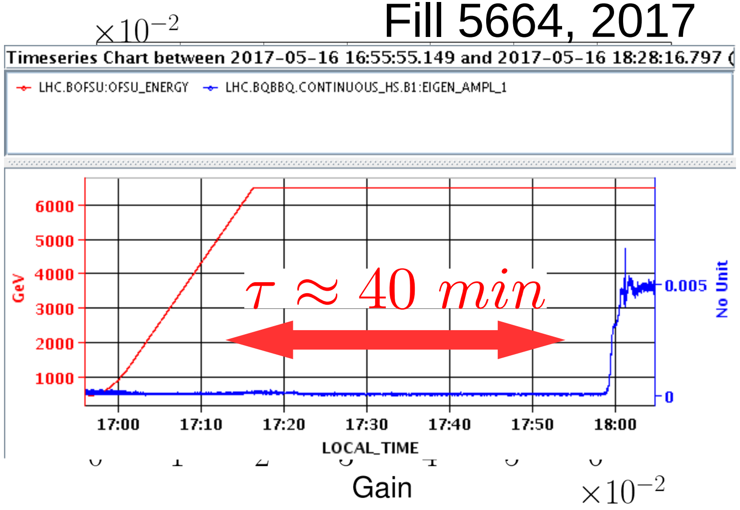
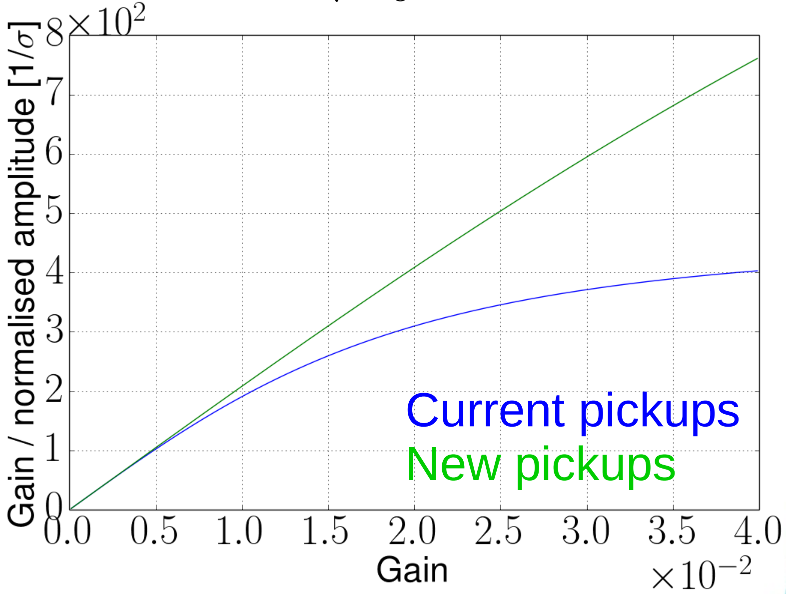


- The extrapolation is compatible with the few events of very long latencies and the time spent at flat top (squeeze)
- In these conditions, in order to explain a factor 2 within 10 minutes, a noise amplitude of $2.6 \cdot 10^{-4}$ is needed

  → Further analysis is needed (dependence on chromaticity, proximity of the tune to noise lines, collision / injection tunes, ...)

Expected benefit of the ADT pickup electronic upgrade

$$\tau \propto \frac{G}{\delta_{tot}} = \frac{G}{\sqrt{\delta_0^2 + (G\delta_{\mathrm{ADT}})^2}}$$



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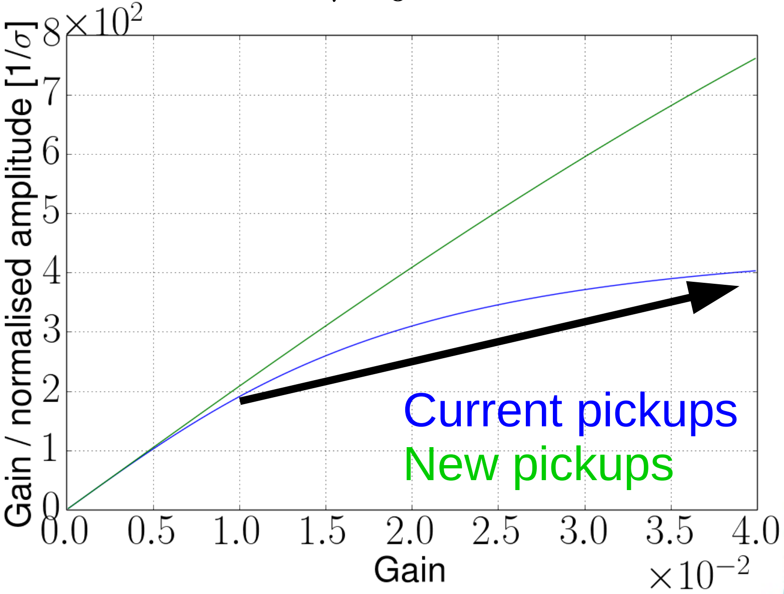

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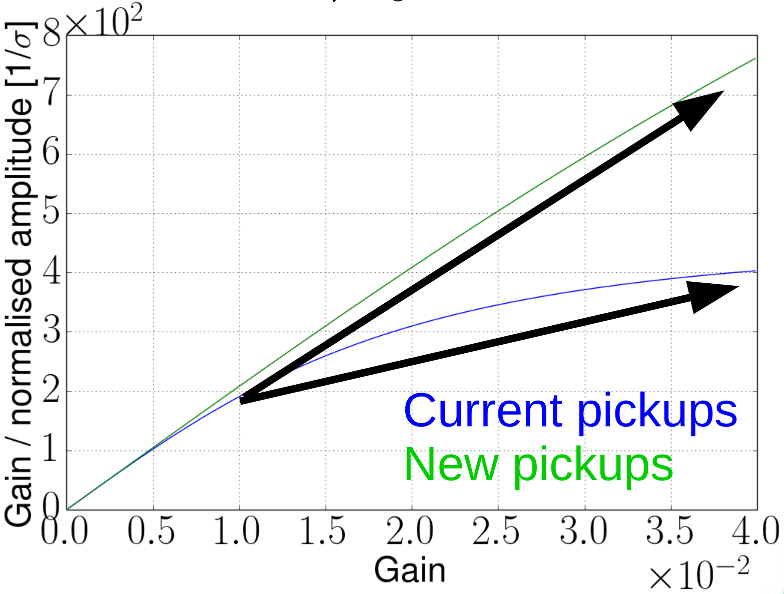

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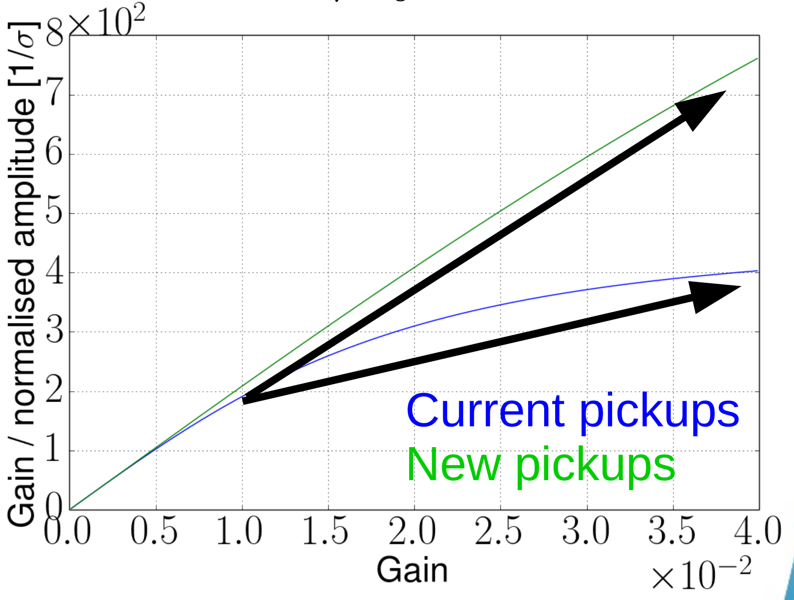
→ To be verified experimentally (MD4)



Experimental test with artificial noise

- The direct measurement of the distortion of the stability diagram through beam transfer function remains a challenge*** → A **novel experimental approach** was needed to study this phenomenon

*** C. Tambasco, PhD thesis, EPFL, 2017

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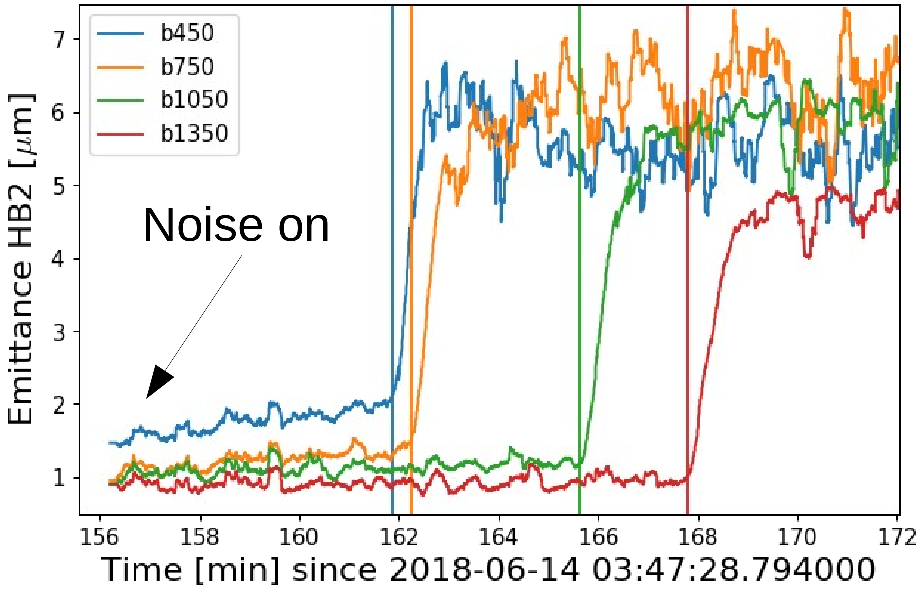
S.V. Furuseth



- Different bunches circulating simultaneously in the machine experience Gaussian white noise of different amplitudes
- Bunches experiencing a higher noise amplitude became unstable first

→ **First evidence of instabilities driven by an external source of noise in a controlled experiment**

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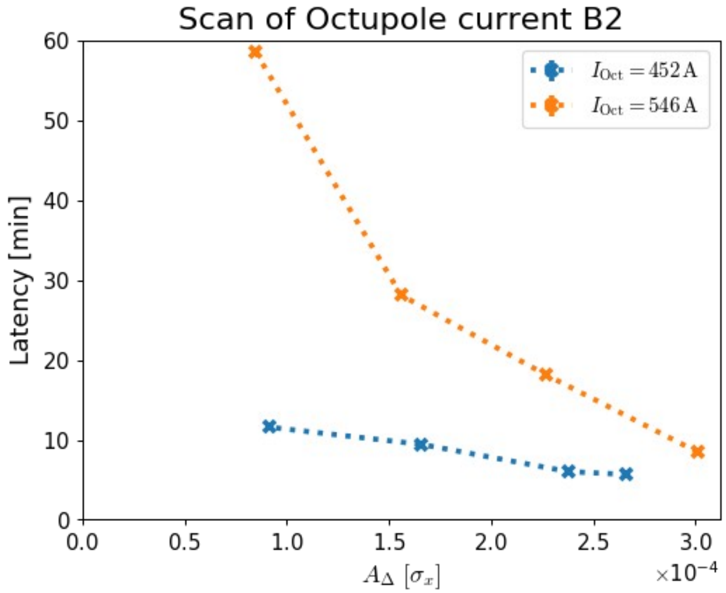
Octupole and chromaticity scans



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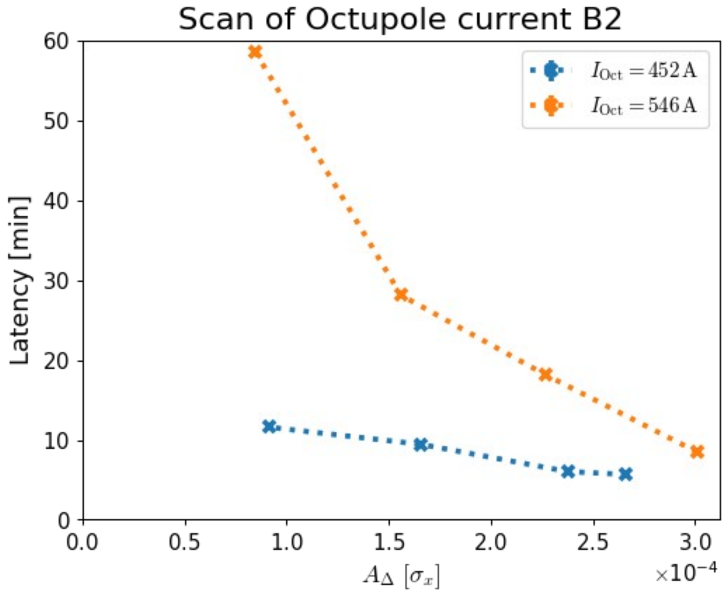

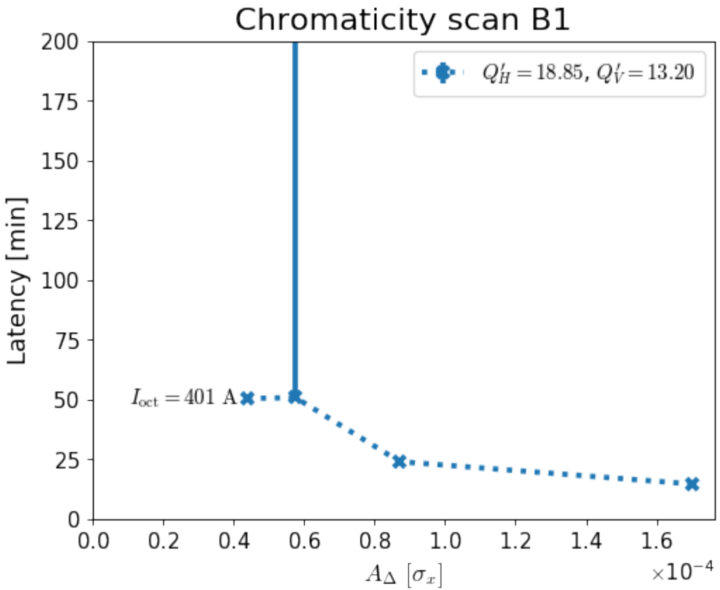

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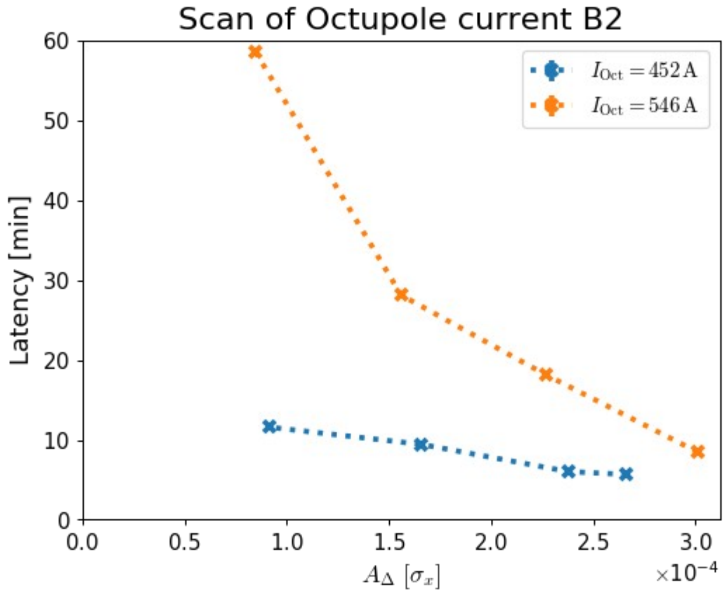

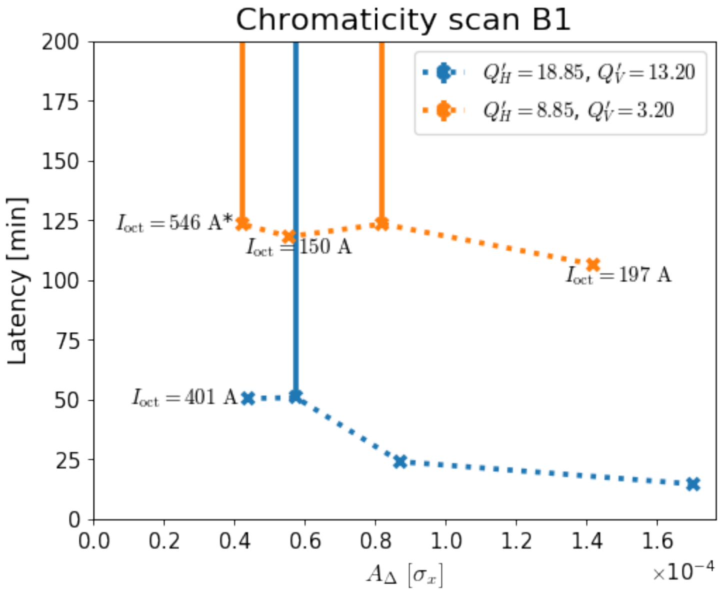

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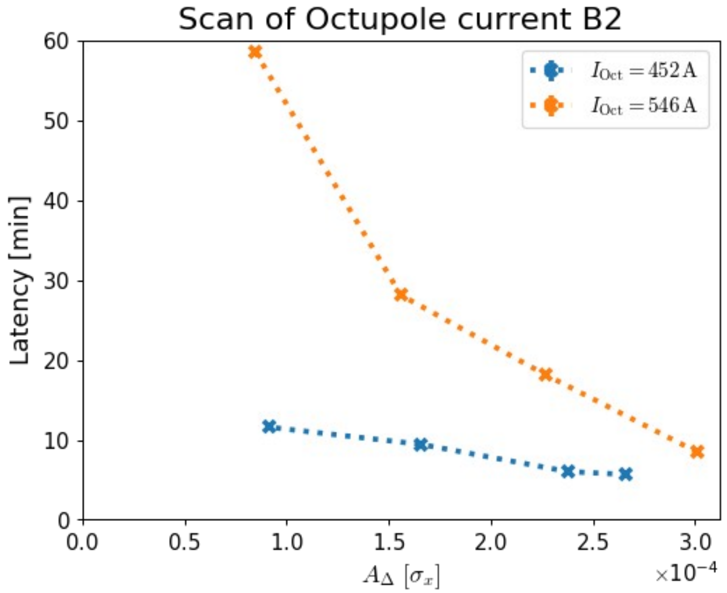
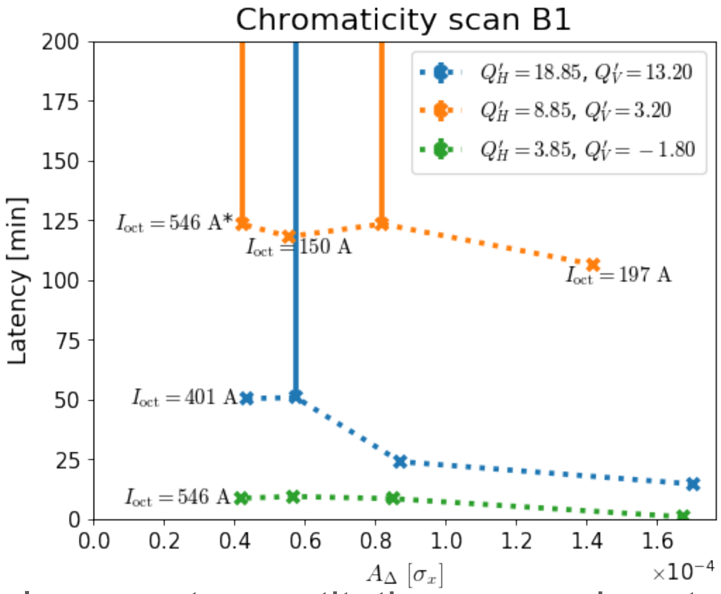




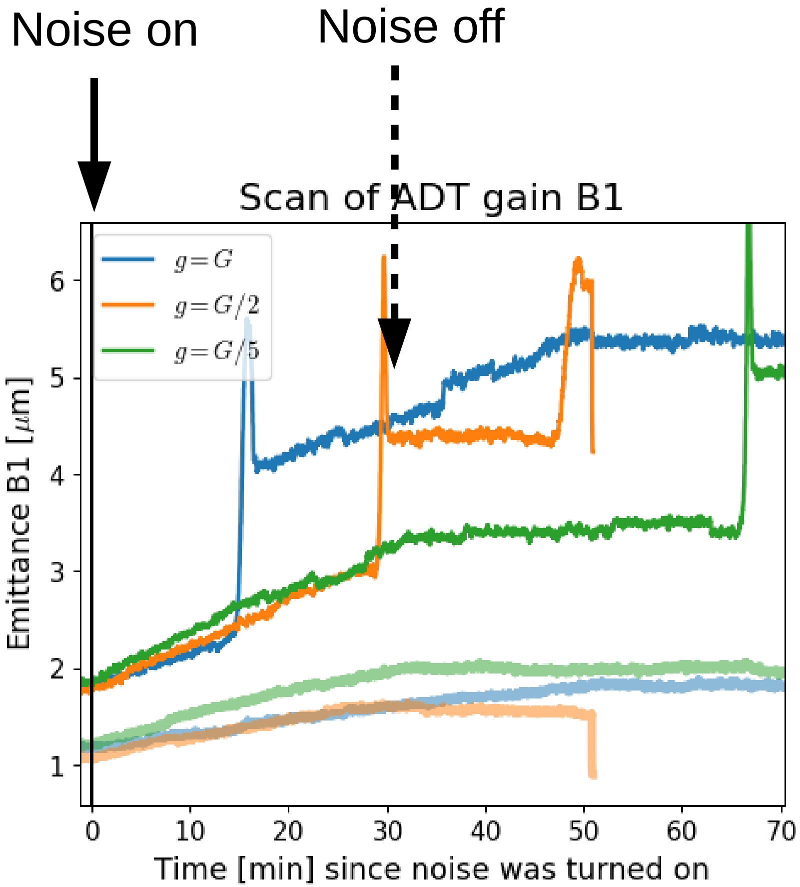
- As expected the latency increases with the octupole current, quantitative comparison to be finalised
- The effect of the chromaticity remains to be understood, with Q'~0 the beam is unstable without additional noise
  - Is it due to a stronger sensitivity to the machine noise, or another mechanism ?

Conclusion

- External sources of noise can significantly compromise the beam stability, with latencies of several minutes
  - In dynamical processes (e.g. collapse of the separation bumps), the noise does not impact the required stability margin if the latency is longer than the process (see backup)
- The effect of an external source of noise on the beam stability observed in simulation could be reproduced in dedicated experimental studies at the LHC
  - Some observations remain to be understood (see backup)
- The postulated mechanism L2D2 couldn't be verified with BTF measurements up to now
- New theoretical developments are ongoing, they are needed to gain confidence in the extrapolation to HL-LHC, in particular to :
  - Confirm that the low-noise pickup upgrade of the ADT is sufficient to ensure the beam stability in the HL-LHC
  - Verify that the current tolerances for the noise amplitude of new devices are sufficient not to jeopardise the beam stability
  - Possibly determine optimal settings to minimise this effect (chromaticity, ADT gain / filter algorithm, process length, tune, ...)

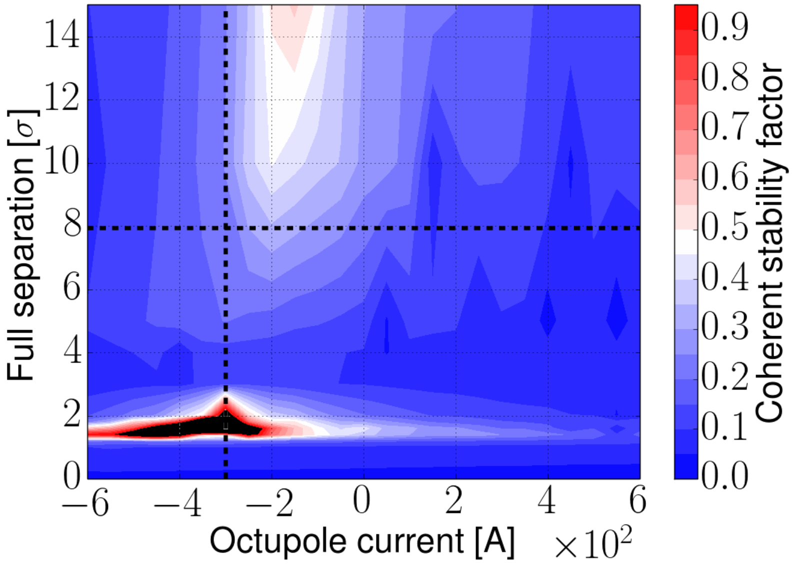
Damper gain scan

- With a lower ADT gain, the latencies were longer
  - Only the bunches with strongest noise became unstable in a reasonable amount of time
- This feature is not compatible with simulations and remains to be understood



Separation scans (In collaboration with S. Fartoukh)

Based on the stability diagram of
PACMAN bunches (MAD'n'PySSD + DELPHI)



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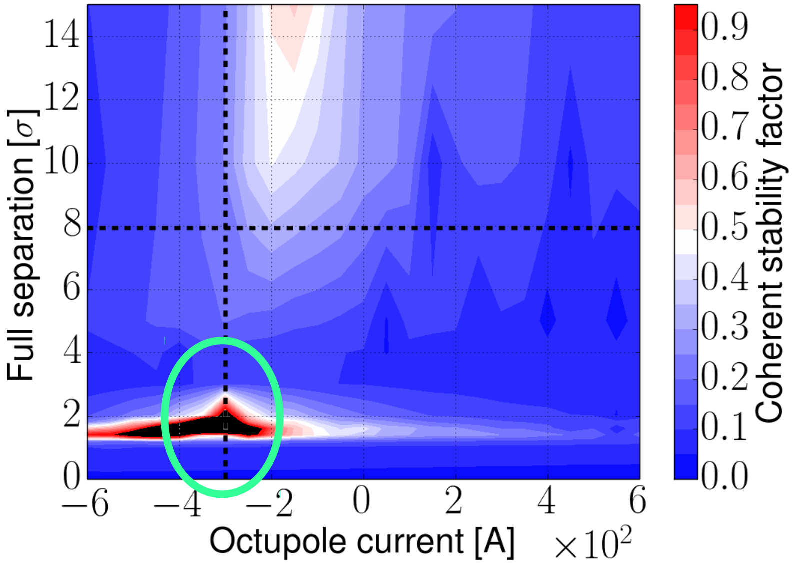

- When colliding with an offset at the IP (in the MD configuration) the PACMAN bunches are expected to loss Landau damping around 1.5 σ

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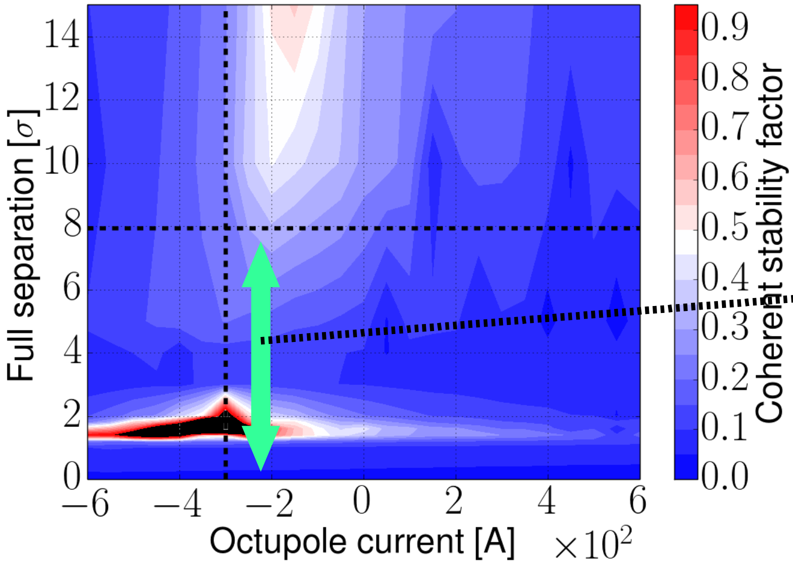

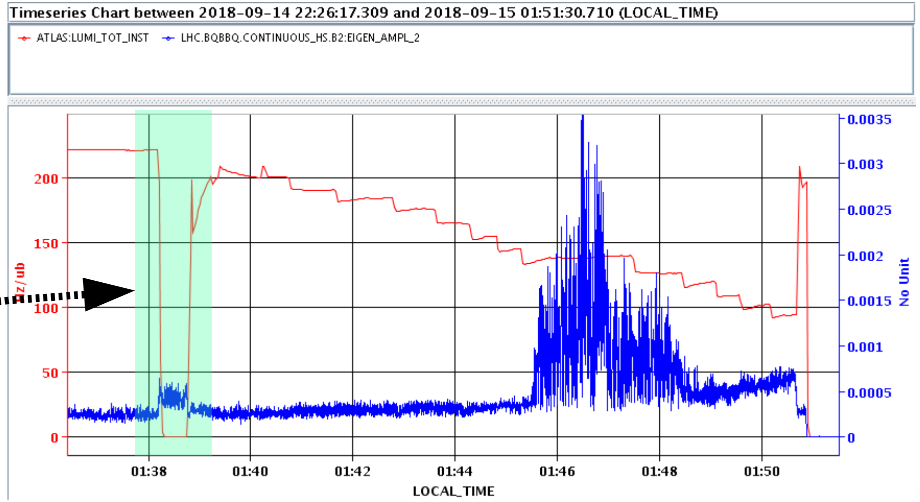

- When colliding with an offset at the IP (in the MD configuration) the PACMAN bunches are expected to loss Landau damping around 1.5 σ
- Crossing this unstable configuration did not lead to an instability with the maximum bump speed

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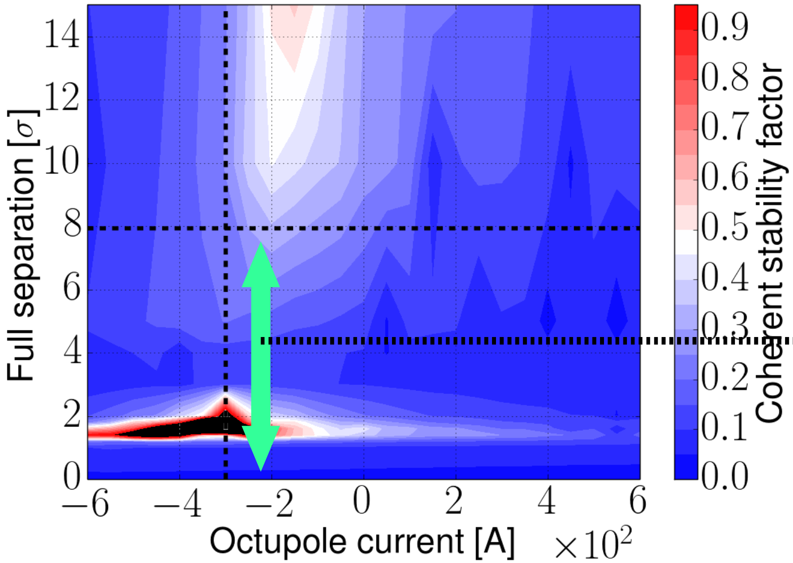

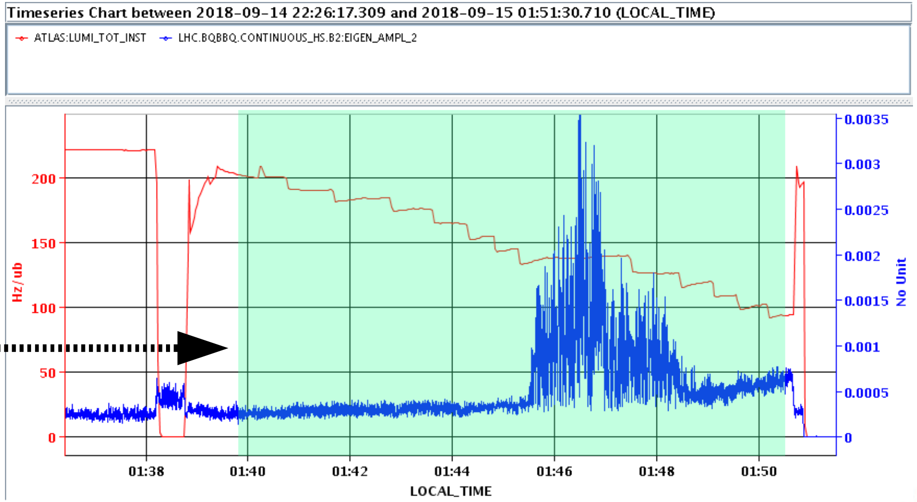

- When colliding with an offset at the IP (in the MD configuration) the PACMAN bunches are expected to loss Landau damping around 1.5 σ
- Crossing this unstable configuration did not lead to an instability with the maximum bump speed
- The instability is visible only when performing a slow scan (→ luminosity levelling)