# The impact of noise on beam stability

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

* EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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

WP2 meeting – 11.10.2018

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

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# Motivation


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

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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)

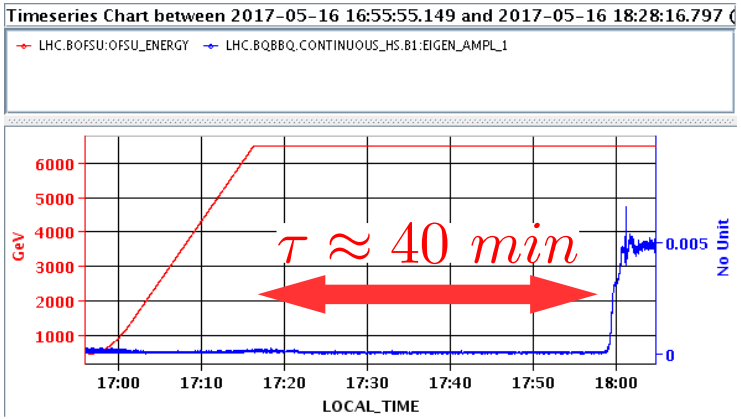
  - The direct measurements of the impedance do not show such a discrepancy

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

# Instability latency

- On few occasions, one of the LHC beam was left steady (non-colliding), leading to an instability after a long latency
- To our best knowledge, these instability cannot be explained with machine or beam parameter variations

Fill 5664, 2017



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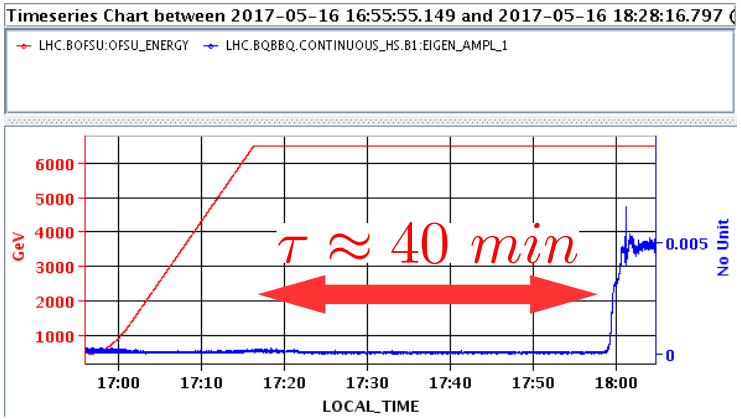


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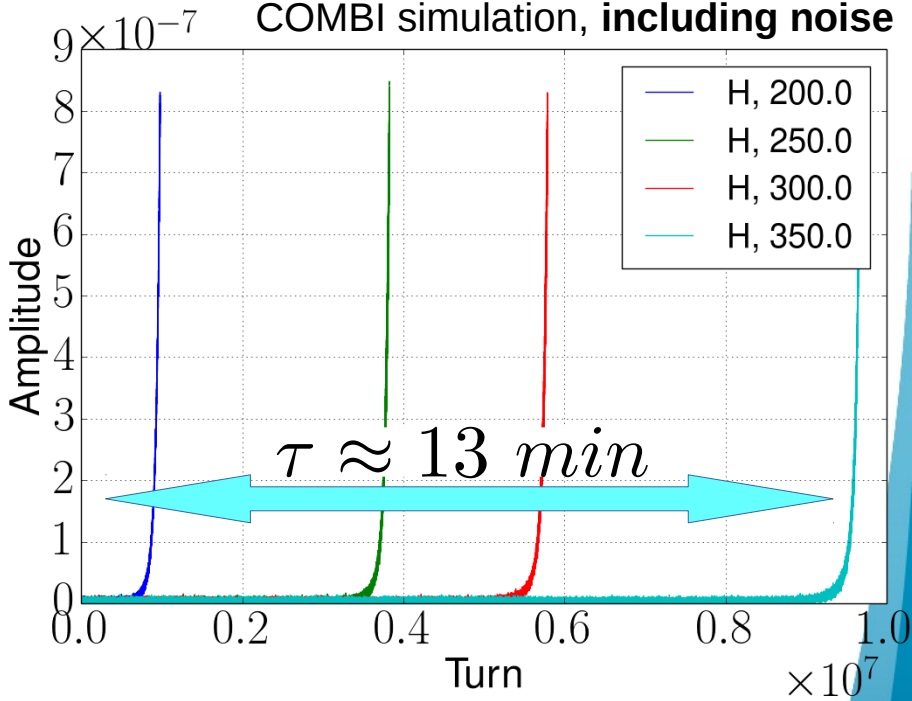
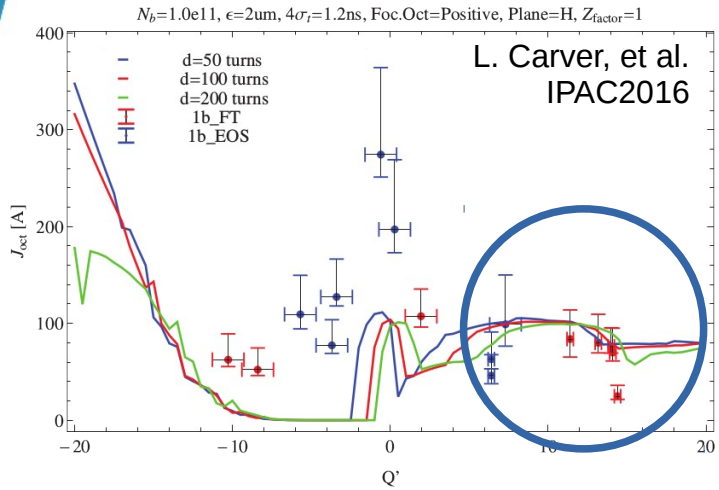



- Such an instability mechanism with latency can be reproduced in macroparticle simulations, including an external source of noise

# Measured thresold vs. operational threshold

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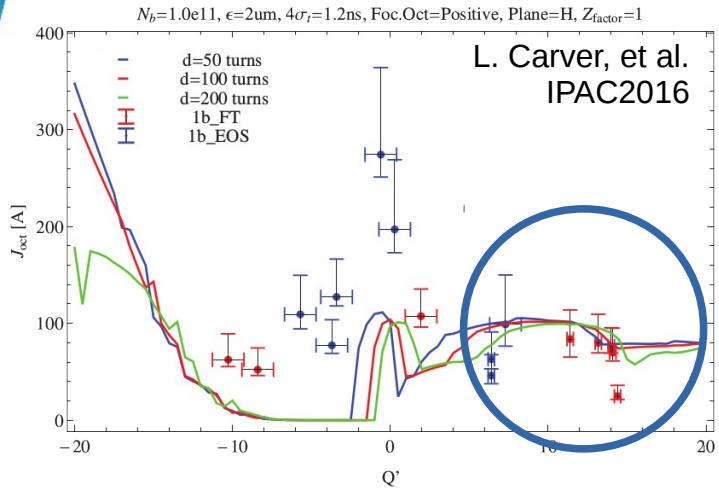


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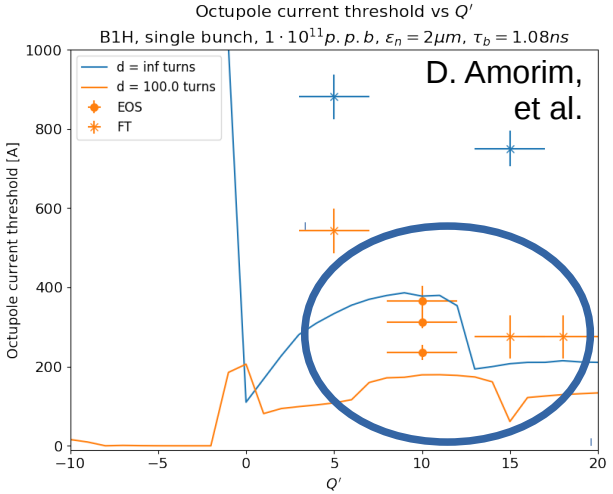


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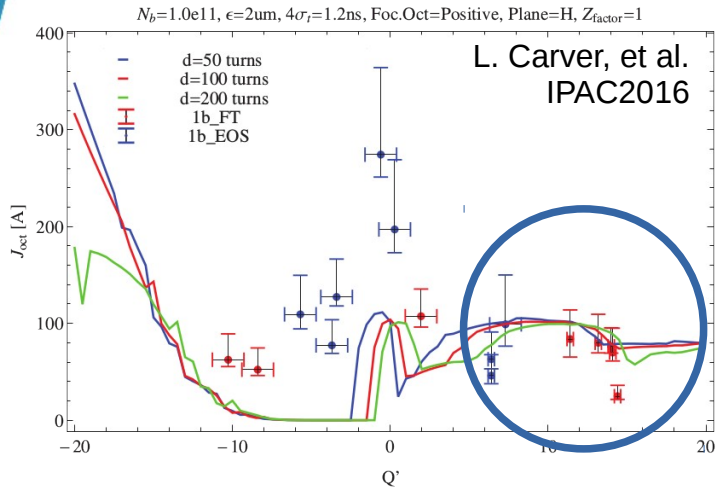


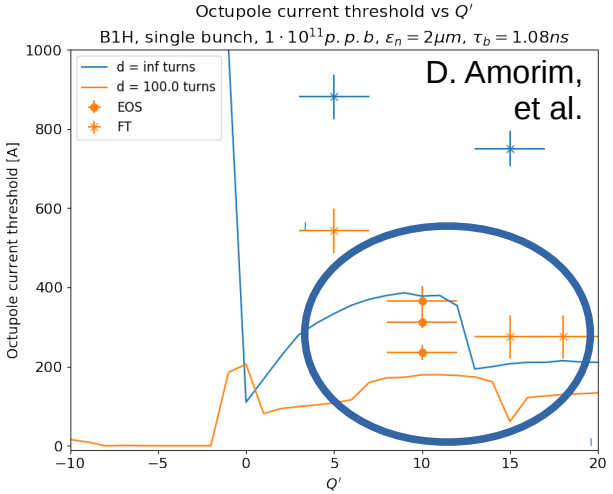


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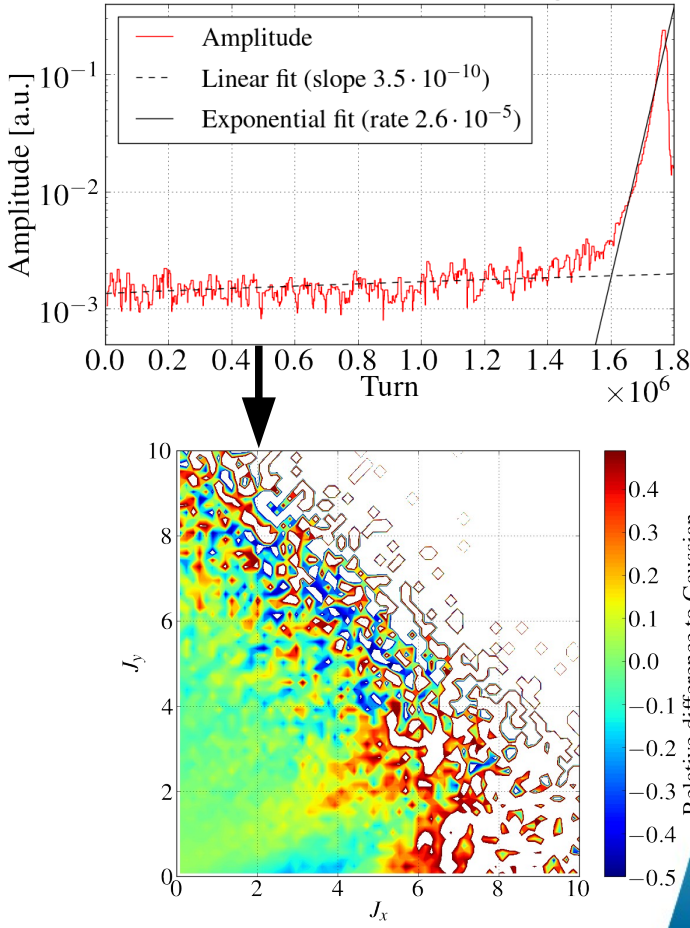
→ Even without understanding of the mechanism, it is clear that the **latency** plays an important role in the instability threshold

# Postulating a mechanism

COMBI simulation, **including noise**

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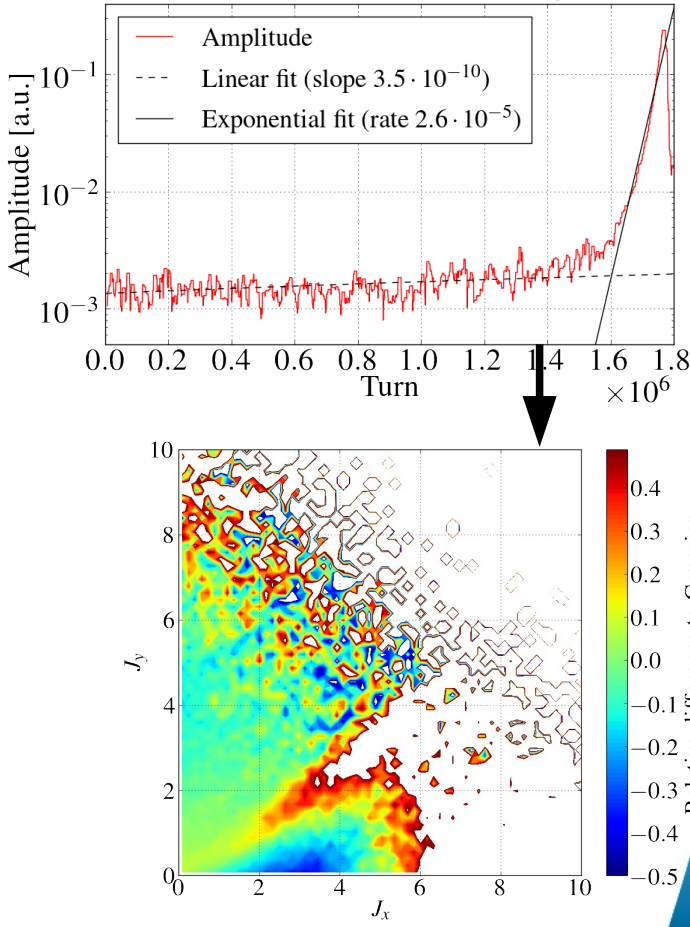


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- Diffusion mechanisms (noise, non-linear resonances) result in a modification of the beam distribution and consequently of Landau damping* → **Loss of Landau damping driven by Diffusion** (L2D2)
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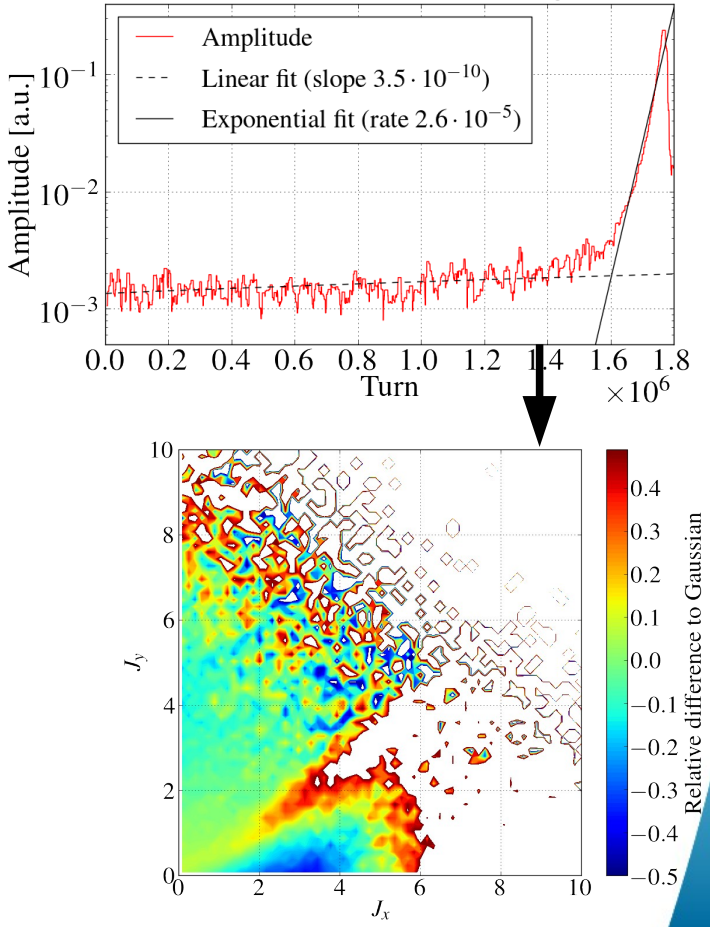


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  - → Today we address this mechanism through multiparticle tracking simulations, including a tune spread and an external noise source
- The direct measurement of the distortion of the stability diagram through beam transfer function remains a challenge***

→ A **novel experimental approach** was needed to study this phenomenon

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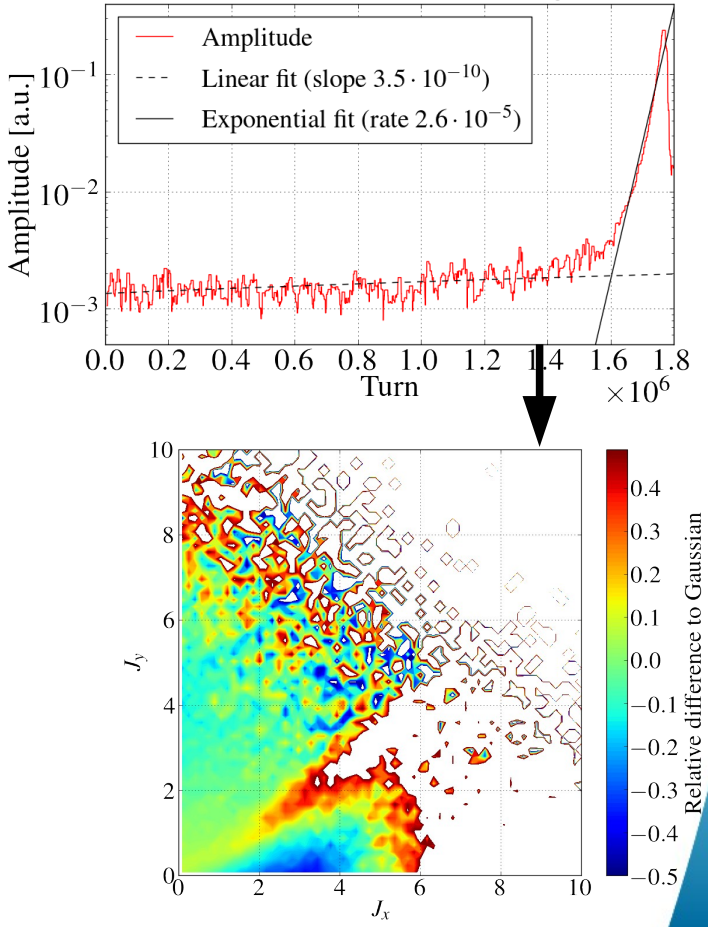


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# Noise amplitude

## Numerical setup (COMBI) :

- Linear transfer map with transverse amplitude detuning (octupoles) and chromaticity
- *Perfect* damper
- Wake fields
- Gaussian white (up to 400MHz) transverse noise with r.m.s. amplitude δ
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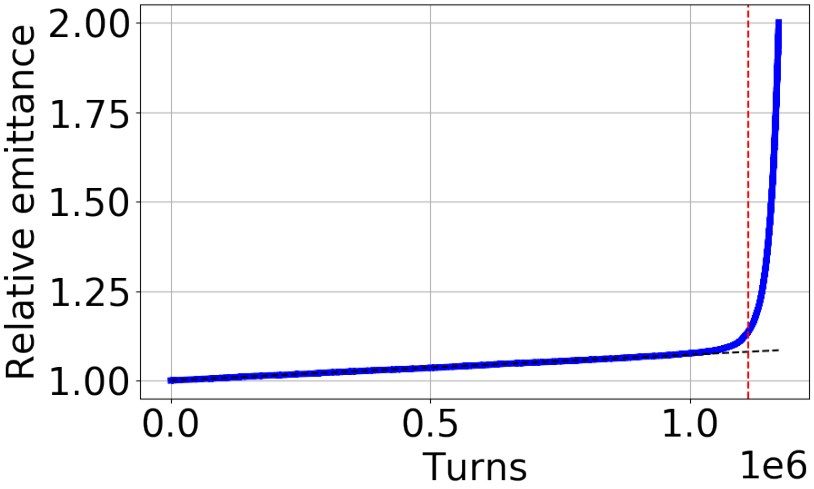

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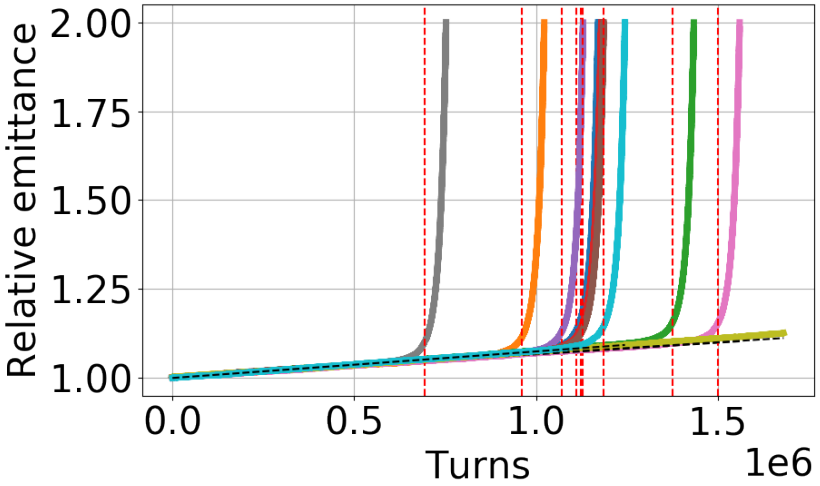

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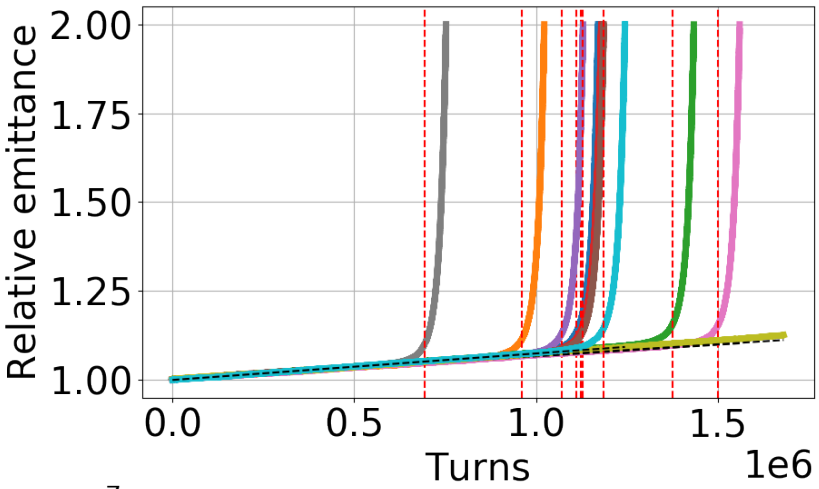


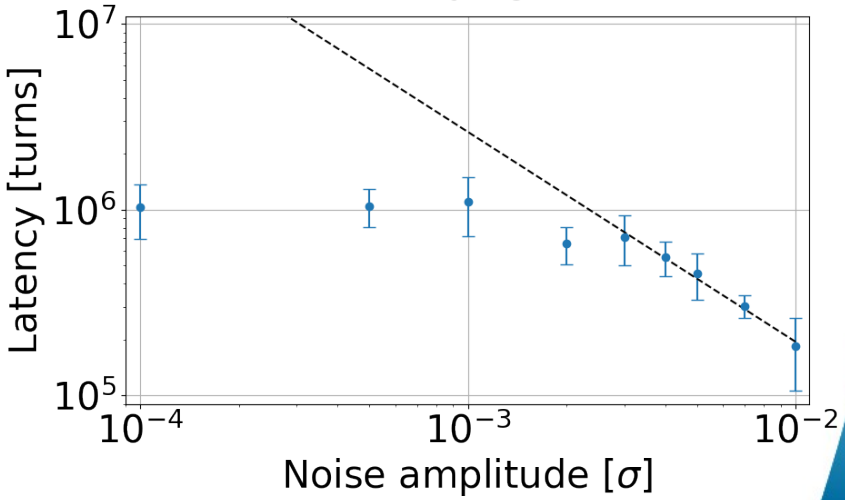

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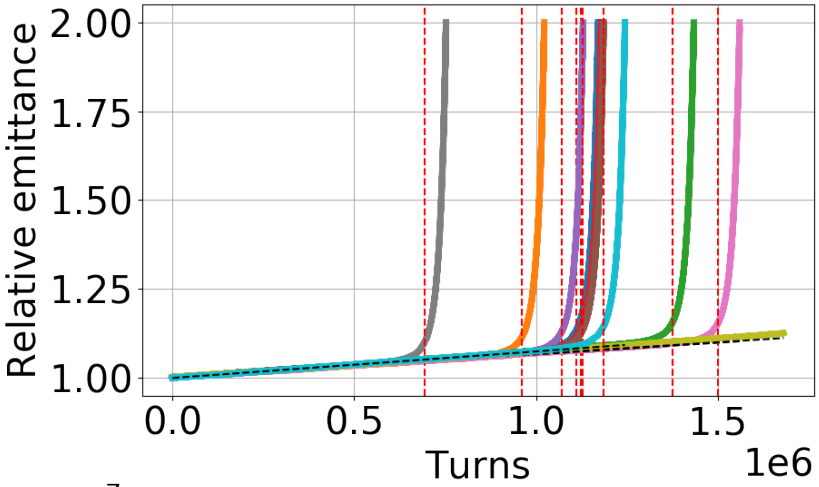


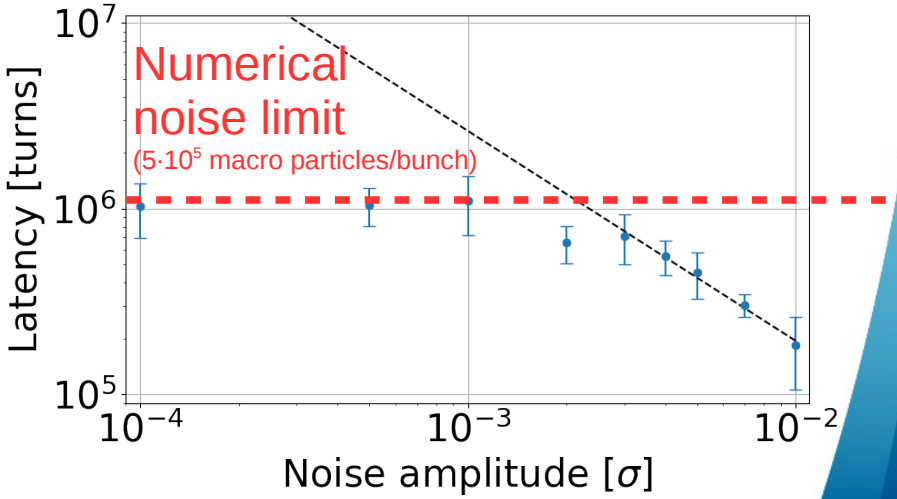

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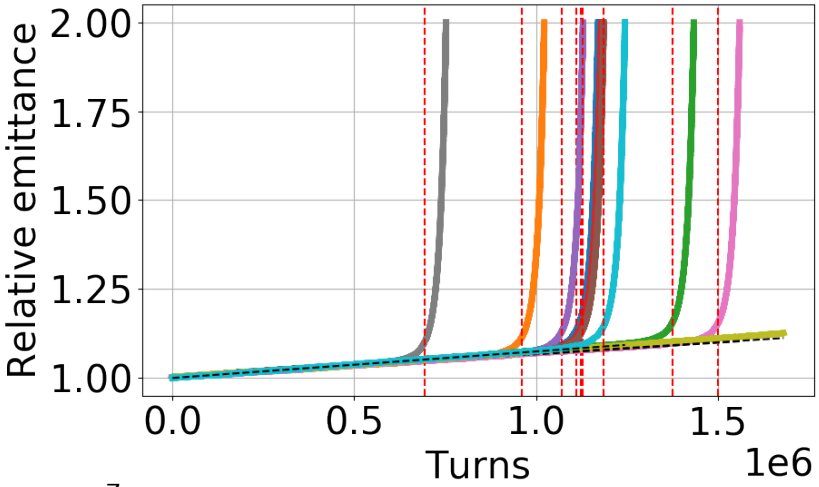
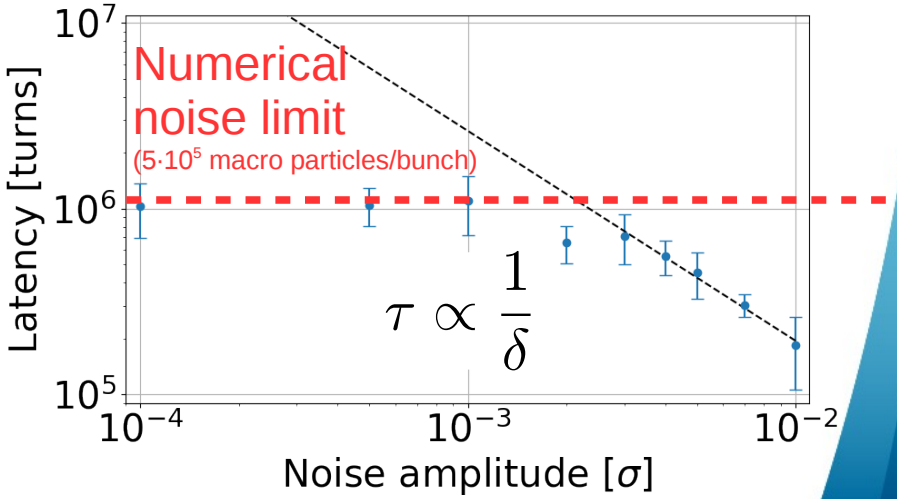
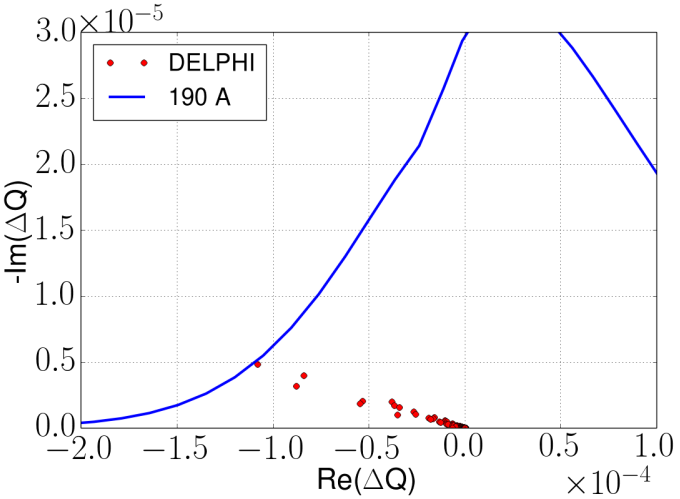
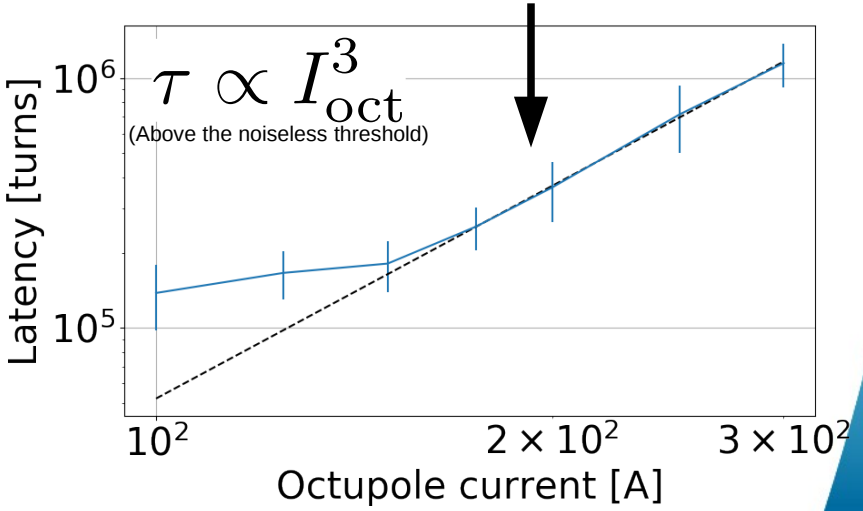


# Octupole strength

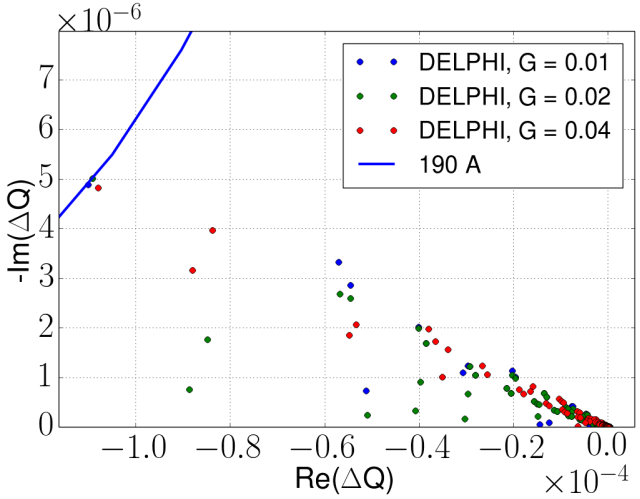
- The presence of an external source of noise leads to long latencies for octupole current larger than the theoretical threshold
  - Even for current a **factor 2** larger than needed without noise, latencies of several minutes are expected

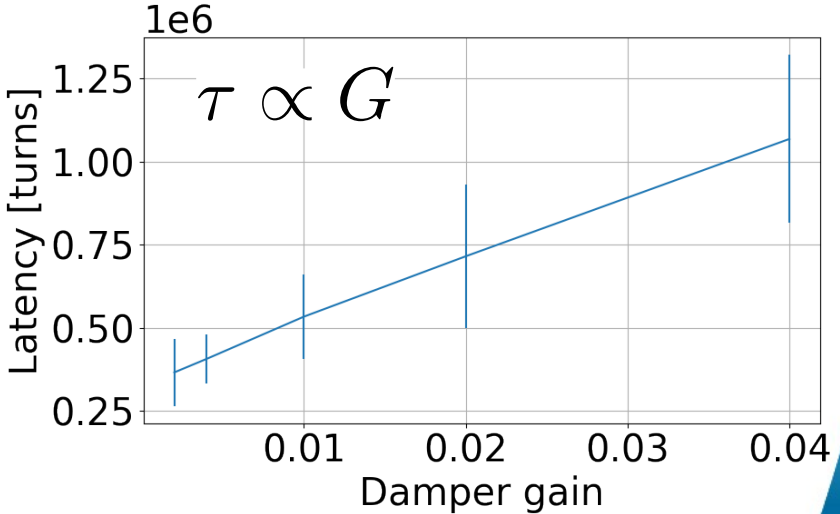


# Damper gain

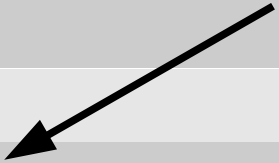
- The stability threshold is almost independent of the gain in the *high-gain regime*
- An *ideal* transverse feedback mitigates the effect of the noise, leading to longer latencies



# Extrapolations

| | COMBI | LHC flat top (single non-colliding bunch) |
|---|---|---|
| Octupole current [A] | 300 | **2***190 |
| Gain | 0.02 | 0.005 |
| Delta | $3 \cdot 10^{-3}$ | $5 \cdot 10^{-5}$ |
| Latency [$10^6$ turns] ([min]) | 1.14 (1.7) | |



Coarse estimation based on the emittance growth in collision (CERN-ACC-NOTE-2018-0036)

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$$\tau \propto \frac{I_{\mathrm{oct}}^3 G}{\delta}$$

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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, ...)

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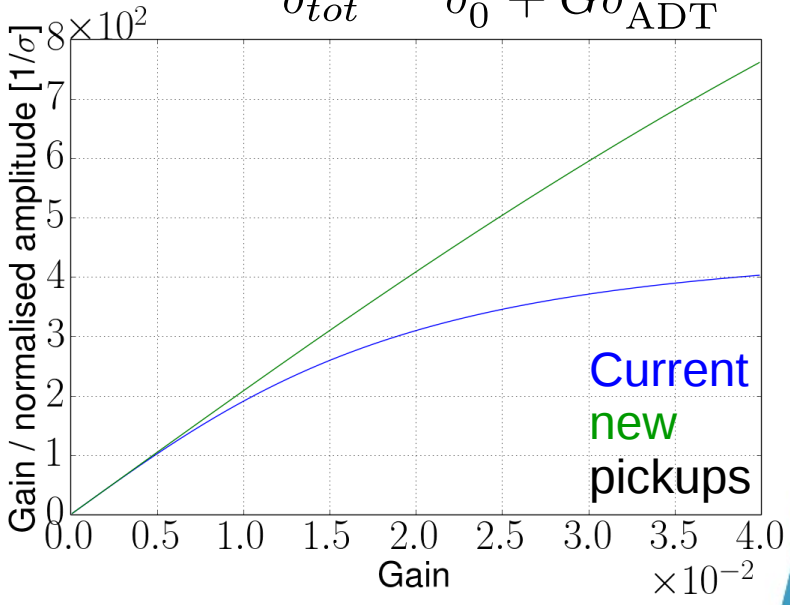
# Expected benefit of the ADT pickup electronic upgrade

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



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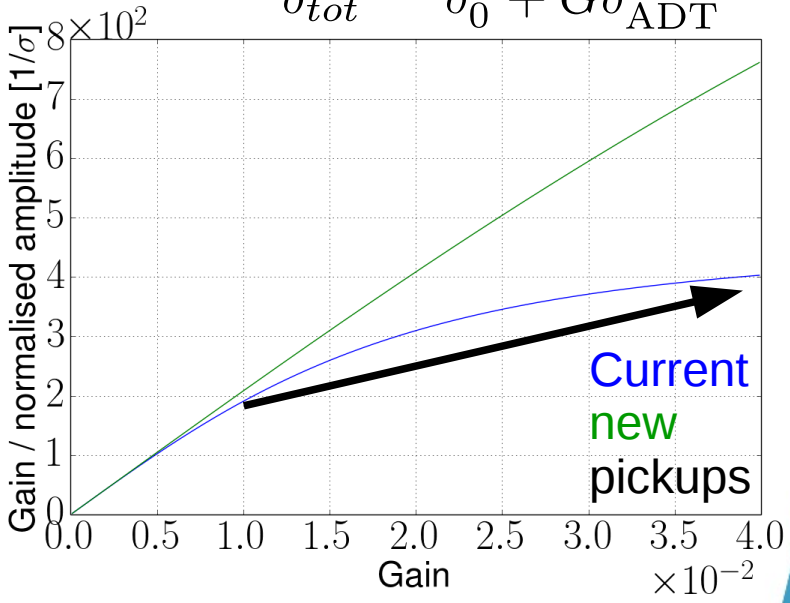

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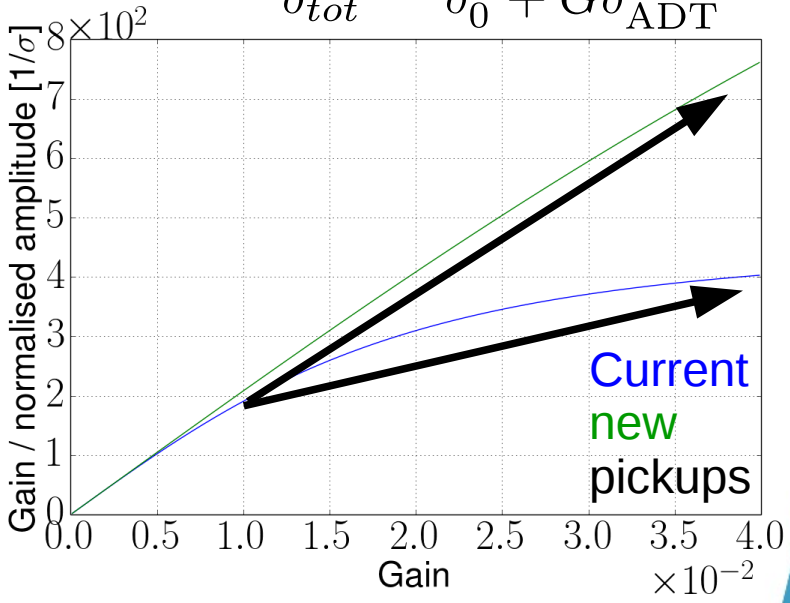

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  → To be verified experimentally

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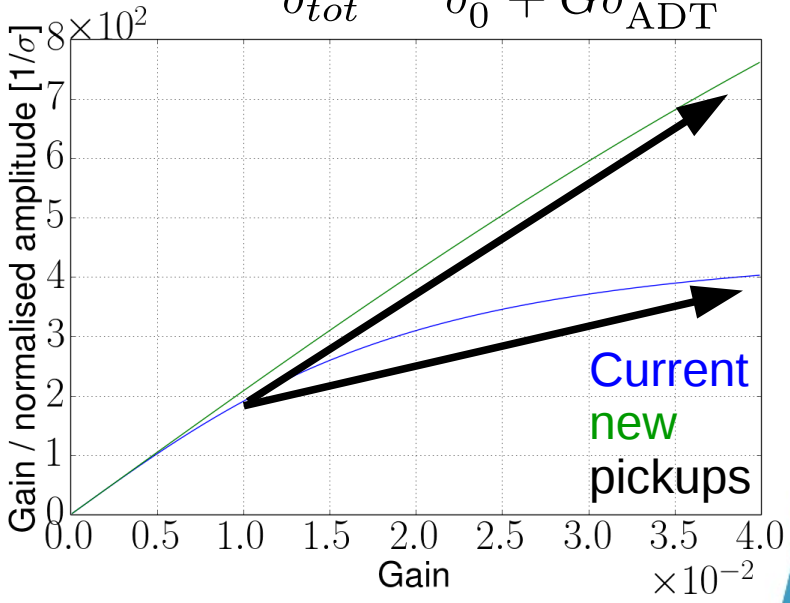
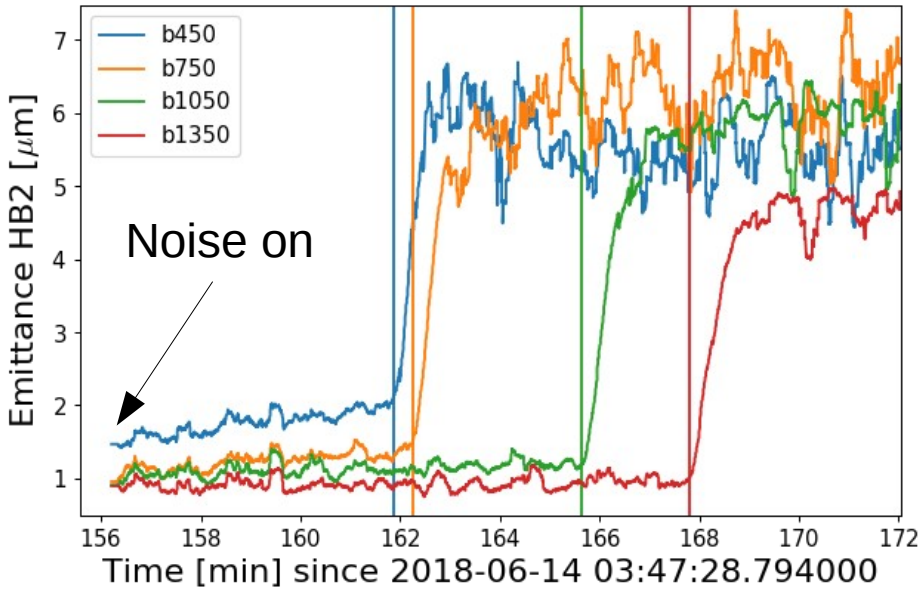


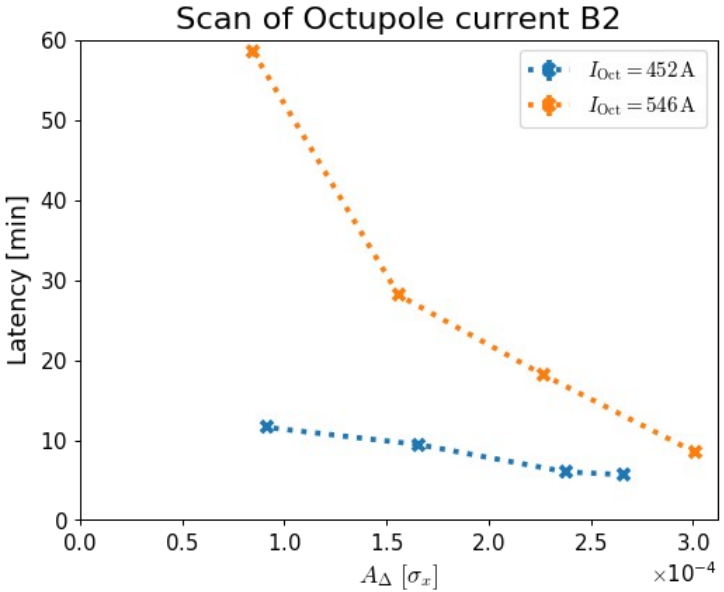
# Experimental test with artificial noise




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

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

# Octupole and chromaticity scans

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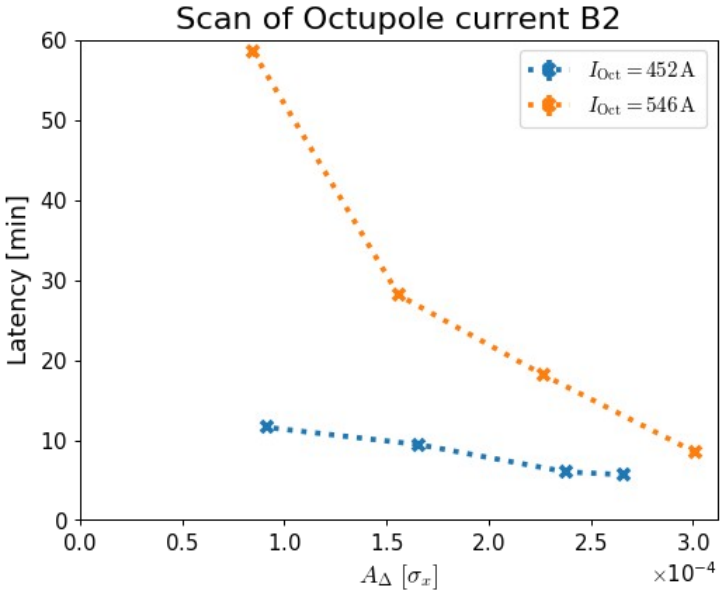


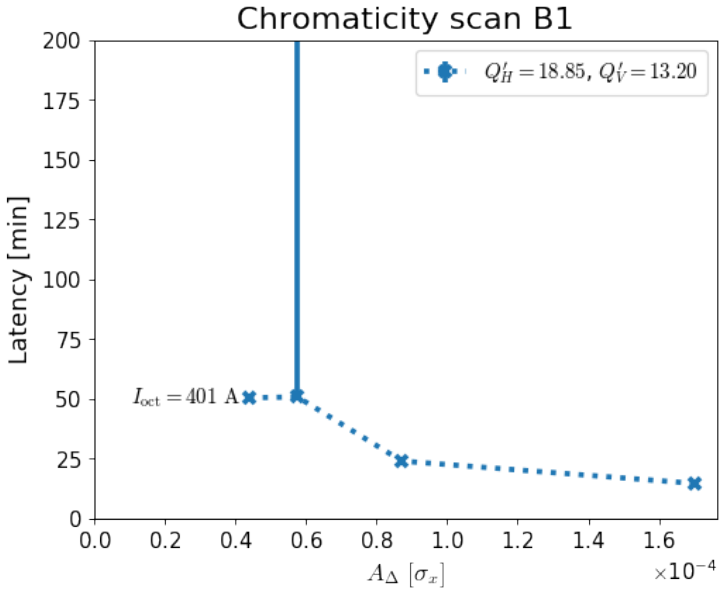


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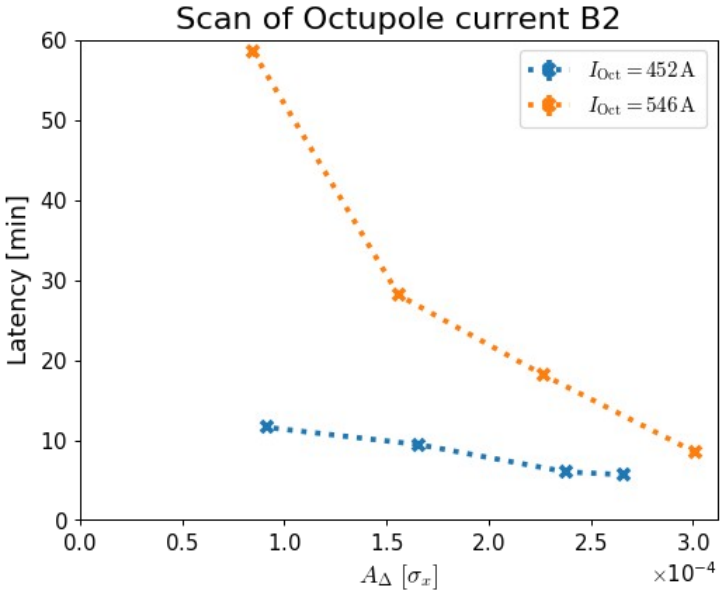


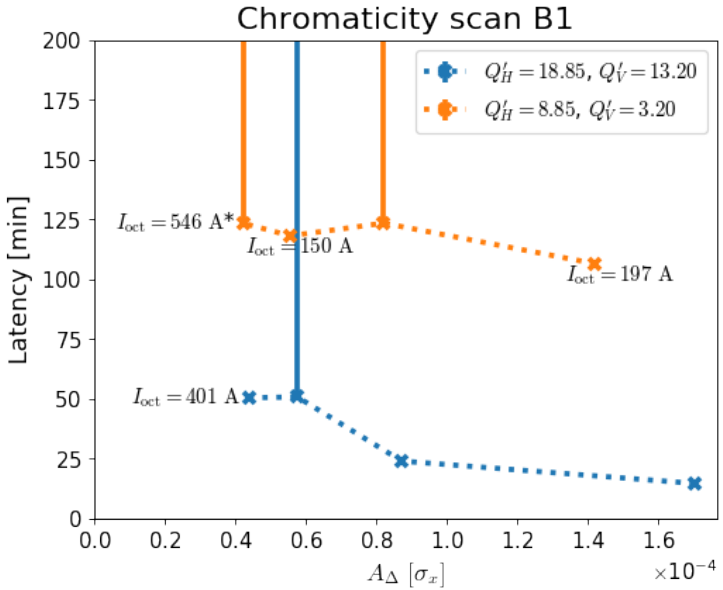


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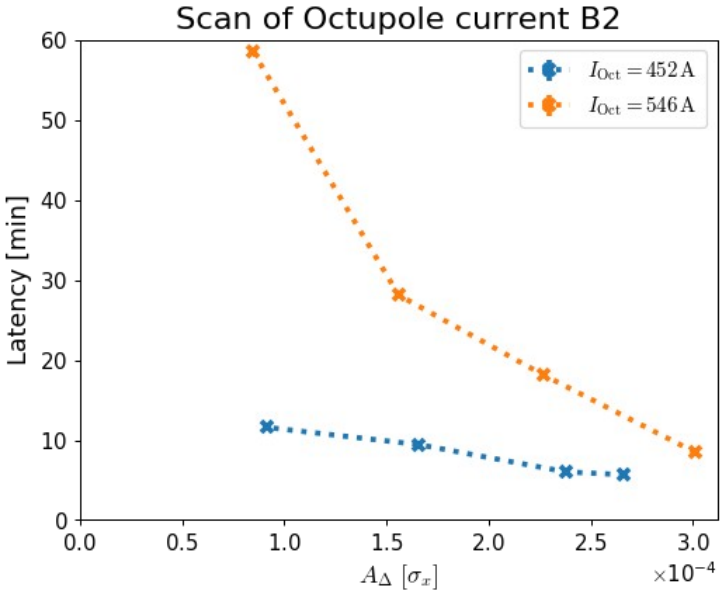
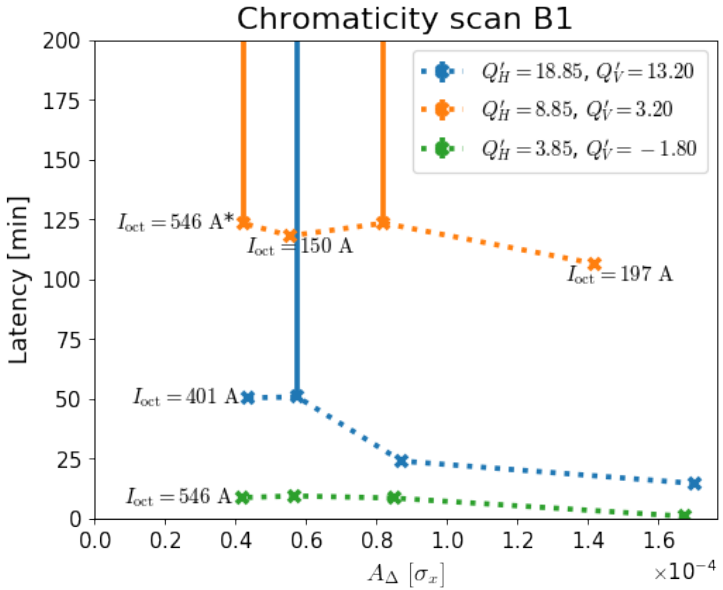
# Octupole and chromaticity scans



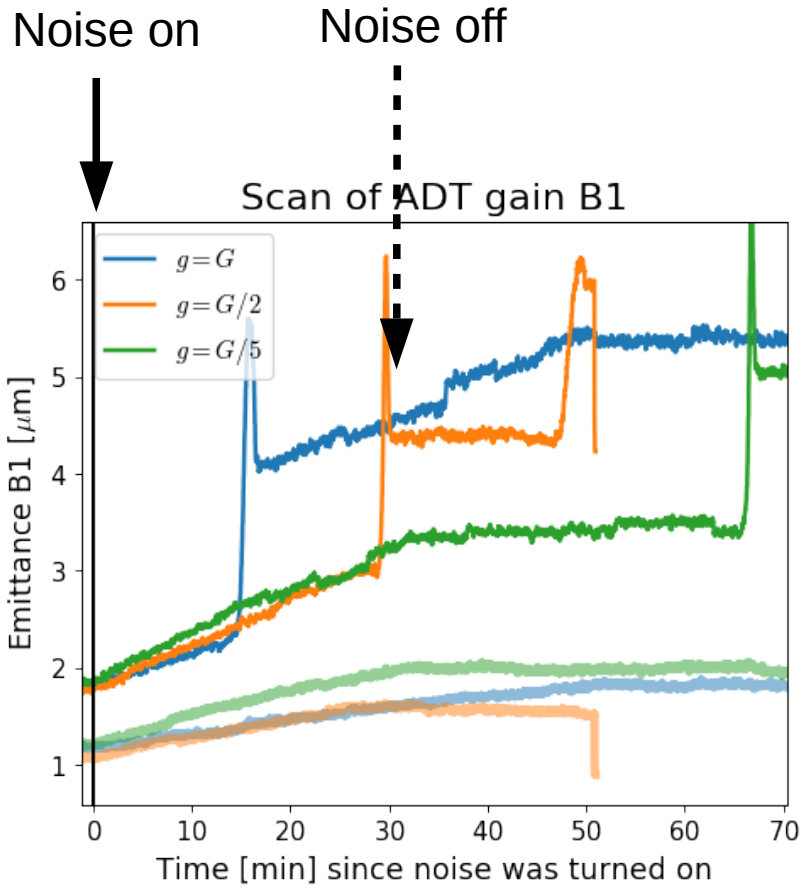

- As expected the latency increases with the octupole current, quantitative comparison to be finalised
- The effect of the chromaticity remains to be understood, with Q'~0 the beam is unstable without additional noise
  - Is it due to a stronger sensitivity to the machine noise, or another mechanism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

# 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, tune, ...)

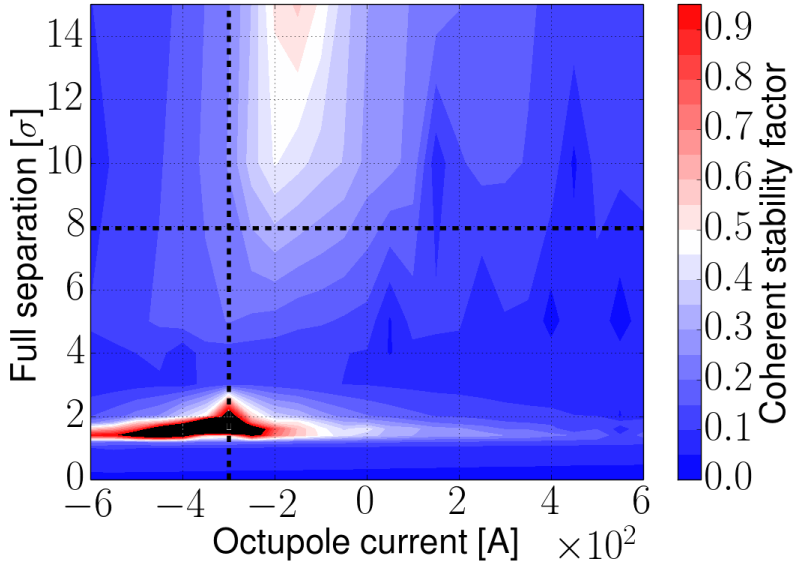
# Damper gain scan

- 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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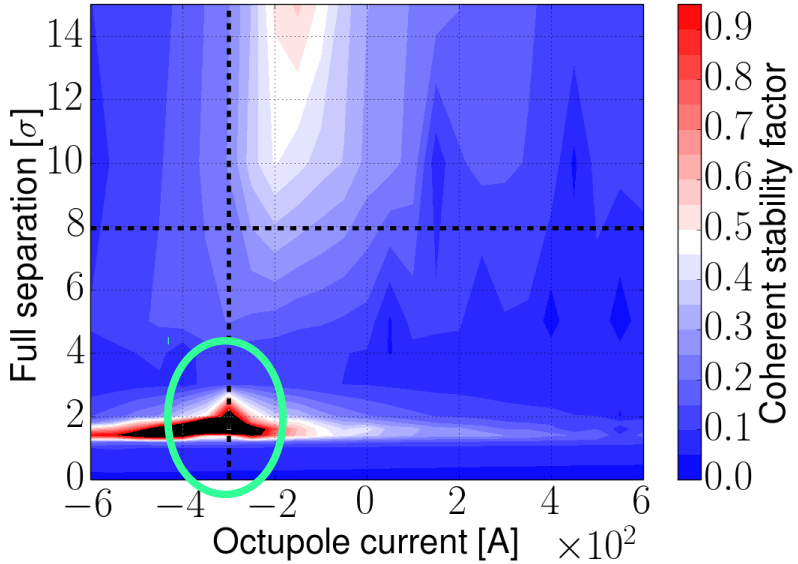


- When colliding with an offset at the IP (in the MD configuration) the PACMAN bunches are expected to loss Landau damping around 1.5 σ

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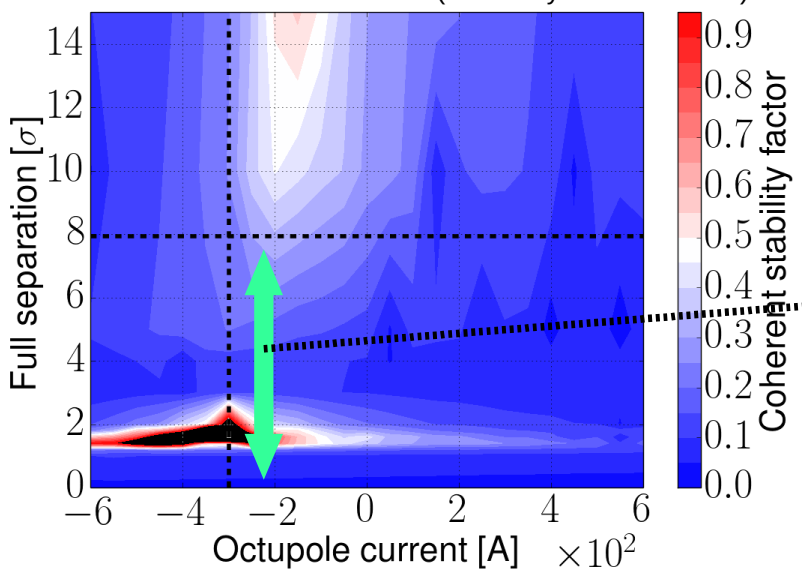


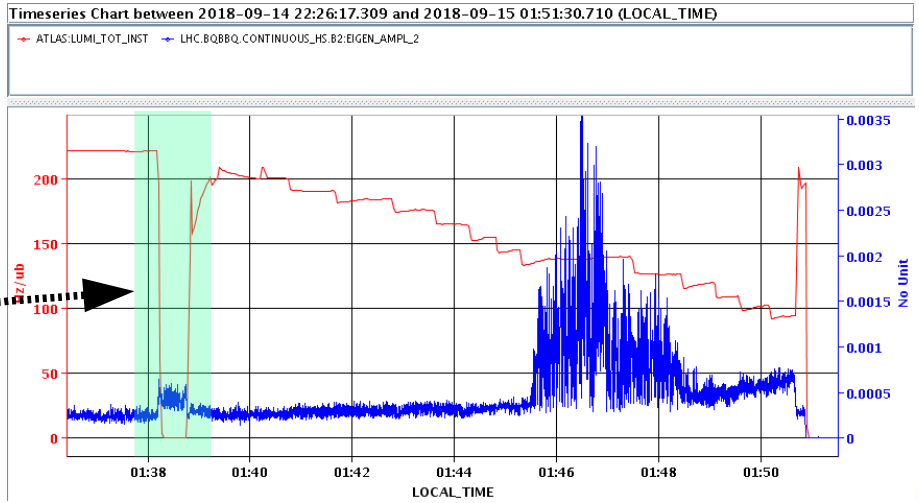


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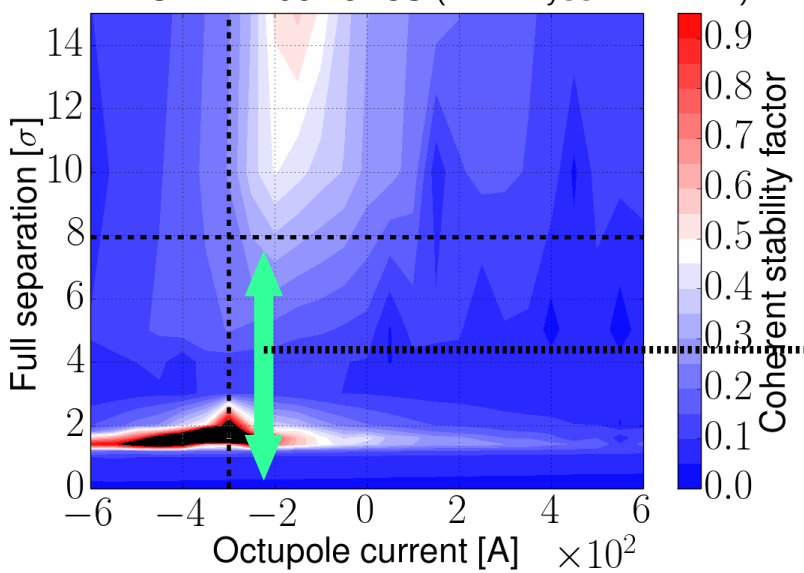


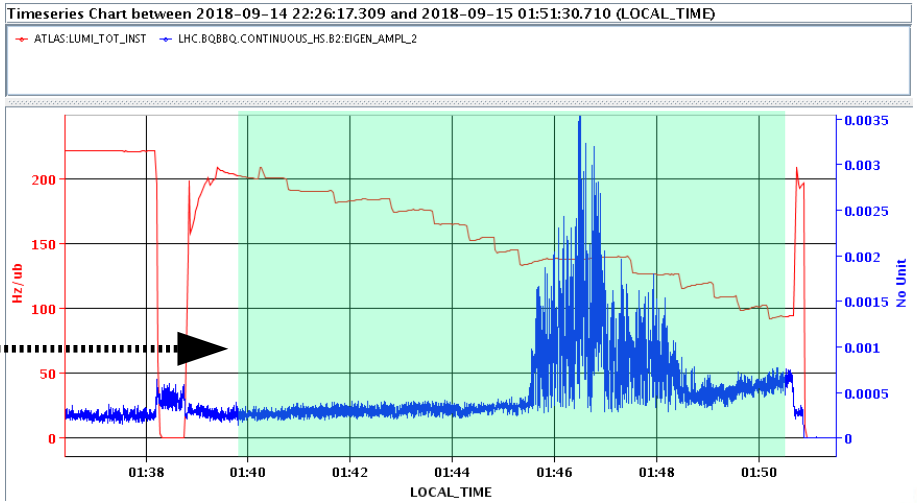


- When colliding with an offset at the IP (in the MD configuration) the PACMAN bunches are expected to loss Landau damping around 1.5 σ
- Crossing this unstable configuration did not lead to an instability with the maximum bump speed
- The instability is visible only when performing a slow scan (→ luminosity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