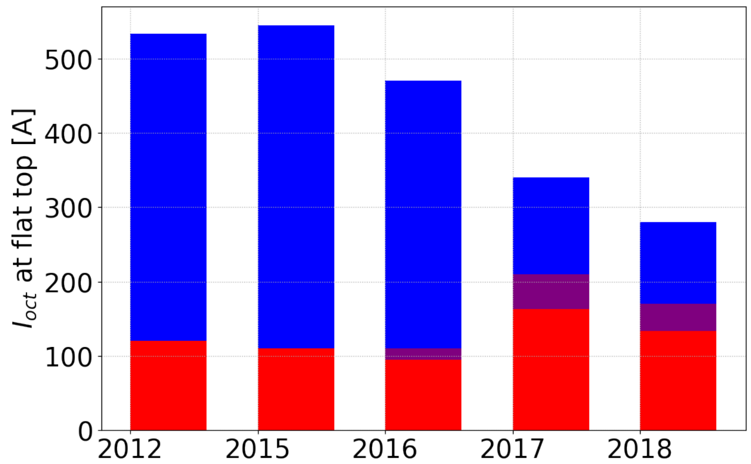
Collective effect LHC-MDs in Run3

X.Buffat, S.A. Antipov, D. Amorim, N. Biancacci, S.V. Furuseth, G. Iadarola,
E. Métral, N. Mounet, B. Salvant, C. Tambasco, T. Pieloni, C. Zannini

- Current knowledge and the missing bits
  - Impedance and instabilities
  - Related diagnostics
  - Decoherence
- Summary
  - Main goals of our MD program
  - Special requirements

Stability threshold



- The LHC profited from the large margins available in octupole current. These margins are significantly reduced for HL-LHC

  → A detailed understanding is required to operate the HL-LHC (octupole polarity, chromaticity and damper gain)

  → This understanding can also serve the optimisation of the LHC performance (lifetime, emittance growth)

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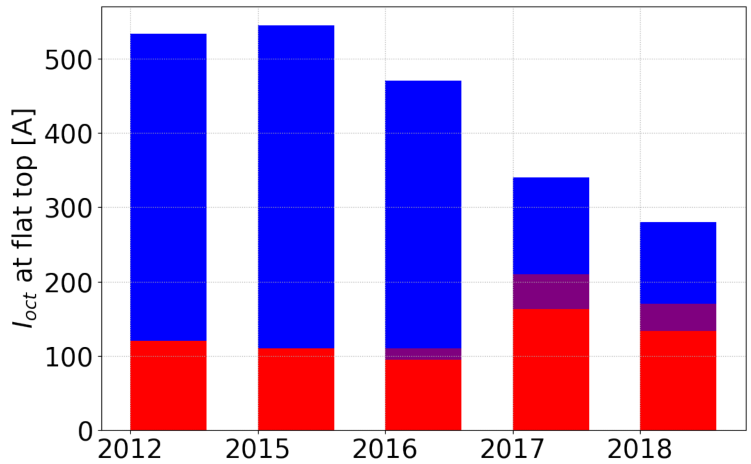

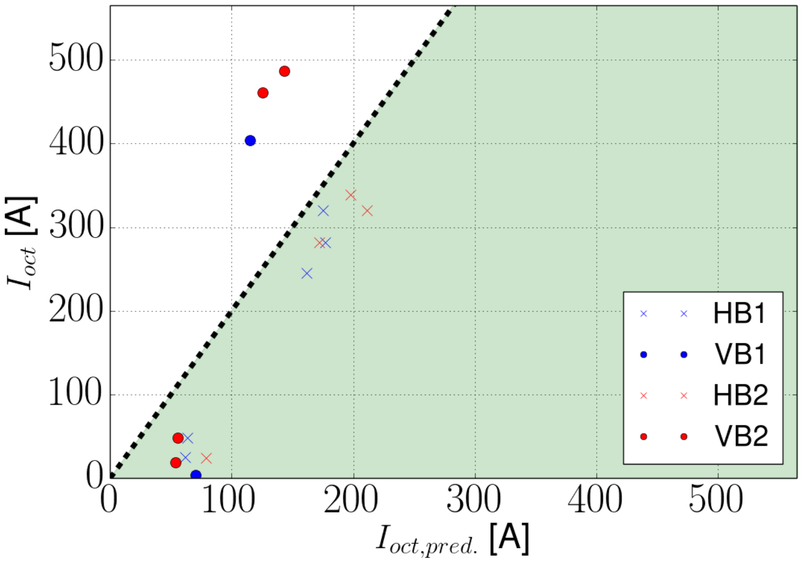

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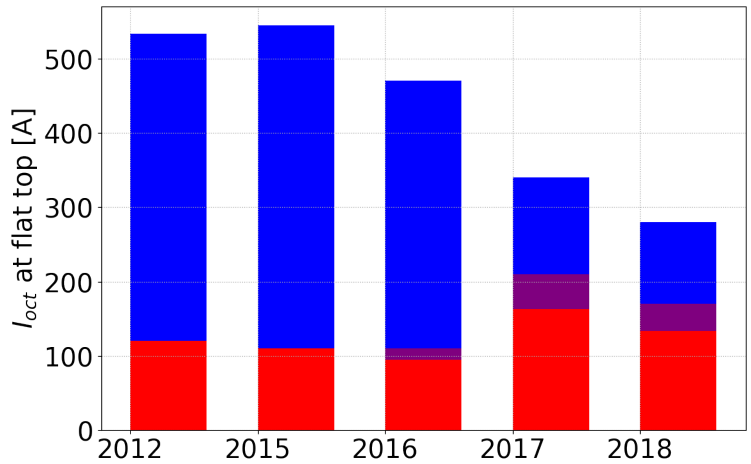

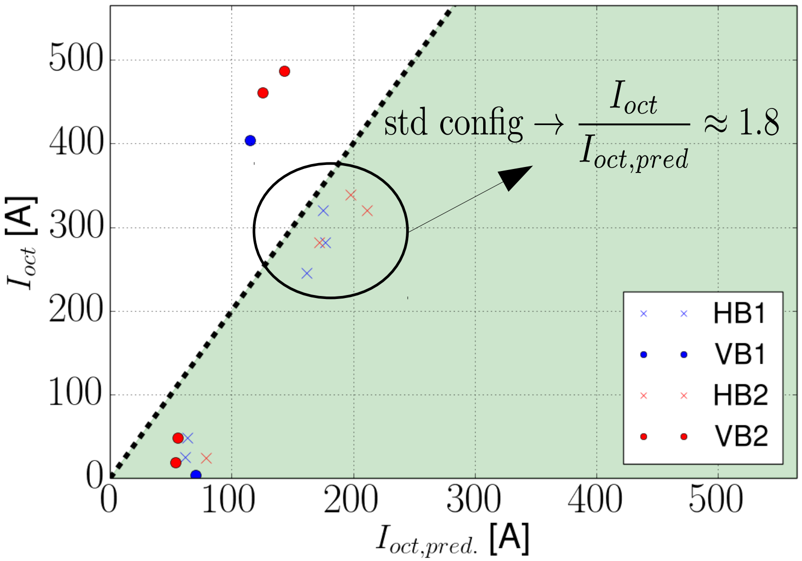

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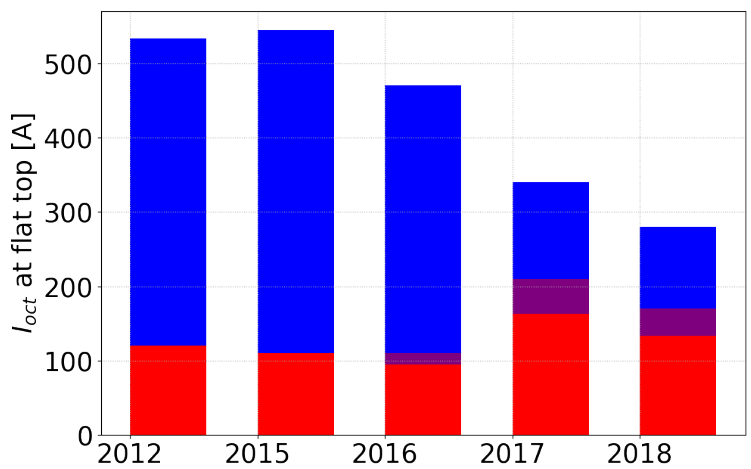

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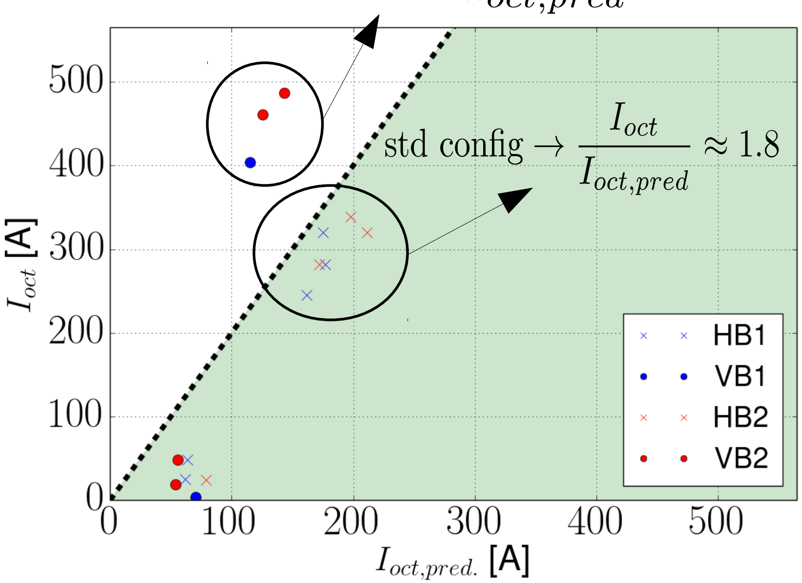

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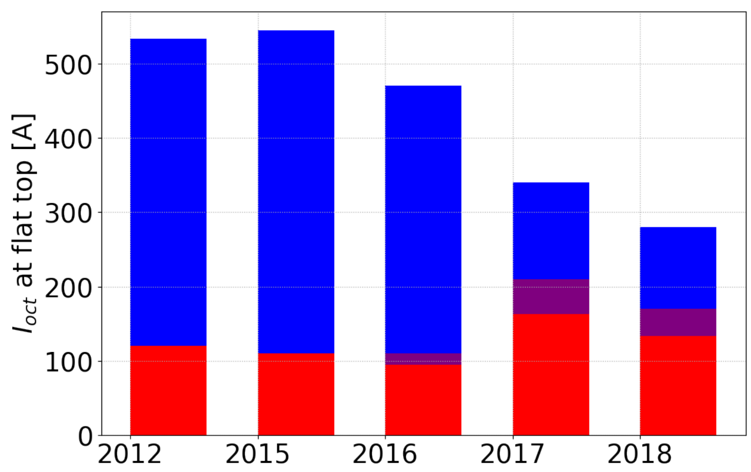

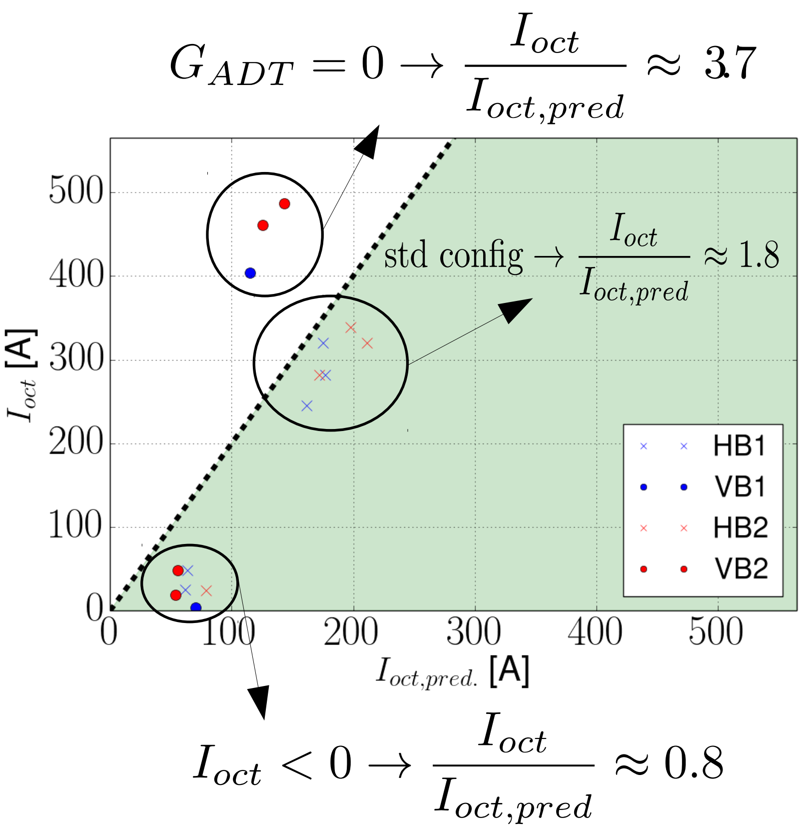

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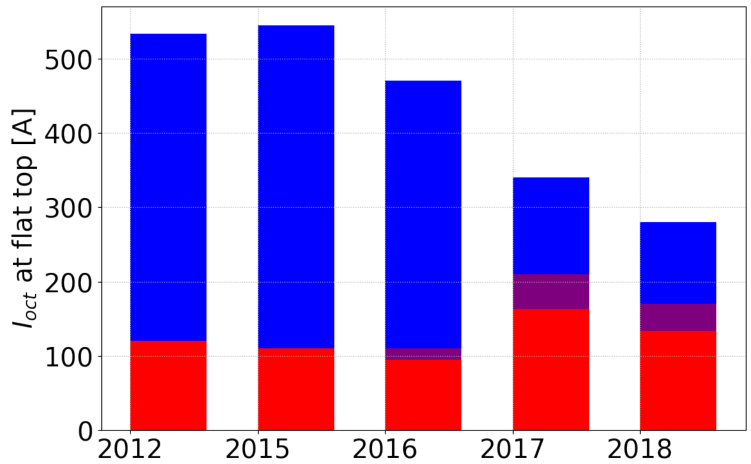

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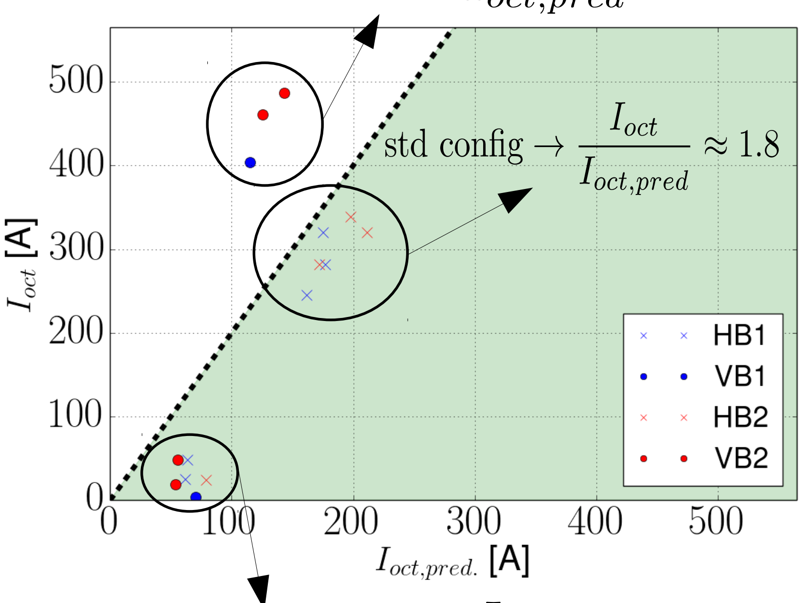

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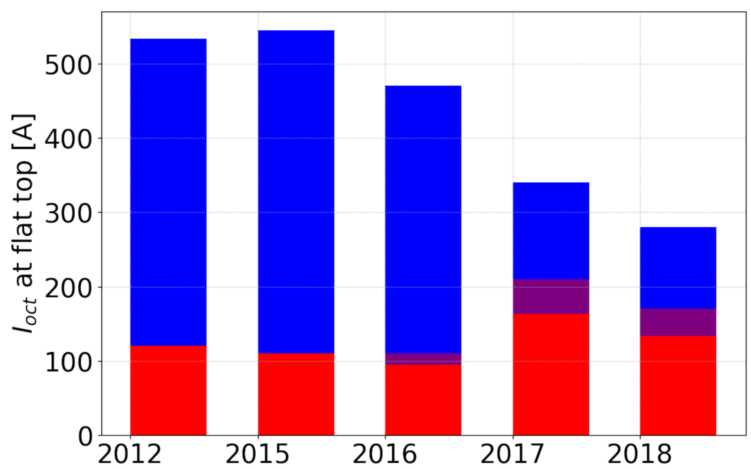

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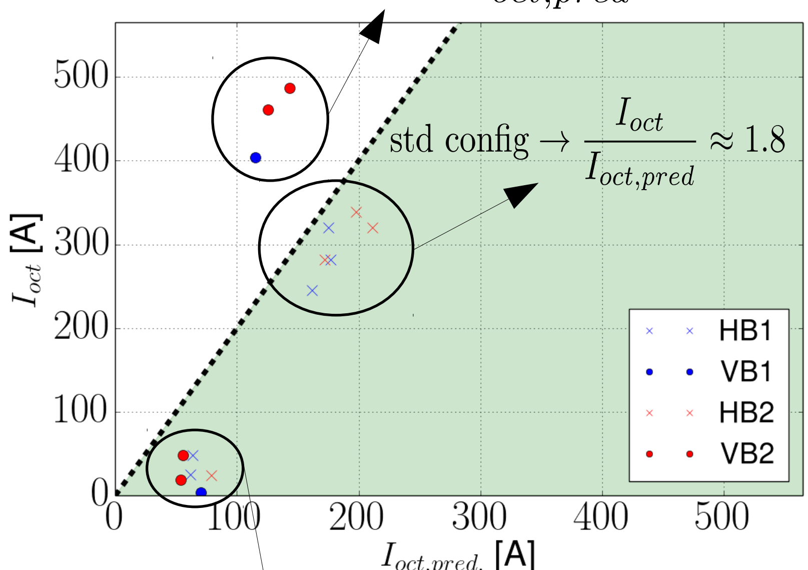

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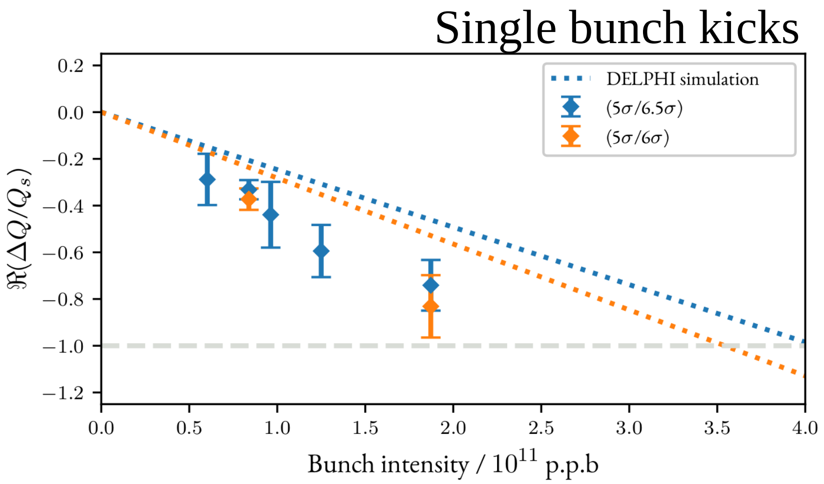
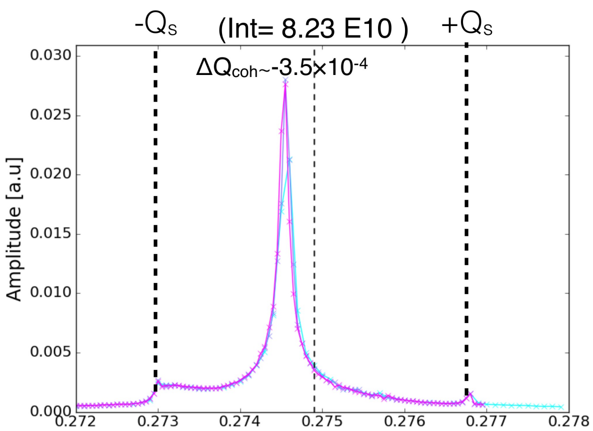
- We believe that the main missing pieces are:
  - **The uncertainty on the impedance model**
  - **The impact of noise on Landau damping**
- Study of alternative collimation scheme
  - Impedance-optimised IR7 optics
  - Asymmetric collimation
  - Impact of cut tails

Imaginary part of the impedance





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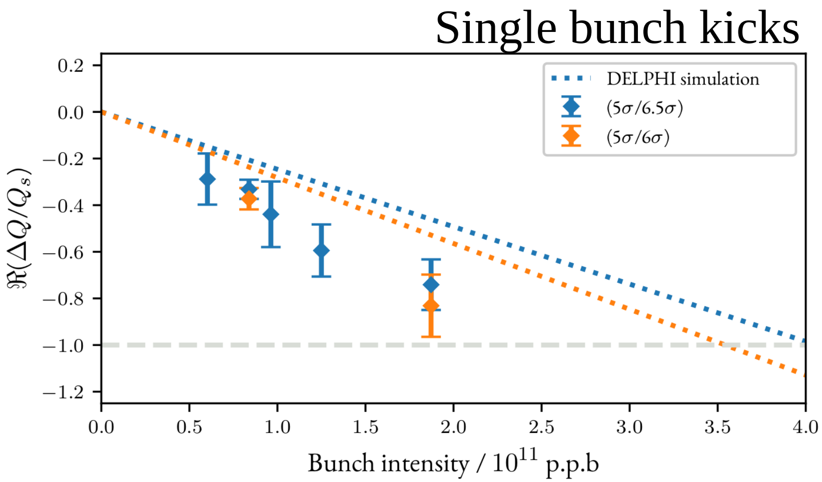

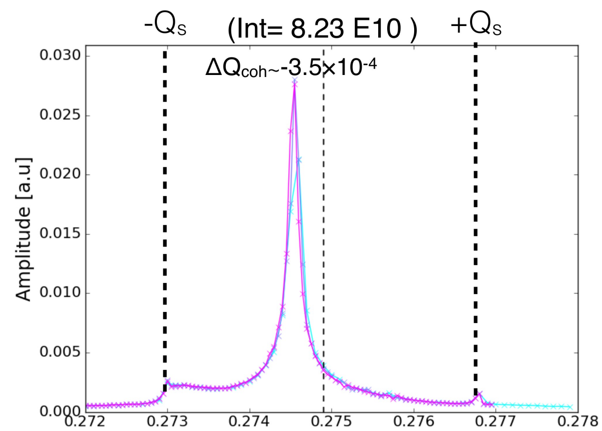

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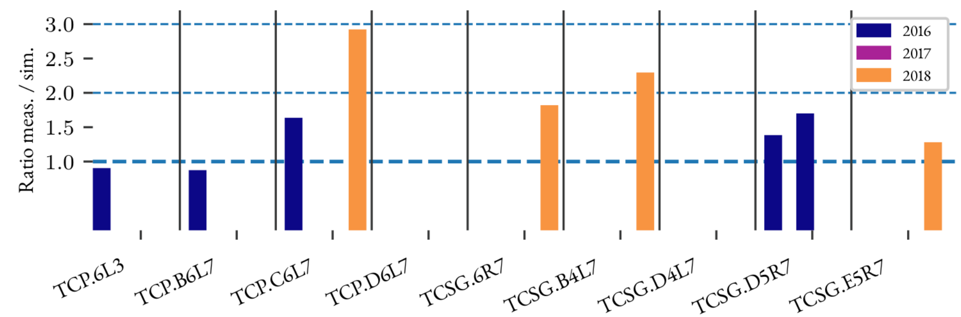

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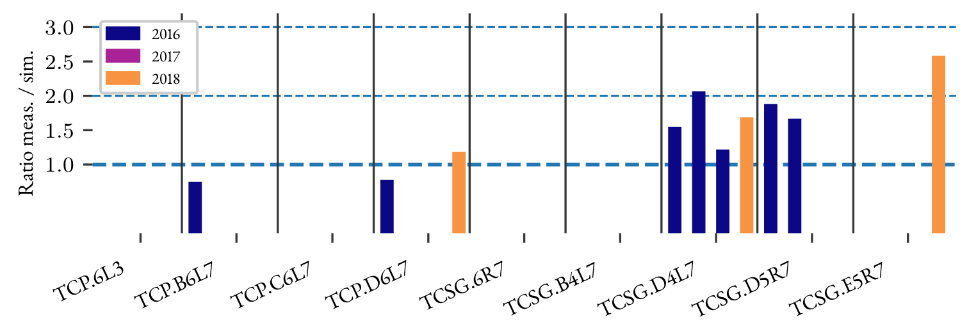

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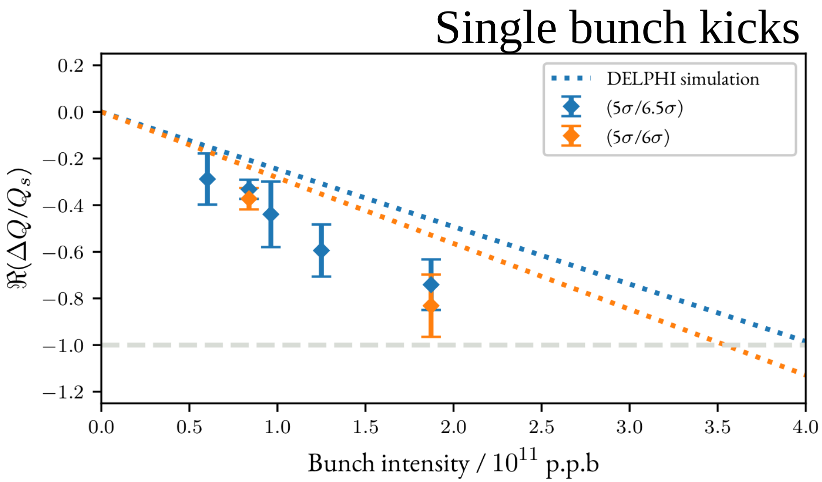

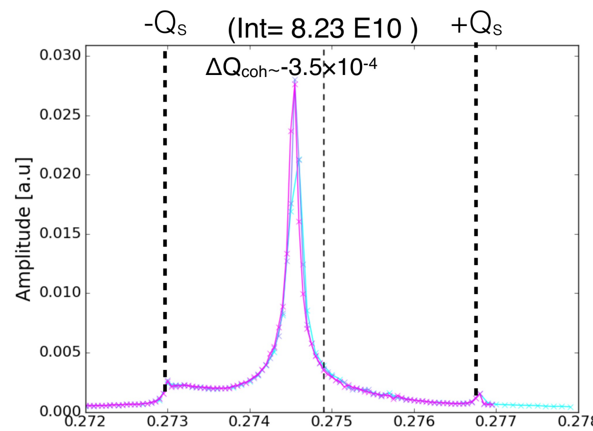

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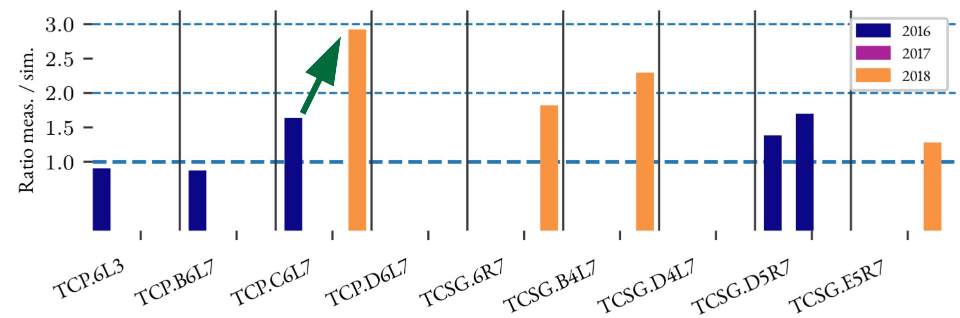

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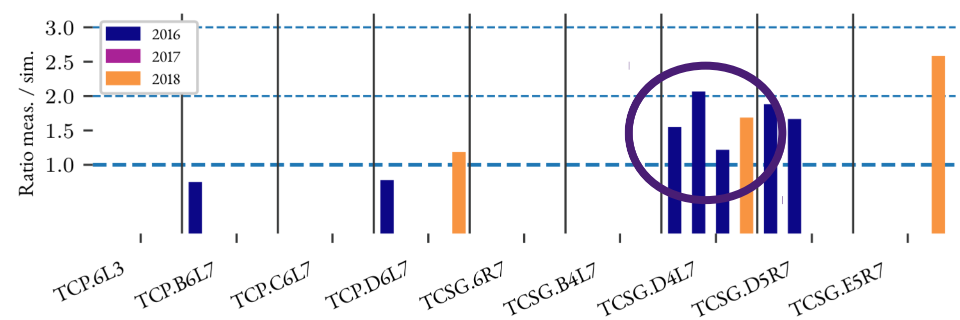

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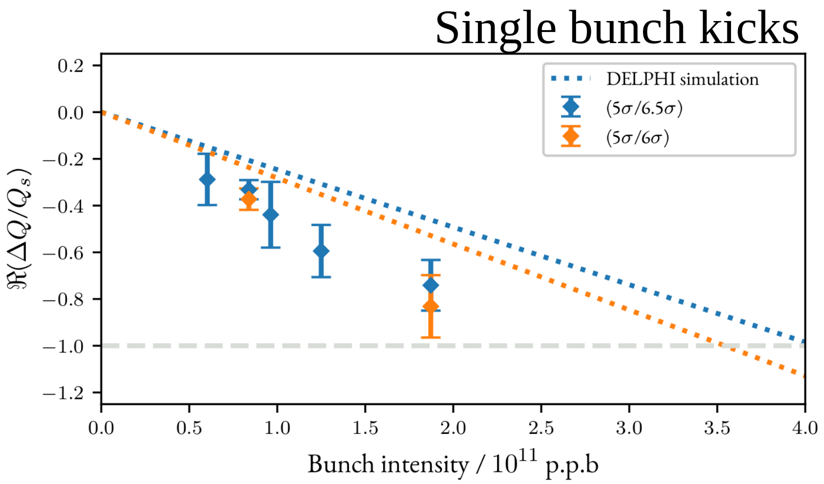

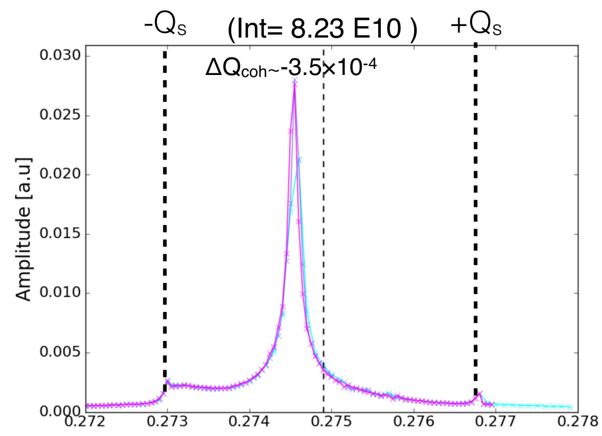

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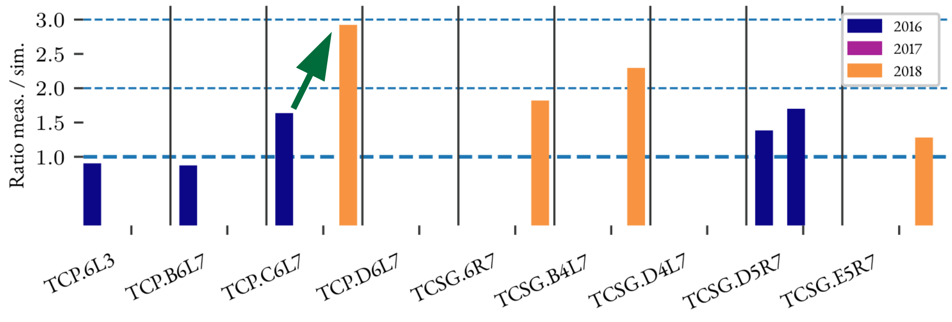

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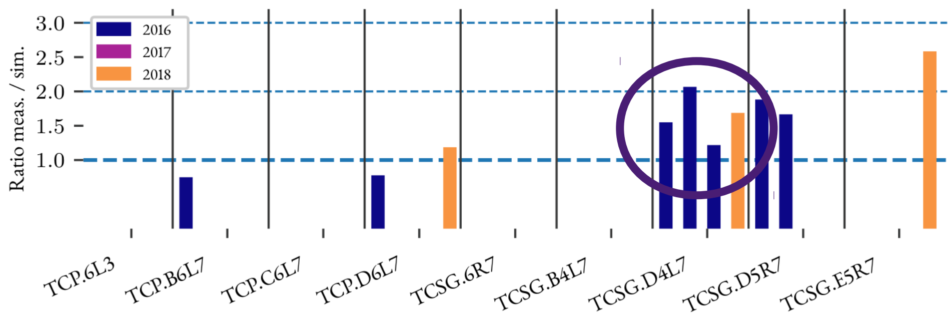

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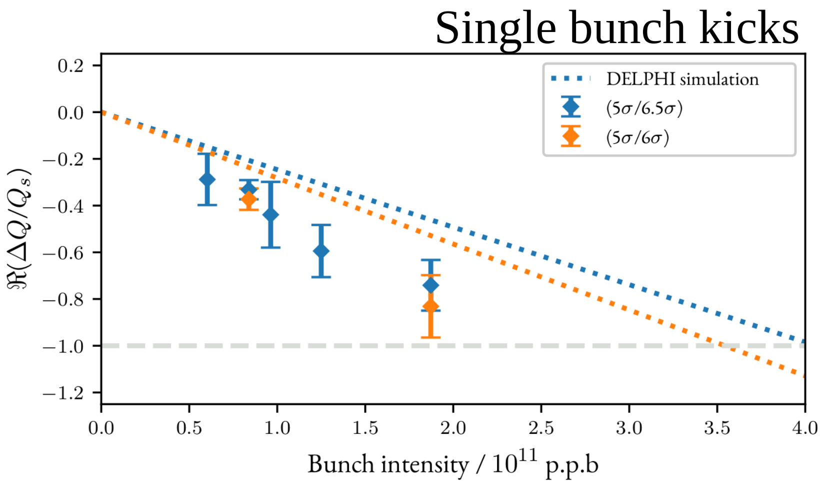

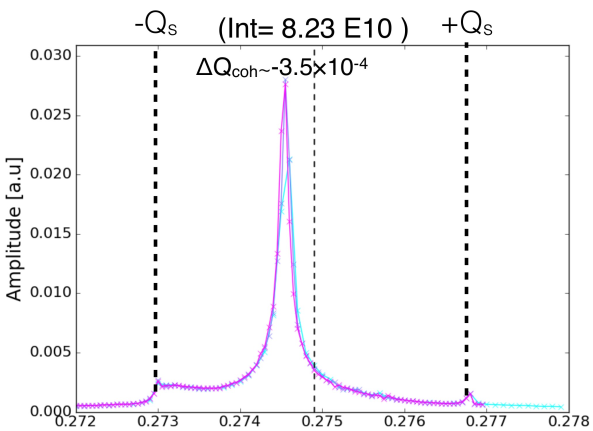

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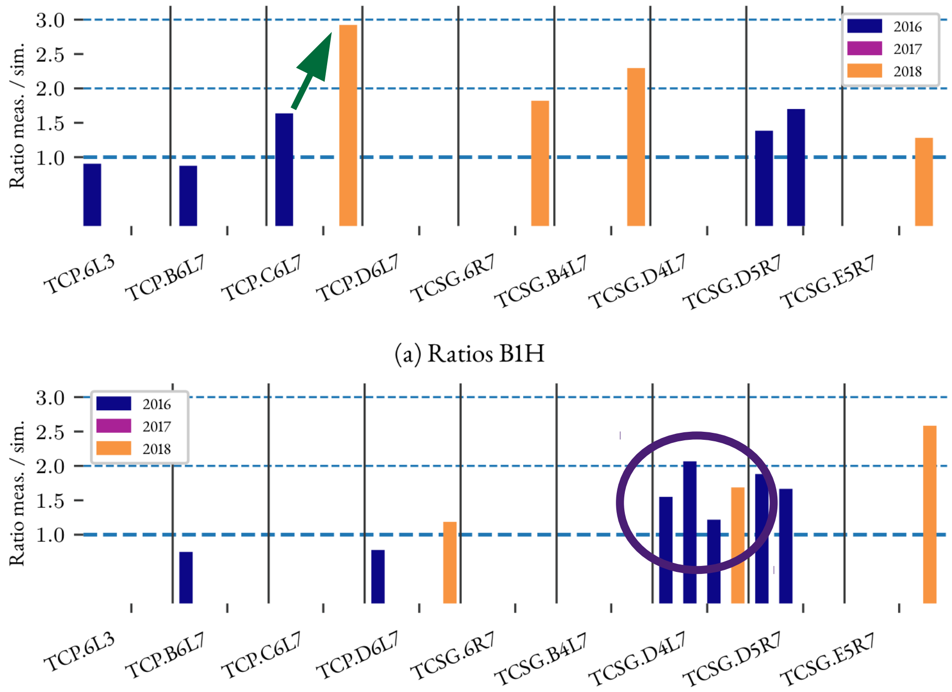

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  → **Monitor systematically** the evolution of the new collimators'impedance

  → Investigate possible causes of non-reproducibility, such as **orbit movements**

Validation and monitoring

- New devices are installed during LS2 and require beam based validation
  - MKI cool prototype (1/8 MKIs)
  - New HL-LHC collimators: 2 TCPPMs and 4 TCSPMs
  - TDIS
  - New LHCb VELO with SMOG2
  - 11T dipoles with TCLD
  - New Alice and CMS beam pipe
  - Carbon coating on 1 to 4 of the stand alone matching quad.
  - Other exchanges (dipoles, RF module, roman pots)

→ Fast validation during commissioning using the total single bunch real tune shift (as in 2017)

→ Monitoring the new collimator’s impedance in MDs early 2021 and over the years for an assessment of the radiation impact

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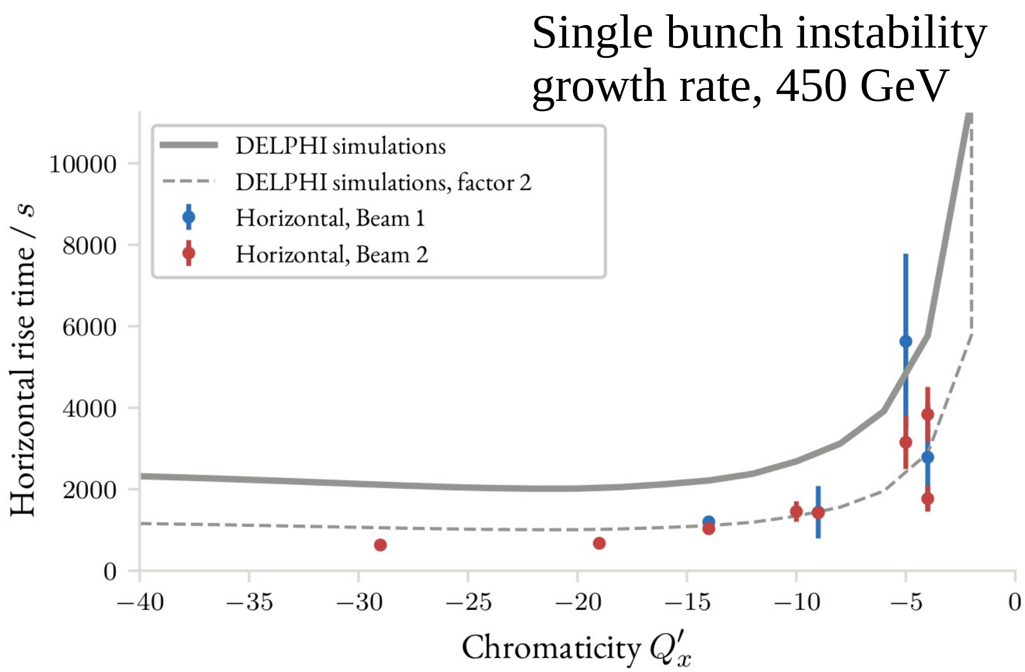
- Monitoring of the beam induced heating can mostly be made parasitically to operation (intensity ramp up)

  → Dedicated tests with high intensity trains when available would be needed to anticipate potential issues with HL-LHC beams (Possibly parasitic to electron cloud head-load MDs, see G. Iadarola’s talk)

Real part of the impedance



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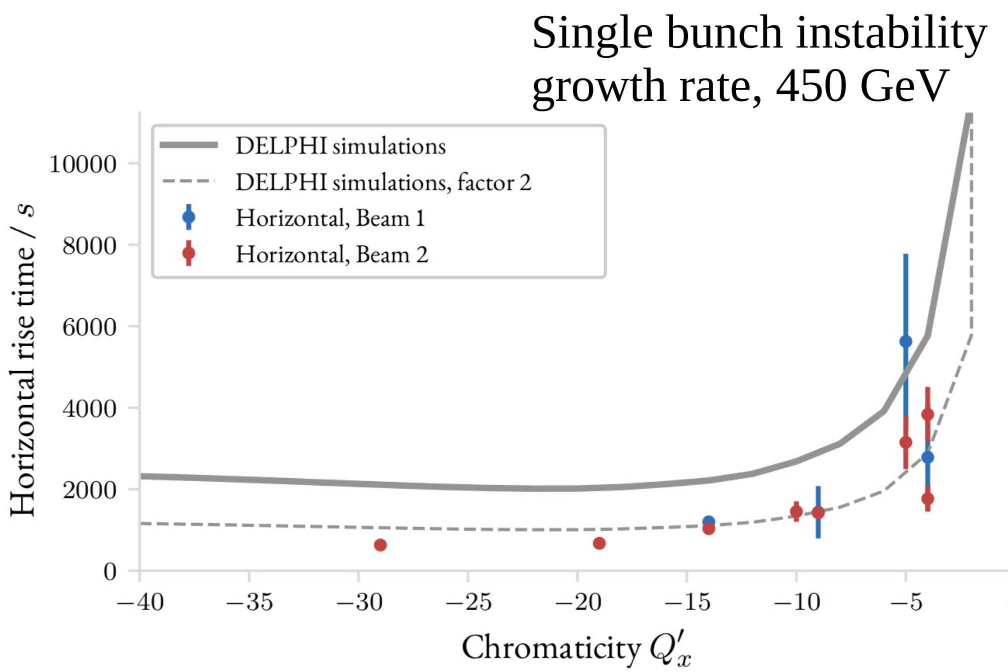

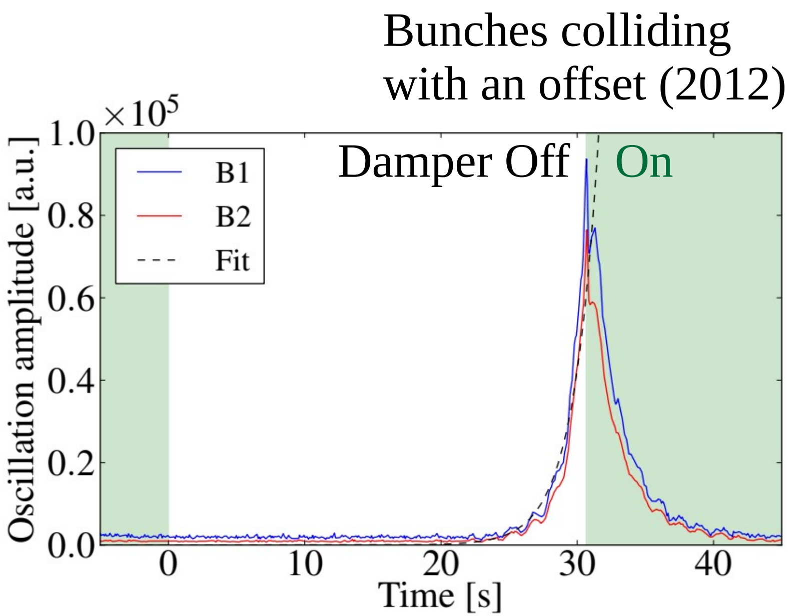

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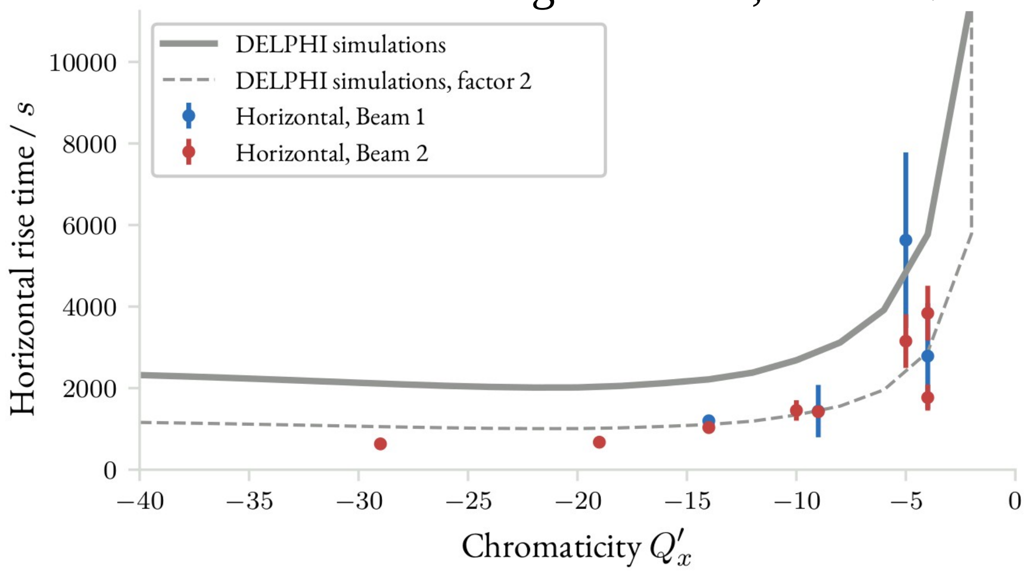
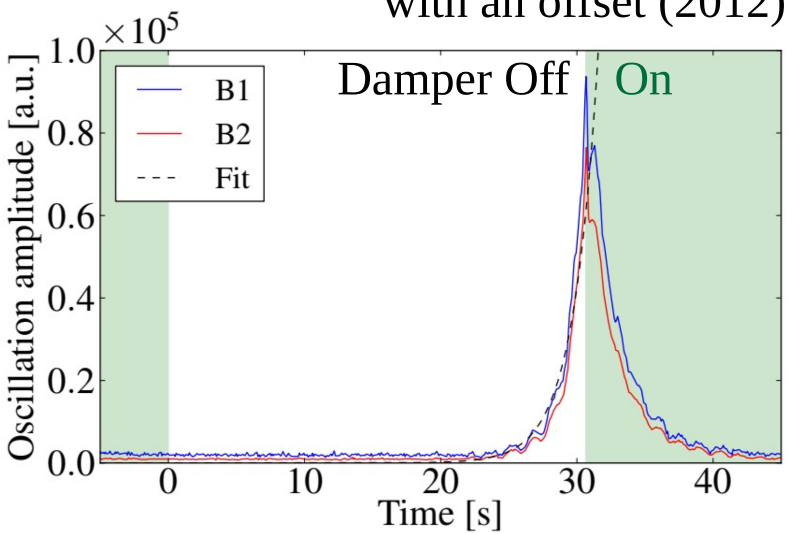
Single bunch instability growth rate, 450 GeV



Bunches colliding with an offset (2012)



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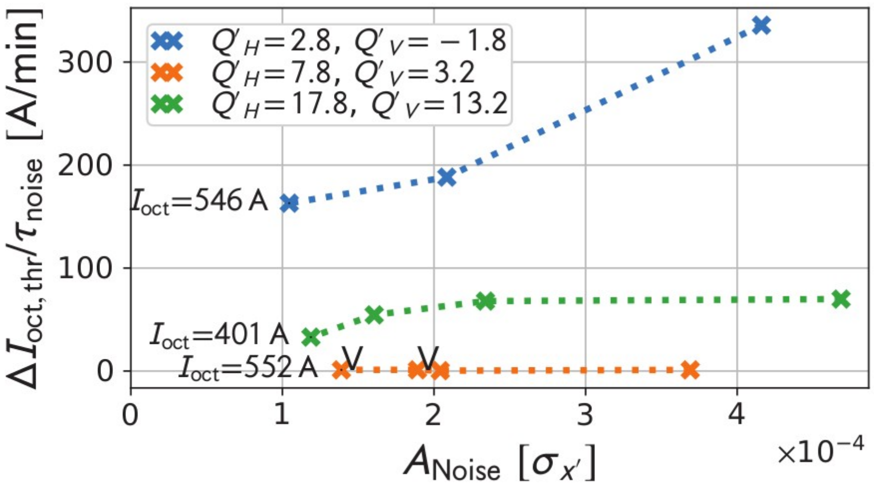
→ We may ramp several bunches using the ADT gating and perform the measurement on individual bunches in different conditions

Latent instabilities



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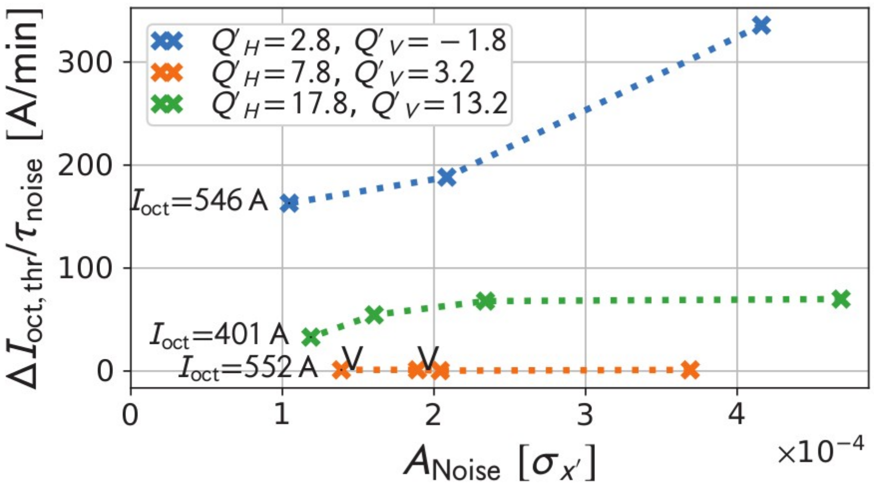

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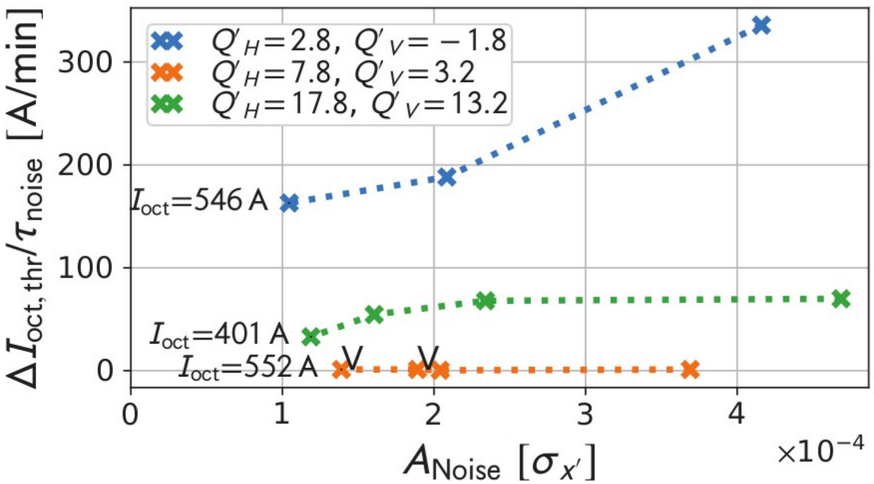

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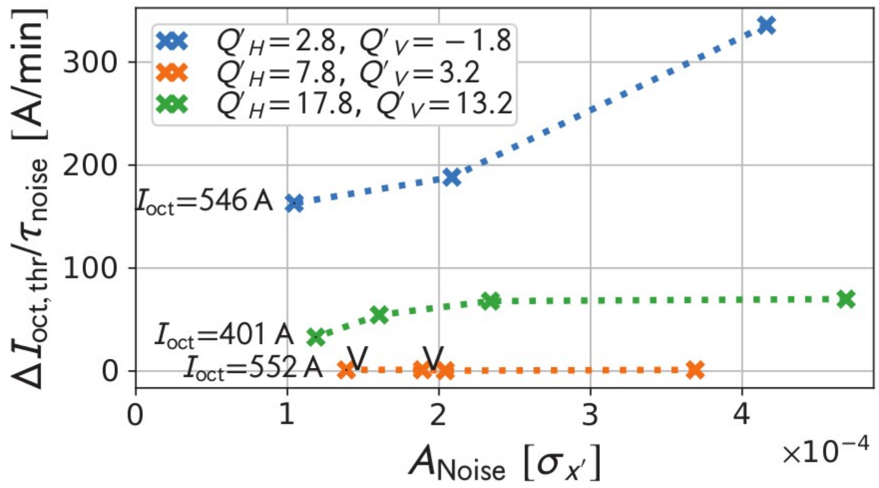

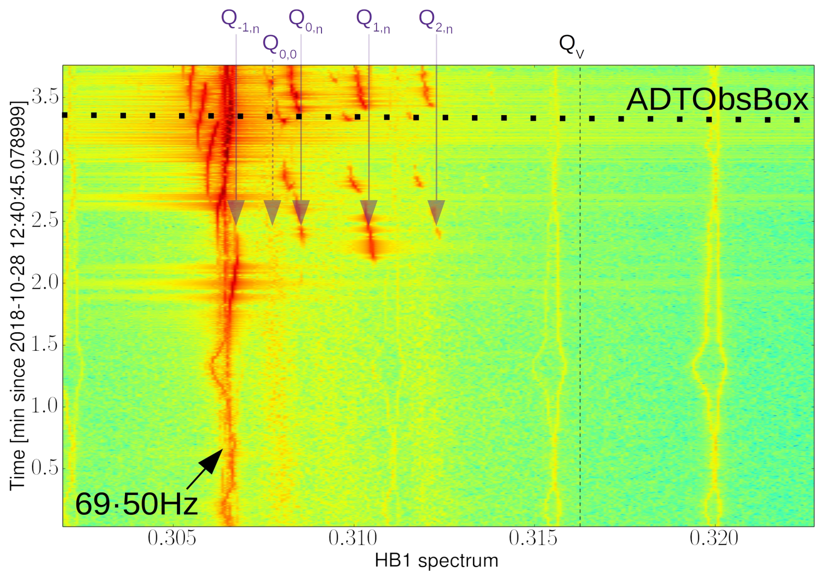

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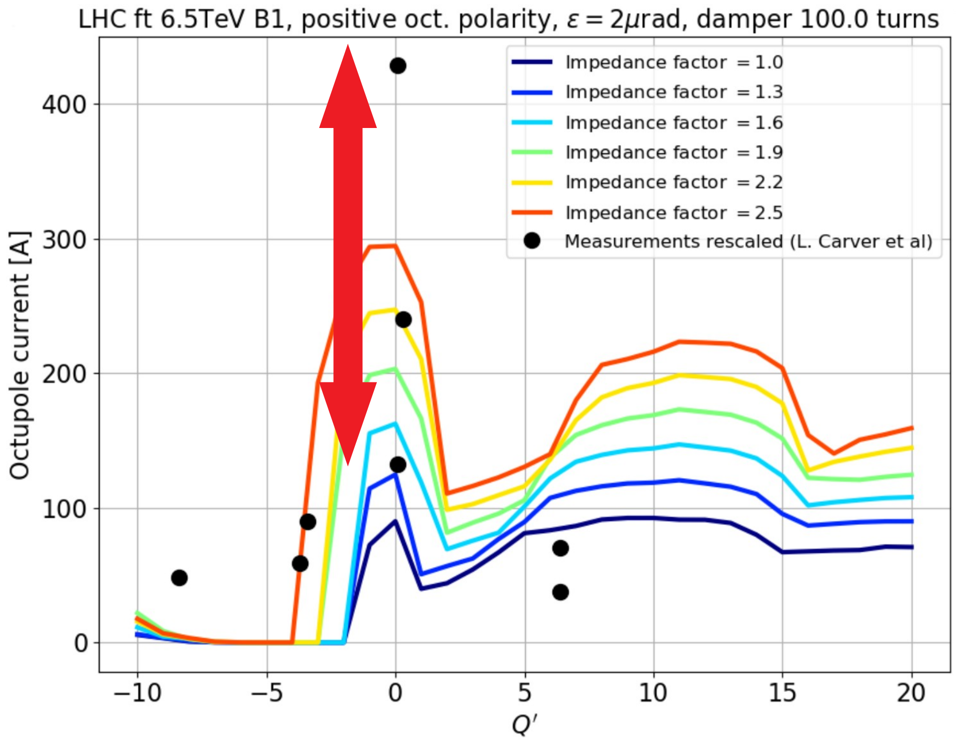
The issue with low chromaticity



PyHEADTAIL (A. Oeftiger)

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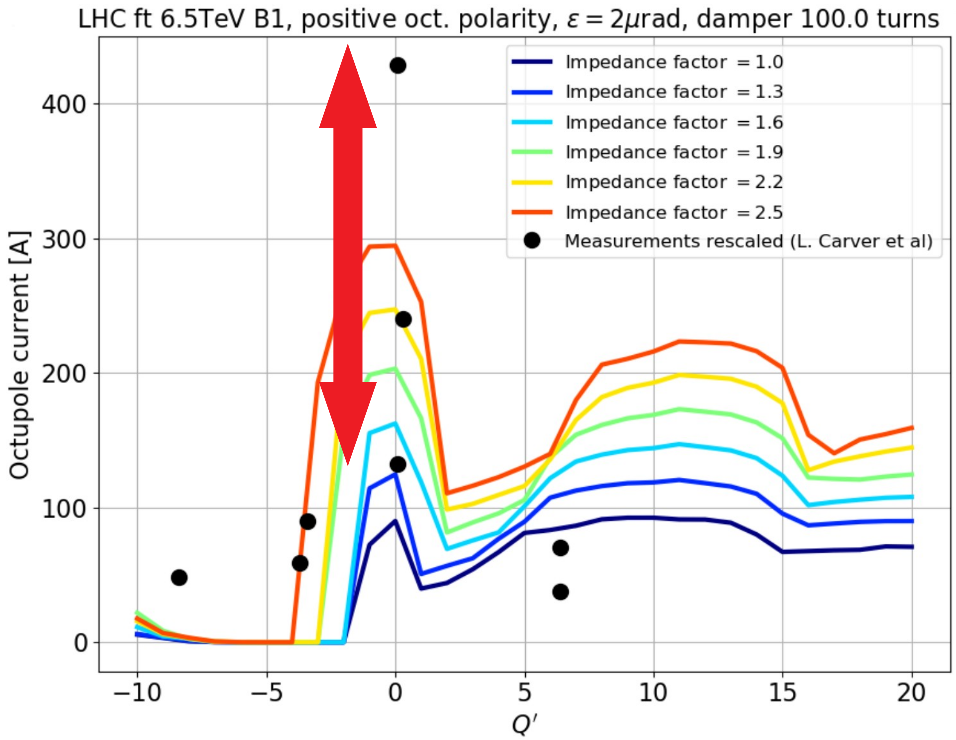

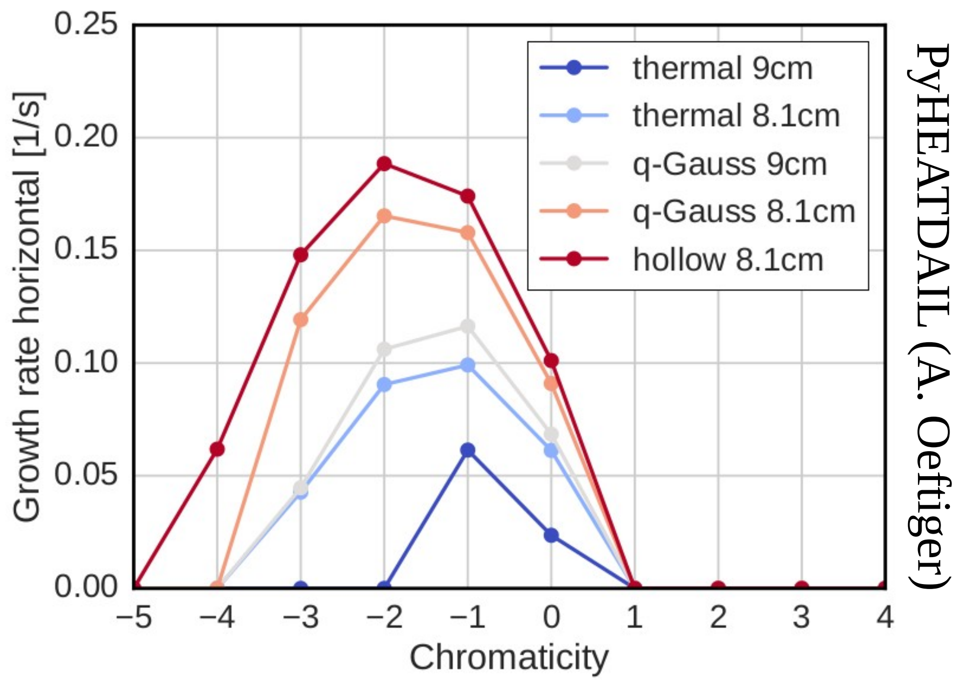

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  - Investigate the role of the **longitudinal distribution** suggested by simulations (exact procedure to be determined in collaboration with RF)

Direct measurement of Landau damping
Beam transfer function measurement

- A direct measurement of Landau damping could validate some instability model which are currently only observed indirectly : Loss of Landau damping due interplay of the octupole with beam-beam driven amplitude detuning, due to linear coupling or due to noise

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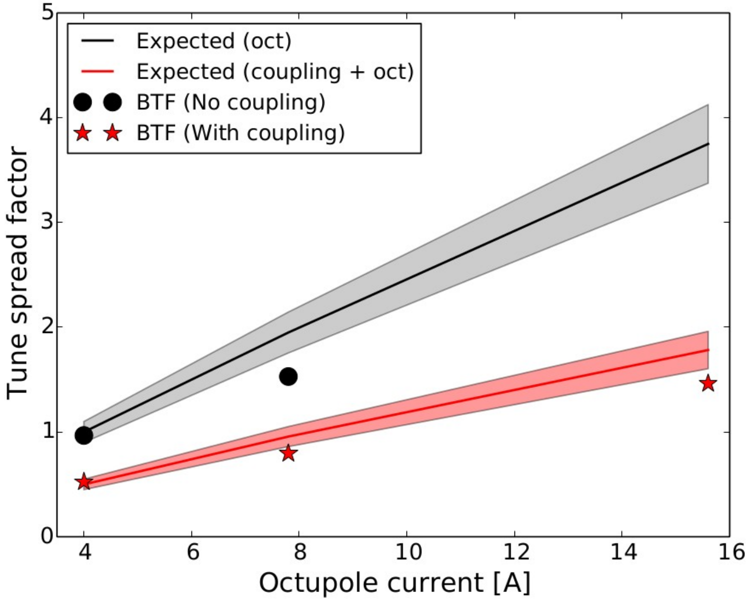

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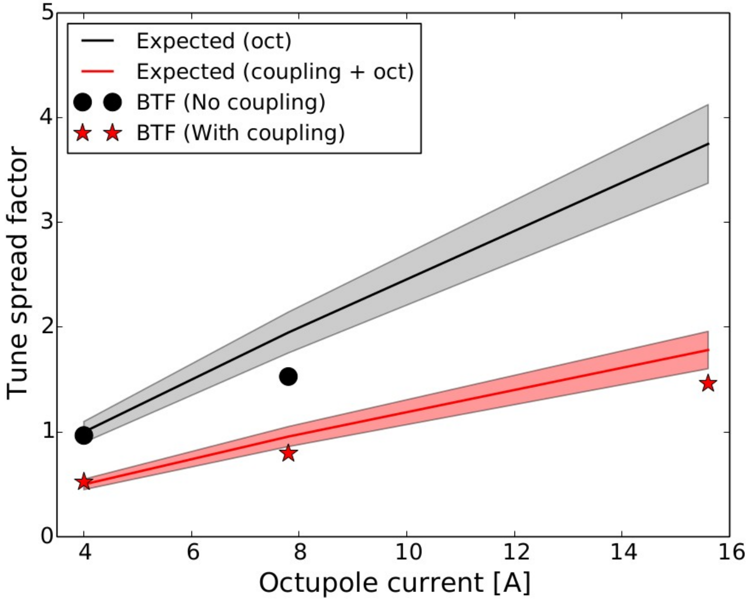

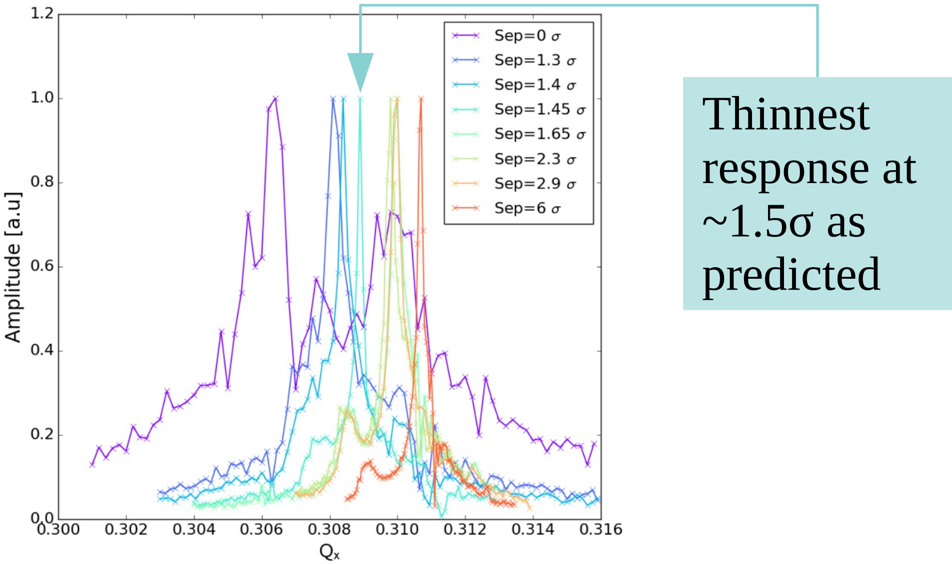

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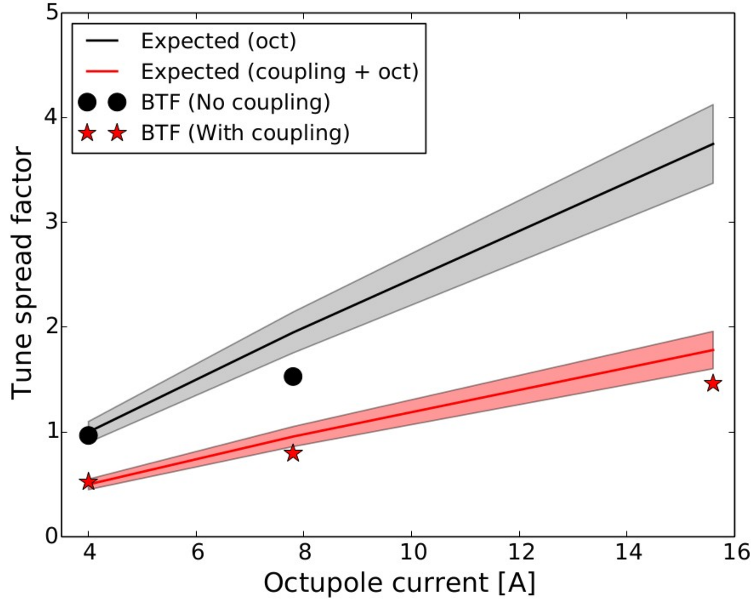

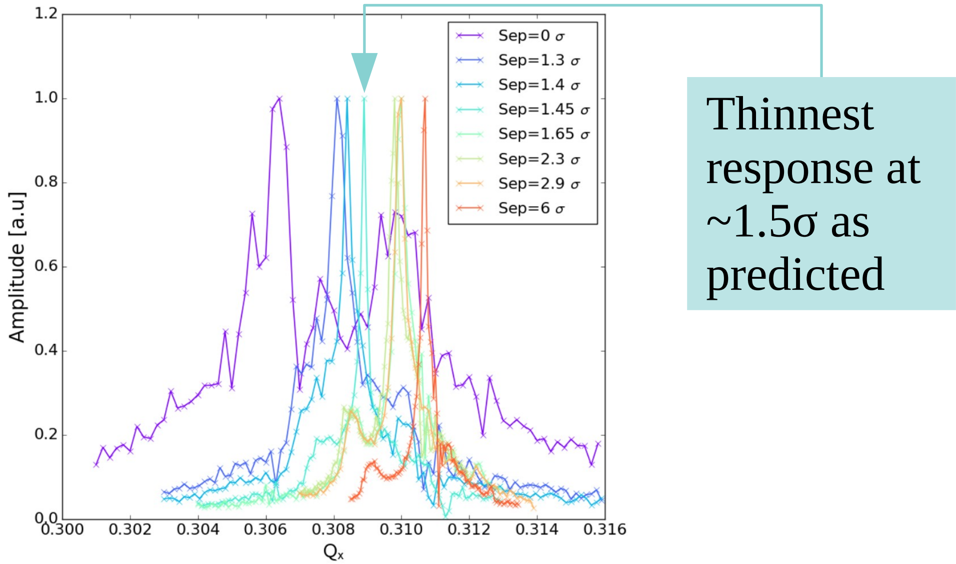

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  → An **improvement of the measurement noise**, in particular of the phase, is needed to obtain a sufficient accuracy on the stability diagram, to be studied in collaboration with BI

  → The accuracy requirement to study latent instabilities are even higher

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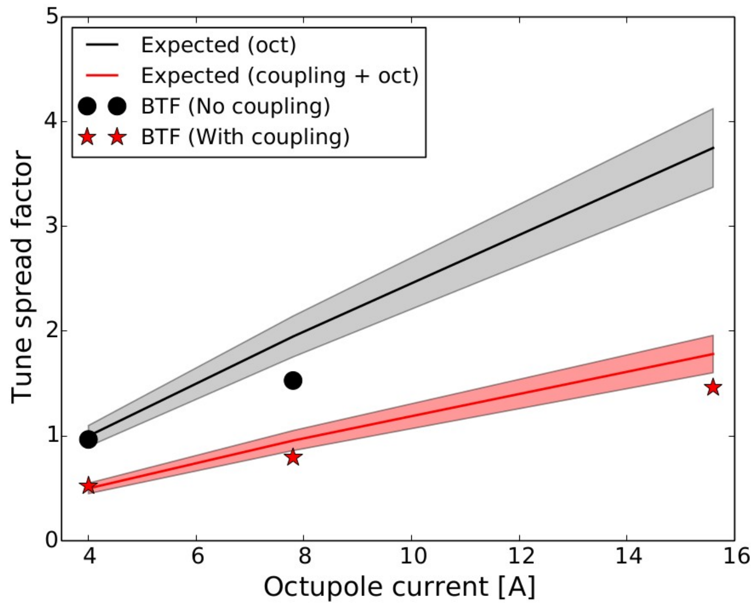
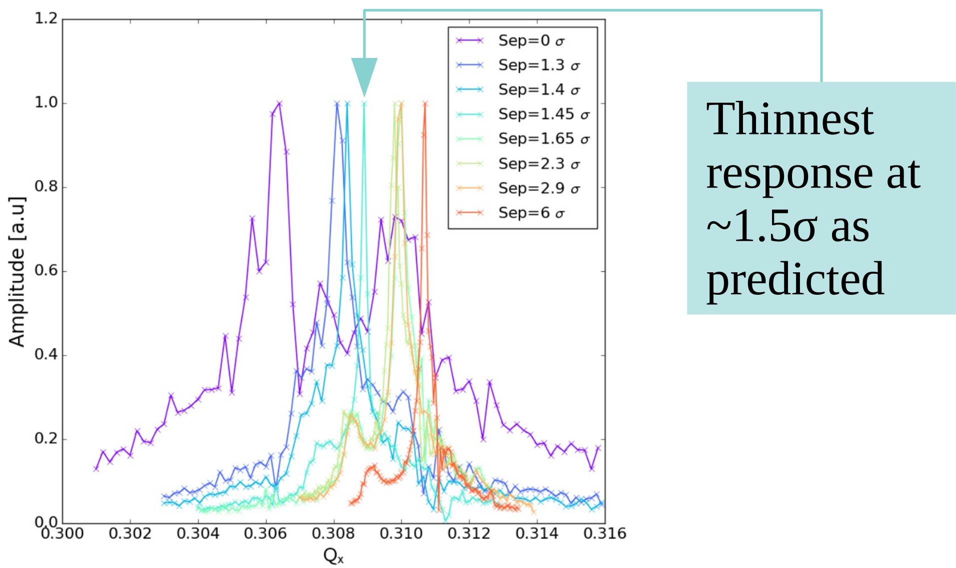
Beam transfer function measurement

- A direct measurement of Landau damping could validate some instability model which are currently only observed indirectly : Loss of Landau damping due interplay of the octupole with beam-beam driven amplitude detuning, due to linear coupling or due to noise





- A direct measurement of the reduction of Landau damping caused by linear coupling was obtained (at injection)
- The quality is still not sufficient to address the original main goal, i.e. measuring the impact of beam-beam interaction on Landau damping

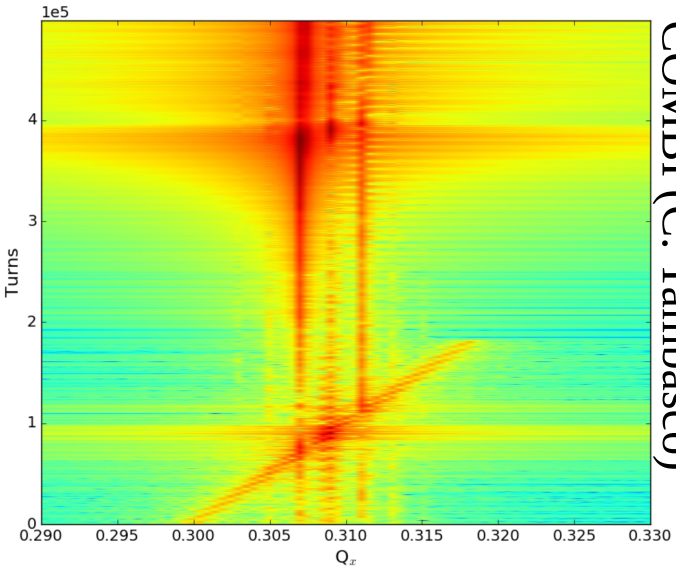
  → An **improvement of the measurement noise**, in particular of the phase, is needed to obtain a sufficient accuracy on the stability diagram, to be studied in collaboration with BI

  → The accuracy requirement to study latent instabilities are even higher

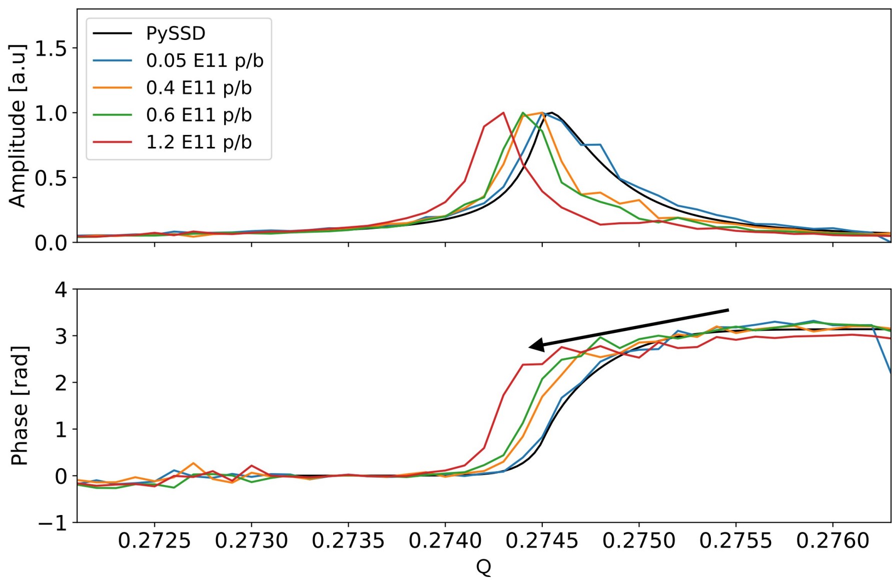
- The possibility to act on single bunches is required to efficiently study bunches with different sets of beam-beam interactions

Direct measurement of Landau damping
Beam transfer function measurement

- Wake fields significantly distort the BTF and lead to instabilities triggered by the excitation



COMBI (C. Tambasco)



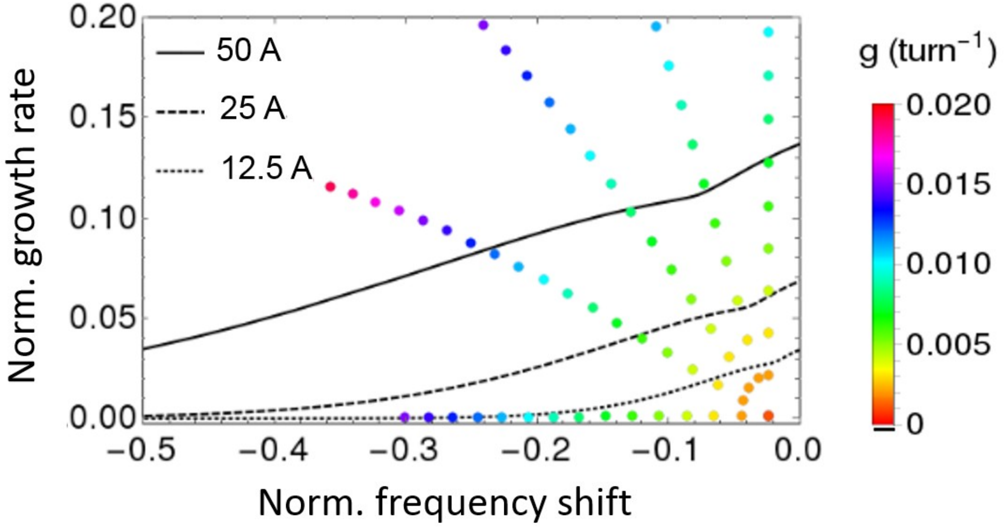
COMBI (C. Tambasco)

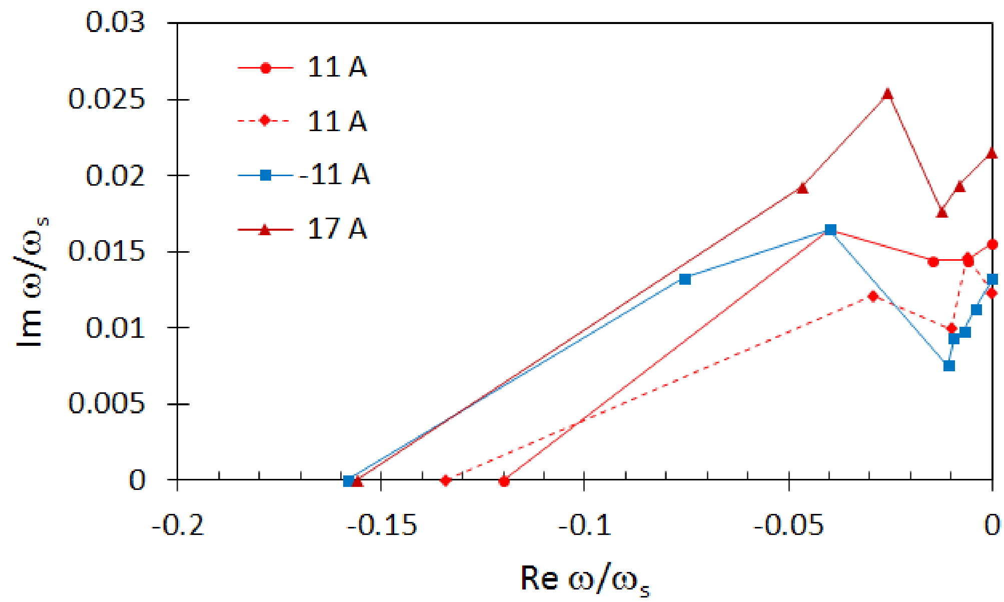
- Investigations of Landau damping needs to be performed with low intensity beams (or relaxed collimator settings)

  → 2018 : Asymmetric beams (trains against low intensity bunches)

  → Next step : **Collimator movements** with safe beams

Direct measurement of Landau damping
The Antidamper method (S.A. Antipov)





- By varying the damper gain and phase (such that the damper becomes a controlled source of impedance) while monitoring the beam stability, the stability diagram can be directly measured

    → Sufficient control on the ADT gain and phase were demonstrated at injection during Run2.

Direct measurement of Landau damping

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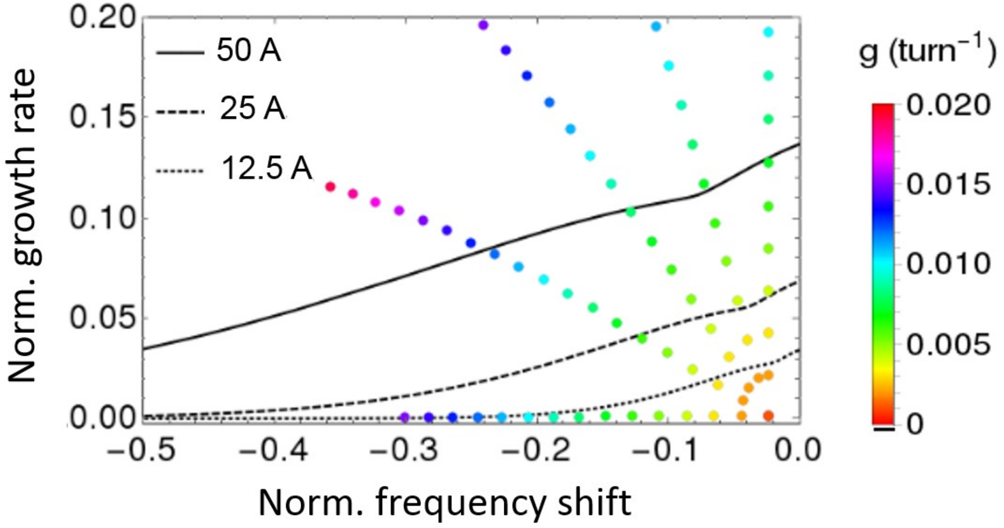

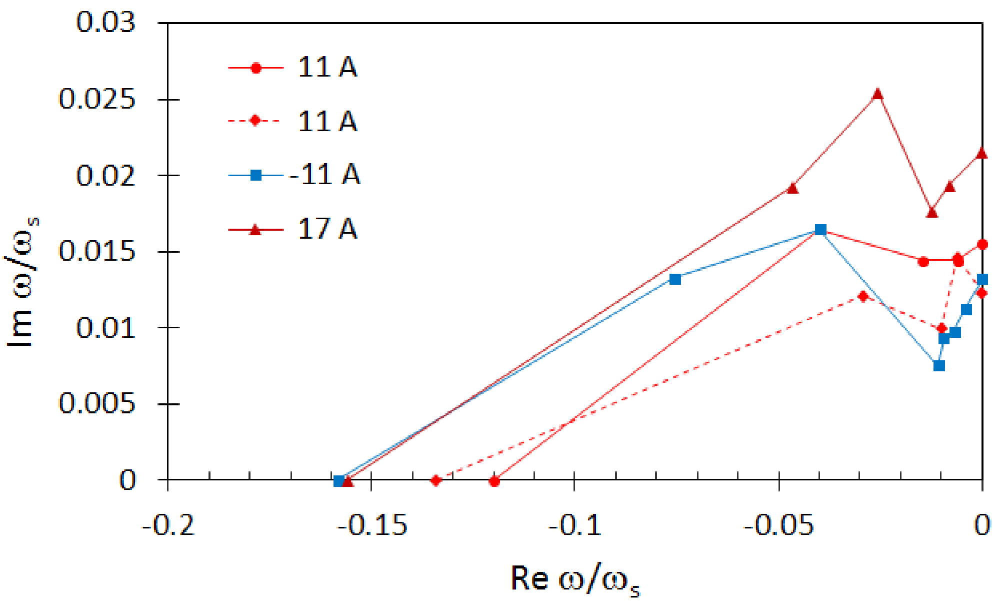

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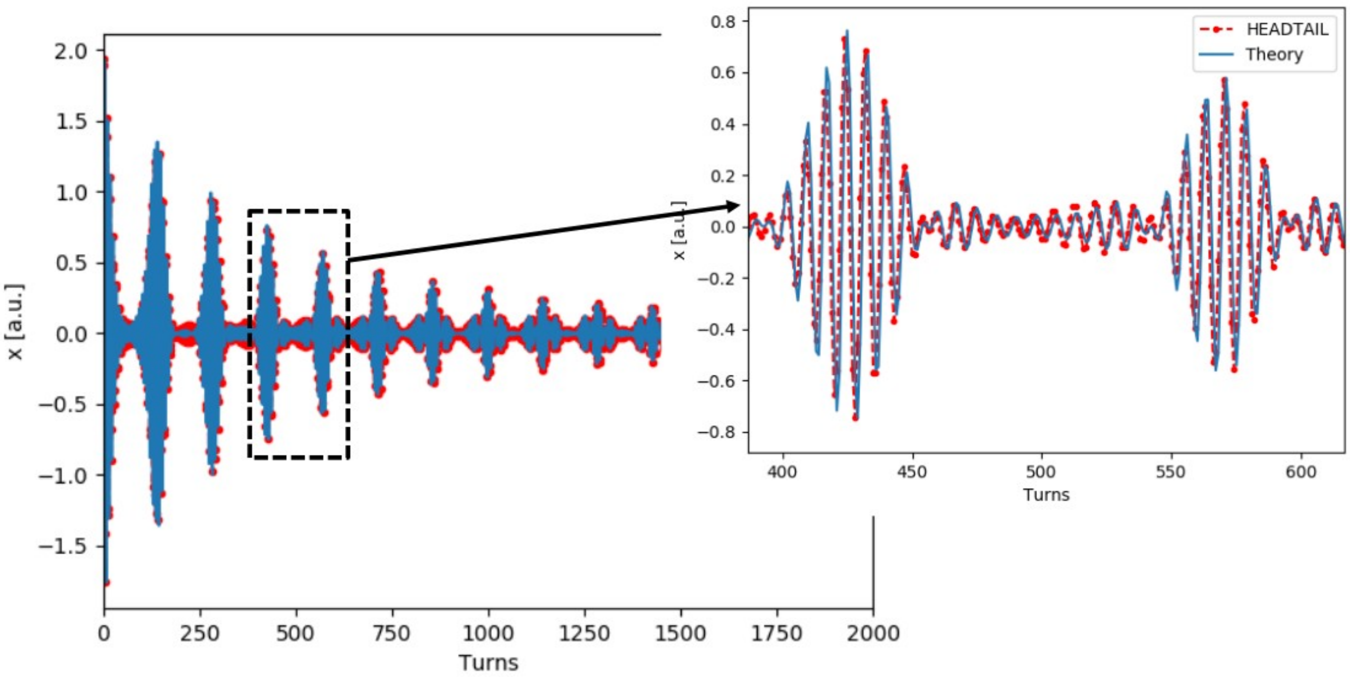
  → Sufficient control on the ADT gain and phase were demonstrated at injection during Run2.

- The stability diagram is significantly affected by lattice non-linearities and space-charge at injection

  → Next step: Demonstration of the accuracy of the method at flat top

Alternative chromaticity and gain measurement



- A new analytical model (N. Mounet) allows for the derivation of the turn by turn position following a transverse kick in the presence of a damper and chromaticity

  → Excellent agreement with simulation data

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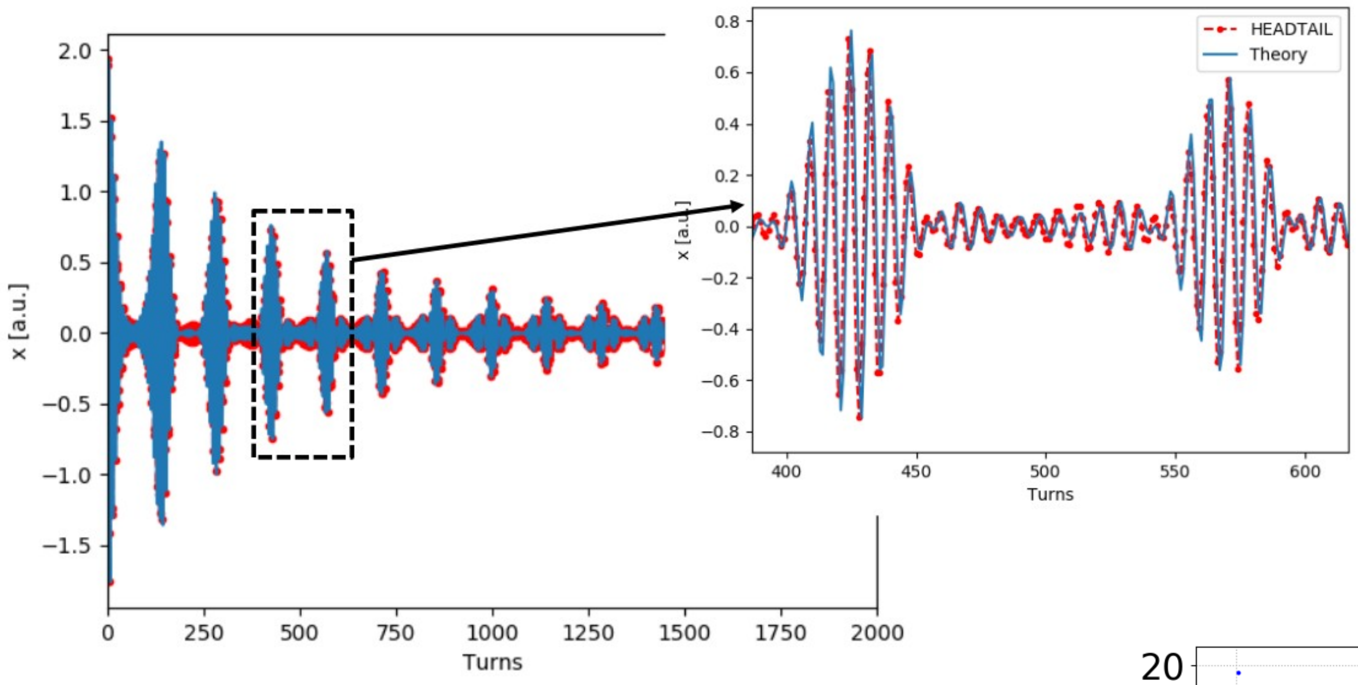

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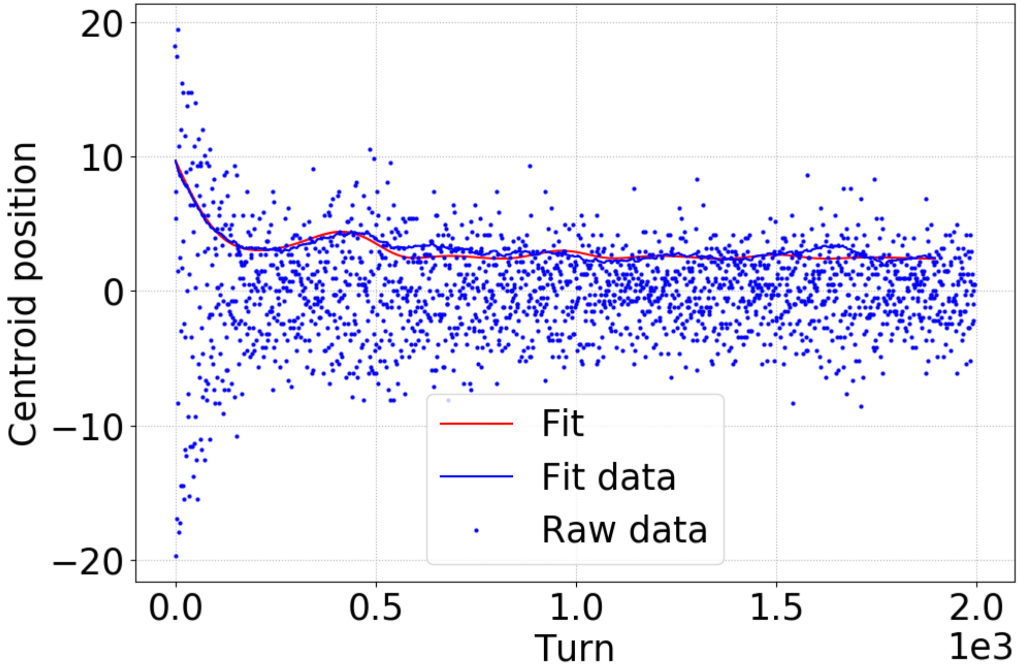

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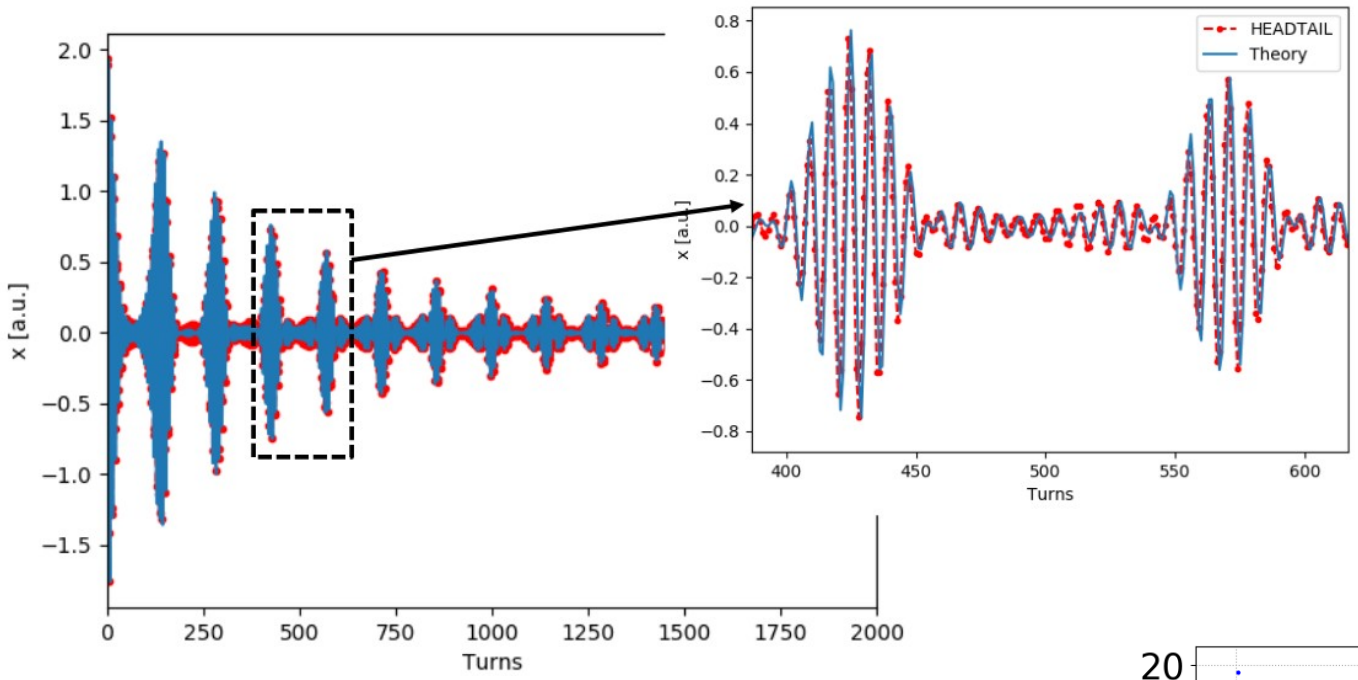

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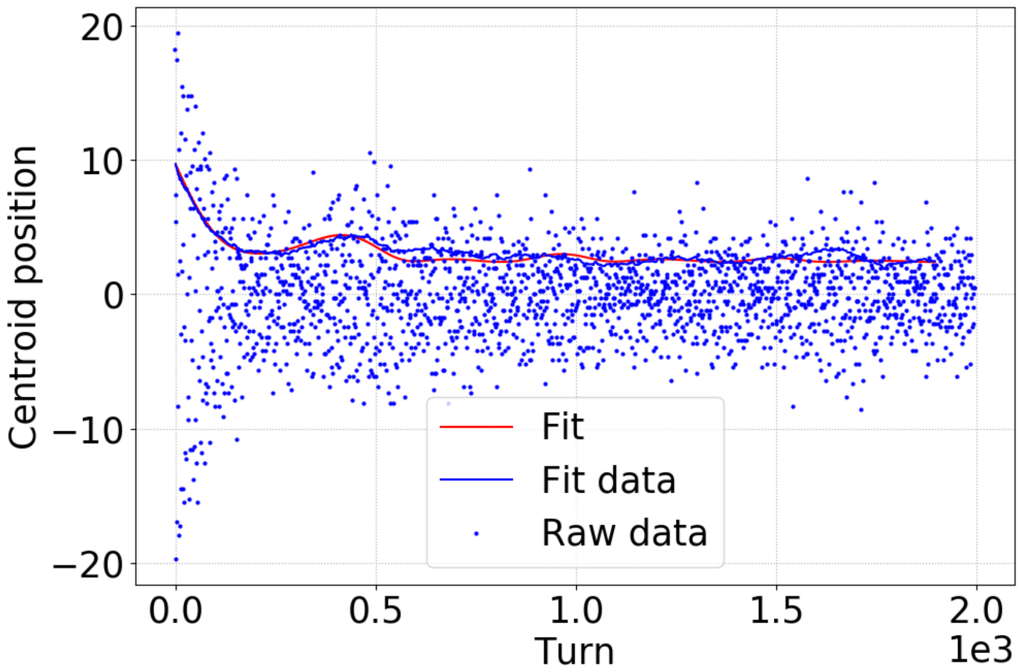
  → High potential for operation: Online bunch-by-bunch chromaticity (without energy modulation) and damper gain



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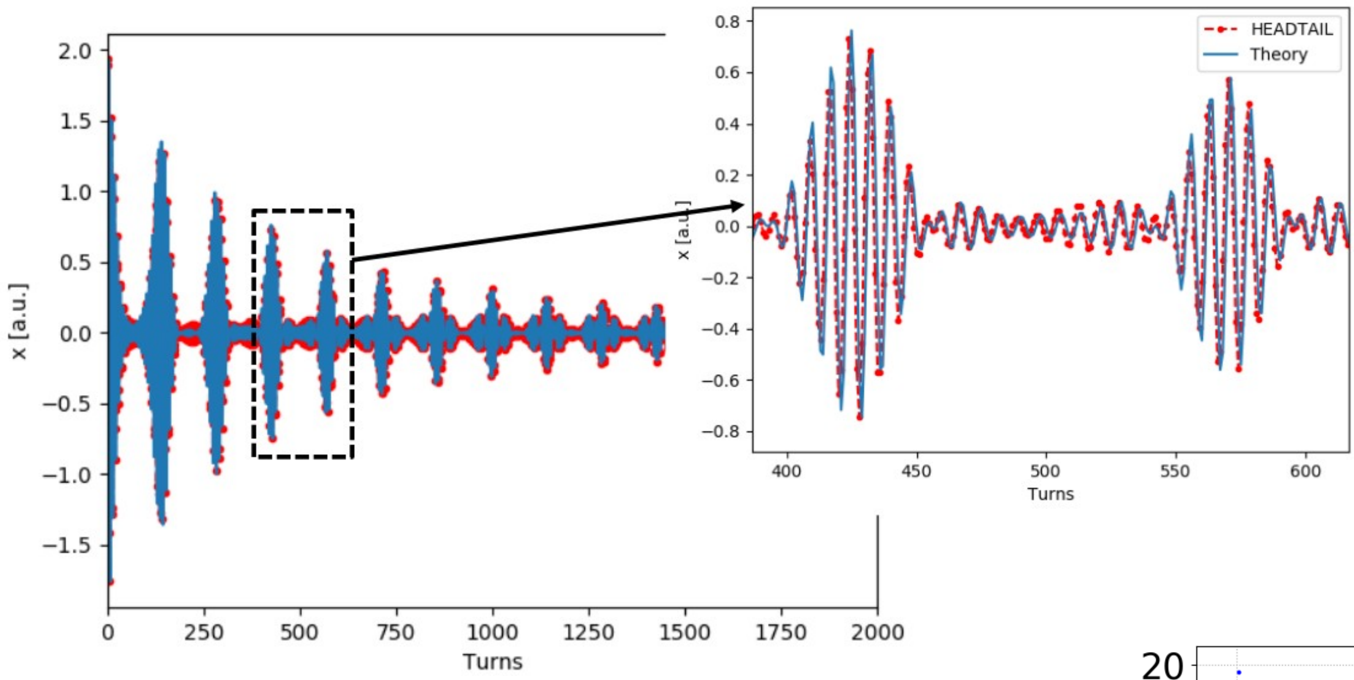

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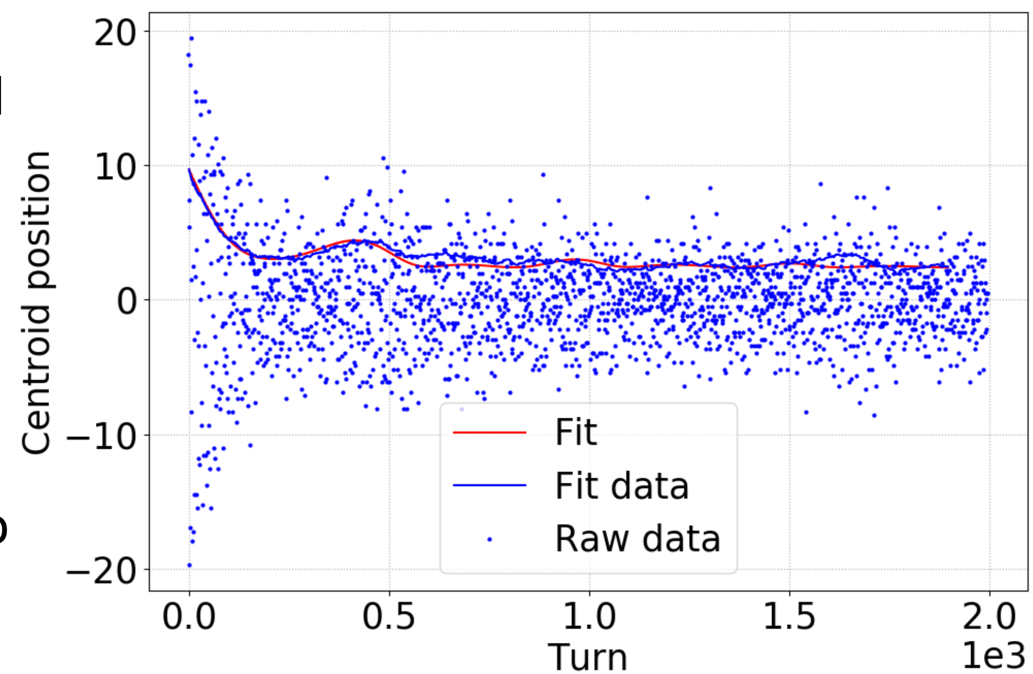
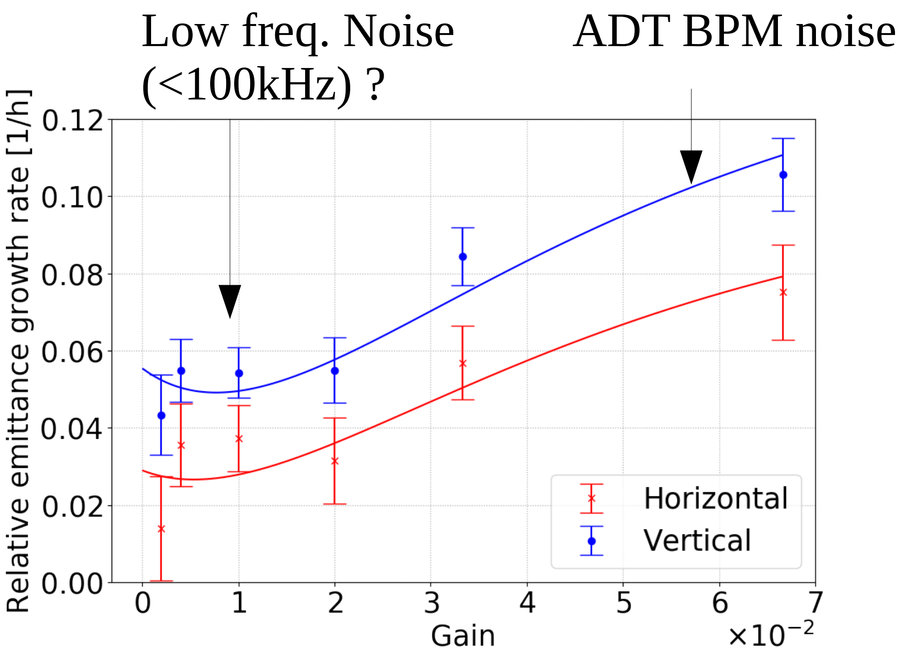
  → Need to qualify its performance (reproducibility, accuracy, sensitivity to wake fields, amplitude detuning and Q'')



Decoherence
(→ emittance growth in collision)



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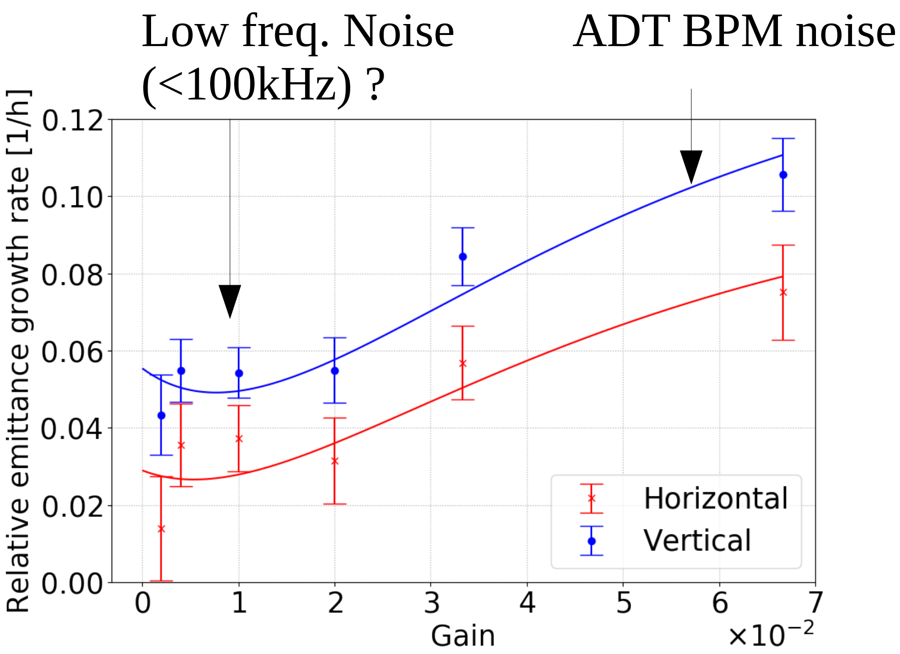

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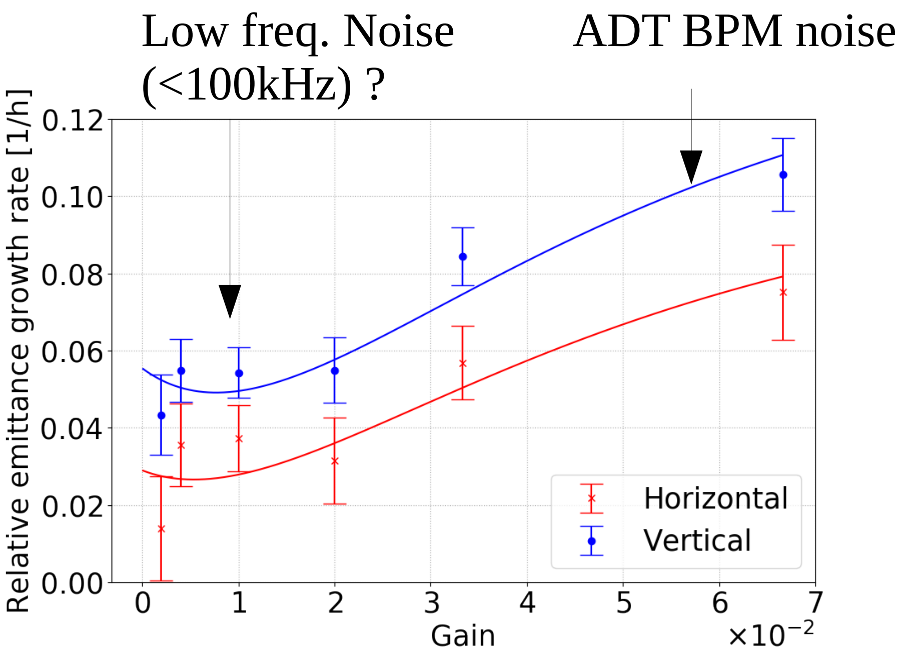

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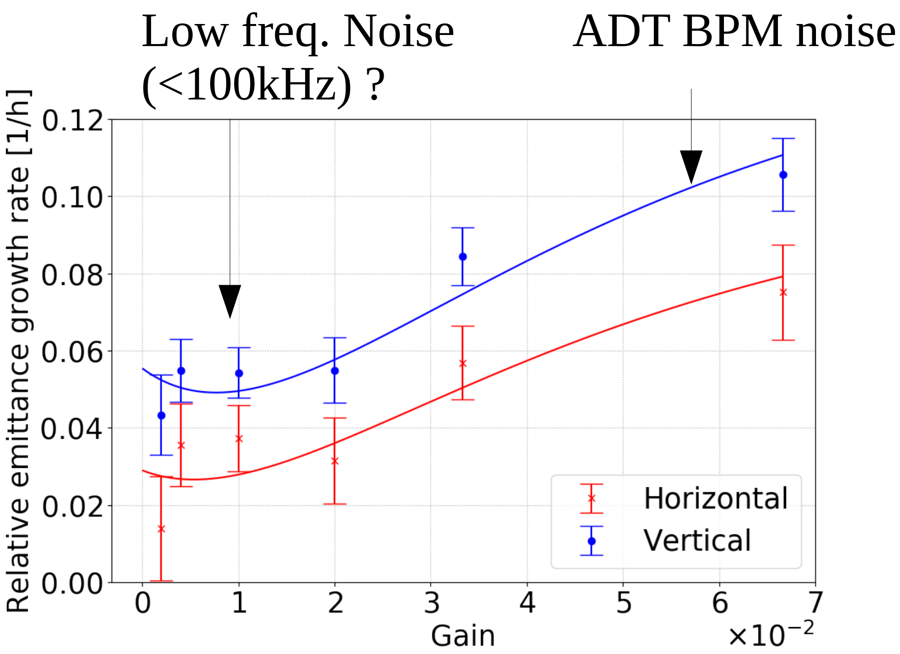

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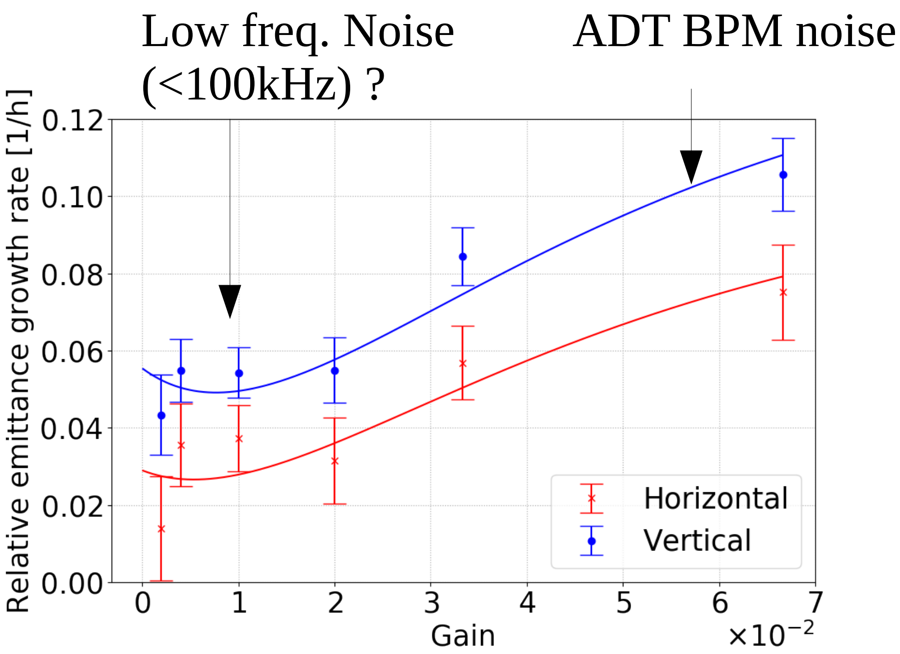

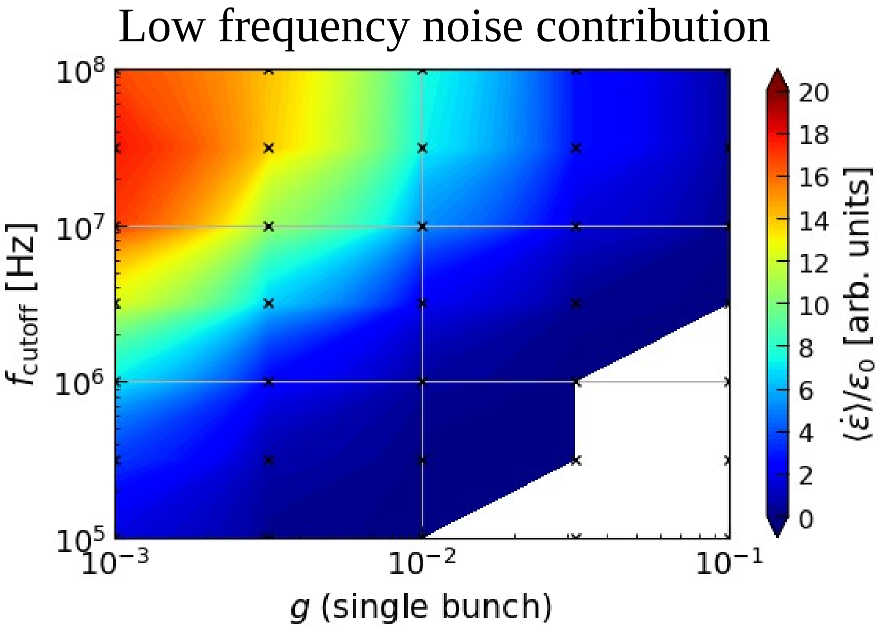

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COMBI (S.V. Furuseth)

Decoherence

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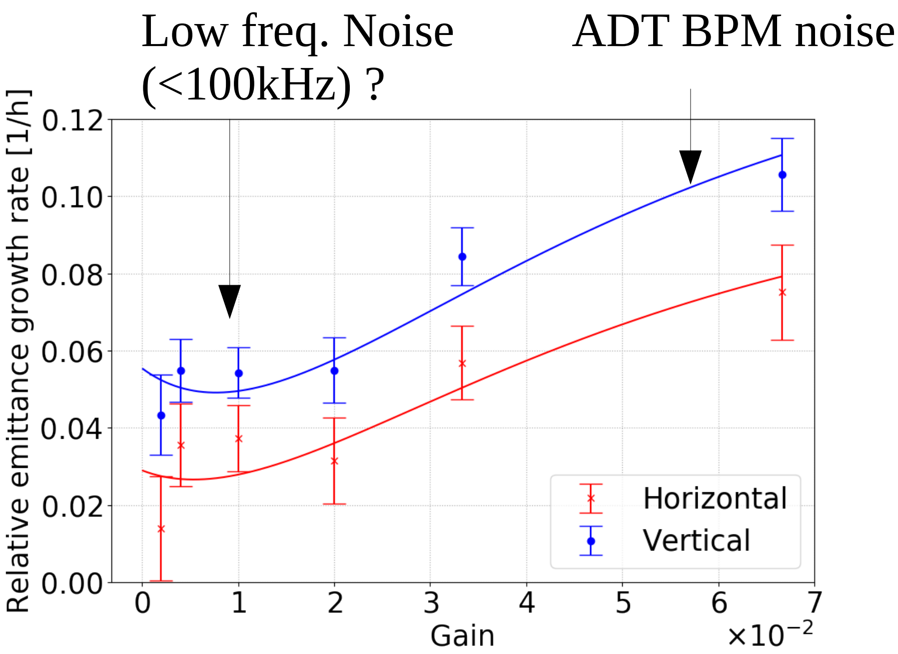
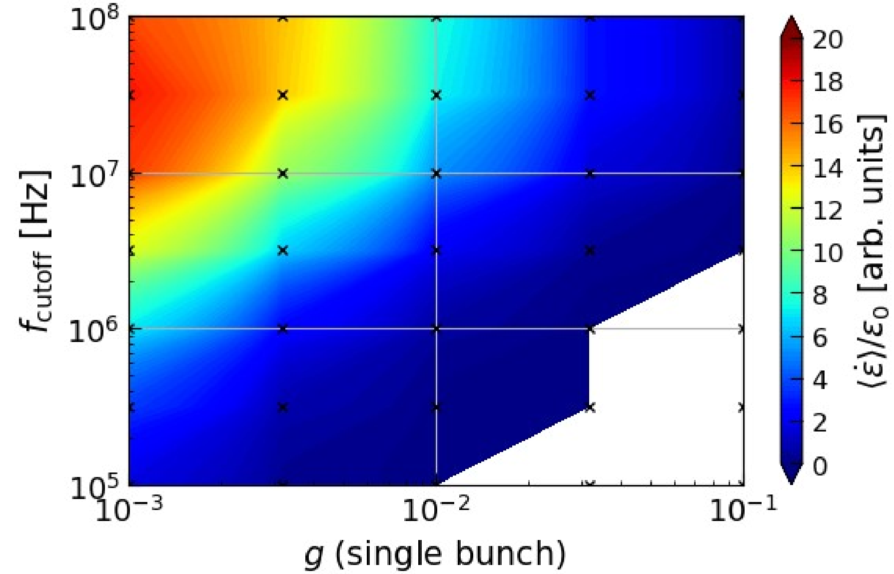


Low frequency noise contribution



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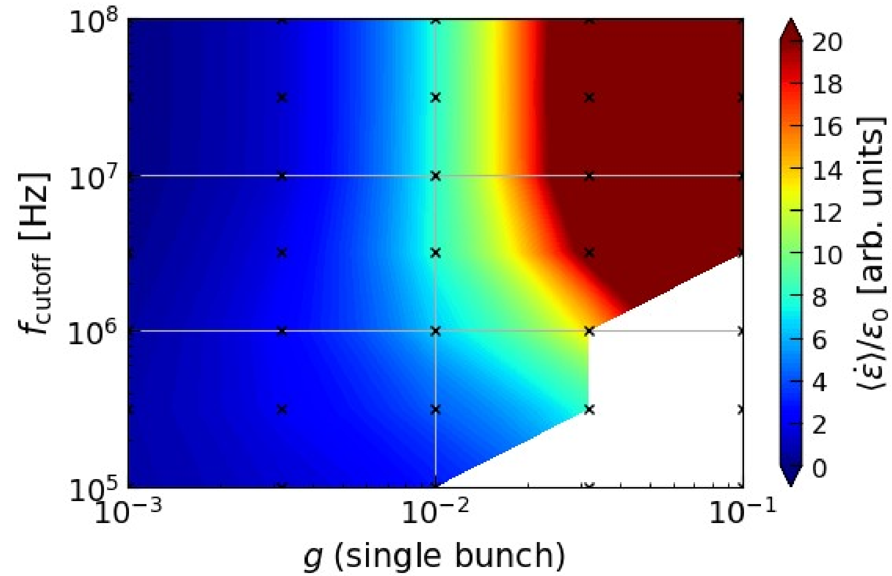
ADT BPM noise contribution



COMBI (S.V. Furuseth)

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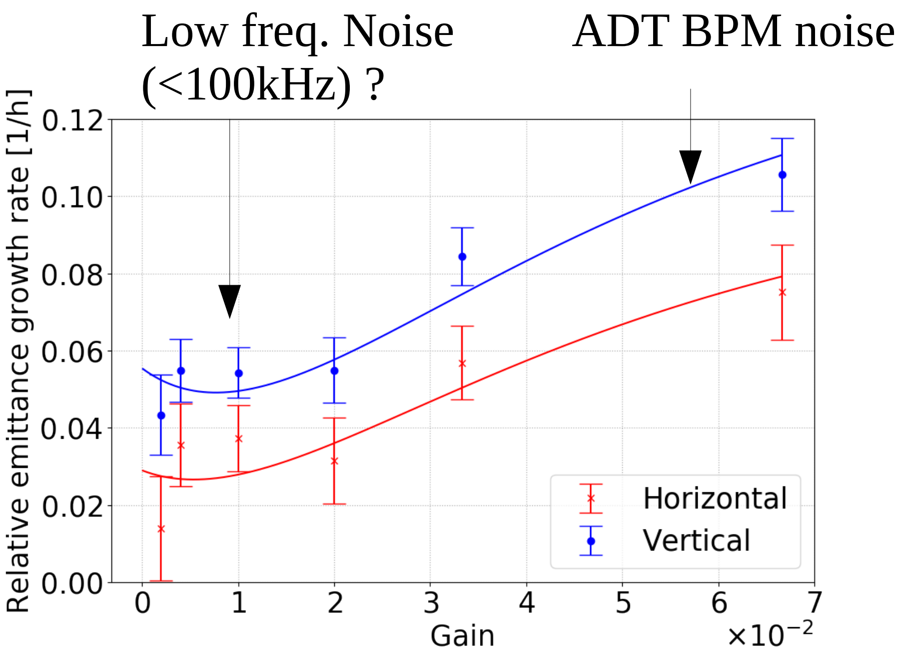

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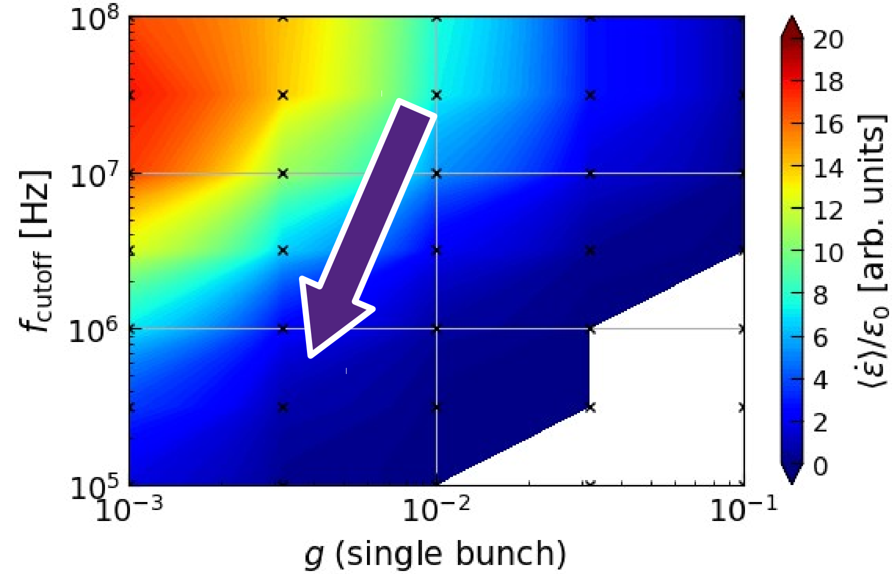

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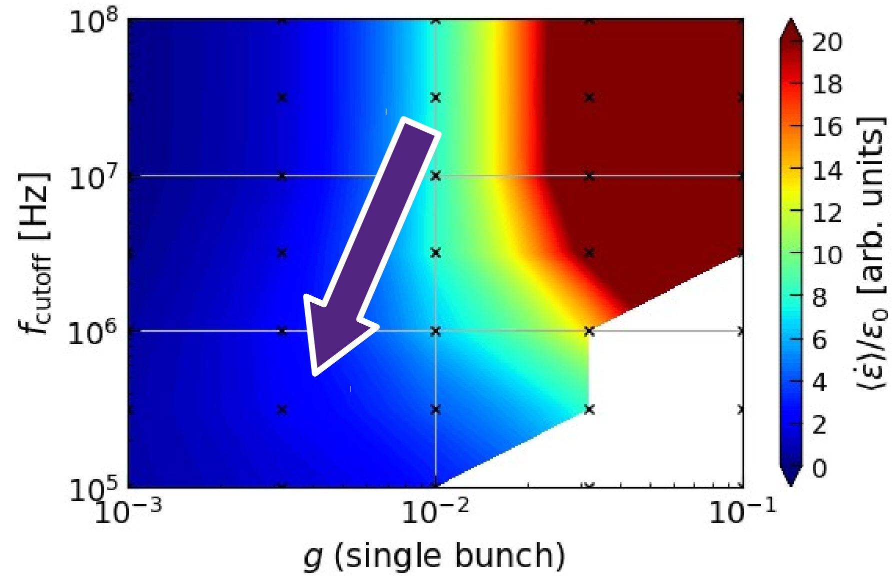

COMBI (S.V. Furuseth)

Summary
Main goals

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- Understand the stability threshold for accurate extrapolation to HL-LHC and optimisation of the beam lifetime / emittance growth (LHC and HL-LHC)
  - Obtain empirically the machine settings (chroma, ADT gain, BW) allowed by collective effects during the cycle and in collision
  - Verify the latent instability model predictions (chromatcity, ADT gain, 50Hz lines)
  - Investigate the instability mechanism observed at flat top with a low chromaticity
  - Refine the impedance model (new collimators and their evolution, impact of the orbit at the collimators)
  - Verify the stability of high intensity bunch trains at top energy

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  - Beam transfer function
  - Antidamper method
- Further develop diagnostics related to collective effects
  - Exploitation of the single bunch kick capabilities (Tune, chromaticity and damper gain measurement)
  - Other exotic ideas (Beam echoes?)

Summary
Special requirements

- Collimator movements and orbit movements at the collimator positions
- Single bunch kick (synchronised ADT gated kick + ADTObsBox acquisitions)
  - Needs to be available with unsafe beams
- Automatic instability detection and change of damper settings for rise time measurements and Landau damping measurement with Antidamper (Dedicated ADT software, ADT gated settings*, ADTObsBox)
- Introduction of artificial noise for instability latency measurement (ADT gated noise + ADT gated settings)
- Beam transfer function for Landau damping and tune shift measurement (BBQ-BTF+ADT kicker, single bunch capabilities is required)
  - Improvements in the signal are required
- Antidamper for Landau damping measurement (ADT software and gating) at flat top
- Amplitude detuning (PACMAN linear coupling, triplet errors) → see OMC talks
- High brightness single bunches to reach HL-LHC beam-beam tune shift
- If available : High intensity trains

Done in Run2
New development

*ADT gated settings : Adjustment of the gain and phase on a dedicated set of bunches (configurable)

Journal publications and thesis based on LHC collective effect MDs during Run2

- R. Tomás, et al., Beam-beam amplitude detuning with forced oscillations, Phys. Rev. Accel. Beams 20, 101002 (2017)
- L.R. Carver, et al., Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider, Phys. Rev. Accel. Beams 21, 044401 (2018)
- S.V. Furuseth, et al., Modeling of nonlinear effects due to head-on beam-beam interactions, Phys. Rev. Accel. Beams 21, 081002 (2018)
- M. Schenk, et al., Experimental stabilization of transverse collective instabilities in the LHC with second order chromaticity, Phys. Rev. Accel. Beams 21, 084401 (2018)
- X. Buffat, et al., Modelling of the emittance growth due to decoherence in collision at the Large Hadron Collider (Submitted to Phys. Rev. Accel. Beams)
- N. Biancacci, et al., Resistivity characterization of Molybdenum coated graphite-based substrates for the upgrade of the High Luminosity LHC collimators (In prep for Coating Materials and Surface Treatments for Applications in Particle Accelerators)
- C. Tambasco, et al., Measurements of transverse Beam Transfer Functions and reconstruction of Landau Damping in the LHC for a single beam (In prep. for Phys. Rev. Accel. Beams)
- S. Antipov, et al., Transverse Beam Stability with Low-Impedance Collimators in the High Luminosity Large Hadron Collider: Status and Challenges (In prep. for Phys. Rev. Accel. Beams)
- S. Antipov, et al., Direct measurement of Landau damping strength at LHC, (In prep. for Phys. Rev. Accel. Beams)
- D. Amorim, Study of the Transverse Mode Coupling Instability in the CERN LHC, CERN-THESIS-2019-272

BACKUP
Potential experimental tests (with coarse time estimates)

Beam based impedance measurement

- Real tune shift of the new collimators at the start and end of the year **(2 times 8 hour, 2021)**
  - Goal: Validation of the impedance reduction and characterization of the radiation effect
  - Method: Multiple single bunches, kick individual bunches several times while moving collimators in and out (using the ADTObsBox data to obtain the tune)
- Total real tune shift measurement **(4 hours, possibly during commissioning 2021 and later)**
  - Goal: Monitor the total effective impedance
  - Method: Multiple single bunches (possibly different intensities), use single bunch kicks and/or BTF to extract the real tune shift at flat top (and end of squeeze if existing)
- Single bunch grow-damp experiment for various chromaticity at top energy **(8h)**
  - Goal: characterization of the impedance via the imaginary tune shift as a function of chromaticity
  - Method: Multiple single bunches. Reduce the octupole current such that the beam is stable with damper and unstable without. Turn off and on the gain on individual bunches (using the ADT gate to vary the gain and the ADTObsBox to obtain the rise time)
- Impedance and orbit tolerance **(8h)**
  - Goal: Quantify the tolerance to orbit variation at the collimators
  - Method: With a single bunch, vary the orbit at a collimator and monitor the real tune shift with kicks (ADTObsBox) and/or BTF

Validation / variation of octupole thresholds

- Determination of the optimal chromaticity and damper gain for single bunch stability **(2 times 8h)**
  - Goal: Determine optimal operational conditions. Validate beam instability models as well as the improvement of the instability latency with the new ADT pickups.
  - Method: Multiple single bunches, adjust the damper gain on individual bunches using the ADT gate, reduce the octupoles in steps of at least 10 minutes. Repeat at various chromaticities
- Single bunch vs train instability threshold at flat top at the start and end of the year **(2 times 4h)**
  - Goal: Monitor the evolution of scrubbing at top energy during the year
  - Method: A single bunch along with bunch trains of various lengths, reduce the octupole current in steps to monitor their stability thresholds
- Stability threshold at low chromaticity **(unknown)**
  - Goal: Understand the role of the longitudinal distribution in the stability threshold at top energy
  - Method: Requires discussion with RF and simulations

Instability latency

- Parametric dependence of the instability latency **(2 times 8h)**
  - Goal: Validate the beam instability model in the presence of noise
  - Method: Multiple single bunches, inject noise with the ADT on a subset of the bunches and reduce the octupole current in steps of 10 minutes and monitor their stability. Once they became unstable, repeat with other settings using other bunches
- The role of 50 Hz lines **(8h)**
  - Goal: Investigate the hypothesis that 50Hz lines may drive the beam unstable
  - Method: With a single bunch at flat top, reduce the octupole current to about 2 times the threshold. Vary the tune in one plane in steps and monitor the beam stability for few minutes at each step. Repeat with a reduced octupole current until the beam becomes unstable
- Landau damping measurement with beam transfer function (BTF) **(2 times 8h)**
  - Goal1: Validate the beam instability model with a direct measurement of the evolution of the stability diagram
  - Method1: Multiple single bunches. Measure the BTF with the octupoles significantly higher than the threshold. Reduce adiabatically the current in the octupoles to about 1.5 times the instability threshold. Introduce artificial noise with the ADT for few minutes and increase the current again to measure the BTF. Repeat the cycle a few times to monitor the evolution of the stability diagram
  - Goal2: Validate the variations of Landau damping driven by long-range and offset collision
  - Method2: Multiple low intensity single bunches in one beam with different collision scheme (single bunches and trains in B2). Perform BTFs on the low intensity bunches at flat top, at the end of the squeeze if existing and in collision with a varying offset at the IP between 0 and 6 sigma.

Related diagnostics

- Fitting the beam response to a kick **(8h)**
  - Goal: chromaticity and damper gain measurement without energy modulation (with full beam)
  - Method: Kick a single bunch and measure the turn-by-turn response with the ADTObsBox. Repeat the procedure for various chromaticity and gain at injection and top energy.
- BTF improvements **(unknown)**
  - Goal: Understand the large noise observed in the BTF phase measurement in run 2
  - Method: To be discussed with BI
- Anti-damper for Landau damping measurement **(8h)**
  - Goal: Assess the potential of the anti-damper method for stability diagram measurement at flat top
  - Method: Multiple single bunches at flat top. Change the damper phase for a given bunch, increase the gain in steps and turn it off the bunch becomes unstable. Repeat the procedure for different damper phase and for different octupole currents

Emittance and beam stability in collision

- Bandwidth requirement in collision **(dedicated 4h and 2 times 1h at end of fill MD)**
  - Goal: Understand whether a damper with a high gain at low frequency can mitigate the emittance growth in collision while maintaining the beam stability
  - Method: In a preparation fill with one train at flat top, setup the ADT with different bandwidth and equalized gain. At the end of a physics fill, change the ADT settings and monitor the beam parameters for at about 1h.