Cohabitation of ADT and Q/Q' Diagnostics Systems

– or –

“Someone's noise is someone-else's signal”

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With input from BE-RF: W. Höfle, D. Valuch et al.

Recap:
Q/Q' Diagnostics and Residual Noise on the Beam I/II

- Initial design assumption: no residual tune signatures on the beam (0 dB S/N)
  - Anticipated constant driving of the beam and – to limit the required excitation levels – the highly-sensitive BBQ system was developed
    - further exploited by a FFT and PLL system
  - Hypothesis: BBQ nm-level sensitivity would be sufficient to operate below the “radar” of excitation impacting operation/protection (less than 1 μm)
    - seemed to be confirmed by tests in the SPS, RHIC, Tevatron, …

- After the start-up we were blessed (and/or cursed):
  1. BBQ proved to provide a turn-by-turn resolution of better than 30 nm
     - 30+dB more sensitivity than other LHC systems (ADT: 1μm, BPM: 50 μm)
  2. Ever-present residual Q oscillations on the few 100 nm to few μm level

- Luxurious 30-40 dB signal-to-noise ratios enabled the passive monitoring, tracking and feedbacks without additional excitation
  - reliable from day-one for more than a year now, controlling large tune variations during basically every LHC ramp (and most squeezes)
  - Helped also to identify other beam perturbation issues (mains, hump, etc.)

Recap: Q/Q' Diagnostics and Residual Noise on the Beam II/II

However...

- While great for passive monitoring, the nm- to µm-level beam oscillations are incoherent ("noise") from a FFT/PLL point of view of using explicit excitations.

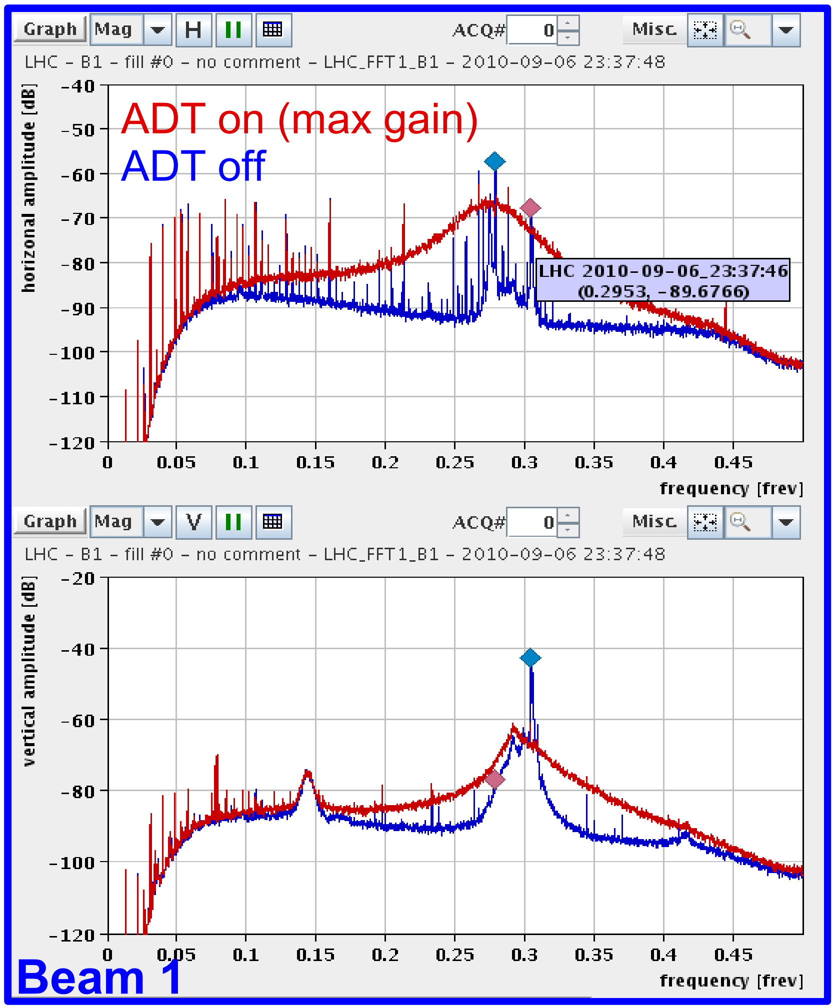
- Regardless of whether using FFT or PLL:
  - Need to excite ~30 dB above this "noise" to recover the performance of using residual oscillations only (→ 60 dB above BBQ noise floor!):
    - Tune tracking: min. ~20 dB (assuming $|C^{-}|$=const)
    - Coupling measurement: min. 18 dB (better 26 dB)

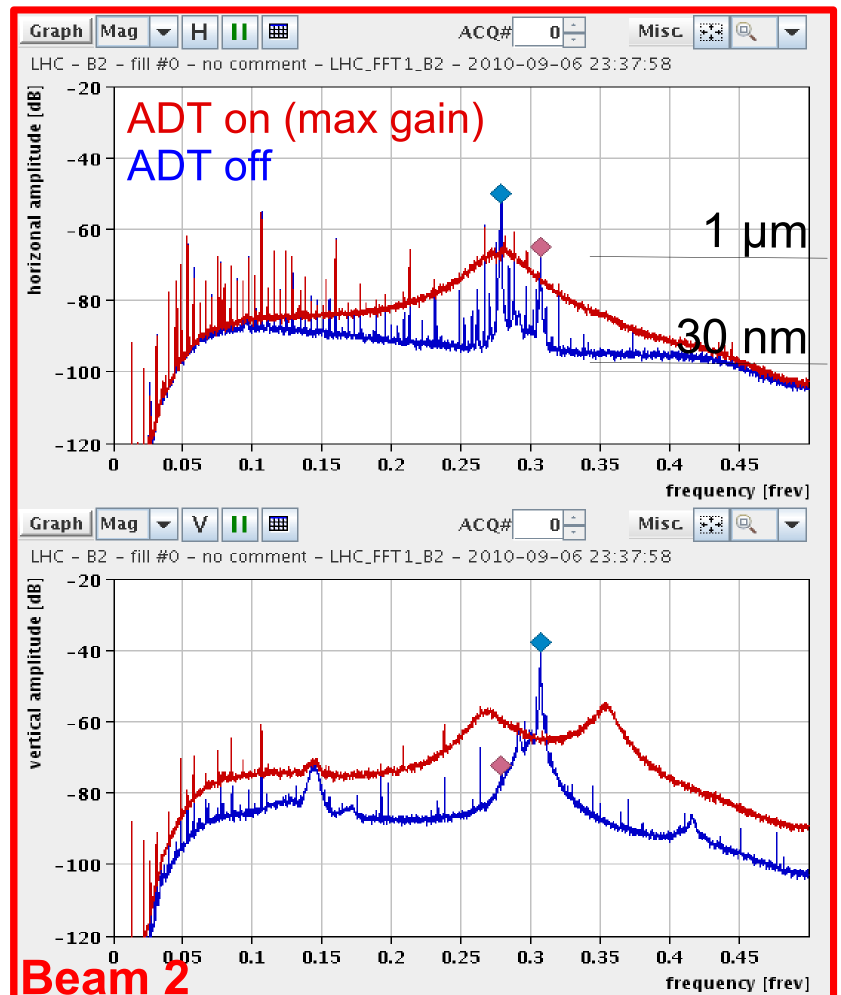
    → corresponds to ~10 to 100 µm oscillations
  - For comparison: collimators tolerances at about 200 µm
    - tight window between not locking/tracking and causing beam loss
    - uncertainties on BTF due to collective effects, ADT phase/gain, …
  - Driving the beam with such ample signals seemed to be inefficient and less robust compared to the performance achieved with the passive-only system and was considered to be used mainly if the signal would drop...

- Since recently, ADT is used to regularly damp injection oscillations and (with exception of flat-top and squeeze) kept 'on' also during ramp and collisions
  - Damping performance improved from a few hundred turns to < 50!!
  - However: as for any other feedback, higher feedback bandwidths ("gain") imply also more measurement noise propagated to the beam...

ADT Interference on Tune Diagnostic
Example: 0.1 Hz-Avg. BBQ Spectra @450 GeV, one nominal bunch

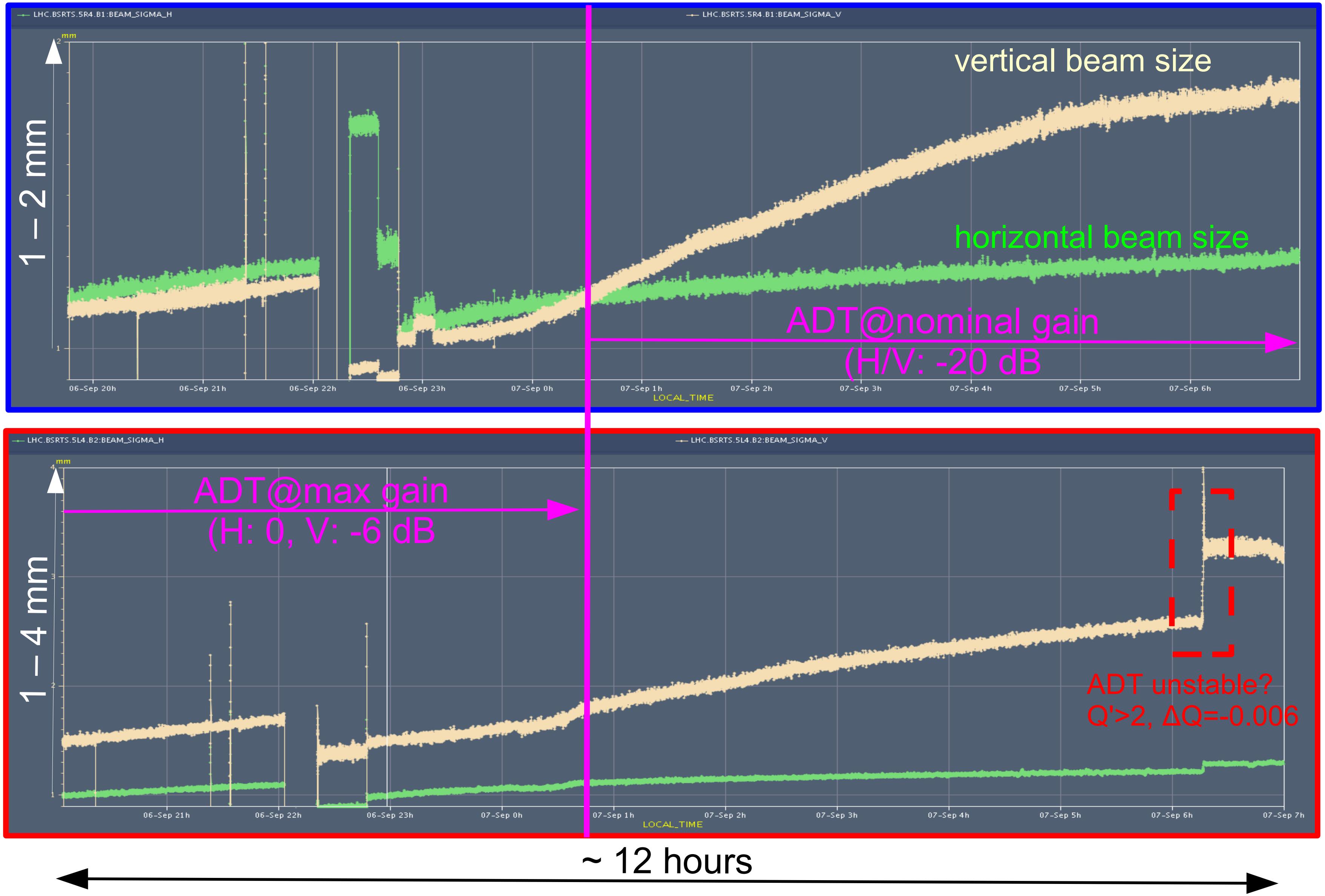
- BBQ noise-floor raised by 30 dB, wide Q-peak → reduces $\Delta Q_{res} \sim 10^{-4} \rightarrow \sim 10^{-2}$
  - Impacts reliable tune (and coupling) measurement & feedback
  - incompatible with Q'-measurements using small Δp/p-modulation
  - loss of additional beam stability diagnostics on mains harmonics, hump, etc.





High-Gain ADT Operation & Transverse Emittance Growth @ 450 GeV

- Not a performance issue: ADT noise/gain does not impact/deteriorate ε_n

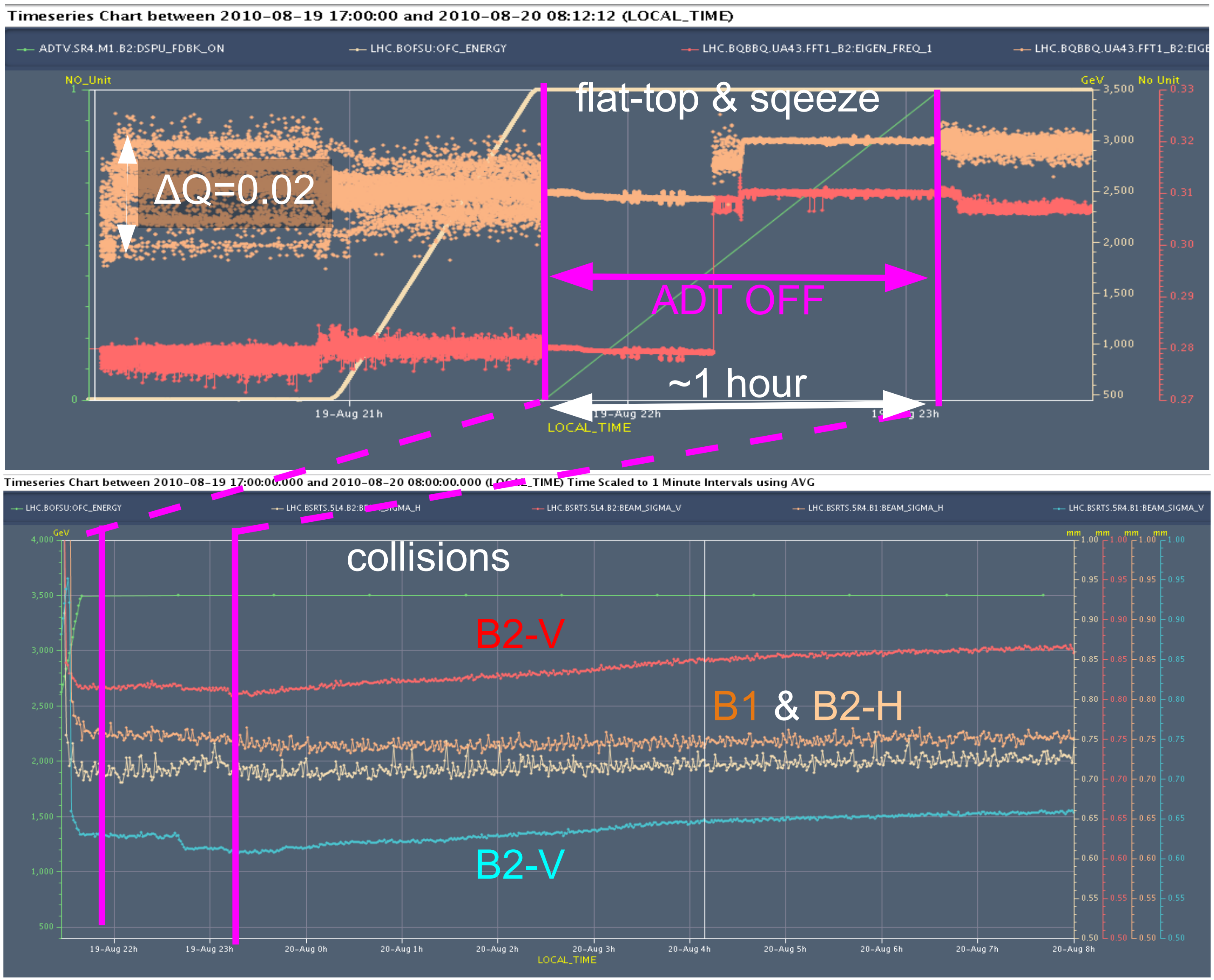


High-Gain ADT Operation & Transverse Emittance Growth @ 3.5 TeV (50b Physics Fill)

- … but has a measurable impact on the achievable tune resolution:

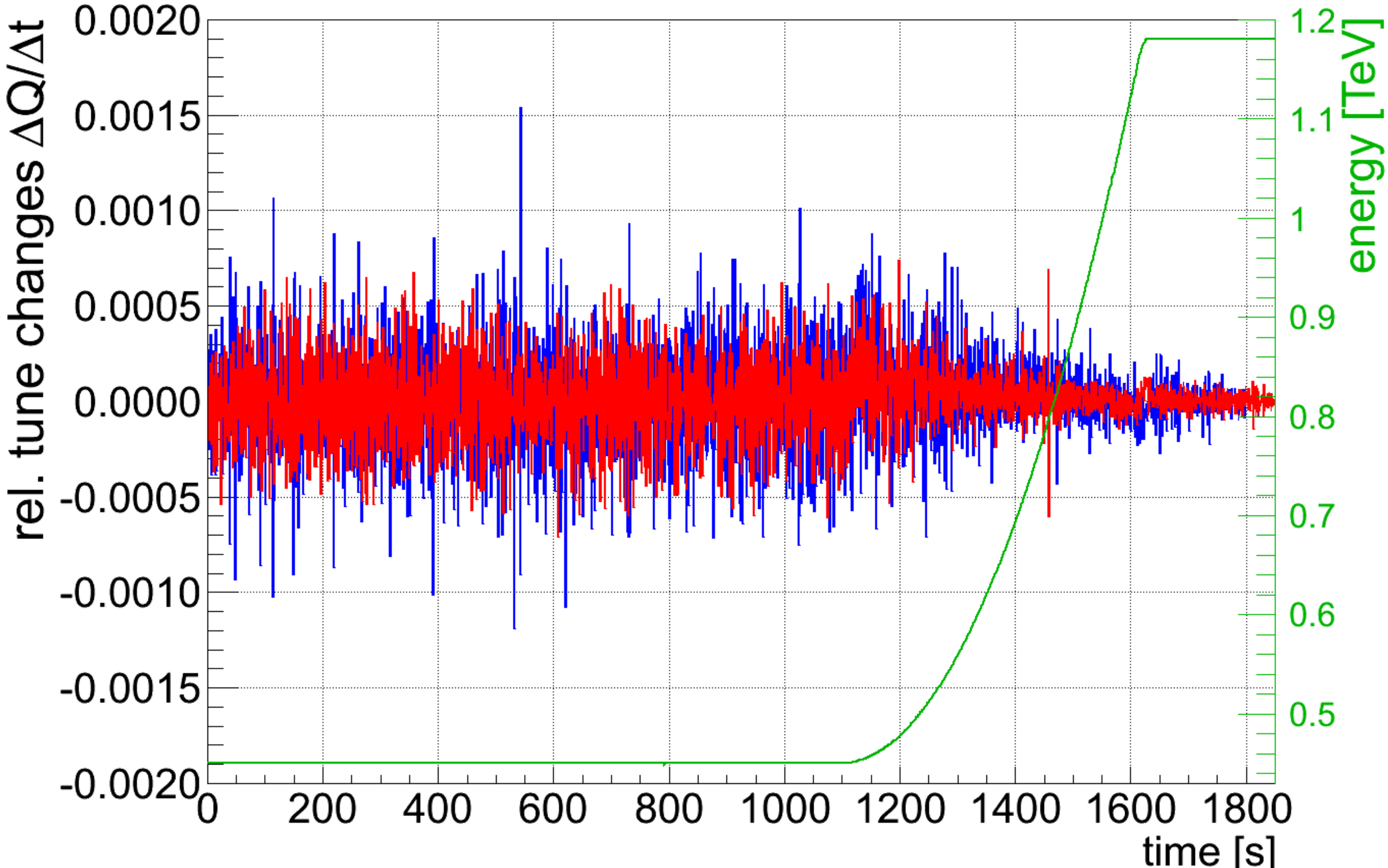
Tunes:

Beam sizes:



For comparison:
Residual LHC Tune Stability without ADT

- Example (3. ramp 2009-11-30 @00:15):



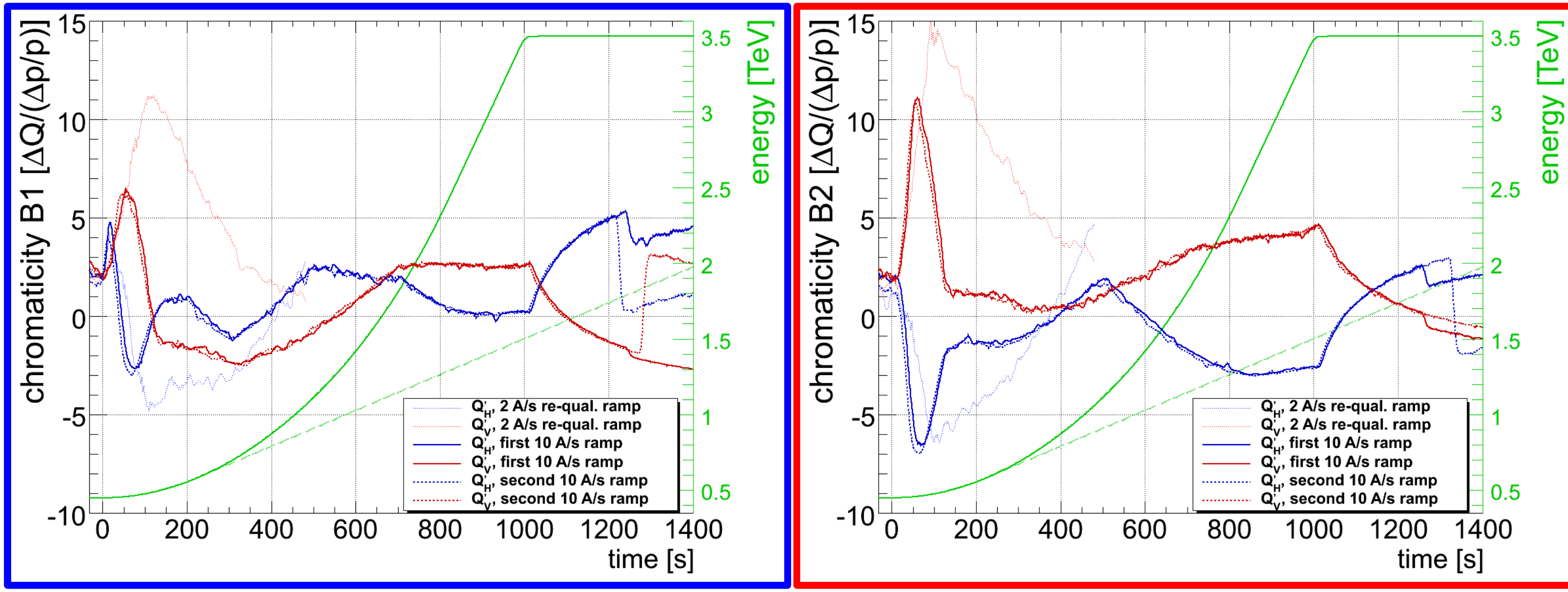
  – Residual tune stability $\Delta Q \approx 5 \cdot 10^{-4}$ at injection energy
    - (in-spec) noise on RQT[D/F] circuits (5mA vs. max. 600 A)

Challenge of Measuring Q'(t)

- Real-life test/challenge for required Q-resolution and measurement bandwidth
  - $Q'(t) \rightarrow \Delta Q_{res} < \sim 10^{-4}$ @ 2.5 Hz
  - $Q(t) \rightarrow \Delta Q_{res} < \sim 10^{-3}$ @ 2.5 Hz

  } Inputs to operators & feedbacks → need to be robust as possible

- Q'(t) via radial modulation ($\Delta p/p = 2\cdot 10^{-4}$@0.25 Hz, limit: res. Q stability @450 GeV)



- With nominal beam (ADT on) "challenging" to measure Q', limits:
  - $\Delta p/p\cdot Q' > \Delta Q_{res} \sim 0.005$ ($\Delta p/p > 2\cdot 10^{-4}$ impractical/incompatible with nominal beam)
- Default OP procedure: switch ADT 'off' → meas. Q' → switch ADT 'on'
  - Switching ADT 'on'/'off' has little/no impact on lifetime/ε-blowup

Options to make Q/Q' Diagnostic compatible with the primary ADT Function I/II

Reduced of tune S/N ratio is primary limiting factor, primary option at hand:

1. Low(er) ADT gain after injection until end-of-squeeze
   - presently the only viable, reliable and available option until end of 2010
2. High ADT gain for first N-turns after injection, then lower-gain
   - same as above, but would simplifies operational procedures at injection

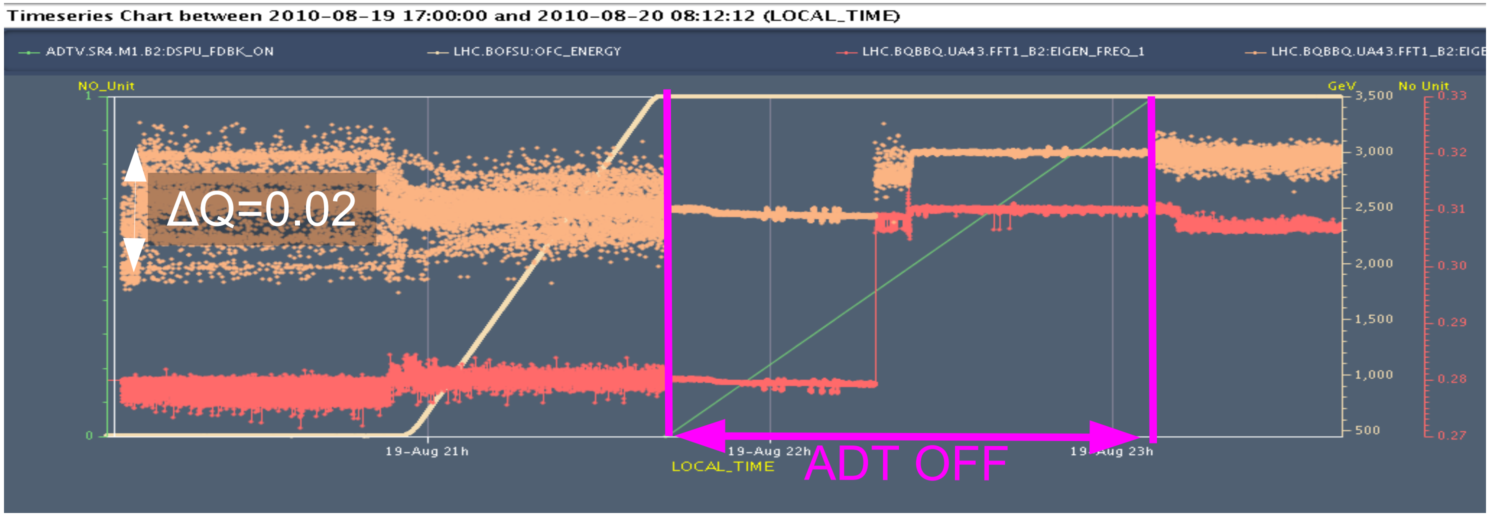
- Three ADT use-cases affecting the Q/Q' diagnostics:
  - A Injection damping (few turns)
  - B Damping during collisions (e.g. beam-beam driven oscillations)
    - very slow tune drifts allow mitigation via longer averaging periods

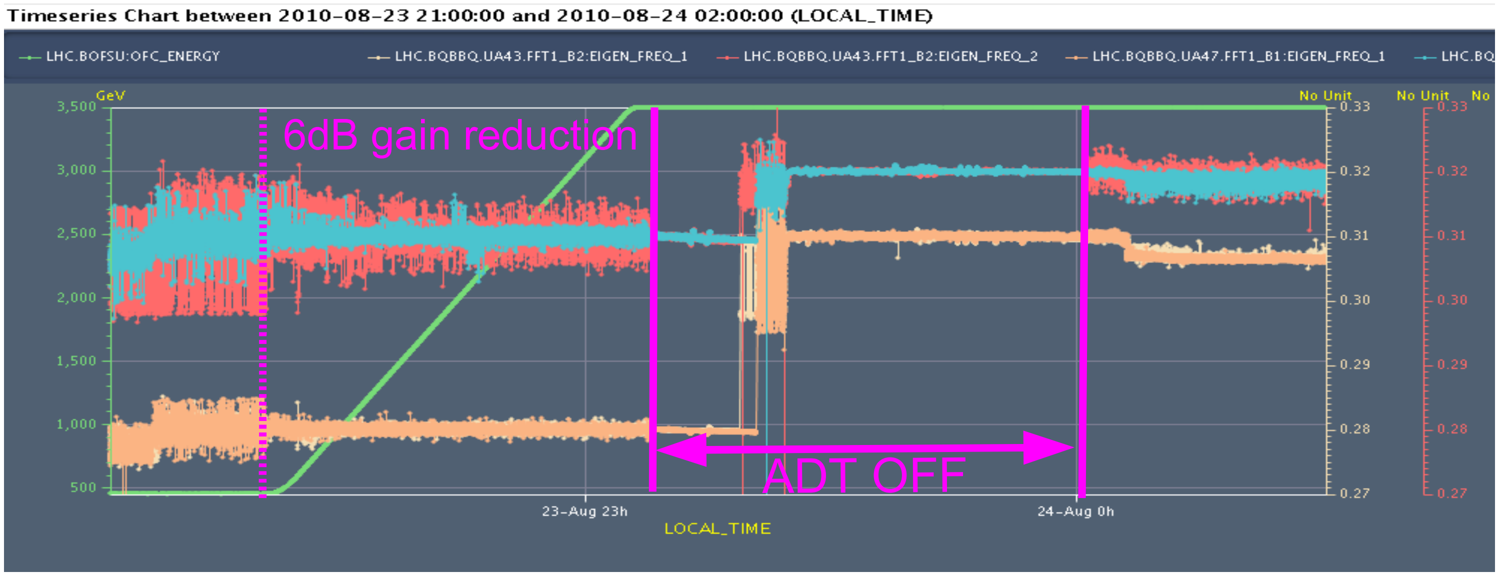
  Present situation OK:

  no or little impact of high-gain operation on Q/Q' diagnostics

  - C Operation after injection until end of squeeze → noise is an issue
    - Impact of gain-reduction on day-to-day operation seems to be is small:
      - Little/no impact on emittance growth or beam losses
      - Rare (no?) single- or coupled-bunch instabilities (provided Q'>0)
    - In addition: some operatonal ε_n-blowup margin in the PS (Mike dicit)

Test: ADT Gain/Noise Impact on Q/Q' performance





- 6dB gain reduction helps but not sufficient for all operational cases (Q', hump, ...)
- Alternative: need to excite the beam... by up to 20 dB more than with ADT 'off'

Options to make Q/Q' Diagnostic compatible with ADT Function II/II

Reduction of tune S/N ratio (30+dB→5dB) is primary limiting factor:

1 Low(er) ADT gain after injection until end-of-squeeze
- presently the only viable, reliable and available option until end of 2010

2 High ADT gain for first N-turns after injection, then lower-gain

3 Sacrifical (e.g. non-colliding) bunch for which ADT is disabled/low-gain
- ADT ready, BBQ bunch selector needs further development (loss of S/N)

4 Dead-band in ADT gain function masking oscillations below noise floor
- Simulation, tests with beam and firmware update required

5 Deriving tune from ADT exciter signal (see additional slides)
- more operational long(er)-term experience needed w.r.t. robustness, resolution, etc.

6 High ADT gain & Q-PLL exciting ~30+ dB above ADT's noise floor
- not without issues: required oscillation amplitudes can reach up to ~100 μm, losses!
- complex dependence on ADT gain, energy, intensity, collective effects,...

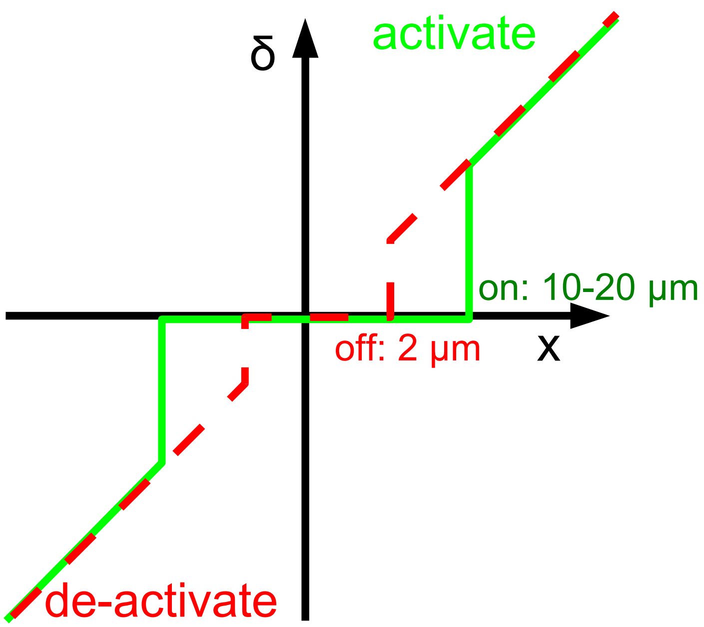
7 High ADT gain & Q-PLL exciting ~30+ dB above 10x lower ADT noise-floor
- same as before, but much preferred as ex. levels are less critical (max. 10 μm)
- feasibility of noise reduction needs to be demonstrated
- more operational long(er)-term experience needed w.r.t. robustness, etc.
- require beam-time for commissioning (e.g. in parallel to regular loss-map checks?)

8 High ADT gain & using tranverse Schottky monitor
- operational long-term experience needed w.r.t. robustness, achievable bw. etc.

Additional supporting slides

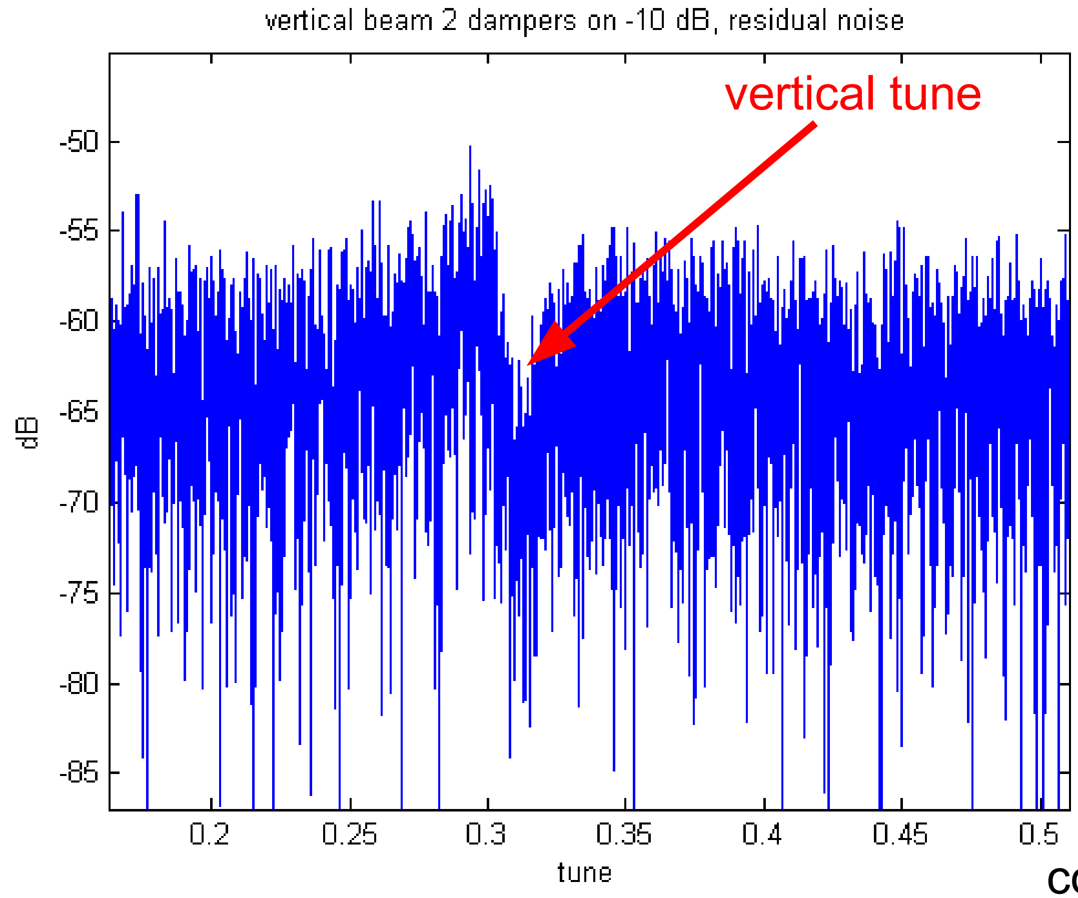
ADT Dead-Band

- Hypthesis: there are no instabilities that are constantly driving the beam
  - 'True' for present beam configuration but needs revisiting for smaller bunch spacing
- Two different thresholds to control the gain (switch 'off'→ 'on' → 'off')
  1. activate damper if instabilities exceed n-um
  2. de-activate damper if oscillations are below m-um (e.g. after x-turns)
  - For example: m = 2 μm < n =10-20 um & x = 50
- Strictly: Non-linear hysteresis filter but keeps it linear if ADT is 'on'
- Would fail if frequency of instability occurrences is too high
  → however, should have strong tune signatures in ADT exciter then..



ADT Dead-Band vs. Deriving the Tune from ADT Exciter Signal

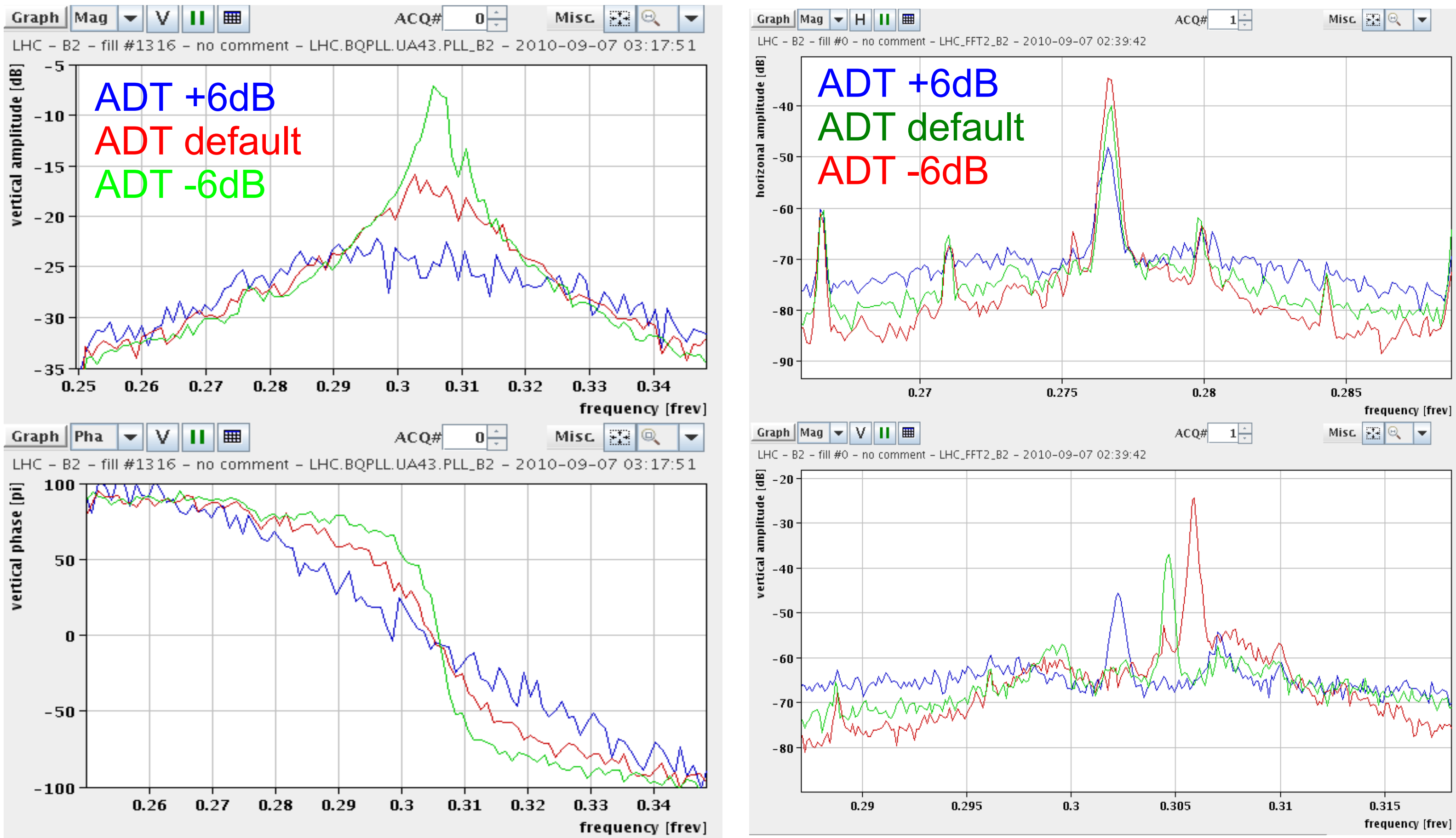
- Two complementary options depending on the actual strength and occurrance frequency of instabilities and coupled bunch modes in the LHC:
  - Rare: → dead-band is the better option (= damp only unstable beam)
  - Frequent: → ADT exciter signal contains modes and their frequencies
    - issue: reliability and achievable meas. bandwidth $\Delta Q_{res} < 10^{-3}$ @ 2.5 Hz?



courtesy W. Höfle

Interdependence between Tune-PLL and ADT

- Tune-PLL not a 'silver bullet' solution but will be further explored:
  - Complex BTF dependence on damper gain/phase, collective effects:



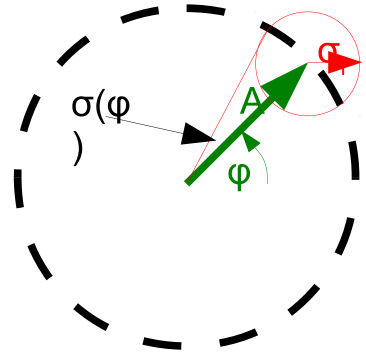
  - Requires excitations 30+ dB above noise floor for reliable signal/lock and coupling measurement: noise ~1 μm → excitation can go up to 100 μm
  - Detected tune peak shifts with effective damper gain: ± 6dB ↔ $\Delta Q \approx 3 \cdot 10^{-3}$

Required S/N ratio for Tune and Coupling Diagnostics I/II

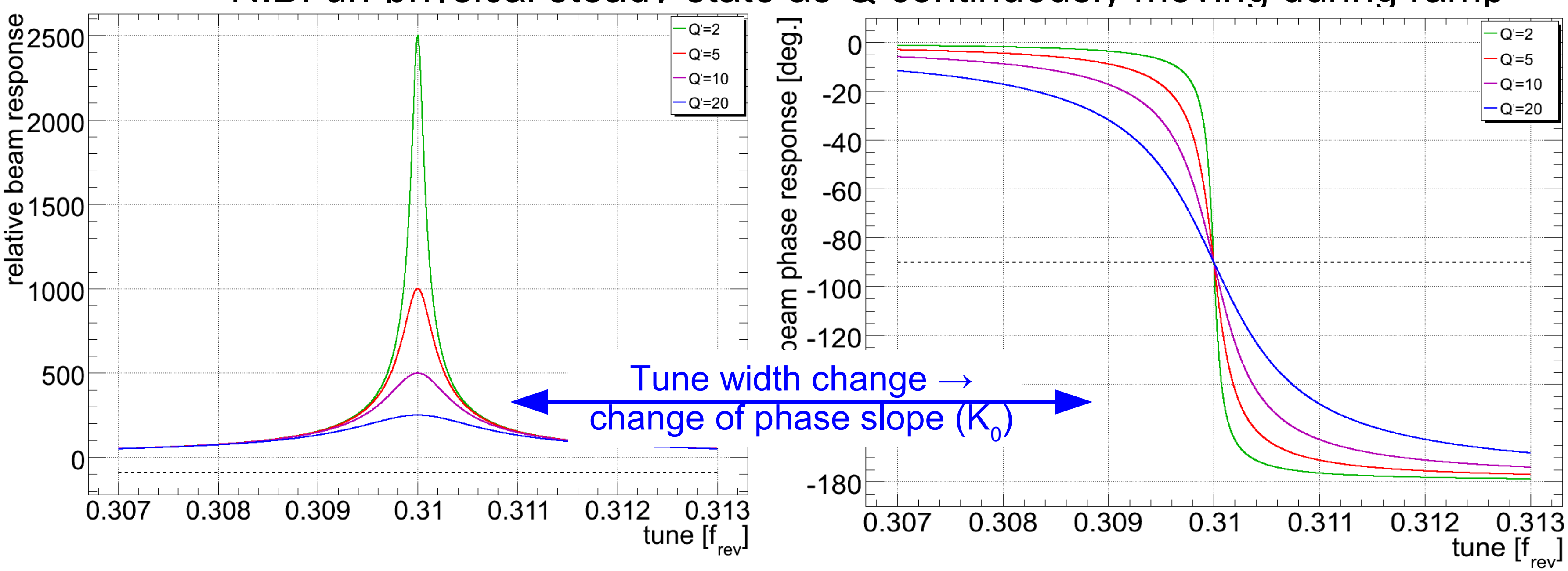
- Initial Q-PLL design assumption violated:
  - no residual tune oscillation, need to drive the beam to get some signal
- Non-PLL “random” signals add vectorial to PLL driven one:

$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$



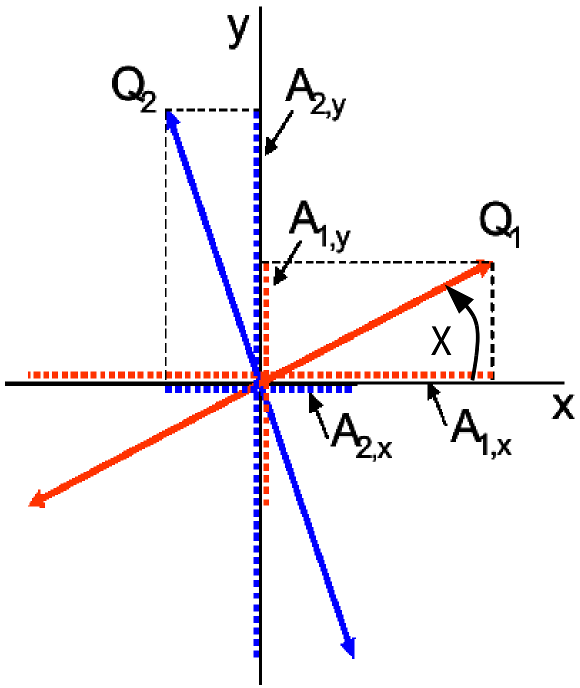
  - To lock ($\Delta Q_{res} \approx 10^{-4}$): ~20 dB S/N
  - Once locked: $\Delta\varphi \approx 0.5°$ → 8 dB S/N@2.5Hz
    - N.B. un-physical steady-state as Q continuously moving during ramp



Required S/N ratio for Tune and Coupling Diagnostics II/II

- Closest-tune approach not practical while ramping
- Use ratio between regular and cross-term instead:
  - $A_{1,x}$: eigenmode amplitude '1' in horizontal plane
  - $A_{1,y}$: eigenmode amplitude '1' in vertical plane

$$r_1 = \frac{A_{1,y}}{A_{1,x}} \quad \wedge \quad r_2 = \frac{A_{2,x}}{A_{2,y}}$$



$$\Rightarrow \quad |C^-| = |Q_1 - Q_2| \cdot \frac{2\sqrt{r_1 r_2}}{(1+r_1 r_2)} \quad \wedge \quad \Delta = |Q_1 - Q_2| \cdot \frac{(1-r_1 r_2)}{(1+r_1 r_2)}$$

  - requiring resolution so that $\Delta|C^-| < 0.1\ |Q_1-Q_2|$, and $r = r_1=r_2 > 0$

    → required N/S ration r < ~0.05 ↔ S/N ~ 26 dB

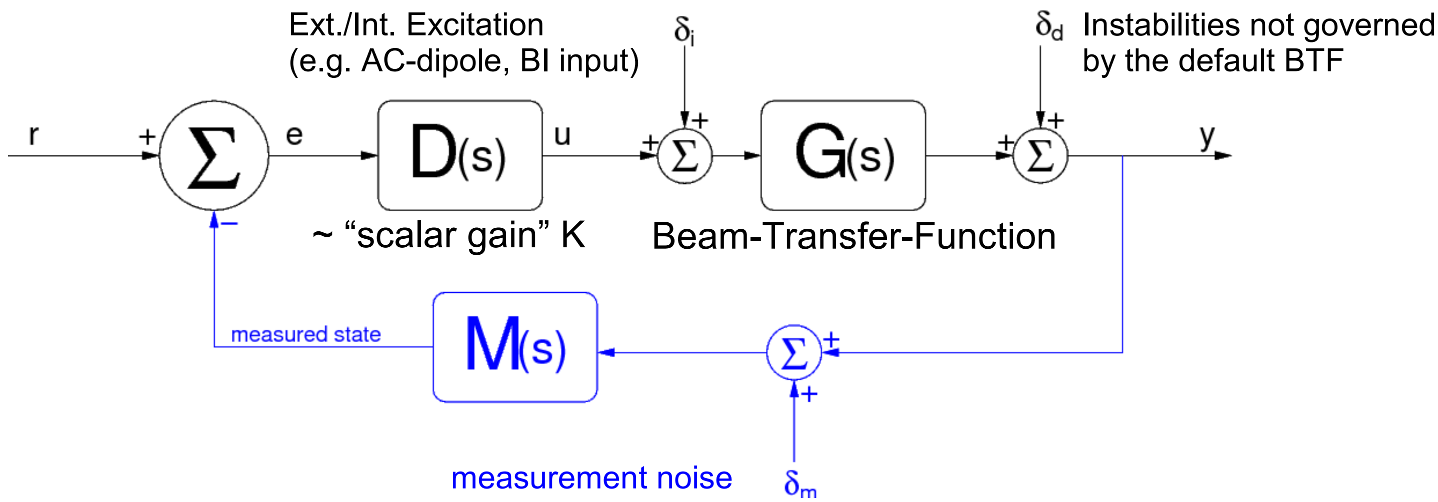
  - requiring resolution so that $\Delta|C^-| < 0.5\ |Q_1-Q_2|$, and $r = r_1=r_2 > 0$

    → required S/N ~ 20 dB

R. Jones e.al., “Towards a Robust Phase Locked Loop Tune Feedback System”, DIPAC'05, Lyon, France, 2005

Simplified ADT Mechanics

- Limit of proportional controller gain and noise



- Increasing the gain of D(s) → ∞ (positive only around Q) implies:

transfer function/ noise sensitivity:	$T_0(s) := \frac{y}{r} = \frac{D(s)G(s)}{1+D(s)G(s)}$	→	**1**
Disturbance rejection:	$S_{d0}(s) := \frac{y}{\delta_d} = \frac{1}{1+D(s)G(s)}$	→	**0**
nominal input sensitivity:	$S_{i0}(s) := \frac{y}{\delta_i} = \frac{G(s)}{1+D(s)G(s)}$	"A bit less fast"/ "hump damping" →	**0**

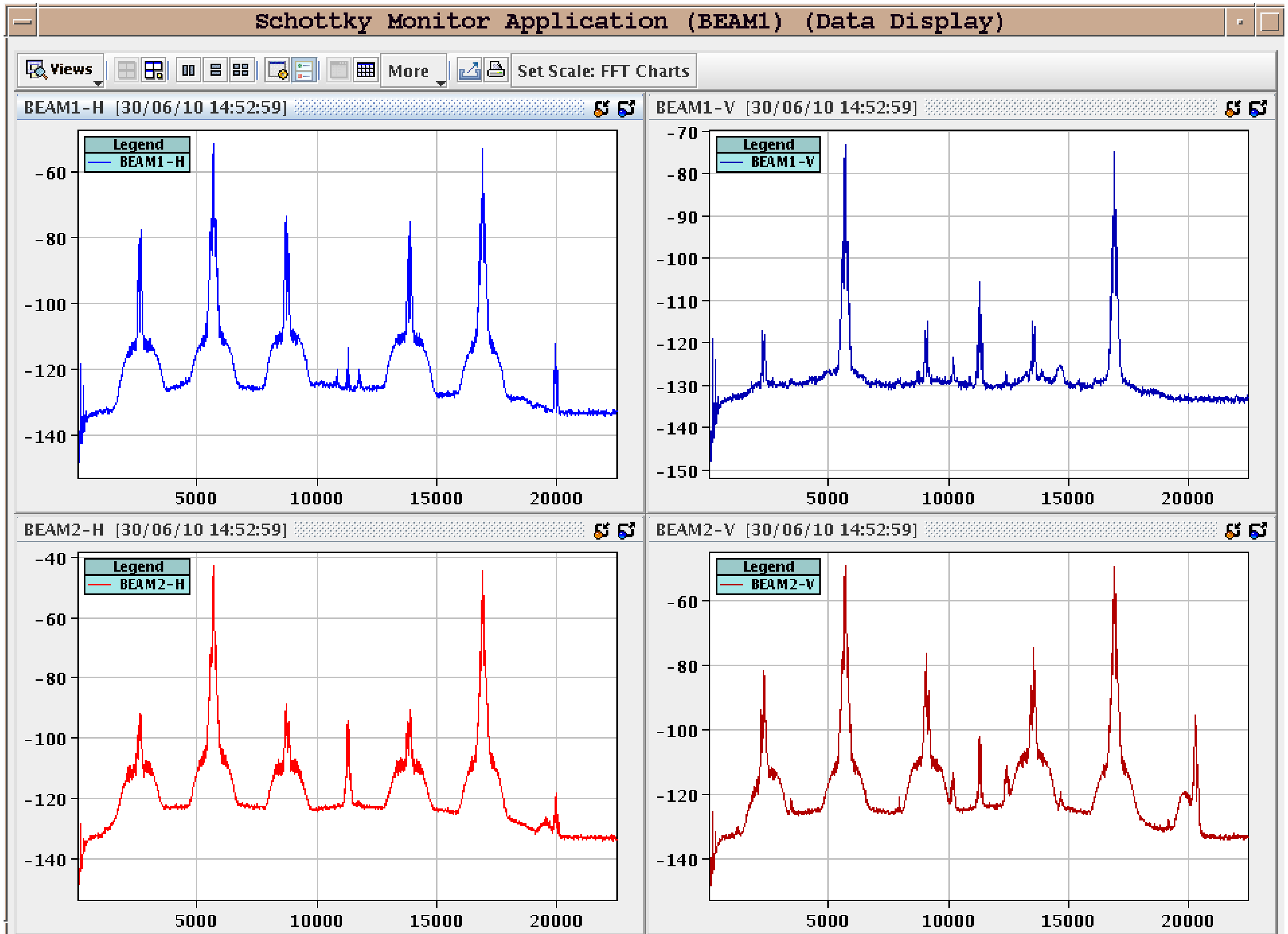
→ better attenuation of instabilities but also more propagated noise

Cannot have one without the other…

…requires a trade-off between reducing and δ_i/δ_d and minimising the impact of δ_m

The forgotten child: Transverse Schottky

- Operates at a frequency well above (4.8GHz) the ADT bandwidth (<20 MHz)
  - issue: reliability and achievable meas. bandwidth $\Delta Q_{res} < 10^{-3}$ @ 2.5 Hz



Beam Loss in Response to ΔQ=0.005 (Q2.L1)

- Switched from PLL- to k-mod studies (ADT back to nominal, Q'>~2):
  - Missing diagnostics: lost 40% of B2 – ADT saviour or culprit?