Feedbacks: Status, Operational Dependencies and Outlook for 2011

Ralph J. Steinhagen, BE-BI

Acknowledgments: M. Andersen, A. Boccardi, S. Fartoukh, M. Gasior, S. Jackson, R. Jones, M. Lamont, E. Metral, B. Salvant, J. Wenninger, operations crew, ..

Main Aim – somewhat criticial Review of:

- Feedback Issues and Reliability
  - What were the main issues? Are they fixed now?
  - Improvements in view of 2010 operation

- Feedback and Q/Q' Diagnostics Performance
  - LHC stability in terms of Q/Q', feedback/-forward operation
    - Can we do better?
    - What about Q' measurements/control?
  - Dependence of LHC operation on feedbacks
    - Could/should we run without feedbacks?
  - Q/Q'-diagnostics and issues related to transverse-feedback

Brief Summary on Feedback and Q/Q' Issues during 2010

- Genuine OFC software bugs and deficiencies/errors in FB logic
  → shaken-out and fixed (by July) and running stably ever-since
- False-positive Quench-Protection-System trigger on real-time trims
  - Several back-and-forth iterations until R. Denz suggested to increase the dead-time for the U_{res} evaluation from 20 to 190 ms → now OK
  - After RQT[D/F] experience we never dared to use sextupoles and MCBX
    → circuits may become critical for orbit stability with small β*
- Unannounced kernel updates and IT's denial-of-service attacks during beam operation → Caused some real beam dumps and down-time!
  - Necessary but should be coordinated and done during e.g. technial stops!
- Most remaining issues related to instrumentation quality and FB integration:
  - Tune-FFT: Locking on interferences → filter chain rejecting non-tune lines
  - Tune-PLL operation OK but not (yet) as robust as the previous one (e-blow-up)
  - Transverse damper/abort-gap-cleaning interference → not resolved!
  - Operational failures → improving integration & automation in sequencer

- Most 'teething' problems sorted and should be OK for 2011 operation, but...

Disclaimer: while designed to have a optimal performance, availability and reliability in mind, the OFC may require further modifications, improvements of its operation, fault-tolerance or other adjustments in response to the changing or new operational requirements. Any resemblance to real persons, living or dead is purely coincidental. Some assembly required. Batteries not included. Use only as directed. No other warranty expressed or implied. Do not use while operating a motor vehicle or heavy equipment. This is not an offer to sell securities. May be too intense for some viewers. If condition persists, consult your BI expert. No user-serviceable parts inside. Subject to change without notice. Times approximate. Please remain seated until the feedback has come to a complete stop. Breaking silence or not replying within 2 minutes constitutes acceptance of agreement. Contains a substantial amount of non-tobacco ingredients. For LHC use only. Not affiliated with the American Red Cross. Keep cool; process promptly. List was current at time of presentation. Not responsible for direct, indirect, incidental or consequential damages resulting from any defect, error or failure to perform. No penalty for private use. Sign here without admitting guilt. Contestants have been briefed on some questions before the show. No purchase necessary. Use only in a well-ventilated area. Keep away from fire or flames. Do not write below this line.

Planned Feedback Updates and Modifications for 2011 I/II

- Dynamic Orbit Reference – basically OK and functionality in place since '08
  - needs further tests and integration into LSA, sequencer and YASP
  - N.B. Masking of BPMs during Squeeze is a 'hack', initially meant for testing but not to be used operationally due to error-prone settings management and intrinsic orbit perturbations at boundaries

- Automatic feedback 'gain-scheduling':
  - Anticipatory using beam mode and energy:
    - Increase bandwidth to counteract fast perturbations during snap-back
    - Reduce bandwidth to minimise measurement noise propagation
  - Depending on magnitude of error signal
    - 'Fast' during initial activation, also fast step response for transients
    - Gradual reduction as the parameter stabilises around reference

- Energy-FB: RF synchronisation (↔ tides) and energy matching (↔ b_1 decay)
  - centres orbit and enables Radial-Loop alongside Orbit-FB after first inj.

- Minor changes → “spring cleaning”
  - com. protocols, logging, clean-up of dead-code or unused functionalities

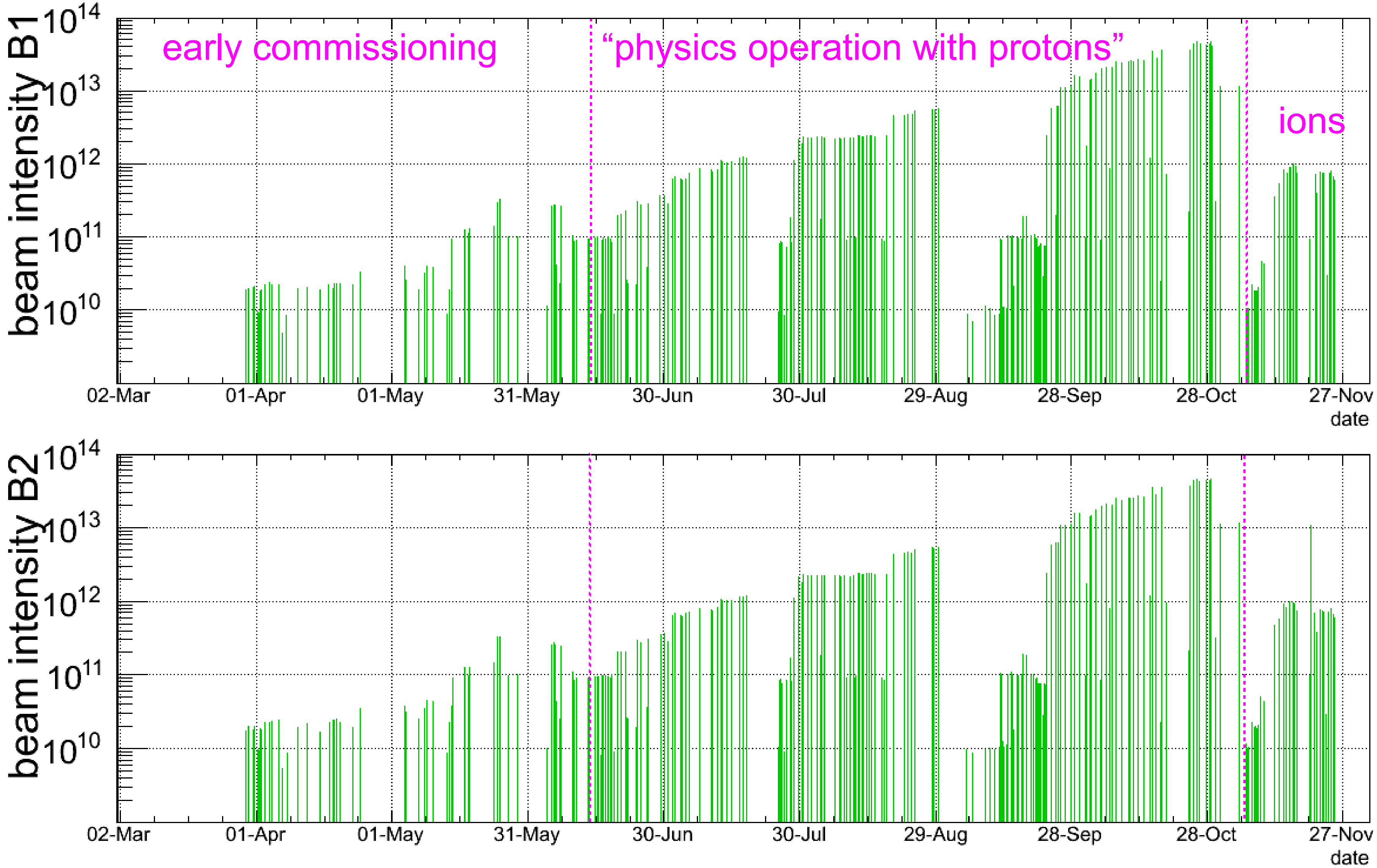
Planned Feedback Updates and Modifications for 2011 II/II

...and of course everything else operations requests from BI Santa Claus.
Our new friendly support team is looking forward to your requests:

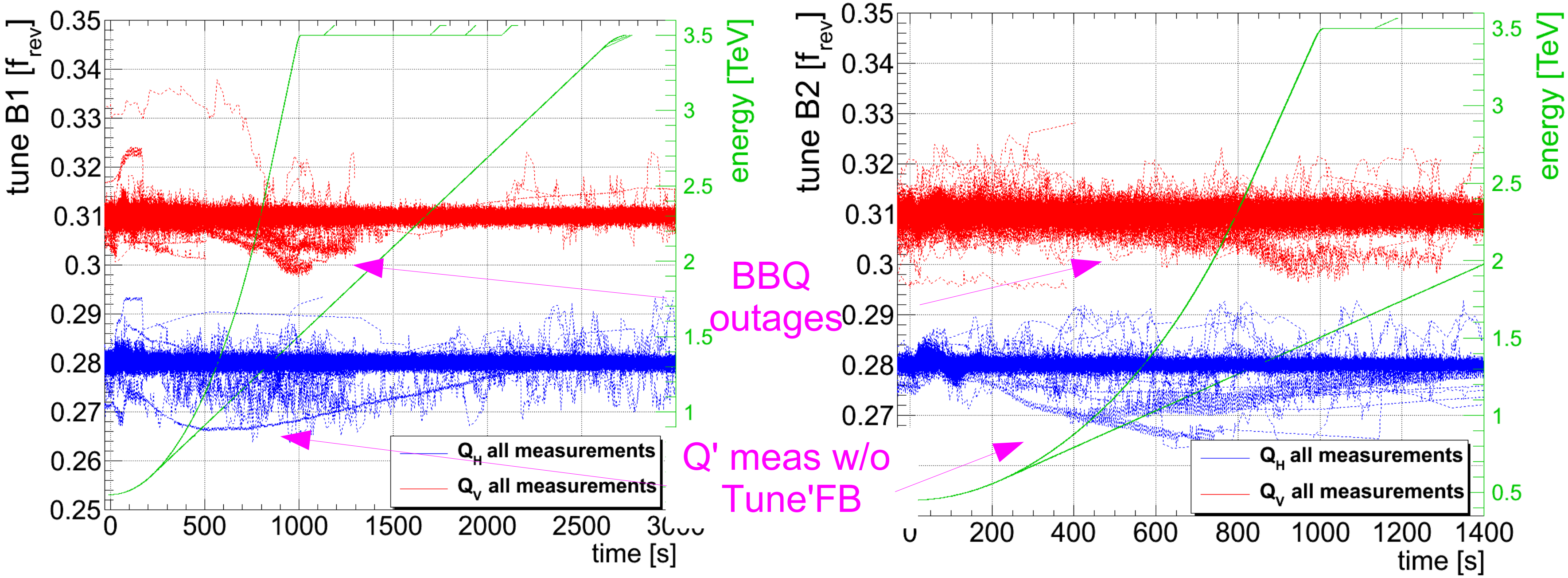
...sorry the others were busy or already booked before Christmas

Q/Q'-Stability and Feedback Performance

- Analysed a total of 275 ramps, excluded most of early ramps in 2009



Residual overall Tune Stability in 2010



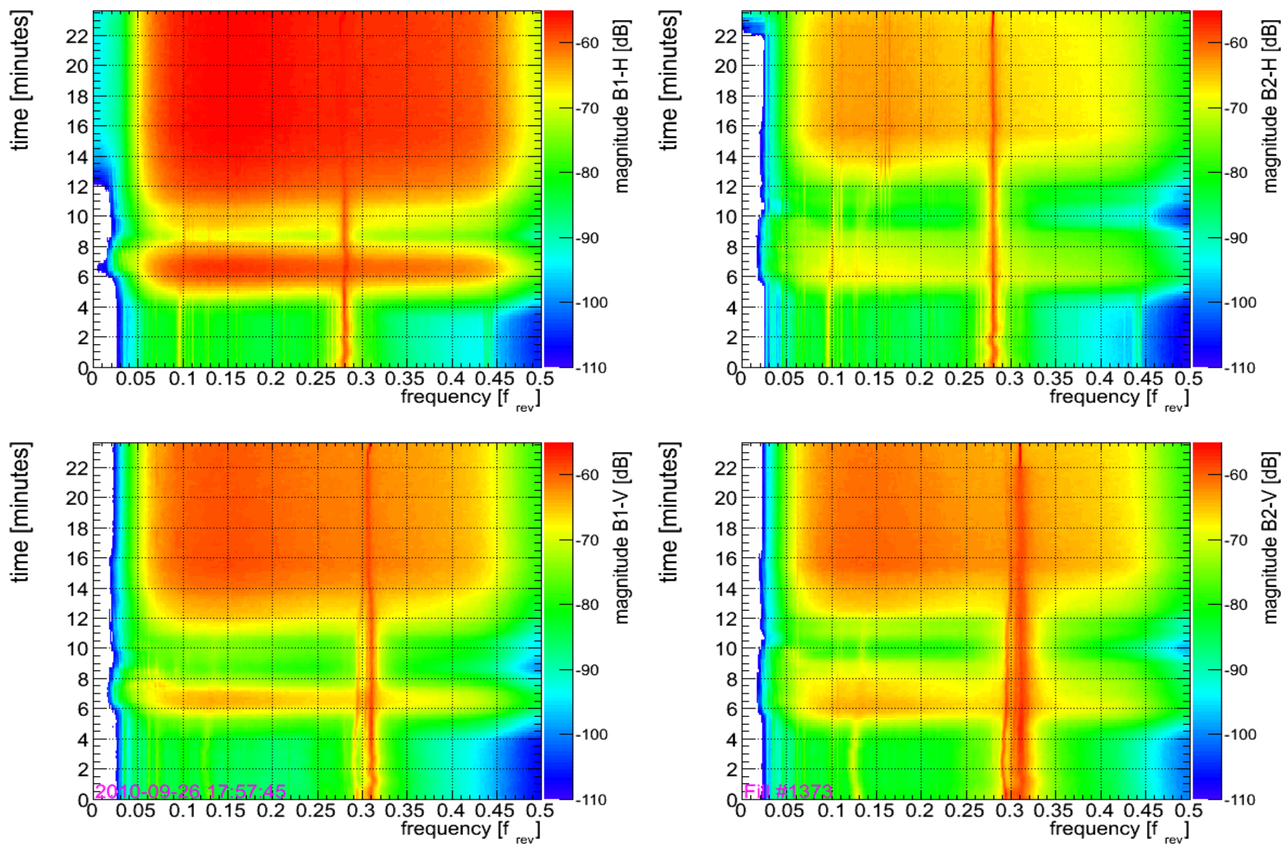
- 155 ramps with > 99% transmission
- 169 ramps with > 98% transmission
- 178 ramps with > 97% transmission
- 12 ramps lost (6 with Tune-FB during initial 3.5 TeV commissioning)

- 122 ramps with > 99% transmission
- 155 ramps with > 98% transmission
- 168 ramps with > 97% transmission
- 10 ramps lost (5 with Tune-FB during initial 3.5 TeV commissioning)

- Impressive performance for the first year of operation and low-ish intensities
  - caution: 1% loss of nominal beam may become more criticial in 2011

BBQ Outages

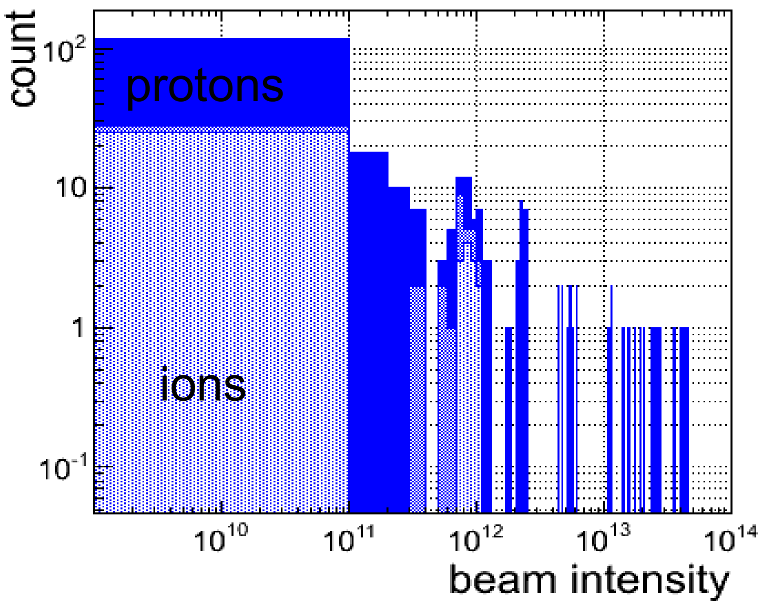
- A bit scary: combination of added low-pass filters and long. bunch shape oscillations (side-effect of long. Blow-up)

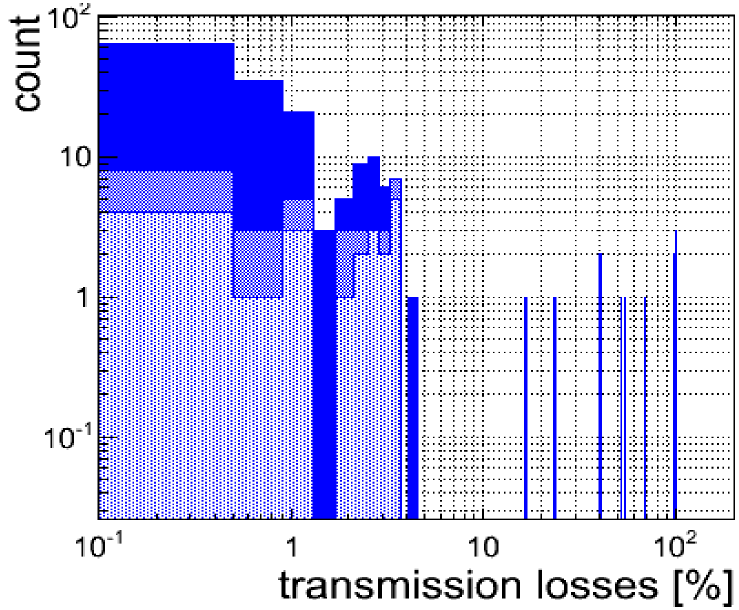


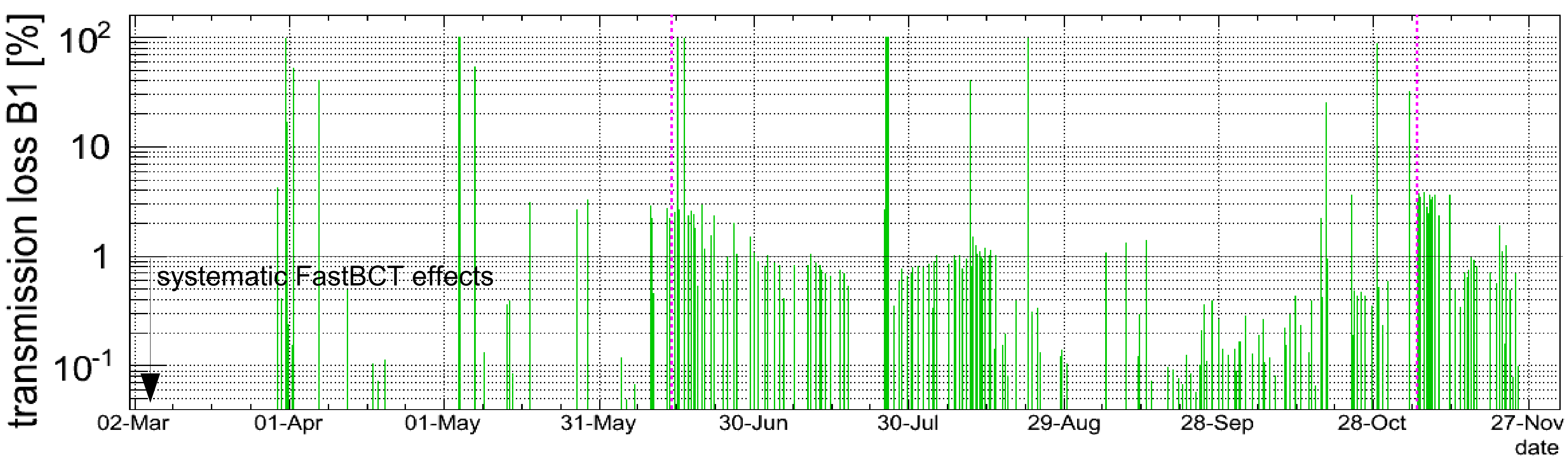
- Reverted to old scheme (no LP filters + improved BBQ) → OK for now
  - Long. perturbations still present but tune lines less attenuated
- Lesson(s) learnt – BBQ diagnostics
  - remains complex and delicate depending on what you throw at it
  - important part of spectra derives from in-bunch motion (f > 400 MHz)

Maximum Intensity and Transmission Loss during the Ramp Beam 1

- Most losses when switching mode of operation (single bunch → trains → ions)

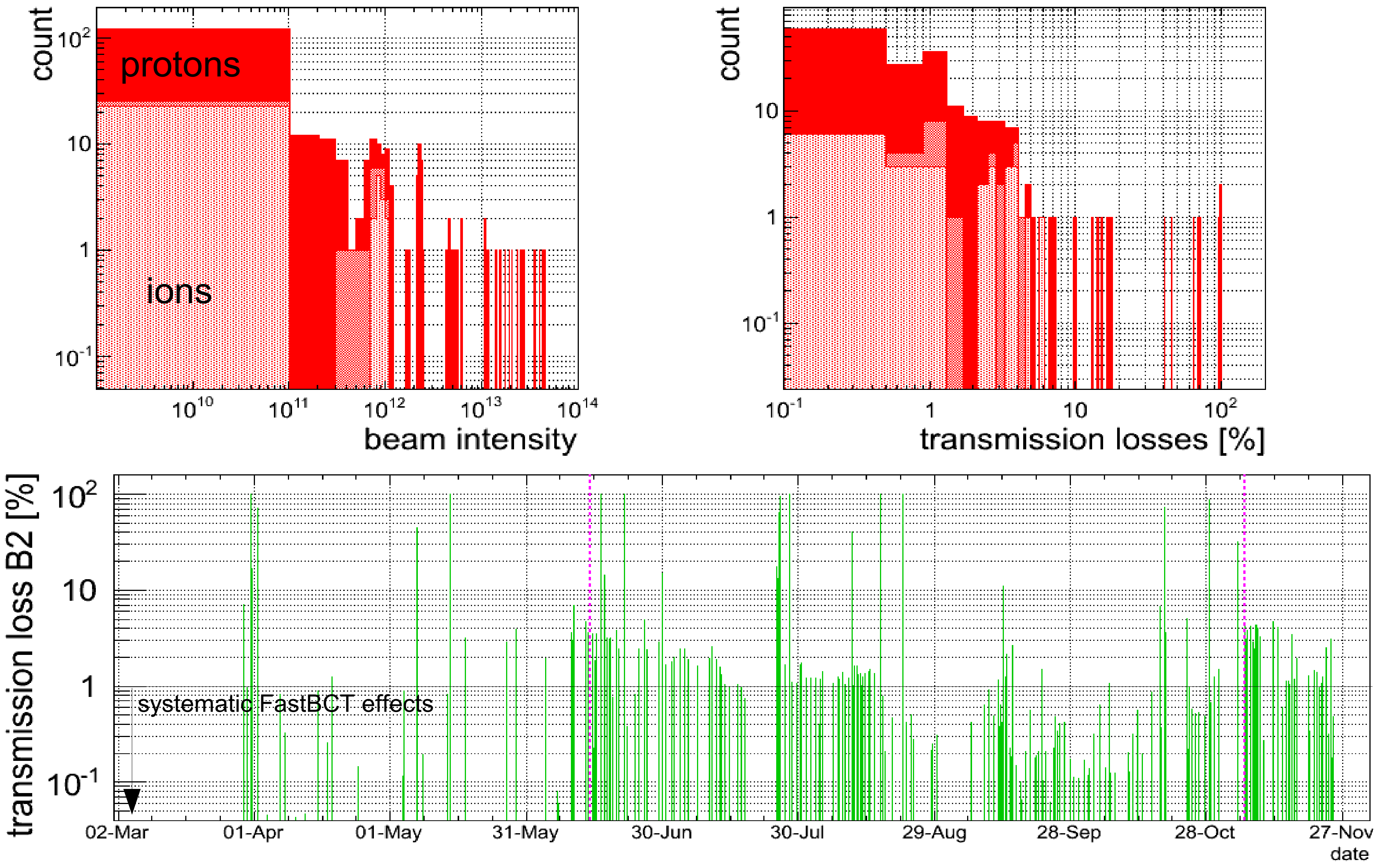






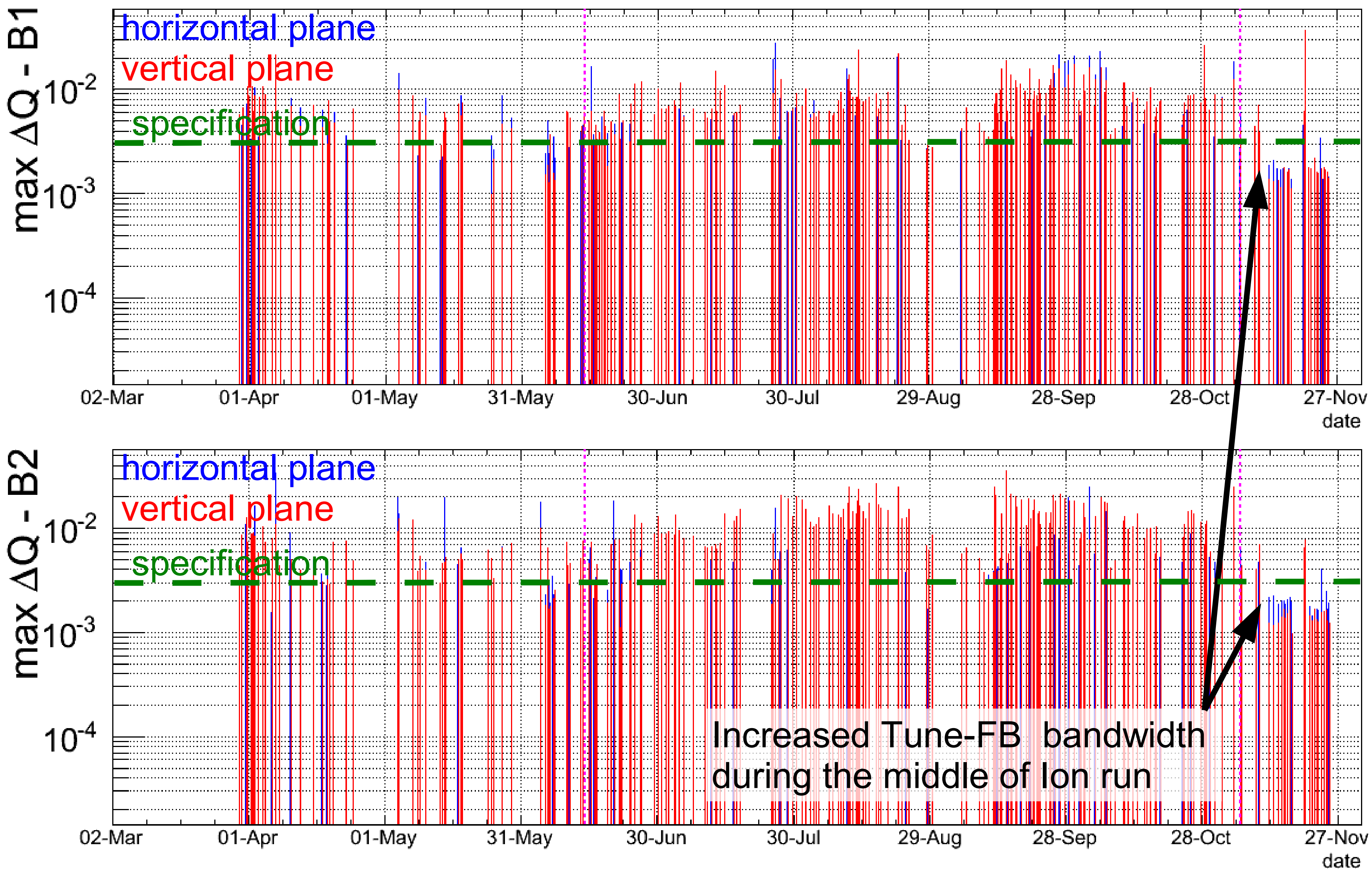
Maximum Intensity and Transmission Loss during the Ramp Beam 2

- Little/no impact of Q'(t) measurements on transmission but on knowledge
  (scraped halo though that wouldn't have contribute to luminosity and eventually been lost anyway on collimators)



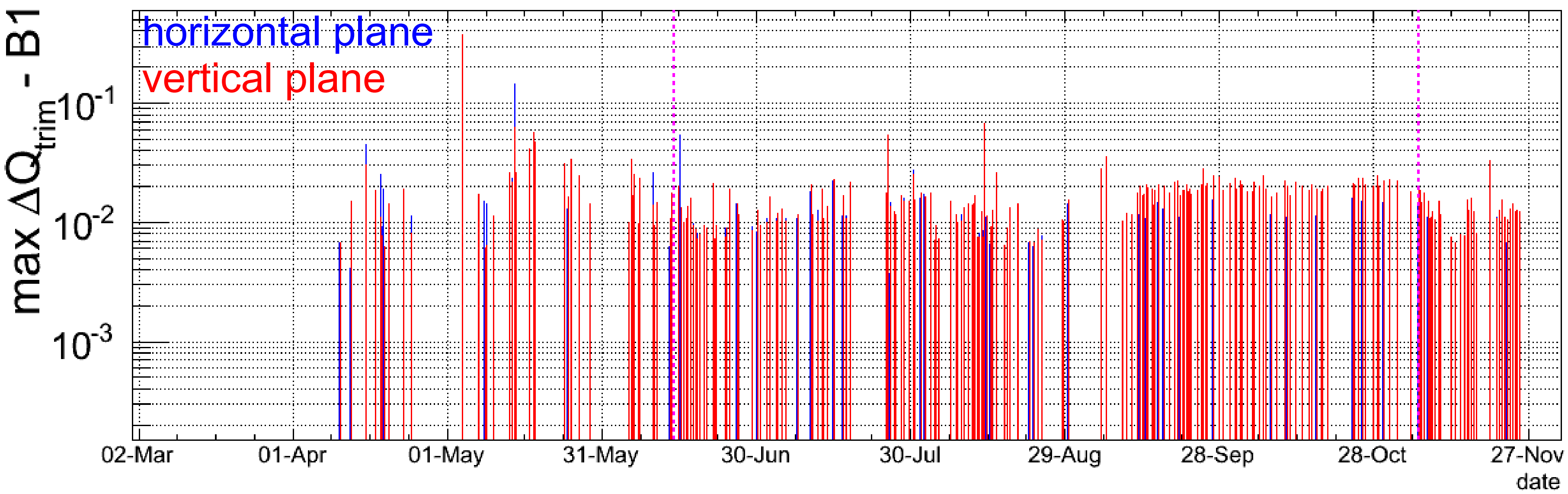
Peak-To-Peak Tune Variations

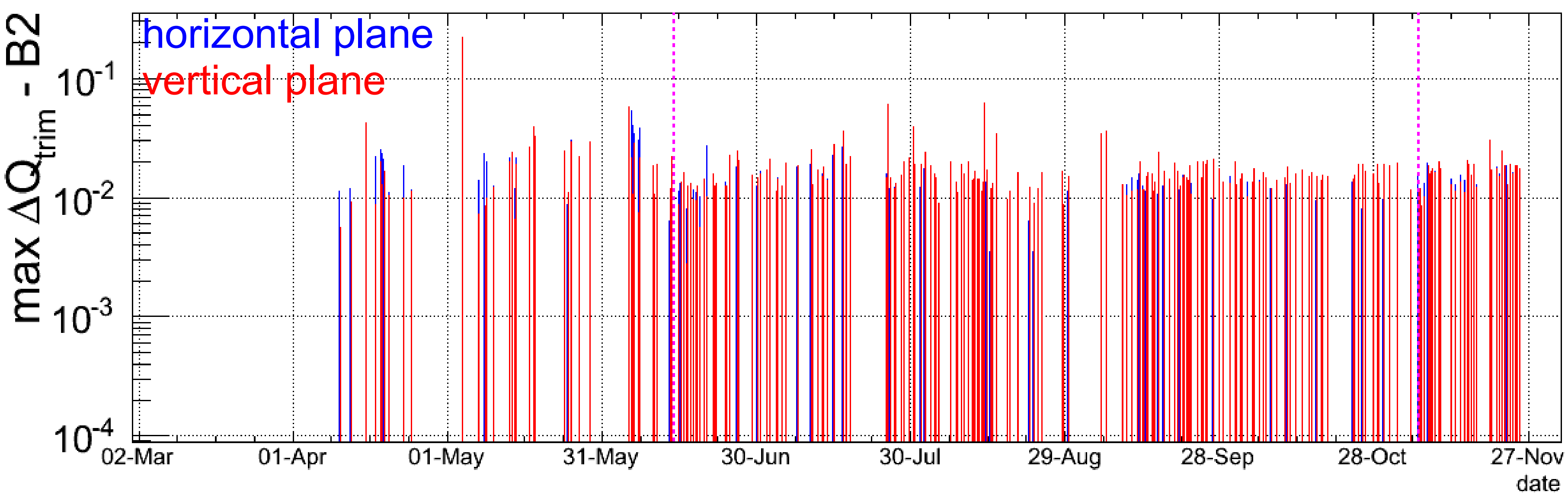
- Steady Tune-FB performance dominated snap-back...



Peak-To-Peak Tune Trim Variations

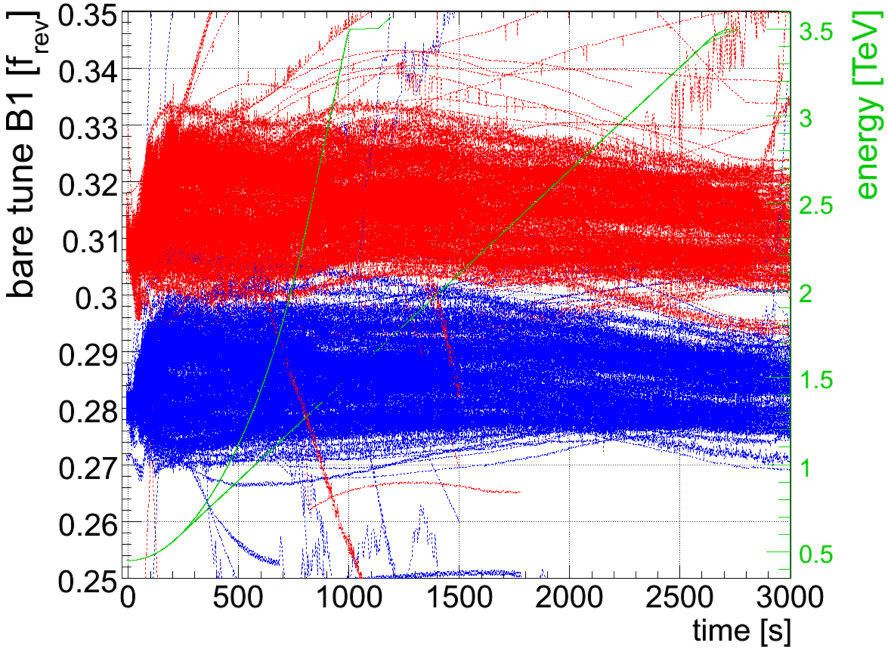
- … tune trims rather increased than decreased over time (lack of feed-forward)

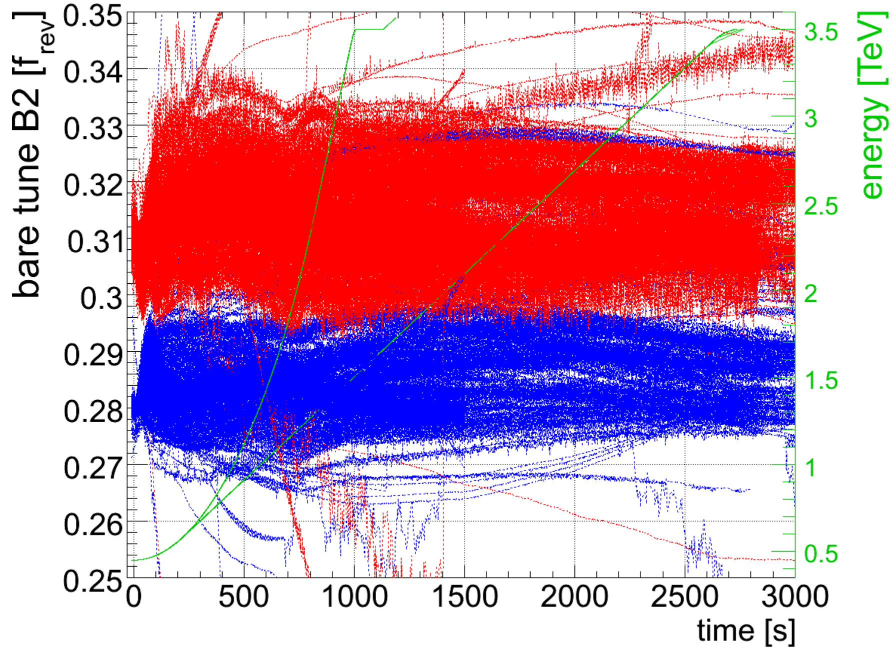




'What-if-... Scenario' Analysis – Out of 191 Ramps...

- Ramp dynamics and variations are compensated/absorbed by Tune-FB



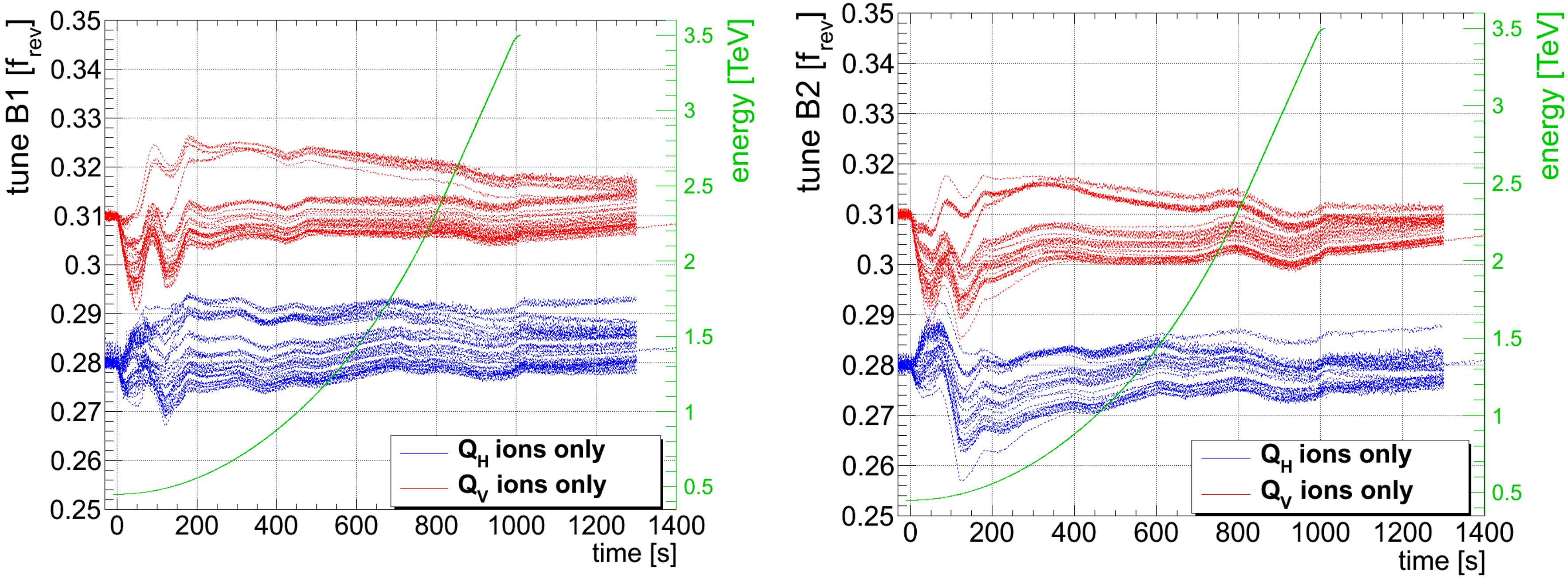


- … 56 lost due to low-order (3^{rd},4^{th},C^{-}) resonance crossing without Tune-FB
- … 150 exceeding ΔQ=±0.01 tolerance
- … all above nominal ΔQ=±0.0015 limit

- … 83 lost due to low-order (3^{rd},4^{th},C^{-}) resonance crossing without Tune-FB
- … 157 exceeding ΔQ=±0.01 tolerance
- … all above nominal ΔQ=±0.0015 limit

Un-Folded or Raw- Tune Stability during Ion Operation

- Stability during ion operation:

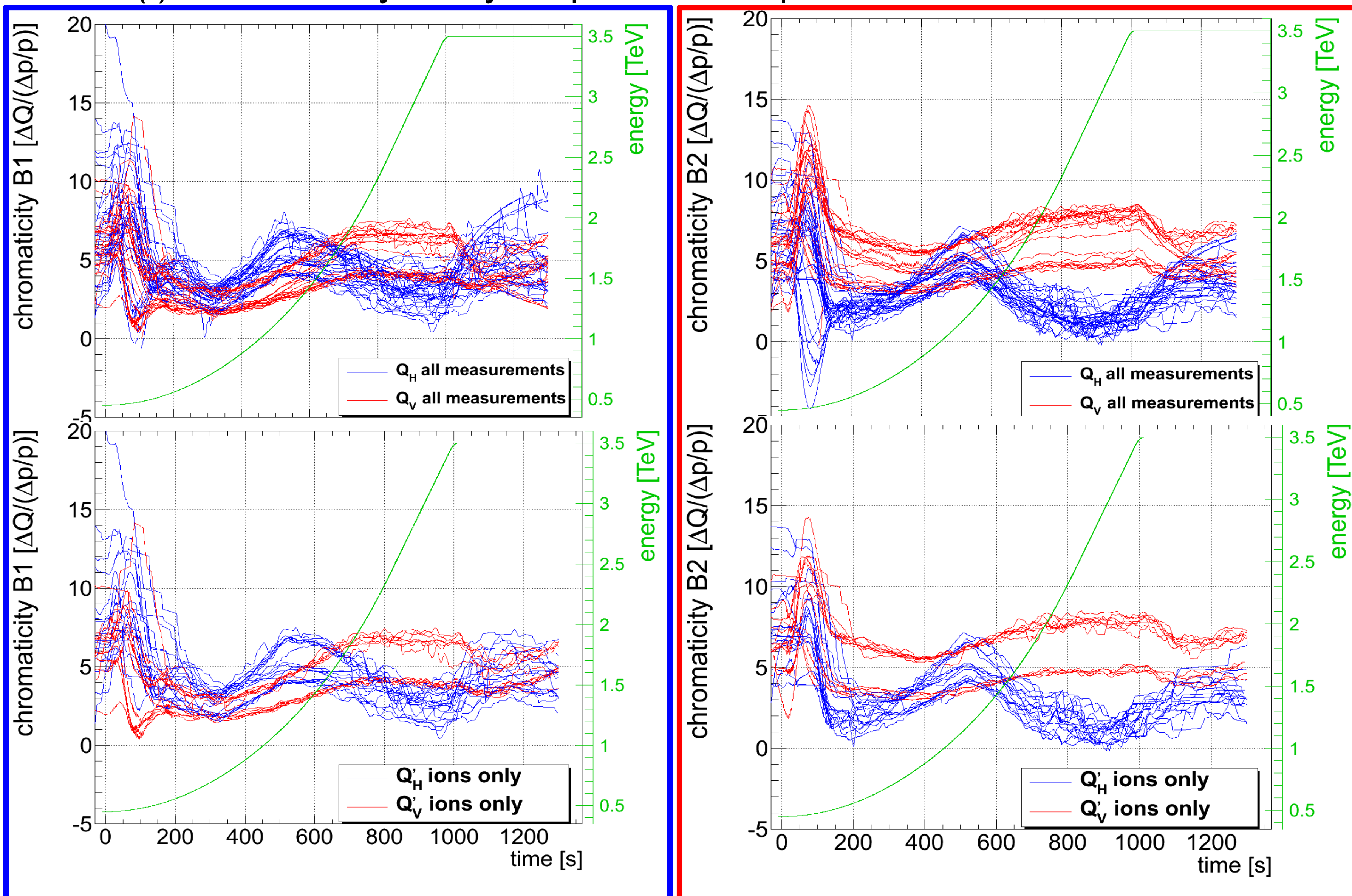


- Biggest fill-to-fill tune variations during snap-back, either
  - direct from MQs (not well modelled/difficult to measure → Ezio's talk), or
  - indirect via feed-down from Q' snap-back (tune trims ↔ Q'(t))
    - Tune-trims are correlated with measured Q'(t)

→ Tune-FB will be probably needed during every ramp and squeeze in 2011

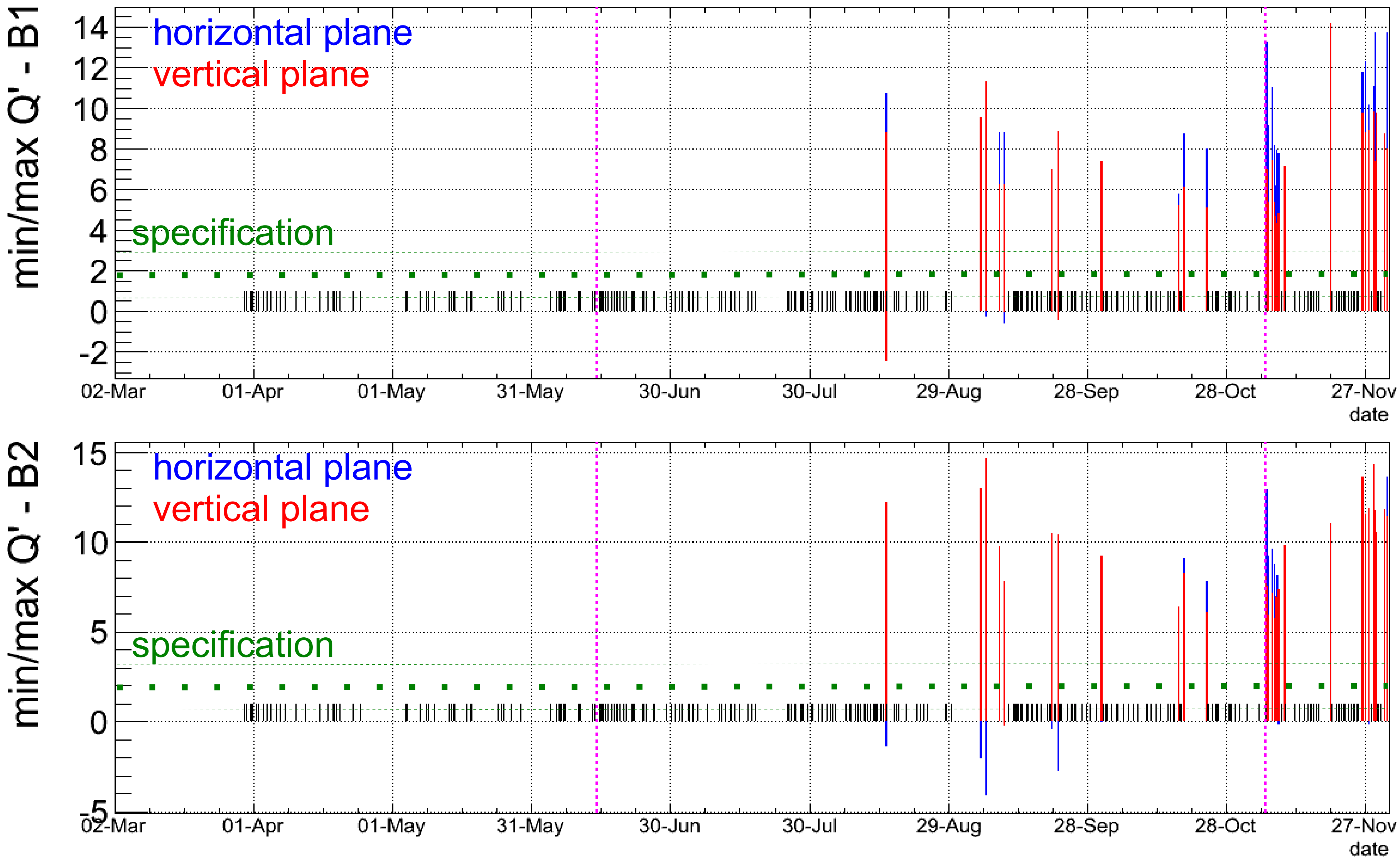
Residual overall Chromaticity Stability

- Q'(t) dominated by decay/snapback at ramp start and end→ Ezio's talk



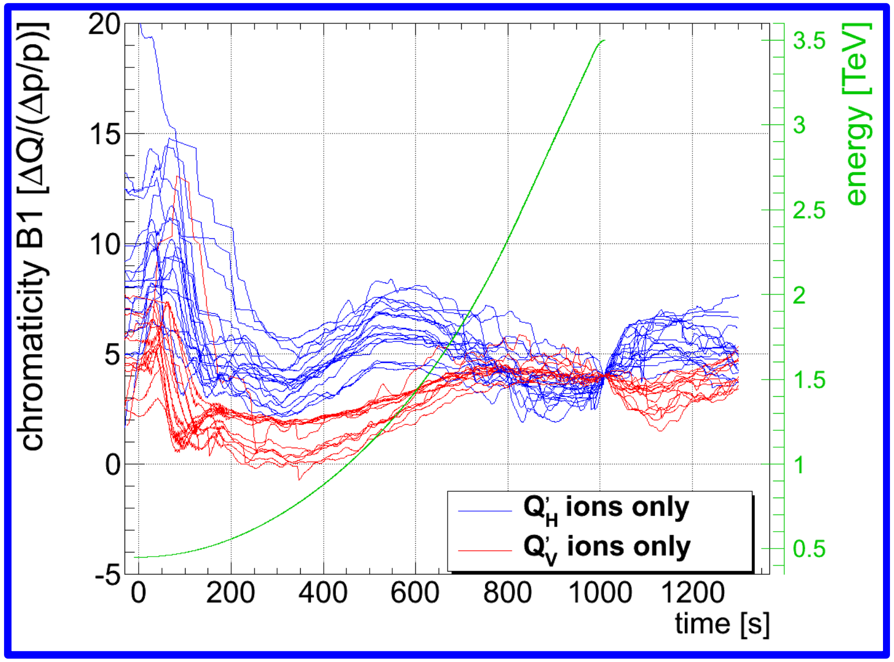
Peak-To-Peak Chromaticity Variations

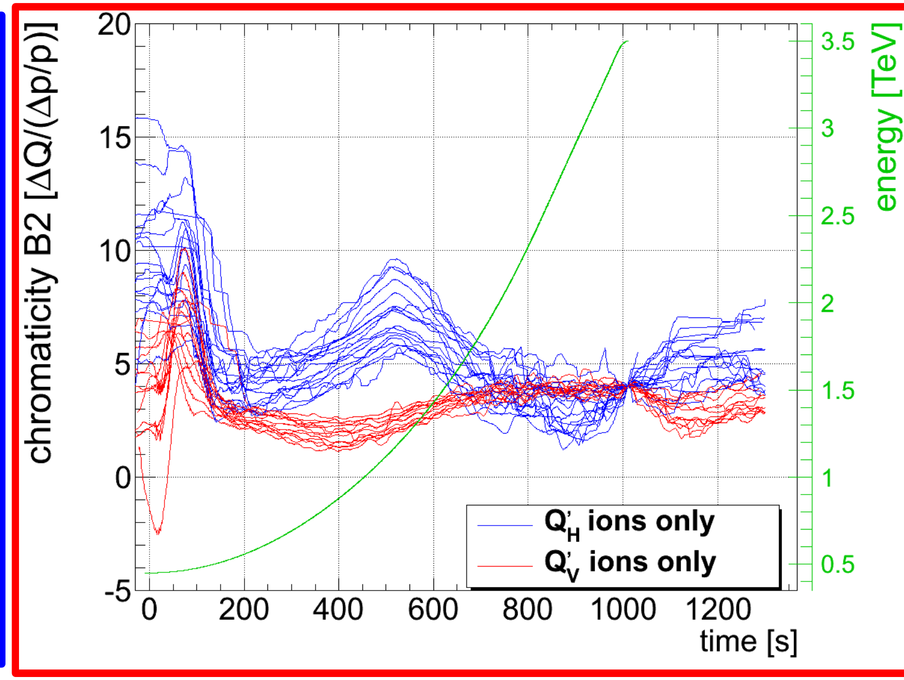
- … all ramps exceed the initially required Q', sometimes systematiclly Q' < 0
  - reluctance from OP and coordinators to measure and fix this!



Re-Normalised Chromaticity

- Remaining Q'(t) variations during snap-back of up to ±5 units
  - Dynamic effects & memory visibly dies-out with energy
  - What we could expect with a perfect feed-forward:





- Remaining fill-to-fill variations still large compared to target of Q'_{ref} = +2 ±1
  - Machine is pretty stable but exceptions may (/do) occur
    - Varying initial Q' reference (sometimes 2, 4, 10, ???), pre-cycles
- Do we need to care about these variations?

A Note on Dependence of LHC Operation on Feedbacks:

- Could/should we run LHC without Feedbacks: – NO

  1 More than 50% of fills would have probably been lost without FBs

  2 Even with perfect feed-forward, FBs provide a robustness to operation by mitigating “unforseen” or feed-down effects

However:

- Safety margin diminishes if underlying systematic perturbations and potential problems are not followed-up or incorporated into feed-forward corrections!
  “Having a car brake or ESP/ABS system does not justify reckless driving!”

- Feedbacks can, may and do shadow systematic machine problems
  - OK to advance and as temporary mitigation, but we should look also into robust long-term solutions.
  - Need logging of all feedback system actions to monitor and identify potential problems, and to facilitate feed-forwarding

Ex. Perturbations vs. Requirements vs. Parameter Stability

- Expected Perturbations pretty much what we expected about 5 years ago:

Expected Dynamic Perturbations vs. Requirements

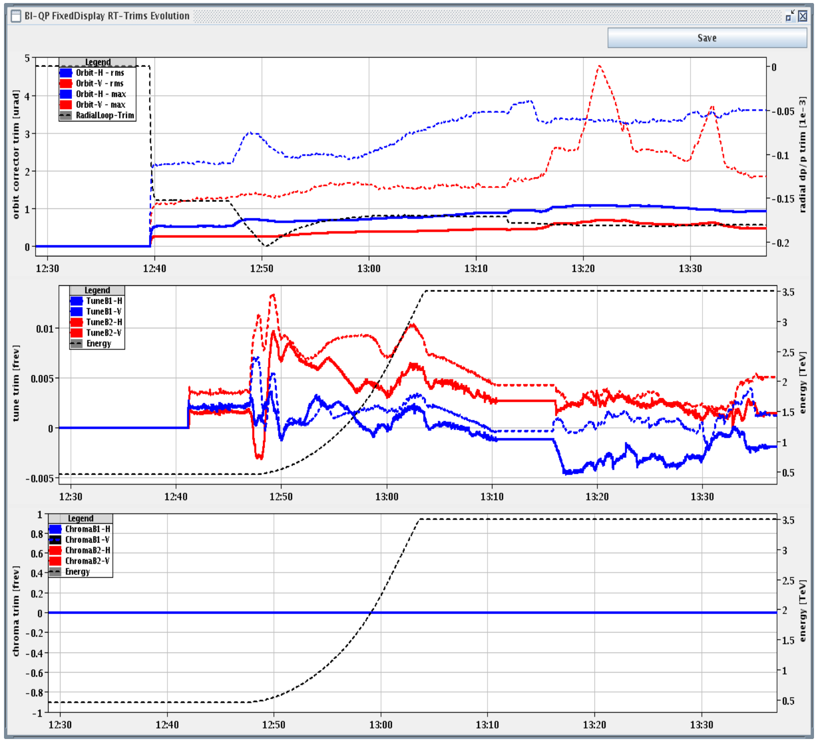
Chamonix'06

- From Decay/Snap-back expected dynamic perturbations* (MB & MQ)
  - For details, please see additional slides

	Orbit [σ]	Tune [0.5·f_{rev}]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Exp. Perturbations:	~ 0.5	0.014 (0.06)	~ 70 (140)	± 1.5e-4	~0.01 (0.1)
Pilot bunch	-	± 0.1	+ 10 ??	-	-
Stage I Requirements	± ~ 1	±0.015→0.003	> 0 ± 10	± 1e-4	« 0.03
Nominal	± 0.3 / 0.5	±0.003 / ±0.001	1-2 ± 1	± 1e-4	« 0.01

- Chromaticity is the most critical parameter to control
  - defines lifetime and dynamic aperture (= losses) inside the ring
  - Tune is less critical but its measurement a pre-requirement for above
- Require coupling control esp. at start of ramp to enable other controls
- Control of orbit is the easiest one
  - Measurement and correction scheme well established
  - consequence of having BPM with 100k turn acquisition: → Energy feedback
- Stage I: injection more relaxed (except Chromaticity)

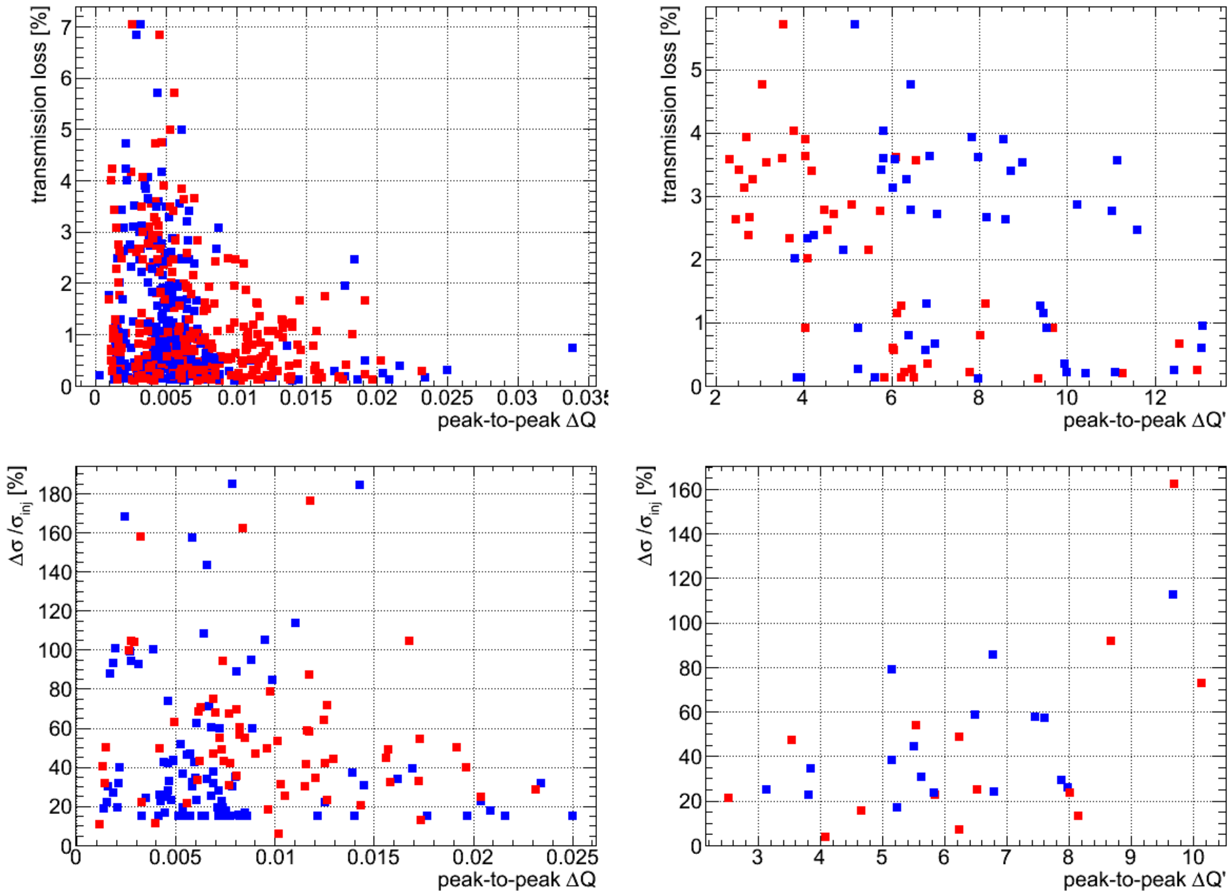
* numbers in brackets are 'worst case'



- Q'(t) much underrated this year → Does it impact machine performance?
  - N.B. FB was ready/tested early on but never been used during the ramp!
- Chose two criteria: transmission (MP & Lumi), beam size growth (Lumi)
  - Uncertainties: gaps in logging, missing Q'(t), ever-changing machine, ε-measurement (WS, BSRT, BGI), no MD time to further test hypothesis

Impact of Q/Q' Performance – Protons

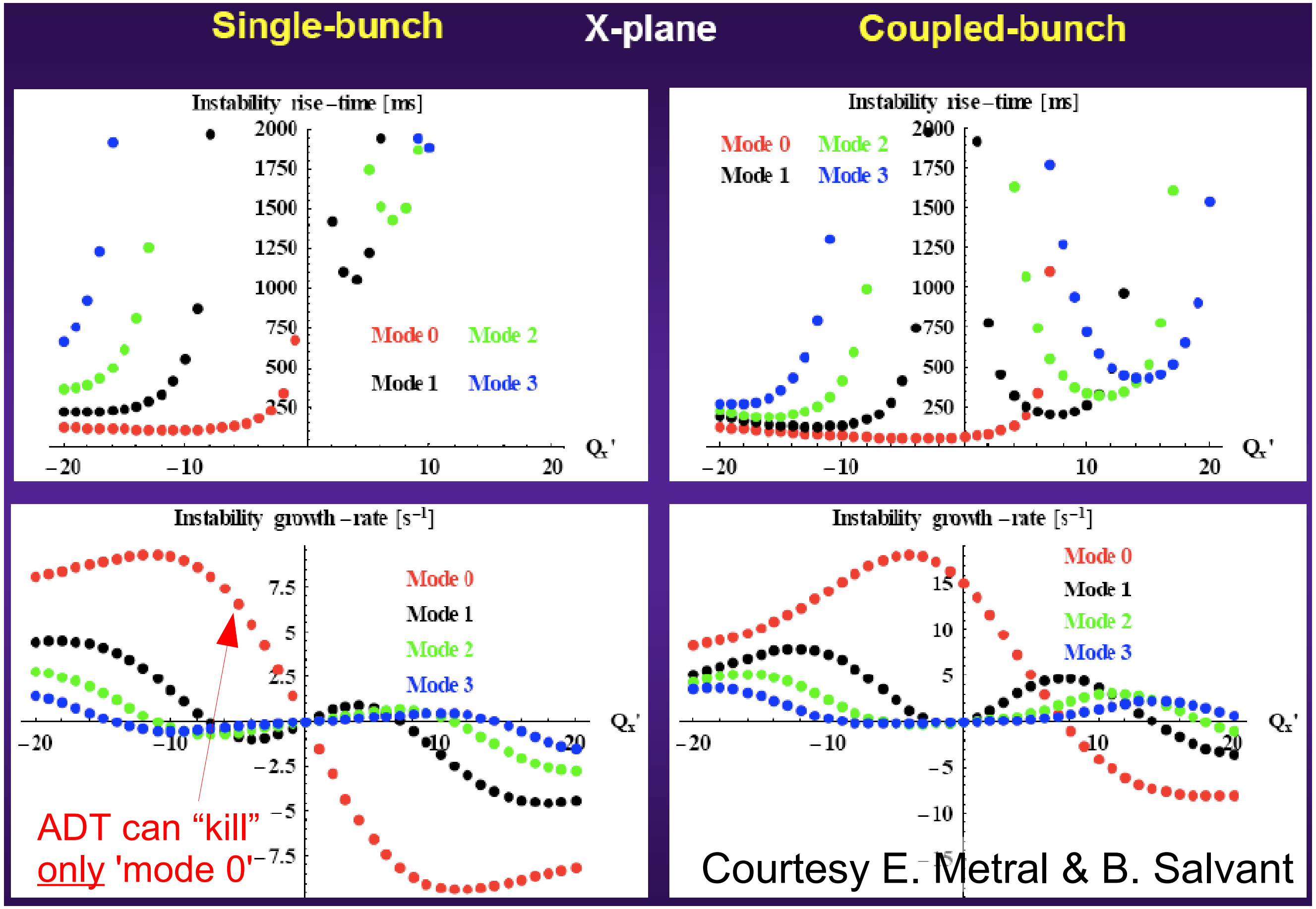
- Limited or no correlation to transmission losses but beam size growth
- Biggest error: emittance growth estimates→ Federico Roncarolo's talk



- Correlation between 0.5..0.7, biggest uncertainty derives from BSRT
→ use only linearity between fill-to-fill but not absolute values → F. Roncarolo

Modeled Single & Coupled-Bunch Instability dependence on Q'

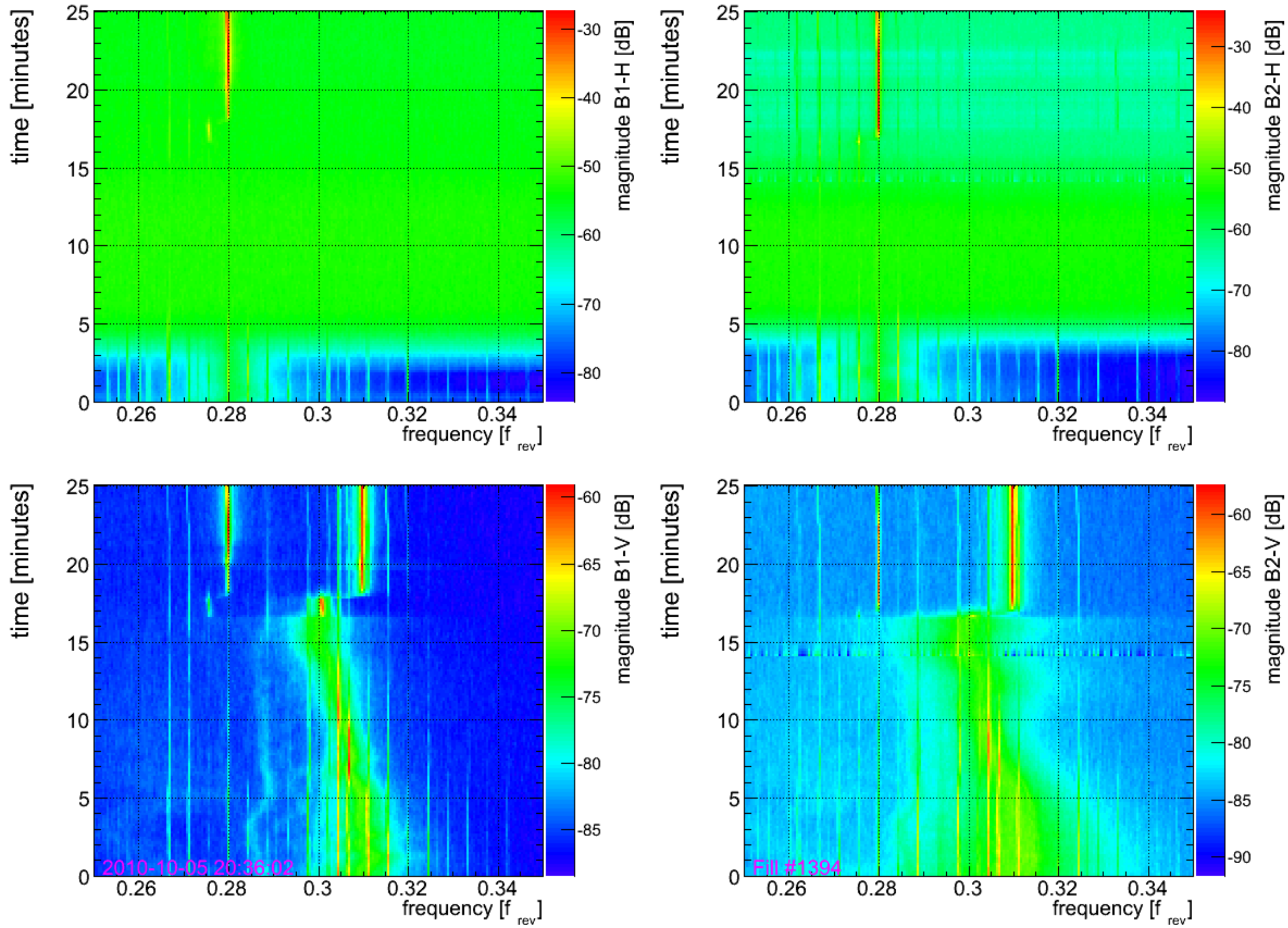
- Effect does not come completely at a surprise:



- Higher modes have been seen by BBQ and Head-Tail Monitor
  - are these modes responsible for the emittance blow-up?
- deserves some more controlled experiments at 450 GeV or flat-top

Other Q/Q' related Sources impacting Machine Performance

- Besides Q'(t), MB mains harmonics can be a source of beam size growth



- No a big problem but nominal working points are exactly on one of them
  - We should allow us a more freedom of Q_{ref} w.r.t. mains and 'hump'

Cohabitation of ADT and Q/Q' Diagnostics Systems

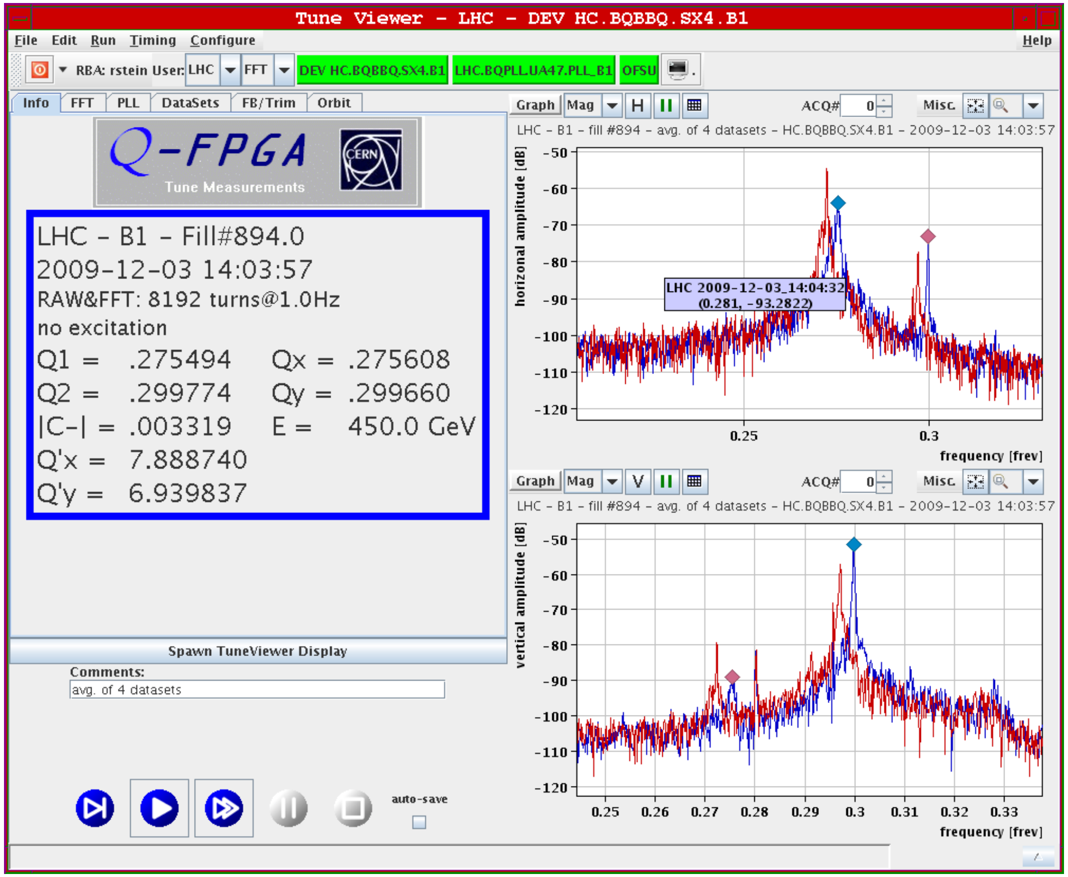
… fighting the 'hump' ...

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

- 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

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



- 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.)

However...

- The µm-level oscillations are incoherent "noise" from a FFT/PLL point of view

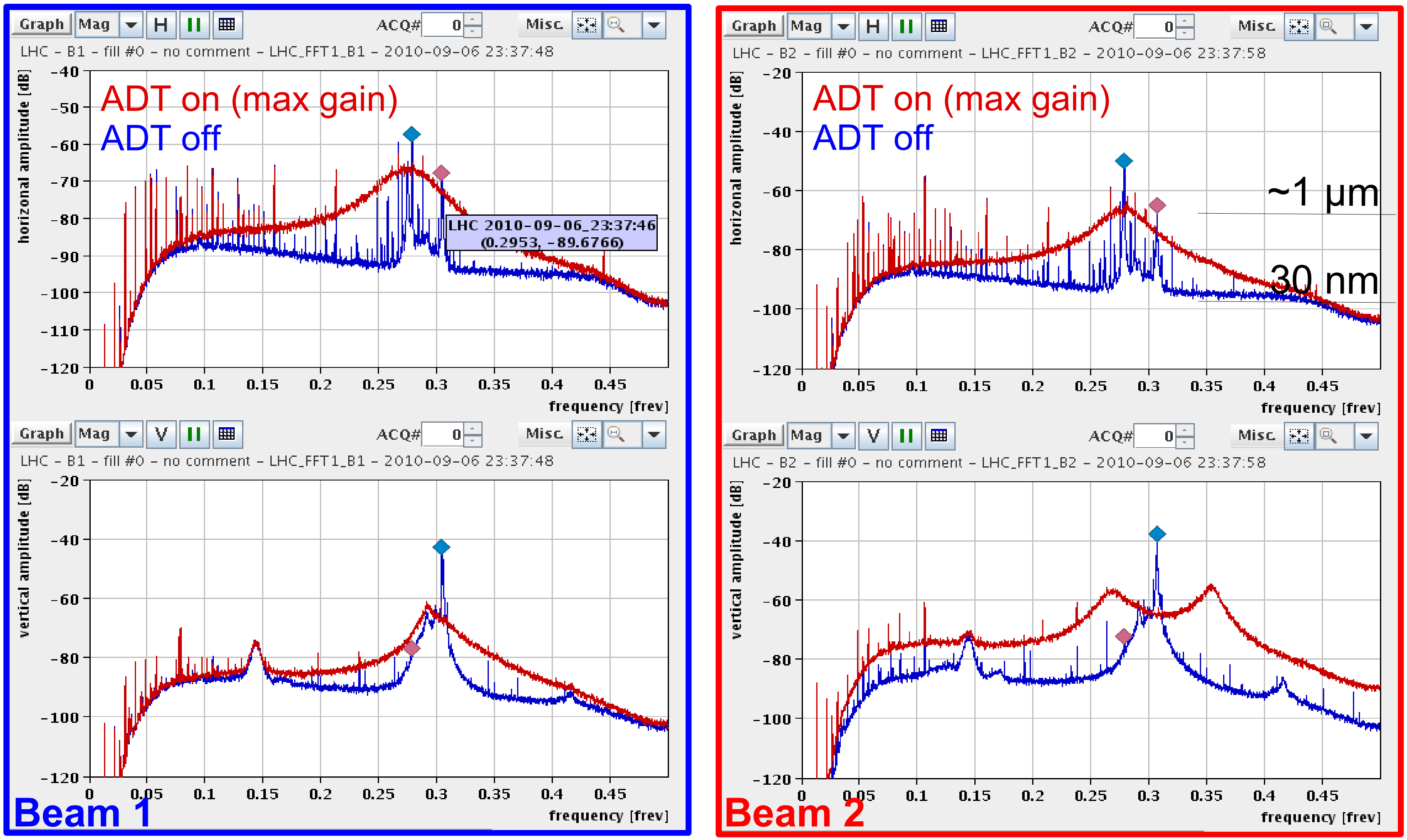
- Regardless of whether using a FFT- or PLL-based system:
  - Need to excite ~30 dB above this "noise" to recover the performance of using residual oscillations only (→ 60 dB above BBQ noise floor!):
    - Tune tracking: min. ~20 dB (assuming $|C^-|$=const)
    - Coupling measurement: min. 18 dB (better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

    → corresponds to ~10 to 100 µm oscillations (↔ collimator tol. <200 µm)
  - 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...

- ADT is used regularly since July to damp injection oscillations, and kept 'on' also during ramp and later collisions
  - Damping 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

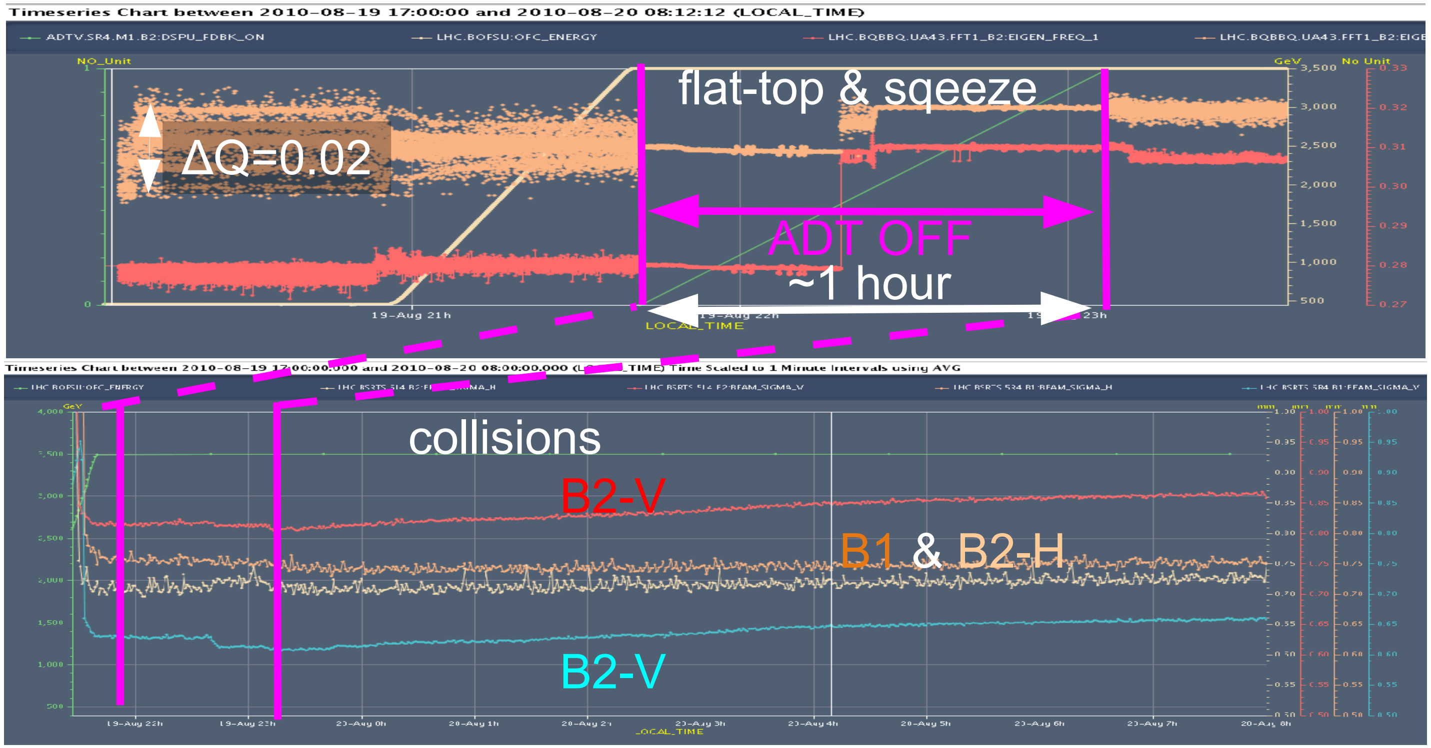
- BBQ noise-floor raised by 30 dB, wide Q-peak → reduces ΔQ_{res}~10^{-4} → ~10^{-2}
  - Impacts reliable tune (and coupling) measurement & feedback
  - incompatible with Q'-measurements using small Δp/p-modulation
  - loss of additional beam stability diagnostics on mains harmonics, hump, etc.



- Limited impact on emittance but notable w.r.t. achievable tune resolution:

Tunes:

Beam sizes:



- Challenge for required Q(t) & Q'(t) resolution and measurement bandwidth
- Issue of Q'(t)<0 → fixing the right thing with the wrong tool (ADT vs. Q'-FF/FB)
- Inputs to operators & FB → needs to be as robust as possible
  – presently: there is no margin to err!

Summary: 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~~2011?

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 not 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.

? 9 Off-resonance excitation and one-turn-phase-advance measurement
- Needs additional HW (possibly pickups) and further feasibility tests with beam

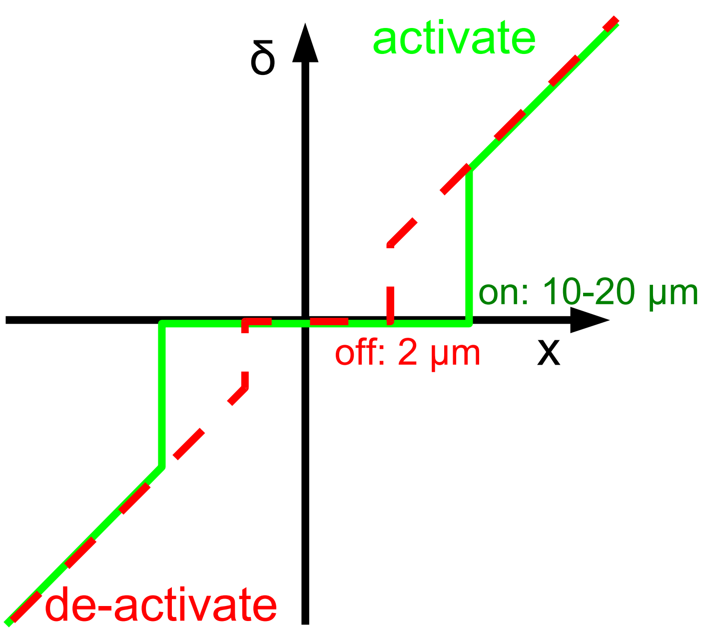
Conclusions

- Feedbacks performed well and facilitated a fast commissioning
  - de-facto required during every ramp and squeeze with nominal beam and expect the same also for next year
    - More than half of all ramps would have been definitely lost without them
  - additional safety margin to operation provided feed-forward is performed regularly
- Good overall performance with little transmission losses and minimal hick-ups related to Q/Q' instrumentation, diagnostics and Q/Q' & orbit feedbacks
  - However: this year's 1% losses may become more criticial in 2011
- Tune peak-to-peak stability typically below 0.02 with margin to push it < 0.003
  - little impact of residual tune error on transmission of
  - Most RT-trims correlated with Q'(t) ↔ a feed-down effect?
- Q'(t) a bit neglected this year → some indication of trade-off:
  beam stability (low transmission losses) vs. beam size growth
  - Could we further explore this via dedicated/controlled measurements?
- Effective ADT noise floor and observed bunch-to-bunch cross-talk hinders reliable operation of LHC's Q/Q'-Diagnostics and related feedbacks
  - Explored alternate BI diagnostic options → the ball is now on the RF group's side

Additional supporting slides

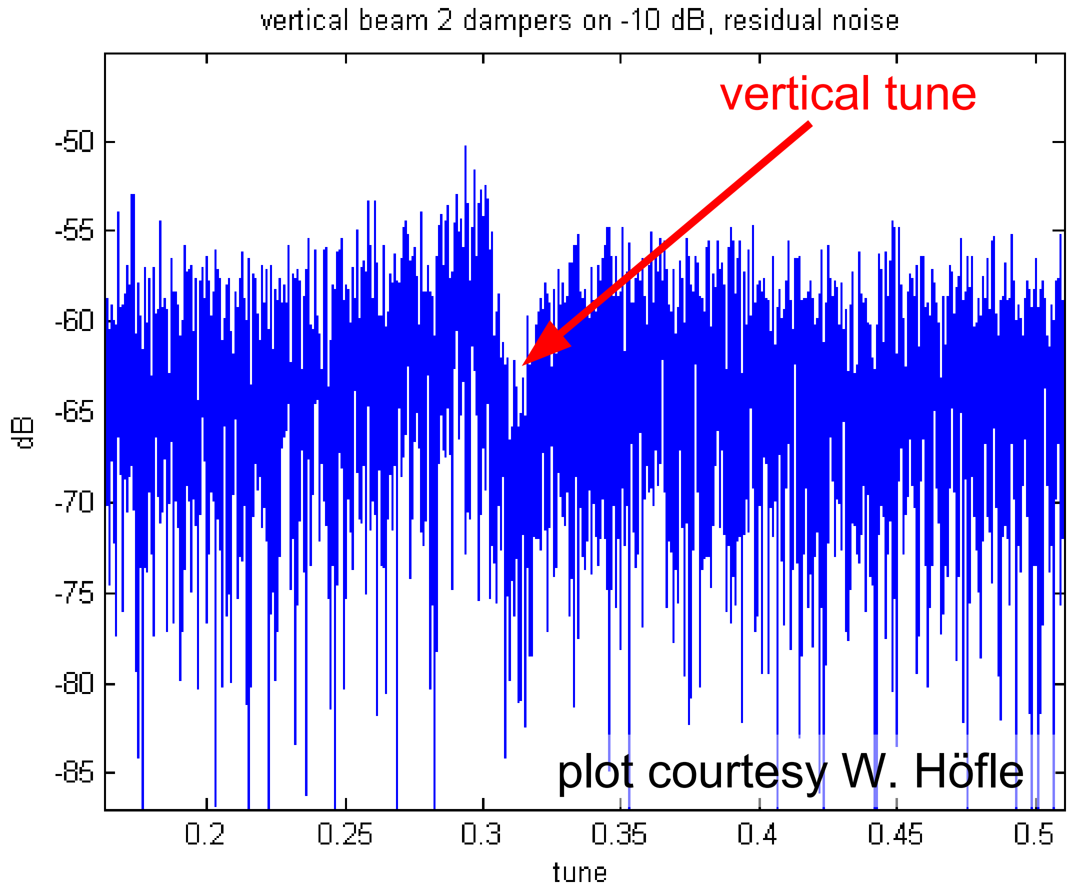
ADT Dead-Band

- 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..



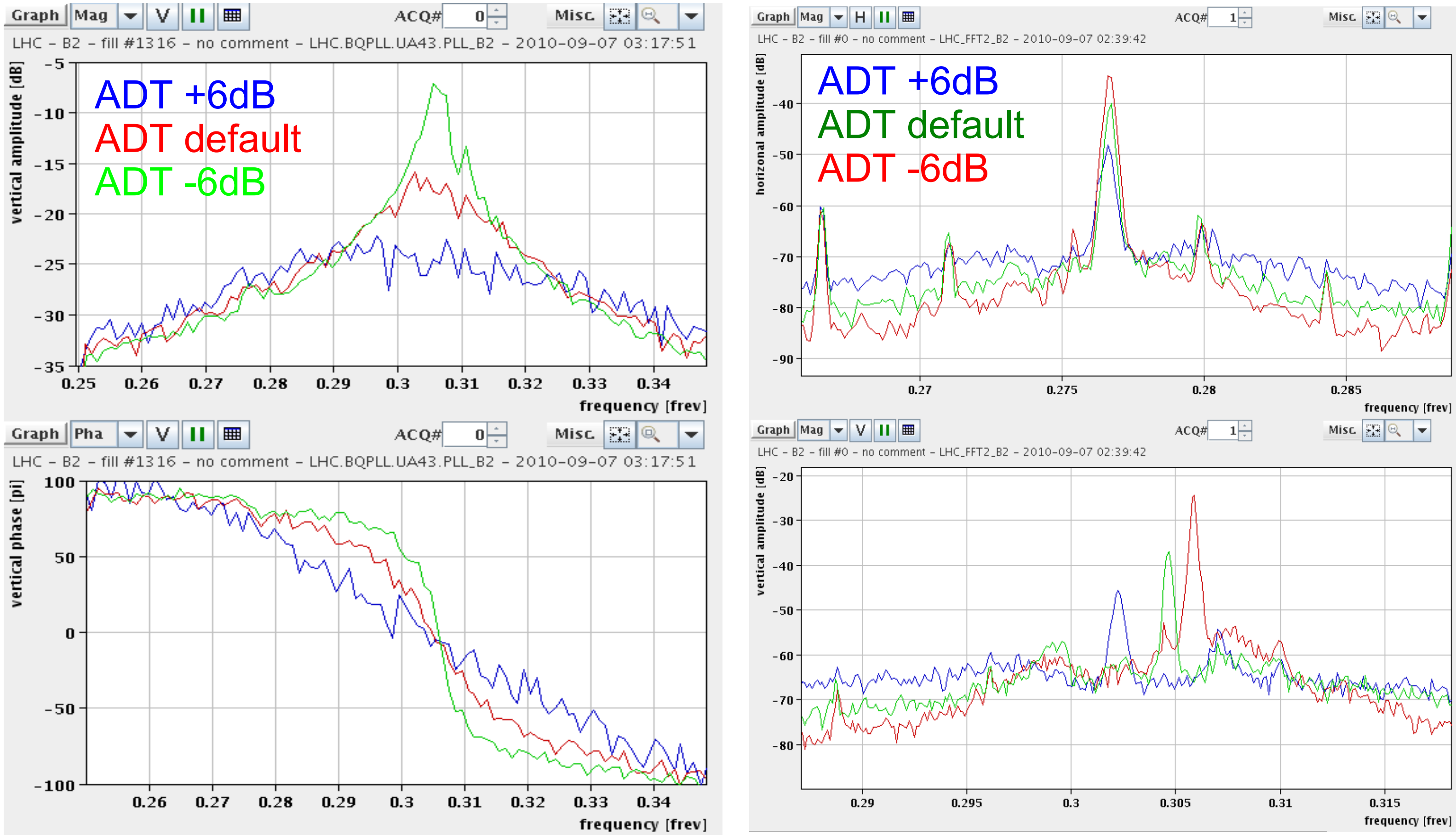
ADT Dead-Band vs. Deriving the Tune from ADT Exciter Signal

- 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?



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:



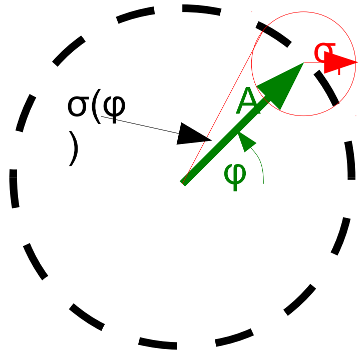
  - Requires excitations 30+ dB above noise floor for reliable signal/lock and coupling measurement: noise ~1 µm → excitation can go up to 100 µm
  - Detected tune peak shifts with effective damper gain: ± 6dB ↔ $\Delta Q \approx 3 \cdot 10^{-3}$

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

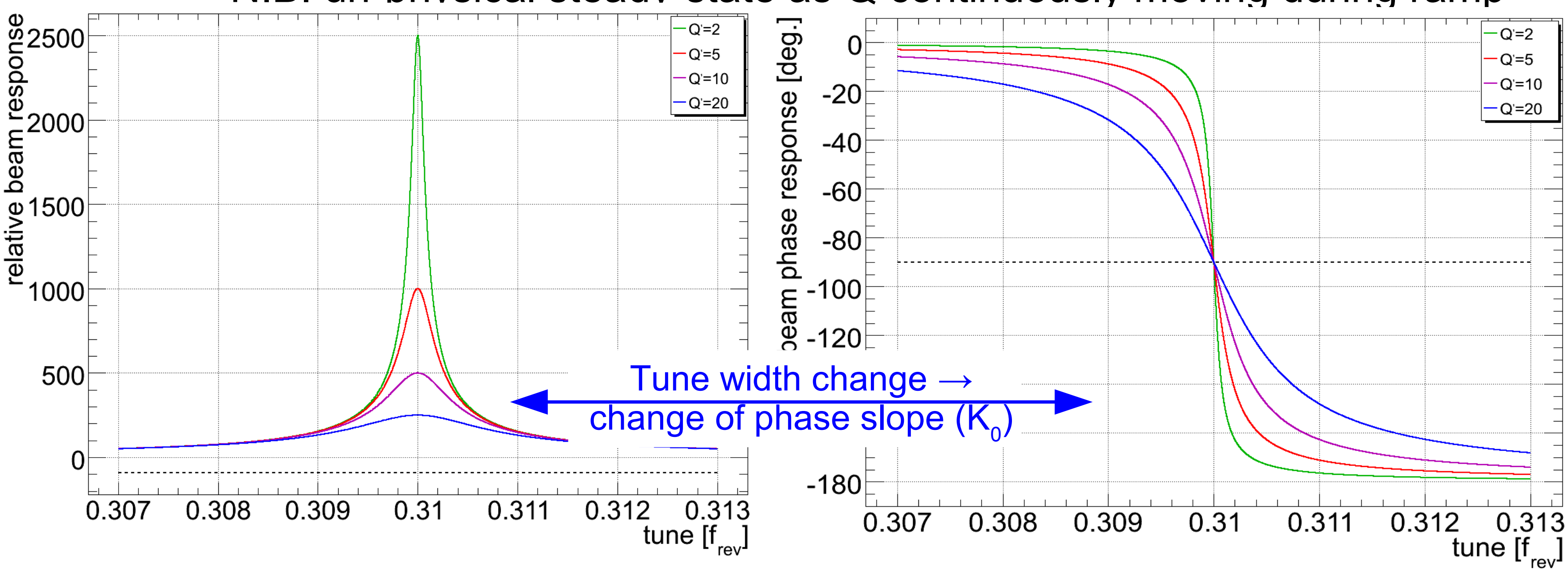
- Initial Q-PLL design assumption violated:
  – no residual tune oscillation, need to drive the beam to get some signal
- Non-PLL “random” signals add vectorial to PLL driven one:

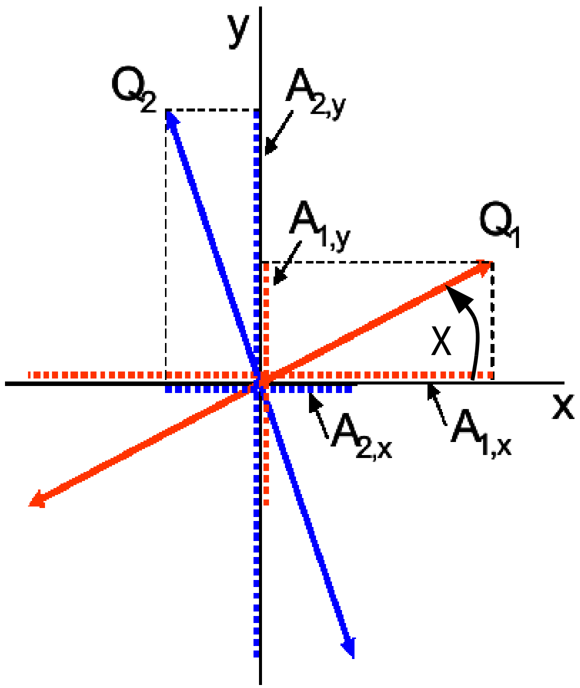
$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

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





- 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

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

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

  - requiring resolution so that $\Delta|C^-| < 0.1\ |Q_1\text{-}Q_2|$, and $r = r_1 = r_2 > 0$
    → required N/S ration r < ~0.05 ↔ S/N ~ 26 dB
  - requiring resolution so that $\Delta|C^-| < 0.5\ |Q_1\text{-}Q_2|$, 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

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