Real-Time Beam Control at the LHC

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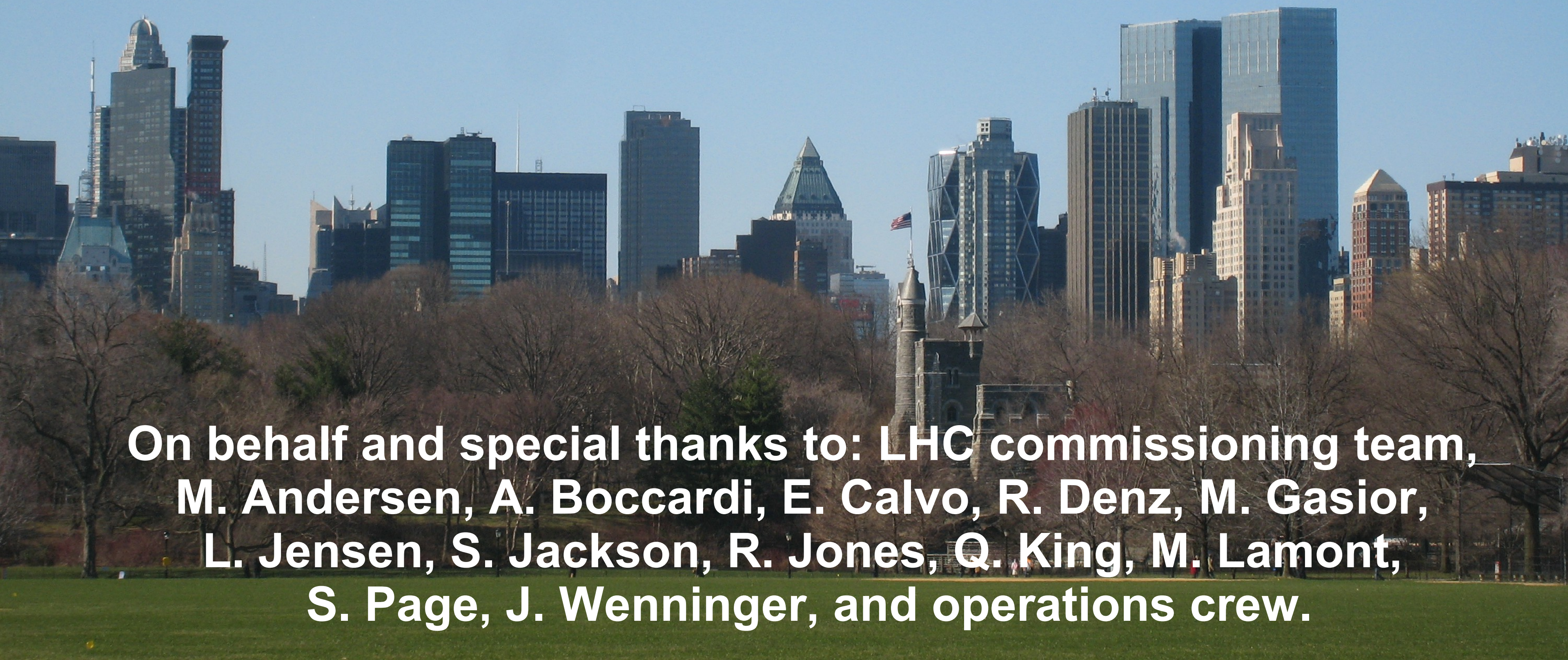

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Outline

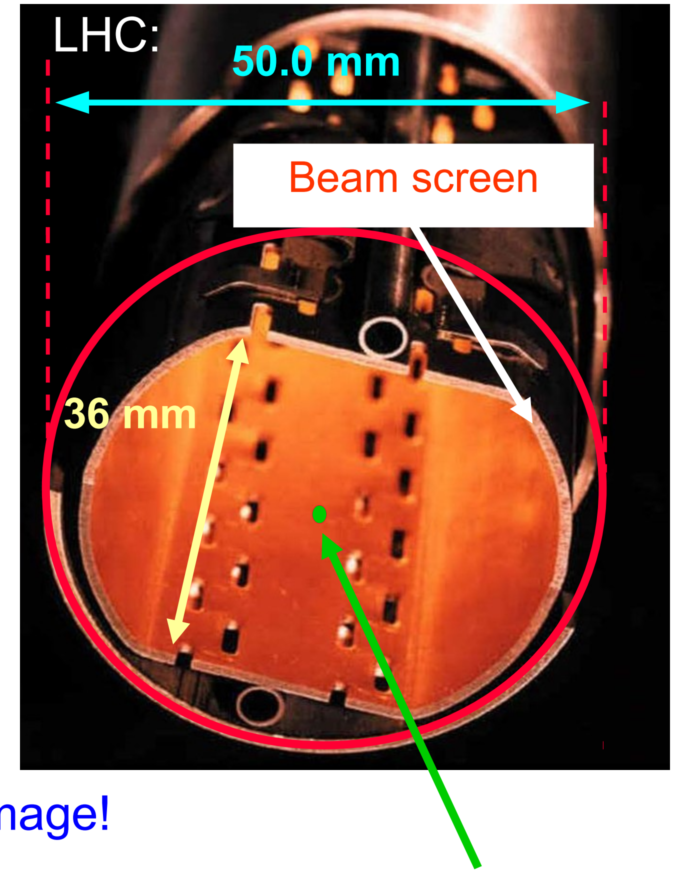
- Requirements: 'What was specified' vs. 'What was/is needed'
- Underlying Feedback Architecture

- Performance and Stability during LHC's First Year of Operation
  - Gretchenfrage: “Could or should LHC run without Feedbacks”
- Required Changes with respect to Initial Design

Beam Parameter Stability in Hadron Machines

- Traditional requirements on beam stability...

... to keep the beam in the pipe!



- Increased stored intensity and energy:
  - up to 75 MJ@3.5 TeV in the beam (2011)
    → can quench all magnets/cause serious damage!

- Requirements depend on:
  1. Capability to control particle losses
     - Machine protection (MP) & Collimation
     - Quench prevention
  2. Commissioning and operational efficiency

Change of Paradigm at the LHC ...

- FBs became a requirement for safe and reliable nominal LHC operation
  - implications on controller reliability, availability and system integration

- The main driving constraints:
  - ensuring collimator hierarchy ↔ minimising local bumps
    - $\Delta x \leq$ 25-50 μm at collimators ↔ constraints max. allowed oscillations
  - Decay- and snap-back of dipole's multipole components
  - Operating close to third order resonances
  - Keep beam excitation to a minimum: transverse emittance preservation

Expected Dynamic Perturbations vs. Requirements – or: Design Assumption vs. Operational Reality

- From Decay/Snap-back expected dynamic perturbations

	Orbit [σ]	Tune [$0.5 \cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Exp. Perturbations ('06):	~ 0.5	0.014	~ 70	± 1.5e-4	~0.01
Nom. Requirements:	± 0.15	±0.001	2 ± 1	± 1e-4	« 0.01
Achieved Stability ('10):	~ 0.1	~ 0.001	± 2 (7)	~1e-5	< 0.003

- Initial assumptions and plans (2006-2009):
  - Chromaticity considered as most critical parameter
  - FB Priority list: Chromaticity → Coupling/Tune → Orbit → Energy

- What turned out to be needed operationally from 2009 → now:
  - **Tune** → **Tune** → …→ Orbit & Energy/Radial-Loop … → Q'(t) →…→ C^-
    - impressive Q'(t), C^- and beta-beat stability and reproducibility

LHC Feedback Success has a long Pedigree: Years of Collaboration, Development and leveraged Experience

1996
- Wide-Band-Time-Normaliser proposed for LHC BPM system
- BNL & CERN collaboration on Q/Q'(-FB) initially BNL's 200MHz resonant BPM

1999
- Radiation testing showed digital acq. needs to be out of tunnel
- Tune-FB included in original US-LARP TWC-based Schottky monitor proposed

2000
- RT control specification, mostly decay-/snap-back and nominal performance (no MP yet)
- Direct-Diode-Detection → Base-Band-Tune (BBQ), prototyped at RHIC/SPS, robust Q-meas. & unprecedented sensitivity
- 1.7 GHz Schottky prototype at SPS

2001
- BPM design and capabilities "inspired" specs. Moving digital processing out of the tunnel

2002
- Recognition that collimation will rely on real-time Orbit-FBs

2003
- Orbit-FB prototype tests at the SPS
- FFT-based Q tracking op. deployed at SPS
- PLL-studies at RHIC
- FNAL-LARP involvement in Schottky design and front-end electronics

2004
- IWBS'04: SLS, ALS, Diamond, Soleil and others → affirmed Orbit-FB strategy

2005
- Orbit(-FB) and MP entanglement recognised → FB: "nice to have" to "necessary"
- Q & Coupling-FB demonstrated at RHIC

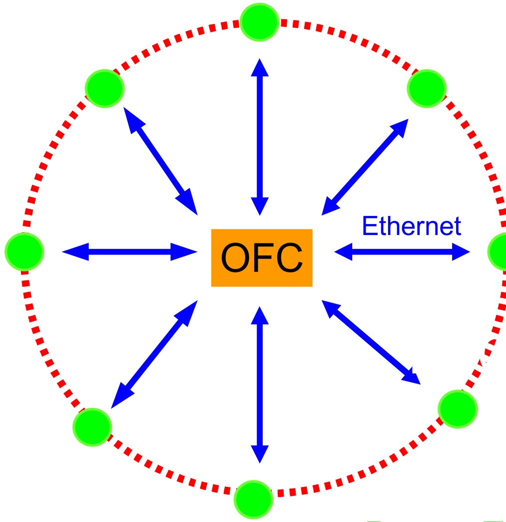
2006
- PLL-Q and Q'(t) tracker demononstrated at SPS
- FNAL-design/CERN-built 4.8GHz TWC Schottky
- Tune Feedback Final Design Review (BNL)

2007
- Joint CARE workshop on Q/Q' diagnostics (BNL, FNAL, Desy, PSI, GSI, …) → affirmed Q/Q' strategy

2009 – the year we established collisions: Q/Q'- & Orbit FBs operational

LHC: Beam-Based Feedback Systems

Specific requirements fairly distributed → opted for central global feedback system

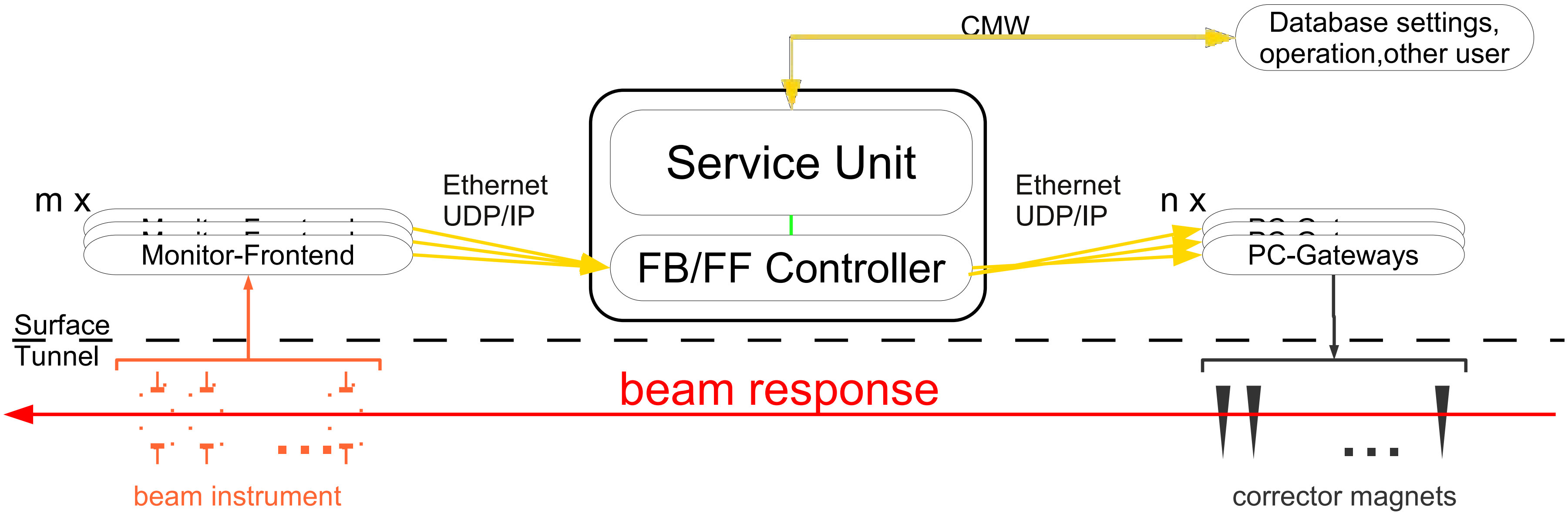


- One central controller (OFC + hot spare):
  - higher numerical load
  - higher network load (↔ 170 front-ends)
  - dependence of machine operation on single device
  - easier synchronisation between front-ends and FBs
  - flexible correction scheme changes and gain-scheduling
  - efficient to handle cross-talk and coupling between FBs
- Orbit-Feedback is the largest and most complex LHC feedback:
  - 1088 BPMs → 2176+ readings @ 25 Hz from 68 front-end computers
  - 530 correction dipole magnets/plane, distributed over ~50 front-end computers
- Total >3500 devices involved ↔ more than half the LHC is controlled by FBs!

Common Feedback/Feed-forward Control Layout
Control implementation split into two sub-systems:

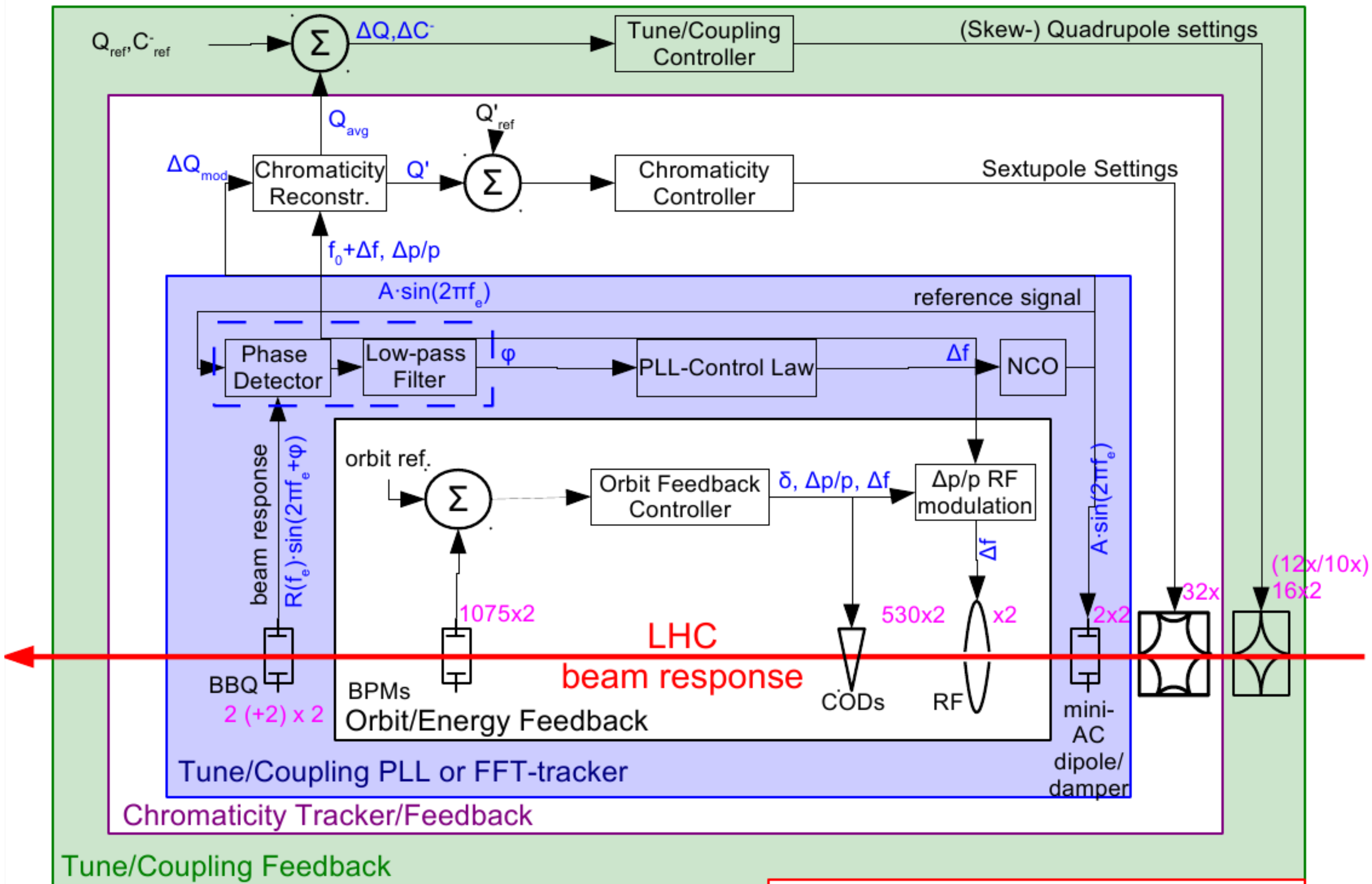
- Feedback Controller (OFC) performing actual feedback controller logic
  - Simple streaming task (10% of total load)
  - Beam data quality checks and real-time filtering (80% of total load)
  - Server running Real-Time Linux OS with periodic constant load
    - multi-core, highly redundant – MTBF > 22 yrs (spec, 120 yrs meas.)
  - Technical Network as robust communication backbone

- Service Unit: Interface to high-level software control and interlock systems
  - Proxies user requests, handles asynchronous non-RT tasks



To avoid inherent Cross-Talk between FBs… … Cascading between individual Feedbacks

- Main strategy: derive meas from FB control variable
  - Q'-tracker using '$Q_{raw} = Q_{meas} - Q_{trim}$'
  - Sub. Δp/p-mod. from Radial-Loop & Orbit-FB reference

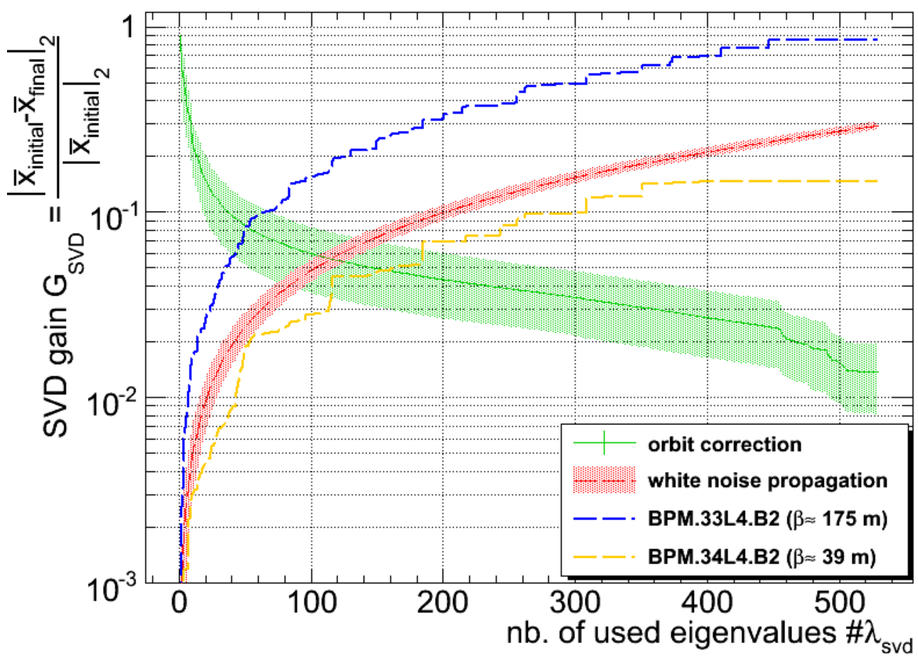


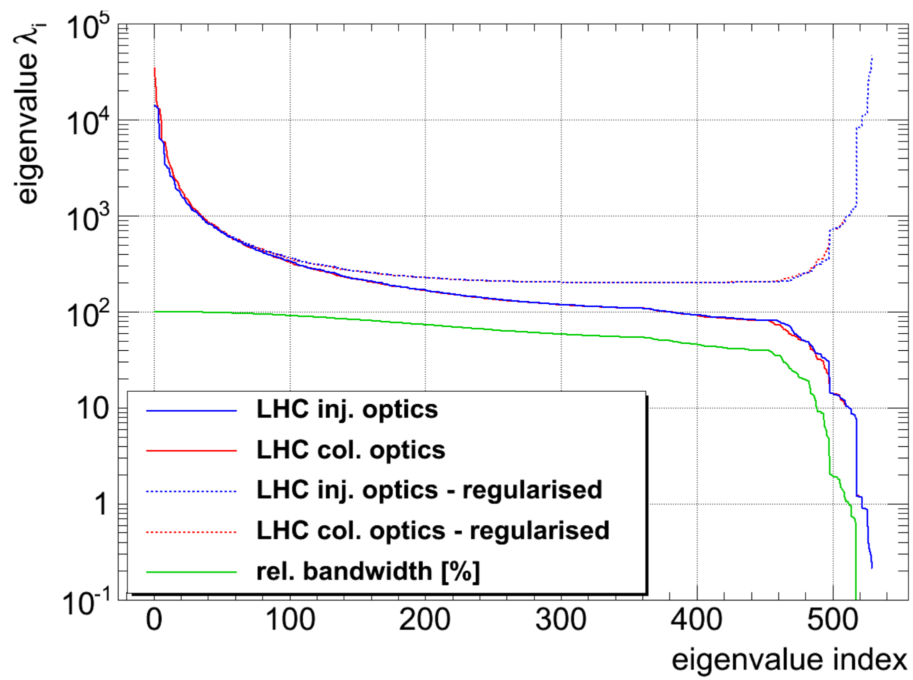
further: $f_{BW}(PLL) \gg f_{BW}(Q') \geq f_{BW}(Q, C^{-})$

Standard Singular-Value-Decomposition based Orbit Correction

- Initially: Truncated-SVD (set $\lambda_i^{-1} := 0$, for $i>N$)
  - not without issues: removed λ_i allowed local bumps creeping in (e.g. collimation)

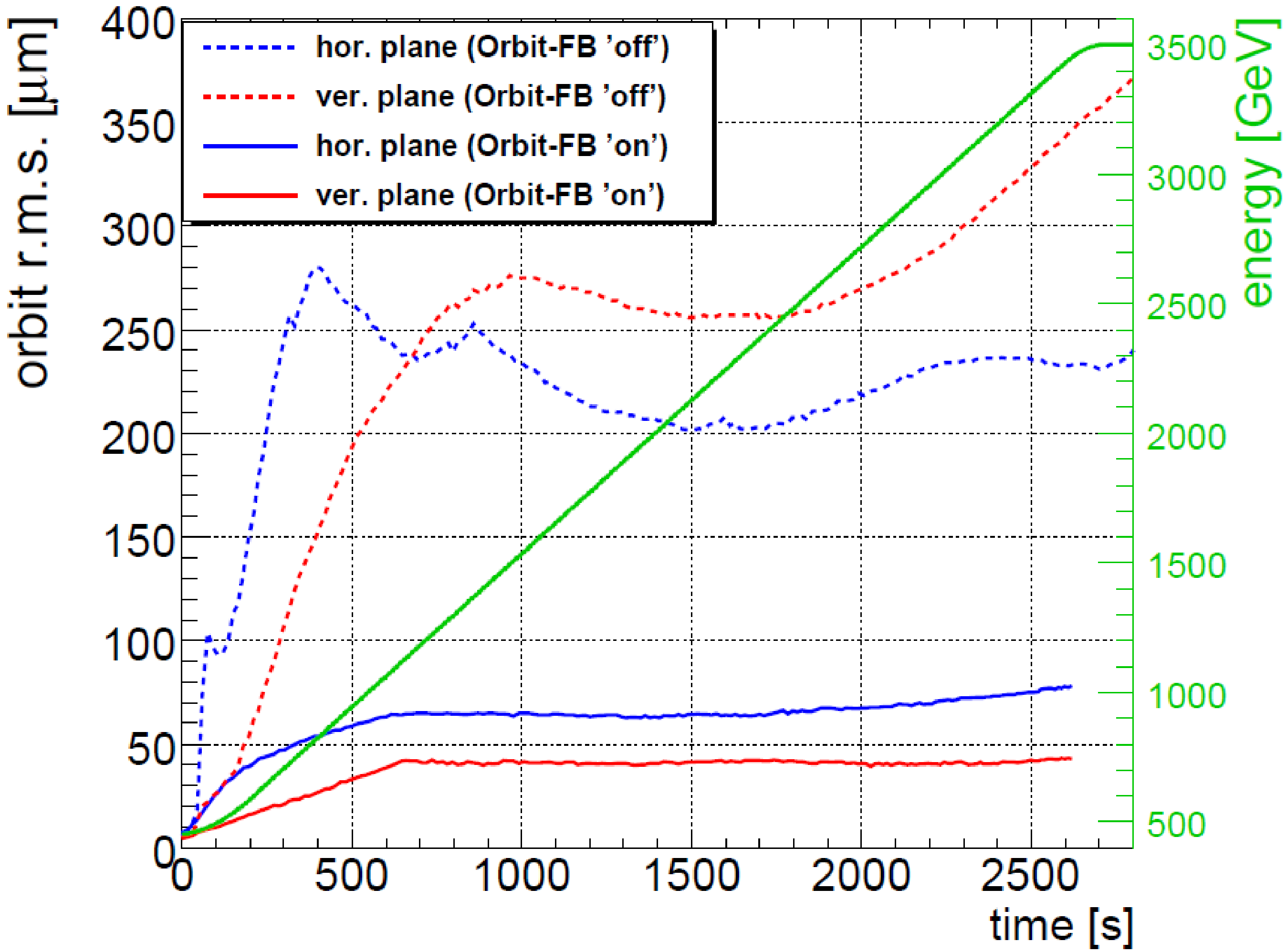
- Regularised-SVD (Tikhonov/opt. Wiener filter with $\lambda_i^{-1} := \lambda_i/(\lambda_i^2 + \mu)$, $\mu>0$)
  - more robust w.r.t. optics errors and mitigation of BPM noise/errors
    → allowed re-using same ORM for injection, ramp and 10+ squeeze steps





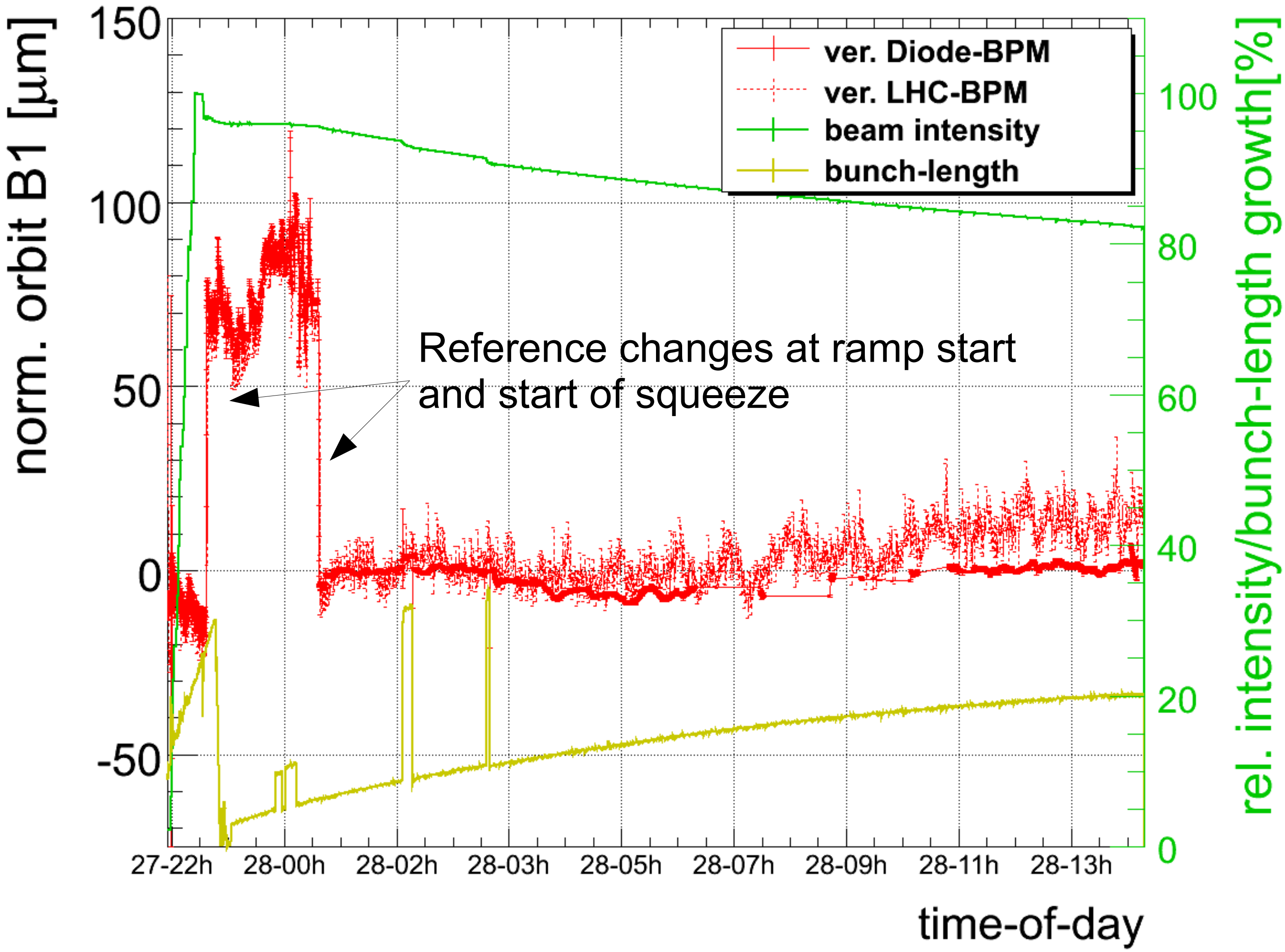
Orbit Feedback Performance

- Orbit feedback used routinely and mandatory for nominal beam



- Typical stability: 80 (20) µm rms. globally (arcs)
- Most perturbations due to Orbit-FB reference changes around experiments

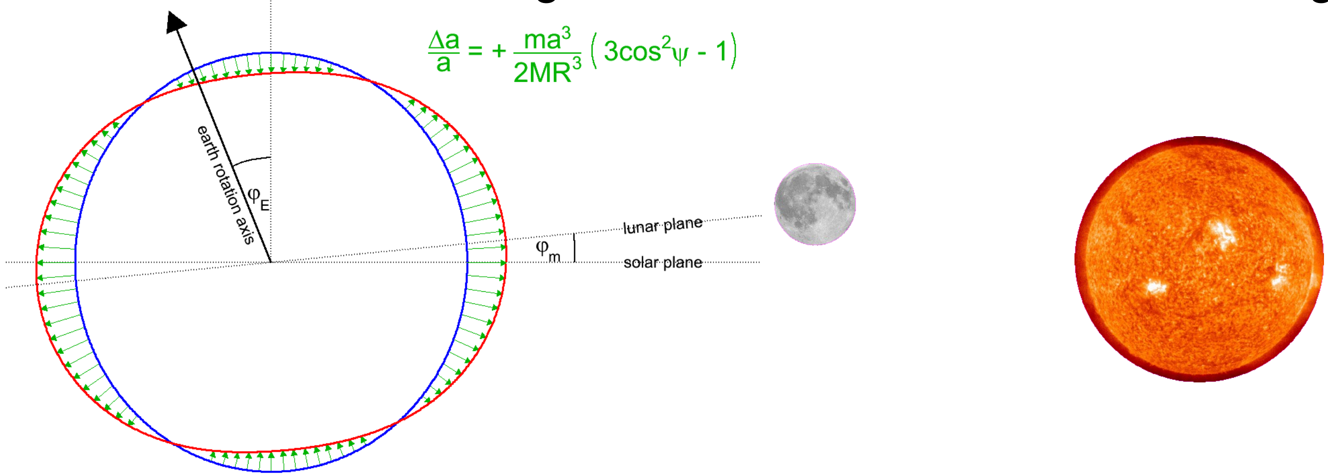
Orbit Stability during one LHC Fill

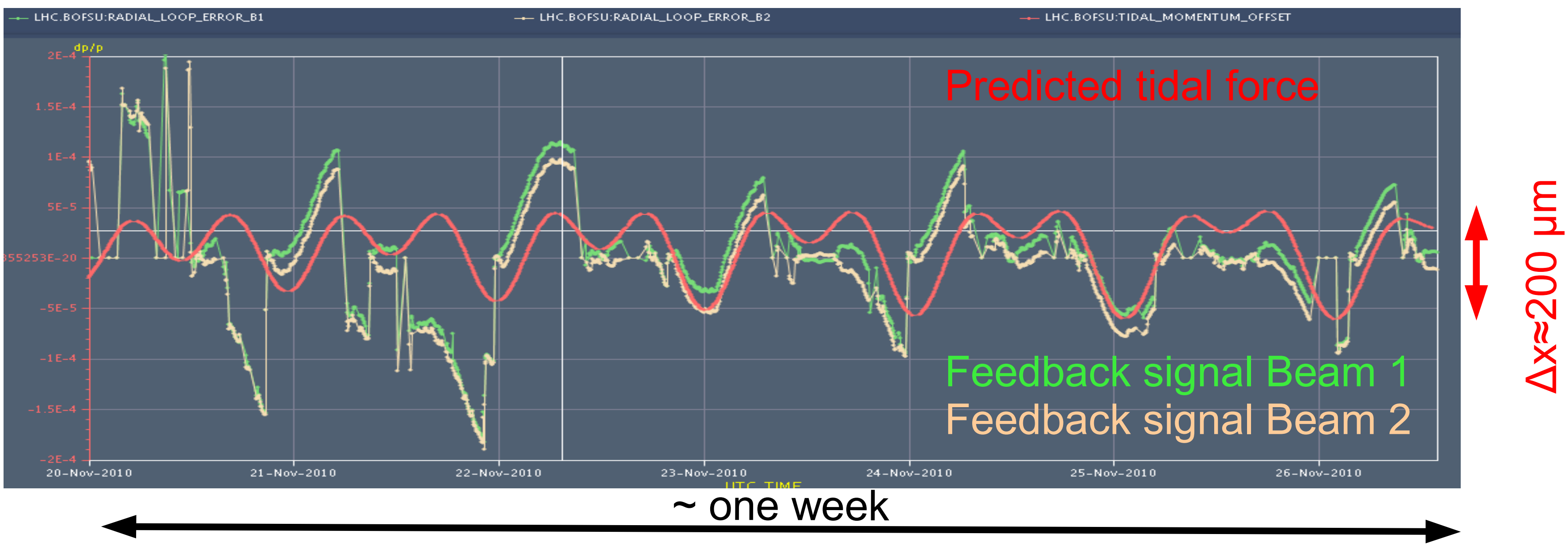


- Orbit stability during physics < 5 μm over 15 hours (Orbit-FB 'off')
  - new high-accuracy diode-based beam position monitor system: Δx_{res} < 0.5 μm

Earth Tides dominating Orbit Stability during Physics:

- Known effect from LEP → changes the machine circumference/energy

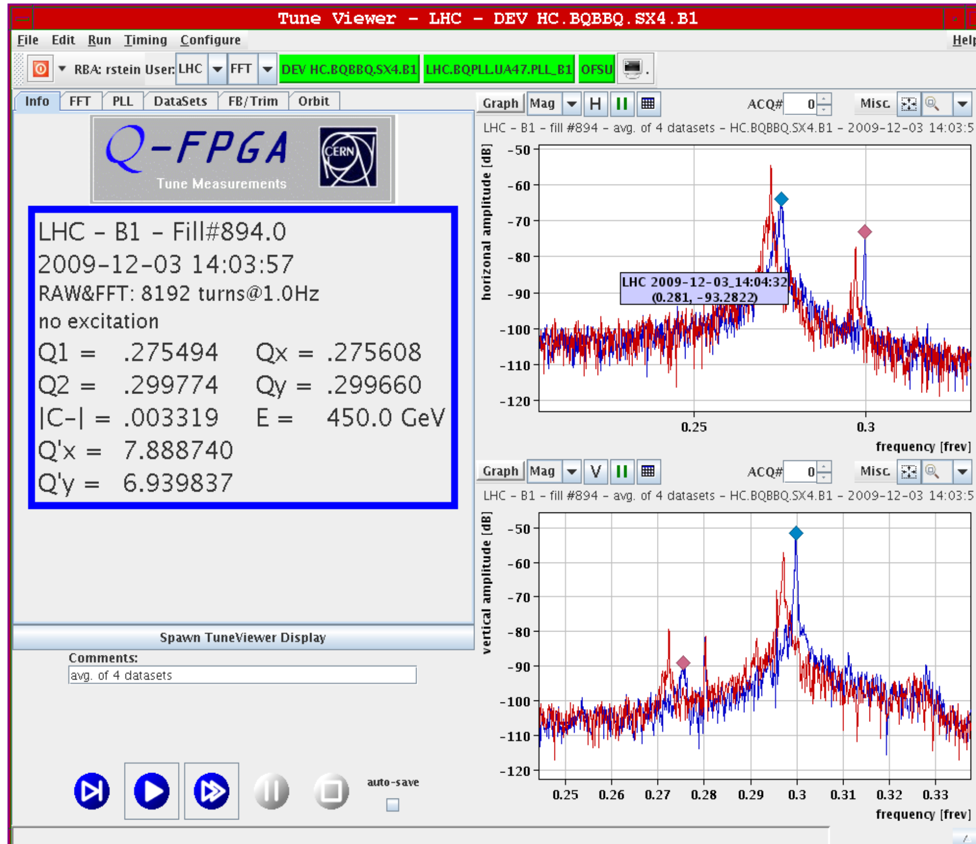




  – Testimony to LHC alignment and beam stability!

LHC Q/Q' Diagnostics and Residual Noise I/II

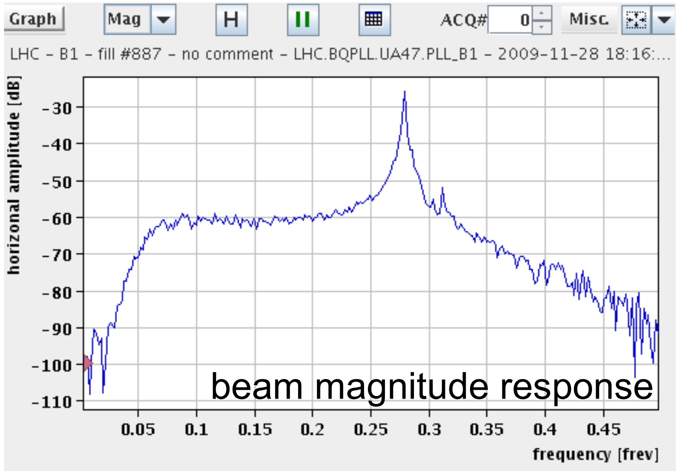
- Initial design assumption: no residual tune signatures on the beam (0 dB S/N)
  - Anticipated constant driving of the beam and – to limit the required excitation levels – the highly-sensitive BBQ system was developed
- Blessing/Curse after start-up:
  1. BBQ turn-by-turn res. < 30 nm
     - 30+dB more sensitivity than other LHC systems
       (e.g. ADT: 1µm, BPM: 50 µm)
  2. Ever-present Q oscillations on the few 100 nm to µm level

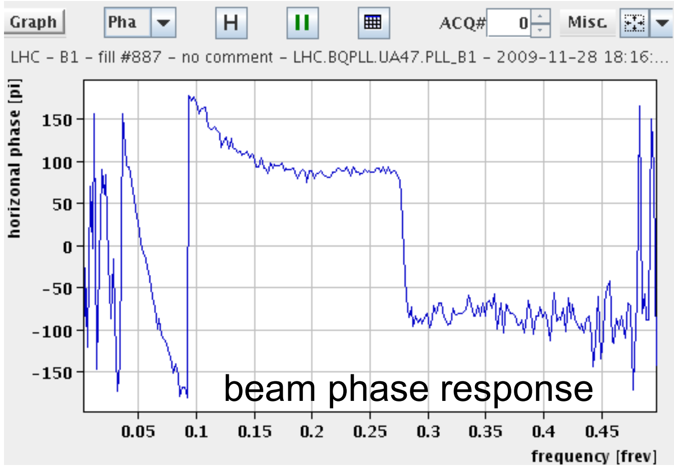


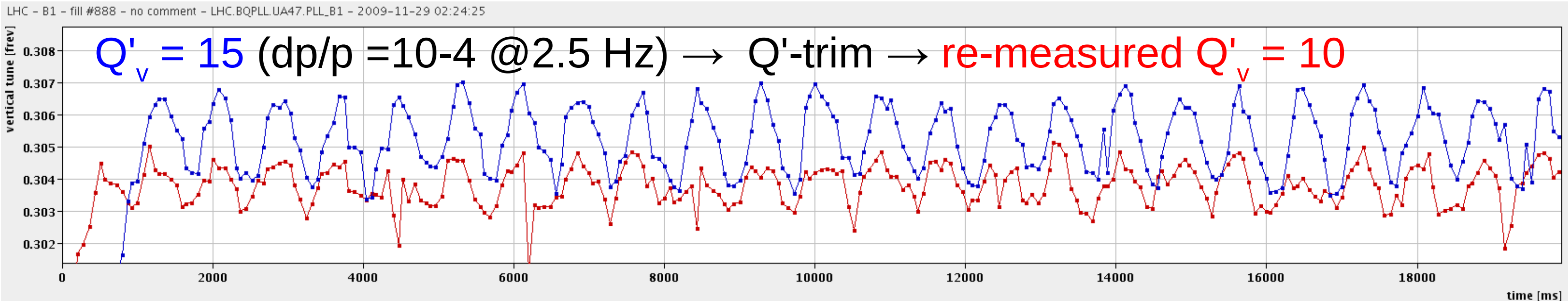
- Luxurious 30-40 dB S/N ratios enabled the passive monitoring, tracking and feedbacks without any additional excitation

LHC Q/Q' Diagnostics and Residual Noise II/II

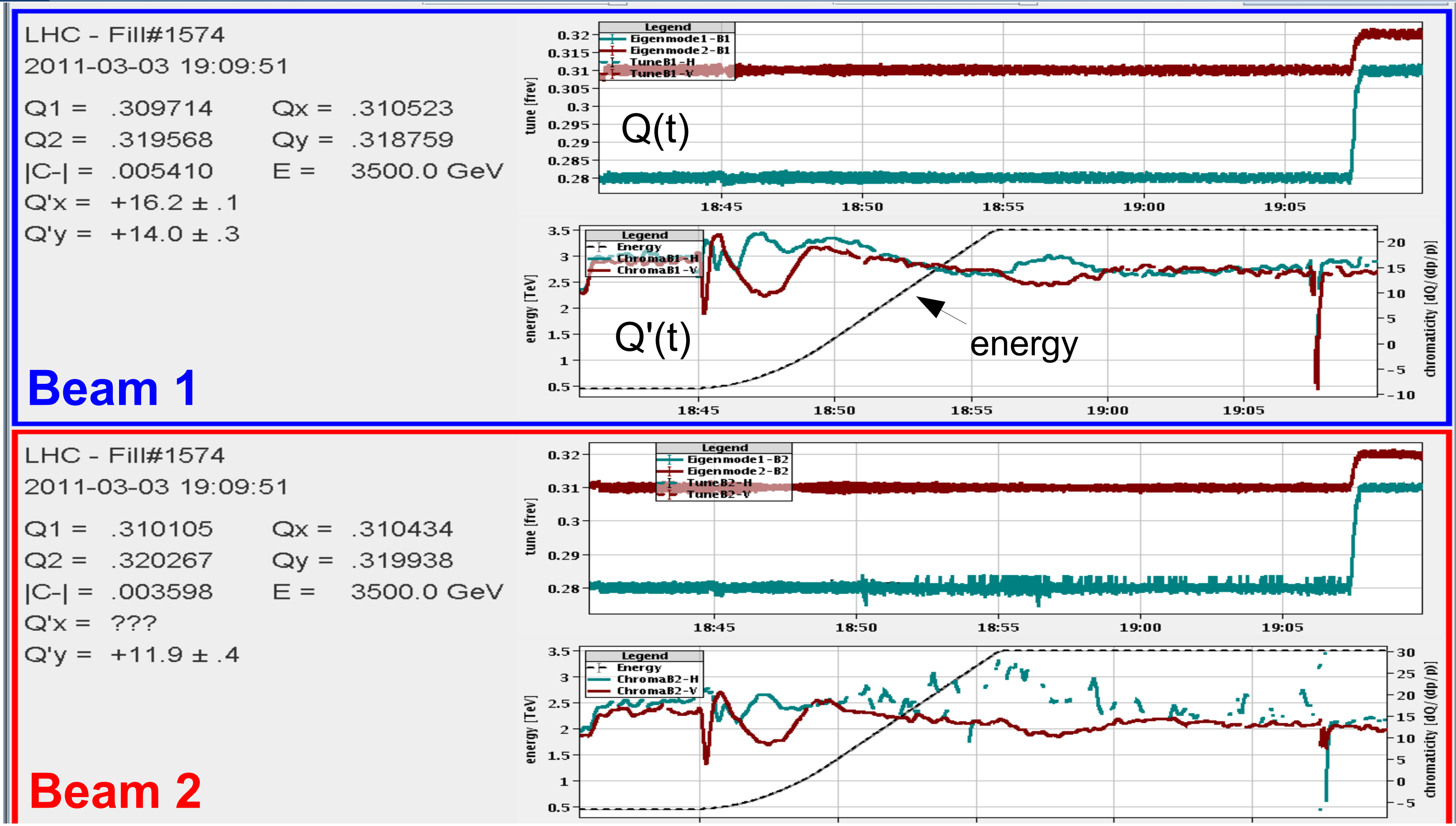
- However: µm-level oscillations are incoherent "noise" from a Tune-PLL point of view
- Need to excite ~30 dB above this "noise" to recover "passive" FFT performance
→ 10...100 µm oscillations vs. collimators <200 µm
- Driving the beam with the present ample signals seemed to be inefficient/less robust
- PLL tracking in action:







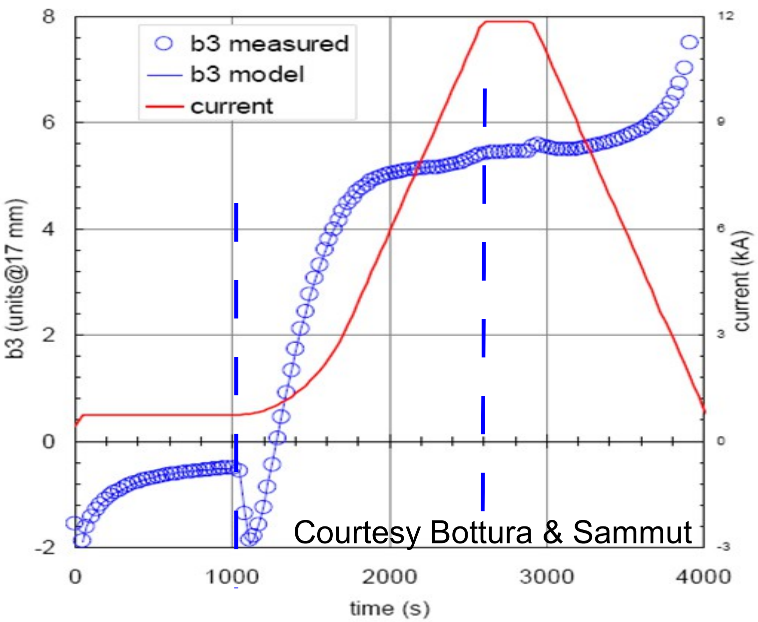
Typical Q/Q'(t) Control Room View
2010 Statistics: Out of 191 Ramps...



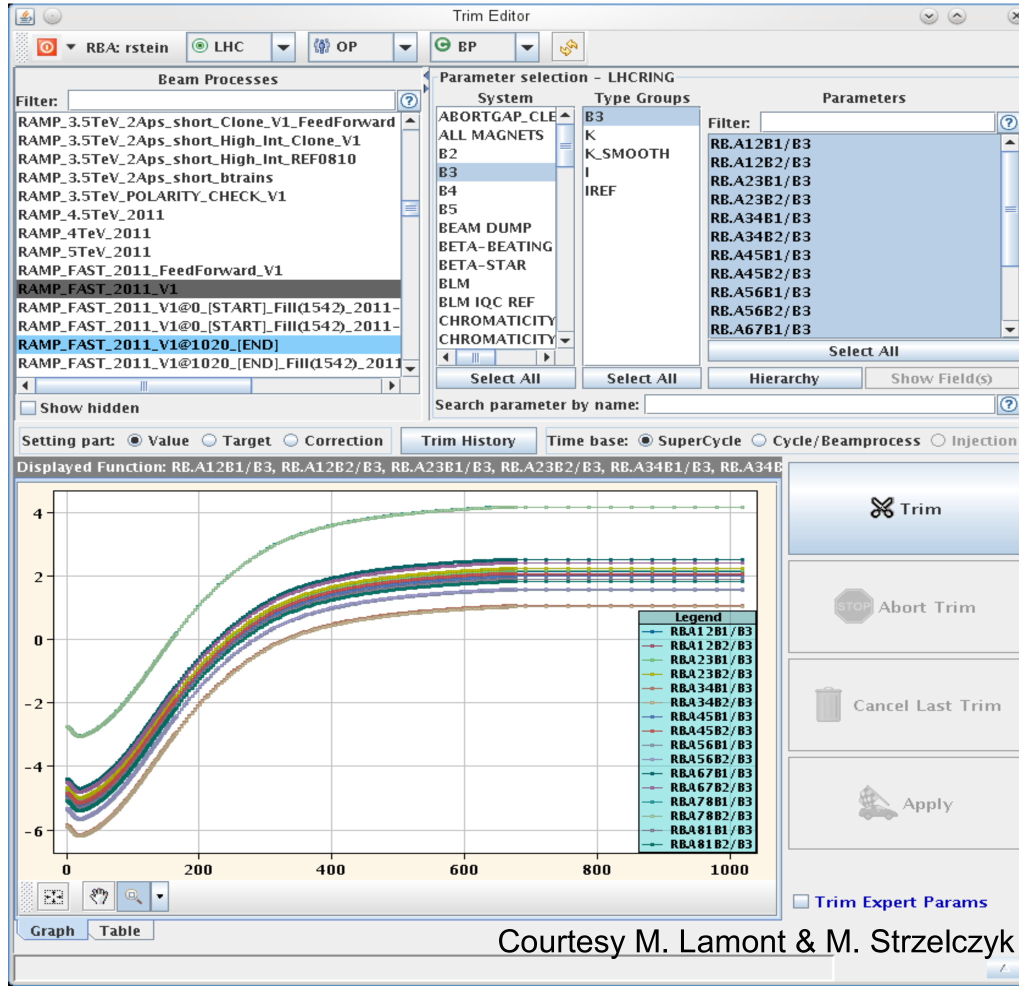
- … 155 ramps with > 99% transmission, 178 ramps with > 97% transmission
- … only 12 ramps lost with beam (6 with Tune-FB during initial 3.5 TeV comm.)
- … "if without FBs": 83 crossings of 3rd, 4th or C- resonance, 157 exceeded |ΔQ|>0.01
- Impressive performance for the first year of operation and low-ish intensities:

Feed-Forward Back-Bone: LHC Software Architecture (LSA) – Magnetic Field Corrections to the “bare” LHC

Field measurements & Model

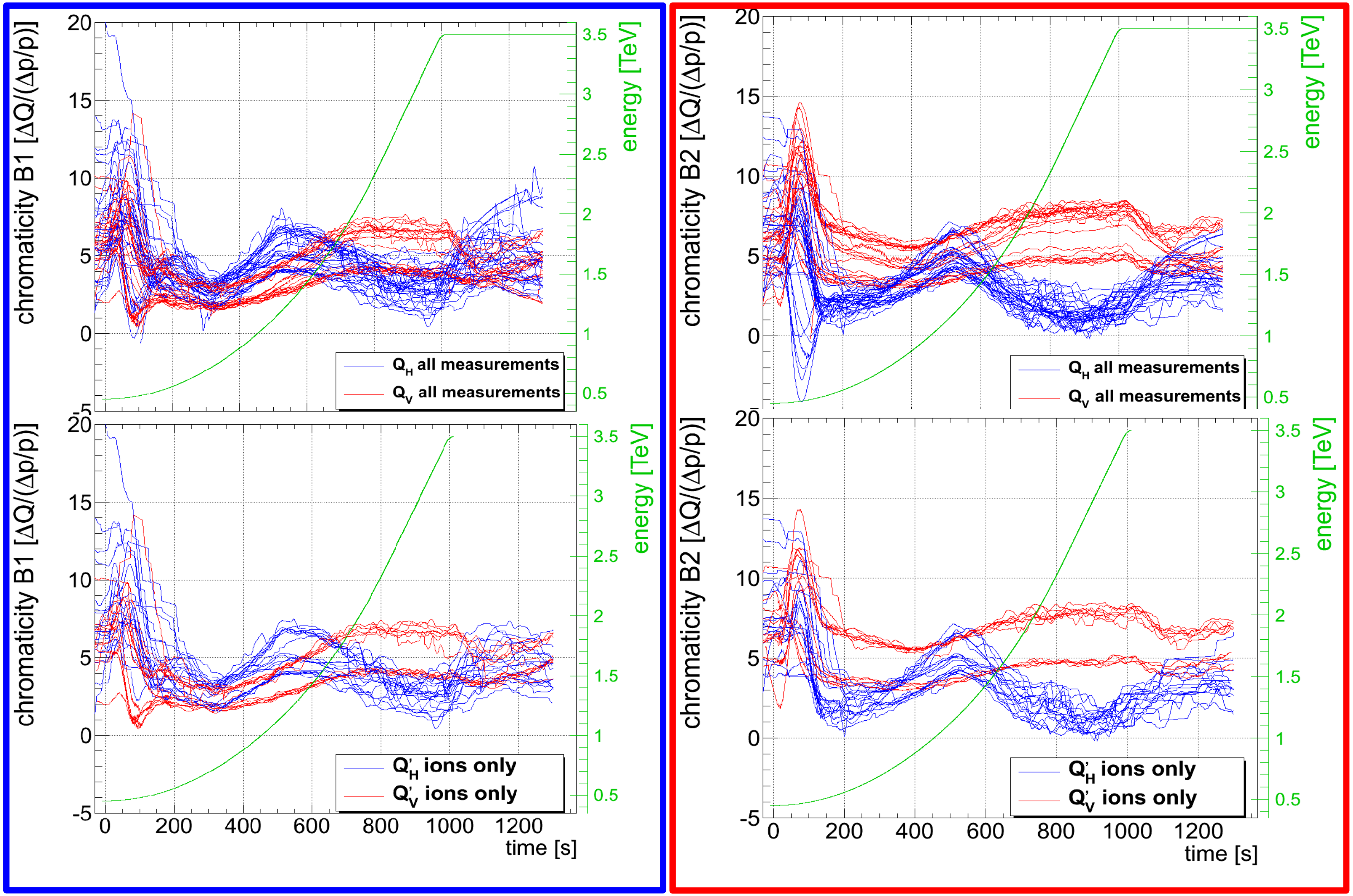


Today's circuit-by-circuit compensation:



- Model-based FF reduced expected 'Q'(t) swing' from 250 to less than 30 units
  - Low intensity beam survived these initial ramps
    → testimony to machine linearity and small machine impedance

- Feed-forward of Q'(t)-Feedback signal for next fill turned out to be sufficient!
  - enforced by strict pre-cycling following physics, access or circuits 'off '...



A Note on Dependence of LHC Operation on Feedbacks:

- Could/should LHC run without Feedbacks: – NO

  1 More than 50% of fills would have probably been lost without FBs
     - mostly during or after of changing the mode-of-operation

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

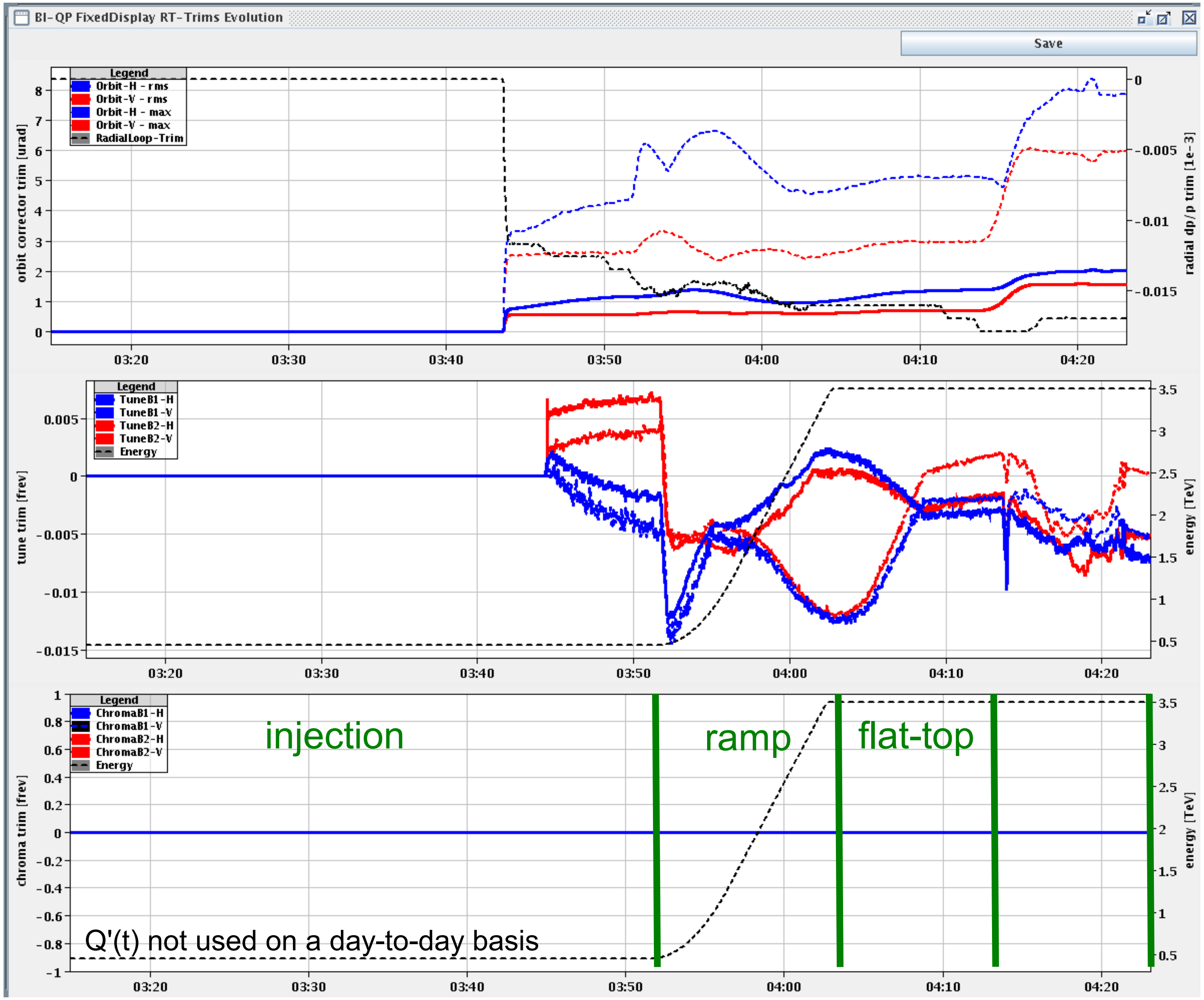
However:

“Having a car brake or ESP/ABS system does not justify reckless driving!”

- Feedbacks may and do shadow systematic machine problems
  → reduces additional safety margin and increases the dependence on them
  - acceptable to quickly advance and as temporary mitigation solution
  - Logging of all feedback system actions used to monitor and identify potential problems, and to facilitate feed-forwarding

Feedbacks in Action : Ramp & Squeeze

- Trims became de-facto standard to assess the FB and machine performance



Orbit-FB & Radial-Loop Trims (µrad)

Tune-FB trims

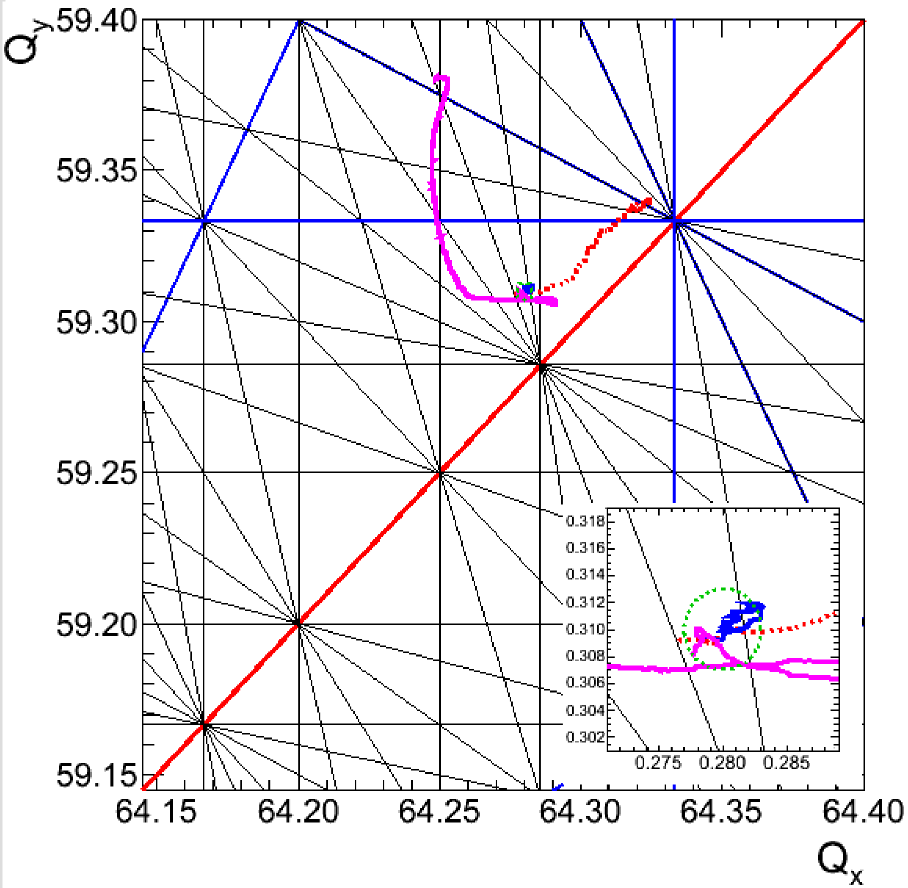
Q'(t)-FB trims

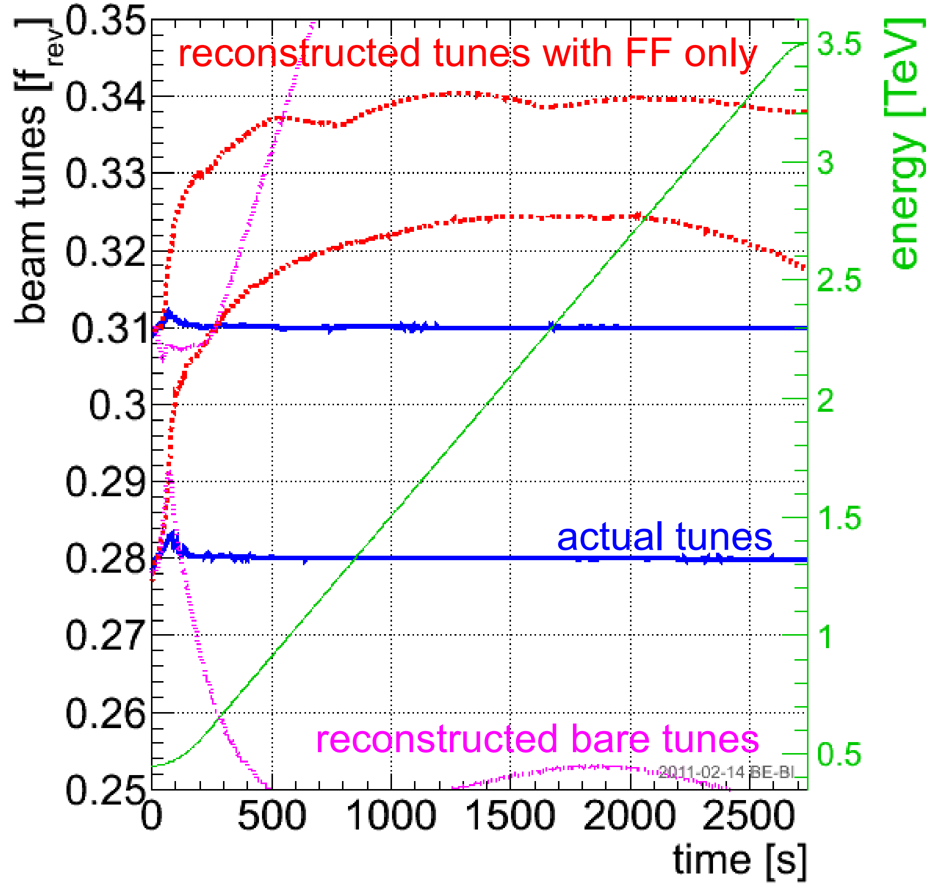
Energy (TeV)

β*-squeeze

'What-if-... Scenario' Analysis

- Tunes kept stable to better than 10^{-3} for most part of the ramp and squeeze



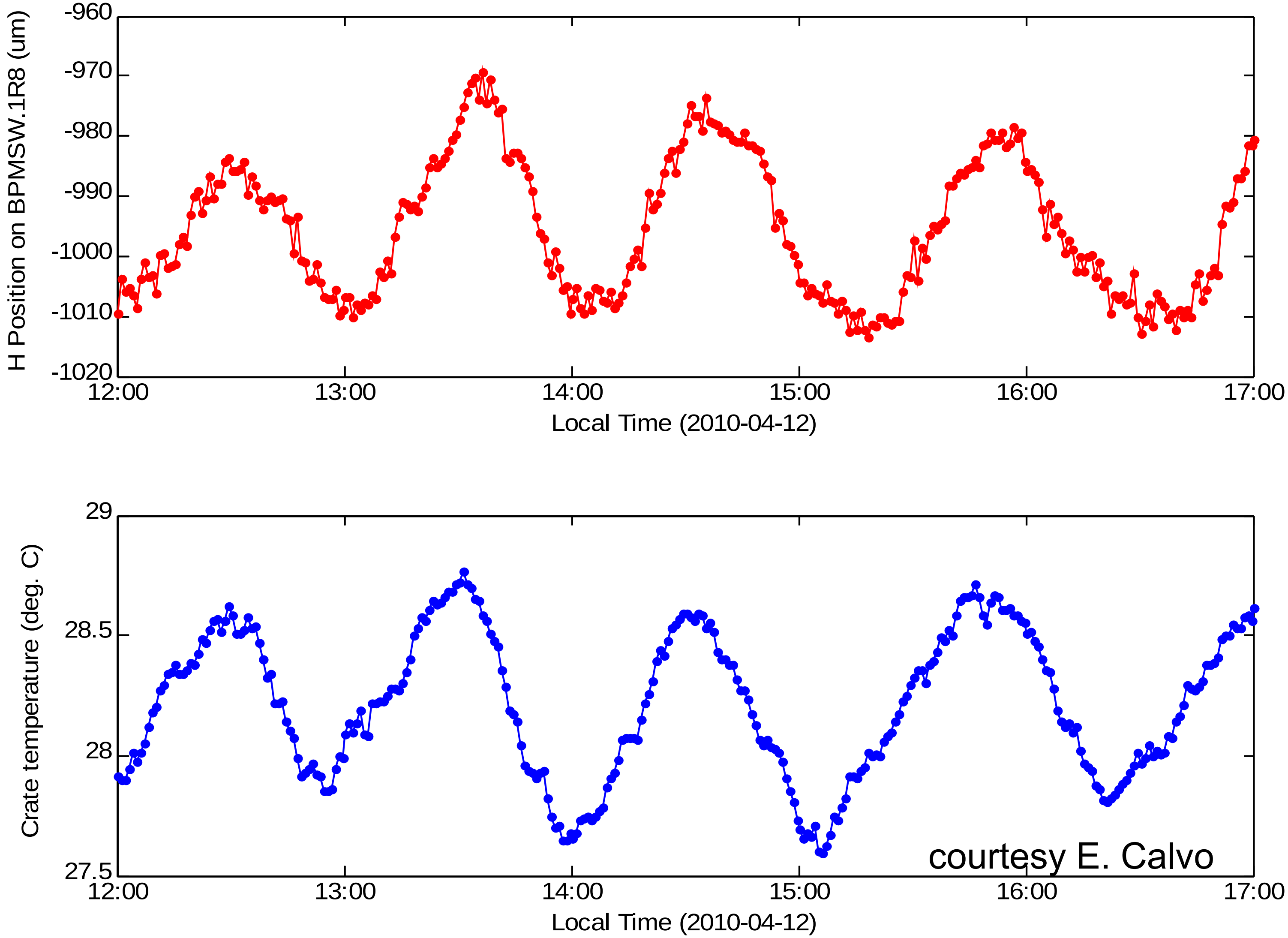


- Feed-forward errors during snapback probably due to feed-down effects

Things that did not go according to the Cunning Plan...
Or: FBs are only as reliable as their Inputs they are based upon.

… fighting instabilities ...

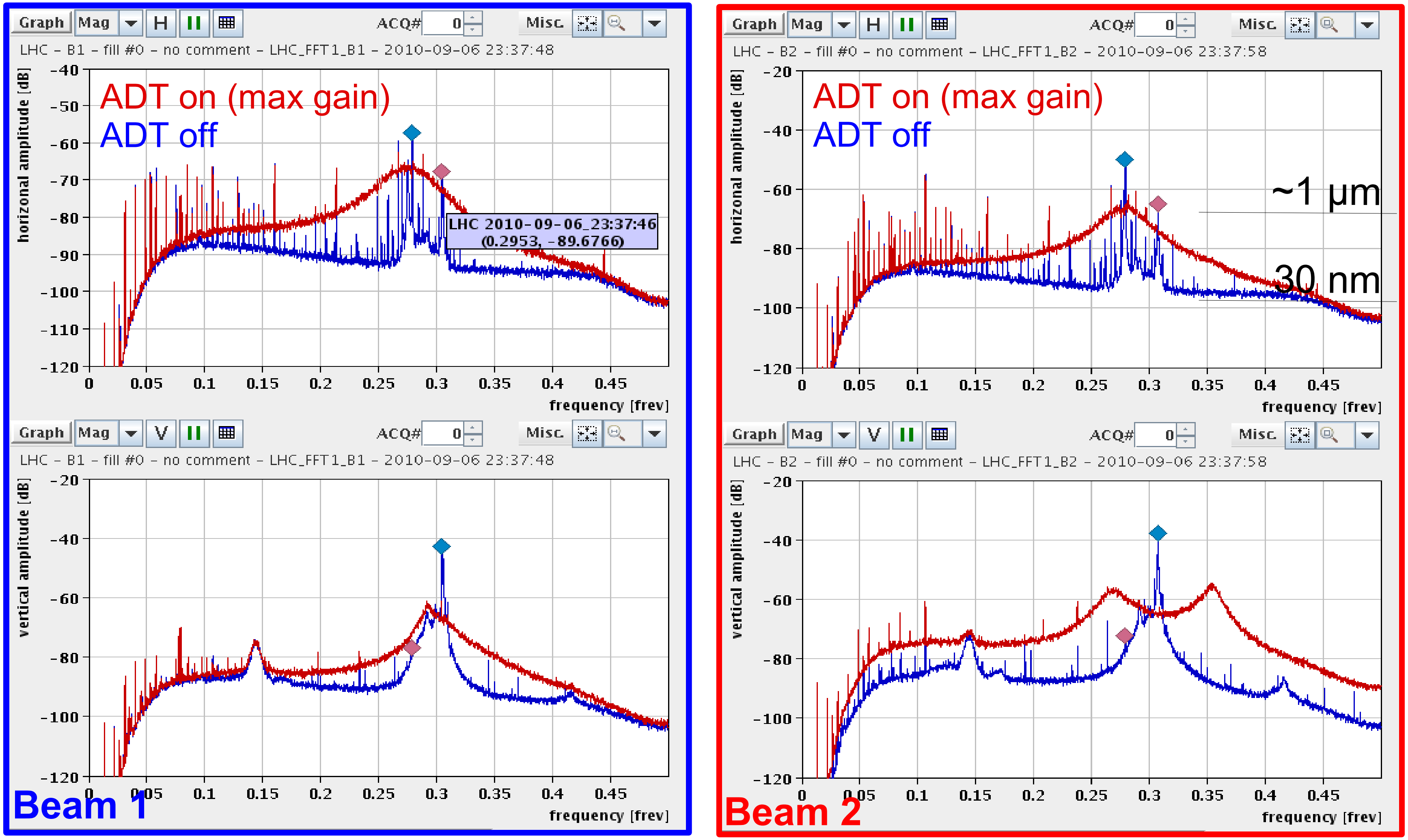
BPM Electronics Dependence on Temperature



- Presently compensated by data post-treatment → max. orbit error < ~ 70 um
  - Full temperature control of the crates are under investigation

Transverse Bunch-by-Bunch FB (ADT) & Tune Diagnostic – Conflicting Requirements

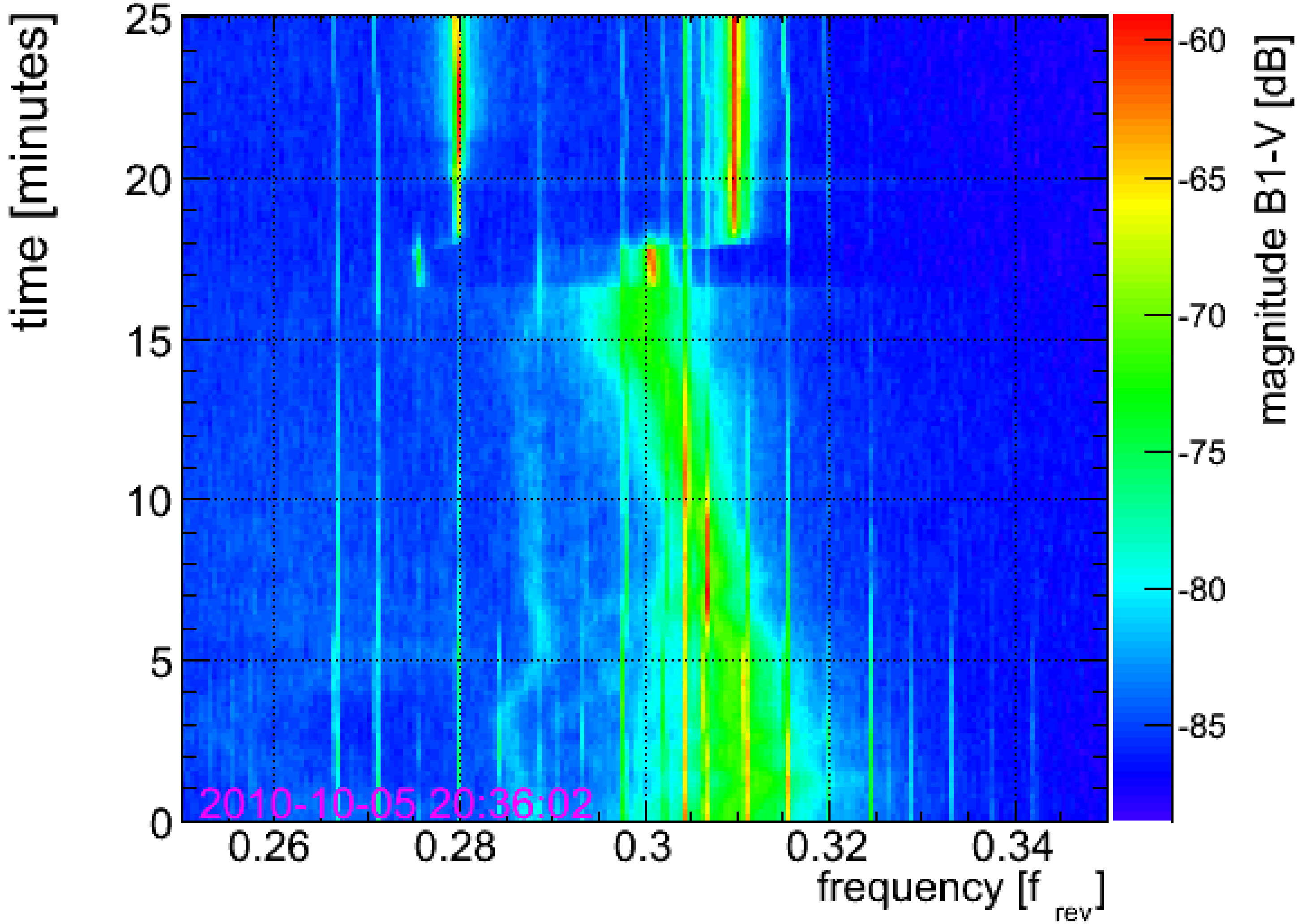
- Higher B-b-B FB gain implies also more meas. noise propagated onto beam...



- For the time being mitigated by reducing ADT gain when Tune-FB is needed
  - Under investigation: tune signal derived from ADT actuator control signal

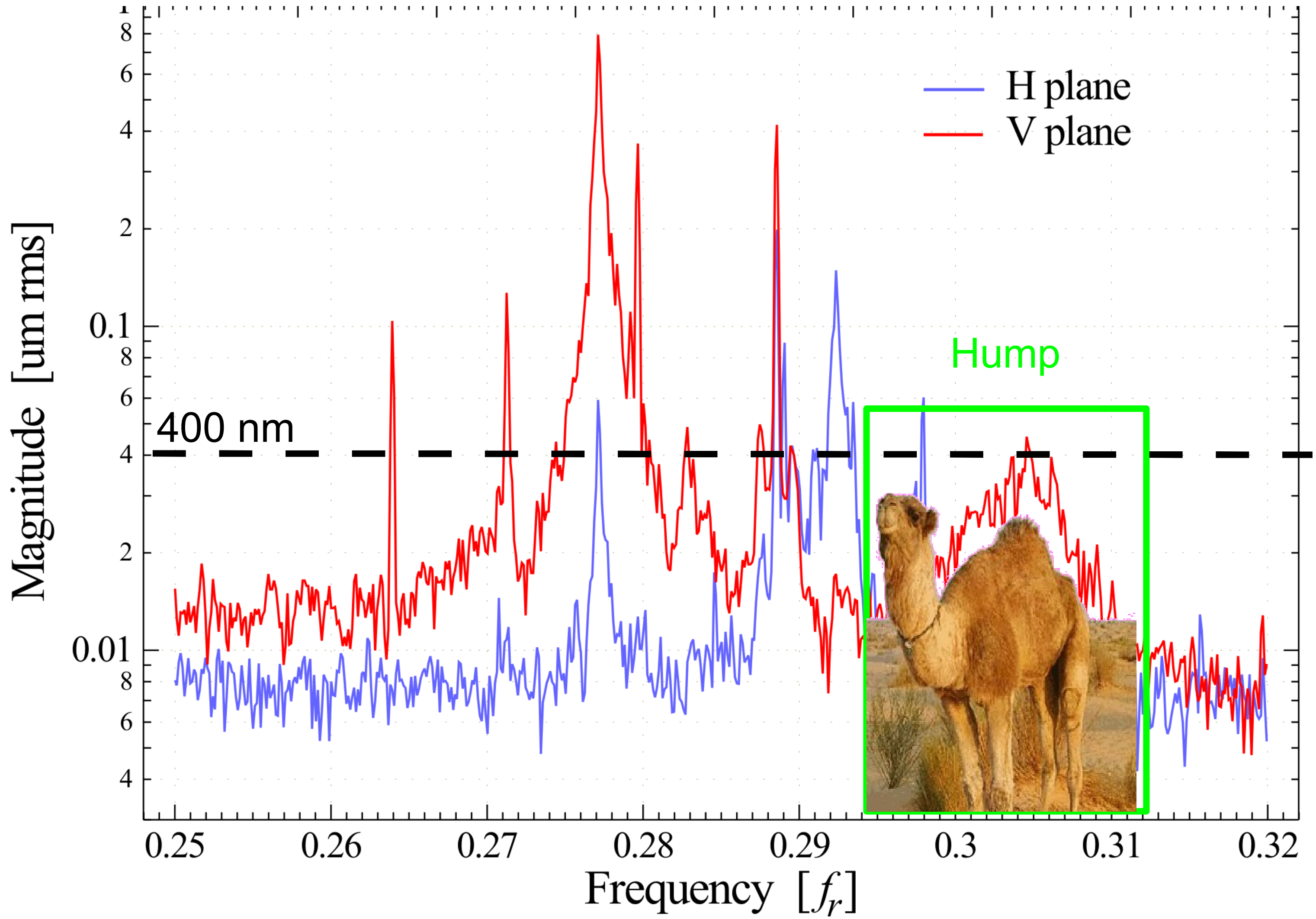
Impact of Mains Harmonics on Beam Stability

- Mains harmonics visible in spectrum and (minor) source of emittance growth



- adapted Q-detection filter to remove this → non issue for LHC Tune-FB

Mystery of the LHC Year 2010:
Broad-band perturbation with shifting mean frequency



- Accepted Control-Room Jargon: of being “humped”
- Origin remains unknown but is less of an issue in now (2011)

Conclusions

- Feedbacks facilitated a fast commissioning and used de-facto during every ramp and squeeze with nominal beam
- Good overall performance with little transmission losses and minimal hick-ups related to Q/Q' instrumentation, diagnostics and Q/Q' & orbit feedbacks
- Impressive machine stability: Q'(t) and Coupling proved to very reproducible
  - enforced by strict pre-cycling following physics, access, circuits 'off', ...
  - fill-to-fill corrections appear to be sufficient for the time being
- With 2010 intensities no serious issues observed but need to revisit conflicting requirements for ADT and Q/Q' diagnostics once reaching the e-cloud barrier
- In the pipeline: beam-based gain-scheduling, polishing user-level interfaces...
- Success is not accident: LHC feedbacks are based on years of accumulated experience at CERN, BNL, FNAL, DESY, PSI, Diamond, Soleil and Triumf.

Thank You for your Attention!