Real-Time Beam Control at the LHC

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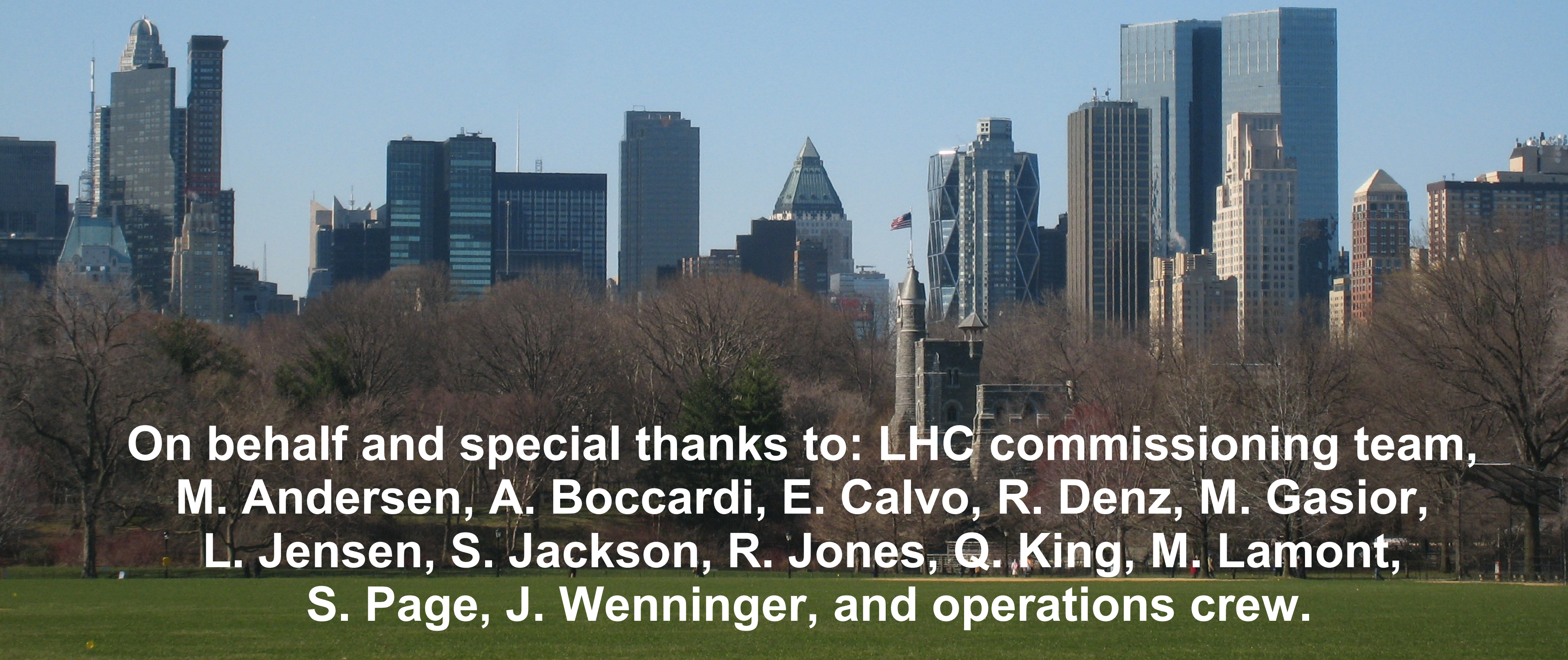


On behalf and special thanks to: LHC commissioning team, M. Andersen, A. Boccardi, E. Calvo, R. Denz, M. Gasior, L. Jensen, S. Jackson, R. Jones, Q. King, M. Lamont, S. Page, J. Wenninger, and operations crew.

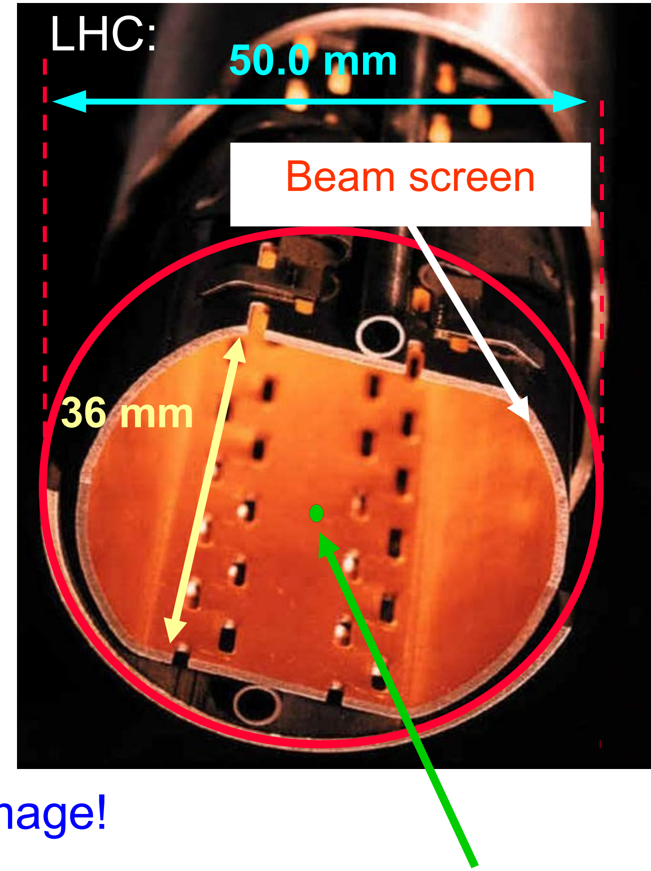
Outline

- 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

FFT-based Q tracking op. deployed at SPS

PLL-studies at RHIC

FNAL-LARP involvement in Schottky design and front-end electronics

2003

Orbit-FB prototype tests at the SPS

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

PLL-Q and Q'(t) tracker demononstrated at SPS

2006

FNAL-design/CERN-built 4.8GHz TWC Schottky

Tune Feedback Final Design Review (BNL)

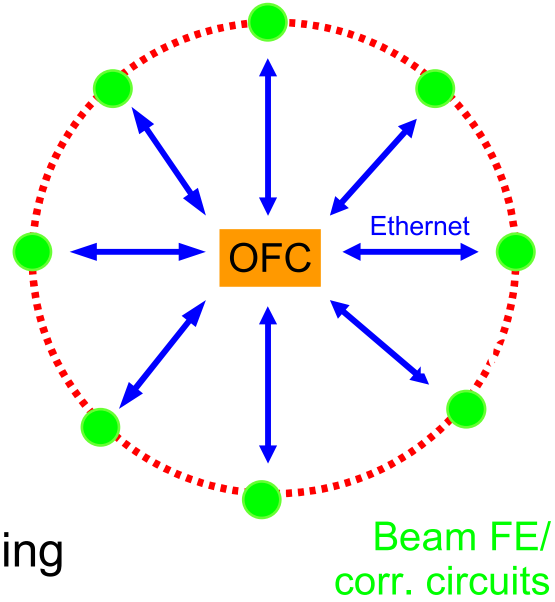
2007

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

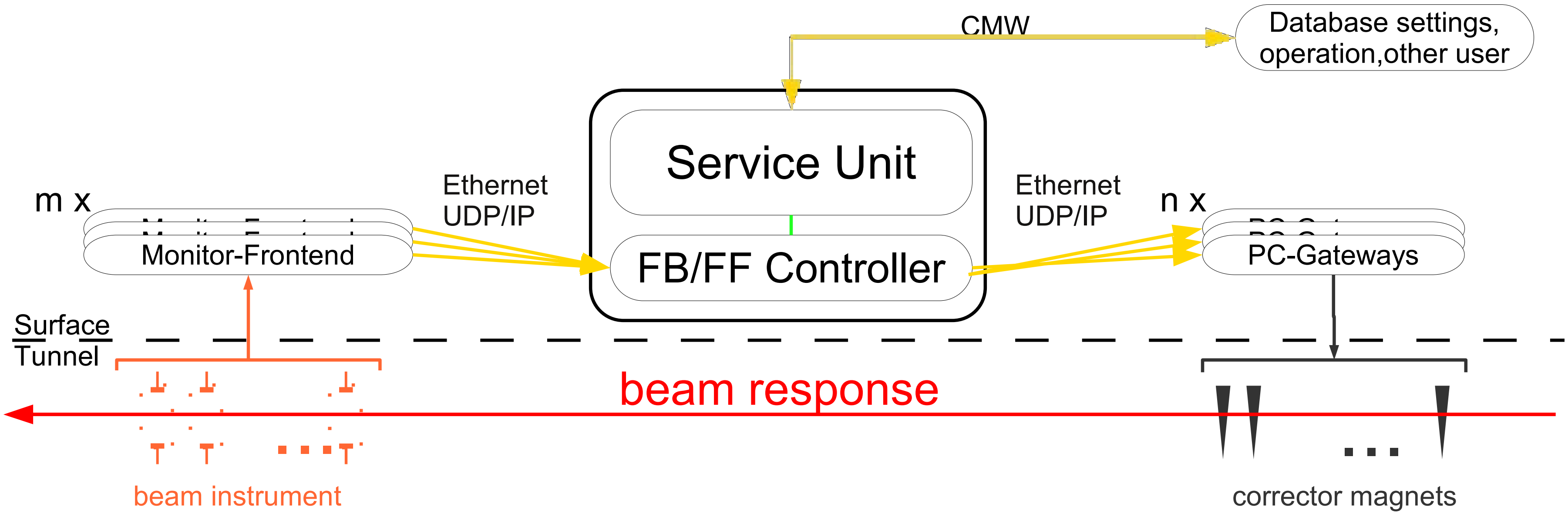
- Orbit-Feedback is the largest and most complex LHC feedback:
  - 1088 BPMs → 2176+ readings @ 25 Hz from 68 front-end computers
  - 530 correction dipole magnets/plane, distributed over ~50 front-end computers

- 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:

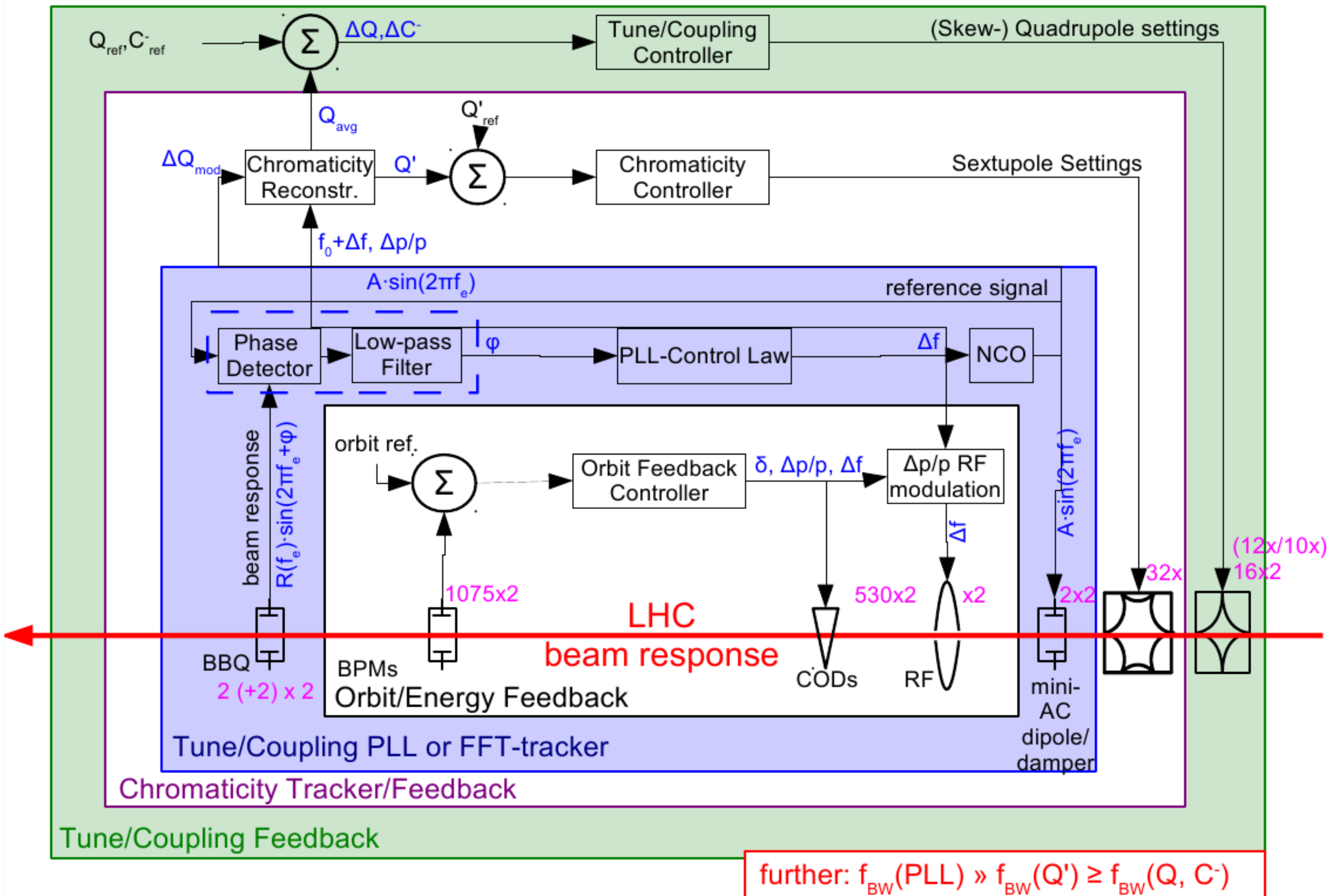
- Feedback Controller (OFC) performing actual feedback controller logic
  - Simple streaming task (10% of total load)
  - Beam data quality checks and real-time filtering (80% of total load)
  - Server running Real-Time Linux OS with periodic constant load
    - multi-core, highly redundant – MTBF > 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

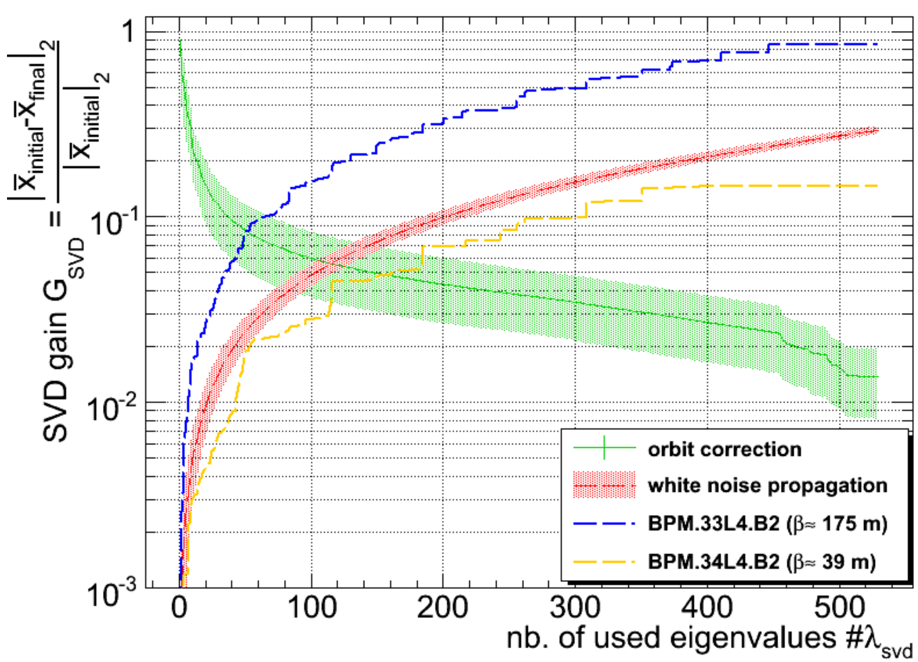
- Main strategy: derive meas from FB control variable
  - Q'-tracker using '$Q_{raw} = Q_{meas} - Q_{trim}$'
  - Sub. Δp/p-mod. from Radial-Loop & Orbit-FB reference

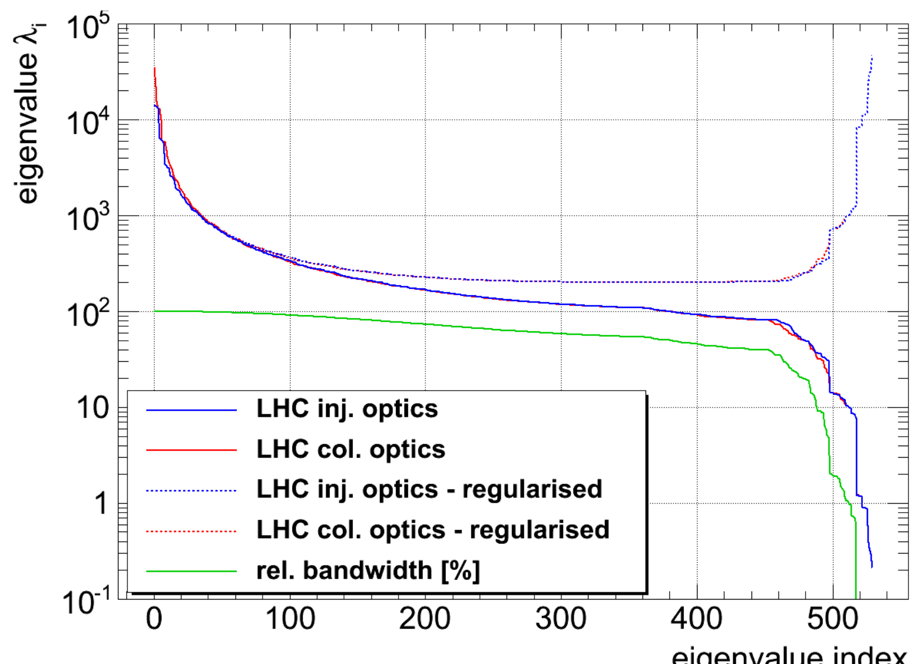


Standard Singular-Value-Decomposition based Orbit Correction

- 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)

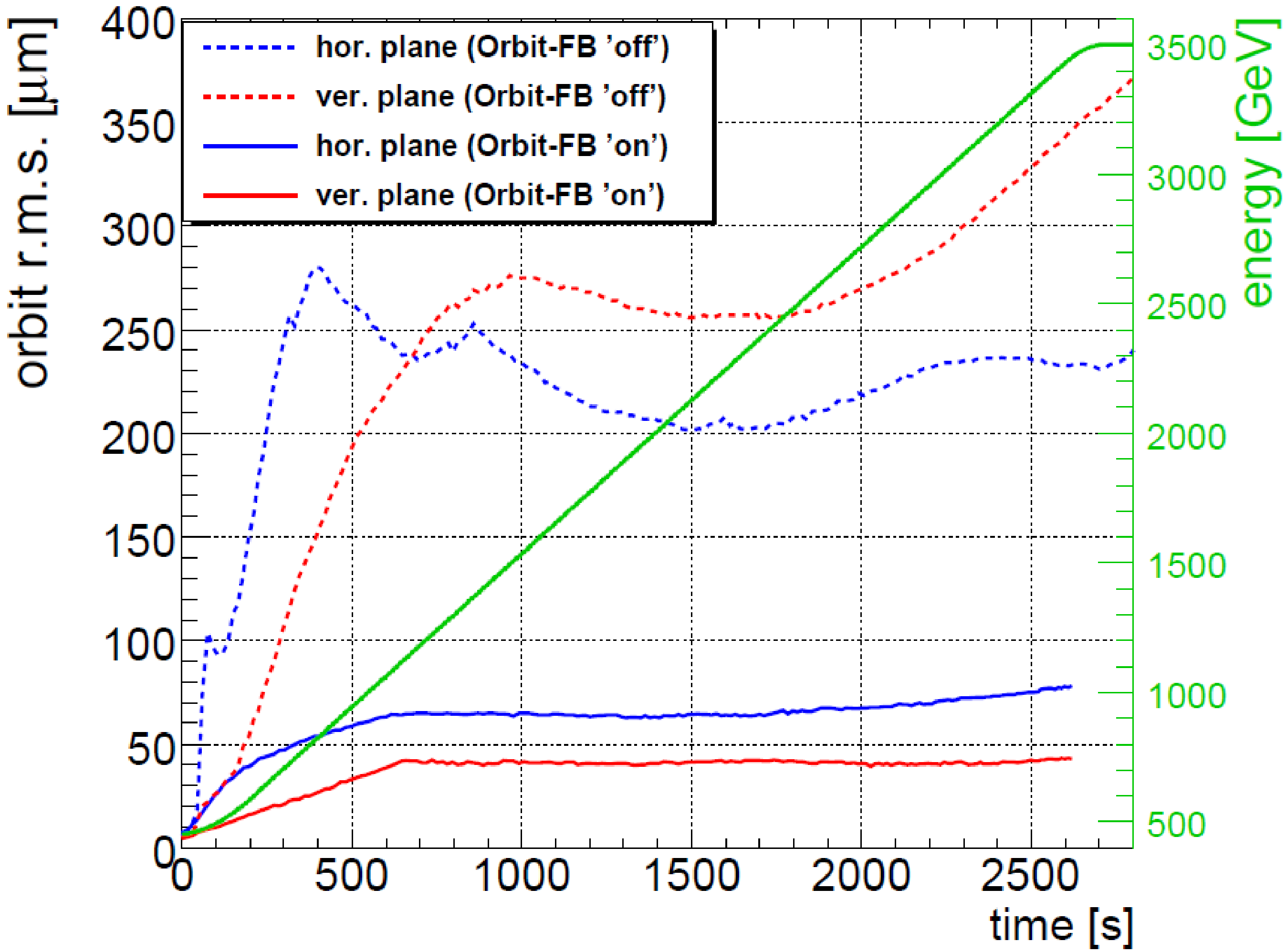
- Regularised-SVD (Tikhonov/opt. Wiener filter with $\lambda_i^{-1} := \lambda_i/(\lambda_i^2 + \mu)$, μ>0)
  - more robust w.r.t. optics errors and mitigation of BPM noise/errors
    → allowed re-using same ORM for injection, ramp and 10+ squeeze steps





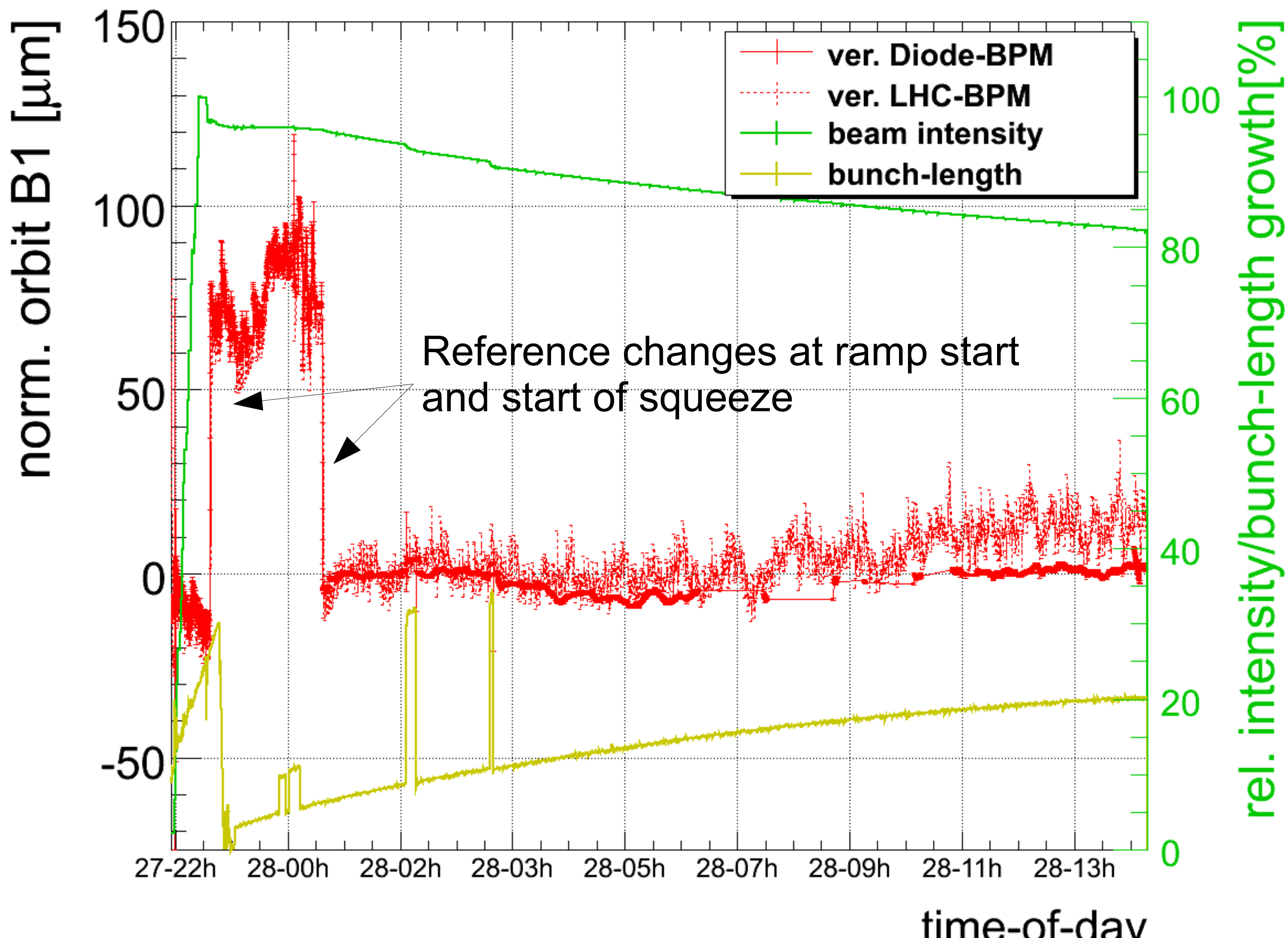
Orbit Feedback Performance

- 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

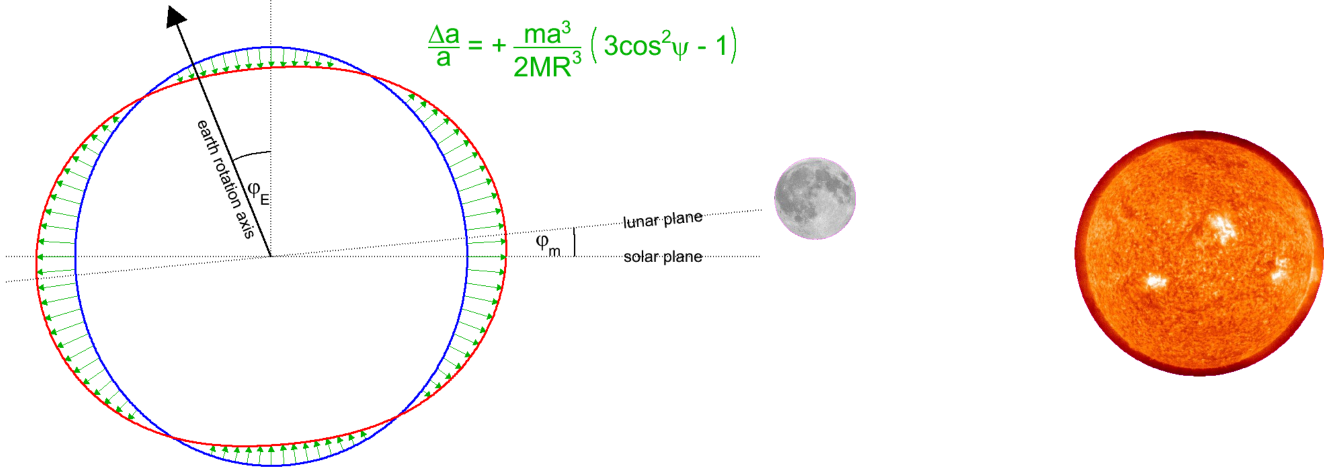
Orbit Stability during one LHC Fill

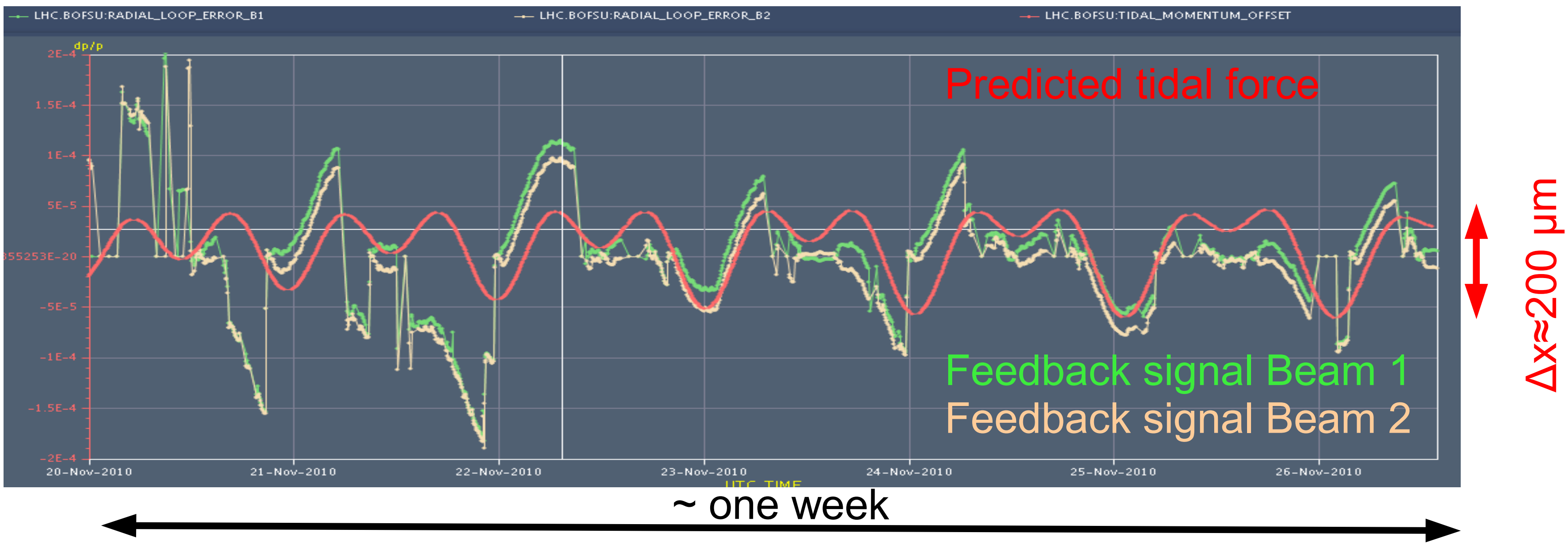


- Orbit stability during physics < 5 µm over 15 hours (Orbit-FB 'off')
  - new high-accuracy diode-based beam position monitor system: Δx_{res} < 0.5 µm

Earth Tides dominating Orbit Stability during Physics:

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



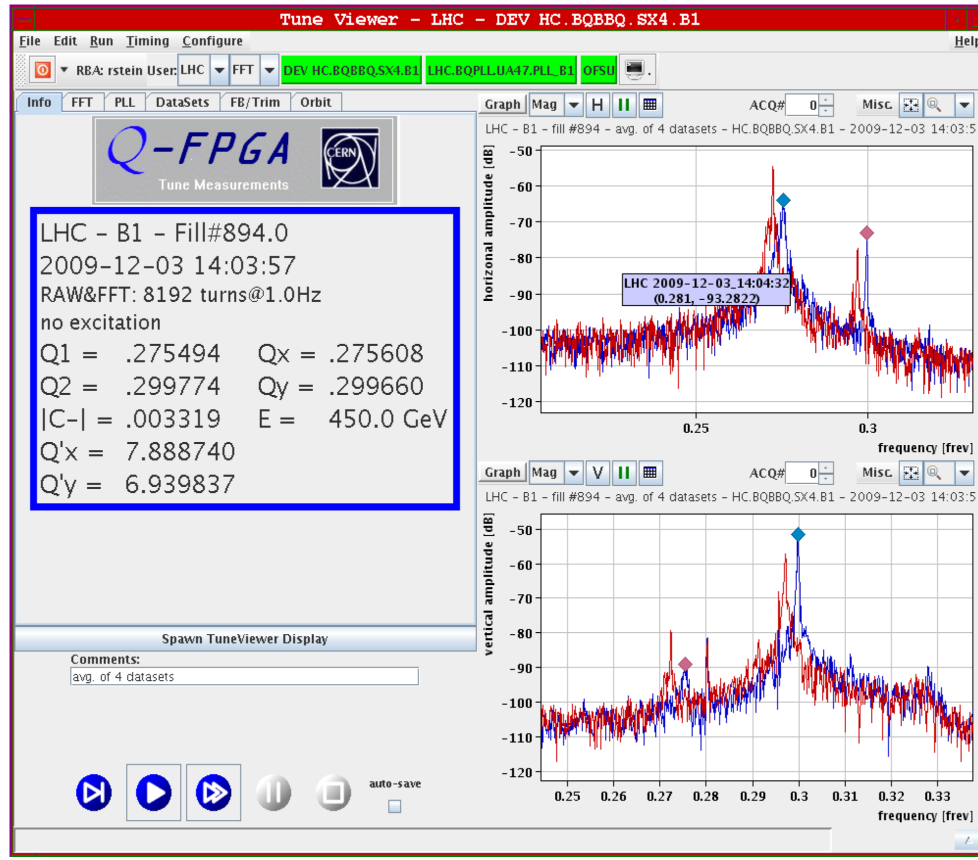


  - Testimony to LHC alignment and beam stability!

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

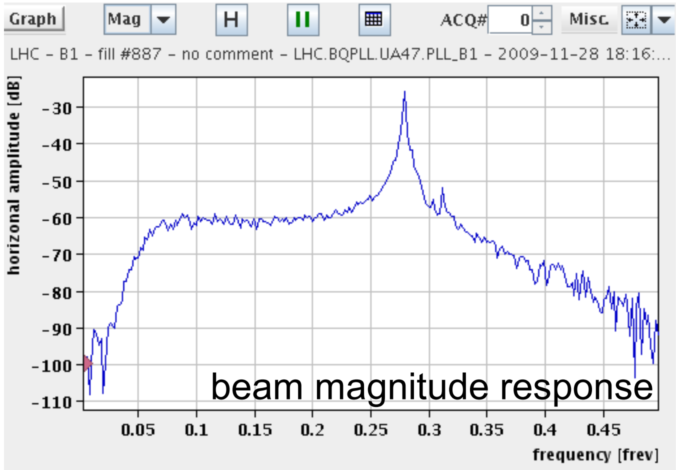
- Initial design assumption: no residual tune signatures on the beam (0 dB S/N)
  - Anticipated constant driving of the beam and – to limit the required excitation levels – the highly-sensitive BBQ system was developed

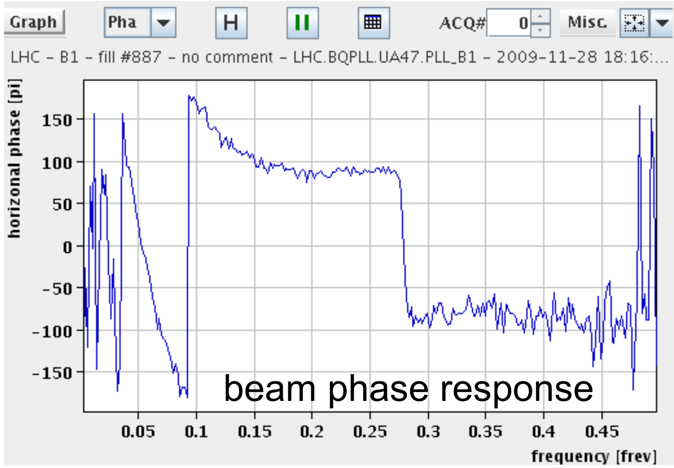
- Blessing/Curse after start-up:
  1. BBQ turn-by-turn res. < 30 nm
     - 30+dB more sensitivity than other LHC systems
       (e.g. ADT: 1µm, BPM: 50 µm)
  2. Ever-present Q oscillations
     on the few 100 nm to µm level

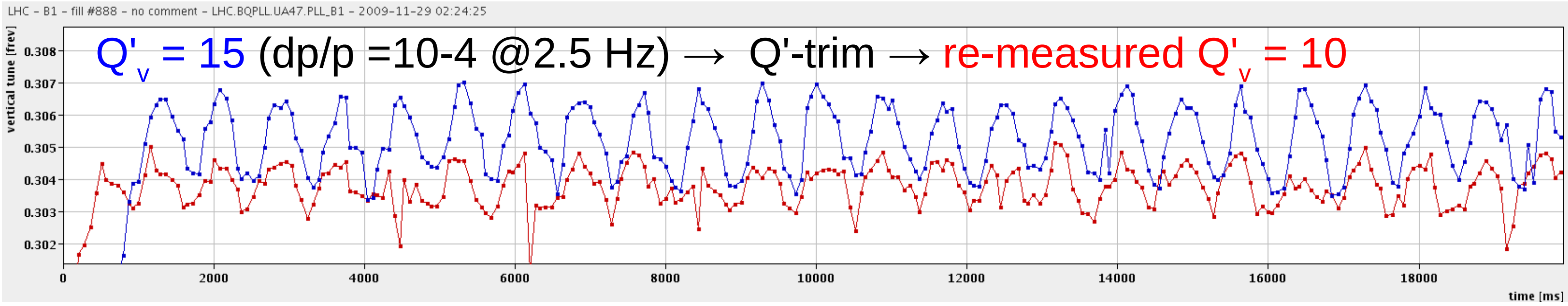


- Luxurious 30-40 dB S/N ratios enabled the passive monitoring, tracking and feedbacks without any additional excitation

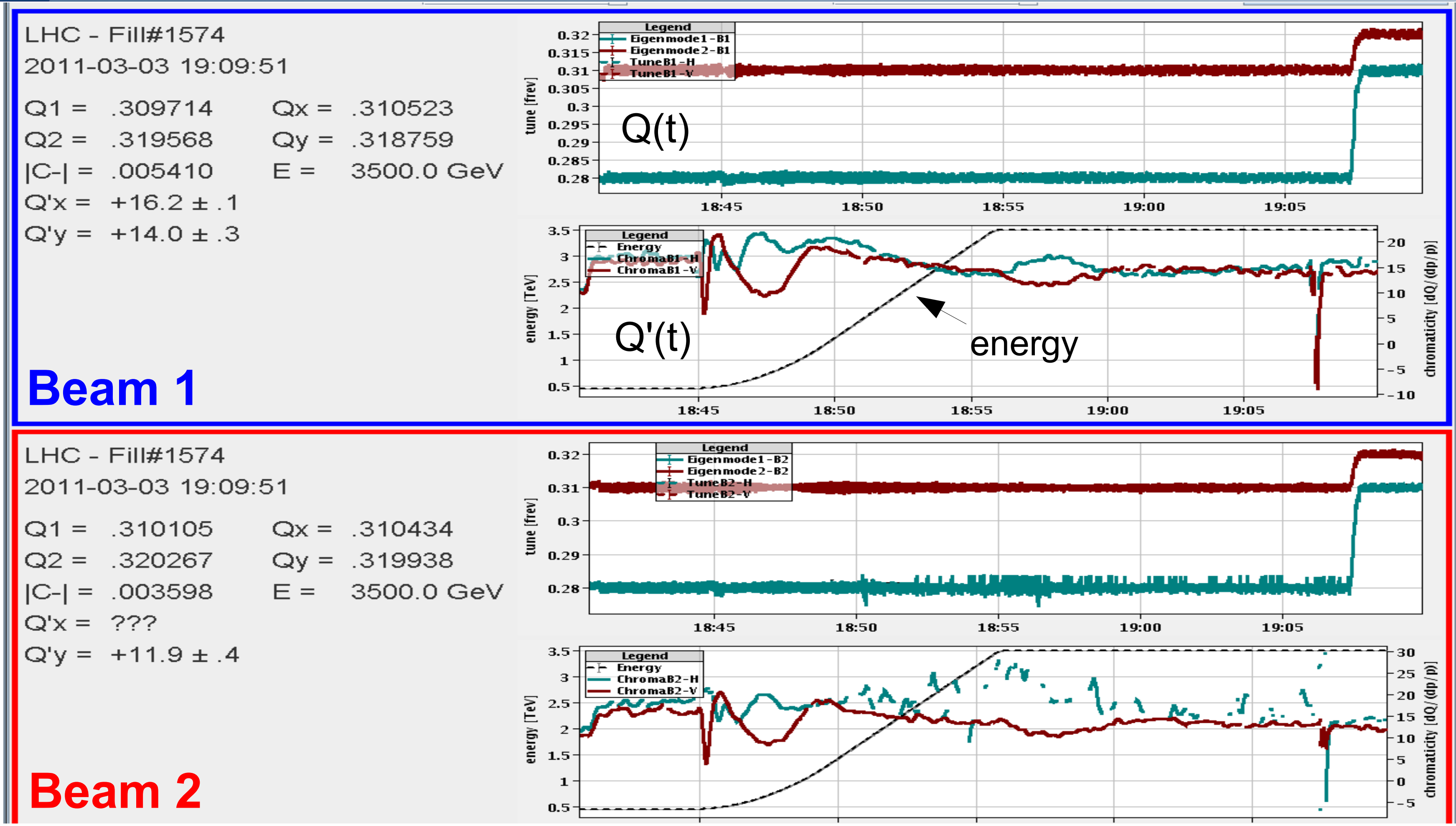
- However: µm-level oscillations are incoherent "noise" from a Tune-PLL point of view
- Need to excite ~30 dB above this "noise" to recover "passive" FFT performance
  → 10...100 µm oscillations vs. collimators <200 µm
- Driving the beam with the present ample signals seemed to be inefficient/less robust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







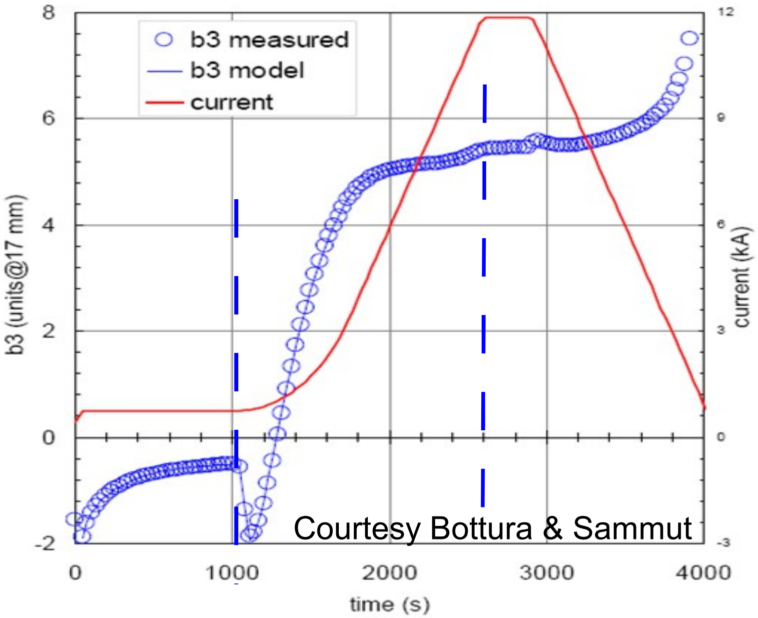
Typical Q/Q'(t) Control Room View
2010 Statistics: Out of 191 Ramps...



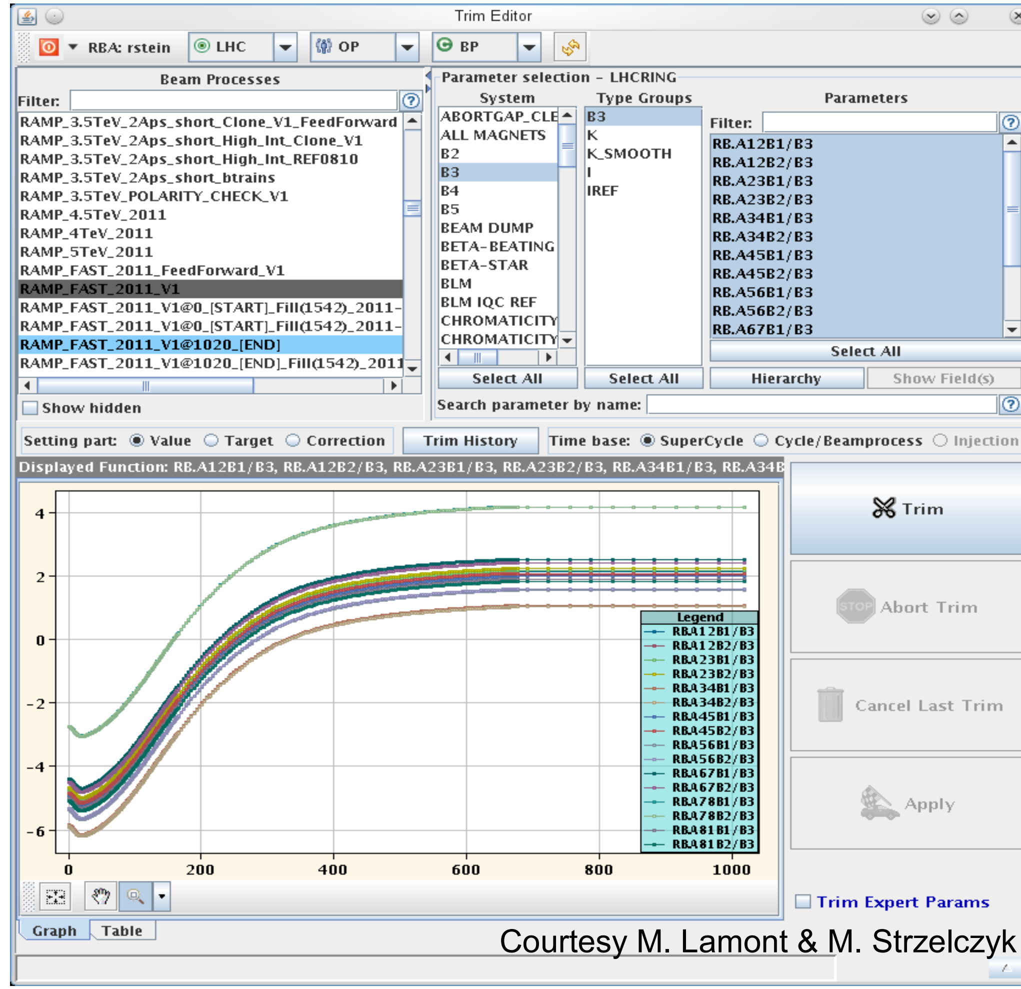
- … 155 ramps with > 99% transmission, 178 ramps with > 97% transmission
- … only 12 ramps lost with beam (6 with Tune-FB during initial 3.5 TeV comm.)
- … "if without FBs": 83 crossings of 3rd, 4th or C- resonance, 157 exceeded |ΔQ|>0.01
- Impressive performance for the first year of operation and low-ish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

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

Field measurements & Model

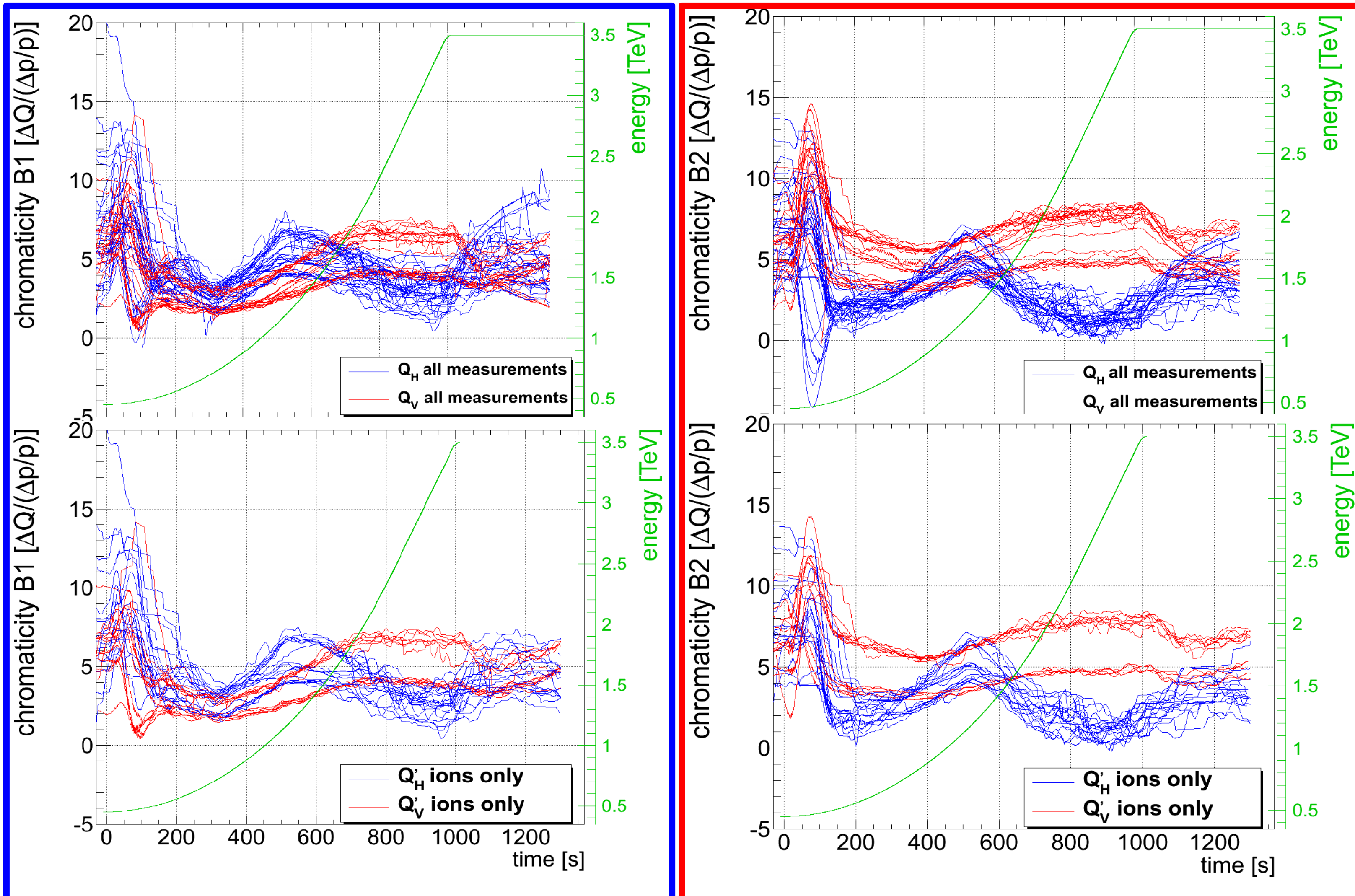


Today's circuit-by-circuit compensation:



- 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

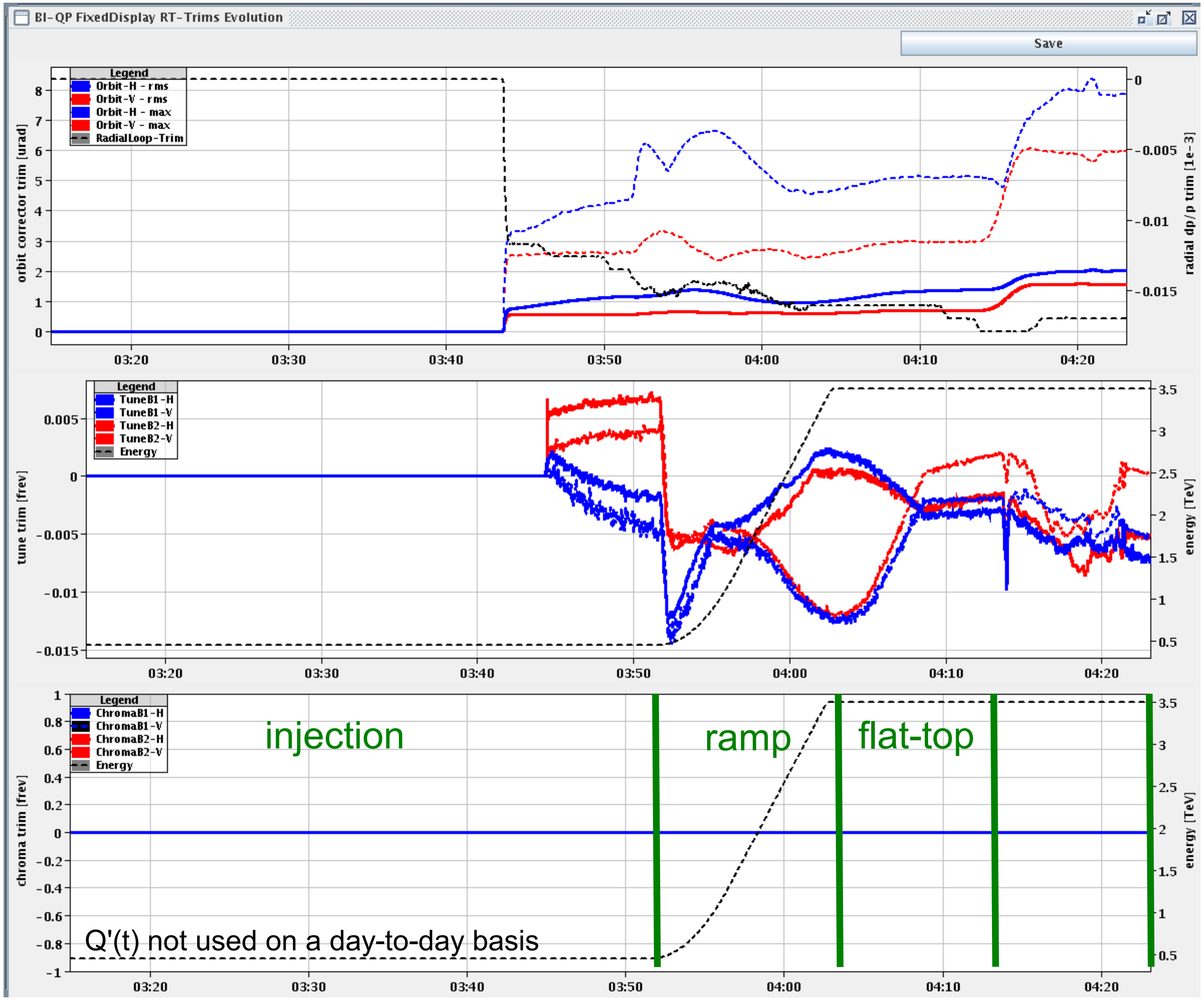
However:

"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



β*-squeeze

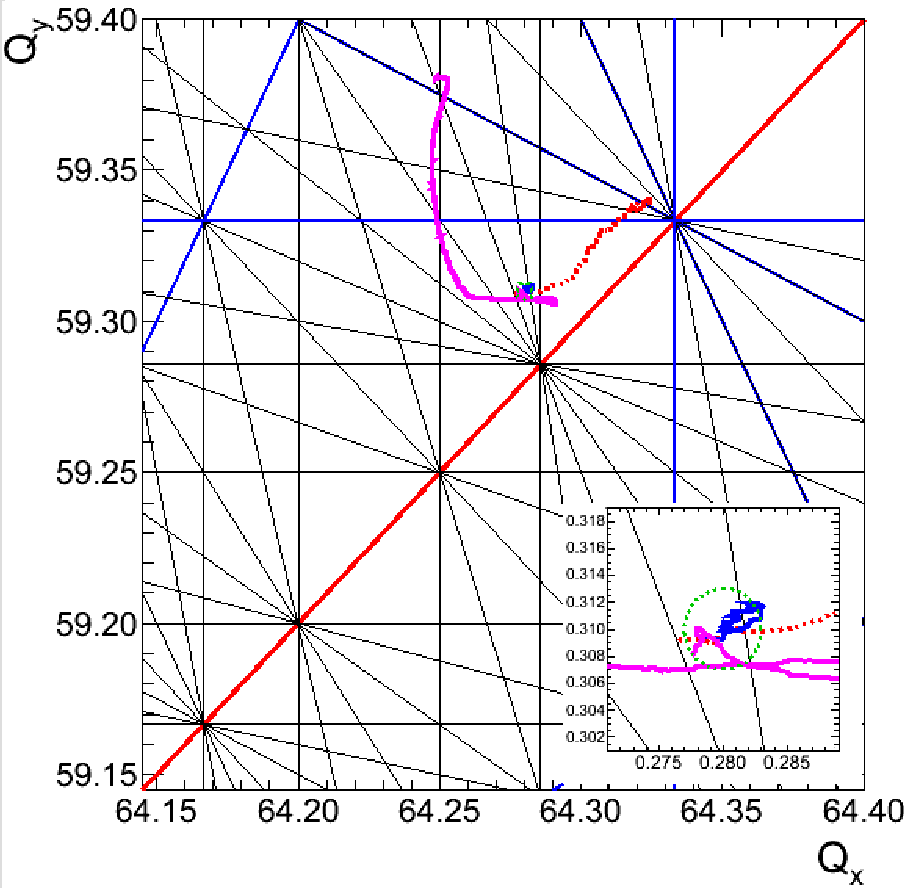
Orbit-FB & Radial-Loop Trims (µrad)

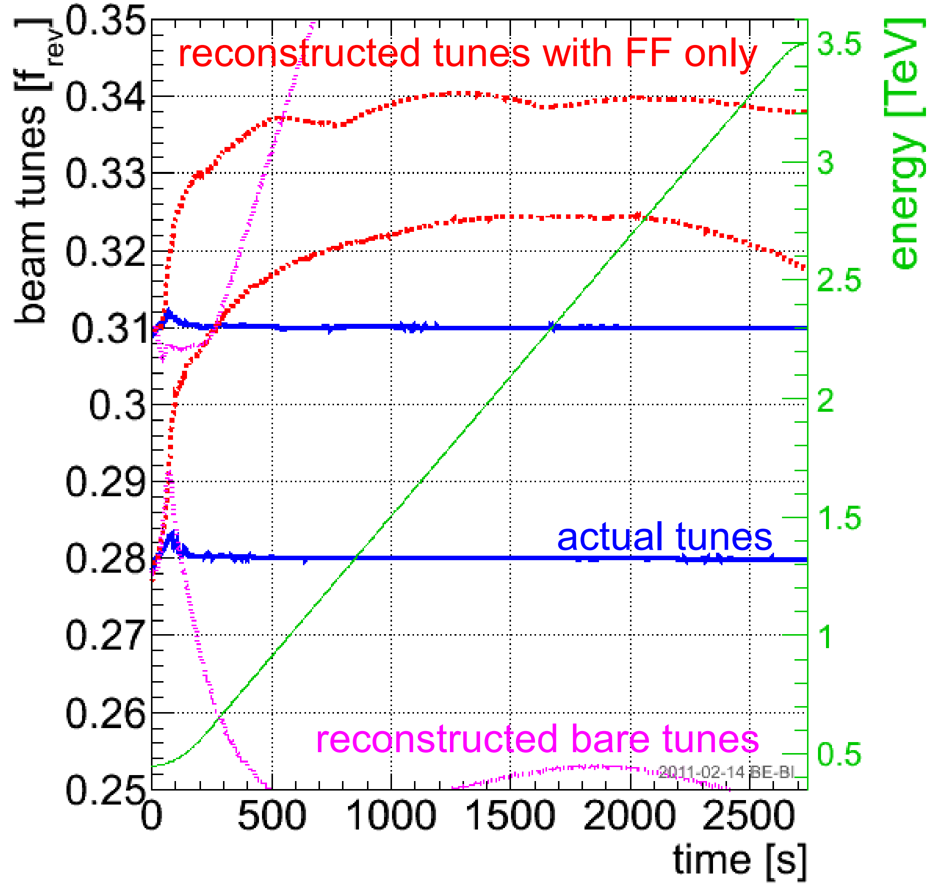
Tune-FB trims

Q'(t)-FB trims

Energy (TeV)

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



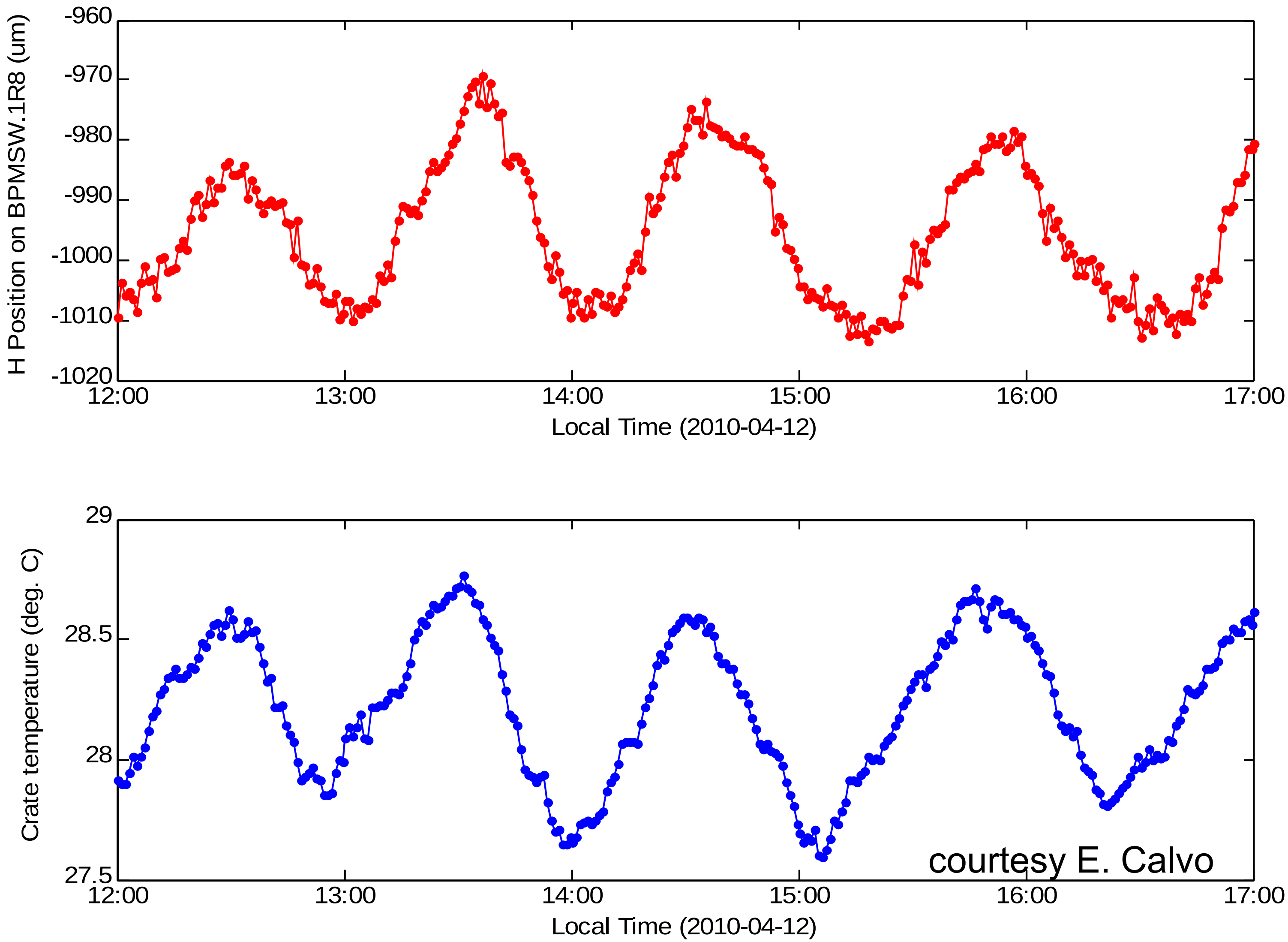


- Feed-forward errors during snapback probably due to feed-down effects

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 ...

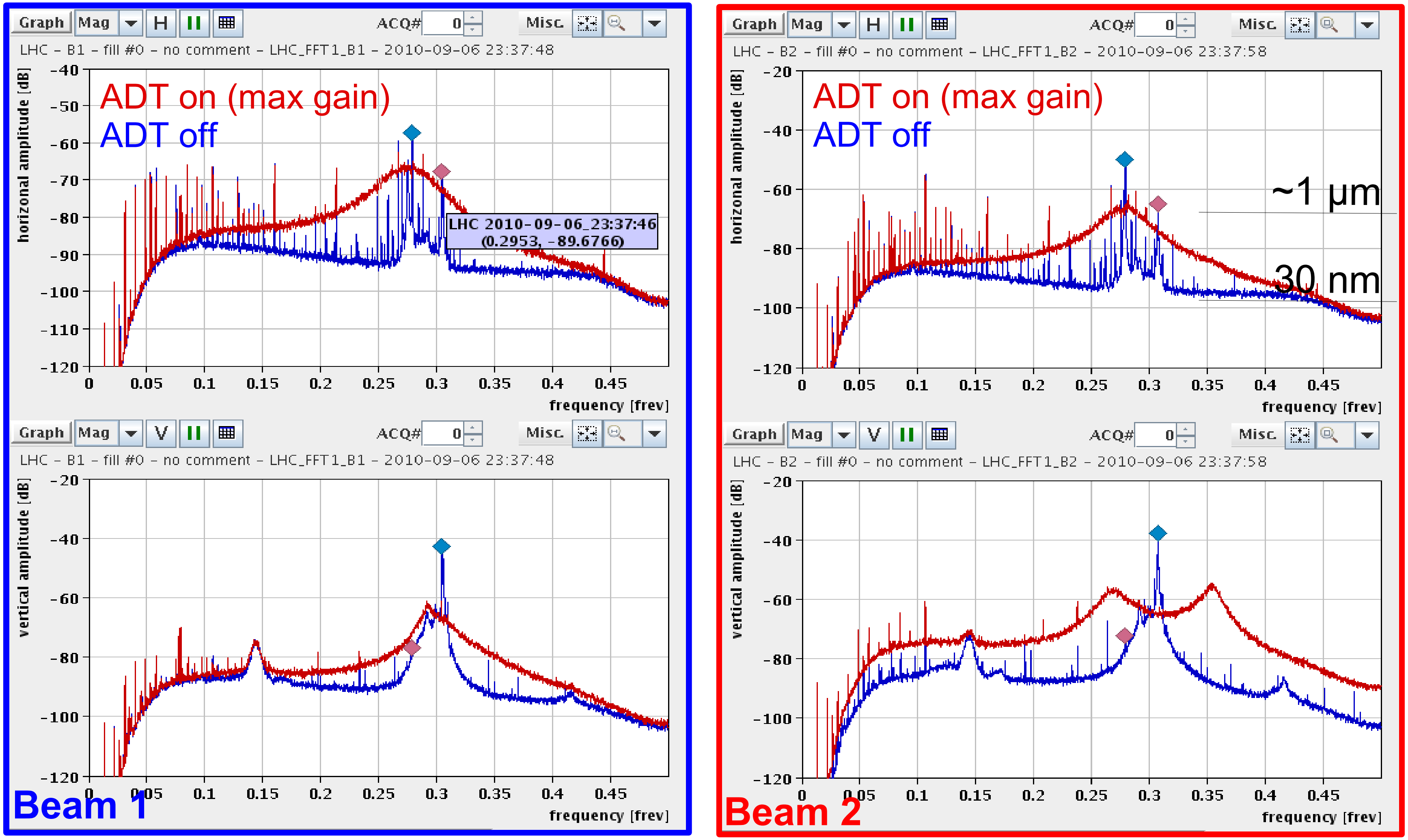
BPM Electronics Dependence on Temperature



- 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

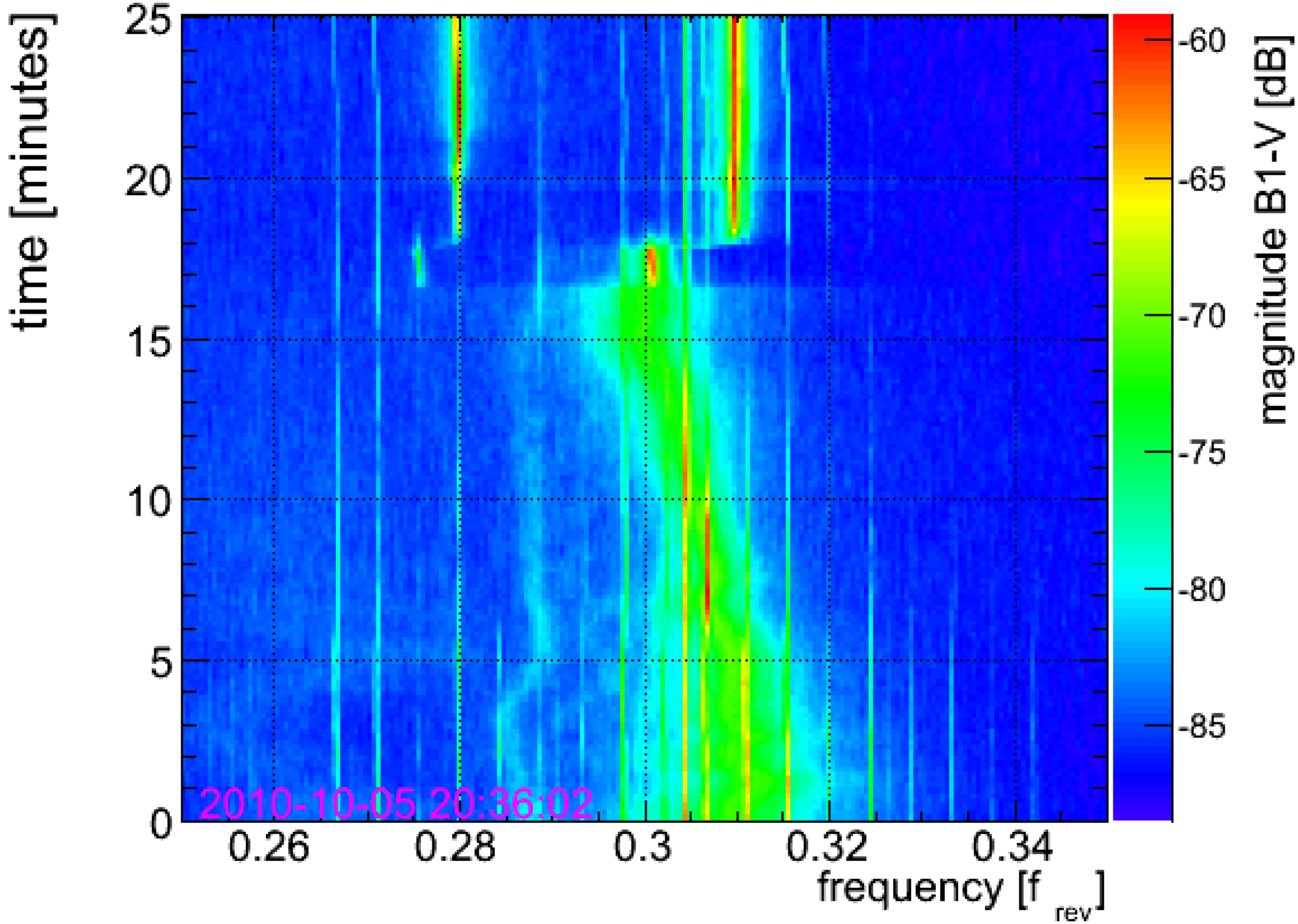
- Higher B-b-B FB gain implies also more meas. noise propagated onto beam...



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

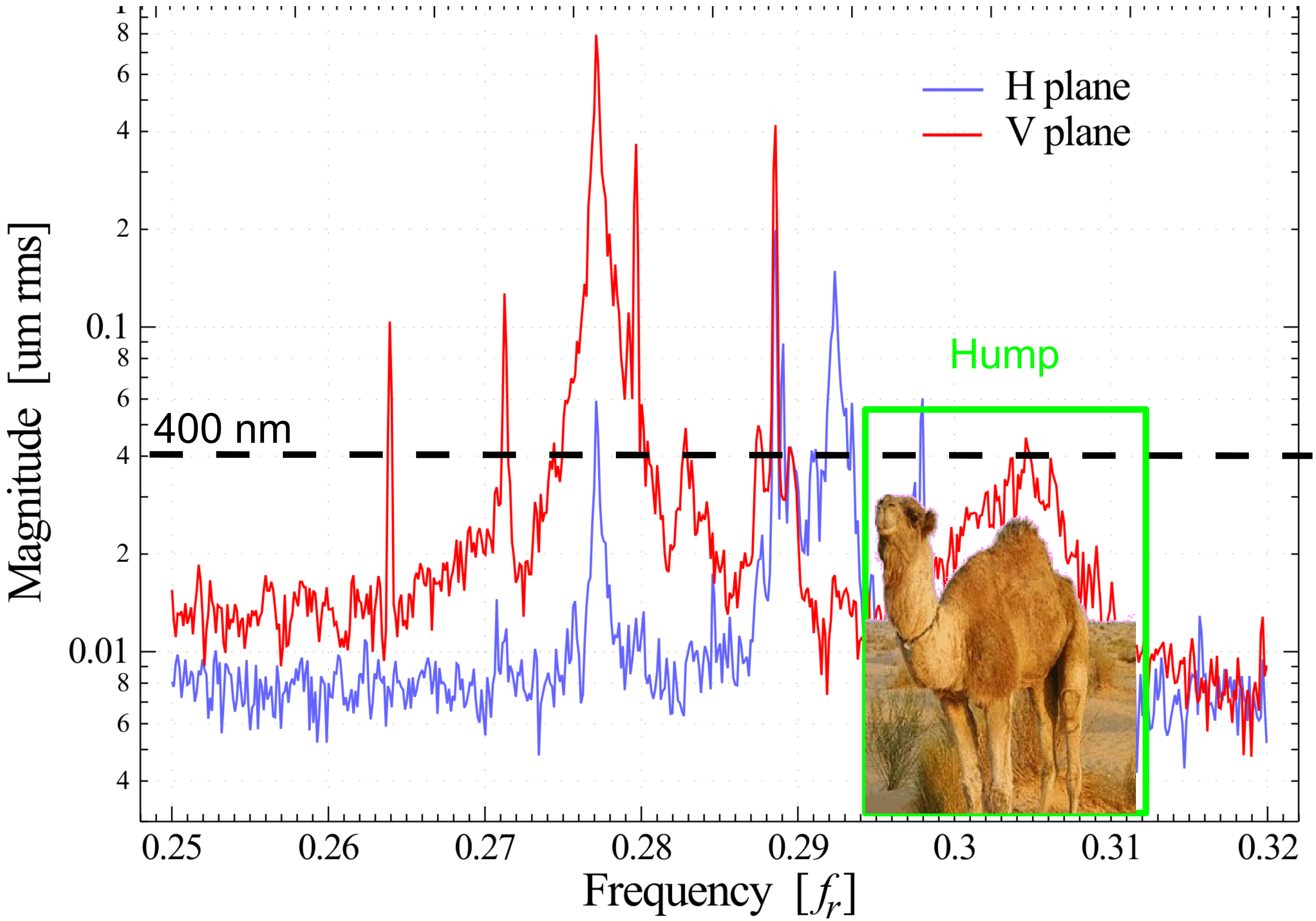
Impact of Mains Harmonics on Beam Stability

- 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)

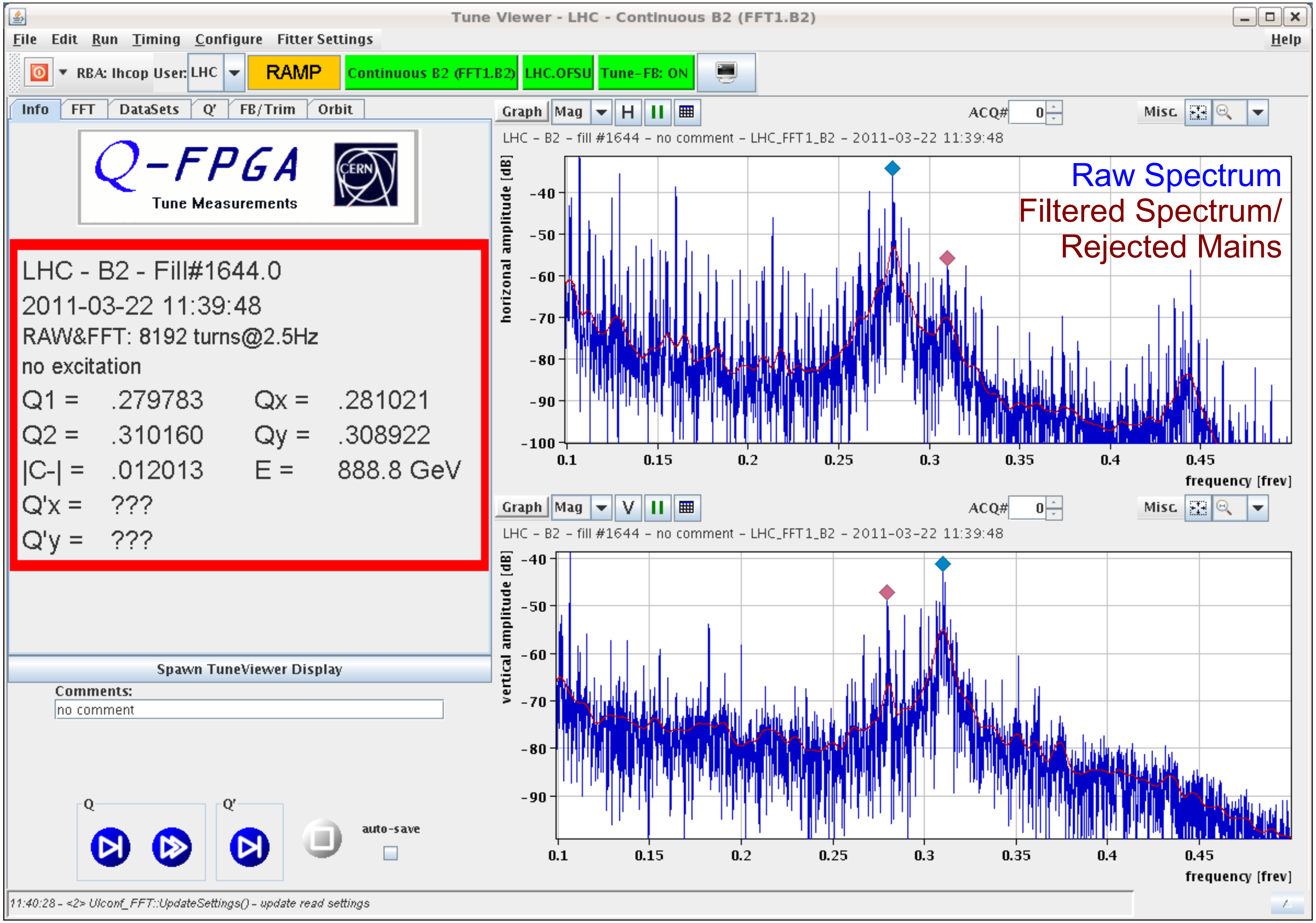
Conclusions

- 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.


Prudential
WEMBLEY STADIUM LONDON 2092?
HSBC
SAMSUNG
LHC
ROCKS
In operation:
2010/11
Kodak
Corona Extra
INGLOT
MONDAYS ARE A DRAG
NEW SEASON
READY SET
Samsung GALAXY Tab
OWN
maxell
Thank You for your Attention!

Tune Spectra during High-Intensity Operation

- Snapshot of the day with removed mains harmonics

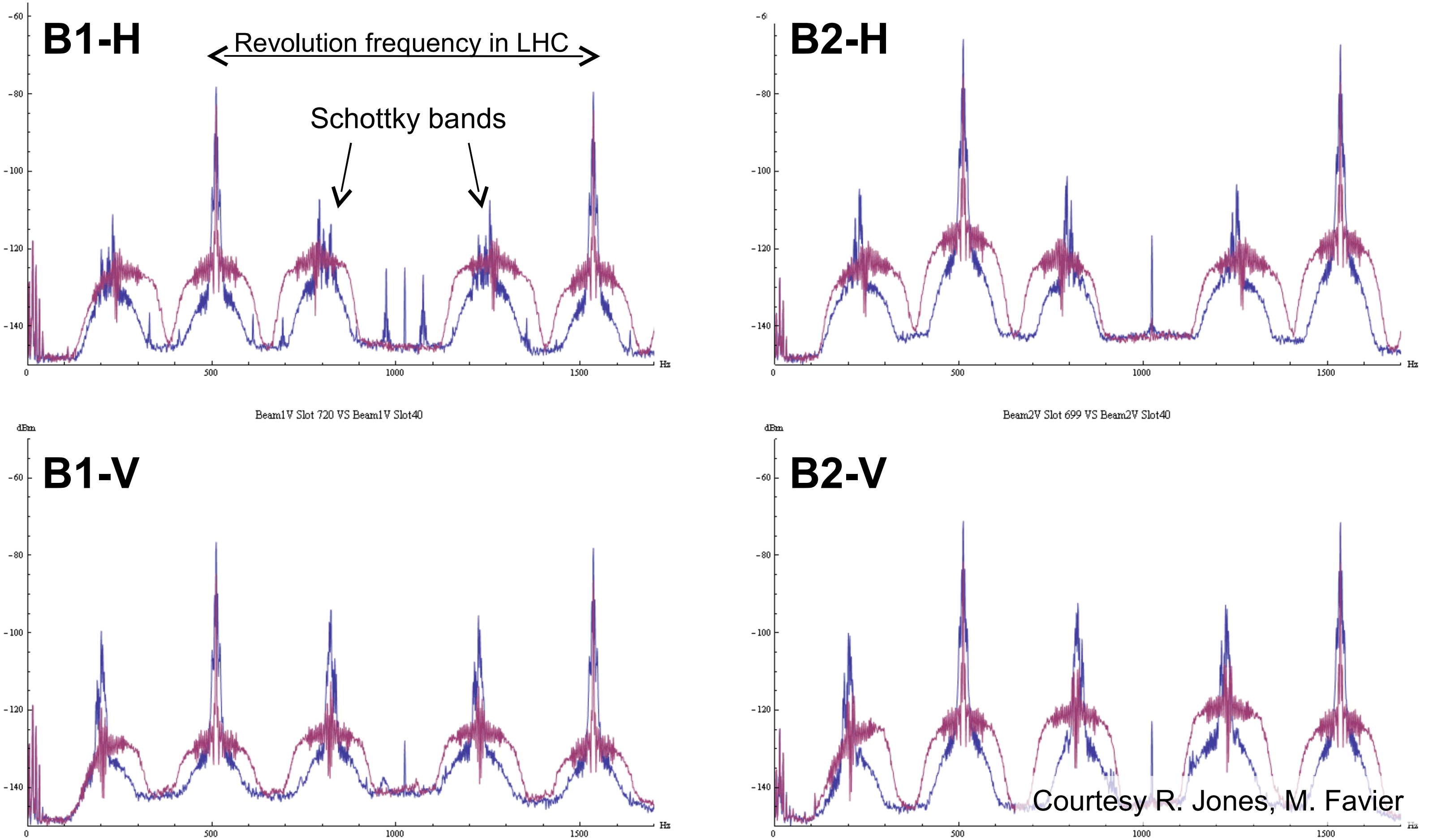


LHC Transverse Schottky (4.8 GHz)

- Nice and useful spectra with stable beams at 3.5 TeV:

Single Bunch: **Prontons** **vs** **Ions**

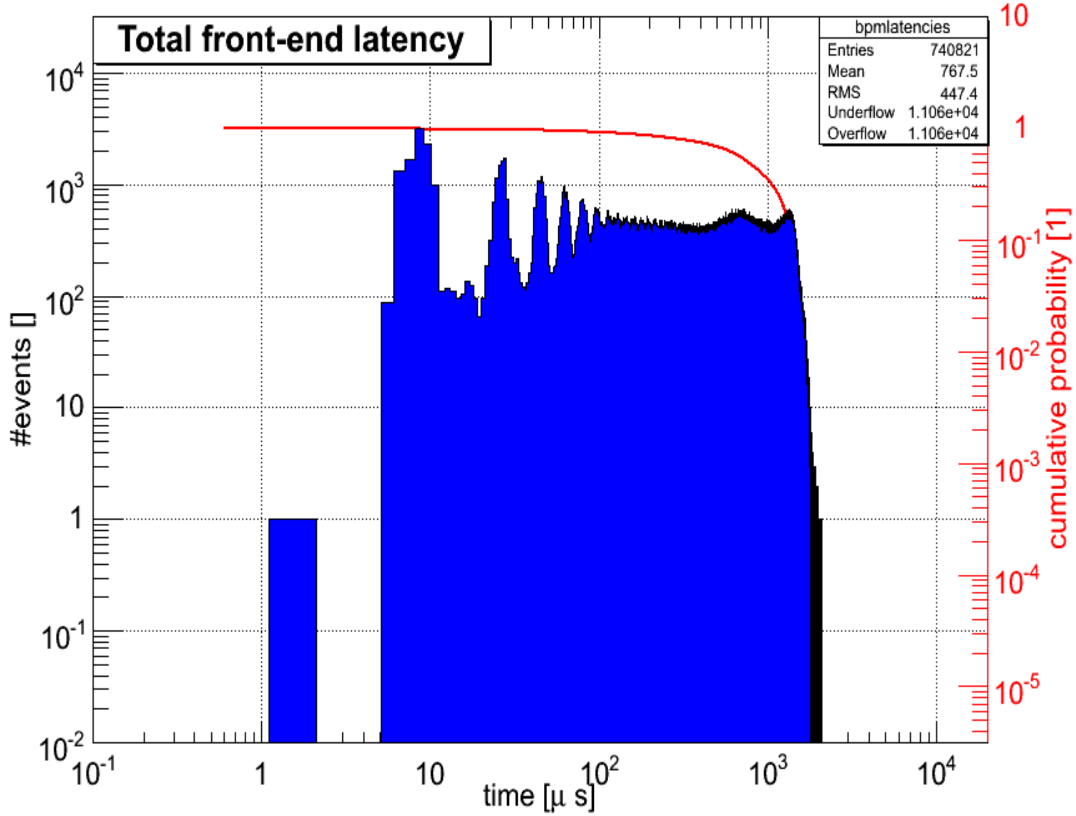
Single Bunch: **Prontons** **vs** **Ions**



- Limited FB usability: reliability and achievable meas. bandwidth during ramp → for the time being limited to measurements during collissions

Technical Network Performance

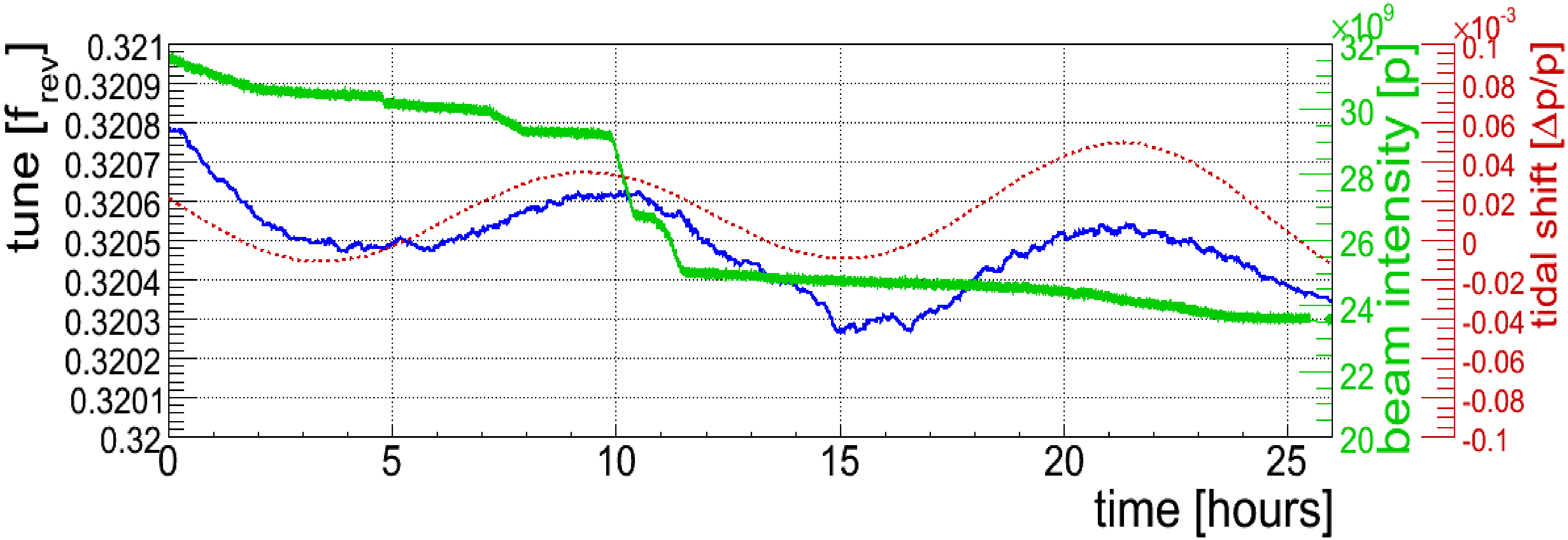
- Double- (tripple-) redundant switched Gigabit Network: no data collisions/loss
  - Max transmission delay ~320 µs (80% due to traveling speed of light)
- Total delays dominated by front-end:



- Communication un-critical: worst case jitter « feedback sampling frequency!
  - Tested (short-term) operation up to 1 kHz (↔ nominal 25 Hz)
  - in case of problems: HW-QoS queue dedicated ↔ private network for RT-FBs

Quirky side effect:

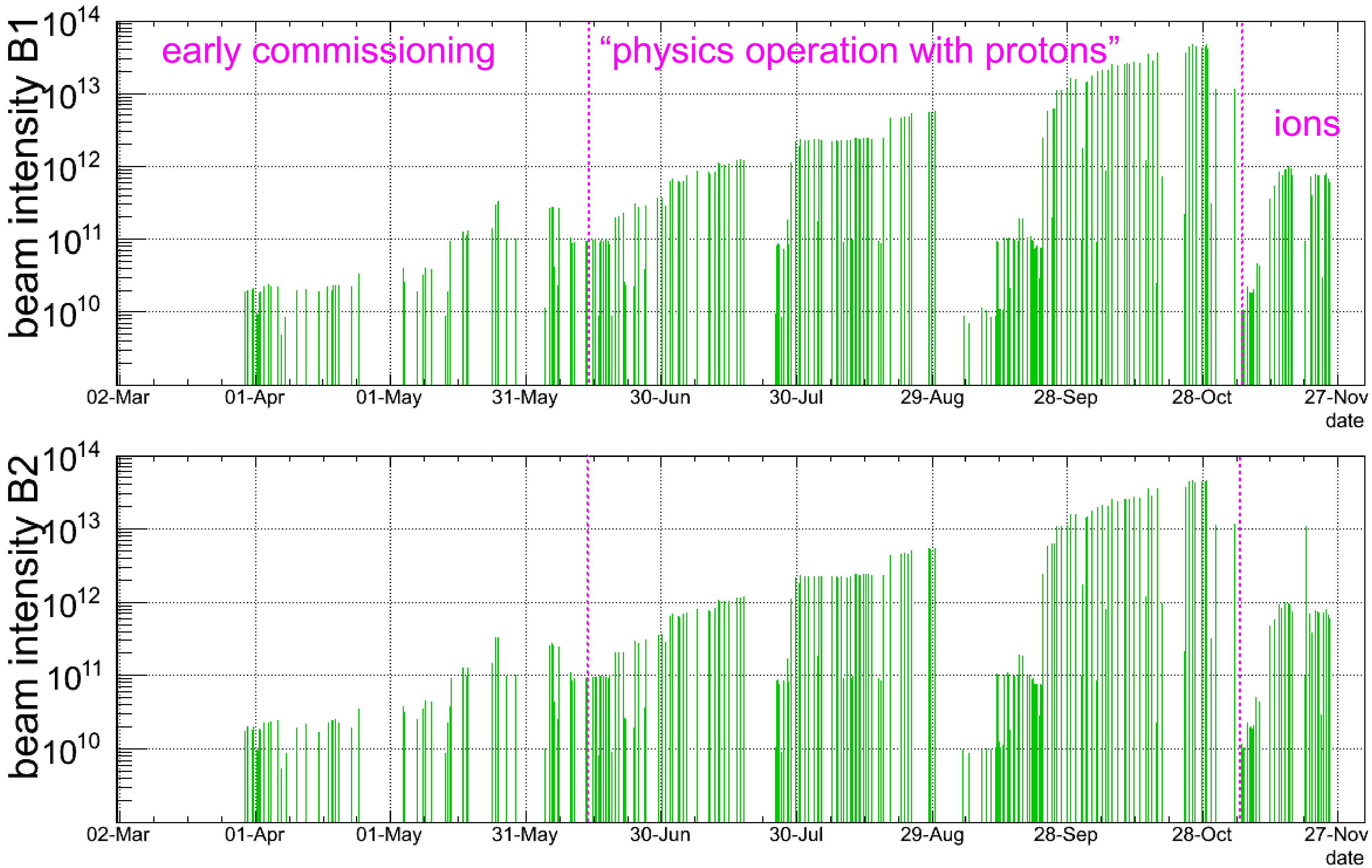
- Machine circumference changes are propagated via Q' also to the tune



- Probably the slowest high-precision Q' measurement in the World
  - Short-Term Tune-Stability of ~10^{-6}!
- However, stability during nominal physics operation is typically driven by impedance and beam-beam related effects.

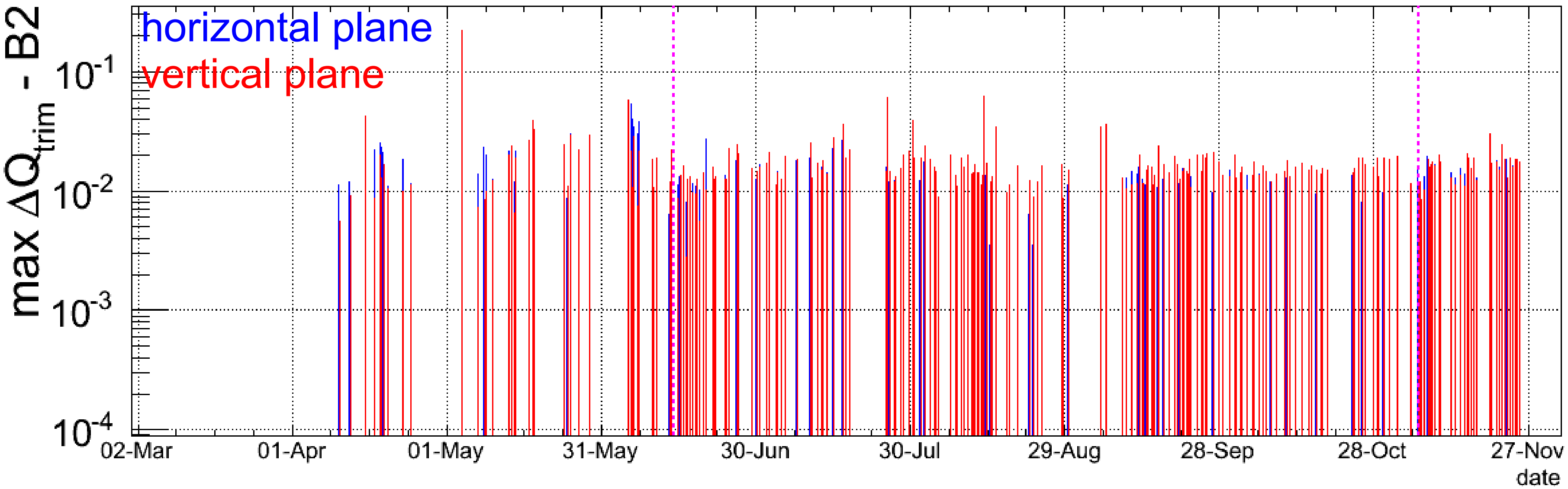
Q/Q'-Stability and Feedback Performance

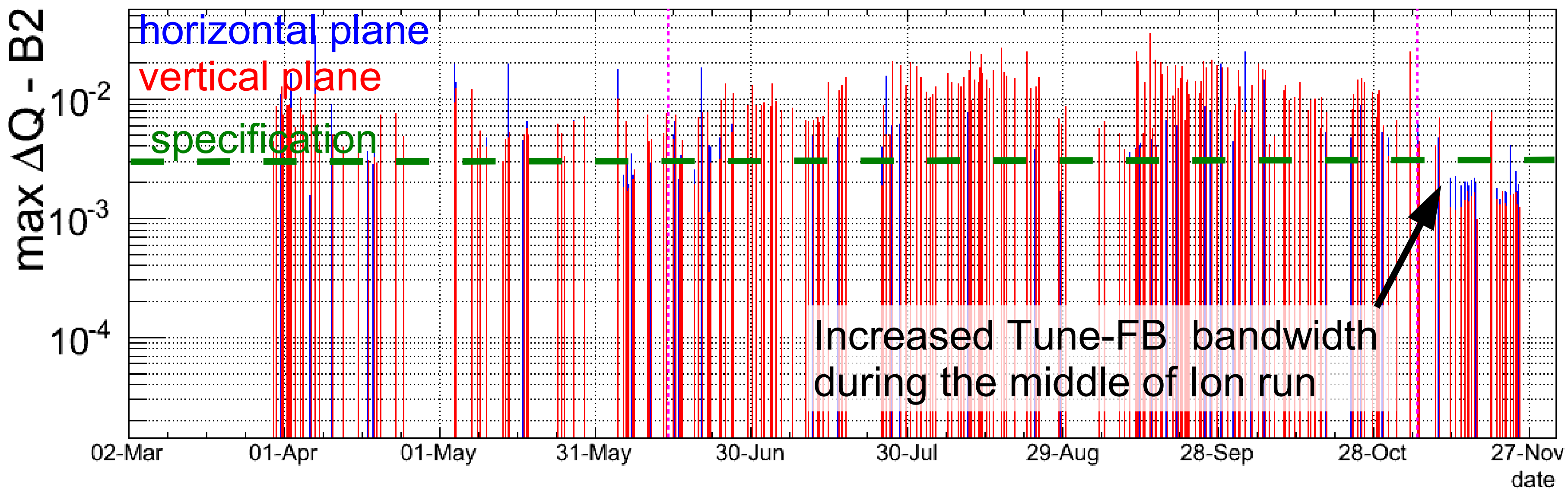
- Analysed a total of 275 ramps, excluded most of early ramps in 2009



Peak-To-Peak Tune Trim and Tune Variations

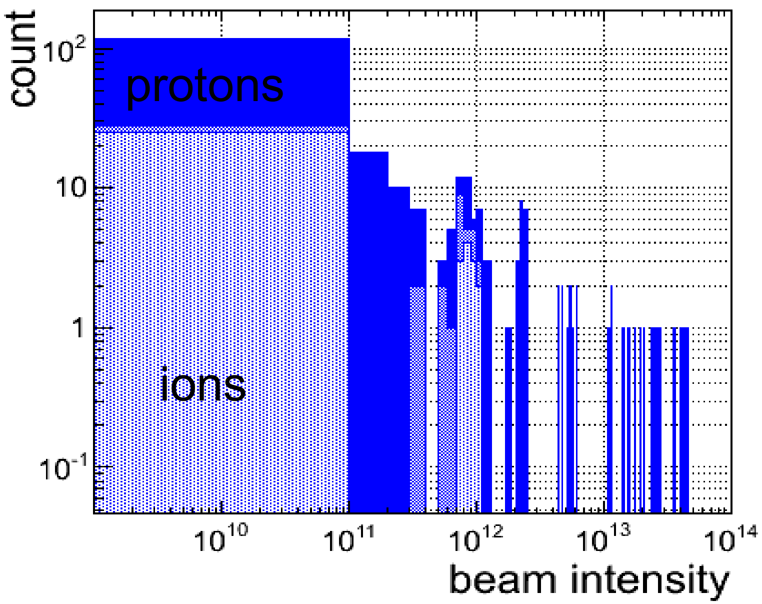
- Steady performance dominated snap-back...

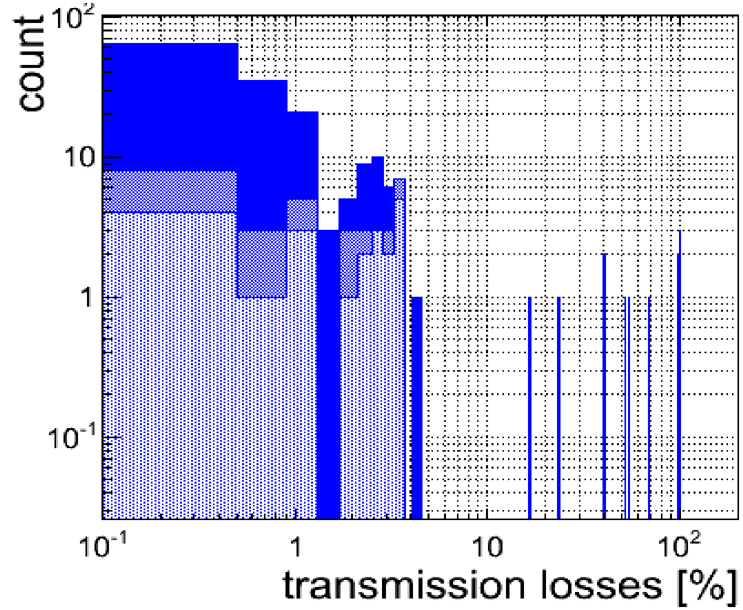


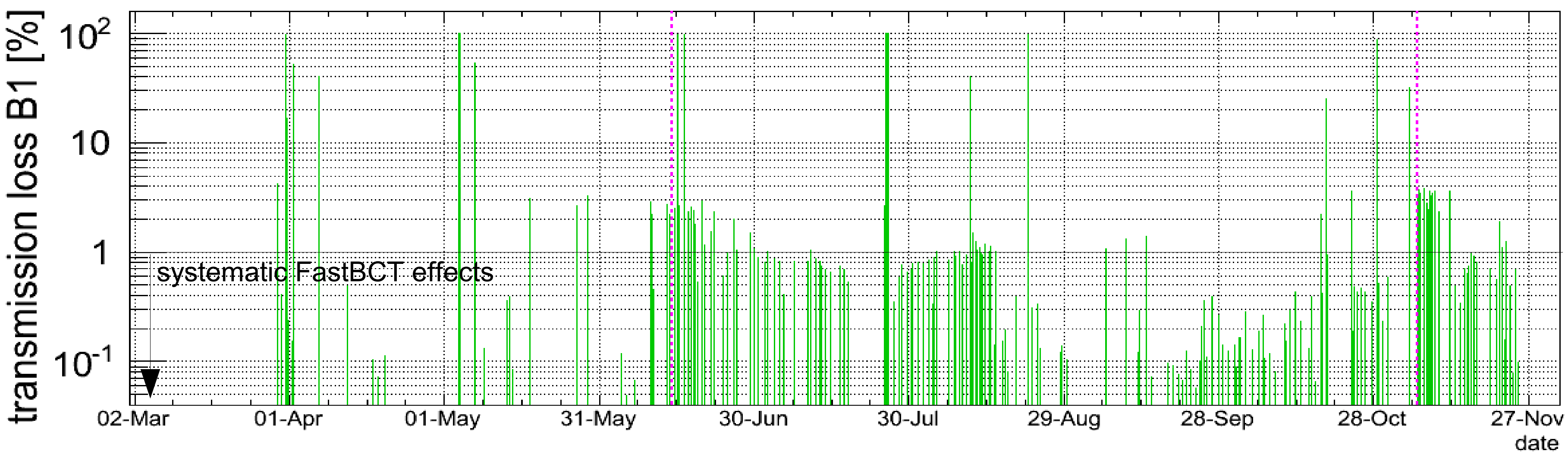


Maximum Intensity and Transmission Loss during the Ramp Beam 1

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

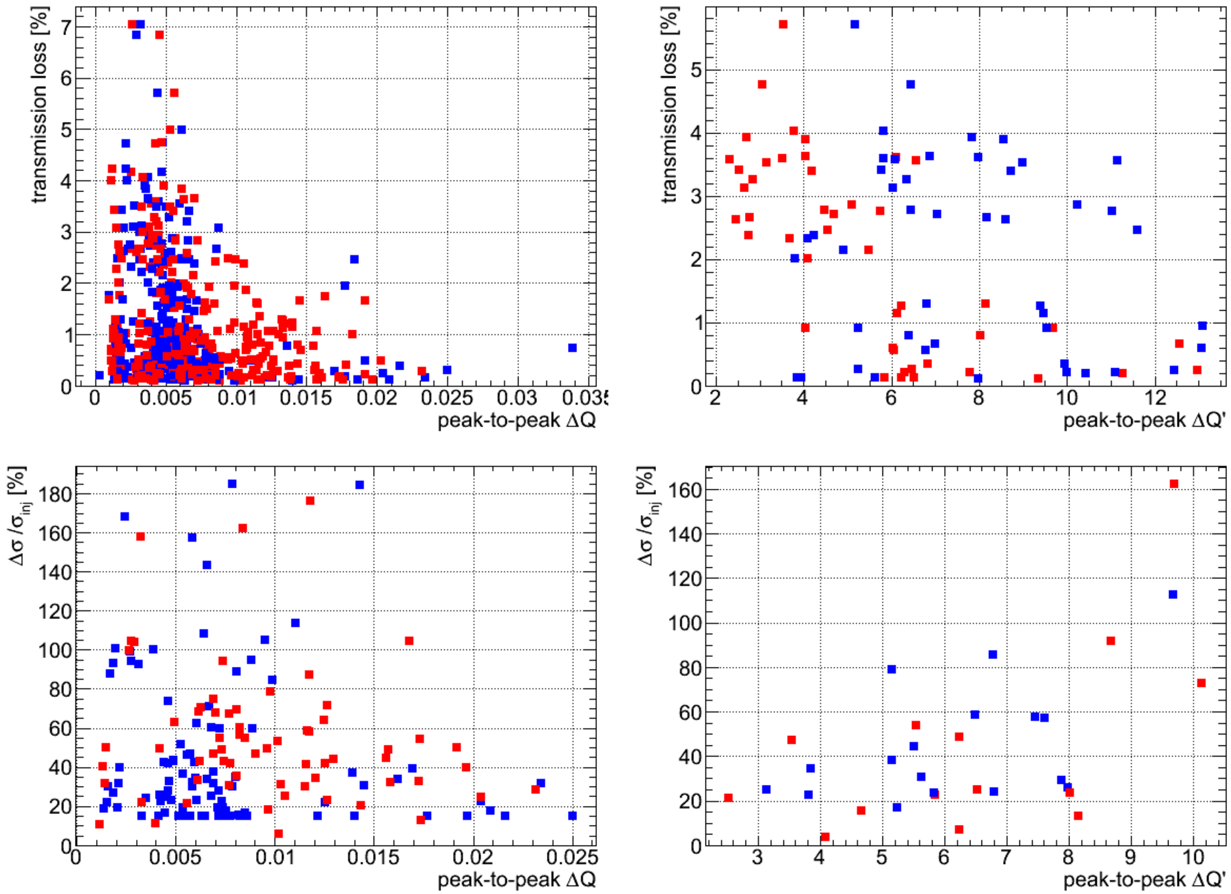






Impact of Q/Q' Performance – Protons

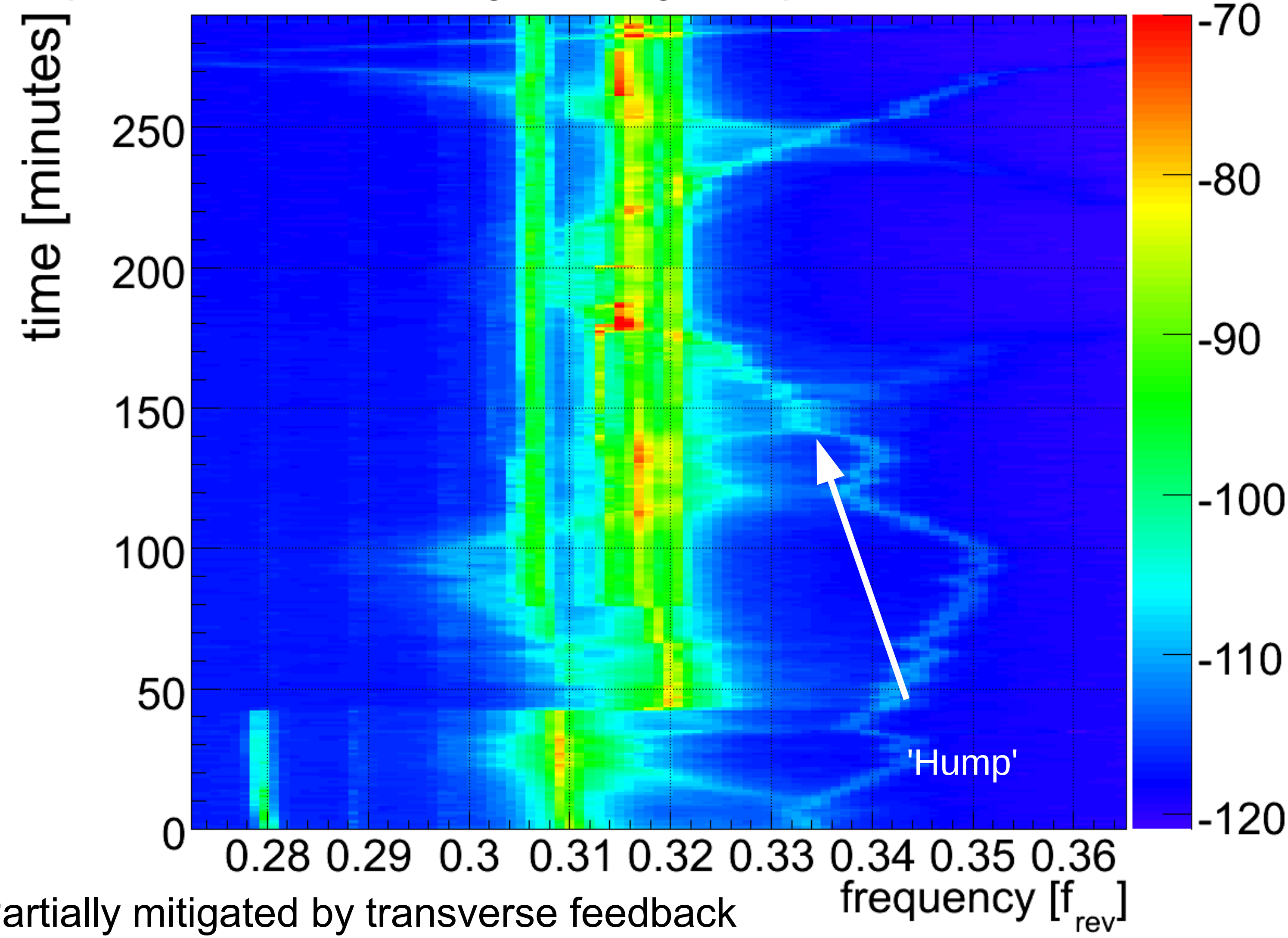
- Limited or no correlation to transmission losses but beam size growth
- Biggest error: emittance growth estimates→ Federico Roncarolo's talk



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

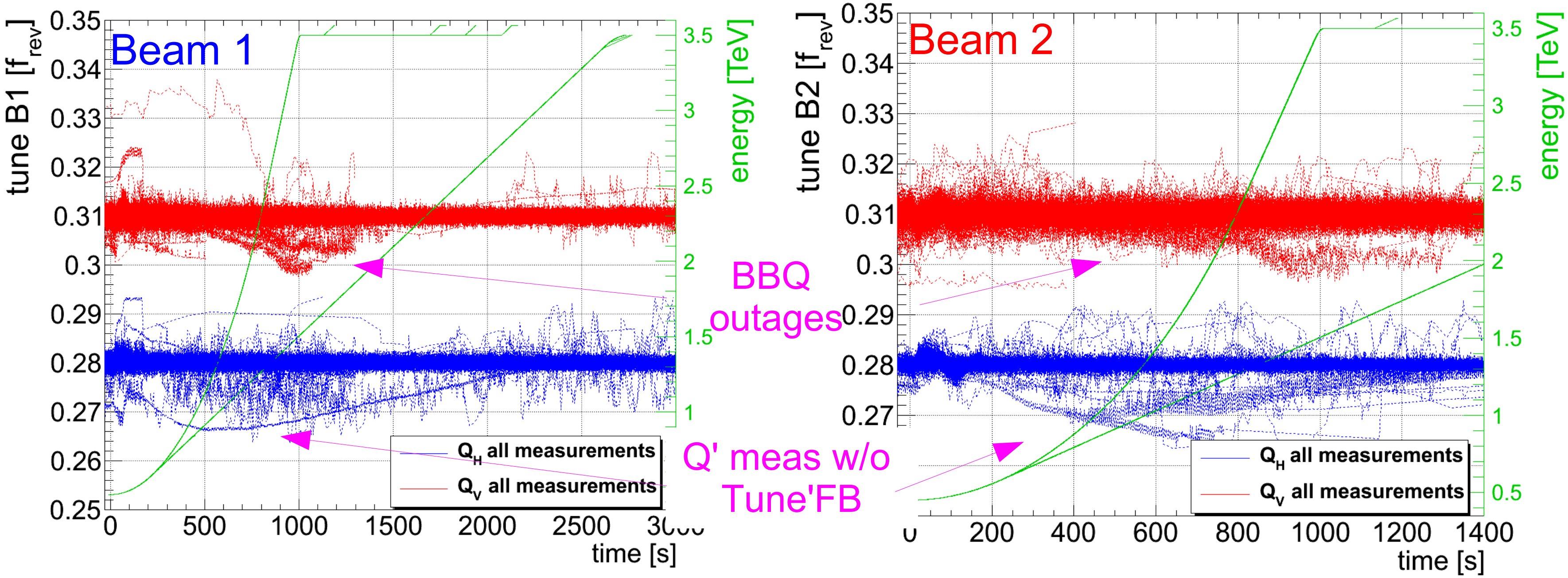
Hump Structure on longer Time-Scales

- Accepted Control-Room Jargon: being “humped”



- Partially mitigated by transverse feedback
- Origin of this perturbation remains unknown but is less of an issue in 2011

Residual overall Tune Stability in 2010
Out of 191 Ramps...

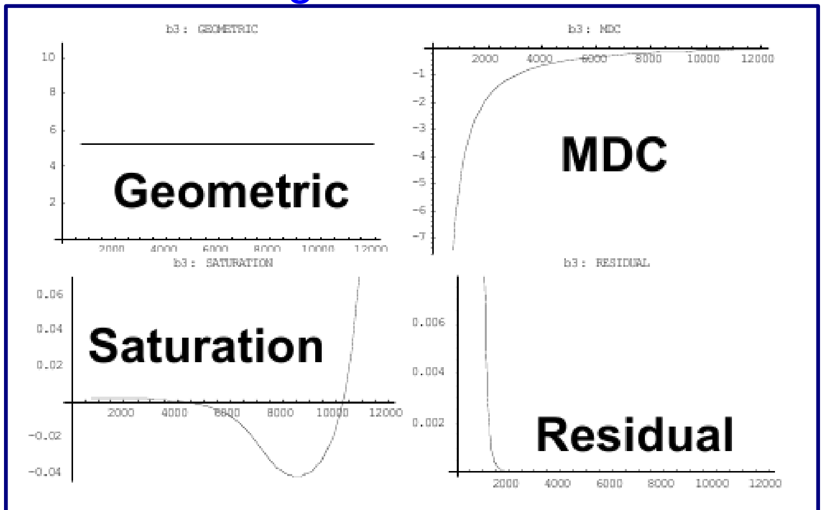


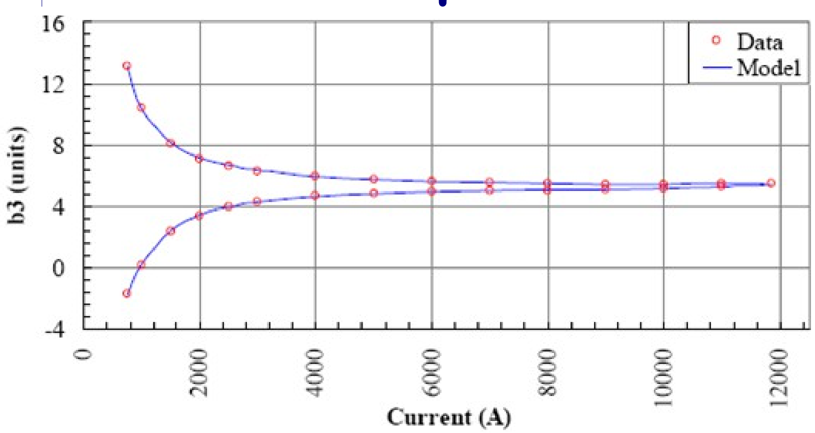
- 155 ramps with > 99% transmission
- 178 ramps with > 97% transmission
- 12 ramps lost (6 with Tune-FB during initial 3.5 TeV commissioning)

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

Example: b_3 – Compensation – Static Part

Based on magnet measurements:





Machine Optics Model

↓

$$k_N = \frac{1}{B\rho}\frac{\partial B_x}{\partial y}$$

↓

$$\frac{\partial B_y}{\partial x} = \frac{p \times k_n}{0.2998}$$ ← **p(t)**

↓

Transfer Function

↓

I(t)

Courtesy M. Lamont