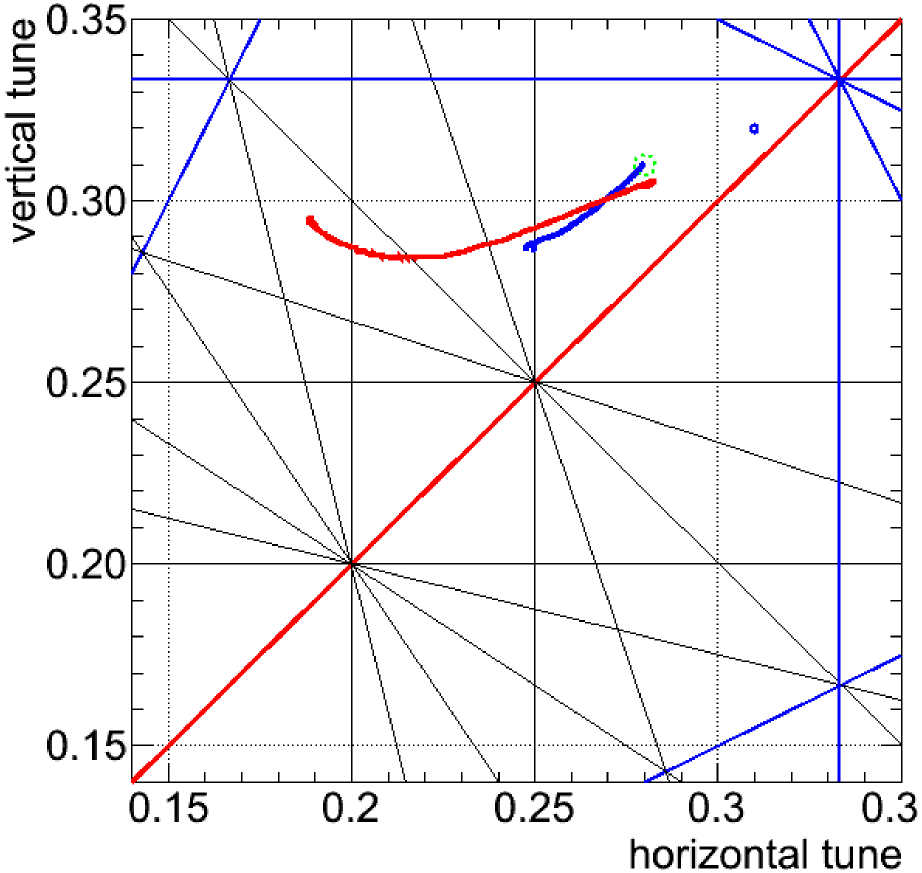
Status of Orbit, Q/Q' & Coupling Diagnostics and FB Systems

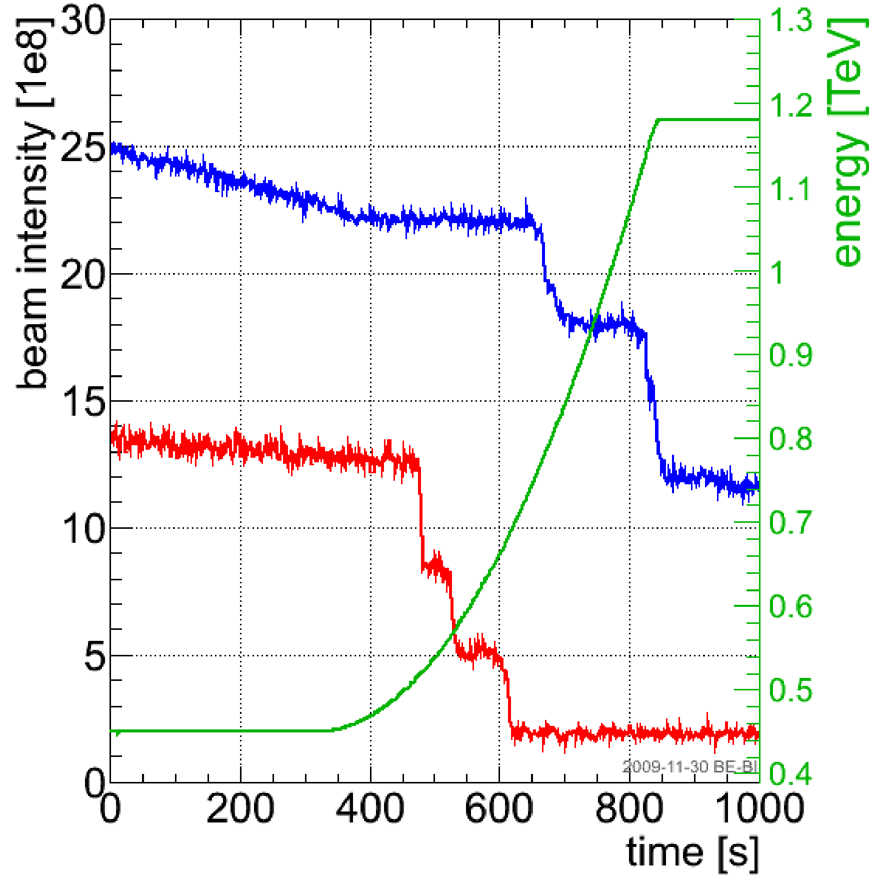
- Main message: All systems operate according to initial specification and facilitated the fast and reliable commissioning of the LHC right away from Day-I

- Slides give an overview of
  - Day-to-day performance of the Orbit, Q, Q' and betatron-coupling instrumentation and diagnostic as well as associated beam-based feedback systems.
  - Some second-order affects that will become important while approaching nominal operation with increased beam intensities.

Base-Band-Tune (BBQ) System Performance
Example: 2009-11-24 @00:15 – First Ramp to 1.2 TeV

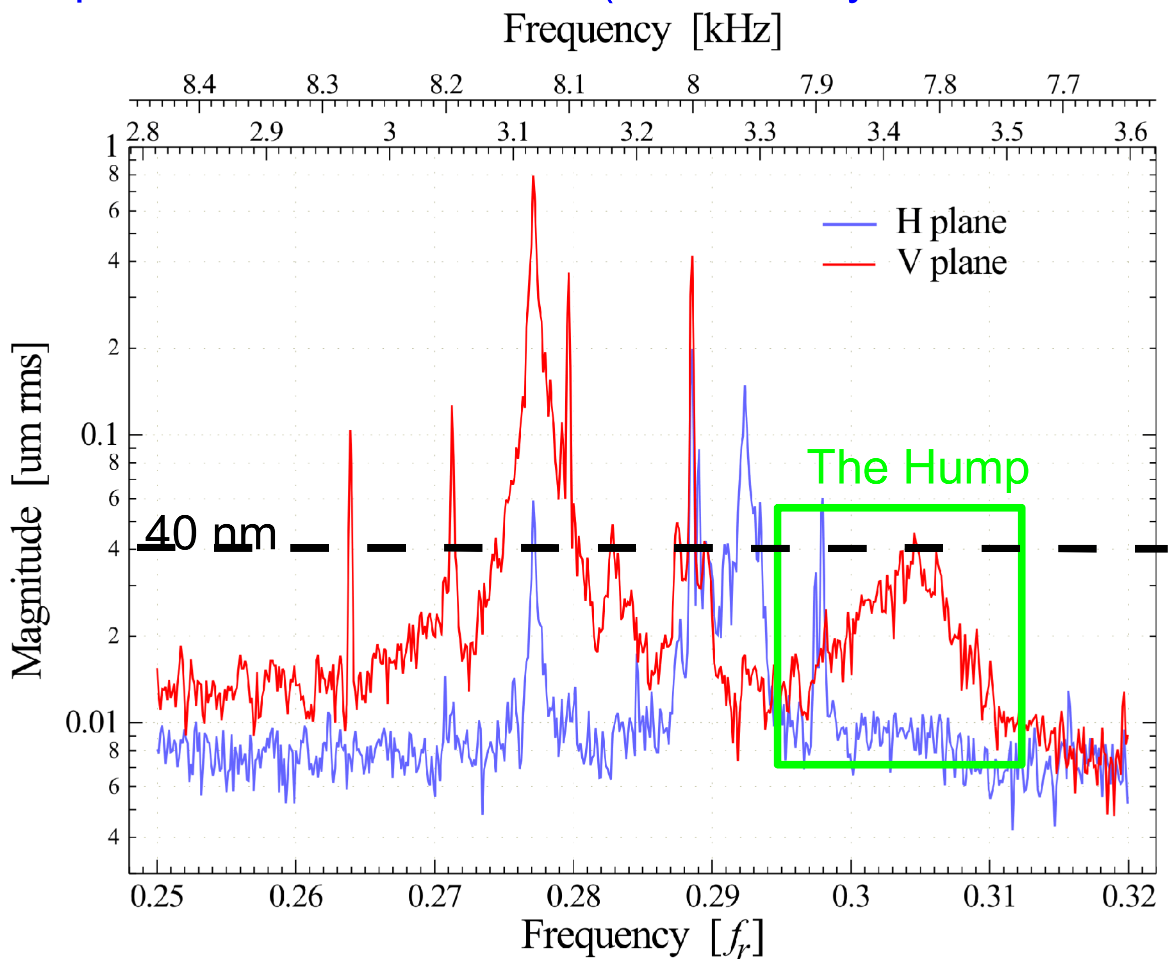
- The Base-Band-Tune (BBQ) system was work horse from LHC Day-I
  - No hardware, minimal software and only a few beam related issues





  - Most measurements were done with residual beam excitation
  - Typ, Q measurements resolution in the range of 10^{-4} … 10^{-6}

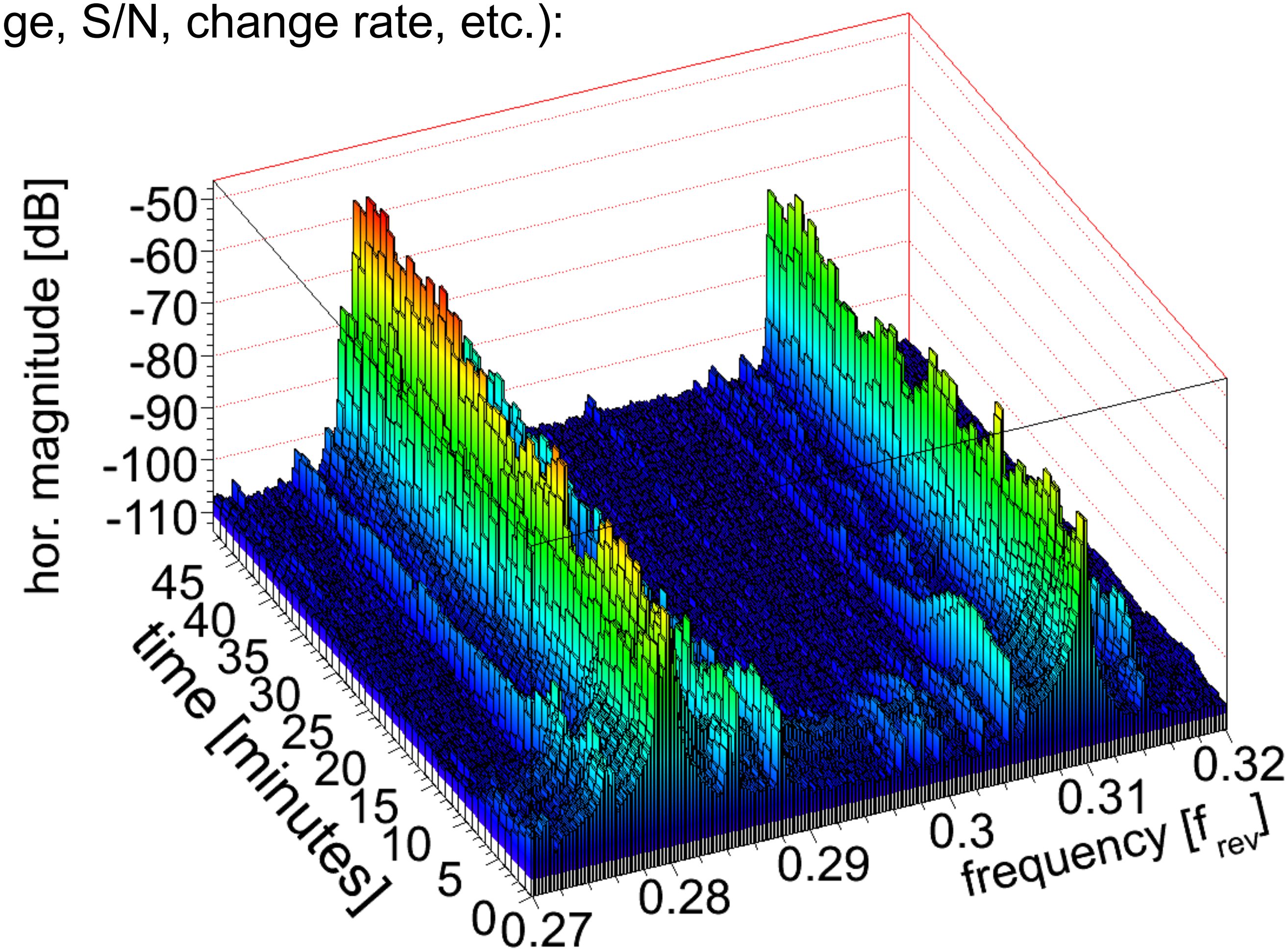
- Coherent 1 µm-level tune oscillation (N.B. turn-by-turn BBQ < 1 µm!)



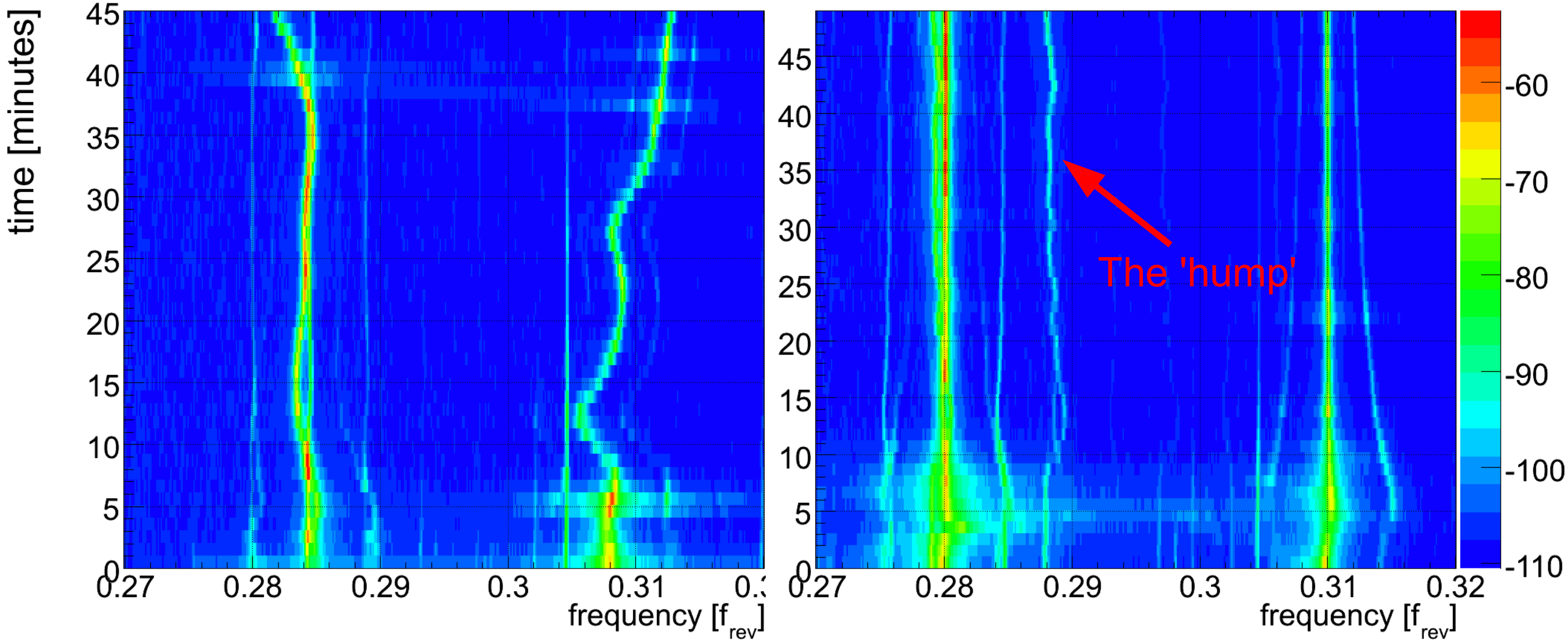
- Hump: assuming single dipolar pertubation → kick < 1 nRad kick only
  - Causing emittance blow-up, beam-loss and thus life-time reduction
  - a non-issue if the present tune working point wouldn't be exactly on it

BBQ Beam Spectra during Energy Ramp

- Residual oscillations and the absence of strong interference lines allows to track the tunes directly using the FFT spectra and some simple filtering (e.g. range, S/N, change rate, etc.):



- Residual tune oscillations about 40-60 dB S/N (!!) → impact Tune-PLL hor. spectrum with Tune-FB 'off': hor. spectrum with Tune-FB 'on':

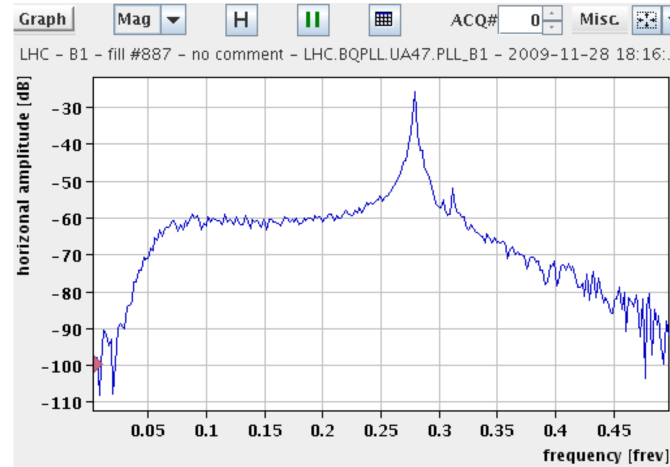


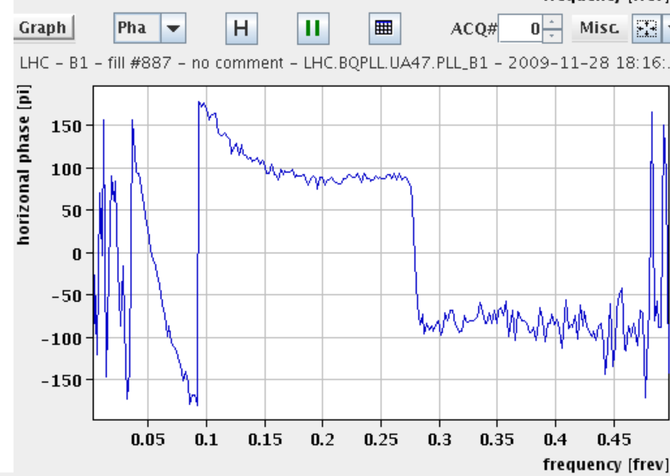
- For perfect pre-cycling the fill-to-fill Q stability is typically 2-3·10^{-3}, however:
  - Variations frequently increase up to ±0.02 due to partial or different magnet pre-cycles after e.g. access, sector trips etc.

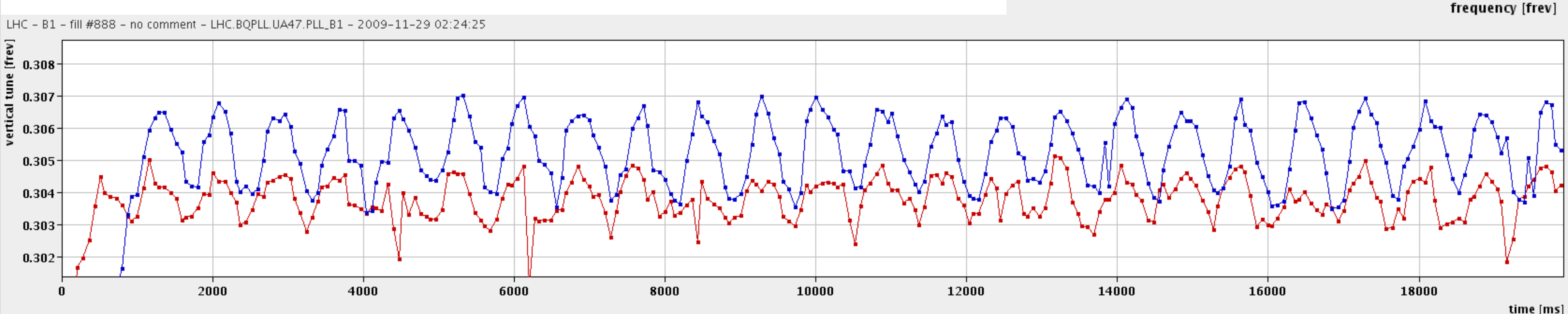
→ Tune-FB routinely used during (almost) every ramp to compensate these effects!

Tune Phase-Locked-Loop Commissioning Results

- Same BBQ as 'Continuous FFT' system (logging)
- Gain relations and BTF agree with model
  - typical tune resolution: 10^{-5}
  - Op. range w/o re-tuning: 0.15 … 0.5
- Deploy low-noise strip-line tune tickler (BQK) for missing planes once production finished
- PLL limited by residual strong tune oscillations:
  - Larger excitation possible but not practical
- Example: Q'_v = 15 (blue, dp/p =10^{-4} @2.5 Hz) → Q'_v trim) = -10 → Q'_v = 10 (red)

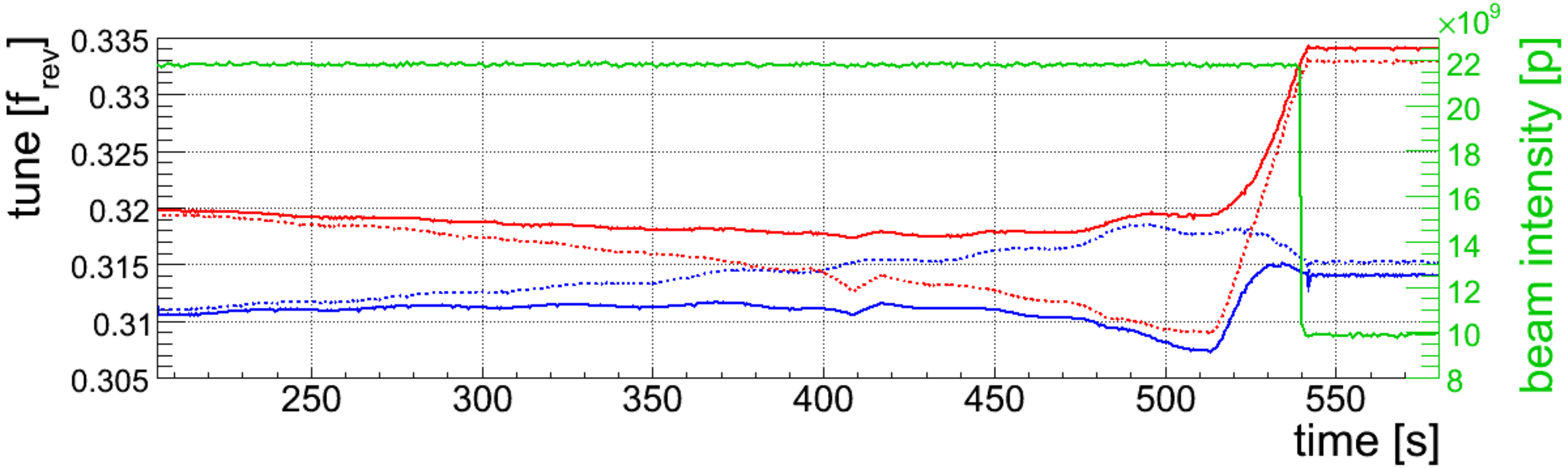




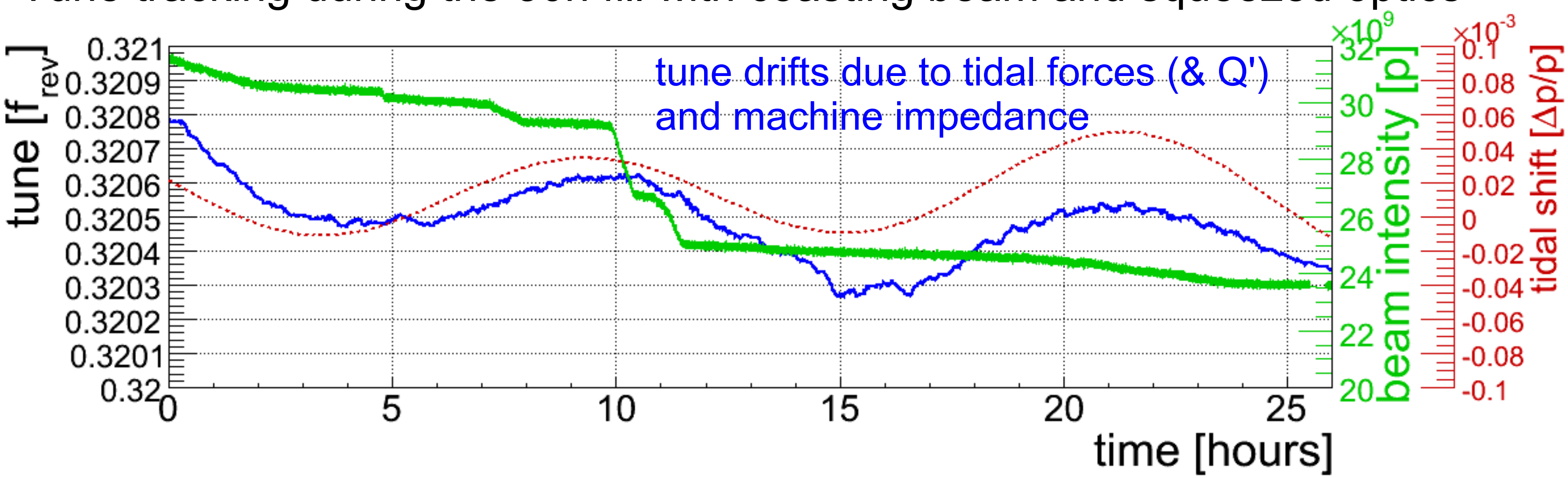


BBQ-based Q/Q' Tracking during Squeeze and Collissions

- Tune & Coupling-Tracker example during early β*-Squeeze commissioning:



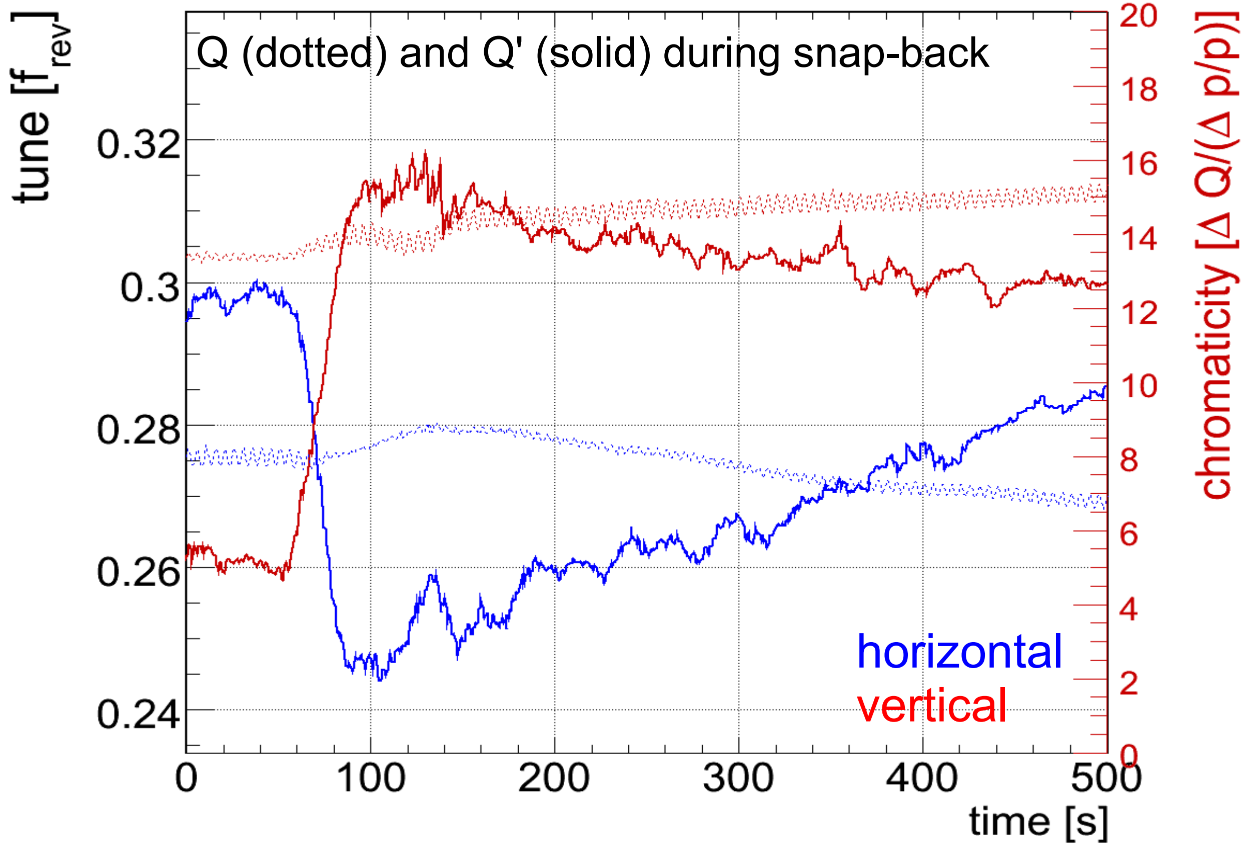
- Tune tracking during the 30h fill with coasting beam and squeezed optics



- Residual tune measurement resolution of about $10^{-5}\ldots10^{-6}$ and essentially only limited by the available tune peak signal-to-noise ratio.

Tune and Chromaticity Evolution

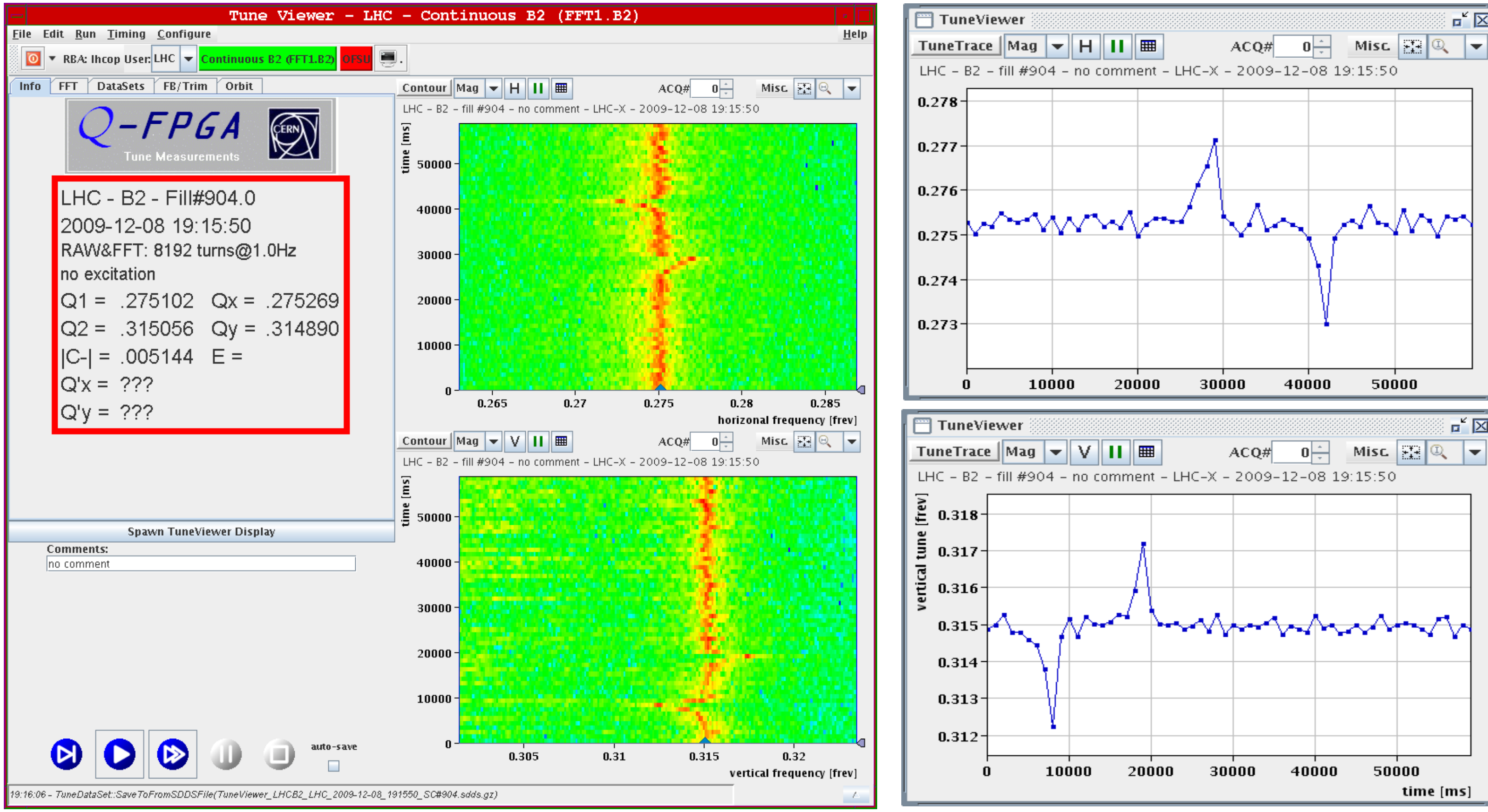
- Base-line Q'-Tracker based on demodulation or sinusoidal frequency trims
  - Increased original modulation of $\Delta p/p = 10^{-5}$ @2.5 Hz to 10^{-4} @2Hz to mitigate tune stability effects at injection (ΔQ_{res} ~3-4·10-4)
  - Achieved nominal Q' resolutions → used as feed-forward for next ramps



- Presently Q-FB and Q'-Tracker/-FB are exclusive to avoid spurious QPS trips of the tune and sextupole corrector magnets → being investigated

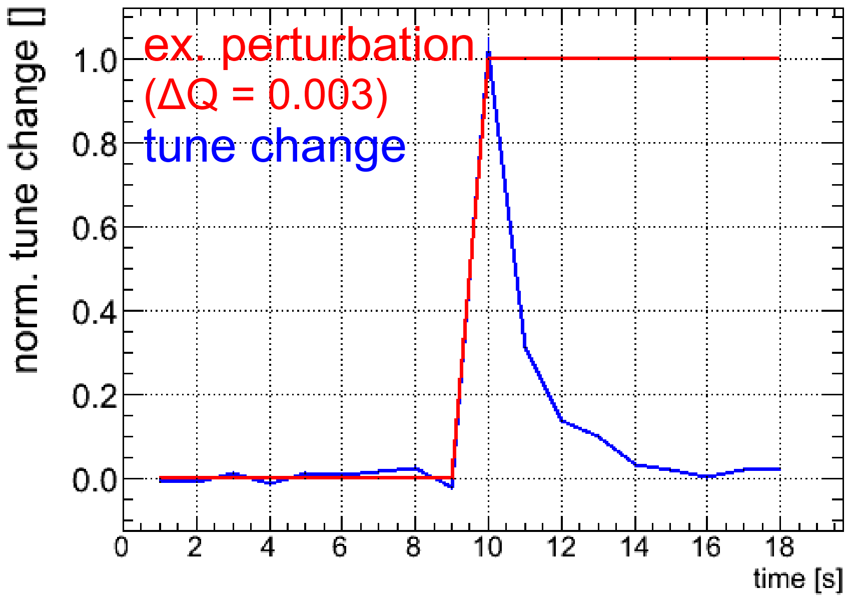
2009-12-08: 5 Magical Minutes of Tune Feedback Commissioning

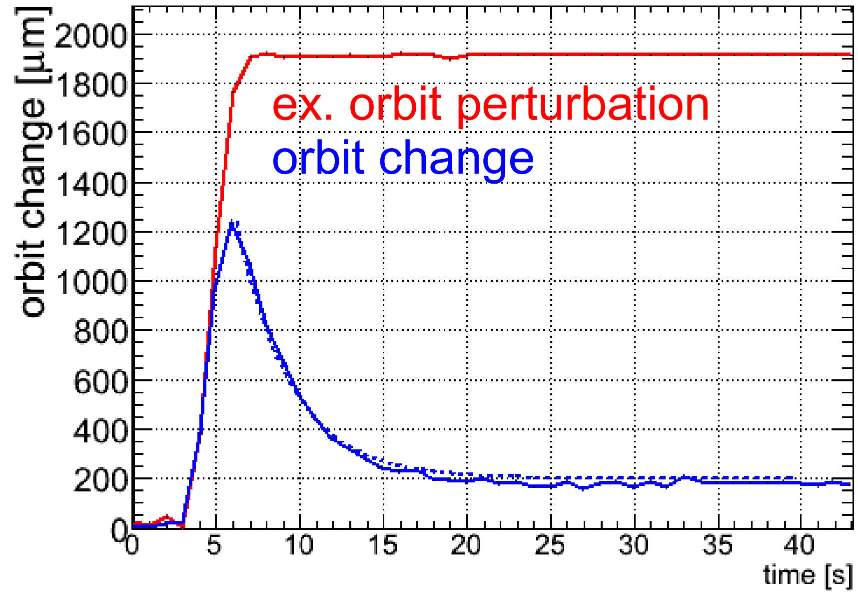
- Quick Q-FB sanity check, here with ΔQ_{trim} = ± 0.003 (via LSA) with Q-FB 'on':



- Any weak link/sub-system error would break the feedback chain, or (reverse logic) since FB was stable ↔ sub-systems work according to model
  - same applies to Q'-FB → weak link: reliability/availability of measurement

LHC Feedback Performance on a Slide





- FB response 1/e - time constants:
  - Tune: 1..2 s ↔ ~ 0.1..0.3 Hz BW (depending on fitting limits)
    - Achieved peak-to-peak tune stability 10^{-3}
    - from Q-FB point-of-view: choice between FFT vs. PLL is transparent
  - Orbit-FB & Radial-loop: 3.3 s ↔ 0.1 Hz BW
    - 200 um steady-state error due to using only 400/520 eigenvalues
      → next step: "SVD++" algorithm (FB-BW dependence on global/local control)
  - In good agreement with model!
    → Going to 0.5 or 1 Hz BW should not pose (big) problems

Tune and Chromaticity FB

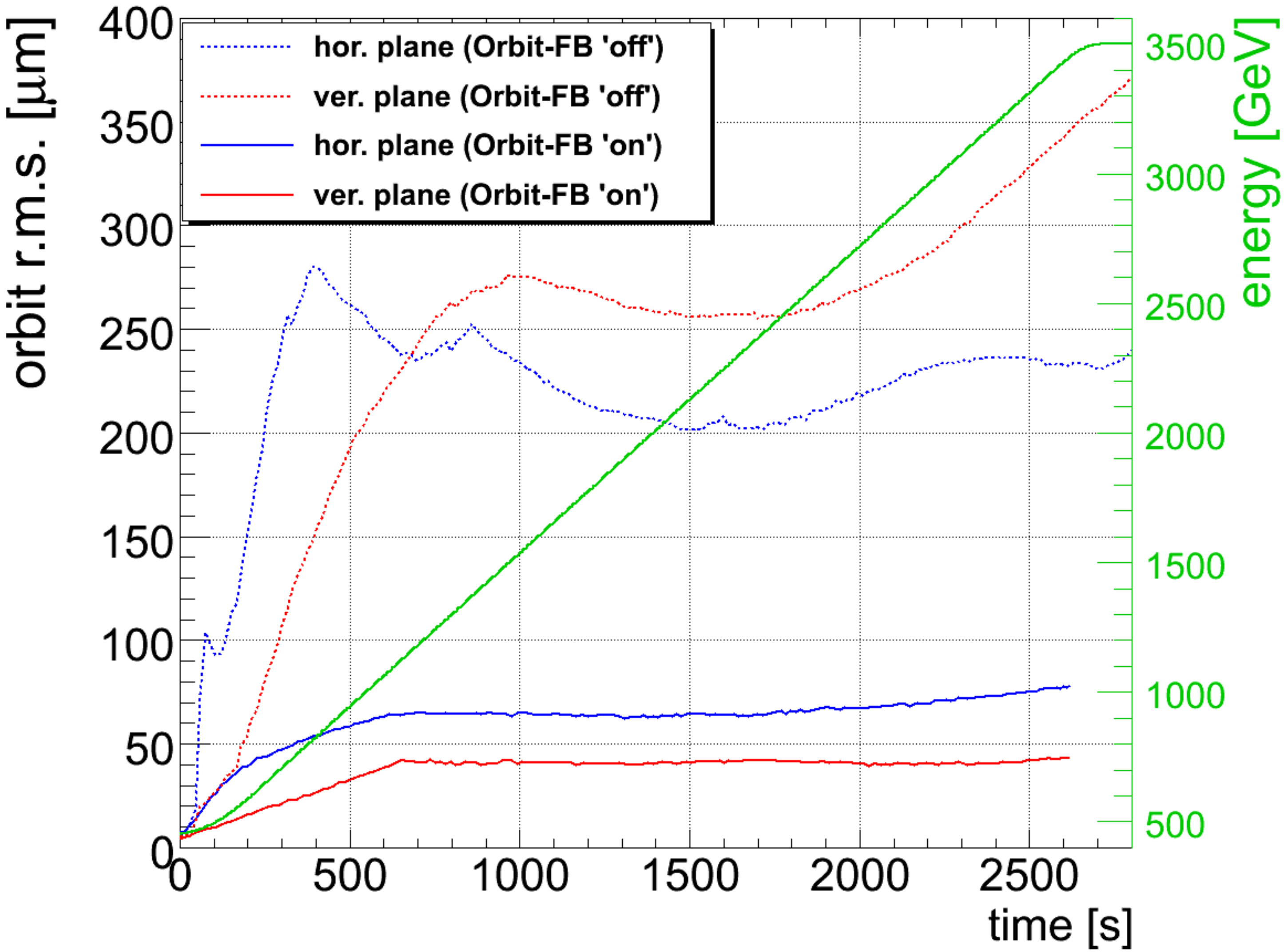
Main limitation:

- Real-time corrections cause spurious QPS trips of Q, Q' and C^- correctors: that are erroneously interpreted as 'quenches'
  - presently: only Q-FB or Q'-Tracker routinely used during energy ramp
  - Mitigations are deployed and being tested

- Tune stability ~$4\cdot10^{-4}$ at injection impacts Q'-Tracker and -FB performance
  - Desired ΔQ'=1 resolutions implies much larger continuous momentum modulation of Δp/p ~10^{-4} than the initially targeted 10^{-5} (↔ 100-200 μm radial orbit change)

- Micro-instabilities ↔ residual tune oscillation (~ 1 um) impacting Q-PLL:
  - Coherent for a few hundred turns but incoherent w.r.t. the sinusoidal exciter and PLL integration time-scales and thus effectively increasing the PLL phase noise. Mitigation
    - Increasing the exciter amplitude by >20-40 dB mitigates this but is impractical for regular operation (↔ 100 um beam oscillations)
    - Limits the Q'-Tracker to sampling @2.5 Hz

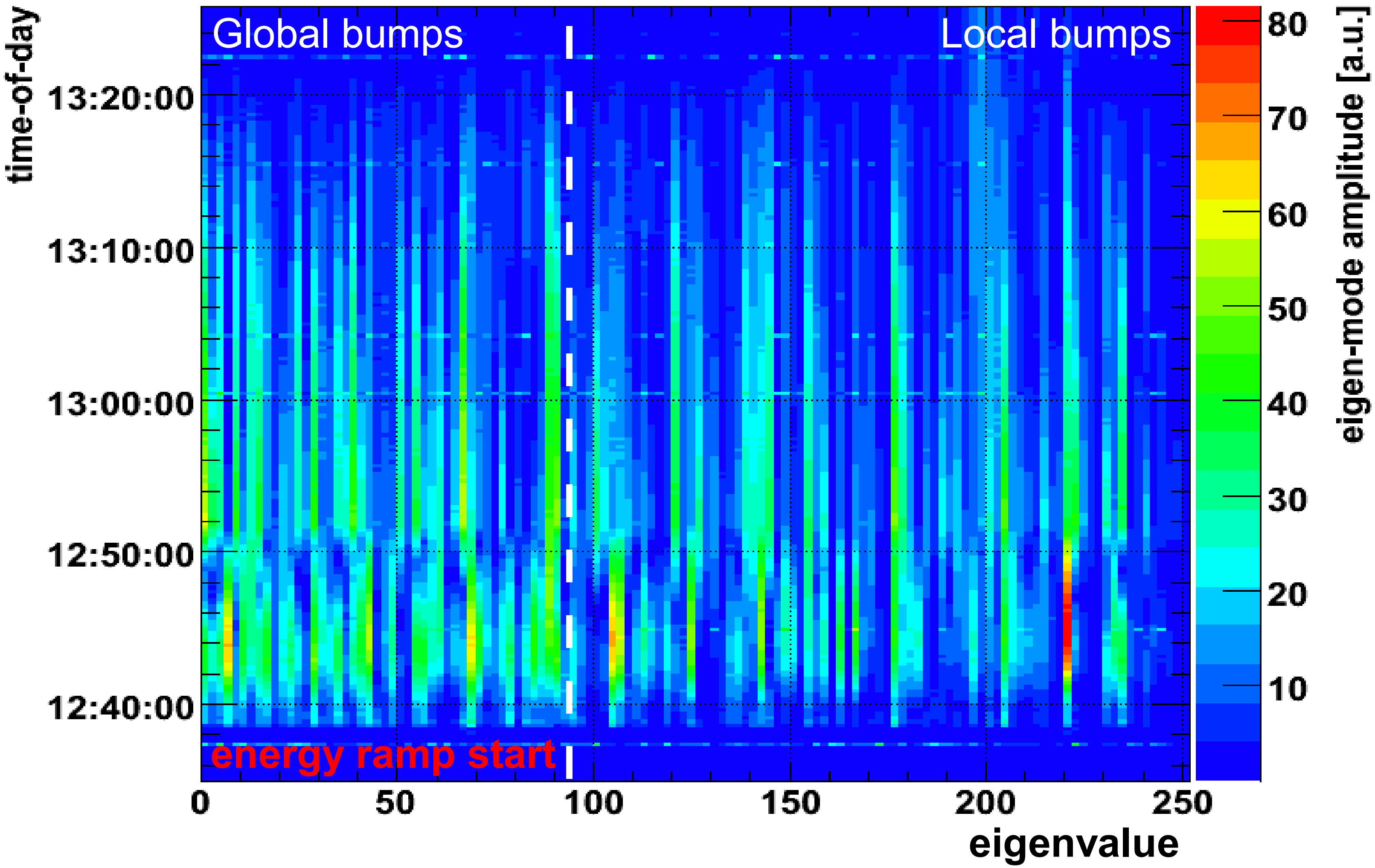
Example: LHC Ramp with and without Orbit-FB



- Residual error corresponds to local bumps that were not corrected by the Orbit-FB (limited number of used eigenvalues of 280 vs. 530 total)

SVD Decomposition of Orbit Perturbation Sources – or – How the Orbit-FB sees the Energy Ramp

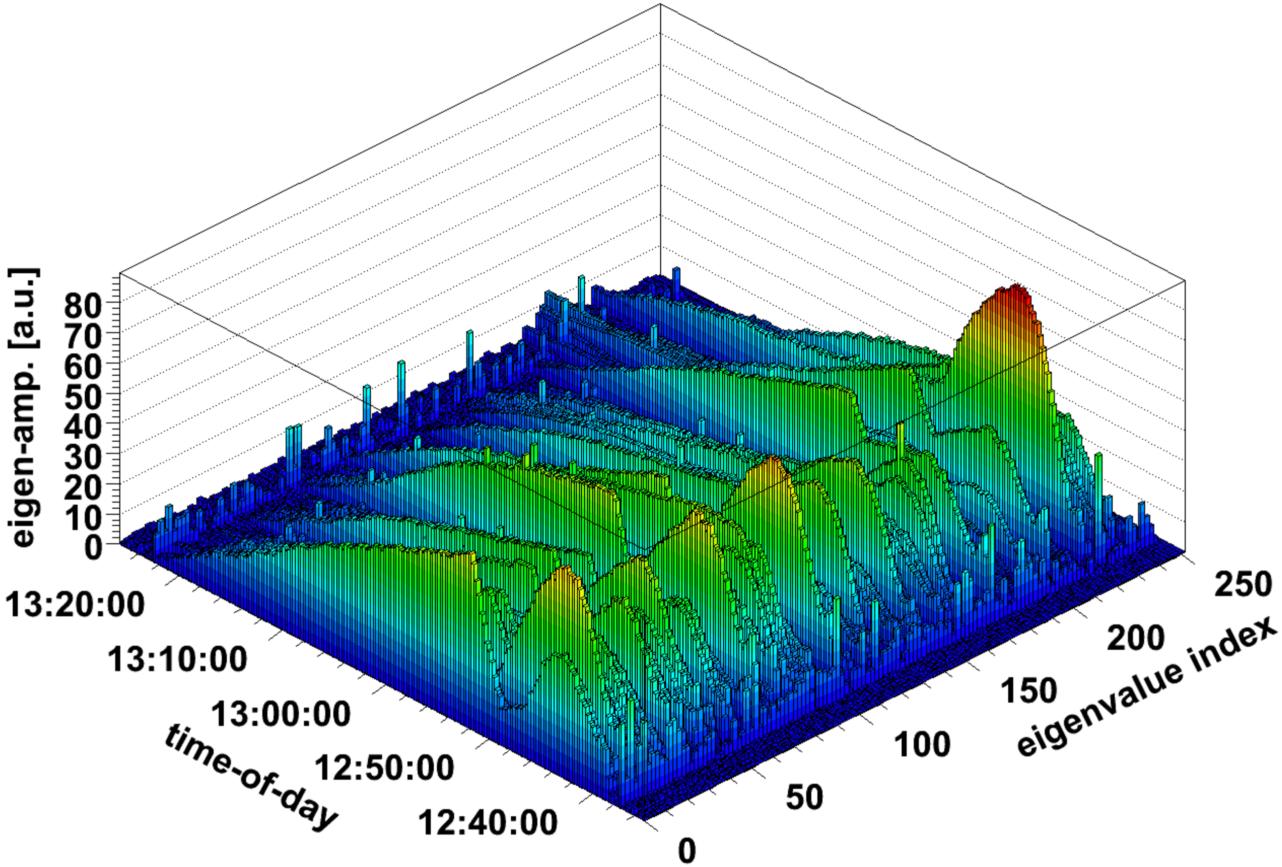
- global bumps ↔ small eigenvalue vs. local bumps ↔ large eigenvalue indices:



- Some global perturbations but also significant local ones
  → need to use more eigenvalues for better local compensation

SVD Decomposition of Orbit Perturbation Sources during the Energy Ramp – ALTERNATE

- Global bumps ↔ small eigenvalue index (↔ large eigenvalues)
- Local bumps ↔ large eigenvalue index (↔ small eigenvalues)



- Some global perturbations but also significant local ones
  → need to use more eigenvalues for better local compensation

Orbit-FB/BPM Limitations and Next Steps

Main limitations so far:

- Spurious QPS trips of special orbit correctors acting on B1 & B2
  → disabled these correctors presently for feedback use, however:
  - limits ability to correct the orbit in the interaction region (triplet quadrupole shifts may become important during the β*-Squeeze with beam-separation)
- Ultimate Orbit-FB and/or beam stability limited by BPM systematics:
  - Affects re-steering to safe collimation orbit reference at injection for nominal intensities
  - Acquisition card electronics temperature effects are being addressed/mitigated by a crate temperature control
  - Noise and bunch reflections signals and to a lesser extend intensity- & bunch-length dependencies need further investigation

Ongoing:

- Integration into operational sequence for day-to-day operation pending:
  - Management of the various reference orbits for injection, collisions, etc.
  - Dynamic change of orbit correction algorithm to accommodate the varying machine optics during the β*-Squeeze (pseudo-inverse-response matrix switching)
  - Synchronisation with BPM sensitivity changes (FB needs to be paused/resumed while switching)

Concept of Orbit- and Tune-FB are still “new” and require 'getting used to' for some in terms of day-to-day operation...