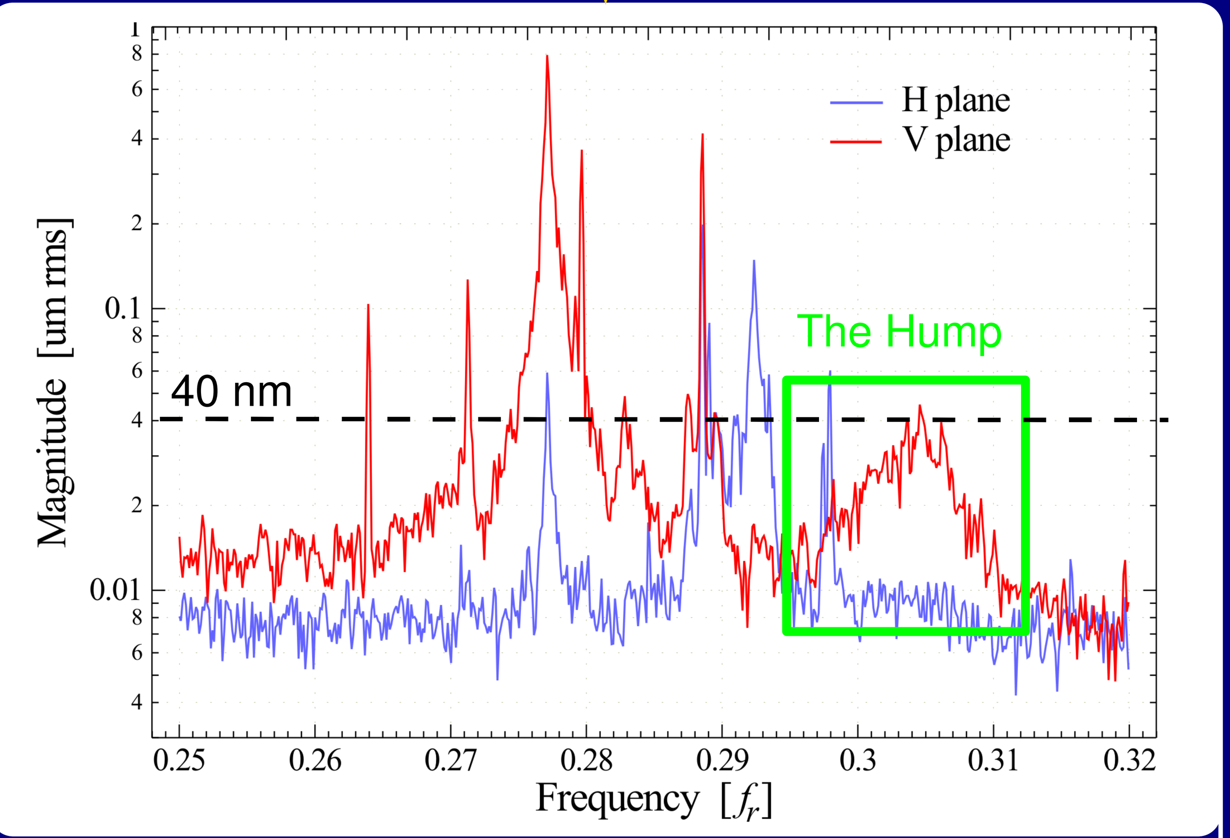
# LHC Beam Stability and Performance of the Q/Q' Diagnostic Instrumentation

M. Gasior, A. Boccardi, S. Jackson, O.R. Jones, R.J. Steinhagen (CERN, Switzerland)


## Abstract

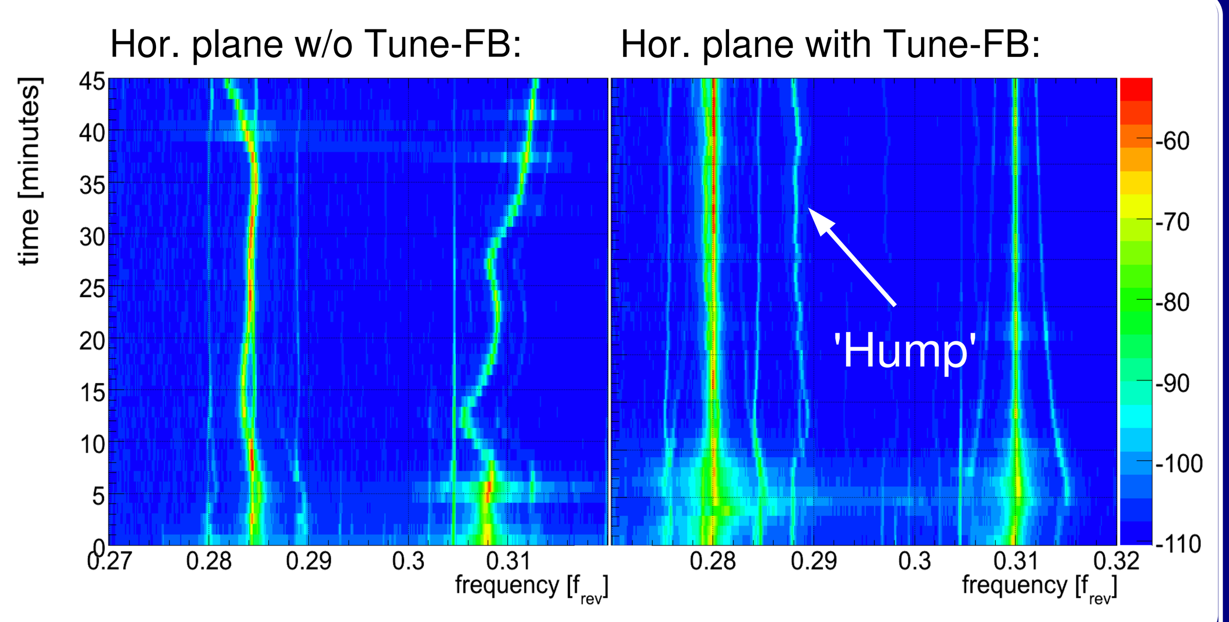
The BBQ tune (Q) and chromaticity (Q') diagnostic systems played a crucial role during LHC commissioning while establishing circulating beam and first ramps. Early on, they allowed to identify issues such as the residual tune stability, beam spectrum interferences and beam-beam effects -- all of which may impact beam life times and that are thus being addressed in view of nominal LHC operation. This contribution discusses the initial beam stability in relation to the achieved instrumentation sensitivity, corresponding tune frequency and Q' resolution.


## BBQ FFT-Resolution:




- Coherent 1 µm-level tune oscillation
- Equivalent turn-by-turn noise of < 1 µm!
- Hump causing emittance blow-up, beam-loss and thus life-time reduction → ongoing investigation

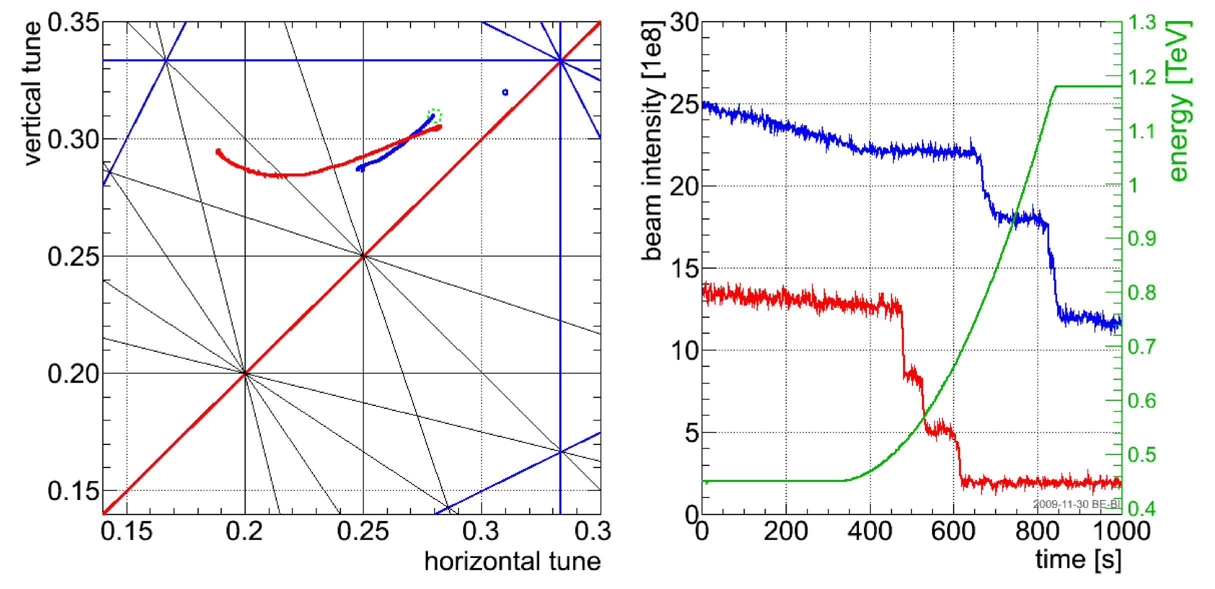
## Q during Ramp with and without Feedback:




- For perfect pre-cycled machine the uncorrected fill-to-fill tune stability is typ. ~$3\cdot10^{-3}$ but often reaches up to ±0.02
- Situation confused with de-facto 3 pre-cycles at the moment:
  - 'Rampdown Combo': MB/MQ down from 6 kA at 2 A/s
  - 'Precycle' (following access etc.): MB/MQ to 2 kA at 2 A/s, &
  - (unfortunately) a mixture of the two (many fills do not end with a 'programmed dump' but some QPS, cryo or other failure)

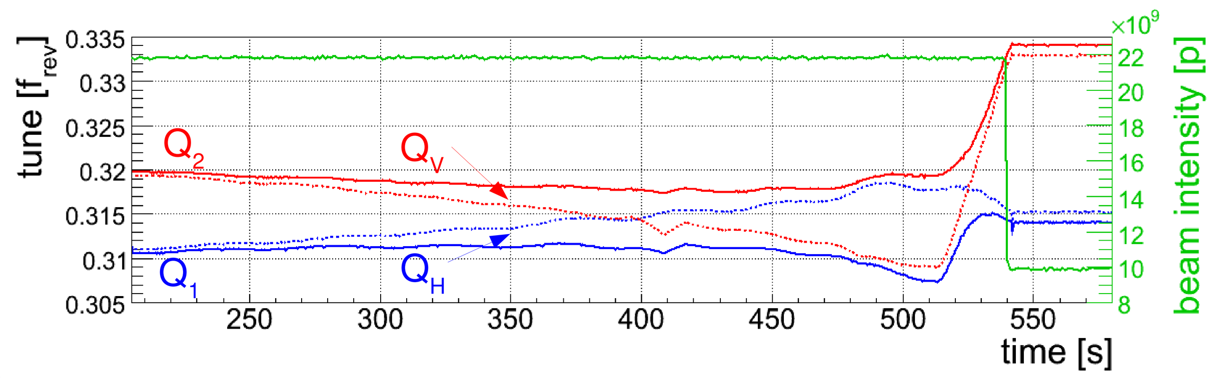
→ Tune-FB routinely used during (almost) every ramp to compensate these effects!

## Initial Ramp Commissioning:



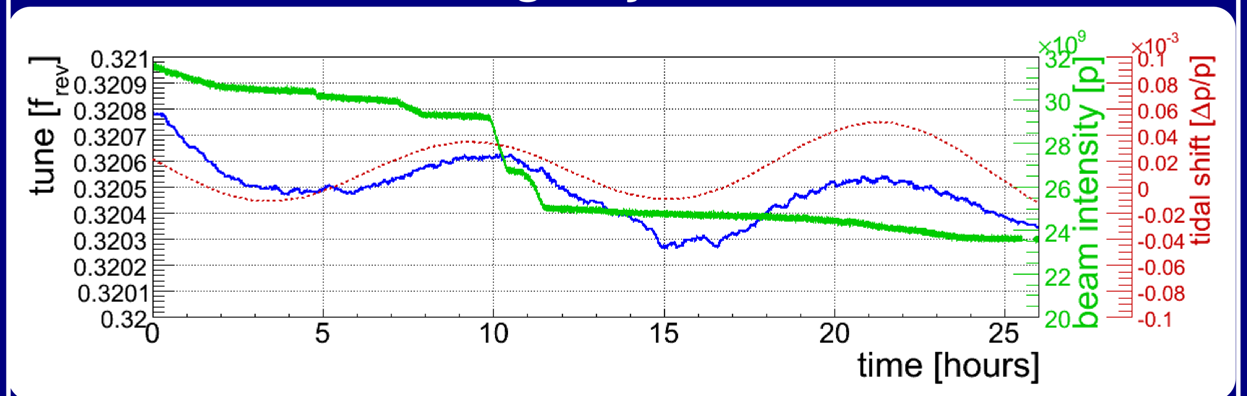

- Base-Band-Tune (BBQ) was work horse from LHC Day-I!!
- No hardware, minimal software and only a few beam related issues
- most measurements were done with residual beam excitation → FFT based analysis
- Typical tune measurements resolution in the range of $10^{-4}$ … $10^{-6}$ $f_{rev}$

## Tune Evolution during β*-Squeeze:




Coupling induced crossing of unperturbed tunes (dashed line) and eventually third-order resonance crossing of the vertical eigen-mode (solid line) leading to particle loss → fixed in the next squeeze iteration

## Tune Evolution during Physics Fill:

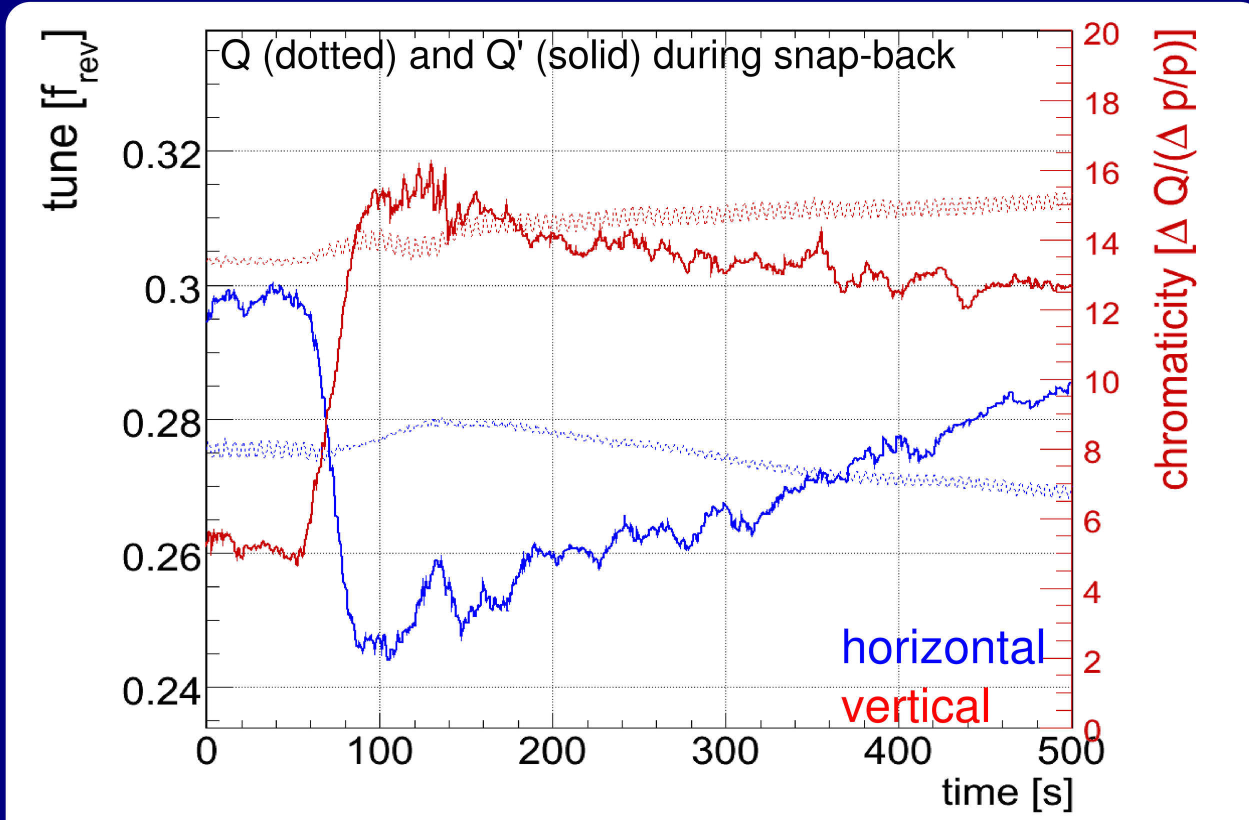



- Short-Term Tune-Stability of ~$10^{-6}$!
- Long-Term Drifts dominated by lunar/solar tides changing the machine circumference (/energy) and propagated via Q' to the tune
- Probably the slowest high-precision Q' measurement in the World!

## BBQ Tune-PLL Commissioning:

- Uses same BBQ-front-end as the 'Continuous FFT' system
- Gain relations and beam-transfer-function (BTF) agree with model
  - Achieved tune resolution: $10^{-5}$
  - Operational range with-out re-tuning: 0.15 … 0.5 $f_{rev}$
- Deployment of additional low-noise strip-line tune tickler (BQK) for missing planes planned
- Presently utility limited by residual strong tune oscillations perturbing the PLL's driven-resonance functioning principle
  - larger excitation are possible but not practical: "Why excite if the tune is anyway visible"

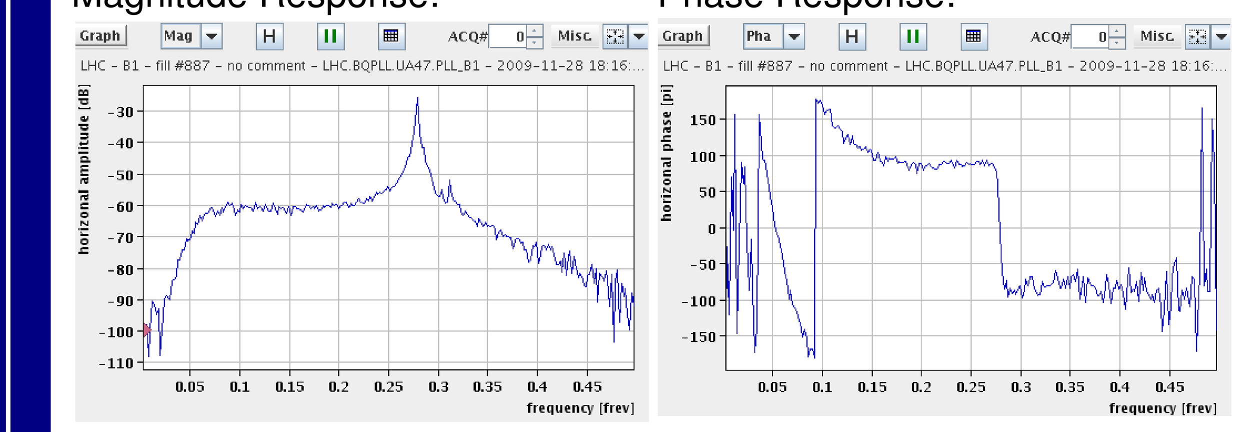
## Chromaticity Tracking during Energy Ramp:



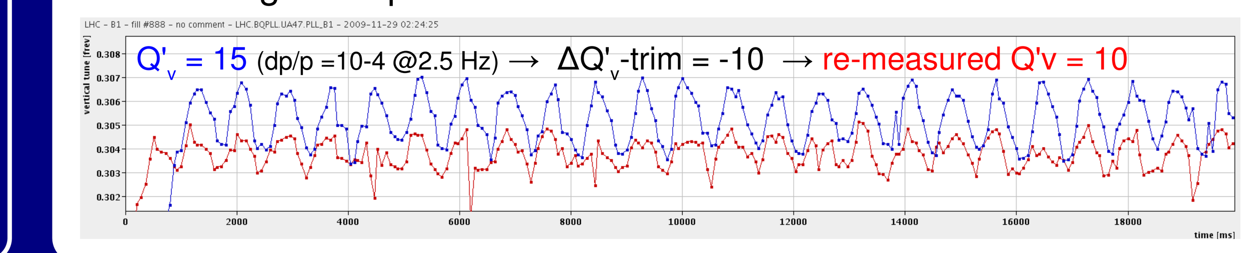

- Partially corrected snap-back of ΔQ'=±10 units visible
- Achieved $\Delta Q'_{meas}$<1 using the classic momentum modulation method with slowly varying Δp/p = 10-4 @0.2 Hz
- Fort the time being the measurements are primarily used to:
  - re-model the magnetic field description model of the LHC
  - used to correct/incorporate the Q' for the next ramps
- Q'-FeedBack partially tested at injection energy but thwarted by spurious triggers of the quench-protection system in response to due to the real-time changes of the sextupole currents.

## Beam Transfer-Function and PLL-Tracking:

Magnitude Response: Phase Response:



PLL-tracking Example:

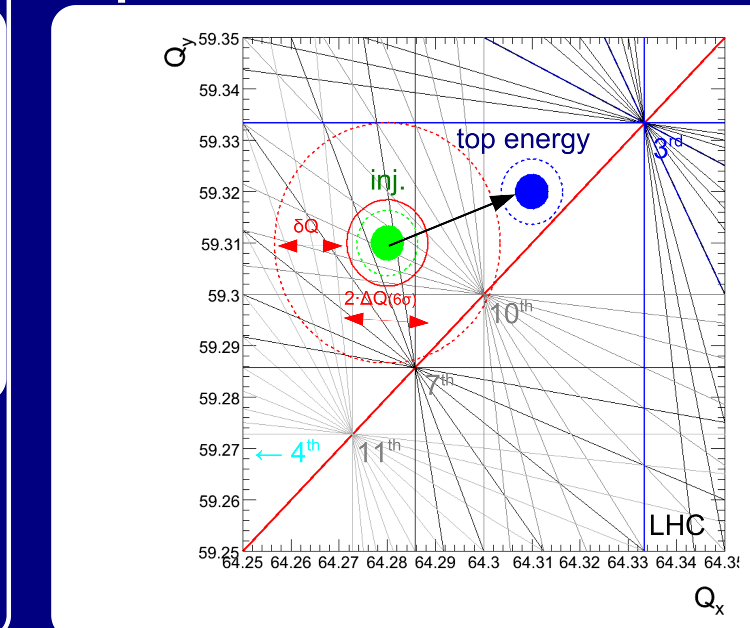



## Issues and further Improvements:

The existing tune and chromaticity diagnostics instrumentation provides an adequate performance, facilitating the fast and safe commissioning of the LHC. Some second-order effects that need to be addressed in view of operation under nominal beam conditions:

- Residual tune stability ~$4\cdot10^{-4}$ at injection impact on 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)
  
    → Power-converter current stability of trim- and insertion quadrupoles is being investigated.
- Impact of Micro-instabilities ↔ residual um-level tune oscillation on the Q-PLL function:
  - 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.
  - Could be mitigated by increasing the exciter amplitude by 20-40 dB but is impractical for regular operation (↔ 100 um beam oscillations/emittance blow-up)
- Limits the Q'-Tracker sampling to < 2.5 Hz

## Expected vs. Measured Perturbations vs. Requirements vs. Achieved Stability:

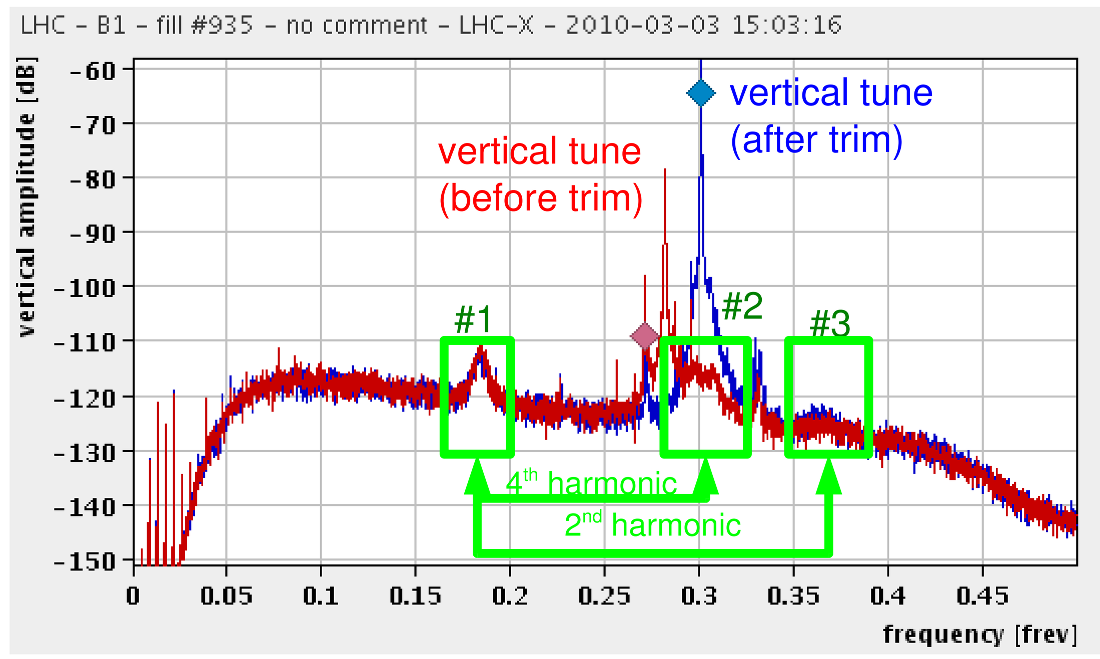



| | Orbit [σ] | Tune [0.5·$f_{rev}$] | Chroma. [units] | Energy [Δp/p] | Coupling [c_] |
|---|---|---|---|---|---|
| Exp. Perturbatior | ~ 1-2 (30 mm) | 0.025 (0.06) | ~ 70 | ± 1.5e-4 | ~0.01 (0.1) |
| Max. Drift Rate: | ~ 25 µm/s | < $10^{-3}$ /s | < 1.3/s | | |
| Meas. Perturbatic | ~4 mm | 0.200 | ~ 30 | < 1e-4 | 0.04 |
| Meas. Drift Rate: | *slow* | < $5\cdot10^{-3}$ /s | < 0.3/s | *slow* | *slow* |
| Pilot | - | ± 0.1 | + 10 ?? | - | - |
| Commissioning | ± ~ 1 | ±0.015→0.003 | > 0 ± 10 | ± 1e-4 | « 0.03 |
| Nominal | ± 0.15 | ±0.003 / ±0.00 | 2 ± 1 | ± 1e-4 | « 0.01 |
| Achieved | ~ 70 µm/s | < 0.001 | < 1 | < 1e-4 | < 1e-3 |

# 'Raiders of the Lost Hump' – or –

## The Broad-Band Perturbation Source in the Vicinity of the Nominal LHC Tune Working Points

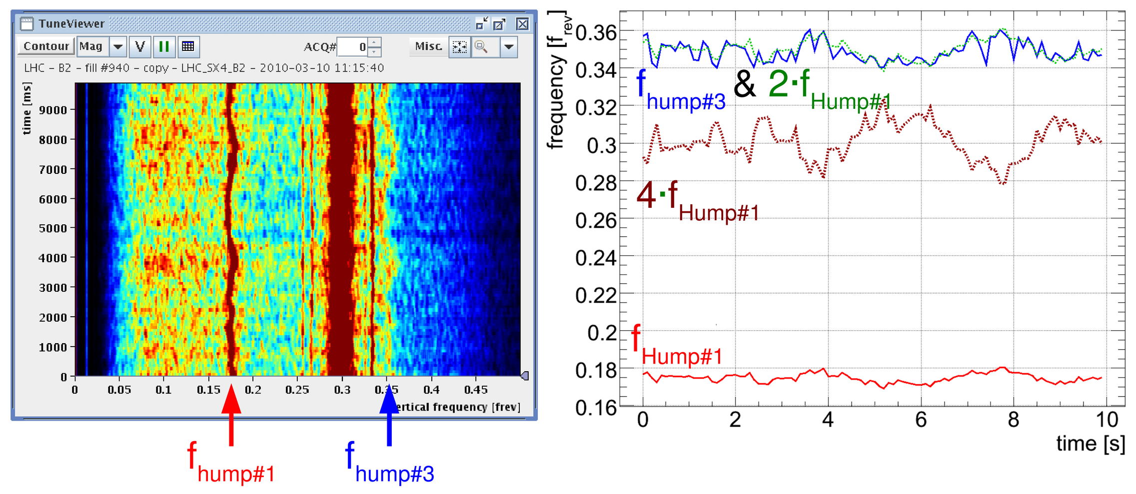
### 'What is the Hump' – Symptoms:



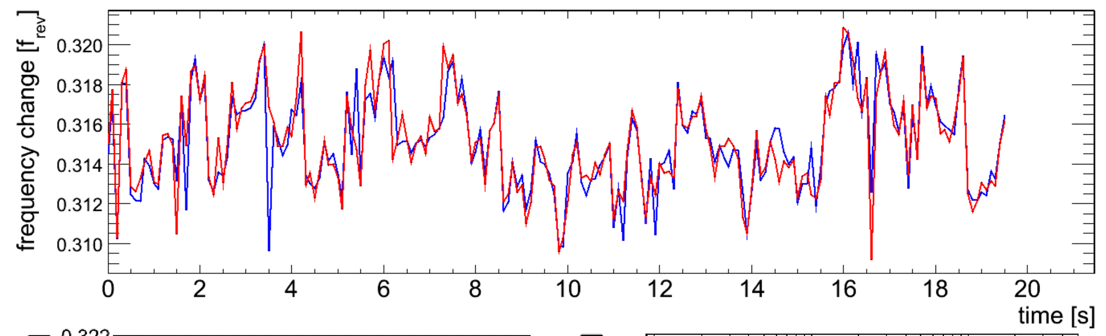

- 'Hump'-Mechanics - Example: $Q_v$ set below 'hump' (red) and after $Q_v$ trim on top of 'hump' #2 (blue):
  Driving of the tune resonance visible → beam size growth → beam losses → reduced life-time → luminosity reduction
- Depending on the observation time-scale appears either as
  - broad-band excitation (periods > 1 s), or
  - fast shifting frequency (period < 1 s)

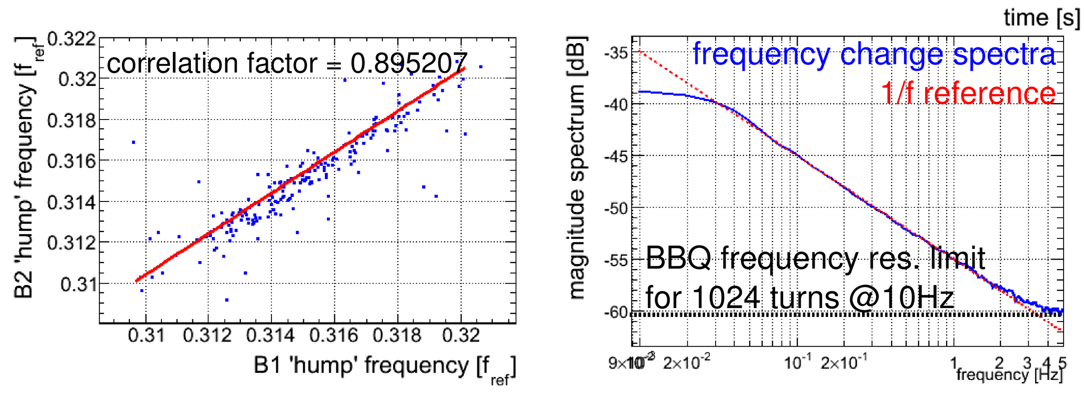
  with slowly-varying mean frequency in both cases.
- There are at least three 'humps', with harmonic relationship
- Slow frequency-shift has sometimes:
  - An approximate period of 7 minutes, or
  - A Brownian motion type (=random) structure.
- Scales (sometimes) down with energy
- High correlation in between both LHC beams, however seems to be stronger for B2
- Assuming a single dipolar perturbation → kick < 0.4 nRad!!
  - … a non-issue if the present tune working point wouldn't be exactly on it.
  - … difficult to identify since it could be generated by a large range of – potentially “exotic” effects.
- Effects/systems eliminated as cause of the 'hump':
  Q/Q'-changes, single/two beam operation, injection septa, orbit correctors, UPS, transfer lines, experimental magnets, pre-injectors, transverse FB, higher-order magnets (from skew-sextupoles up to decapoles), changing or locking of RF frequencies, β*-Squeeze

### Hump Structure on Short Time-Scales:

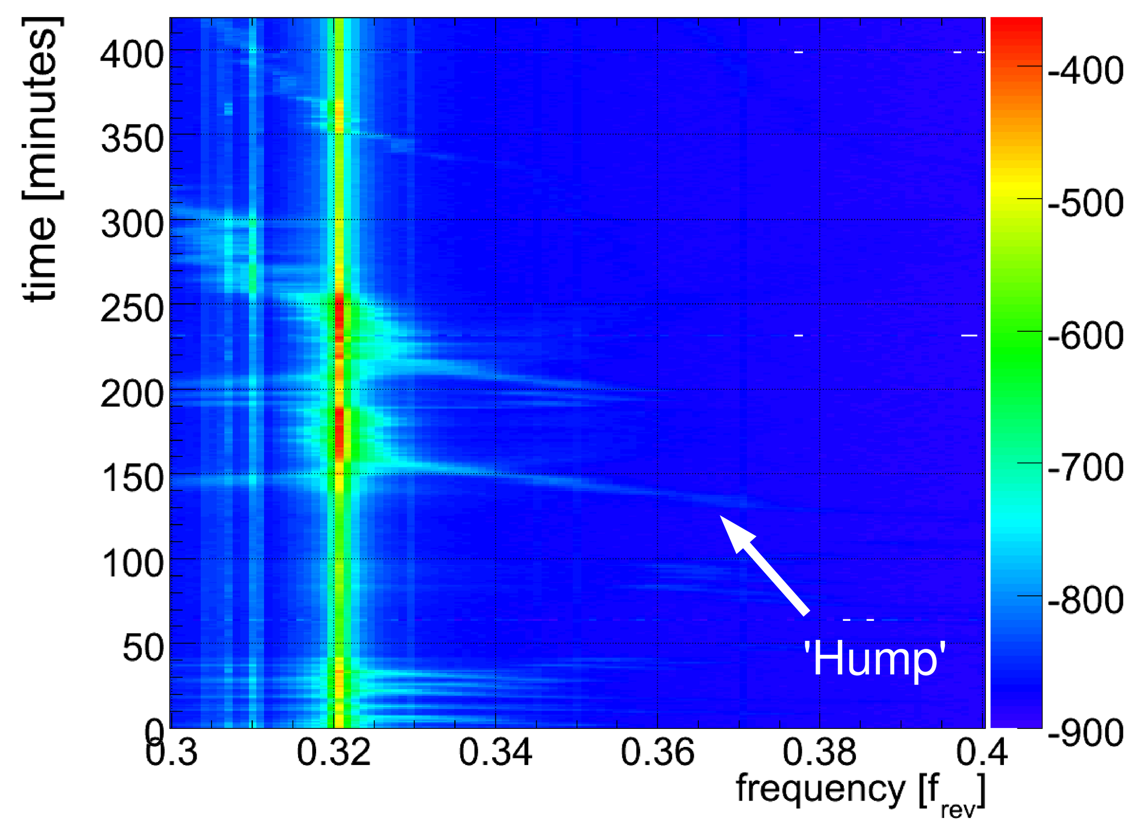



Beam 1 /Beam 2 Correlation:

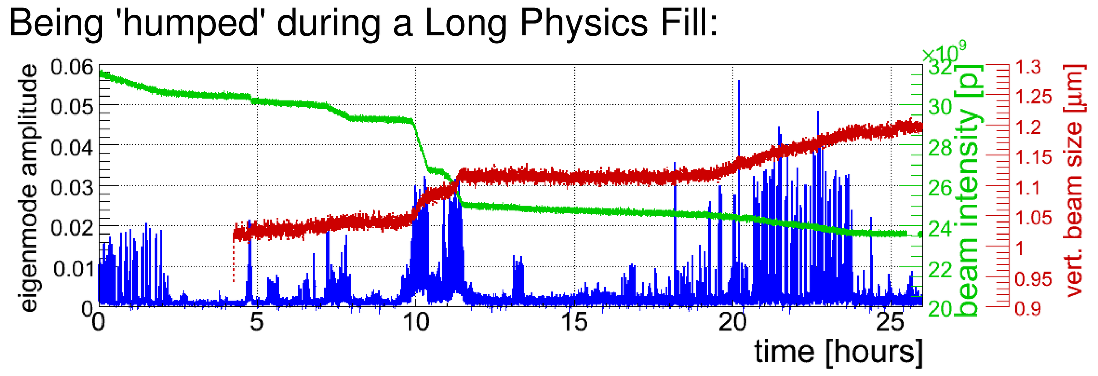



### Hump Structure on Long Time-Scales:




Being 'humped' during a Long Physics Fill:




→ significant intensity/luminosity loss over a few minutes @3.5 TeV

… true origin of the 'Hump' 'til date remains elusive.

BIW'10, TUPSM066, R. J. Steinhagen 2010