First Results of the PLL Tune Tracking in the SPS

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- The measurement and control of

  -- orbit, tune, chromaticity, energy and coupling --

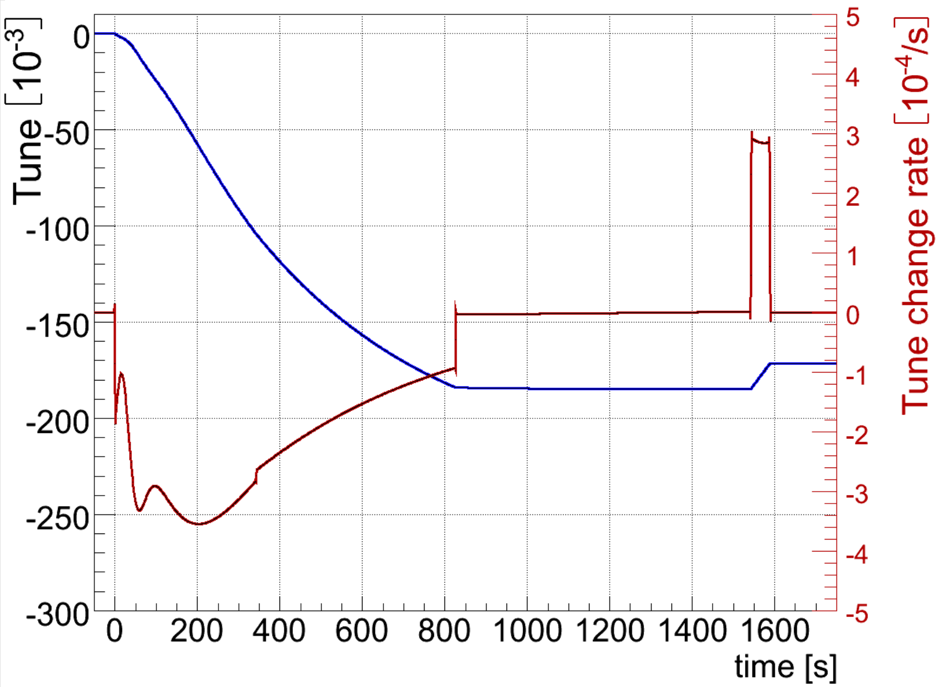
  will be an integral part of the LHC operation

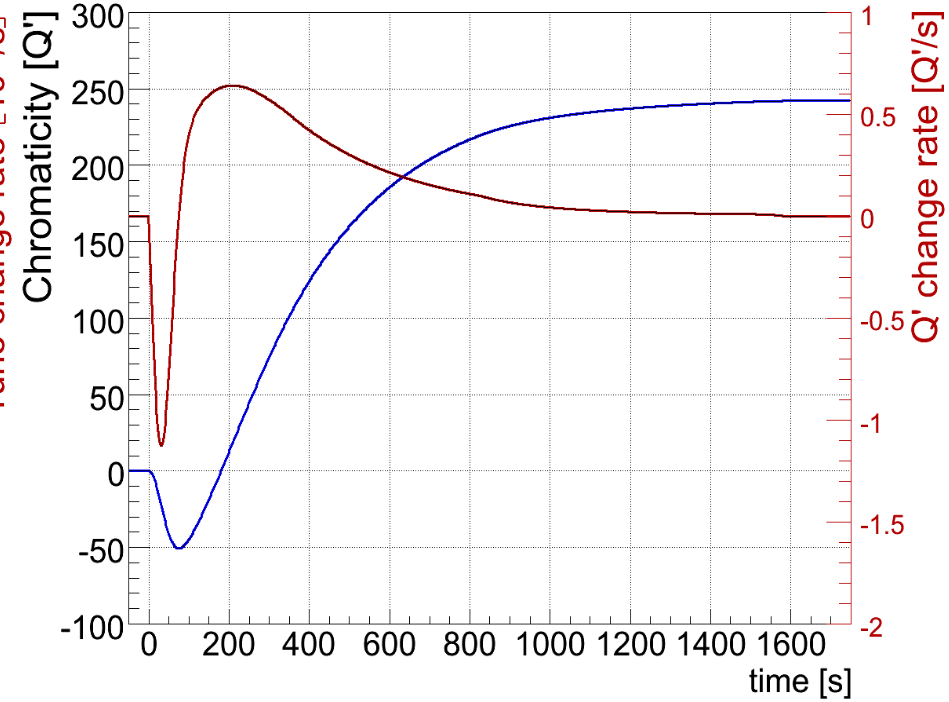
- Requirements summary:

	Orbit [σ]	Tune [$0.5 \cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Exp. Perturbations:	~ 1-2 (30 mm)	0.025 (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

today's focus!

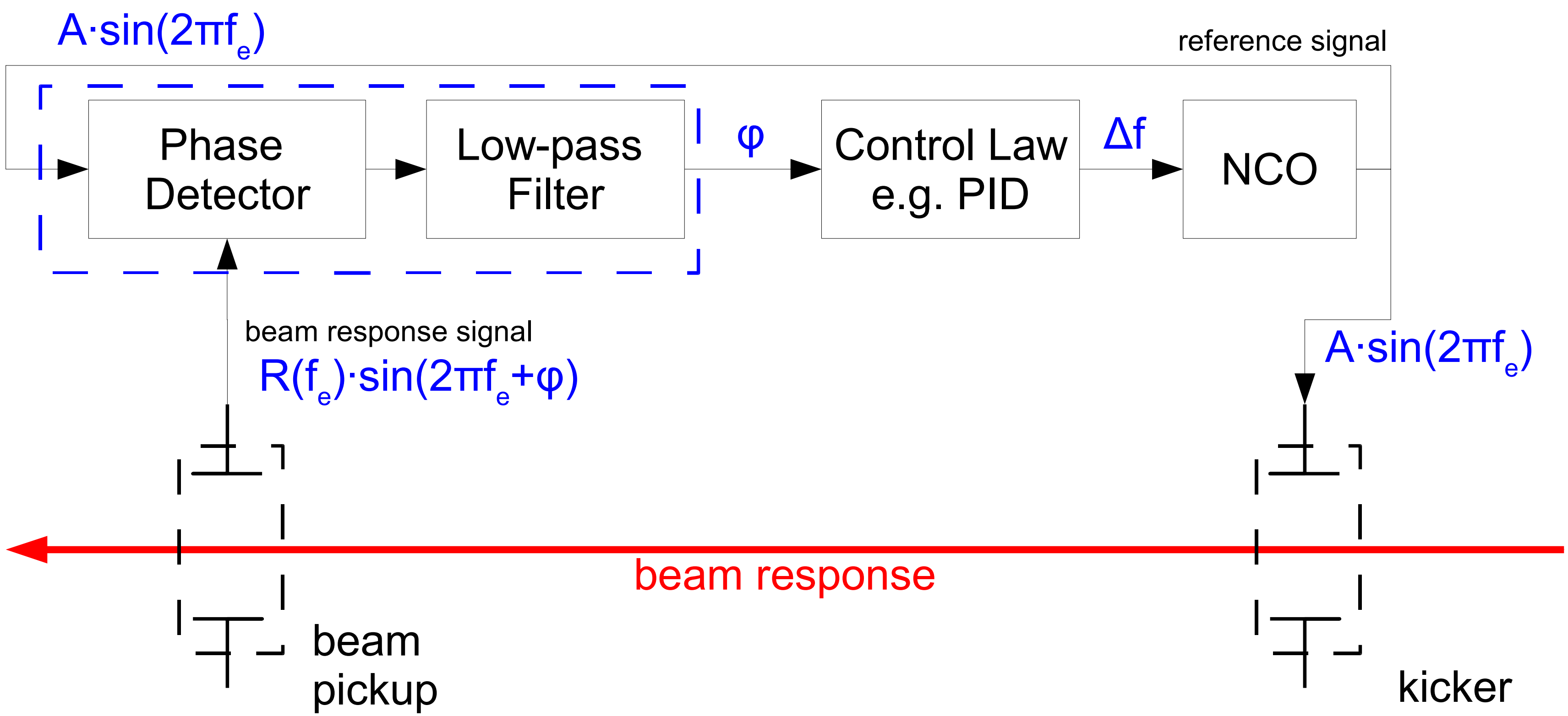
Expected Tune and Chromaticity Drifts during LHC ramp



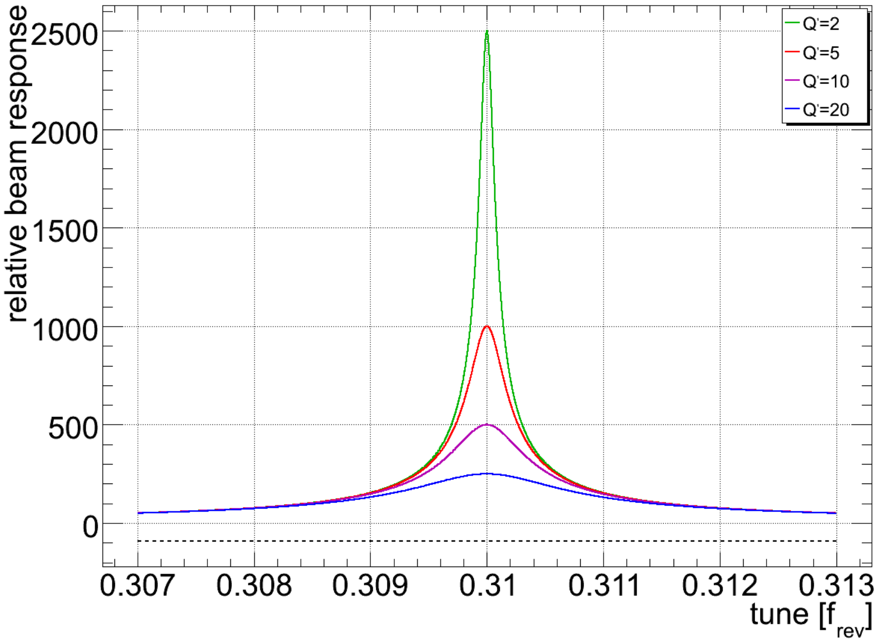


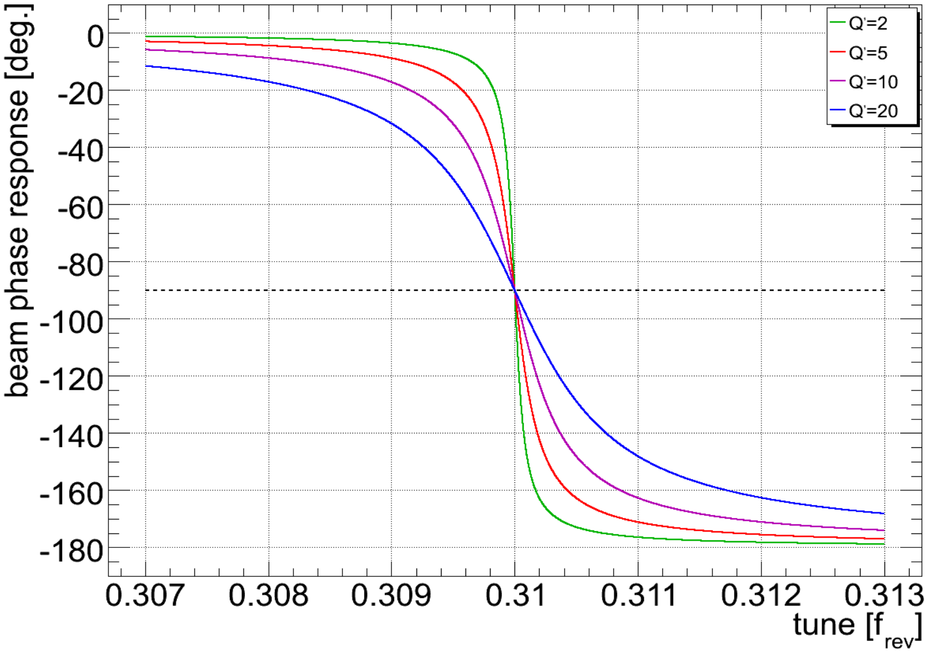
- Exp. perturbations are about 200 times than required stability!
- however: maximum drift rates are expected to be slow in the LHC
  - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
  - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2\ s^{-1}$
- Requires active control relying on beam-based measurements

Basic Phase Locked Loop in a Slide



- NCO: Numerically Controlled Oscillator = digital sine wave generator
- Aim of the PLL control law:
  - regulate the frequency in order to minimise Δφ (match to 90°)
  - first iteration choice: e.g. classic proportional-integral (PI) controller





- In addition to the tune, the beam response also depends on the chromaticity

- The PLL dynamic and its design split into two parts:
  - PLL low-pass filter: → controller gains
  - Beam response: → open loop gain K_0
    - first order: K_0 = const.

- PLL low-pass:

$$G(s)=\frac{K_0}{\tau s+1} \qquad with \qquad \tau\approx 25\,ms\,(\Leftrightarrow f=40\text{Hz}) \tag{1}$$

- Youla's affine parameterisation[1] for stable plants:

$$\boxed{D(s)=\frac{Q(s)}{1-Q(s)G(s)}} \tag{2}$$

- Using the following ansatz

$$Q(s)=F_Q(s)G^i(s)=\frac{1}{\alpha s+1}\cdot\frac{\tau s+1}{K_0} \tag{3}$$

- (1)+(2)+(3) yields:

$$\boxed{D(s)=K_P+K_i\frac{1}{s} \qquad with \qquad K_p=K_0\frac{\tau}{\alpha}\ \wedge\ K_i=K_0\frac{1}{\alpha}}$$

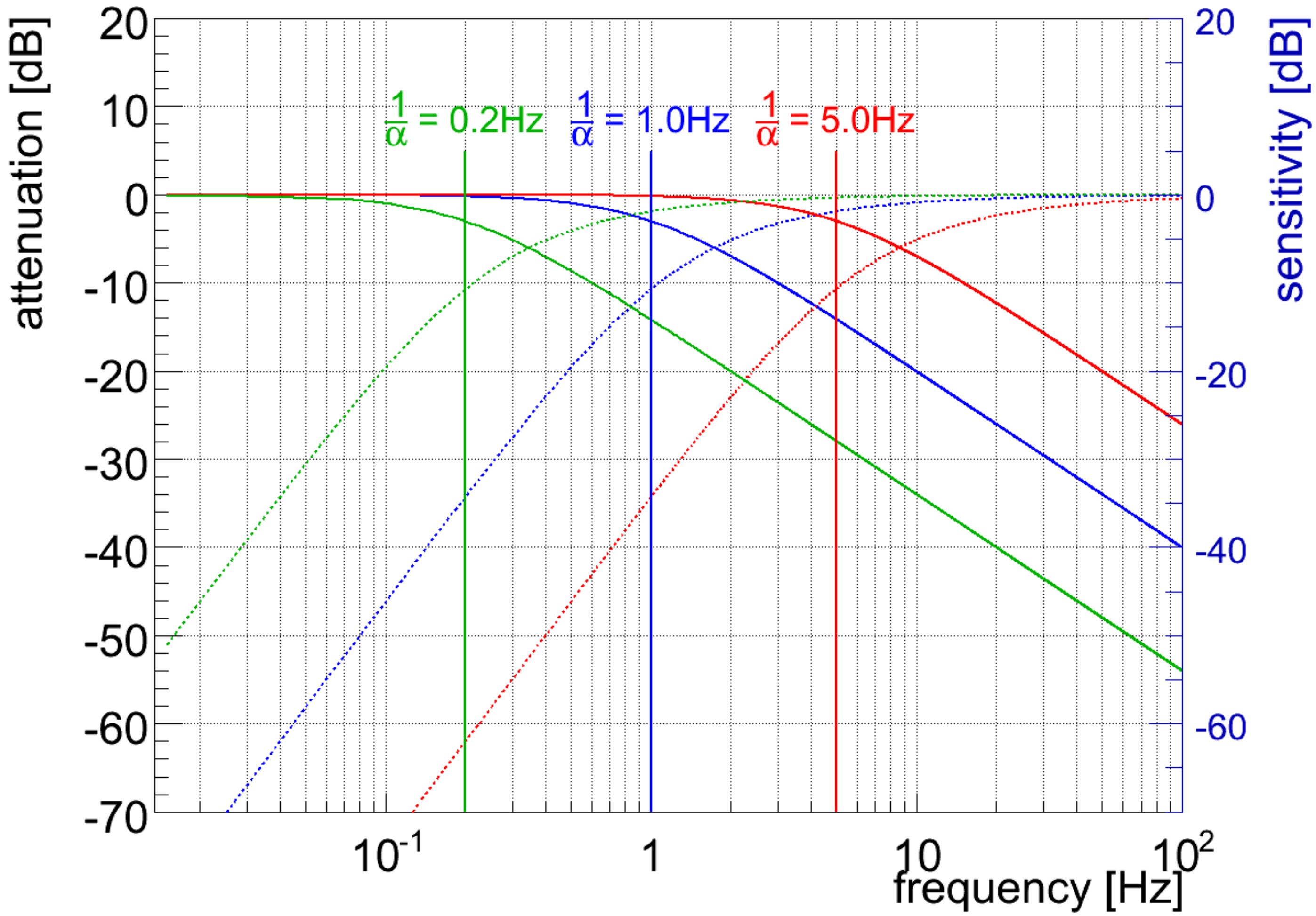
- α > τ…∞ moderates closed loop response between (trade-off):
  – fast and less accurate tracking vs. slow and more accurate tracking

[1] D. C. Youla et al., *“Modern Wiener-Hopf Design of Optimal Controllers”*, IEEE Trans. on Automatic Control,1976, vol. 21-1,pp. 3-13 & 319-338

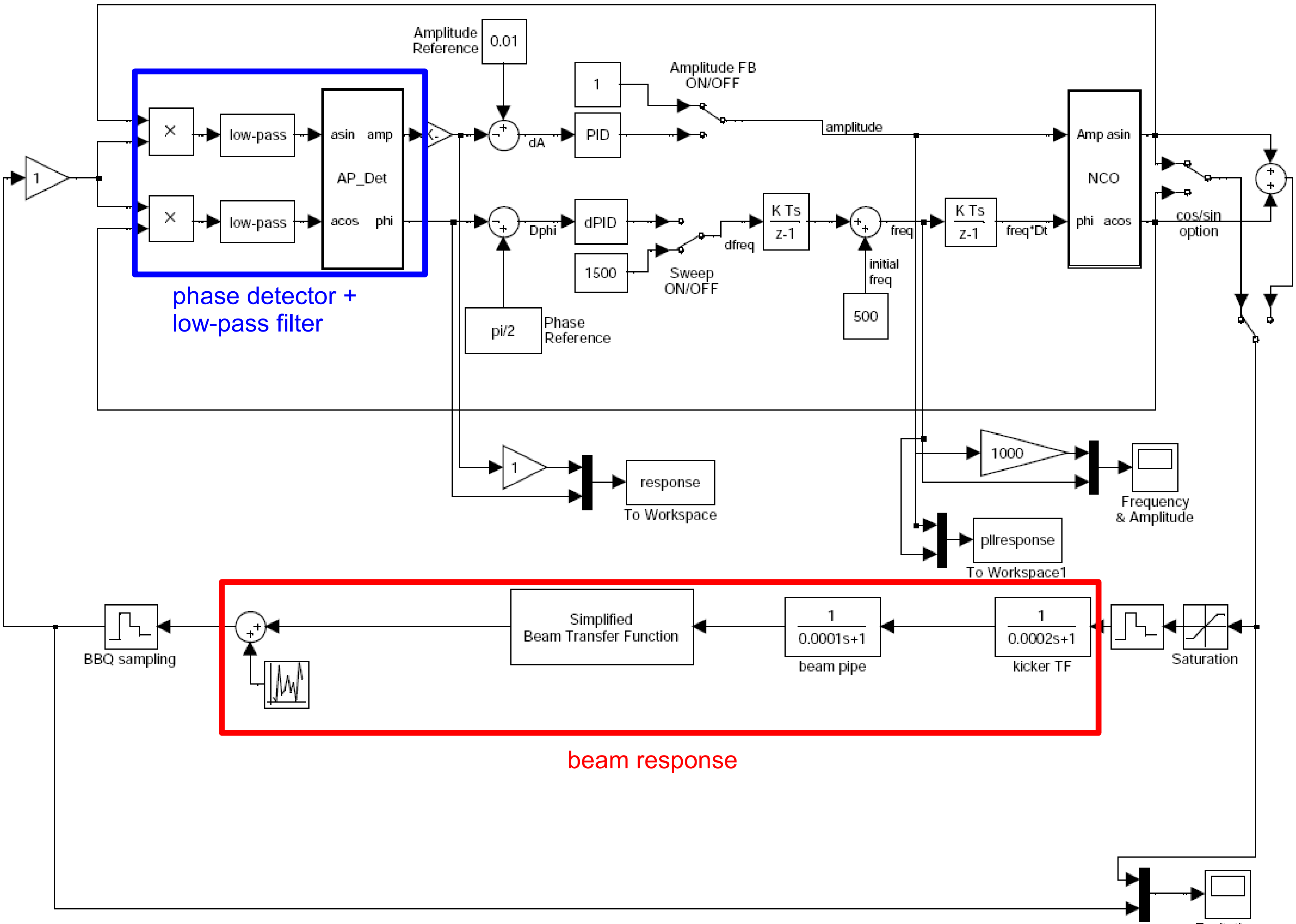
Robust vs. Fast Tracking PLL

- Similar to the other feedback designs: 1/α ~ effective PLL bandwidth
- α facilitates the closed-loop trade-off:

fast and noise sensitive vs. slow and robust PLL loop



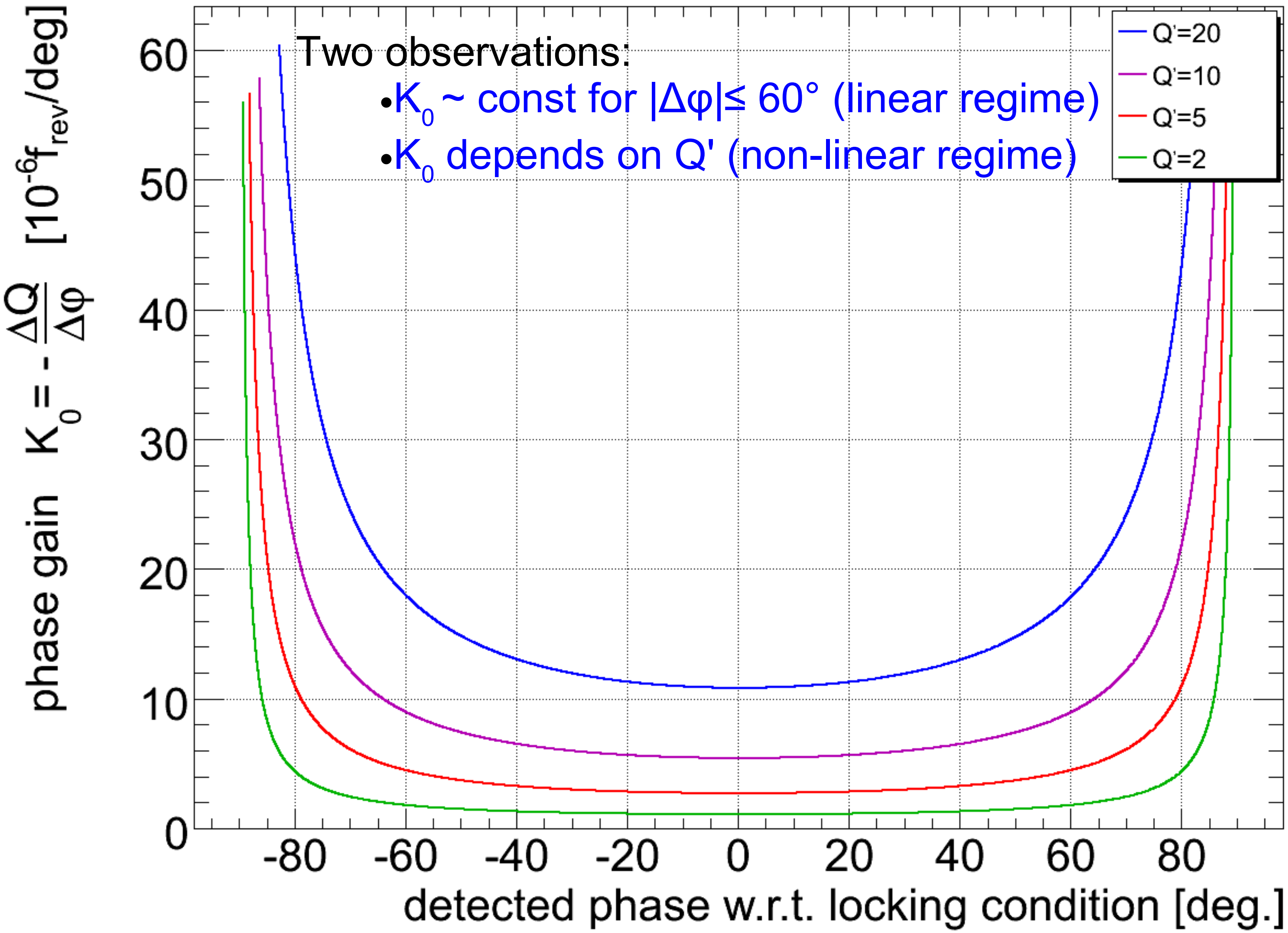
A more complete PLL schematic



N.B. the phase reference includes correction for constant delays and BBQ filter systematics

Chromaticity and PLL Non-linearities

- The first order PLL controller assumed a constant open-loop gain K_0
- Real open-loop response depends also on the actual phase and



Tune PLL and Chromaticity

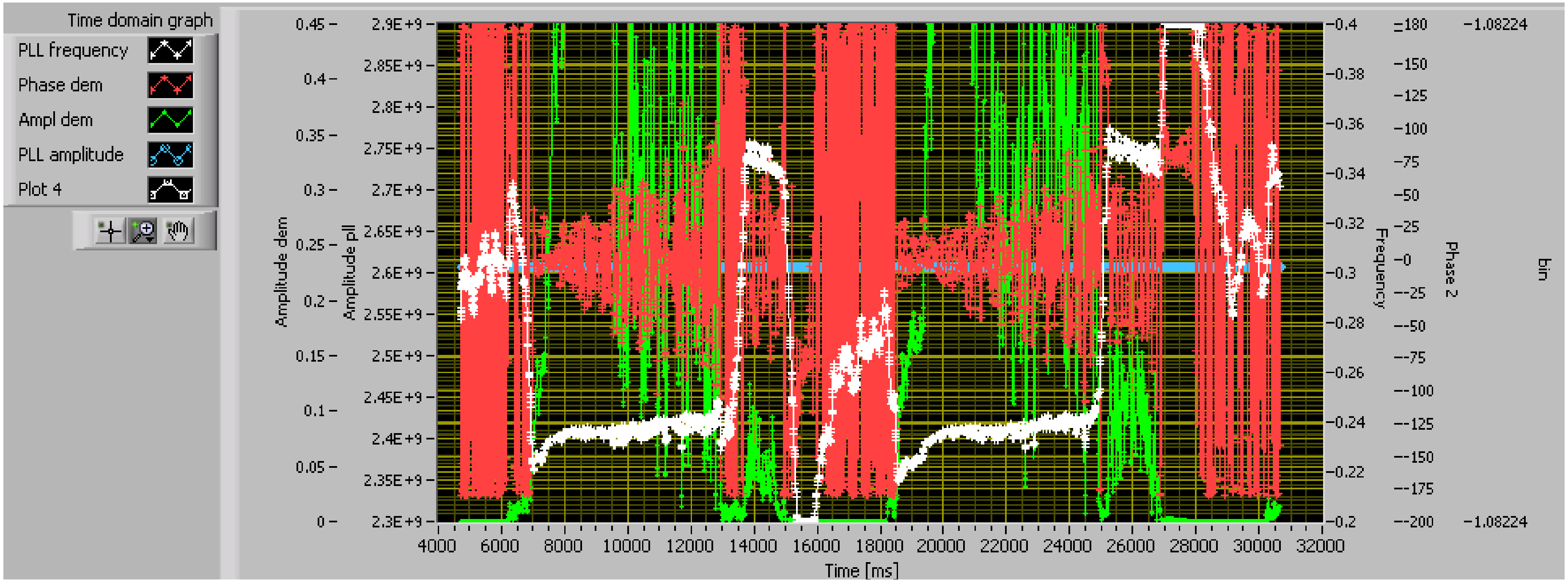
- Optimal PLL parameters (tracking speed, etc.) depend - beside measurement noise – on the chromaticity inside the machine.

- Intrinsic trade-off:
  - Optimal PI for high Q' ↔ sensitivity to noise (unstable loop) for low Q'
  - Optimal PI for small Q' ↔ slow tracking speed for large Q'
    - the choice for commissioning

- Can be improved by putting knowledge into the system: “gain scheduling”
  - injection: expect slow Q' changes → slow but robust tracking
  - ramp: expect faster Q' changes → faster but less robust tracking

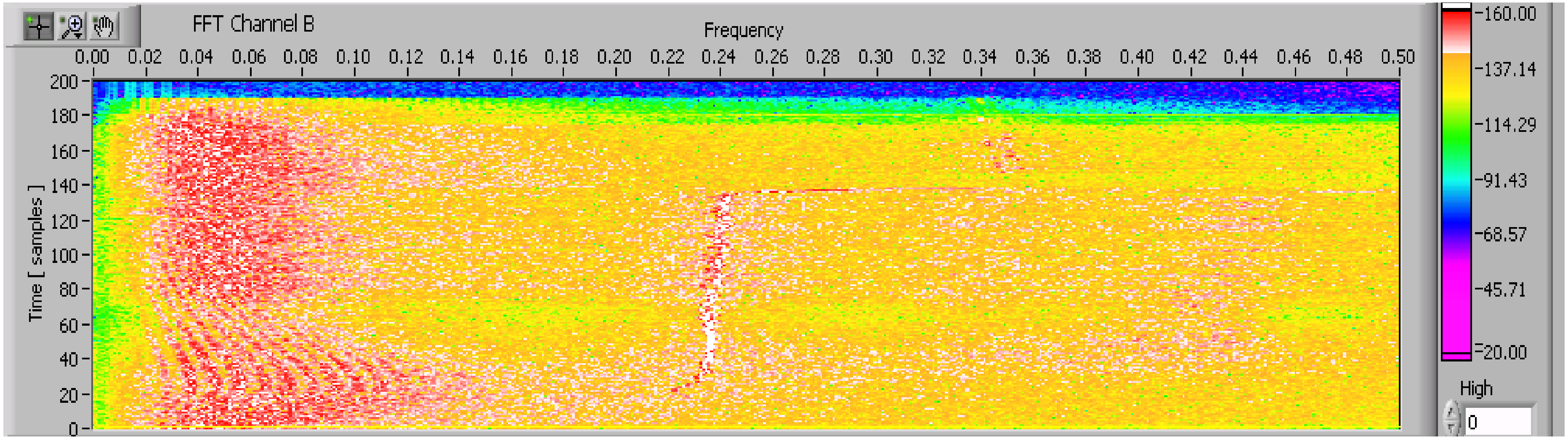
- Testing favours 'coasting beam' (e.g. @ RHIC):
  Can separate temporal from systematic effects that affect the phase

21 September 2006: First successful BBQ based PLL



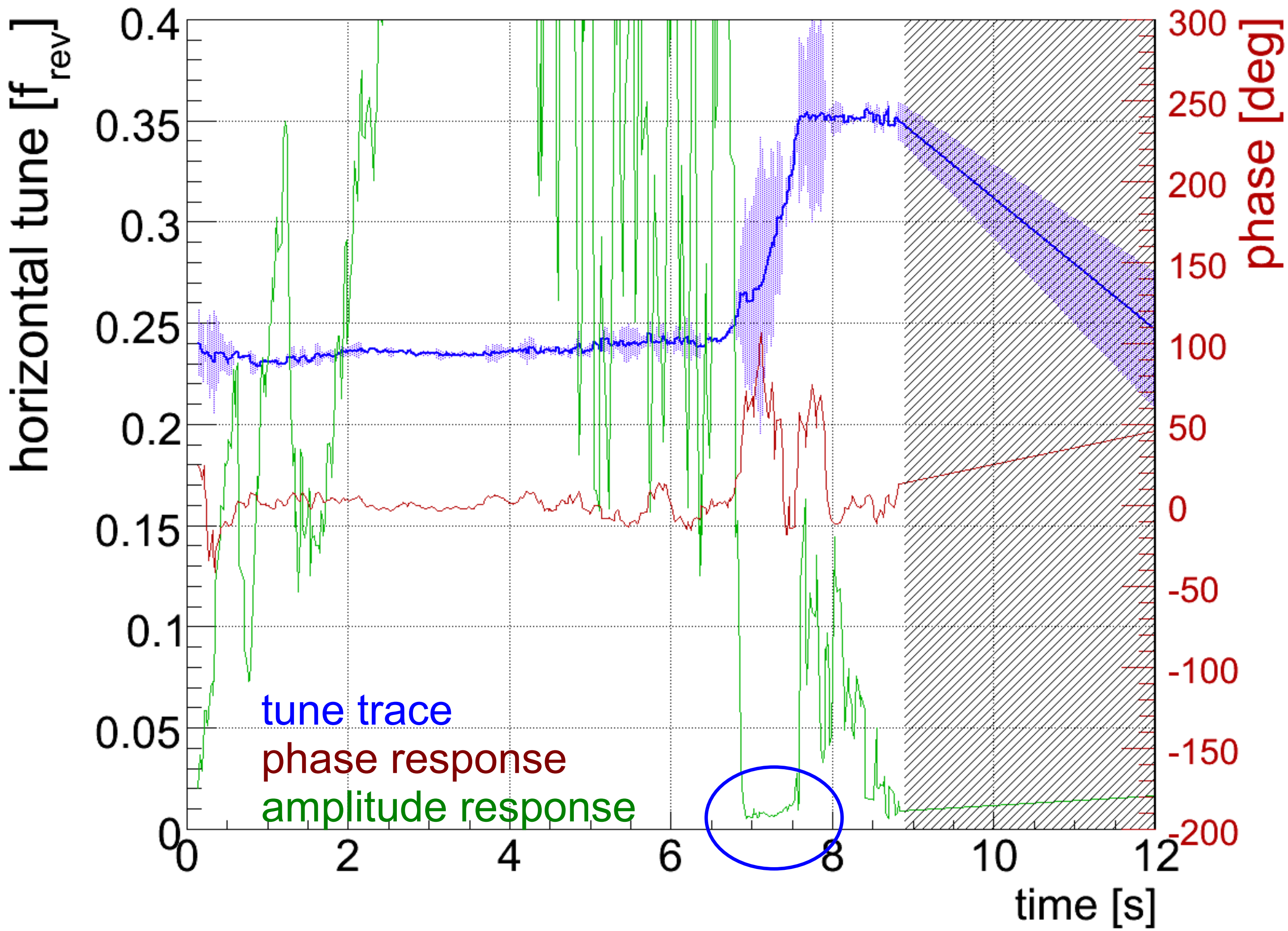
- SPS 25ns fixed target beam: 26GeV → 450GeV, ~ 3e12 protons/beam
  - Horizontal tune: Q_h≈ 26.76 → 26.66 (slow resonant extraction)
  - kept lock during ramp
  - Fastest tracked tune change: ΔQ≈0.1 within about 200-300 ms
    - much faster than the maximum expected tune drift in the LHC!

- Temporal evolution of the individual FFT acquisition:



- Tune resolution:
  - FFT based (1024 turns): $\Delta Q_{res} \approx 10^{-3}$
  - PLL based: $\Delta Q_{res} \ll 10^{-4}$-$10^{-5}$
    - limited by underlying tune stability → SPS is a tough testbed
    - excitation below the 1 μm level (factor 10++ below MultiQ Settings)
      - negligible/no emittance blow-up
  - Seem(ed) to be a very robust measurement!

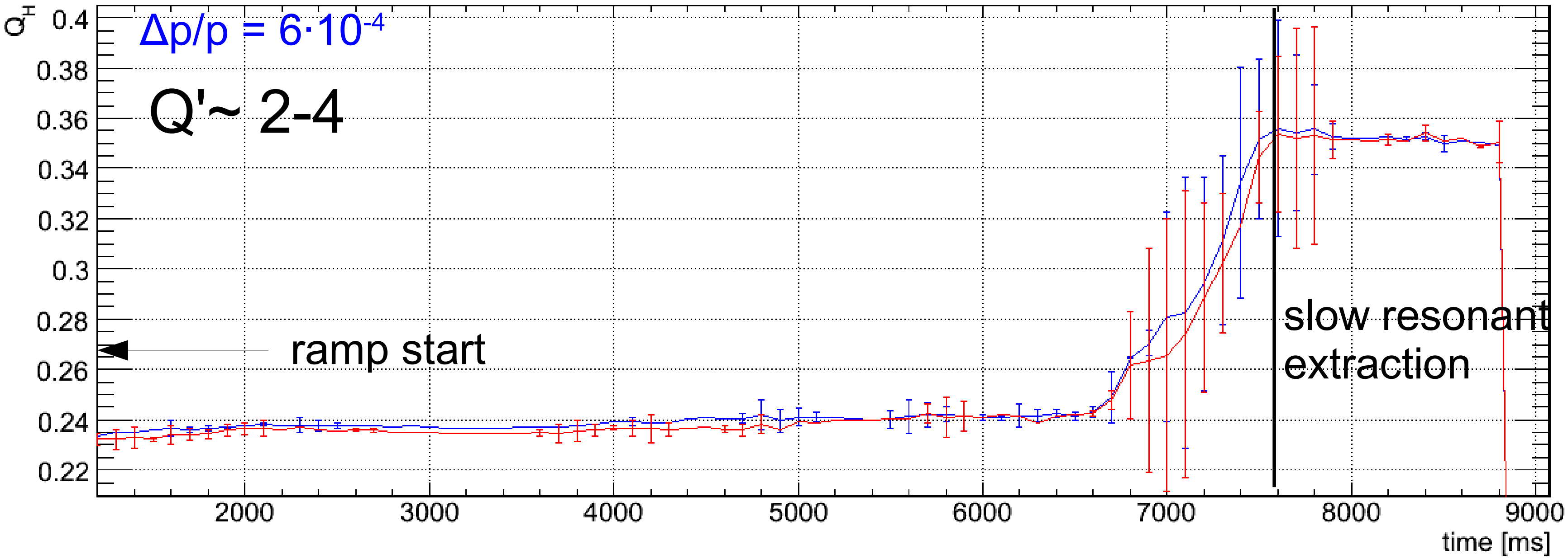
A Brief Comment on the Measurement Resolution I/II



- phase error and non-vanishing amplitude indicate lock during ramp
- $\Delta Q/\Delta t|_{max} \approx 0.3$ about two orders of magnitude faster than required for LHC

Q' measurement trough slow Δp/p modulation

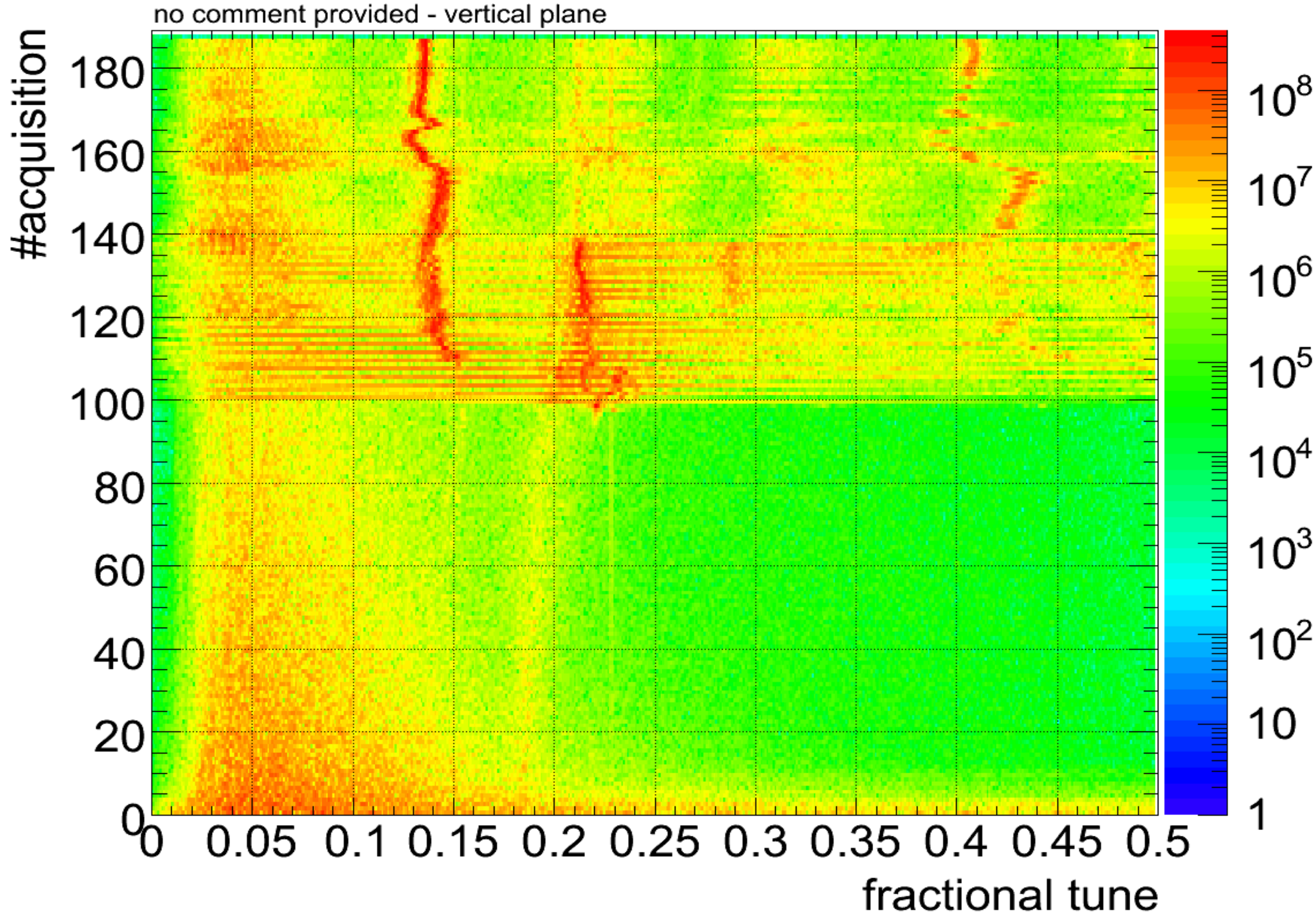
- Used PLL to track Q' (measurement during ramp)



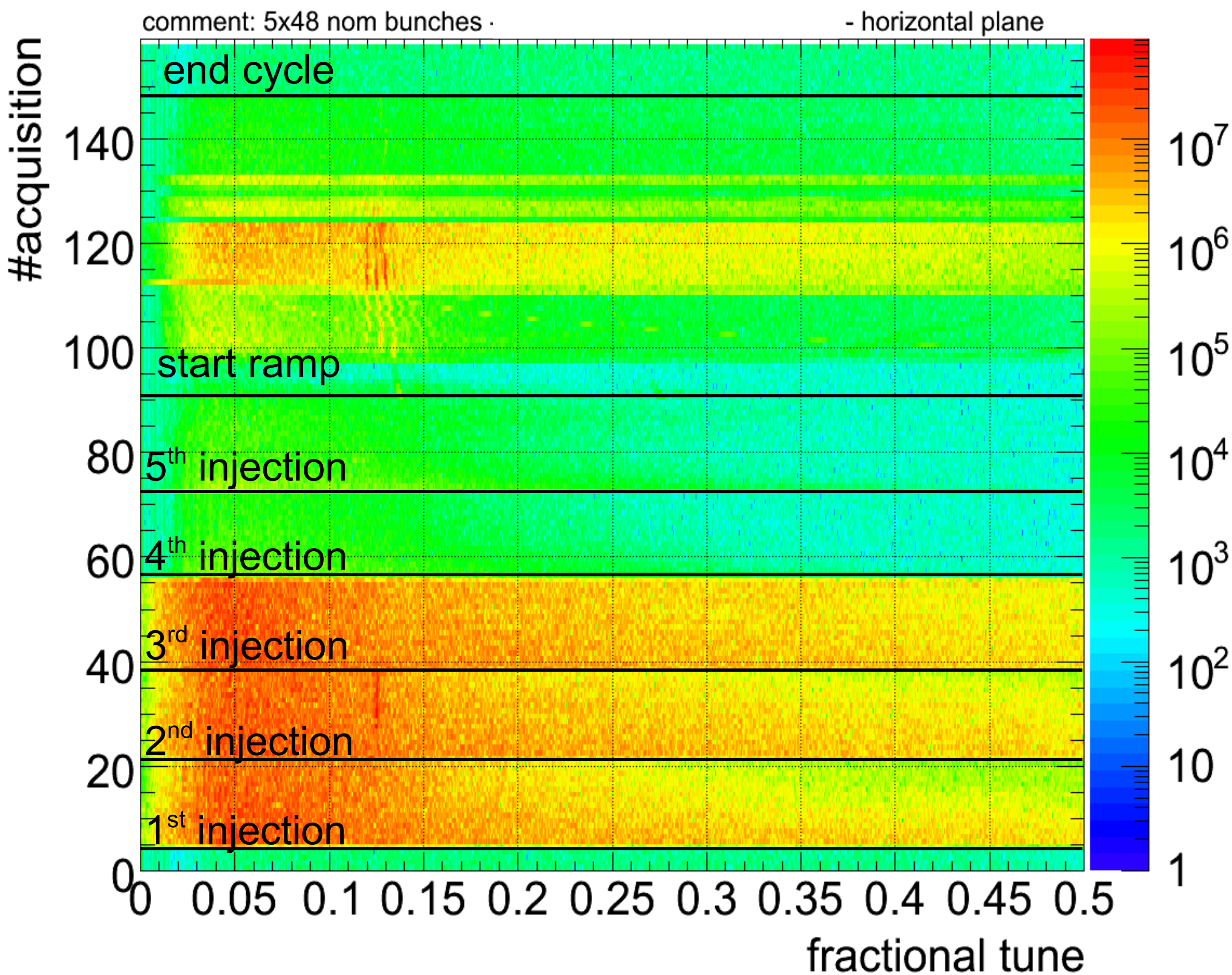
- SPS operation: $\Delta p/p > 10^{-3}$ & $\Delta Q_{res} \approx 10^{-3} \rightarrow \Delta Q'_{res} \sim 1$
- LHC: $\Delta p/p < 10^{-4}$ & $\Delta Q'_{res} \sim 1 \rightarrow \Delta Q_{res} < 10^{-4}$
  - tough, still not established!
- Further tests with averaging over several tune measurement and slow underlying systematic Q,Q' changes
- Testing requires coasting beam for this and other Q' methods (→ RHIC)

Some notes on BBQ measurement I/II

- BBQ impresses with incredible sensitivity w.r.t. to oscillations
- This year we got swamped with large residual (tune) oscillation



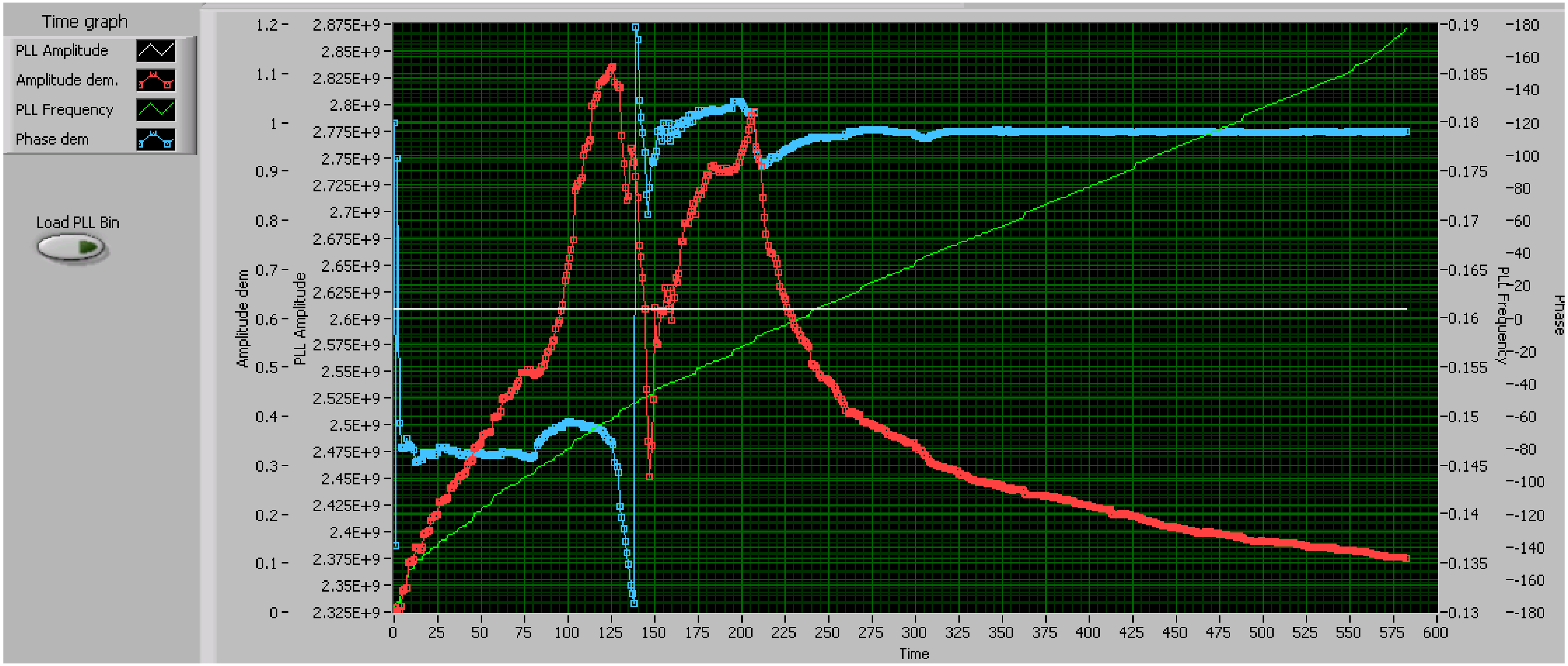
- clamped the BBQ front end that resulted in multiple large harmonics
→ tune could and did lock on the harmonics



- An additional diode in series may address this issue!

Some "unexpected" Beam Response I/II

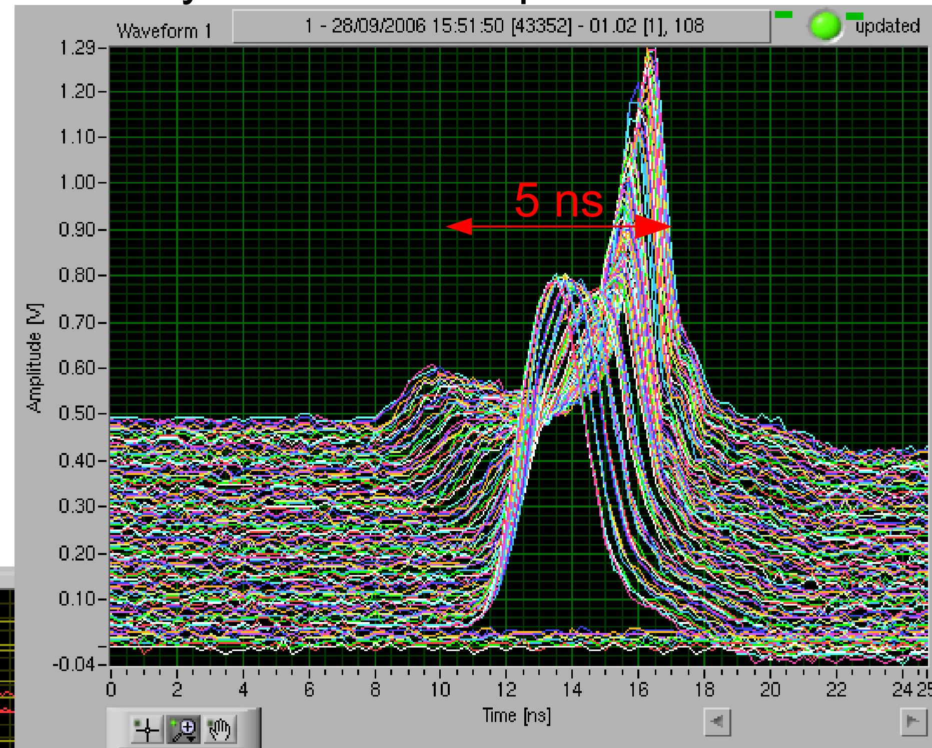
- Broke the PLL due to change of beam response (red), particularly the phase advance (turquoise):

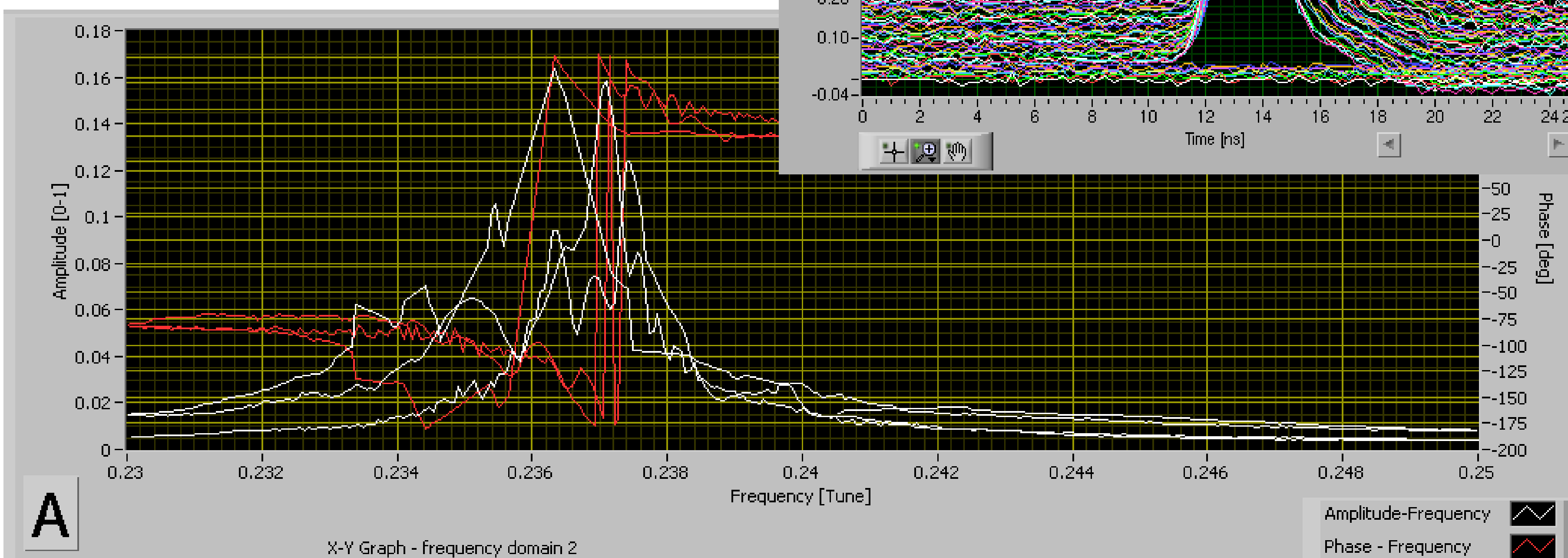


- ....gave food for thought

Some “unexpected” Beam Response I/II

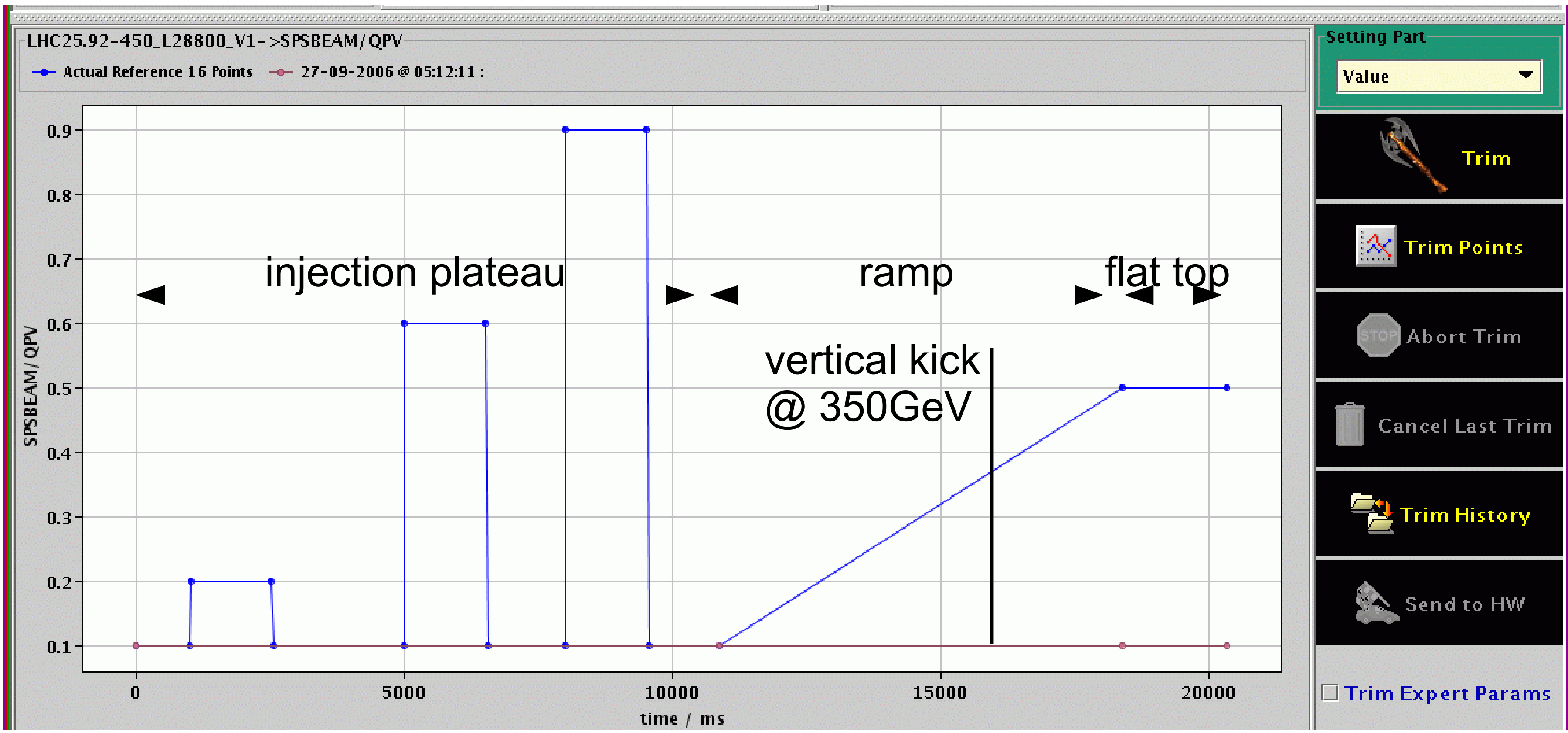
- Observed during the next day: Mismatched synchronous RF phase → bunch splitting!
  - Resistive wall impedance
    - large bunch oscillation
    - bunch dependent tune shifts
  - Crosstalk with RF feedbacks
  - my opinion: a pathologic effect!





Chromaticity Measurement Methodology

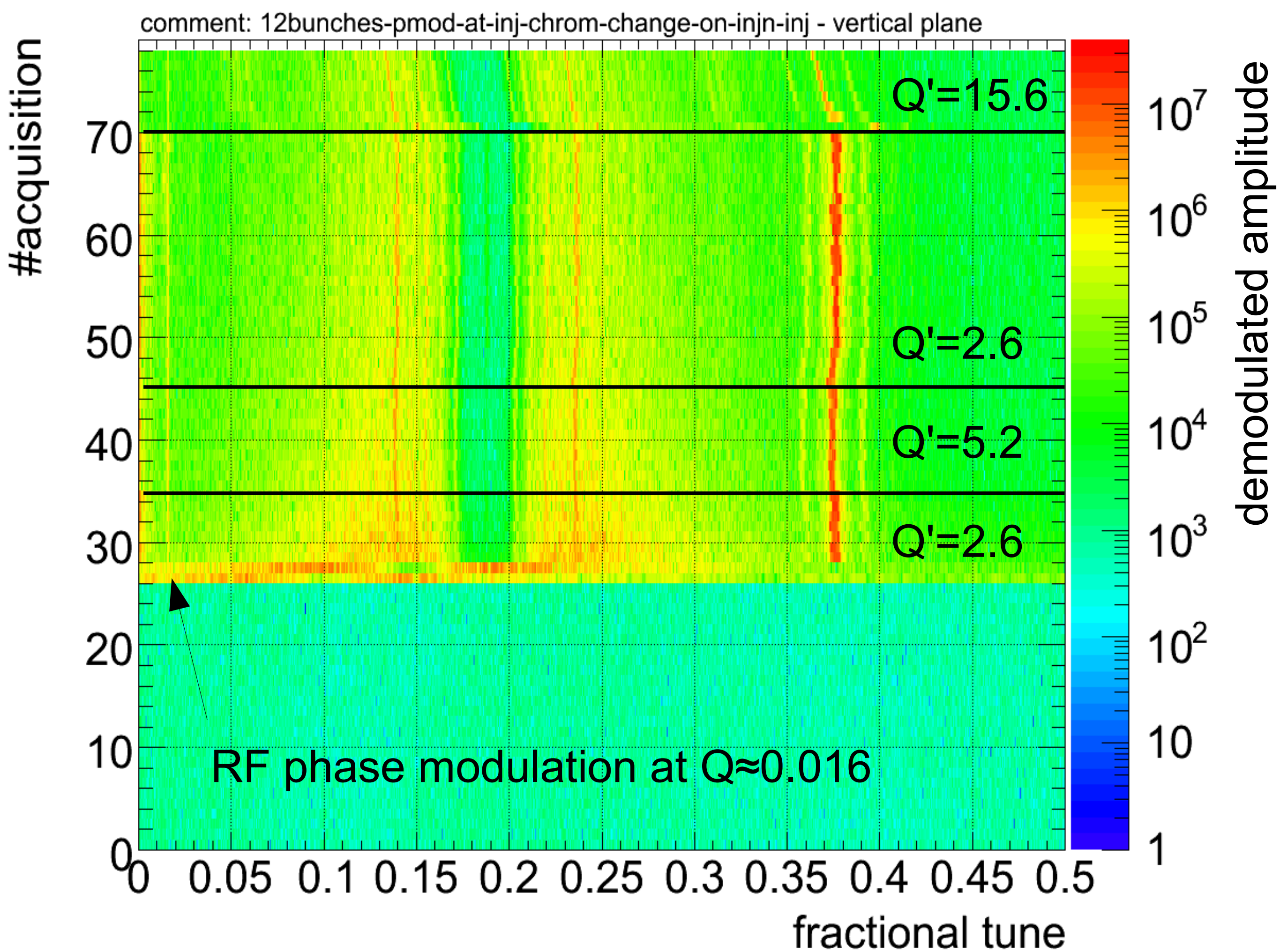
- Initial Chromaticity setting was $\xi_{H/V}$= 0.1 ($Q'_{H/V} \approx 2.7$, $\Delta Q'_{err}<1$)
  - static chromaticity bumps during the injection plateau (26GeV)
  - varied the chromaticity a flat top (450GeV) up to $\xi_{H/V}$= 0.9



  - absence/not using of transverse damper required large Q' during ramp

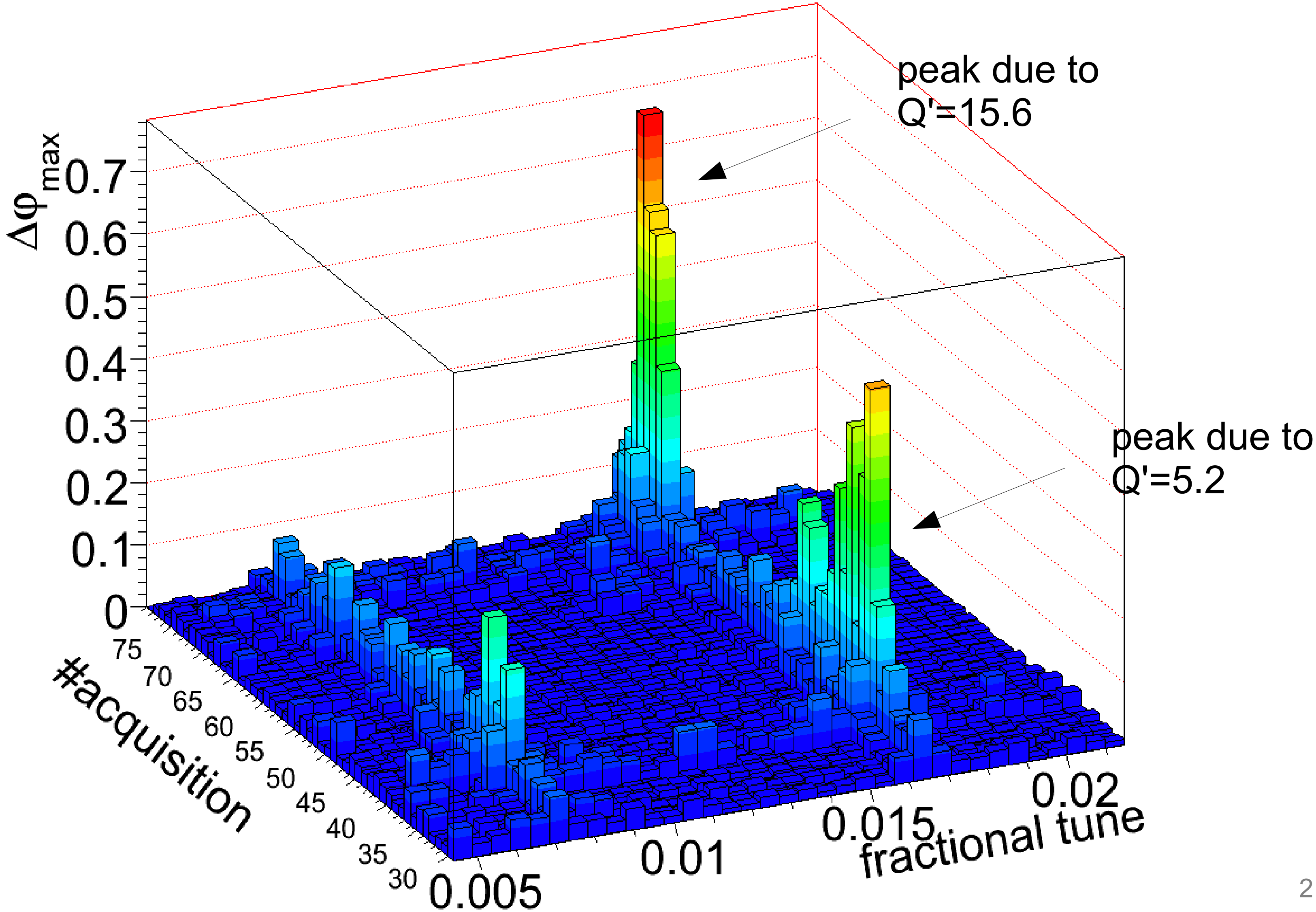
McGinnis Method I/IV

- Modulated RF frequency at 700 Hz, $\Delta\varphi_{RF} \approx 5°$
  - demodulated amplitude ~ chromaticity



McGinnis Method II/IV

- Visible but modest signal

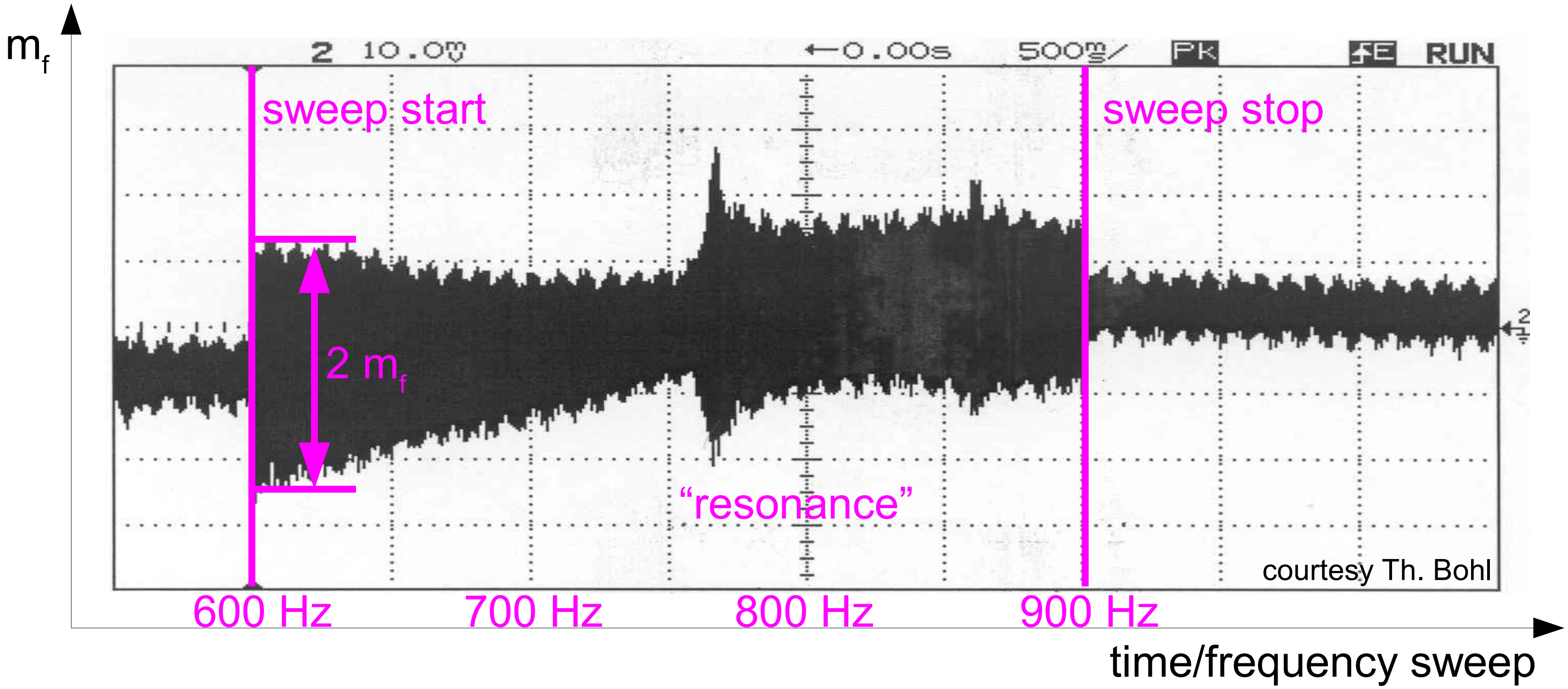


McGinnis Method III/IV

- Calibration of effective phase modulation m_f at high frequency depends on the superimposition of RF cavity and beam response:

$$e = a \cdot \sin(\omega_0 t + m_f \cdot \sin(\omega_{mod} t)) \quad with \quad m_f = \frac{\Delta f}{f_{mod}}$$

  – SPS tests: f_{mod}=700 → Δf ≈ 10...15 Hz



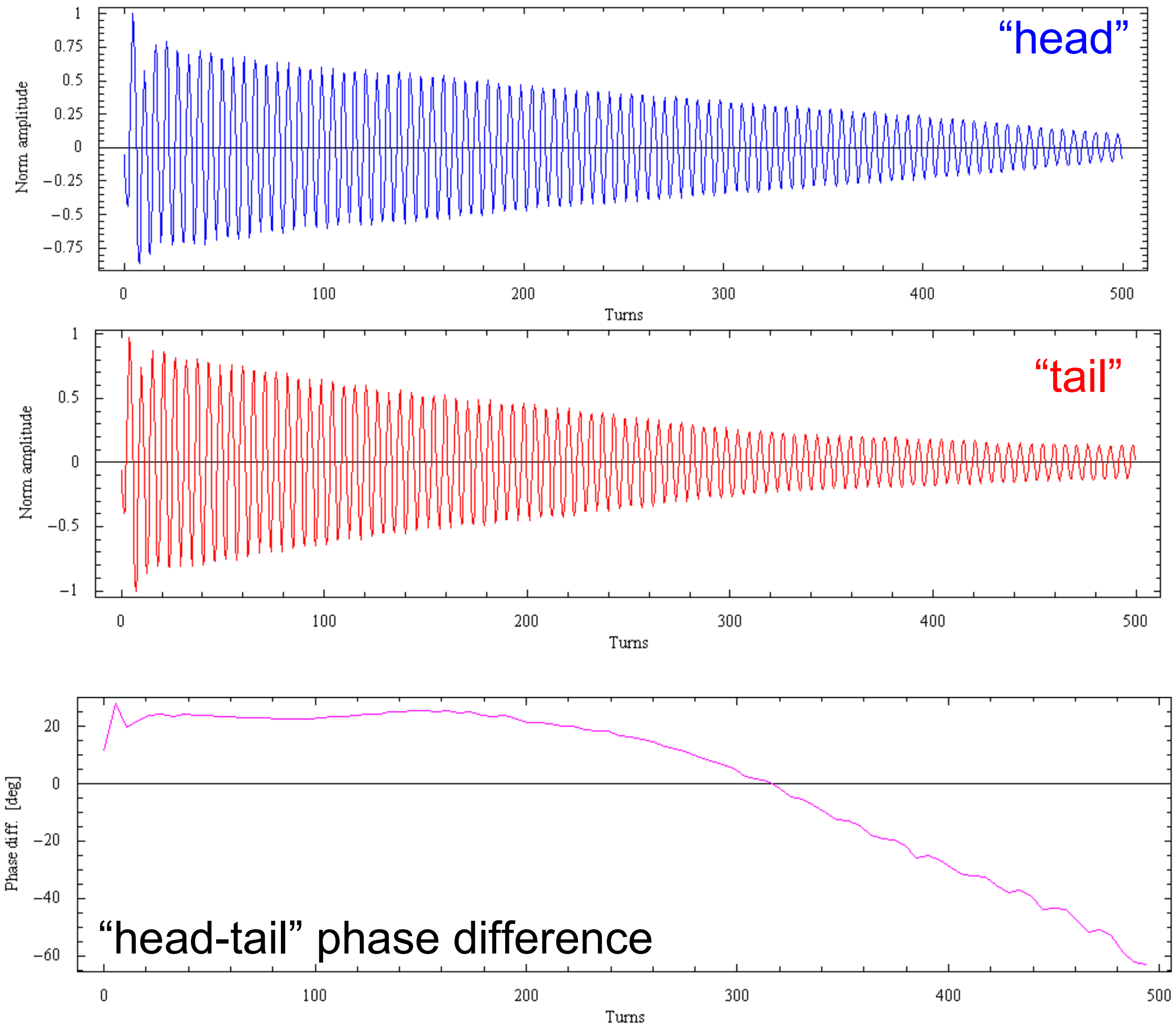
McGinnis Method IV/IV

- McGinnis method proved to be feasible after fixing a “data reconstruction bug”

- Some observations in the SPS:
  - minimal longitudinal emittance blow-up - good
  - no cross-talk w.r.t. longitudinal damper - good
  - However: Cross-talk between transverse damper - can be fixed
    - Result of phase modulation on global RF reference
  - Similar Q' resolution as for slow RF modulation - soso
    - possibly: requires more stable tune and high precision tune tracking
  - $\Delta\varphi \approx 0.1° \leftrightarrow \Delta p/p \approx 1.2 \cdot 10^{-4}$
    - LHC: max allowed RF phase modulation $\Delta\varphi \approx 0.4°$ ($\leftrightarrow \Delta p/p \approx 10^{-4}$)
    - may require large RF power due to high Q of cavities
- Will repeat the measurement with “real” coasting beam

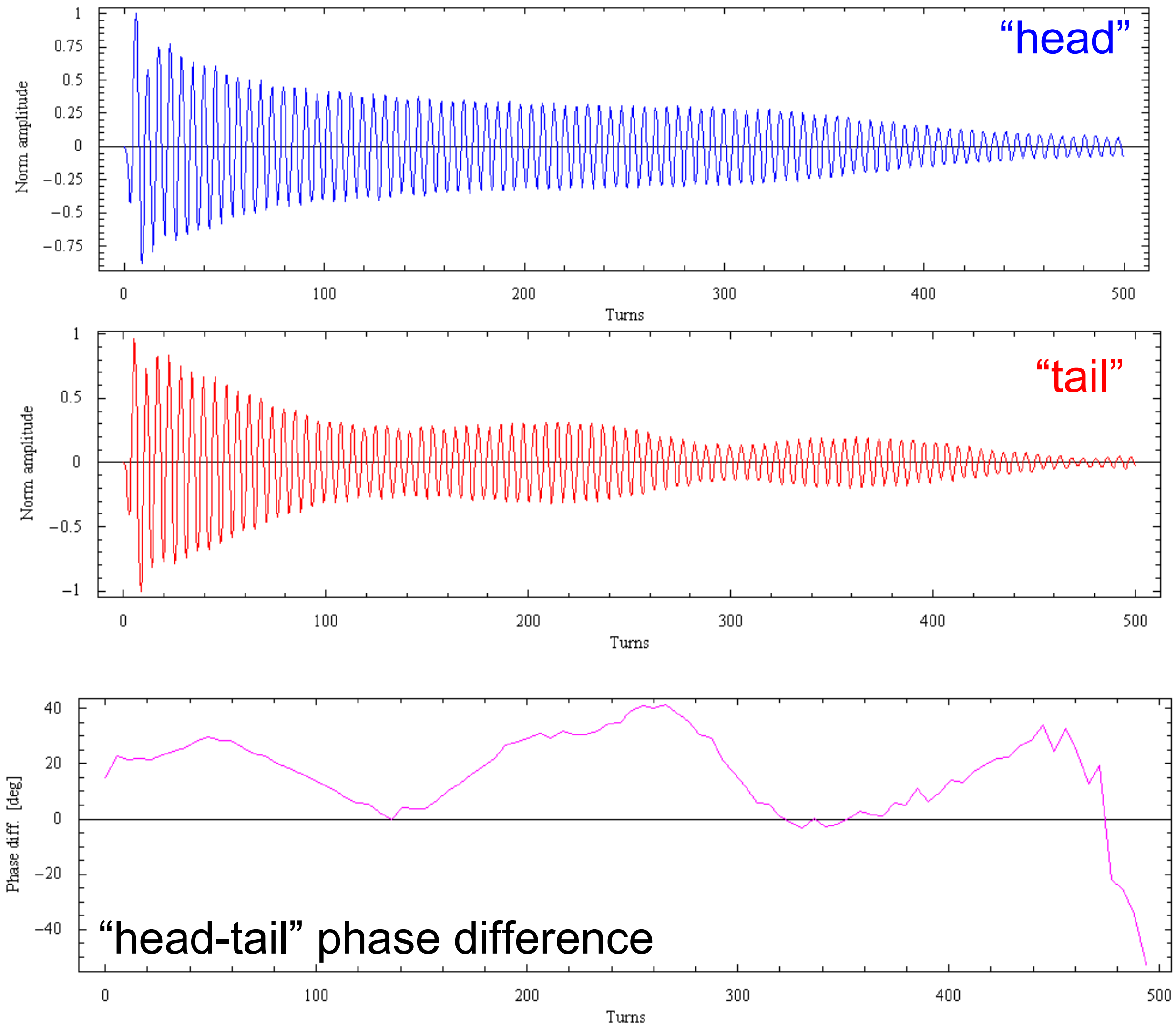
BBQ based head-tail Measurement I/II

- 2KV kick @ 270GeV, Q'≈2.6



BBQ based head-tail Measurement II/II

- 2KV kick @ 270GeV, Q'≈10.5



MD Summary I/II

- The prototype test of the BBQ based tune PLL were very successful!
- Mutually exclusive modes of PLL operation:
  - either: track tune changes during the SPS ramp with $\Delta Q/\Delta t \approx 0.1/s$
  - or: achievable tune resolution $\Delta Q_{res} \approx 10^{-4} \ldots 10^{-5}$
- Required PLL excitation was very low
  - at least a factor 10 smaller than standard SPS MultiQ
  - measurements were done with a S/N ratio of less than 3..10dB
- BBQ based PLL showed to be very robust as long as:
  - the excitation level is above the noise floor (no mains problem)
  - bunch-to-bunch coupling was small
    - IMHO: should be addressed through selecting only single bunch

MD Summary II/II

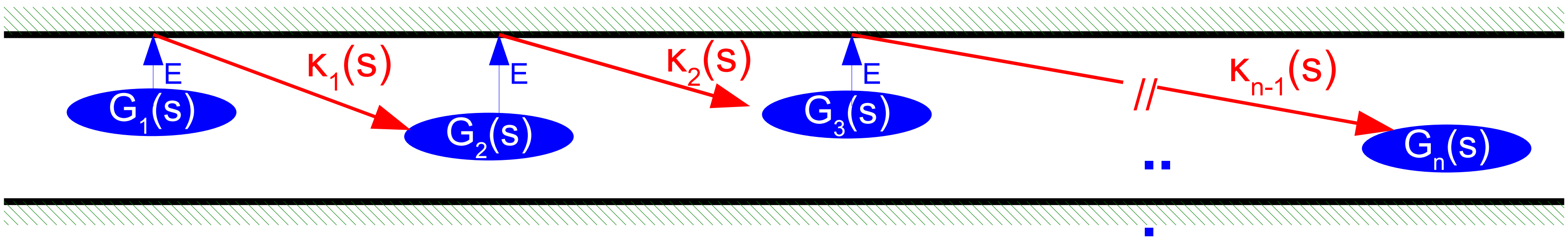
- Some preliminary comments on tested chromaticity measurement methods:
  - Slow $\Delta p/p$ modulation:
    - works but requires fairly stable tune and demanding tune measurement resolution for nominal operation
  - Fast $\Delta p/p$ modulation (McGinnis, Brüning, ...):
    - Q' resolution similar to slow modulation
  - BBQ based Head-tail method:
    - results not conclusive, require further studies

- Question is not: “Can we measure chromaticity?”
- But: “Can we measure Q' with a given precision and minimal excitation?”
  - Test at SPS are limited cycle length, systematic Q/Q' changes and rare costing beams
  - Require studies of systematics at “slow” machines such as RHIC to prove feasibility of LHC Q' baseline ($\Delta Q'=1$ & $\Delta p/p \ll 10^{-4}$)

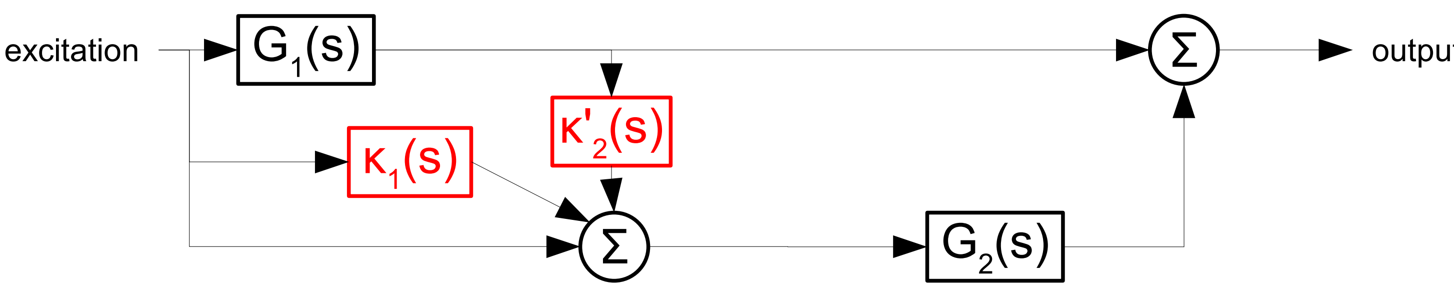
reserve slides

Coupled Bunch Instabilities

- Coupled bunch effect became more pronounced during later MDs
  - possible causes: impedance driven wake fields, e-cloud, ...

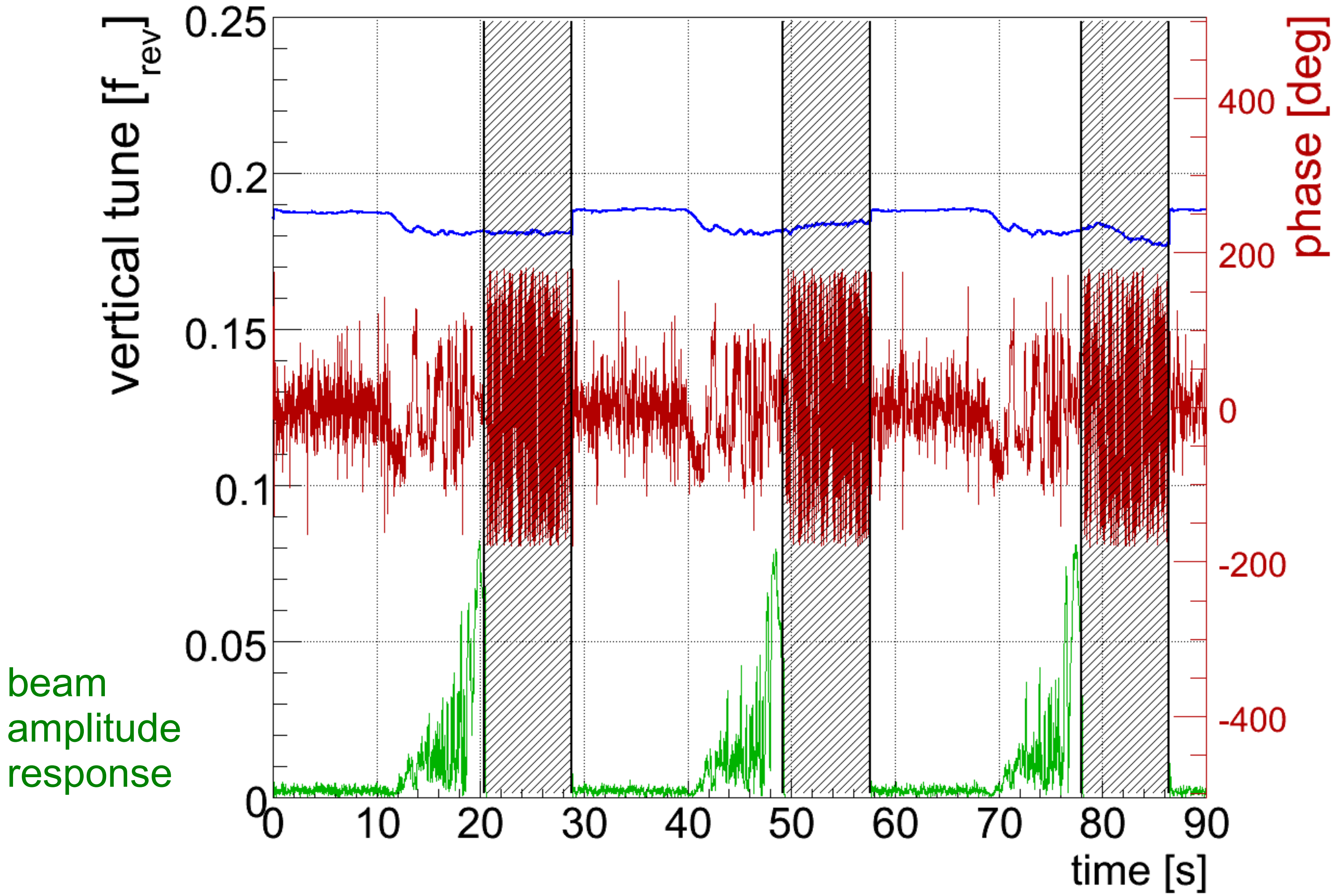


- Phase response can be explained by simple first order model:
  - e.g. classic Landau resonator $G_n(s)$ and first order coupling $K_n(s)$
  - example: two coupled bunches



- Possible remedy: BBQ selects and measures only one (first) bunch

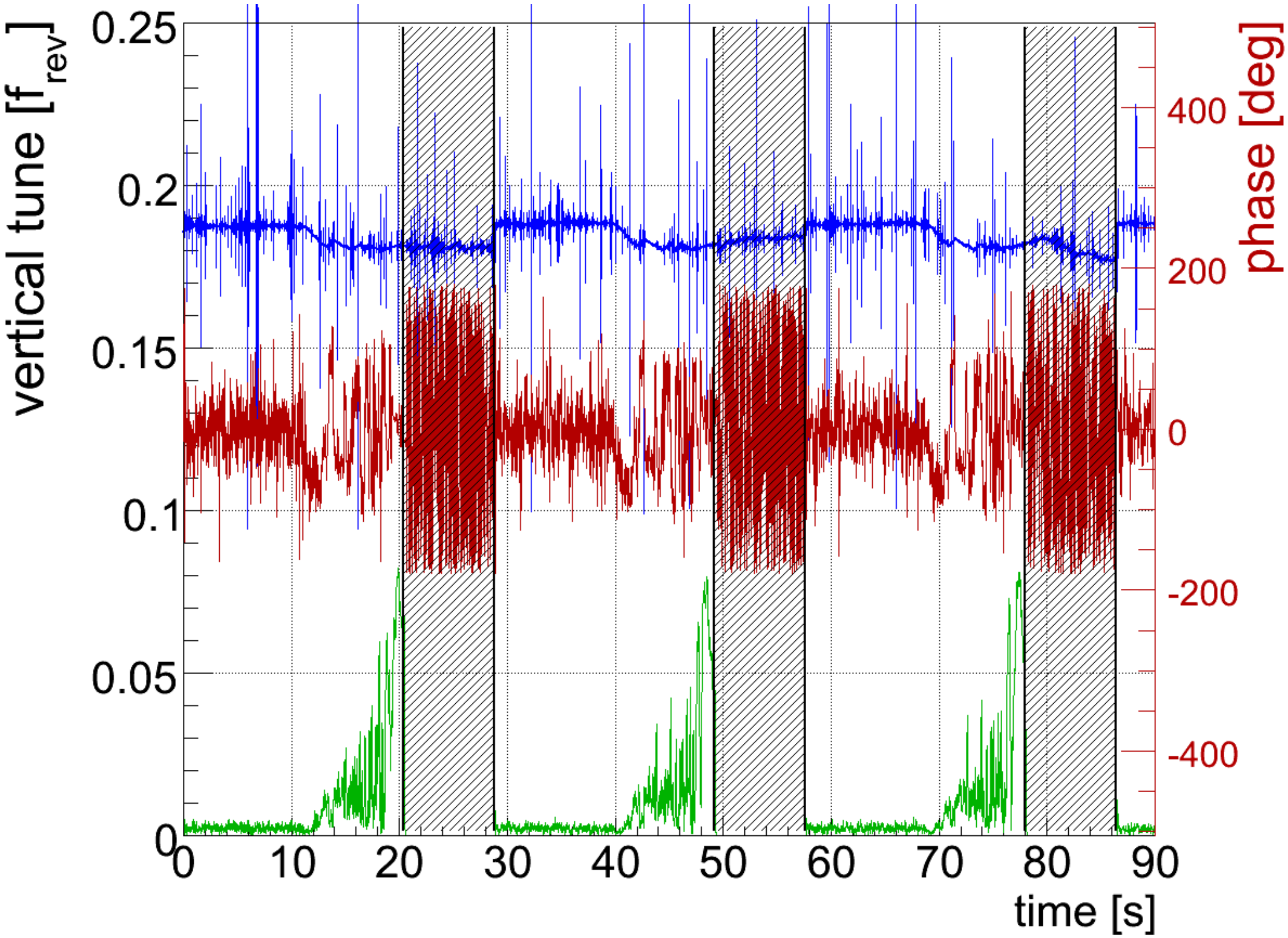
PLL Measurement Resolution I/II



- change of beam response amplitude indicates changing chromaticity
  - showed later to be cause for instabilities during the ramp

PLL Measurement Resolution I/II

- Phase can be used as an estimate for tracking error (for a given chromaticity)

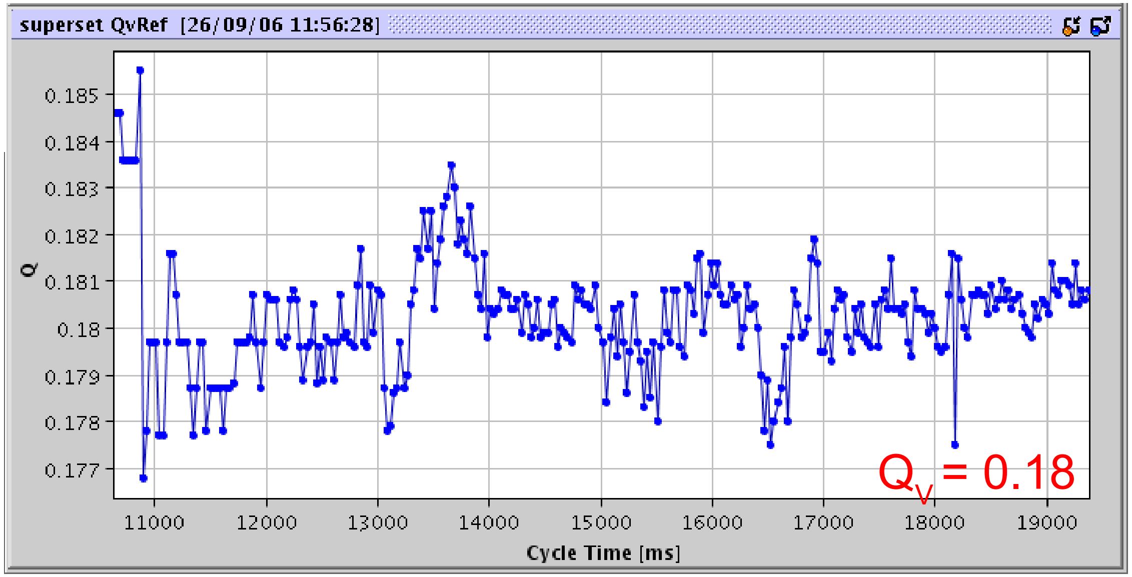


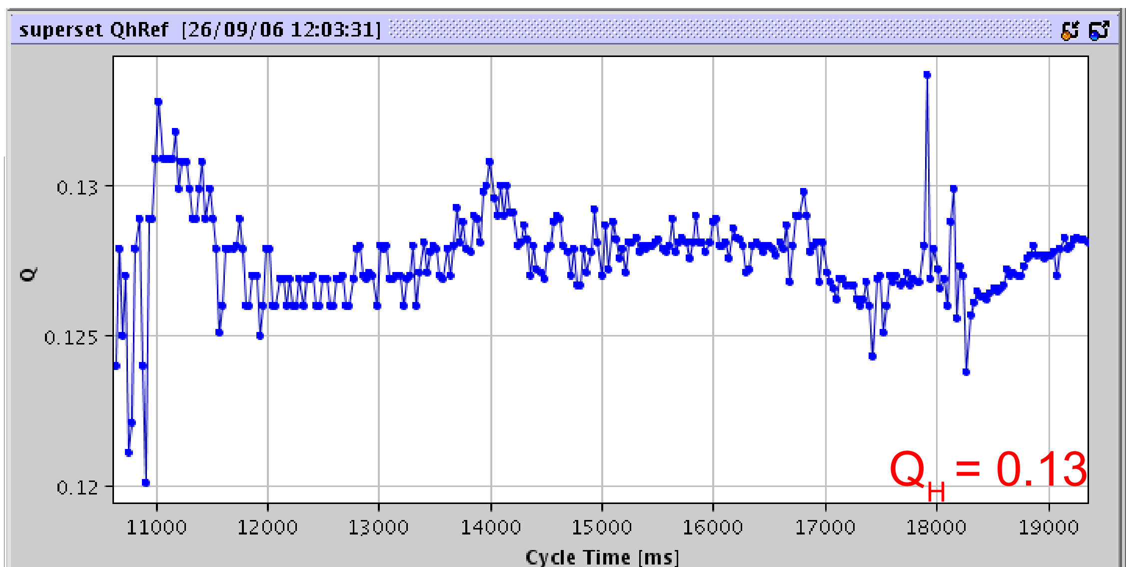
- After some spike filter routine: $\Delta Q_{res} \approx 10^{-4} - 10^{-5}$ @ 10 Hz

(compare traditional kick + FFT yields usually $\Delta Q_{res} \approx 10^{-3}$)

Measurement Methodology I/III

- Tune reference measurements (MultiQ) – (zoom in ramp):

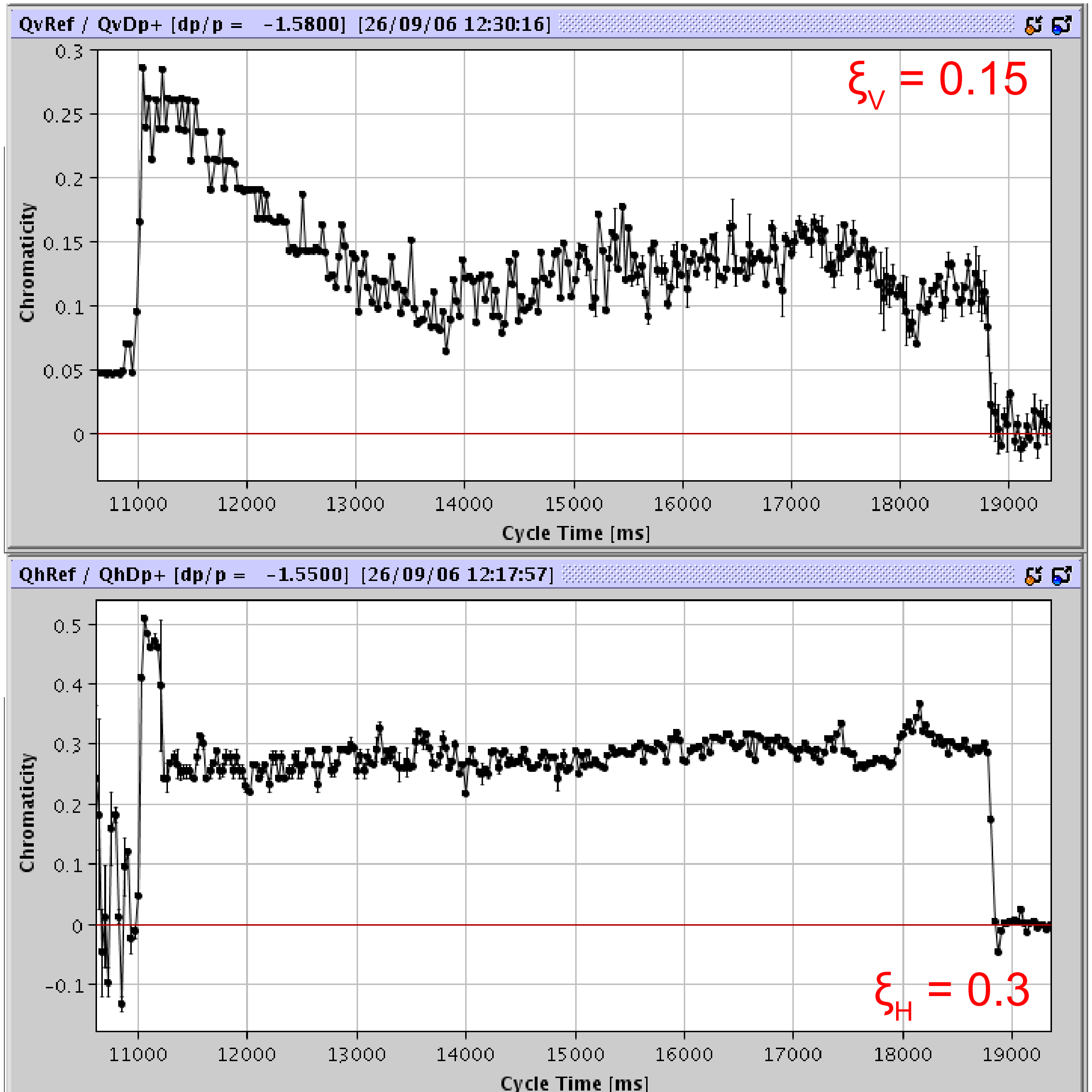




- Slow variation of Q
- $\Delta Q_{res} \approx 10^{-3}$ visible

Measurement Methodology II/III

- Chromaticity Reference Measurement during ramp (slow Δp/p + MultiQ):



- Injecition: Q'≈2
- ΔQ_{res} (~ΔQ_{res}) visible
- $\Delta p/p \approx 1.6 \cdot 10^{-3}$