First Results of the PLL Tune Tracking in the SPS

Ralph J. Steinhagen

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LHC Tune and Chromaticity Requirements

- The measurement and control of

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

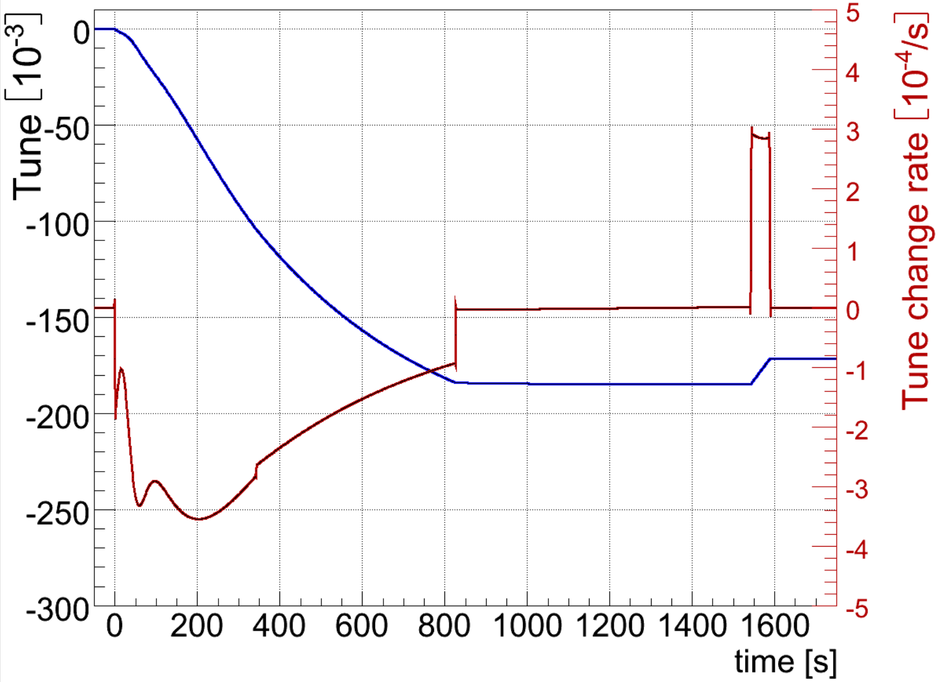
  will be an integral part of the LHC operation

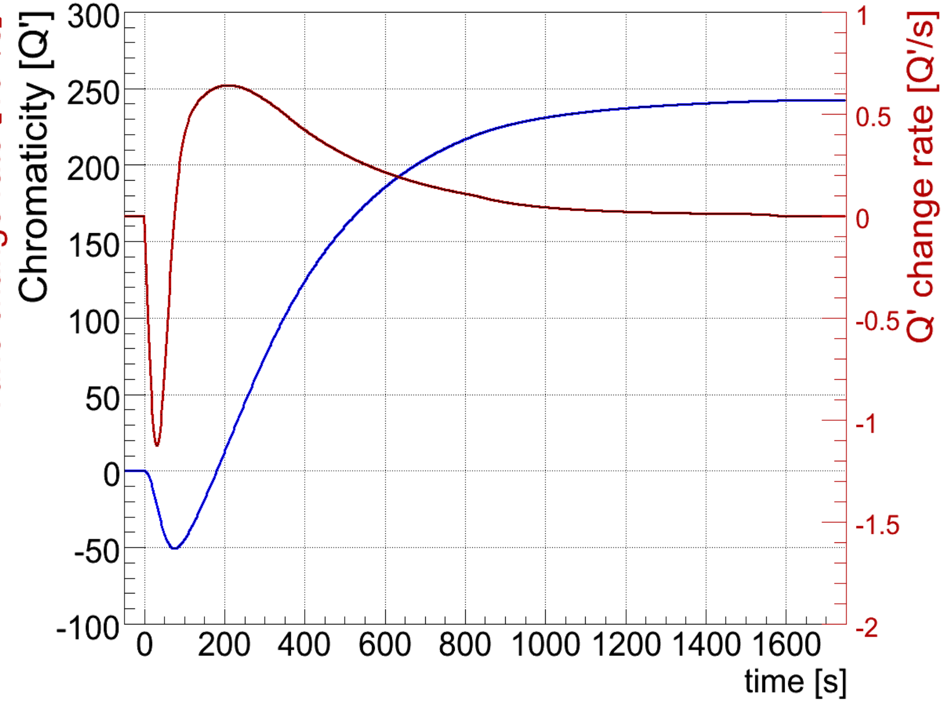
- Requirements summary:

	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!

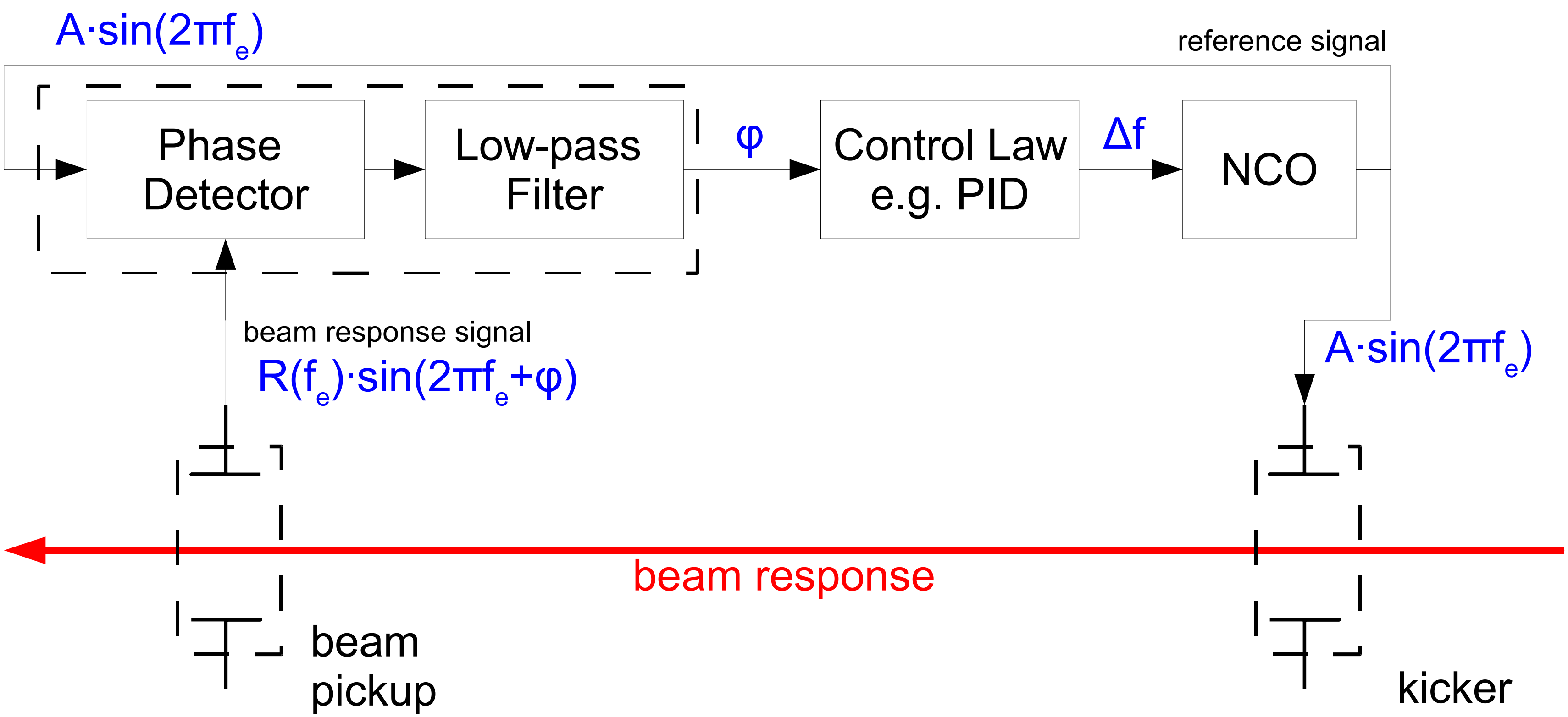
Expected Tune and Chromaticity Drifts during LHC ramp





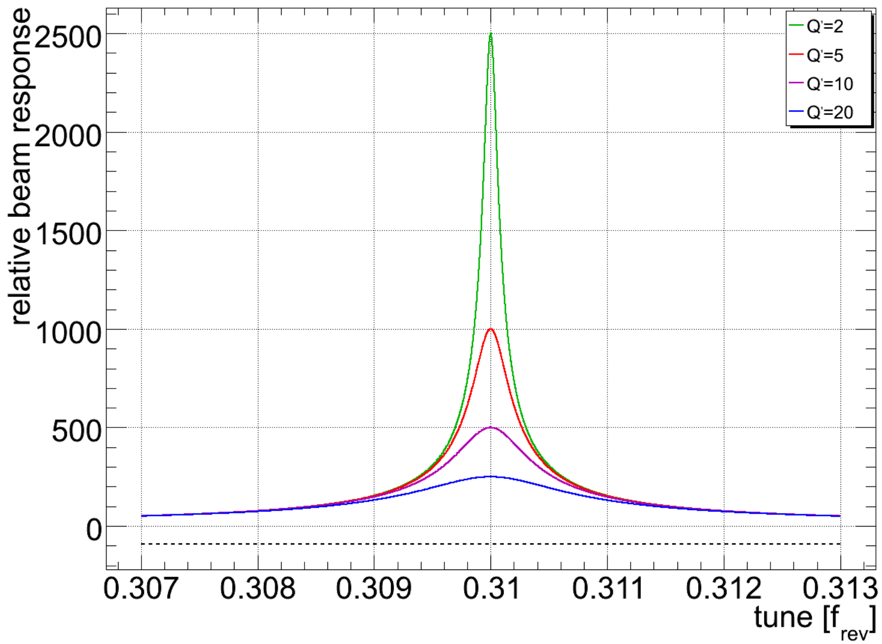
- Exp. perturbations are about 200 times than required stability!
- however: maximum drift rates are expected to be slow in the LHC
  - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
  - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2\ s^{-1}$
- Requires active control relying on beam-based measurements

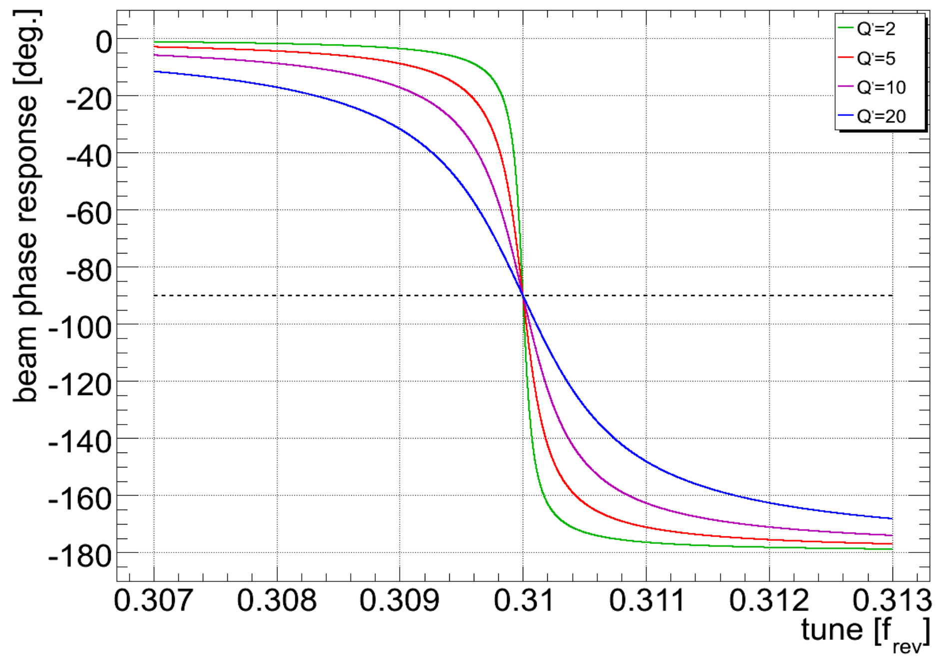
Basic Phase Locked Loop in a Slide



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

PLL Beam Response

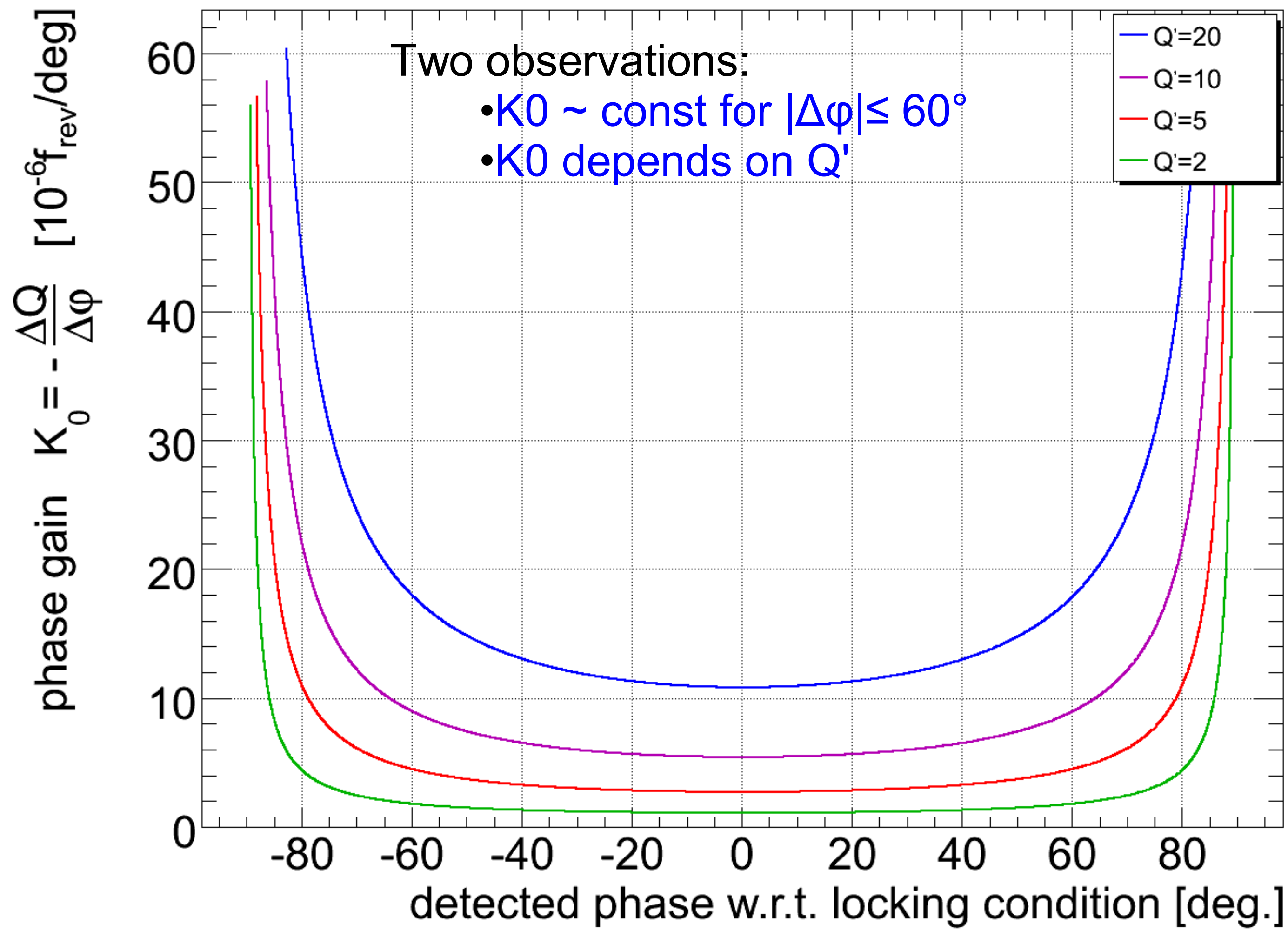




- In addition to the tune, the beam response also depends on the chromaticity
  - small chromaticity: sharp peak/phase transition
  - large chromaticity: sharp peak/phase transition

- This dependence can also be exploited to measure chromaticity:
  - two additional side exciter with constant frequency offset w.r.t. tune
  - measure small phase difference (order of a degree)

- The PLL can be split in first order into two parts:
  - PLL low-pass filter: → PI gains K_p & K_i
  - beam response: → loop gain K_0



Quick PI(D) controller gain HOWTO II/II

- PLL low-pass:

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

- Youla's affine parameterisation for stable plants:

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

- Using the following ansatz

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

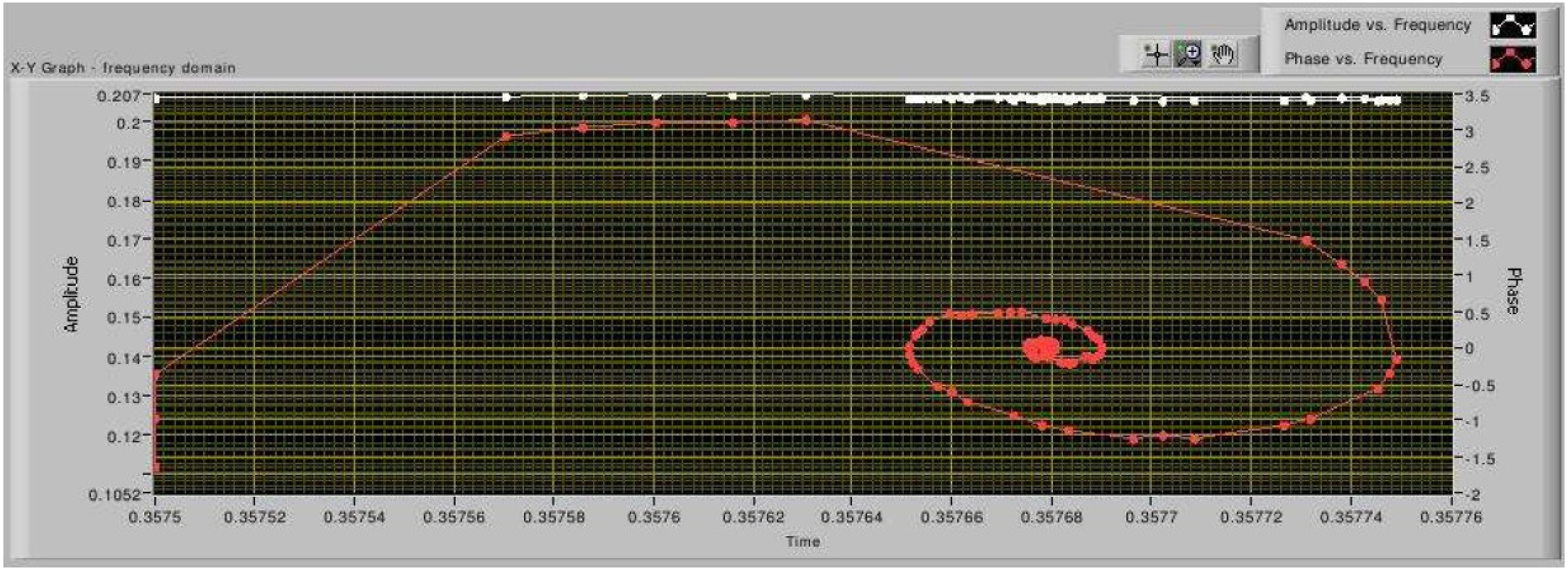
- (1)+(2)+(3) yields:

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

- parameter $\alpha > \tau \ldots \infty$ moderates closed loop response between:
  - fast and less accurate tracking vs. slow and more accurate tracking

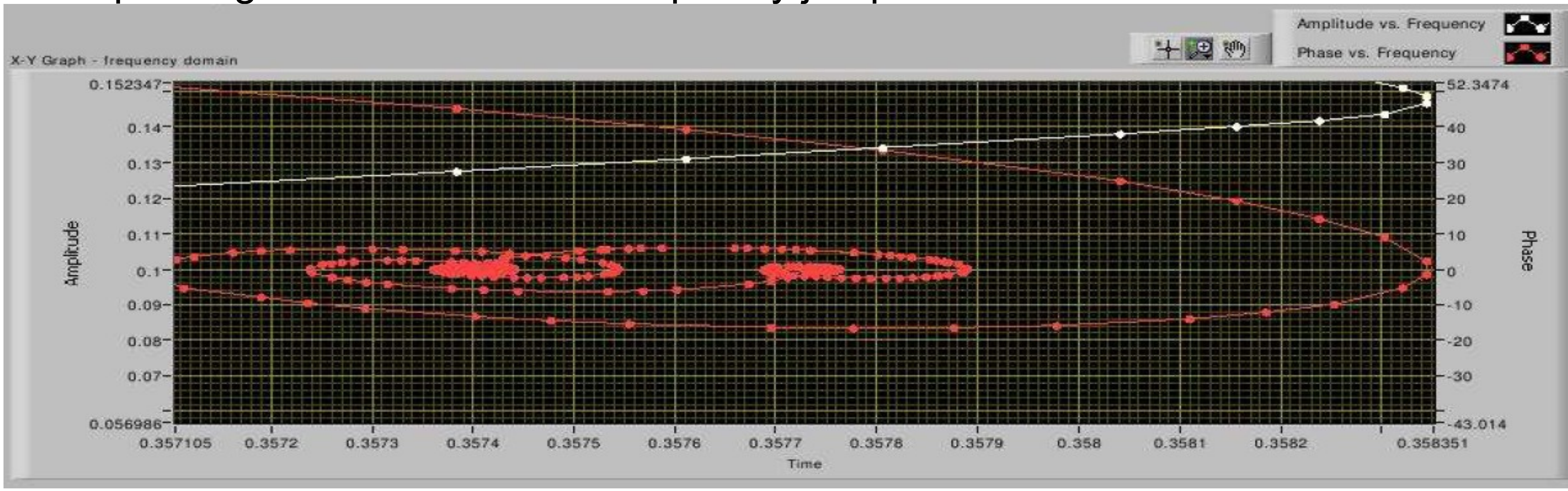
Krzysztof's presentation:
“Tracking on the Bench”

- Phase of the tune tracker as it spirals into lock

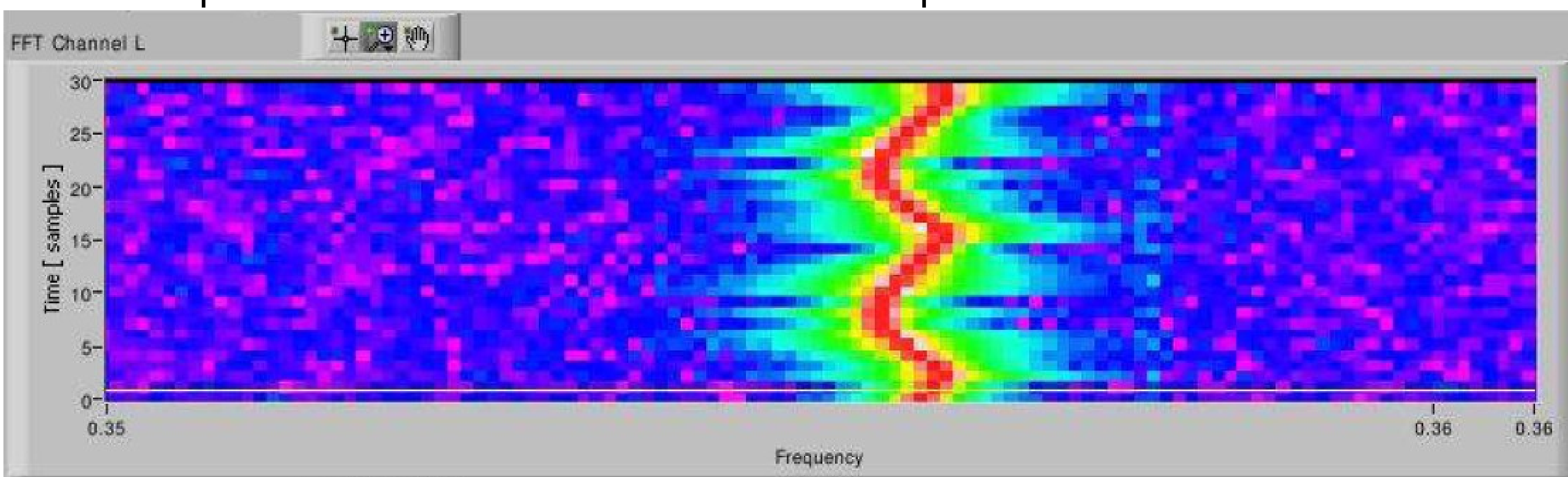


Tracking on the Bench I/III

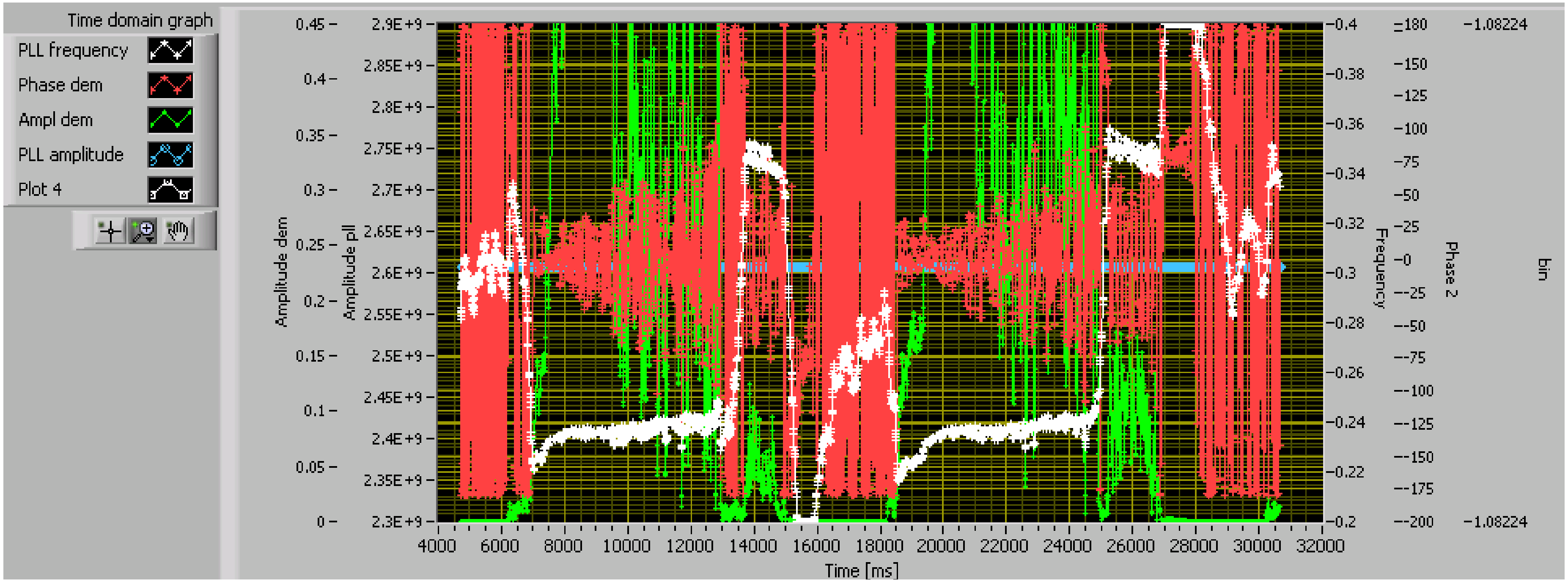
- Spiralling in when there is a frequency jump in the resonance



- Temporal evolution of the individual FFT acquisition:



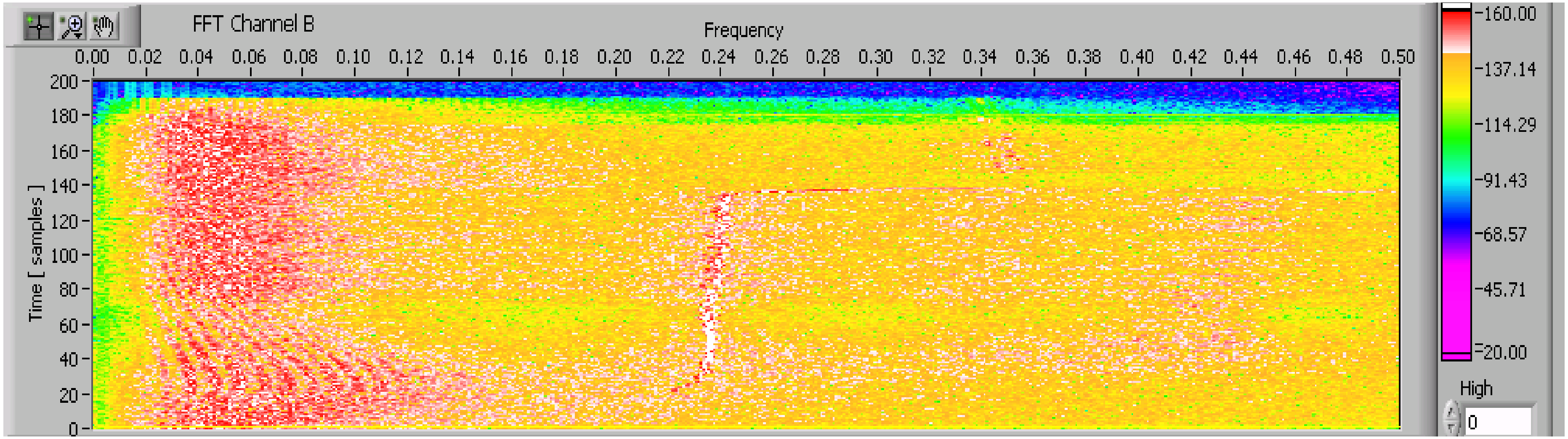
21 September 2006: First successful BBQ based PLL



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

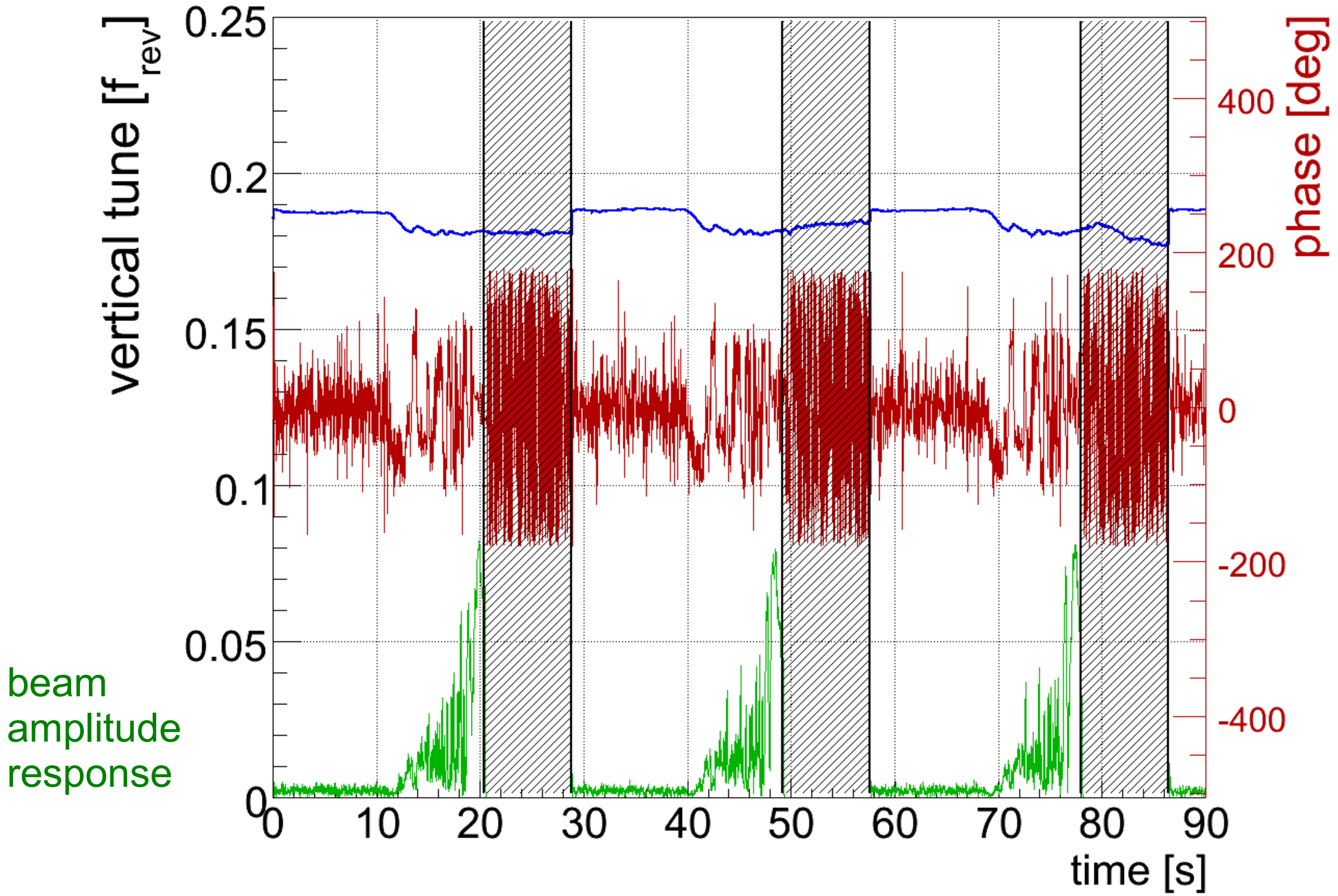
BBQ based Tune Tracking

- Temporal evolution of the individual FFT acquisition:



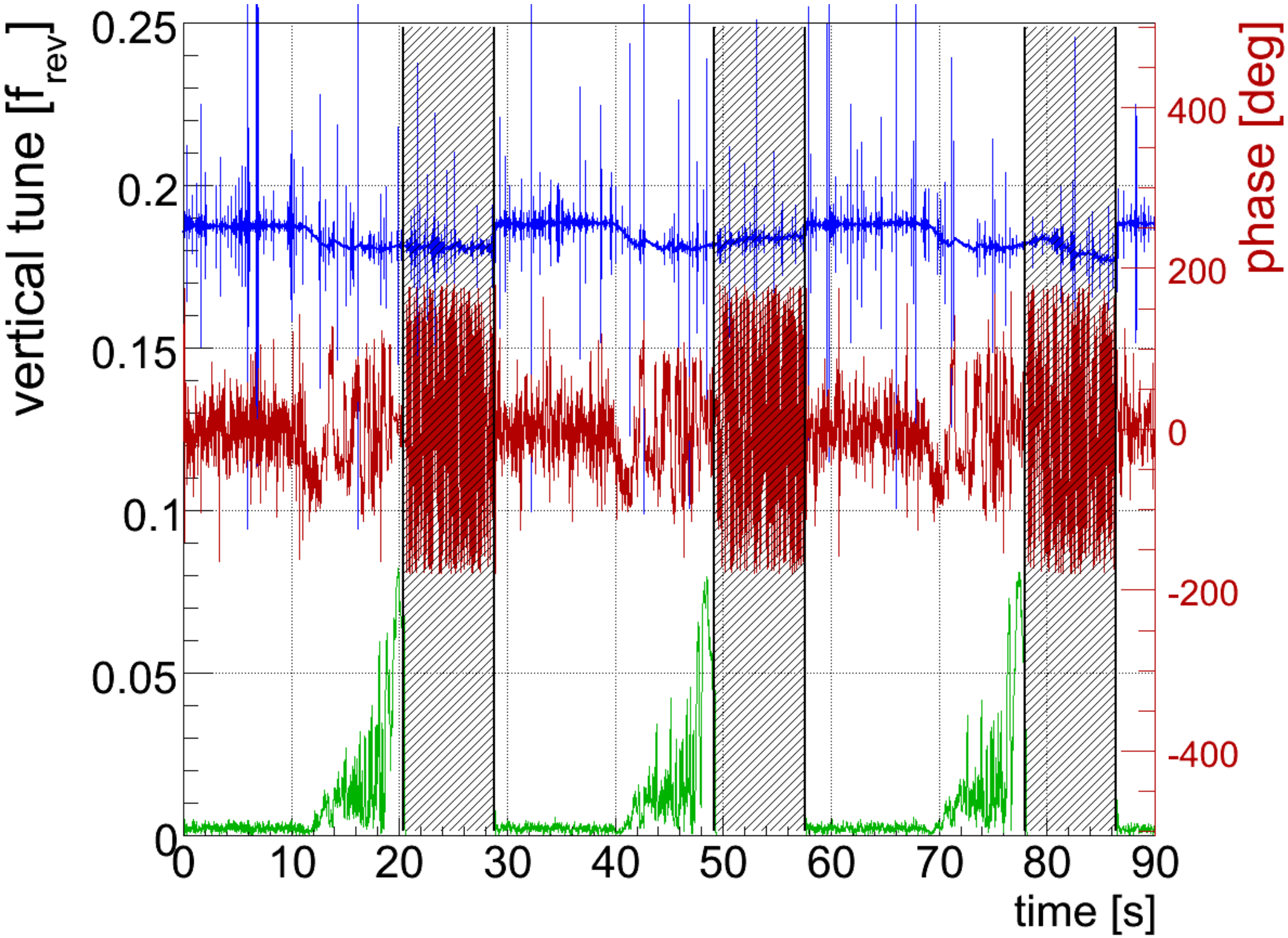
- Tune resolution:
  - FFT based (1024 turns): $\Delta Q_{res} \approx 10^{-3}$
  - PLL based: $\Delta Q_{res} \ll 10^{-4}\text{-}10^{-5}$
    - limited by underlying tune stability → SPS is a tough testbed
    - excitation below the 1 µm level (factor 10++ below MultiQ Settings)
      - negligible/no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

A Brief Comment on the Measurement Resolution I/II



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

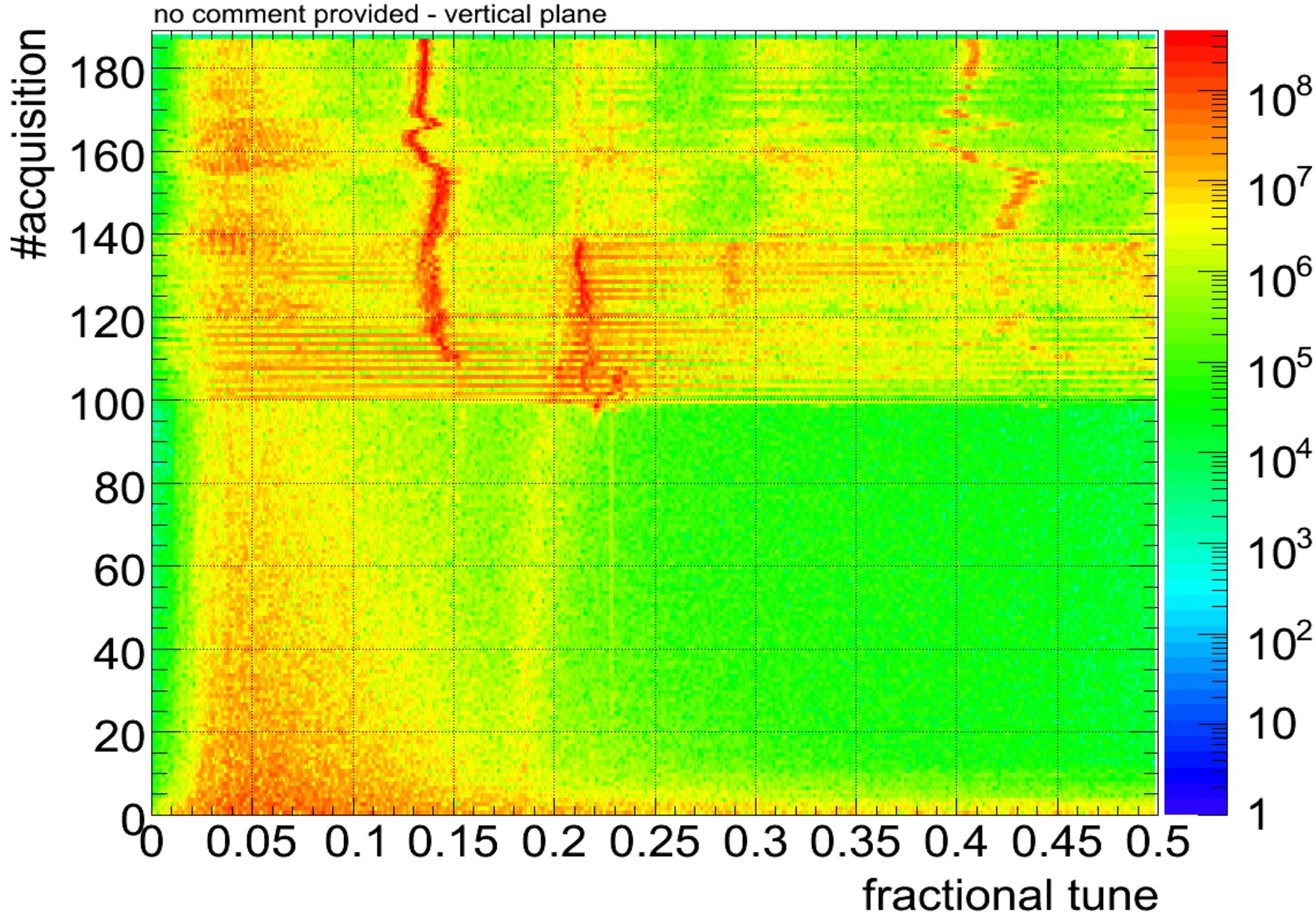
- Phase can be used as an estimate for tracking error (for a given chromaticity)



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

Some notes on BBQ measurment

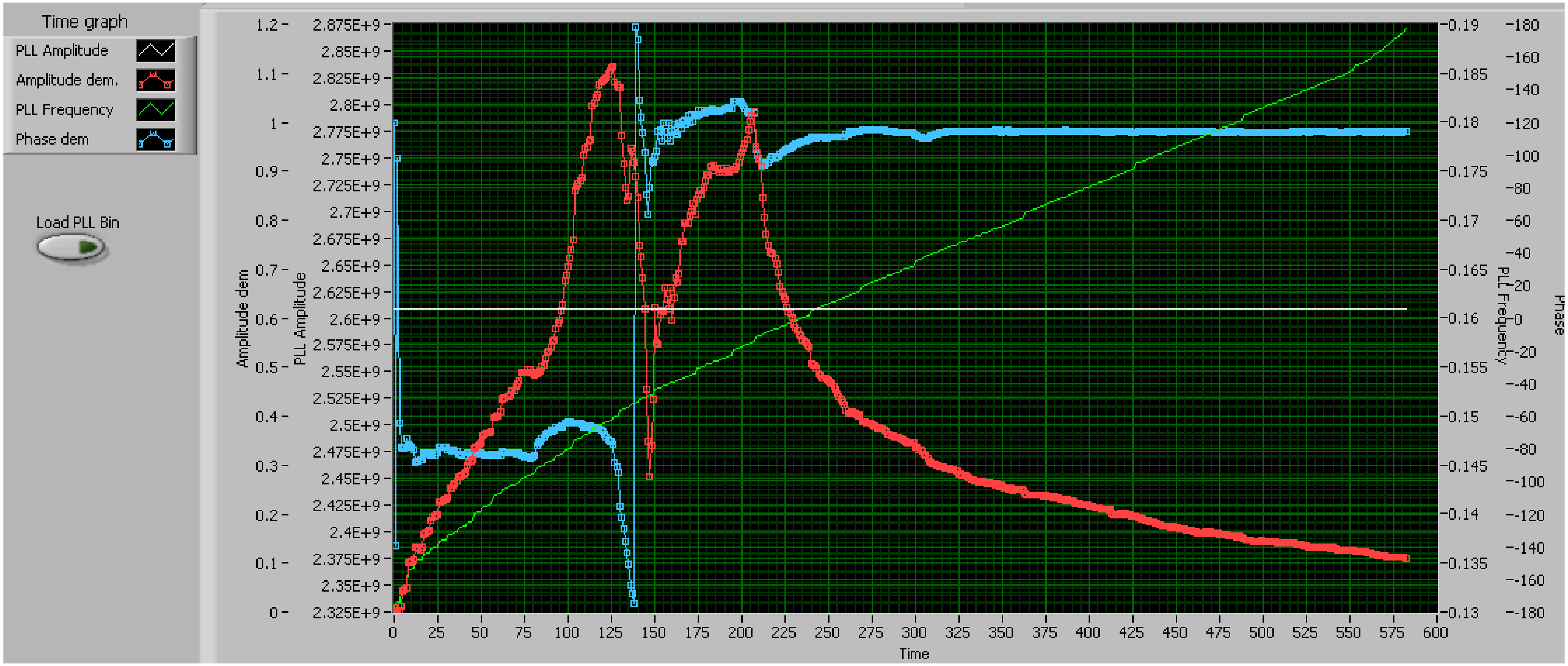
- BBQ impresses with incredible sensitivity w.r.t. to oscillations
- This year we got swamped with large residual (tune) oscillation



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

Some "unexpected" Beam Response I/II

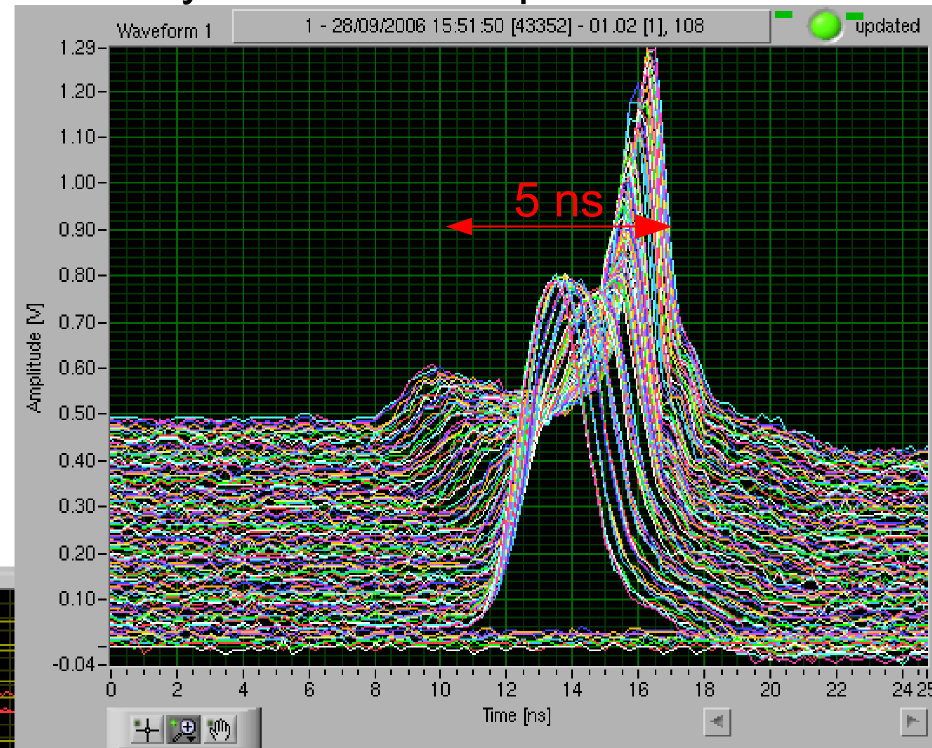
- Broke the PLL due to change of beam response (red), particularly the phase advance (turquoise):

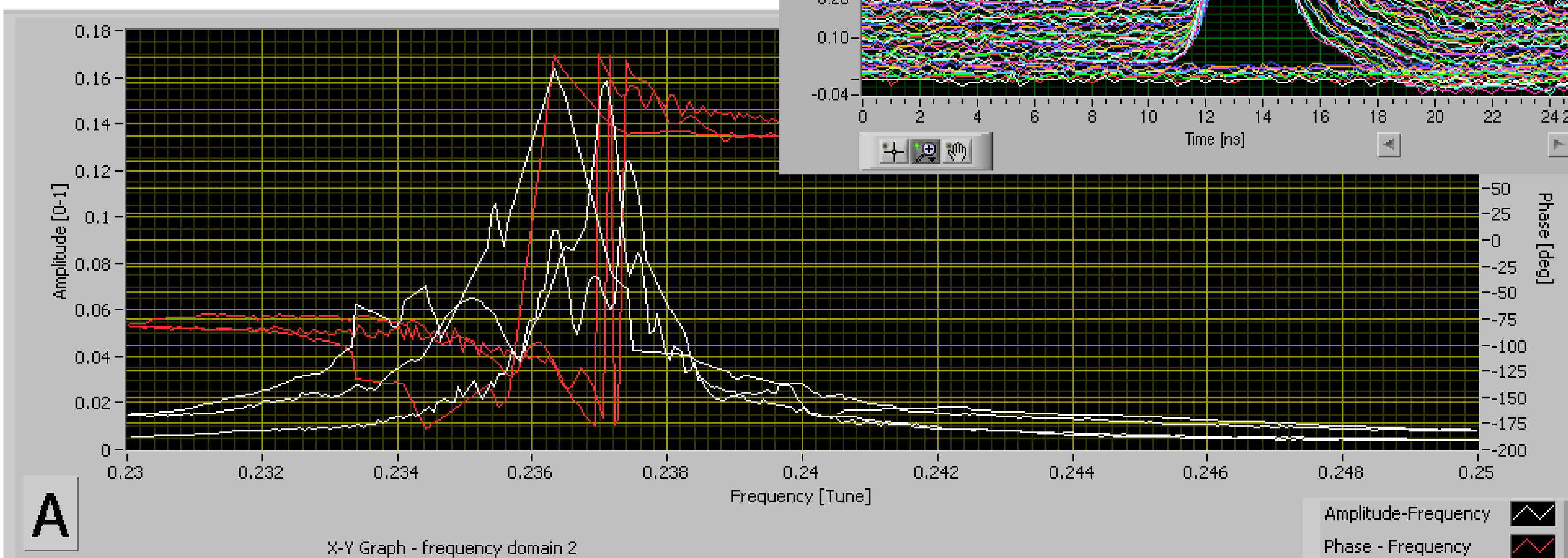


- ....gave food for thought (new physics, ...)

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!





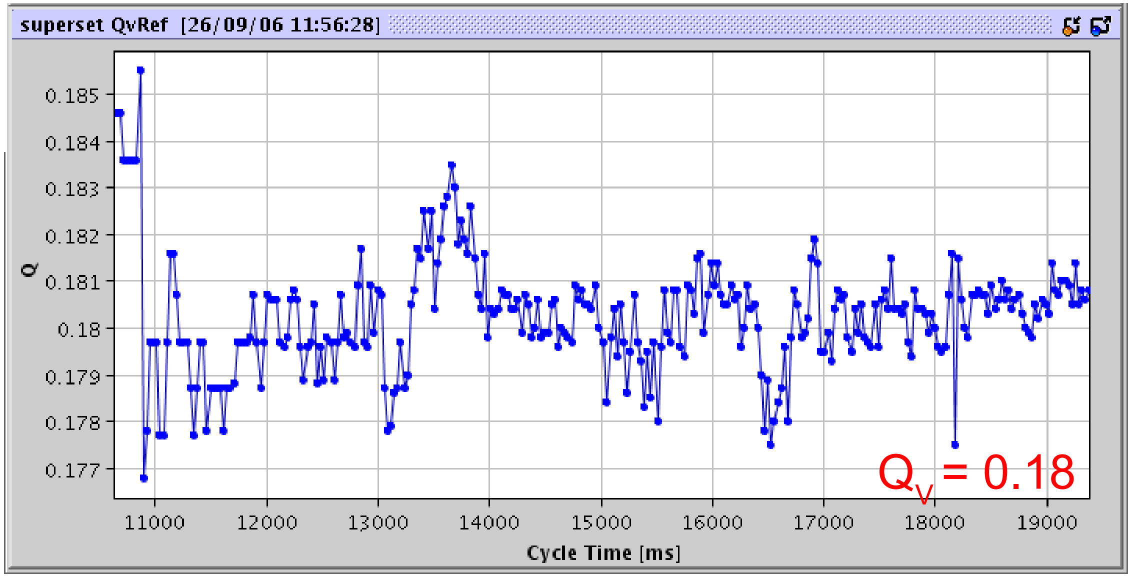
SPS long MD on 27th of September 2006

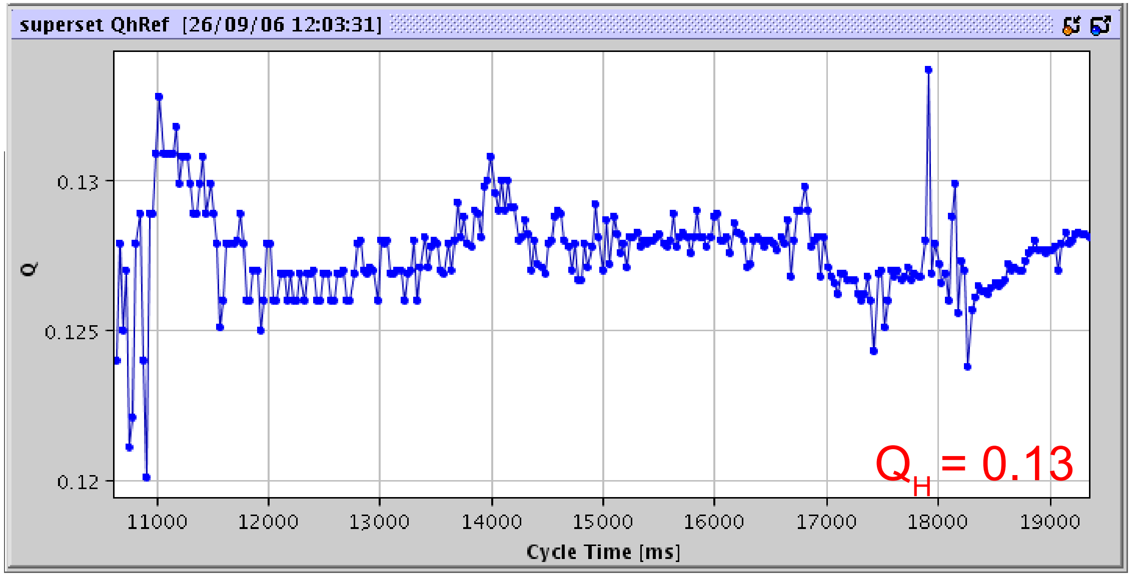
Tried to evaluate several chromaticity measurement methods:

- slow RF frequency modulation + tune tracking (PLL & MultiQ = reference)
- fast RF phase modulation @ ~ 700 Hz (McGinnis method)
  - demodulate the RF phase modulation w.r.t. locked tune
- Head-Tail methods
  - strong kick + fast sampling oscilloscopes connected to a strip-line BPM
  - ~~weak kick + BBQ connected to a button BPM~~ (not successful)
  - weak kick + BBQ connected to a strip-line BPM (to be tested)
  - continuous excitation (to be tested)
- Two-Side-Exciter method: to be tested

Measurement Methodology I/III

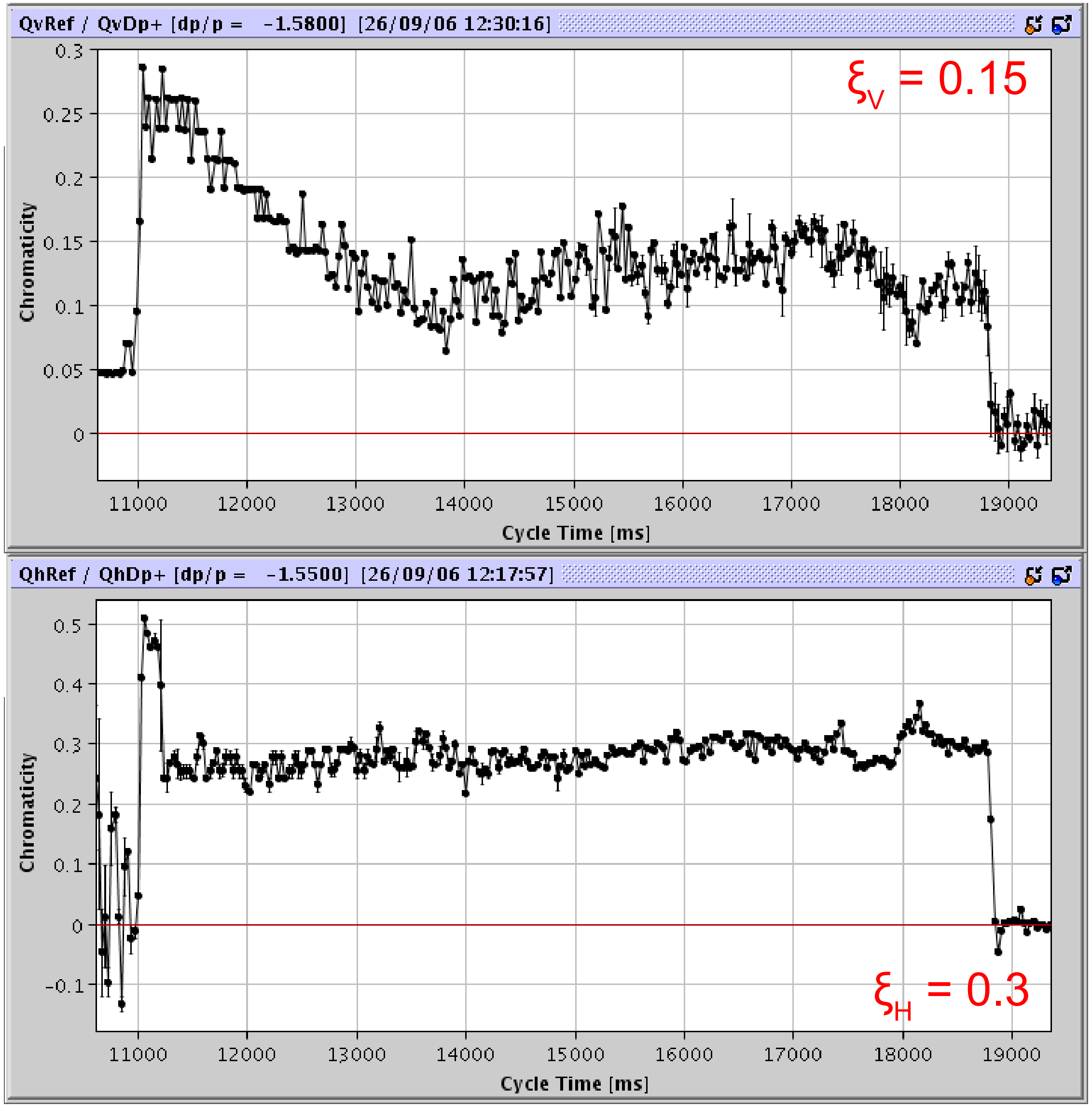
- Tune reference measurements (MultiQ):



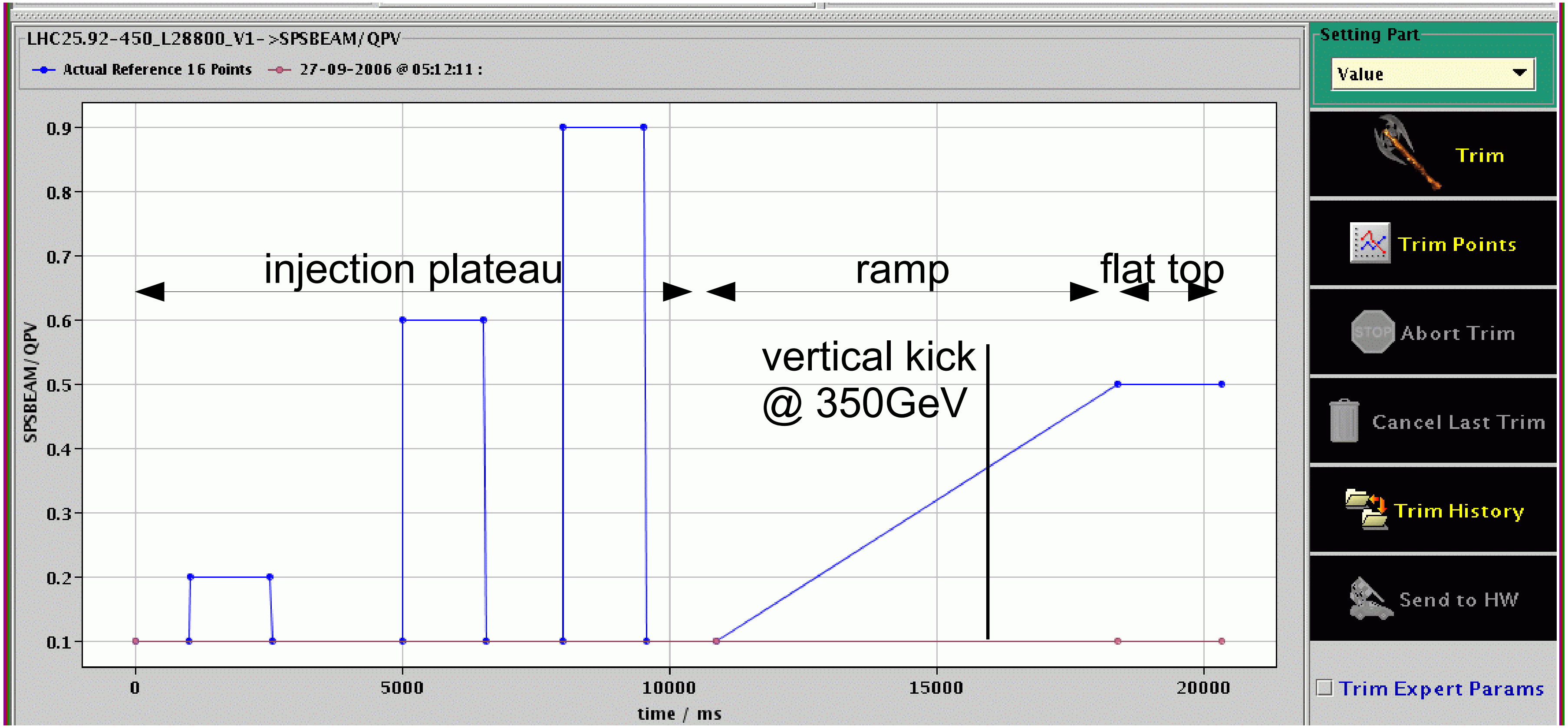


Measurement Methodology II/III

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



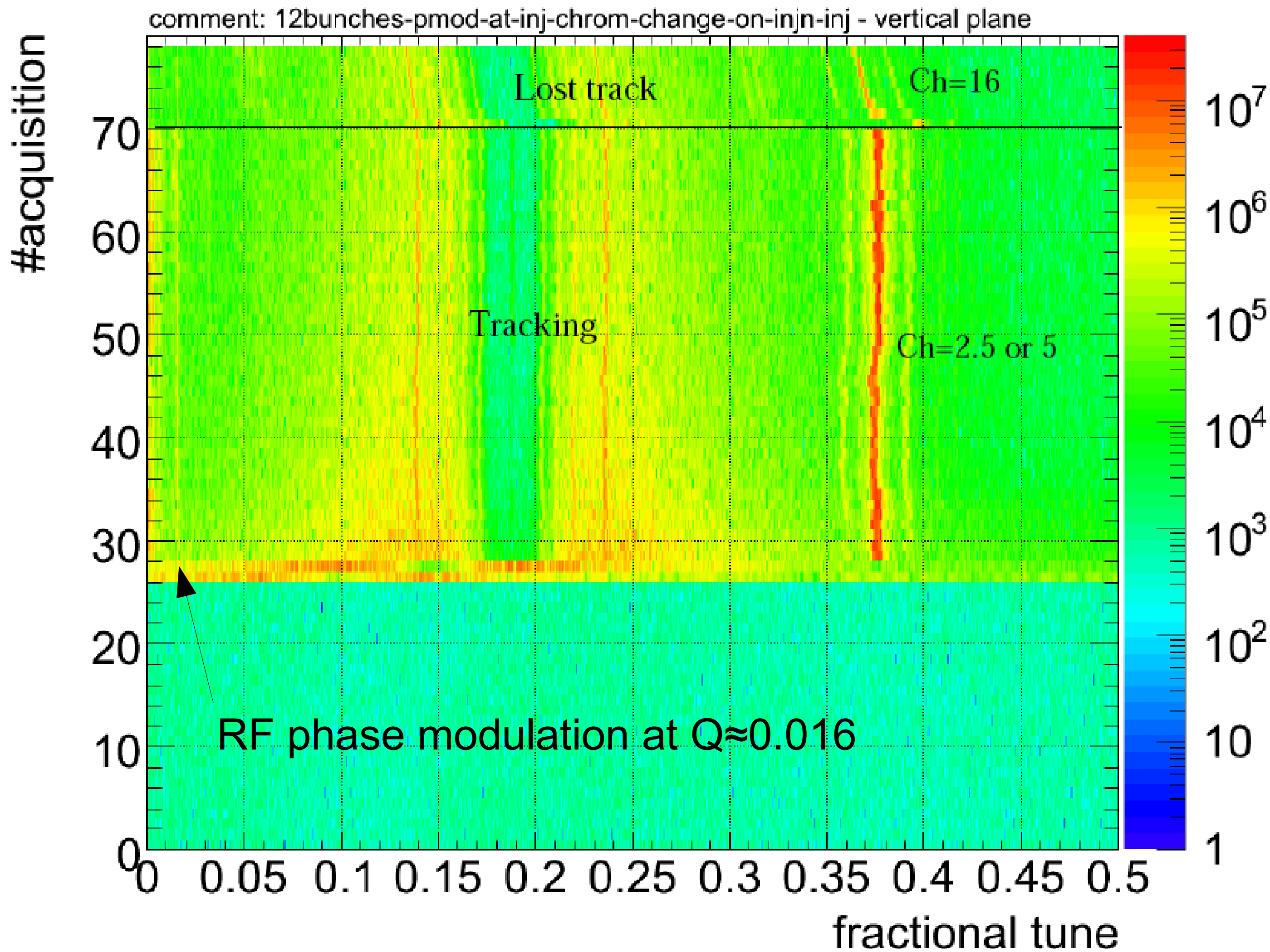
- Initial Chromaticity setting was $\xi_{H/V}$= 0.1 ($Q'_{H/V} \approx 2.7$, $\Delta Q'_{err}<1$)
  - static chromaticity bumps during the injection plateau (26GeV)
  - varied the chromaticity a flat top (450GeV) up to $\xi_{H/V}$= 0.9



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

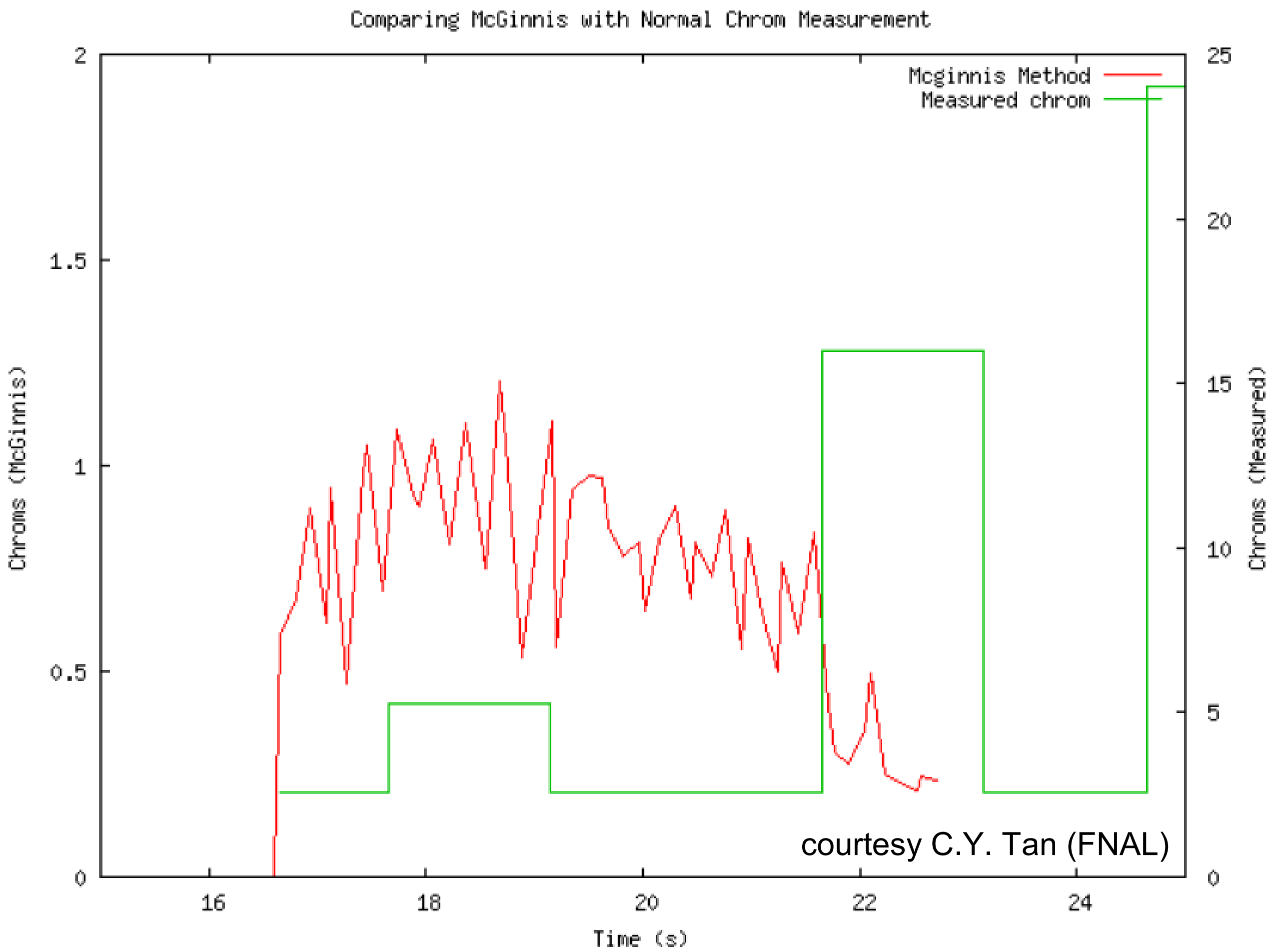
McGinnis Method I/II

- Modulated RF frequency at 700 Hz, maximum phase angle ~ 1 deg
  - demodulated amplitude ~ chromaticity



McGinnis Method II/II

- Comparison: McGinnis vs. 'Set Chromaticity'



- McGinnis method seem to be a factor 3.5 to 4 to small!

MD Summary

- The prototype test of the BBQ based tune PLL were very successful
  - could track even very fast tune changes during the SPS ramp
  - Required PLL excitation was very low
    - more than a factor 10 smaller than the standard MultiQ settings
  - very robust as long as the excitation level is above the noise floor

- Some preliminary comments on chromaticity measurement evaluation:
  - McGinnis method works, observed the RF induced modulation
    - however: underestimates Q' by a factor of 3.5 to 4
    - next MD: redo tests but with much slower Q' modulation
  - Classic head-tail: same status as in 2004:
    - works but with up to 50% measurement uncertainty
- Accumulated a large amount of chromaticity related data
  - analysis ongoing!

A more complete PLL schematic