BBQ based tune PLL
Collimator impedance measurements in the SPS

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Acknowledgements:
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Overview

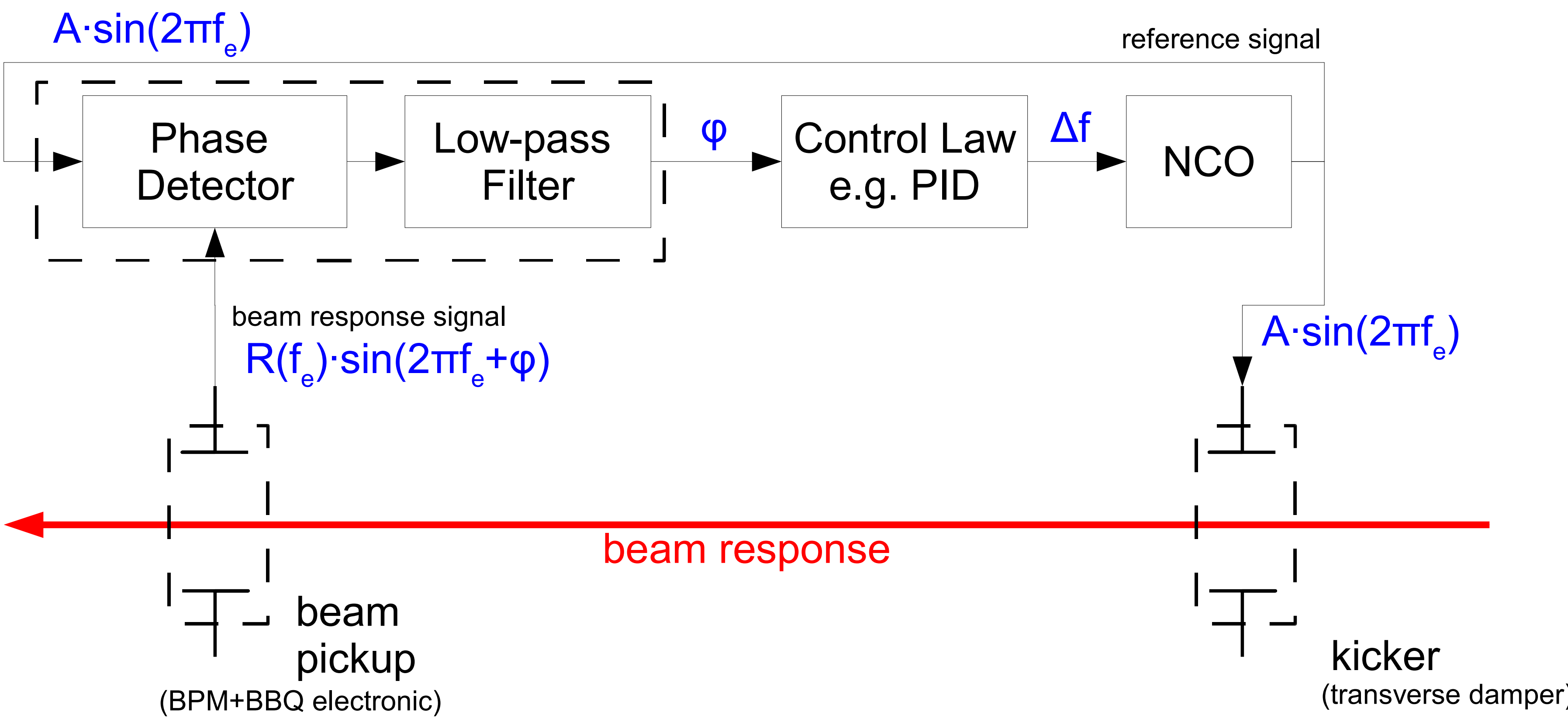
- Brief description of measurement principle
  - Tune PLL studies at the SPS

- Preliminary results of collimator impedance measurements:
  - Horizontal tune shift versus collimator jaw opening → $Im(Z_{eff})$
  - Vertical tune shift due to SPS machine impedance → $Im(Z_{SPS})$@270GeV
  - Instability rise-time due to collimator → $Re(Z_{eff})$
  - Instability rise-time due to SPS machine impedance → $Re(Z_{SPS})$

For more details on PLL design and architecture (USLARP TF review):

http://www.agsrhichome.bnl.gov/LARP/061024_TF_FDR/index.html

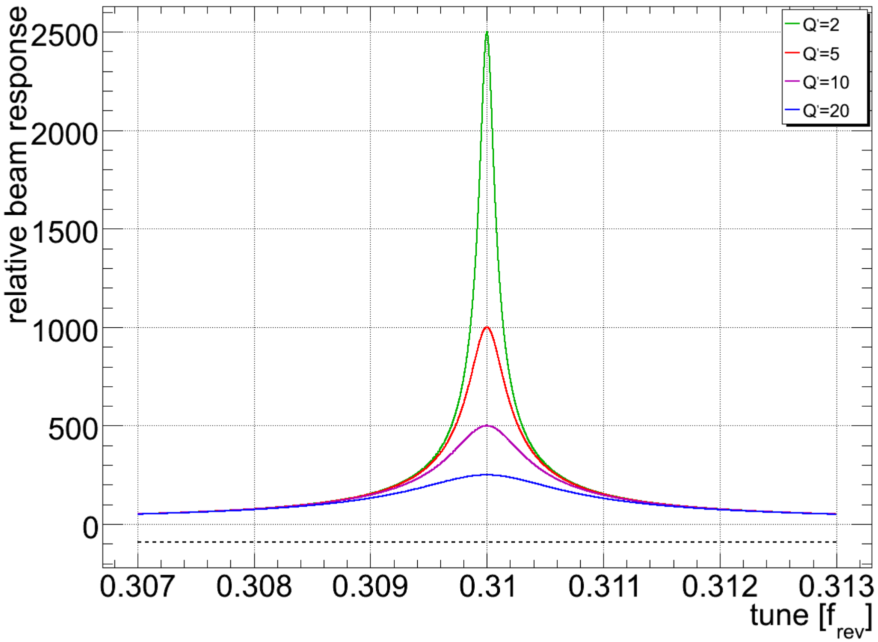
Basic Phase Locked Loop in two Slides I/II



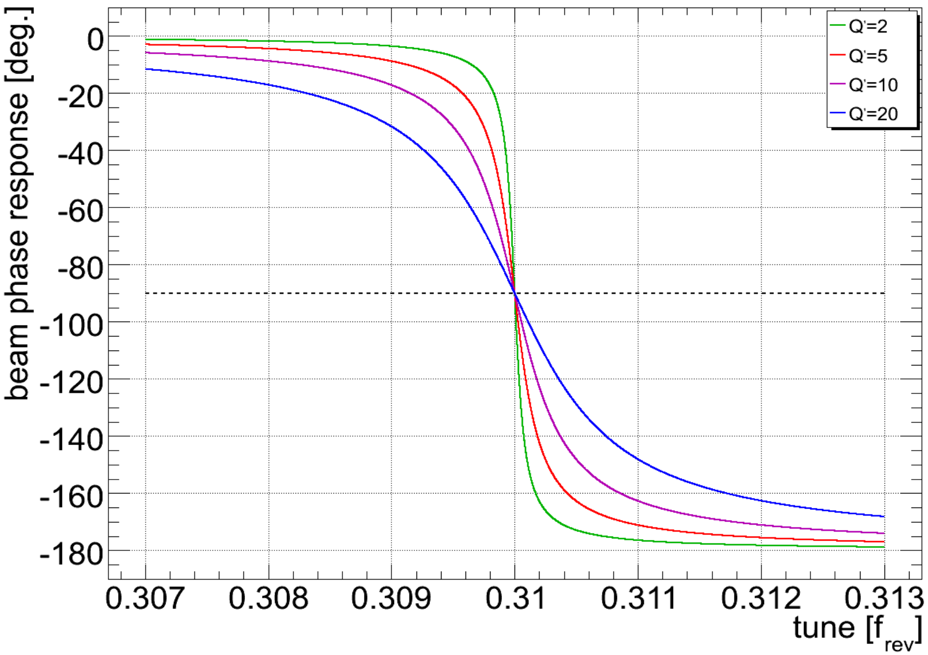
- NCO: Numerically Controlled Oscillator = digital sine wave generator
- Aim of the PLL control law:
  - regulate the frequency in order to minimise Δφ (match to 90°)
  - first iteration choice: e.g. classic proportional-integral (PI) controller

- Phase Locked Loop Principle: shift of excitation frequency till $\Delta\varphi = 0$

amplitude response:

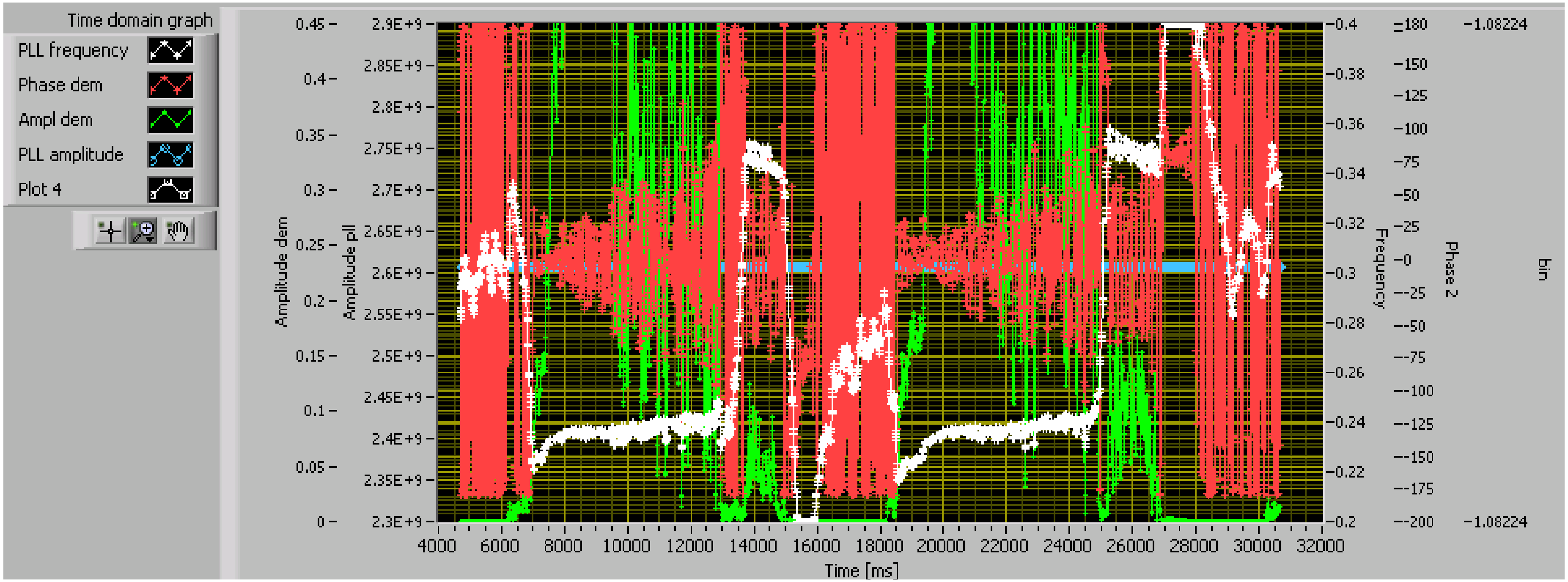


phase response:



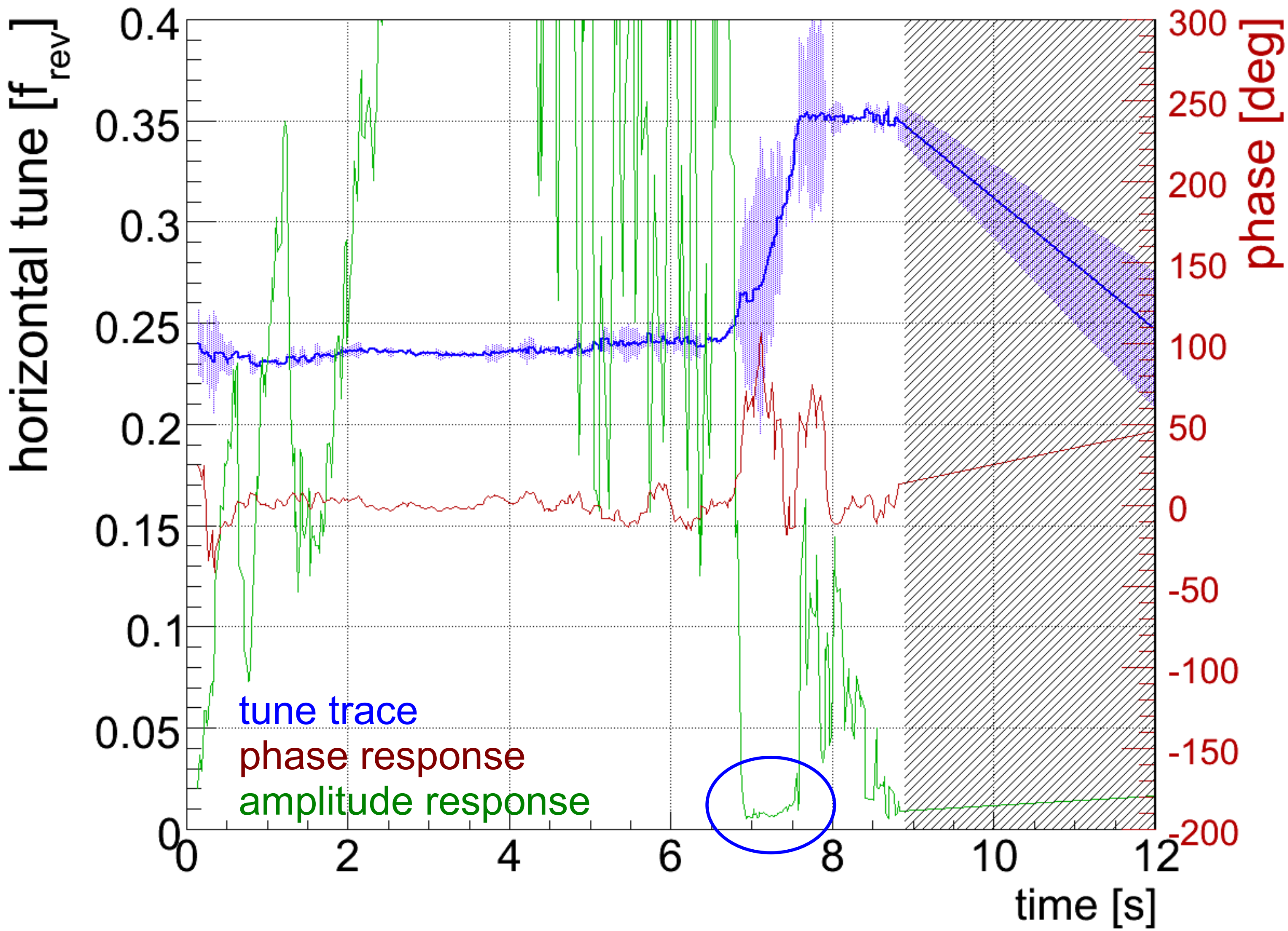
- (N.B In addition to the tune, the beam response also depends on the chromaticity → affects the tune PLL tracking speed but not the resolution)

21 September 2006: First successful BBQ based PLL



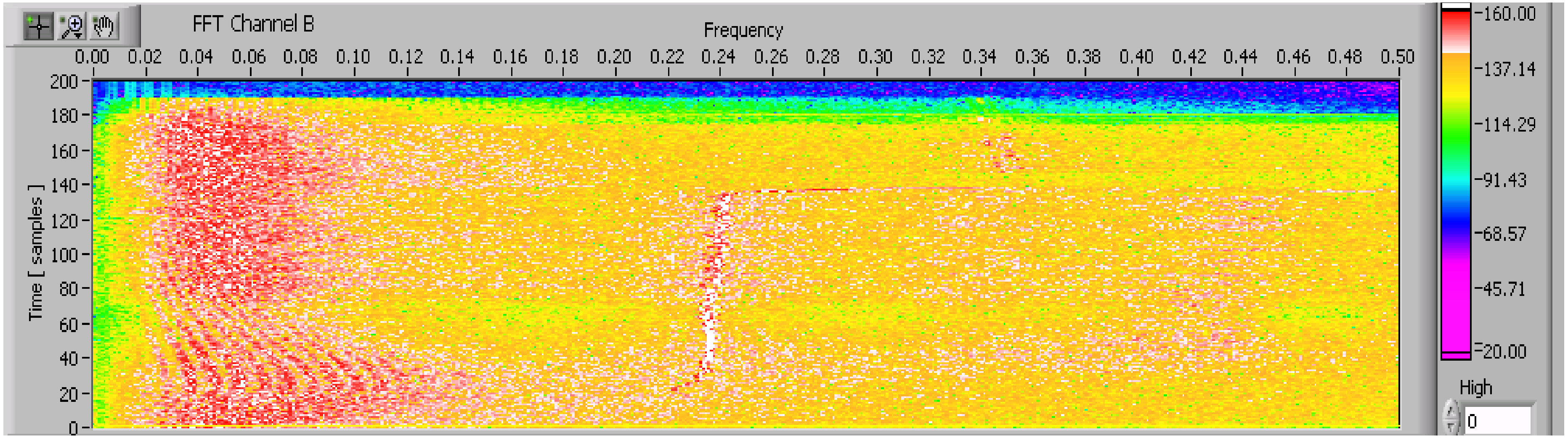
- SPS 25ns fixed target beam: 26GeV → 450GeV, ~ 3e12 protons/beam
  - Horizontal tune: Q_h≈ 26.76 → 26.66 (slow resonant extraction)
  - Fastest tracked tune change: ΔQ≈0.1 within about 200-300 ms
    - much faster than the maximum expected tune drift in the LHC!

Horizontal tune during ramp



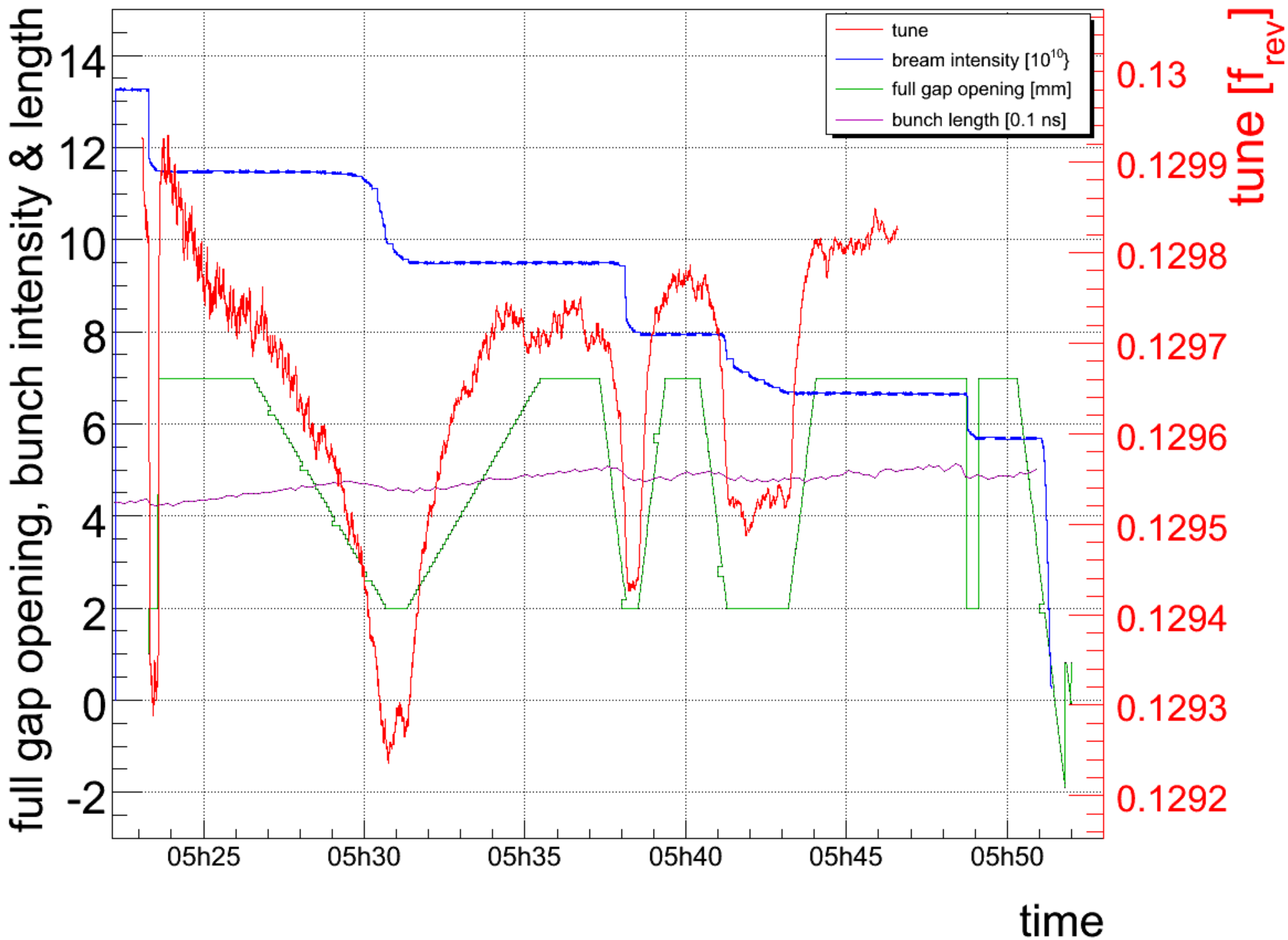
- phase error and non-vanishing amplitude indicate lock during ramp

- Temporal evolution of the individual FFT acquisition:



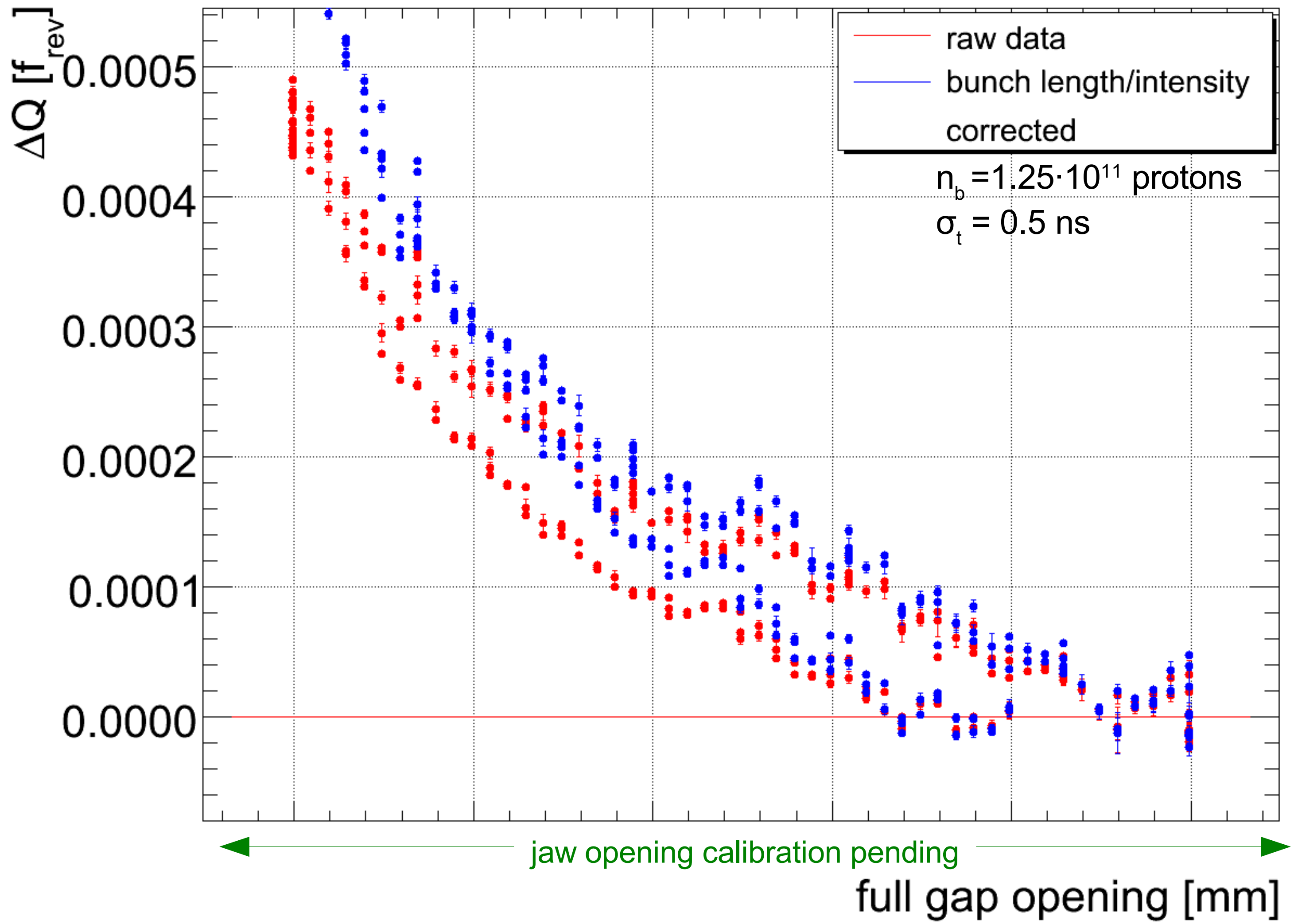
- Tune resolution:
  - FFT based (1024 turns): $\Delta Q_{res} \approx 10^{-3}$ - depends on Q'!
  - PLL based: $\Delta Q_{res} \ll 10^{-4}$-$10^{-6}$ - independent on Q'!
    - limited by underlying tune stability → SPS is a tough testbed
    - excitation well below the 1 μm level (factor 10-600 below MultiQ Settings) → negligible emittance blow-up
  - Seem(ed) to be a very robust measurement!

Imaginary Part of Collimator Impedance: Horizontal Tune versus Full Gap Opening I/II



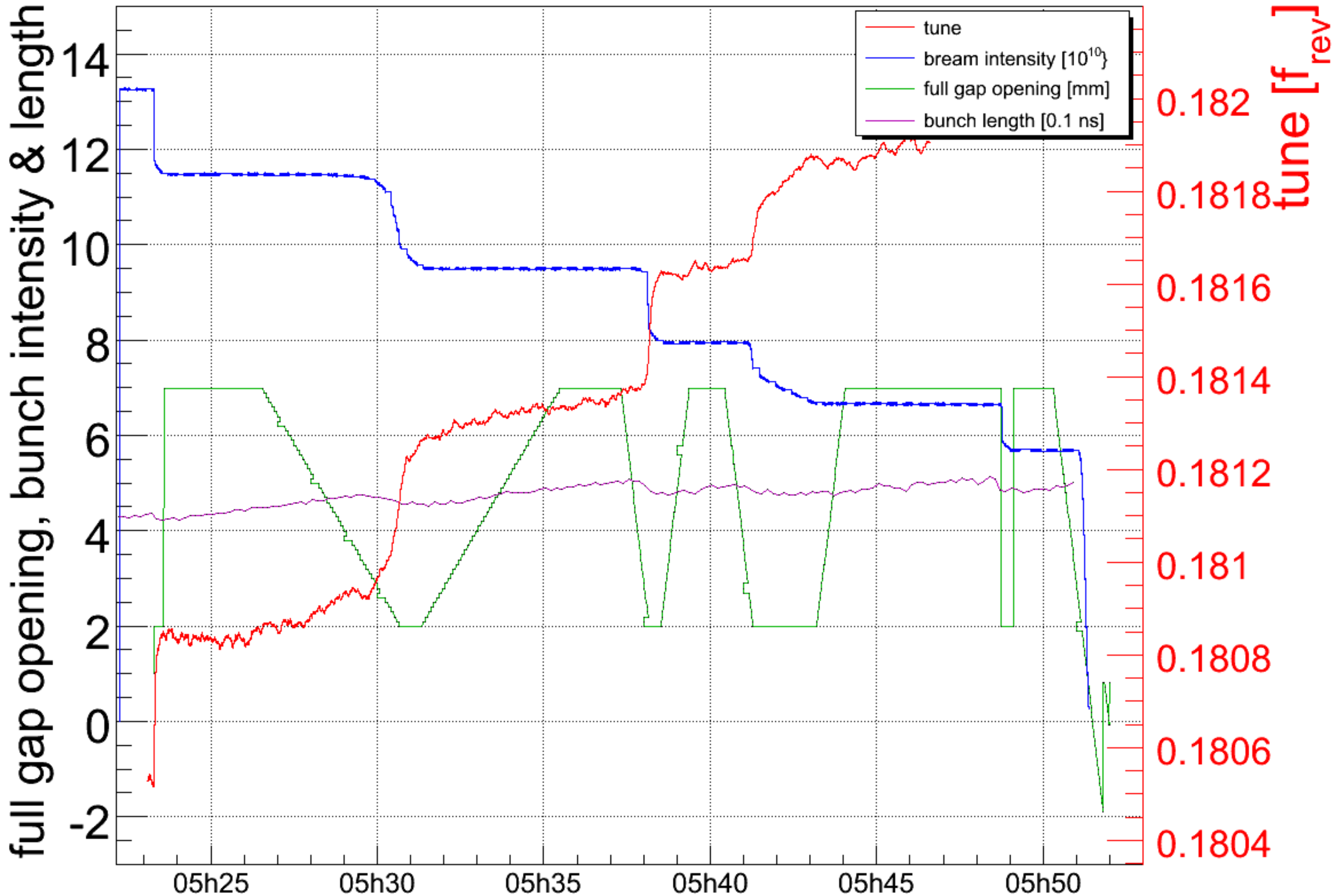
- Correlation between tune shift and collimator opening

Imaginary Part of Collimator Impedance: Horizontal Tune versus Full Gap Opening II/II



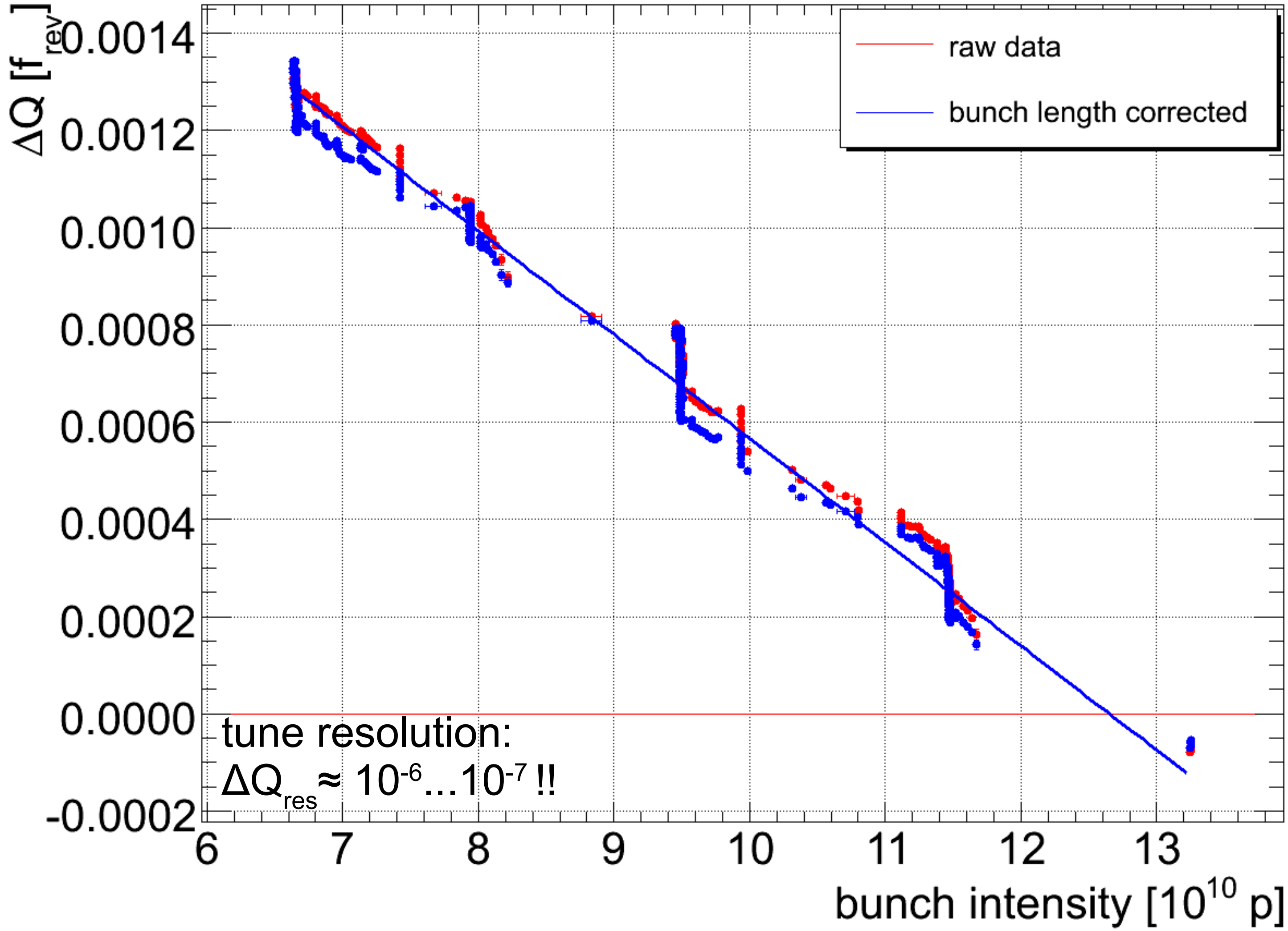
- “Official” jaw opening calibration still pending!
- Further optimisation: systematic tune shift and PLL intrinsics (delays)
- N.B. classic tune shift measurement (FFT using BBQ) was limited by large Q'

"Free" measurement: Vertical Tune Shifts due to SPS Impedance



- Vertical tune shift are a result of:
  - SPS transverse impedance and changing bunch length/intensity

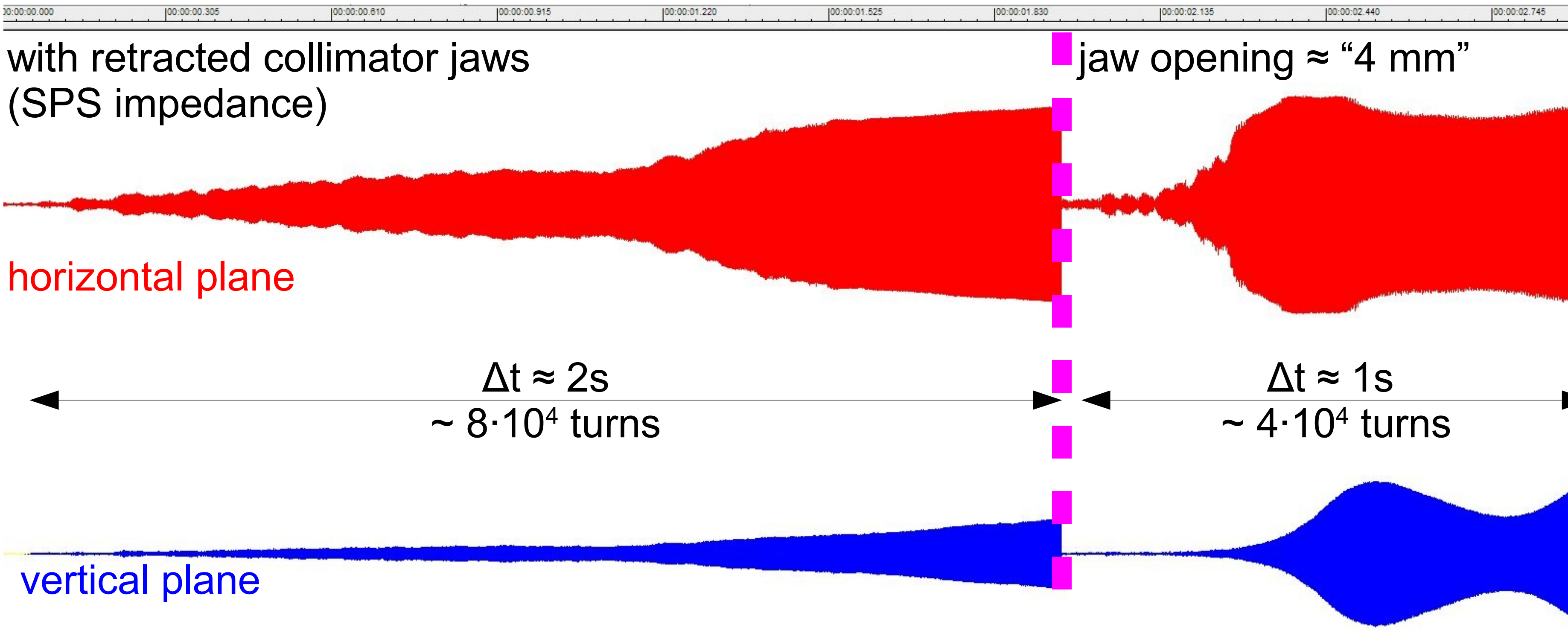
“Free” measurement: SPS Impedance at 270 GeV



- Using Sacherer's impedance approximation: $Z_{eff} \approx 21.54$ MΩ/m

Real Part of Collimator Impedance: Vertical Tune versus Full Gap Opening I/II

- instability rise-time due to chromaticity change: Q' ≈ 22 → 1.1



Plot courtesy K. Kasinski

- Effect of the collimator on the beam instability rise-time is visible/evident
- Detailed analysis of rise times including intensity normalisation pending (B. Savant et al.)

Real Part of Collimator Impedance: Vertical Tune versus Full Gap Opening II/II

Disclaimer:

- Model calculations were performed assuming heaviside step functions of parameter change

- However: the real machine does not reveal such sharp responses
  - change of Q' limited by sextupole circuit time constant
    - time-constants are amplitude dependent
    - particularly slow at 270 GeV
  - change of collimator gap is limited by maximum slew rate of ≈ 2 mm/s

→ The observed rise-times are a convolution of impedance, slew rate collimator jaw opening change - a detailed analysis should reflect this property.

MD Summary

- Prototype tests 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 $\Delta Q_{res} \approx 10^{-4} \ldots 10^{-6}$
- Required PLL excitation was very low
  - factor 10 up to 600 times smaller than standard SPS MultiQ
  - measurements were done with a S/N ratio of less than 3..10dB
- First "real world" test:
  - Measured real and imaginary part of collimator impedance
  - First results look promising but certainly require more detailed studies of systematics in particular "official" agreement on jaw opening calibration

reserve slides

- PLL low-pass:

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

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

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

- Using the following ansatz

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

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

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

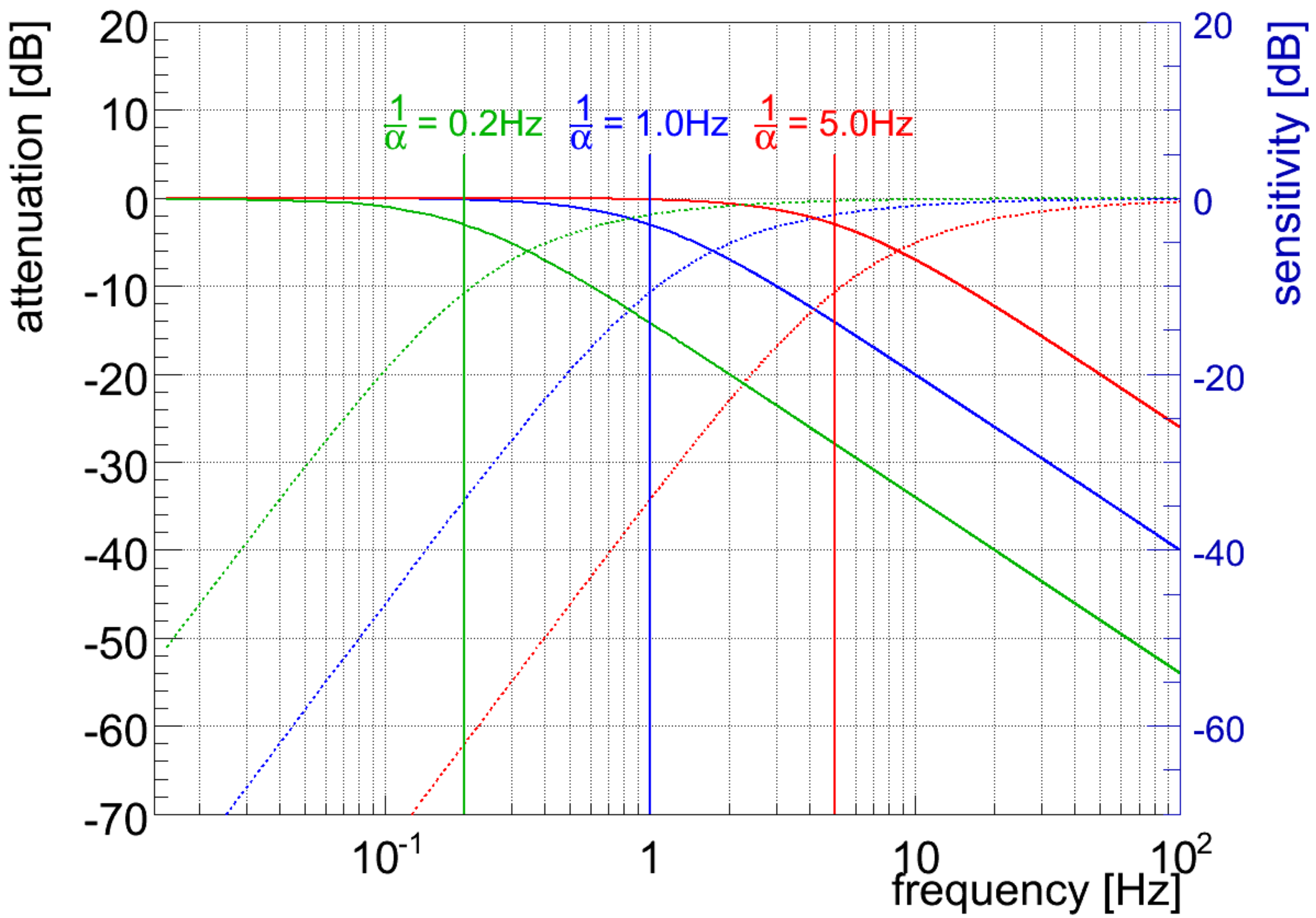
- α > τ...∞ moderates closed loop response between (trade-off):
  - fast and less accurate tracking vs. slow and more accurate tracking

[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

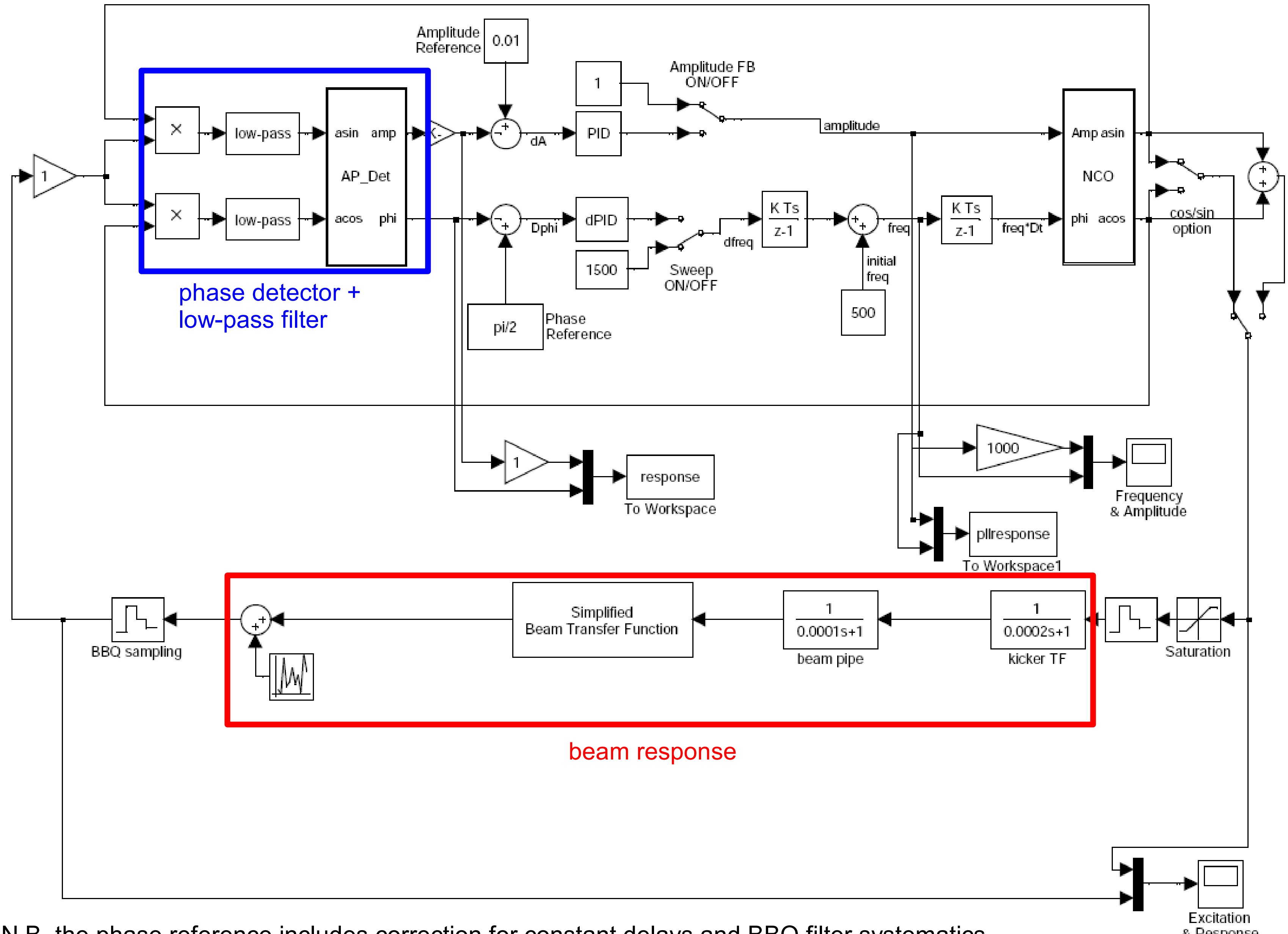
Robust vs. Fast Tracking PLL

- 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



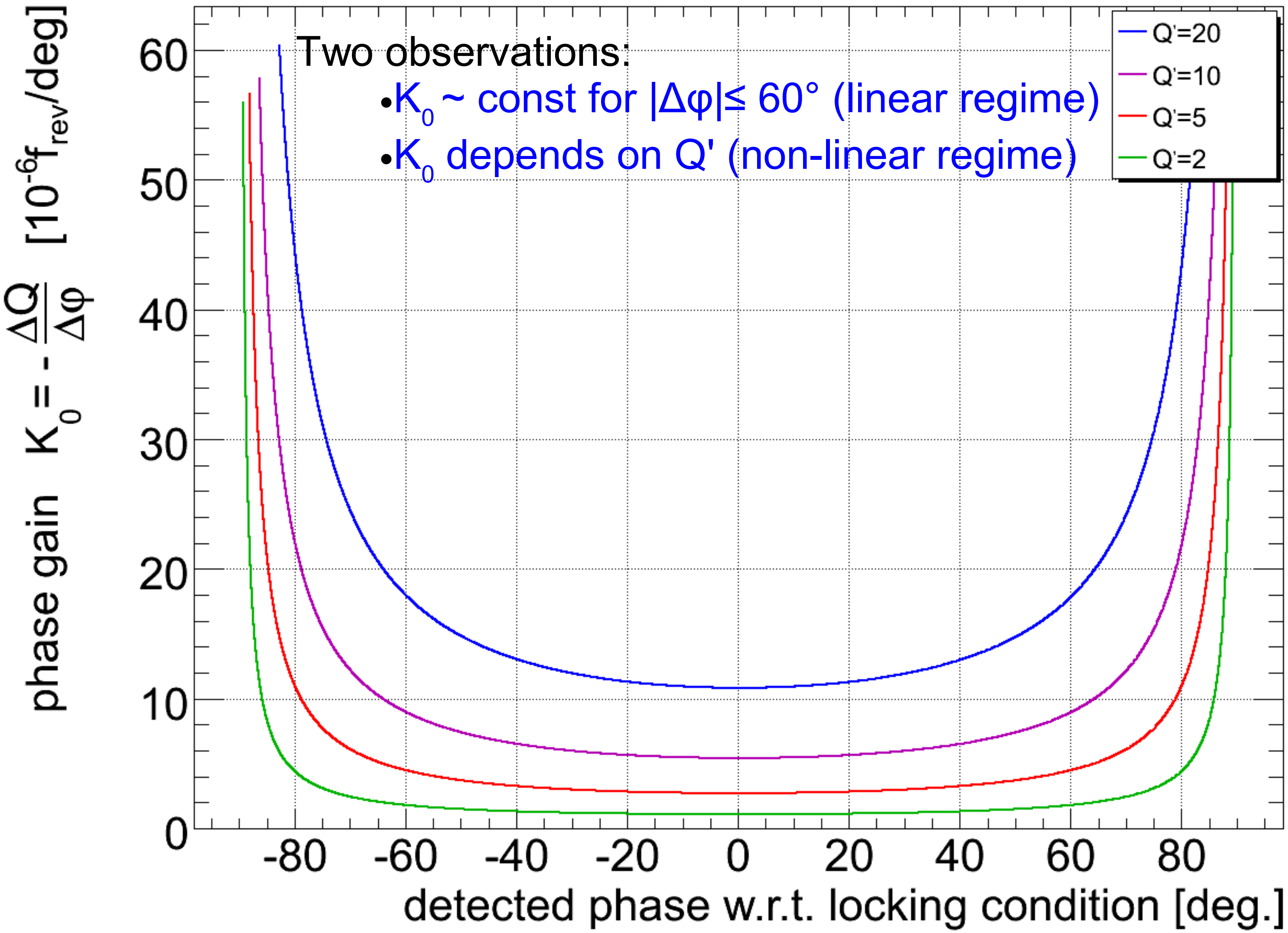
A more complete PLL schematic



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

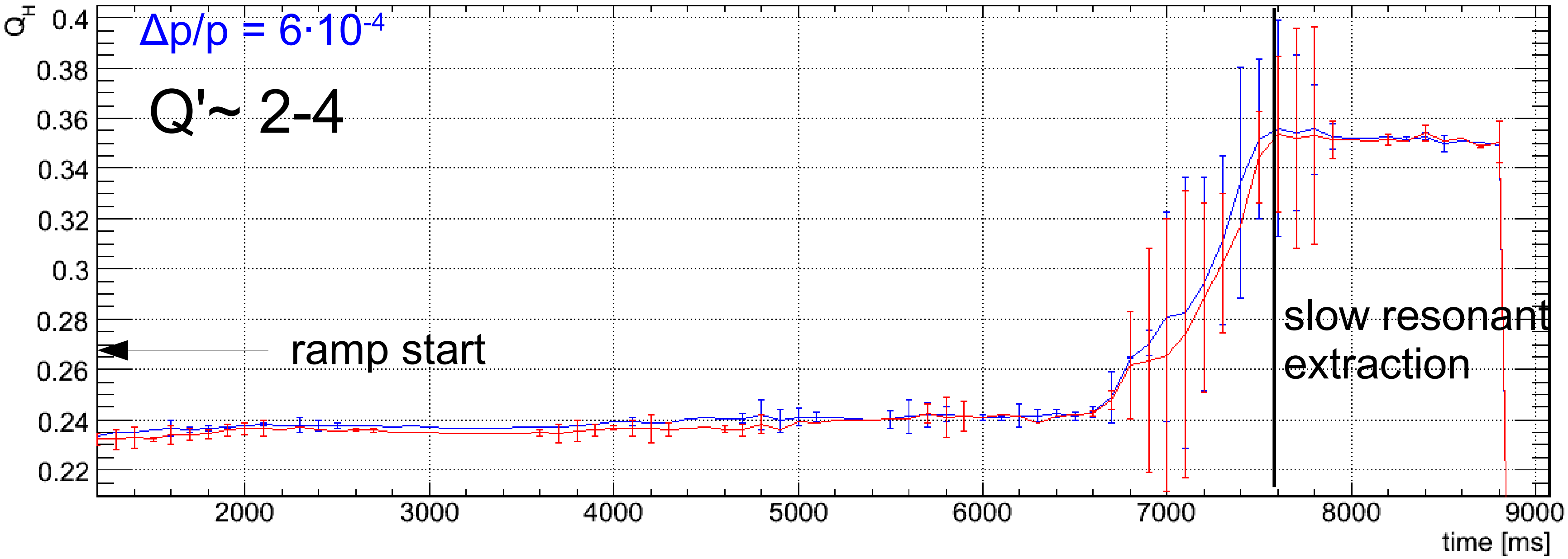
Chromaticity and PLL Non-linearities

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



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