PLL Tune and Chromaticity Measurements

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Acknowledgements: A. Boccardi, M. Gasior, K. Kasinski & R. Jones

➔References:
APC 2006-11-10(slides), Tune Feedback FDR (BNL, slides), DIPAC'07 (paper)

LHC Tune and Chromaticity Requirements

- The measurement and control of

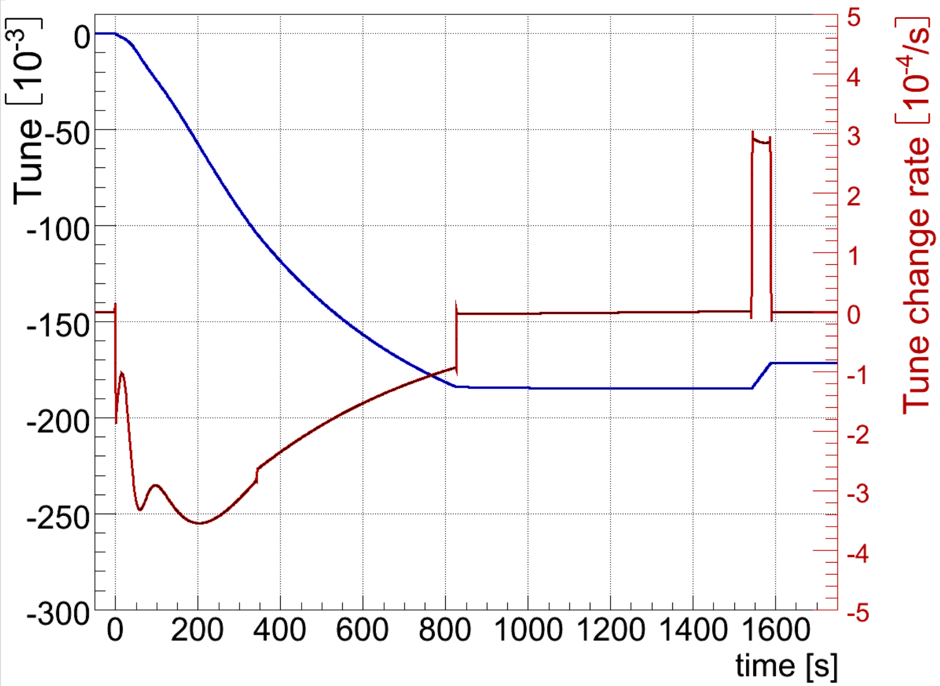
  -- orbit, tune, chromaticity, energy and coupling --

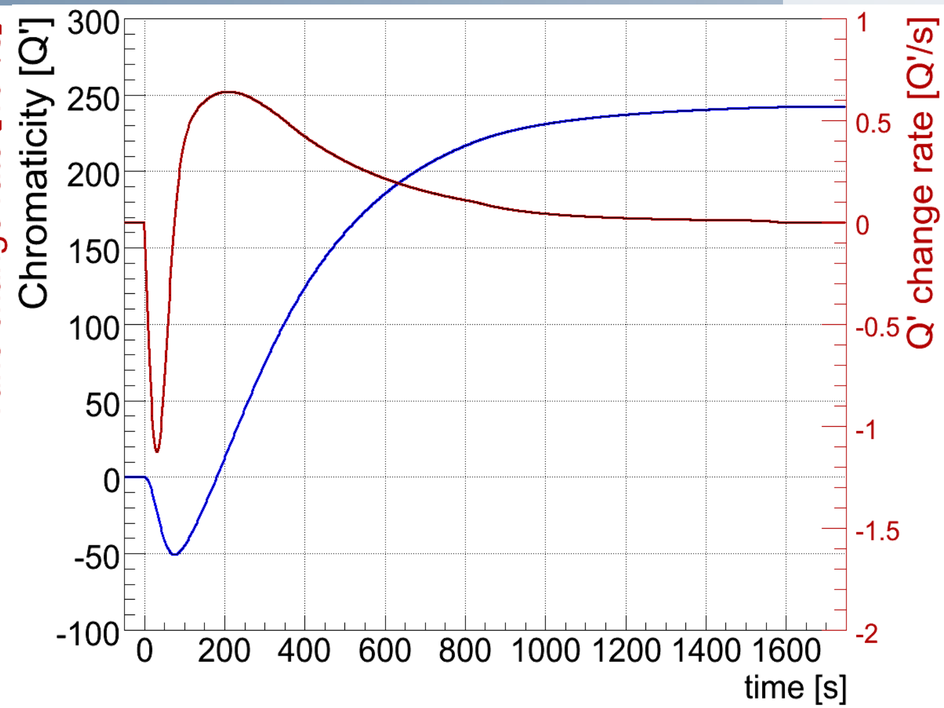
  will be an integral part of the LHC operation

- Requirements summary (Chamonix'06):

	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

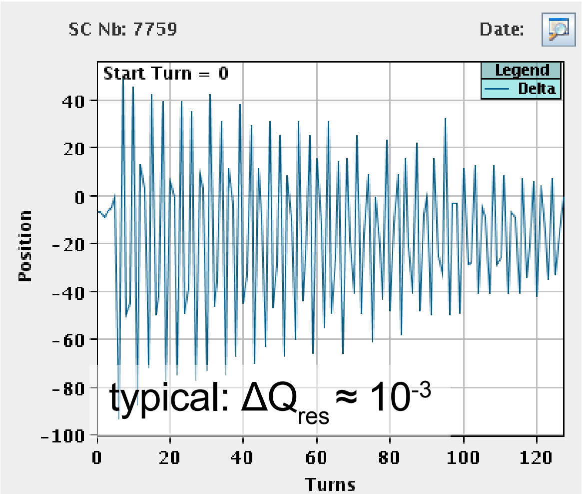
Expected Tune and Chromaticity Drifts during LHC ramp



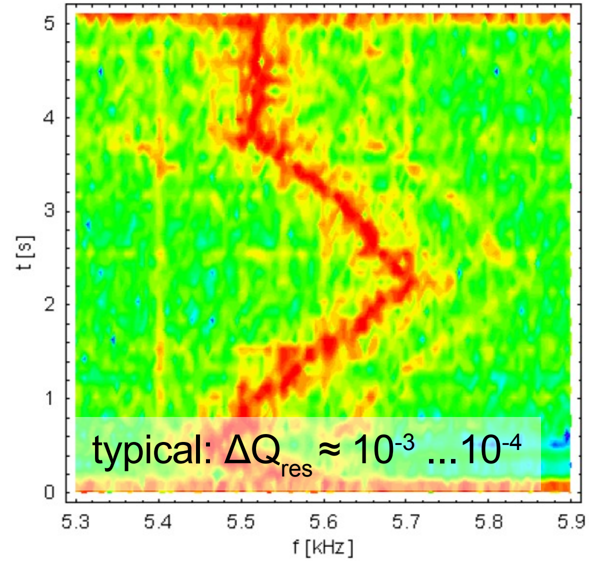


- Exp. perturbations are about 200 times than required stability!
- however: maximum drift rates are expected to be slow in the LHC
  - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
  - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2\ s^{-1}$ ← the critical/difficult parameter
- Requires active control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

- Classic kicked or chirp excitation:
  - limited by aperture constraints
    - Performance reduction
      - typically: $\Delta z \leqslant 0.1\sigma$
    - Loss of particles & protection
      - LHC: $\Delta z \leq 25\ \mu m$ & $\Delta p/p \leq 5 \cdot 10^{-5}$
  - limited by emittance blow-up (LHC: ~10 kicks)



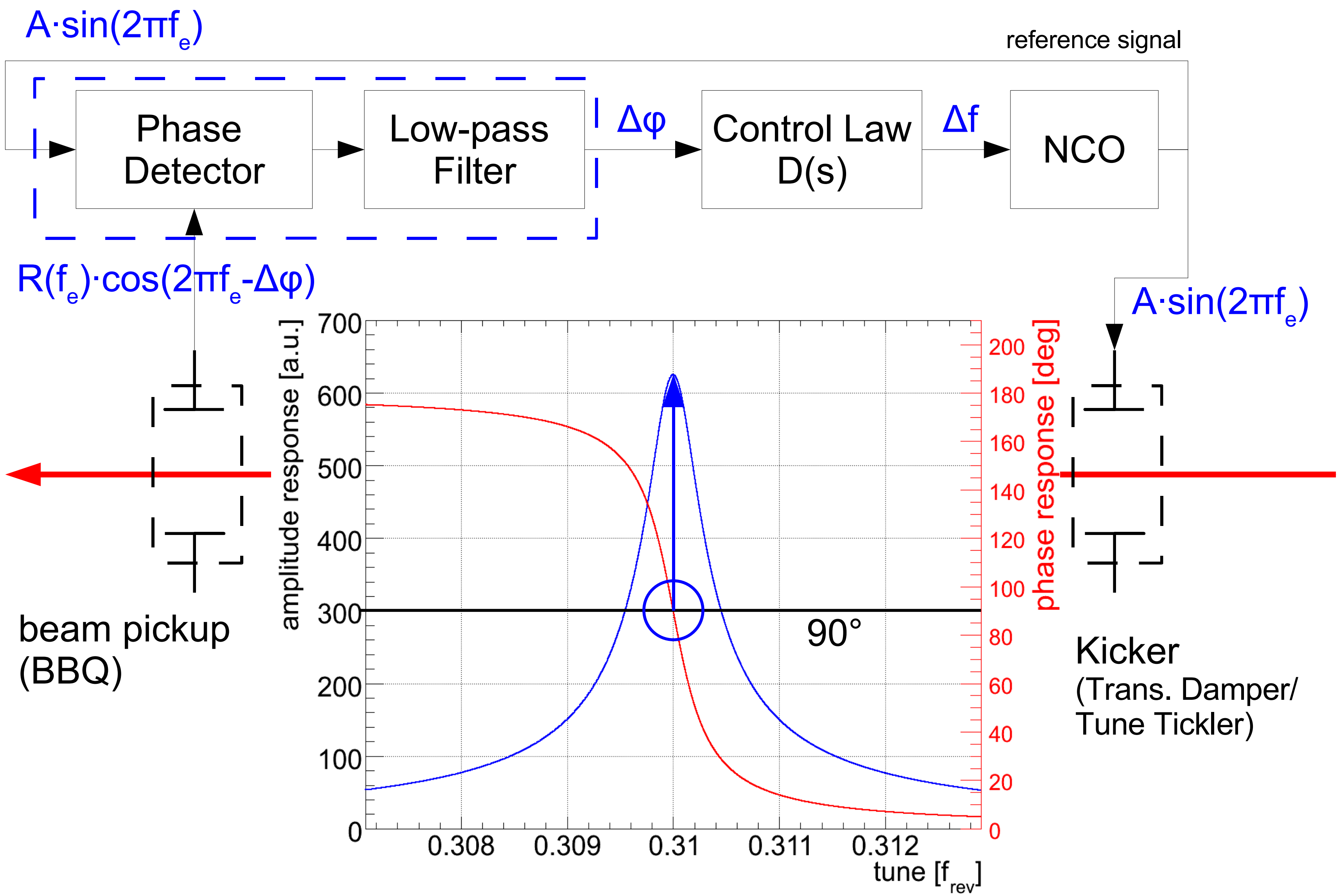
- Passive monitoring of residual oscillations:
  - Schottky monitors
  - Diode-based Base-Band-Q (BBQ) meter
  - → also measures incoherent external noise propagating onto the beam



- Active Phase-Locked-Loop (PLL) systems
  - In combination with RF modulation → chromaticity tracking

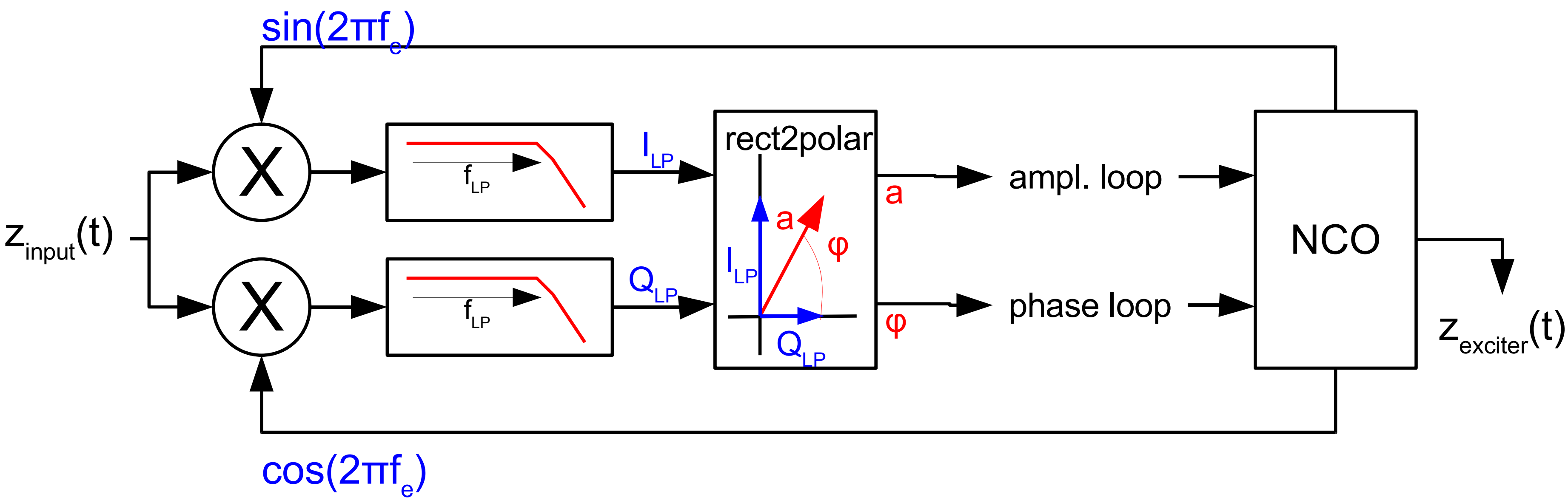
typical: $\Delta Q_{res} \approx 10^{-3} \ldots 10^{-5}$

Classic Phase-Locked-Loop Scheme



$$G_{Beam}(\omega) = R(\omega) \cdot e^{i\varphi(\omega)}$$

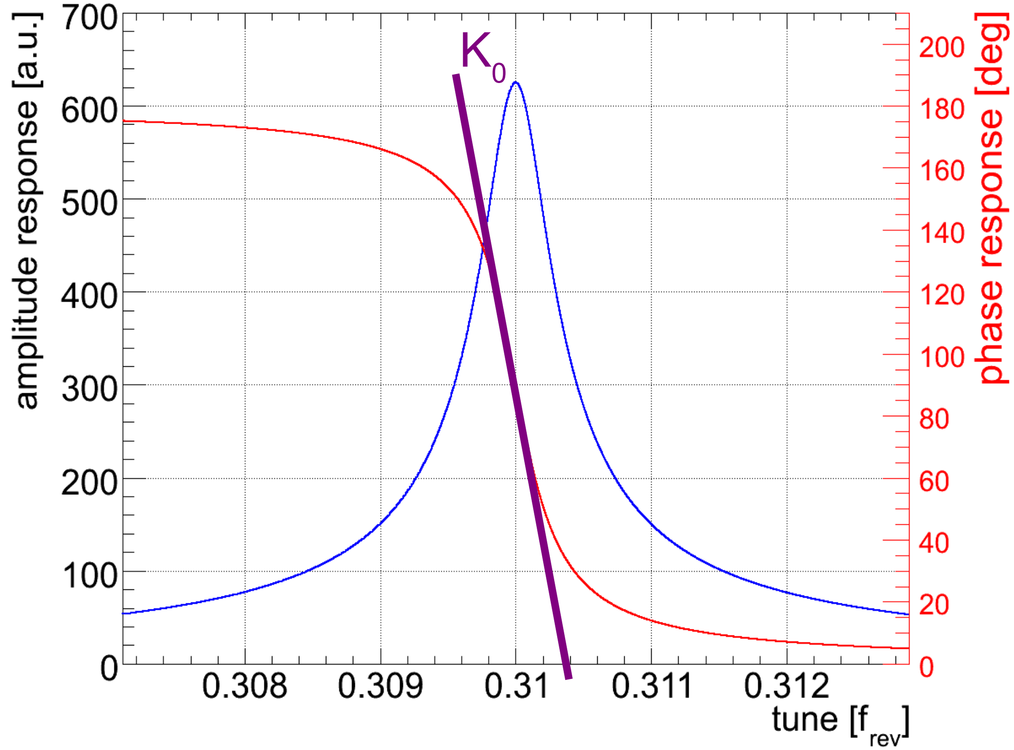
LHC PLL schematic: Phase – Amplitude Decoupling



- FPGA based decoupled loop implementation:
  - phase-locked-loop (→ tune)
  - excitation amplitude loop
- Further compensation for other non-beam related phase responses:
  - constant lag (data processing, cables),
  - analogue pre-filters, beam exciter response...

- The PLL control loop dynamics and its design split into two parts:
  - PLL low-pass filter:
    → $$\tau = \frac{1}{f_{BW}}$$
  - Beam response:
    → open loop gain K_0
    - first order: K_0 = const.

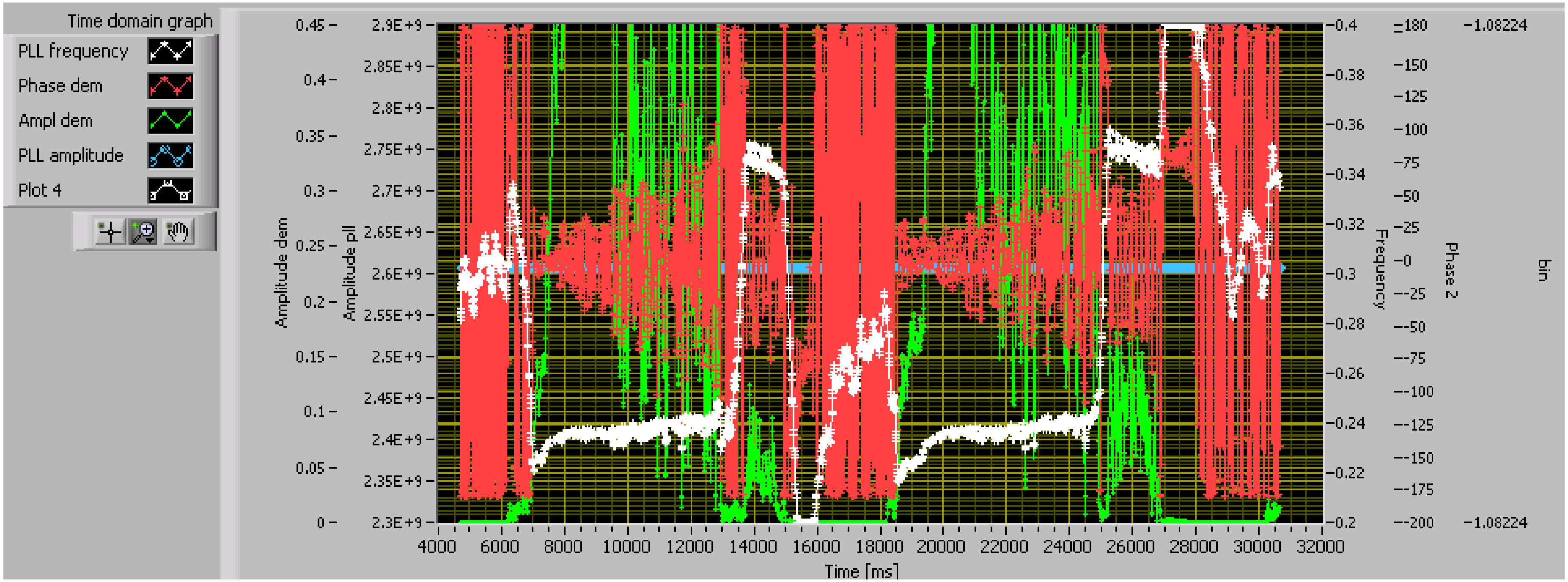
$$G_{PLL}(s) = \frac{K_0}{\tau s + 1} \quad with \quad \tau = \frac{1}{f_{bw}}$$



  - Youla's affine parameterisation: → yields optimal PI controller

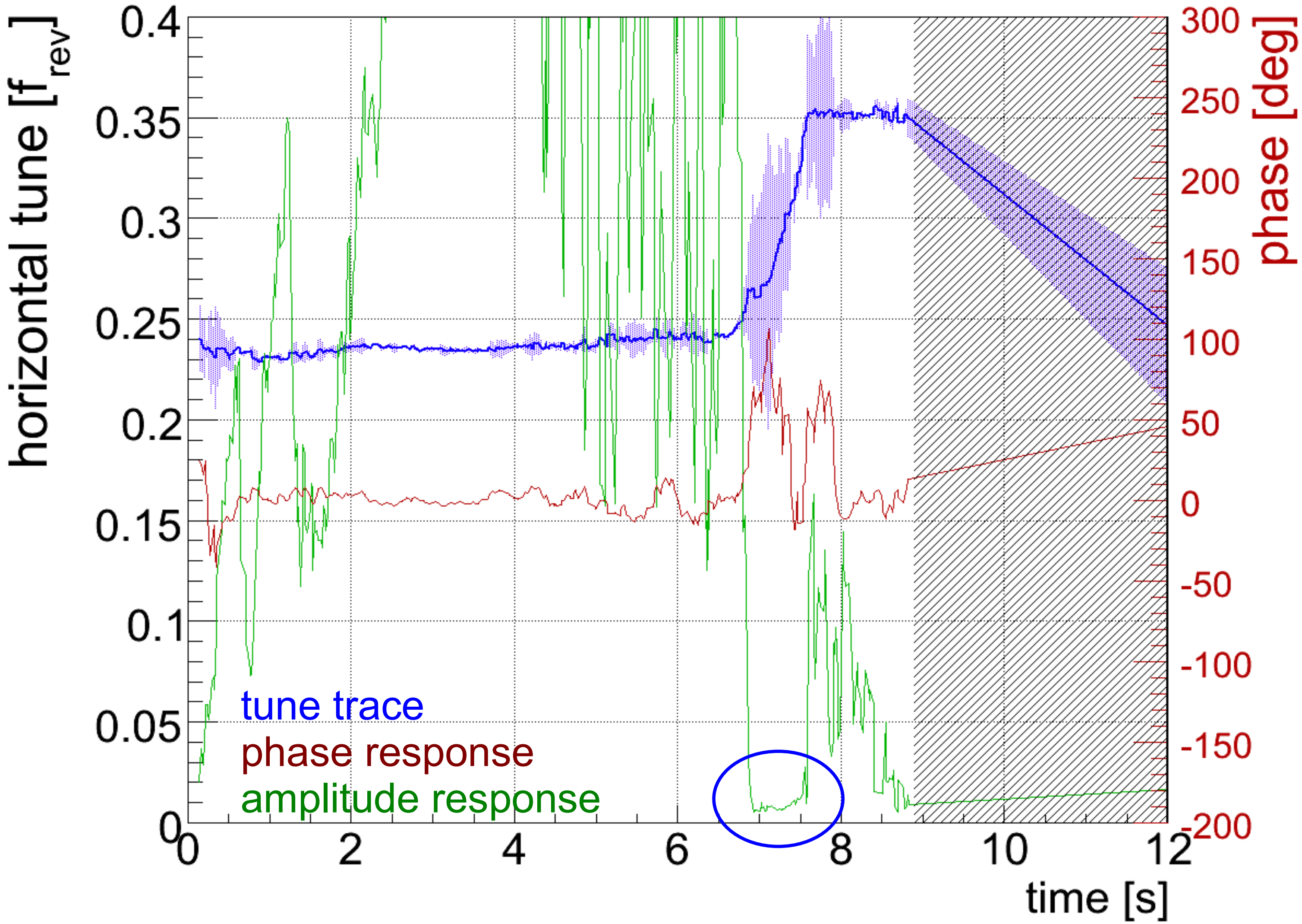
$$D(s) = K_P + K_i \frac{1}{s} \quad with \quad K_p = K_0 \frac{\tau}{\alpha} \wedge K_i = K_0 \frac{1}{\alpha}$$

21 September 2006: First successful BBQ based PLL



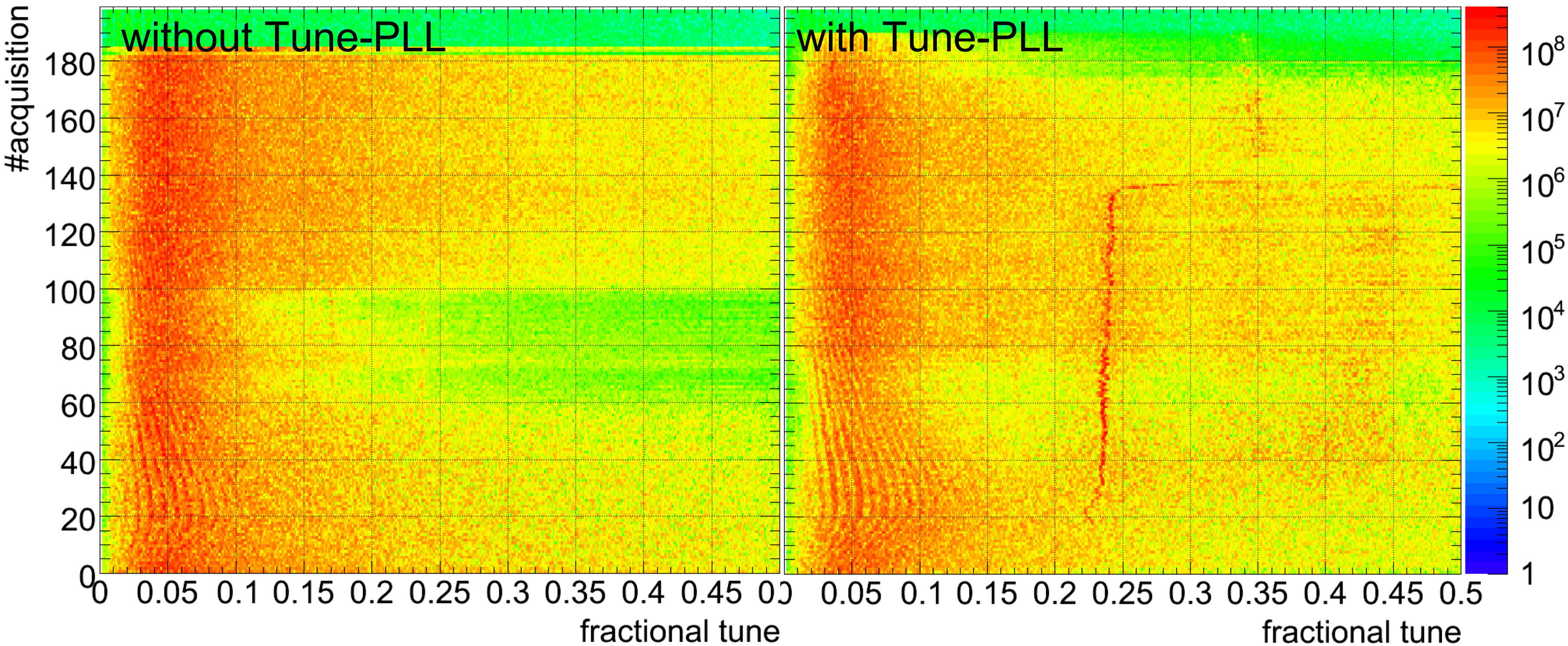
- SPS 25ns fixed target beam: 26GeV → 450GeV, ~ 3e12 protons/beam
  - Horizontal tune: Q_h≈ 26.76 → 26.66 (slow resonant extraction)
  - Fastest tracked tune change: ΔQ≈0.1 within about 200-300 ms
    - much faster than the maximum expected tune drift in the LHC!

Horizontal tune during ramp I/II



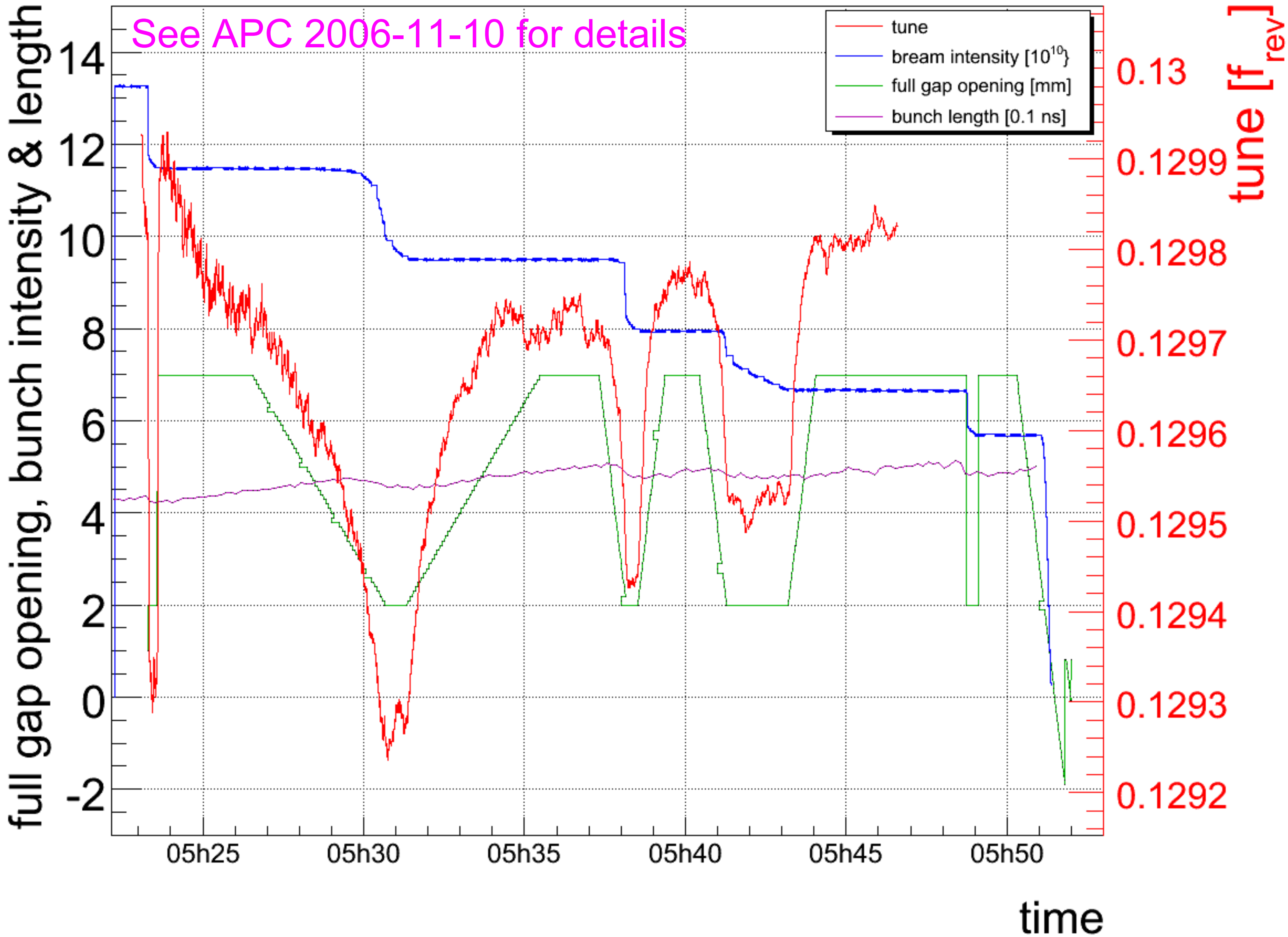
- phase error and non-vanishing amplitude indicates lock during ramp

- PLL – FFT Comparison:



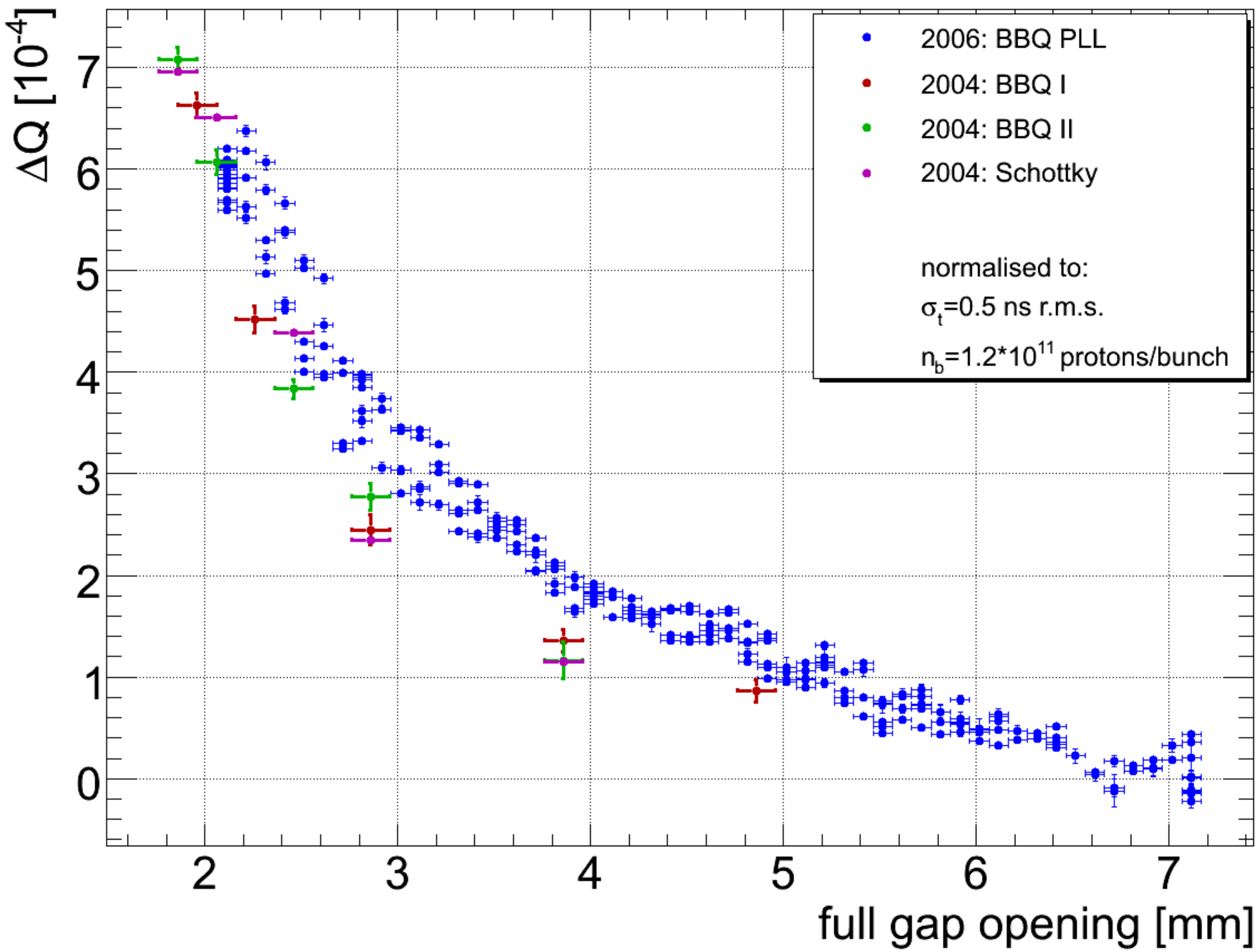
- excitation well below the 1 μm level (factor 10-600 below MultiQ)
  → negligible emittance blow-up

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



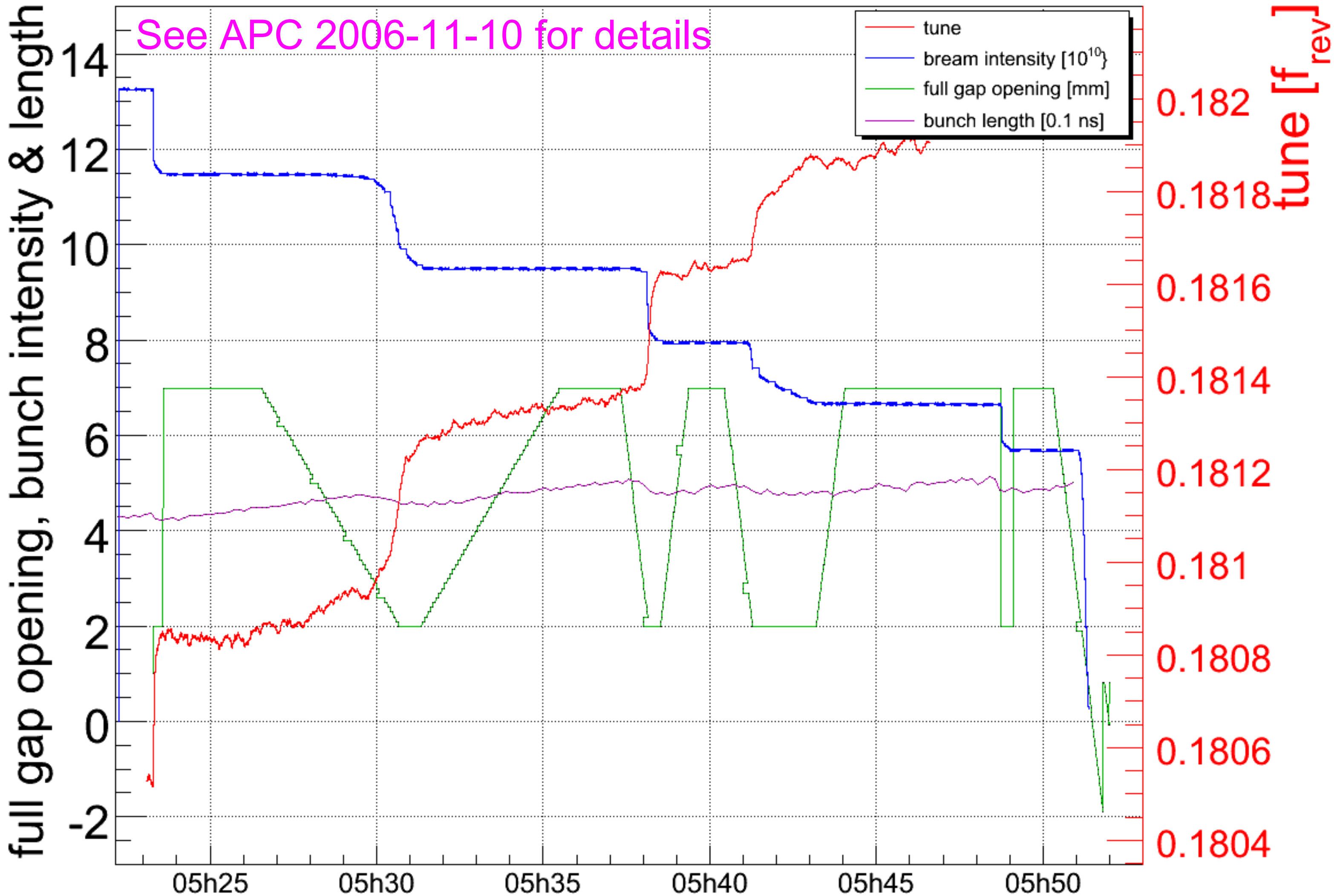
- Correlation between tune shift and collimator opening

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



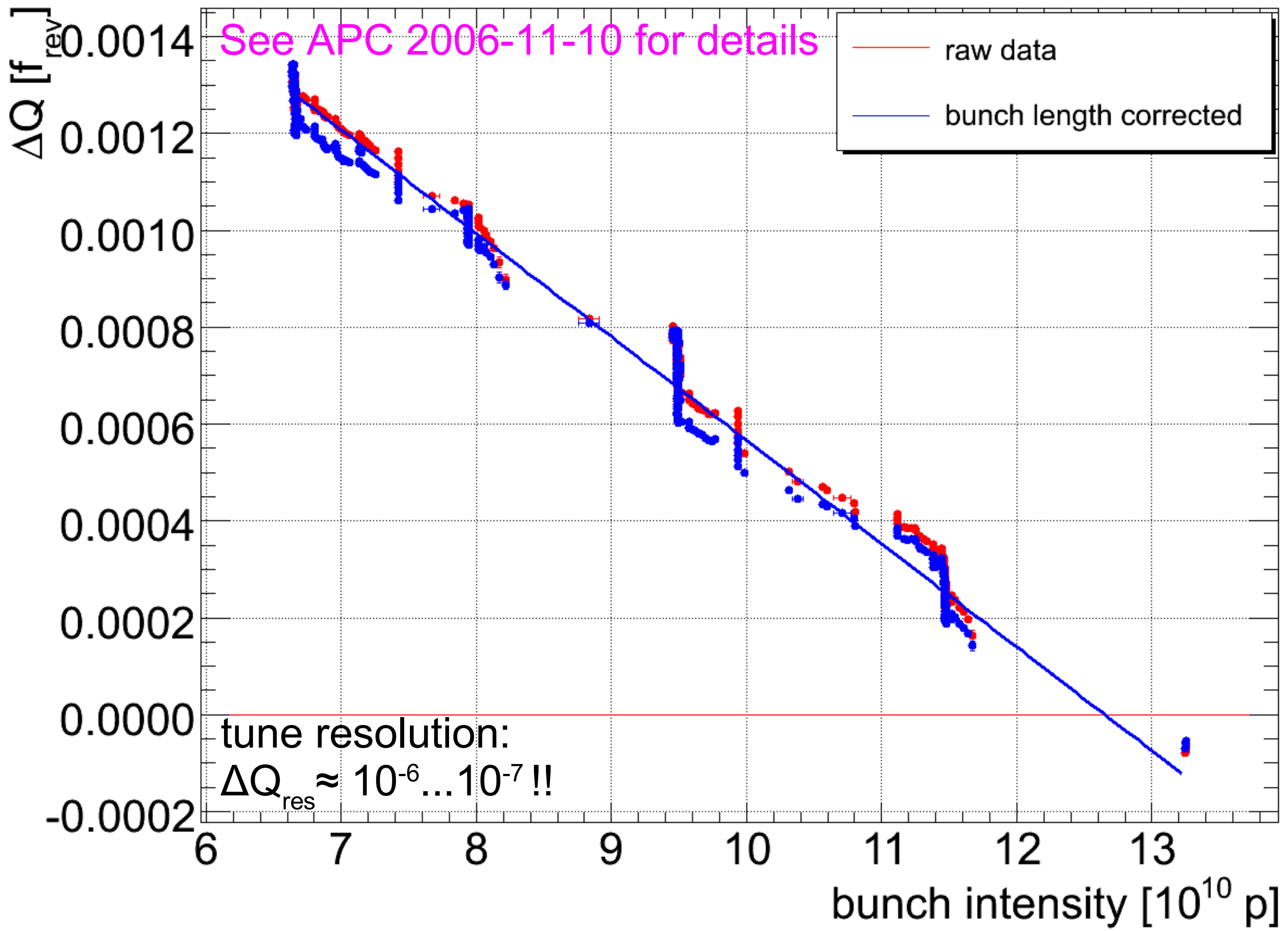
- N.B. classic tune shift measurement (FFT using BBQ) was limited by large Q'

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



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

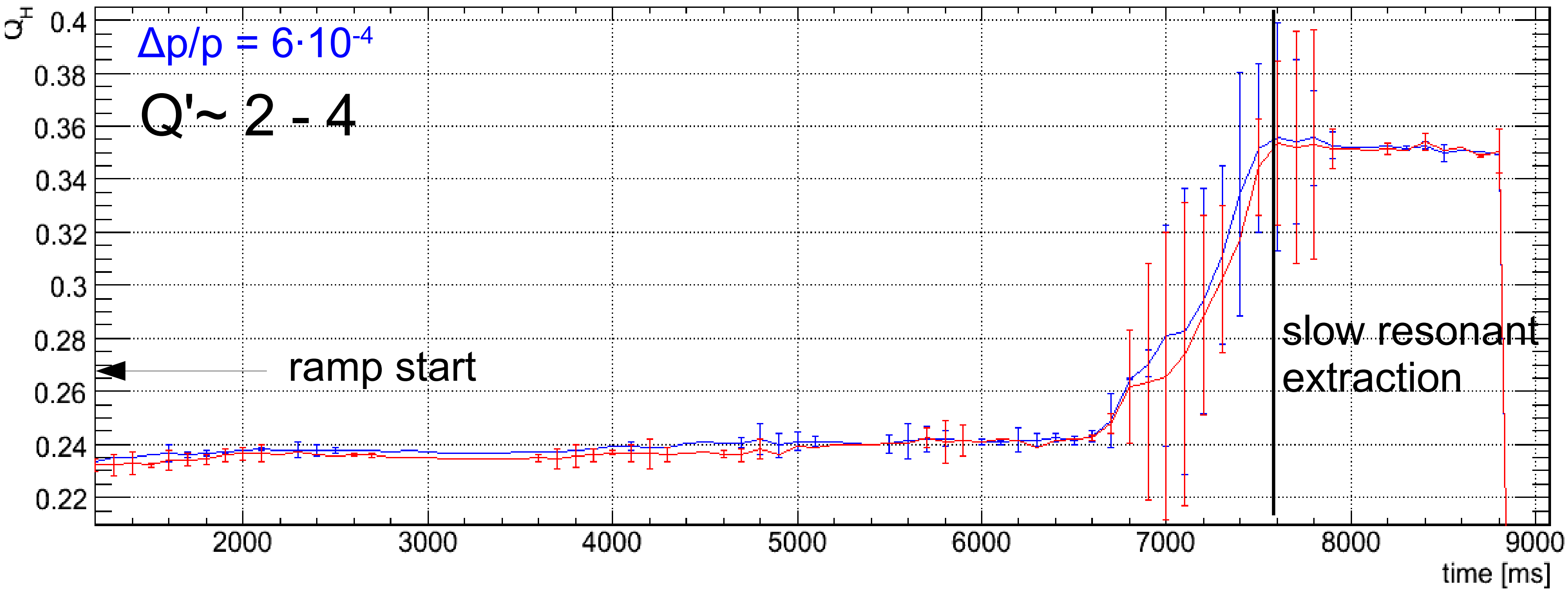
“Free” measurement: SPS Impedance at 270 GeV



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

Q' measurement trough slow Δp/p modulation

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



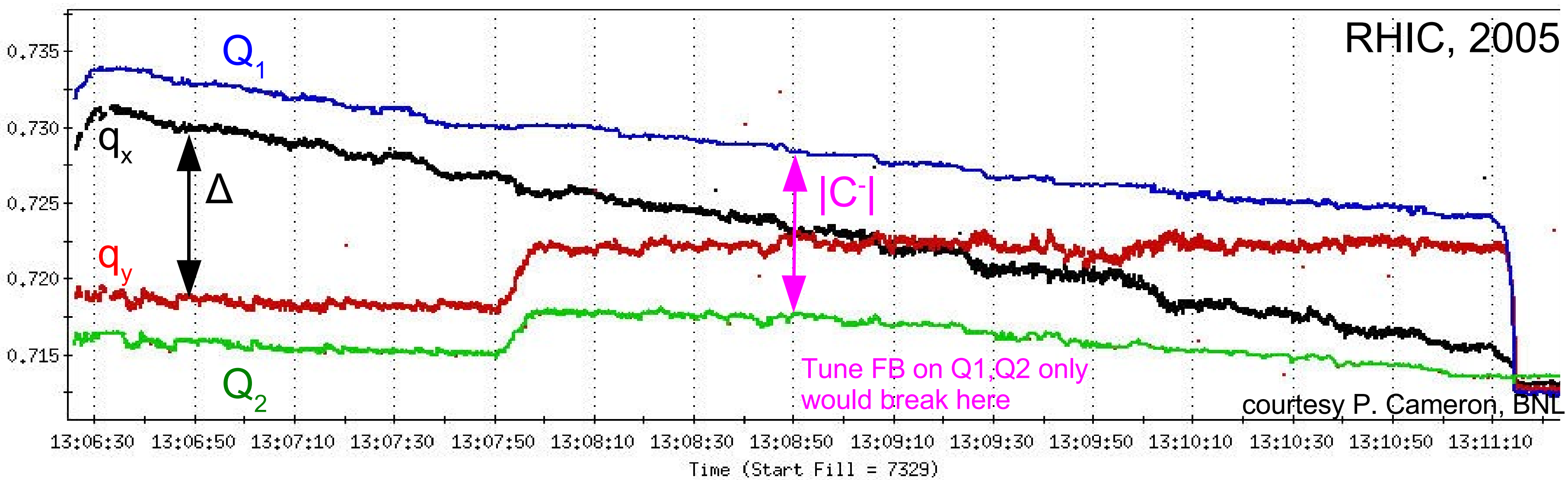
- SPS operation: $\Delta p/p > 10^{-3}$ & $\Delta Q_{res} \approx 10^{-3} \rightarrow \Delta Q'_{res} \sim 1$
- LHC: $\Delta p/p < 10^{-4}$ & $\Delta Q'_{res} \sim 1 \rightarrow \Delta Q_{res} < 10^{-4}$
  - limited by LHC Collimation orbit 'budget': Δx < 35 μm (nominal)
  - tough, still not established! → 2007 MD Target #1/3

If the accelerator world would be perfect.....

Cross-Dependability and Constrains of FB Loops II/III - Coupling I/II

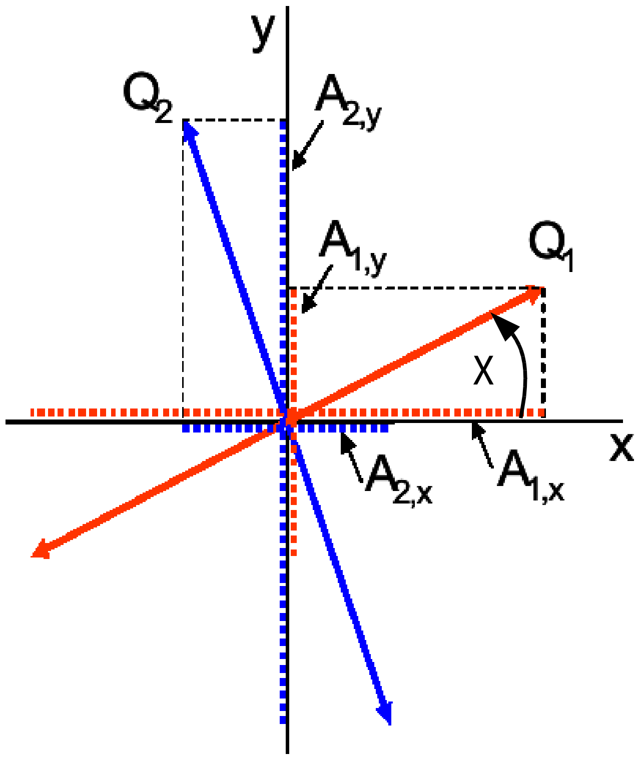
- Strictly speaking: PLL measures eigenmodes (Q_1, Q_2) which in the presence of coupling may be rotated w.r.t. unperturbed tunes (q_x, q_y, $\Delta = |q_y - q_y|$):

$$Q_{1,2} = \frac{1}{2}\left(q_x + q_y \pm \sqrt{\Delta^2 + |C^-|^2}\right)$$



- Possible improvement:
  - optimise tune working point (larger tune-split),
  - vertical orbit stabilisation in lattice sextupoles,
  - active compensation and correction of coupling

- Measure ratio between regular and cross-term:
  - $A_{1,x}$: "horizontal" eigenmode in vertical plane
  - $A_{1,y}$: "horizontal" eigenmode in horizontal plane



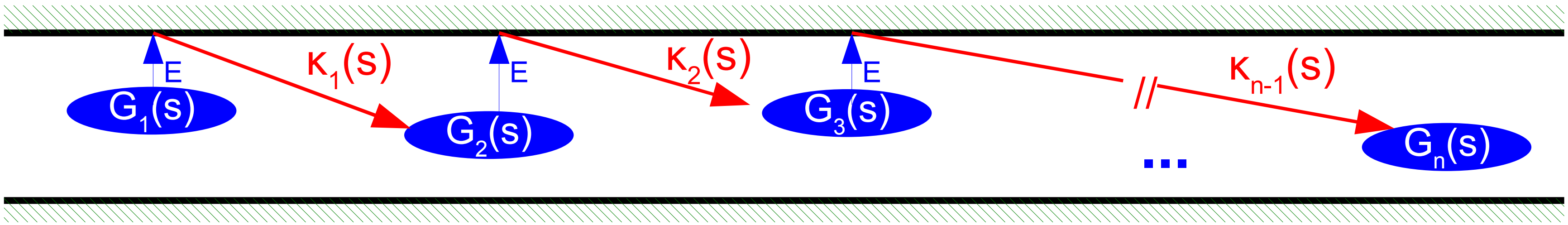
$$r_1 = \frac{A_{1,y}}{A_{1,x}} \quad \wedge \quad r_2 = \frac{A_{2,x}}{A_{2,y}}$$

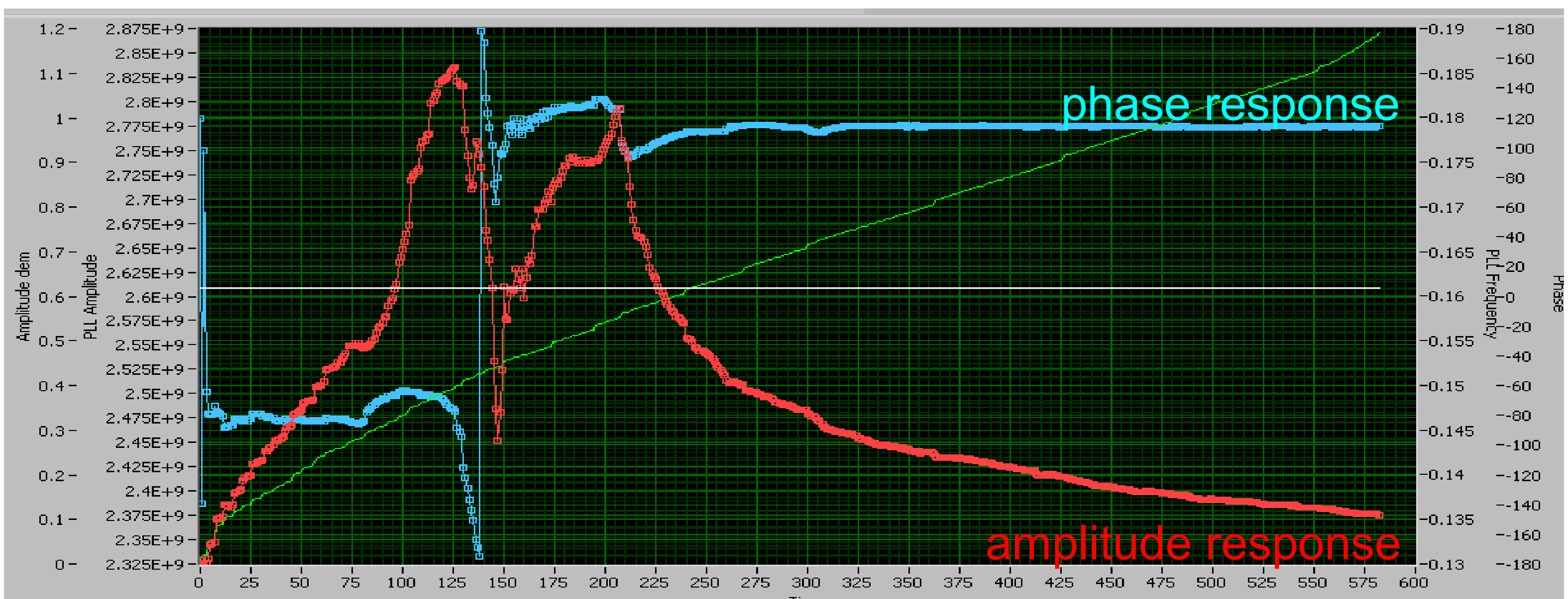
$$\Rightarrow \boxed{|C^-| = |Q_1 - Q_2| \cdot \frac{2\sqrt{r_1 r_2}}{(1 + r_1 r_2)} \quad \wedge \quad \Delta = |Q_1 - Q_2| \cdot \frac{(1 - r_1 r_2)}{(1 + r_1 r_2)}}$$

- Decoupled feedback control
  - q_x, q_y → quadrupole circuits strength
  - $|C^-|$, χ → skew-quadrupole circuits strength
    - Requires local control of strong coupling sources

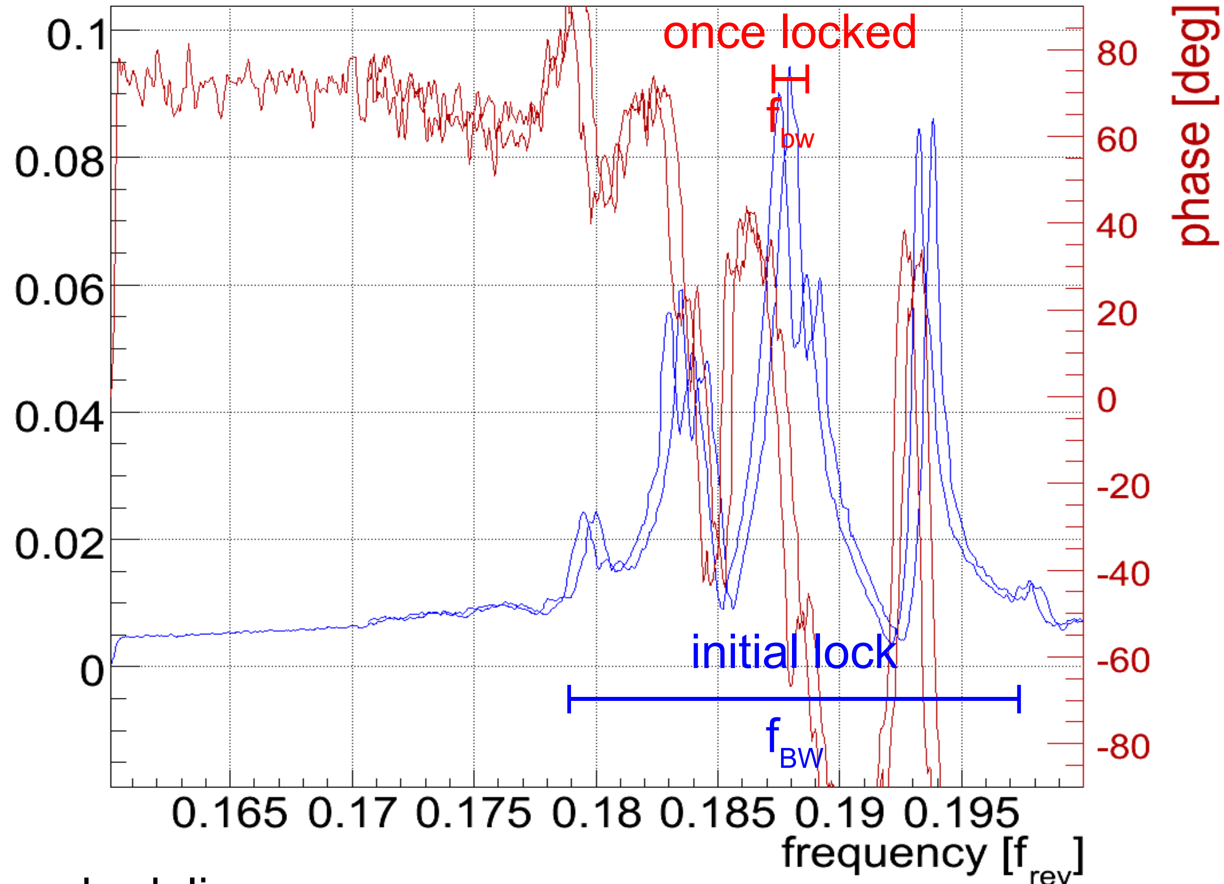
What Makes the PLL Break
- Coupled-Bunch Instabilities

- High-sensitivity PLL that operates within the transverse feedback “noise” (alternative: pilot/sacrificial bunch)
  - Pro: range separation minimises inter-loop coupling effects
  - Con: PLL does not benefit from suppression of coupled bunch modes
    - e-cloud, impedance, beam-beam, ...





What Makes the PLL Break
- Synchrotron Sidebands: PLL locks on the largest peak



Option I: gain scheduling

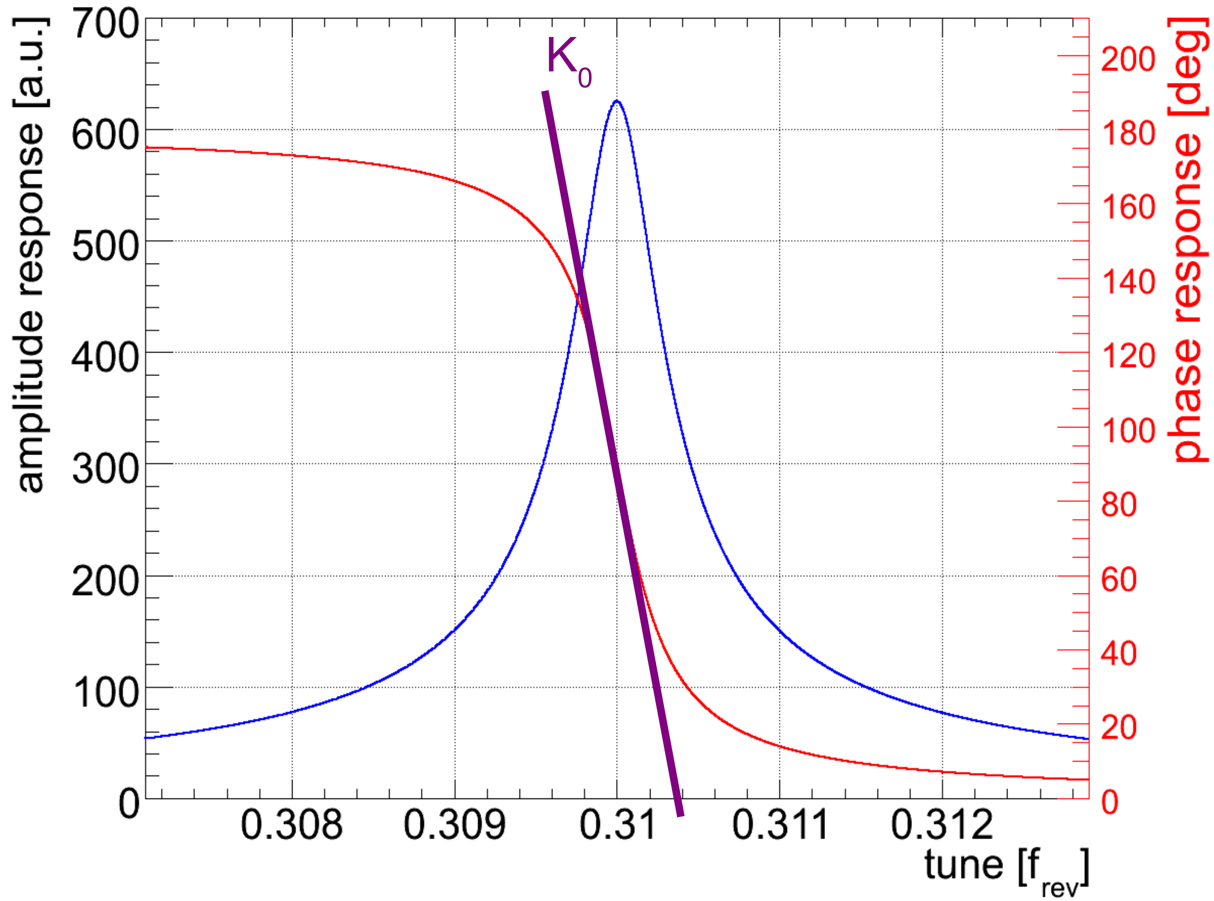
initial lock: open bandwidth to cover more than one side band (PLL noise ~ chirp)

- side-bands “cancel out”, strongest resonance prevails

once locked: reduce bandwidth for better stability/resolution

Option II: larger excitation bandwidth, multiple exciter or broadband excitation(FNAL)

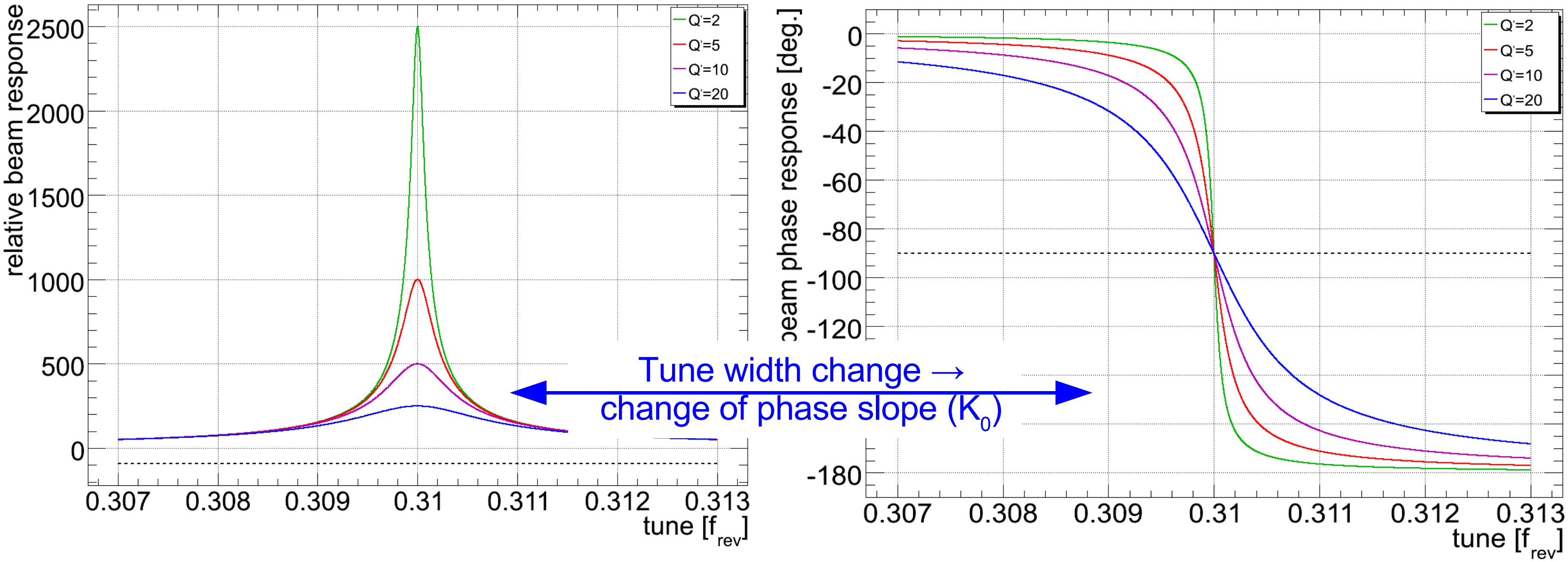
What Makes the PLL Break - Tune Width Dependence



- Reminder: optimal PLL Settings:

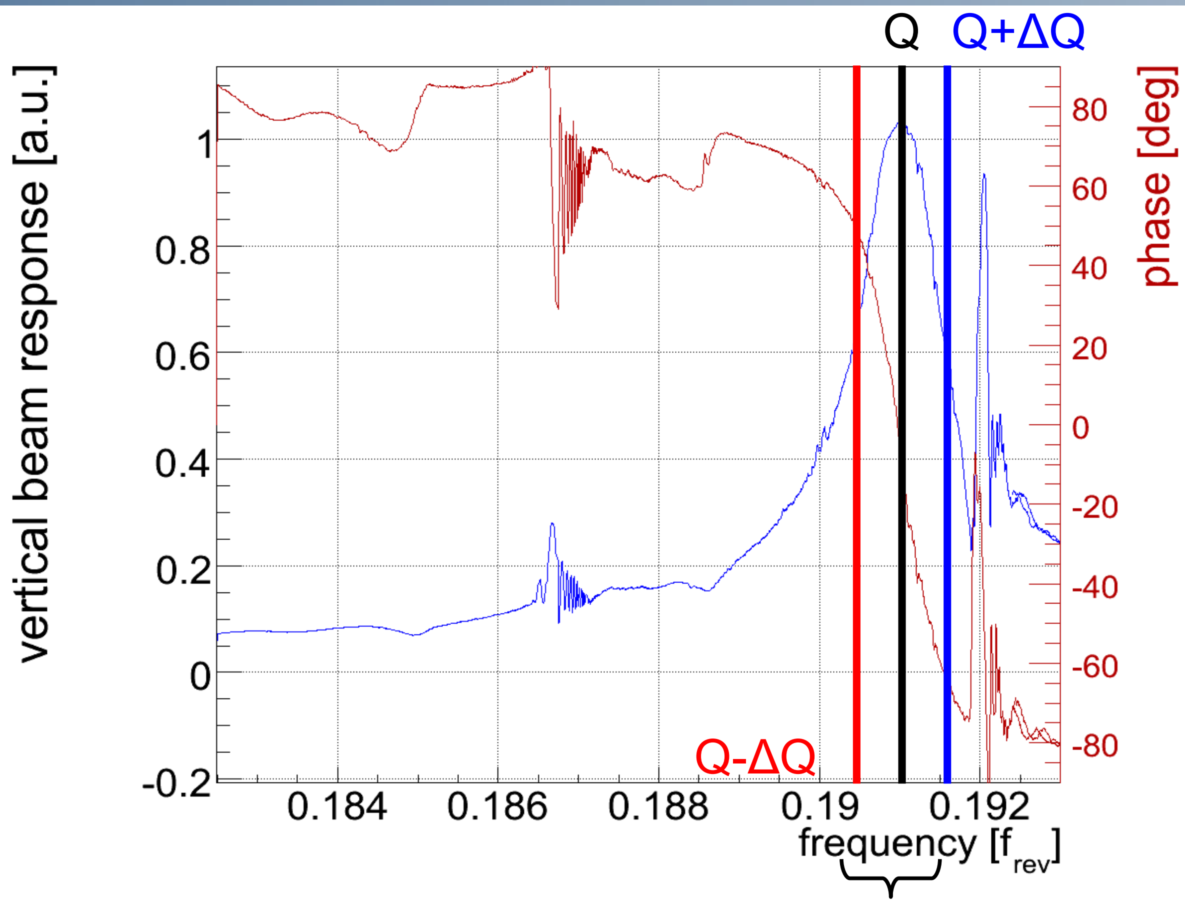
$$D(s) = K_P + K_i \frac{1}{s} \quad with \quad K_p = K_0 \frac{\tau}{\alpha} \wedge K_i = K_0 \frac{1}{\alpha}$$

What Makes the PLL Break - Tune Width Dependence



- Optimal PLL parameters (tracking speed, etc.) depend - beside measurement noise – on the effective tune width.
- Intrinsic trade-off:
  - Optimal PI for large ΔQ ↔ sensitivity to noise (unstable loop) for small ΔQ
  - Optimal PI for small ΔQ ↔ slow tracking speed for large ΔQ
- Can be improved by putting knowledge into the system: "gain scheduling"

Tune Width Measurement using PLL Side Exciter



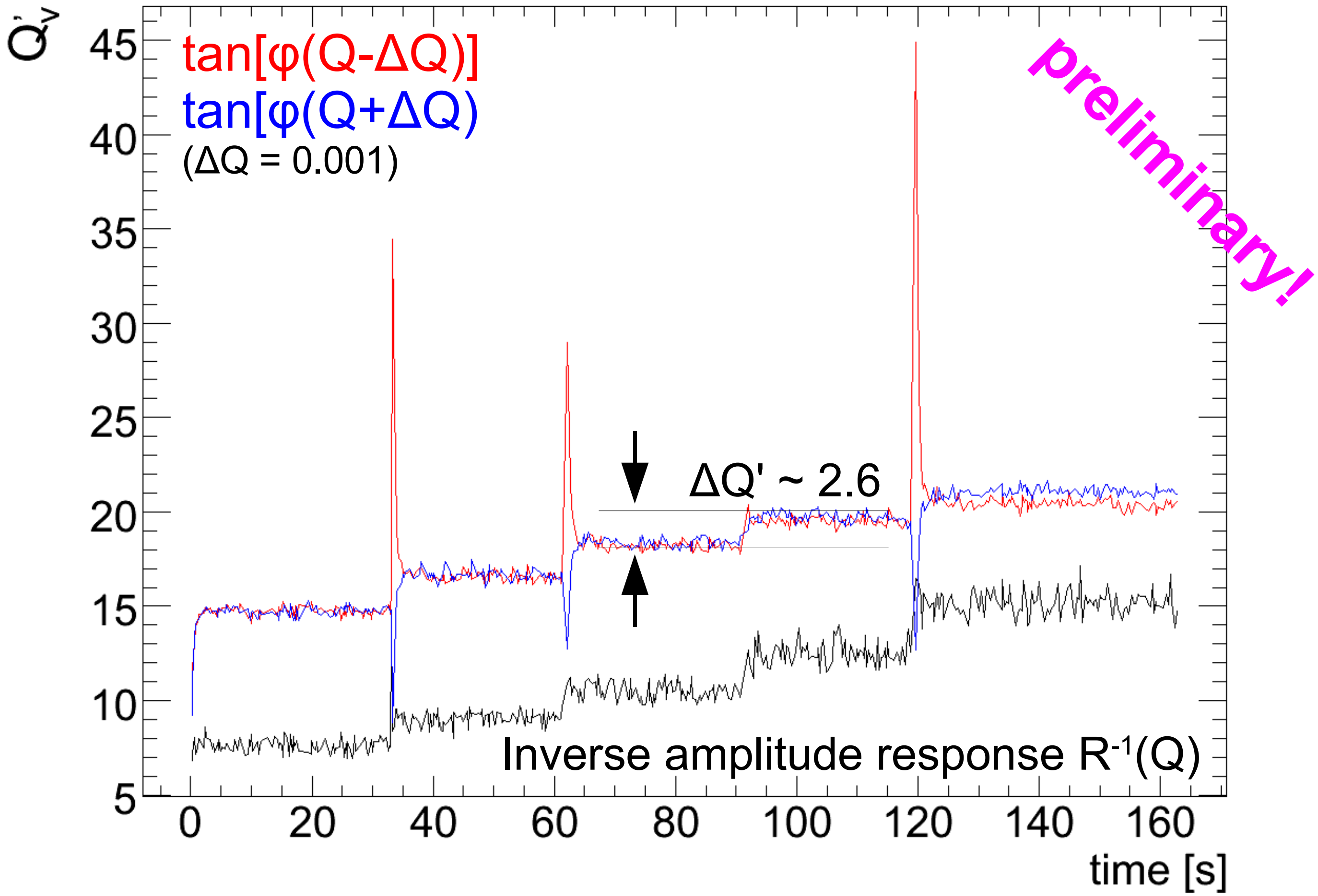
$2\Delta Q \approx 0.002 \ll 2Q_s$

- Resonant phase change ↔ tune width change
  - → “free” real-time tune footprint measurement
  - → measurable dependence of ΔQ ~ Q'

<u>driven</u> resonance:

$$\tan(\varphi) = \frac{\Delta Q \cdot \omega_Q \omega_D}{\omega_Q^2 - \omega_D^2}$$

16th November 2006: Apparent Tune Width ΔQ dependence on Q'



- Side-exciter phase appears to change linearly with Q'
  - No additional momentum modulation
  - Absolute scale requires calibration w.r.t. to classic Q' measurement
  - Non-linear effects require further assessment → 2007 MD Target #2/3

Machine Development Summary of 2006 activities

- The prototype test of the BBQ based tune PLL were very successful!
  - Mutually exclusive modes of PLL operation:
    - either: track tune changes 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...
  - at least a factor 10 smaller than standard SPS MultiQ
  - done with a S/N ratio of less than 3..10 dB

- BBQ based PLL showed to be very robust as long as bunch-to-bunch coupling was small
  - will be addressed through selecting only single bunch

- Question is not: “Can we measure chromaticity?”, but “Can we measure Q' with a given precision and minimal excitation?”
  - Requires studies of systematics with “slow” coasting beam to prove feasibility of LHC Q' baseline ($\Delta Q'=1$ & $\Delta p/p \ll 10^{-4}$)

Outlook Machine Development Studies in 2007

Measurement programme:

a) LHC Q' baseline via slow $\Delta p/p$ modulation, 3x8h

b) Indirect Q' through ΔQ measurement, 3x8h

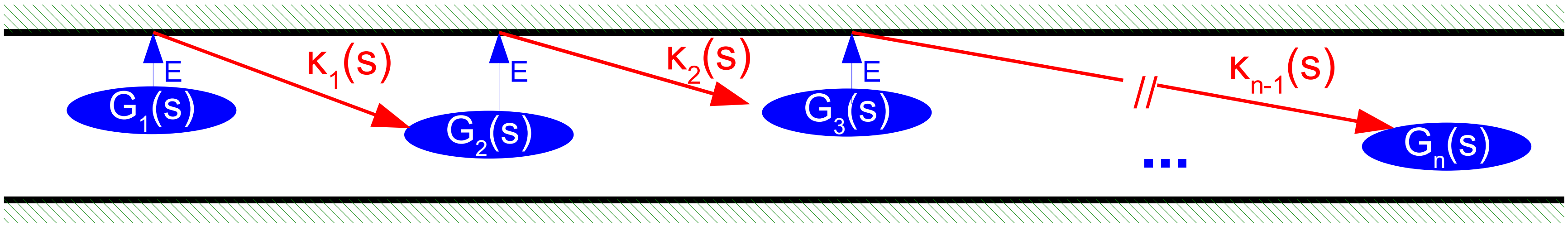
c) Q' through continuous head-tail phase shift, 3x8h

d) HW tests, mostly in parallel to regular physics programme

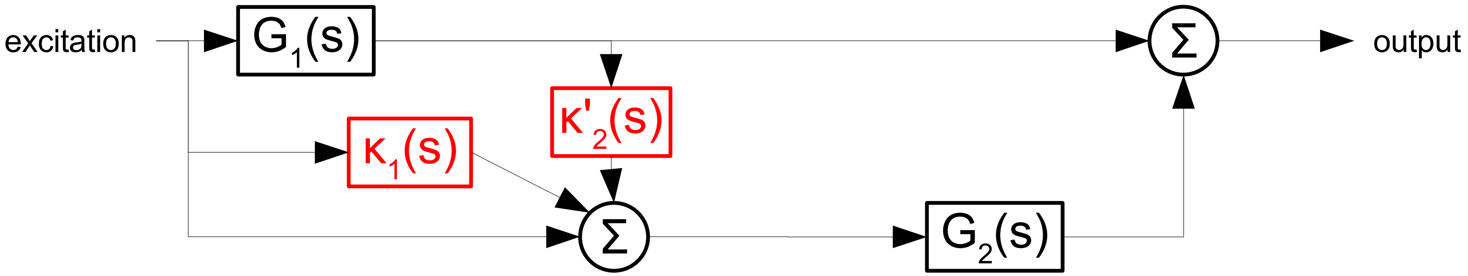
- Total dedicated MDs:
  - coasting beam @ 270GeV: W28, W32, W35, W37, W42
  - coasting beam @ 26GeV: W30, W34
  - Reminder: assumed accelerator efficiency of about 60%

Reserve Slides

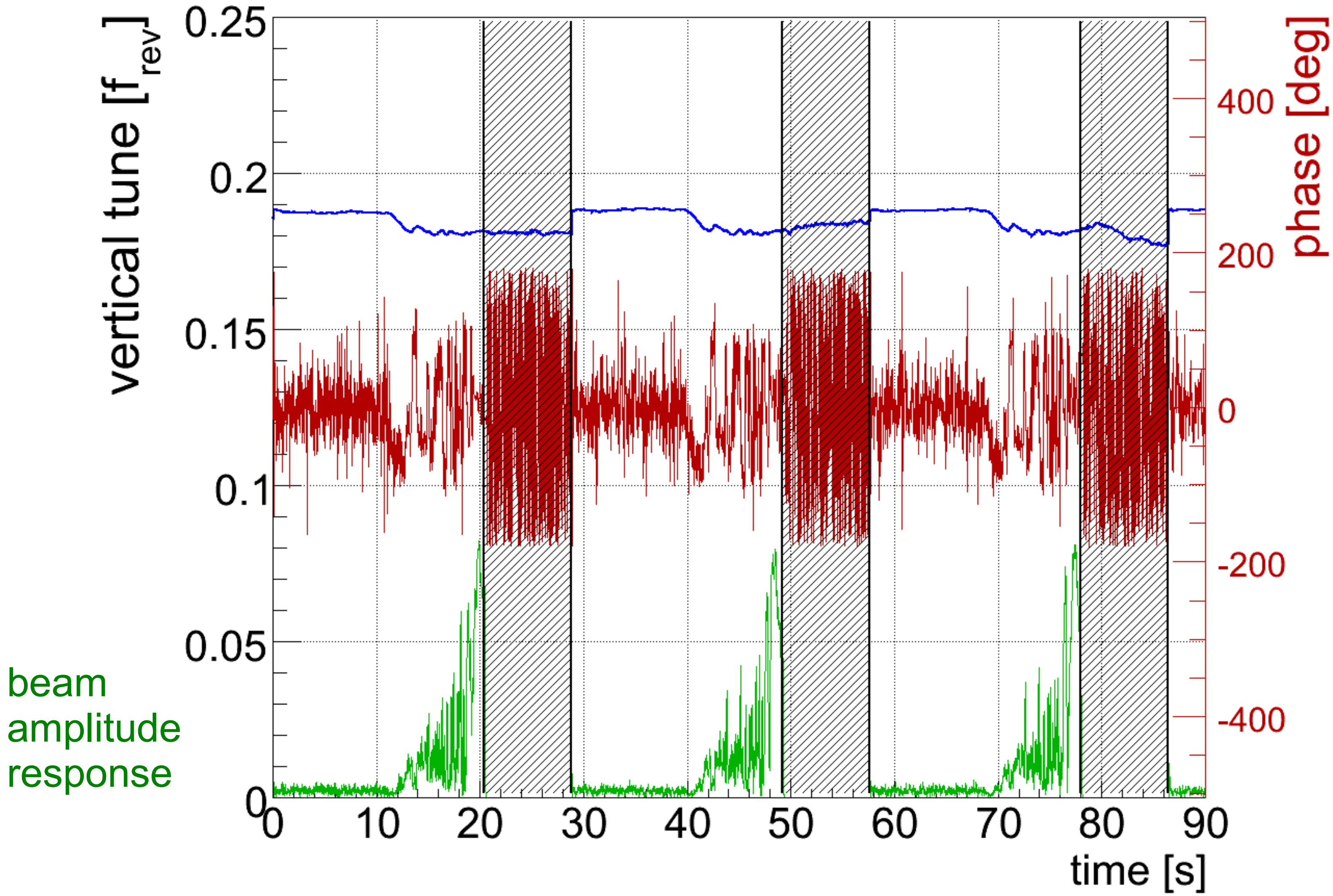
- Coupled bunch effect became more pronounced during later MDs
  - possible causes: impedance driven wake fields, e-cloud, ...



- 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



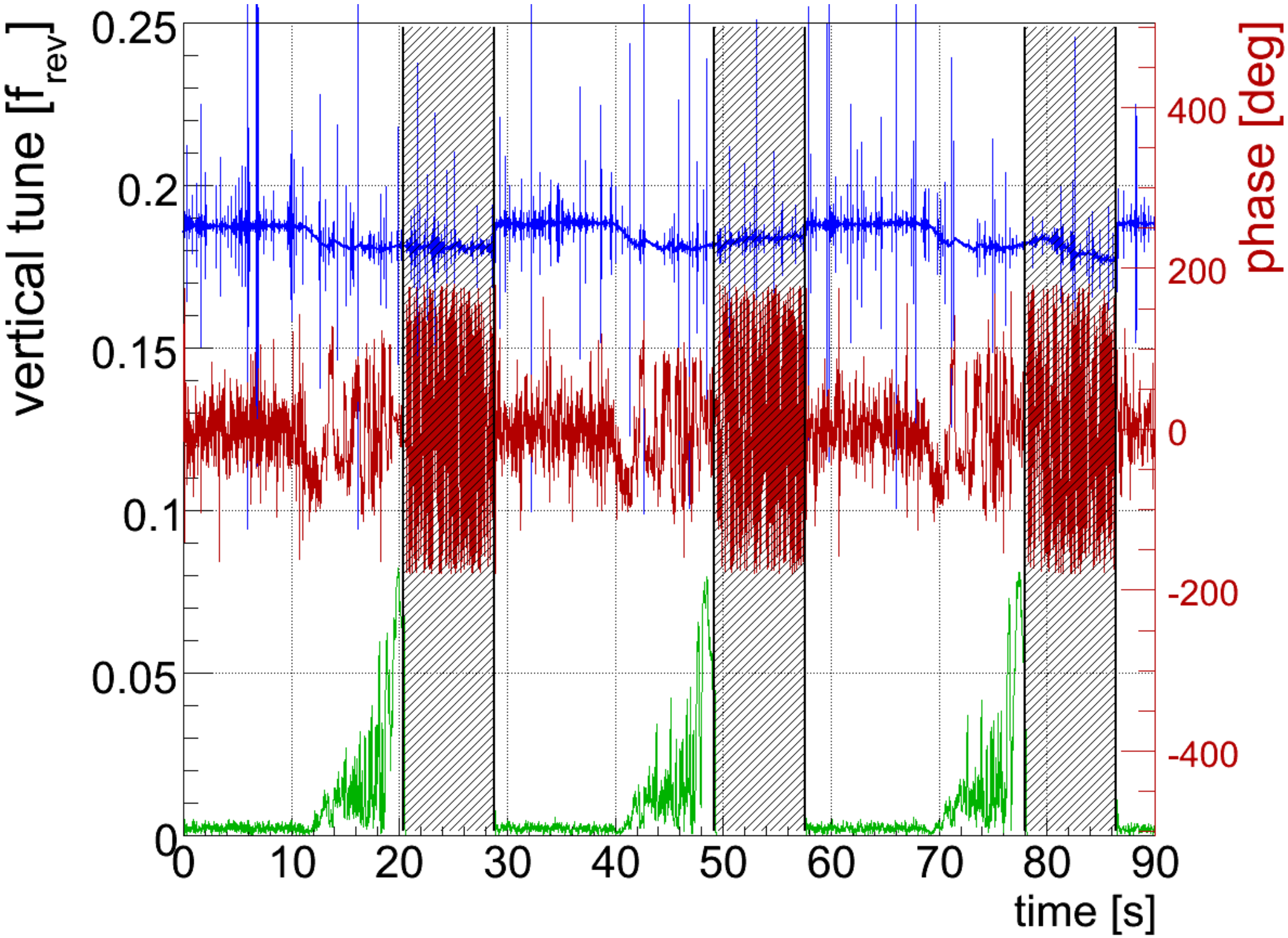
- Possible remedy: BBQ selects and measures only one (first) bunch



- 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)

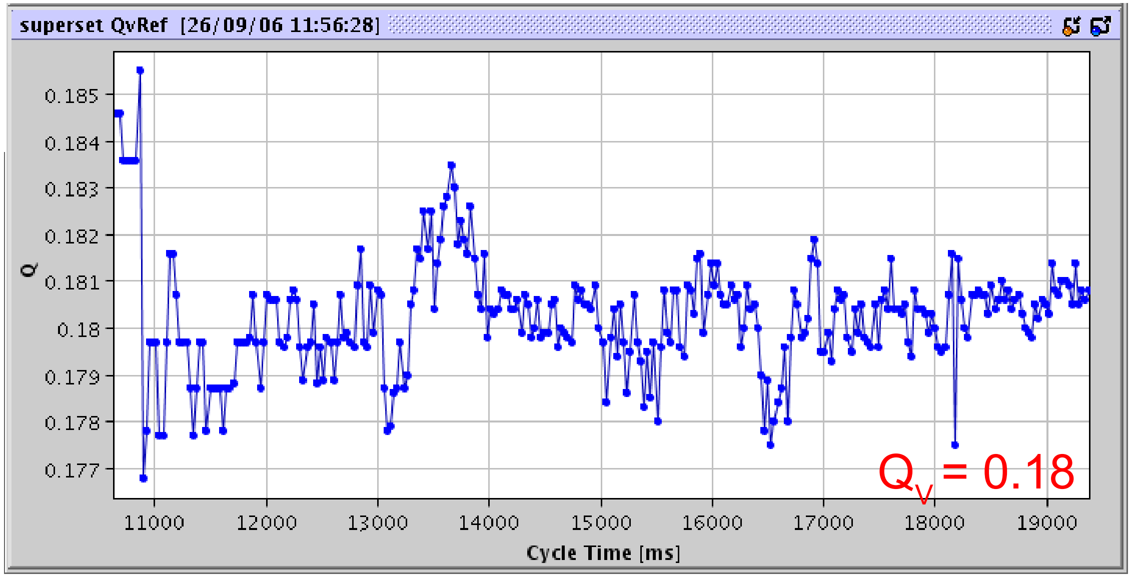


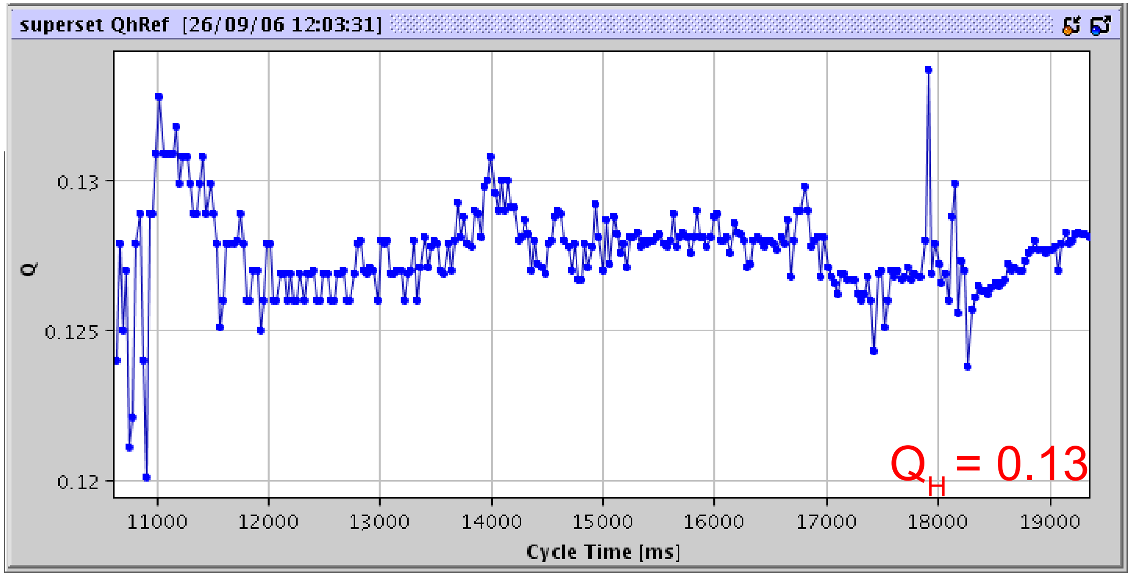
- After some spike filter routine: $\Delta Q_{res} \approx 10^{-4} - 10^{-5}$ @ 10 Hz

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

Measurement Methodology I/III

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



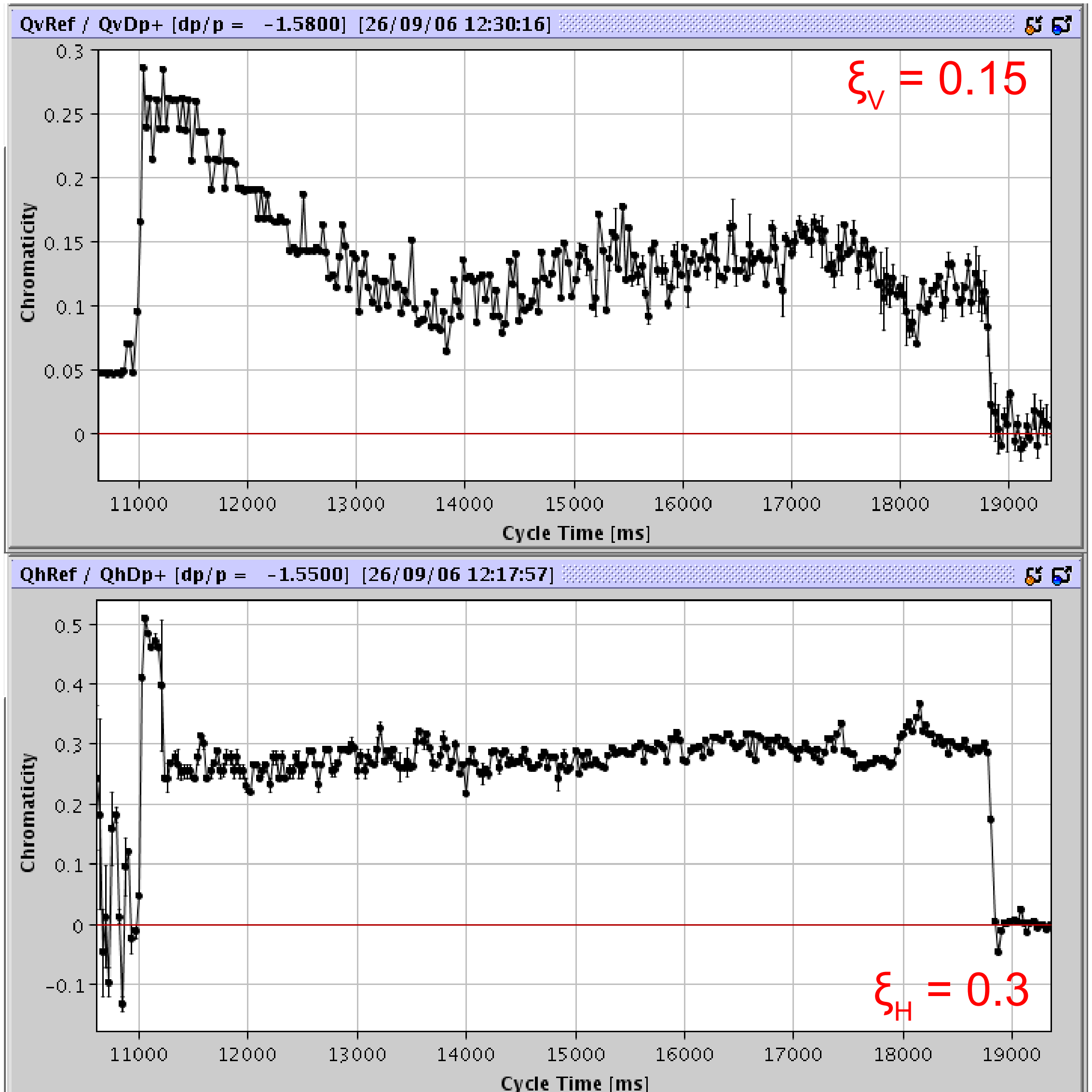


- Slow variation of Q
- $\Delta Q_{res} \approx 10^{-3}$ visible

APC, PLL Tune and Chromaticity Measurements, Ralph.Steinhagen@CERN.ch, 2007-06-08

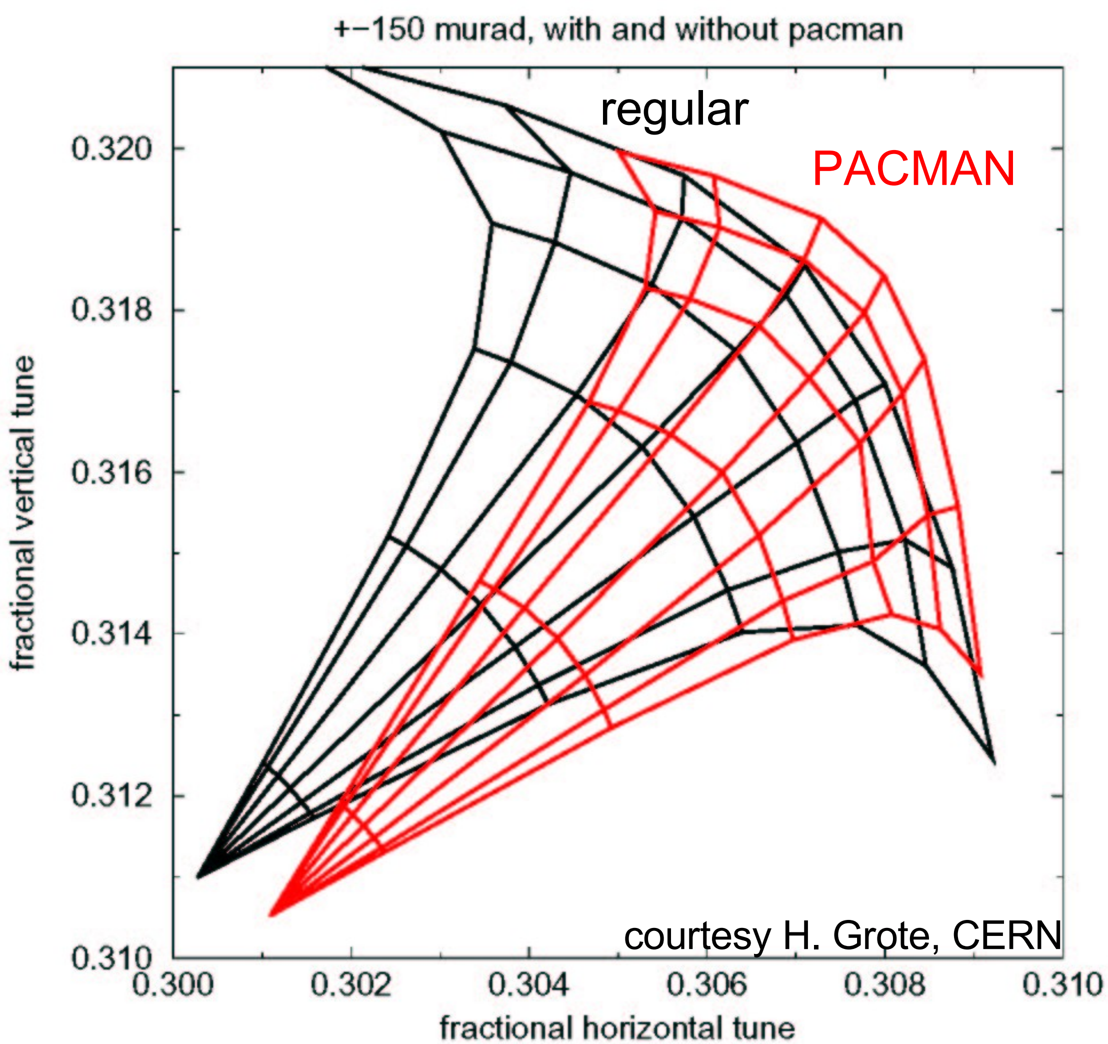
Measurement Methodology II/III

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

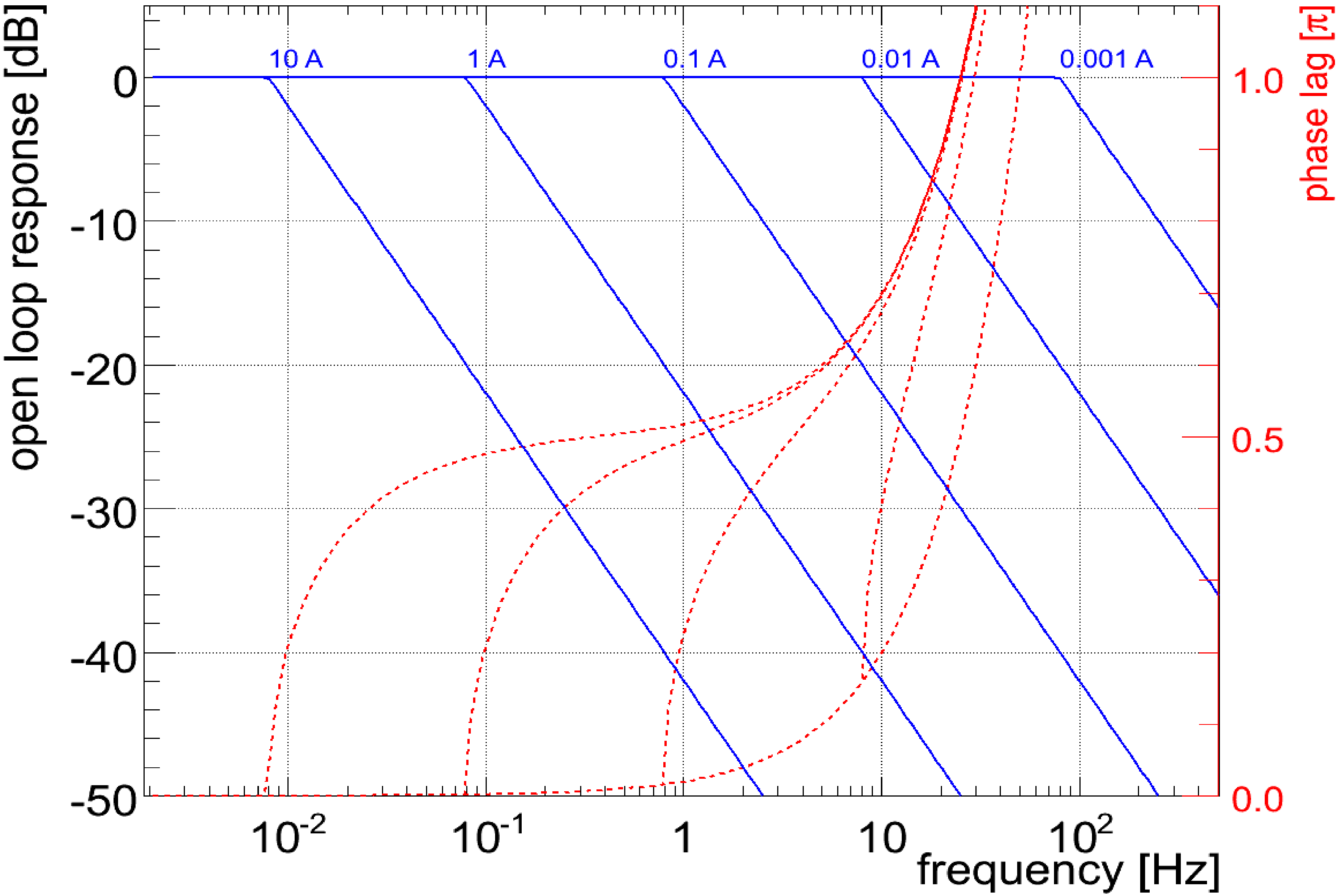


- Injecition: Q'≈2
- ΔQ_{res} (~ΔQ_{res}) visible
- $\Delta p/p \approx 1.6 \cdot 10^{-3}$

Expected LHC Tune Footprint



Non-linear Slew-rate Limited Exciter Response



LHC orbit dipole corrector: ΔI=0.01 ↔ Δx ≈ 15 μm @7TeV