Results of the

Tune and Chromaticity MDs in the SPS

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for the BI-QP team

Outline

- Motivation for extensive Q' MDs in the SPS
- Base-line LHC Q' measurement techniques
  - slow Δp/p modulation based
  - Beam-Transfer-Function based Side-Exciter method
  - Results with Beam at the SPS
- Outlook and 2008 MD programme

Reminder: LHC Tune and Chromaticity Requirements

- The measurement and control of

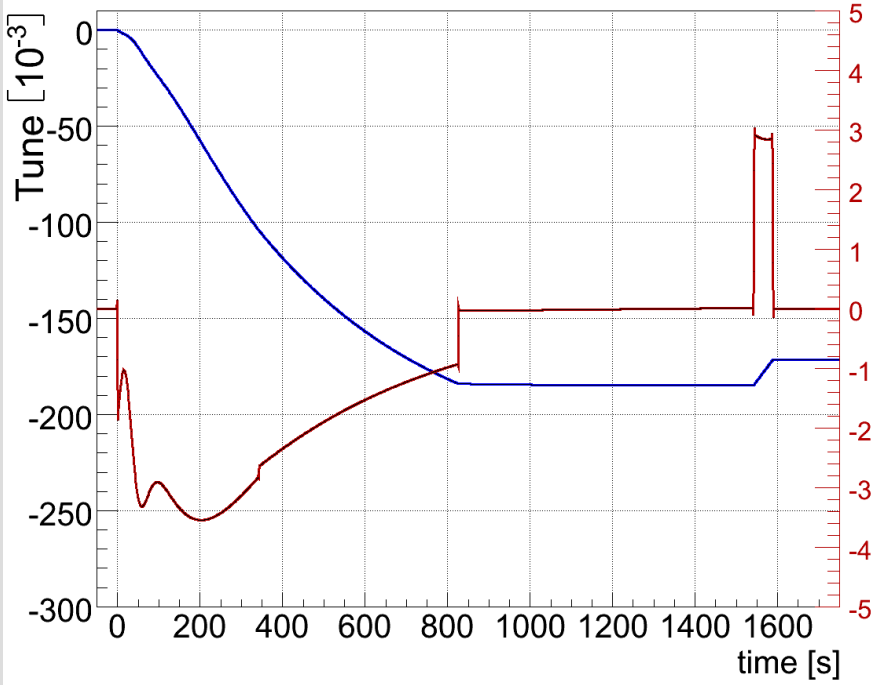
  -- orbit, tune, chromaticity, energy and coupling --

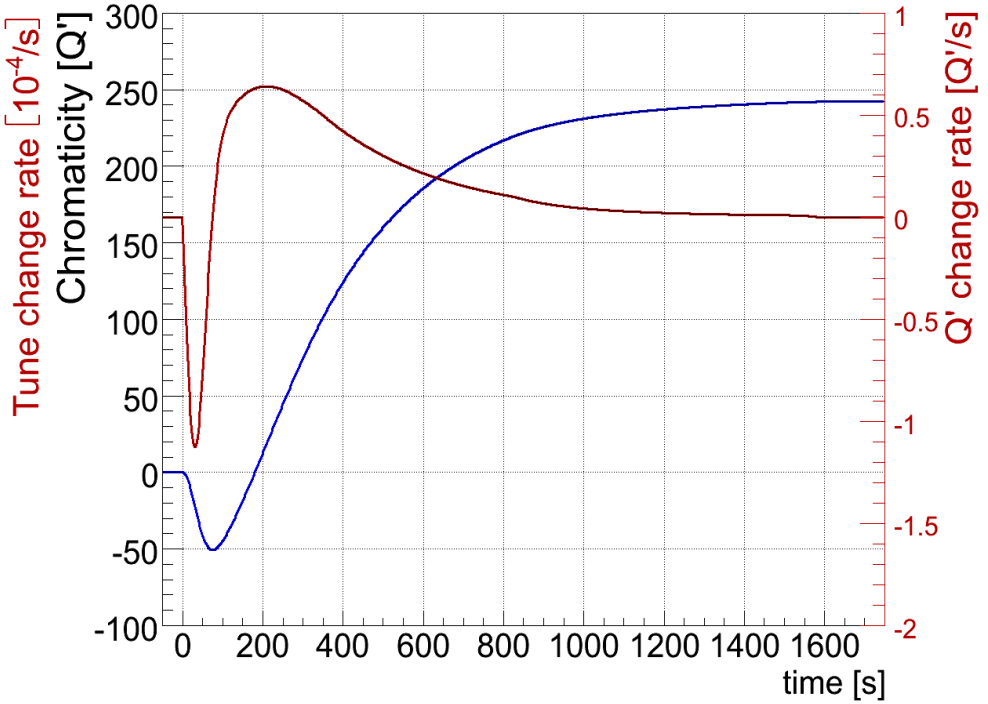
  will be an integral part of the LHC operation

- Stability requirements summary (Chamonix'06):

	Orbit [σ]	Tune [0.5·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

Reminder Exp. Tune and Chromaticity Drifts during LHC ramp

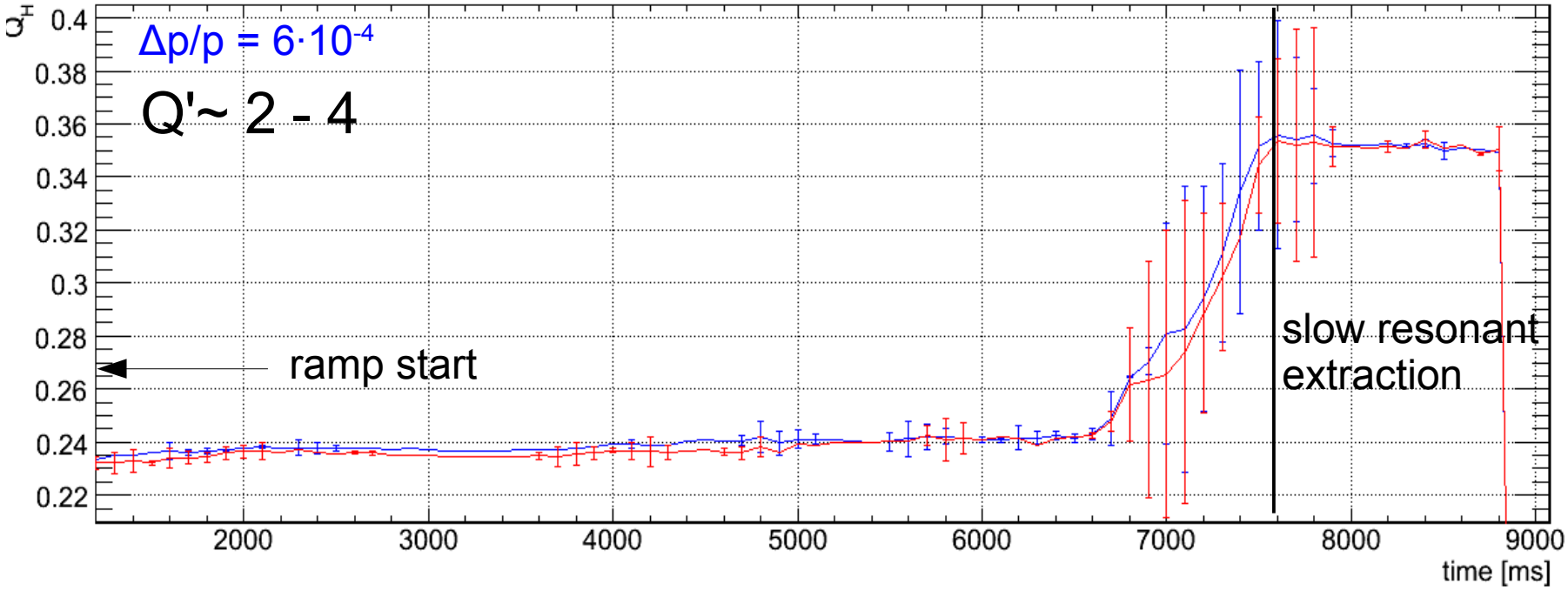




- Exp. perturbations are about 200 times than required stability!
- however: maximum drift rates are expected to be slow in the LHC
  - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
  - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2\ s^{-1}$ ← the critical/difficult parameter
- Requires active control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

Flash Back: APC 2007-06-08

- 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': $\Delta x < 35$ µm (nominal)
  - tough, still not established! → 2007 MD Target #1/3

Today ~ one year later: → this presentation's focus

Flash Back: APC 2007-06-08
Outlook Machine Development Studies in 2007

Measurement programme:

a) LHC Q' baseline via slow Δp/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%

- End of 2007: half of our MD time was lost to due to
  - machine setup (timing table setup errors, going-into-coast errors, ...)
  - tardy users prior to our MDs (clean-up of previous settings, ...)

- However, we express our gratitude to OP, Elias and many others for the good cooperative environment that nevertheless made these measurements under these circumstances possible.

LHC Base-Line Q/Q' Diagnostics Overview – Q'

- Slow RF momentum modulation – LHC Commissioning Phase A.3
  - class: Q' is proportional to momentum induced tune changes

$$Q' = \frac{\Delta Q}{\Delta p / p}$$

the measured tune change

the RF induced momentum change (known)

- Kicked Head-Tail Phase-Shift – LHC Phase A.3 (~ copy++ of SPS installation)
  - Status Quo (with a few detection improvements/GUI though)
  - multiple dependences on beam parameter other than Q'
    - impedance, non-linear damping (Q'/Q'', RF damper), non-lin. Q_s, Q_s
  - limited by emittance growth/orbit budget
    → however: still a good cross-reference and diagnostics tool for MDs
- Side-exciter based method – end 2008/beginning of 2009
  - needs broader acceptance (human component) and assessment with LHC beam (parameters)
- Continuous Head-Tail Phase-Shift – 2009++
  - Tested various schemes in2007 at the SPS but need further assessment.

Q' trough RF momentum modulation based method

$$Q' = \frac{\Delta Q}{\Delta p / p}$$

← *the measured tune change*

← *the RF induced momentum change (known)*

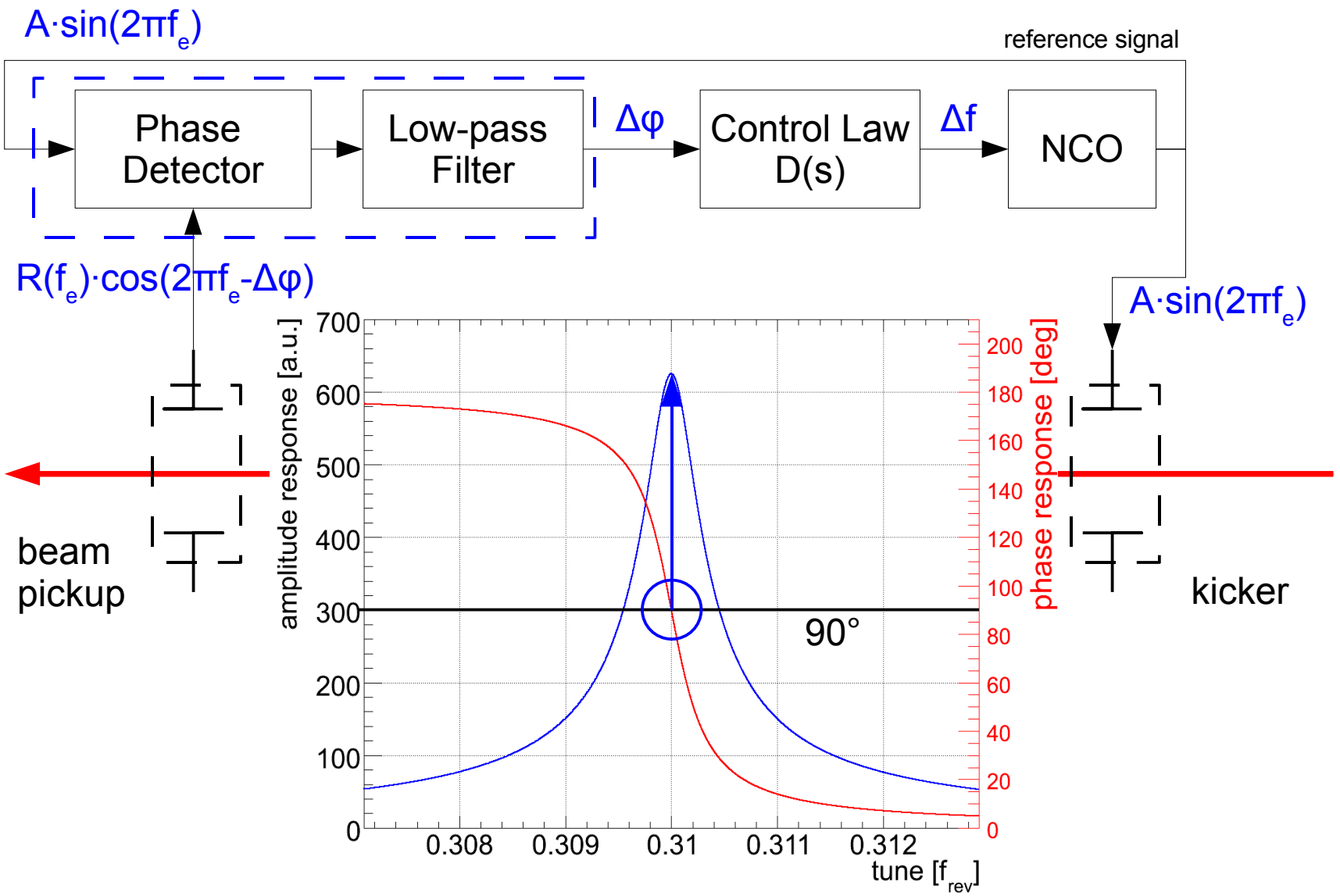
- There are multiple but similar detection techniques (classic, Brüning, McGinnis, ...)
  - LHC RF cooling power permits only slow modulation (J. Tückmantel et al.)
- Controllability of Q' depends on ability to track the tune both accurately & fast, two options:
  - Fourier based: $\Delta Q_{res} \propto \frac{1}{\sqrt{t_{meas}}}$ t_{meas}: duration of measurement
  - Phase-Locked-Loop based: $\Delta Q_{res} \propto \frac{1}{t_{meas}}$
- Also intrinsic to this problem: $\Delta Q_{res}^{(,)} \cdot \Delta t_{res} = const.$
  - LHC expectations:
    - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
    - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2\ s^{-1}$

  } "slow" compared to Q/Q' drifts e.g. in the SPS/CPS/PSB

→ Choose to tackle the Q/Q' measurement in the high accuracy limit.

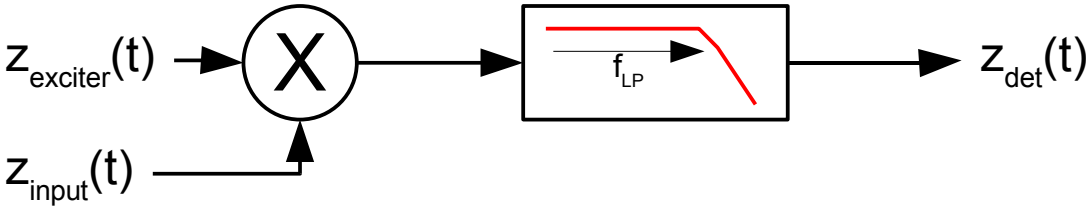
→ very small but slow (few Hz) Δp/p modulation while tracking Q with a PLL

Quick-Reminder: Classic Phase-Locked-Loop Scheme



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

Quick Reminder: Classic PLL Detector



$$z_{det}(t) = LP\left(z_{input}(t)\cdot z_{exciter}(t)\right)$$
$$= LP\left(R(f_e)\cdot\cos(2\pi f_e - \Delta\varphi(t))\cdot A\sin(2\pi f_e)\right)$$
$$= \frac{AR}{2}\sin(\Delta\varphi(t)) + \frac{AR}{2}\sin(4\pi f_e - \Delta\varphi(t))$$

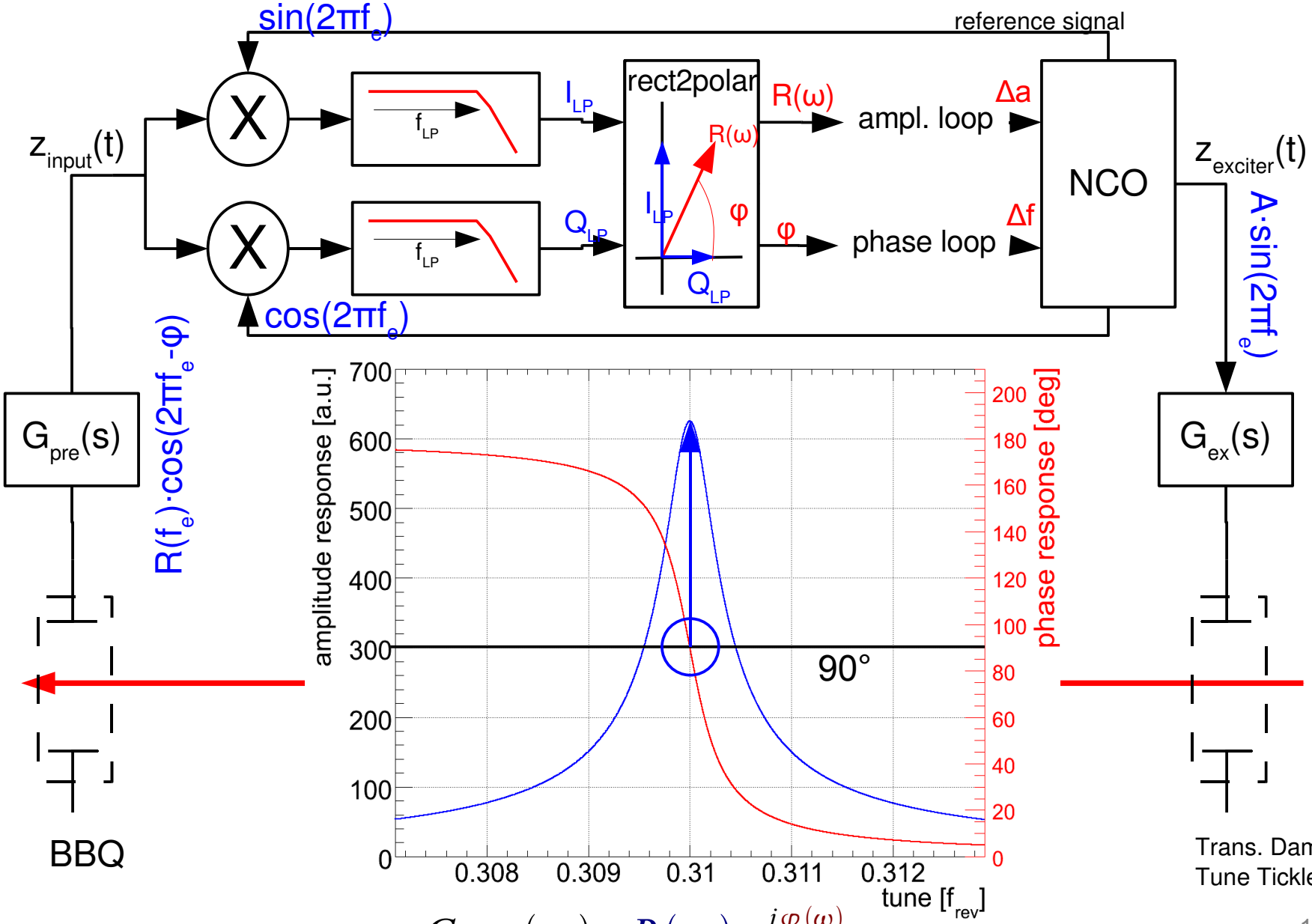
for small phases

$$\approx \Delta\varphi(t)$$

removed by low-pass filter

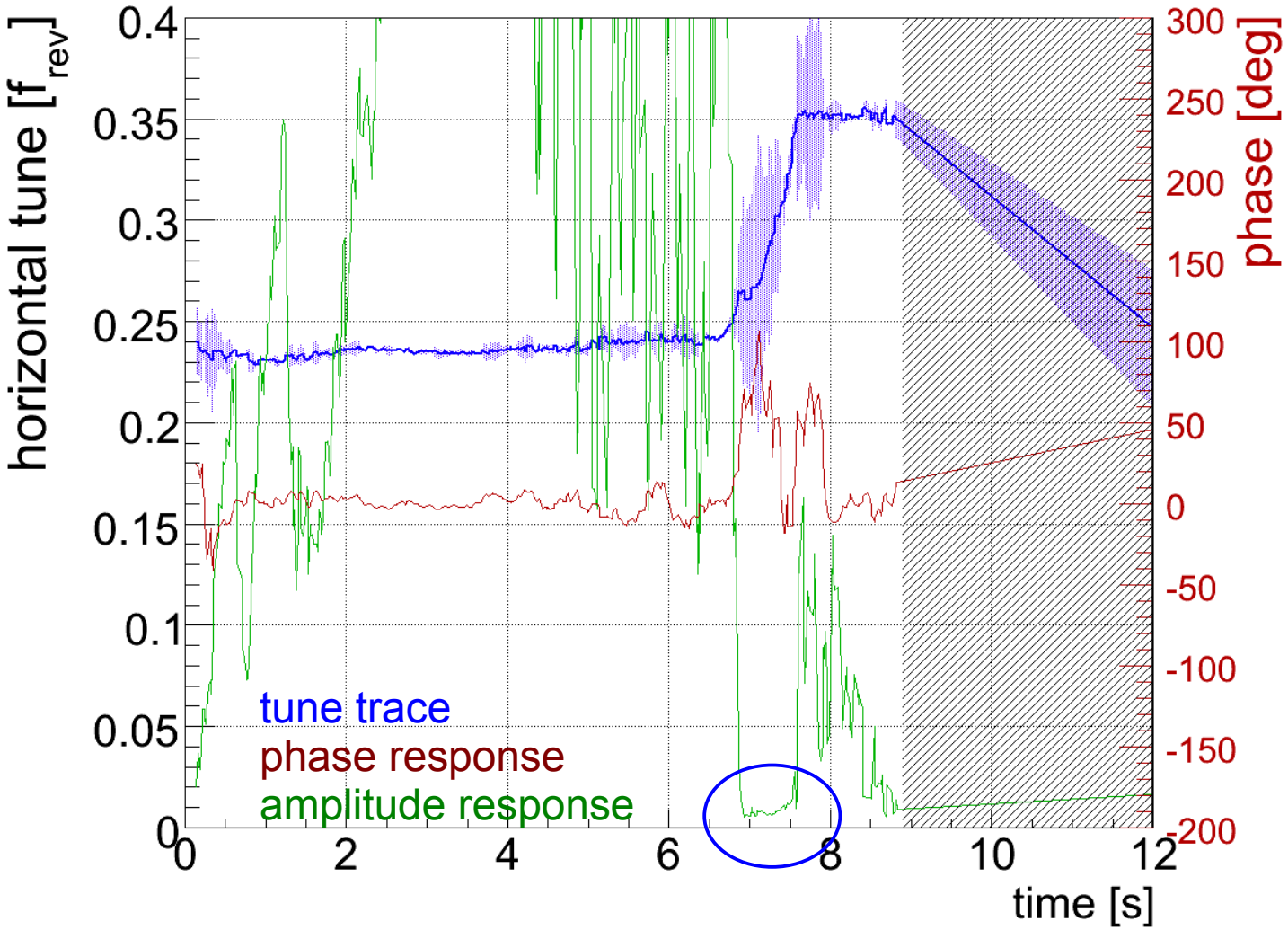
- Pro: robust analogue circuit implementation possible
- Con:
  - non-linear control signal for large phase difference Δφ
  - Control signal depends on beam response's amplitude R(f_e)

Quick Reminder: LHC Phase-Locked-Loop Scheme



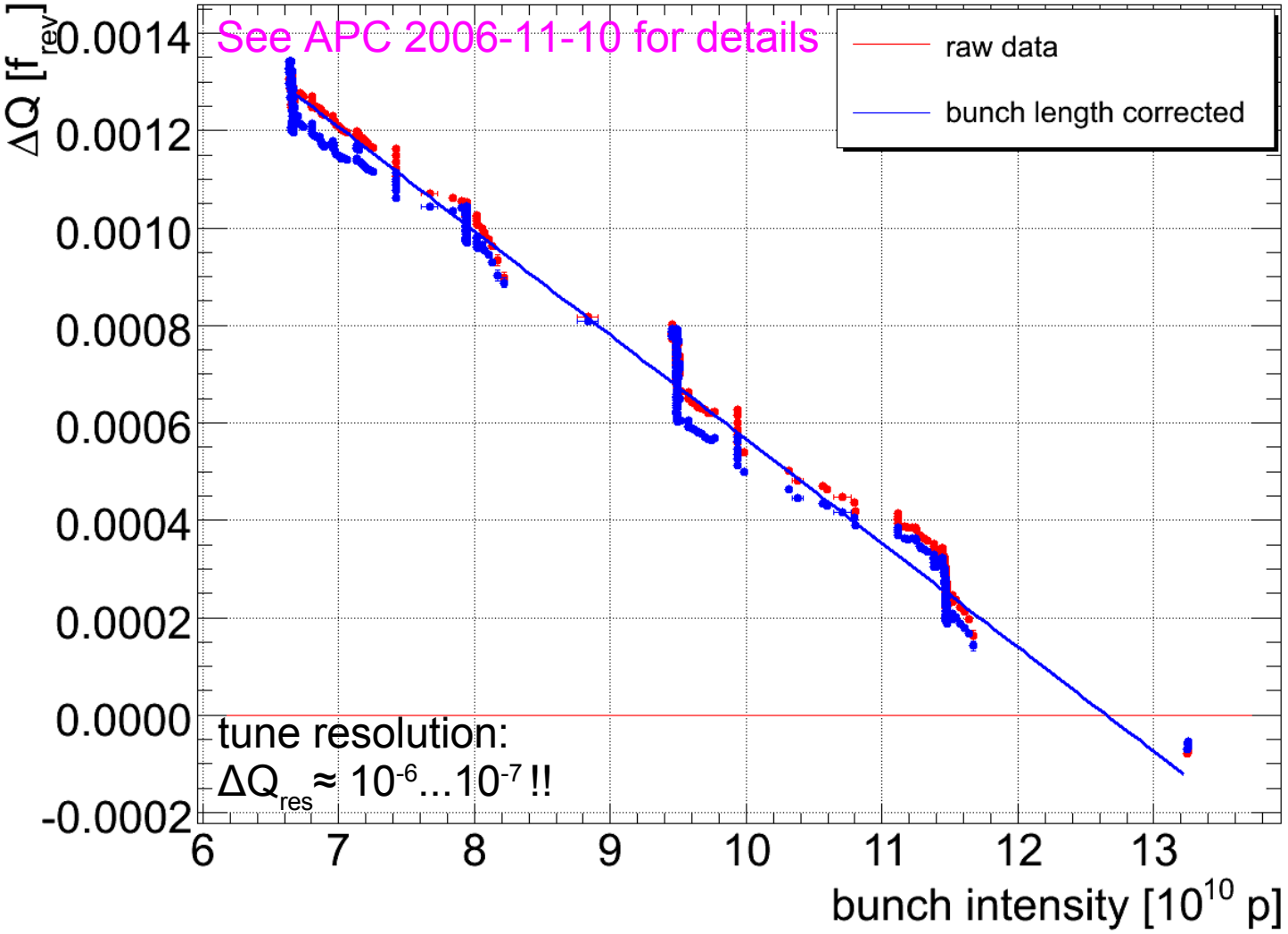
$$G_{Beam}(\omega) = R(\omega) \cdot e^{i\varphi(\omega)}$$

Flash Back: APC 2007-06-08
SPS PLL Tune Tracking – fast tracking



- Phase error and non-vanishing amplitude indicate lock during ramp
- $\Delta Q/\Delta t|_{max} \approx 0.3$ within 300 ms, two orders of magnitude faster than LHC req.
  $f_{rev} \approx 43$ kHz

Flash Back: APC 2007-06-08
SPS Impedance at 270 GeV – precise tracking



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

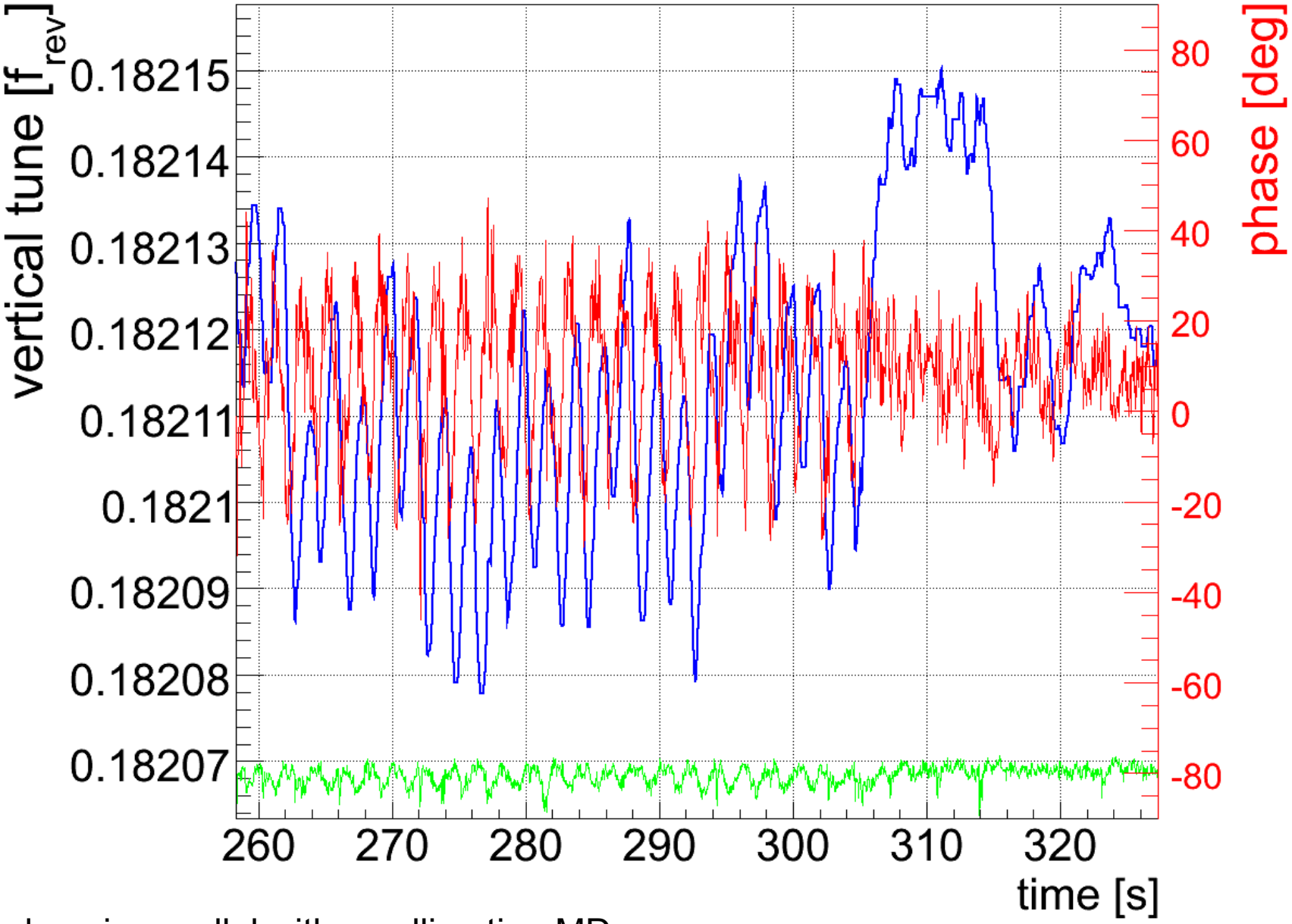
2007 Q' Milestone: High-Res. Q Measuremnt of RF Induced Δp/p Modulation

- SPS Q' MD parameters:
  - RF modulation frequency: 0.5 Hz (fixed frequency external generator)
    - $\Delta p/p < 2 \cdot 10^{-5}$ & $\Delta Q_{res} \sim 10^{-6}$!!
    - limited by RF DAC generator quantisation (f_{max}-f_{min} ↔ ~ 6 bins)
  - Foreseen LHC parameter: $\Delta p/p \sim 10^{-5}$ @ f_{mod} = 1-2 Hz
    - essentially limited by whether:

$$\frac{Q' \cdot \Delta p/p}{\Delta t} > \left| \frac{\Delta Q}{\Delta t} \right|_{max}$$

    - possible optimisations:
      - either: increasing Q'_{ref} to e.g. 10 units (LHC Stage-1)
      - or: increasing Δp/p amplitude
        - » only possible with low-intensity beam (depreciated)
      - or: increasing fmod (PLL limit: << 60 Hz)
        - » estimated maximum analogue PLL bandwidth ~ 6- 10 Hz
    - Multiple detection techniques available:
      - linear regression, full X^2-fit, amplitude demodulation (LHC),

PLL based Q/Q' tracking study at the SPS
Radial RF modulation dp/p=1.6·10^{-5}, set ξ := 0.05



N.B. done in parallel with a collimation MD

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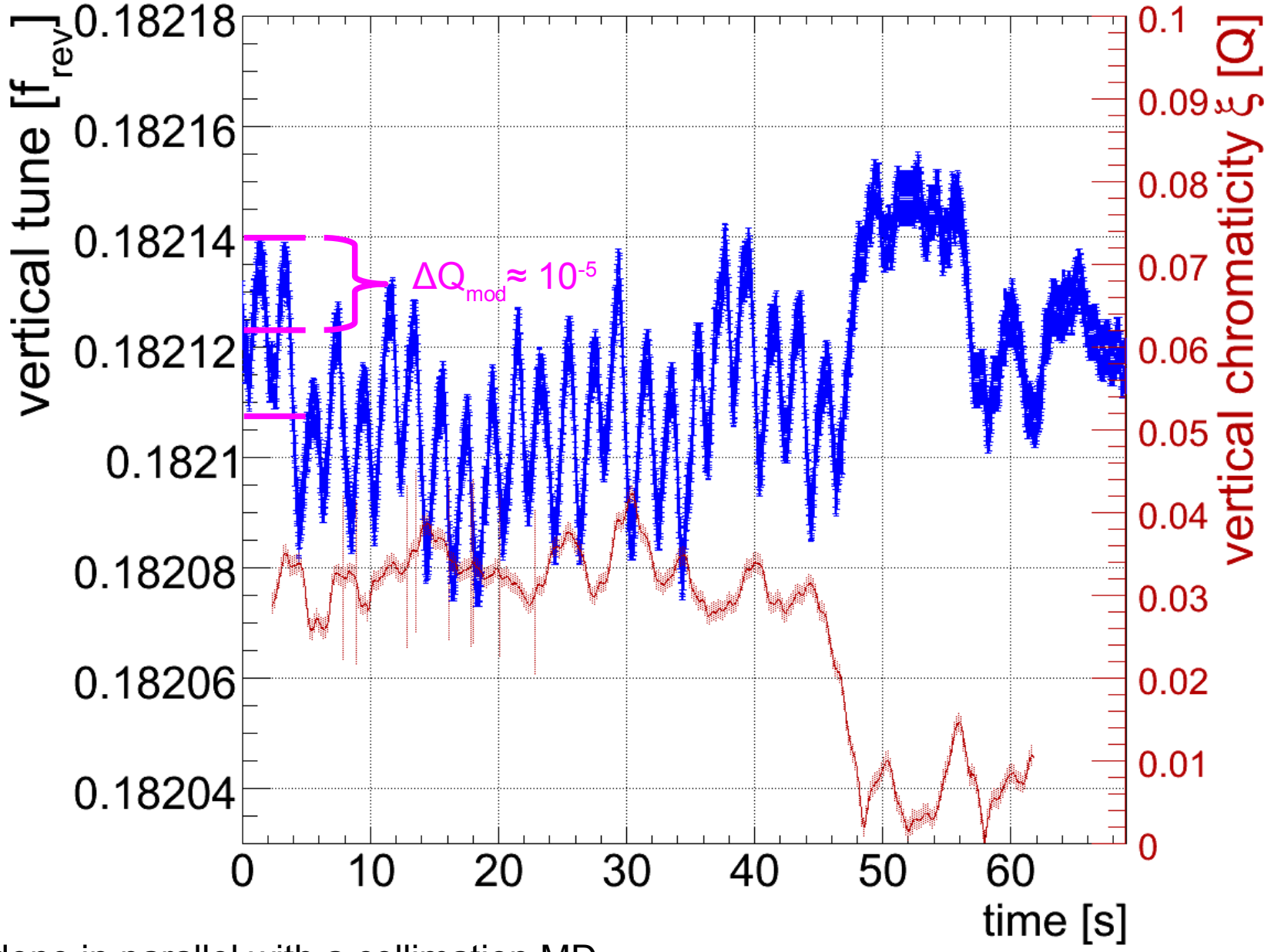

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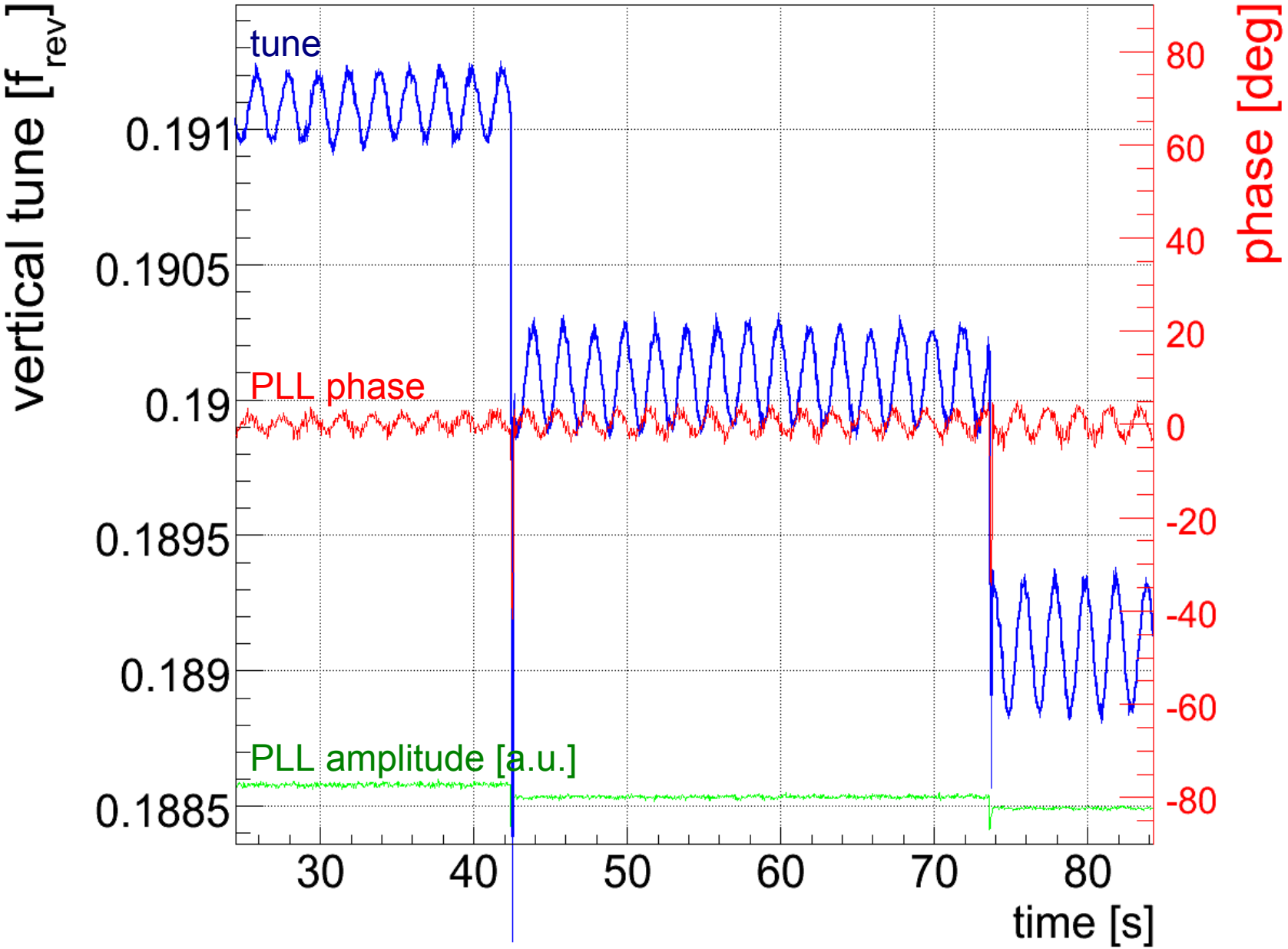
Dedicated PLL based Q/Q' tracking study at the SPS
Modulation Amplitude: $\Delta p/p \approx 1.85 \cdot 10^{-5}$



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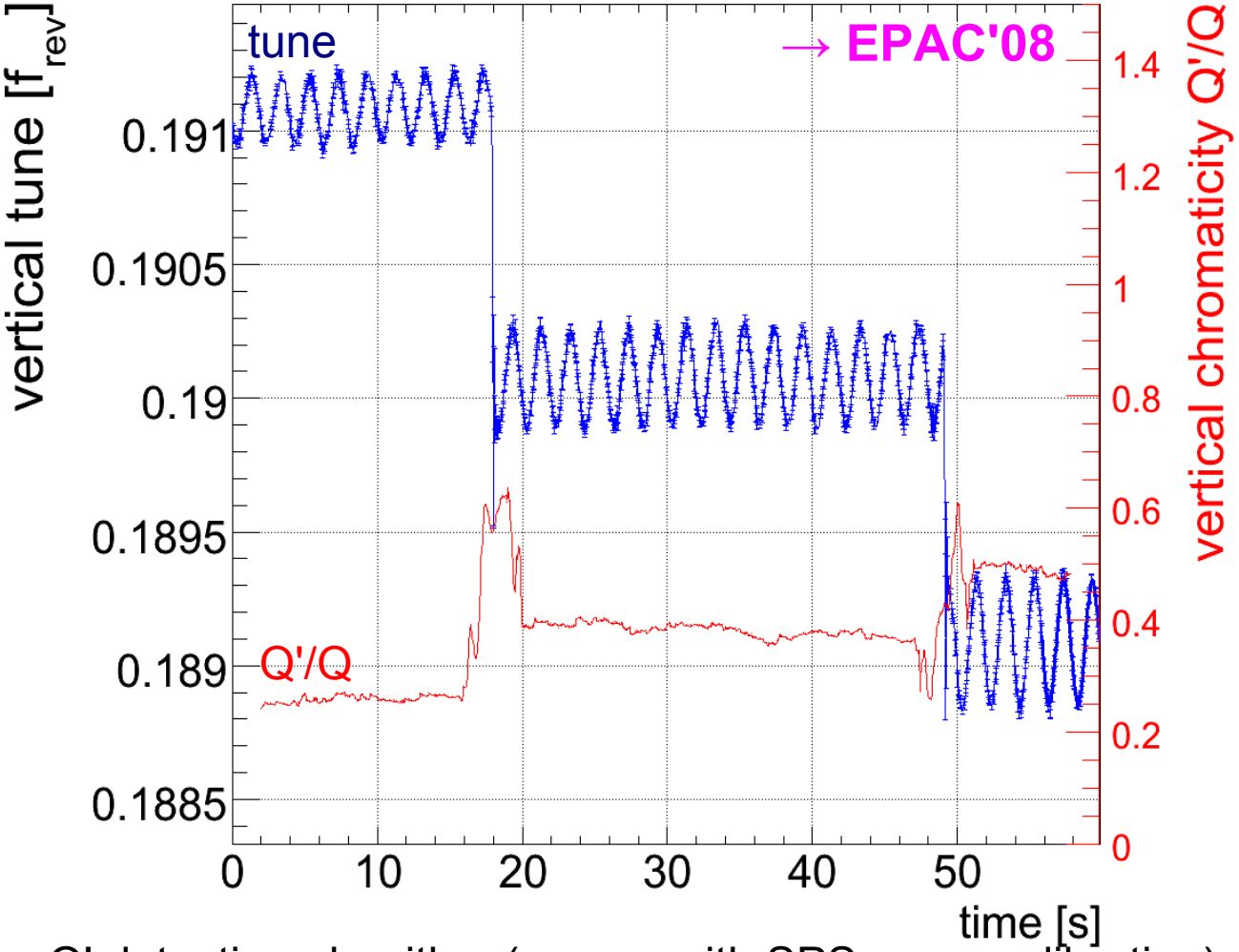

- real-time Q' detection algorithm (agrees with SPS cross-calibration):
  - Q' resolution better than 1 unit (nominal performance)
  - N.B. tracking transients: ΔQ' feed-down on ΔQ (non-centred orbit)
    - $\Delta Q/\Delta t \gg \Delta Q'/\Delta t \rightarrow$ SPS specific, LHC: $\Delta Q/\Delta t|_{max} < 10^{-4}$/s

Dedicated PLL based Q/Q' tracking study at the SPS
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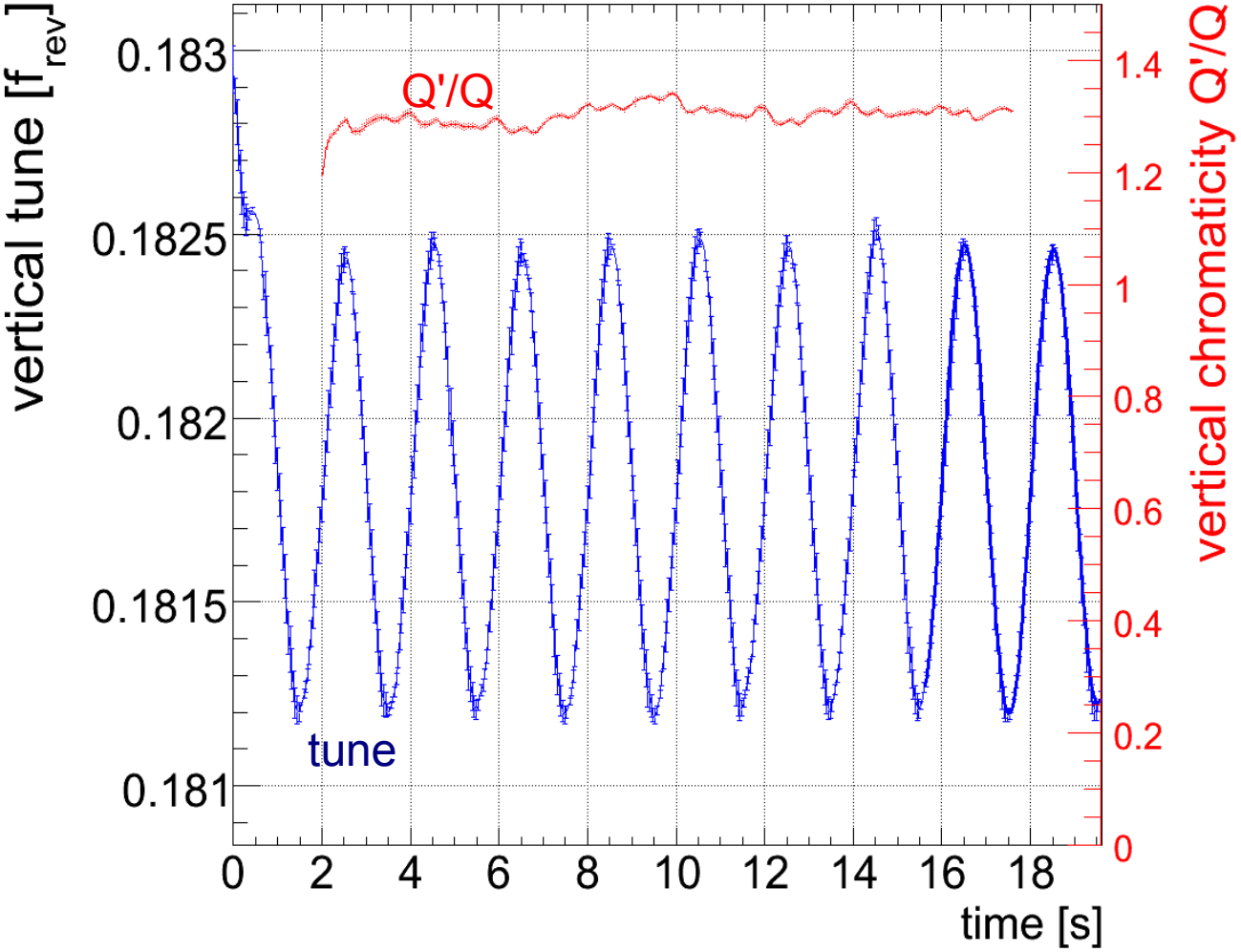
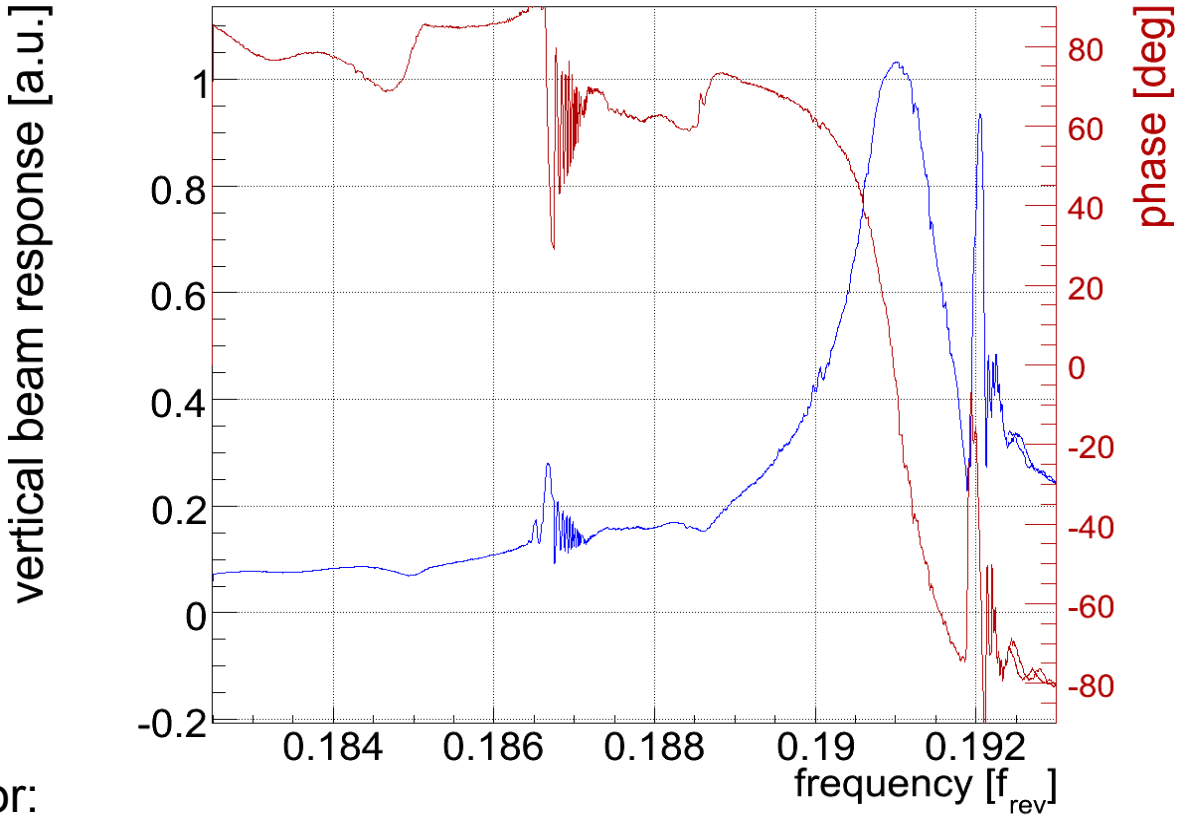


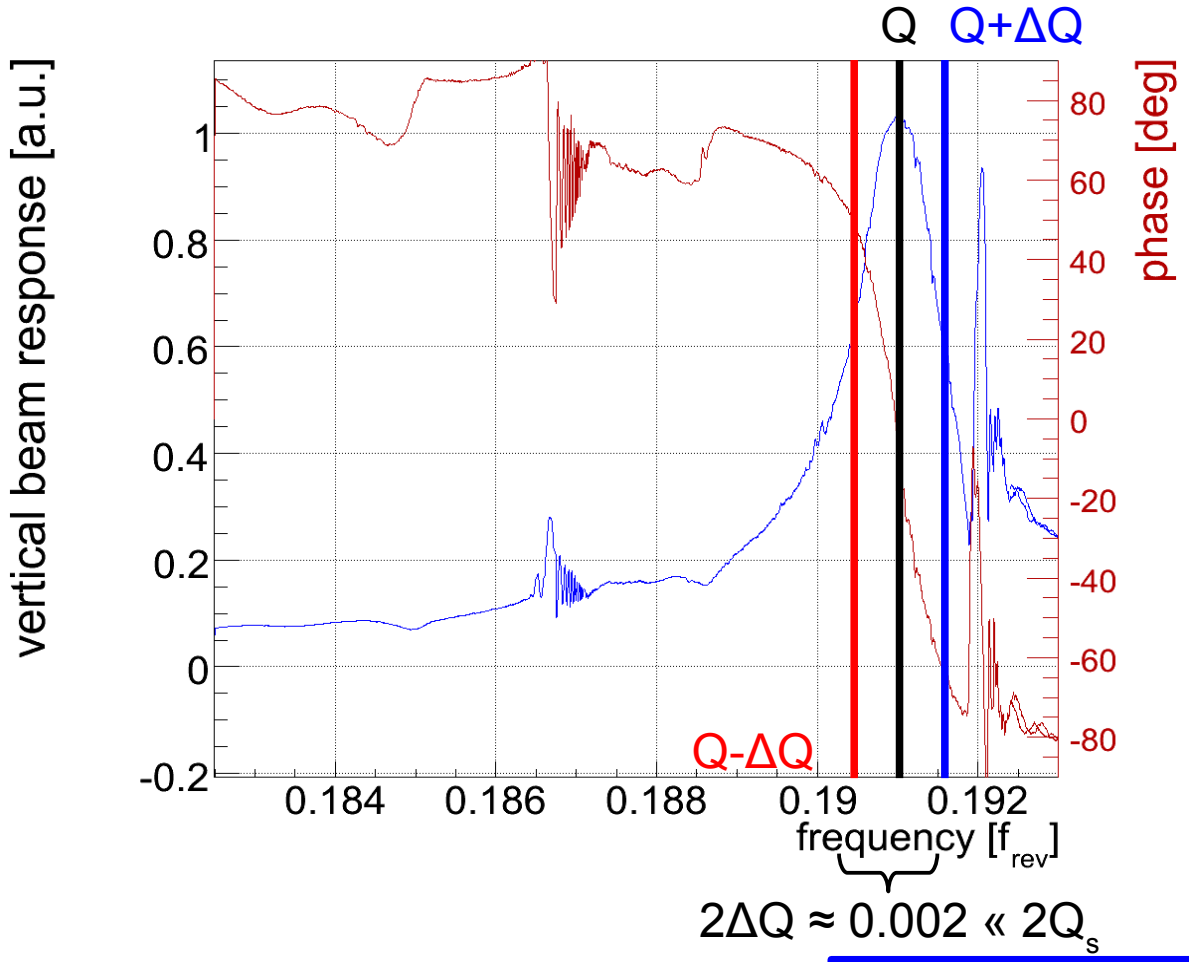
- Scans to assess the maximum useful range yield showed that this method can cope with values of Q' up to at least 34 units.
  - larger than (any other) Fourier based method ... (usually damping limited)

PLL based Q/Q' tracking study at the SPS Beam-Transfer-Function



- Require for:
  - LHC: PLL setup and re-calibration: phase/amplitude adjustments, ...
- “Free” fast tune footprint measurement that can be used to measure:
  - Impedance, Q', Q'', Q''', other advanced beam measurements, ...
- Thus, we plan to deploy this facility in 2008 as an MD tool also for the SPS.

PLL based Q/Q' tracking study at the SPS
PLL Side Exciter (SEX) based Tune Width/Q' Measurement

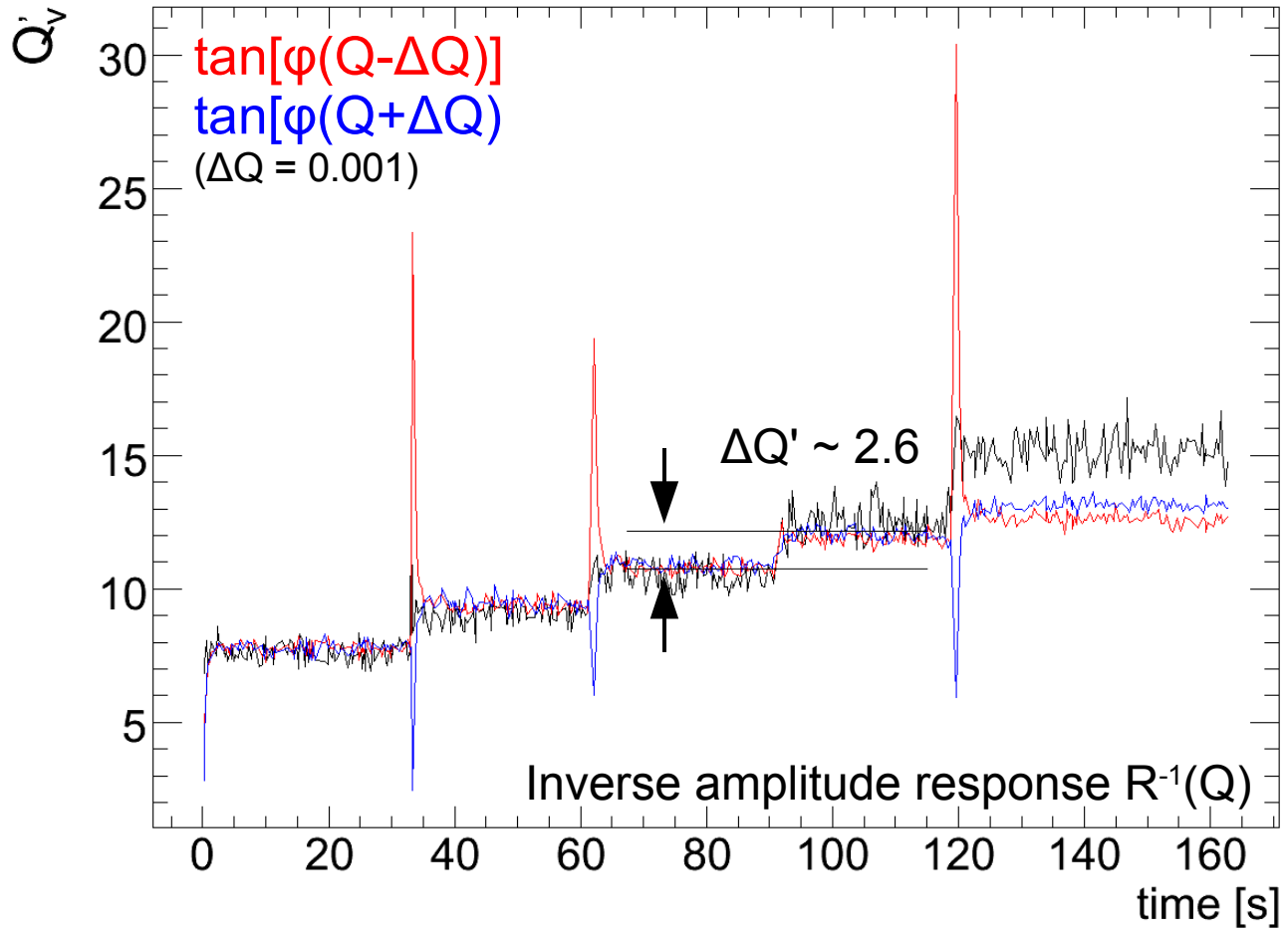


- Resonant phase change ↔ tune width change
  → "free" real-time tune footprint measurement
  → measurable dependence of ΔQ ~ Q'

driven 2nd order resonance:

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

PLL based Q/Q' tracking study at the SPS
PLL Side Exciter (SEX) based Tune Width/Q' Measurement



- Side-exciter phase ~~appears to~~ changes linearly with Q' (2007 MDs)
  - 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

PLL based Q/Q' tracking study at the SPS
Tune Width Dependence on Chromaticity

- ... common believe/dogma: $\Delta Q = \Delta p/p$
- Since then: 2007 SPS MDs
  - many additional BTF/side-exciter data taken which seem to confirm previous observation → need cross-verification on other machines (LHC)
  - Sketch of possible mechanism (/best candidate?) to explain the effect:
    - Sextupole intrinsically include/create Landau damping
      - lowest-order non-lin. accelerator element (Hamil. ~ J, $J^{1/2}$, $J^{3/2}$)
      - strong pre-set fields to compensate usually the large 'natural chromaticity' → intrinsic non-linearities are strong
    - However: classic/operational control relies on small variation around the pre-set Q' value only ($Q' > 0$ & $\sigma Q' < 10$) which make the non-linearities “appear” linear in this regime.
    - depends on the lattice and likely scales with accelerator size
- Further assessment of higher order feed-down effects required (octupoles...)
- Q'', octupole strengths are measurable as an asymmetry in the ΔQ distrib. → net effect on the SEX-based Q' method seems to be small.
  - Further simulations in progress → paper/report in preparation

Machine Development Summary of 2007 activities

- The prototype test of the PLL based Q' measurement were very successful!
  - 1 unit of Q' resolution with $\Delta p/p < \sim 10^{-5}$ @ 0.5 Hz (target ~ 2-5 Hz)
  - compatible with large values of chromaticity and LHC operation

  → baseline Q' control in good shape for nominal LHC

- Tune-Width dependence on Q' was verified to be a reproducible effect
  - Exploited through using Side-Exciter
  - Better understanding on dependence on other non-linear elements/effects
    - Intrinsic sextupole non-linearities are important aspect in this

- Many thanks to all who helped in participated in these MDs
  - special thanks to T. Bohl and J. Wenninger who helped with SPS setup

Outlook Machine Development Studies in 2008

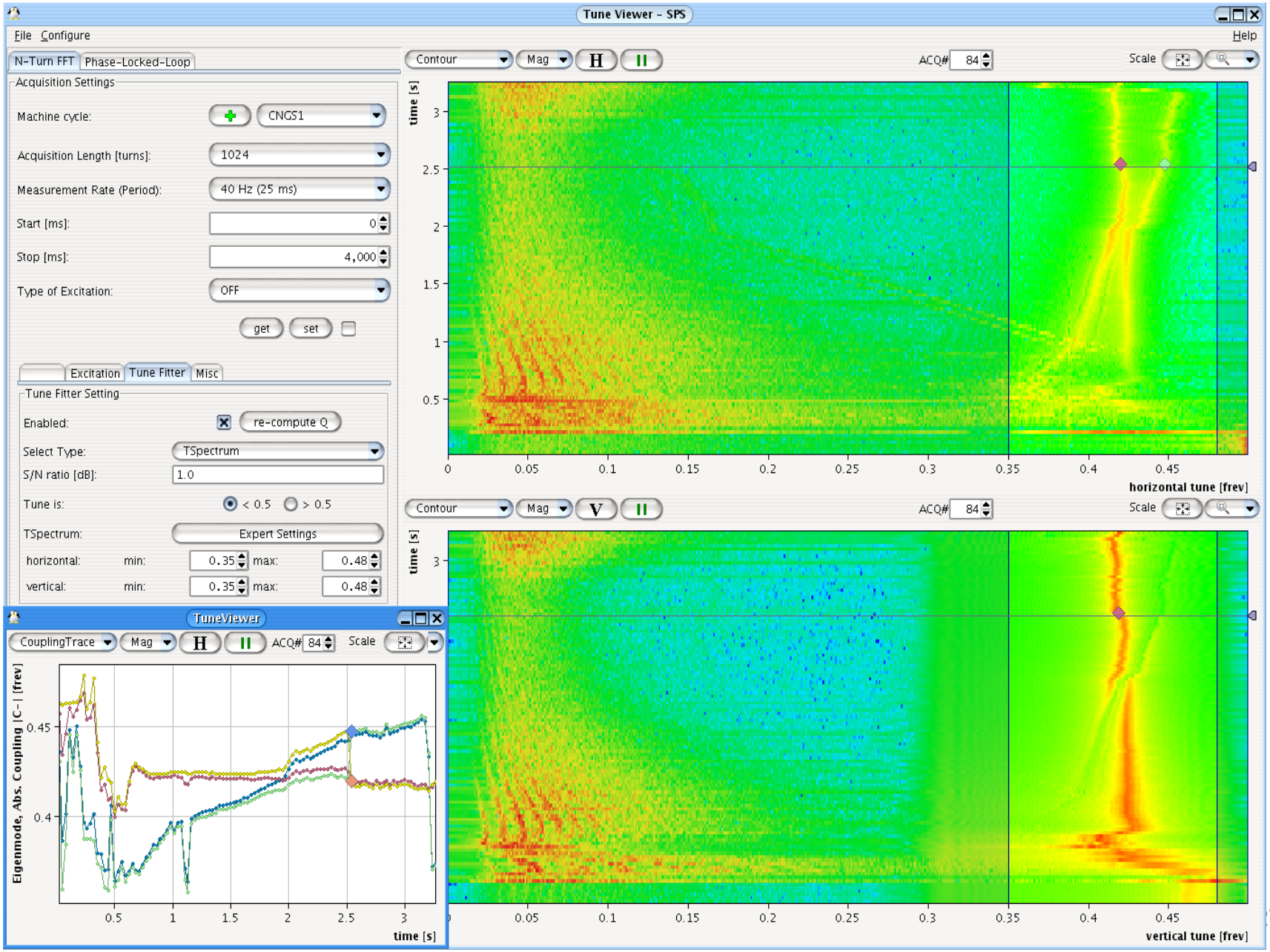
Measurement programme:

- Dedicated MDs:
  - Continuous beta-beat measurement
  - Q' through continuous head-tail phase shift
  - Side-Exciter based Q'
- MDs in parallel with other users/physics operation:
  - Fast/continuous measurements of Q'', Q''', ...
    - using the PLL Beam-Transfer-Function scan facility
    - using the side-exciter type method
  - Further LHC related BBQ improvements
    - bunch selector, diode-detector

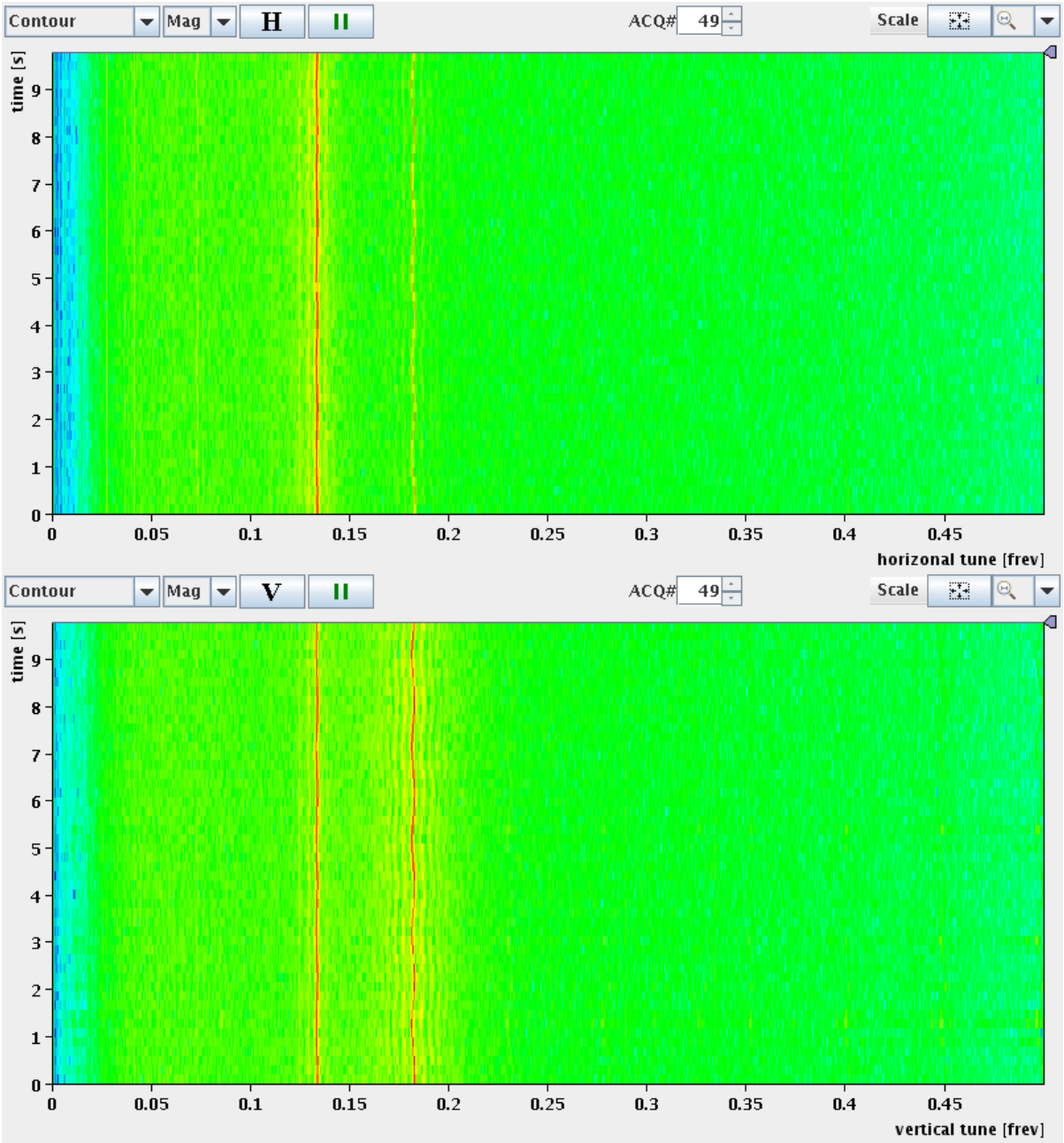
"... to boldly do what no one thought or dared before."

additional supporting slides

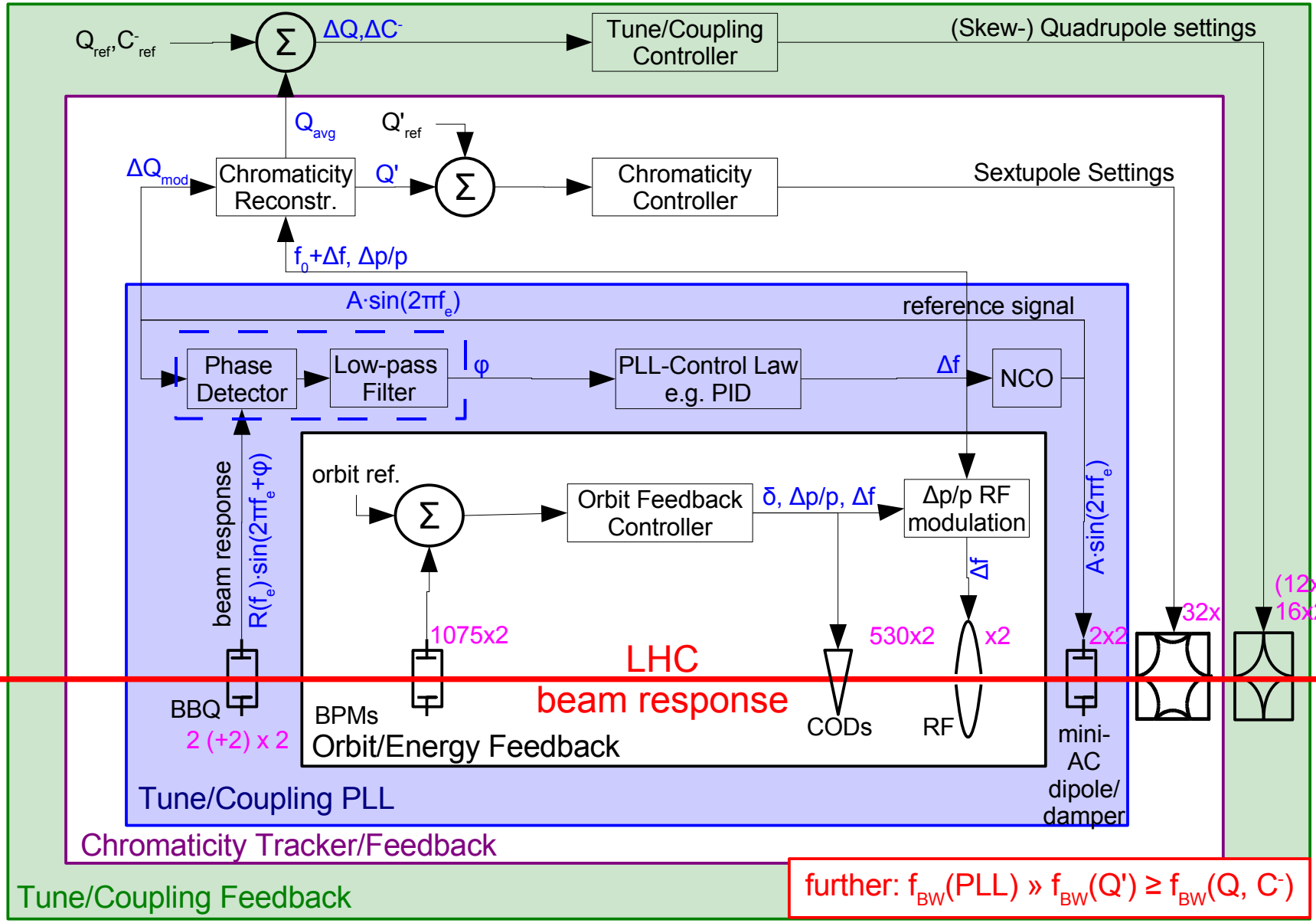
FFT Based Q Acquisition – 'On Demand'
Example: Tests at the SPS - Real-Beam Data



FFT Based Q Acquisition
$\Delta p/p \sim 2 \cdot 10^{-5}$ driven Q modulation ($Q'_v \sim 36$ units)



Future Integration of Q/Q' Measurements for Q/Q' Control
Full LHC Beam-Based Control Scheme



LHC FBs: 2158 input devices, 1136 output devices → total: ~3300 devices!