LHC Tune and Chromaticity Diagnostic and Feedback Control Systems

Ralph J. Steinhagen, AB-BI

for the 'invincible Gauls'

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Outline

- Base-line LHC Q, Q' and C^- diagnostics overview
  - System overview and hardware status
- Application overview
- Commissioning of Q, Q' and C^- beam parameter control
  - Instrumentation, diagnostics and related corrector circuits
  - Feedback options and setup

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):

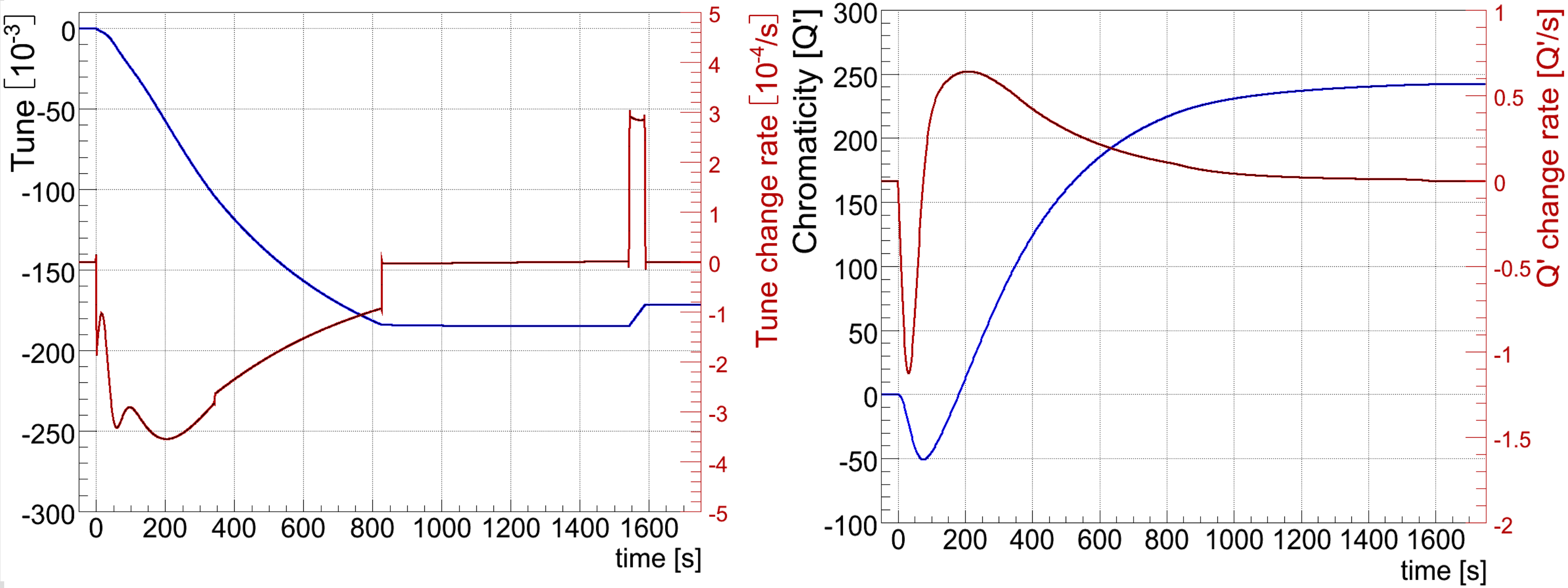
	Orbit [σ]	Tune [$0.5\cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Exp. Perturbations:	~ 1-2 (30 mm)	0.025 (0.06)	~ 70 (140)	± 1.5e-4	~0.01 (0.1)
Pilot bunch	-	± 0.1	+ 10 ??	-	-
Stage I Requirements	± ~ 1	±0.015→0.003	> 0 ± 10	± 1e-4	« 0.03
Nominal	± 0.3 / 0.5	±0.003 / ±0.001	1-2 ± 1	± 1e-4	« 0.01

- ... "FBs are most beneficial and (likely) required before the very first ramp!"

- after two years, experience from RHIC/Tevatron and many MDs in the SPS

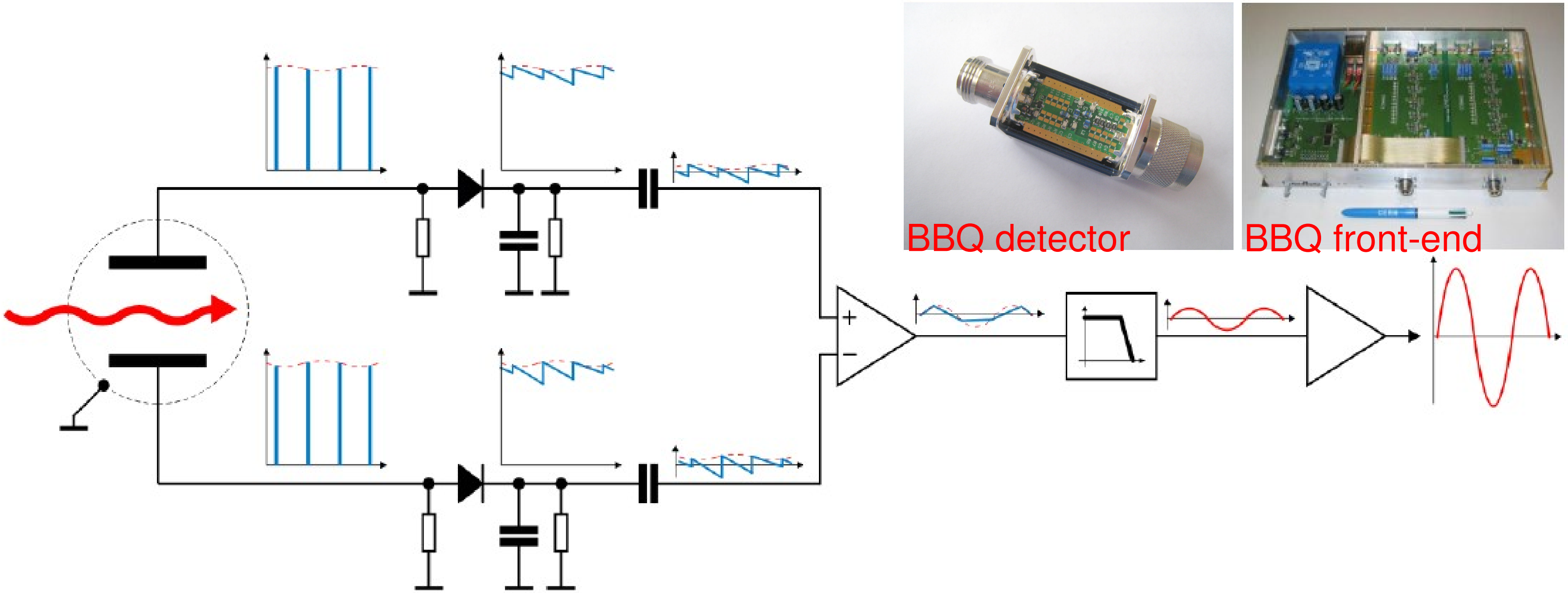
  ... we are ready and believe to be prepared to meet the LHC challenge!

Reminder: 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

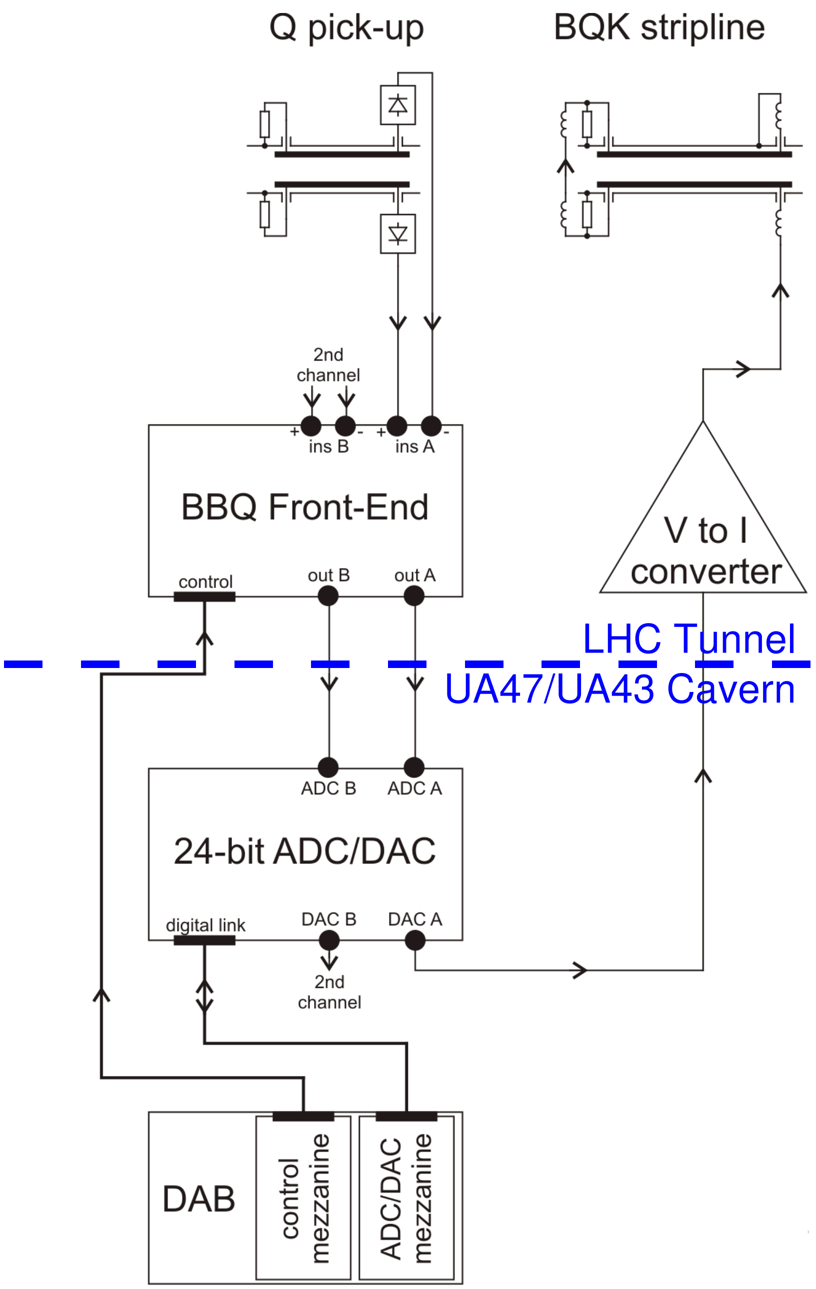
LHC Q Base-Line Q Instrumentation
Back-bone: Base-Band-Q Principle on a Slide



- Basic principle: AC-coupled peak detector
  - no saturation, self-triggered, no gain changes between pilot and nominal
  - intrinsically down samples spectra: ... 6 GHz → 1kHz ... f_{rev}
    - Base-band operation: very high sensitivity/resolution ADC available
    - Measured resolution estimate: < 10 nm → ε blow-up is a non-issue
- One of the few turn-key systems in the LHC
  - easy/very fast commissioning – done in parallel with RF capture

LHC Q Base-Line Q Instrumentation
BBQ System Overview

- Back-bone: Base-Band-Q Meter[1] (BBQ)
  - well tested and proven solution:
    SPS, LEIR, PSB, RHIC, Tevatron, ...
- Pick-ups: 40 cm strip-lines
- Shakers: 1 m strip-lines
  - magnetic deflectors driven ± 3 A max.
  - working bandwidth: 1 - 6 kHz
  - maximum kick angle: 0.1nrad@7TeV
    → 23 nm@β = 180m per turn
- 3 x 2 (nearly) identical installation (tunnel
  (2 development/hot-spare systems on the surface)
- ... some redundancy:
  8 systems available vs. 2 needed



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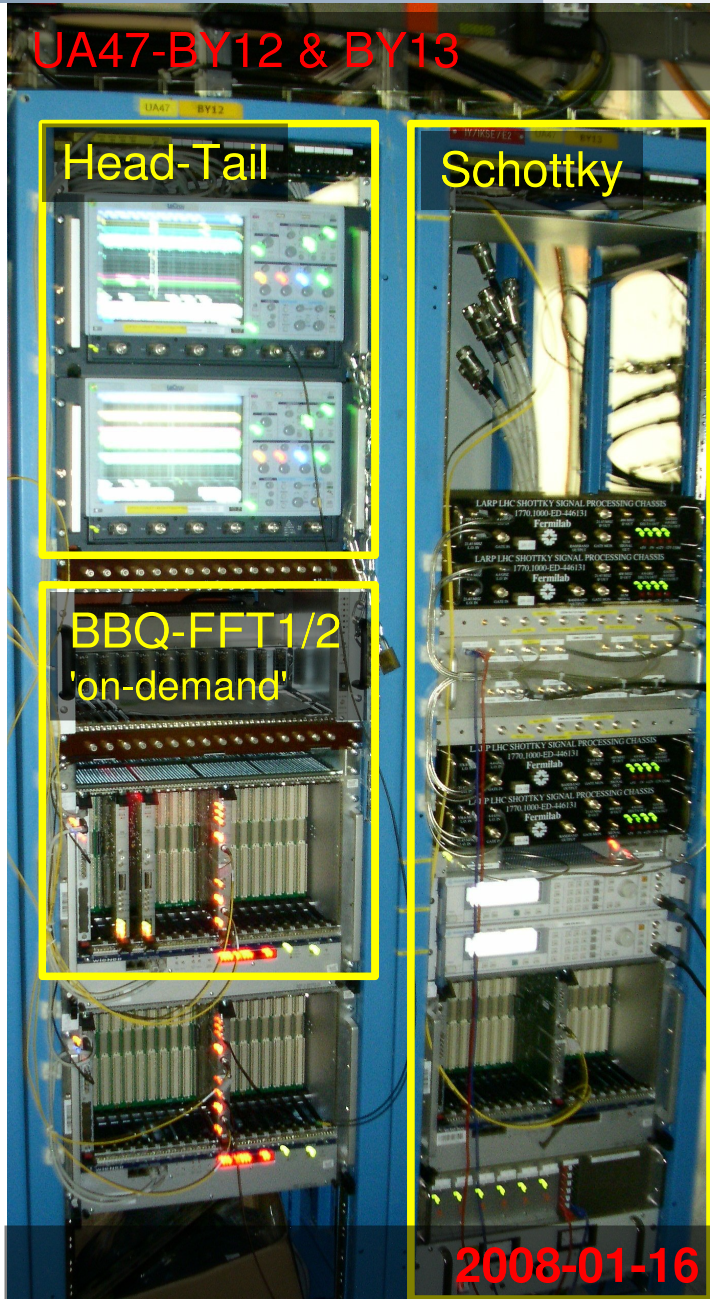
[1] M. Gasior: LHC-Project-Report-853

LHC Q Base-Line Q Instrumentation Hardware Status

- BBQ based systems: (~ 1 more week)
  - all acquisition systems are in place
  - remaining: front-end installation, final cabling and HW acceptance test
  - N.B. transverse damper available as exciter
- Head-Tail/Fast-Intra-Bunch-Position Monitor
  - acquisition system (scopes) in place
  - final cabling pending (~ 2 days, April)
- Schottky: US-LARP responsibility (soonish)
  - cabling, detectors in place
  - HW, SW acquisition and control system pending
- we are in good shape and ready for first beams... whenever we get the 'go-ahead'



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LHC Base-Line Q/Q' Diagnostics Overview – Q/C$^-$ BPM and BBQ exploitation

Commissioning Phase A.3 (choices first circulating beam):

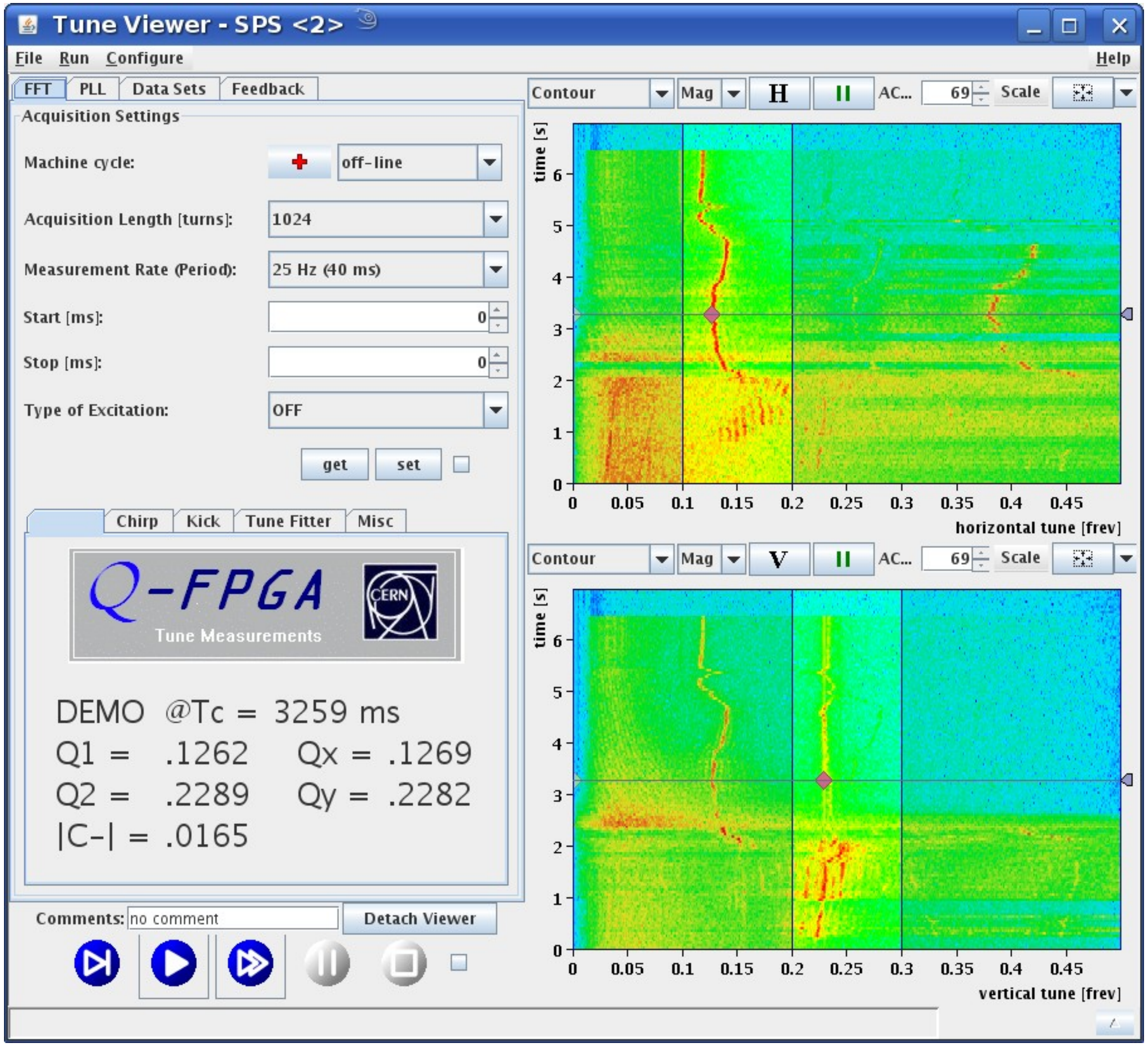
- FFT based acquisition using LHC BPMs - Phase A.2 → J. Wenninger, V. Kain
  (excite and/or analyse injection oscillation spectra)
  - initial tune adjustments (first 100 turns, integer Q, local C$^-$ correction, etc.)
  - CON: slow, no fast periodic acquisition possible, problematic with large Q'
- FFT based acquisition using LHC BBQ with either
  - simply no excitation! - yields sufficient data in most cases...

  ...for the others: fall-back to one of the following excitation based methods:
  - 'RF transverse damper' or 'BQK' (aka. 'tune shaker'),
    - preferred choice: no timing required, fast and easy amplitude tuning
  - 'MKQA' (aka. 'tune' or 'aperture kicker') triggered by the MTG
    - mainly for cross-calibration and measurements involving BPMs or HT
  - CON: slower tune (→ chromaticity) tracking, problematic with large Q'
- Phase-Locked-Loop (PLL) based acquisition
  - requires excitation using either the 'BQK' or 'RF transverse damper'
  - can cope with wide range of Q', SPS experience: robust measurement

LHC Base-Line Q/Q' Diagnostics Overview – Q/C^-
BBQ Use-Cases Abstraction

- Three independent BBQ Tune/Coupling diagnostic chains available per beam:
  - PPL based acquisition of Q, Q'...
    - one measurement at high/reduced acquisition frequency, targets:
      - 100 Hz for feedbacks (driven by need to reduce feedback latencies)
      - 1 Hz for general purpose logging
    - expert: high frequency data that is event synchronised and buffered (post-mortem, PLL setup), typical length: 5 min ↔ < 1 MB of data
    - main use: monitoring/logging, feedbacks, fill-to-fill studies, ...
  - FFT based acquisition of Q,Q'... – 'periodic'
    - one measurement every 1 second starting from first-injection
    - intended use: monitoring/logging, (feedbacks), fill-to-fill studies, ...
  - FFT based acquisition of Q,Q'... – 'on demand'
    - n-measurements synchronised to an external event (BPM, BQ, ...)
    - intended use: expert diagnostics, detailed studies, ...

LHC Base-Line Q/Q' Diagnostics Overview – Q/C^- Operational & BI-Expert Interface: TuneViewer



Machine cycle: off-line

Acquisition Length [turns]: 1024

Measurement Rate (Period): 25 Hz (40 ms)

Start [ms]: 0

Stop [ms]: 0

Type of Excitation: OFF

Comments: no comment

DEMO @Tc = 3259 ms

Q1 = .1262 Qx = .1269

Q2 = .2289 Qy = .2282

|C-| = .0165

- Tested and/or used at SPS, PSB, PS, LEIR for about a year now (~debugged)
- Main responsibility: R. Steinhagen (AB-BI),
  co-maintained and input from F. Follin, J. Wenninger (AB-OP)

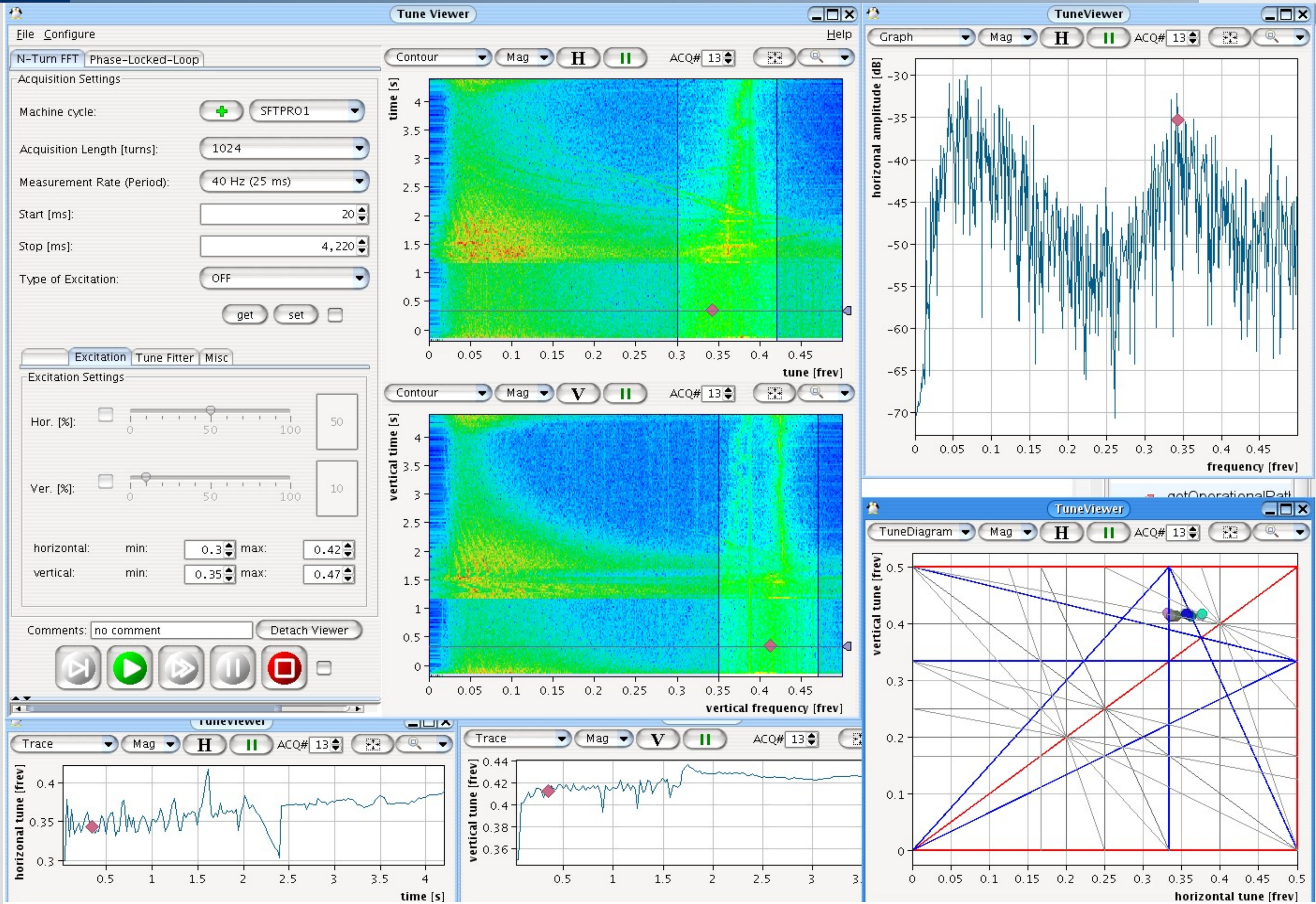
LHC Base-Line Q/Q' Diagnostics Overview – Q/C⁻ TuneViewer – Functional Overview I/II

- Same interface/can acquire from any CERN BBQ-FFT/PLL based system
  - same diagnostics look-and-feel across accelerators
  - several different FFT analysis tools available
  - Standard displays: Q/Q' traces, FFT-vs-time, FFT spectra, S/N ratios, raw oscillation data, BTF, ... → modular, can be used as a fixed-display
  - standard CO interfaces: SDDS, LSA, JAPC, timing where applicable
  - developed having commissioning and expert diagnostics in mind
    - however: provides reduced level of detail for day-to-day operation
  - off-line diagnostics, re-tuning, comparison and expert analysis of multiple Q/Q' parameters and data sets possible

- additional LHC specific 'plugins':
  - Q/Q' 'slow' steering ('one point trim'), kick/BPM timing synchronisation,
  - Q/Q' real-time feedback control:
    - implements the same algorithms as the Q/Q' feedback controller
    - any tested settings are easily applied to the Q/C⁻/Q' FB controller

- Some features in the testing/development pipeline...

LHC Base-Line Q/Q' Diagnostics Overview – Q/C-
TuneViewer – Functional Overview II/II



Tune Viewer

N-Turn FFT | Phase-Locked-Loop

Acquisition Settings

Machine cycle: SFTPRO1

Acquisition Length [turns]: 1024

Measurement Rate (Period): 40 Hz (25 ms)

Start [ms]: 20

Stop [ms]: 4,220

Type of Excitation: OFF

Excitation Settings

Hor. [%]: 50

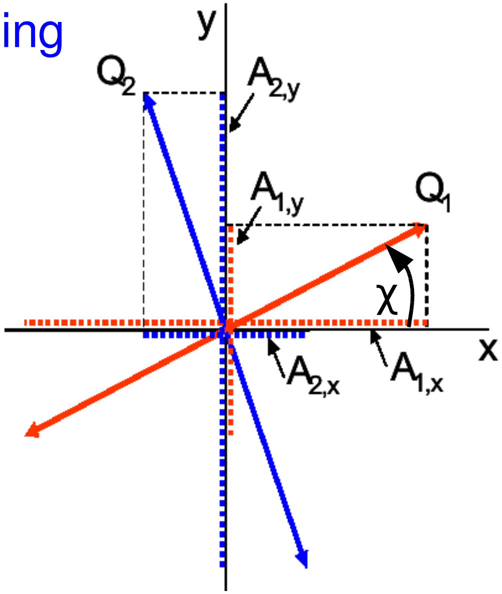
Ver. [%]: 10

horizontal: min: 0.3 max: 0.42

vertical: min: 0.35 max: 0.47

Comments: no comment

LHC Base-Line Q/Q' Diagnostics Overview – Q/C⁻ Betatron-Coupling Measurement



- No orbit, Q, Q' feedback without control of betatron-coupling
- FFT/PLL measures eigenmodes that in the presence of coupling are rotated w.r.t. "true" horizontal/vertical tune
  - $A_{1,x}$: "horizontal" eigenmode in vertical plane
  - $A_{1,y}$: "horizontal" eigenmode in horizontal plane

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

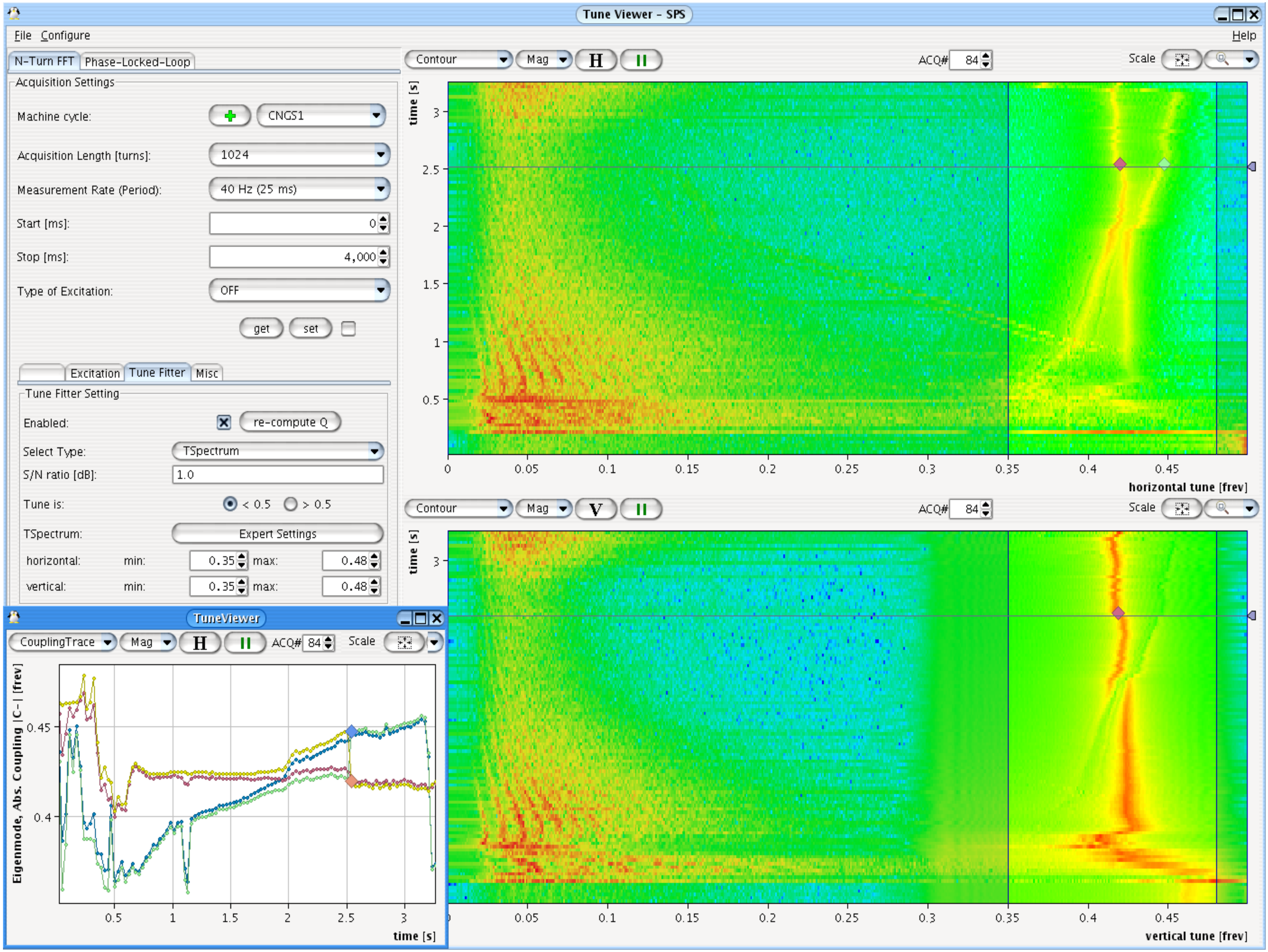
$$\Rightarrow \boxed{|C^-| = |Q_1 - Q_2| \cdot \frac{2\sqrt{r_1 r_2}}{(1+r_1 r_2)} \quad \wedge \quad \Delta = |Q_1 - Q_2| \cdot \frac{(1-r_1 r_2)}{(1+r_1 r_2)}}$$

- Decoupled feedback control:
  - q_x, q_y → quadrupole circuits strength
  - $|C^-|$, χ → skew-quadrupole circuits strength

first implemented and tested at RHIC/
tested/operational at CERN

R. Jones et.al., "Towards a Robust Phase Locked Loop Tune Feedback System", DIPAC'05, Lyon, France, 2005

LHC Base-Line Q/Q' Diagnostics Overview – Q/C^- Betatron-Coupling Measurement (Real-Beam Data)



Tune Viewer - SPS

File Configure Help

N-Turn FFT | Phase-Locked-Loop

Acquisition Settings

Machine cycle: CNGS1

Acquisition Length [turns]: 1024

Measurement Rate (Period): 40 Hz (25 ms)

Start [ms]: 0

Stop [ms]: 4,000

Type of Excitation: OFF

get set ☐

Excitation | Tune Fitter | Misc

Tune Fitter Setting

Enabled: ☒ re-compute Q

Select Type: TSpectrum

S/N ratio [dB]: 1.0

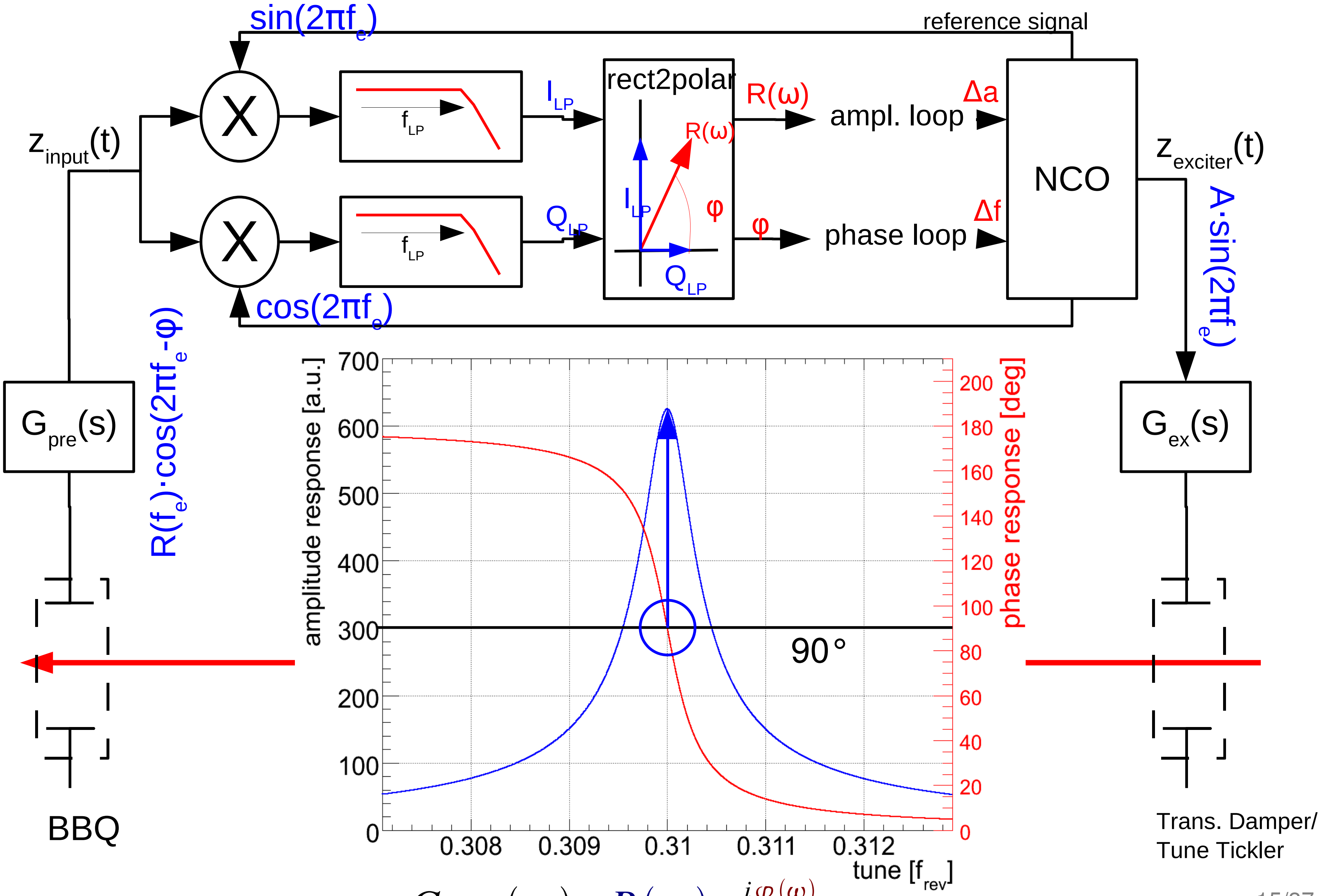
Tune is: ● < 0.5 ○ > 0.5

TSpectrum: Expert Settings

horizontal: min: 0.35 max: 0.48

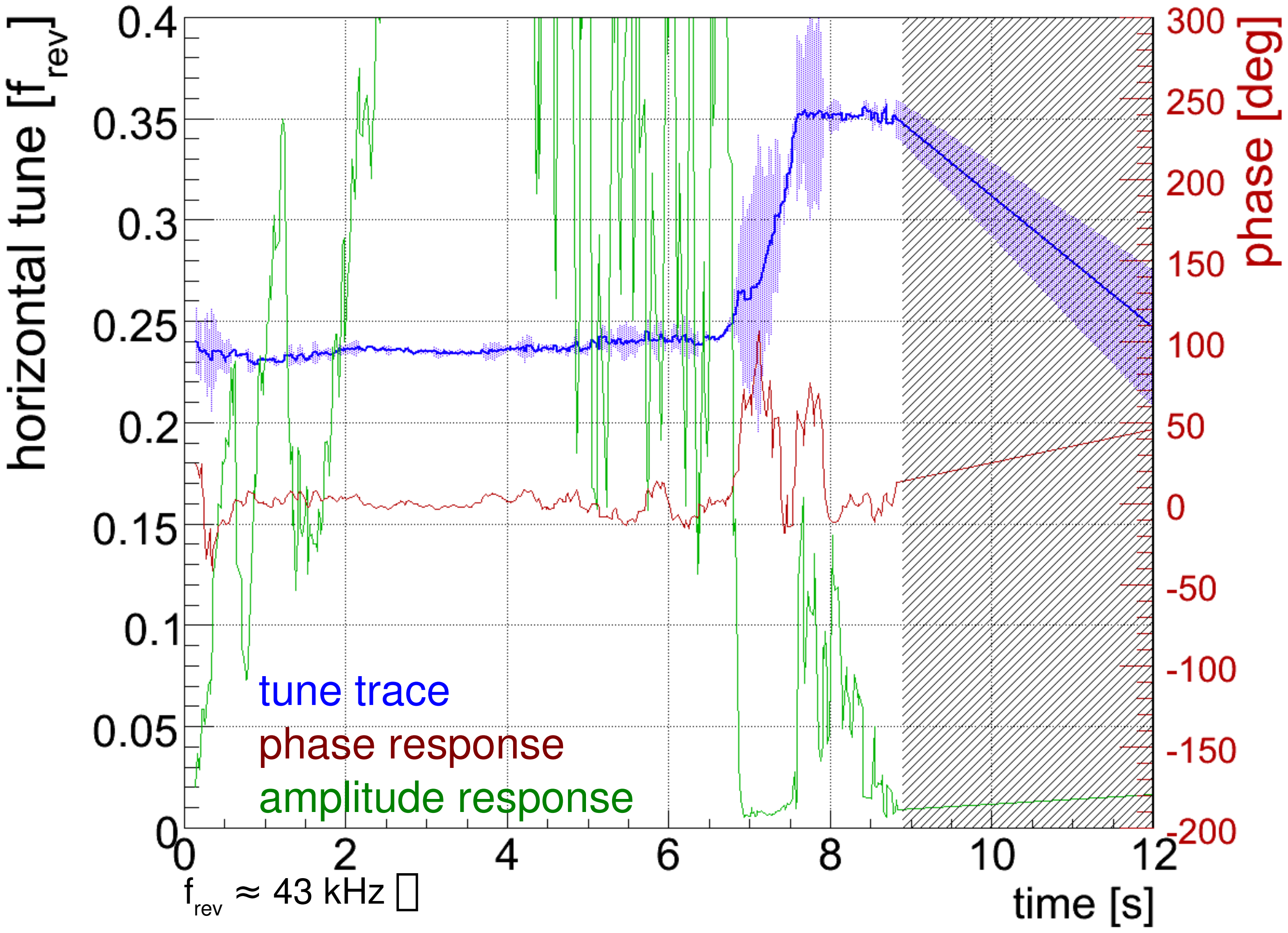
vertical: min: 0.35 max: 0.48

LHC Base-Line Q/Q' Diagnostics Overview – Q/C⁻
Simplified LHC Phase-Locked-Loop Scheme



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

LHC Base-Line Q/Q' Diagnostics Overview – Q/C$^-$
Since 2006: SPS PLL Operation



- either: $\Delta Q/\Delta t|_{max}$ ≈ 0.3 within 300 ms, (o. of magnitude faster than LHC requirement)
- or: tune resolution: $\Delta Q_{res} \approx 10^{-6} \ldots 10^{-7}$ but reduced bandwidth (~1..2 Hz)

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

- 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

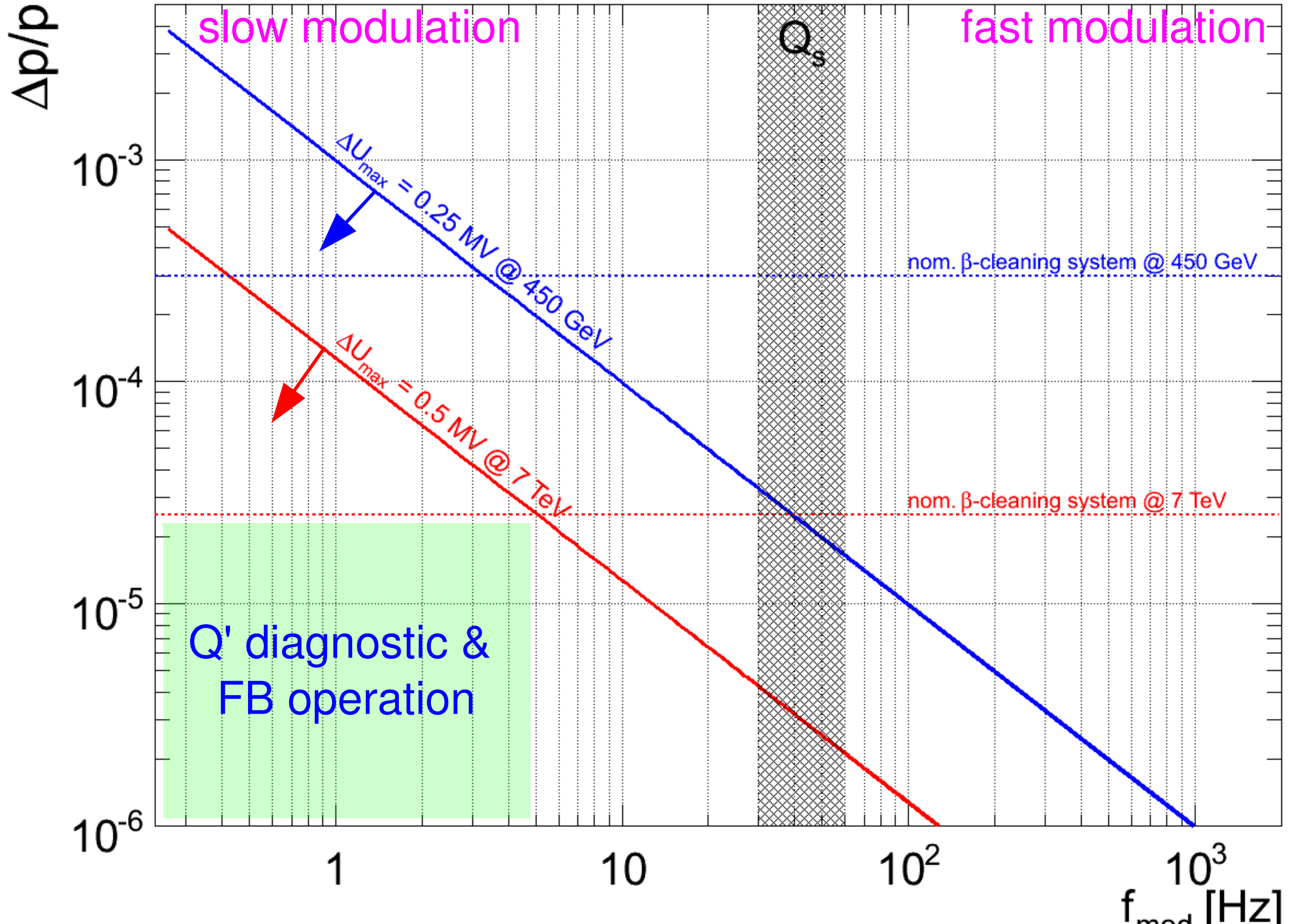
the RF induced momentum change (known)

- Kicked Head-Tail Phase-Shift – LHC Phase A.3 (~ copy++ of SPS installation)
  - multiple dependences on beam parameter other than Q'
  - limited by emittance growth/orbit budget → it's an MD tool
    - still provides good cross-reference and general beam diagnostics!
- Side-exciter/BTF 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 in 2007 at the SPS but need further assessment

Q' through RF momentum modulation based method

- There are multiple but similar detection techniques:
  - modulation below Qs → classic schoolbook example
  - modulation above Qs → Brüning's and/or McGinnis' method

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



- LHC RF power permits only slow modulation (J. Tückmantel et al.)

Q' through RF momentum modulation based method

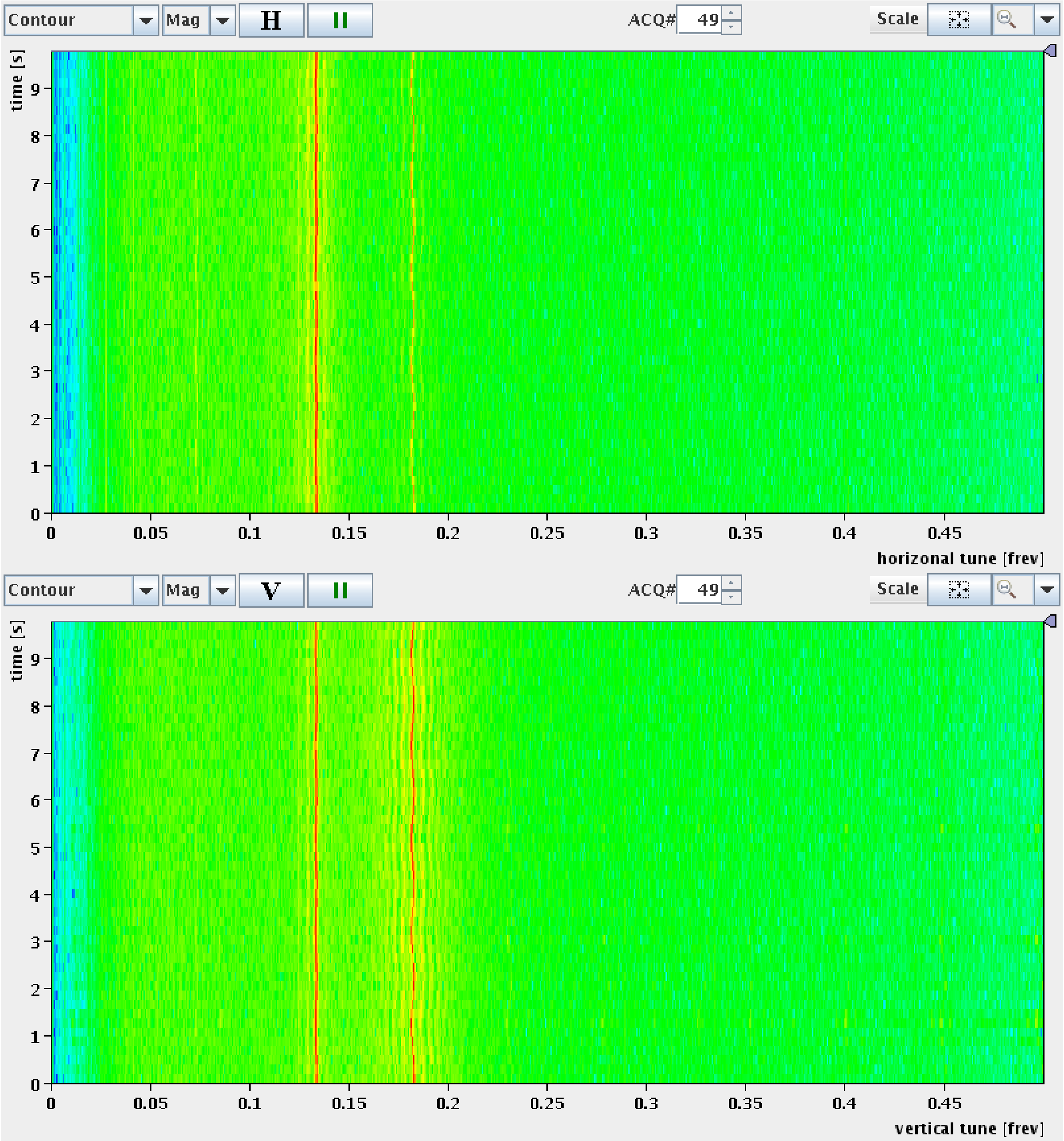
- Controllability of Q' depends on ability to track the tune both accurately & fast
  - intrinsic to this problem: $\boxed{\Delta Q^{(,)}_{res} \cdot \Delta t_{res} = const.}$
  - LHC expectations:
    - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}$ s^{-1}
    - Chromaticity: $\Delta Q'/\Delta t|_{max} < 2$ s^{-1}

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

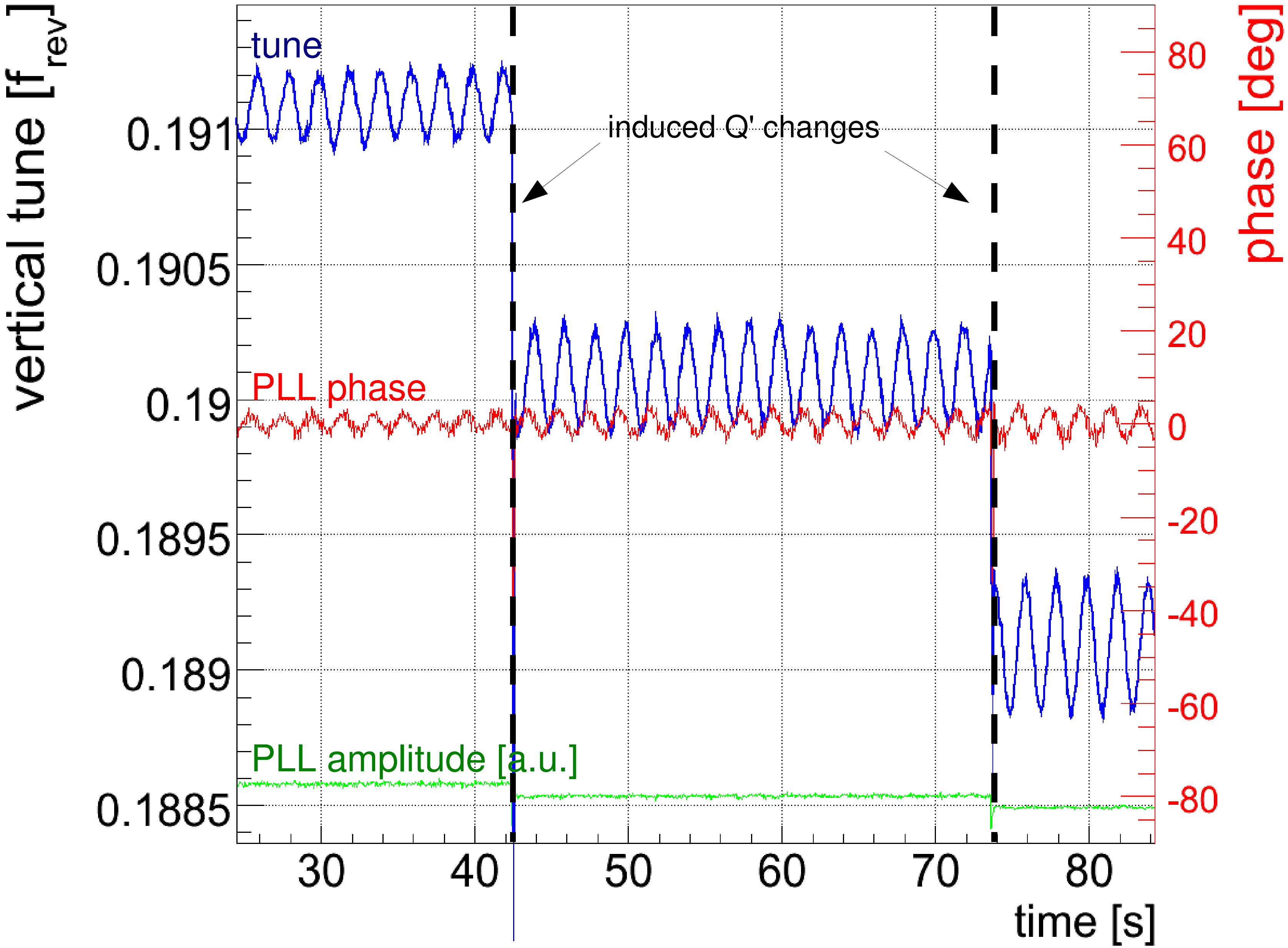
→ Chose to tackle the LHC Q' measurement in the high accuracy limit:

- very small but slow Δp/p modulation while tracking Q with a PLL
  - f_{mod}: 0.5 Hz (setup) → 5 Hz (nominal)
  - Δp/p: $\sim 10^{-4}$ (setup) → $\sim 10^{-5}$ (nominal)
- Feasibility supported by LHC Q' tracker prototype tests in the SPS
  - $f_{mod} = 0.5$ Hz, $\Delta p/p = 2 \cdot 10^{-5}$: $\Delta Q_{res} \sim 10^{-5}$, $\Delta Q'_{res} < 1$
  - limited by the f_{mod} DAC quantization

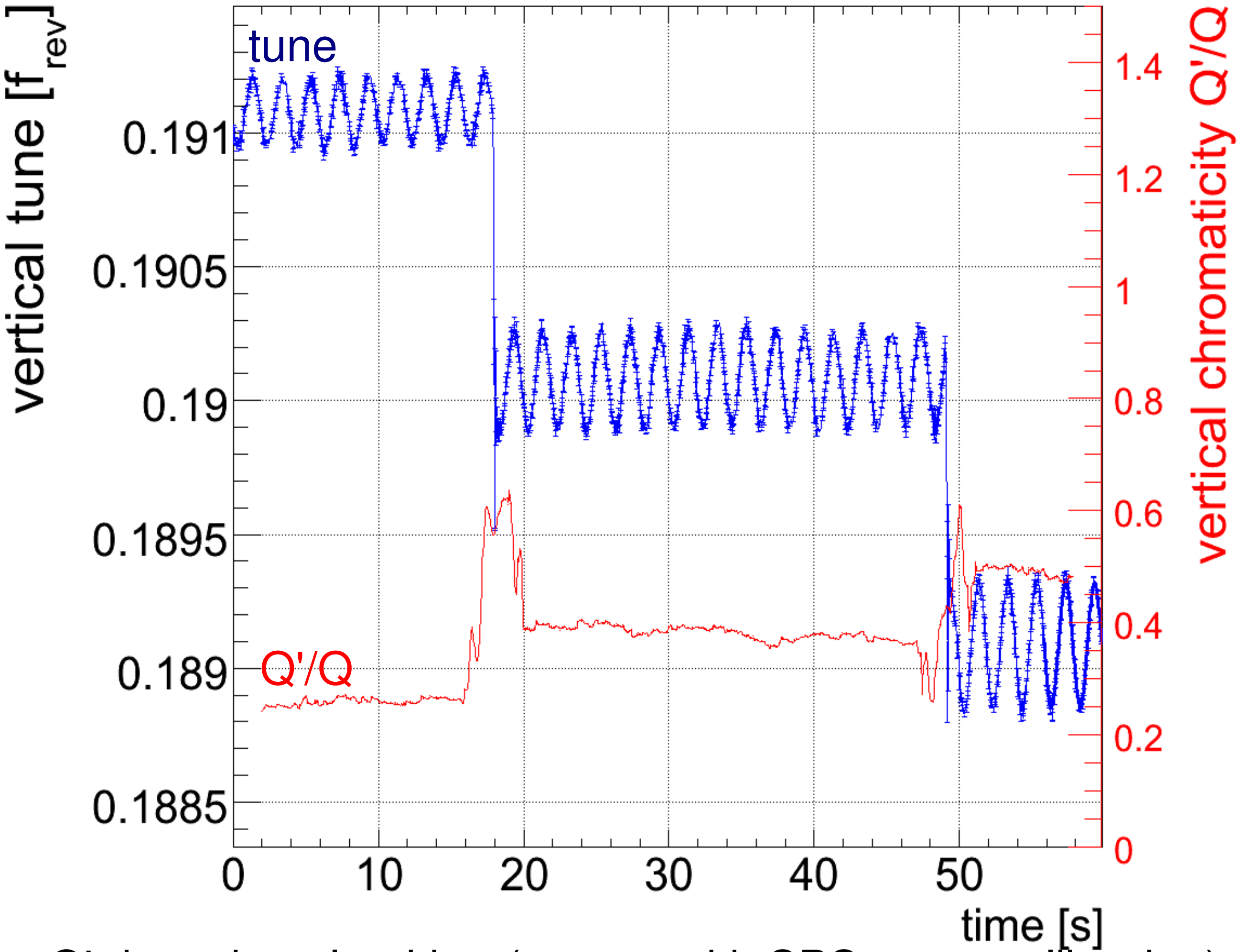
FFT Based Q Acquisition
Δp/p ~ 2·10^{-5} driven Q modulation (Q'$_v$ ~ 36 units)



Dedicated PLL based Q/Q' tracking study at the SPS
Modulation Amplitude: Δp/p ≈ 1.85·10⁻⁵

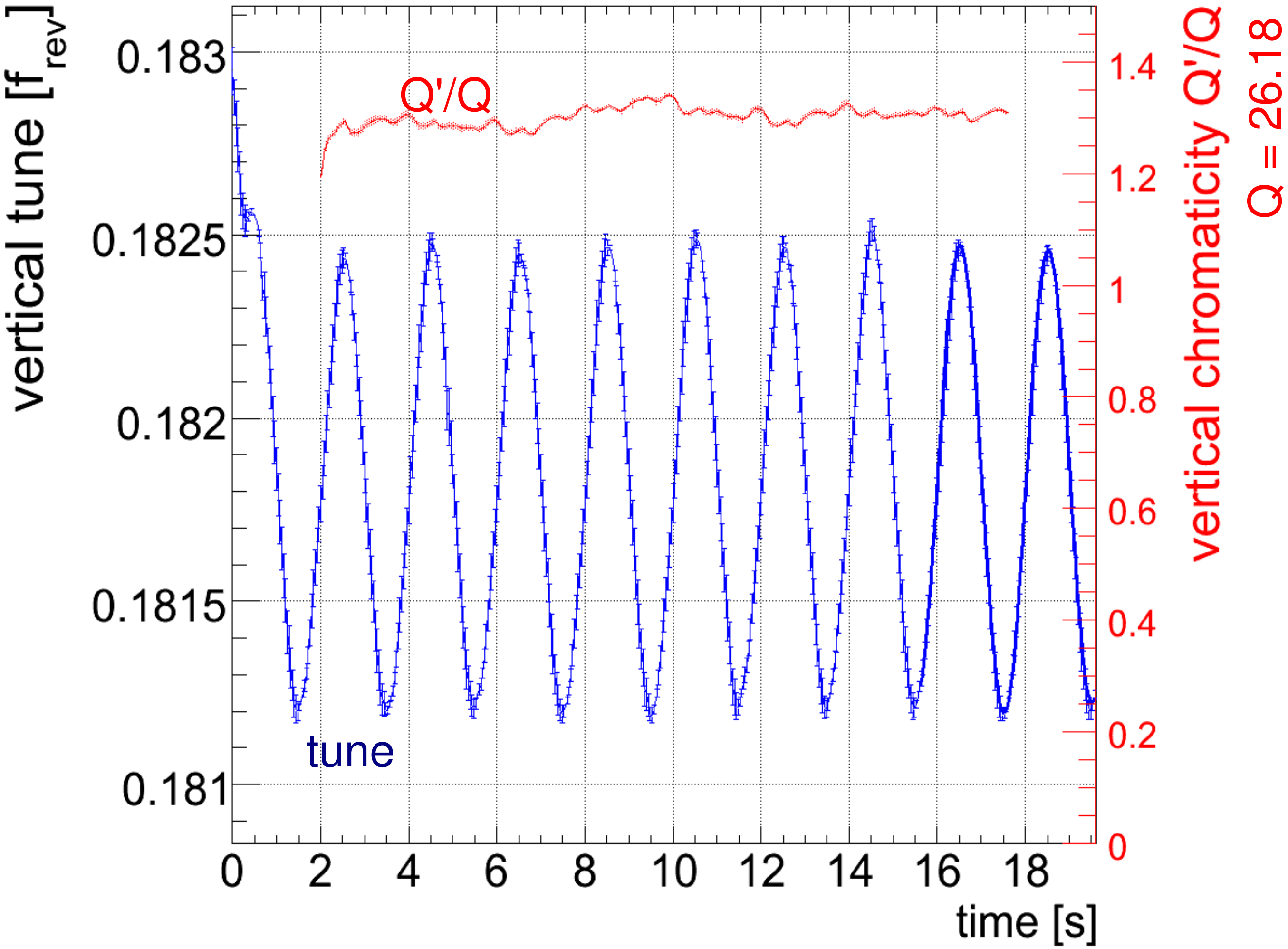


Dedicated PLL based Q/Q' tracking study at the SPS
Modulation Amplitude: $\Delta p/p \approx 1.85 \cdot 10^{-5}$



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

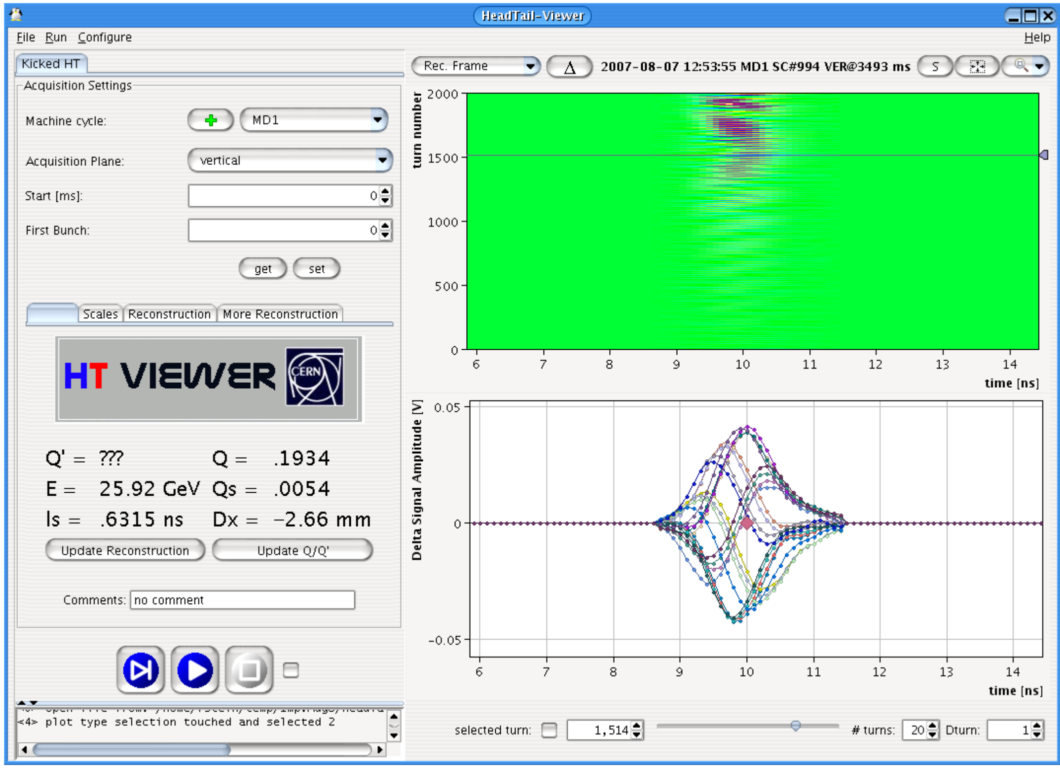
Dedicated PLL based Q/Q' tracking study at the SPS Modulation Amplitude: Δp/p ≈ 1.85·10⁻⁵



- 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)

LHC Base-Line Q/Q' Diagnostics Overview – Q'
Q' Through Kicked Head-Tail Phase Shift

- First order: copy of SPS system
  - increased sampling:
    5000 (LHC) vs. 2000 (SPS)
  - increased bandwidth:
    > 3 GHz vs. 2 GHz
  - switch on & use system
- Some intrinsic limitations:
  - requires large kicks; issues:
    - sig. emittance blow-up
    - machine protection → measurement remains a MD/pilot beam tool!



Machine cycle: MD1
Acquisition Plane: vertical
Start [ms]: 0
First Bunch: 0

Q' = ???   Q = .1934
E = 25.92 GeV   Qs = .0054
ls = .6315 ns   Dx = −2.66 mm

Comments: no comment

```
<4> plot type selection touched and selected 2
```

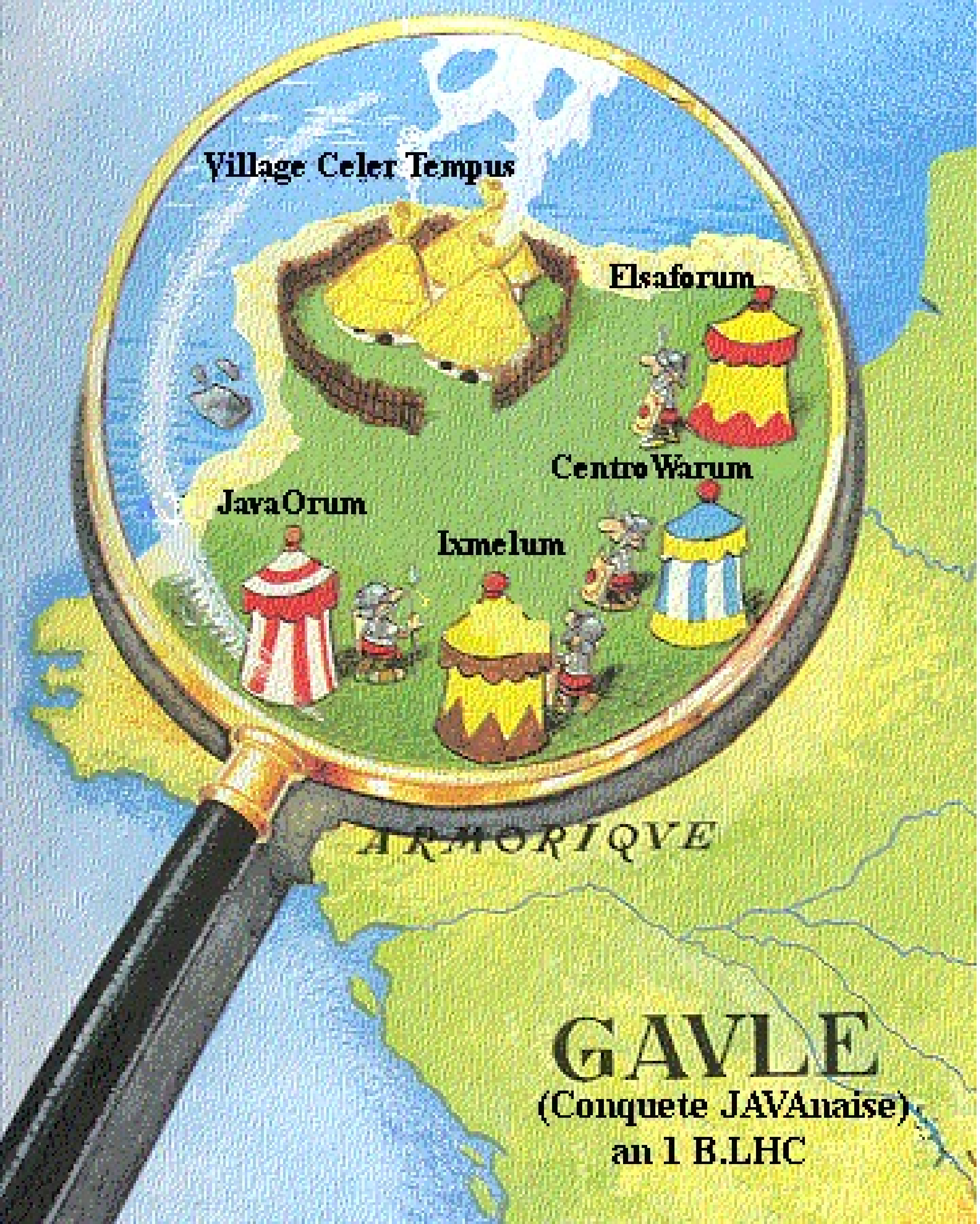
2007-08-07 12:53:55 MD1 SC#994 VER@3493 ms

selected turn: ☐ 1,514   # turns: 20   Dturn: 1

- uncertainties due to multiple dependences on beam parameter other than Q':
  - Impedance, non-linear damping (Q'/Q'', RF damper), non-lin. Q_s,
  - Very low LHC Q_s = 30 Hz issue
    → oscillations need to prevail > 350++ turns for useful Q' analysis

LHC Base-Line Q/Q' Diagnostics Overview – Q' HeadTail Viewer – Functionality

- BI-expert tool known and used by many in ABP, BI, OP & RF
- Misnomer: 'Head-Tail' is actually a 'Fast-Intra-Bunch-Position-Monitor'
  - many long. and trans. beam diagnostics cross-calibrations possible
  - Implements standard analysis/displays for:
    - Raw and phase compensated Sum/Difference signal oscillation data
    - Tune, betatron-coupling, closed orbit, bunch length-vs-time
    - Phase-evolution-vs-turn → Q'-vs-turn, HT-Q' estimate
    - Amplitude-envelope (damping/instability growth times),
    - 1D-trace & 2D longitudinal and transverse bunch spectra
      - in-bunch & coupled bunch mode instabilities, chromatic frequencies
    - ...
    - in the pipeline: fast relative bunch intensity changes, BPM type acquisitions, processing speed performance
  - off-line diagnostics, re-tuning, comparison and expert analysis of multiple longitudinal, Q, Q' data sets possible
- If you have questions, feel that something is missing or is too much (= bugs) → please let me know

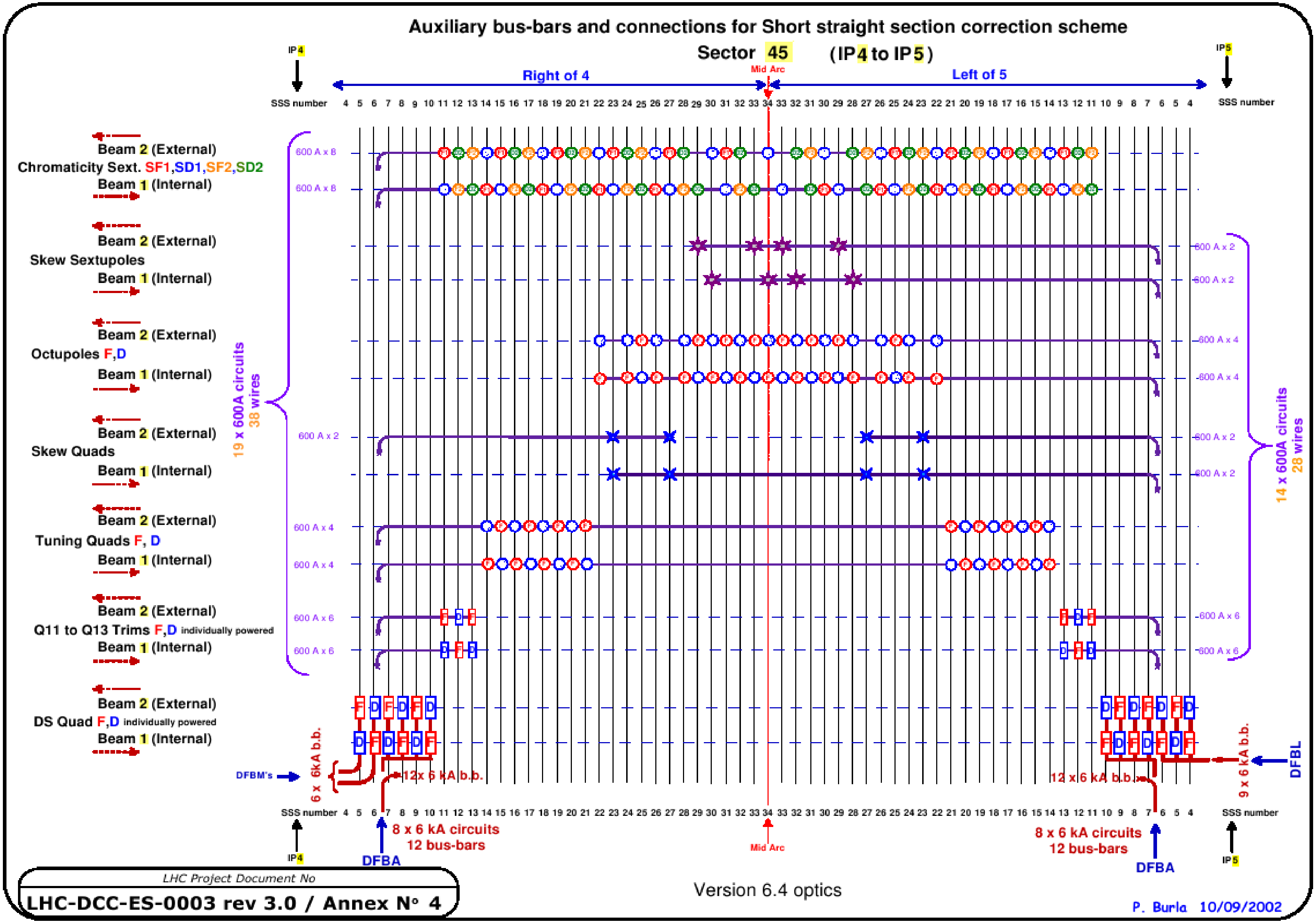


Commissioning of the

Q, C$^-$ & Q'

Feedback Loops

Total Number of (FB) Corrector Circuits
Powering Layout of the SSS Correction Scheme IP4↔IP5



Summary: Total Number of (FB) Corrector Circuits

- Orbit: 530 correction dipole magnets/plane (71% are of type MCBH/V, ±60A)
  - total 1060 individually powered magnets (60-120 A)
  - ~30 shared between B1 & B2

- Tune:
  - 16x ±600A circuits powered from even IPs (2, 4, 6, 8), 2 families
  - independent for Beam 1&2, but coupling between planes
  - can use them independently, optional use of DS quadrupoles

- Chromaticity:
  - 32x ±600A circuits powered from even IPs,4 families (ΔQ'~1→1A@7TeV)

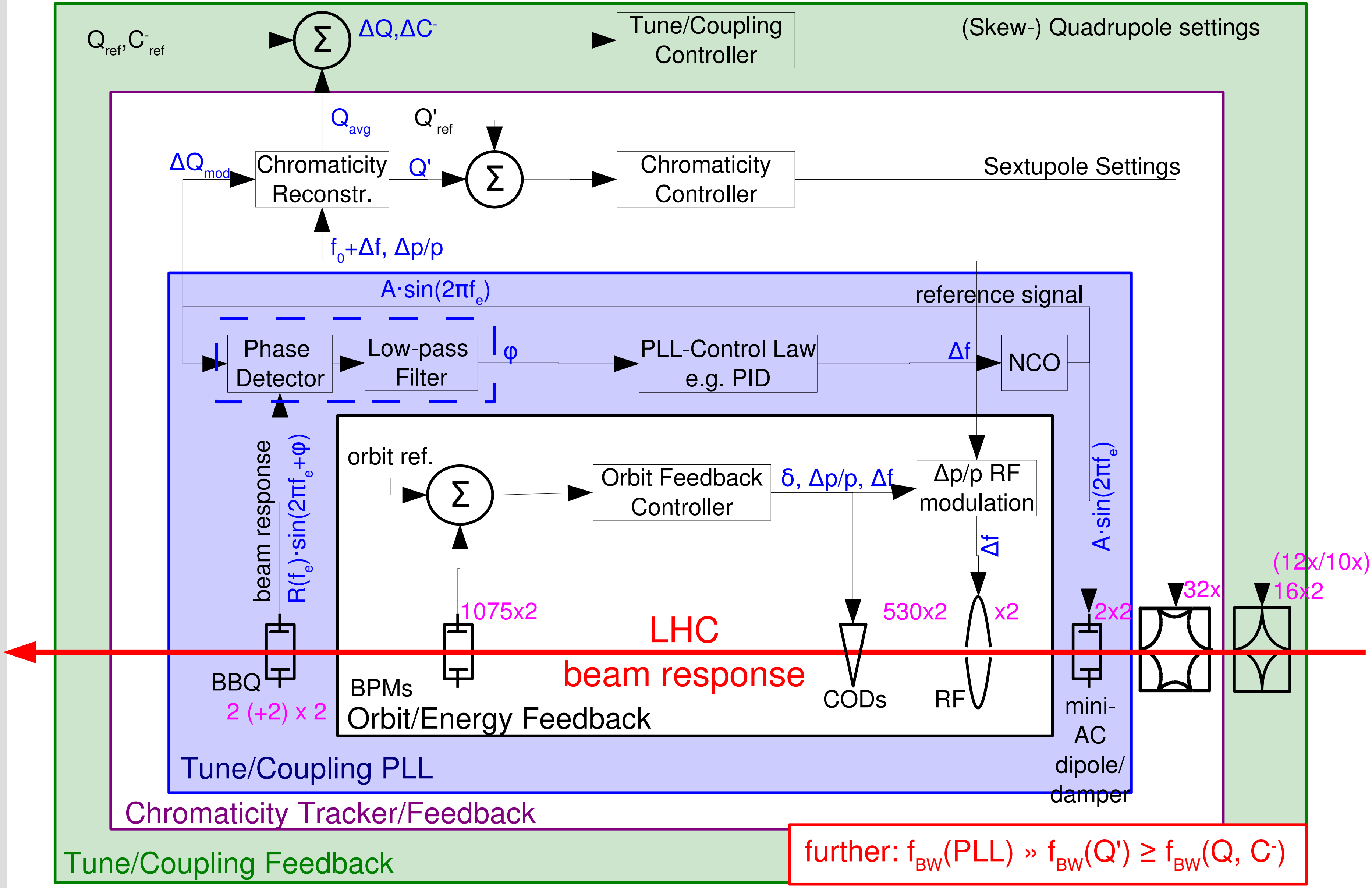
- Coupling: four skew quadrupoles per arc, 1/2 families
    - Beam 1: 12x ±600A
    - Beam 2: 10x ±600A

- Total: 1130 of 1720 circuits/power converter → more than half the LHC is controlled by beam based feedback systems!

LHC: Divide-and-Conquer Feedback Architecture

- Divide:
  - FB zoo: Orbit, Tune, Chromaticity, β-Coupling, Energy, ..., Luminosity, (Beta-Beating)
    - develop/commission on a one-by-one basis
  - Feedback controller into:
    - Space Domain: $\Delta Q_{x/y}$ → quadrupole circuits currents, etc.
      - classic parameter control – pre-requisite for any beam steering
    - Time Domain: compensate for dynamic behaviour
      - relaxed controller for commissioning (low-bandwidth PI controller)
- Conquer:
  - Once feedback operation on a per-parameter basis is established, reintegrate and test/commission inter-loop coupling and other constraints.
- LHC Feedback hierarchy:
  - Orbit (Energy) → Tune/Coupling PLL → Q' Tracker → Q/C^{-}/Q' feedback

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



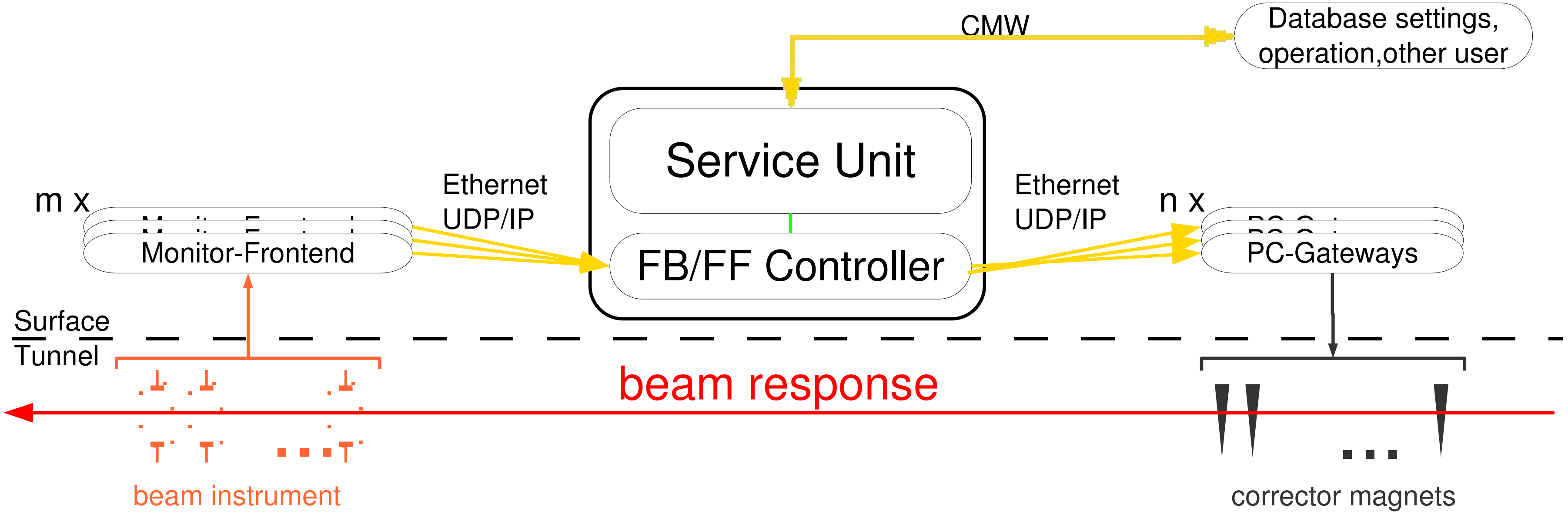
further: $f_{BW}(PLL) \gg f_{BW}(Q') \geq f_{BW}(Q, C^-)$

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

Common Feedback/Feed-Forward Control Layout

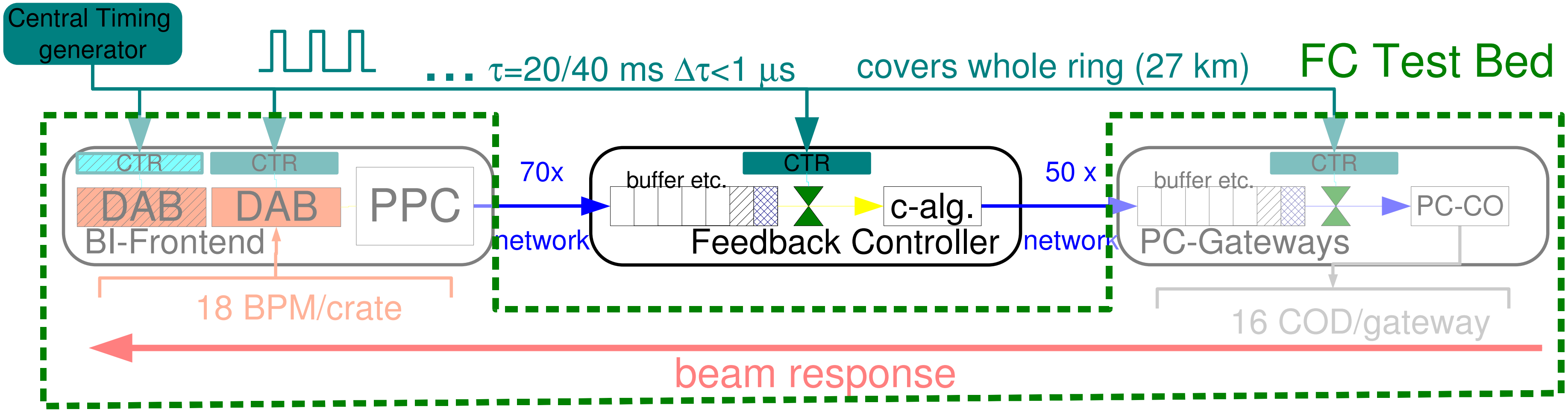
Each LHC feedback controller implementation split into two sub-systems:

- Service Unit: Interface to users/software control system
- Feedback Controller: actual parameter/feedback control logic
  - Simple streaming task for all feed-forwards/feedbacks:
    (Monitor → Network)$_{FB}$→ Data-processing → Network → PC-Gateways
  - Can run auto-triggered (first beams)
  - Hardware and functional specifications already available



Commissioning the Orbit Feedback Controller – Test Bed

- Test-bed complementary to Feedback Controllers:
  - Simulates the open loop and orbit response of COD→BEAM→BPM
    - Decay/Snap-back, ramp, squeeze, ground motion simulations, ...
    - Keeps/can test real-time constraints up to 1 kHz
  - Same data delivery mechanism and timing as the front-ends
    - transparent for the FB controller



Commissioning of Feedbacks I/IV

- Most feedbacks checks can be and are done during hardware commissioning:
  - Interfaces and communication from BI and to PO front-ends (done)
  - Interfaces to databases, tune kicker, PLL FESA integration (soon)
- Using the 'test-bed' we will do the further tests without beam: (in progress)
  - analysis routines, time-domain and circuit failure interception routines
- Things that have to and can only be checked with beam:
  - PO-Circuits/BI-Instrument polarities, planes, mapping
    - reduced number of corrector circuits → ~ 1-2 shifts/FB
  - PLL: beam transfer function and rough test of calibrations

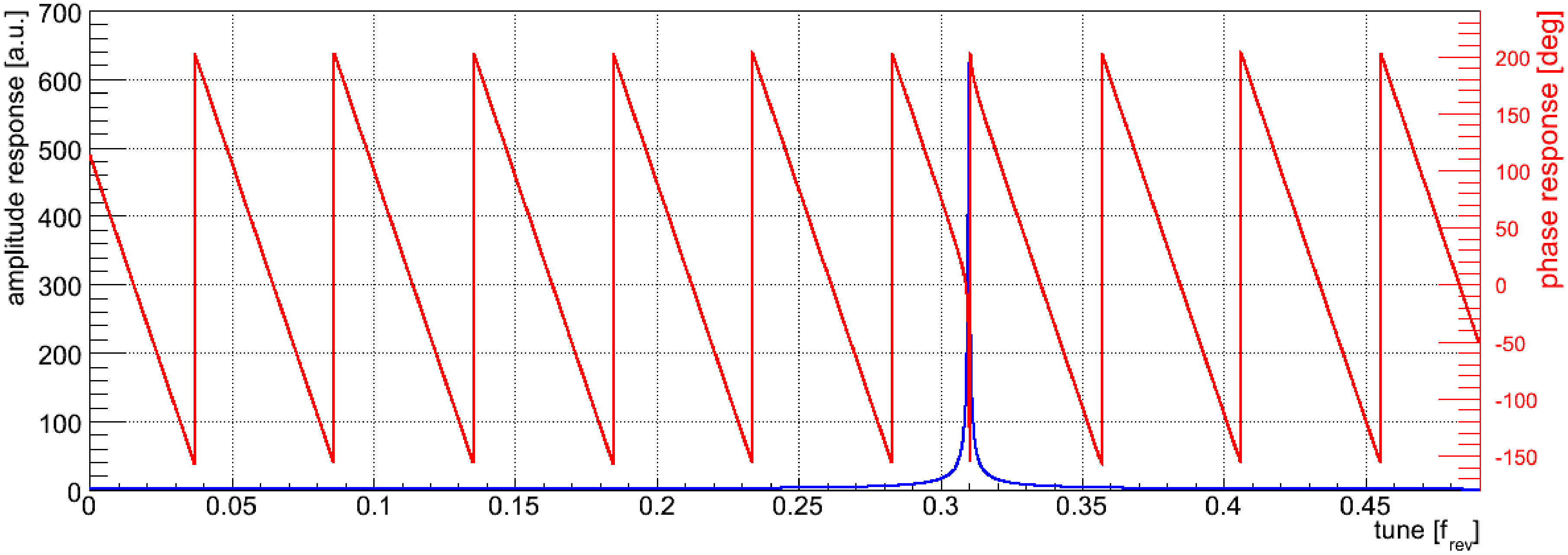
is done
while threading
the first beam!

- It is possible to run feedbacks already after above procedures:
  - auto-triggered at 0.1 – 1 Hz & lower closed loop bandwidth – “day 1..N”
  - In case of Q, Q' we will have the following options:

a) Input: 'FFT + peak detector' or PLL
b) Control level: TuneViewer GUI (slow) or Tune Feedback Controller (fast)
  - both implement the same algorithms!

Commissioning of Feedbacks with Beam II/IV
Example: PLL Setup – Step I (HW lag compensation)

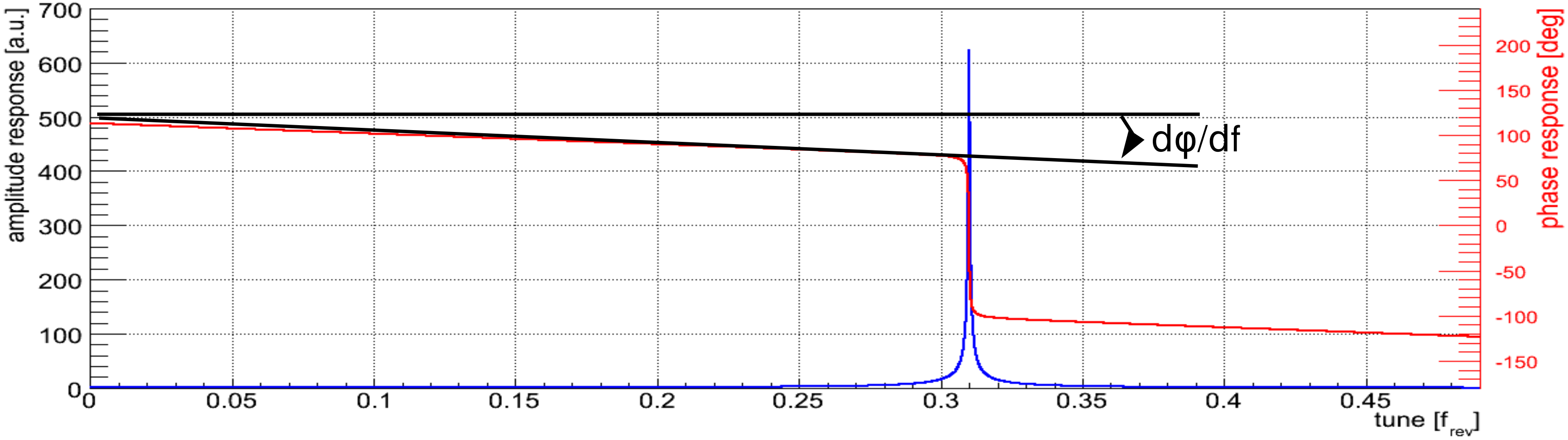
- Essentially BTF and compensation consists of the adjustment of four parameters, preferably during injection plateau (stable tune and chromaticity)
  - 1st step: verify necessary excitation amplitude and plane mapping
  - 2nd step: verify long sample delay (once per installation, constant)
    - full range BTF (will be partially done also without beam)



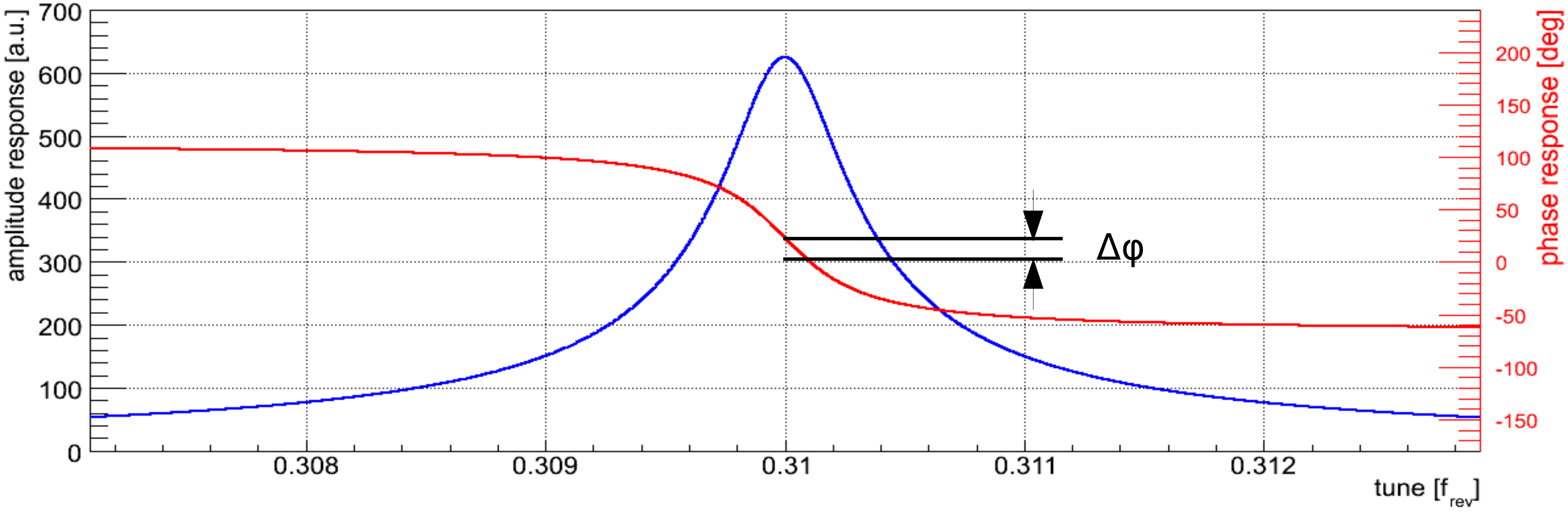
    - count ±π wrap-around → number of delayed samples

Commissioning of Feedbacks with Beam III/IV
Example: PLL Setup – Step II (beam phase compensation)

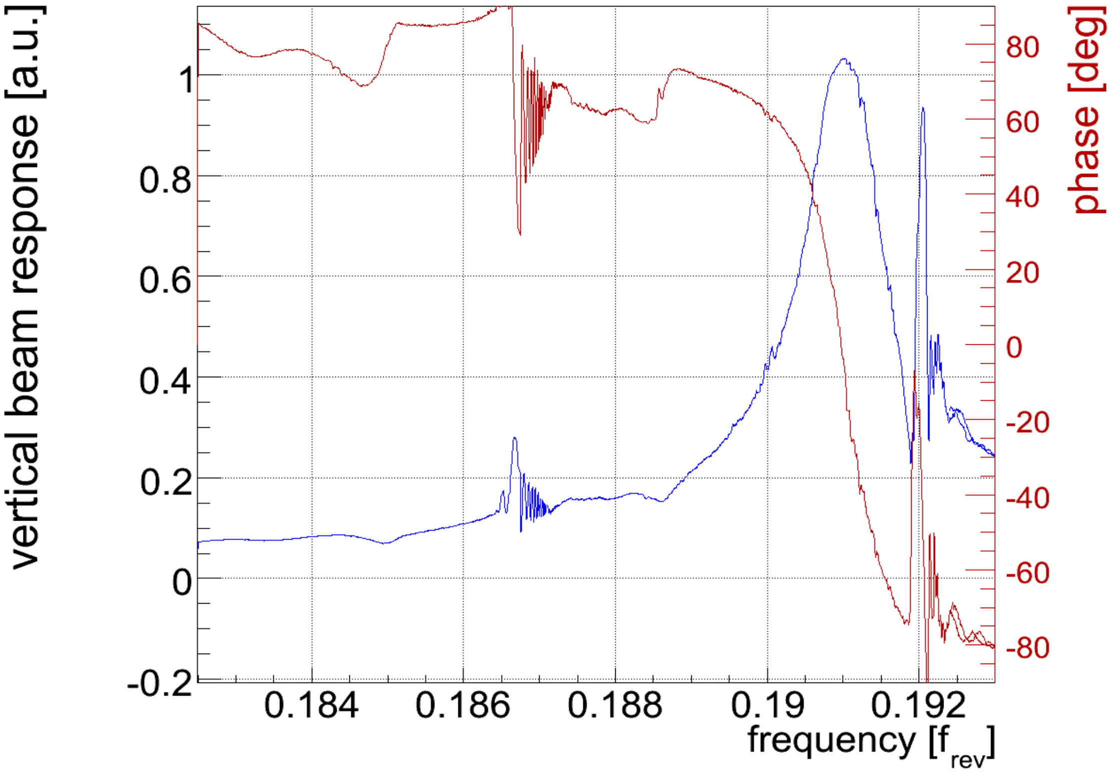
- Measure dφ/df slope (~ front-end non-lin. phase and kicker cable length)



- Adjustments of the locking phase (tune-peak – phase matching)



Commissioning of Feedbacks with Beam IV/IV
Example: PLL Setup – Step III → Ready for Q/C⁻/Q' Tracking



- Based on commissioning experience at the SPS and RHIC:
  - provided stable circulating beam and absence of "surprises", the initial PLL setup with beam can be quite fast: < 30 minutes net!
  - verification of proper loop operation in less than a minute (= one BTF)
- Including verification of circuit mapping and polarities:
  - ~2-4 half-shifts with per beam per feedback loop

Conclusions

- Baseline Q/Q' diagnostics and controls is in good shape
  - compatible with large values of chromaticity and nominal LHC operation
  - Feedback architecture, strategies and algorithms are well established
    - same feedback architecture for orbit, tune/coupling, chromaticity...
  - LHC priorities: Orbit/Energy FB → Q/C$^-$ PLL → Q' Tracker → Q/Q'/C- FB

- Commissioning of feedbacks:
  - Most of the requirements for a minimum workable feedback systems are already fulfilled after threading and establishing circulating beam
    - about two to four half shifts/beam/feed-back for PLL/FB specific procedures
  - Feedbacks are most useful when used at an early stage
    - feedback signals provide feed-forward information for next cycles

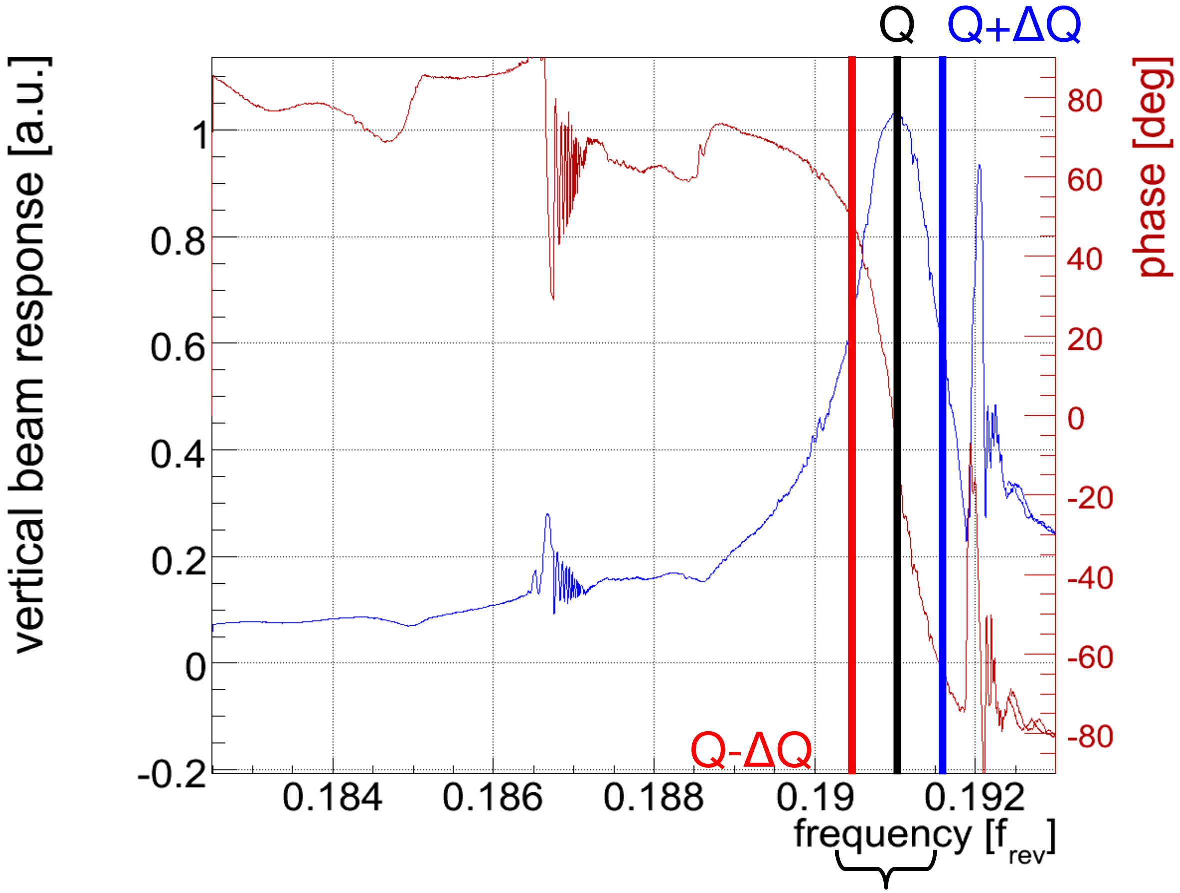
- 'Egg of Columbus' principle: LHC is not the first machine with a BBQ, Q/Q' PLL system or beam-based feedback system, however: there is no guarantee for 'no surprises' or perfect commissioning prior to real LHC operation!
  - We are well prepared but some things need to be tested with real beam!

... after the Q/Q' commissioning

Thank you for your attention
the Q$^{(')}$auls

additional supporting slides

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



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

driven 2^{nd} order resonance:

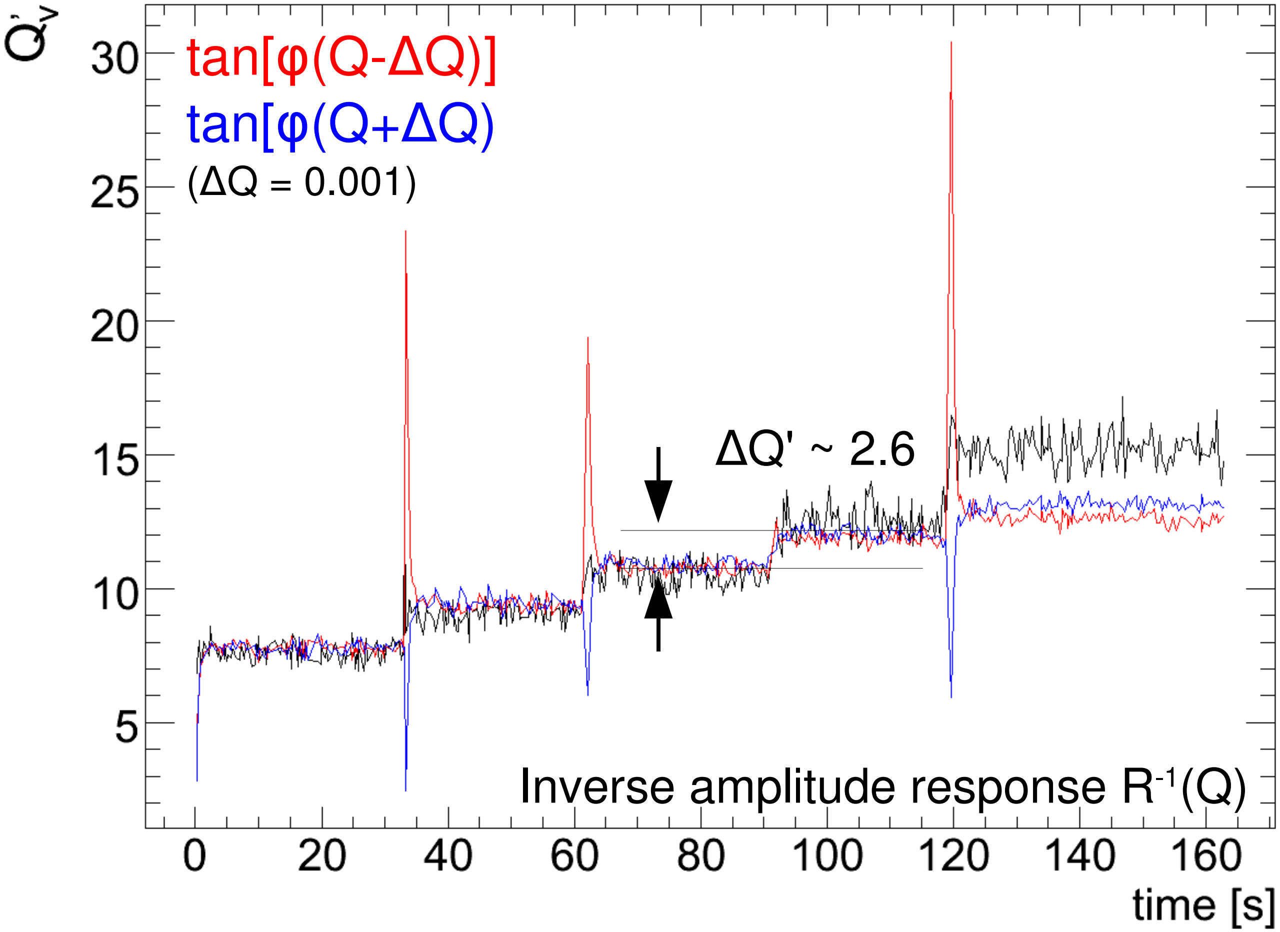
$$\tan(\varphi) \approx \frac{\Delta Q \cdot \omega_Q \omega_D}{\omega_Q^2 - \omega_D^2}$$

- Resonant phase change ↔ tune width change

  → "free" real-time tune footprint measurement

  → measurable dependence of ΔQ ~ Q'

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



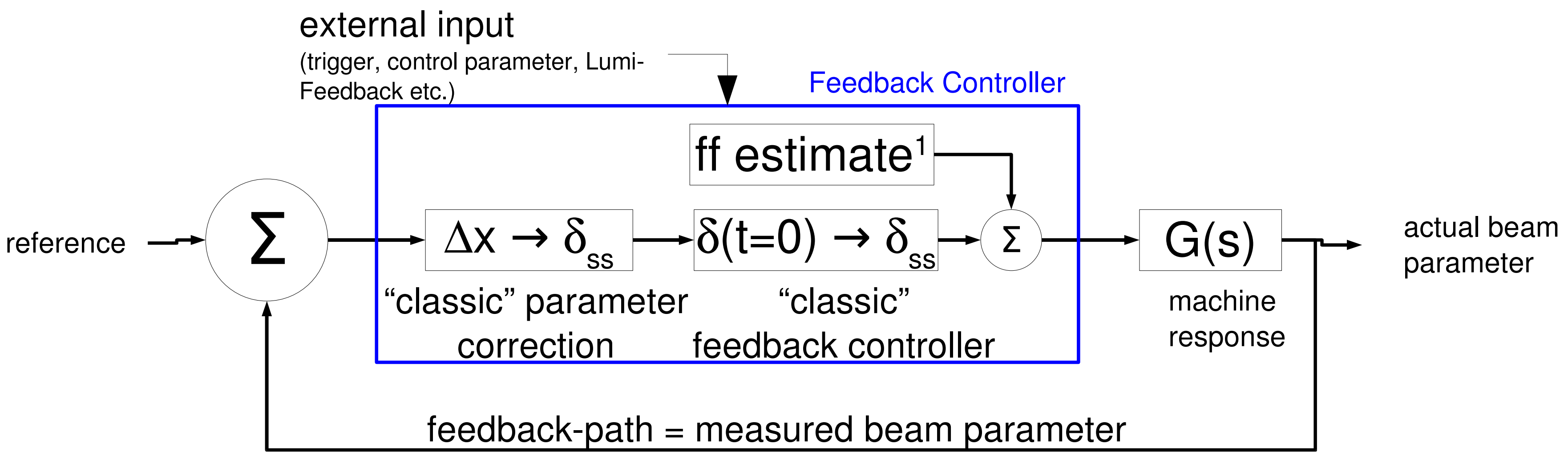
- Side-exciter phase ~~appears to~~ changes linearly with Q' (2007 MDs)
  - No additional momentum modulation
  - Absolute scale requires calibration w.r.t. to classic Q' measurement
  - Non-linear effects require further assessment → 2007 MD Target #2/3

Orbit Feedback/Feed-Forward Control Scheme

- The feedback controller consists of three stages:
  1. Compute steady-state corrector settings $\vec{\delta}_{ss}=(\delta_{1,}\dots,\delta_n)$ based on measured parameter shift $\Delta x=(x_1,\dots, x_n)$ that will move the beam to its reference position for t→∞.
  2. Compute a $\vec{\delta}(t)$ that will enhance the transition $\vec{\delta}(t=0)\rightarrow\vec{\delta}_{ss}$
  3. Feed-forward: anticipate and add deflections $\vec{\delta}_{ff}$ to compensate changes of well known sources

space domain

time domain


external input

(trigger, control parameter, Lumi-Feedback etc.)

Feedback Controller

ff estimate[1]

reference

Σ

$\Delta x \rightarrow \delta_{ss}$

$\delta(t=0) \rightarrow \delta_{ss}$

Σ

G(s)

actual beam parameter

“classic” parameter correction

“classic” feedback controller

machine response

feedback-path = measured beam parameter

Reminder: Solution in Time-Domain

- LHC PC (LR circuit) model G(s): rate-limited first order system with delays:

$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}G_{NL}(s)$$

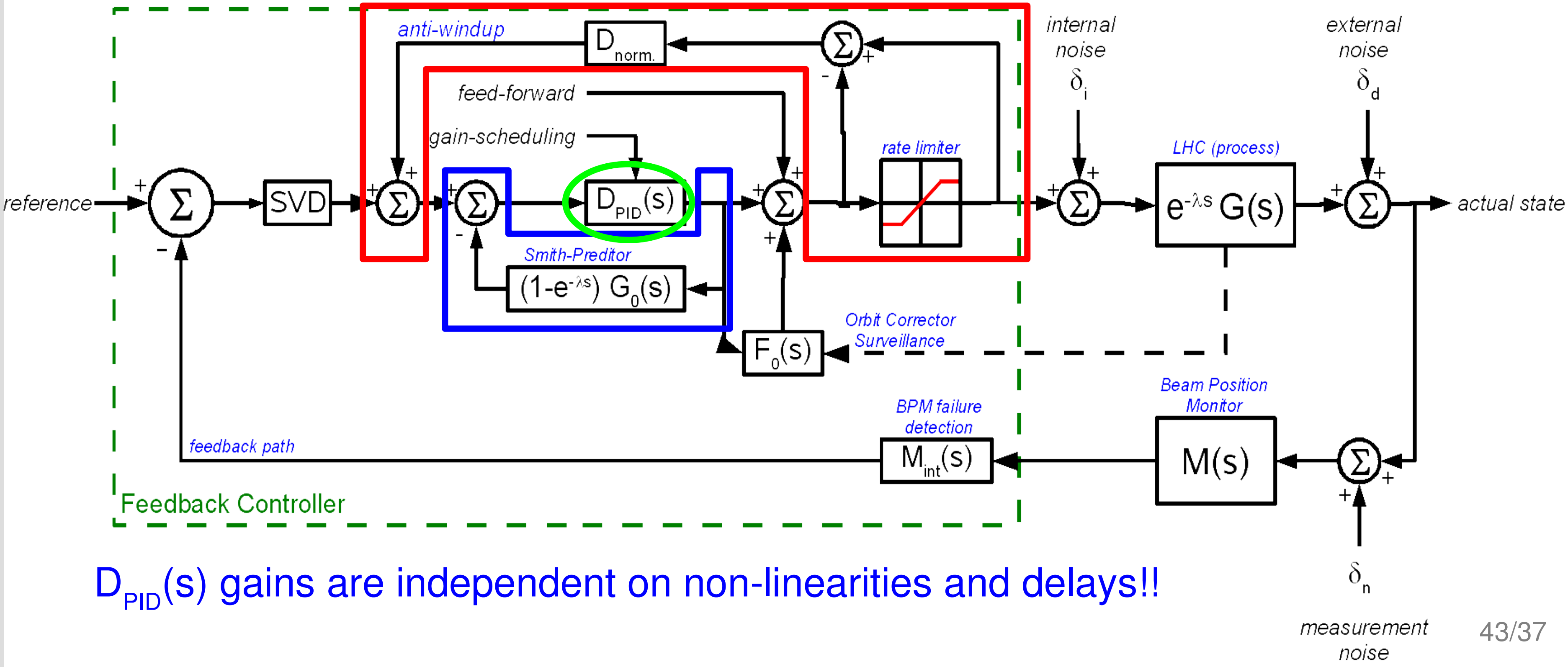
τ : being the circuit time constant

  - Linear optimal PI controller: $D(s)=K_0\cdot\left(\frac{\tau}{\alpha}+\frac{1}{\alpha}\right)$

K$_0$:I-to-δ transfer func.

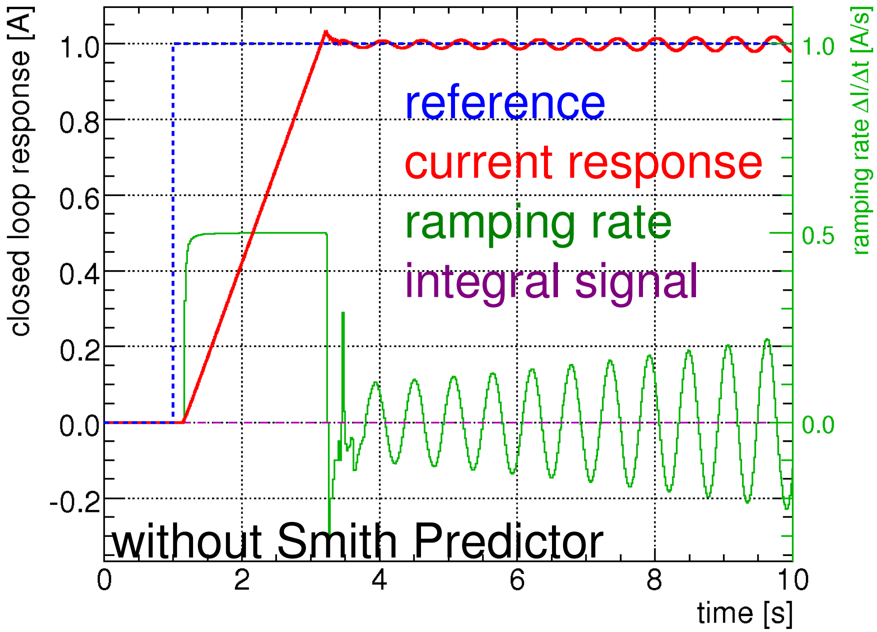
1/α: “effective” FB freq.

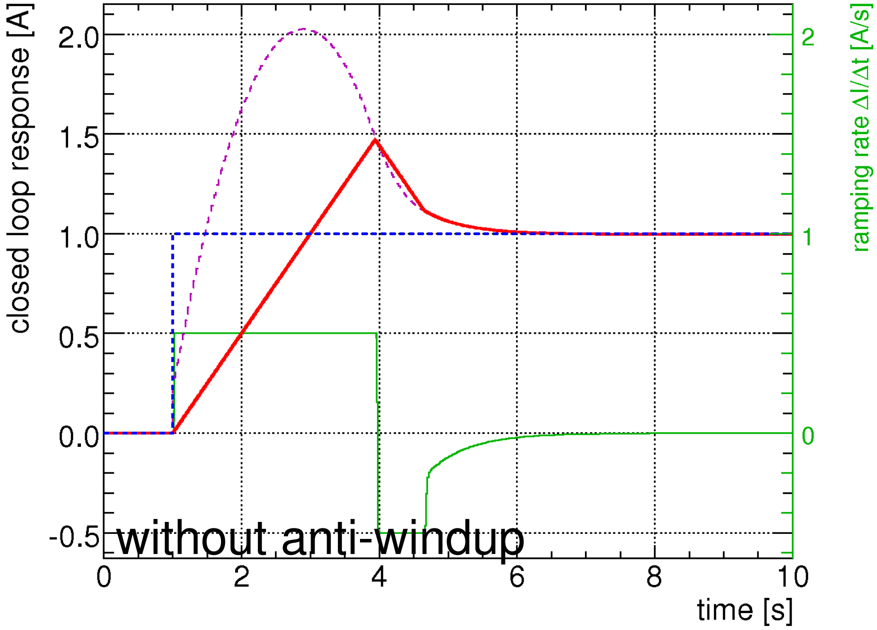
  - including non-linearities (delay & rate-limit):



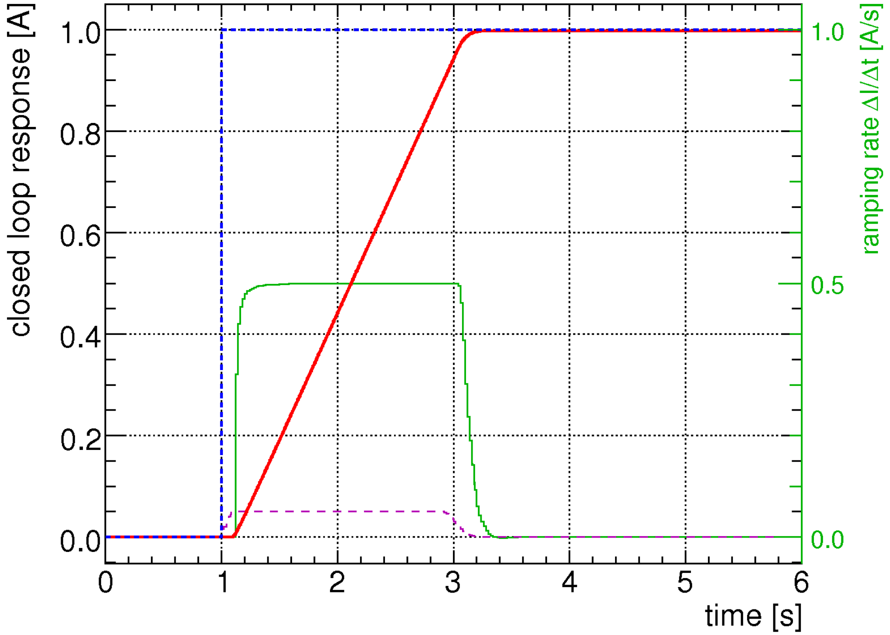
D_{PID}(s) gains are independent on non-linearities and delays!!

Some Results: Smith-Predictor and Anti-Windup



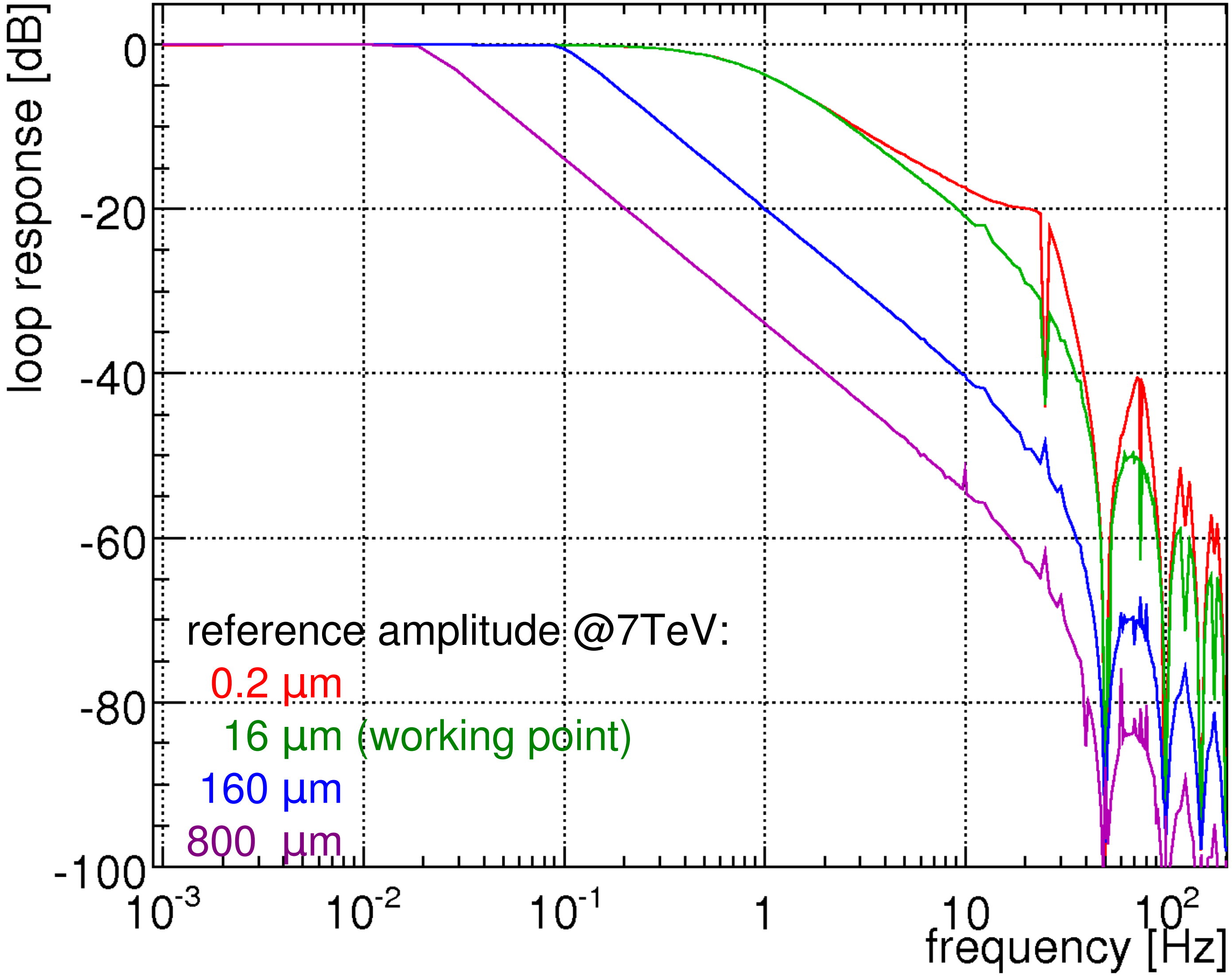


with full delay and windup compensator scheme:



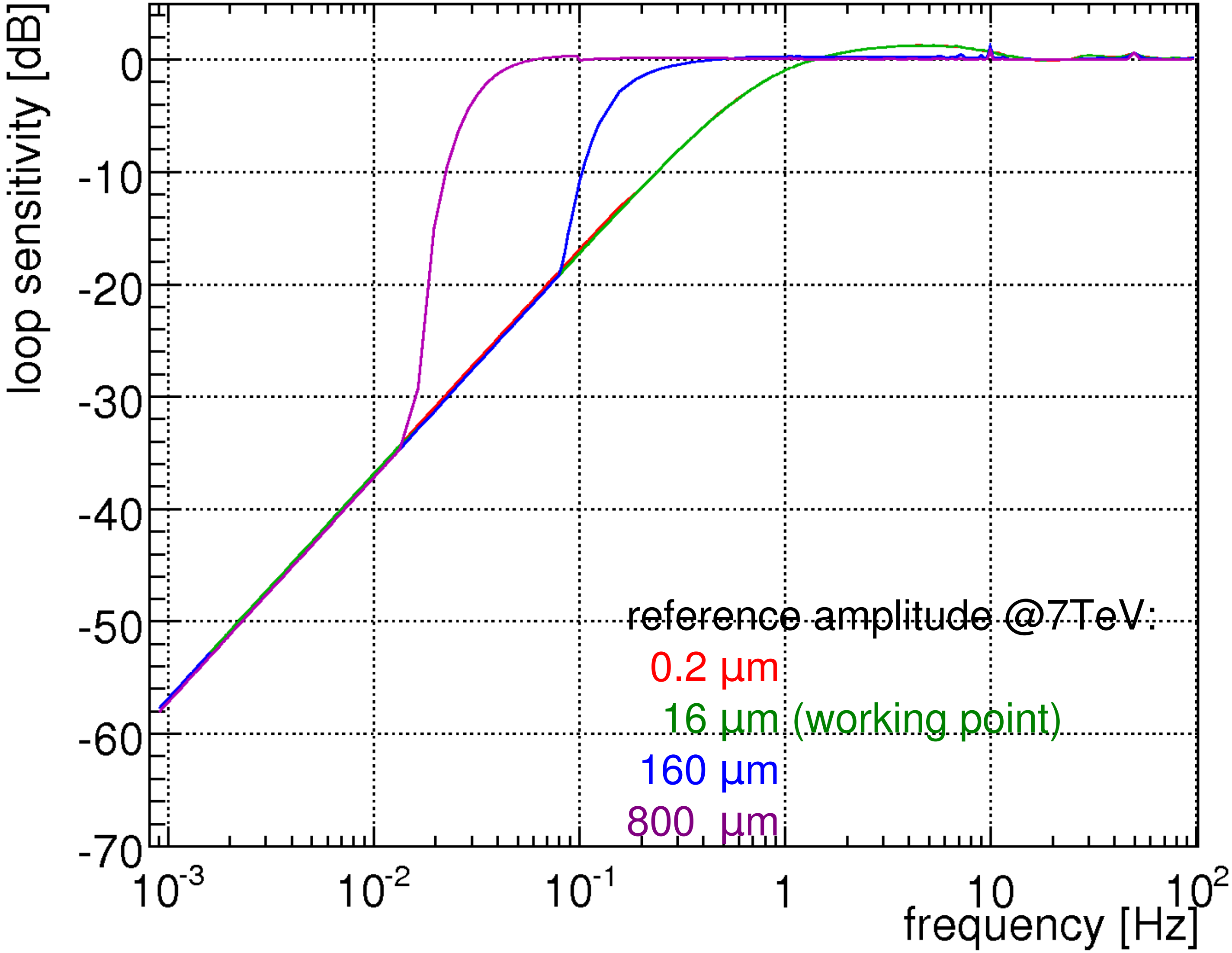
Nominal Feedback Response T_0

- Full LHC orbit simulation @1KHz sampling, (BPM sampling: 25Hz)



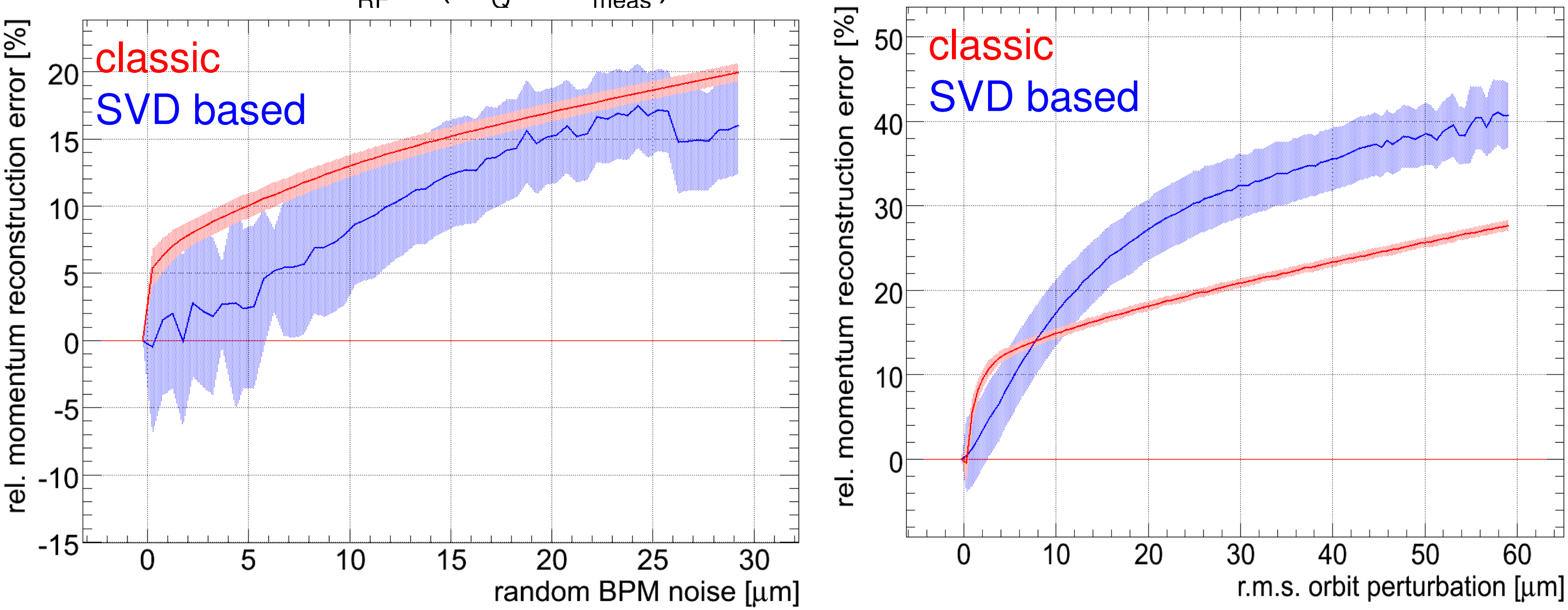
Nominal Feedback Disturbance Rejection S_{d0}

- Full LHC orbit simulation @1KHz sampling, (BPM sampling: 25Hz)



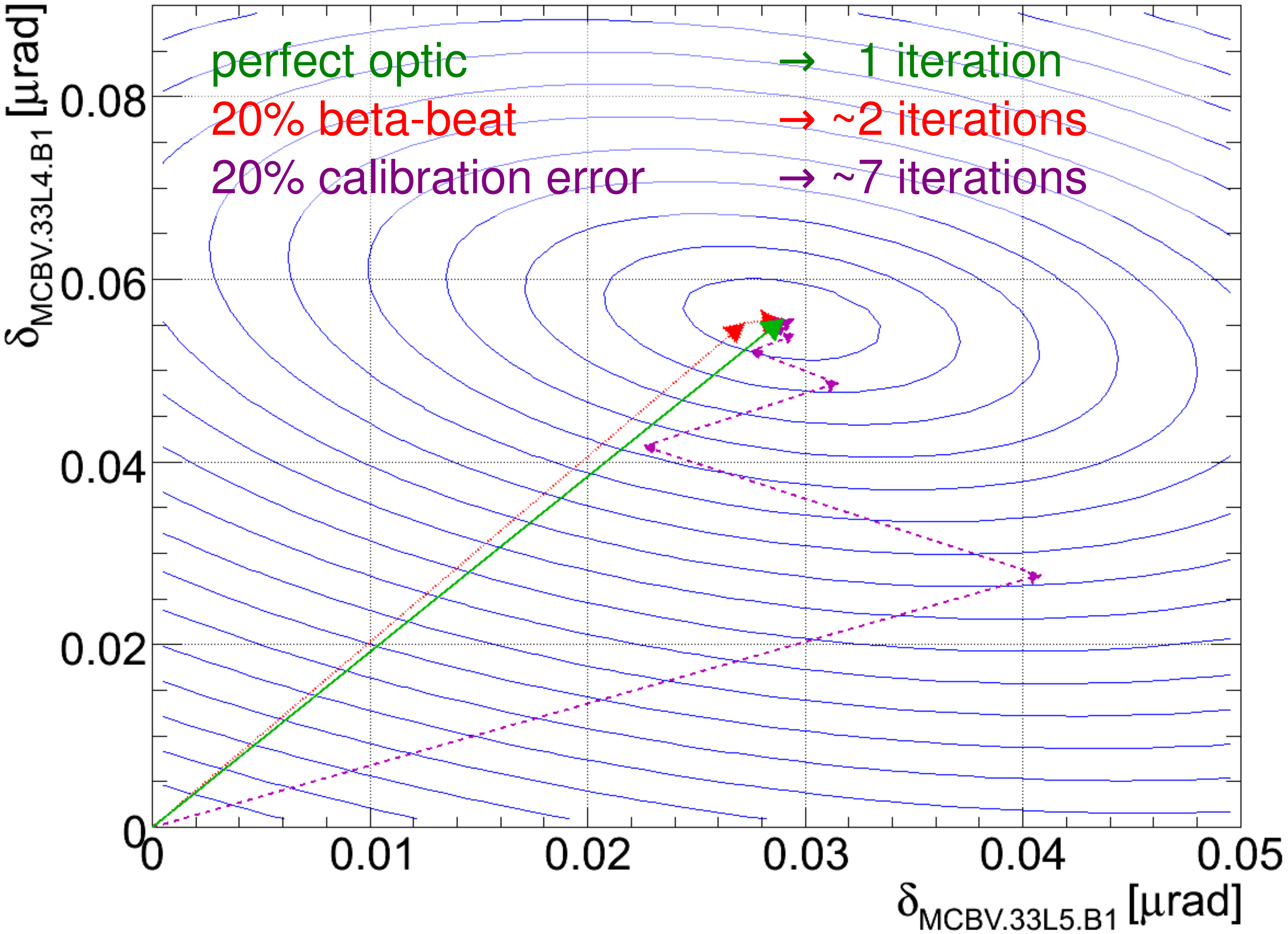
Loop Interdependences and Cross-Talk II/III

- Multiple FBs and measurements acting on the same RF cavity frequency (N.B. radial position limited by collimator gap)
  - Q' tracker, energy FB (≈'radial loop'), Q'' and other optics measurements
  - strategy: orbit feedback acts as a slave system controlling the RF
    - dispersion orbit is subtracted/not corrected by 'regular OFB'
    - energy FB corrects w.r.t. to the by the Q' tracker set reference
      - $\Delta f_{RF} = (\Delta f_{Q'} - \Delta f_{meas})$



Reminder: Solution in Space-Domain
Response Matrix and Calibration Uncertainties

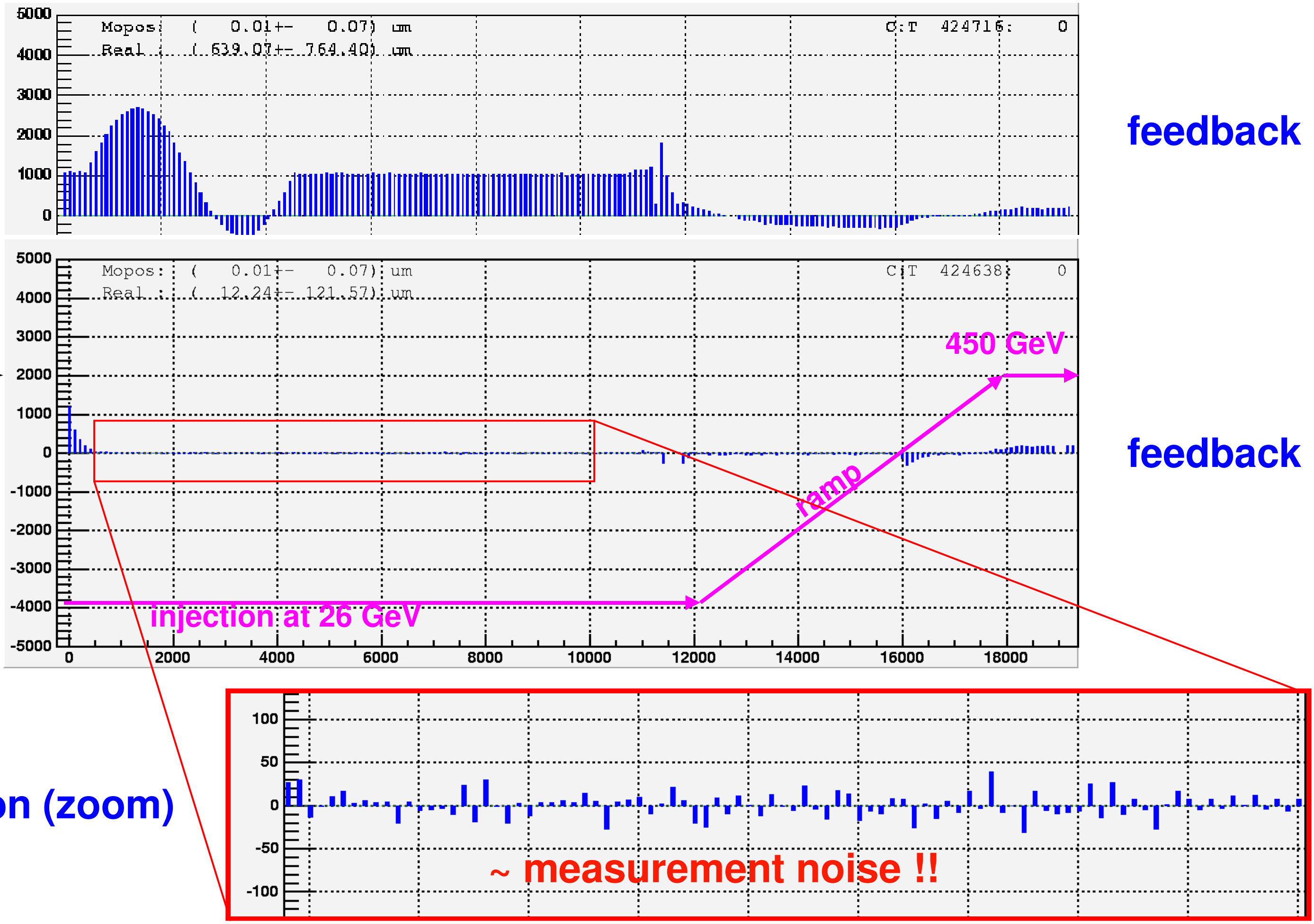
- Matrices are direct observables and can thus be measured with beam!
  - Imperfect optics and calibration errors may deteriorate convergence speed but not the convergence accuracy
  - Example: 2-dim error surface projection



Example: LHC Orbit Feedback Test at the SPS I/II Real-Beam Data

BPM Reading (µm)

Time (ms)

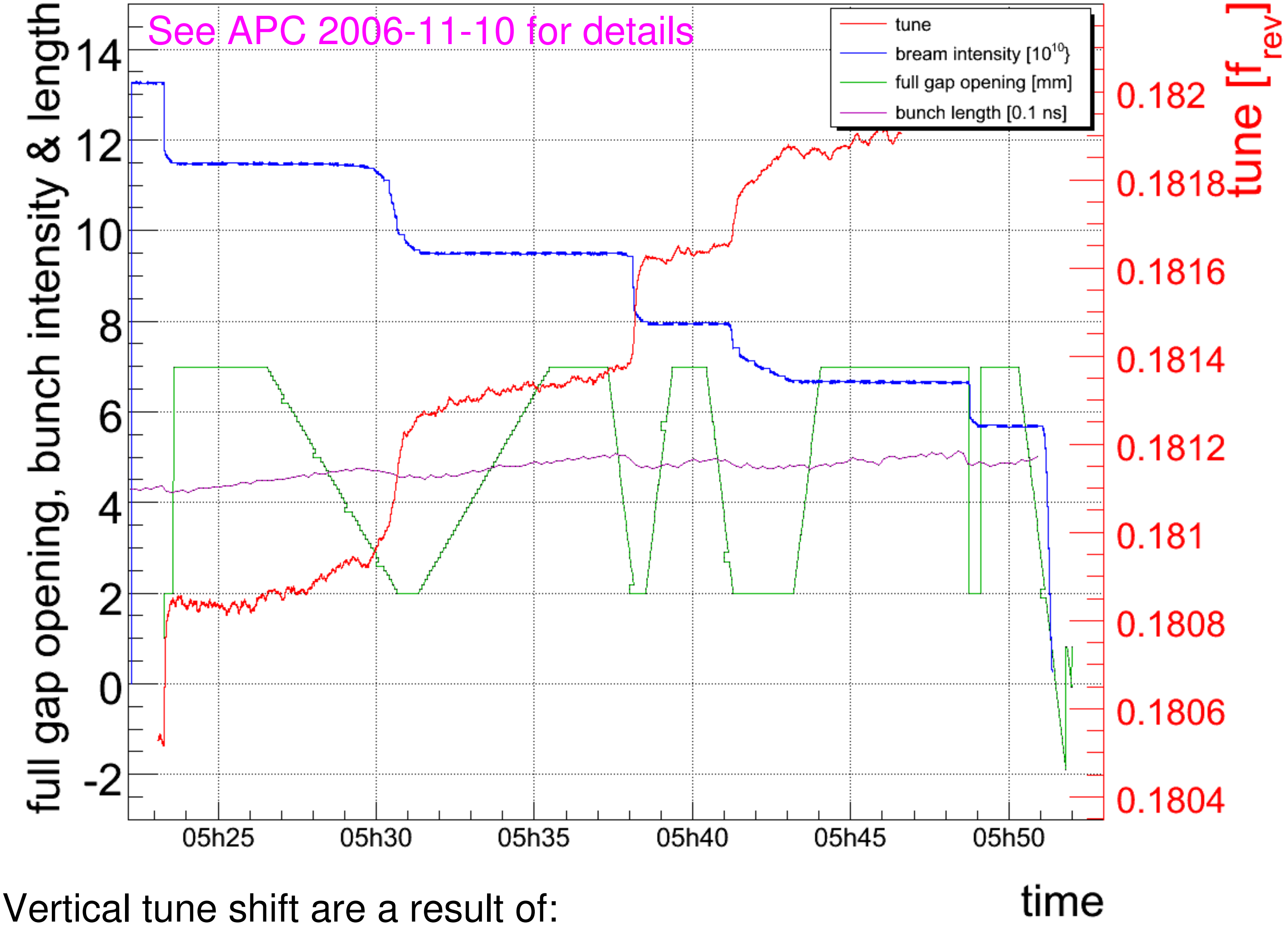


feedback off

feedback on

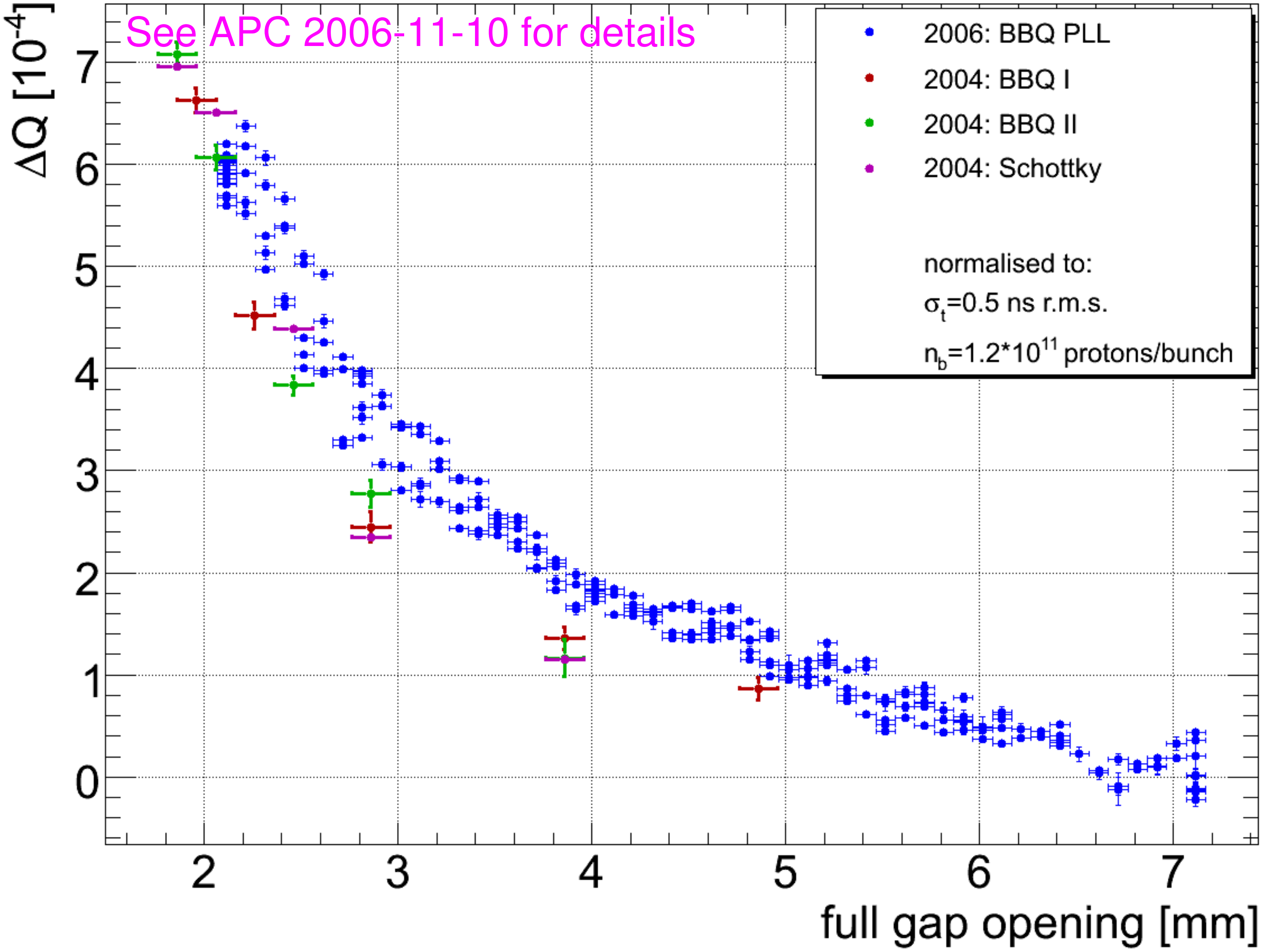
feedback on (zoom)

BBQ-PLL based Q/Q' tracking
Since 2006: Vertical Tune Shifts due to SPS Impedance



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

BBQ-PLL based Q/Q' tracking
Since 2006: Collimator Imp. Q_x versus Full Gap Opening



- Tune resolution: $\Delta Q_{res} \approx 10^{-6}...10^{-7}$

LHC Q/Q' System Overview

LHC Q/Q' system: 5 racks, 9 VME crates, 10 DAB front-ends:

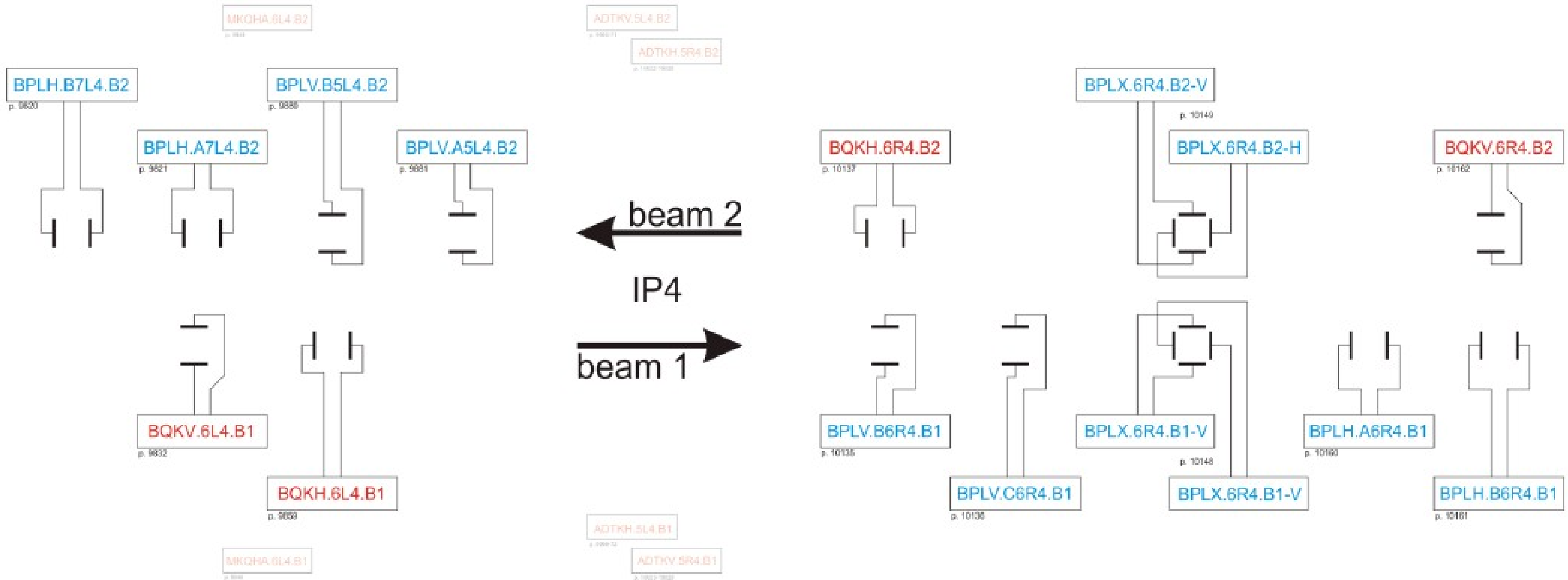
- UA43-BY10 - support cavern left of IP4 [*CFV-UA43-BQB2*]
  - PLL-B2 (operation): Q/C$^-$ Phase-Locked-Loop System Beam 2
    - connected to BQK.6R4 (aka. 'Q shaker')
  - FFT-B2 (operation): periodic acq., logging, fill-to-fill studies, Beam 2

- UA47-BY07 - support cavern right of IP4 [*CFV-UA47-BQB1*]
  - PLL-B1 (operation): as above but Beam 1
    - connected to BQK.6L4
  - FFT-B1 (operation) as above but Beam 1

- UA47-BY12 [*CFV-UA47-BQ → CFV-UA47-BQFFT?*]
  - FFT-B1, FFT-B2: on demand FFT spectra acquisition
    - connected to RF damper system
    - software + hardware (TTL) link to MKQA
    - N.B. can be also used for periodic acquisition
  - (BQSHT-B1/B2: 'Head-Tail' acquisition system)

- SX4-BY11 – surface building [CFV-SX4-*BQDEVB1, CFV-SX4-BQDEVB2*]
  - DEV-B1: LHC FFT/PLL/HT development system
  - DEV-B2: (Q: move to SPS? - “easier”/more available test-bed)

BBQ-PLL and -FFT Installation Overview



PLL.B2
FFT1.B2

BY10.UA43

BPLH.A7L4.B2 (2c+m26)
BPLH.B7L4.B21 (2c)
BPLV.A5L4.B2 (2c+m26)
BPLV.B4L4.B2 (2c)

BY11.SX4 (2c+m48)

BY08.UA47 (4c+m48)

FFT1.B2, PLL.B2
CFV-UA43-BQPLL

PLL.B1
FFT1.B1

BY07.UA47

BPLH.A6R4.B1 (2c+m26)
BPLH.B6R4.B1 (2c)
BPLV.B6R4.B1 (2c+m26)
BPLV.C6R4.B1 (2c)

BY11.SX4 (4c+m48)

damper tunnel (2c)

FFT1.B1, PLL.B1
CFV-UA47-BQPLL

FFT2.B1
FFT2.B2

BY12.UA47

BPLX.6R4.B1-H (2c+m26)
BPLX.6R4.B1-V (2c)
BPLX.6R4.B2-H (2c+m26)
BPLX.6R4.B2-V (2c)

BY10.SX4 (4c+m48)

damper tunnel (4c)

FFT2.B1, FFT2.B2
CFV-UA47-BQ

DEV.B1
DEV.B2

BY11.SX4

BY09.UA43 (4c+m48)
BY10.UA43 (2c+m48)

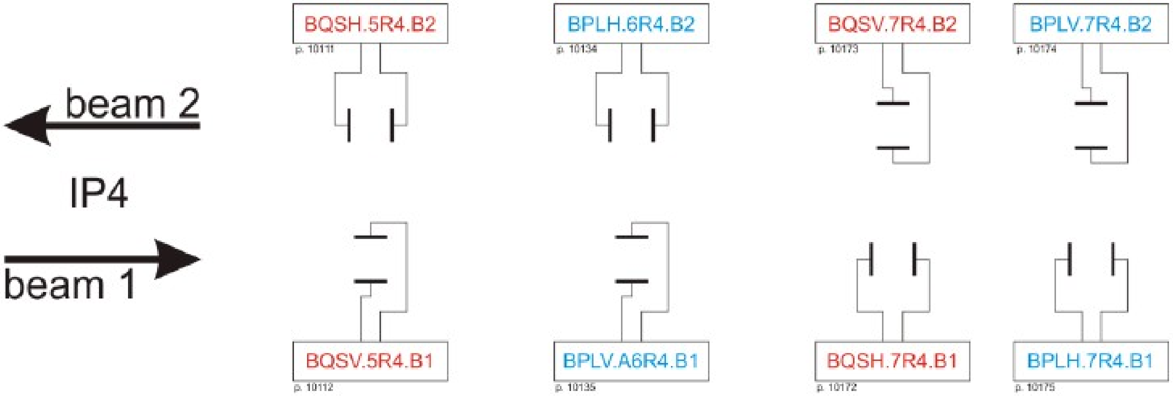
BY06.UA47 (2c+m48)
BY07.UA47 (4c+m48)

damper surface (4c)

DEV.B1
CFV-SX4-BQPLLB1

DEV.B2
CFV-SX4-BQPLLB2

Head-Tail and Schottky Installation Overview



HT.B1
HT.B2

BQS.B1
BQS.B2

BY12.UA47

BPLH.7R4.B1 (2c+m26)
BPLV.A6R4.B1 (2c)
BPLH.6R4.B2 (2c+m26)
BPLV.7R4.B2 (2c)

CFV-UA47-HT

BY13.UA47

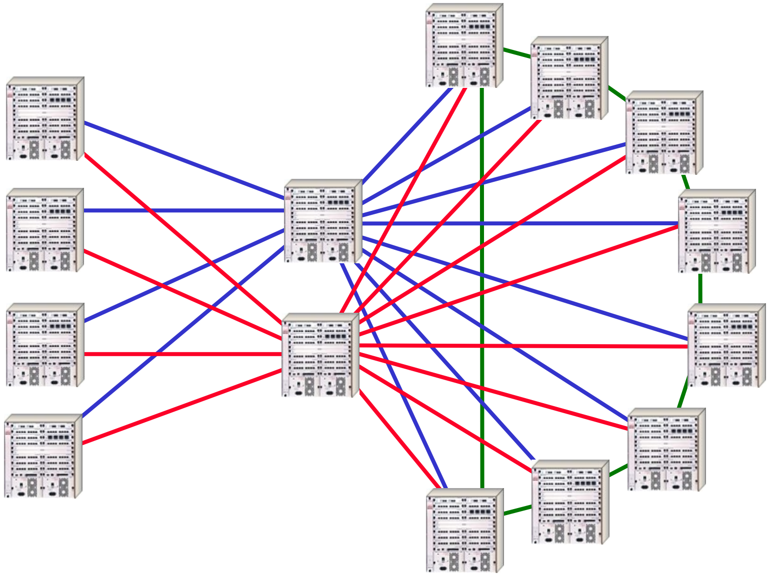
BQSH.7R4.B1 (2c)
BQSV.5R4.B1 (2c)
BQSH.5R4.B2 (2c)
BQSV.7R4.B2 (2c)

BY12.SX4 (8c)

CFV-UA47-BQS

Technical Network and Data Communication I/II

- CERN's Technical Network as backbone
  - Switched network
    - no data collisions
    - no data loss
  - double (triple) redundancy



- Core: “Enterasys X-Pedition 8600 Routers”
  - 32 Gbits/s non-blocking, $3 \cdot 10^7$ packets/s
  - 400 000 h MTBF
  - hardware QoS
    - One queue dedicated to real-time feedback
    - ~ private network for the orbit feedback
- Routing delay ~ 13 µs
- longest transmission delay (exp. verified) ~ 320 µs

  (500 bytes, IP5 -> Control room ~5 km)
  - 20% due to infrastructure (router/switches)
  - 80% due to traveling speed of light inside the optic fibre
- worst case max network jitter « targeted feedback frequency!

Technical Network and Data Communication II/II

- The maximum latency between CCC and IR5
  - tail of distribution is given by front-end computer and its operating system