Status of Tune, Chromaticity, and Coupling Measurements

– Take 2 –

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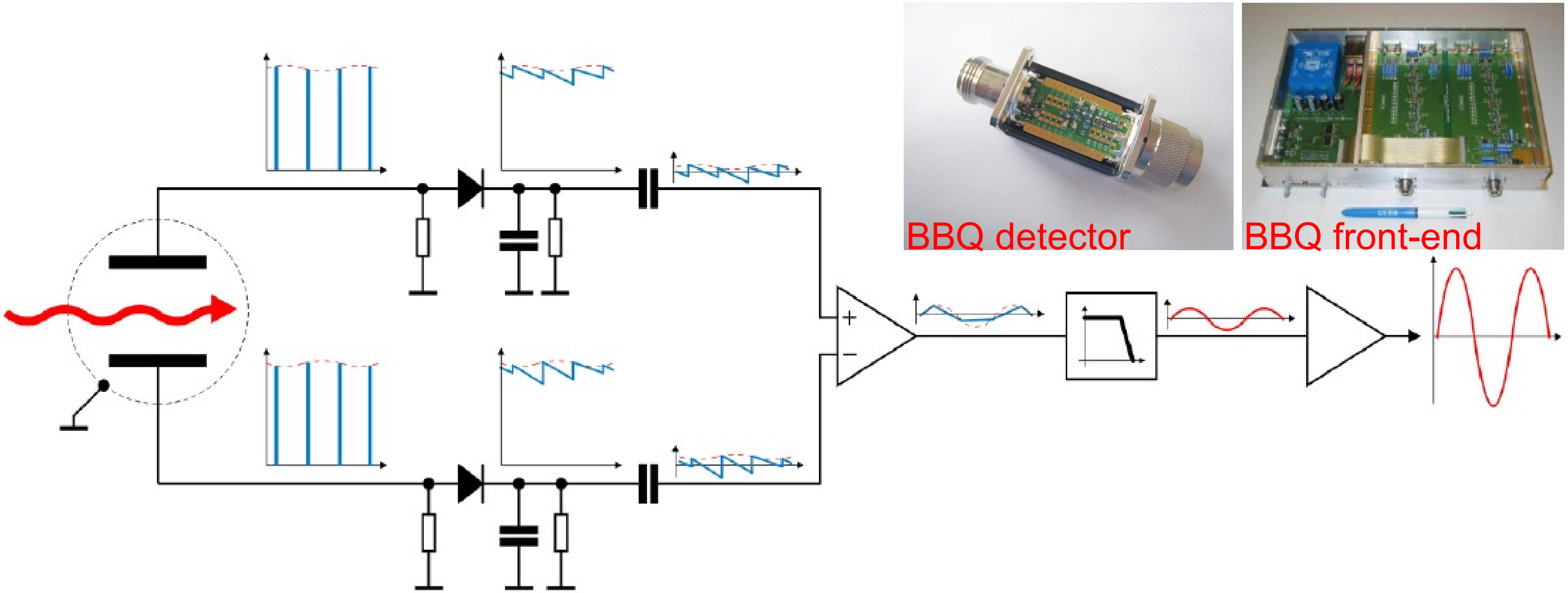
Outline

- Base-line LHC Q, Q' and C^- diagnostics
  - Status Quo: what was available in '08 is also in '09
    - BBQ FFT-based Systems: continuous, on-demand
      - hardware re-tested, RBAC access maps, ...
    - Partially: semi-automated Q' measurement

- New functionalities and not commissioned items in 2008:
  - Tune-PLL (though tested in the SPS)
  - Radial (de-)modulation → continuous Q' measurement
    - Q' expected to be more critical than Q
    - Prerequisite for any Q' monitoring even more Q'-FB

Back-bone: Base-Band-Q Principle on a Slide



- Basic principle: AC-coupled peak detector
  - no saturation, self-triggered, no MTG timing required, no gain changes between pilot and nominal beam
    - Measured resolution estimate: < 10 nm → ε blow-up is a non-issue
- One of the turn-key systems in the LHC
  - ... some redundancy: 8 systems available vs. 2 needed

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

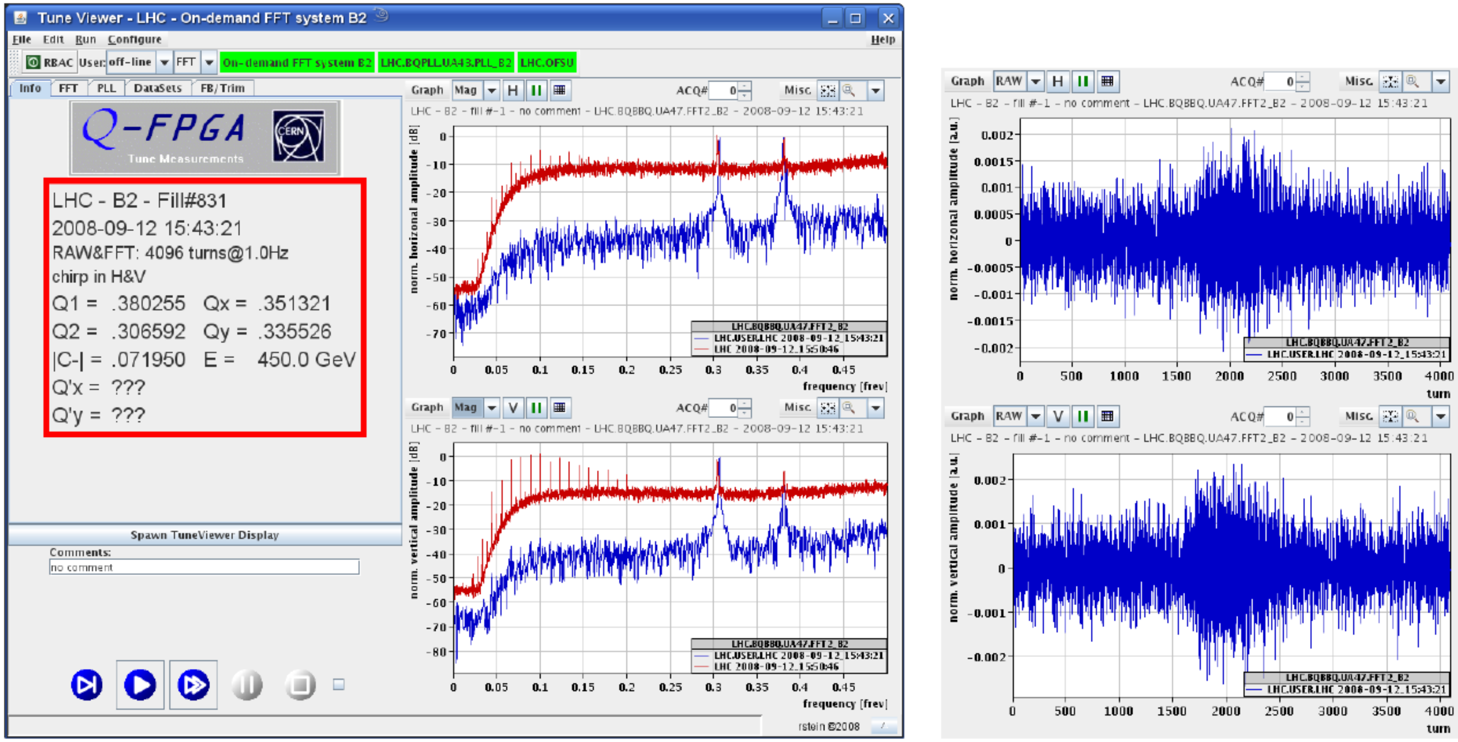
- Three independent BBQ Tune diagnostic chains available per beam:
  - FFT based acquisition of Q,Q'... – 'periodic' – tested in 2008
    - one measurement every second (8192 turns ↔ ~0.7 seconds)
    - intended use: monitoring/logging, (feedbacks), fill-to-fill studies, …
      - post-mortem provides beam oscillation for the last ~ 22 seconds
  - FFT based acquisition of Q,Q'... – 'on demand' – tested in 2008
    - n-measurements synchronised to an external event (BPM, BQ, …)
    - intended use: exp.-diagnostics, detailed studies, semi-automated Q'

  → most people in the CCC will probably use this device

  - PPL based acquisition of Q, Q'... – t.b. commissioned in 2009
    - one measurement at high/reduced acquisition
      - 25 Hz for feedbacks, 1 Hz for general purpose logging
    - main use: monitoring/logging, feedbacks, fill-to-fill studies, …
      - However: by itself, no Q' diagnostics

LHC BBQ 'on-demand' System
Mode of Operation:

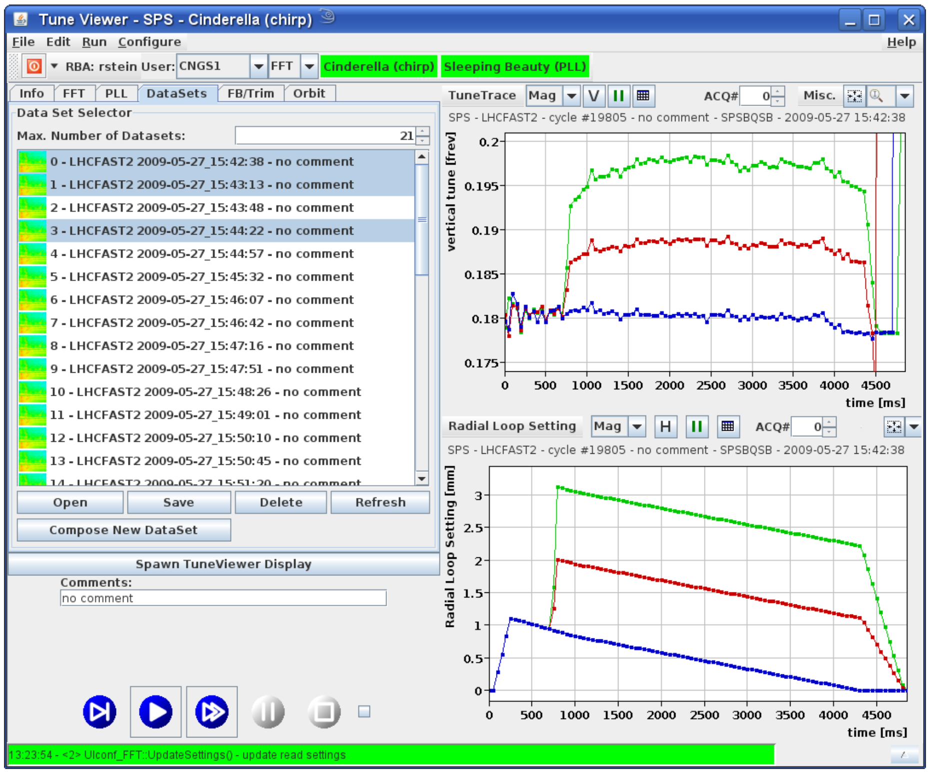
- FFT based Q acquisition using either
  - simply no excitation! - yielded sufficient data in most cases in '08



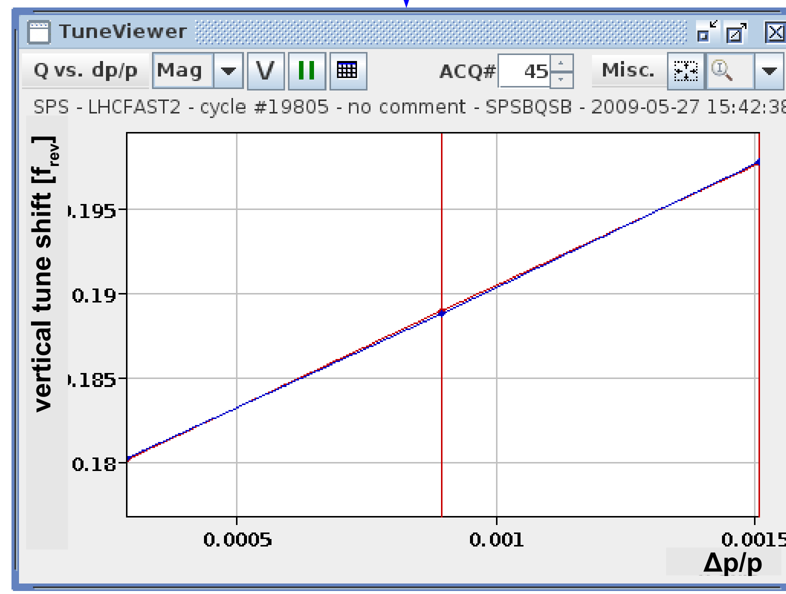
- ...if necessary: fall-back to one of the following excitation methods:
  - Chirp-type excitation using the 'RF transverse damper' ↔ Q-PLL
    - for (local) coupling measurement, $Q_h \leftrightarrow Q_v$ mapping, …
  - Single-turn kick using the 'MKQA' (aka. 'tune kicker' via MTG trigger)
    - for special machine studies, measurements involving BPMs or HT, injection

Semi-Automatic Q' Measurement here: SPS Example

- TuneViewer GUI further stores a set of machine settings (LSA) : Q/Q'-reference, trim settings, radial loop, E, ...
  – Enables comparison/re-verification: Q^(')-vs-Δp/p, Q^(')-vs-trim, …

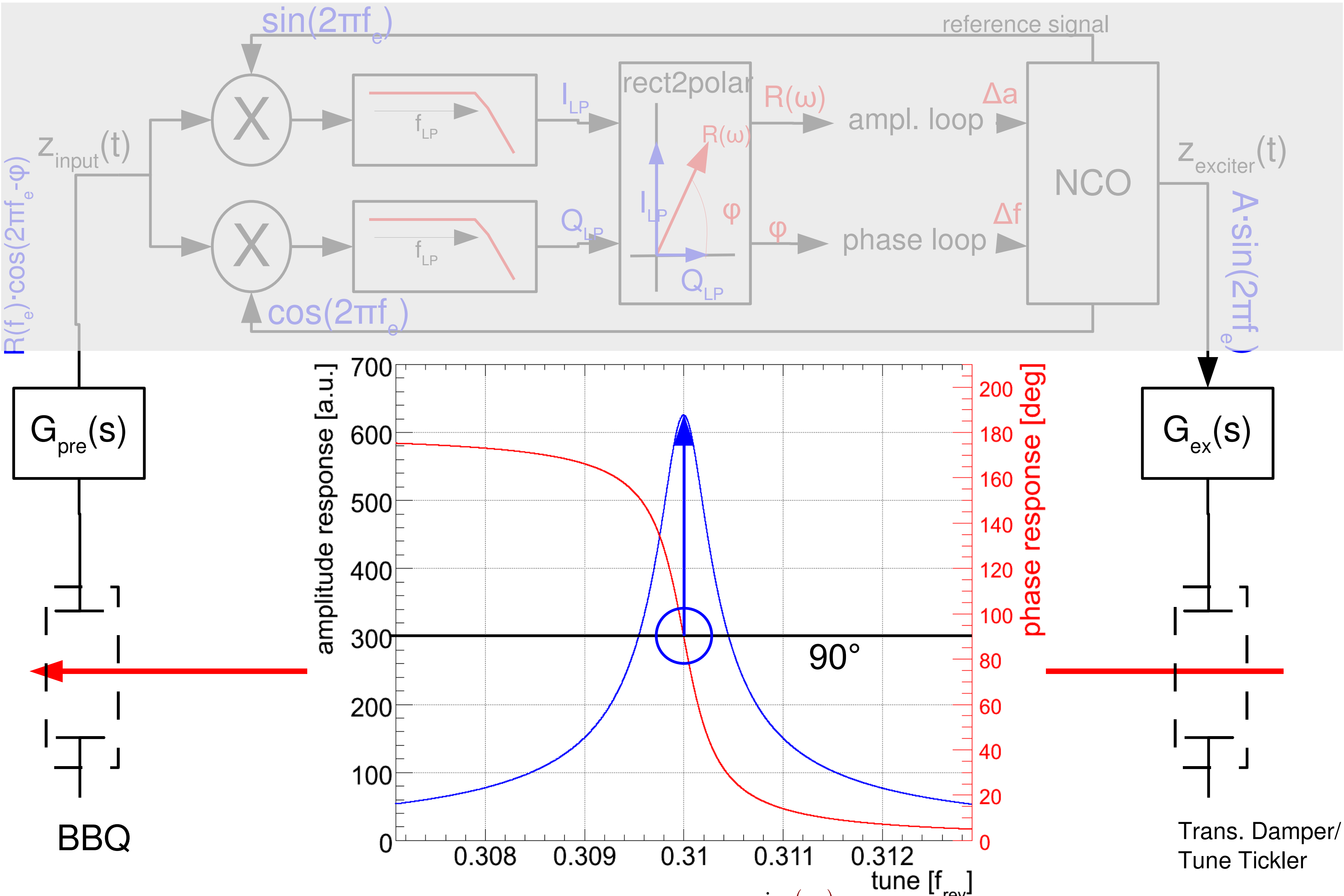


FIDEL perf. assess



- While there is some automatisation (auto-Δp/p trim missing), this remains a cross- or sanity-check only. → nom. requirements: $\Delta Q'_{res}$ ~ a few units/s
  – Limited: DB access, high-level data retrieval → The rationale for a Q/Q' PLL

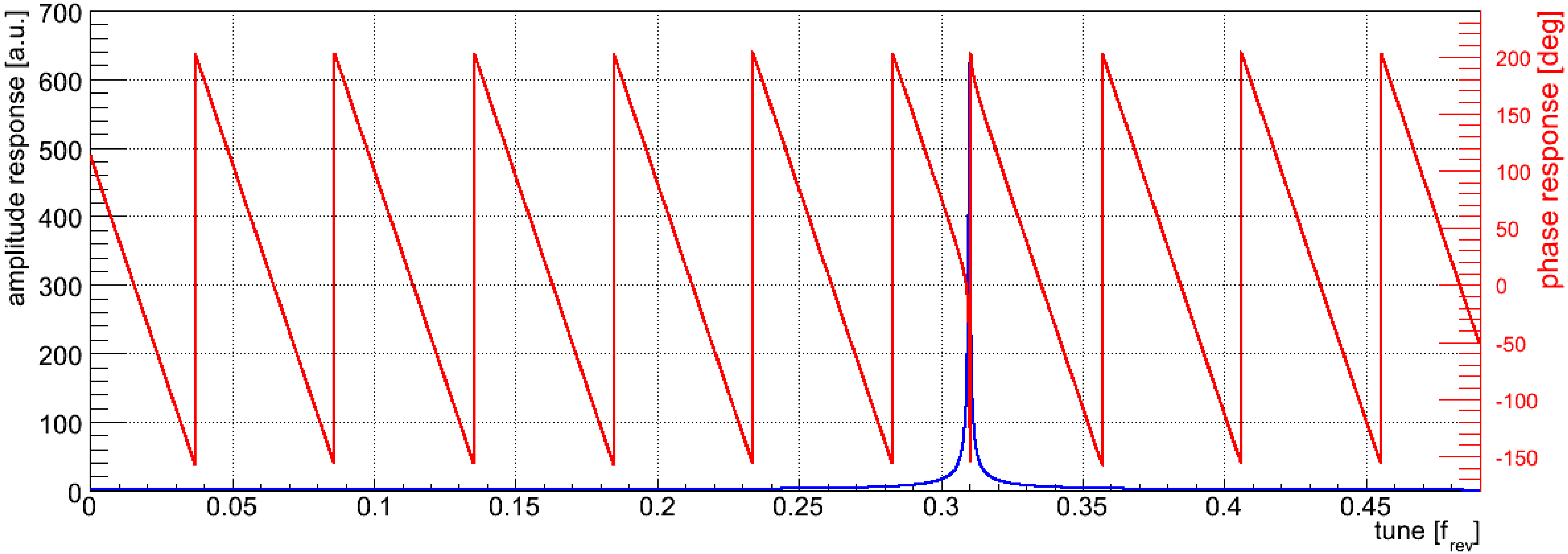
Q Phase-Locked-Loop Scheme on a slide



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

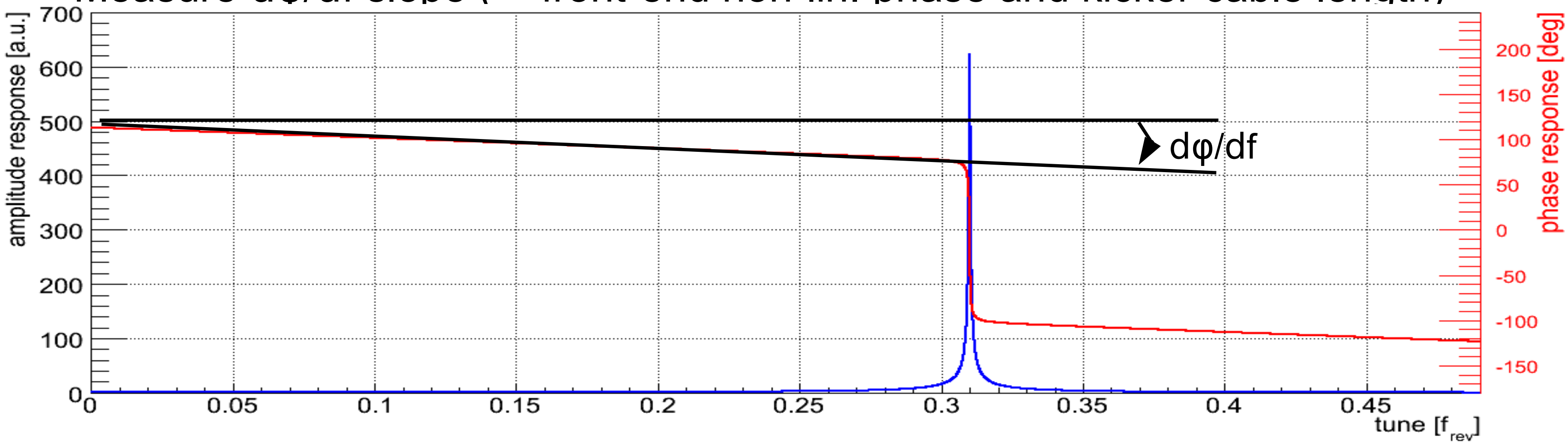
Example: PLL Setup – Step I (HW lag compensation)

- 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)

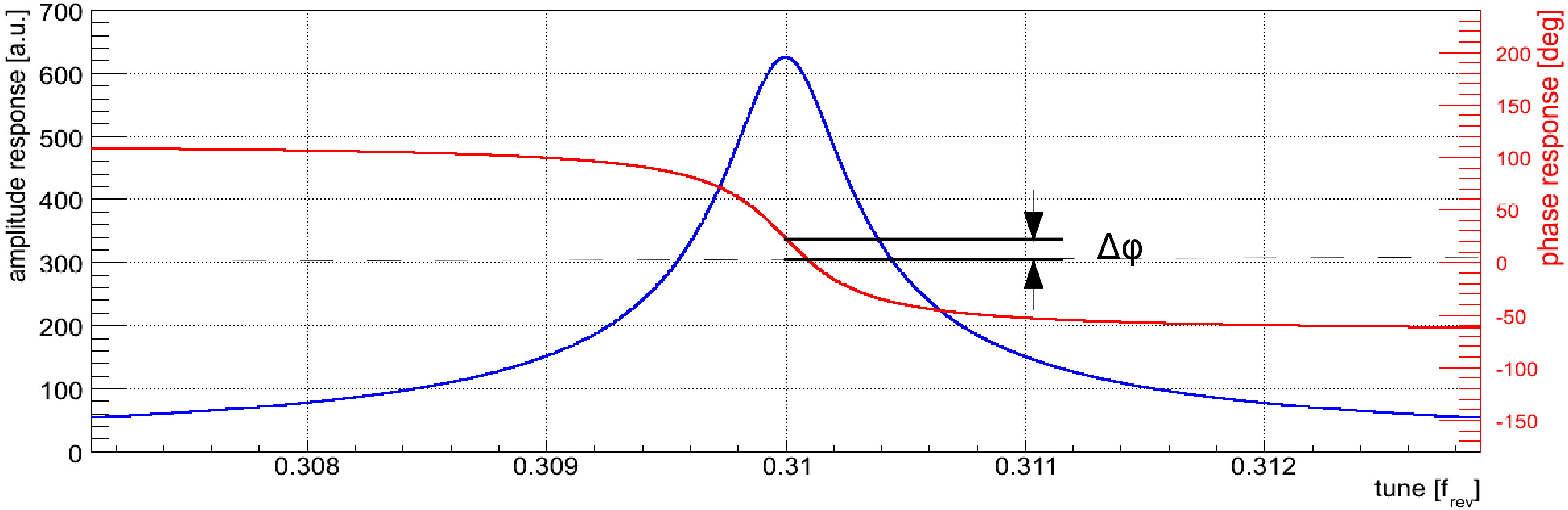


Example: PLL Setup – Step II (beam phase compensation)

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

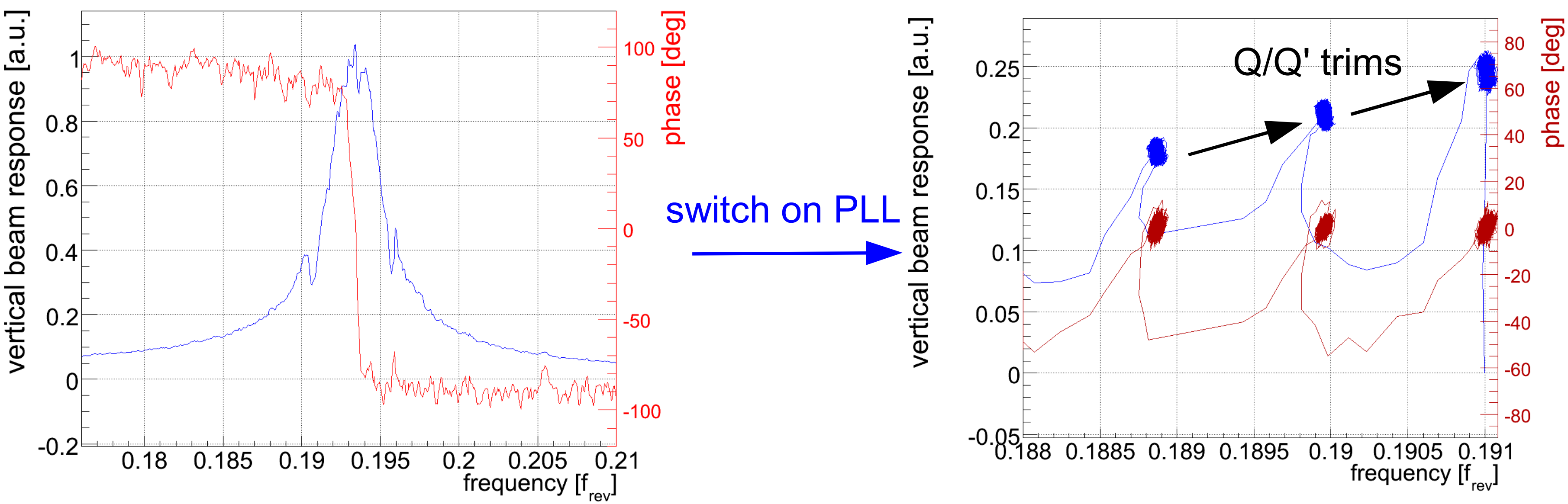


- Adjustments of the locking phase (tune-peak – phase matching)



Example: PLL Setup – Step III → Ready for Q/C-/Q' Tracking

- Beam-Transfer-Function → PLL lock

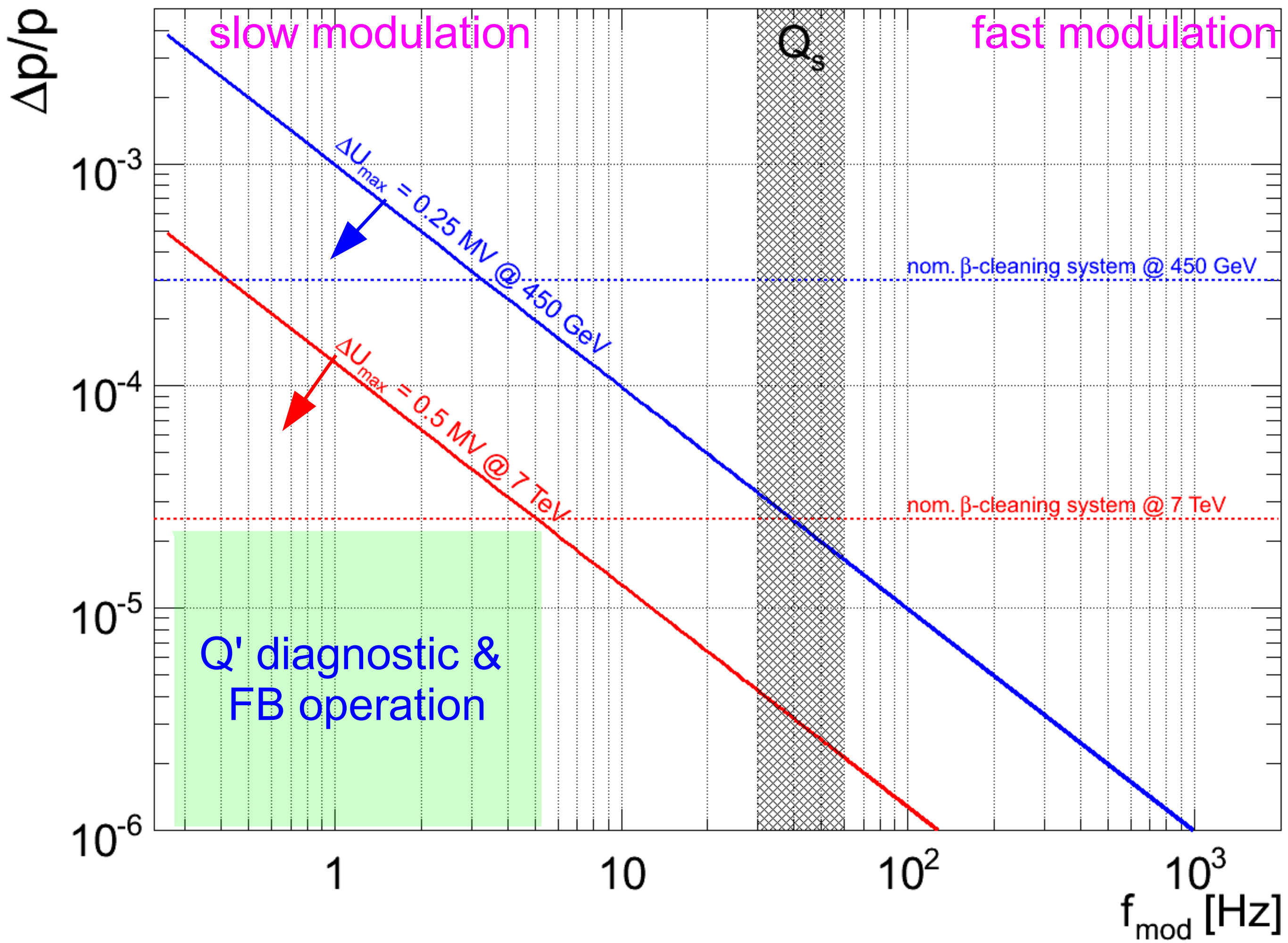


- Above step may need to be repeated several times
  - see additional slides on, what can break the loop
- provided absence of “surprises”, initial PLL setup with beam can be quite fast
- Including verification of circuit mapping and polarities:
  - ~2-4 half-shifts with per beam per feedback loop

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)

Q' through RF momentum modulation based method

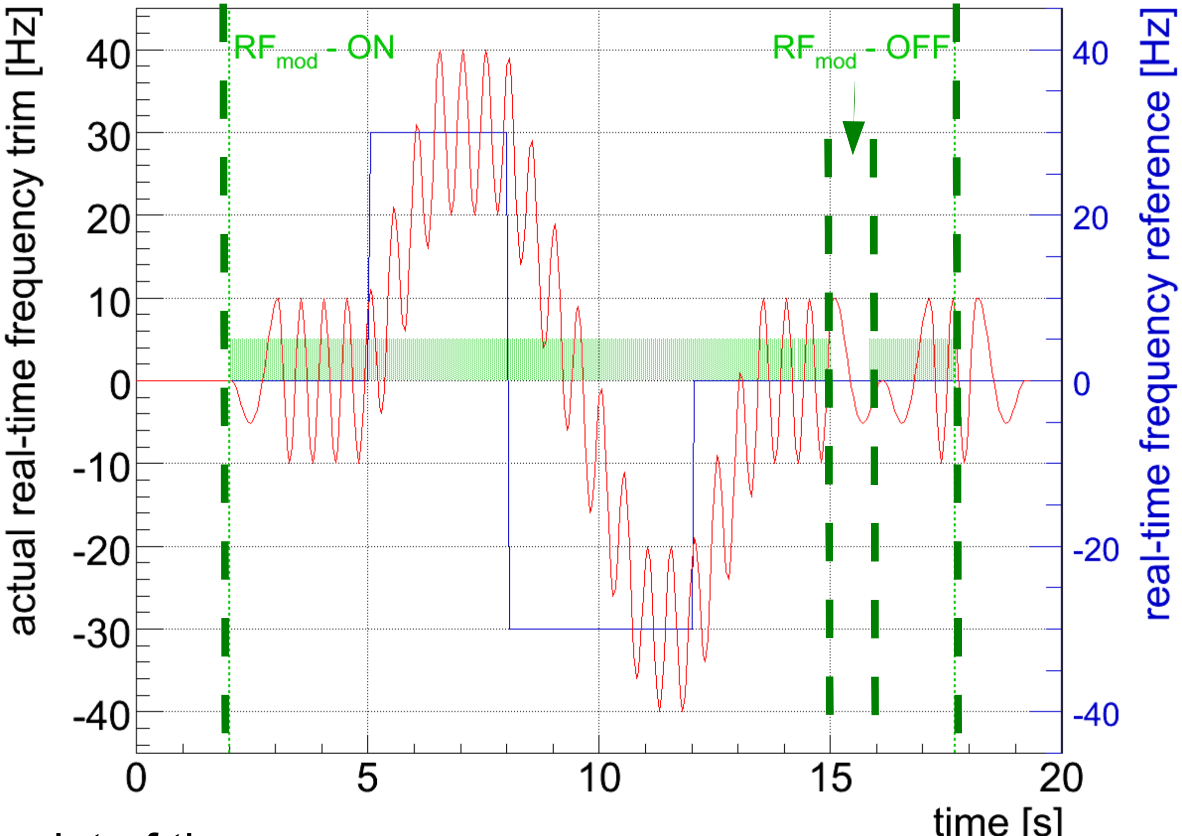
- Controllability of Q' depends on ability to track the tune both accurately & fast
  - intrinsic to this problem: $$\Delta Q_{res}^{(,)} \cdot \Delta t_{res} = const.$$
  - LHC expectations (nominal, expect '09 to be about a factor of five less):
    - Tune: $\Delta Q/\Delta t|_{max} < 10^{-3}\ s^{-1}$
    - 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:

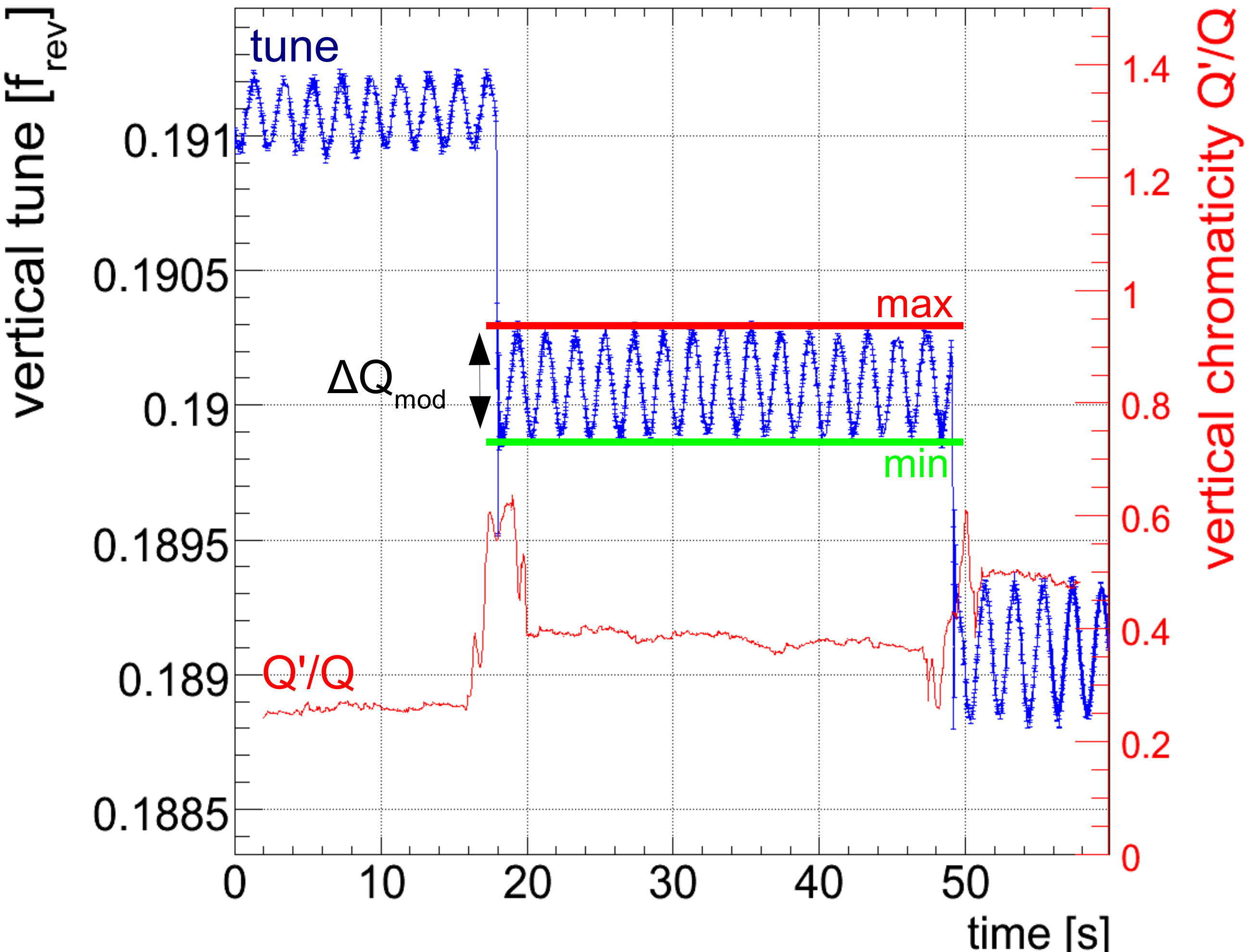
- very small but slow Δp/p modulation while tracking Q with a PLL
  - f_{mod}: 0.5 Hz (setup) → 2.5 Hz (nominal)
  - Δp/p: $\sim 10^{-4}$ (setup) → $\sim 10^{-5}$ (nominal)

- RF frequency modulation tested in collaboration with OP/RF
  - N.B. necessity also for radial loop (freq. limits are hard-coded), OFC output:



- At some point of time:
  - Systematic logging of modulation state (there is no fast FGC read-back)
  - Synchronisation with injections: 'on→off→on' at each injection
- Time estimate: ~1-2 half-shifts net (assuming no surprise)

Q'-PLL Commissioning II/II
Modulation Amplitude: $\Delta p/p \approx 1.85\cdot10^{-5}$



- Will commence with a peak-detection based Q' de-modulation
  - re-iteration necessary to optimise Q-PLL bandwidth > f_{mod}
- Time estimate: ~2-4 half-shifts with per beam per feedback loop

(tracking transients: $\Delta Q'$ feed-down on ΔQ (non-centred orbit) $\Delta Q/\Delta t$ >> $\Delta Q'/\Delta t$ → SPS specific, LHC: $\Delta Q/\Delta t|_{max} < 10^{-4}/s$)

Summary

- Base-line LHC Q, Q' and C^- diagnostics
  - Status Quo: what was available in '08 is also in '09
    - BBQ FFT-based Systems: continuous, on-demand
      - hardware re-tested, RBAC access maps, ...
    - Partially: semi-automated Q' measurement
      - GUI features, cross-checks
  - Most features have been tested without beam as part of the dry-runs
    → only minor re-commissioning expected (tests), 1-2 half-shifts/beam

- New functionalities/not commissioned items in 2008:
  - Tune-PLL (though tested in the SPS) → 2-4 half-shifts/beam
  - radial (de-)modulation → continuous Q' measurement → Q'-FB
    - RF radial loop/modulation → 1-2 half-shifts/beam
    - should be commissioned done prior to first ramp for diagnostic not necessarily FB reasons → 2-4 half-shifts/beam

→ Need real beam to see which functionalities, conveniences & safety features are actually needed for day-to-day operation

– Additional supporting slides –

Why we need time for commissioning the Q-PLL:

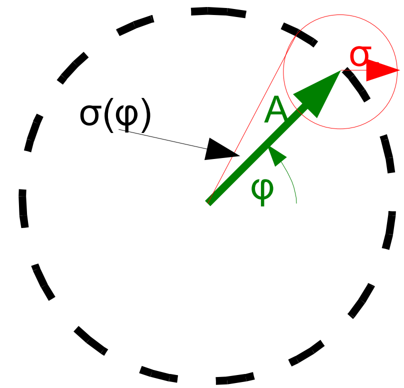
Phase-Locked-Loop Locking in the Presence of
Coupled Bunch Instabilities, Synchrotron Side Bands and
Tune Width Dependences

Advanced PLL Lock issues
Residual Tune Oscillations (e.g. HT instabilities)

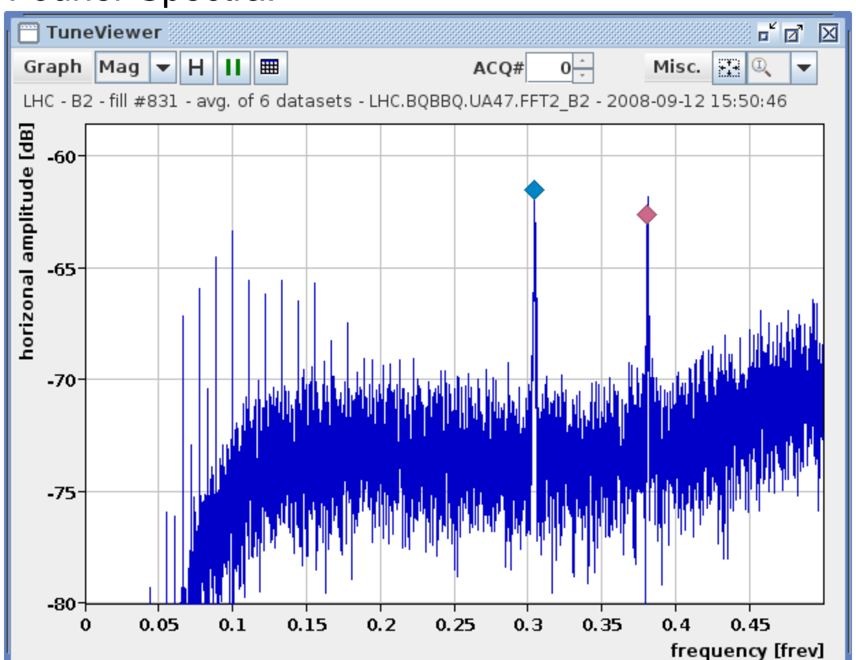
- adds vectorial to the carrier signal:
  - excitation amplitude (carrier signal): A
  - noise in time (frequency) domain: σ_t (σ_f)
  - Equivalent number of turns: N

$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

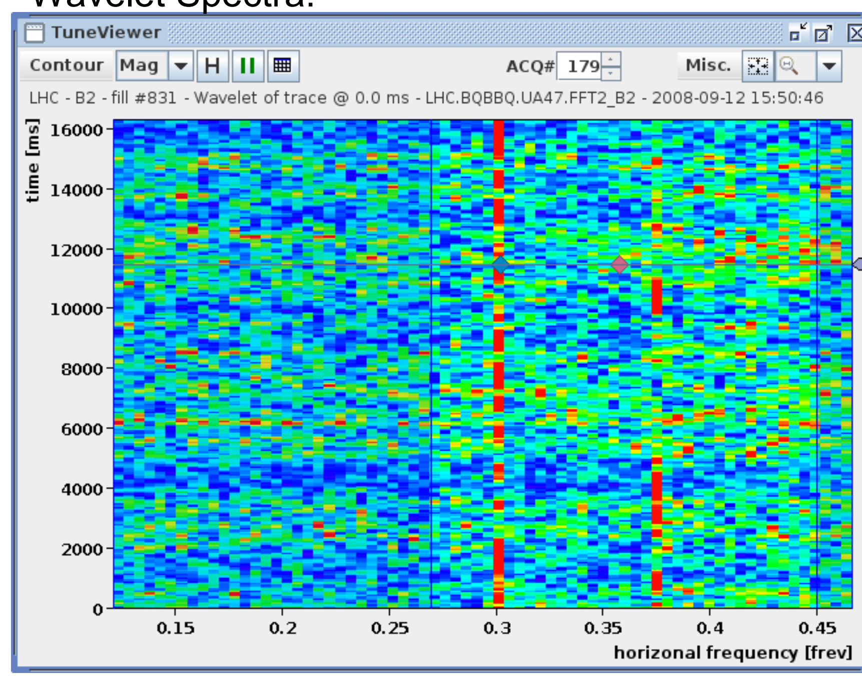
for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$



Fourier Spectra:

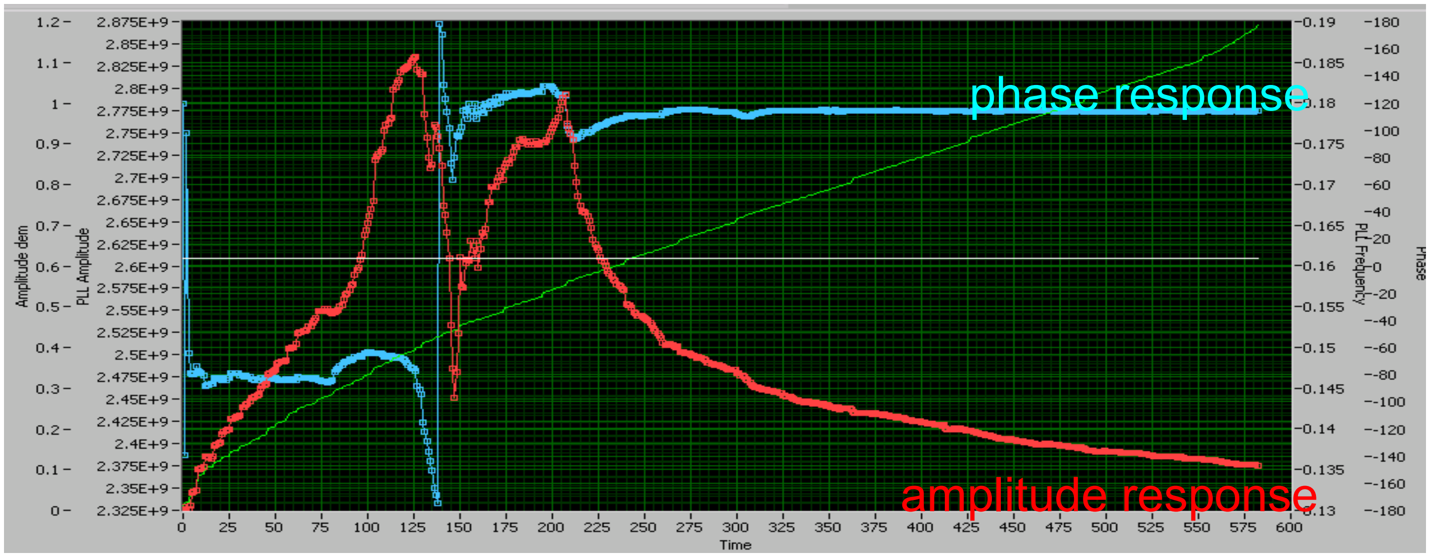


Wavelet Spectra:

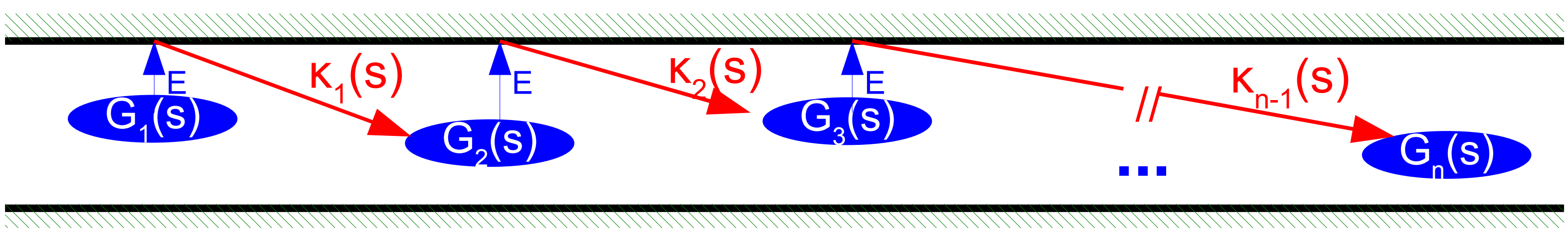


Advanced PLL Lock Issues
Coupled Bunch Instabilities

- Coupled bunch effects can hamper lock
  - possible causes: impedance driven wake fields, e-cloud, beam-beam, ...

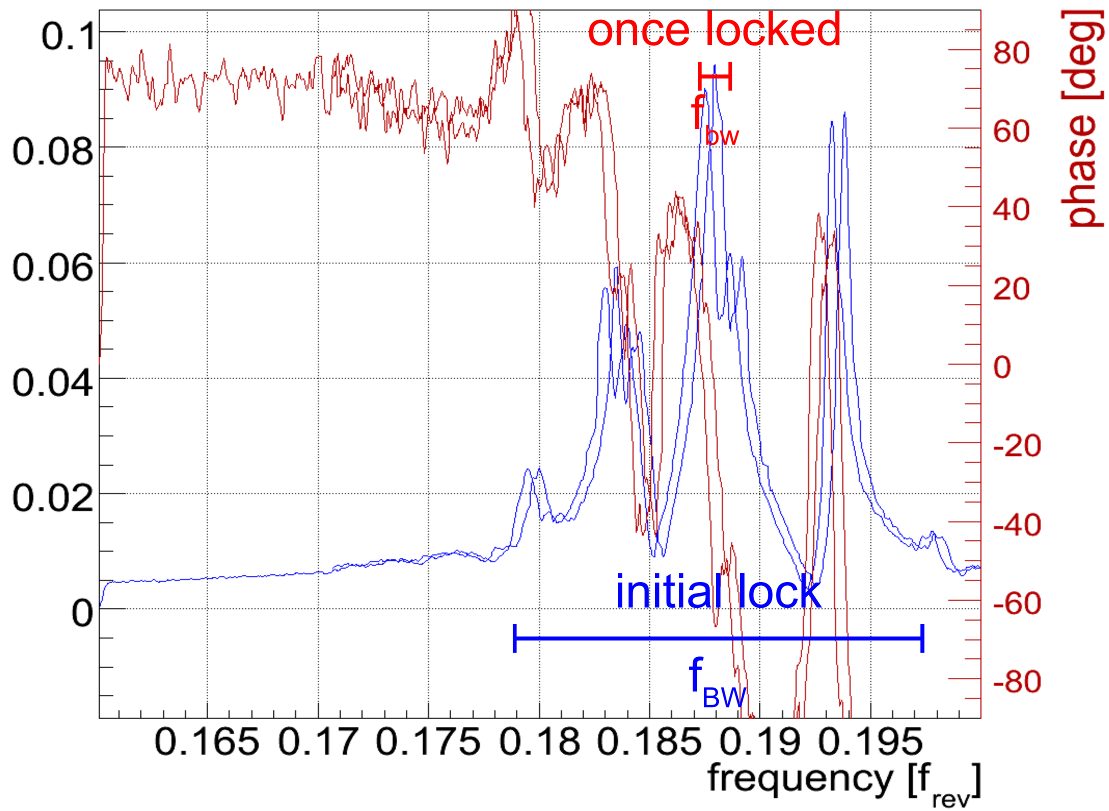


- Mechanism (impedance):



- Possible remedy:
  - Detector selects and measures only one (/first) representative bunch

Advanced PLL Lock Issues
Synchrotron Sidebands: PLL locks on the largest peak



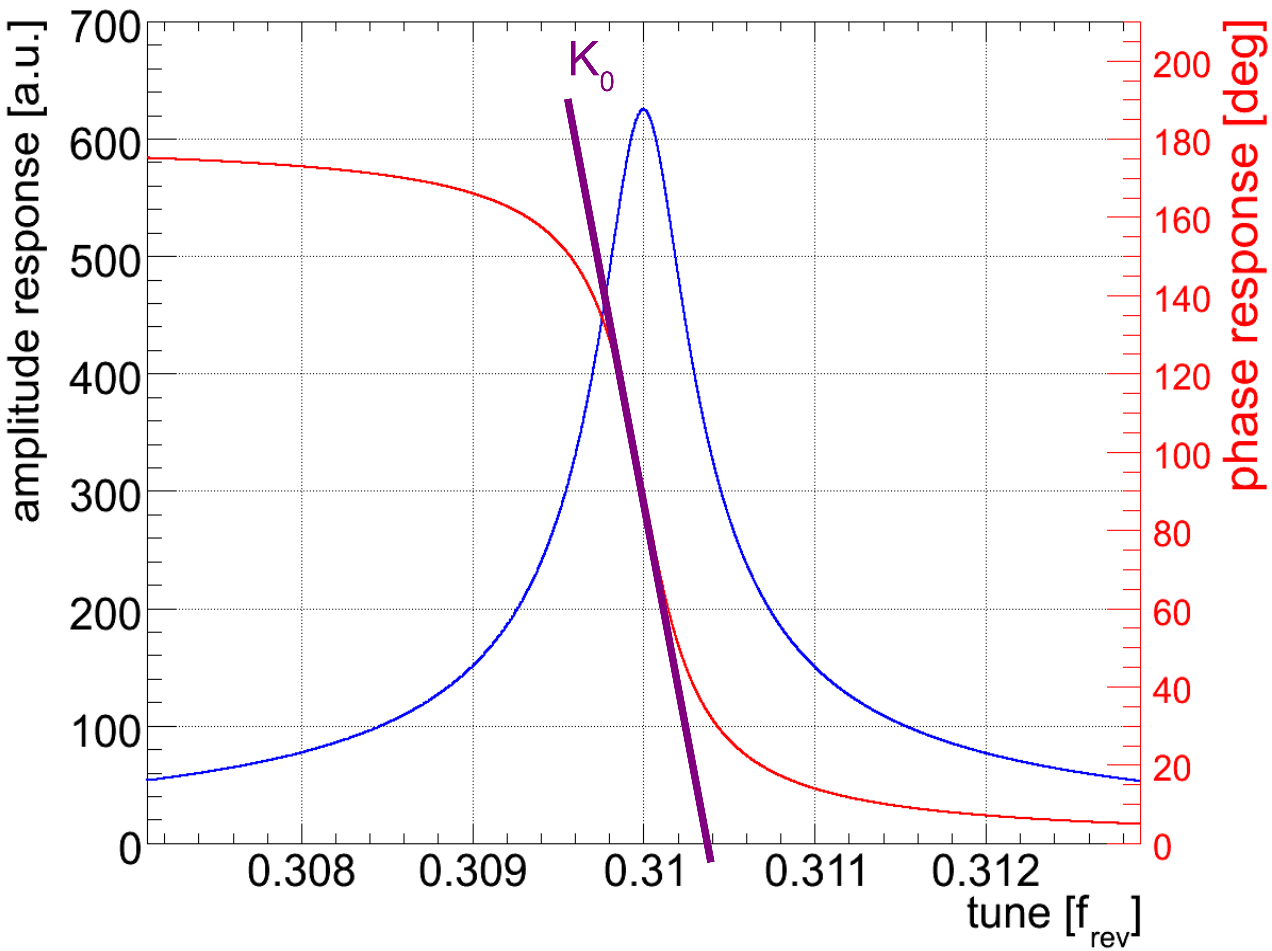
Option I: gain scheduling

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

- side-bands "cancel out", strongest resonance prevails

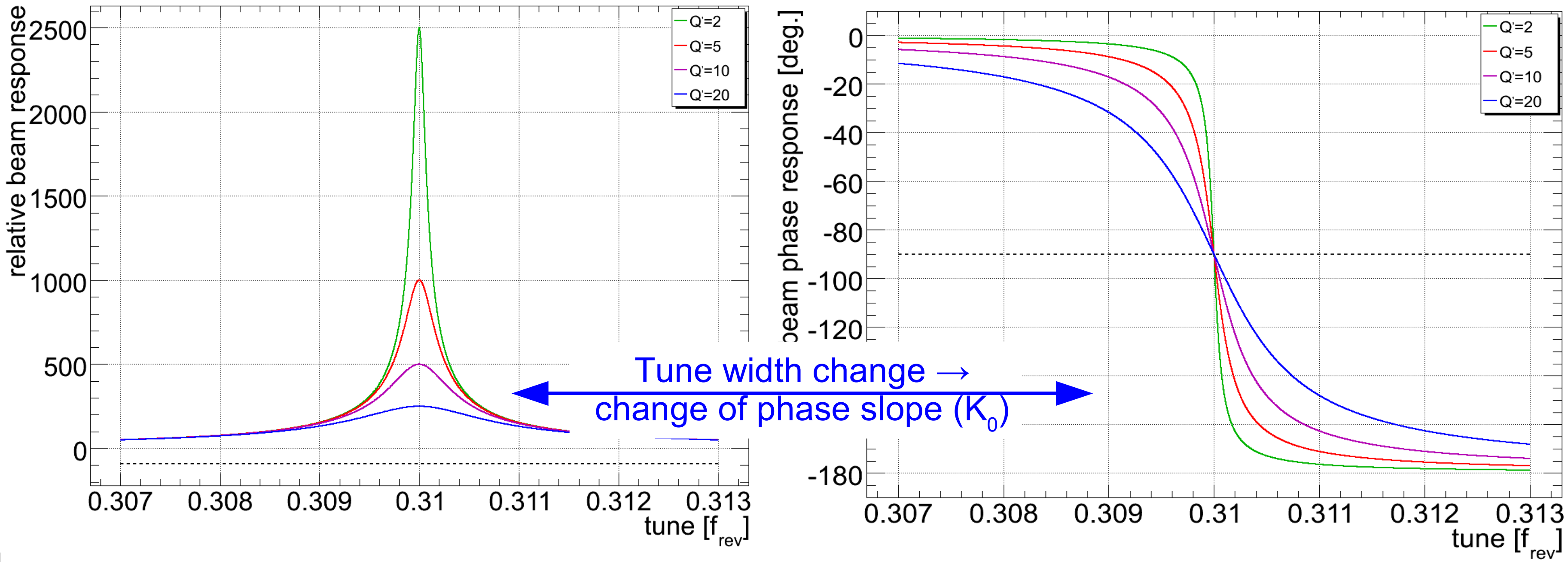
once locked: reduce bandwidth for better stability/resolution

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



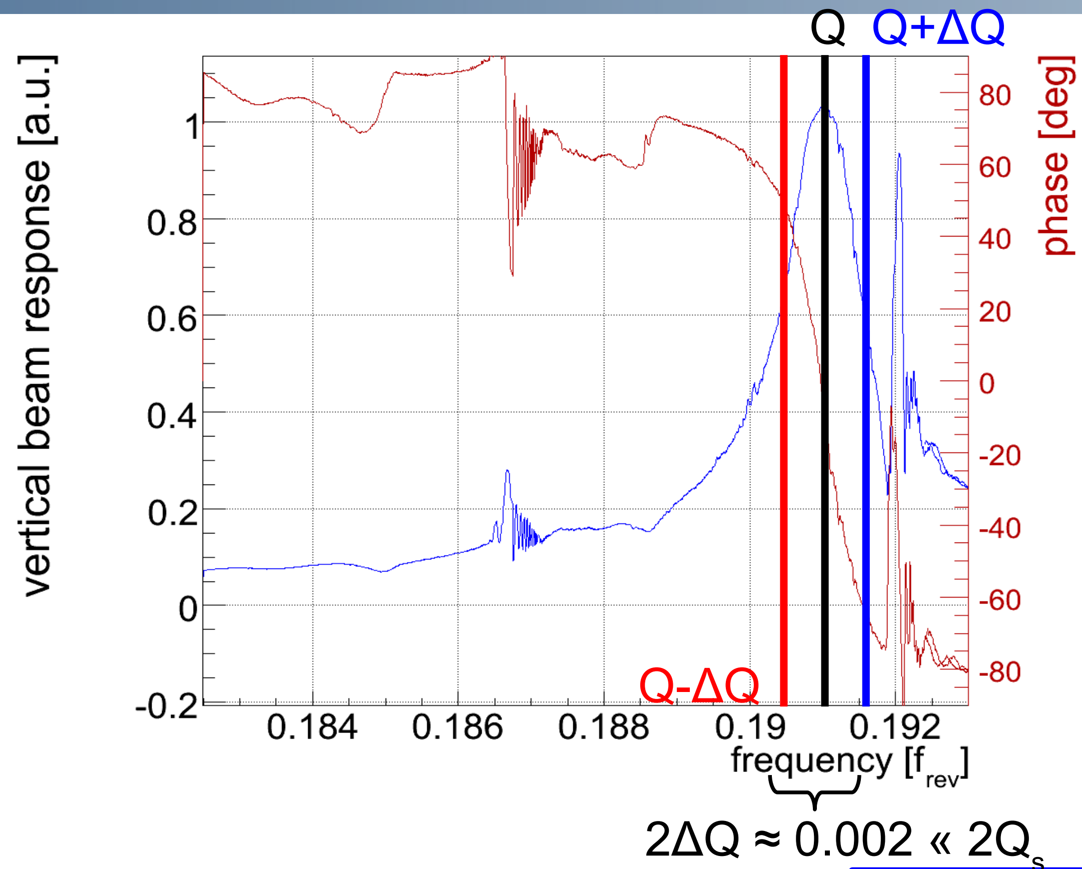
- Reminder: $D(s) = K_P + K_i \frac{1}{s} \quad with \quad K_p = K_0 \frac{\tau}{\alpha} \wedge K_i = K_0 \frac{1}{\alpha}$
  – optimal PLL Settings (1/α ~ PLL bandwidth/tracking speed):

Advanced PLL Lock Issues
Tune Width Dependence II/III



- 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"

Exploitation: Tune Width Measurement using PLL Side Exciter



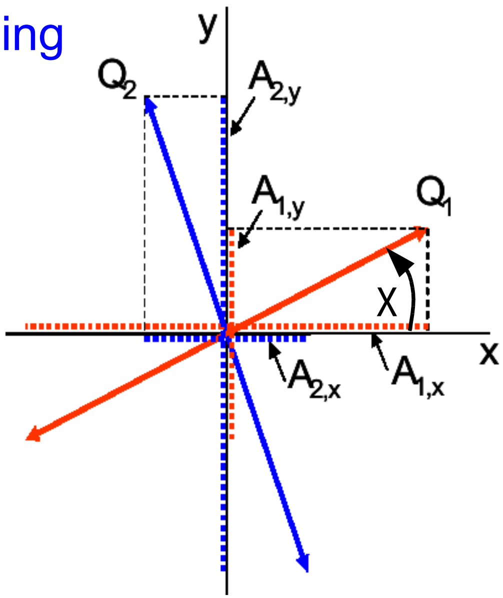
driven resonance:

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

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

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



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

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

- 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)