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Feedbacks on Tune and Chromaticity

the essentials....

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Overview

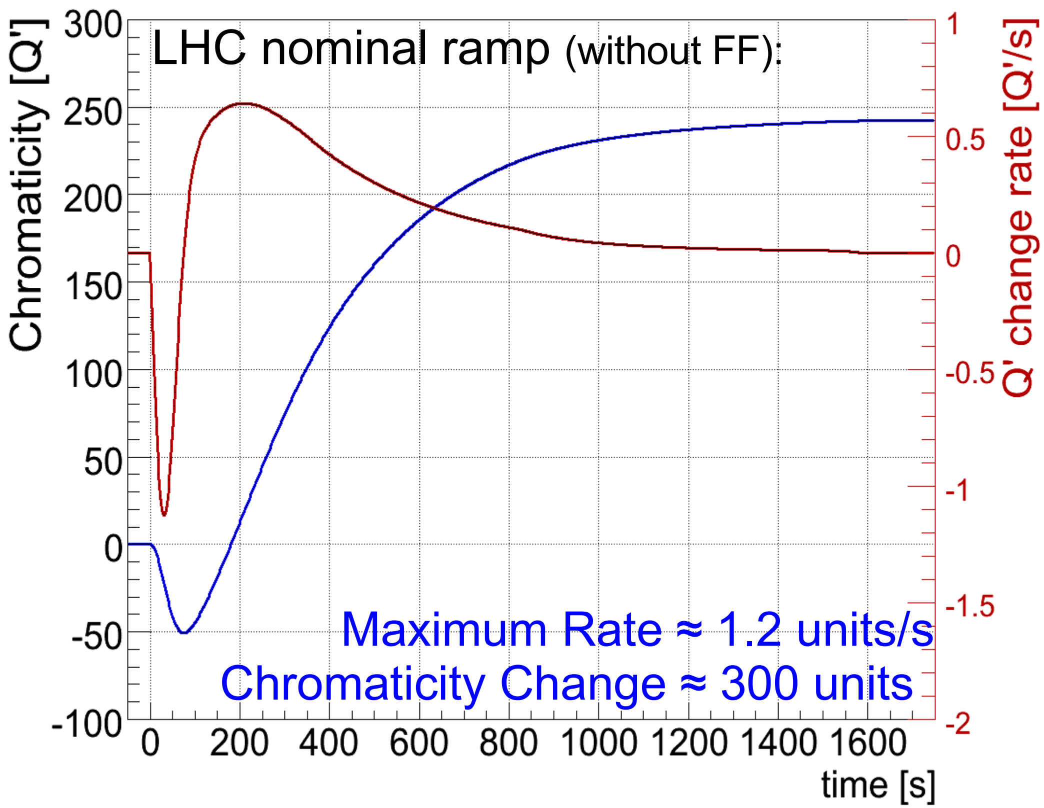
- Optimal Beam-Based Feedback Design:
  - simple linear and
  - non-linear example (delay + rate limiter)
- Tune & Chromaticity Measurements
  - Phase-Locked-Loop Systems
  - Cross-Dependability and Cross-Constraints between Feedback loops
  - What can break the PLL
- Goal: provide roadmap to avoid less obvious pot holes

Tune and Chromaticity Perturbations Sources

- Lepton and warm hadron accelerator
  - systematic quadrupole and dipole power supply drifts and ripples
  - hysteresis and temperature effects of magnet yokes
  - dipole to quadrupole tracking errors during ramp
  - beam-beam
  - e-cloud

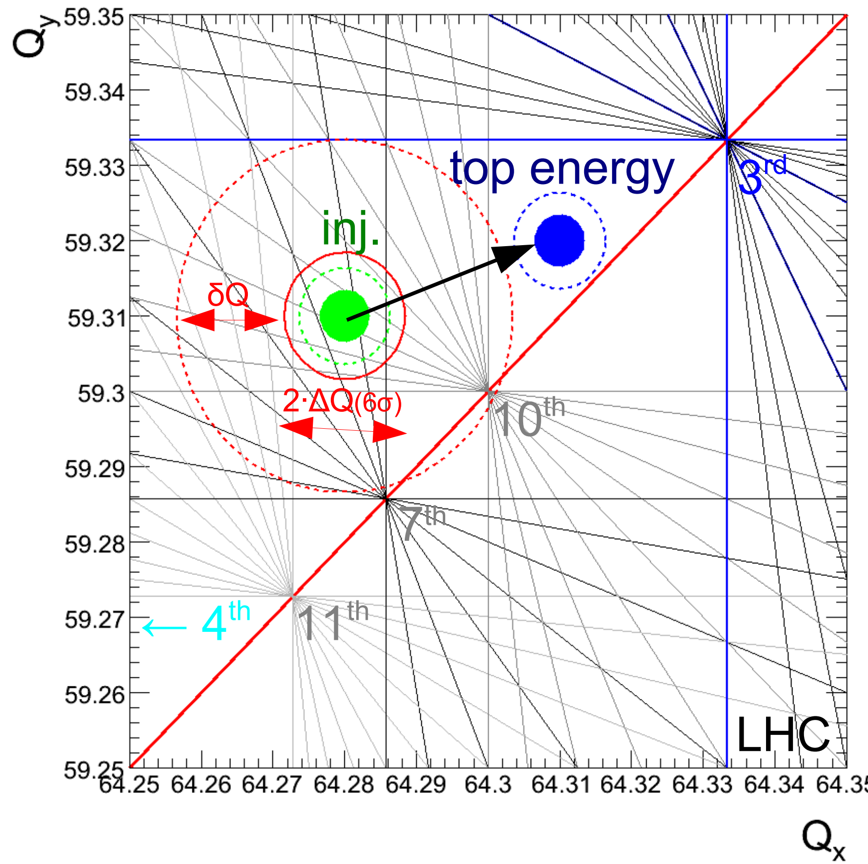
  } esp. KEK-b, PEP-II & LHC

- Superconducting Accelerators
  - Decay & snap-back
  - Reduction of persistent currents while ramping



Requirements on Tune and Chromaticity

- Lepton machines: $\delta Q \sim 10^{-2} \dots 10^{-3}$
  - avoid up to ~3rd order resonance
  - some have tough working points, e.g.:
    - PEP-II: q_x= 0.505 (LER), 0.503 (HER)
    - KEK-b: q_x= 0.504 (LER), 0.510 (HER)



- Hadron machines:
  - negligible synch. radiation damping
  - large tune footprints
  - avoid up to 12th order resonances
- Example LHC:
  - Tune spread $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$
    (fixed by available space in Q-diagram)

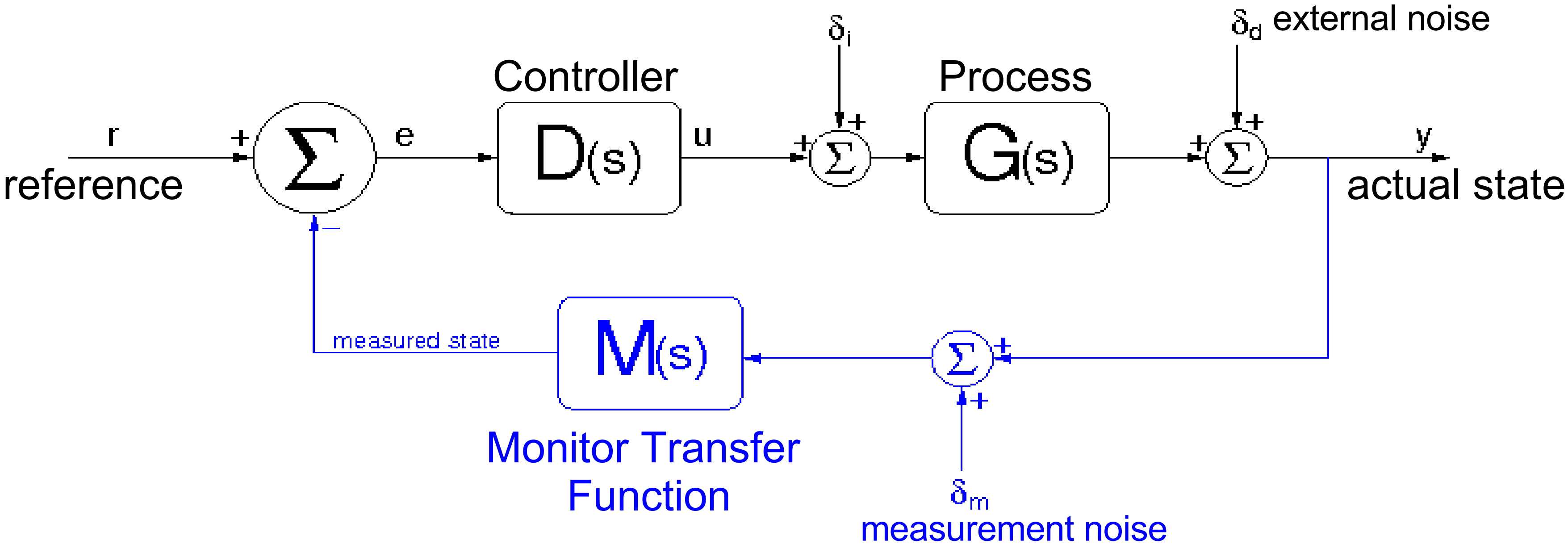
    $\rightarrow \delta Q \leq 0.003 \dots 0.001$ (nominal)
  - Allowed max lin. chromaticity[14,15] (5-6 σ, first order): $\rightarrow Q'_{max} \approx 2 \pm 1$ & $Q' > 0$
- N.B.: We want to stabilise the tune-footprint, not just Q' alone

Orbit Feedback/Feed-Forward Control Scheme

- Feedback controller usually decomposed into three stages:
  1. Compute steady-state corrector settings based on measured parameter shift that moves the beam parameter to its reference in a steady state case
  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 or non-measurable effects:

space domain (1)

time domain (2–3)

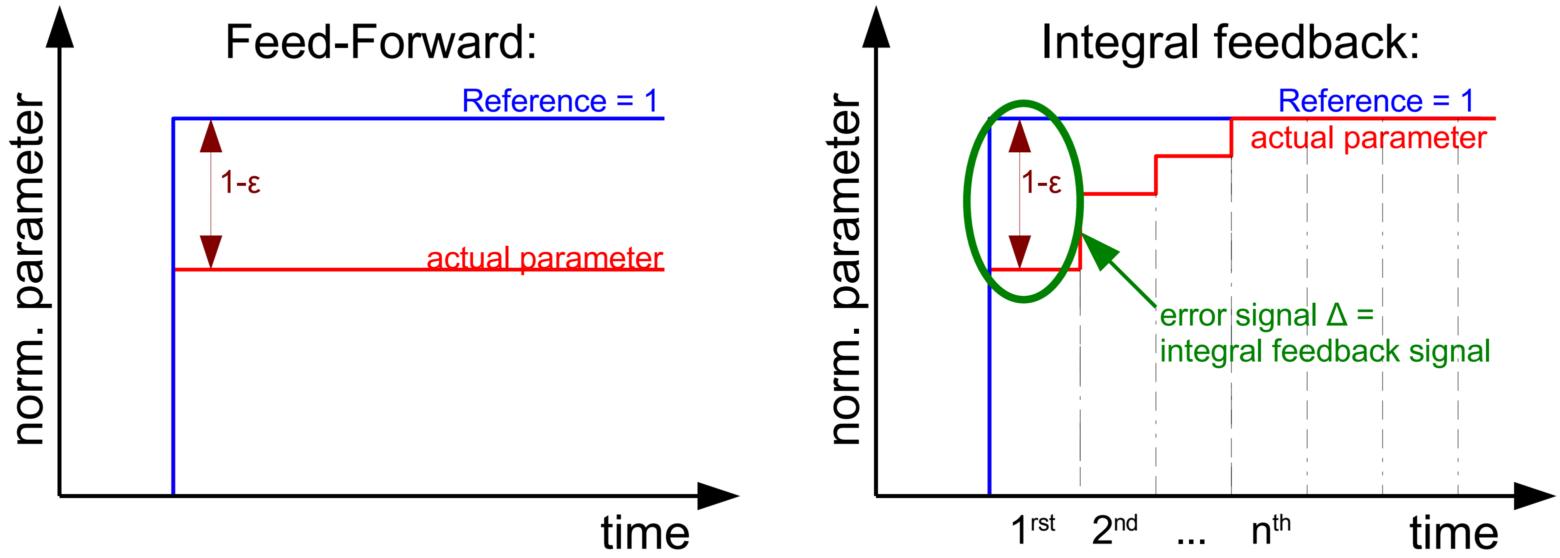


$T_0(s)$: Closed loop transfer function

$S_0(s)$: Complementary sensitivity

- Machine imperfections (beta-beat, hysteresis....), calibration errors and offsets can be translated into a steady-state ε_{ss} and scale error ε_{scale}:

$$\Delta x(s) = R_i(s)\cdot\delta_i \;\rightarrow\; \Delta x(s) = R_i(s)\cdot(\epsilon_{ss} + (1+\epsilon_{scale})\cdot\delta_i)$$



- Uncertainties and scale error of beam response function affects convergence speed (= feedback bandwidth) rather than achievable stability
- Can be improved through measured or adjusting the actual response matrices

- Controller design often regarded as specialists' topic only - wrong!
- Youla[17,18] showed that all stable closed loop controllers D(s) can be written as:

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

- Example: first order system

$$G(s)=\frac{K_0}{\tau s+1} \qquad \text{with } \tau \text{ being the circuit time constant} \qquad (2)$$

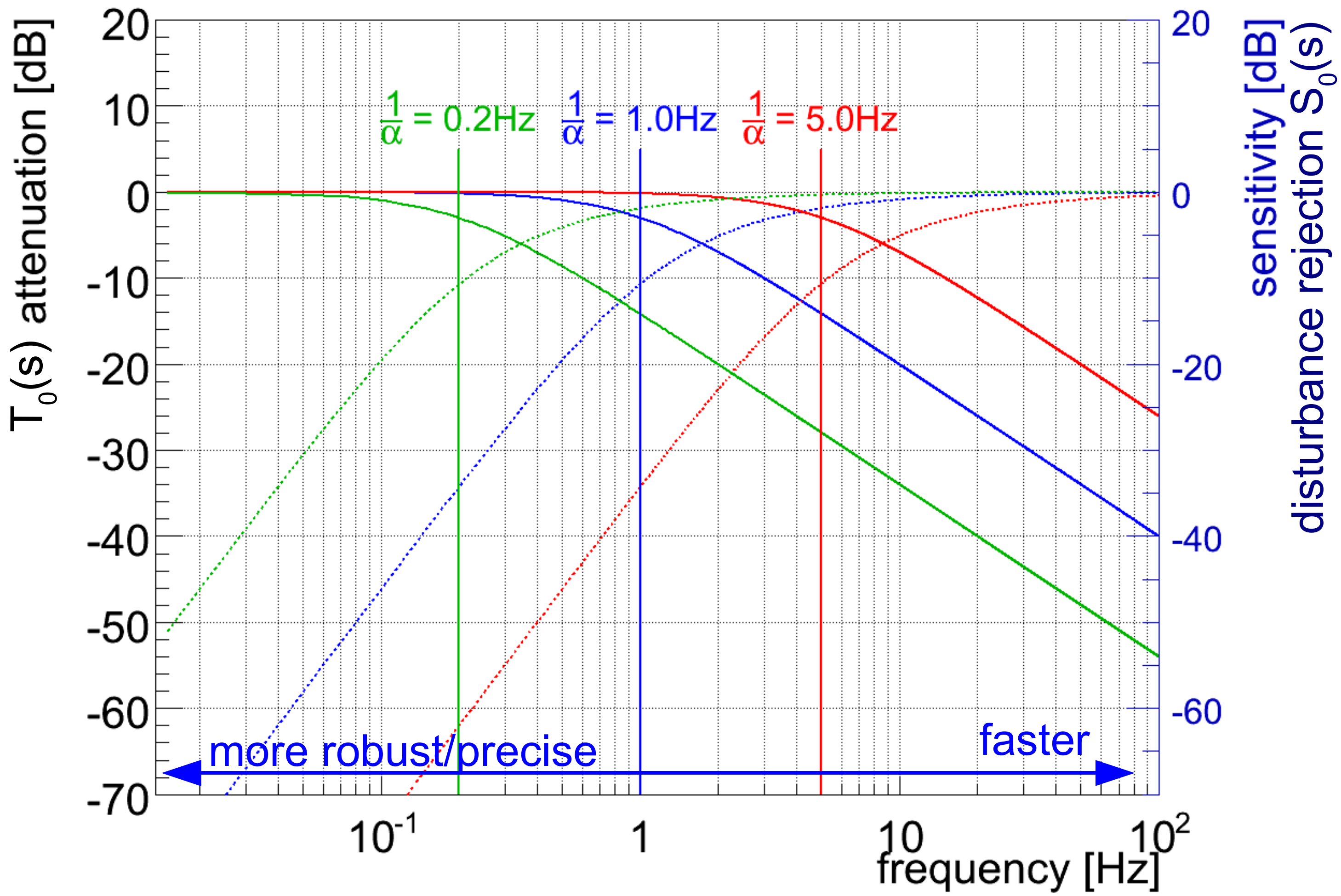
- Using for example the following ansatz:

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

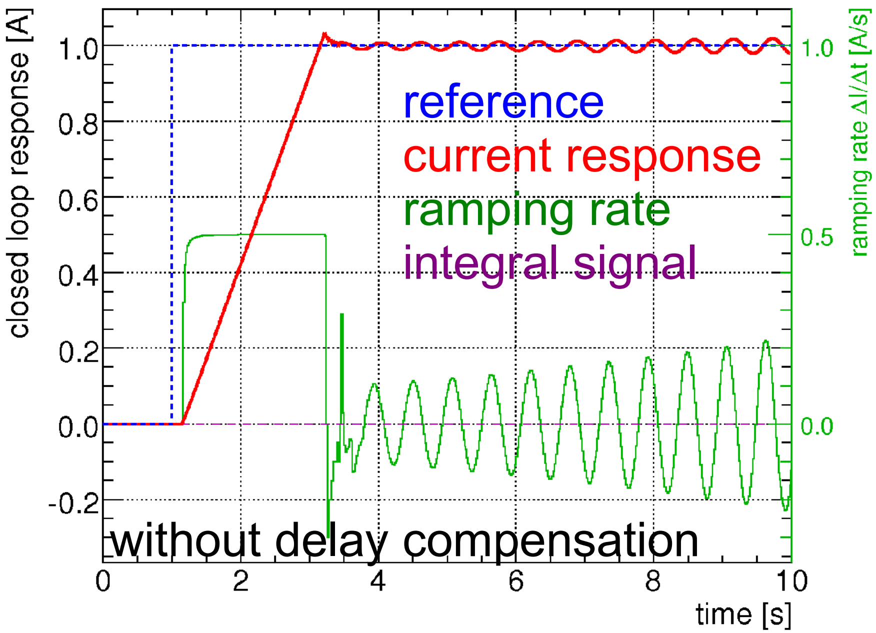
  - $F_Q(s)$ models the desired closed-loop response $\rightarrow T_0(s)=\frac{1}{\alpha s+1}$
  - $G^i(s)$ being the pseudo-inverse of the nominal plant G(s)
- (1)+(2)+(3) yields PI controller:

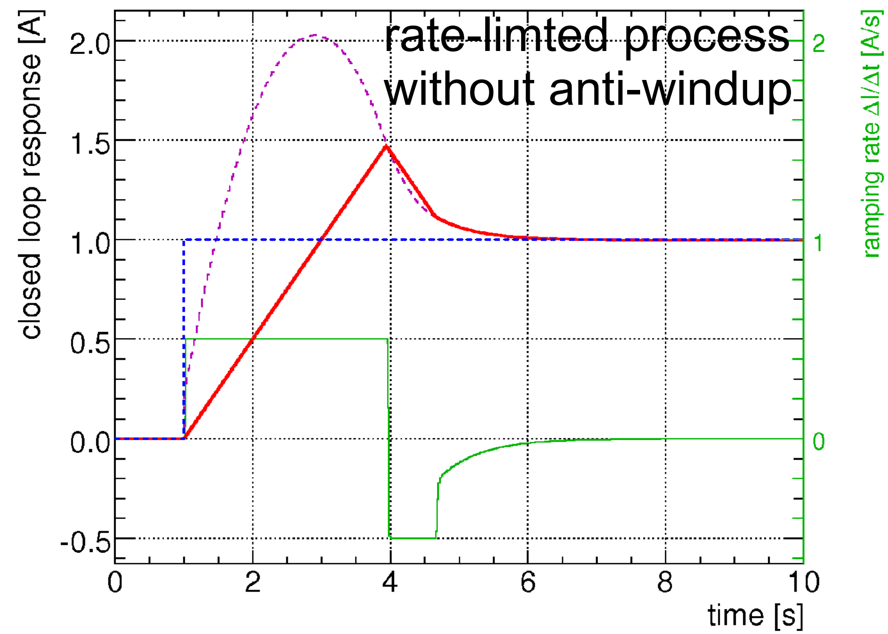
$$\boxed{D(s)=K_P+K_i\frac{1}{s} \quad \textit{with} \quad K_p=K_0\frac{\tau}{\alpha} \wedge K_i=K_0\frac{1}{\alpha}}$$

- $\alpha > \tau \ldots \infty$ facilitates the trade-off between speed and robustness
  - operator has to deal with one parameter → enables simple adaptive gain-scheduling based on the operational scenario!

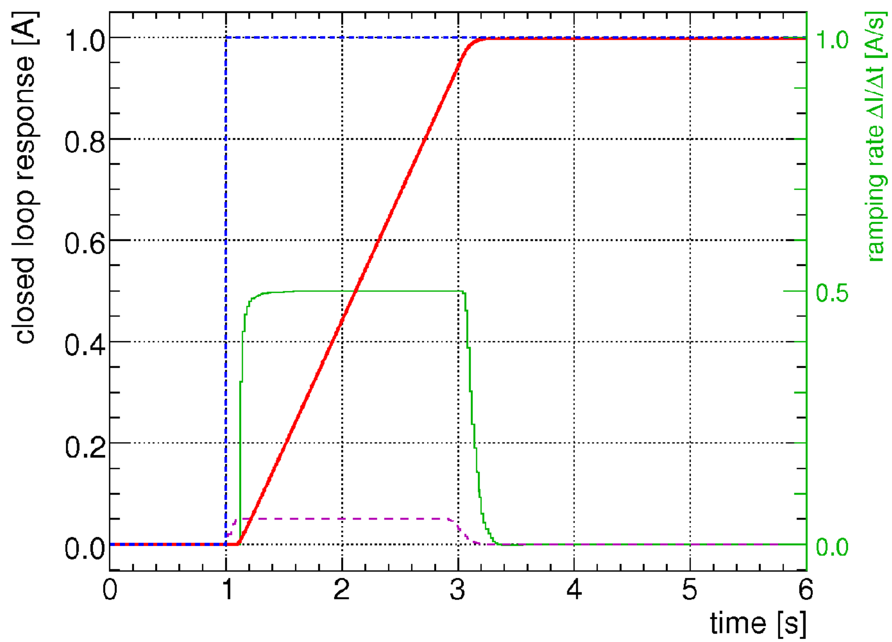


Motivation for Delay and Rate-Limiter Compensation
Example: LHC orbit feedback control





with full delay and windup
compensator scheme:

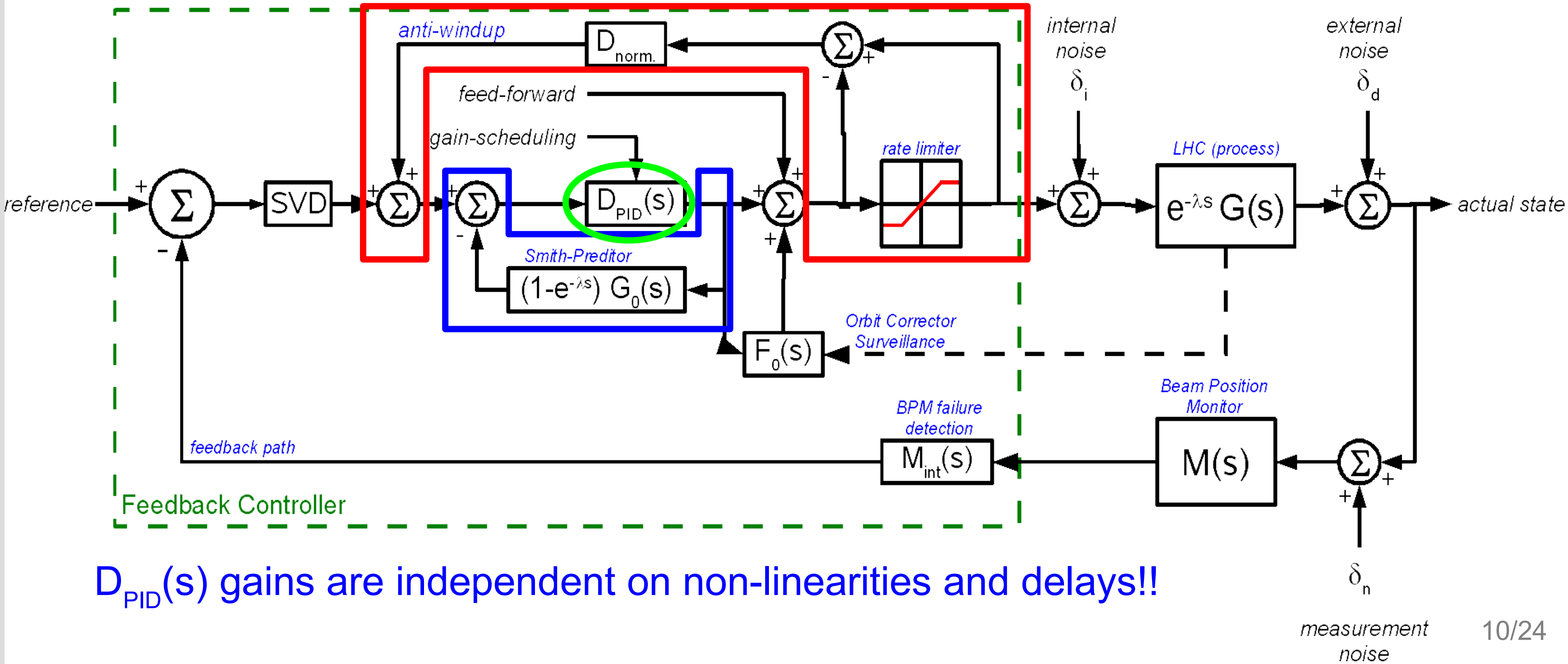


Time Domain: Optimal Controller Design Including Non-Linearities

- If G(s) contains non-stable zeros e.g. delay λ & non-linearities $G_{NL}(s)$

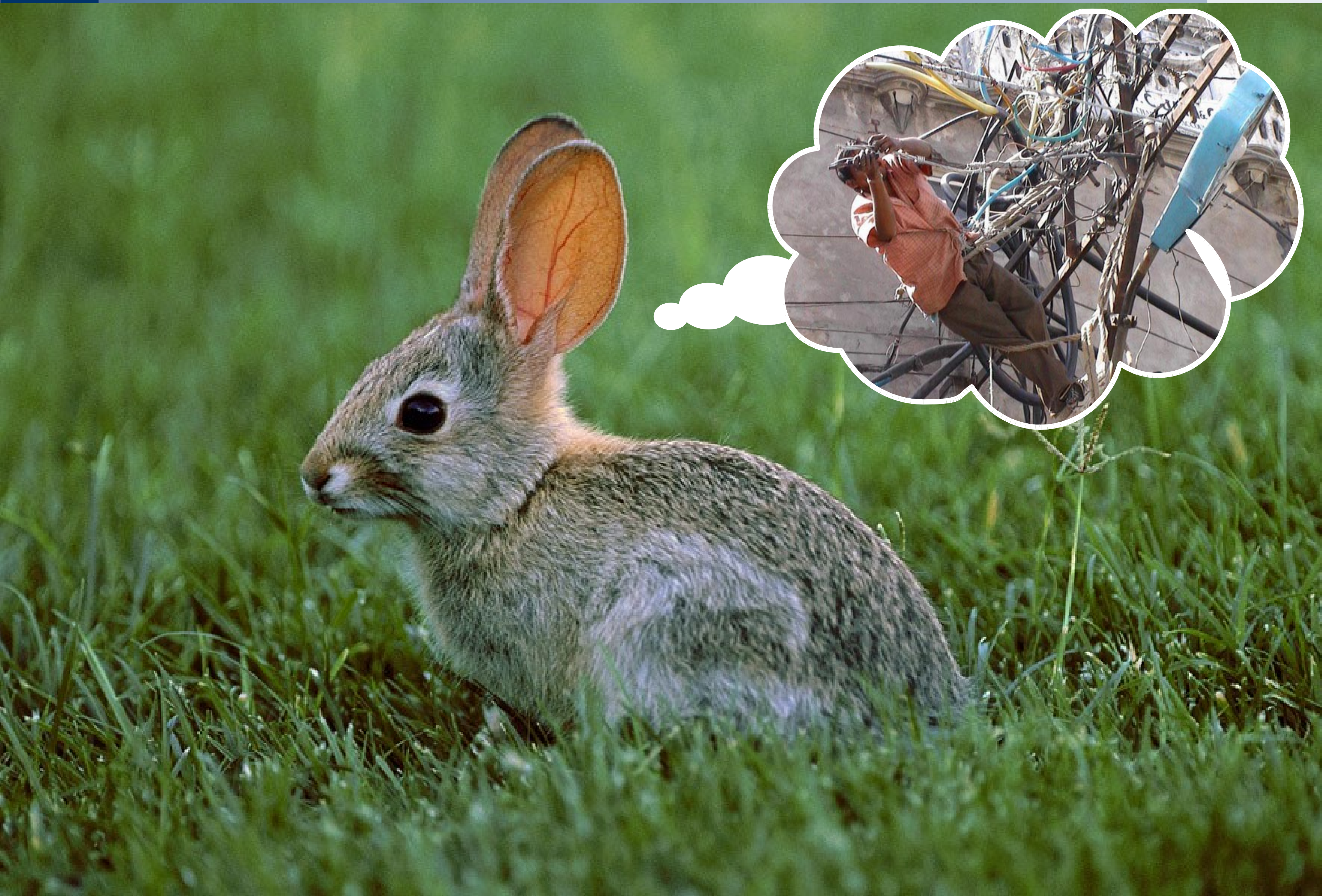
$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}G_{NL}(s)$$

- with τ the power converter time constant, then: $G^i(s)=\frac{\tau s+1}{1}$
- Using (1) and (3) yields $T_0(s)=F_Q(s)\cdot e^{-\lambda s}G_{NL}(s)$
- Inserting in (1) yields Smith-Predictor and Anti-Windup schemes:



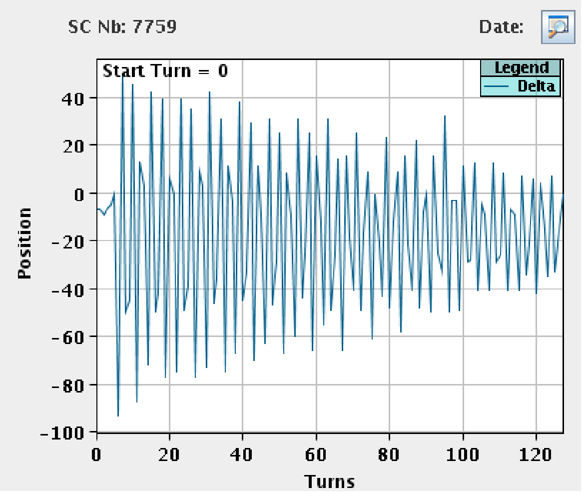
$D_{PID}(s)$ gains are independent on non-linearities and delays!!

Part I: Tune and Chromaticity Measurements

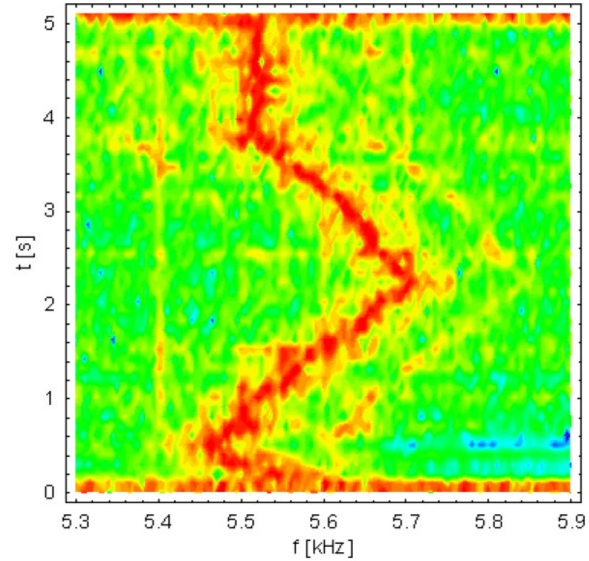


Performing Tune/Q' FB: Measurement Options

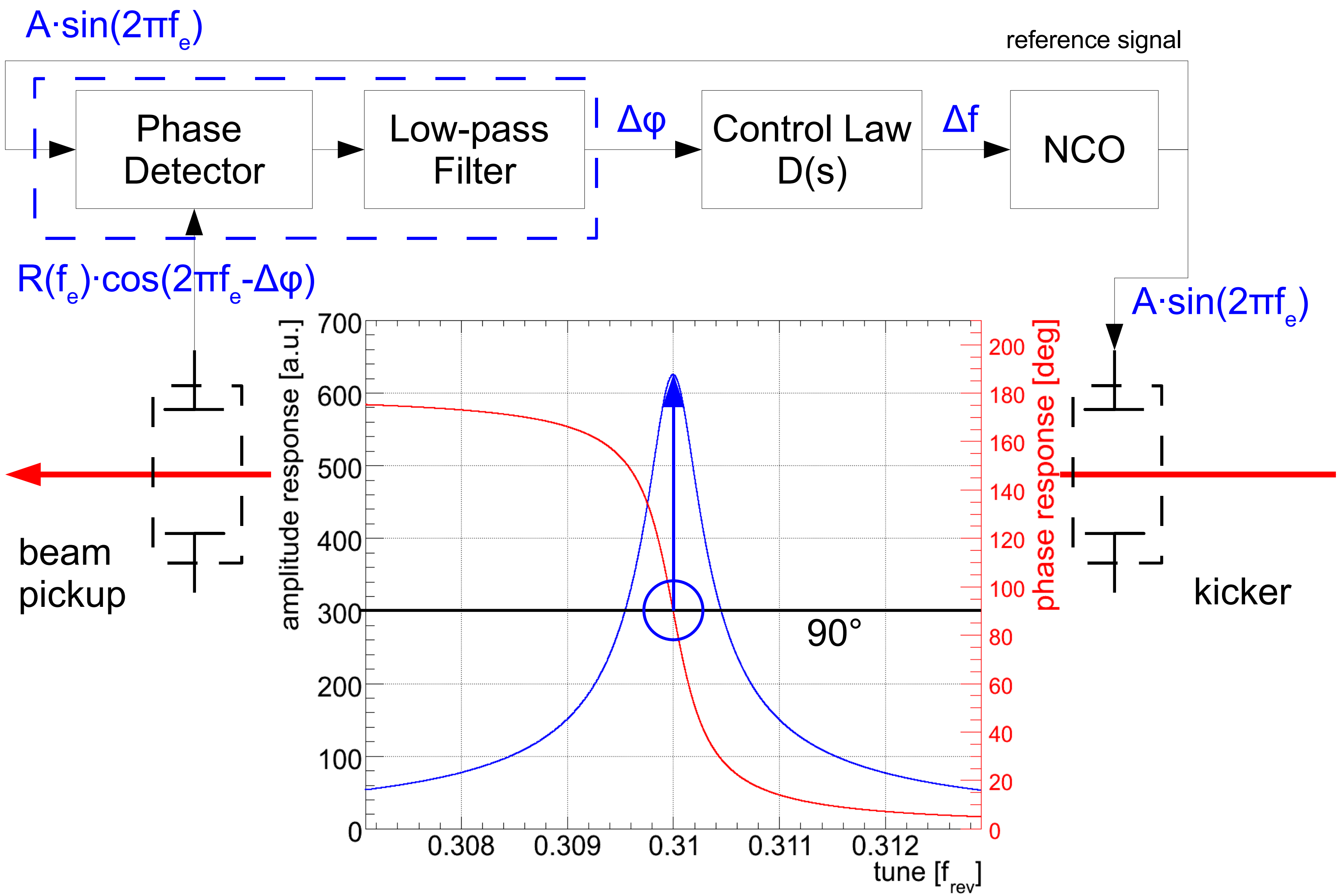
- Classic kicked or chirp excitation followed by amplitude detection
  - limited by aperture constraints
    - Performance reduction (lepton machines)
      - typically: $\Delta z \leqslant 0.1\,\sigma$
    - Loss of particles & protection (hadron machine)
      - LHC: $\Delta z \leq 25\ \mu m$ & $\Delta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



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

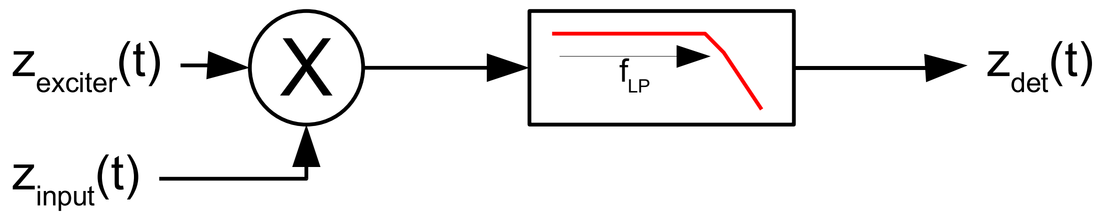


- Active Phase-Locked-Loop (PLL) systems
  - deploy in combination with RF modulation for chromaticity tracking



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

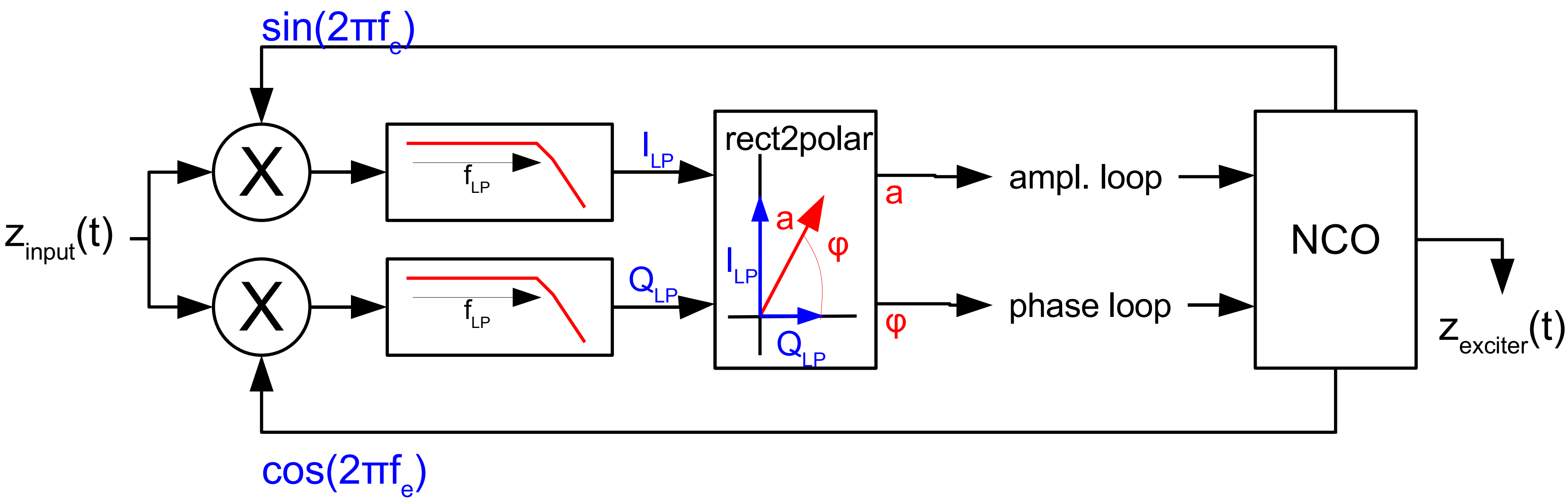
Classic PLL Detector



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

$$= \frac{AR}{2}\underbrace{\sin(\Delta\varphi(t))}_{\text{for small phases } \approx \Delta\varphi(t)} + \underbrace{\cancel{\frac{AR}{2}\sin(4\pi f_e - \Delta\varphi(t))}}_{\text{removed by low-pass filter}}$$

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



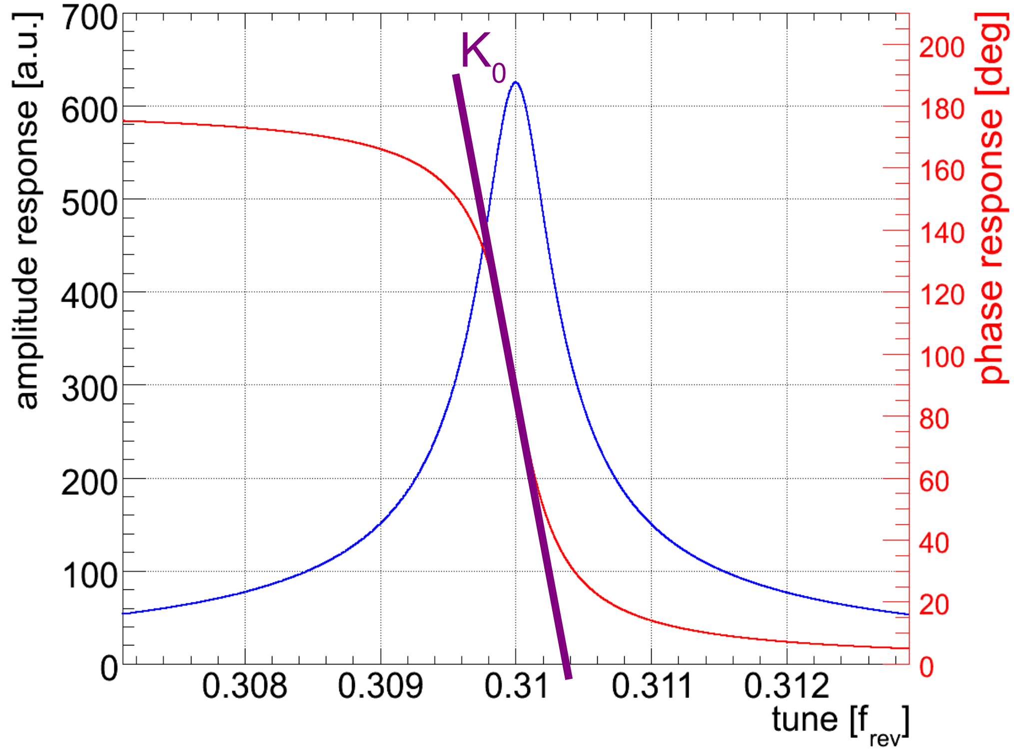
- Usually further compensation for other non-beam related phase responses:
  - constant lag (data processing, cables),
  - analogue pre-filters, beam exciter response...

- Rectangular-to-Polar conversion
  - e.g. CORDIC algorithm (implements "atan2(y,x)")
    - twice the dynamic range

PLL Closed Loop Controller

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

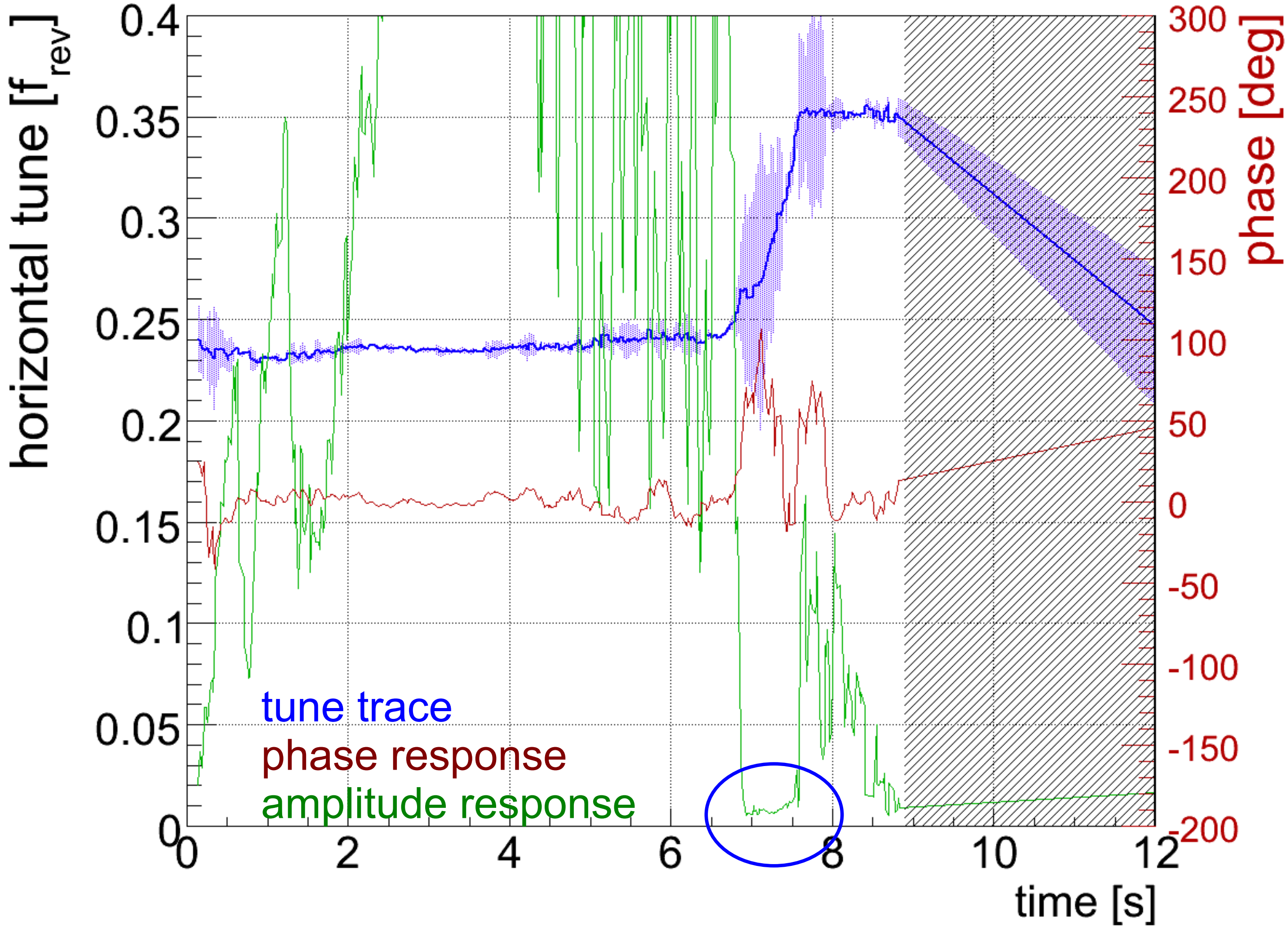
$$G_{PLL}(s) = \frac{K_0}{\tau s + 1} \quad with \quad \tau = \frac{1}{f_{bw}}$$



  - Youla's affine parameterisation: $\rightarrow$ yields optimal PI controller

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

Working Example: SPS PLL Tune Tracking



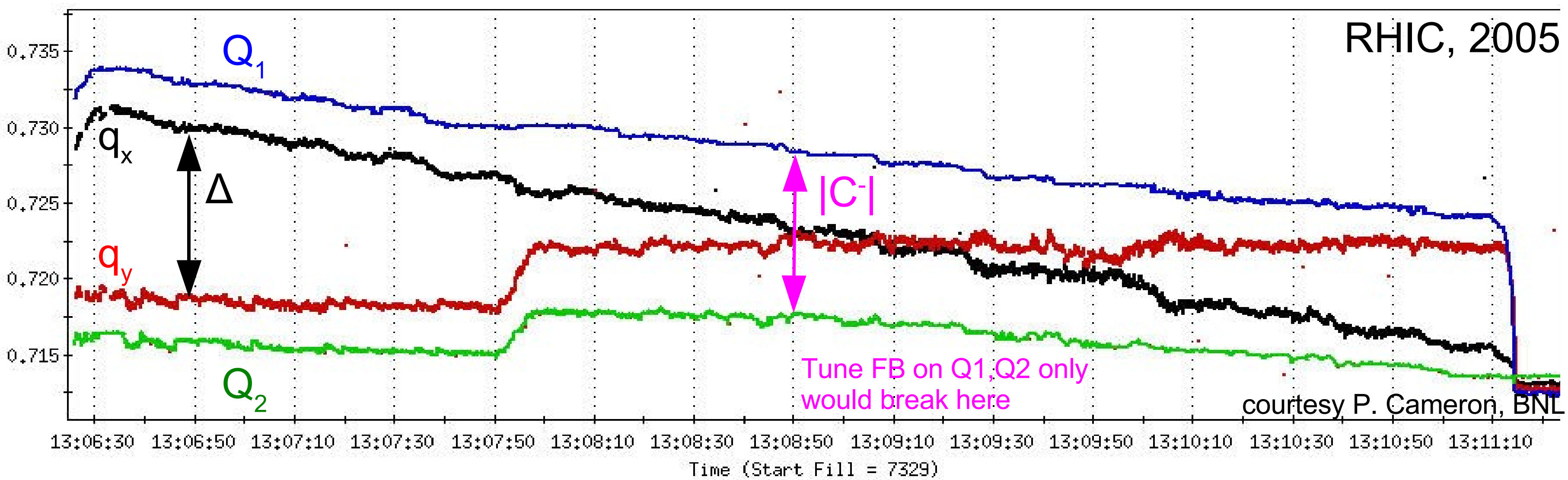
- Phase error and non-vanishing amplitude indicate lock during ramp
- $\Delta Q/\Delta t|_{max} \approx 0.3$ about two orders of magnitude faster than required for LHC

  $f_{rev} \approx 43$ kHz

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

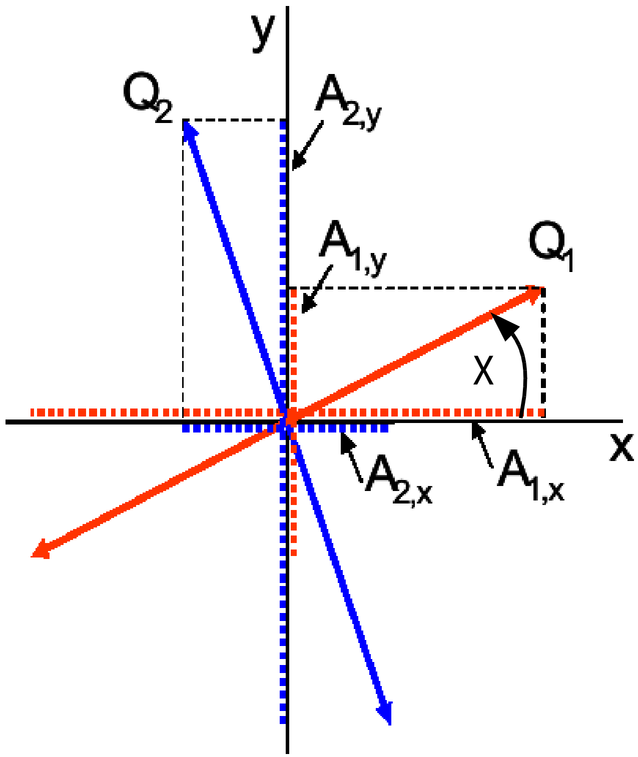
- Strictly speaking: PLL measures eigenmodes (Q_1, Q_2) which in the presence of coupling may be rotated w.r.t. unperturbed tunes (q_x, q_y, $\Delta = |q_y - q_y|$):

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



- 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



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

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

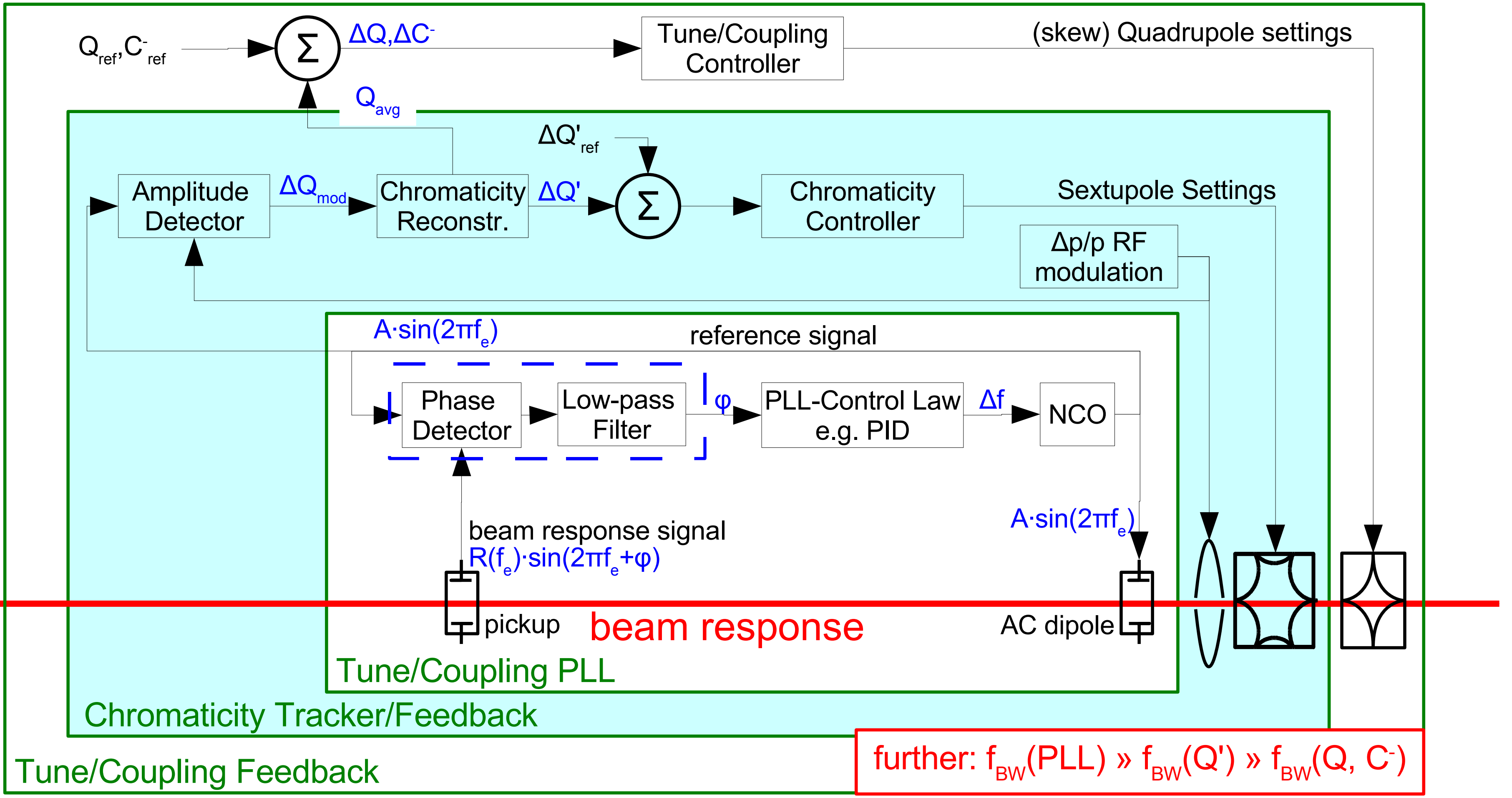
- Decoupled feedback control
  - q_x, q_y → quadrupole circuits strength
  - $|C^-|$, χ → skew-quadrupole circuits strength

implemented and tested at RHIC

R. Jones e.al., "Towards a Robust Phase Locked Loop Tune Feedback System", DIPAC'05, Lyon, France, 2005
P. Cameron, this workshop's Poster Session

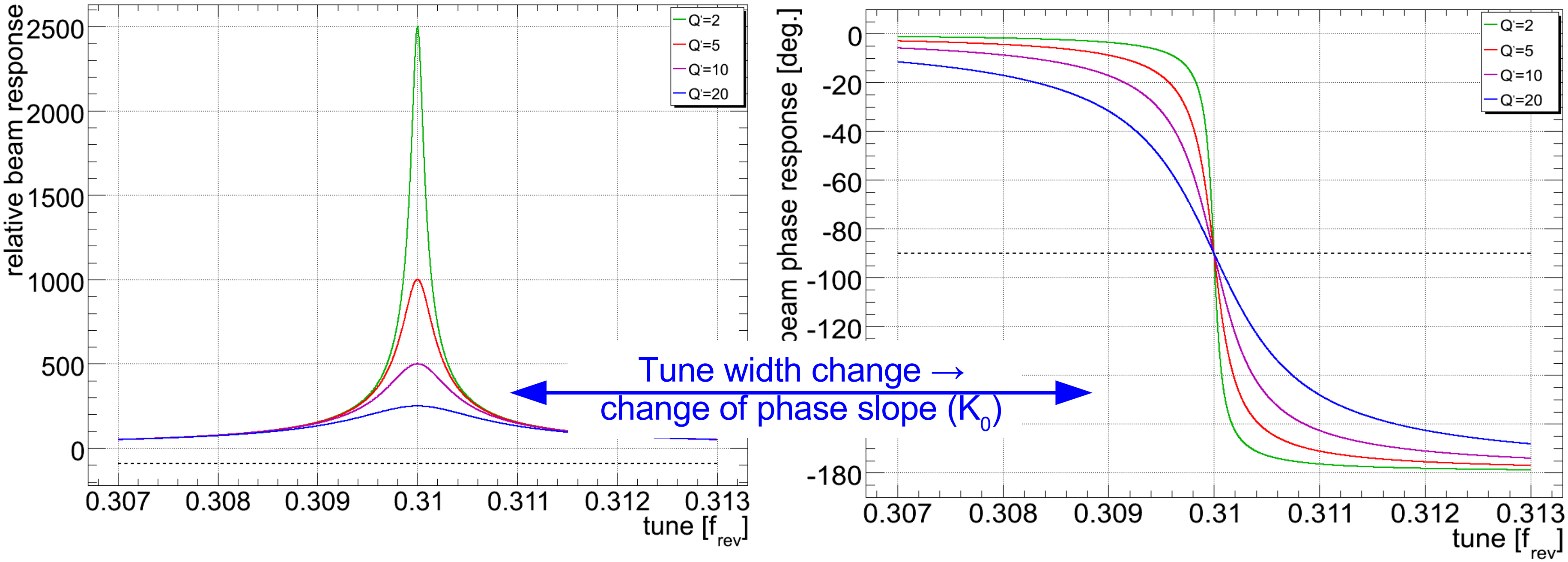
Cross-Dependability and Constrains of FB Loops III/III - Nested Feedback Loops

- Traditionally loop designs are often addressed one-by-one
  – neglects cross-dependence and cross-constraints w.r.t. other nested FB loops



- cascading & separation of operational range (e.g. bandwidth or amplitude)
- cross-dependence with orbit and energy feedback (dispersion orbit)

What Makes the PLL Break - Tune Width Dependence



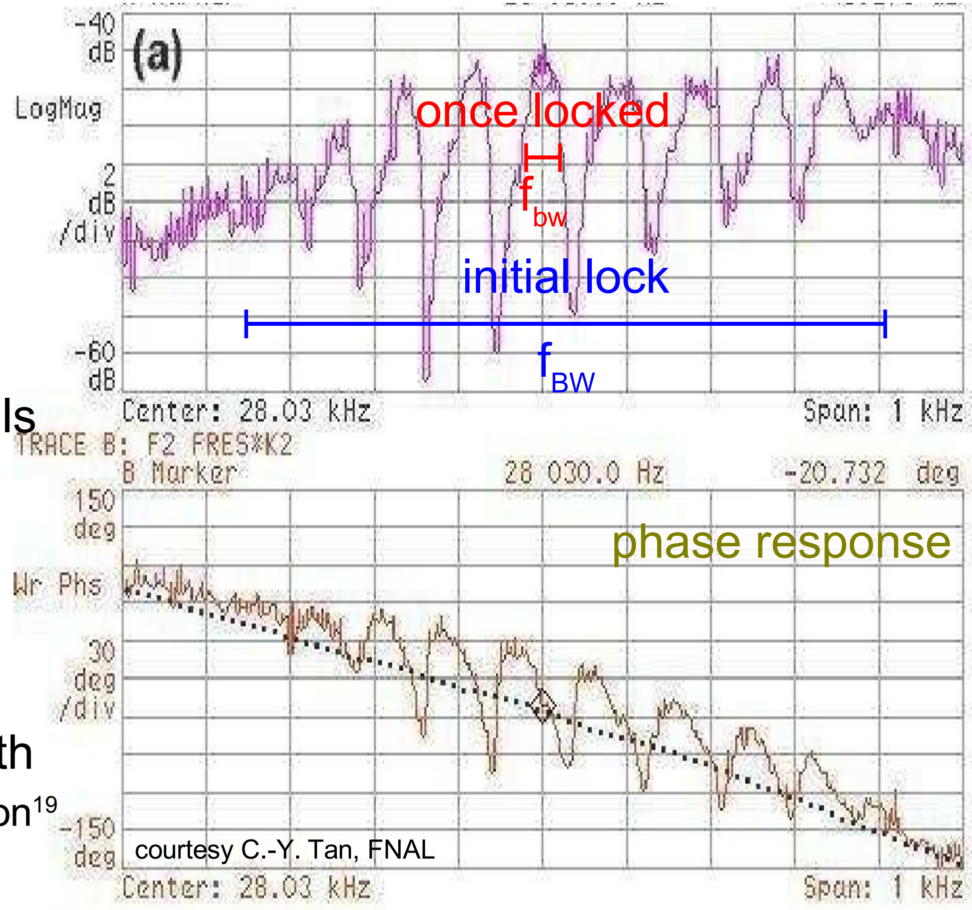
- Optimal PLL parameters (tracking speed, etc.) depend - beside measurement noise – on the effective tune width.
- Intrinsic trade-off:
  - Optimal PI for large ΔQ ↔ sensitivity to noise (unstable loop) for small ΔQ
  - Optimal PI for small ΔQ ↔ slow tracking speed for large ΔQ
- Can be improved by putting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

What Makes the PLL Break
- Erroneous Locking on Synchrotron Sidebands

- Qualitatively: PLL locks on the largest peak within the bandwidth

- Option I: gain scheduling
  - initial lock: open loop band-width 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

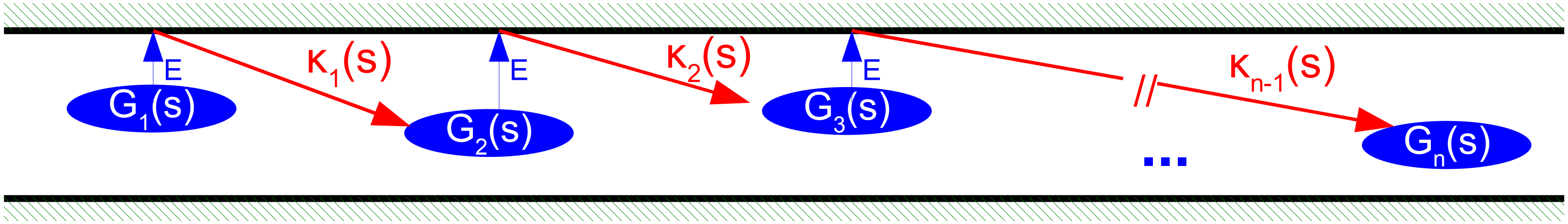
- Option II: larger excitation bandwidth
  - multiple exciter or broadband excitation[19]

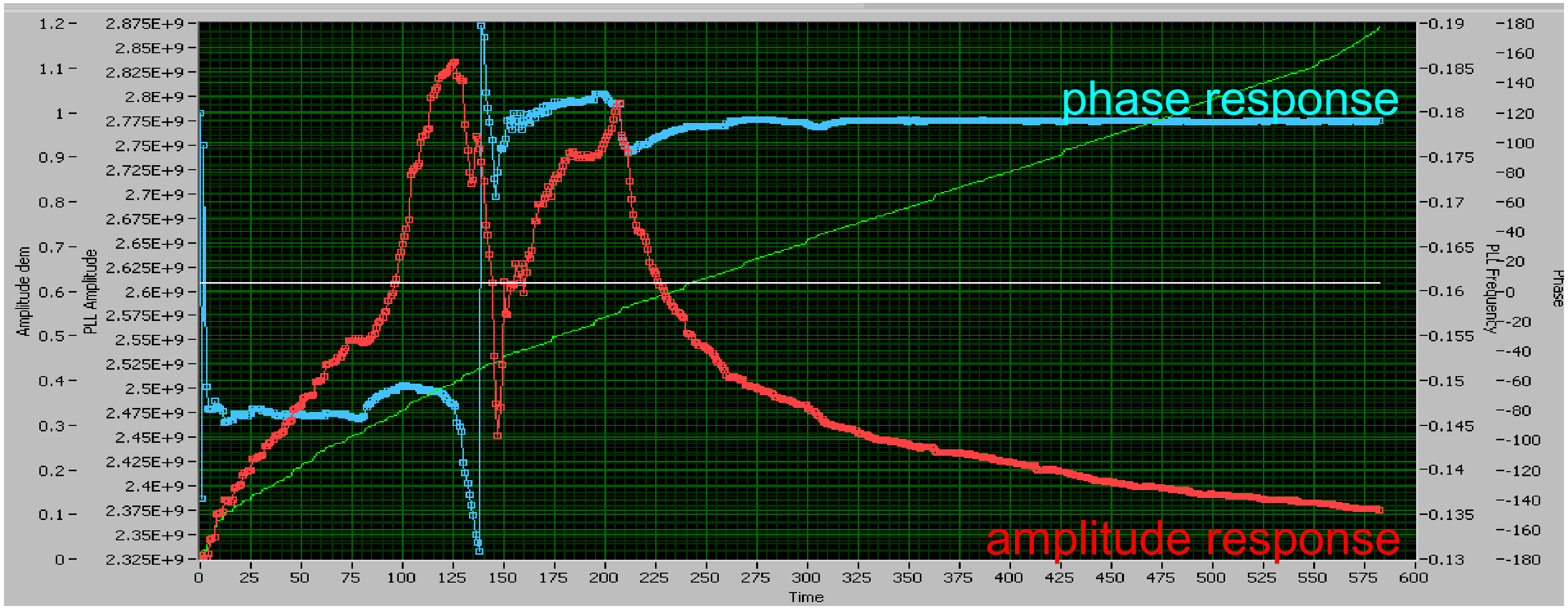


courtesy C.-Y. Tan, FNAL

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, ...





Summary

- Beam-based FBs are remedies for perturbations on slow/medium time scales
  - Feedbacks on orbit/energy are standard, tune feedbacks quite common
    - Hadron machines starting to recognise their necessity
  - Chromaticity feedbacks still require pioneering work (LHC first?)
- Feedbacks are only as good as the measurements they are based upon!
  - Systematic and thorough analysis of involved beam instrumentation and corrector circuits is essential!
- Youla's affine parameterisation facilitates optimal adaptive non-linear control
  - enables gain-scheduling based on operational scenario
  - (Ziegler-Nichols/Coohen-Coon PID tuning are outdated!)
- Beware of cross-constraints/coupling of simultaneous nested loops
  - May break a loop near you
  - Feedbacks should be designed as an ensemble

The author gratefully acknowledges contributions from many colleagues!

Reserve Slides

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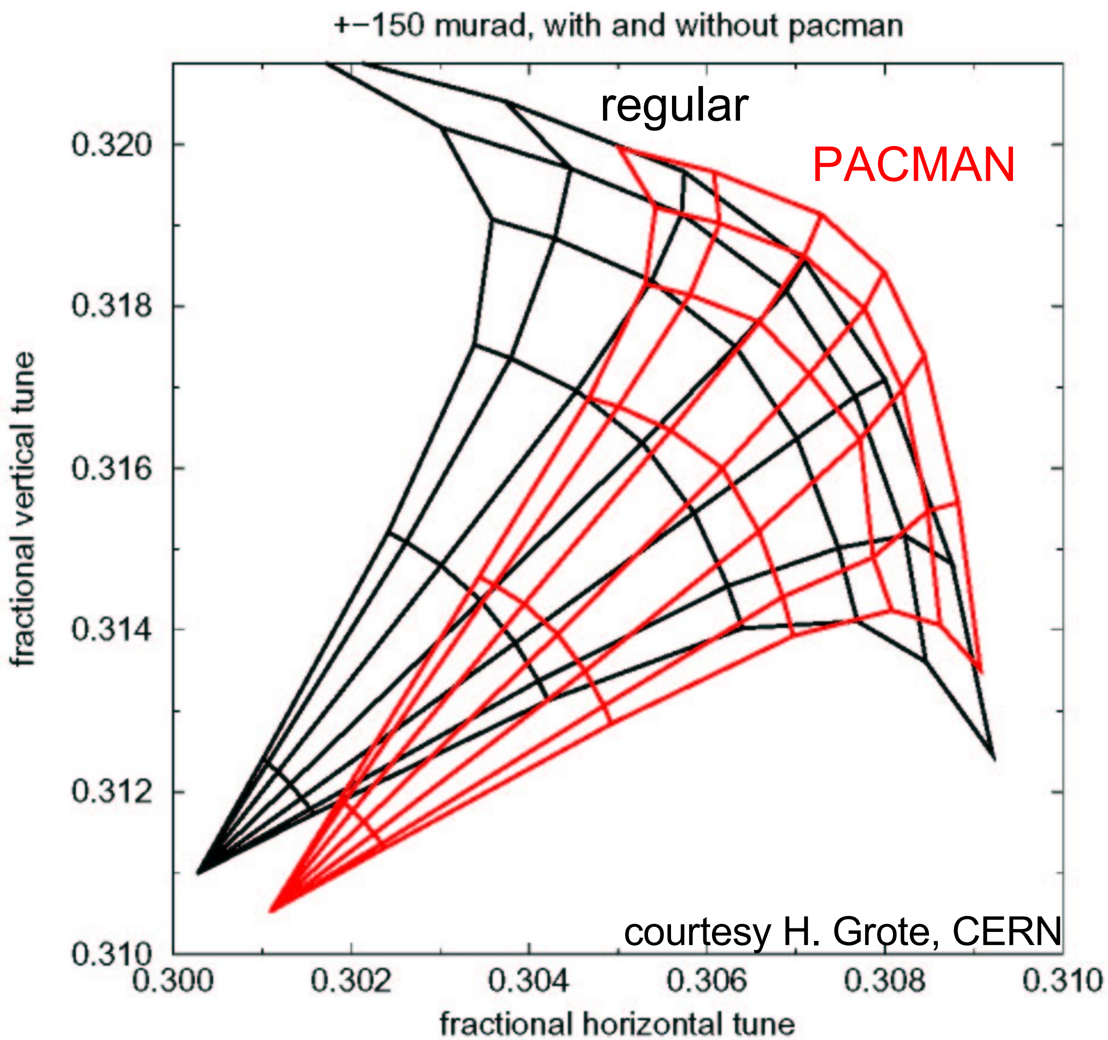
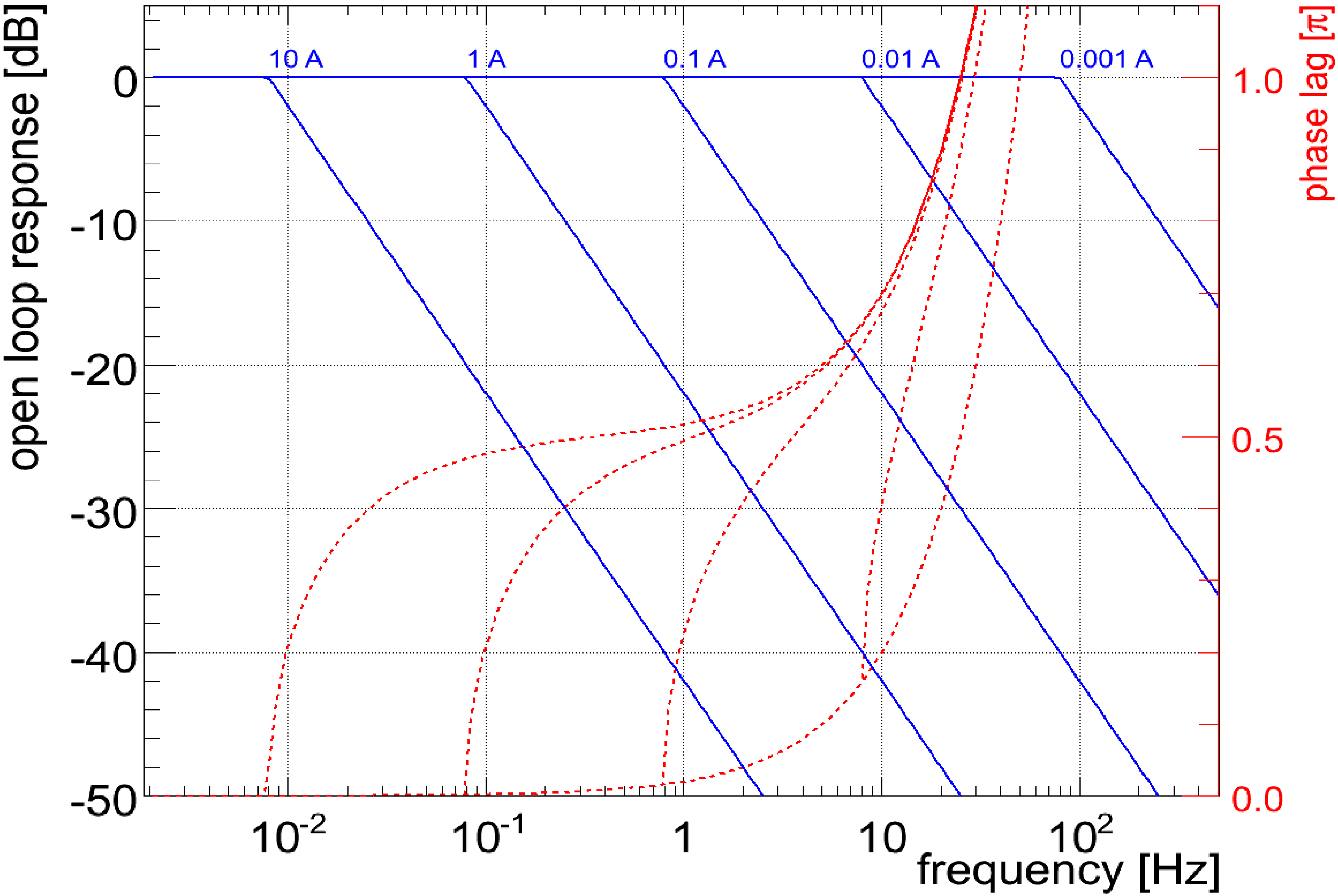
Expected LHC Tune Footprint



Non-linear Slew-rate Limited Exciter Response



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