LHC Feedbacks on Tune, Chromaticity and Betatron Coupling

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Overview

- Requirements vs. Expected Perturbation Sources

- LHC Feedback Architecture
  - orbit feedback and its testbed
  - corrector circuit layout
  - some examples

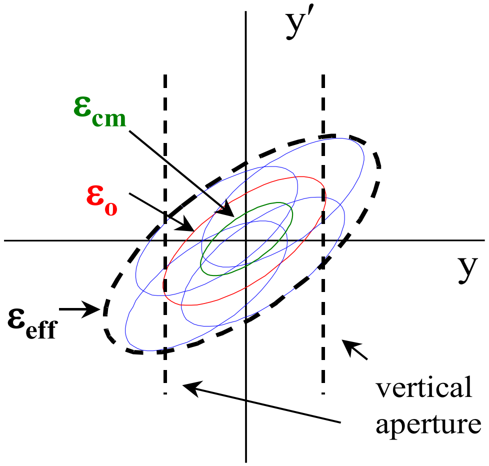
- Inter-Loop cross-dependences
  - betatron-coupling, shared instruments
  - nesting of nasty loops

- (Few comments on commissioning)

Beam Parameter Stability

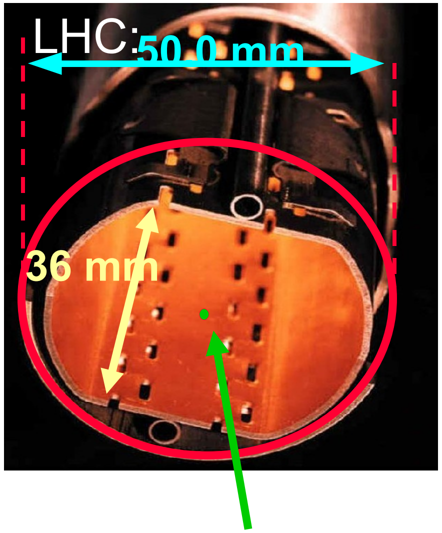
- Lepton accelerators:
  - Effective emittance preservation
  - Minimisation of coupling (orbit in sextupoles)
  - Minimisation of spurious dispersion (orbit in quadrupoles)
  - Collider Luminosity and collision point stability

→ Nearly all 3rd generation light-sources deploy at least orbit/energy feedbacks



- Hadron Colliders:
  - Traditionally: ... keep the beam in the pipe!
  - Present: sig. increased stored intensity and energy → quenches and/or serious damage

    1. Capability to control particle losses in the machine
    2. Commissioning and operational efficiency



Beam 3 σ envel. ~ 1.8 mm @ 7 TeV

Summary of LHC Orbit Stability Requirements

LHC cleaning System:	< 0.15 σ*	IR3,IR7
Machine protection & Absorbers:		
– TCDQ (prot. asynchronous beam dumps)	< 0.5 σ	IR6
– Injection collimators & absorbers	~ 0.3 σ	IR2,IR8
– Tertiary collimators for collisions	~ 0.2 σ	IR1,IR5
• absolute numbers are in the range: ~100-200 µm		
Inj. arc aperture w.r.t. prot. devices and coll.*:	< 0.3-0.5 σ	global
(estimated arc aperture 7.5 σ vs. Sec. Coll. @ 6.7 σ)		
Active systems :		
– Transverse damper, Q-meter, PLL BPM, Schottky	~ 200 µm	IR4
– Interlock BPM	~ 200 µm	IR6
Performance :		
– Collision points stability	minimize drifts	IR1,2,5,8
– TOTEM/ATLAS Roman Pots	< 10 µm	IR1,IR5
– Reduce perturbations from feed-downs	~ 0.5 σ	global
– Maintain beam on clean surface (e-cloud)	~ 1 σ ??	global

... requirements are similar → distinction between local/global less obvious!

*(orbit stability primary vs. secondary collimator 0.3 σ → single jaw 0.15 σ ≈30µm)

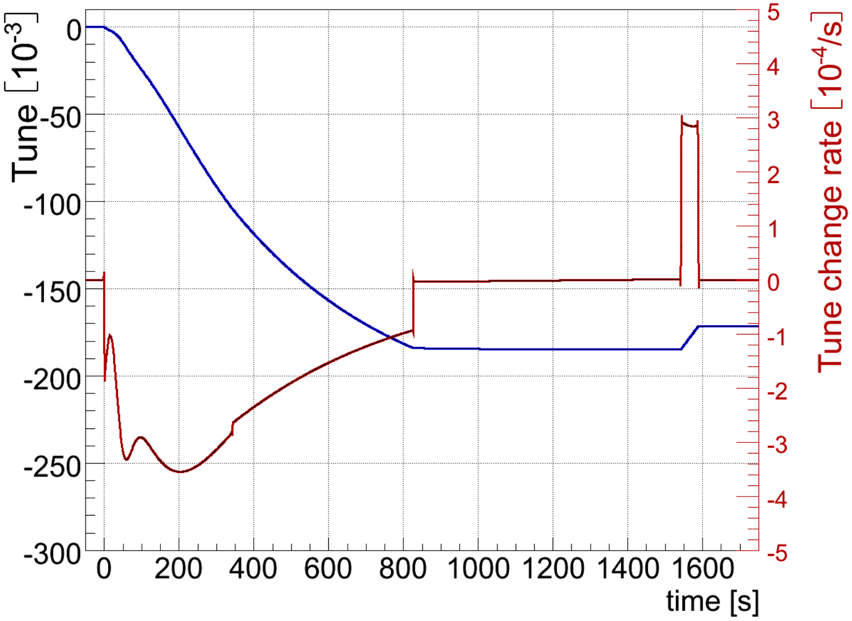
Summary of Dynamic Orbit Perturbations

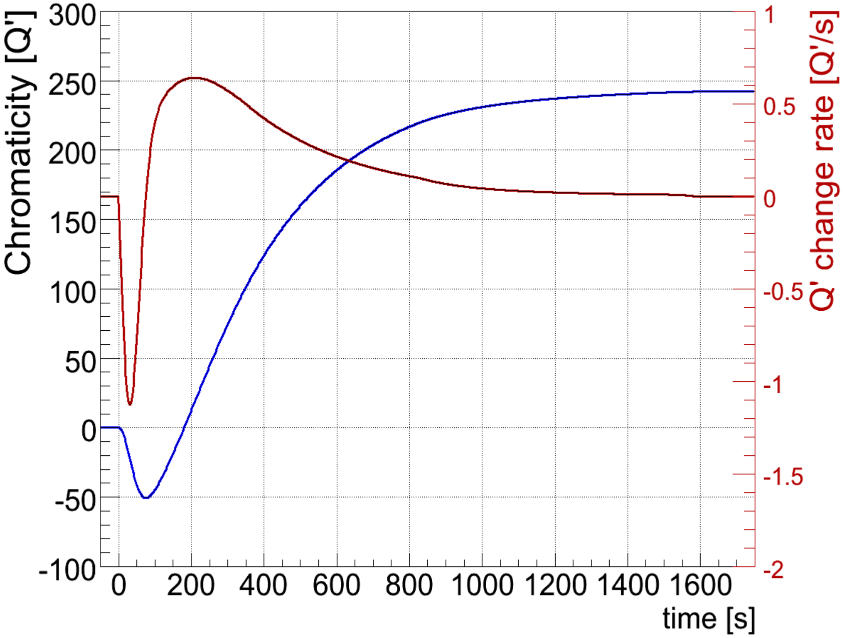
Perturbation Source	**Orbit r.m.s.**	$\|\Delta x/\Delta t\|_{max}$	$\Delta p/p$	**Phase**
	[μm]	[$\mu m/s$]	[10^{-4}]	
Random Ground Motion	$(200 - 300)$	< 0.01	$8 \cdot 10^{-3}$	all
Tides (max/min)	$+100/-170$	< 0.01	$+0.5/-0.9$	all
Thermal Girder Expansion	$(9.5\ldots16)/^{O}C$	$< 10^{-3}/^{O}C$	-	all
Cryostat vibration	unknown	-	-	all
Decay	530	< 0.5		injection
Snapback	530	< 15		start ramp
Eddy currents	129	< 0.3	-1	ramp
Persistent currents	340	< 0.2	-9	ramp
Ramp total	600-700	< 15	8	ramp
β^* squeeze[1]	< 30 mm	< 25	-	squeeze
COD power supply ripple	6	noise	-	injection
	0.4	noise	-	collision
COD hysteresis	50	static	0.2	first injection

- Largest and fastest expected contributions:
  - Snapback: $\sigma(x) \approx$ 530 μm r.m.s. & $|\Delta x/\Delta t|_{max} \leq 15$ μm/s
  - β^* Squeeze: $\sigma(x) \approx$ 30 mm r.m.s. & $|\Delta x/\Delta t|_{max} \leq 25$ μm/s

Tune and Chromaticity: Requirements vs. Perturbations

- Nominal requirements: $\Delta Q < 10^{-3}$, $\Delta Q' < 1$
  - commissioning/low-intensity/pilot: $\Delta Q < 0.015$, $\Delta Q' < 10$





- 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

Expected Dynamic Perturbations vs. Requirements

- Expected dynamic perturbations*
  - For details, please see additional slides

	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

- Requires FB "Zoo": Tune/Coupling → Chromaticity → Orbit → Energy
- Feedback list of "what's easiest to commission":
  - 1rd: Orbit → functional BPM system → OK
  - 1½: Energy → consequence of 100k turn acquisition → OK
  - 2nd: Tune/Coupling → functional Q-meter (-PLL) → ~ OK
  - 3rd: Chromaticity → functional Q-meter and Δp/p modulation → Day I-N+1
- Foresee time to commission feedbacks at an early stage
  - Most instruments are commissioned parasitically with first circulating beam
  - Feedbacks can significantly speed up commissioning if used at an early stage

* numbers in brackets are 'worst case'

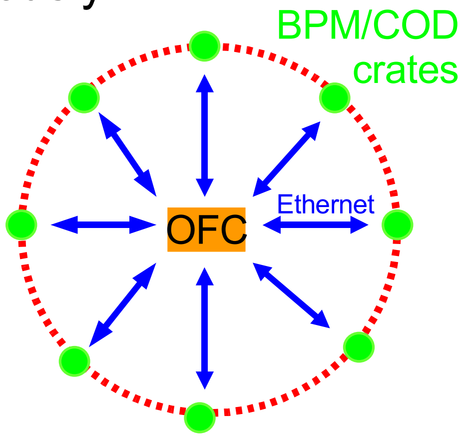
LHC: Divide-and-Conquer Feedback Architecture

- Divide:
  - FB zoo: Orbit, Tune, Chromaticity, β-Coupling, Energy, ..., Luminosity, (Beta-Beating)
    - develop/commission on a one-by-one basis
  - Parameter measurement ↔ feedback controller
    - (N.B. Q-PLL is a FB in itself)
  - Feedback controller into:
    - Space Domain: classic parameter control $\Delta Q_{x/y}$ → quadrupole circuits currents, etc. (assuming steady-state)
    - Time Domain: compensate for dynamic behaviour

- Conquer:
  - Once feedback operation on a per-parameter basis is established, reintegrate and test/commission inter-loop coupling and other constraints.

LHC: orbit feedback system

- Small perturbations around the reference orbit will be continuously compensated using beam-based alignment through a central global orbit feedback with local constraints:



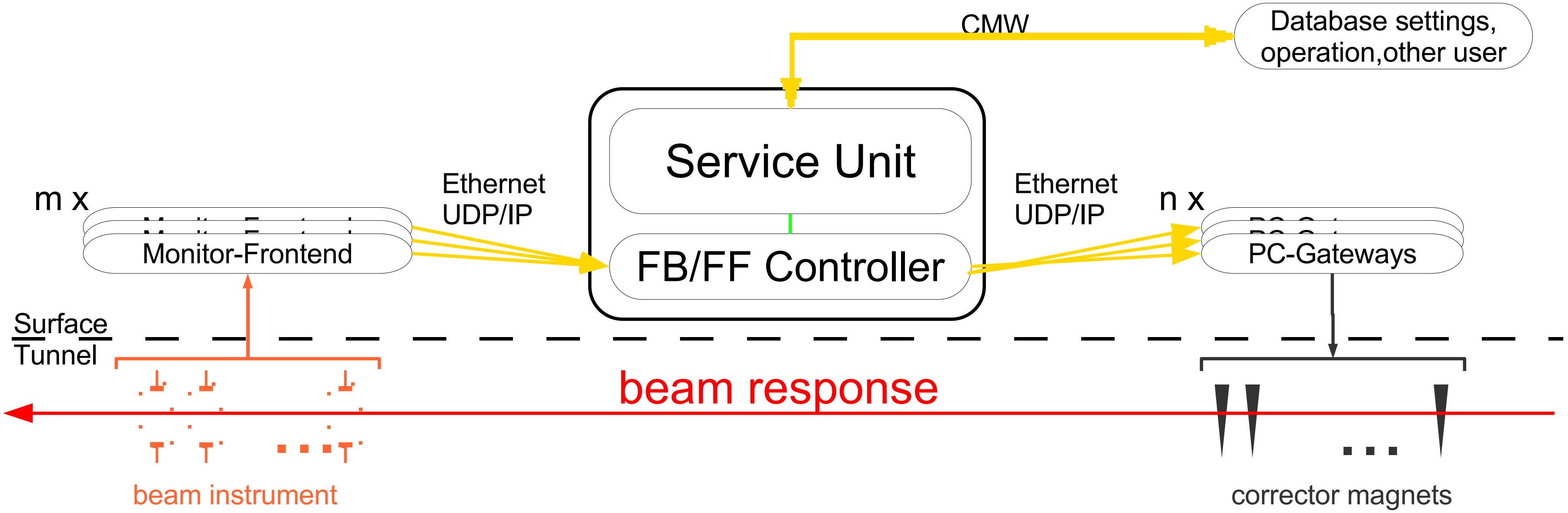
  - 1056 beam position monitors
    - BPM spacing: $\Delta\mu_{BPM} \approx 45°$ (oversampling → robustness!)
    - Measure in both planes: > 2112 readings!
  - One Central Orbit Feedback Controller (OFC)
    - Gathers all BPM measurements, computes and sends currents through Ethernet to the PC-Gateways to move beam to its reference position:
      - high numerical and network load on controller front-end computer
      - a rough machine model is sufficient for steering (insensitive to noise and errors)
      - most flexible (especially when correction scheme has to be changed quickly)
      - easier to commission and debug
  - 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

- With more than 3100 involved devices the largest and most complex system

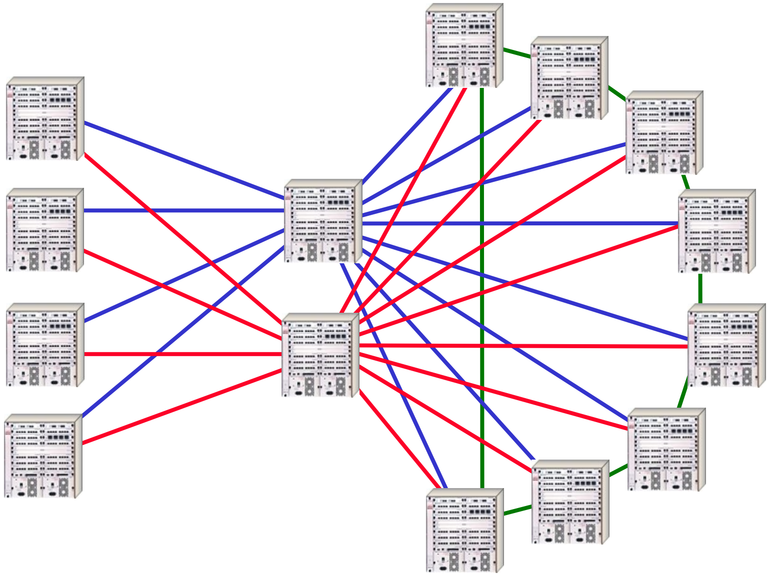
Common Feedback/Feed-forward Control Layout

LHC feedback control scheme implementation split into two sub-systems:

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



Technical Network and Data Communication I/II

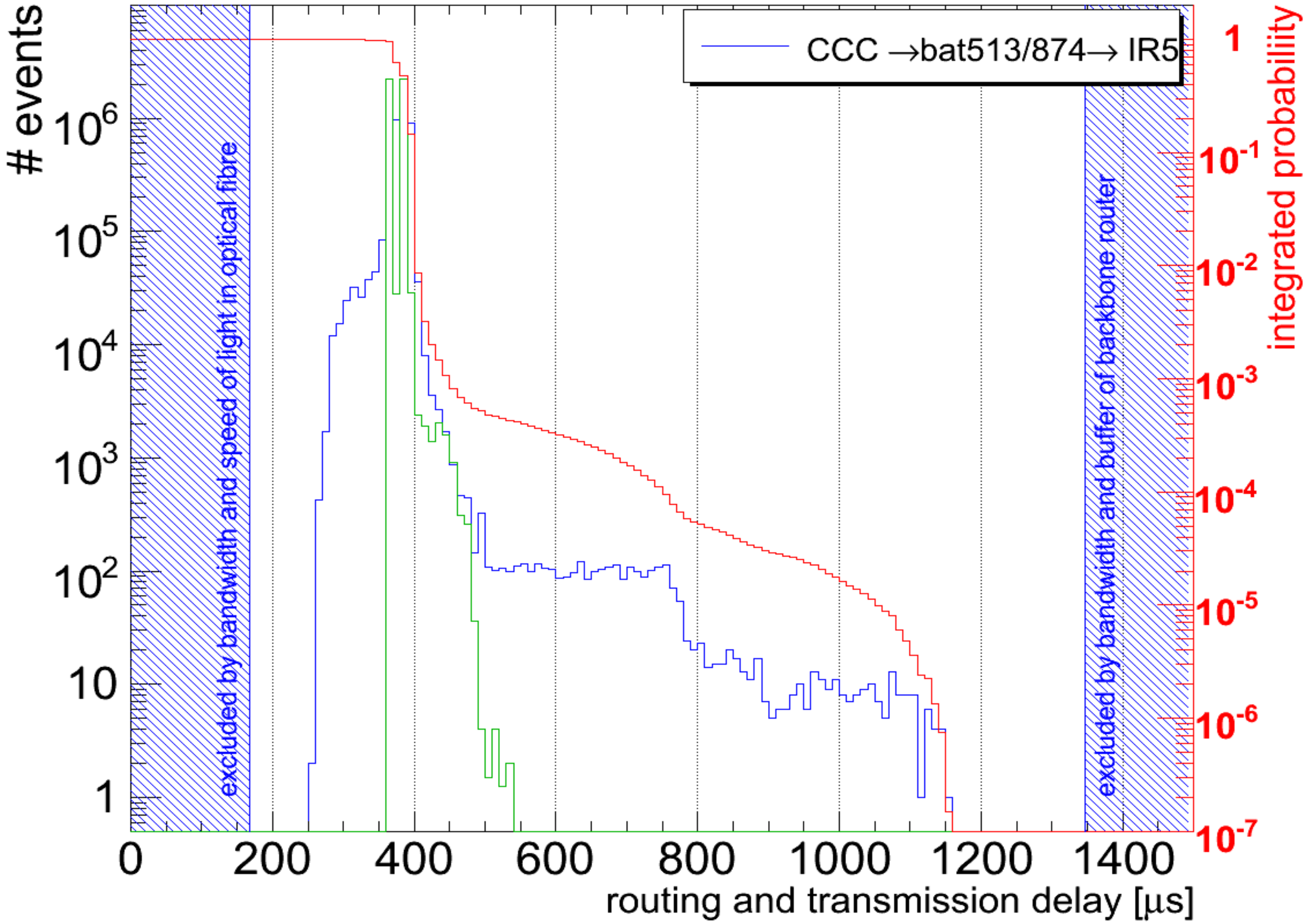


- CERN's Technical Network as backbone
  - Store & Forward switched network
    - no data collisions/data loss
  - double (triple) redundancy
- Core: “Enterasys X-Pedition 8600 Routers”
  - 32 Gbits/s non-blocking, $3 \cdot 10^7$ packets/s
  - 400 000 h MTBF
  - hardware QoS
    - One queue dedicated 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)
  - 80% due to traveling speed of light inside the optic fibre
- worst case max network jitter « targeted feedback sampling!

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

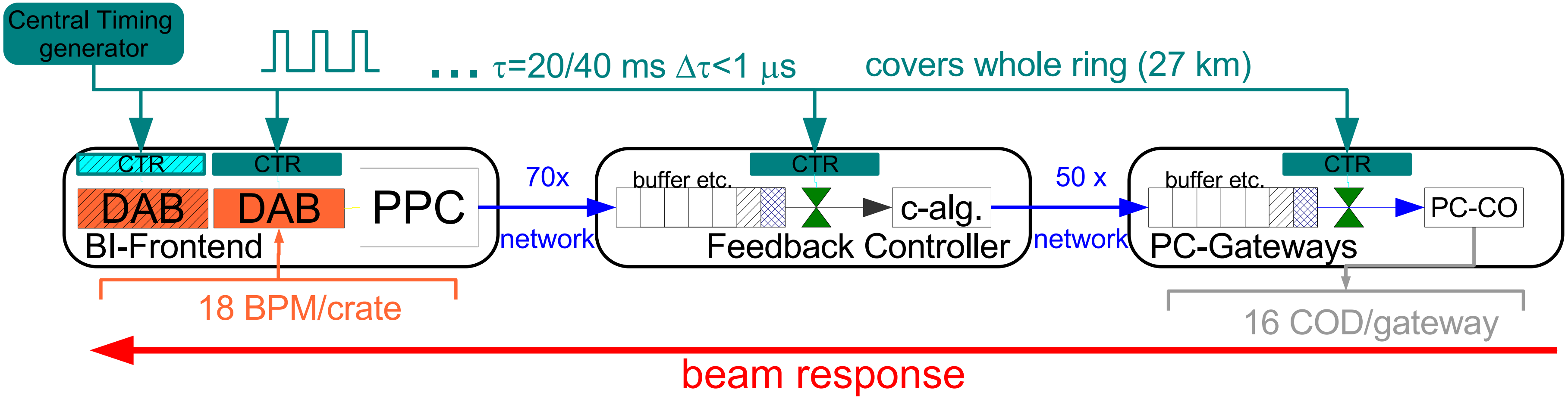


Remaining Jitter Compensation: Fix Max Loop Delay

Two main strategies:

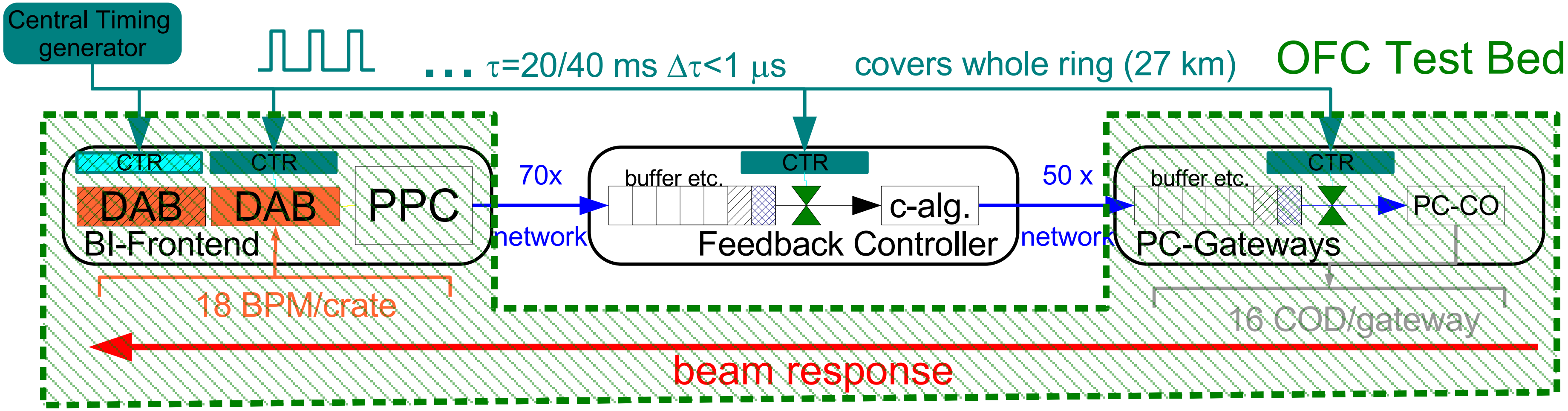
- actual delay measurement and dynamic compensation in SP-branch:
  - only feasible for small systems

- Jitter compensation using a periodic external signal:
  - CERN wide synchronisation of events on sub ms scale
  - The total jitter, the sum of all worst case delays, must stay within “budget”.
  - Measured and anticipated delays and their jitter are well below 20 ms.
  - feedback loop frequency of 50 Hz feasible for LHC, if required...



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
    - same code for real and simulated machine:
      - possible and meaningful “offline” debugging for the FB controller



LHC: Feedbacks on Tune, Chromaticity and Coupling

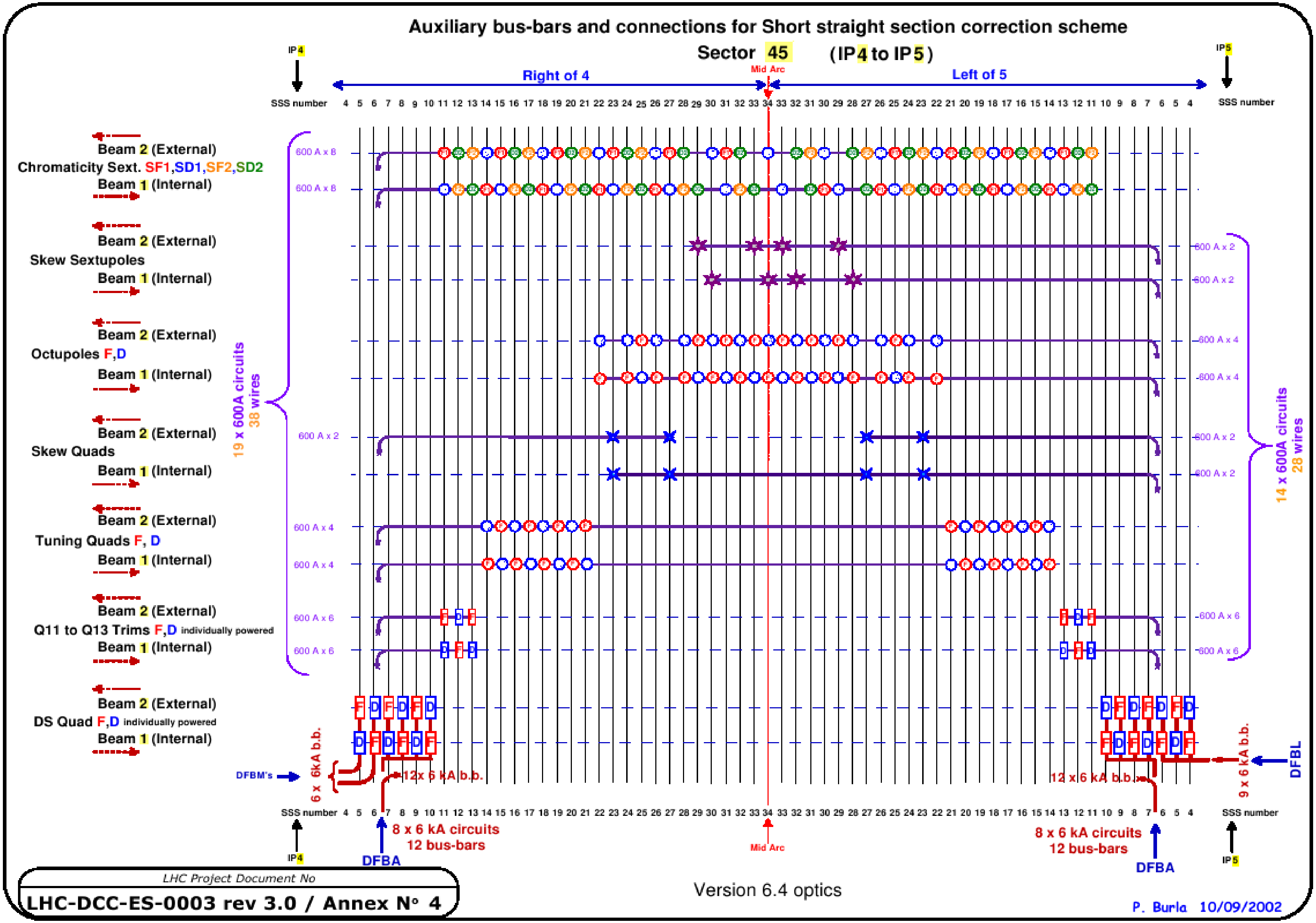
- Tune, Chromaticity and Betatron-coupling Loops can from a controls point of view be based on the same principles/scheme/architecture as used for the orbit/energy feedback.

- Reduced dimension with essentially two sources of input:
  - BBQ based acquisition: FFT + PLL (3 independent systems per beam)
    - yields: Q, Q' and C^- measurements (6 input variables per beam)
  - Schottky based acquisition: FFT (2 per beam)
    - yields: Q and possibly Q' measurement
      - foreseen once LHC is in collisions

LHC Q, Q' and C^- feedback Systems
Total Number of (FB) Corrector Circuits

- 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, possible use of DS Quadrupoles
- Chromaticity:
  - 32x ±600A circuits powered from even IPs, 4 families
- 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 FB systems!

Powering Layout of the SSS Correction Scheme IP4↔IP5



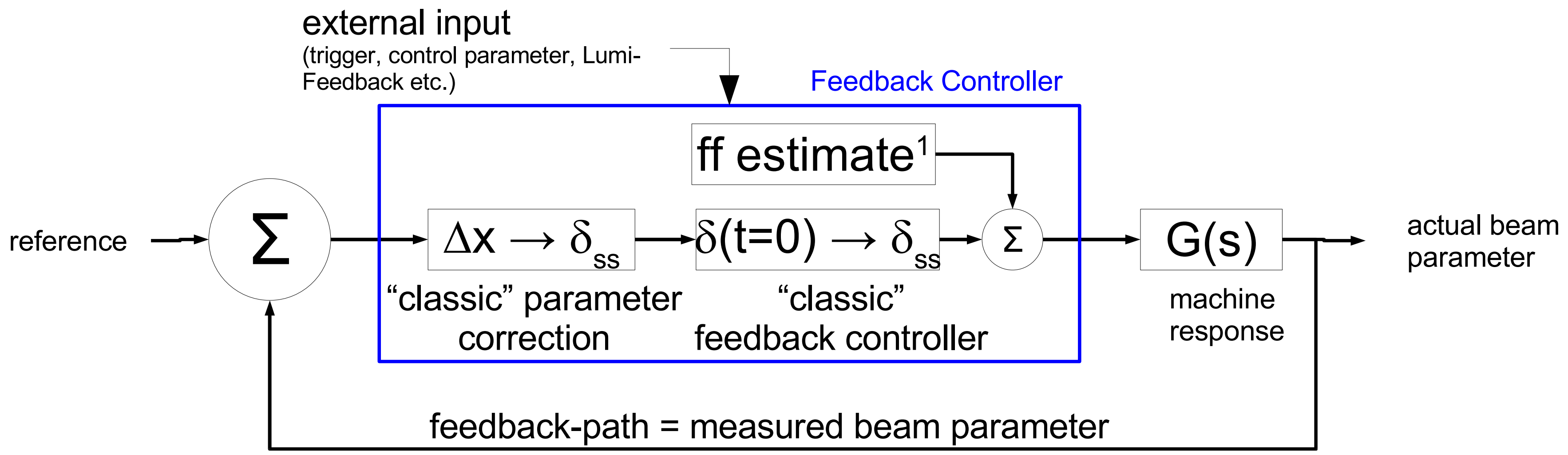
Orbit Feedback/Feed-Forward Control Scheme

- The feedback controller consists of three stages:
  1. Compute steady-state corrector settings $\vec{\delta}_{ss} = (\delta_1, \ldots, \delta_n)$ based on measured parameter shift $\Delta x = (x_1, \ldots, x_n)$ that will move the beam to its reference position for $t \rightarrow \infty$.

     space domain

  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

     time domain



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

Feedback Controller

ff estimate[1]

reference

Σ

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

"classic" parameter correction

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

"classic" feedback controller

Σ

G(s)

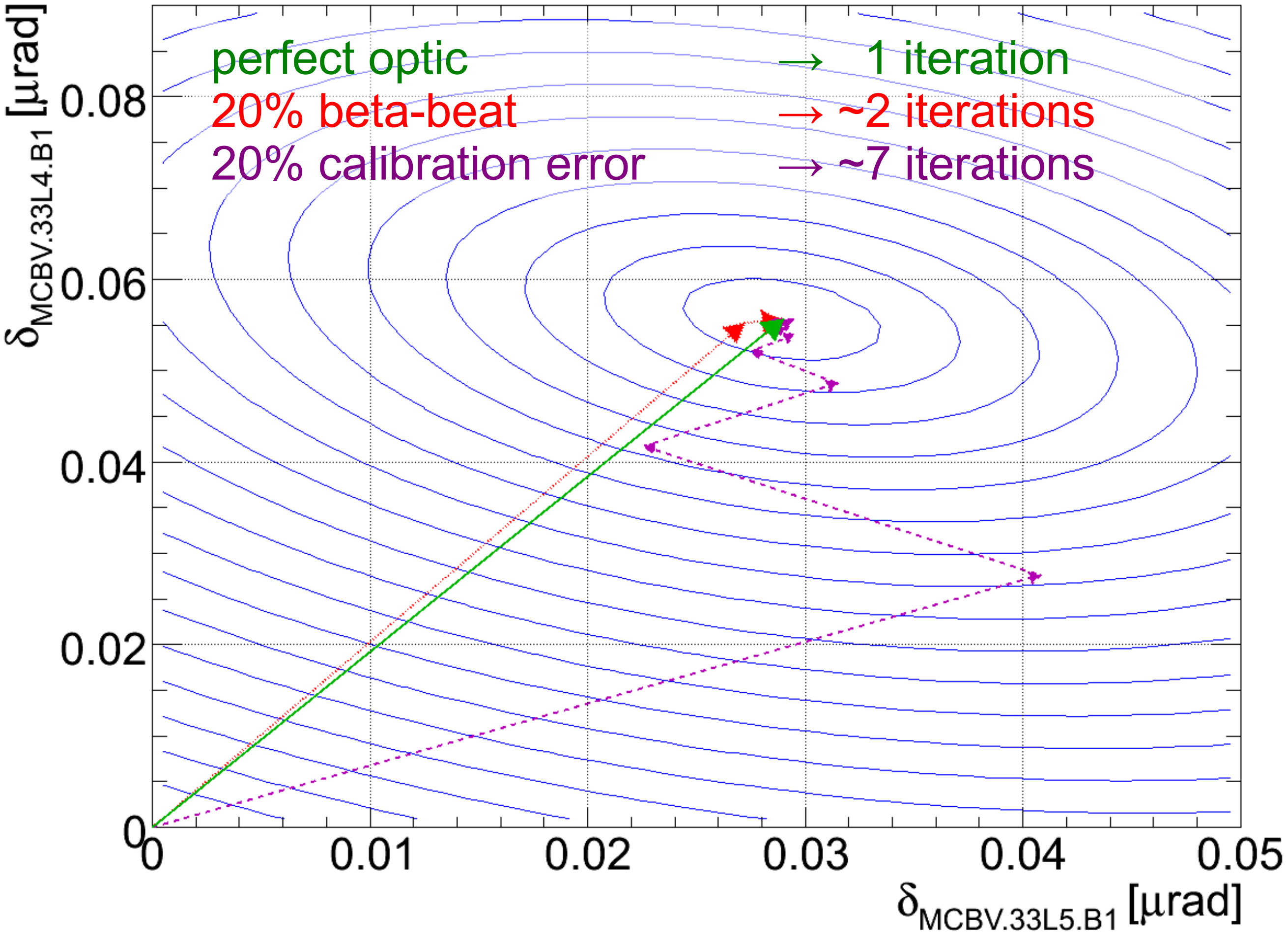
machine response

actual beam parameter

feedback-path = measured beam parameter

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



Reminder: Solution in Time-Domain

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

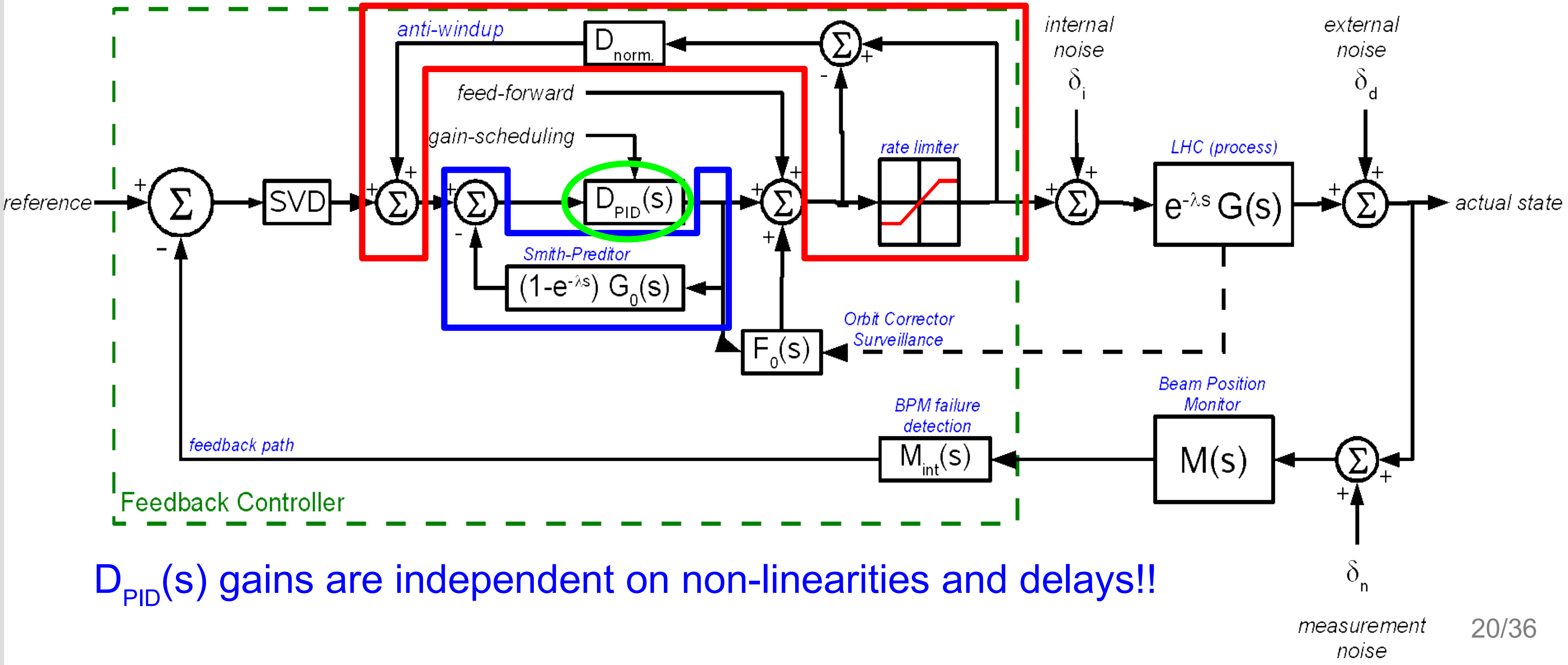
$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}\,G_{NL}(s)$$

τ : being the circuit time constant

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

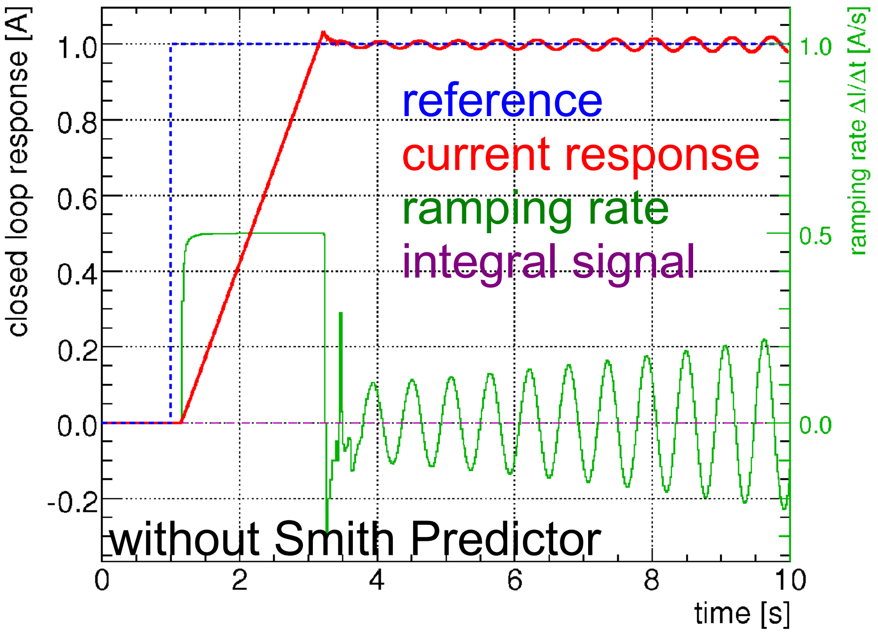
K_0:I-to-δ transfer func.
1/α: "effective" FB freq.

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

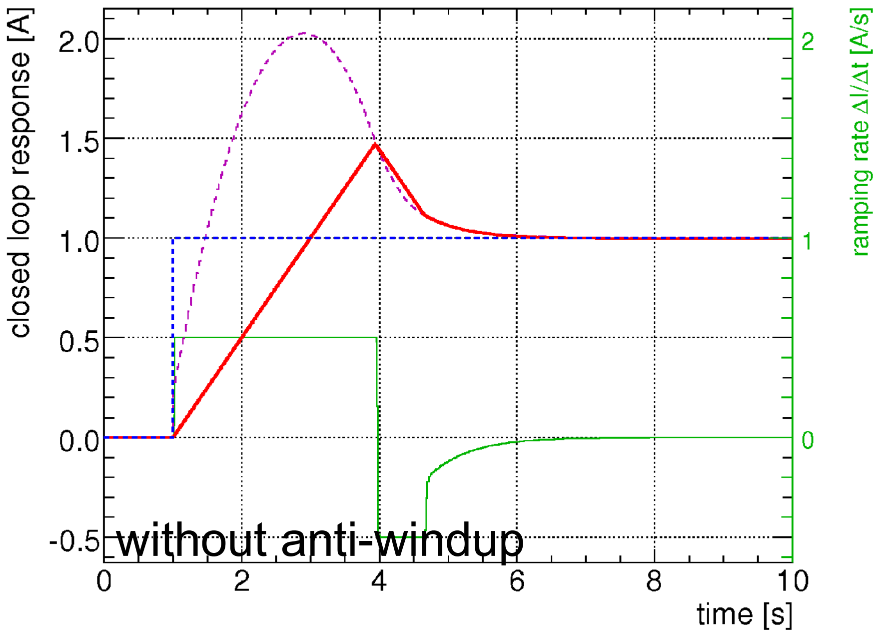


$D_{PID}(s)$ gains are independent on non-linearities and delays!!

Some Results: Smith-Predictor and Anti-Windup

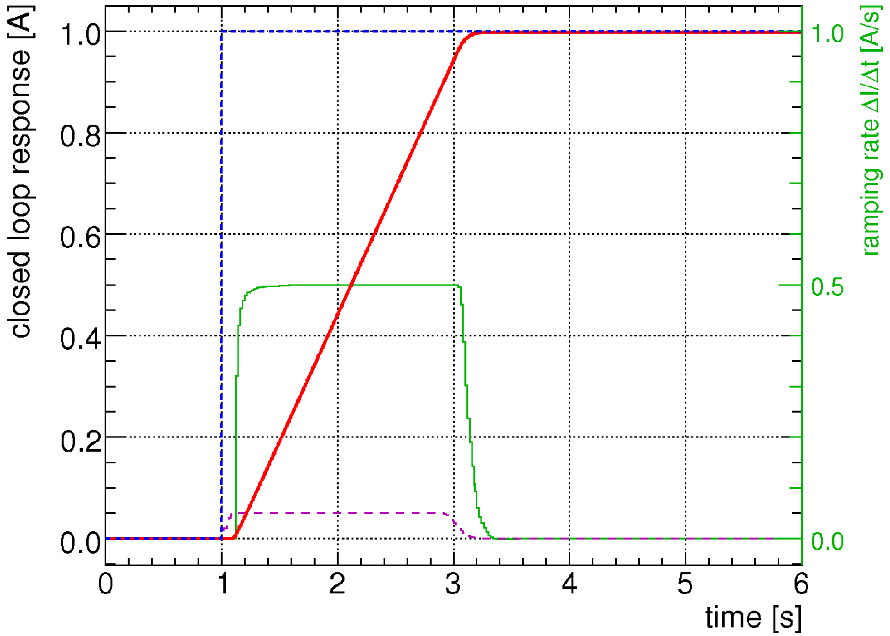


without Smith Predictor



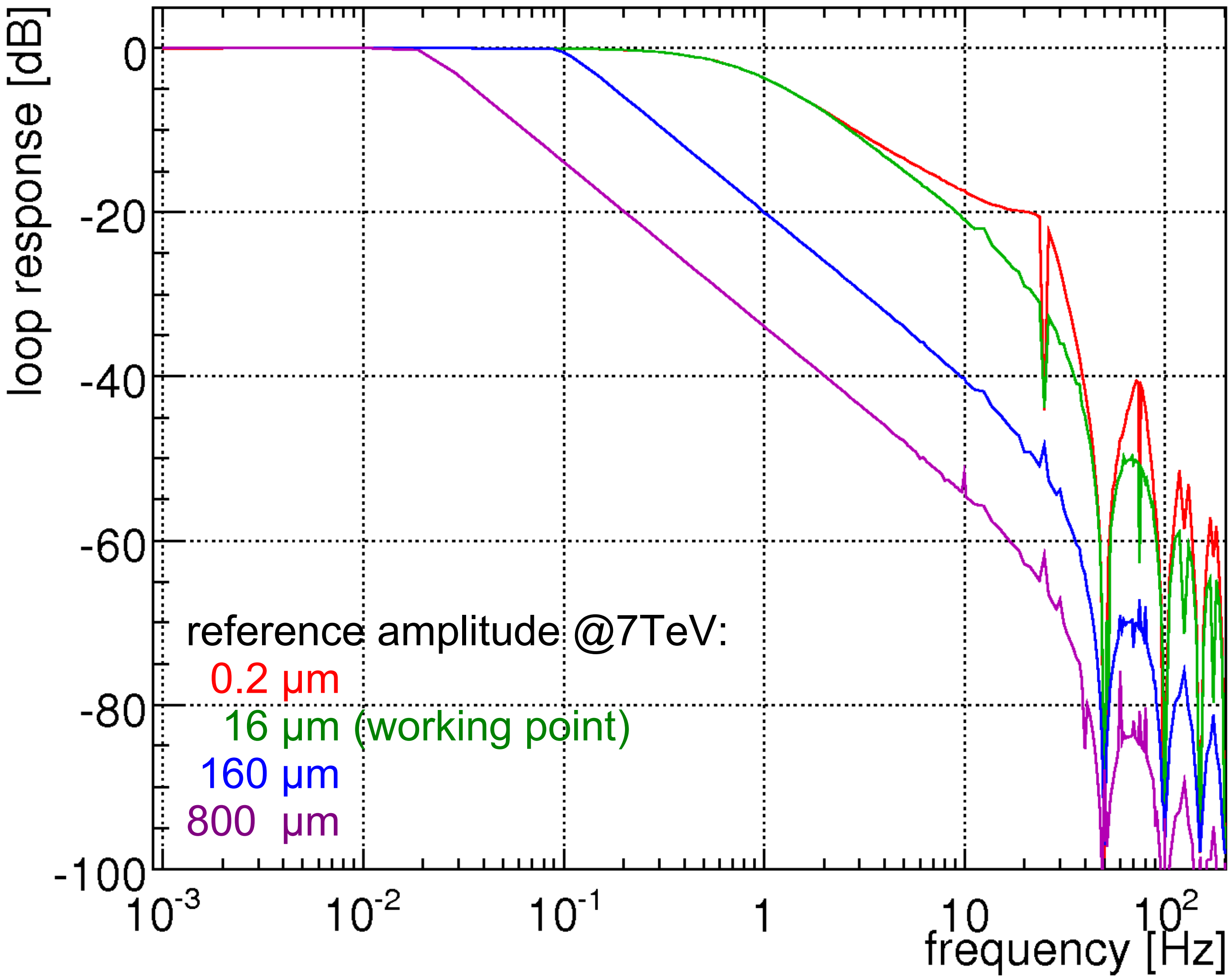
without anti-windup

with full delay and windup compensator scheme:



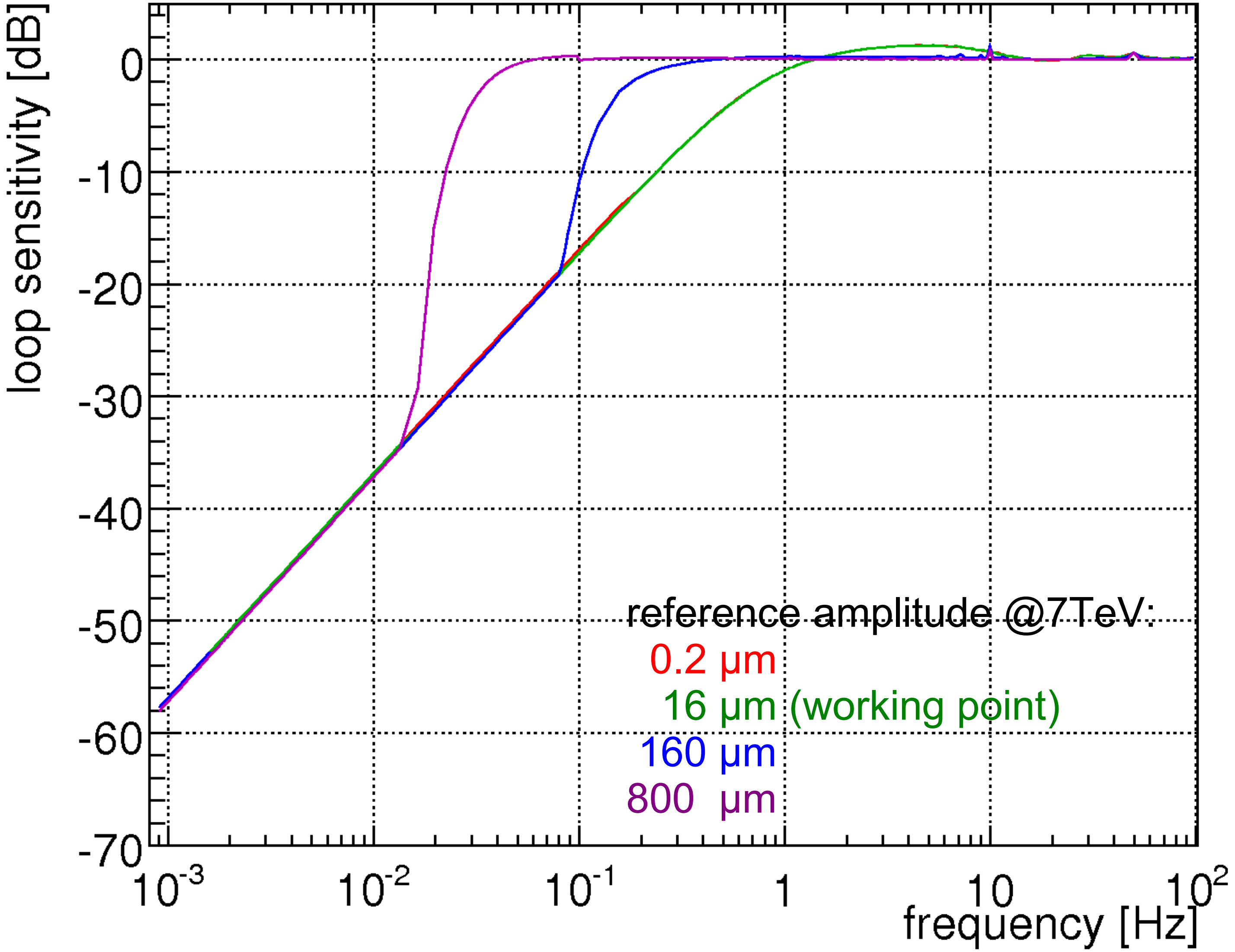
Nominal Feedback Response T_0

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



Nominal Feedback Disturbance Rejection S_{d0}

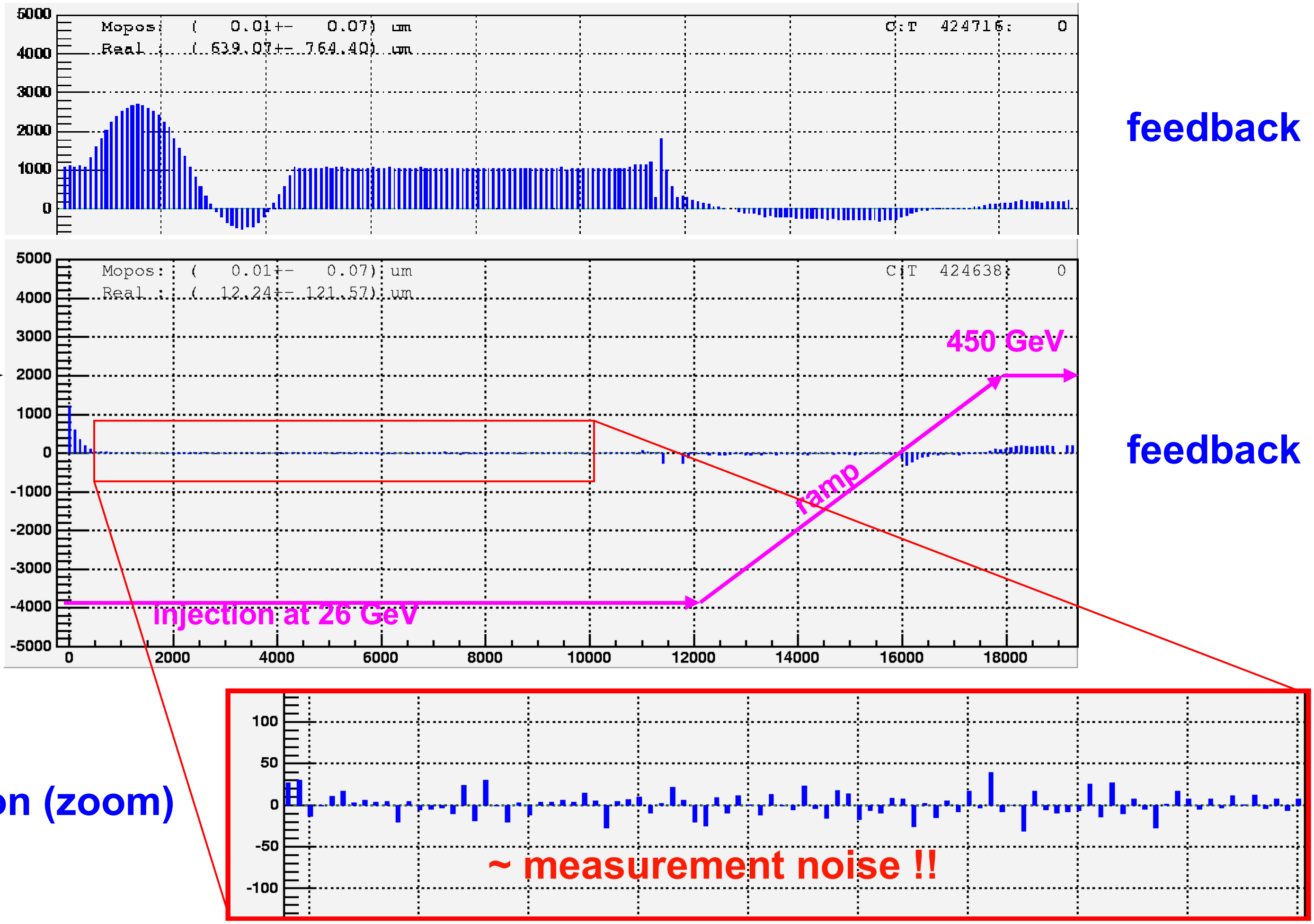
- Full LHC orbit simulation @1KHz sampling, (BPM sampling: 25Hz)



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

BPM Reading (µm)

Time (ms)



feedback off

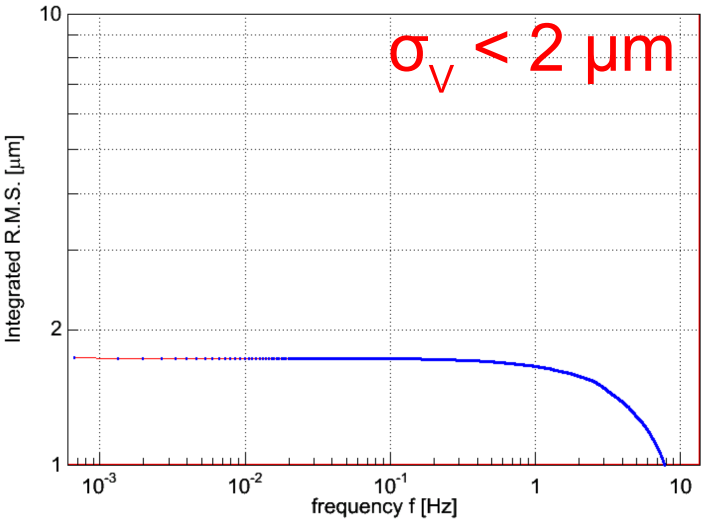
feedback on

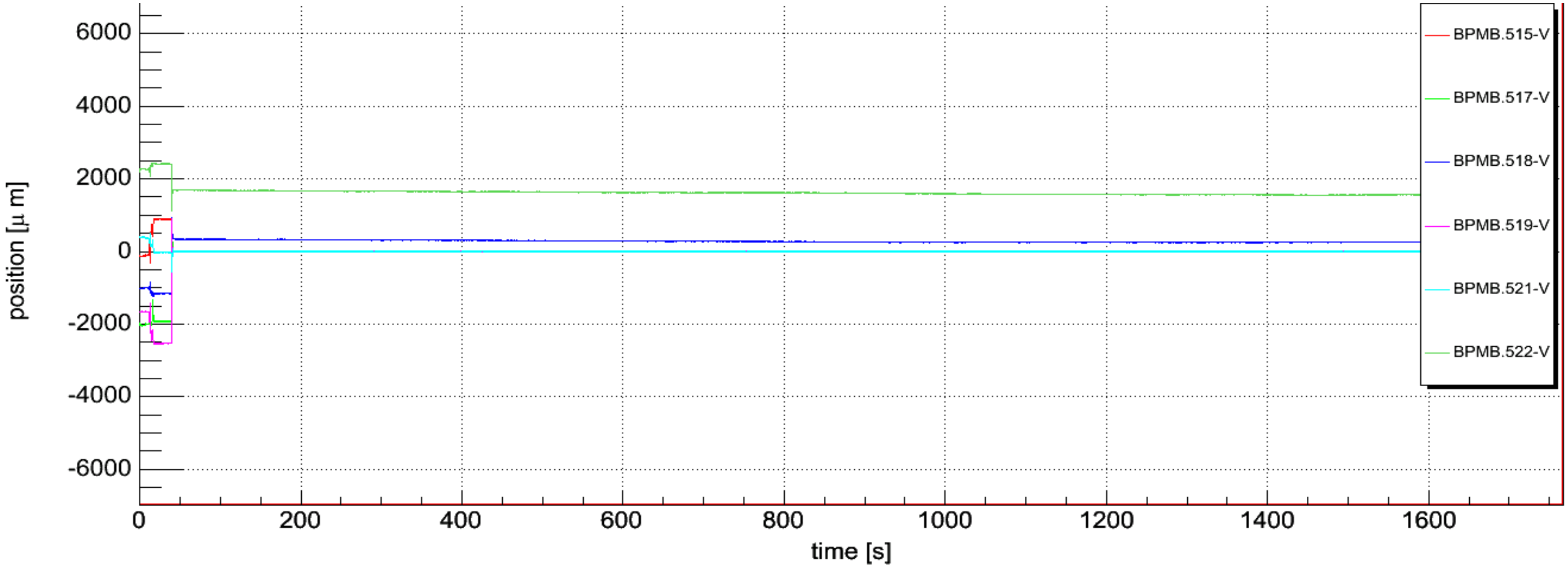
feedback on (zoom)

~ measurement noise !!

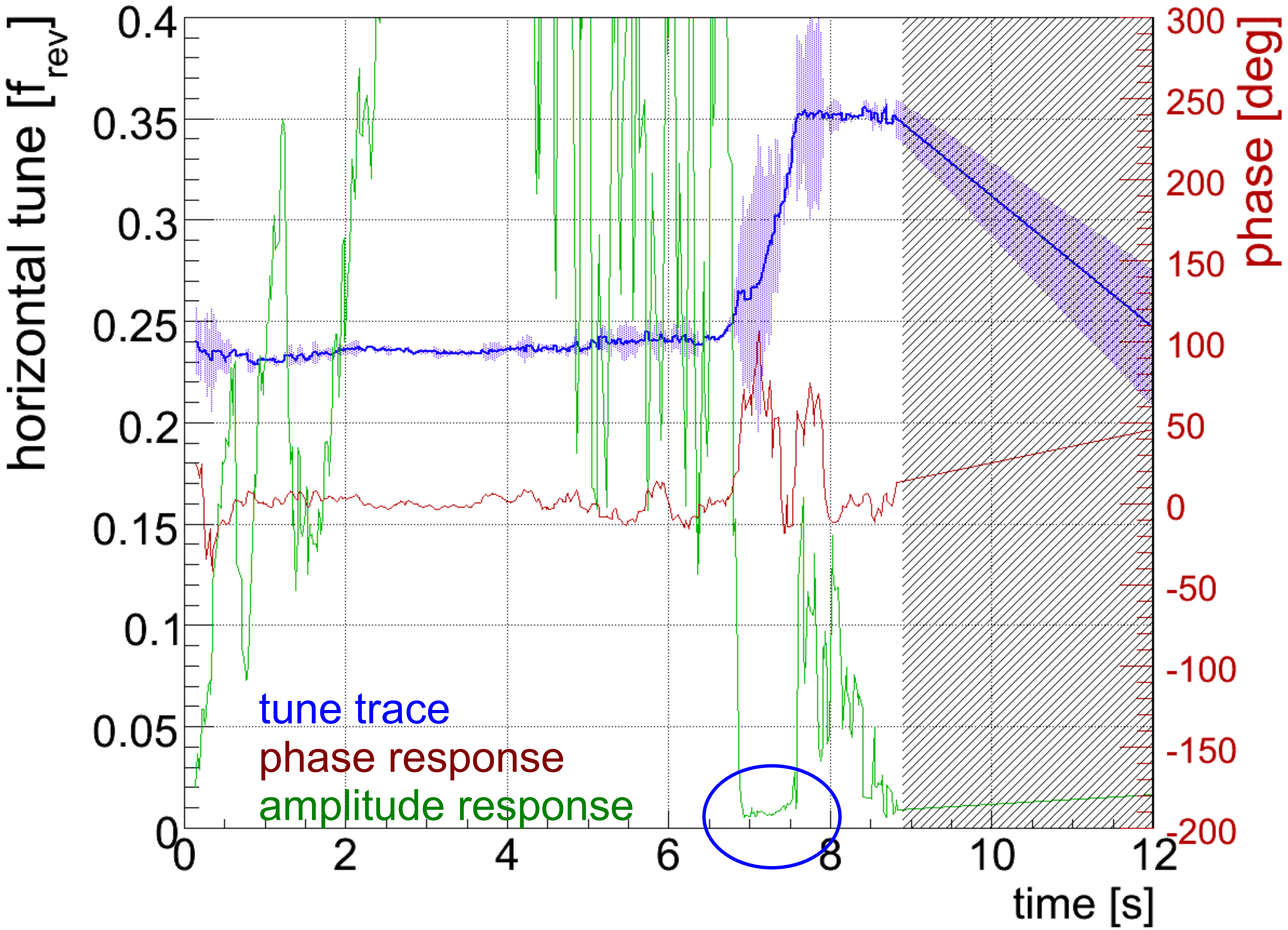
Example: LHC Orbit Feedback Tests at the SPS II/II Real-Beam Data

- Stabilisation “record” in the SPS
  - 270 GeV coasting (proton) beam, 72 nom bunches, $\beta_v \approx 100$ m
  - rivals most modern light sources
  - magnitudes better than required
- Target: maintain same longterm stability





Example: LHC PLL Tune Tracking at the SPS Real-Beam Data

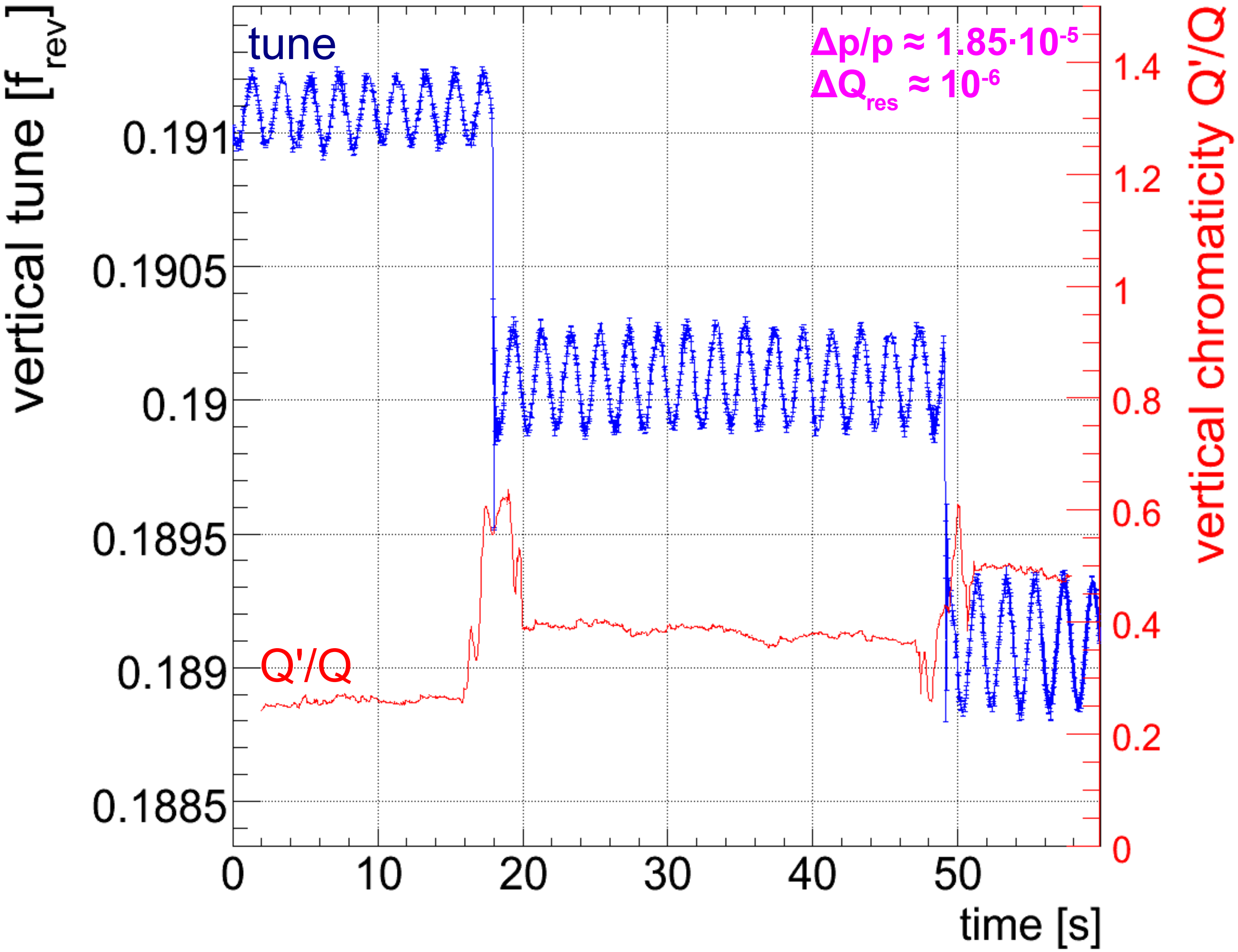


- Phase error and non-vanishing amplitude indicate lock during ramp
- $\Delta Q/\Delta t|_{max} \approx 0.3$ ~ two orders of mag. faster than required for LHC

  $f_{rev} \approx 43$ kHz

details:
→ Andrea's presentation

Example: LHC Chromaticity Tracker at the SPS Real-Beam Data

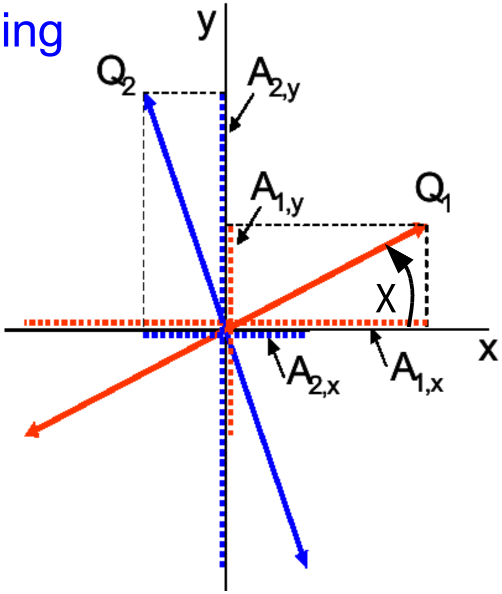


- real-time Q' detection algorithm (agrees with SPS cross-calibration):
  - Q' resolution better than 1 unit (nominal performance)

details:
→ Andrea's presentation

Loop Interdependences and Cross-Talk I/III

- No orbit, Q, Q' feedback without control of betatron-coupling
- 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



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

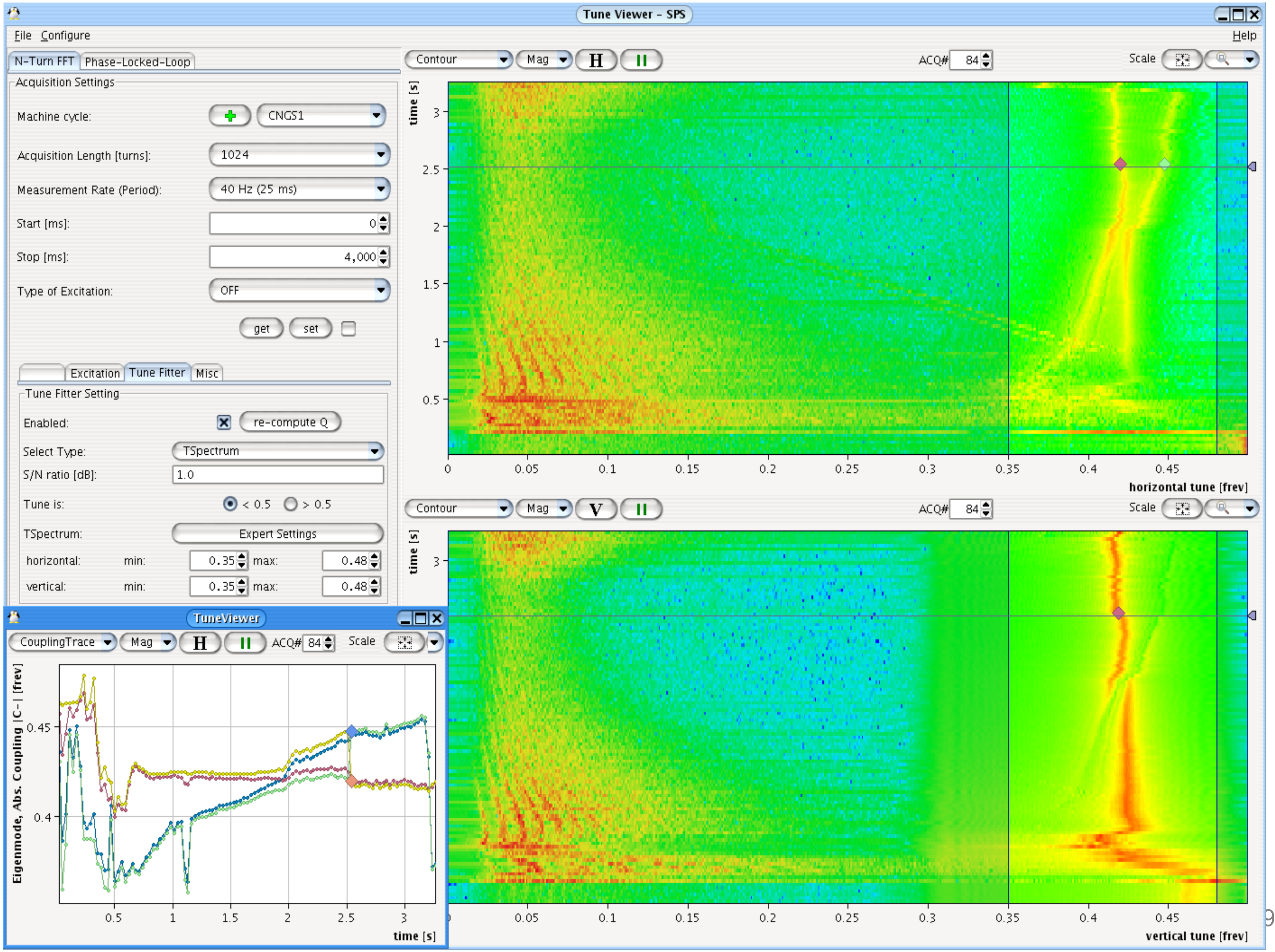
$$\Rightarrow \quad \boxed{|C^-| = |Q_1 - Q_2| \cdot \frac{2\sqrt{r_1 r_2}}{(1 + r_1 r_2)} \quad \wedge \quad \Delta = |Q_1 - Q_2| \cdot \frac{(1 - r_1 r_2)}{(1 + r_1 r_2)}}$$

- 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

Example: BBQ based Betatron-Coupling Measurement Real-Beam Data



Tune Viewer - SPS

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

Excitation | Tune Fitter | Misc

Tune Fitter Setting

Enabled: ☒

Select Type: TSpectrum

S/N ratio [dB]: 1.0

Tune is: ● < 0.5 ○ > 0.5

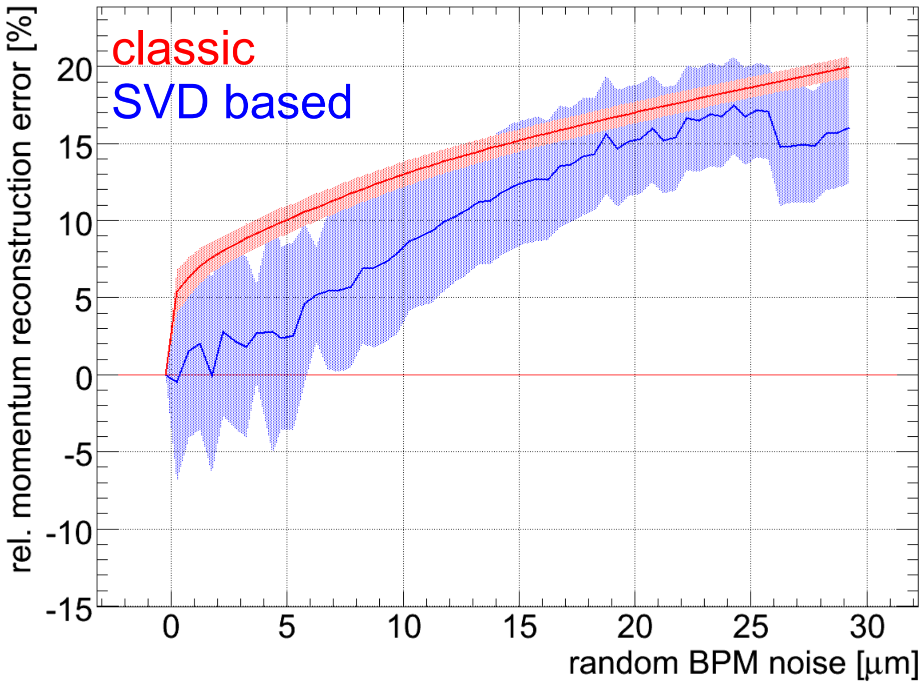
TSpectrum: Expert Settings

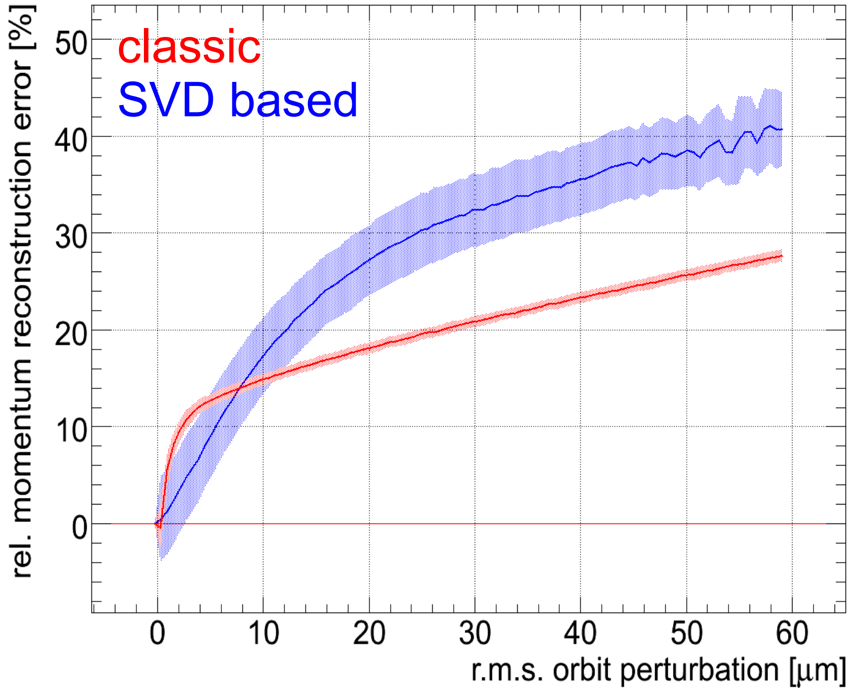
horizontal: min: 0.35 max: 0.48

vertical: min: 0.35 max: 0.48

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
      - $\Delta f_{RF} = (\Delta f_{Q'} - \Delta f_{meas})$





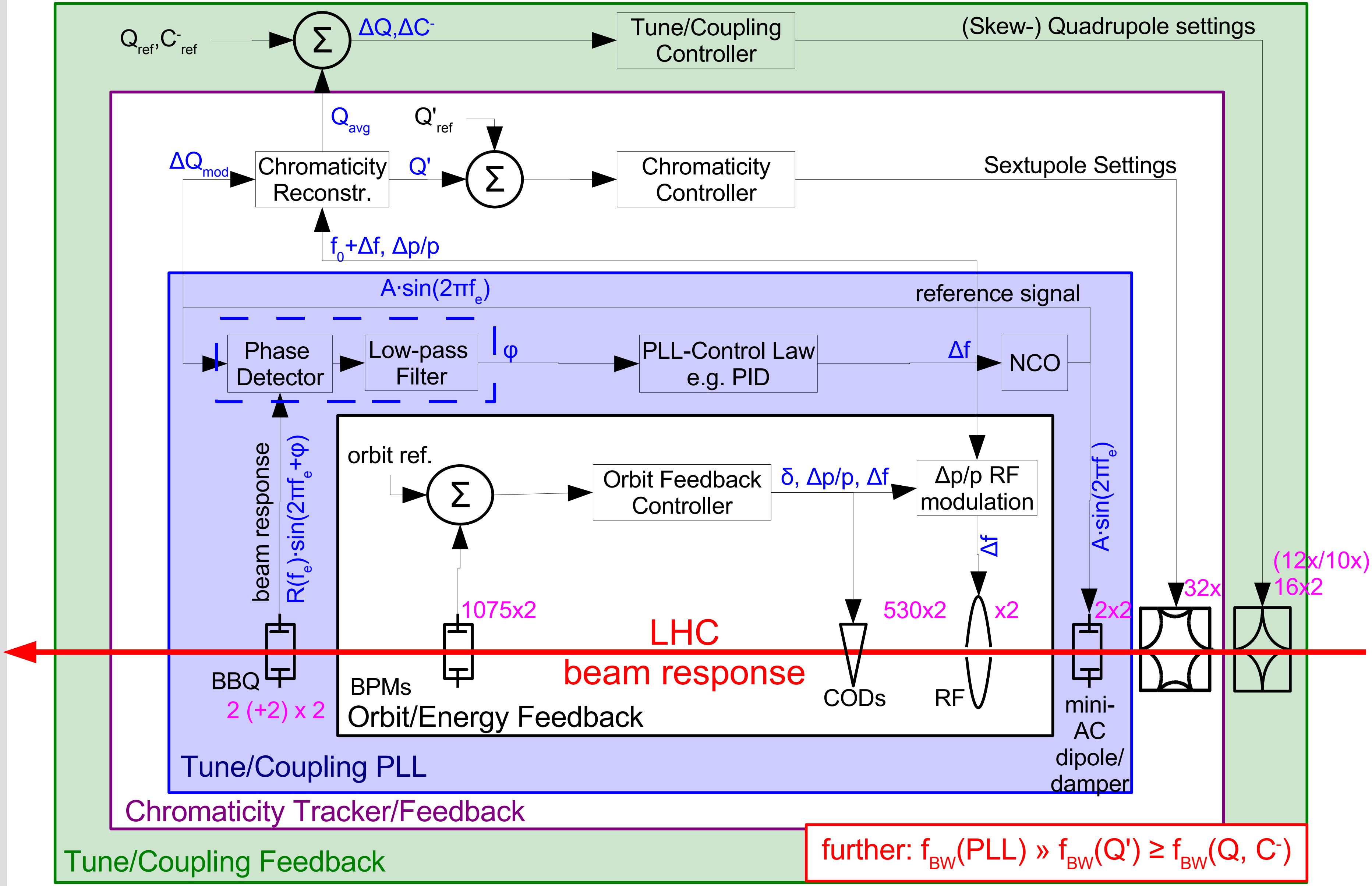
Loop Interdependences and Cross-Talk III/III

- Tune PLL vs. Bunch-by-Bunch Feedbacks (Transverse Damper)
  - use the same exciter/operate on the same beam
  - Mitigation:
    - either: operate PLL below damper “noise floor”
    - or: operate on non-colliding bunch exempted from the damper

Some additional comments on using PLL & radial modulation for Q' tracking:

- There are two paradigms:
  - either: ~ equal bandwidth for Q' measurement vs. Q feedback (LHC)
    - better accuracy on chromaticity (LHC priority)
    - possibly reduced tune/coupling stability
  - or: faster Q feedback and derive Q' from the quadrupole currents (RHIC)
    - less accuracy on chromaticity (magnet calibration systematics)
    - better tune/coupling stability (RHIC priority)

...Conquer:
Cascading between individual Feedbacks



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

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

Commissioning of Feedbacks without Beam

- Most feedbacks checks can be and are done during hardware commissioning:
  - Interfaces and communication between BI and PO front-ends
  - Synchronisation of BPM acquisition
    (using e.g. the BPM's 'calibration' mode)
  - Synchronisation of PO-Gateways
    (using the provided 50 Hz status feedback channel)
  - Interfaces to databases

- Using the 'test-bed' we can do the further tests without beam:
  - PID/Smith-Predictor/anti-windup at nominal/ultimate feedback frequency
  - Test automated countermeasures against failing BPMs or circuits
  - other parts of the feedback architecture:
    controls, non-beam-physics issues

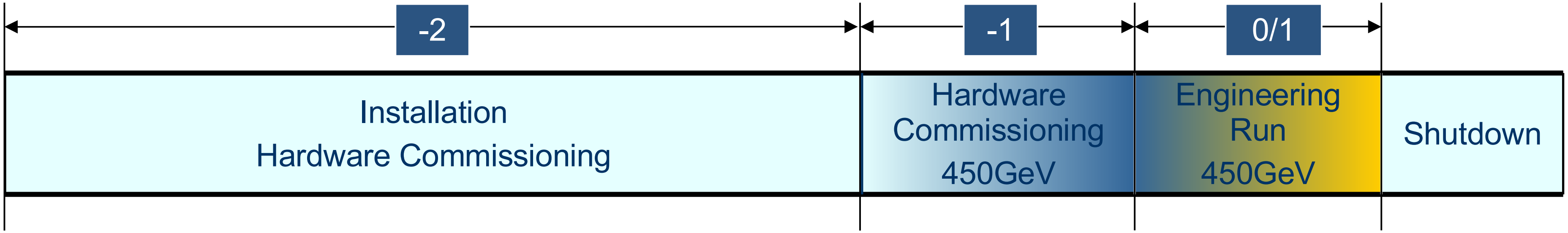
Commissioning of Feedbacks with Beam

- Things that have to and can only be checked with beam:
  - Beam instrumentation: polarities, planes, mapping
  - Corrector circuits: polarities, planes, mapping (longitudinal and beam1/beam2)
  - Transfer function and rough test of calibrations
    - TI8/TI2: hardware based calibrations compatible with those performed with beam
  - Circulating beam
  - Static coupling is under control

partially done while threading the first beam!

- It is possible to run feedbacks already after above procedures:
  - e.g. auto-triggered at 0.1 – 1 Hz
  - lower closed loop bandwidth (through parameter α)

Commissioning of Transverse Feedback Sketch



- Phase “-2” - NOW/ONGOING
  - Software interfaces and mapping
  - low-level tests of acquisition electronics
  - addressing of corrector circuits
  - feedback loop logic tests

most of the tedious work can/will be done without beam

- Phase “-1”:
  - while threading the beam: rough polarity/mapping of BPMs and corrector circuits, followed by more detailed test of (omitted) circuits
  - Priority: Orbit/Energy → Tune/Coupling → Chromaticity (relevant only if ramping)
  - Should take advantage to commission all feedbacks at 450 GeV
- Phase 0: reaching “nominal” performance ...
  - refined lattice checks
  - instrumentation and circuit calibration below the 20% level

Summary

- Feedback architecture, strategies and algorithms are well established
  - The 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.
  - Redo the optics measurements and calibration with higher accuracies for nominal performance.

- Feedbacks are most useful when used at an early stage
  - Possibility to use tracker/feedback signals as feed-forward for next cycles

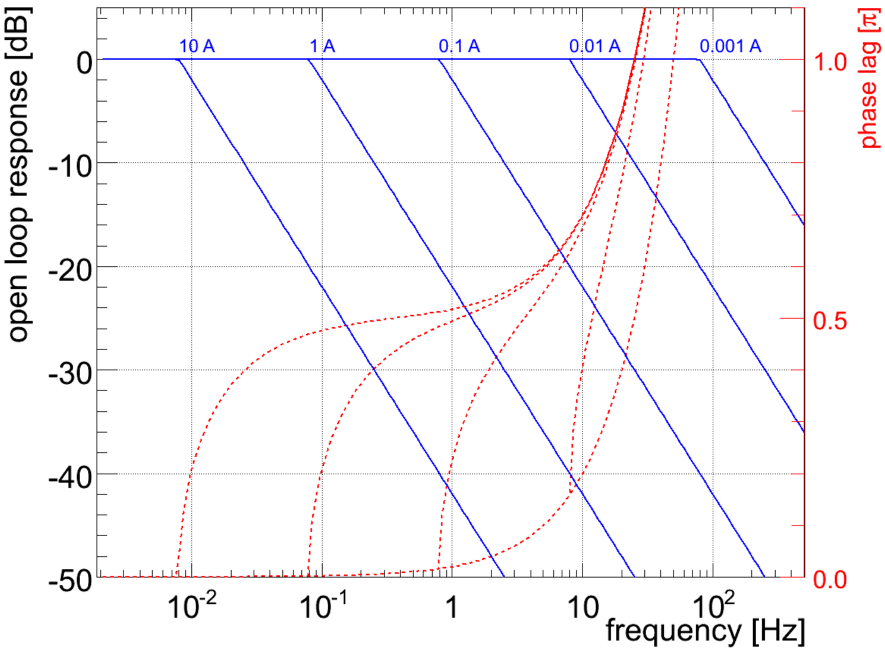
- Beware of cross-constraints/coupling of simultaneous nested loops
  - May break a loop near you
  - Feedbacks should be designed as an ensemble

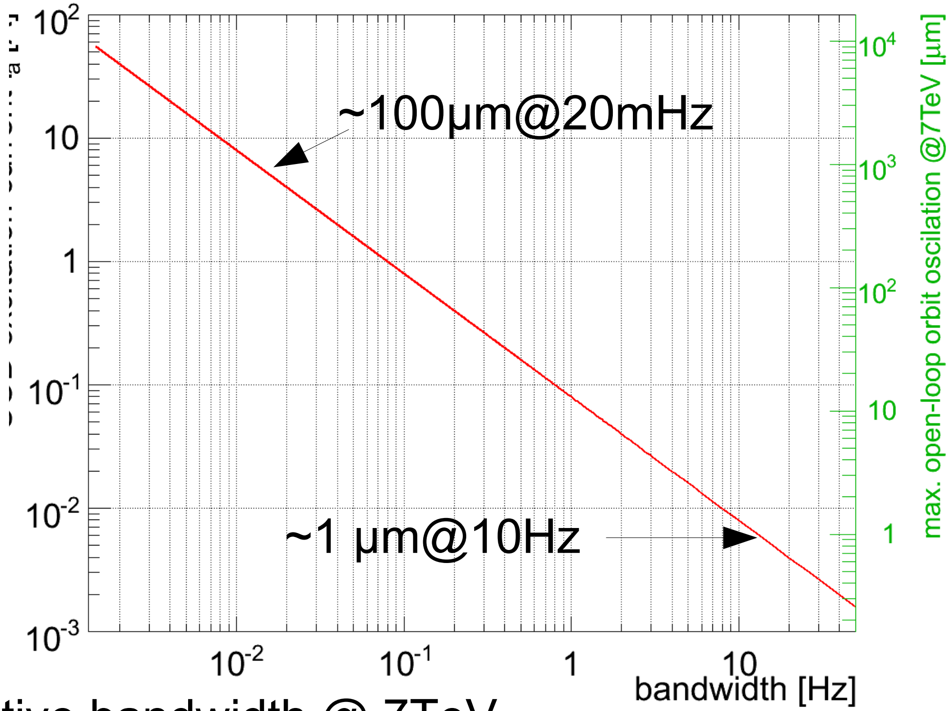
Reserve Slides

Time-Domain: Non-Linearities III/IV

- LHC: Two main dynamic contributions
  - Delays: computation, data transmission, etc.
  - Slew rate of the corrector circuits (voltage limitation):
    - ±60A PC: $\Delta I/\Delta t|_{max} < 0.5$ A/s, ±600A PC: $\Delta I/\Delta t|_{max} < 10$ A/s

$\Delta I=0.1A \leftrightarrow \Delta x \approx 16\ \mu m@\beta=180m$





- Working point: ~16μm@1Hz as effective bandwidth @ 7TeV

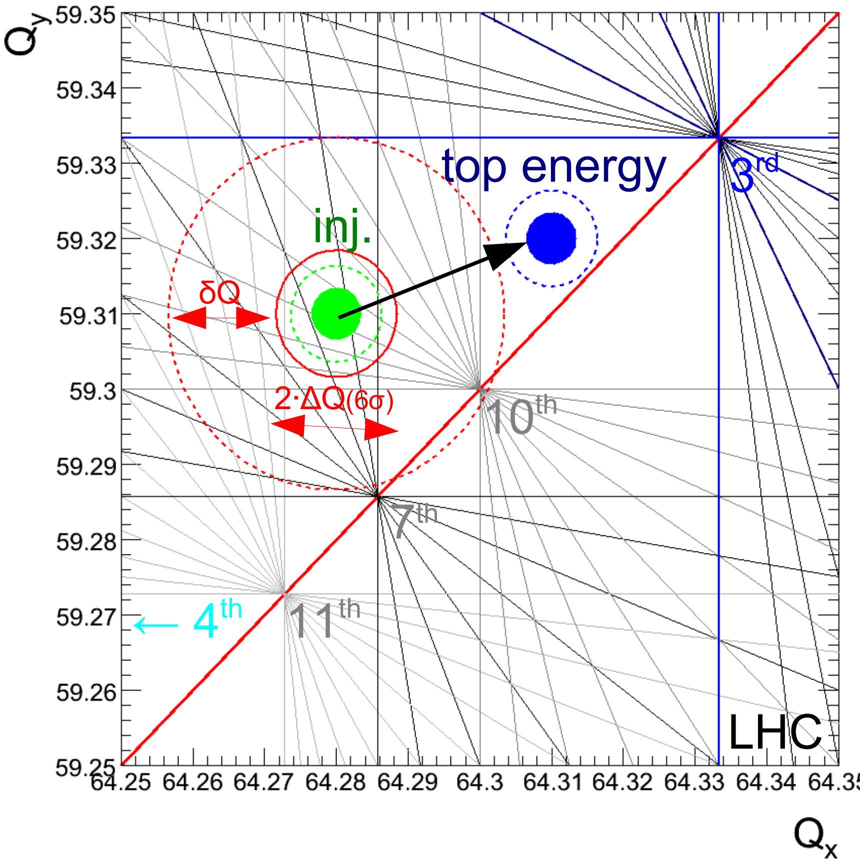
Commissioning of Feedbacks: nominal performance

- Already after rough calibration of feedback controller/instruments/circuits:
  - BPM orbit resolution: pilot $\Delta x_{turn} \approx 200\ \mu m$ → orbit: $\Delta x_{res} \approx 13\text{-}20\ \mu m$
    - Energy: $\Delta p/p_{res} \approx 10^{-5} \ldots 10^{-6}$
  - Tune resolution (pilot): $\Delta Q_{res} \approx 10^{-3} \ldots 10^{-4}$
  - Chromaticity: $\Delta Q'_{res} \approx 10 \rightarrow \Delta Q'_{res} \approx 1$

- Nominal feedback performance requires calibration of instrumentation/circuits well below the 20% level
  - one simple instrument → “easy” → required time: 14 s (best case), ~ one hours without automation
  - 1100++ simple instruments → “less easy”
  - requires fully automated procedures scripts (in development)
  - estimated time (if fully automated):
    - 4 hours without margin (pure excitation/measurement time)
    - 8-16 hours = 1-2 shifts including some operational margin

Requirements on Tune and Chromaticity

- Lepton machines: $\delta Q \sim 10^{-2} \ldots 10^{-3}$
  - 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: $\delta Q \leq 0.003 \ldots 0.001$
    - Space in Q-diagram: $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$
    - Allowed max lin. chromaticity[14,15] (5-6 σ): $\rightarrow Q'_{max} \approx 2 \pm 1$ & $Q' > 0$
    - N.B.: $\Delta p/p \approx 10^{-5} \rightarrow \Delta Q_{res} \approx 10^{-5}$

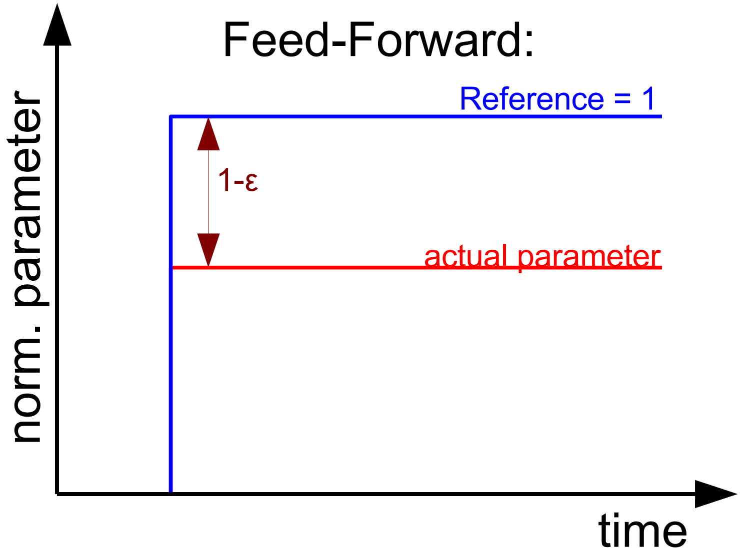


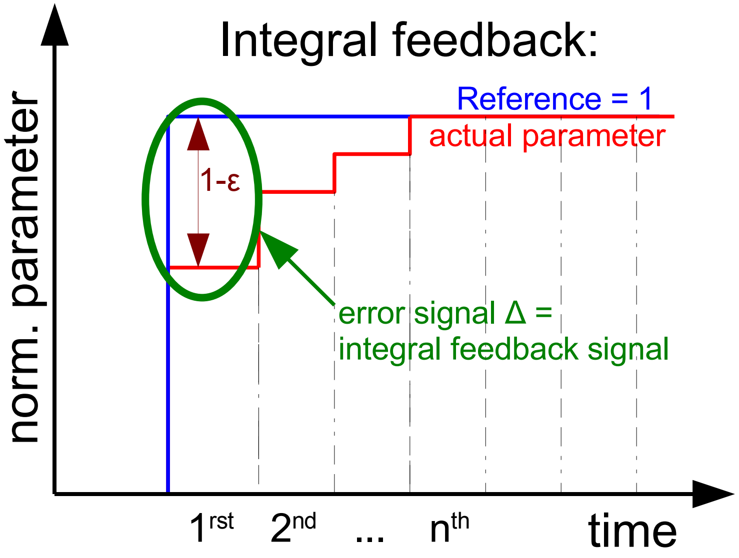
- Sources: supply drifts and ripples, hysteresis, ramp tracking errors, beam-beam, e-cloud, ...s.-con. accelerators: decay & snap-back, persistent currents
  - LHC: Chromaticity change ≈ 300 units, maximum rate ≈ 1.2 units/s

Lattice Imperfections

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

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

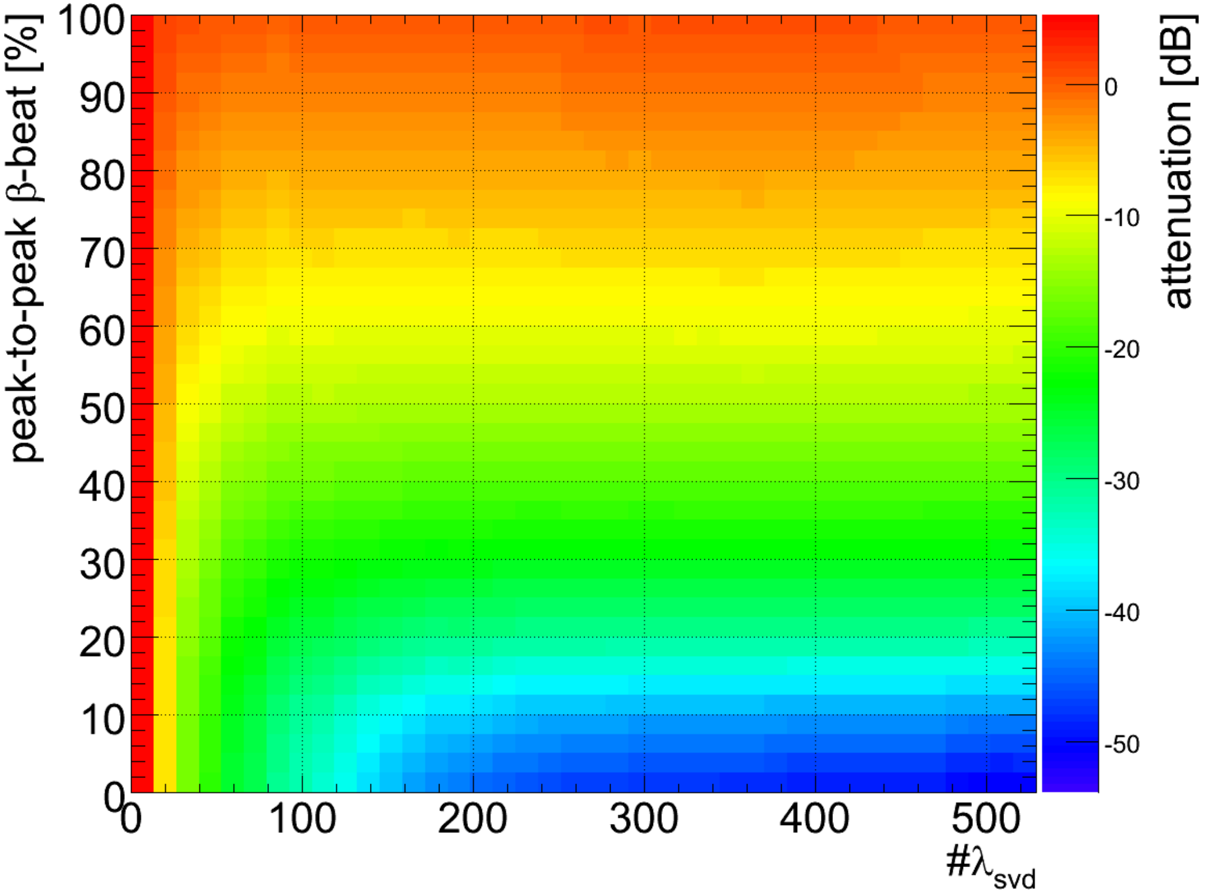




- Uncertainties and scale error of beam response function affects rather the convergence speed (= feedback bandwidth) than achievable stability
- Stability limit: BPM noise and external perturbations w.r.t. FB bandwidth

Example: Sensitivity to beta-beat

- Low sensitivity to optics uncertainties = high disturbance rejection:
  - LHC simulation: Inj. Optics B1&B2 corrected



$\#\lambda_{svd}$ controls correction precision

attenuation =

$$20\cdot\log\left|\frac{orbit\ r.m.s.\ after}{orbit\ r.m.s.\ before}\right|_{ref}$$

- Robust Control: OFB can cope with up to about 100% β-beat!
  - Robustness comes at a price of a (significantly) reduced bandwidth!

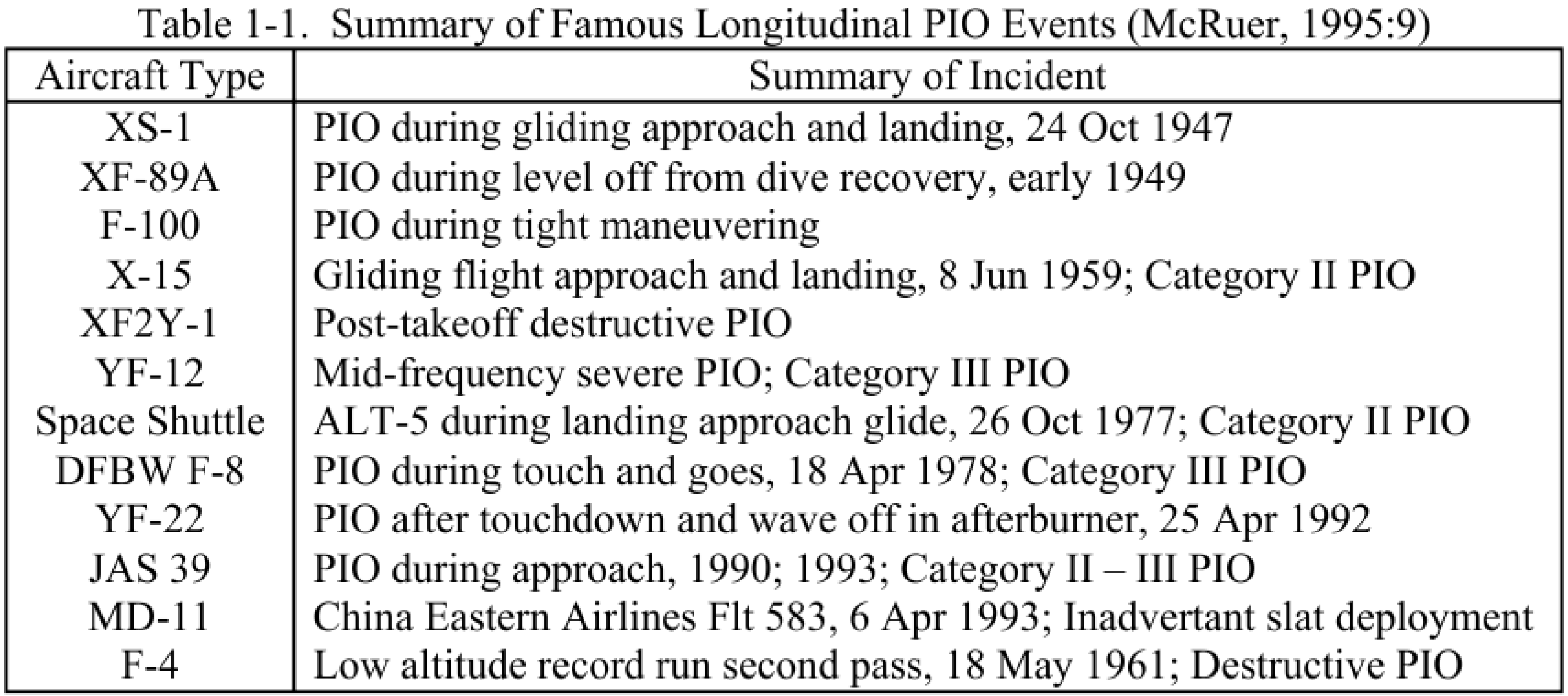
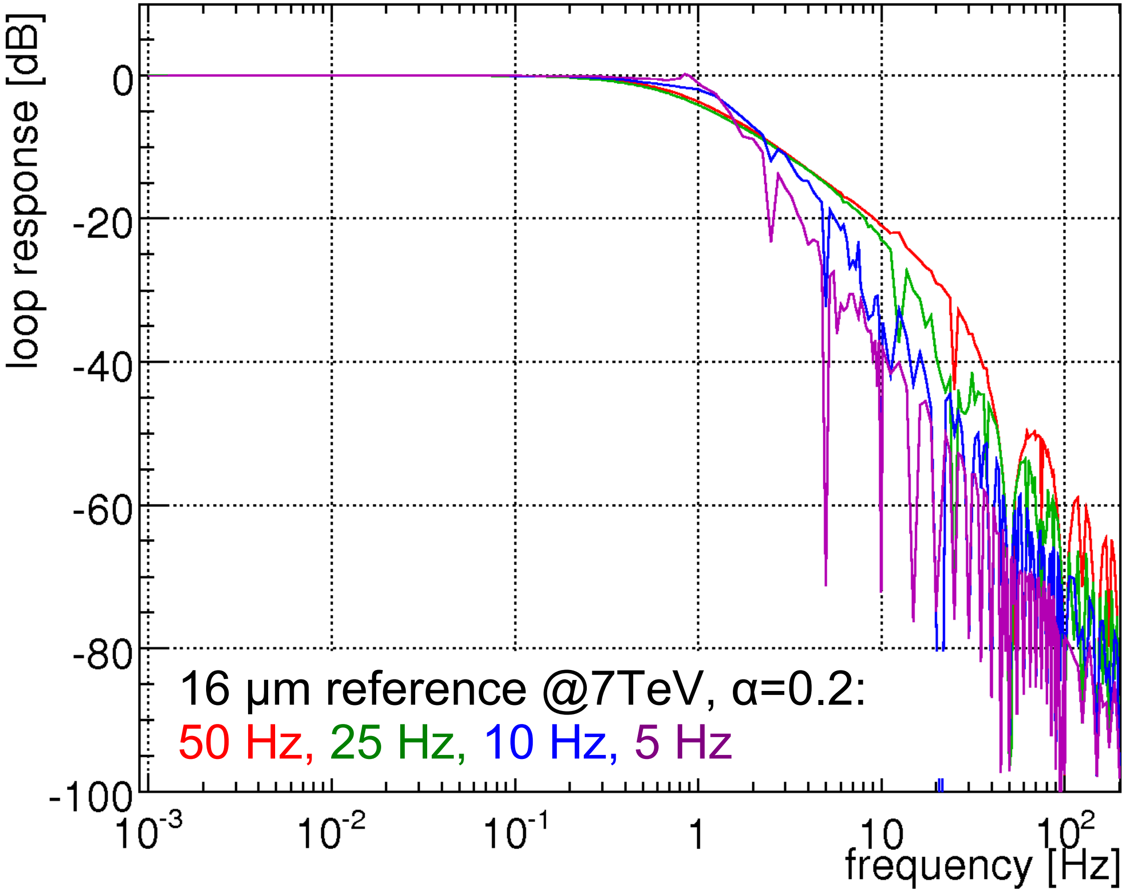


Table 1-1. Summary of Famous Longitudinal PIO Events (McRuer, 1995:9)

Aircraft Type	Summary of Incident
XS-1	PIO during gliding approach and landing, 24 Oct 1947
XF-89A	PIO during level off from dive recovery, early 1949
F-100	PIO during tight maneuvering
X-15	Gliding flight approach and landing, 8 Jun 1959; Category II PIO
XF2Y-1	Post-takeoff destructive PIO
YF-12	Mid-frequency severe PIO; Category III PIO
Space Shuttle	ALT-5 during landing approach glide, 26 Oct 1977; Category II PIO
DFBW F-8	PIO during touch and goes, 18 Apr 1978; Category III PIO
YF-22	PIO after touchdown and wave off in afterburner, 25 Apr 1992
JAS 39	PIO during approach, 1990; 1993; Category II – III PIO
MD-11	China Eastern Airlines Flt 583, 6 Apr 1993; Inadvertant slat deployment
F-4	Low altitude record run second pass, 18 May 1961; Destructive PIO

Loop Bandwidth versus Sampling frequency

- ... sample the position (Q, ...) at 10Hz to achieve a closed loop 1Hz bandwidth

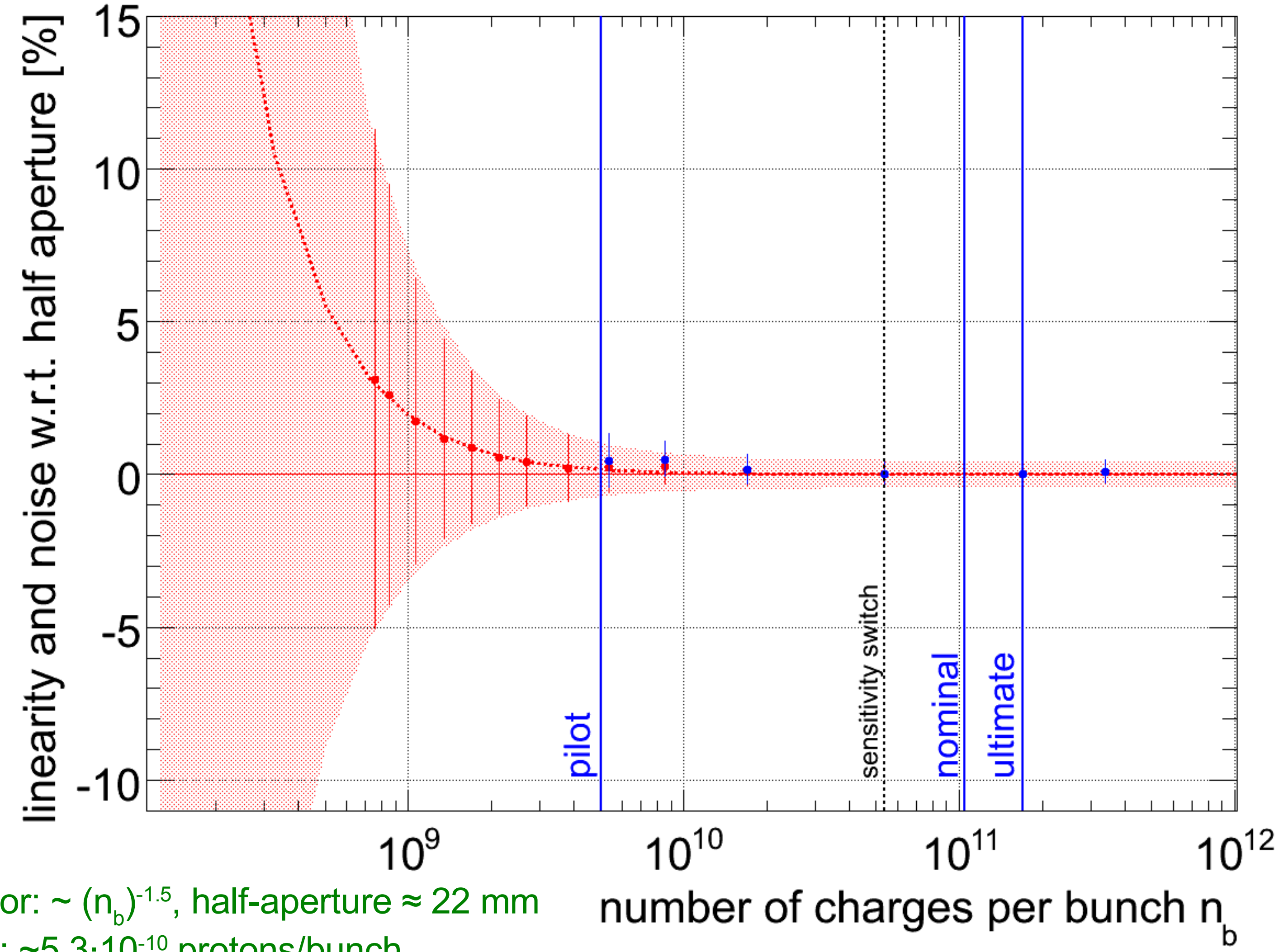


  - ... a theoretic limit assuming a perfect system!
  - common: sampling frequency > 25 ...40 desired closed-loop bandwidth

From threading the first pilot to 43x43 bunches

- 43x43 operation: max. intensity 4·10^{10} protons/bunch

→ No gain-switching: BPMs will always operate at 'high' sensitivity



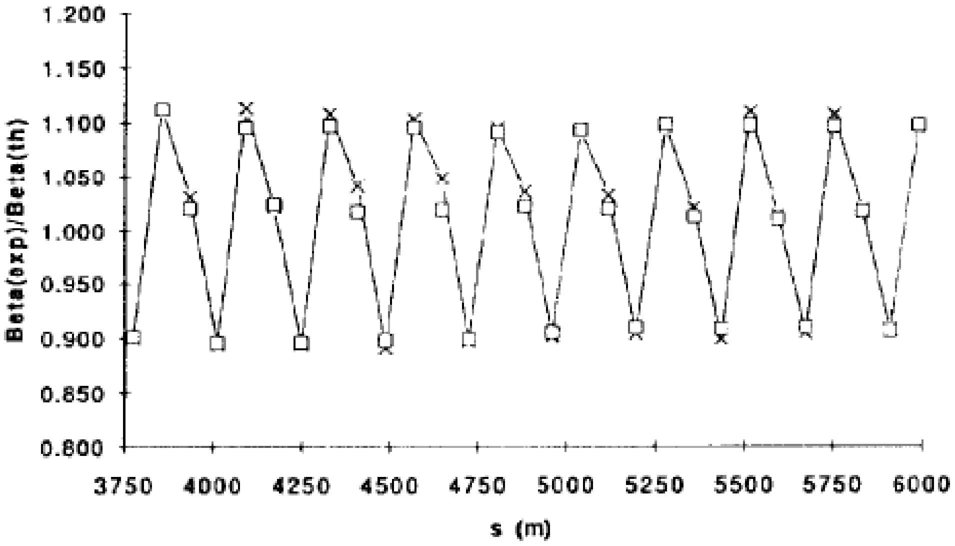
noise/error: ~ $(n_b)^{-1.5}$, half-aperture ≈ 22 mm
switch at: ~5.3·10^{-10} protons/bunch

Measurement of Response matrix

- Direct measurement of the orbit, tune, chromaticity, ... response matrix
  - perfect response matrix
  - no disentangling between beam measurement and lattice uncertainties
  - requires significant amount of time to excite/measure the response of each individual circuit: minimum of 15 s per COD circuit (1060!)
    - optics might change more often during commission

- Optics measurement through phase advance between three adjacent BPMs[1]
  - Design μ_{ij} versus measured (kick+1024 turns) ψ_{ii} phase advance:

$$\beta=\beta_0\cdot\frac{\cot(\psi_{12})-\cot(\psi_{13})}{\cot(\mu_{12})-\cot(\mu_{13})} \longrightarrow$$



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[1] P. Castro, “Betatron function measurements at LEP [..]”, CERN, SL/Note 92-63-BI

LHC Q' Tracking and Parameters

Baseline: RF/energy induced tune change $Q' = \Delta Q_{mod}/(\Delta p/p)$

- SPS standard operation: $\Delta p/p > 10^{-3}$ & $\Delta Q_{res} \approx 10^{-3} \rightarrow \Delta Q'_{res} \sim 1$
- LHC operation (requirement): $\Delta p/p < 10^{-4}$ & $\Delta Q'_{res} \sim 1 \rightarrow \Delta Q_{res} < 10^{-4}$
  - limited by LHC Collimation orbit 'budget': $\Delta x < 35\ \mu m$ (nominal)
  - Important milestone:
    - feasibility established during 2007 SPS MD tests (see examples):
      - modulation frequency: 0.5 Hz
      - $\Delta p/p < 2 \cdot 10^{-5}$ & $\Delta Q_{res} \sim 10^{-6}$!! (limited by RF ADC quantisation)
  - 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 remedies:
        - » either: increasing Q'_{ref} to e.g. 10 units
        - » or: increasing $\Delta p/p$ amplitude (if low-intensity beam)
        - » or: increasing f_{mod} (PLL limit: << 60 Hz)

Example: Prototype in the SPS (measurement) modulation amplitude: Δp/p ≈ 1.85·10^{-5}