LHC Beam-Based Feedbacks
on
Orbit, Energy, Tune, Chromaticity and Betatron Coupling

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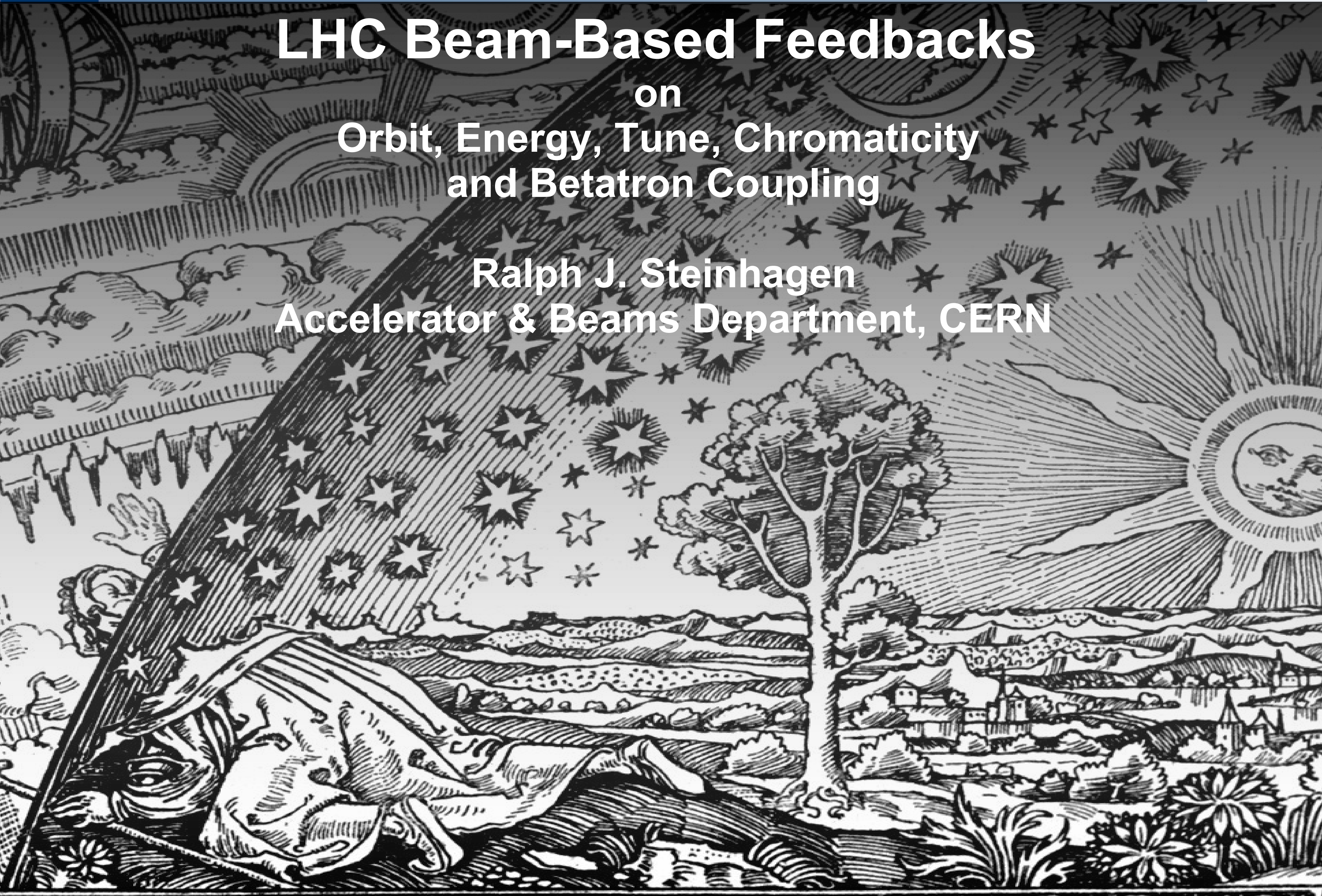


- Requirements vs. Expected Perturbation Sources
  - Collimation & Machine Protection, ...
- LHC Feedback Architecture
  - Controller Design
    - Space vs. Time Domain
    - Non-Linearities: effect of delays, rate-limiter and sampling
  - Some Examples
- Erroneous/Faulty BPM Detection
- LHC individual Loop Nesting and Coupling

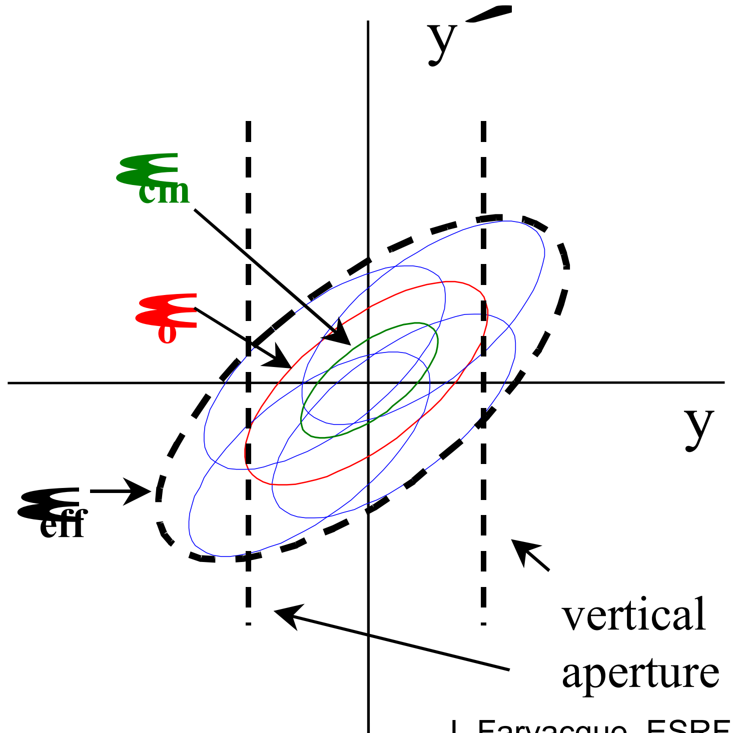
Feedback Overview Worldwide

- Accelerators can be grouped into three groups
  - Light Sources: (list not exhaustive[1-3])
    ALBA, ANKA, ALS, APS, BSRF, BESSY, CLS, DELTA, ELETTRA, ESRF, INDUS2, LNSLS, SLS, DIAMOND, SOLEIL, SPEAR3, Spring-8, Super-ACO...
    - mostly orbit and energy feedback (radial steering) only
  - Lepton Collider: LEP[4], PEP-II[5], KEK-B
    - orbit and tune feedback (mostly during ramp)
  - Hadron Collider: Hera, LHC, RHIC, Tevatron
    - mostly slow orbit feedback, except:
      - Hera: Orbit, Tune
      - RHIC: Tune[6]/Coupling, Chromaticity[7]
      - LHC: Orbit/Energy, Tune/Coupling, Chromaticity, ...

- Main requirements for orbit stability[8]:
  - Effective emittance preservation
    (τ_d sampling/integration time, τ_f fluctuation time)

$$\tau_d \gg \tau_f: \quad \epsilon_{eff} = \epsilon_0 + \epsilon_{cm}$$

$$\tau_d \ll \tau_f: \quad \epsilon_{eff} \approx \epsilon_0 + 2\sqrt{\epsilon_0 \epsilon_{cm}} + \epsilon_{cm}$$



L.Farvacque, ESRF

  - Minimisation of coupling
    (vertical orbit in sextupoles)
  - Minimisation of spurious dispersion
    (vertical orbit in quadrupoles)
  - Collider Luminosity and collision point stability (in case of two separated rings)

$$L = L_0 \cdot \exp\left\{\frac{(\Delta x)^2}{2\sigma_x^2} + \frac{(\Delta y)^2}{2\sigma_y^2}\right\} \cdot 1/\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_{x/y}}\right)^2} \cdot \quad \ldots$$

Δx/Δy [σ]	0	0.5	1	2	3	4
L/L_0 [%]	100	≈ 94	≈ 79	≈ 37	≈ 11	≈ 2

- Traditional requirements on beam stability...

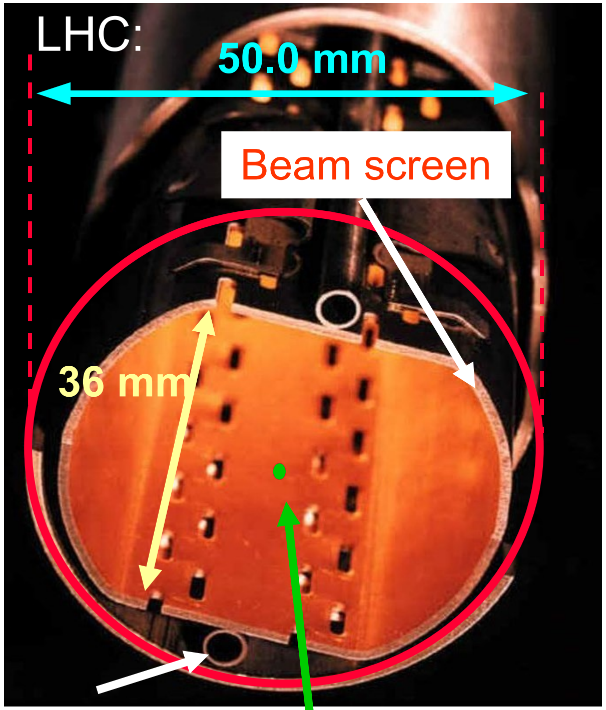
  ... to keep the beam in the pipe!

- Increased stored intensity and energy:

  → sufficient to quenches all magnets and/or to cause serious damage[9]

- Requirements depend on:

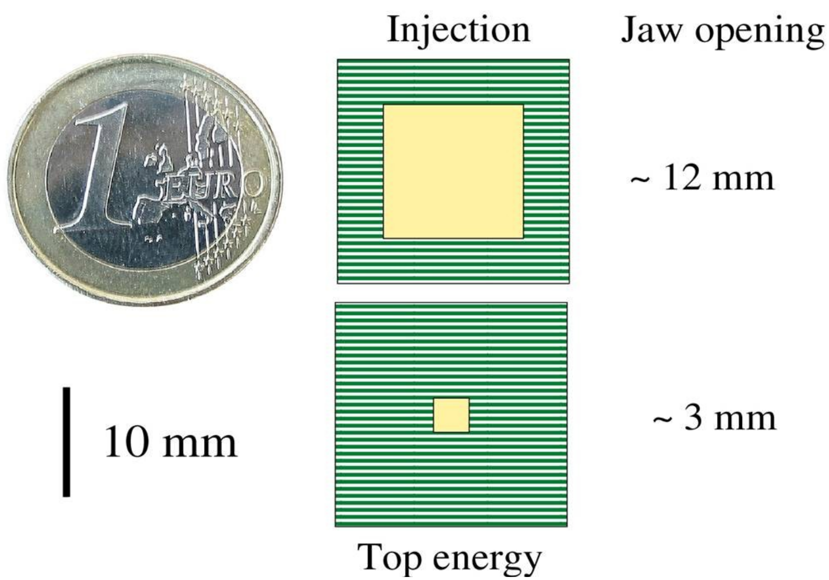
  1. Capability to control particle losses in the machine
     - Machine protection & Collimation
     - Quench prevention
  2. Commissioning and operational efficiency

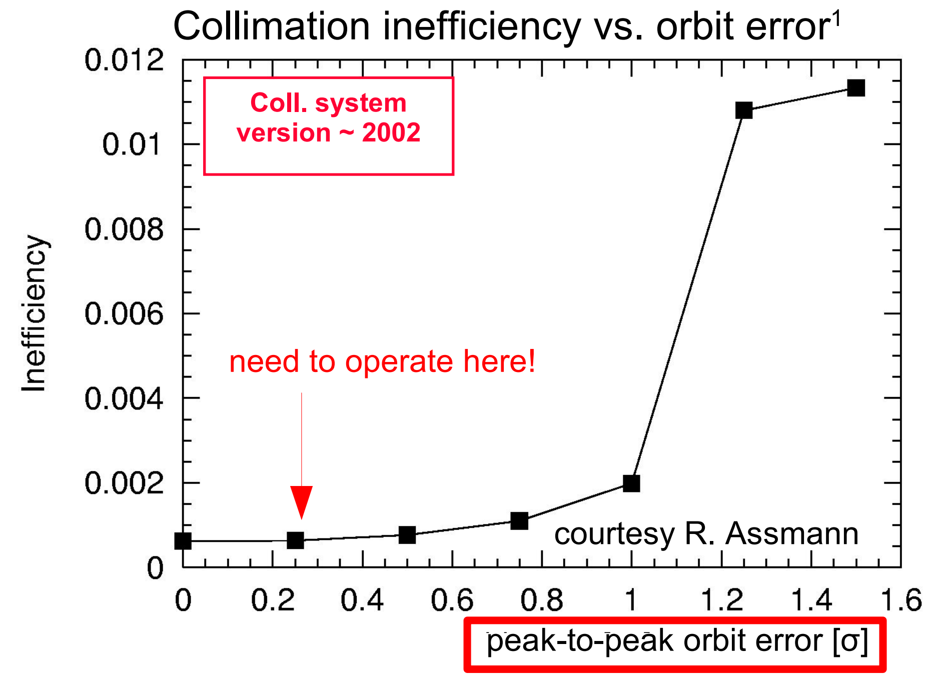


Cooling channel (He)

Beam 3 σ envel.
~ 1.8 mm @ 7 TeV

Hadron Collider Requirements
LHC Collimation System and Closed Orbit





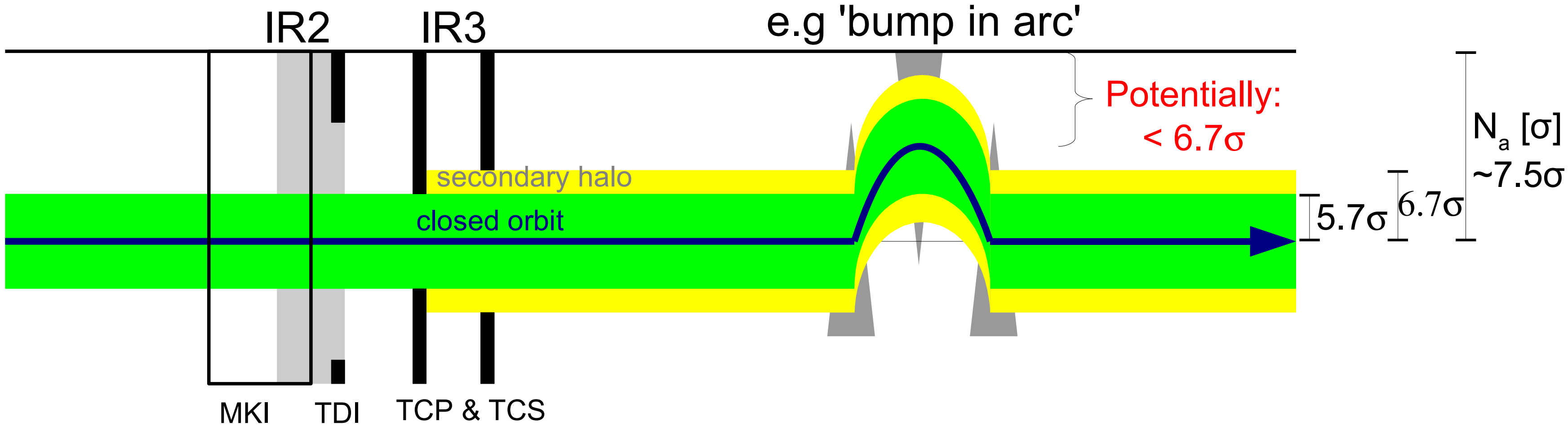
- LHC Collimation System, $N_{max} \approx 5 \cdot 10^{14}$ protons/beam (nominal)
  - required collimation inefficiency[1,2]:

$$\eta = \frac{number\ of\ \ particles\ escaping\ collimation}{number\ of\ \ particles\ impacting\ collimation} \qquad \rightarrow \text{LHC: } \eta < 0.001$$

- Orbit stability requirement better than σ/6 < ~ 25 µm at collimator jaws
  - This is the toughest requirement...

[1] R. Assmann, "Collimation and Cleaning: Could this limit the LHC Performance?", Chamonix XII, 2003
[2] S. Redaelli, "LHC aperture and commissioning of the Collimation System", Chamonix XIV, 2005

- Combined failure[1]: Local orbit bump and collimation efficiency (/kicker failure):



- To guarantee (two stage) cleaning efficiency/machine protection:
  – TCP (TCS) defines the global primary (secondary) aperture

- The orbit is not a "play-parameter" for operation, except at low intensity.
  (*'Playing' with the orbit will result in quasi-immediate quench at high intensity.)*

  → Bumps may potentially compromise collimation function
  – machine protection may require regularly aperture check aperture

[1] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

Nominal Requirements on Orbit

▪ LHC cleaning System:	< 0.15 σ	IR3,IR7
▪ Machine protection & Absorbers:		
– TCDQ (prot. asynchronous beam dumps)	< 0.5 σ	IR6
– Injection collimators & absorbers (TDI)	~ 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, 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!

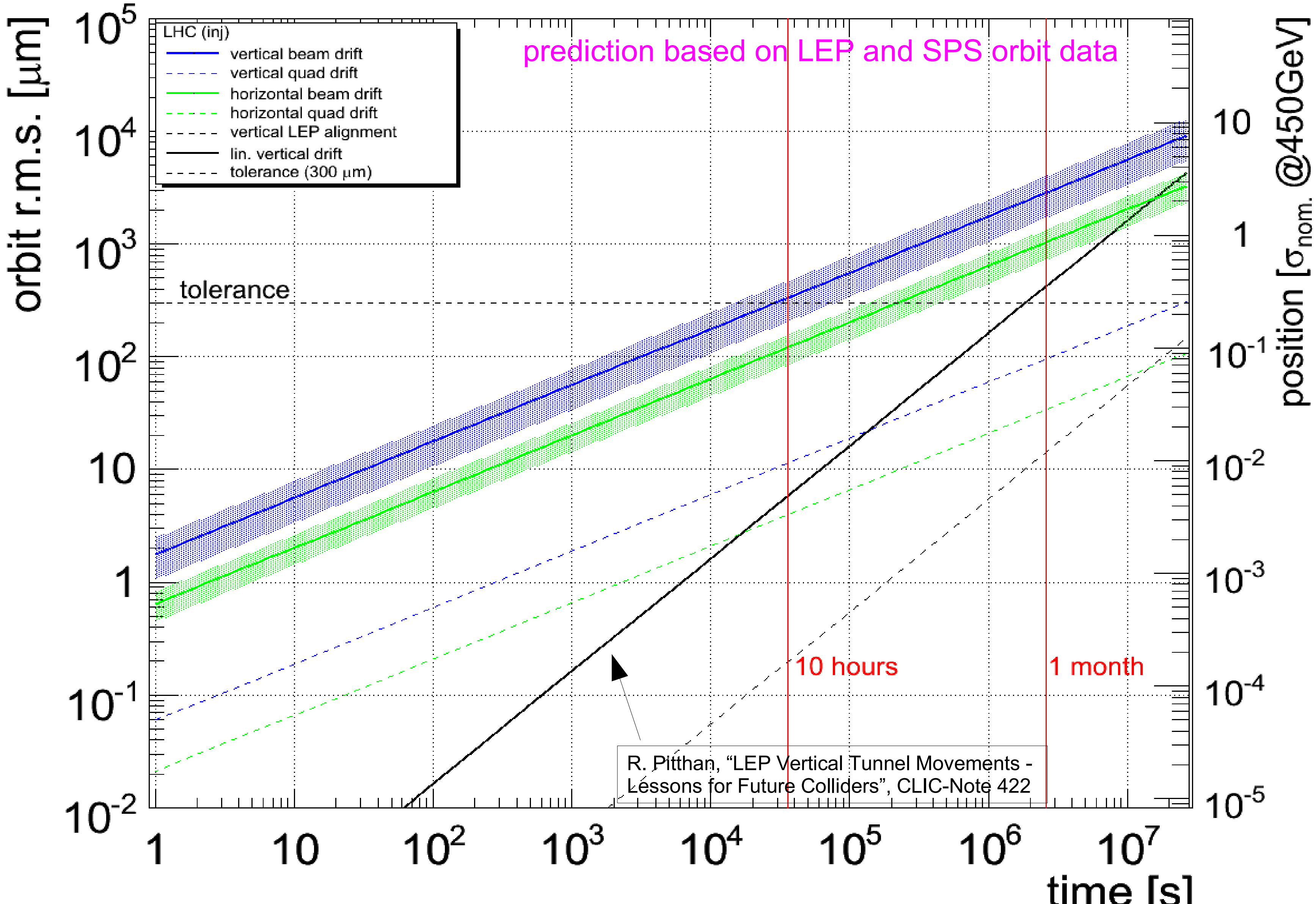
Perturbation of Orbit, E, Q, Q', C⁻, ...

- ...can be grouped into:
  - Environmental sources:
    (mostly propagated through quadrupoles/girders)
    - temperature and pressure changes,
    - ground motion, tides,
    - cultural noise
  - Machine inherent sources:
    - decay and snap-back of multipoles,
    - cooling liquid flow, pumps/ventilation vibrations
    - eddy currents
    - changes of machine optics (final focus)
  - Machine element failures:
    - corrector circuits (LHC: 1300++ circuits)

Timescale:

months ↓ weeks ↓ days ↓ hours ↓ minutes ↓ sec ↓ msec

... will present some of the more interesting/less publicly known sources



→ closed Orbit drifts after 10 hours ≈ 0.3 -0.5 σ

Orbit Transient due to Squeeze

- Mechanism: Off-centre beam in quadrupoles with varying focusing strength (e.g. due to crossing angle, quadrupole misalignments, ...)

$$\delta_{kick} = (k + \Delta k_{squeeze})\, l_{mag} \cdot \Delta x_{quad.-misalign.}$$

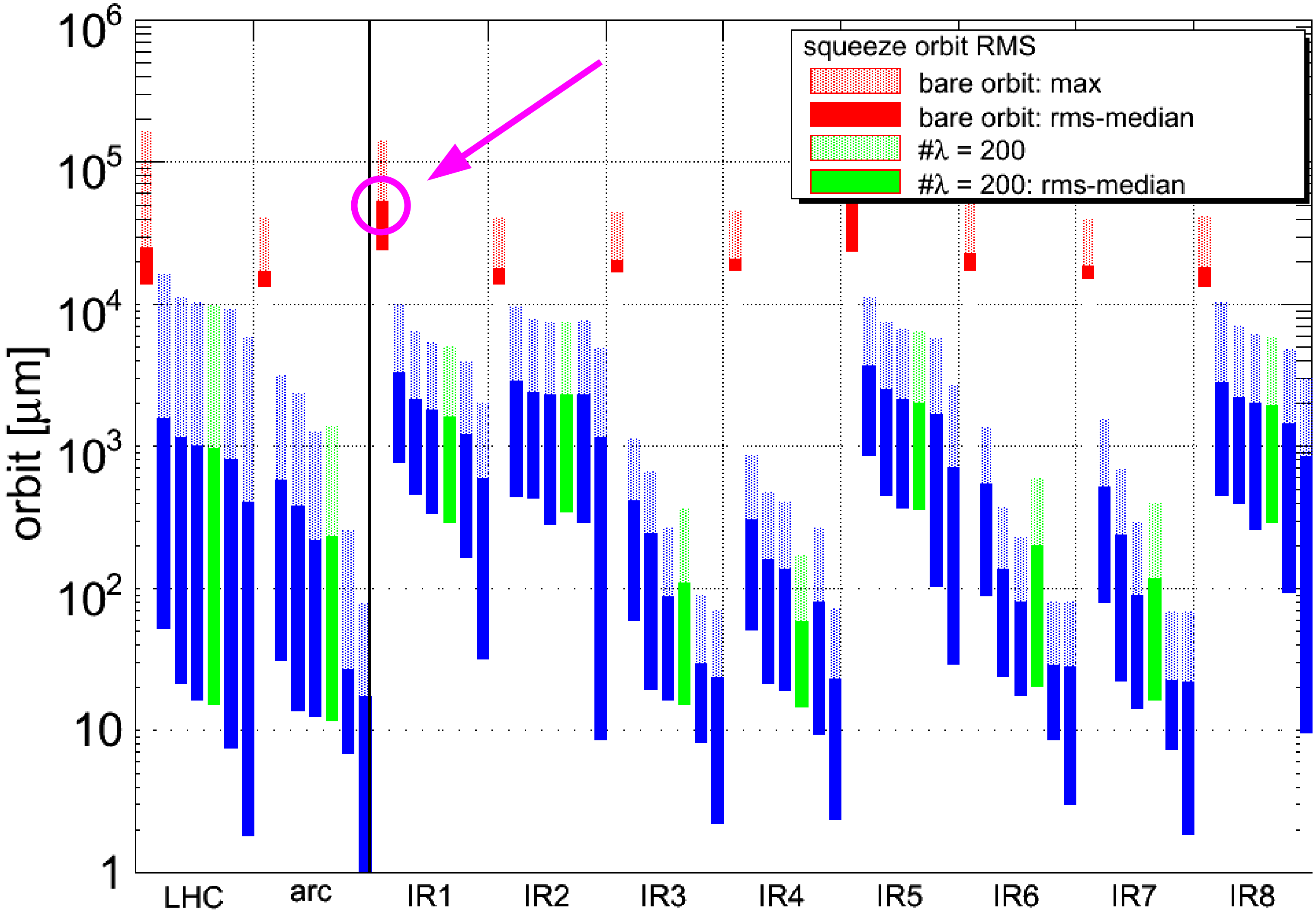
  – Misalignment causes systematic a priori static kick/orbit perturbation
  – Change of quadrupole strength makes this a dynamic effect

- Assume Δx=0.5 mm r.m.s. random quadrupole and BPM misalignment
  – Survey group targets: 0.2 mm r.m.s. Globally, 0.1 mm r.m.s. over 10 neighbouring magnets.
  – N.B. without k-modulation: BPM offsets w.r.t. quadrupole are unknown

- Transient is an issue w.r.t. beam stability and COD current rate limit (0.3 A/s)

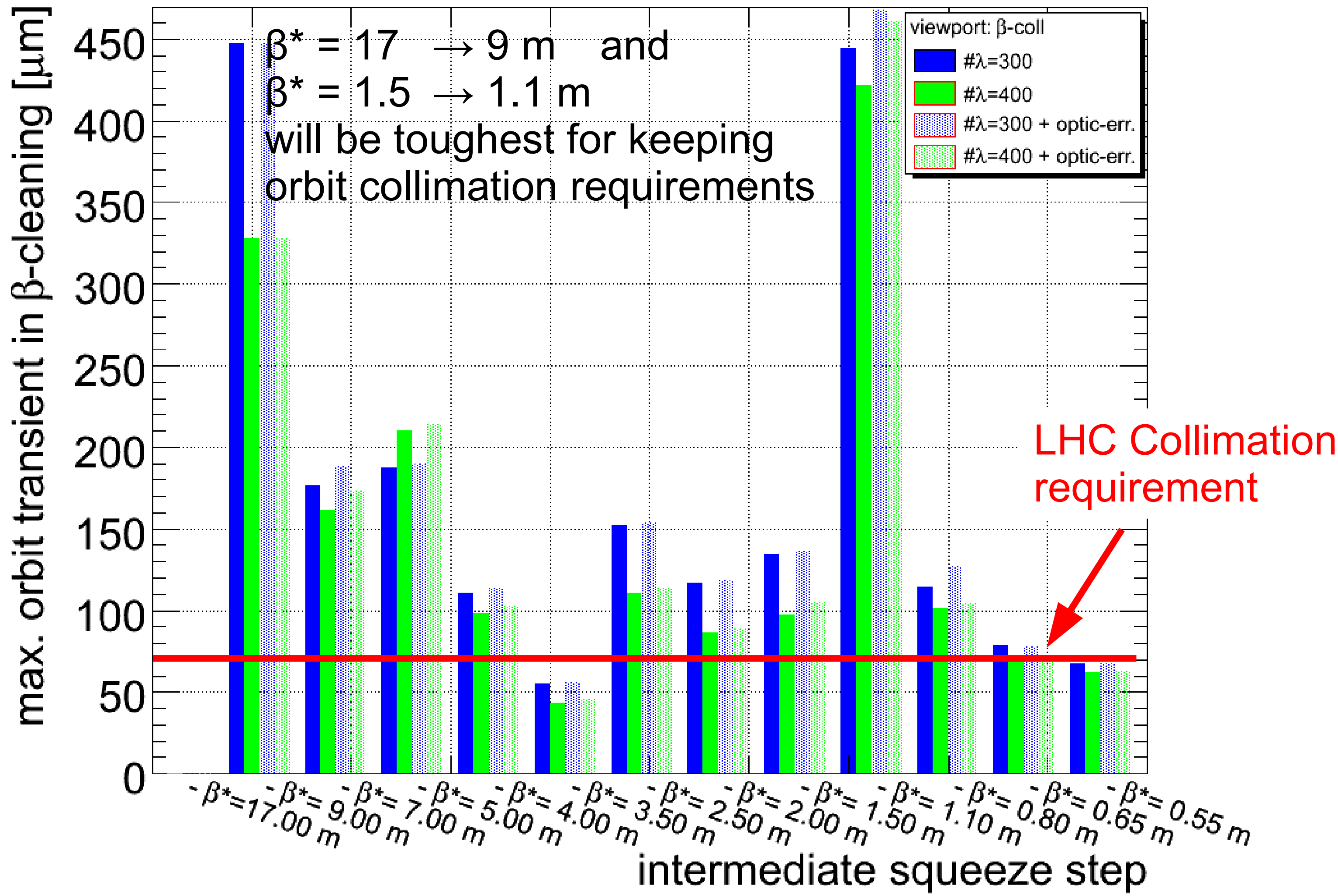
→ We should spend some time and tune the orbit inside IR1 and IR2 before squeezing the first time.

Transient due to low beta Squeeze: Overview LHC



- Studied cases (sample: 10^5) showed a median orbit perturbation exceeding 30 mm inside the IRs if not compensated!

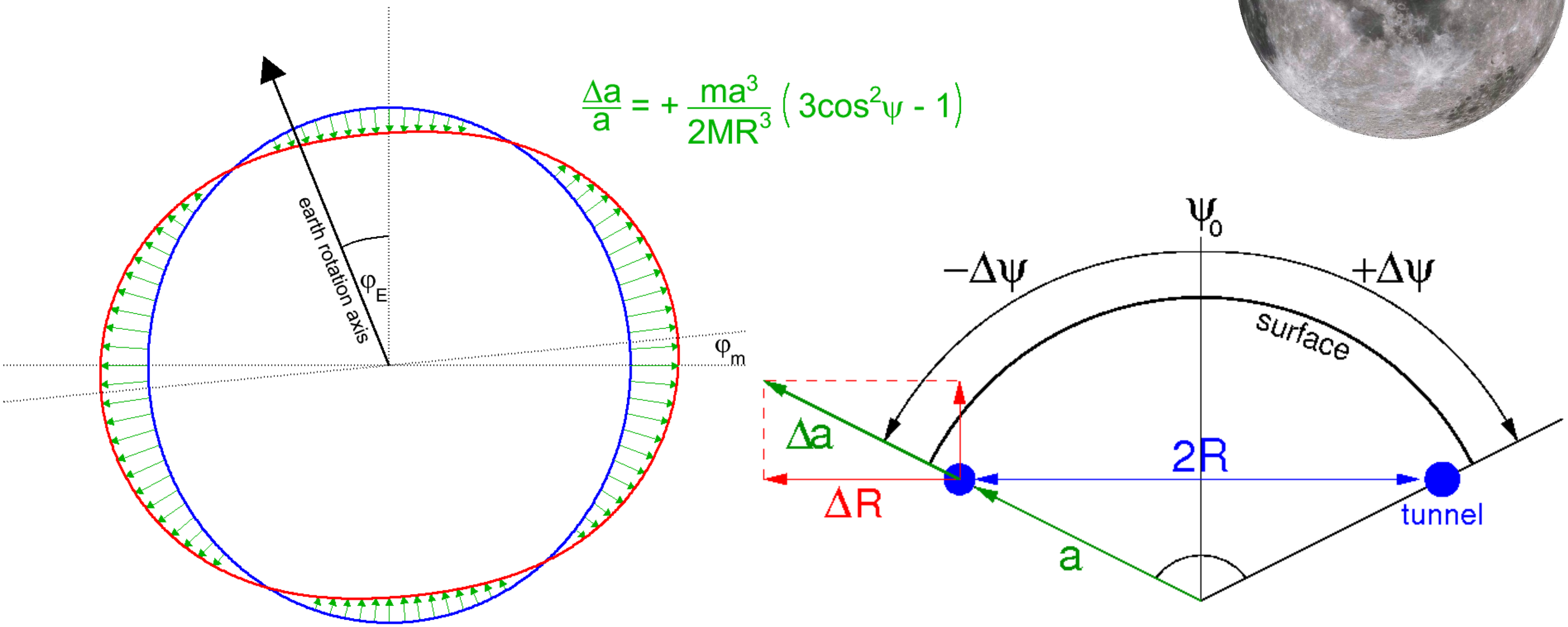
Transient in Collimation Insertion vs. Squeeze Step



- Makes a fast orbit feedback practically mandatory during squeeze and nominal beam operation.

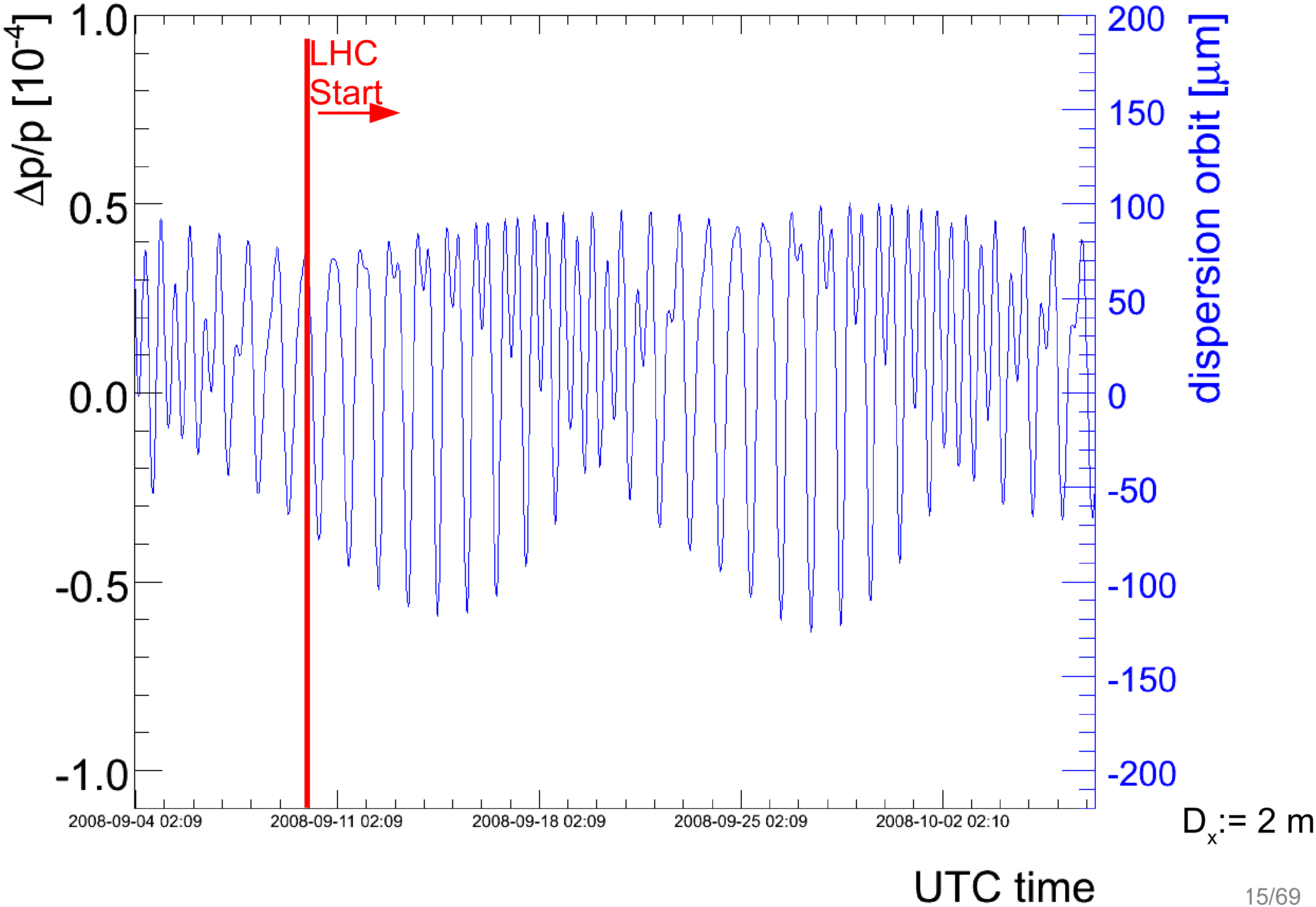
Lunar and Solar Tides

- Moon/sun tides change circumference of the machine:



  - Changes LHC circumference by $\Delta C \approx \pm 0.5$ mm
    - $\Delta p/p \approx 5.8 \cdot 10^{-5}$ $\rightarrow 2\Delta x = 2 \cdot D_{max} \cdot \Delta p/p \cdot = 326\ \mu m \approx 0.29\ \sigma$
  - Effect well tested at LEP: → J. Wenninger, CERN-SL-99-025-OP

Solar/Lunar Tides Prediction for September 2008



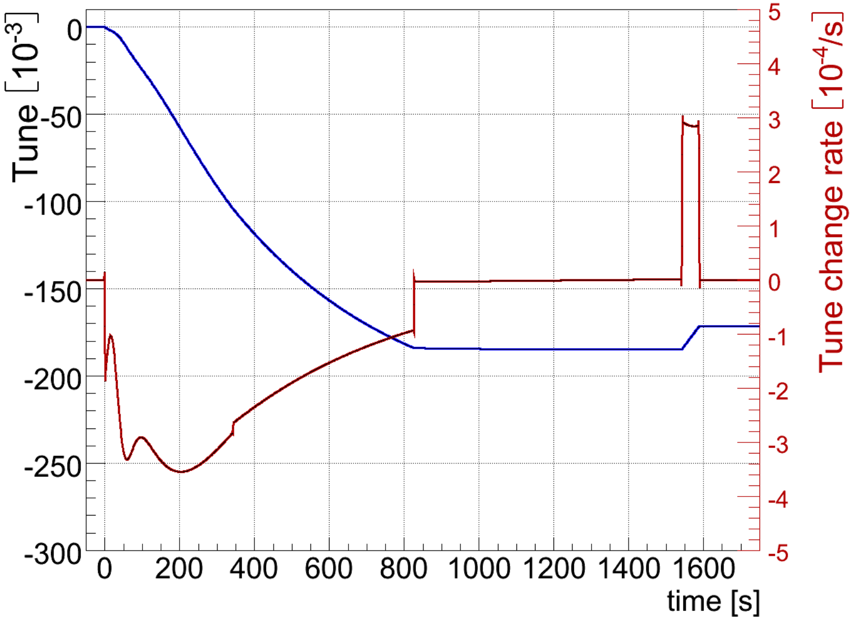
Summary of Dynamic Orbit Perturbations

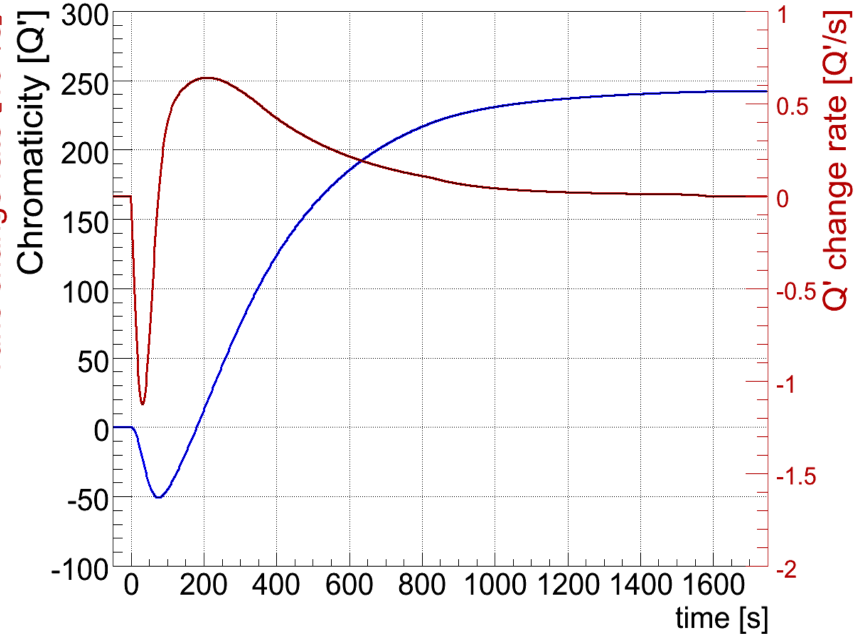
Perturbation Source	Orbit r.m.s.	$\lvert\Delta x/\Delta t\rvert_{max}$	$\Delta p/p$	Phase
	$[\mu m]$	$[\mu m/s]$	$[10^{-4}]$	
Random Ground Motion	$(200 - 300)$	< 0.01	$8 \cdot 10^{-3}$	all
Tides (max/min)	$+100/-170$	< 0.01	$+0.5/-0.9$	all
Thermal Girder Expansion	$(9.5\ldots16)/^{O}C$	$< 10^{-3}/^{O}C$	-	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. & $\lvert\Delta x/\Delta t\rvert_{max} \leq 15$ µm/s
  - β* Squeeze: $\sigma(x) \approx$ 30 mm r.m.s. & $\lvert\Delta x/\Delta t\rvert_{max} \leq 25$ 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

- Feedback priority list: Chromaticity → Coupling/Tune → Orbit → Energy

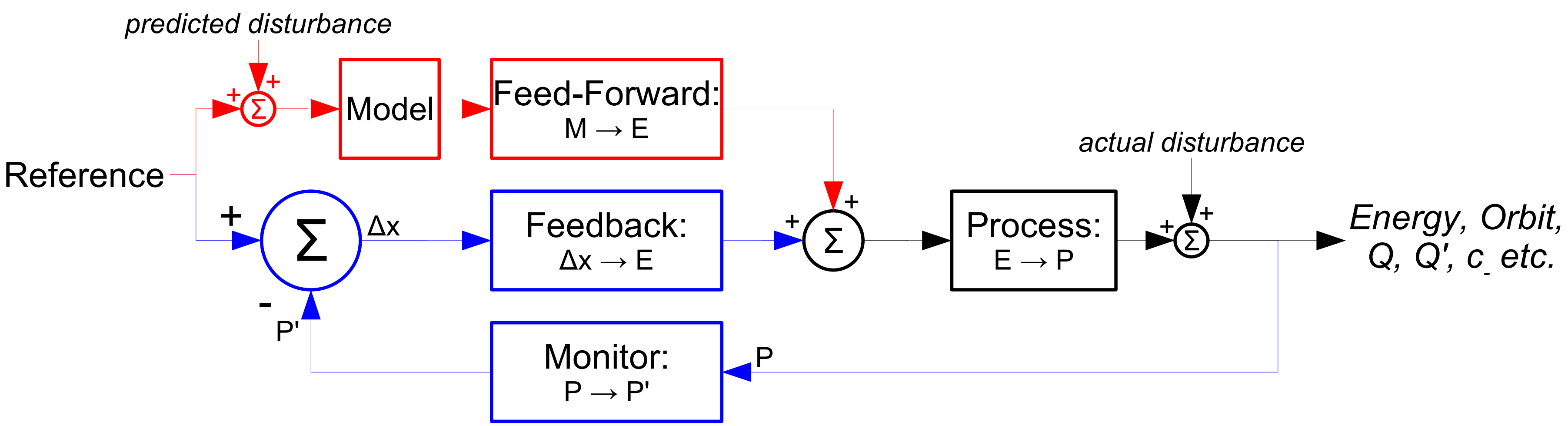
- Feedback list of “what's easiest to commission”:
  - 1rd: Orbit → functional BPM system → OK
  - 1½: Energy → consequence of 100k turn acquisition → OK
  - 2nd: Coupling/Tune → functional Q-meter (-PLL) → Day I - N
  - 3rd: Chromaticity → functional Q-meter and Δf/f modulation → Day II - N+1

- Feedback commissioning with beam already started

* numbers in brackets are 'worst case'

Parameter control, either through...

- Feed-Forward: (FF)
  - Steer parameter using precise process model and disturbance prediction
- Feedback: (FB)
  - Steering using rough process model and measurement of parameter
  - Two types: within-cycle (repetition Δt<<10 hours) or cycle-to-cycle (Δt>10 hours)



- Both do not mix well if the FB is not the slave of the FF, paradigm change:
  - Feed-Forward: trims the actual parameter (e.g. PC currents)
  - Feedback: trim the parameter reference

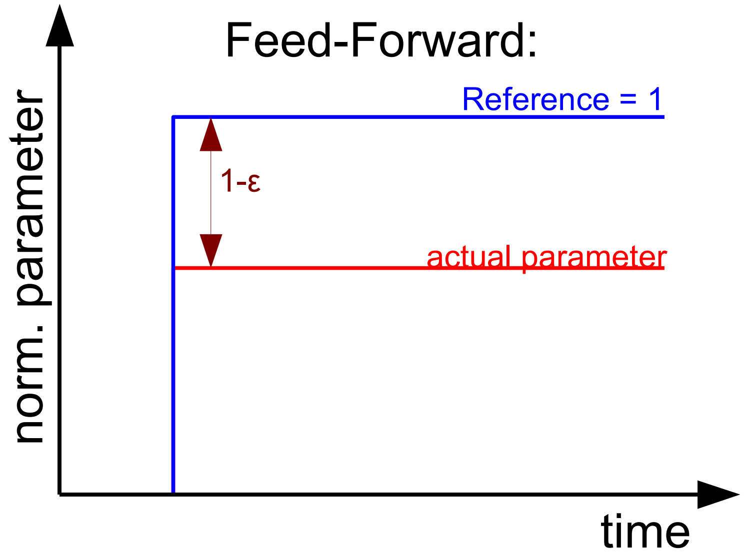
Control Paradigms II/III

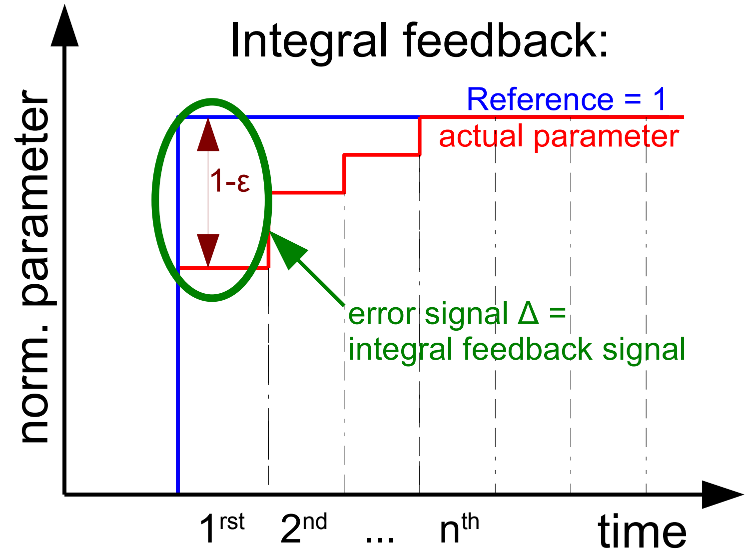
- Either:
  - Initial setup: “Find a good parameter reference” (mostly feedback “off”)
    - establish circulating beam
    - compensate for each fill recurring large perturbations:
      - static quadrupole misalignments, dipole field imperfections
      - ...
    - tune for optimal orbit/tune working point
      - keep aperture limitation, beam life-time
      - rough jaw-orbit alignment in cleaning insertions
      - ...

    → reference orbit (aka “golden orbit”)
  - During fill: “Stabilise around the reference working point” (feedback “on”):
    - correct for small and random perturbations Δx
      - environmental effects (ground-motion, girder expansion, ...)
      - compensate for residual decay & snapback, ramp, squeeze
  - (above step may alternate repetitively)
- Alternatively: directly change reference functions or 'golden orbit' (feedback “on”)
  - LSA Parameter (trim editor): '<X>/QH_REF', '<X>/QV_REF', '<X>/CMINUS_RE', '<X>/CMINUS_IM', '<X>/QPH_REF', '<X>/QPV_REF' (<X>: LHCBEAM1 or LHCBEAM2)

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

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



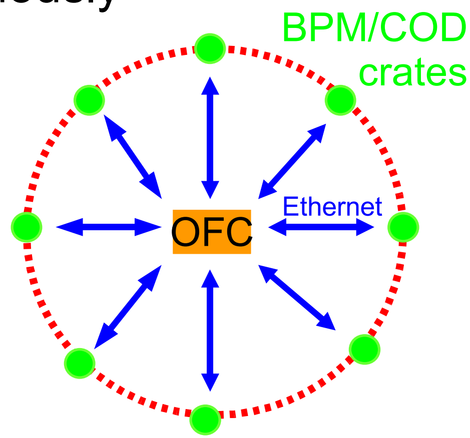


- Uncertainties and scale error of beam response function affects convergence speed (= feedback bandwidth) rather than achievable stability

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)
- 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

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



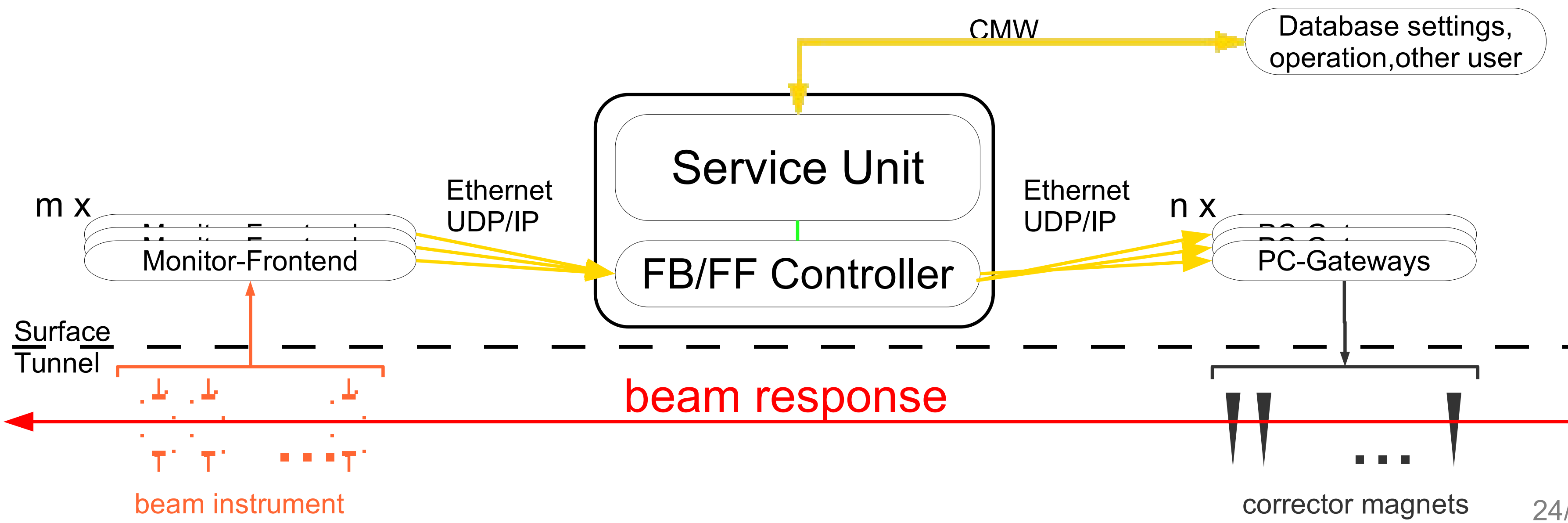
  – 1070 beam position monitors
    - BPM spacing: $\Delta\mu_{BPM}\approx 45°$ (oversampling → robustness!)
    - Measure in both planes: > 2140 readings!
  – One Central Orbit Feedback Controller (OFC)
    - Gathers all BPM measurements, computes and sends currents through Ethernet to the PC-Gateways 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

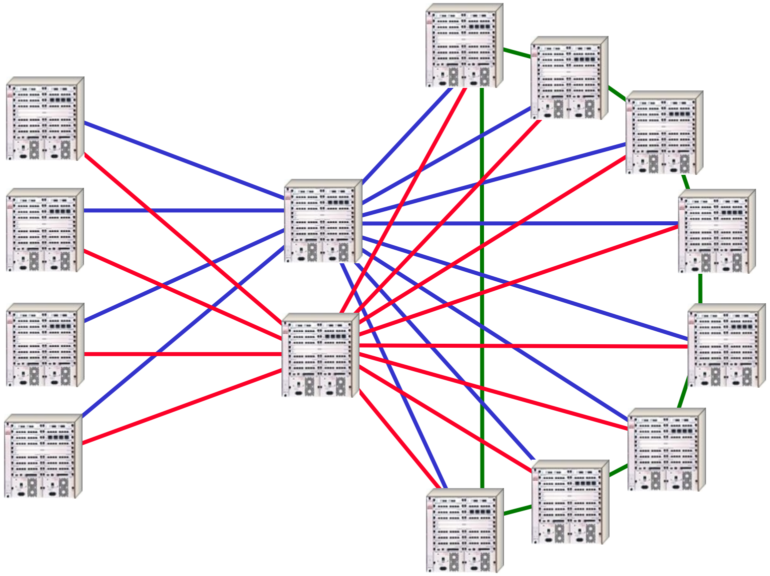
Common Feedback/Feed-forward Control Layout

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
  - Runs real-time operating system
  - Average load:
  - Can run auto-triggered
- Service Unit: Interface to users/software control system

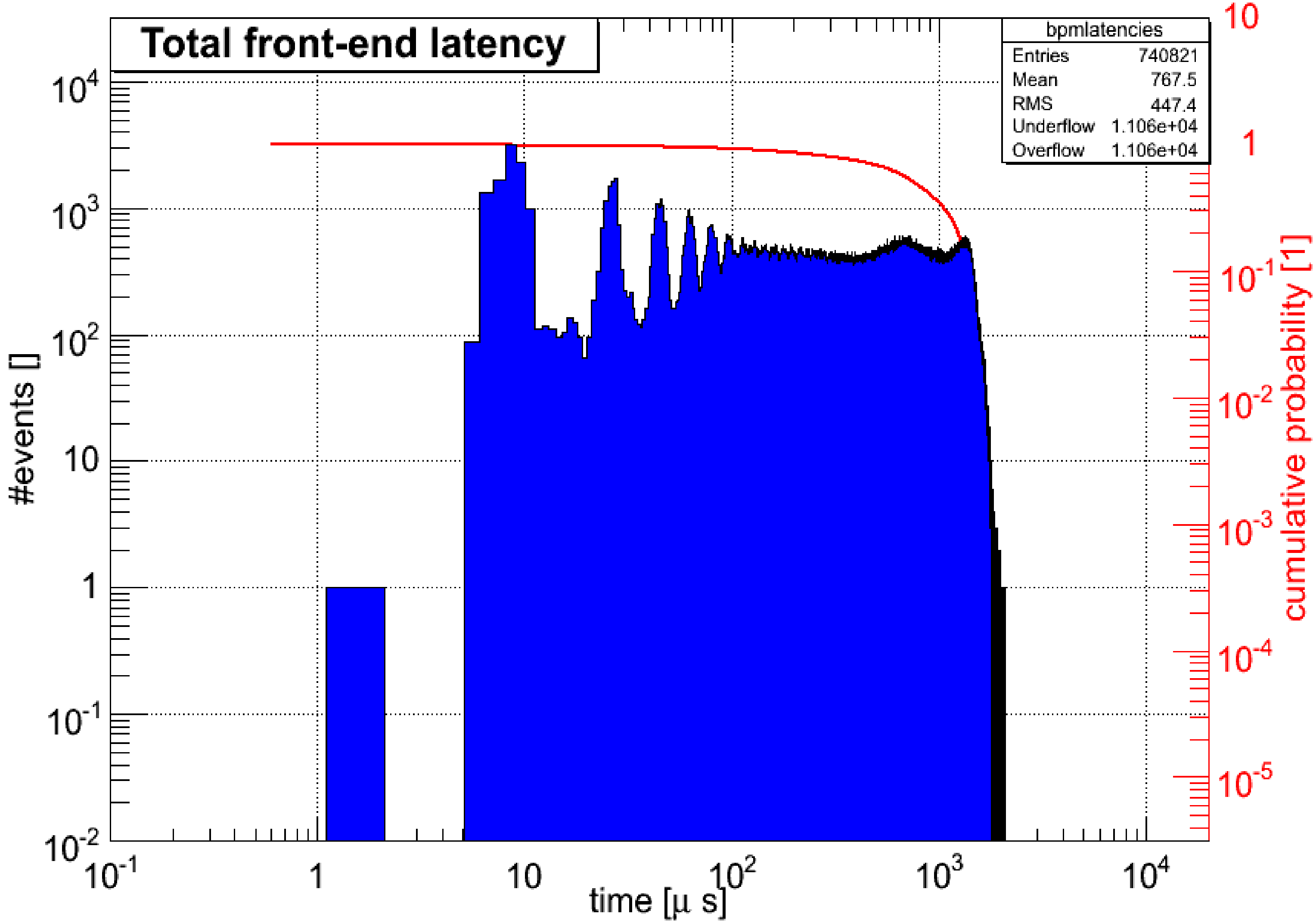


Technical Network and Data Communication I/II



- 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, $3\cdot10^7$ 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 (25 Hz)!

- Total arrival latency for full feedback system (≈ 120 front-ends)
  - tail of distribution is given by front-end computer and its operating system



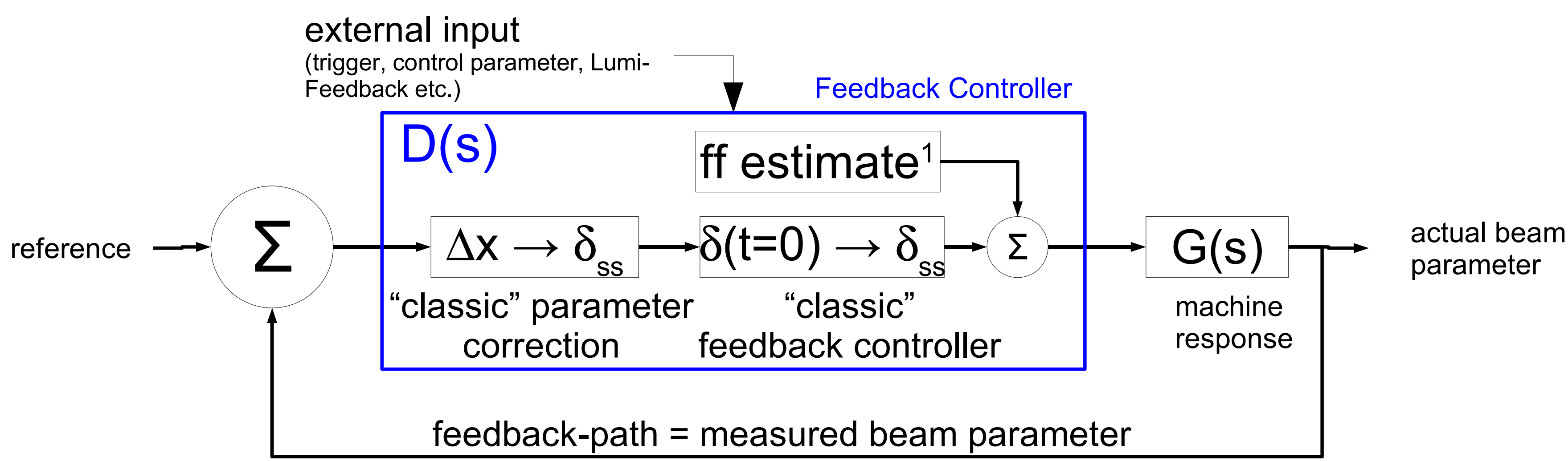
Multiple-Input-Multiple-Output (MIMO) Process Control

- 'Divide and Conquer' feedback controller design approach:
  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 and properly described sources

     time domain



- (N.B. here G(s) contains the process and monitor response function)

- Effects on orbit, Energy, Tune, Q' and C⁻ can essentially cast into matrices:

$$\boxed{\Delta\vec{x}(t)=\underline{R}\cdot\vec{\delta}(t)}\quad with\quad R_{ij}=\frac{\sqrt{\beta_i\beta_j}}{2\sin(\pi Q)}\cdot\cos(\Delta\mu_{ij}-\pi Q)+\frac{D_i D_j}{C(\alpha_c-1/\gamma^2)}$$

matrix multiplication

  - LHC matrices' dimensions:

$$\underline{R}_{orbit}\in\mathbb{R}^{1070\times 530}\qquad \underline{R}_{Q}\in\mathbb{R}^{2\times 16}\qquad \underline{R}_{Q'}\in\mathbb{R}^{2\times 32}\qquad \underline{R}_{C^-}\in\mathbb{R}^{2\times 10/12}$$

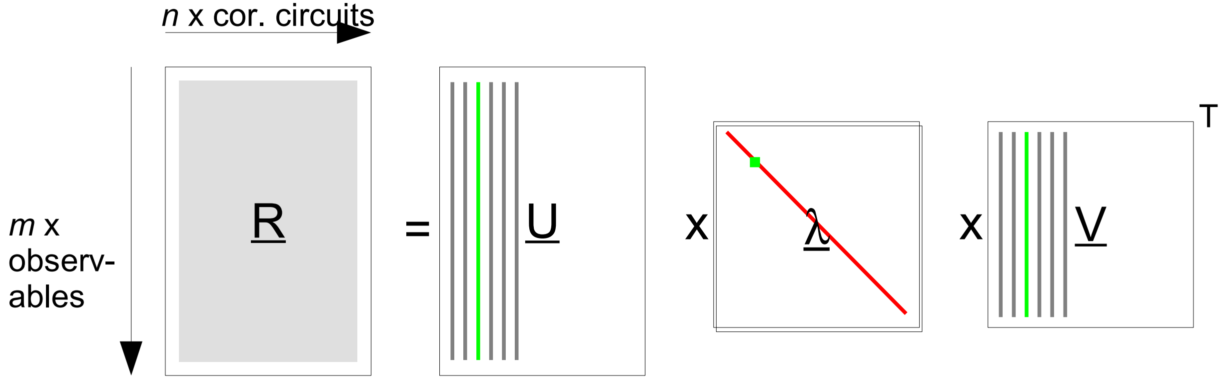
  - control consists essentially in inverting these matrices:

$$\boxed{\left\|\vec{x}_{ref}-\vec{x}_{actual}\right\|_2=\left\|\underline{R}\cdot\vec{\delta}_{ss}\right\|_2<\epsilon\ \rightarrow\ \vec{\delta}_{ss}=\tilde{R}^{-1}\Delta\vec{x}}$$

- Some potential complications:
  - Singularities = over/under-constraint matrices, noise, element failures, spurious BPM offsets, calibrations, ...
  - Time dependence of total control loop → "The world goes SVD...."

Space-Domain: Singular Value Decomposition (SVD) on a slide

Linear algebra theorem*:



eigen-vector relation:

$$\lambda_i \vec{u}_i = \underline{R} \cdot \vec{v}_i$$

$$\lambda_i \vec{v}_i = \underline{R}^T \cdot \vec{u}_i$$

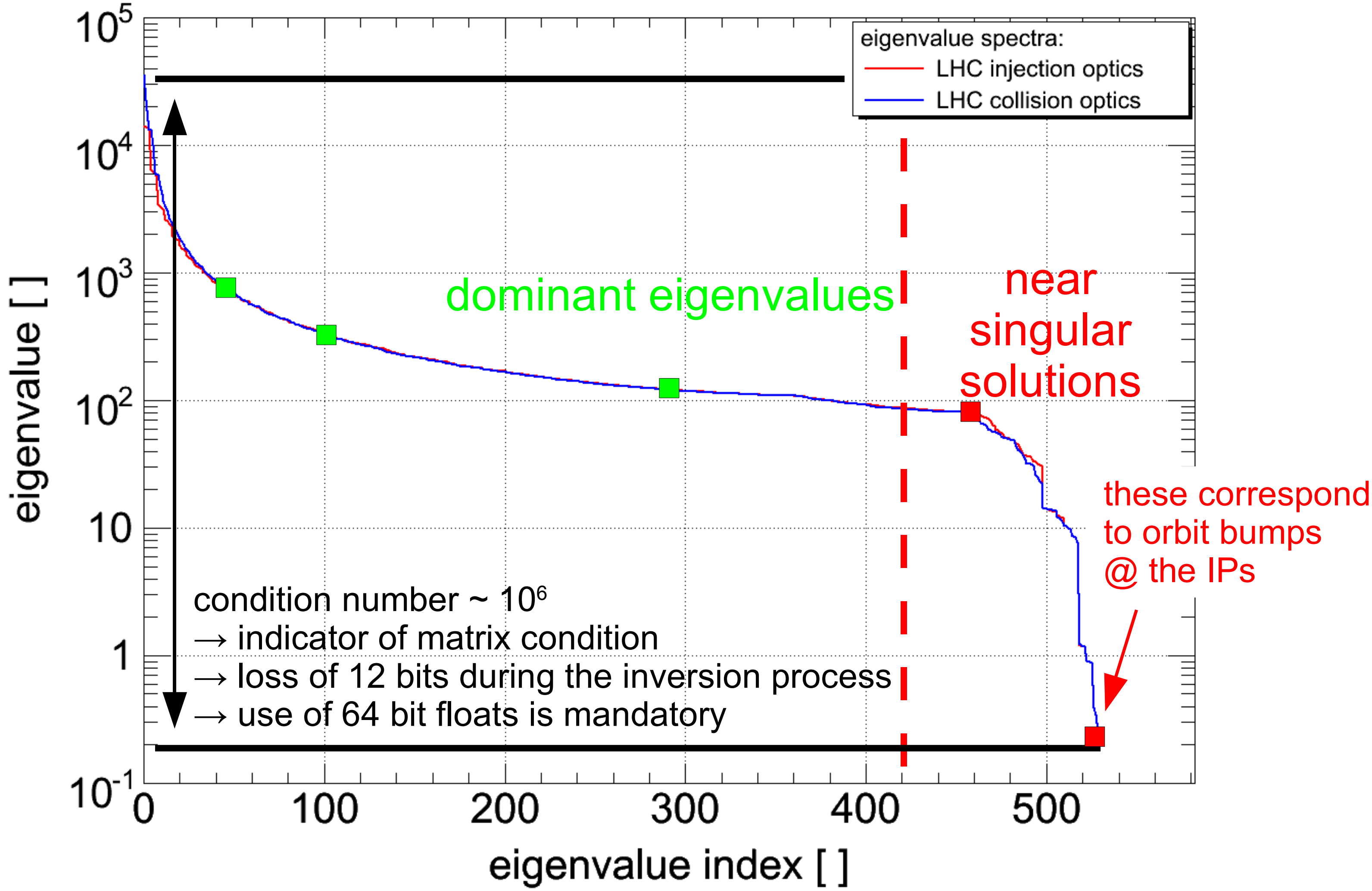
- though decomposition is numerically more complex final correction is a simple vector-matrix multiplication:

$$\boxed{\vec{\delta}_{ss} = \tilde{R}^{-1} \cdot \Delta\vec{x} \quad with \quad \tilde{R}^{-1} = \underline{V} \cdot \underline{\lambda}^{-1} \cdot \underline{U}^T} \Leftrightarrow \quad \vec{\delta}_{ss} = \sum_{i=0}^{n} \frac{a_i}{\lambda_i} \vec{v}_i \quad with \quad a_i = \vec{u}_i^T \Delta\vec{x}$$

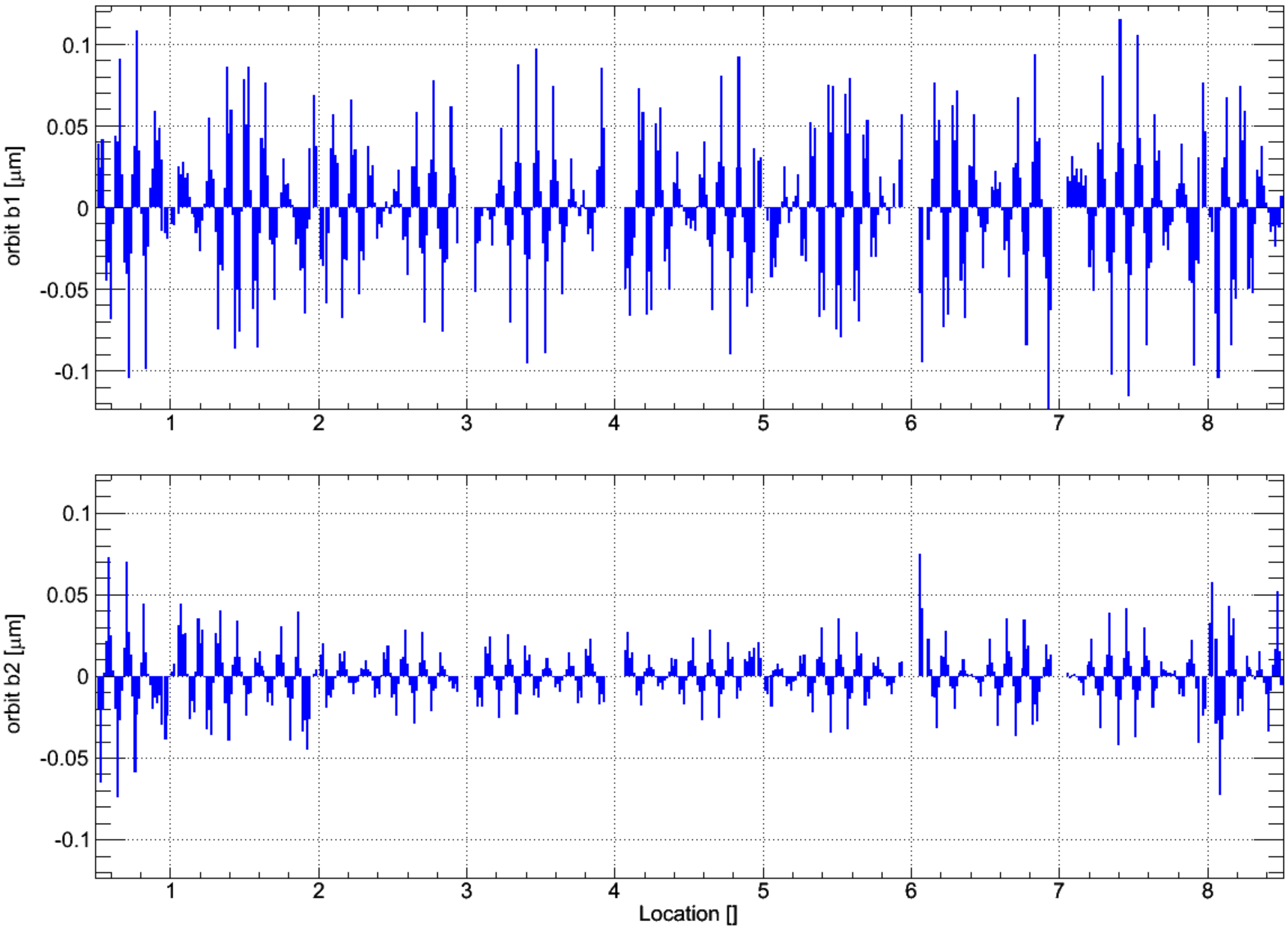
- numerical robust, minimises parameter deviations Δx <u>and</u> circuit strengths δ
- Easy removal of singularities, (nearly) singular eigen-solutions have $\lambda_i \sim 0$
  - to remove those solution: if $\lambda_i \approx 0 \rightarrow$ '$1/\lambda_i := 0$'
  - discarded eigenvalues corresponds to solution pattern unaffected by the FB

*G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971

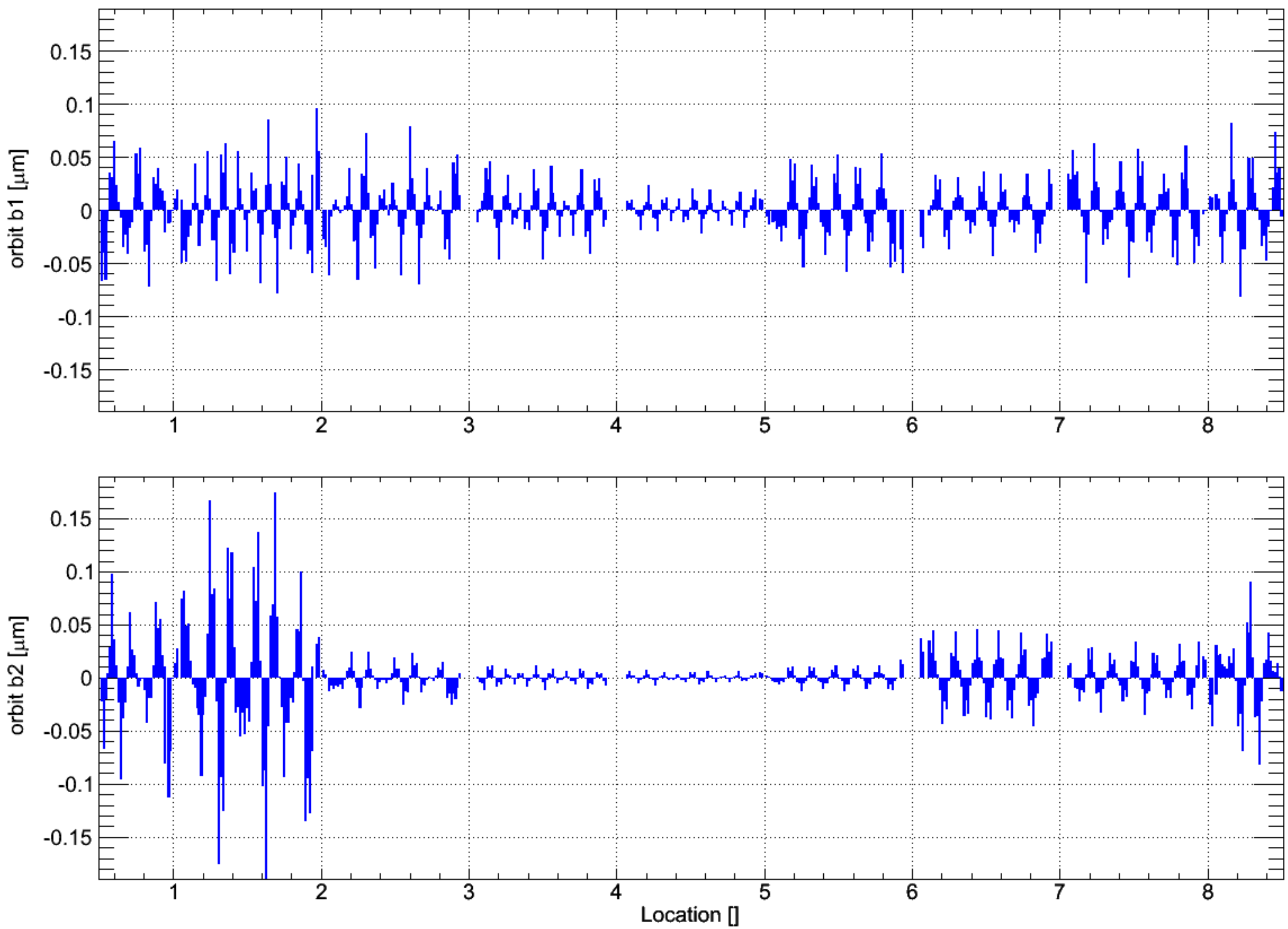
Eigenvalue spectra for vertical LHC response matrix using all BPMs and CODs:



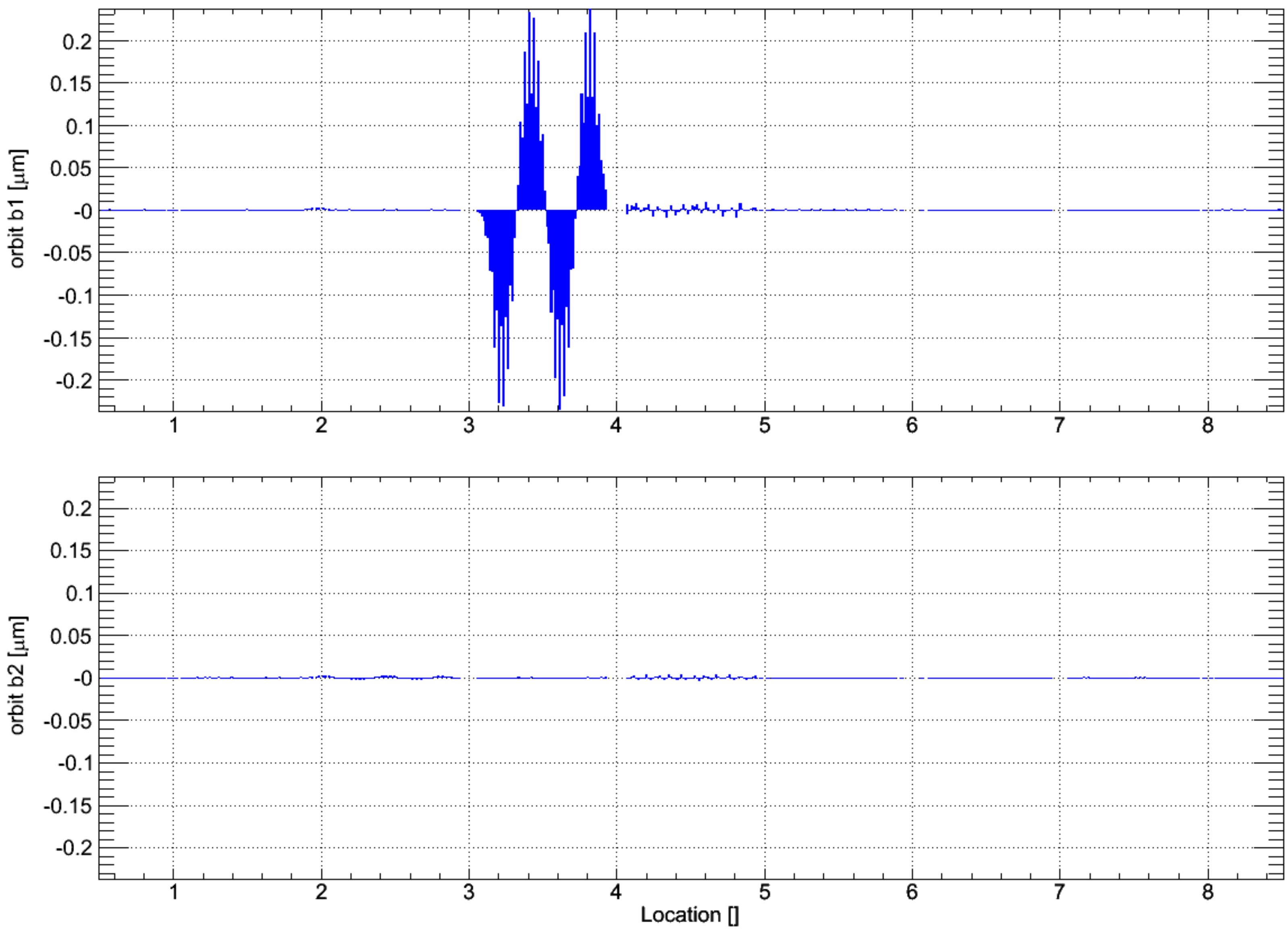
Space Domain:
LHC BPM eigenvector #50 λ_{50}= 6.69•10^2



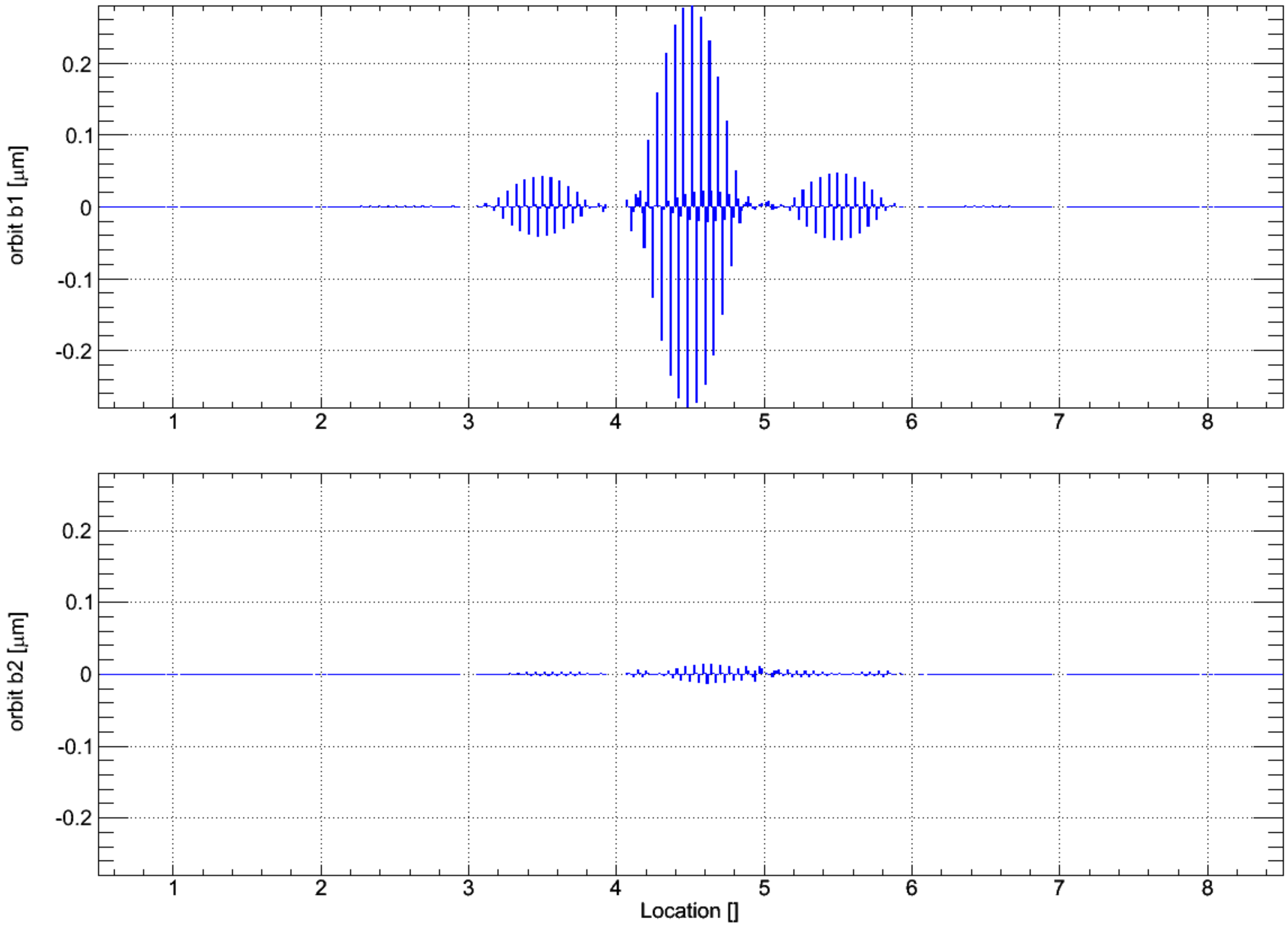
Space Domain:
LHC BPM eigenvector #100 λ_{100}= 3.38•10^2



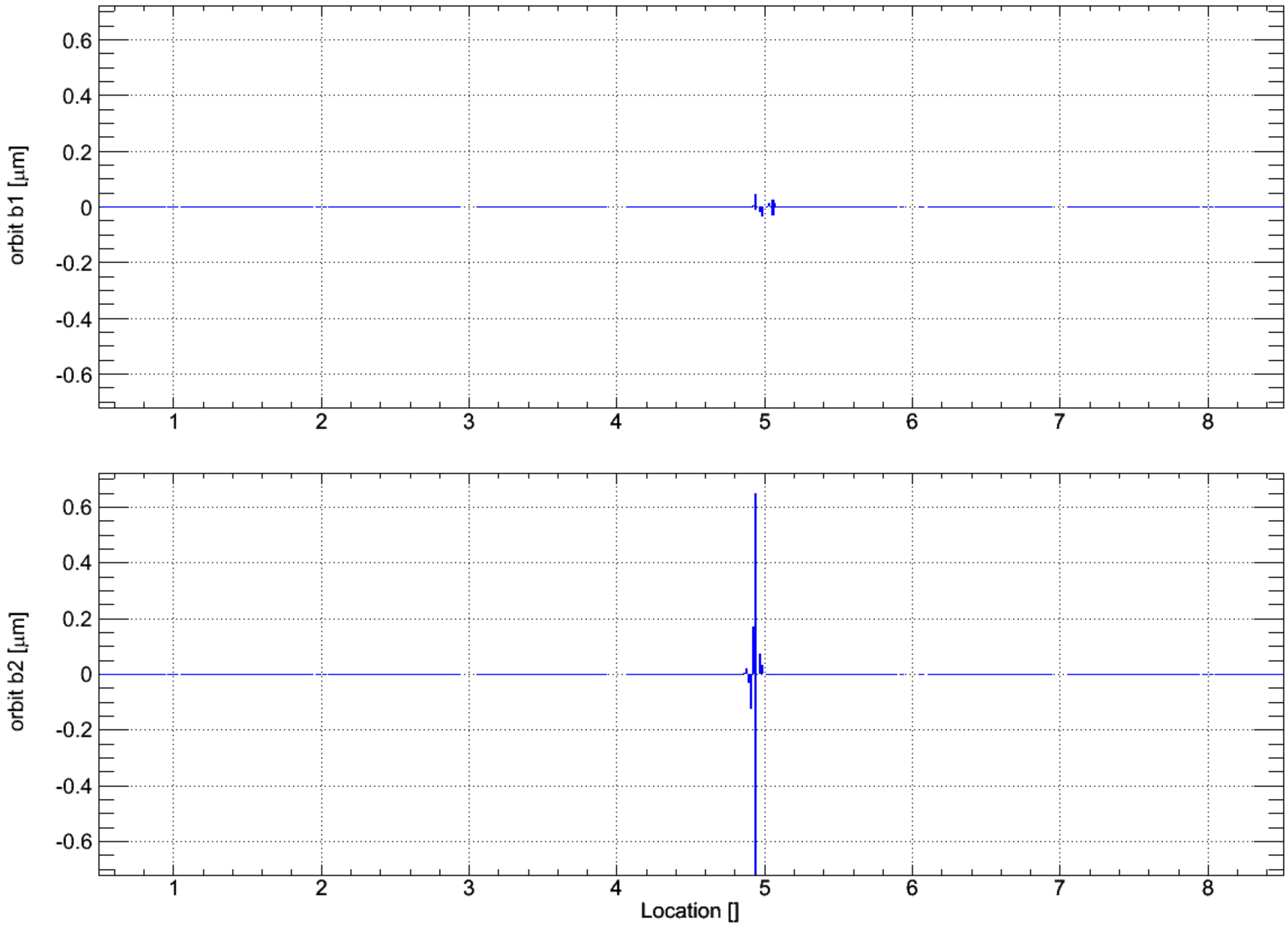
Space Domain:
LHC BPM eigenvector #291 $\lambda_{291}= 2.13 \cdot 10^2$



Space Domain:
LHC BPM eigenvector #449 λ_{449}= 8.17•10[1]

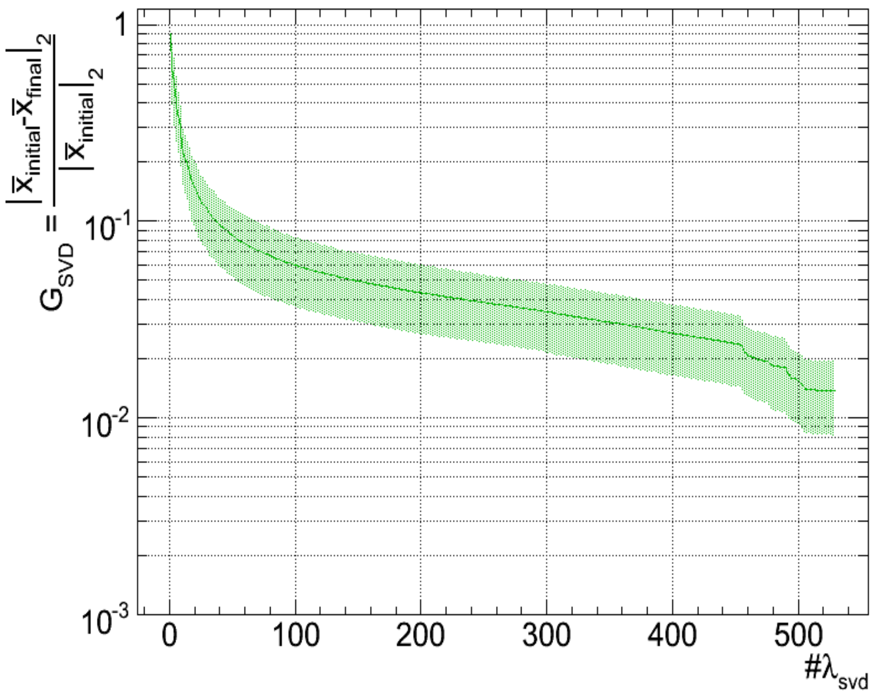


Space Domain: LHC BPM eigenvector #521 $\lambda_{521} = 1.18 \cdot 10^0$

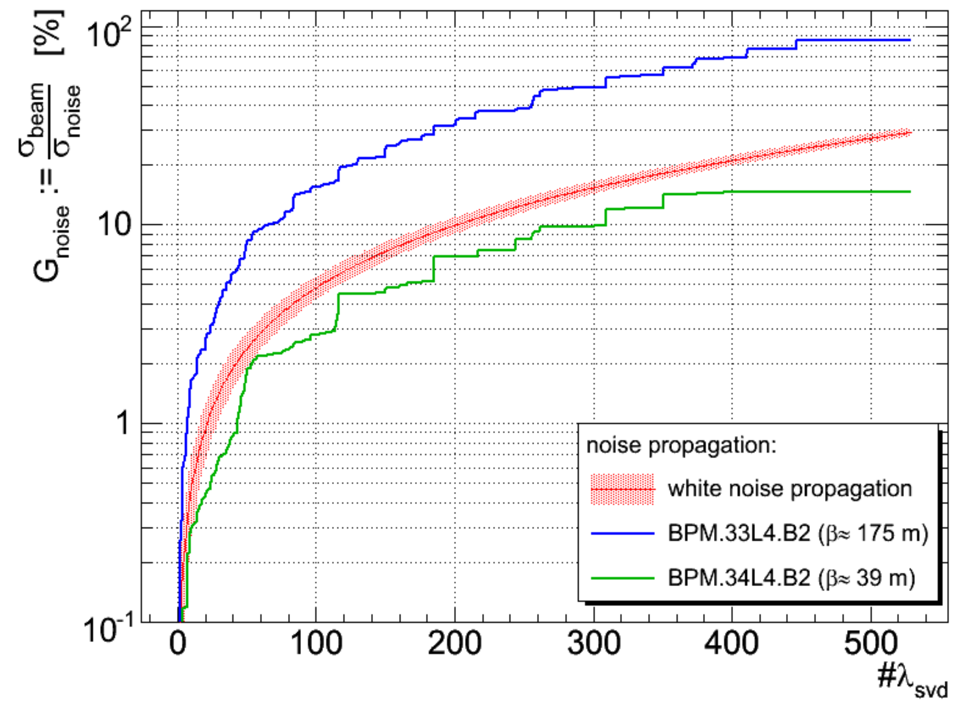


Space-Domain: Orbit Attenuation Performance vs. Noise Propagation

- Orbit attenuation

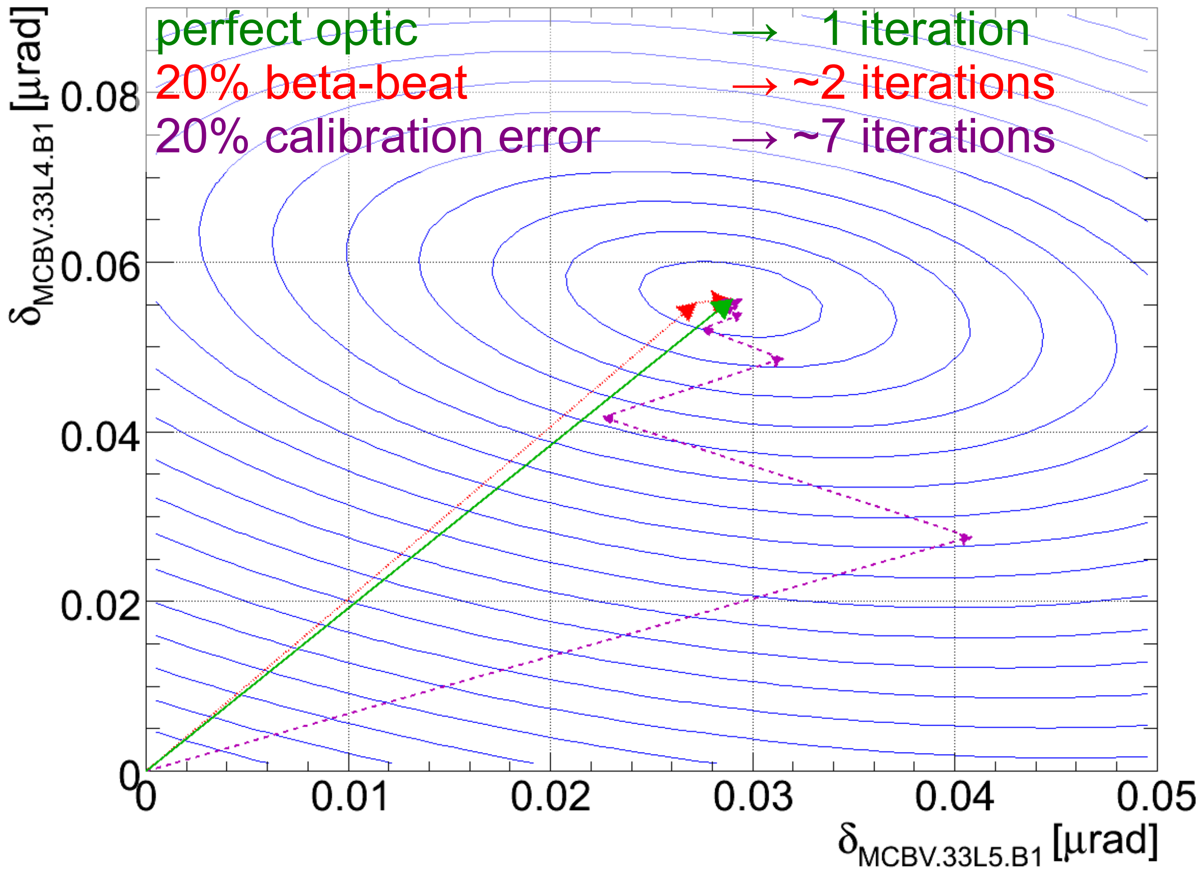


- Sensitivity to BPM noise



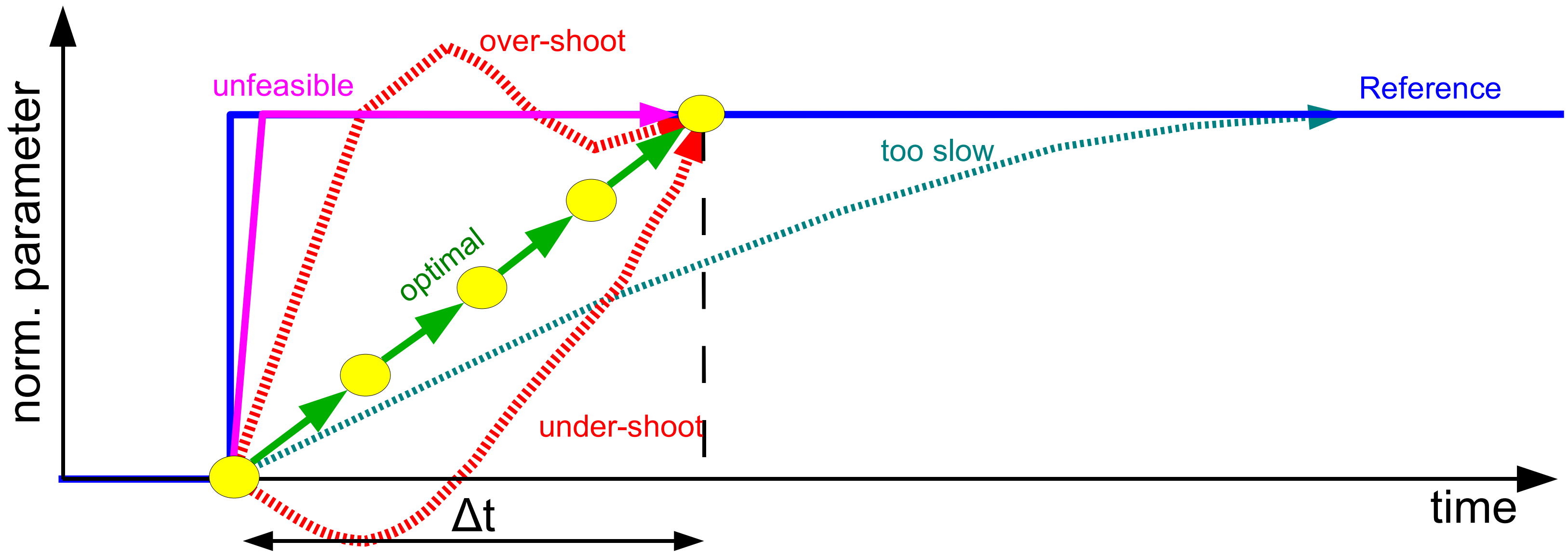
- Number of for the inversion used eigenvalues steers accuracy versus robustness of correction algorithm
- Likewise applies for Tune, Chromaticity and Coupling correction
  - However: Only two out of '*n*' eigenvalues are non-singular

- Optics imperfections may deteriorate the convergence speed but do not affect absolute convergence (response functions are 'monotonic'):
- Example: 2-dim orbit error surface projection



- LHC feedbacks are practically insensitive to optics (= beta-beat) errors
  - However, pickup and corrector magnet polarities are crucial

Time-Domain: Optimal Controller Design
Youla's affine parameterisation I/II – Cartoon



- Optimal control [or design] ...

  "... deals with the problem of finding a control law for a given system such that a given optimality criterion is achieved. A control problem includes a cost functional that is a function of state and control variables."

  – Common criteria: closed loop stability, minimum bandwidth, minimisation of action integral, power dissipation, ...

- classic closed loop: $T_0(s)=\frac{D(s)G(s)}{1+D(s)G(s)}$ $\longrightarrow$ "this tells me???"

- Using Youla's method: “design closed loop in a open loop style”:
- Youla showed[1] 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

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

- Using for example the following ansatz:

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

  - Response/optimality can be directly deduced by construction of $F_Q(s)$
  - $G^i(s)$, pseudo-inverse of the nominal plant G(s)

$$\rightarrow T_0(s)=\frac{1}{\alpha s+1}$$

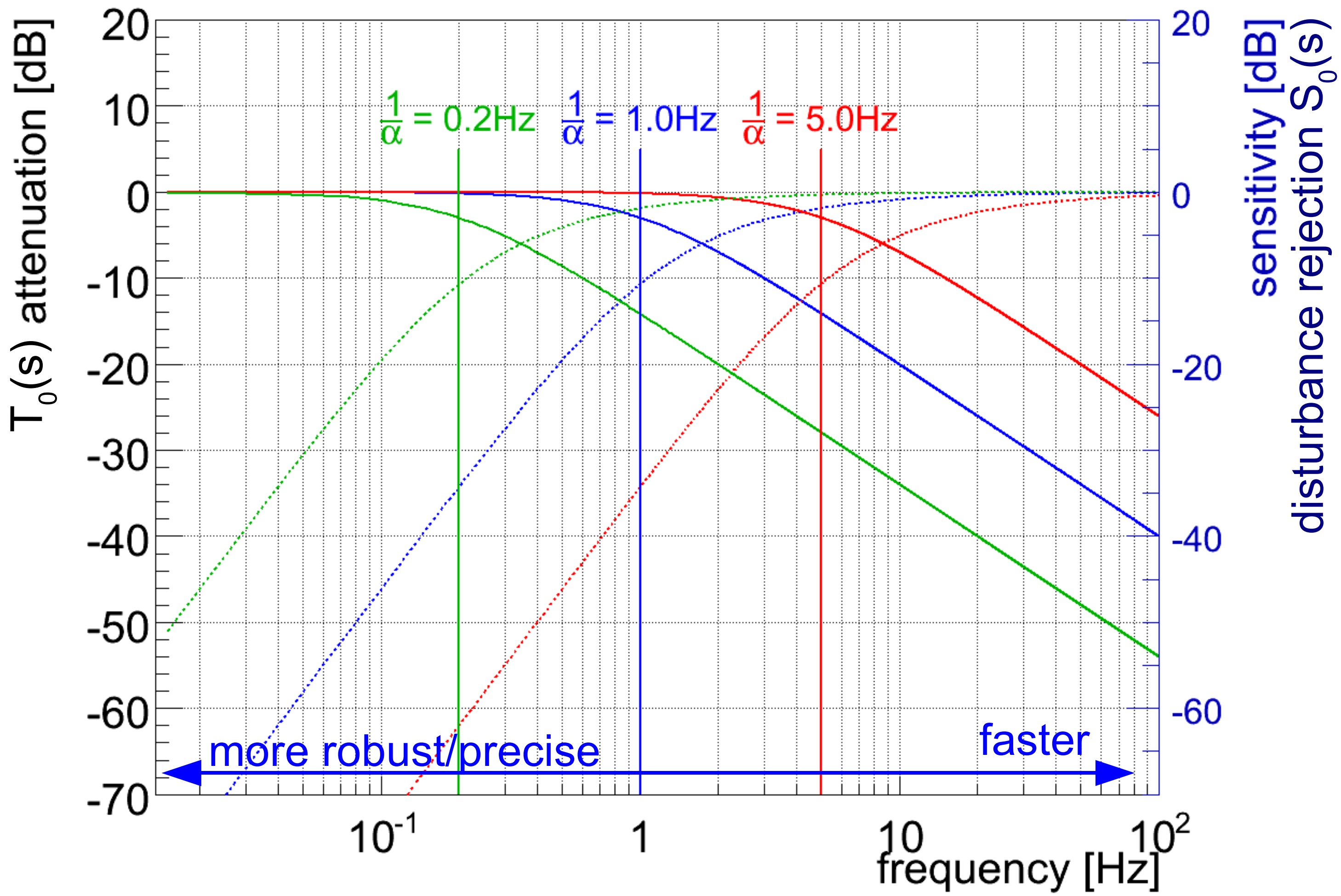
- (1)+(2)+(3) yields the following PI controller:

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

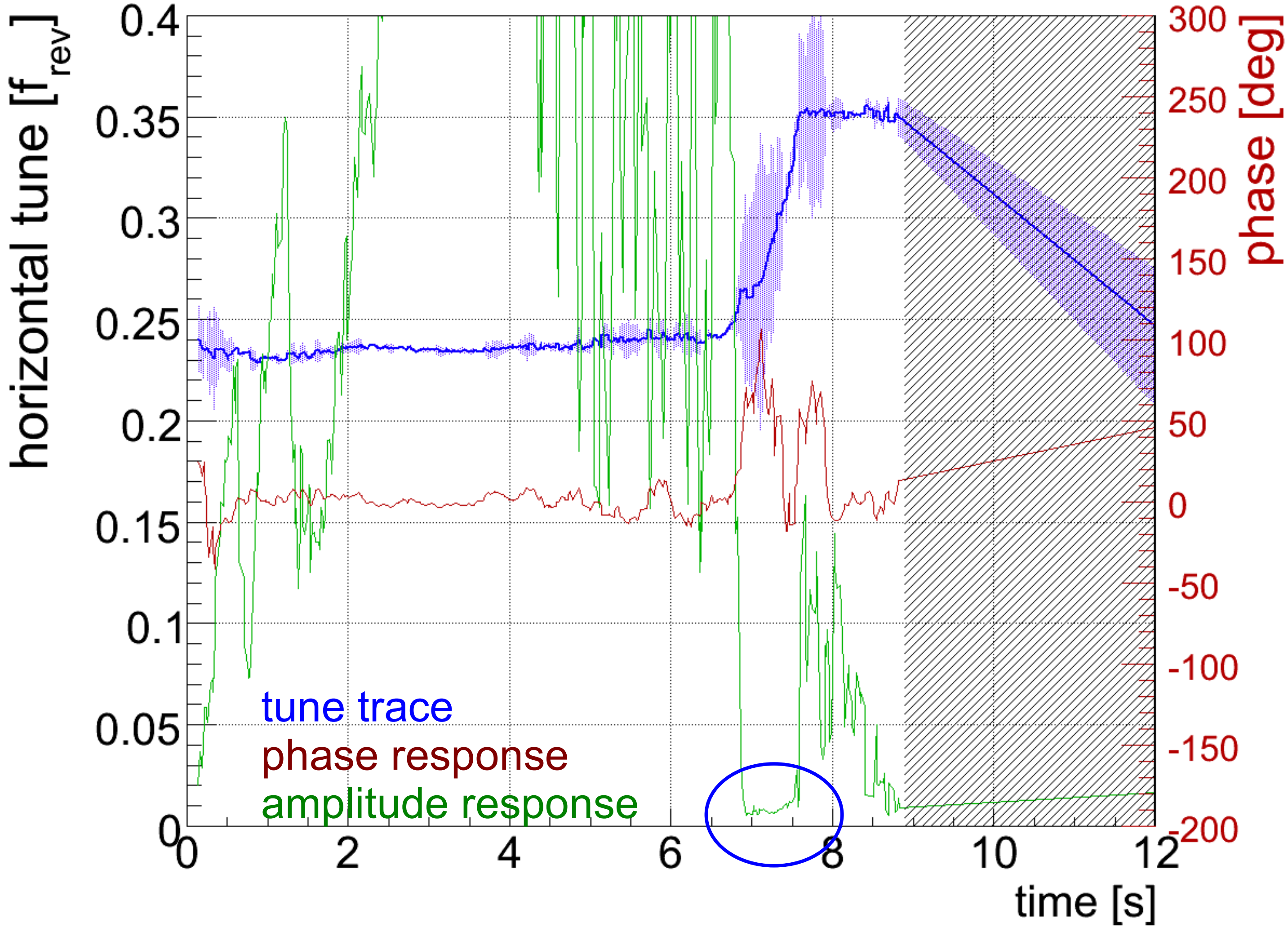
[1]D. C. Youla et al., *“Modern Wiener-Hopf Design of Optimal Controllers”*, IEEE Trans. on Automatic Control,1976, vol. 21-1,pp. 3-13 & 319-338

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

- $\alpha > \tau \ldots \infty$ 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!



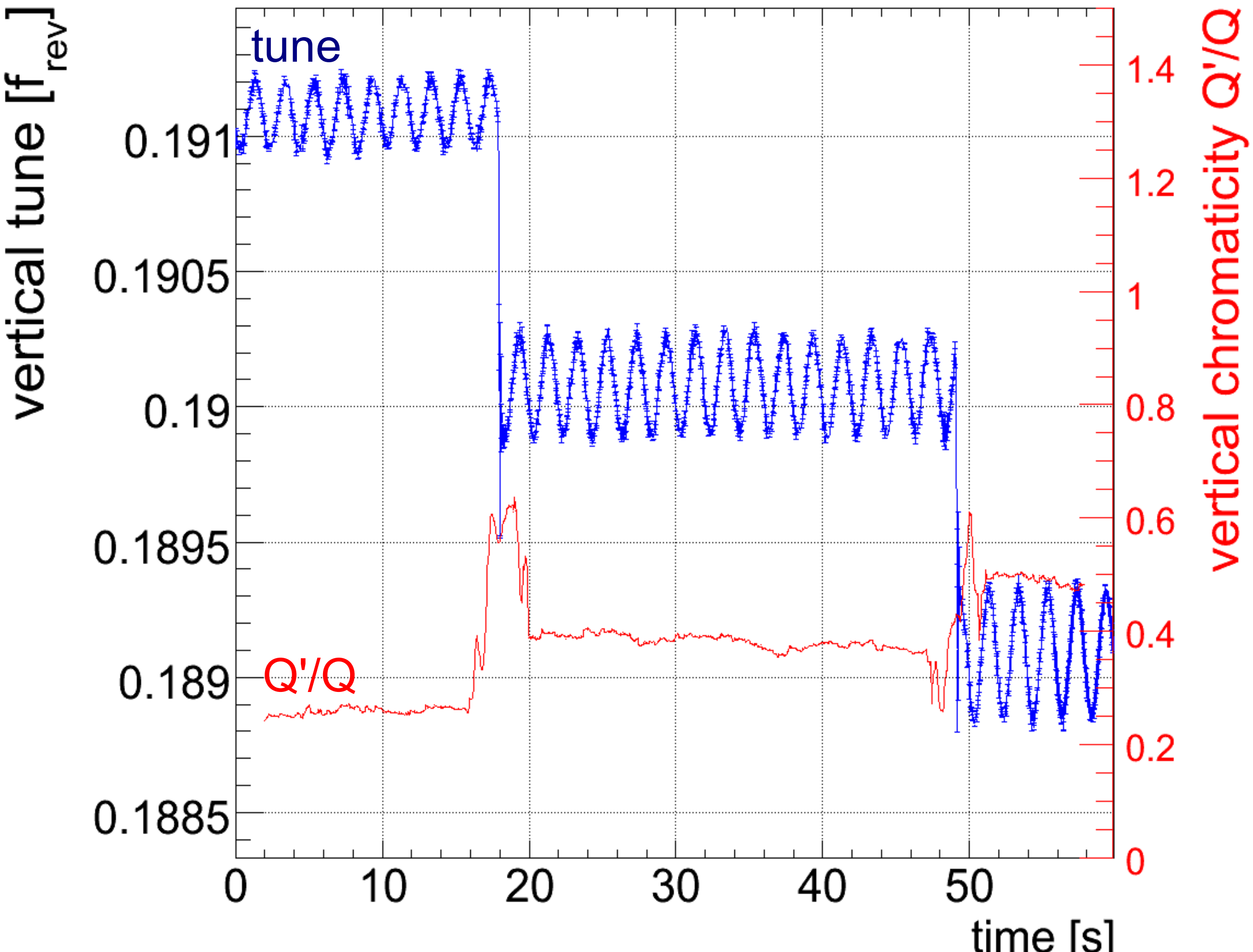
Example: LHC PLL Tune Tracking at the SPS



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

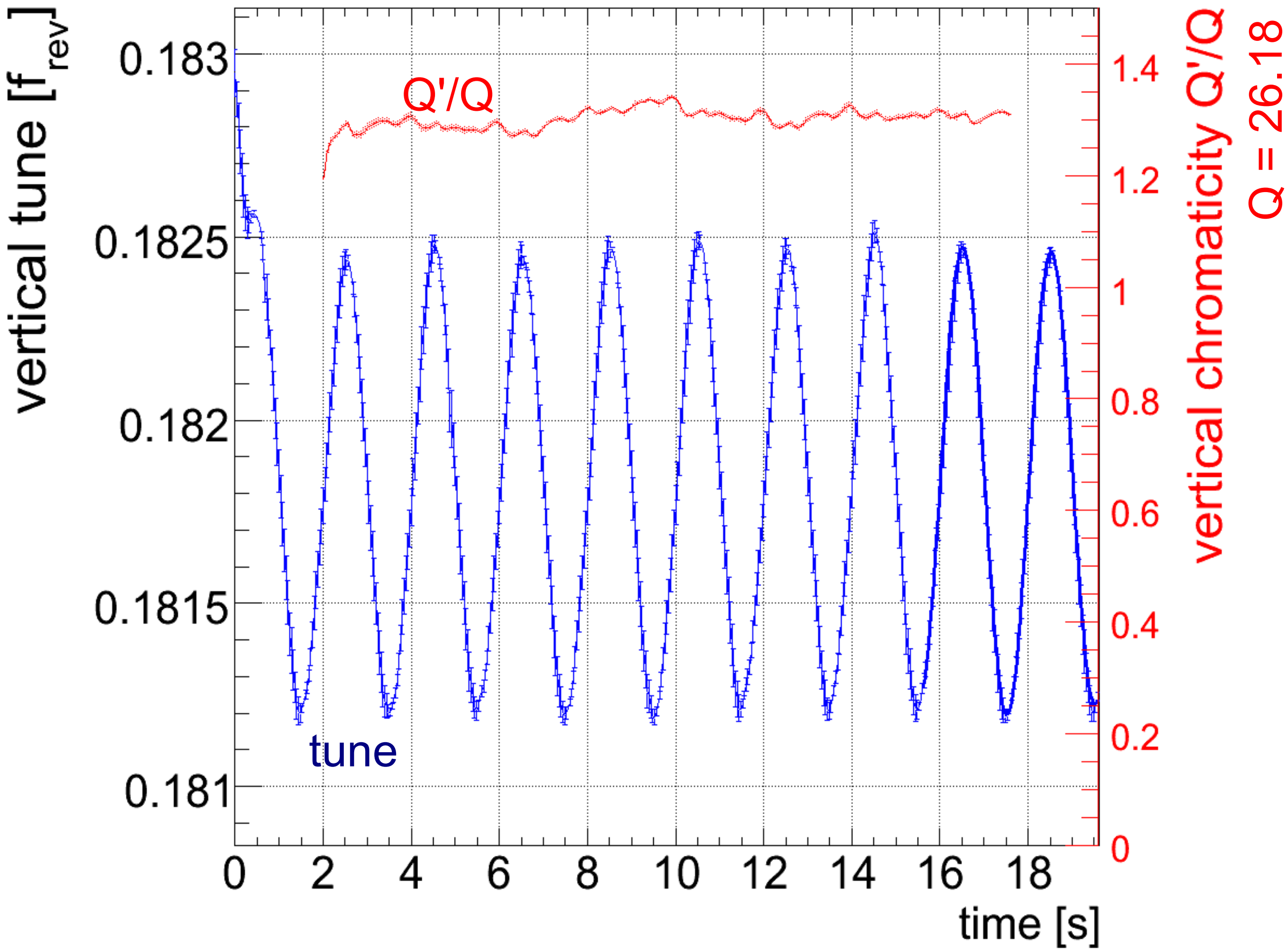
  $f_{rev} \approx 43$ kHz

Example: LHC PLL based Q/Q' tracking 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: $\Delta p/p \approx 1.85 \cdot 10^{-5}$

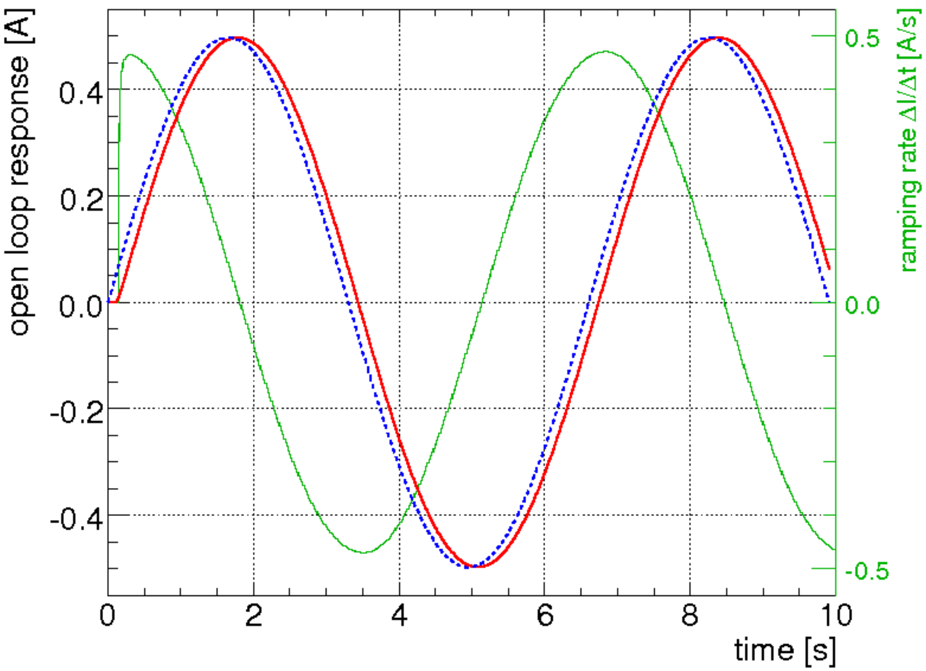


- Scans to assess the maximum useful range yield showed that this method can cope with values of Q' up to at least 34 units
  - larger than (any other) Fourier based method ... (usually damping limited)

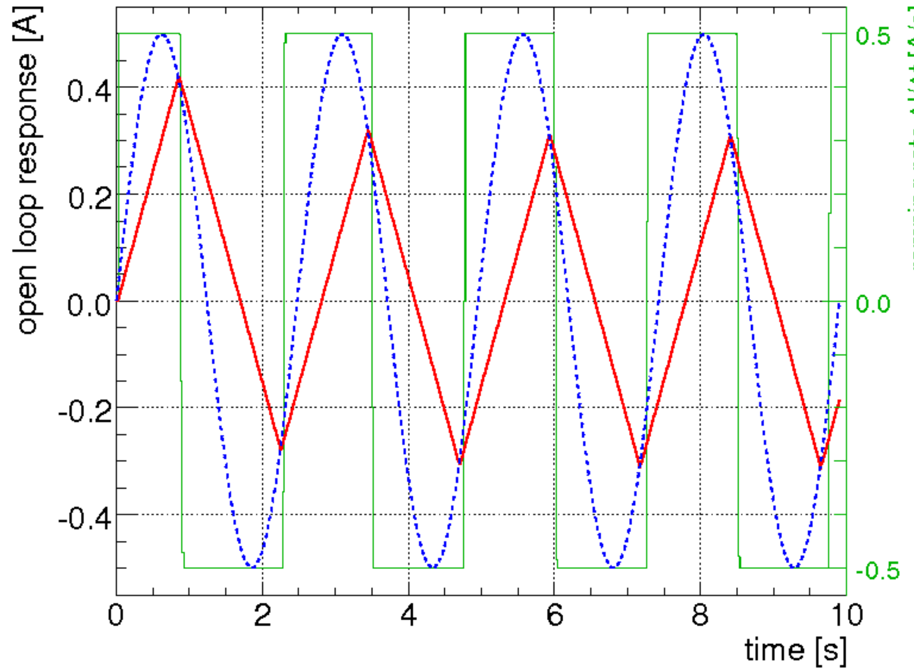
Two common non-linear effects in accelerators:

- Delays: computation, data transmission, dead-time, etc.
- Rate-Limiter: limited slew rate of corrector circuits (due to voltage limitations)
  - e.g. LHC: ±60A converter: $\Delta I/\Delta t|_{max} < 0.5$ A/s

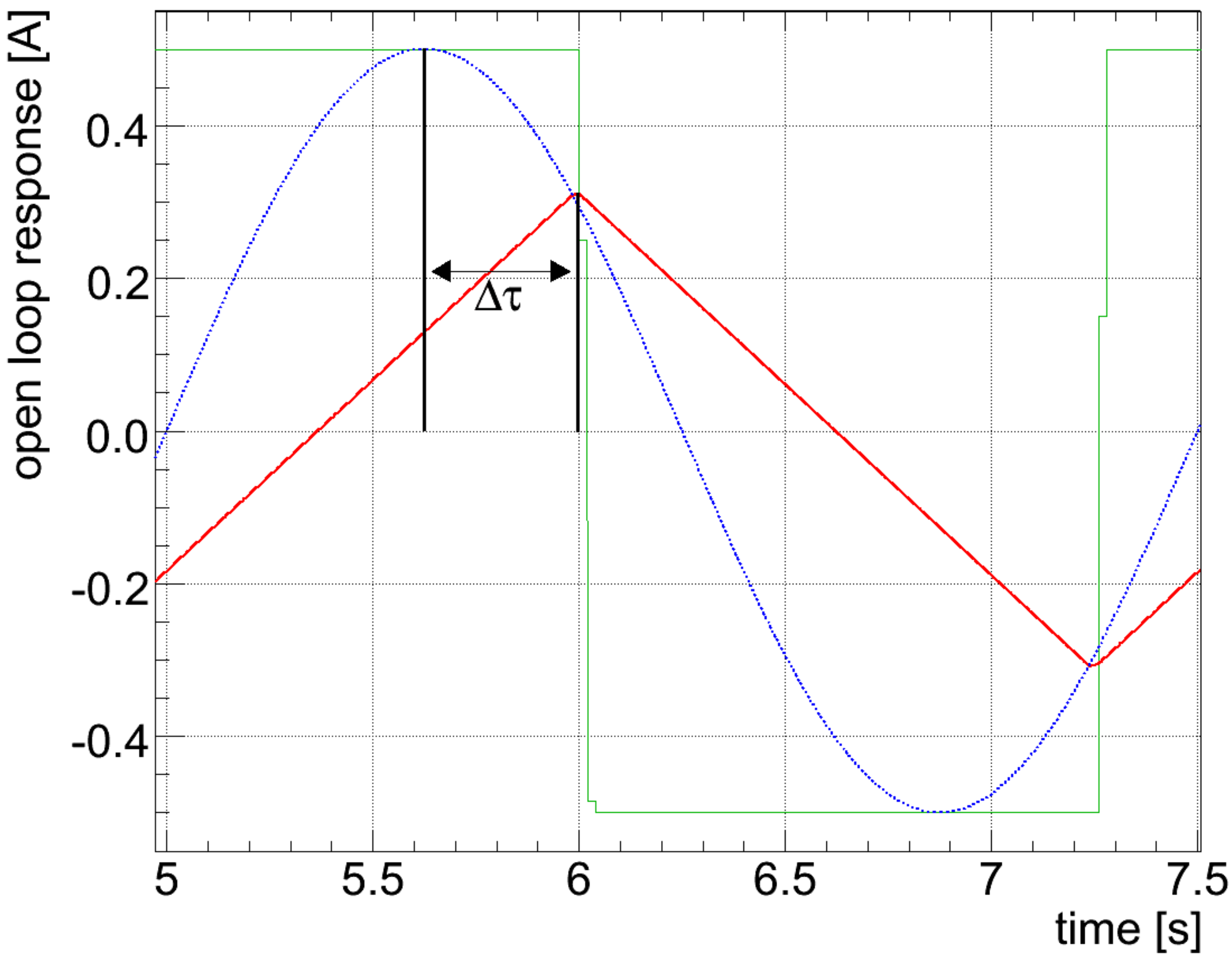
slow perturbation: perfect tracking



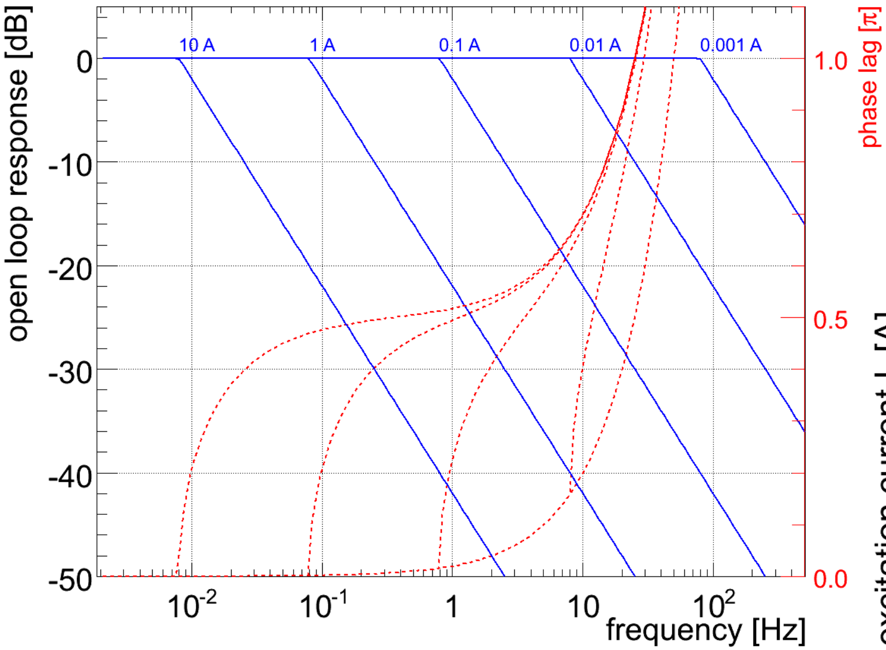
fast perturbation: saw-tooth



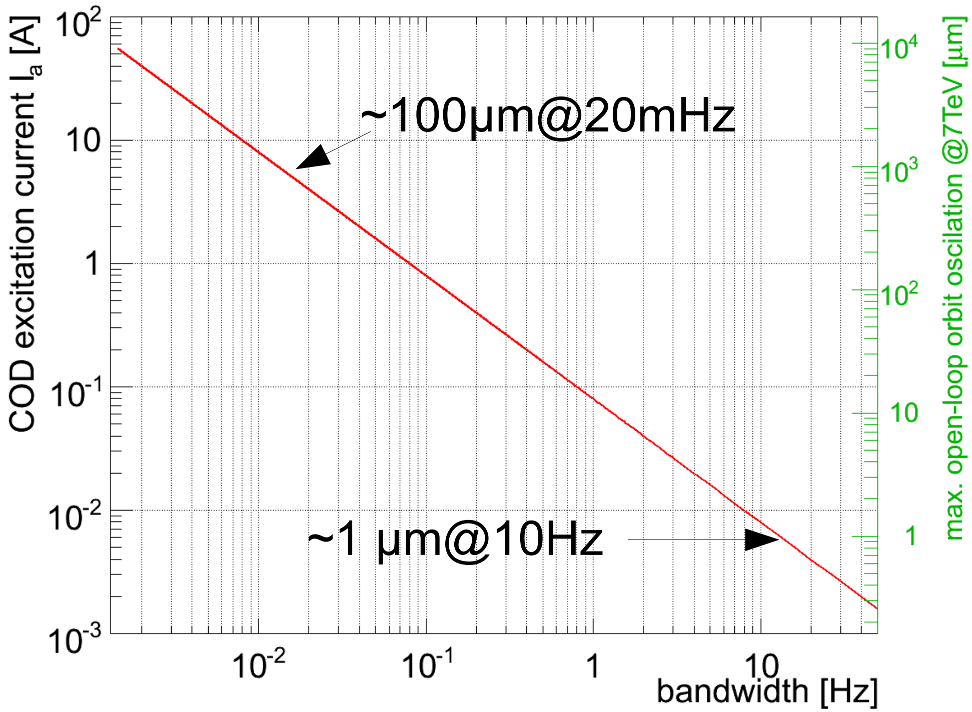
- Rate-limiter in a nut-shell:
  - additional time-delay Δτ that depends on the signal/noise amplitude
  - (secondary: introduces harmonic distortions)



- Open-loop circuit bandwidth depends on the excitation amplitude:
  - + non-linear phase once rate-limiter is in action...



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



- Consider ~16µm@1Hz as effective bandwidth @ 7TeV

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

- ... cannot a priori be compensated.
  - however, their deteriorating effect on the loop response can be mitigated by taking them into account during the controller design.
- Example: process can be split into stable and instable 'zeros'/components

$$G(s)=\frac{A_0(s)A_u(s)}{B(s)}=G_0(s)\cdot G_{NL}(s) \quad e.g. \quad G(s)=G_0(s)\cdot \underbrace{e^{-\lambda s}}_{\lambda\text{: delay}}$$

- Using the modified ansatz ($F_Q(s)$: desired closed-loop transfer function):

$$Q(s)=F_Q(s)\cdot G^i(s)=F_Q(s)\cdot G_0^{-1}(s)$$

- yields the following closed loop transfer function

$$\rightarrow \quad T(s) = Q(s)G(s)=F_Q(s)\cdot G_{NL}(s) \underbrace{=}_{here:} F_Q(s)\cdot e^{-\lambda s}$$

  - Controller design $F_Q(s)$ carried out as for the linear plant
  - Yields known classic predictor schemes:
    - delay → Smith Predictor
    - rate-limit → Anti-Windup Predictor

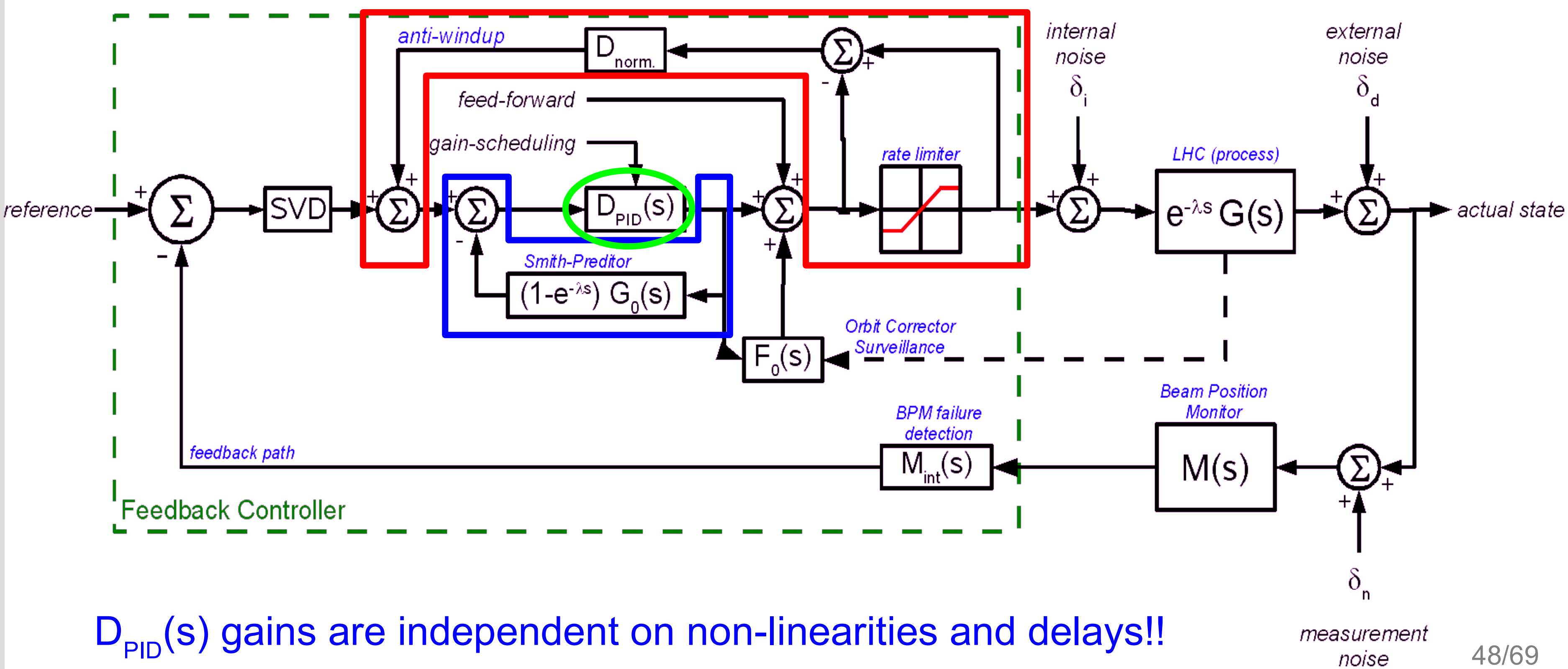
Time Domain: Example: LHC Feedbacks & Delays + Rate-limiter

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

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

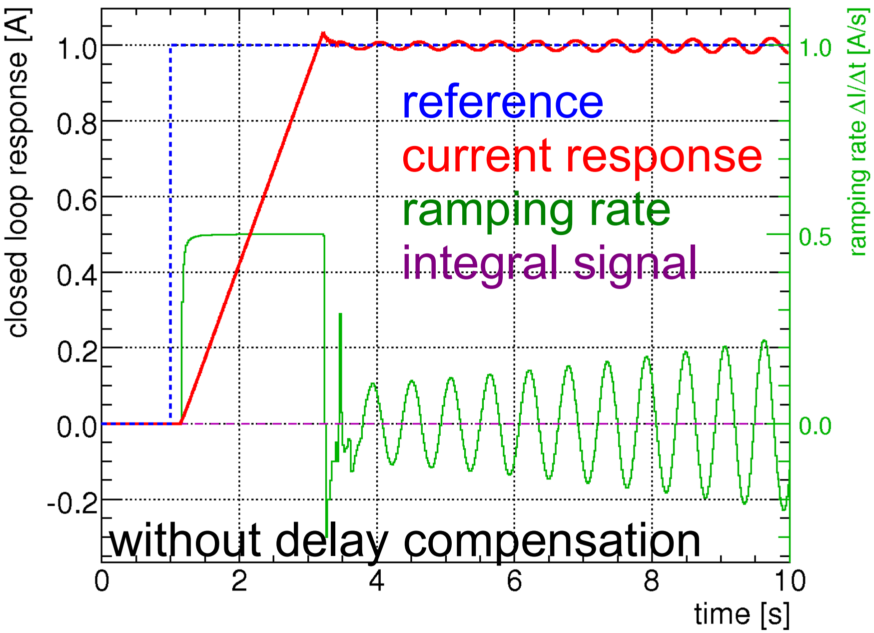
$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}G_{NL}(s)$$

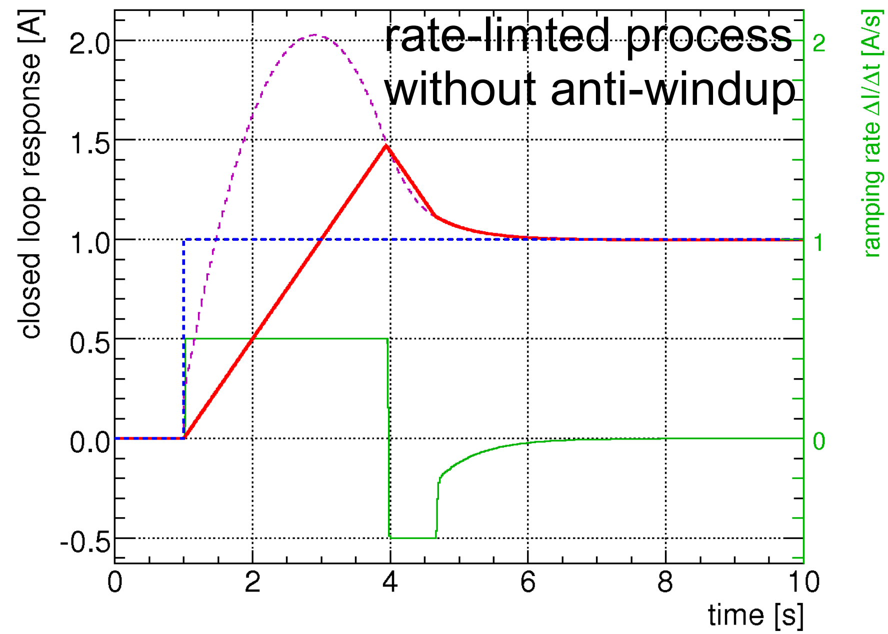
- with τ the power converter time constant and $G^{i}(s)=\frac{\tau s+1}{1}$
- yields Smith-Predictor and Anti-Windup paths: $T(s)=F_Q(s)\cdot e^{-\lambda s}G_{NL}(s)$



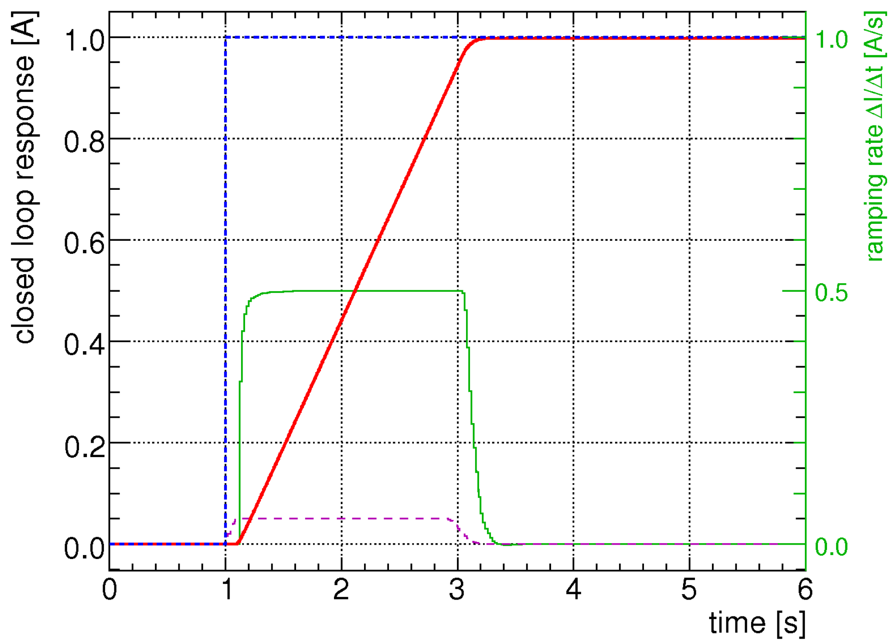
$D_{PID}(s)$ gains are independent on non-linearities and delays!!

Example: LHC orbit (Q,Q',C⁻, ...) feedback control

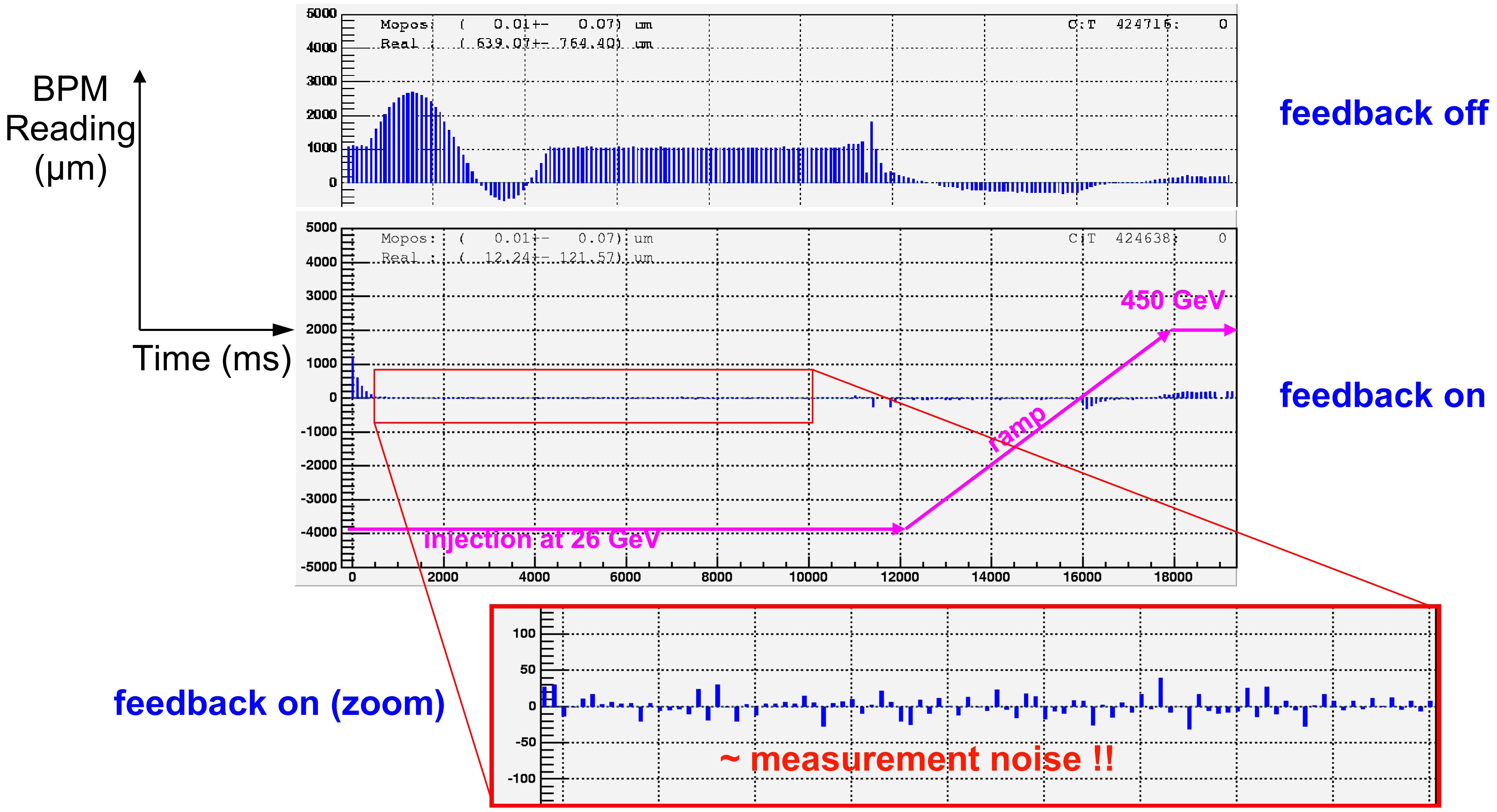




with full delay and windup compensator scheme:



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



- Looking forward to perform the same test, but with beam in the LHC....

- Feedback is only as good as the measurement and control actuators (power converter, cavity controls) it is based on!
  Robust feedback design needs to take noise, systematics, error and faults of involved devices into account. two main sources of errors/faults in the LHC:
  - Beam Position Monitors (BPMs): huge system with over 2200 devices
  - Power Converter Failure: about 1060 orbit correctors
    (expected failure rate: about one every 5 days → additional slides)

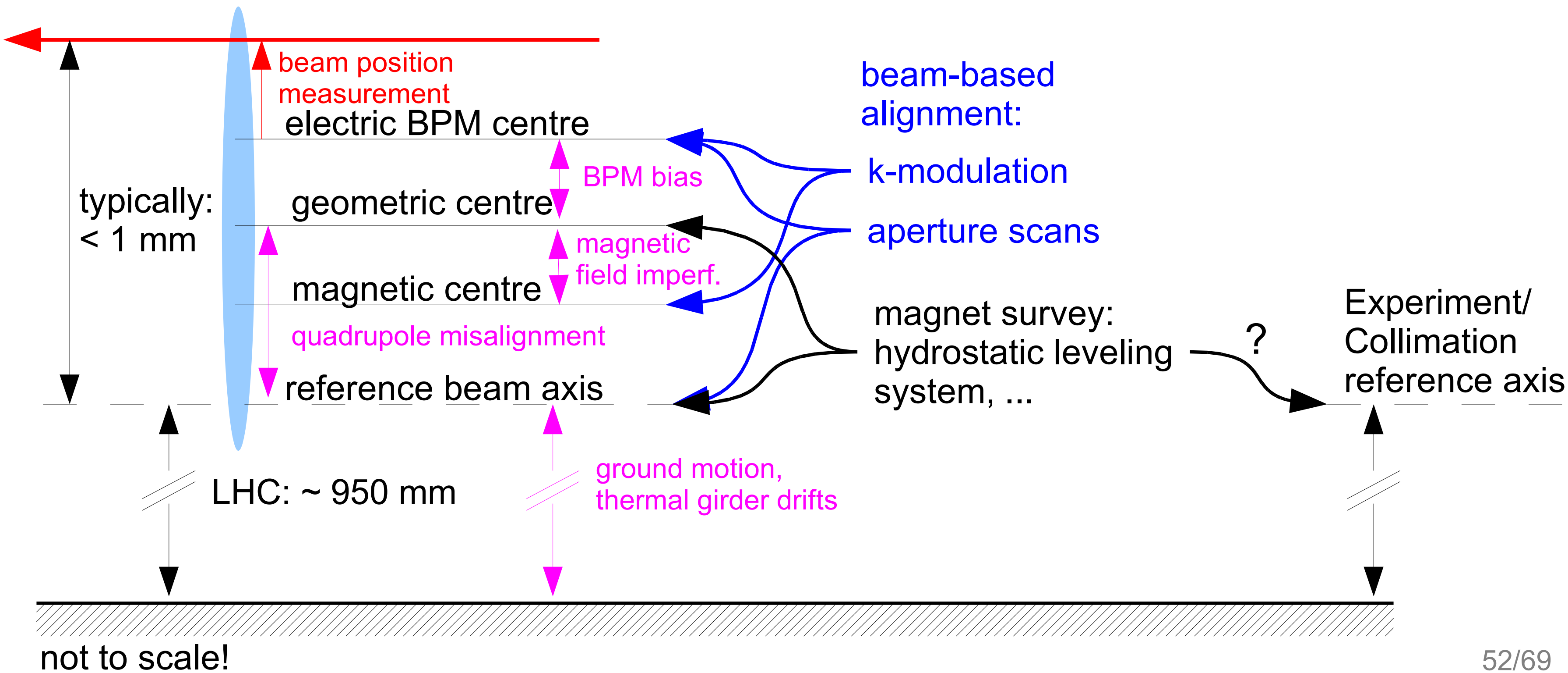
Example LHC BPMs:

- Errors can be decomposed into an 'offset', 'calibration' and 'noise':

$$x_{meas} = x_{offset} + a_{cal} \cdot x_{true} \pm f_{noise}(t)$$

  - (some) errors affect either offset or slope only
  - absolute offset often not required (provided it is constant):
    → e.g. beam-based alignment of LHC Collimation
    → e.g. orbit response or equivalent lattice response measurements
  - systematic calibration factor is minimised by beam-based steering

- BPM stability analysis depends on the choice of reference system:
  - magnetic quadrupole centre (minimising feed-down effects)
  - geometric centre of beam screen (maintaining aperture constraints)
  - external reference
- Several reference system definitions possible:
  - LHC's choice: Safety first → beam screen centre as reference



Known Error Sources: BPM Offset and Alignment II/II

- Beam Position Measurement:
  - electrical BPM bias: 100 μm r.m.s.
  - electrical BPM centre w.r.t. geometric BPM centre: 200 μm r.m.s.
  - mech. BPM centre w.r.t. beam screen centre: < “200 μm r.m.s.”
    - after aperture scan: ~ 130 μm
  - electrical BPM centre w.r.t. magnetic quad. centre: 200 μm r.m.s.
    - after k-modulation: < 50 (5?) μm

      (mostly limited to insertion regions)

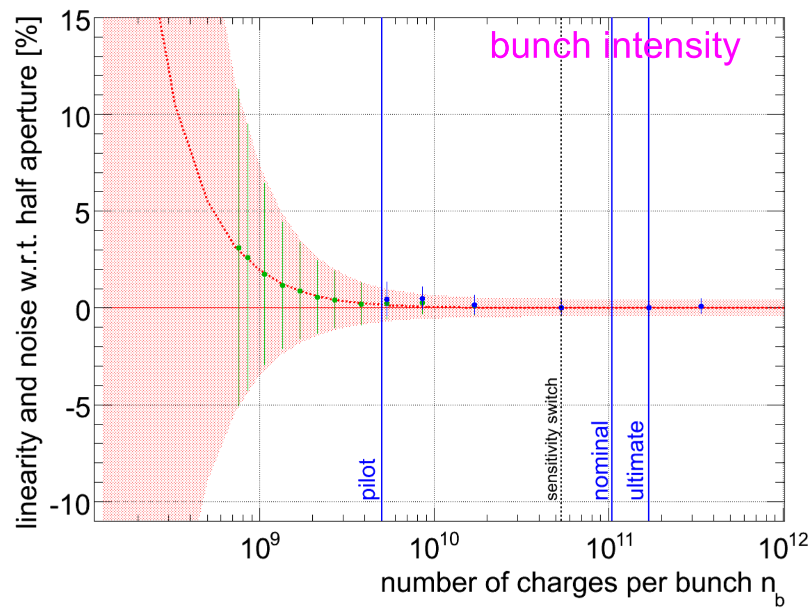
- Survey group targets for magnet alignment:
  - 0.2 mm r.m.s. globally , 0.1 mm r.m.s. as an average over 10 cells
  - N.B. Orbit FB: working assumption: 0.5 mm r.m.s.
  - Watch out: CLIC-Note-422, CERN-THESIS-2001-010
    → final focus stability might be determined by systematic drifts

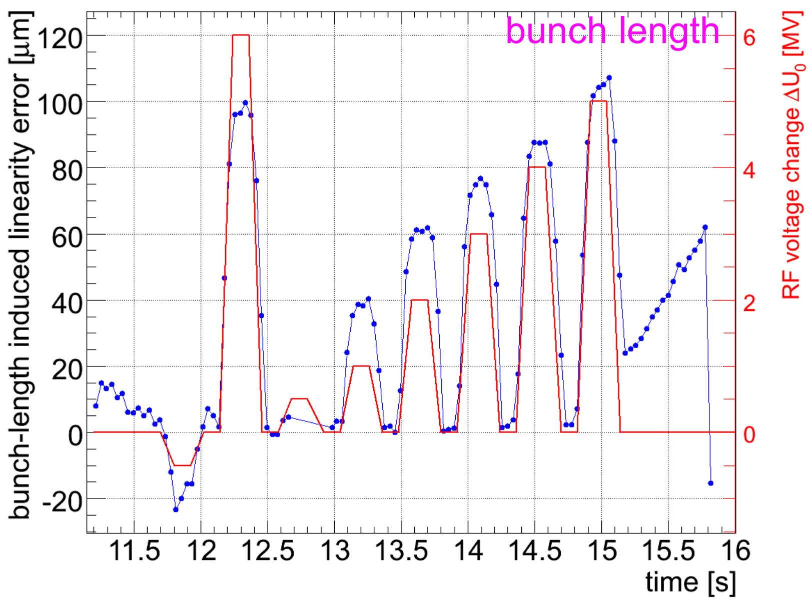
Known Error Sources: BPM dependence on

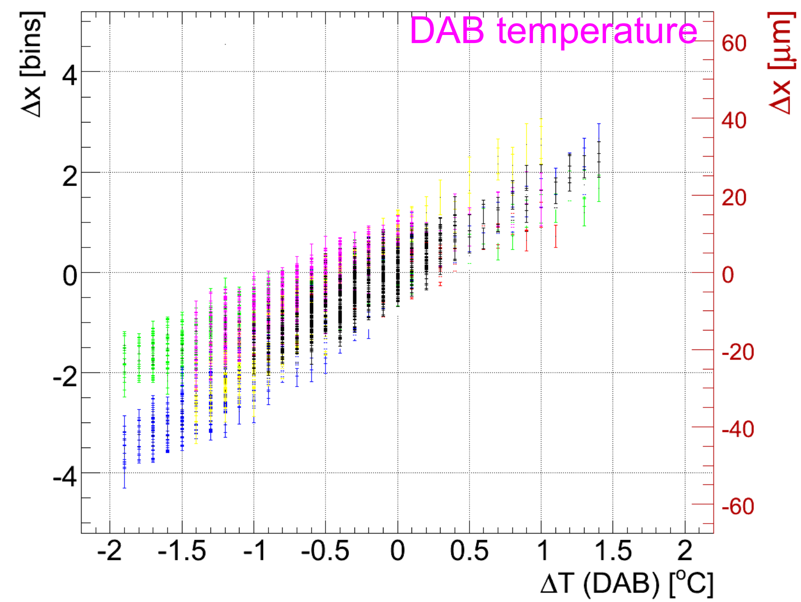
- bunch length σ_b, intensity n_b (σ_f: filter time constant) and integrator temperature changes ΔT, filling pattern, ...:

$$\Delta x_{error} \sim \frac{\sigma_{eff}^3}{n_b^{1.5}} + \approx 15-20 \frac{\mu m}{^oC} \cdot \Delta T$$

$$with \quad \sigma_{eff} \approx \sqrt{(\sigma_b^2 + \sigma_f^2)}$$







BPM Functionality Test Procedure

- Three main lines of defense against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
     - eliminates open/closed circuits, dead circuits/element candidates
  2. Pre-checks with Pilot and Intermediate beams
     - verifies calibration offset (guarantee) and slope (golden orbit)
     - verifies/guarantees proper function of machine protection
  3. Continuous data quality monitoring through Orbit Feedback
     - detects spikes, steps and BPMs that are under verge of failing

- (k-modulation can for a few (insertion) BPMs provide some additional limited cross-checks for BPM misalignments w.r.t. magnetic quadrupole limits. However: no hard limits!)

1.Pre-checks without beam using the in-built calibration unit

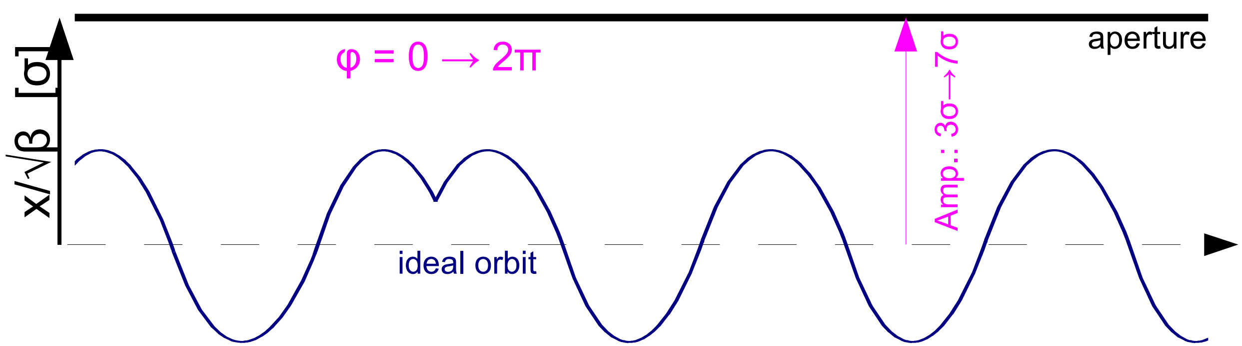
Prior each run:

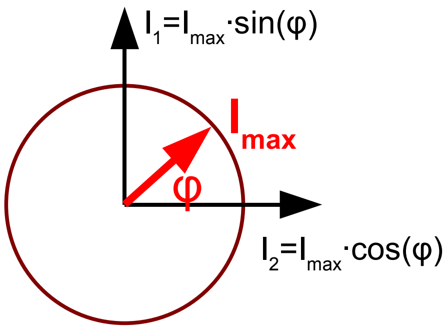
- Each LHC WBTN can be put into an in-situ calibration mode
  - verifies active links/unbroken cabling
  - verifies that WBTN and rest of the acquisition chain is alive
  - verifies/removes drifts of electronic components
- However: With beam, from the beam position measurement point of view, calibration or intensity mode are equivalent to a BPM failure:
  - will/should be monitored through
    - LHC Sequencer/Software Interlock System
    - BPM turn-by-turn data concentrator and/or
    - LHC Orbit Feedback Controller/Service Unit
      - small additional status flag in orbit data
      - ceasing of feedback operation till:
        ('calibration mode' v 'intensity mode') == false

- Two simple functional tests to check whether BPMs are working.
  Idea: “Every non-moving position reading indicates a dead BPM”.

1. free betatron oscillation with rotating phase
   - non-moving BPM readings → faulty BPM
   - Fast test of calibration factor and/or optics
   - provides data for stability/reliability analysis and improvements

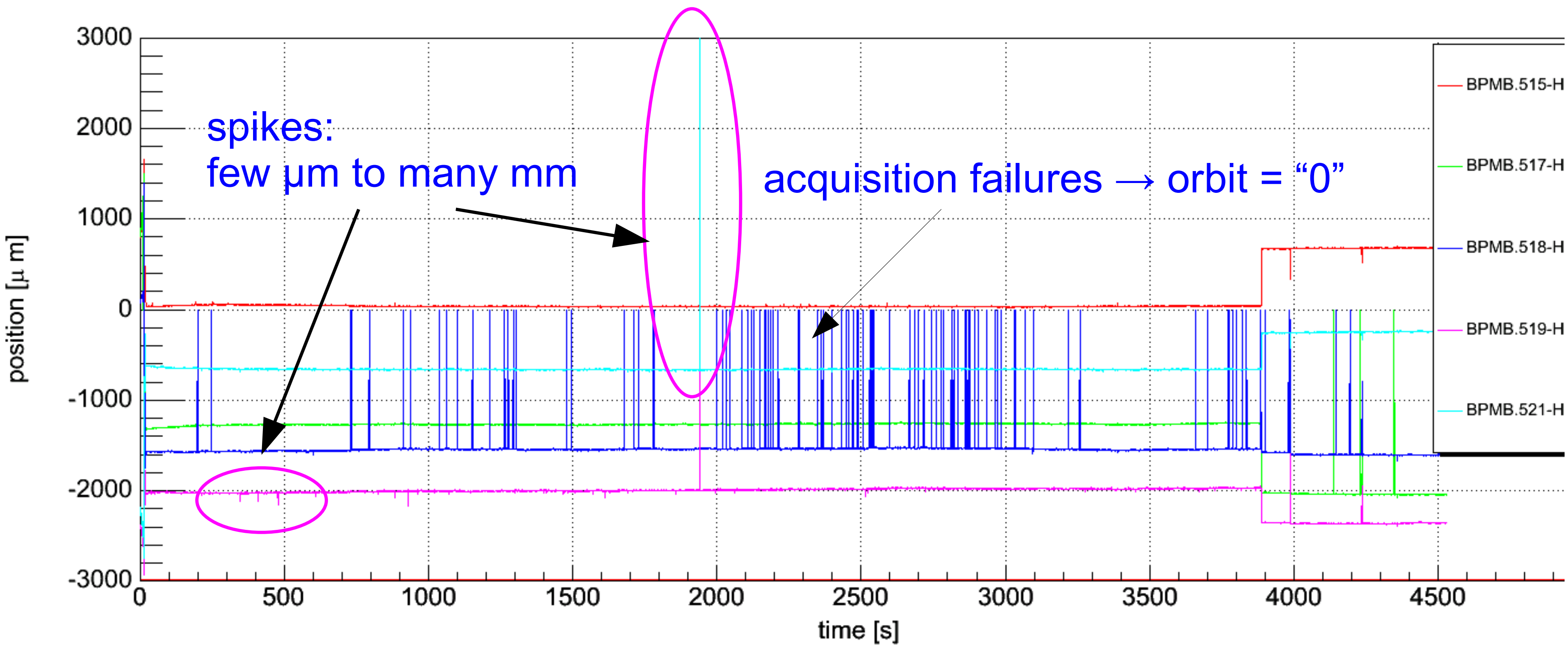
2. aperture scan to verify abs. BPM offsets and machine protection setup:
   → checks the absence of local bumps that may potentially compromise proper function of collimation
   - takes < 25 second/beam/plane @ 7σ (COD power converter speed)





LHC BPM Prototype in the SPS:

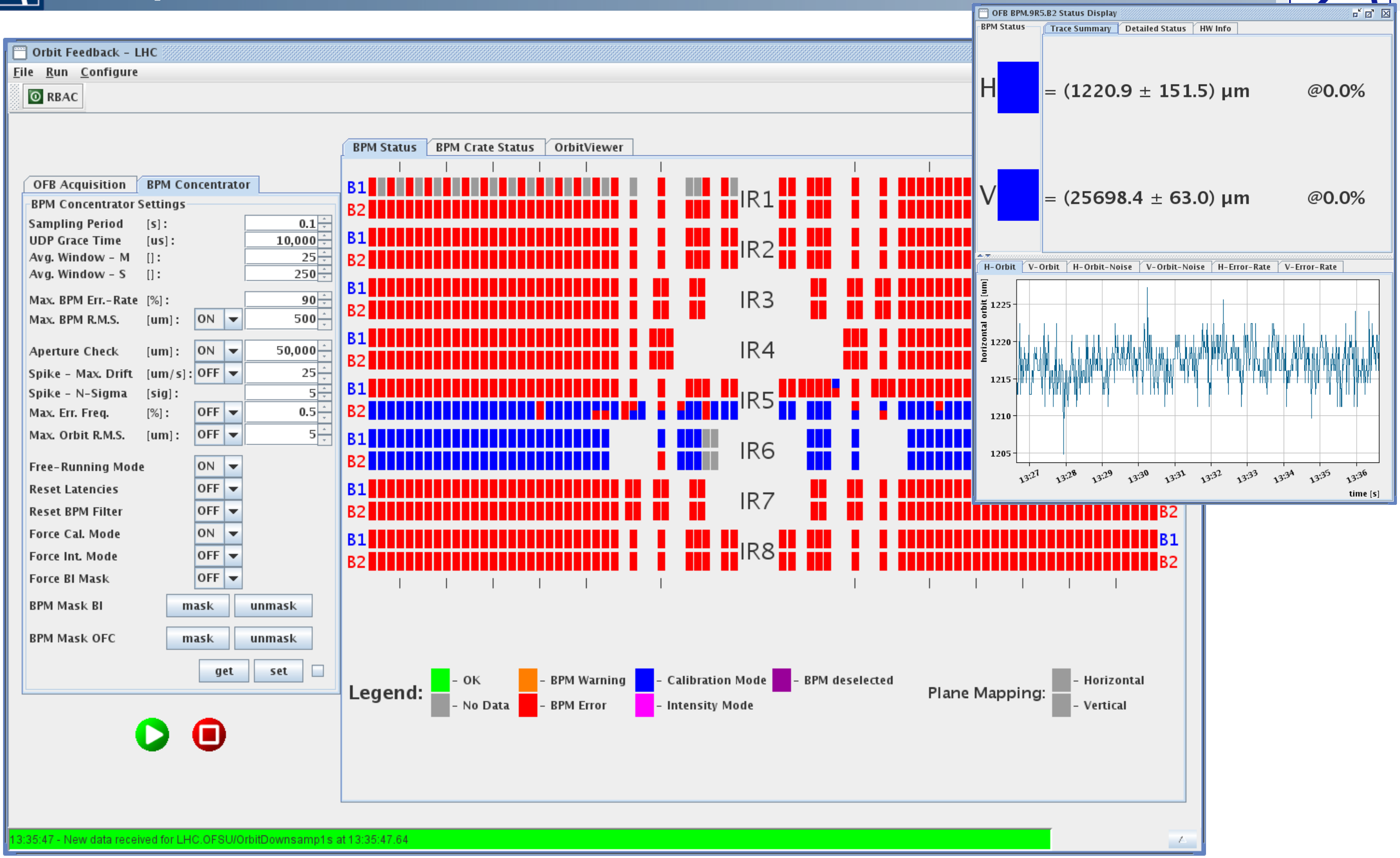
- Most common failure symptoms: no orbit info available, spikes and steps
  - Short term (few ms-s): Zero Order Holder (ZOH)
  - Long term: Disable BPM in feedback and recalculate SVD pseudo-inverse matrix
- Only a few drifts observed: systematic on bunch length & bunch intensity



1. BPM phase advance of ~π/4:
   - Twice the sampling than minimum required to detect β-oscillation
   - Distribution of consecutive BPMs on different front-ends (minimise impact of front-end drop outs)
2. Detection of erroneous BPMs, reject if the following applies:
   ($x_i(n)$=position at i^{th} monitor, n: sampling index; σ_{orbit}= residual orbit r.m.s.)
   - Cuts in Space Domain:
     - $x_i(n)$ > machine aperture
     - $x_i(n) - x_{i,ref} > 3\cdot\sigma_{orbit}$
     - Option: interpolate position from neighbouring BPMs (as done in APS)
   - Cuts in Time Domain (Spike/Step detection!):
     - $\Delta x_i(n)=x_i(n)-x_i(n-1) > 3\cdot\Delta x_{rms}(n\rightarrow n-m)$ (dynamic r.m.s. of last 'm' samples)
     - filters to reduce noise (e.g. low integrator gain)
     - re-enable BPMs with new reference if dynamic r.m.s. is stable for n seconds
     - ...
   - Difficult to detect coherent, very slow or systematic drifts

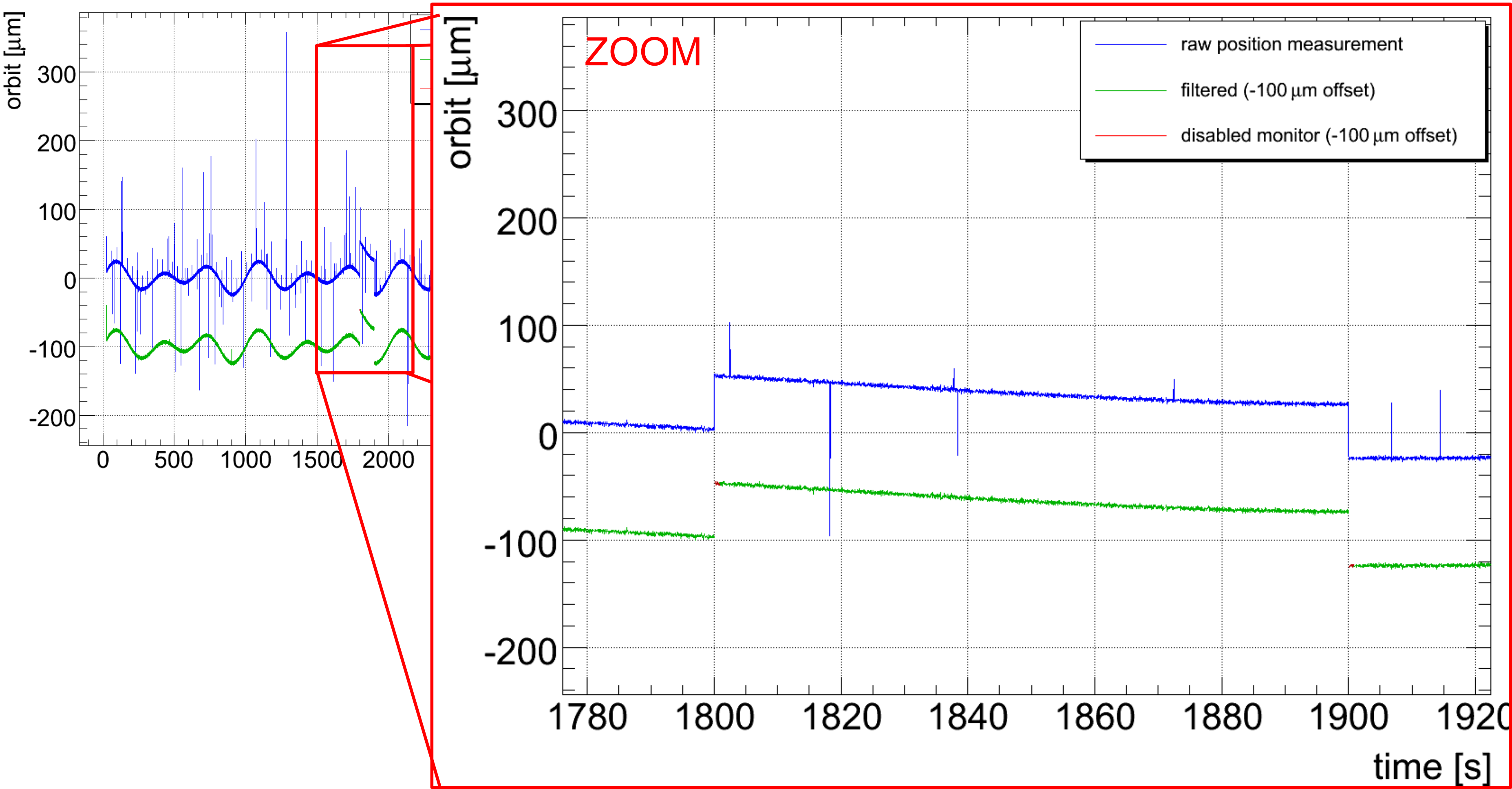
     (e.g drift of BPM electronics vs. systematic ground motion, temperature drifts ... etc.)
3. Use SVD based correction → less sensitive to BPM errors

LHC Orbit Feedback BPM Surveillance I/II
Graphical User Interface



AB Seminar – LHC Beam-Based Feedbacks, Ralph.Steinhagen@CERN.ch, 2008-09-04

- Orbit feedback procedure in case of a
  - spike: fail-safe choice of assuming that orbit is at reference position
  - step: pause feedback, average orbit before and after detected step (used for a-posteriori calibration) and continue from new averaged orbit



LHC Orbit Feedback BPM Surveillance II/II
First LHC Beam – As seen by the Orbit Feedback

LHC: Feedbacks on Tune, Chromaticity and Coupling

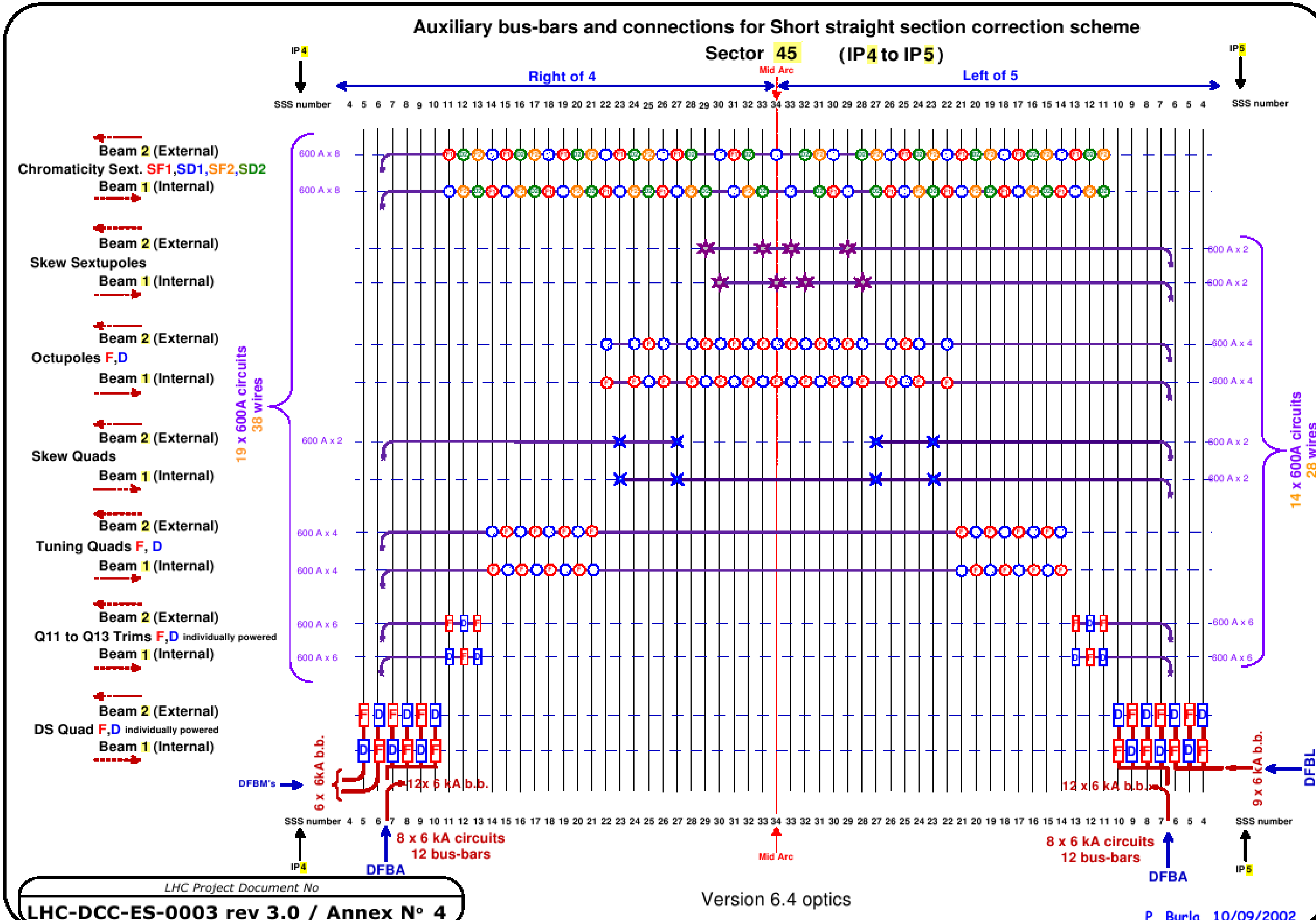
- Tune, Chromaticity and Betatron-coupling Loops can from a controls point of view be based on the same principles/scheme/architecture as used for the orbit/energy feedback.

- 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

Total Number of (FB) Corrector Circuits

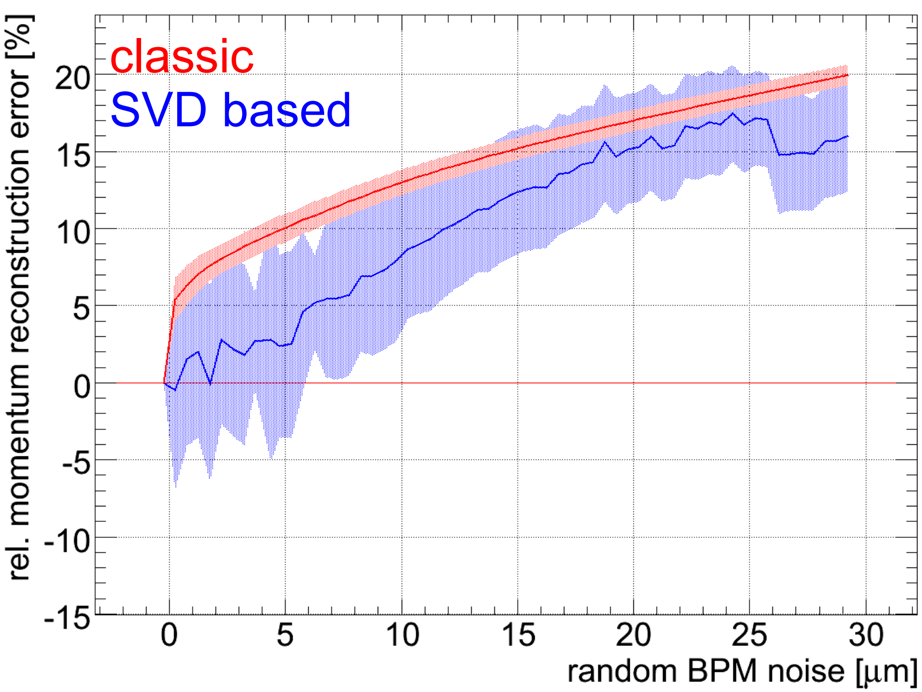
- Orbit: 530 correction dipole magnets/plane (71% are of type MCBH/V, ±60A)
  - total 1060 individually powered magnets (60-120 A)
  - ~30 shared between B1 & B2
- Tune:
  - 16x ±600A circuits powered from even IPs (2, 4, 6, 8), 2 families
  - independent for Beam 1&2, but coupling between planes
  - 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!

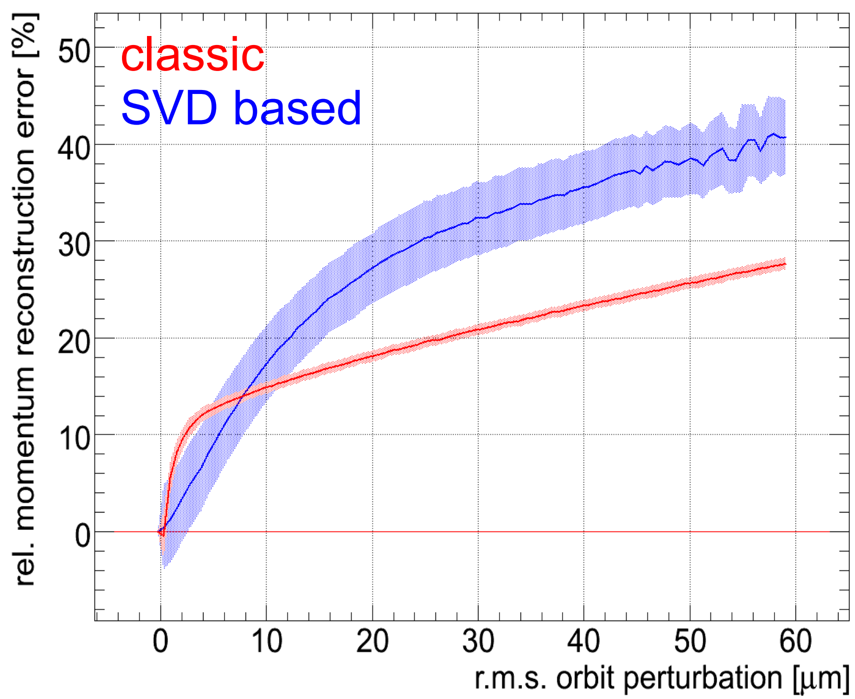
Total Number of (FB) Corrector Circuits
Powering Layout of the SSS Correction Scheme IP4↔IP5



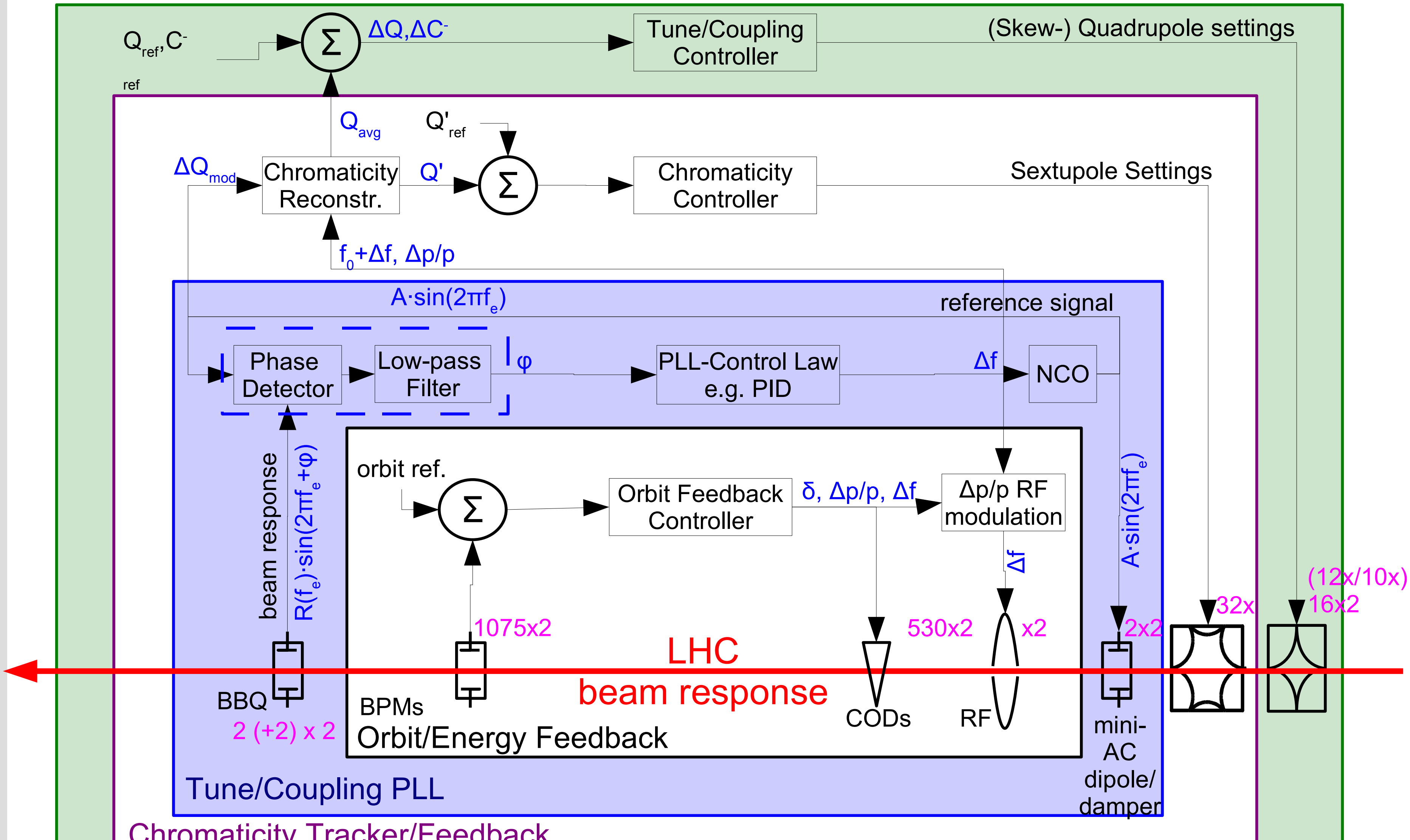
- LHC relies with multiple feedback loops that simultaneous act on the beam:
  - beam-based feedbacks on: orbit, energy (radial loop), tune, chromaticity, coupling, luminosity, fast transverse feedback (damper), synchro-loop, ...
  - (N.B. Most other machines rely only on one, two rarely three feedbacks)
- Feedbacks on non-orthogonal/non-independent parameters can/will cause cross talks and even instabilities if not designed properly! Some choices:
  - Decoupling of the parameter space:
    - Orbit FB (betatron-pertubations) vs. Energy FB (dispersion orbit)
  - Decoupling of operational ranges (either e.g. amplitude or time scales)
    - Q-PLL being faster than Q' tracker faster than actual Q loop
    - Q-PLL – transverse feedback cross-talk:
      - PLL operates within transverse feedback's “noise”
      - PLL operates on single bunch exempted from other fast Fbs.
  - Introducing a Master-Slave Structure:
    - Energy FB & Q' Tracker sharing the same reference
    - Orbit FB being the slave to the luminosity FB, local bumps ...

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





...Conquer: Cascading between individual Feedbacks



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

Summary

- Feedback architecture, strategies and algorithms are well established
  - The same feedback architecture for orbit, energy, tune, chromaticity and betatron coupling correction
- Feedbacks are most useful when used at an early stage
  - Possibility to use tracker/feedback signals as feed-forward for next cycles
- Paradigm change: trim of parameter reference rather than PC currents
- Feedbacks are only as good as the measurements they are based upon!
  - Three main lines of defense against BPM errors and faults:
    1. Pre-checks without beam using the in-build calibration unit
    2. Pre-checks with Pilot and Intermediate beams (aperture scans)
    3. Continuous data quality monitoring through Orbit Feedback
- LHC relies on multiple simultaneously running feedback loops
  - Cross-talk between Feedback is minimised by early stage design

... after the LHC feedback commissioning

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

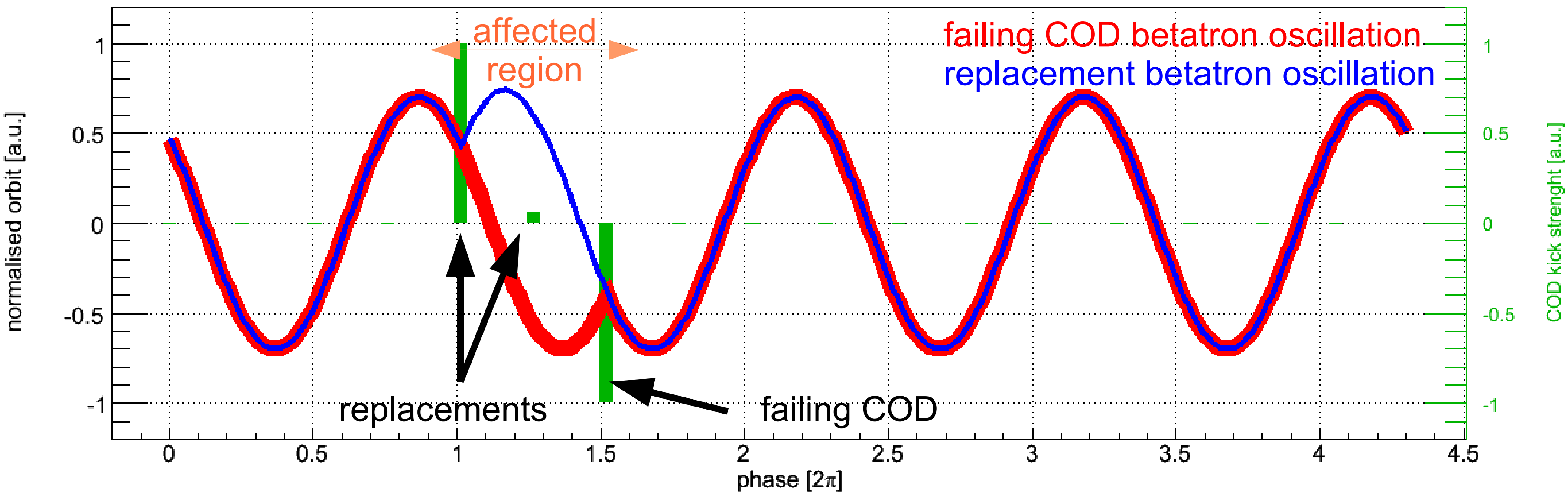
Special thanks to: L. Jensen, P. Karlsson, M. Lamont, S. Redaelli, G. Sivatskiy

Reserve Slides

Backup Scenario: COD/Power-Converter Failure

What will the feedback do in case of a fast COD drop-out?

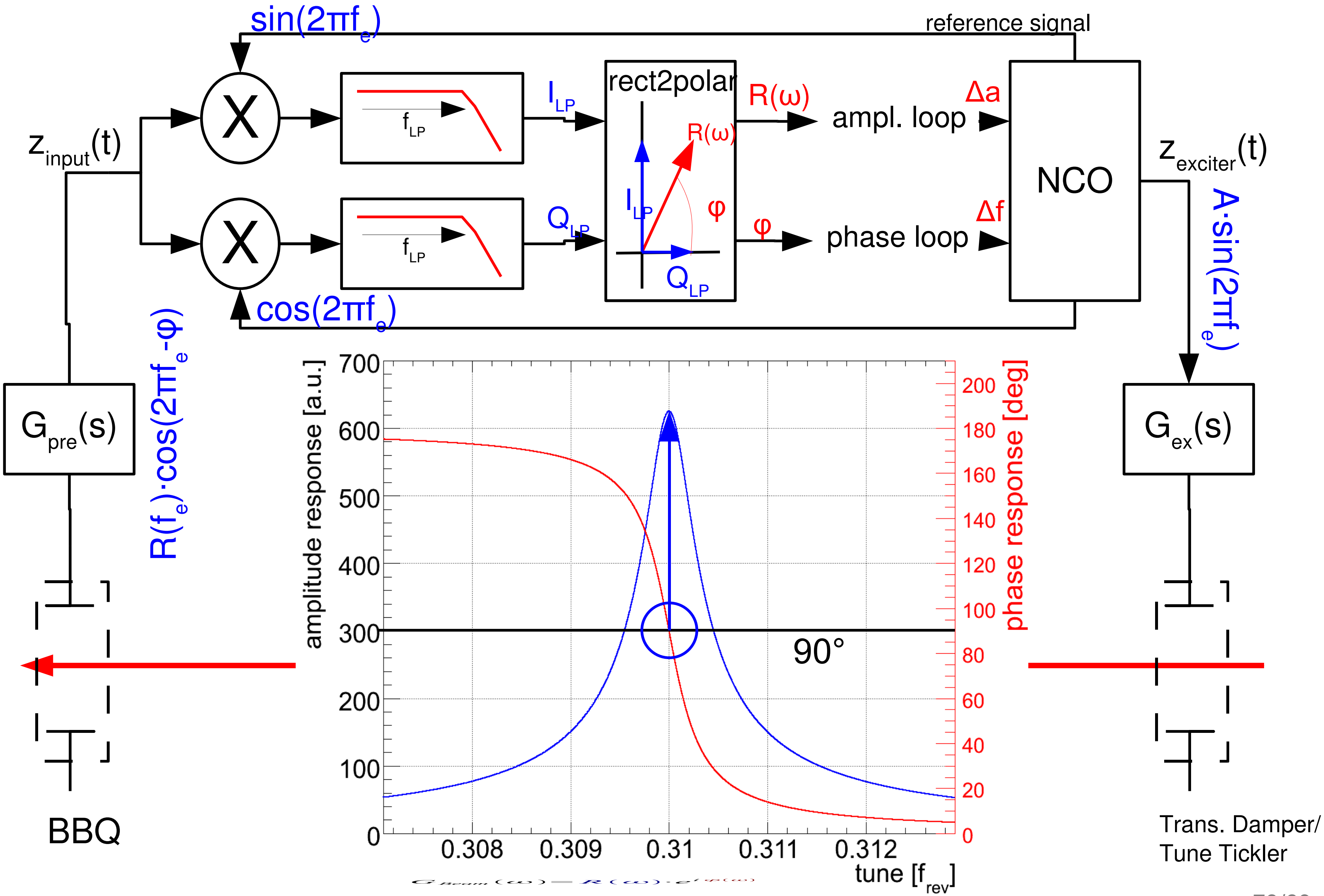
- The effect of the failing COD can for sufficiently long (spacial) distances be compensated and replaced through a pattern of correctors:



– Though a minimum two correctors are required, it is favourable to spread replacement pattern over more CODs (e.g. use intrinsic SVD property):

– smaller maximum currents in the pattern
  - avoid hitting individual COD's maximum current
  - single COD failure becomes less critical
  - faster reaction time since max $\Delta I/\Delta t = n \cdot 0.5$ A/s (speed determined by time to reach pattern's largest COD current)

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



Gretchen Frage: "How many eigenvalues should one use?"

low number of eigenvalues:

(e.g. ~20% of total # e-values)

- more global type of correction:
  - use arc BPM/COD to steer in crossing IRs
  - less sensitive to BPM noise
  - less sensitive to single BPM faults/errors
  - less sensitive to single COD/BPM faults/errors
- robust wrt. machine imperfections:
  - beta-beat
  - calibration errors
- easy to set up
- ...
- poor correction convergence
- leakage of local perturbations/errors
  - not fully closed bump affects all IRs
  - squeeze in IR1&IR5 affects cleaning IRs
- ...

high number of eigenvalues:

(still without using singular solutions)

- more local type of correction
  - more precise
  - less leakage of local sources onto the ring
  - perturbations may be compensated at their location
- good correction convergence
- ...
- more prone to imperfections
  - calibration errors more dominant
  - instable for beta-beat > 70%
- more prone to false BPM reading
  - Errors & faults
- ...

orbit stability requirement

feedback stability requirement

Space Domain: local within global correction

- The orbit and feedback stability requirements vary with respect to the location in the two LHC rings. In order to meet both requirements:
  - Implement robust global correction (low number of eigenvalues)
  - fine local correction where required (high number of eigenvalues or simple bumps):
    - Cleaning System in IR3 & IR7
    - Protection devices in IR6
    - TOTEM

coarse global SVD with fine local “SVD patches” (no leakage due to closed boundaries)

minor disadvantage: longer initial computation
(global + local SVD + merge vs one local SVD)

coarse global SVD with weighted monitors where required (ω = 1 ... 10)

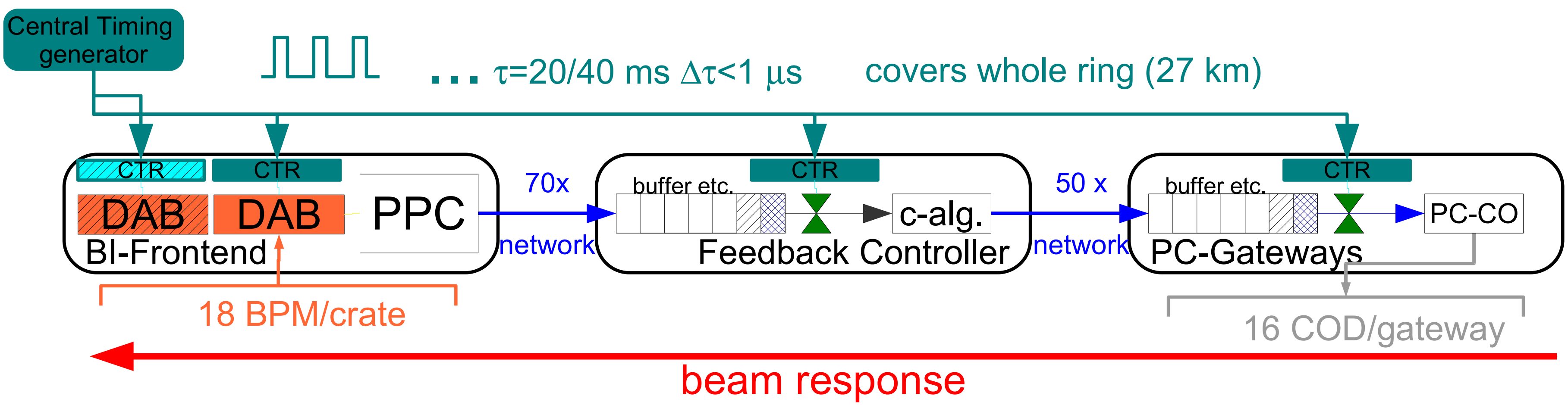
disadvantage:
•total number of to be used eigenvalues less obvious
•Matrix inversion may become instable

free orbit manipulation (within limits) while still globally correcting the orbit

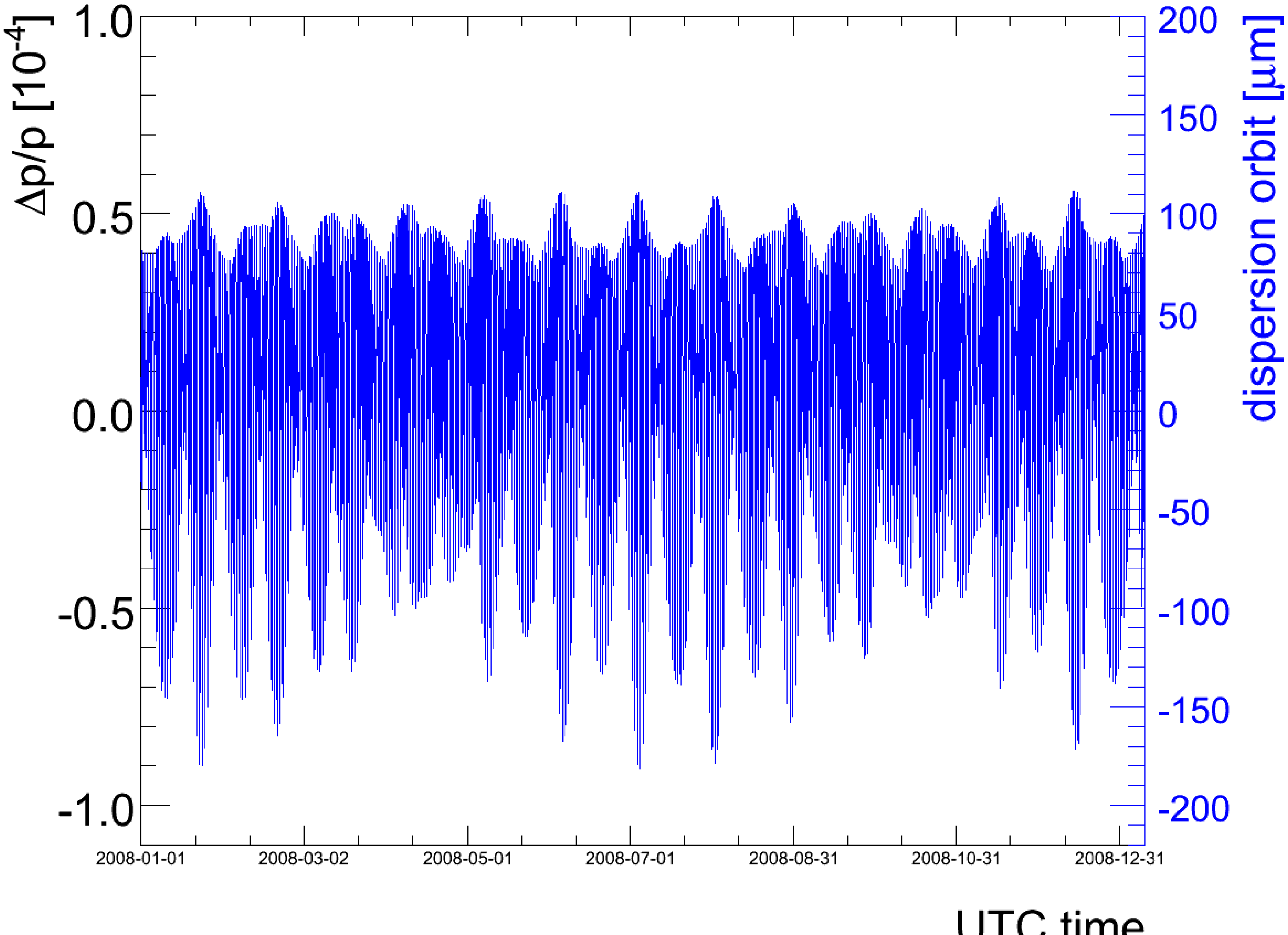
Remaining Jitter Compensation: Fix Max Loop Delay

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...

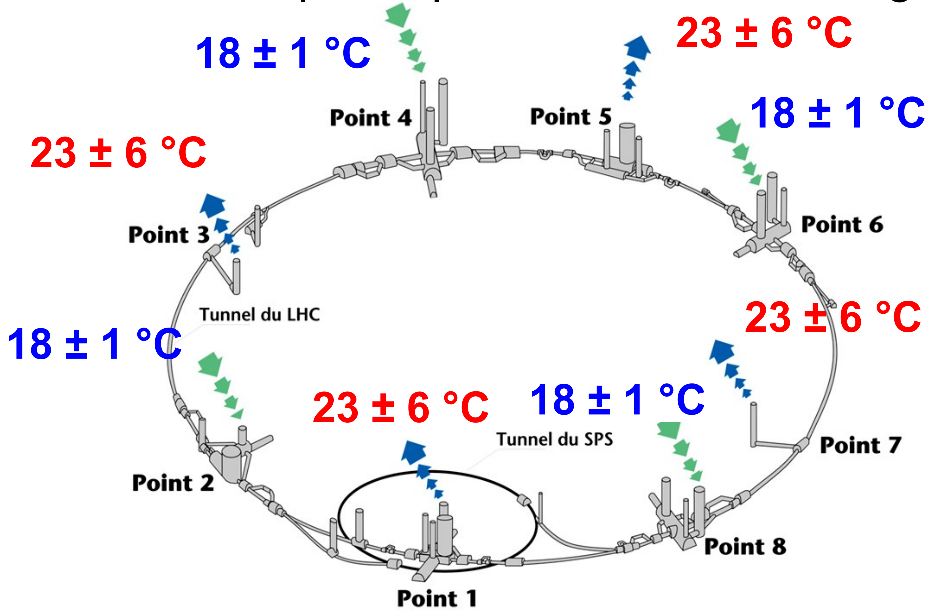


This Years Solar/Lunar Tides Prediction



Thermal Expansion of Girders

- Mechanism: Orbit feedback intrinsically aligns with respect to the BPMs that are either attached to the quadrupoles or have similar girders



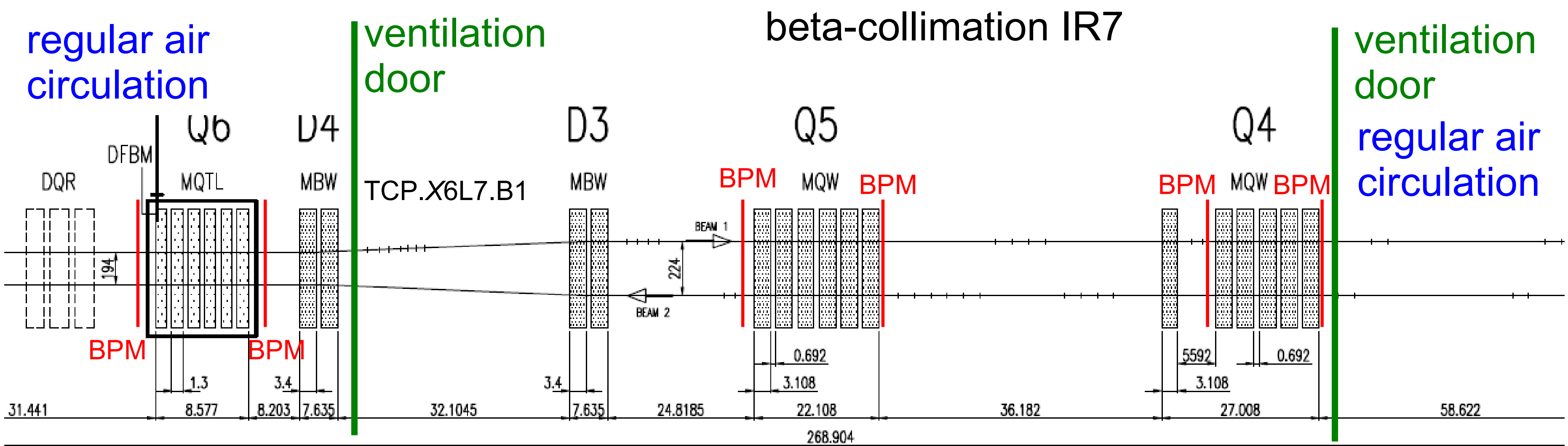
- Thermal expansion, steel $\alpha_{steel} \approx 10\text{-}17 \cdot 10^{-6}\,K^{-1}$ (BS:970, DIN18800):

$$\Delta x = x_0 \cdot \alpha \cdot \Delta T$$

- Systematic shift of beam reference system with respect to non-moving external reference (e.g. potentially collimators):
  - Cryo-Magnets: $x_0 \geq (340 \pm 20)$ mm → Δx ≈ 3.4 - 5.8 μm/°C
  - Warm equipment: $x_0 \approx 950$ mm → Δx ≈ 9.5 – 16 μm/°C

Thermal Expansion of Girders

- However, temperature variations in odd IRs might be larger due to different thermal loads in neighbouring arcs.
- Special case: Collimation in IR7



- Closed air circulation in IR7: T estimate as high as 35°C
- Already $\Delta T = \pm 2°C \rightarrow \Delta x \approx \pm 20$ µm, Collimation: ± 50 µm might be tolerable (TOTEM 10 µm requirements – a midnight summer dream?)
- CNGS/Ti8: Estimates where ≈ 10°C off (measured 25°C vs. estimated 35°C)
- Wait for LHC commissioning with beam and real temperature experience

back

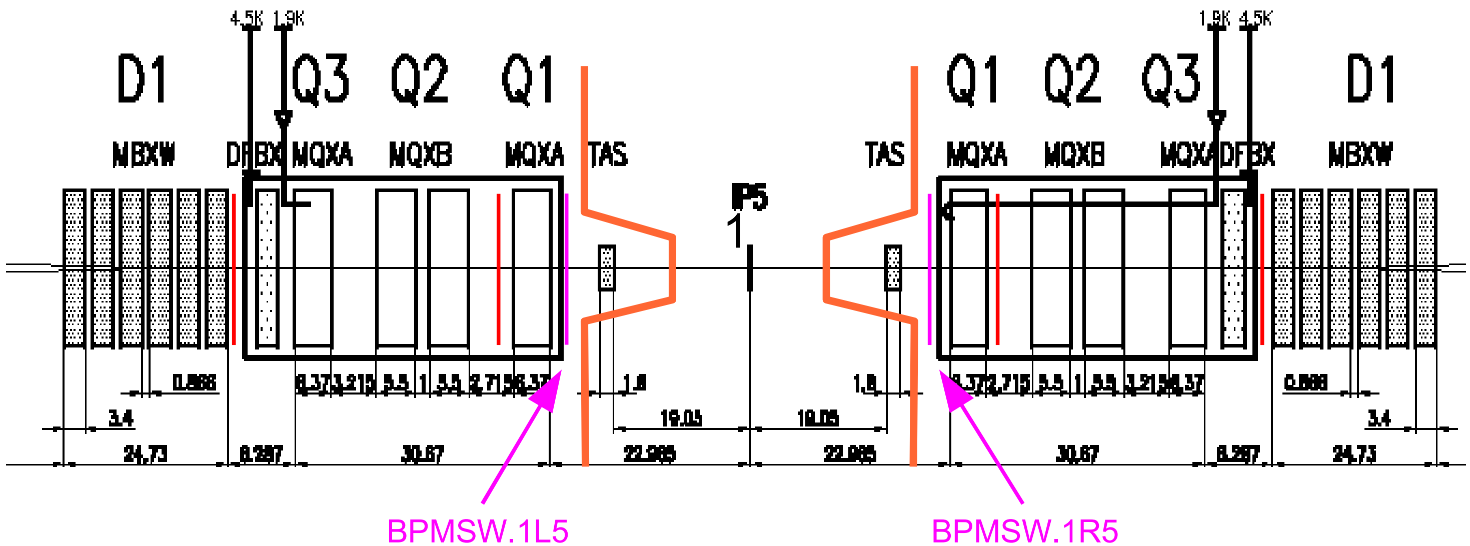
Thermal Expansion of Girders - Experimental Insertions

- Left-Right temperature gradient:

tunnel air:
$T_1 \approx 23 \pm 6$ °C

cavern:
$T_3 \approx 23 \pm 6$ °C (?)

tunnel right:
$T_2 \approx 23 \pm 6$ °C

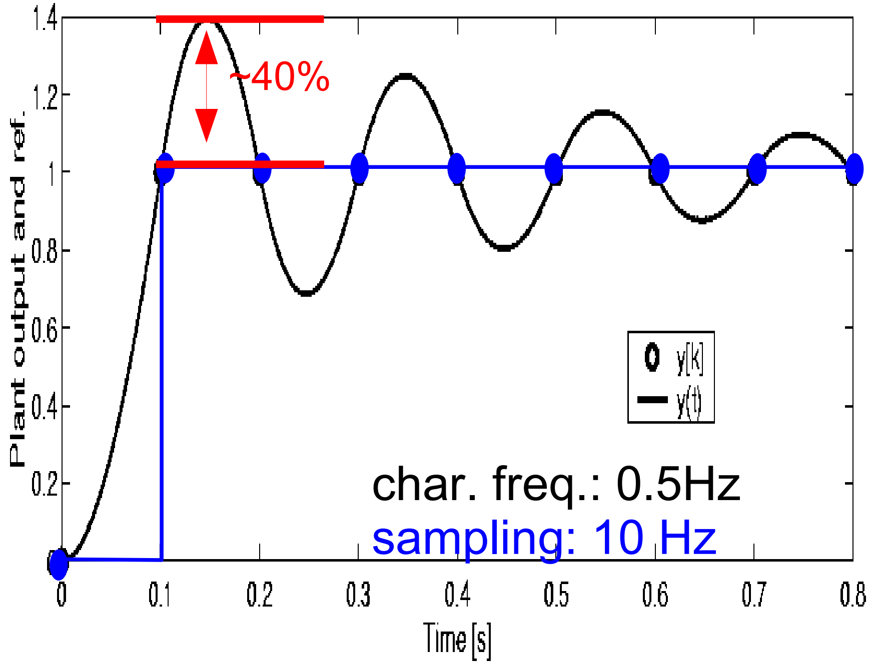


- $T_1 \neq T_2 \neq T_3$
  - powering of arc equipment (CODs, ...) → dyn. heat-load asymmetry
  - IR4 (RF, BI) → IP5 ← IR6 (beam extraction)
- Working assumption: $\Delta T = |T_2 - T_1| \approx \pm$ 1...2 °C → $\Delta x_{thermal} \approx$ 16-32 μm

Classic argument: Analogue vs. Digital Design

- Among many arguments:
  - Pro analogue: most process to be controlled are analogue
  - Pro digital: most controller are nowadays digital
    - "Con-example": digital only controller design (inter-sample response)

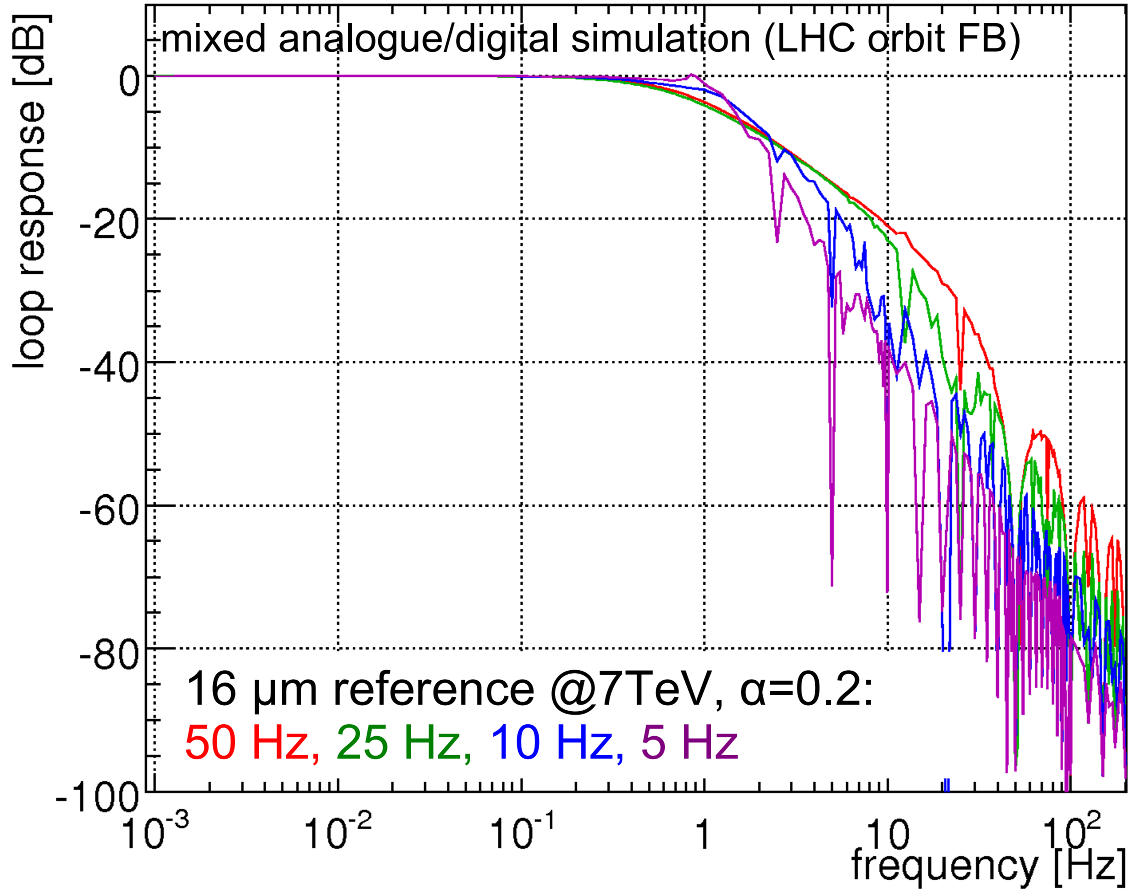
time domain:



perfect digital response
but ~40% "analog" overshoot

- Mitigation: iterative design approach between analogue and digital domain
  - sampling of simulation needs to be significantly larger than FB sampling
  - can be time consuming (especially for large MIMO systems)
  - beware of numerical instabilities and artefacts

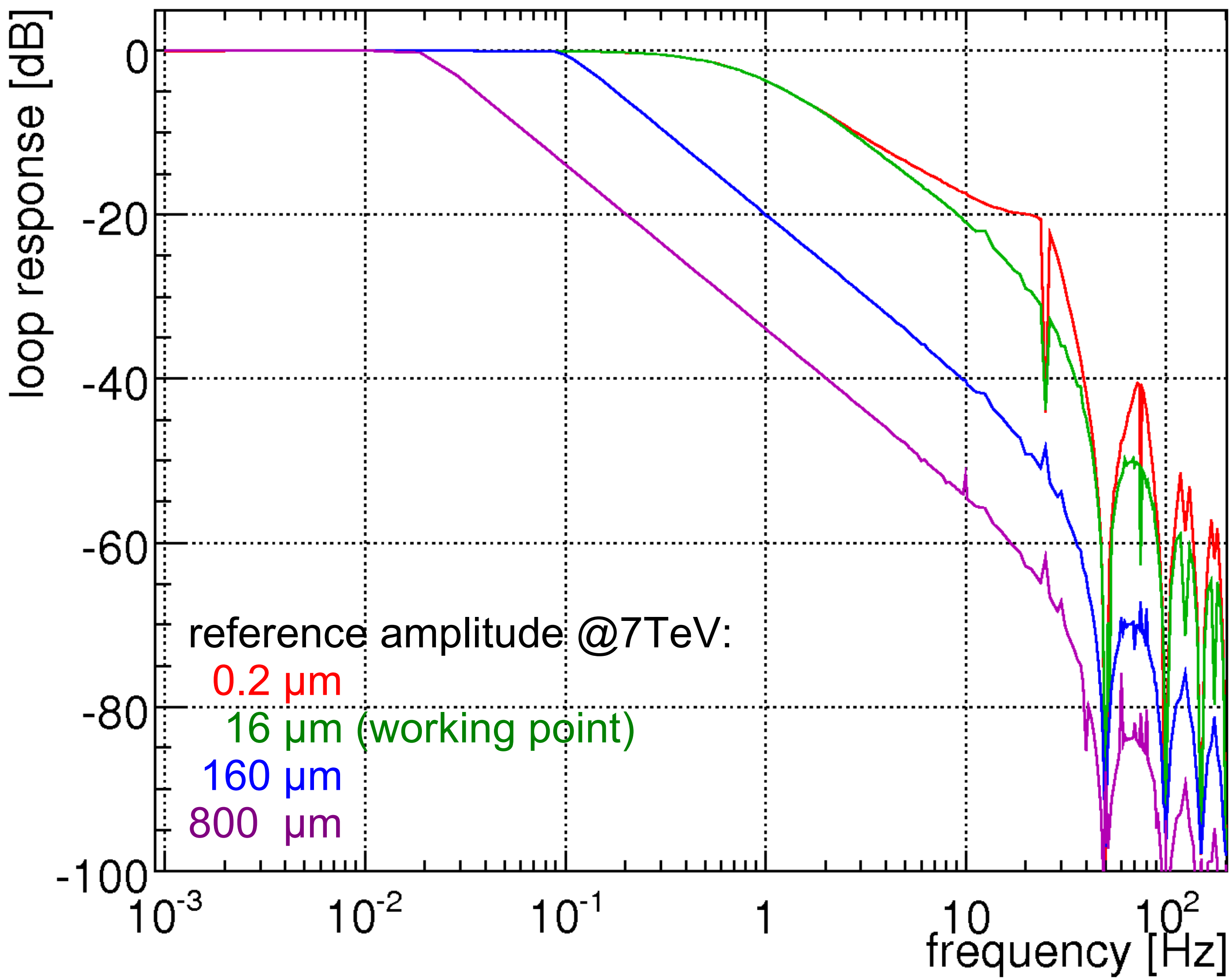
- ... 10Hz sampling to achieve a closed loop 1Hz bandwidth:



  - ... a theoretic limit assuming a perfect system (no noise, model errors)!
  - common sense/advise: f_s > 25 ...40 x desired closed-loop bandwidth f_{BW}

Nominal Feedback Response T_0

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



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

- 2nd Example: classic 2nd order process:

$$G(s)=\frac{K_0\omega_0^2}{s^2+2\zeta\omega_0\ s+\omega_0^2}$$

K_0: open loop gain, ω_0: characteristic frequency
ζ_0: attenuation

- Using standard ansatz:

$$Q(s)=F_Q(s)\cdot G^i(s)=\frac{\omega_{cl}^2}{s^2+2\zeta_{cl}\omega_{cl}\ s+\omega_{cl}^2}\cdot G^i(s)$$

- yields classic PID controller (optimal gains):

$$D(s) = K_p+K_i\cdot\frac{1}{s}+K_d\cdot\frac{s}{\tau_d s+1}$$

with:

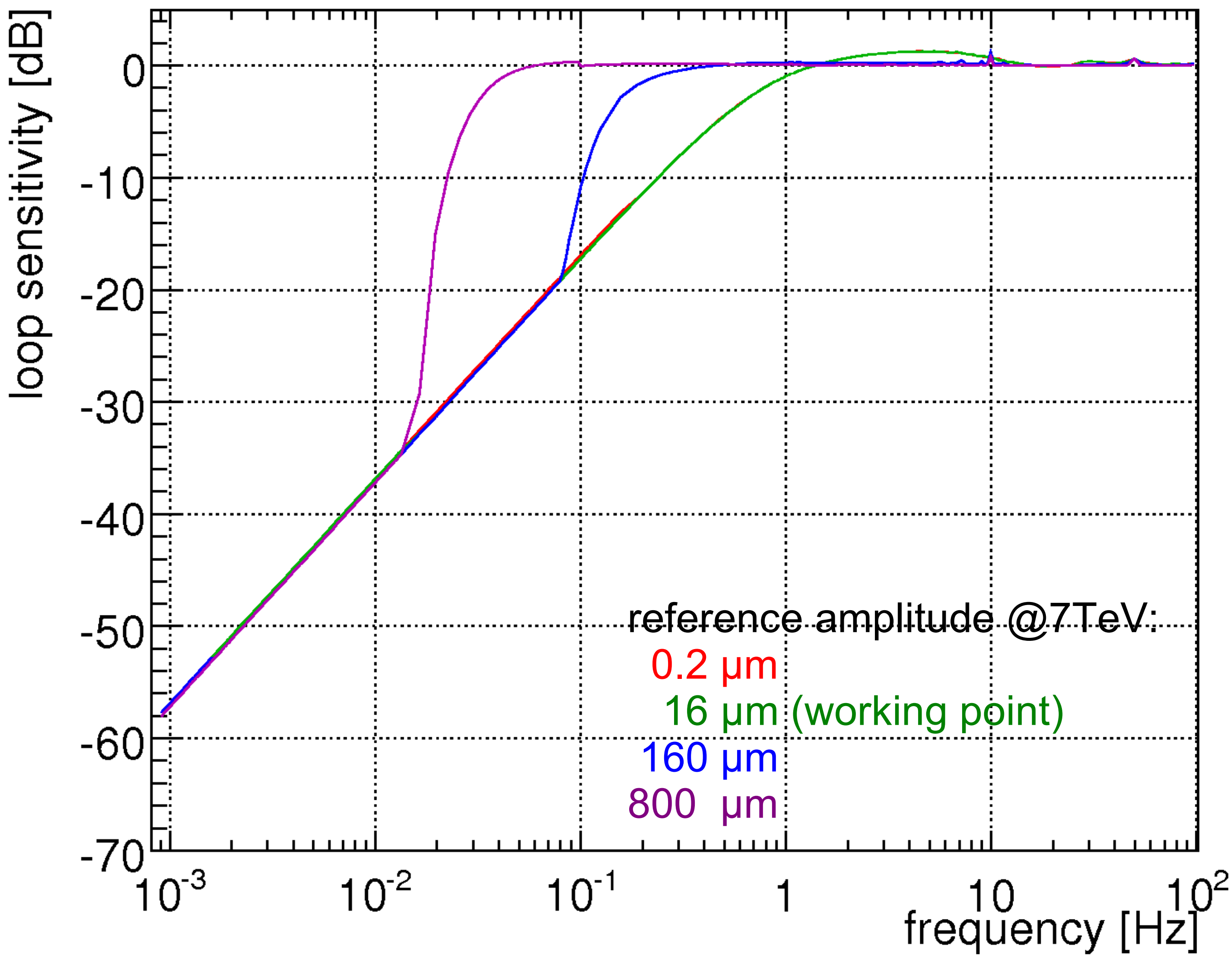
$$K_p = \frac{4\zeta_{cl}\zeta_0\omega_0\omega_{cl}-\omega_0^2}{4\mathrm{K}_0\zeta_{cl}^2} \qquad K_i = \frac{\omega_0^2\omega_{cl}}{2\mathrm{K}_0\zeta_{cl}}$$

$$K_d = \frac{4\zeta^2\omega_{cl}^2-4\zeta_0\omega_0\zeta_{cl}+\omega_0^2}{8\mathrm{K}_0\zeta_{cl}^3\omega_{cl}} \qquad \tau_d = \frac{1}{2\zeta_{cl}\omega_{cl}}$$

– further simplification: require critical damping $\rightarrow \zeta_{cl}:=1$
  - ω_{cl} ~ 'open loop bandwidth' is the remaining free parameter

Nominal Feedback Disturbance Rejection S_{d0}

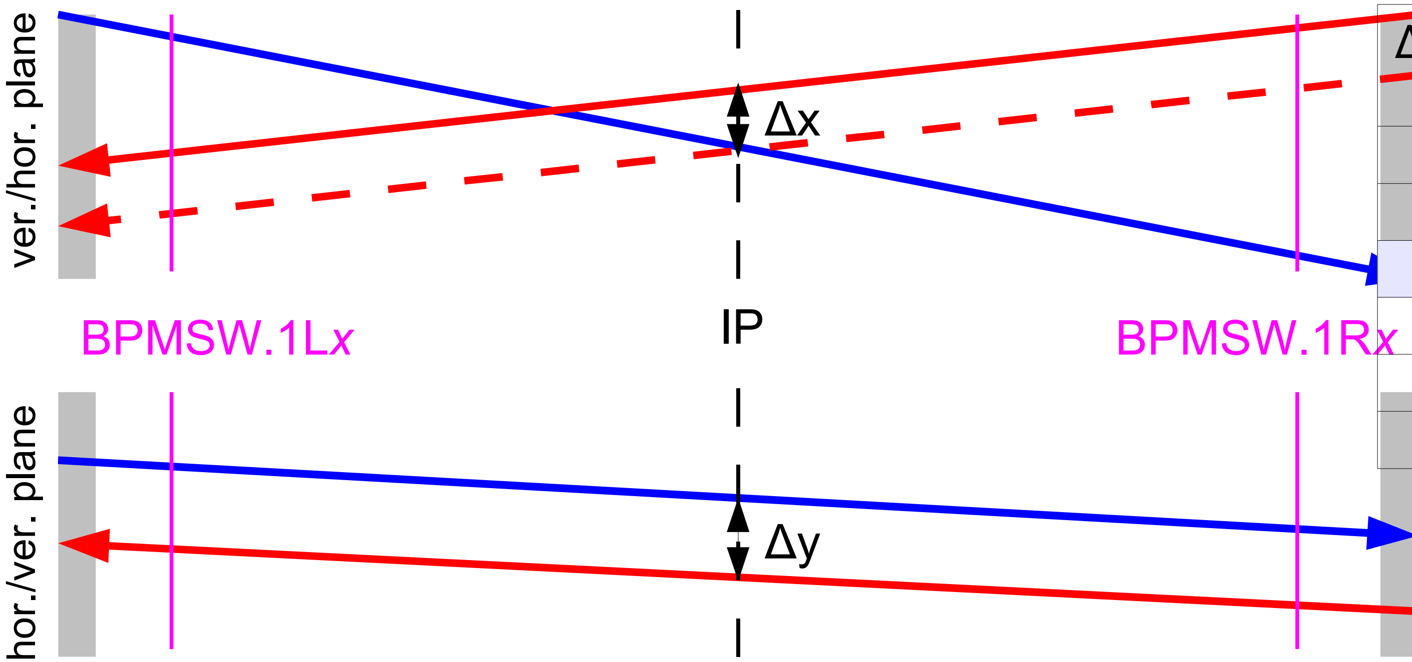
- Full LHC orbit simulation @1KHz sampling, (BPM sampling: 25Hz)



Degradation of Nominal Luminosity

$$L = L_{٠} \cdot e^{-\frac{١}{٤}\left[\left(\frac{\Delta x}{\sigma_x}\right)^{٢}+\left(\frac{\Delta y}{\sigma_y}\right)^{٢}\right]} \cdot F_{crossing} \cdot F_{hour\ glass} \cdot \ldots$$

- Effective beam overlap:



Δx/Δy [σ]	L/L_0 [%]
٠	١٠٠
٠.٥	≈ 94
١	≈ 79
٢	≈ 37
٣	≈ 11
٤	≈ ٢

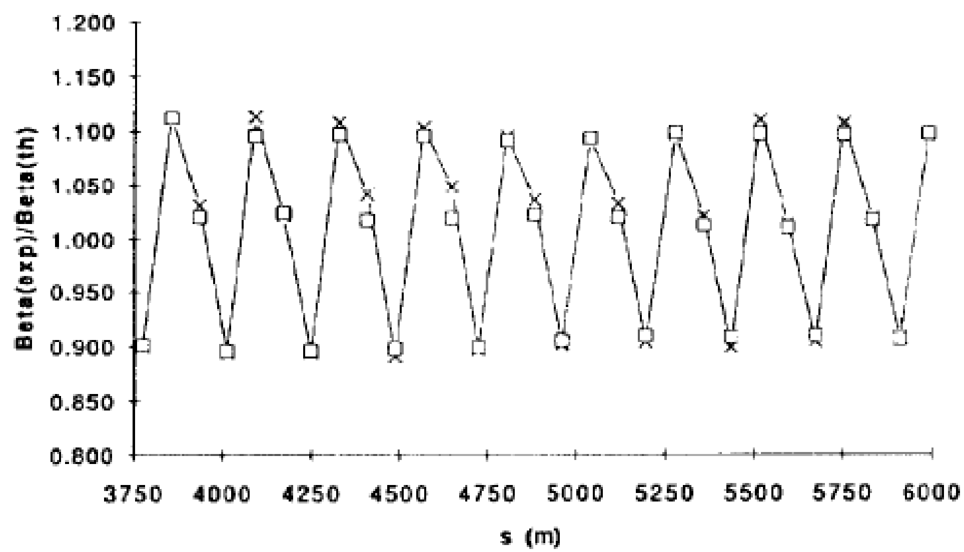
- geometric optics: beam overlap at IP ↔ beam position stability at BPMSW
  - nominal: σ* ≈ 15 µm, e.g. 1σ overlap at IP → 15 µm stability at BPMSW
- N.B. crossing angle “guarantees” one plane overlap (long. shift « 20 µm)

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:

$$\beta = \beta_1 \cdot \frac{\cot(\psi_{12}) - \cot(\psi_{13})}{\cot(\mu_{12}) - \cot(\mu_{13})}$$



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

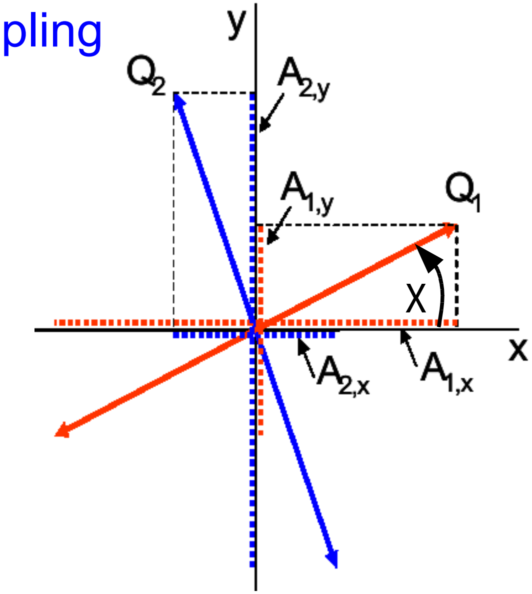
Space- & Time Domain vs. Full MIMO only design

- 'Space domain' corresponds to a "traditional" parameter control
  - numerous strategies/algorithms available: SVD, MICADO/SIMPLEX, ...
  - easy cross-check with slow feedback control (aka. "measure & correct")
- Easier and possible to compensate time-variable and non-linear processes
- Robust and easier to adjust in case of FB element failures/errors
- enables staged commissioning or partial operation of FBs
  - from simple to complex (↔ "operational learning-process")
  - (re-)commissioning has to/will/can be done my non-FB experts

- Alternative: MIMO only approach (using Youla, Kucera, ...)
  - real-world, non-linear and/or time-varying system cannot be inverted
  - mixes beam-physics with accelerator control aspects
  - Requires re-design in case of unavailability of one single device
    - BPM failures, COD failures, ...
  - employment guarantee: FB expert knowledge "mandatory" for follow-up modifications, tuning and operation of the feedback loops

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



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

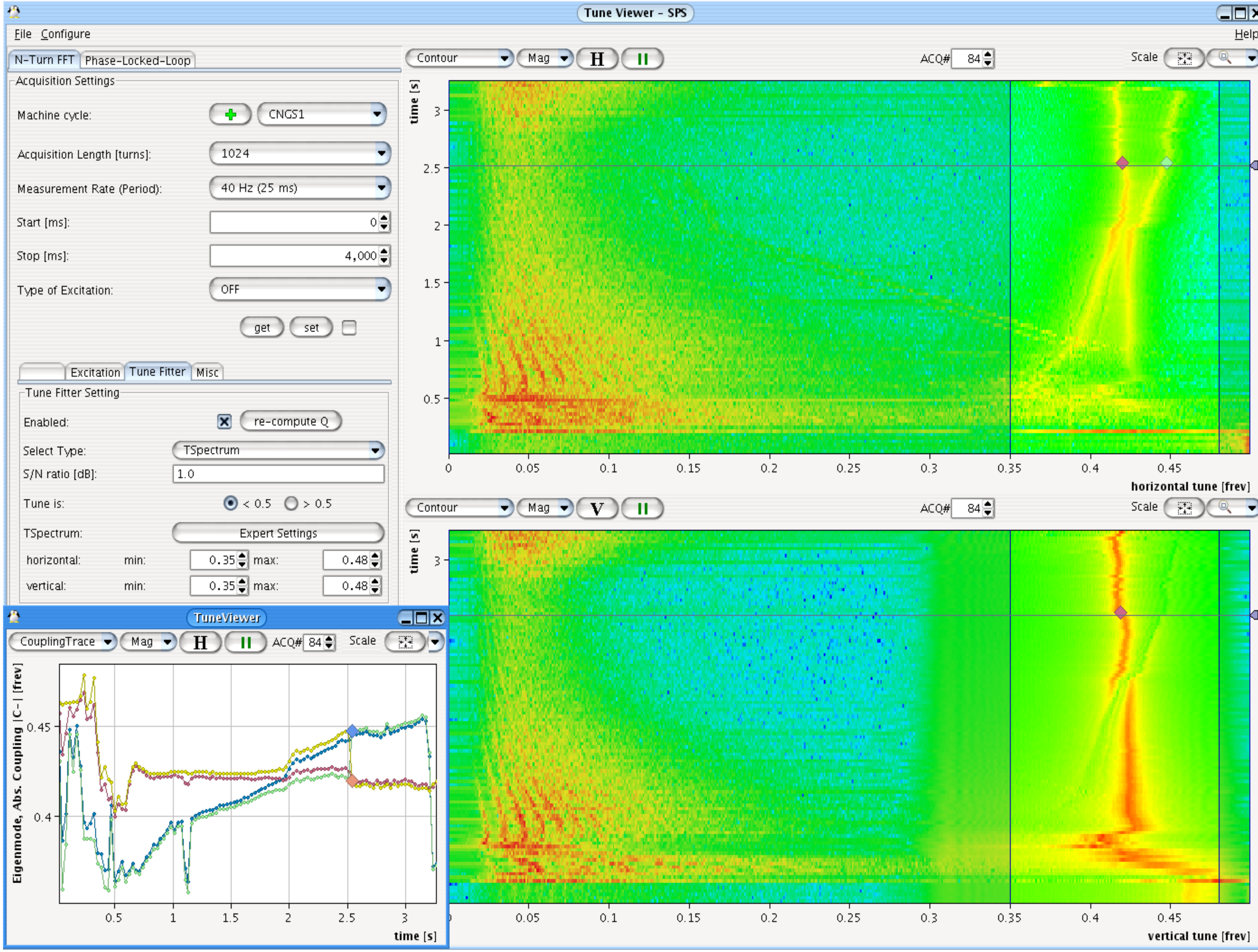
$$\Rightarrow \boxed{\left|C^-\right| = \left|Q_1 - Q_2\right| \cdot \frac{2\sqrt{r_1 r_2}}{(1 + r_1 r_2)} \quad \wedge \quad \Delta = \left|Q_1 - Q_2\right| \cdot \frac{(1 - r_1 r_2)}{(1 + r_1 r_2)}}$$

- Decoupled feedback control:
  - q_x, q_y $\rightarrow$ quadrupole circuits strength
  - $|C^-|$, χ $\rightarrow$ 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 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)

Known Failure Sources:

- From the point of view that the BPM should measure position...
- The measurement may fail if:
  - open connections, short circuits, broken optical fibre, etc.
    - observable: no beam position related change or reading
  - the Wide-Band-Time-Normaliser card is in 'CALIBRATON' mode
    - observable: no true beam position related change or reading
  - BPM 'POSITION/INTENSITY' switch to 'INTENSITY'
    - observable: no beam position related change or reading
  - BPM is set to 'HIGH-SENSITIVITY' ($n_b < 5 \cdot 10^{10}$) though bunch intensity $n_b \gg 5 \cdot 10^{10}$ ($\rightarrow$ 'LOW-SENSITIVITY') and vice versa
    - BPM will trigger on bunch reflection and ghosts, observable: spikes
  - Sensitivity switch not triggered by/synchronised with the orbit feedback
    - observable: steps

...plus lots of other sources which usually cause the absence of orbit acquisitions.