Real-Time Feedback on Beam Parameters

... the essentials

Ralph J. Steinhagen
Accelerator & Beams Department, CERN

- Stability Requirements
- Medium and Long Term Stability
- 3rd Generation Beam-Based Feedback Design:
  - Space & Time Domain
  - Optimal Controller Design and Non-Linear Control
  - Cross-Dependability and Cross-Constraints between Feedback loops

- Disclaimer: cannot go into/bore you with
  - tedious details
  - details on instrumentation

- Goal: provide roadmap to avoid less obvious pot holes

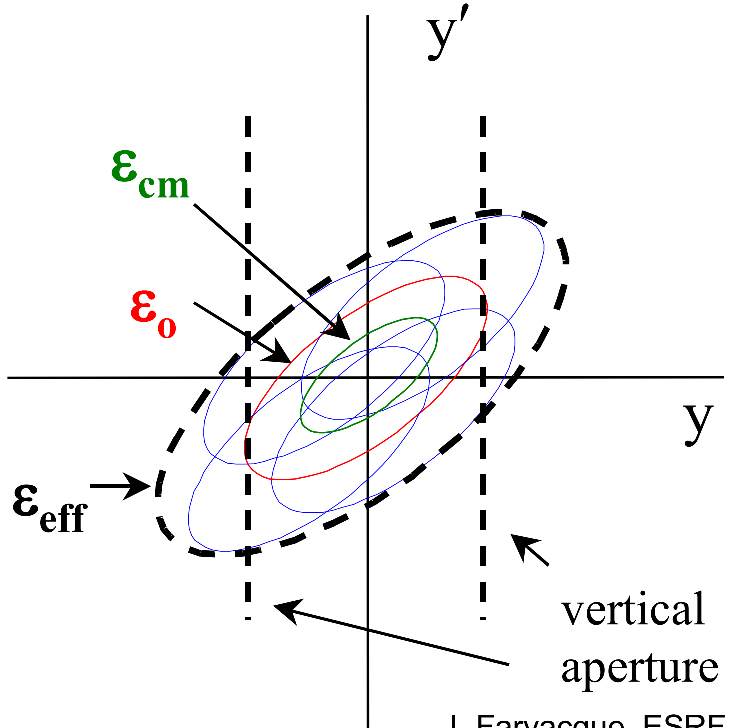
Feedback Overview Worldwide

- 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)

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

→ Nearly all 3rd generation light-sources deploy at least orbit/energy feedbacks[1-3]

- Traditional requirements on beam stability...

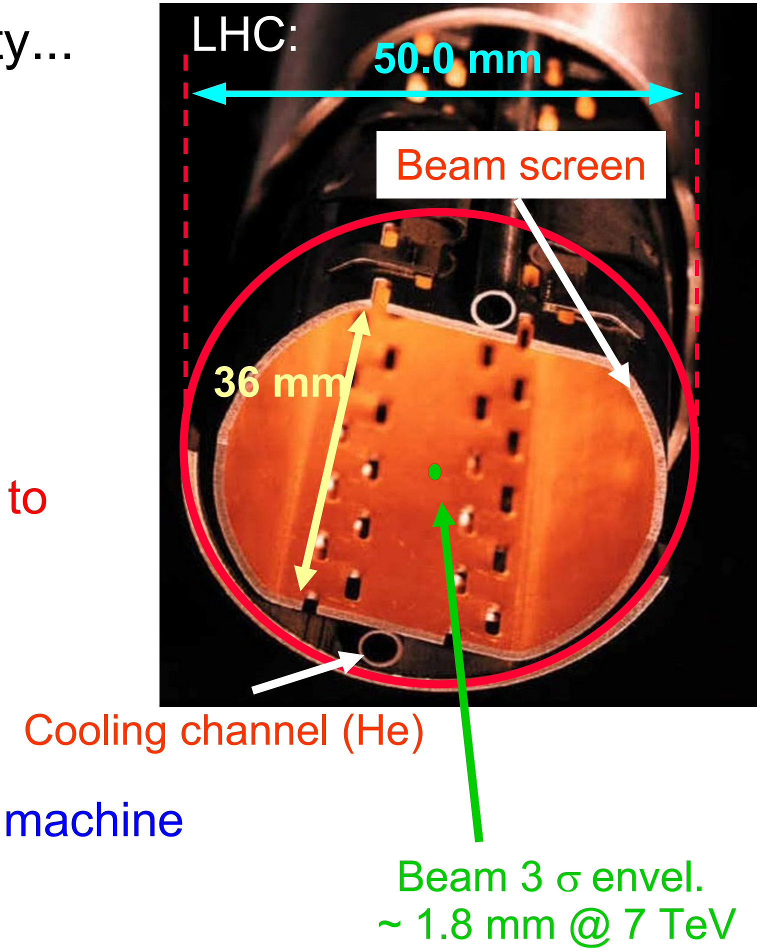
... to keep the beam in the pipe!

- Increased stored intensity and energy:

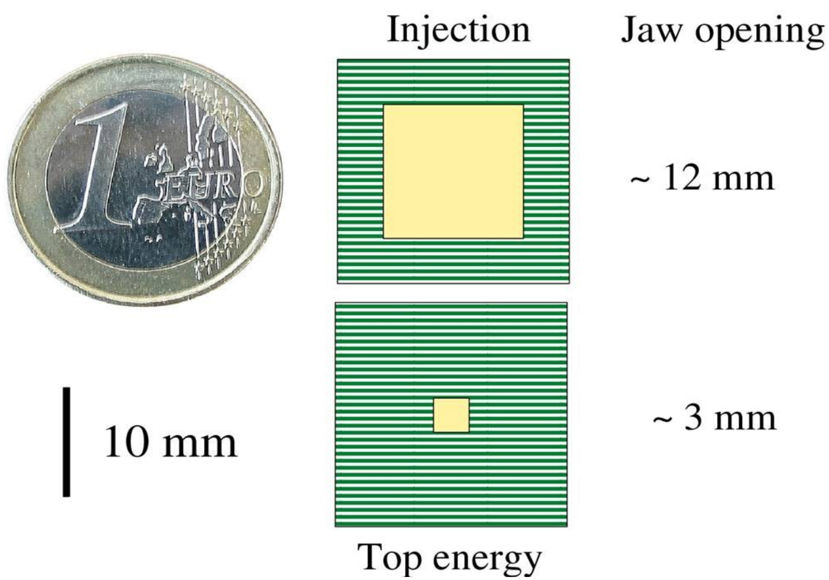
→ sufficient to quenches all magnets and/or to cause serious damage[9]

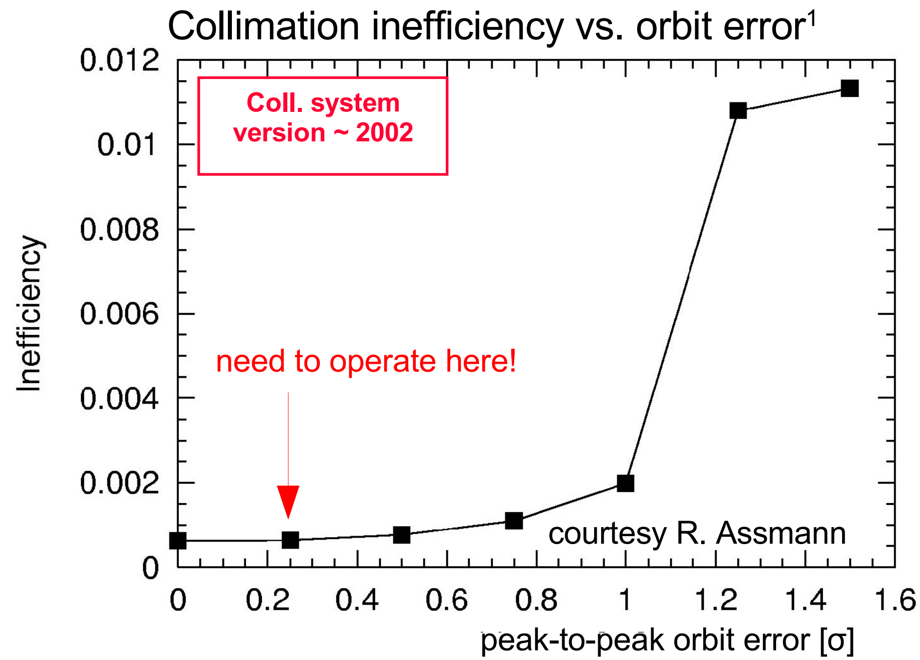
- Requirements depend on:

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



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[10,11]:

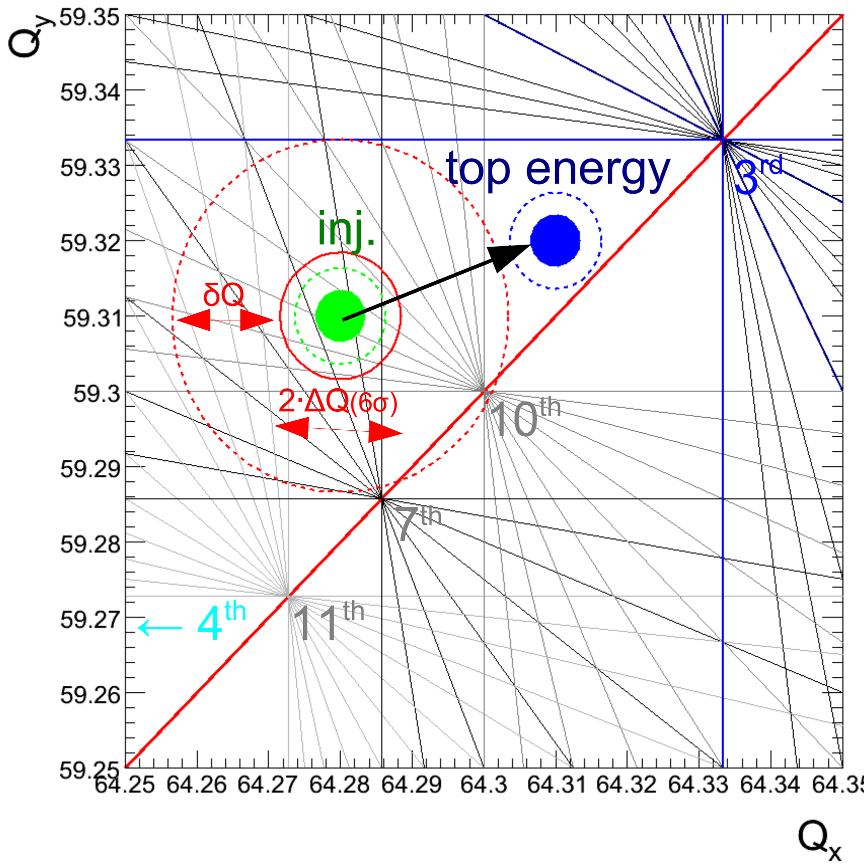
$$\eta = \frac{number\ of\ \ particles\, escaping\, collimation}{number\ of\ \ particles\, impacting\ collimation}$$

$\rightarrow$ LHC: $\eta < 0.001$

- Orbit stability requirement better than $\sigma/6 <\sim 25\ \mu m$ at collimator jaws
- Several other similar and distributed requirements:
  - local ≈ global requirements[13]

Hadron Collider Requirements on Tune and Chromaticity

- Lepton machines: $\delta Q \sim 10^{-2} \dots 10^{-3}$
  - avoid up to ~3rd order resonance
- Hadron machines:
  - negligible synch. radiation damping
  - large tune footprints
  - avoid up to 12th order resonances
- Example LHC:
  - Tune spread (LHC) $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$
    (fixed by available space in Q-diagram)
    → $\delta Q \leq 0.003 \dots 0.001$ (nominal)



  - Chromaticity (SPS: $\Delta p/p \approx 2.8 \cdot 10^{-4}$)
    - allowed max lin. chromaticity[14,15] (5-6 σ, first order):

$$Q'_{max} \propto \frac{\Delta Q_{av}}{\Delta p / p}$$

→ $Q'_{max} \approx 2 \pm 1$ & $Q' > 0$

(expected drifts[1]: $\Delta Q' \approx 140$)

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)

months → weeks → days → hours → minutes → sec → msec

stability defined by accelerator design

stability defined by feedback design

- Feedbacks perform well on short to medium term time scales

- Corrector circuit noise and systematics
  - Hysteresis, eddy-currents, ADC quantisation noise, element failure
    - trend: 10/12 ADC bits → 16 ADC bits[26] → 18/20 ADC bits[27,28,29]
- Beam instrumentation noise and its systematic
  - Dependence on bunch length and intensity (charge)
  - Thermal expansion of girders, drift of electronics
    - mechanically decoupling/stiffening of BPM girders (Invar, Carbon Fibre)
    - extensive temperature stabilisation:
      - tunnel and cooling water
      - discrete photon absorbers
      - water cooled vacuum chambers
      - 'top-up' operation[1,2]

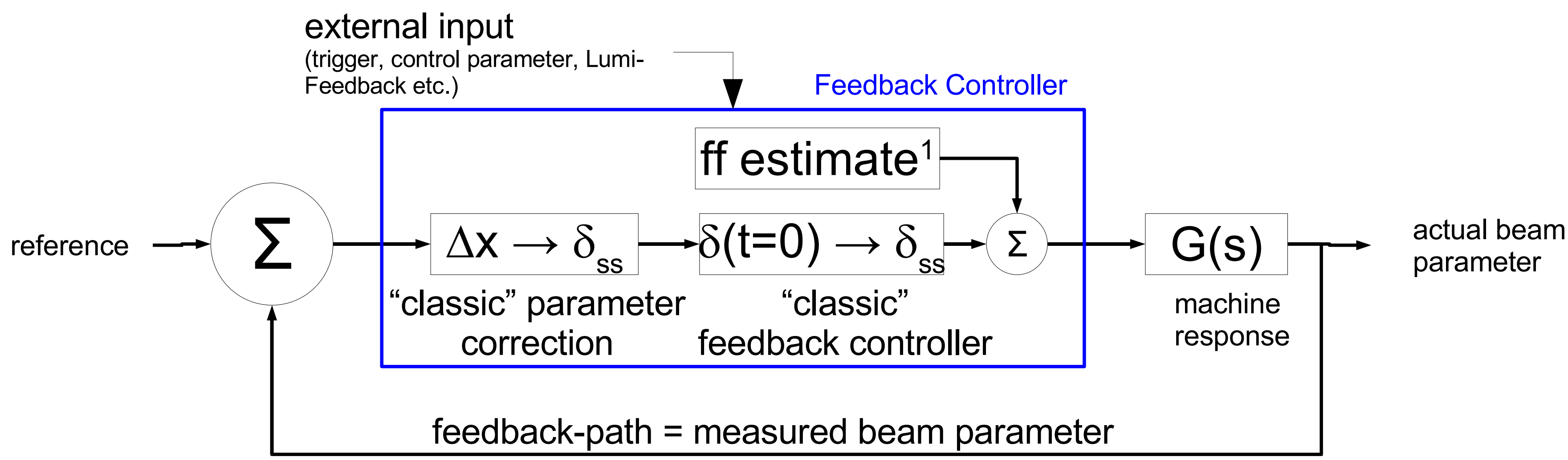
thermal exp. of steel:
1m of steel, 1 $^{\circ}$C:
$\Delta x \approx$ 10.. 17 μm

e.g. SLS[25]:
electronics: ± 0.1 $^{\circ}$C
experimental hall: ± 1.0 $^{\circ}$C

- Feedback controller usually decomposed into 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 $t\rightarrow\infty$.
  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[1] sources:

space domain (1)

time domain (2, 3)



[1] properly described = accurate & fast real-time model of the source

Space-Domain: No "black feedback magic"

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

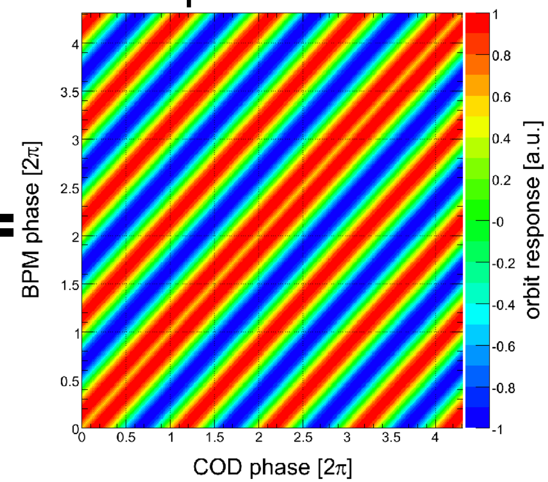
$$\boxed{\Delta\vec{x}(t)=\underline{R}\cdot\vec{\delta}(t)} \quad with \quad R_{ij}=\frac{\sqrt{\beta_i\beta_j}}{2\sin(\pi Q)}\cdot\cos(\Delta\mu_{ij}-\pi Q)+\frac{D_i D_j}{C(\alpha_c-1/\gamma^2)}$$

matrix multiplication

  - similar for other parameters:
    - Tune, Coupling,
    - Chromaticity,
    - Energy, ...

orbit response matrix

$$\begin{pmatrix}\Delta x_1\\ \Delta x_2\\ \cdots\\ \\ \Delta x_m\end{pmatrix} =$$

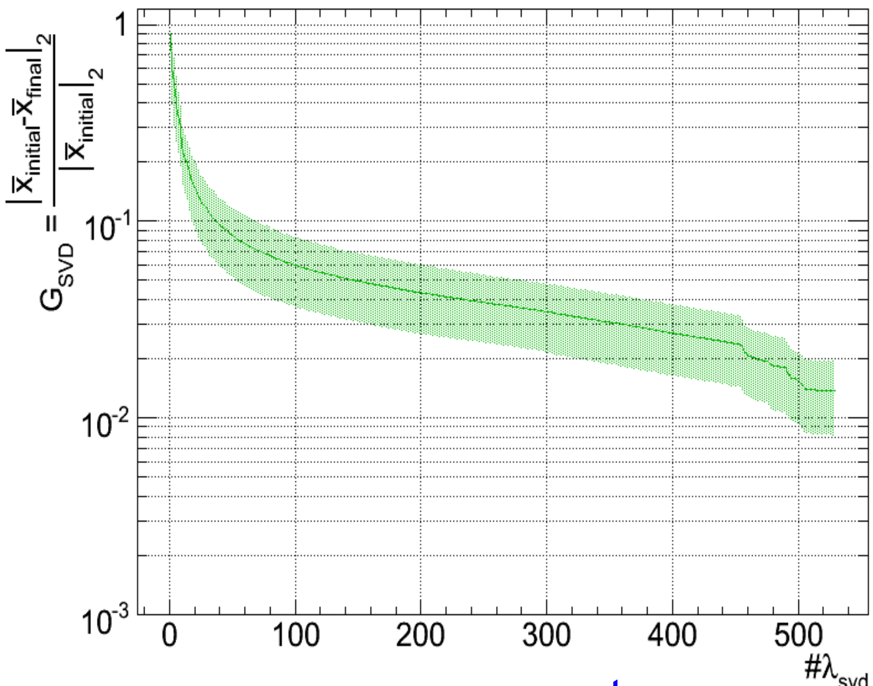


$$\times \begin{pmatrix}\delta_1\\ \delta_2\\ \cdots\\ \\ \delta_n\end{pmatrix}$$

- Control consists essentially in inverting above matrices
  - Potential complications: singularities = over/under-constraint matrices, noise, element failures, spurious BPM offsets, calibrations errors, ...
  - Common Workhorse: Singular-Value-Decomposition (SVD[16])
    - all light sources (& LHC) go in this direction!!

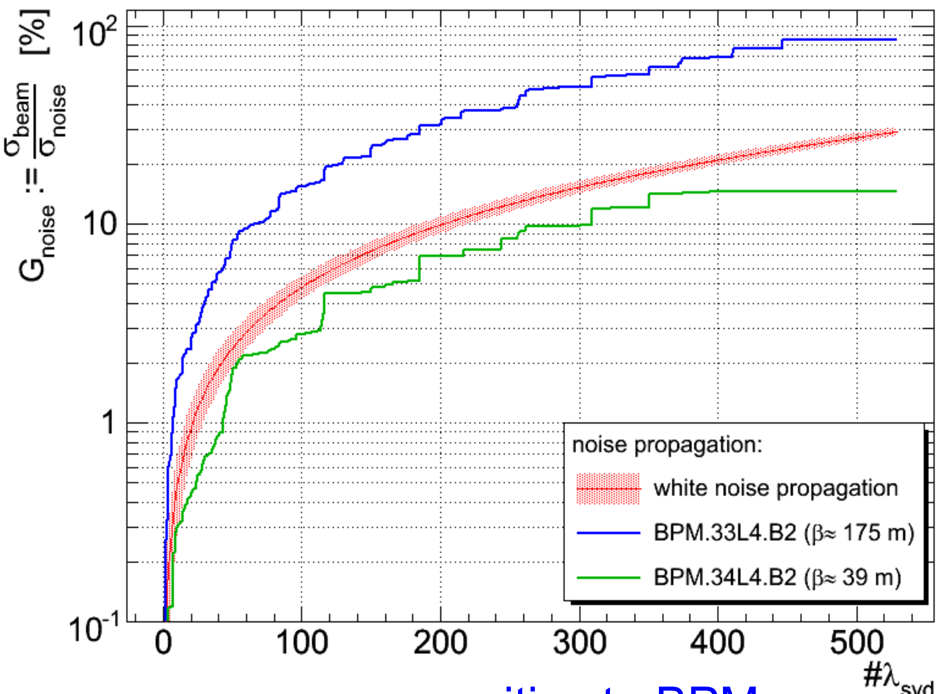
- Number of for the inversion used eigenvalues $\#\lambda_{svd}$ steers accuracy versus robustness of correction algorithm

- Orbit attenuation



more accurate

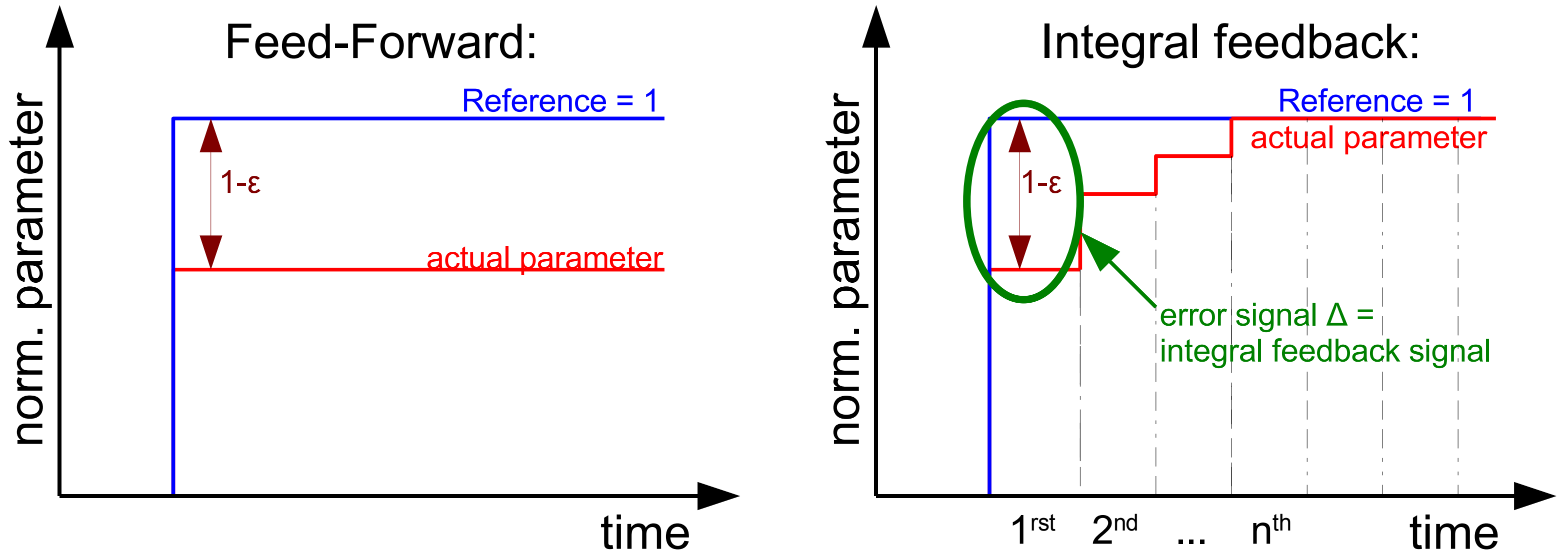
- Sensitivity to BPM noise



more sensitive to BPM noise and failures

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

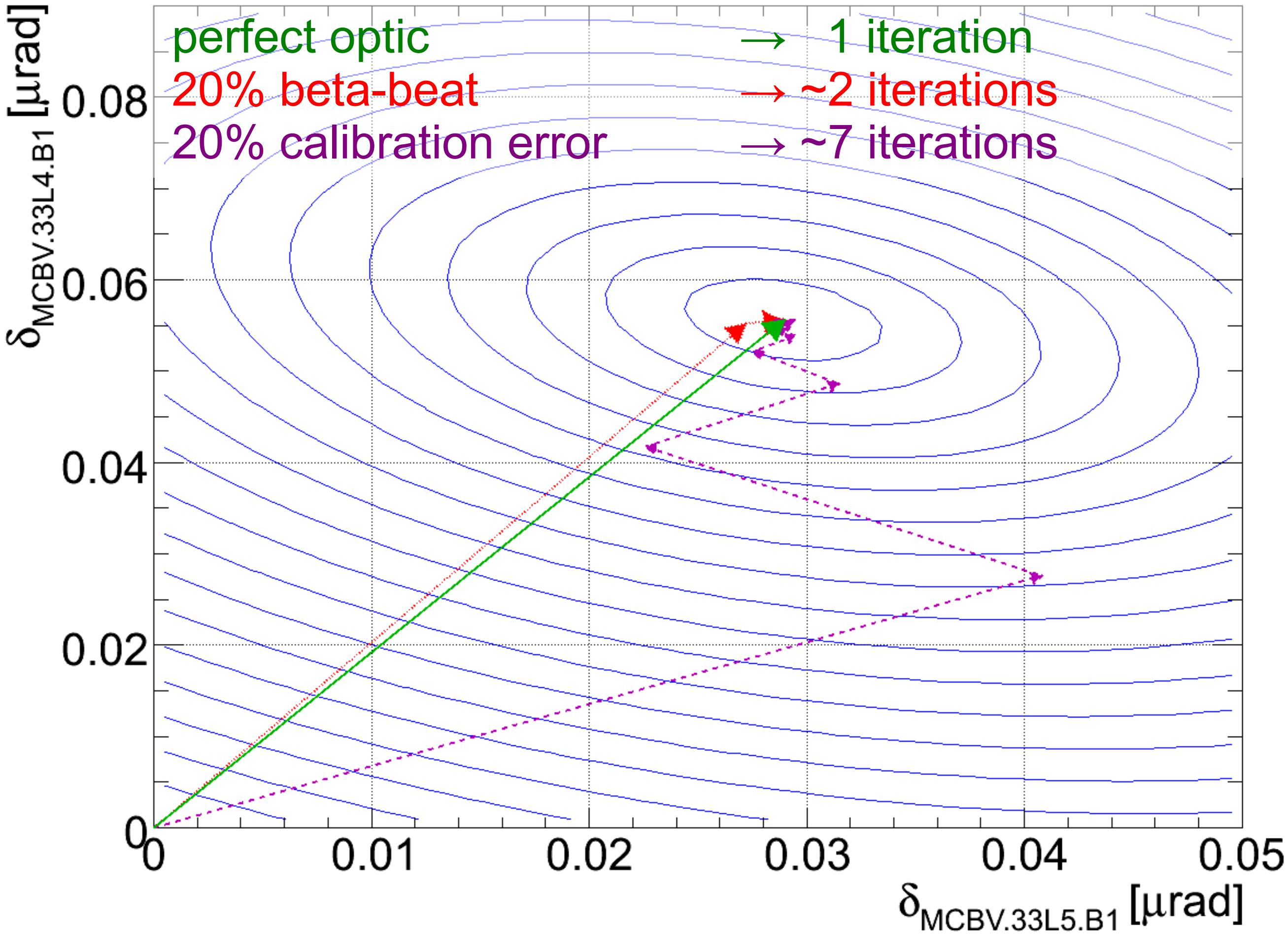
$$\Delta x(s)=R_i(s)\cdot\delta_i \;\rightarrow\; \Delta x(s)=R_i(s)\cdot(\epsilon_{ss}+(1+\epsilon_{scale})\cdot\delta_i)$$



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

Lattice and Calibration Uncertainties
Usage of Designed vs. Measured Beam response

- SVD algorithm part of the class of gradient based minima searches



Example:
LHC arc
(FODO Lattice)

- Implication on optimal feedback sampling frequency:
  - digital approx. of analogue system: $f_s > 10...20 \cdot f_{bw} \xrightarrow{\text{imperf.}} f_s > 20...40{+}{+} \cdot f_{bw}$
  - Example f_s/f_{bw} ratios: SLS: 40, ALS: 45, LHC: 25/50 (budget limited)

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

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

- Example: first order system

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

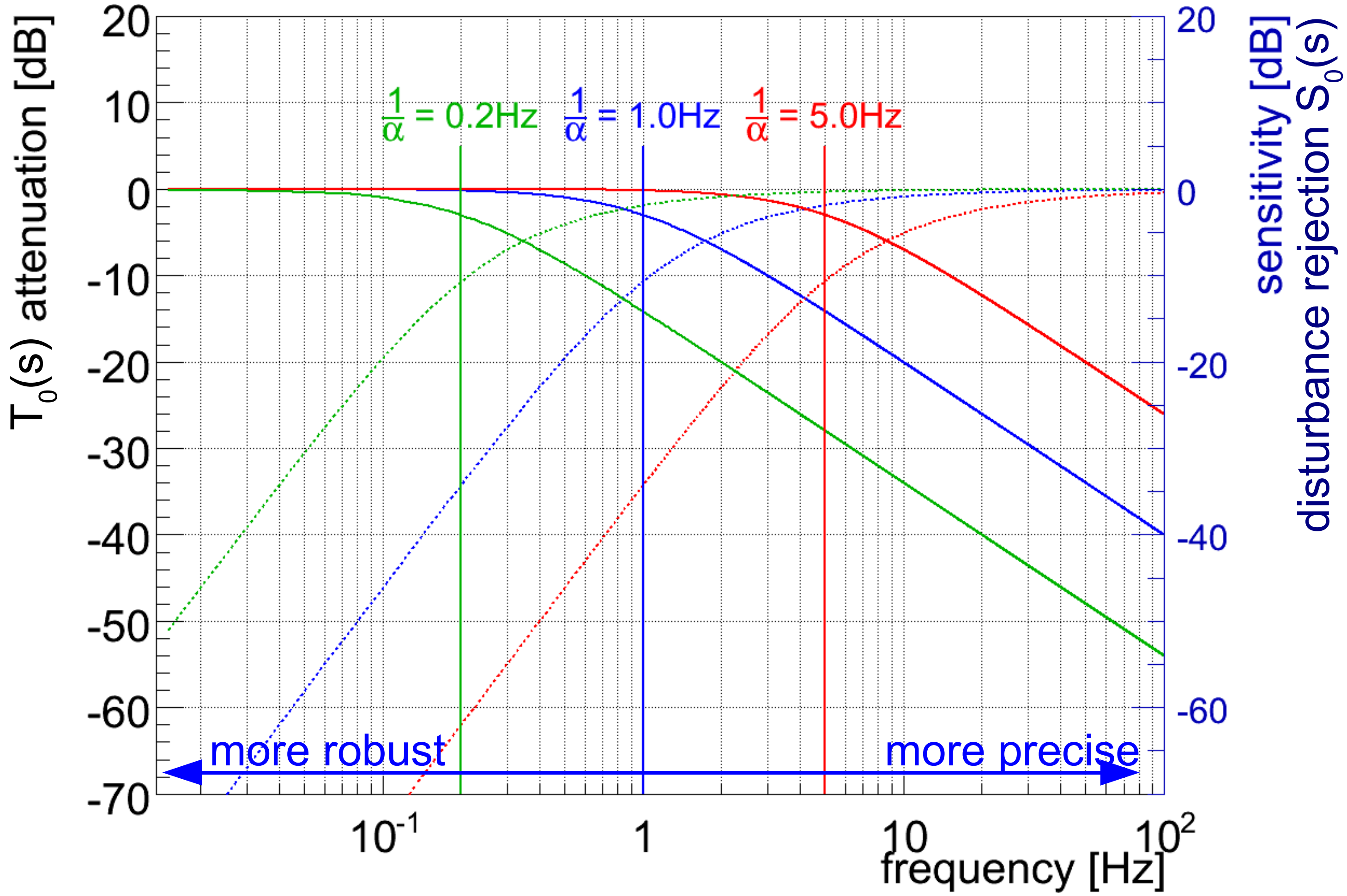
- Using for example the following ansatz:

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

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

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

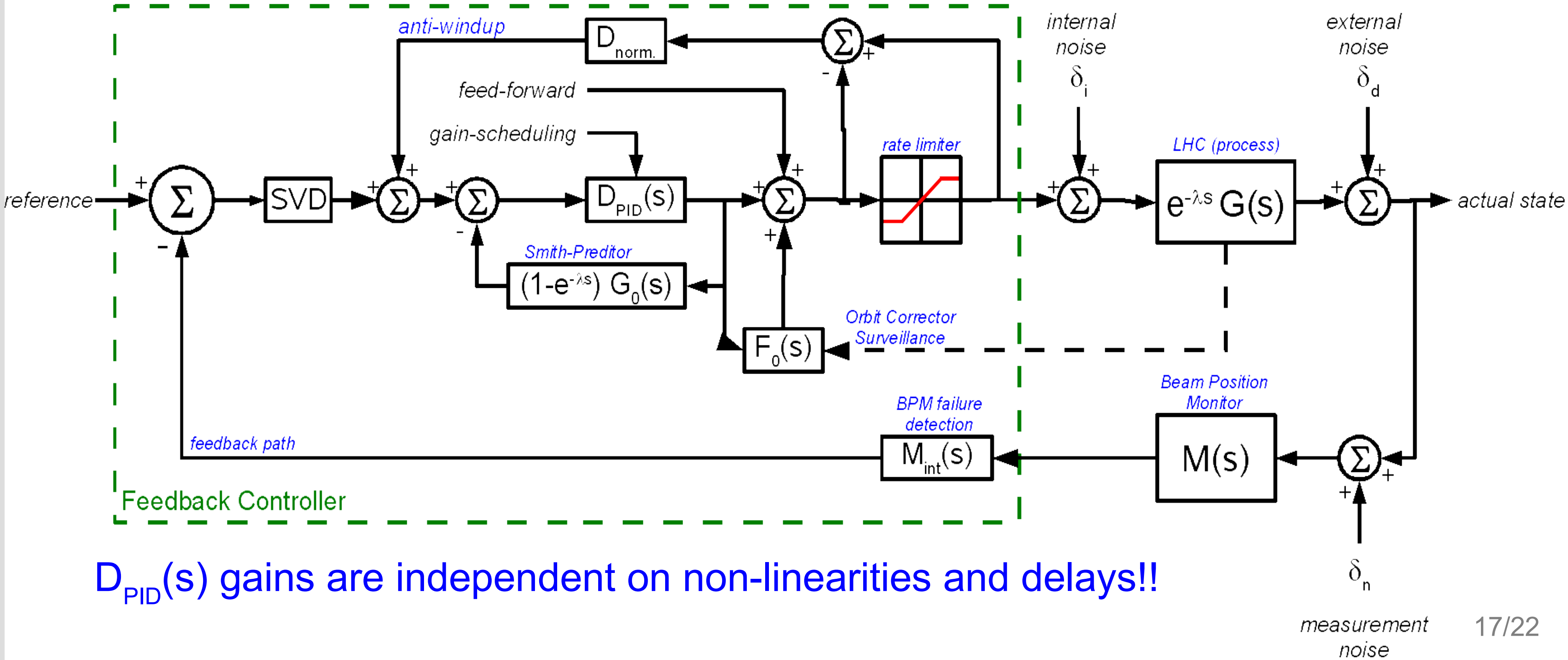
- $\alpha > \tau \ldots \infty$ facilitates the trade-off between speed and robustness
  - quantitative verification of loop stability w.r.t. noise, model errors ...
  - operator has to deal with one parameter → enables simple adaptive gain-scheduling based on the operational scenario!



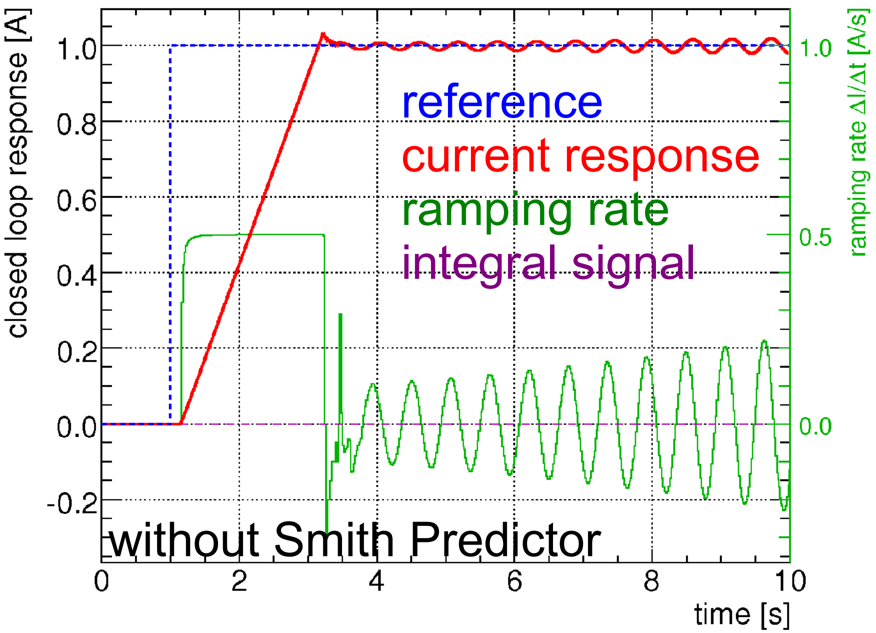
- If G(s) contains non-stable zeros e.g. delay λ & non-linearities $G_{NL}(s)$

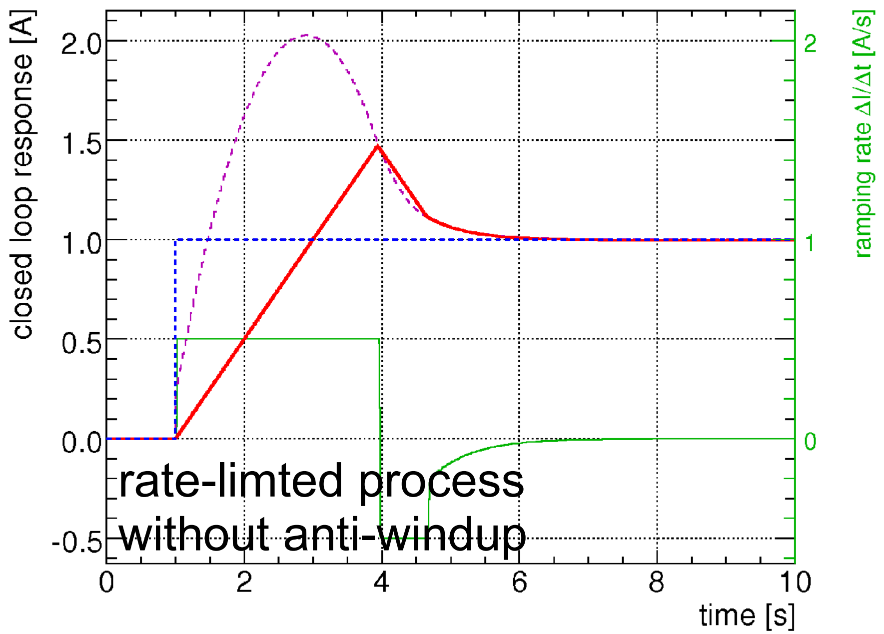
$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}\cdot G_{NL}(s)$$

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

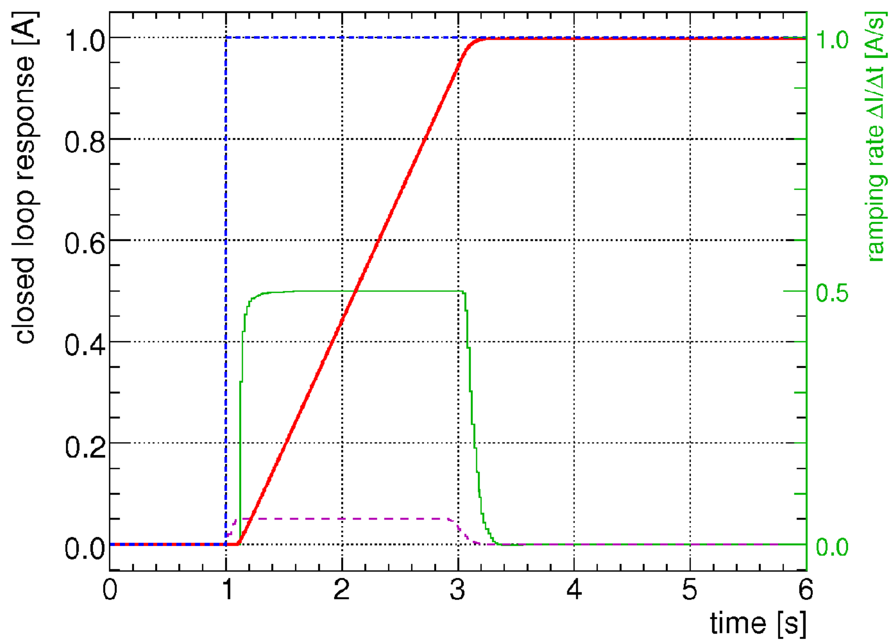


$D_{PID}(s)$ gains are independent on non-linearities and delays!!



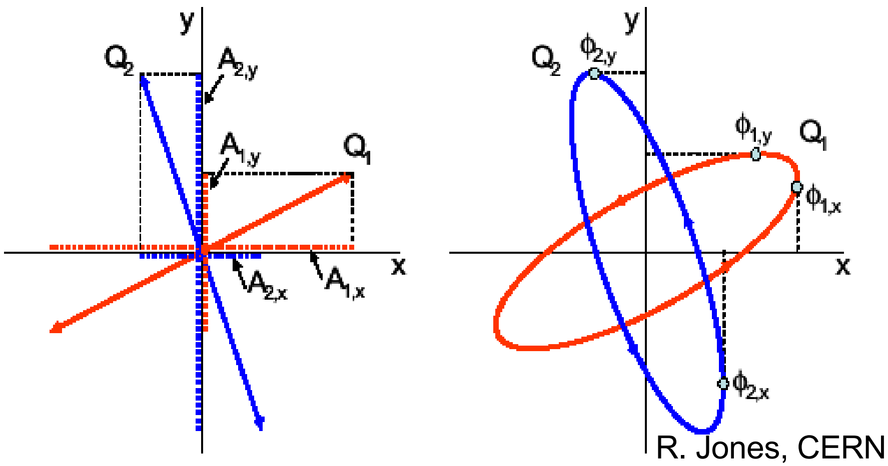


with full delay and windup compensator scheme:



- orbit micrometer constraint
  - Improves machine performance
  - Significantly minimises feed-down effects of higher multipoles (esp. coupling)
  - No (large) kicks/momentum modulation:
    Q/Q' measurements have to measure within the stability requirements
    - Development of new tune measurement techniques[23]
    - CERN SPS/LHC tune PLL operates within < 1 µm excitation level[21,22]

- Robust tune feedback requires measurement/control of Coupling[24]
  - Additional decoupling between PLL phase and amplitude[22]



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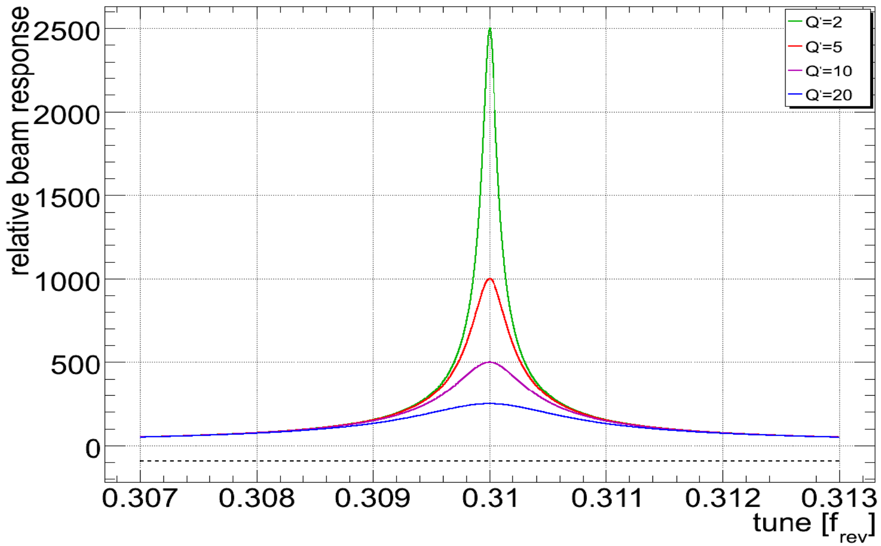
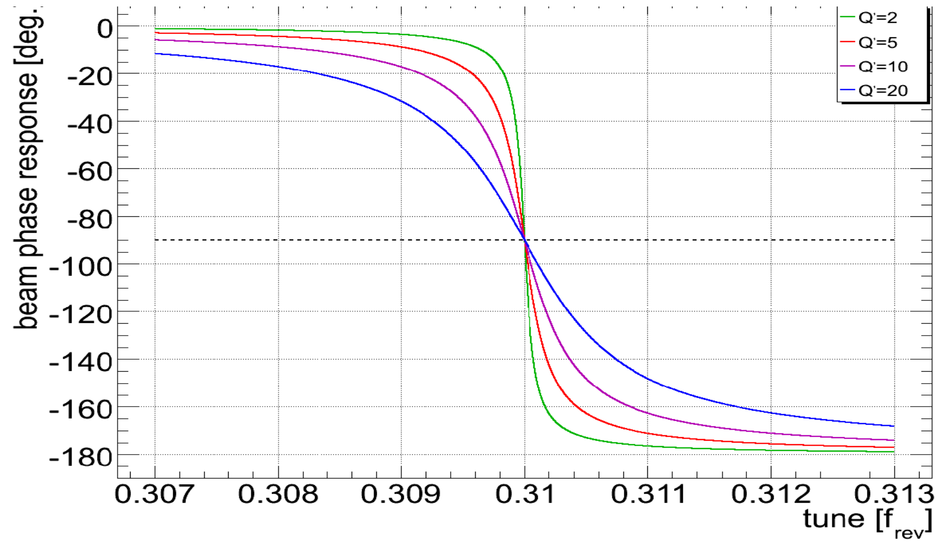
Cross-Dependability and Constrains of FB Loops II/III





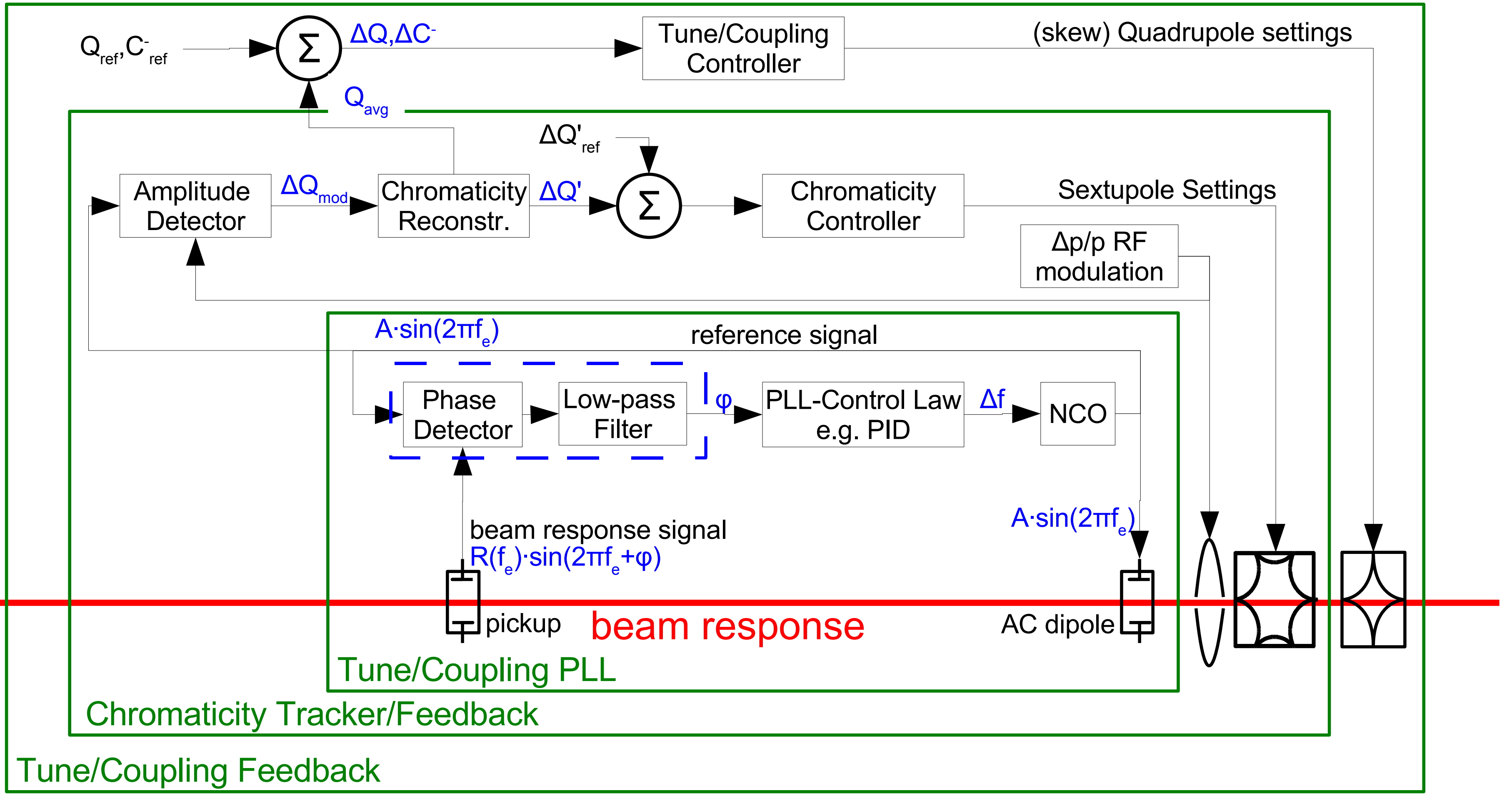
- Beam response: open loop gain K_0 ~phase response slope
- Common[4-6,19] (classic) PLL loop design: K_0 = const. & filter bandwidth = 1/τ
  → PLL low-pass:

$$G(s) = \frac{K_0}{\tau s + 1}$$

Note:
K_0 const. for $|\Delta\varphi| \leq 60°$ (linear. regime)
K_0 depends on Q' (non-linear. regime)

- Optimal tune PLL gain parameters depend on chromaticity[20,21]
  - Optimal PI for high Q' ↔ sensitivity to noise (unstable loop) for low Q'
  - Optimal PI for small Q' ↔ slow tracking speed for large Q'

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



- Additional cross-dependence with orbit and energy feedback (dispersion orbit)

Conclusion

- Beam-based FBs are remedies for perturbations on slow/medium time scales
  - Limited by thermal drifts, noise and systematics of involved devices
  - Systematic and thorough analysis of involved beam instrumentation and corrector circuits is essential!
- Use of imperfect (design) beam response for SVD based FB Systems:
  - does not affect the precision of the correction but reduces rather the effective bandwidth → favours higher feedback sampling frequencies
- Youla's affine parameterisation facilitates optimal adaptive non-linear control
  - enables gain-scheduling based on operational scenario
  - (Ziegler-Nichols/Coohen-Coon PID tuning are outdated!)
- Beware of cross-constraints/coupling of simultaneous nested loops:
  - Feedbacks should be designed as an ensemble

The author gratefully acknowledges contributions from many colleagues!

Reserve Slides

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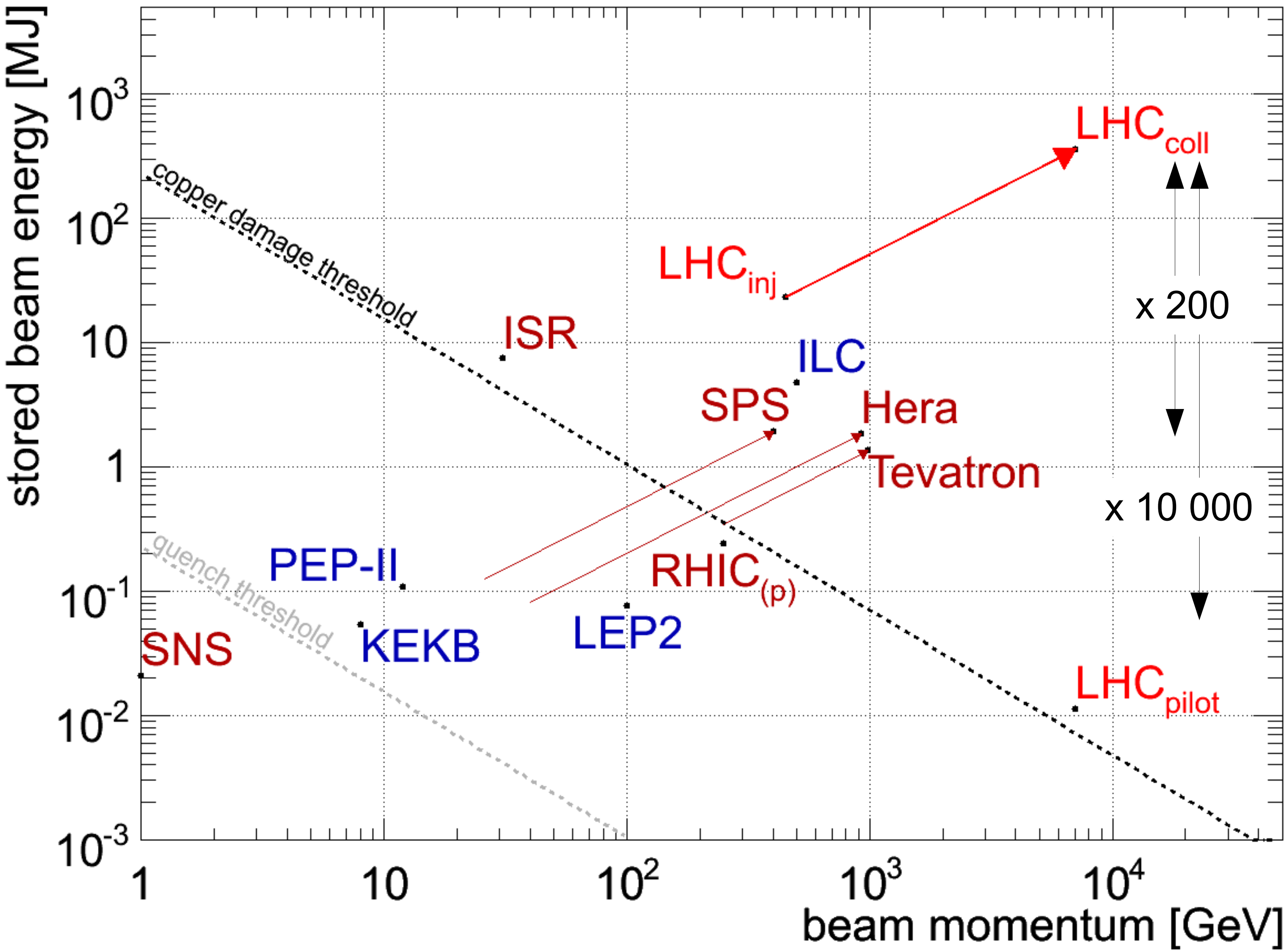
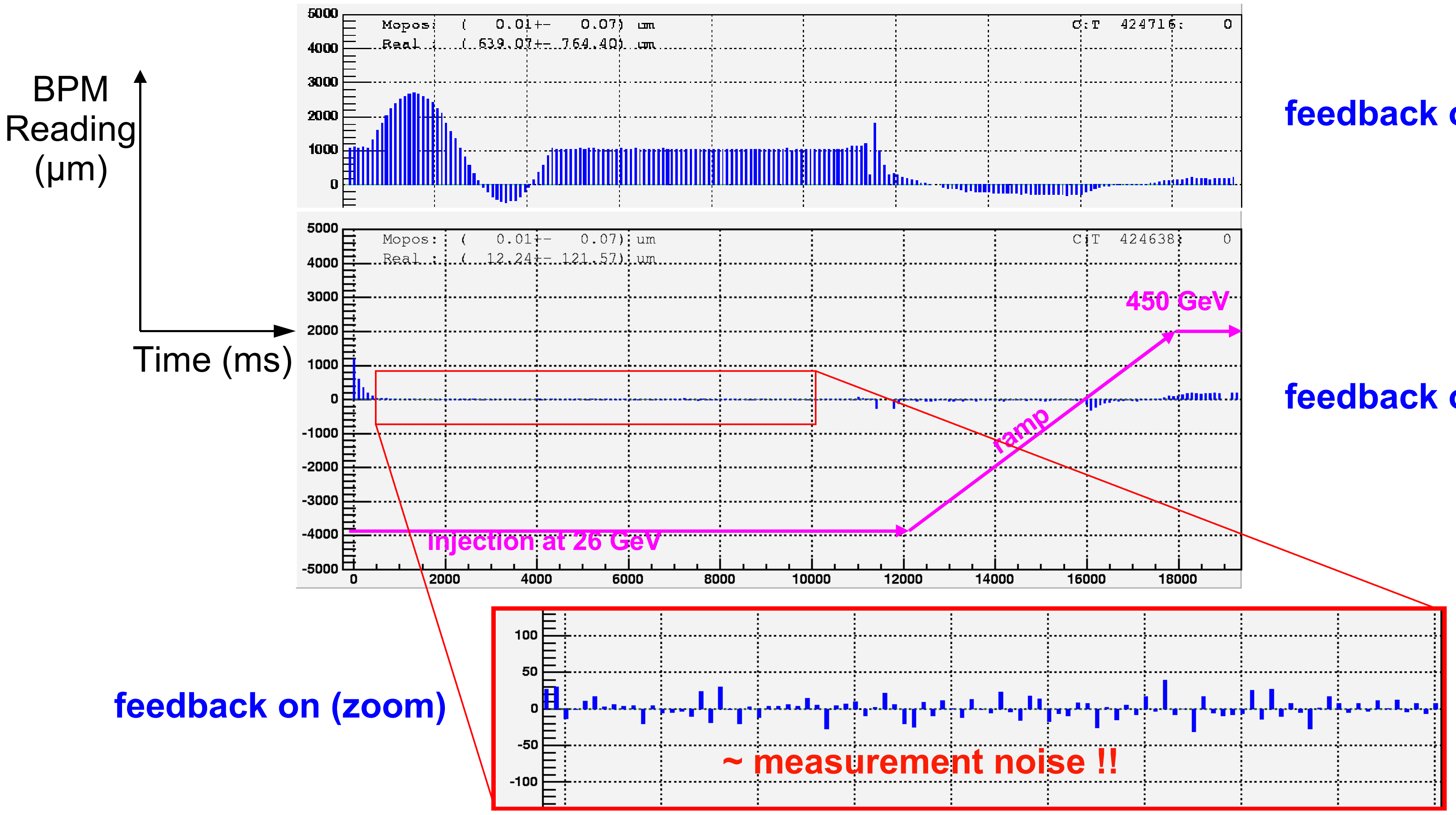
IWBS'04: "LHC is a pretty dangerous machine" Livingston Style plot

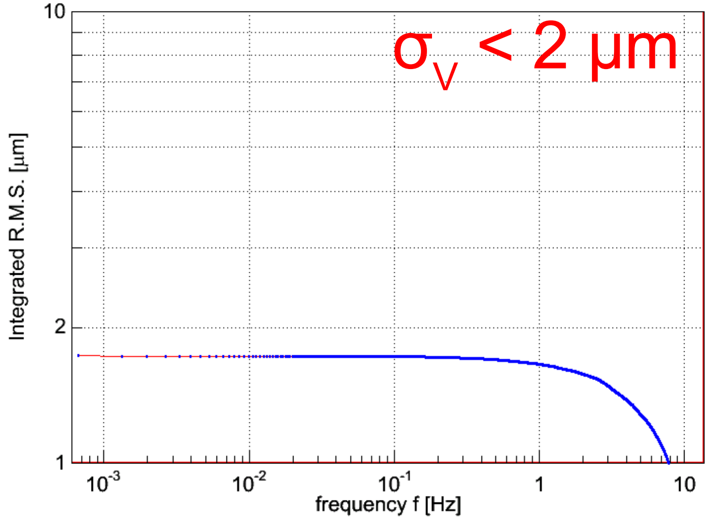


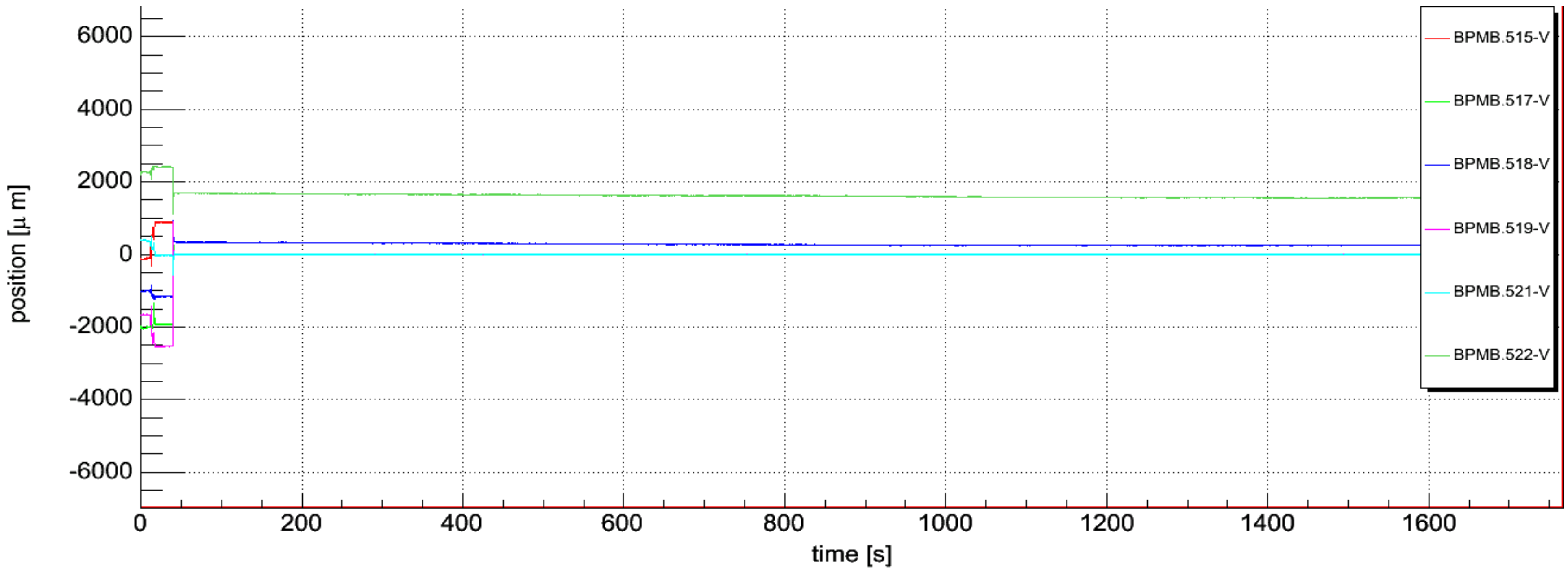
see Chamonix XIV: "Damage levels - Comparison of Experiment and simulation" and PAC'05 for details

LHC Orbit Feedback Test at the SPS I/II



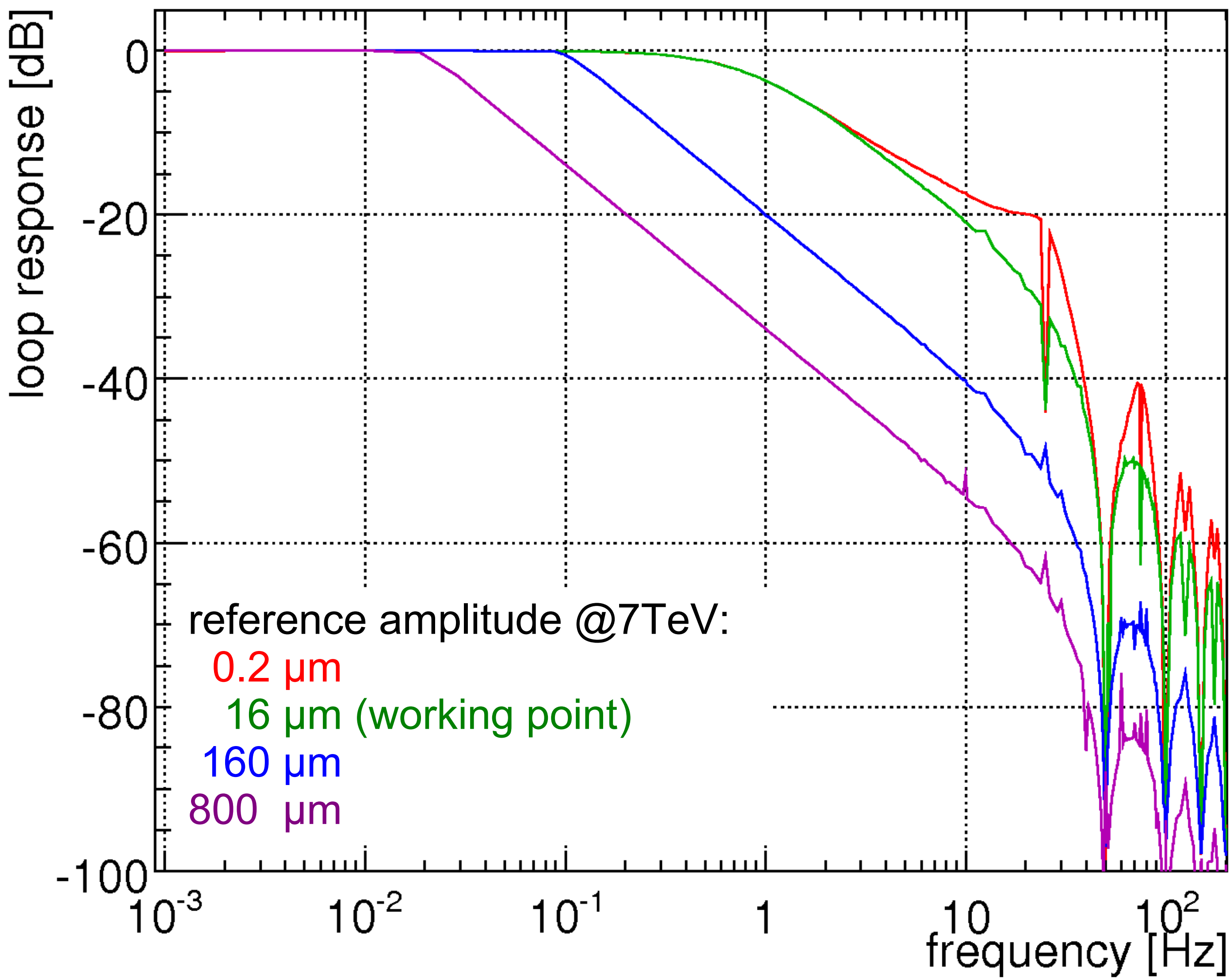
- Stabilisation “record” in the SPS
  - 270 GeV coasting (proton) beam, 72 nom. bunches, $\beta_v \approx 100$ m
  - rivals most modern light sources
  - magnitudes better than required
- Target: maintain same long term stability





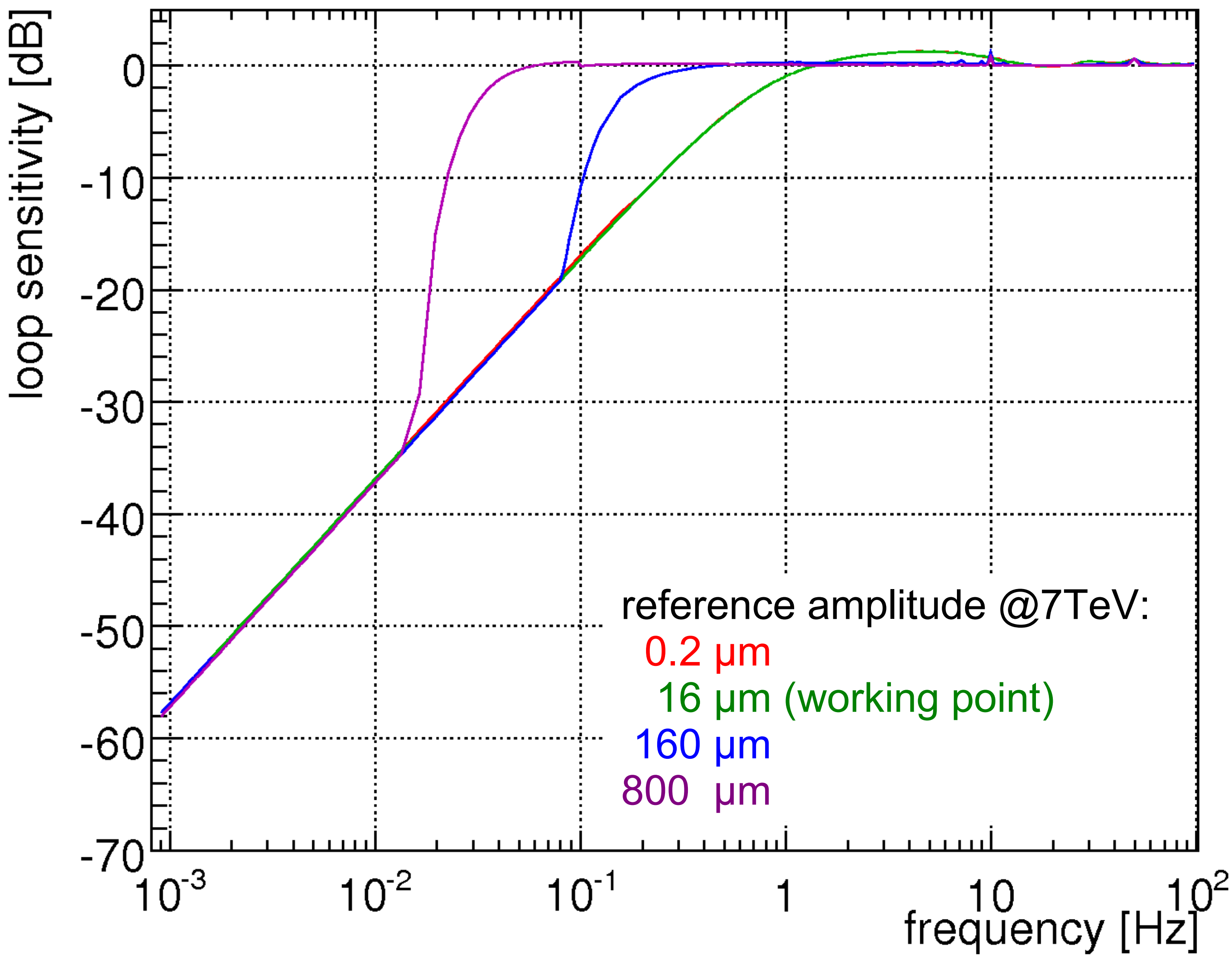
Nominal Feedback Response T_0

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



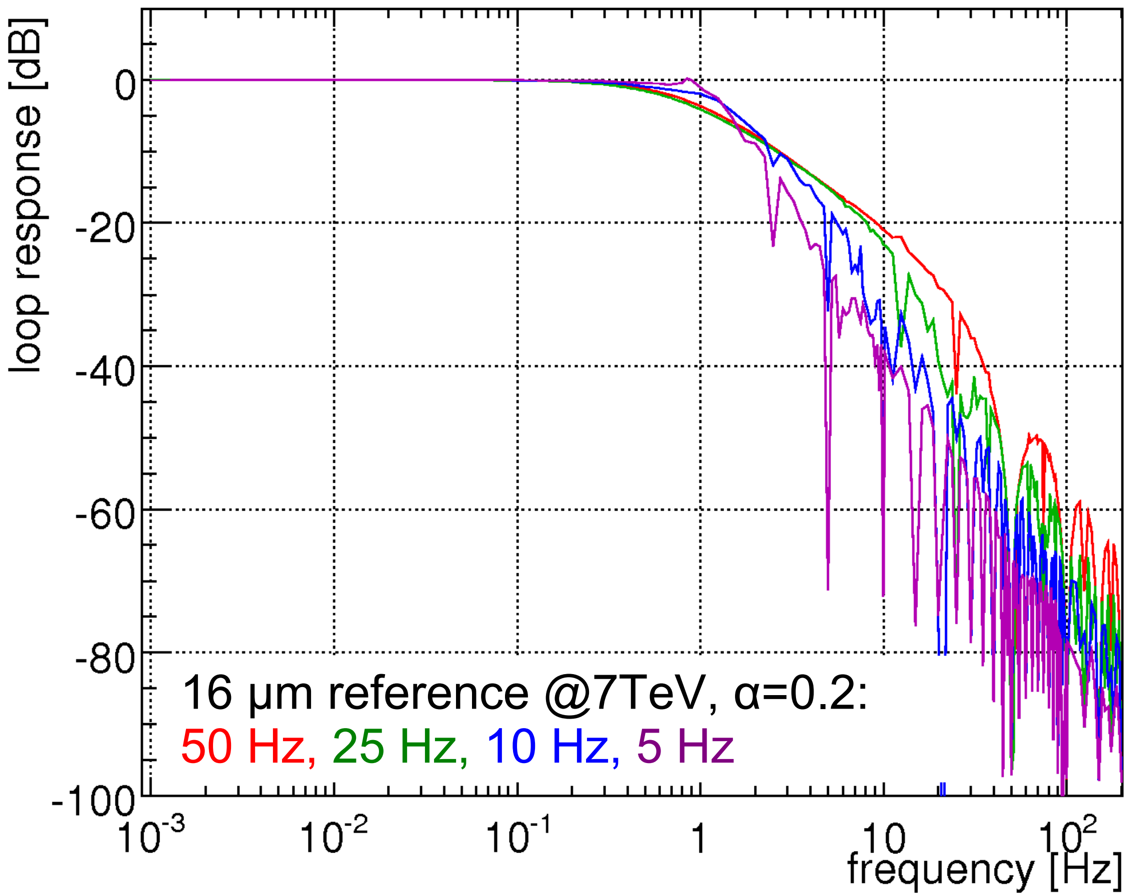
Nominal Feedback Disturbance Rejection S_{d0}

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



Loop Bandwidth versus Sampling frequency

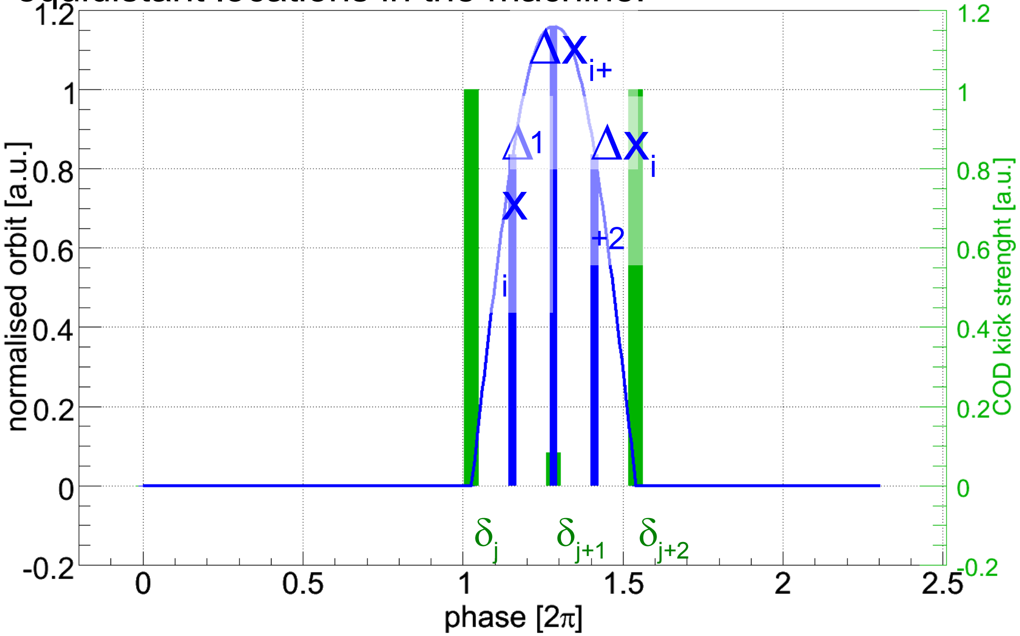
- ... sample the position (Q, ...) at 10Hz to achieve a closed loop 1Hz bandwidth



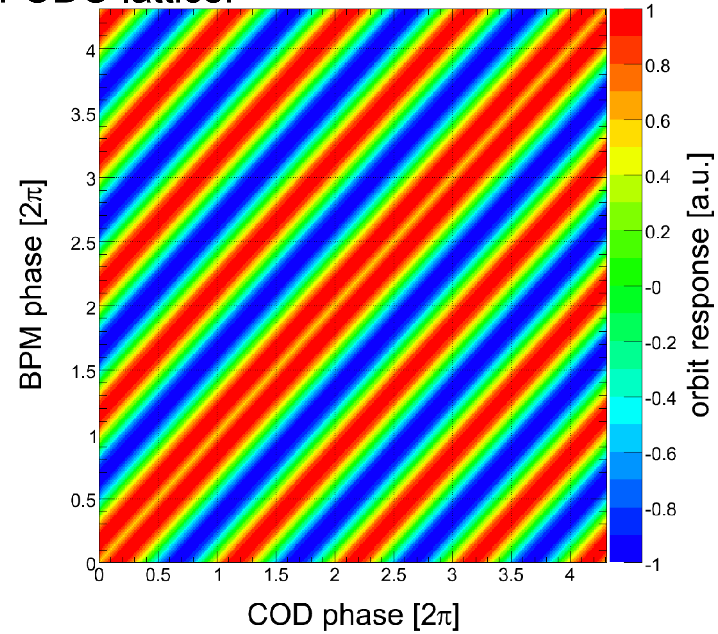
  - ... a theoretic limit assuming a perfect system!
  - common: sampling frequency > 25 ...40 desired closed-loop bandwidth

Automated Orbit Correction using Singular Value Decomposition

The orbit is sampled at *m* discrete not necessarily equidistant locations in the machine:



orbit response matrix example of a regular FODO lattice:



The superimposed beam position shift at the i^th monitor due to single dipole kicks is described through the orbit response matrix R. It can be written as

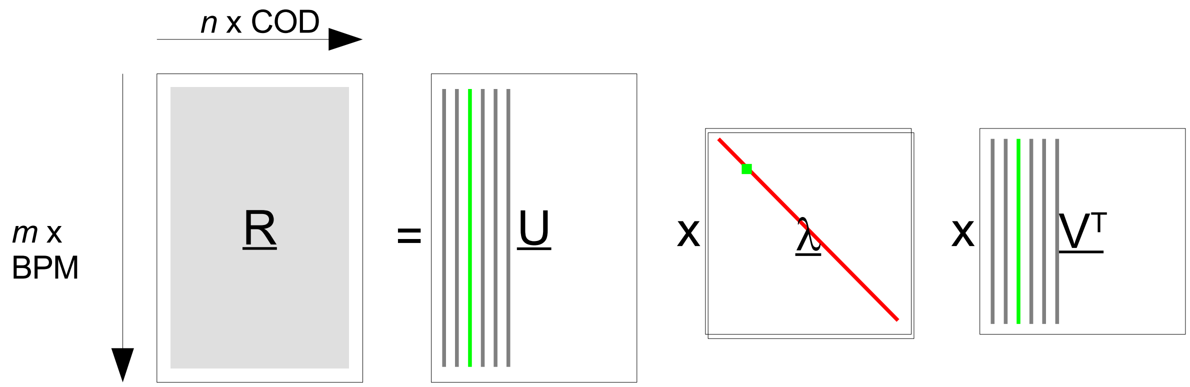
$$\Delta x_i = \sum^{n} R_{ij} \cdot \delta_j \quad with \quad R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi Q)} \cdot \cos(\Delta \mu_{ij} - \pi Q)$$

$$\Leftrightarrow \quad \Delta \vec{x} = \sum_{j=0}^{n} \delta_j \vec{u}_j \quad with \quad \vec{u}_j = (R_{1j}, \ldots, R_{mj})^T \Leftrightarrow \boxed{\Delta \vec{x}(t) = \underline{R} \cdot \vec{\delta}_{ss}}$$

where (β,μ,Q) depends on the machine optic (example: Q=4.31).

Singular Value Decomposition (SVD) on a slide

Theorem from linear algebra*:



eigen-vector relation:

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

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

- final correction is a simple matrix multiplication
- large eigenvalues ↔ bumps with small COD strengths but large effect on orbit

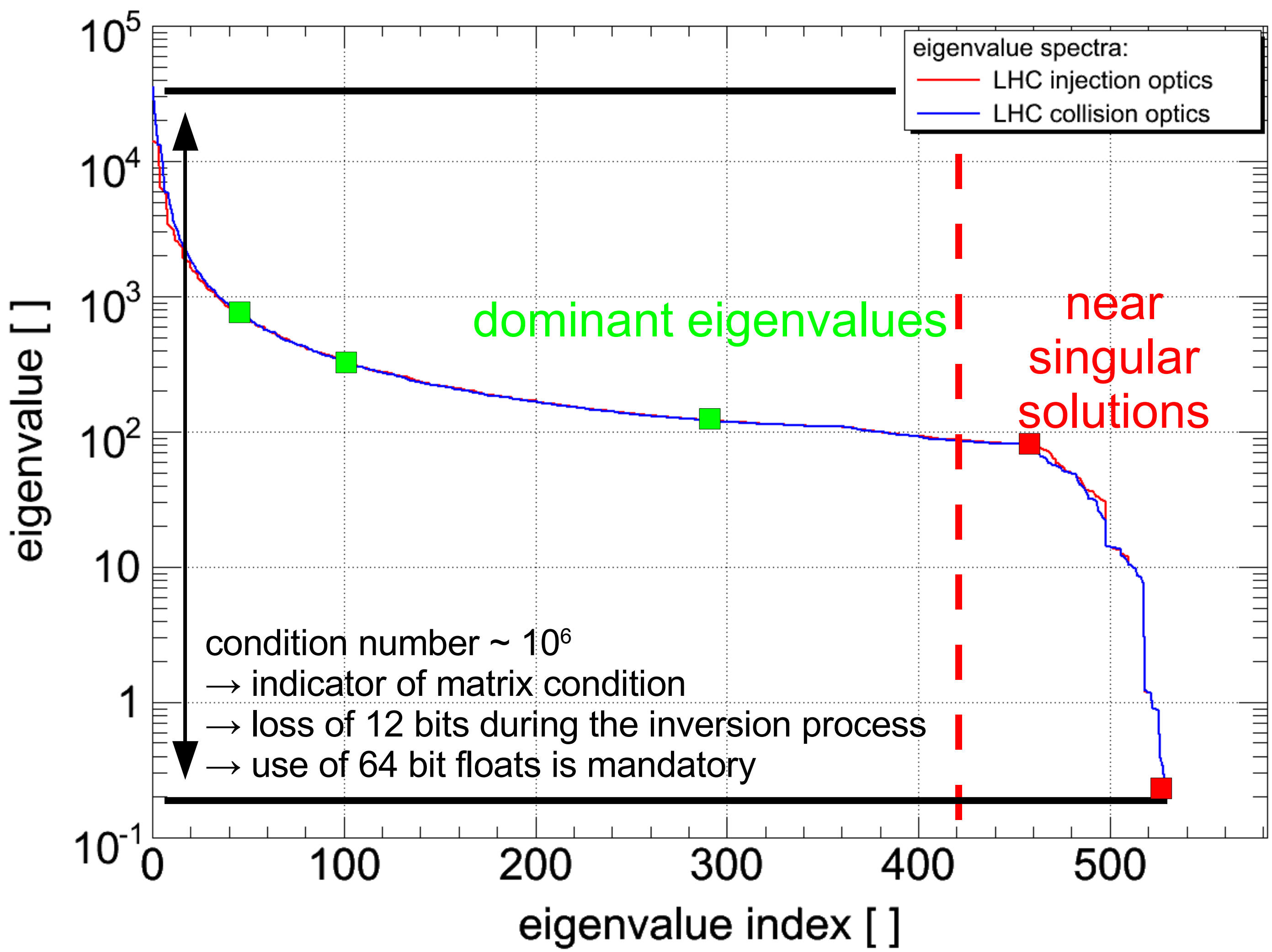
$$\boxed{\vec{\delta}_{ss} = \tilde{R}^{-1} \cdot \Delta \vec{x} \quad with \quad \tilde{R}^{-1} = \underline{V} \cdot \underline{\lambda}^{-1} \cdot \underline{U}^T} \quad \Leftrightarrow \quad \vec{\delta}_{ss} = \sum_{i=0}^{n} \frac{a_i}{\lambda_i} \vec{v}_i \quad with \quad a_i = \vec{u}_i^T \Delta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

- Easy removal of singular (=undesired, large corrector strengths) eigen-values/solutions:
  - near singular eigen-solutions have $\lambda_i \sim 0$ or $\lambda_i = 0$
  - to remove those solution: $\lim_{\lambda_i \to \infty} 1/\lambda_i = 0$
- discarded eigenvalues corresponds to bumps that won't be corrected by the fb

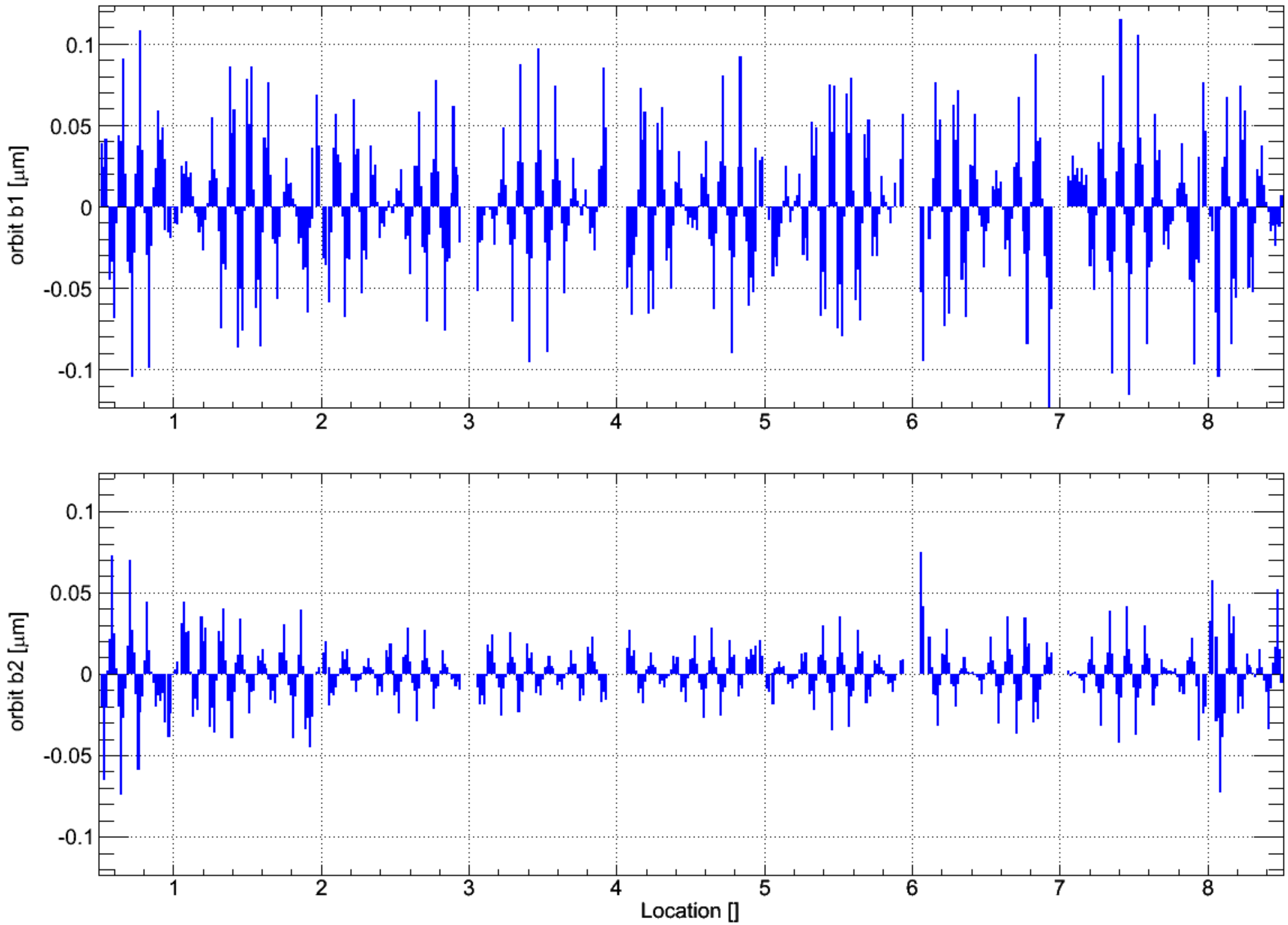
*G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971

SVD example: LHC eigenvalue spectrum

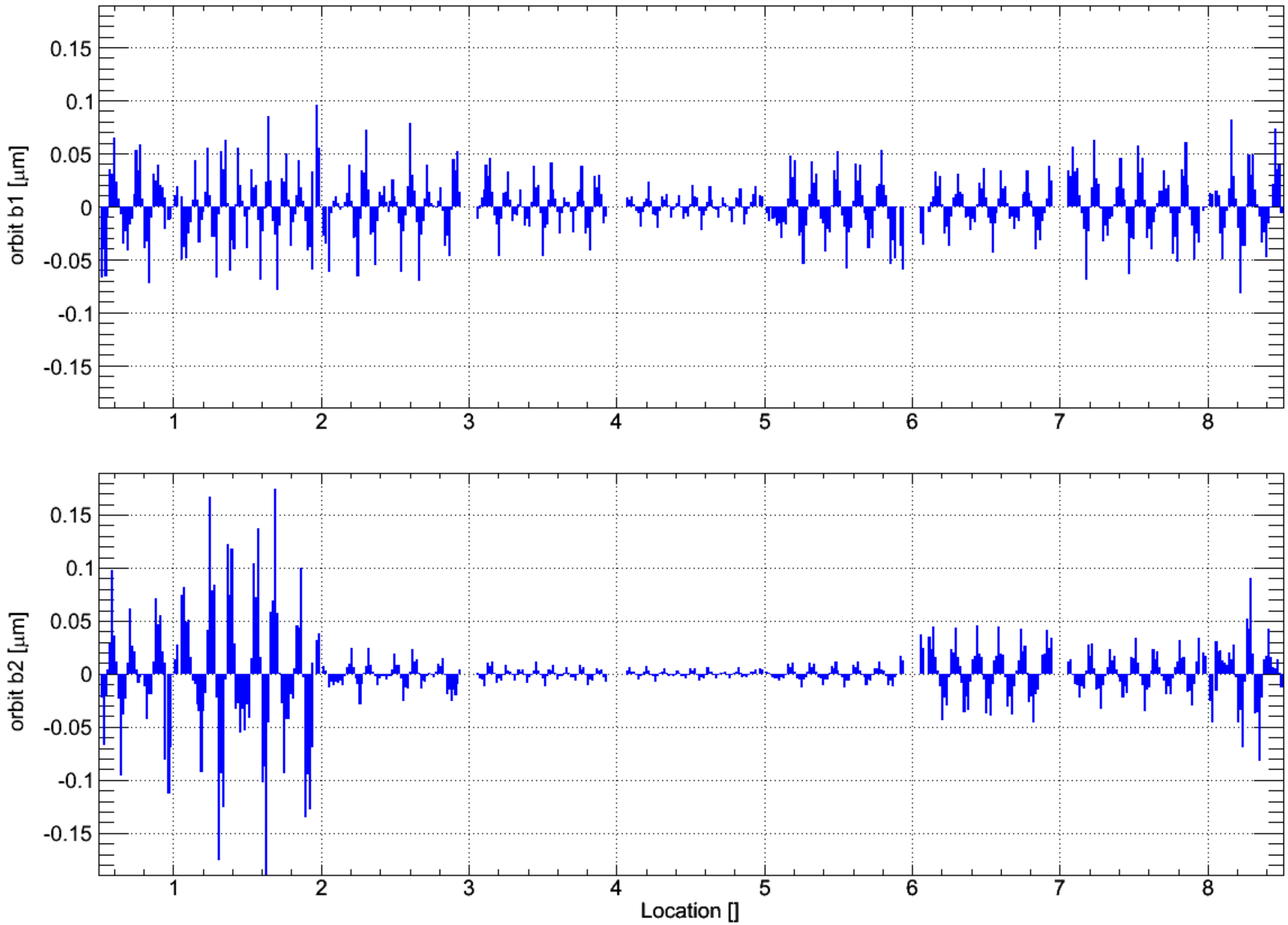
Eigenvalue spectra for vertical LHC response matrix using all BPMs and CODs:



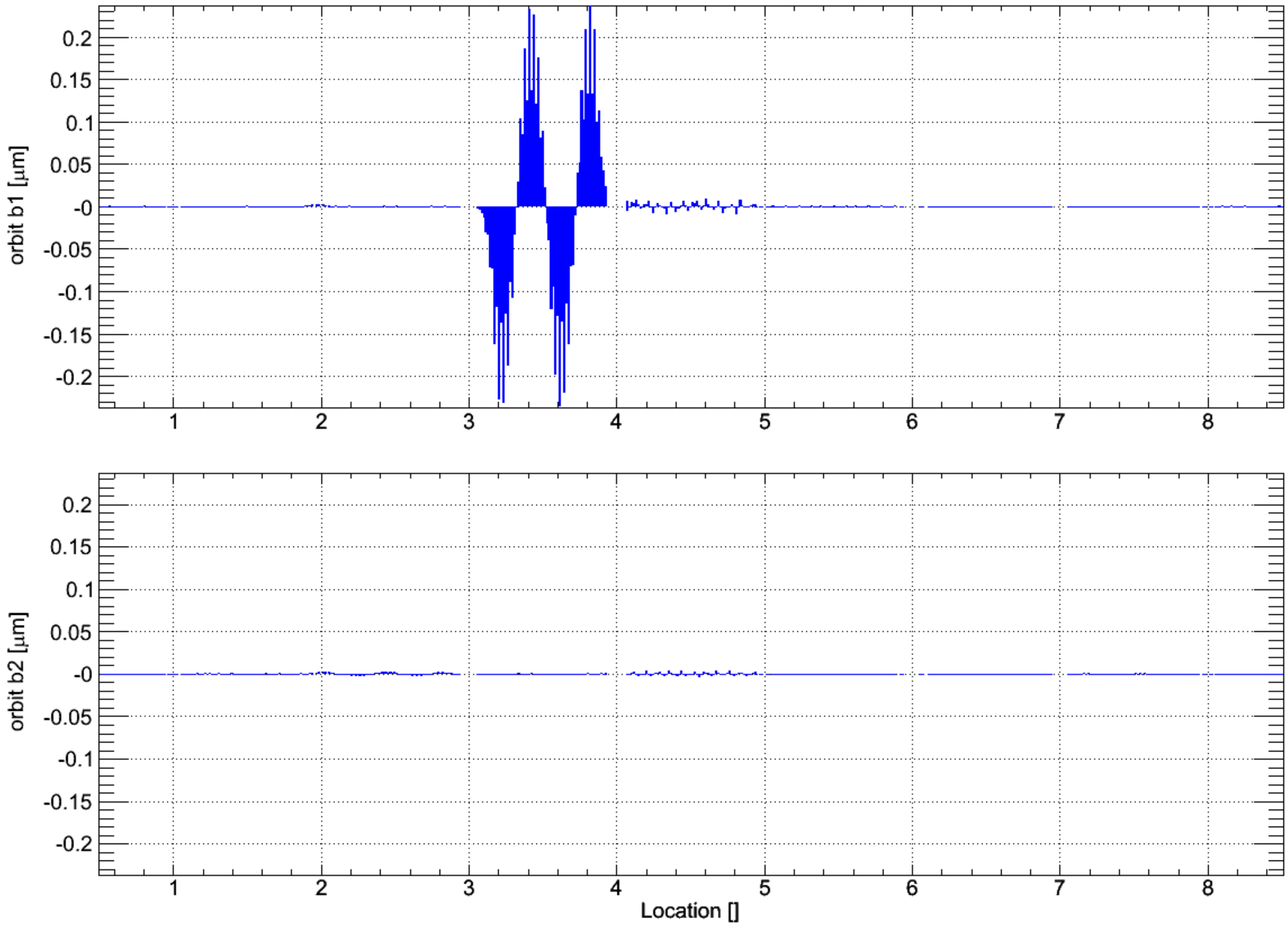
LHC example: BPM eigenvector #50 $\lambda_{50} = 6.69 \cdot 10^2$



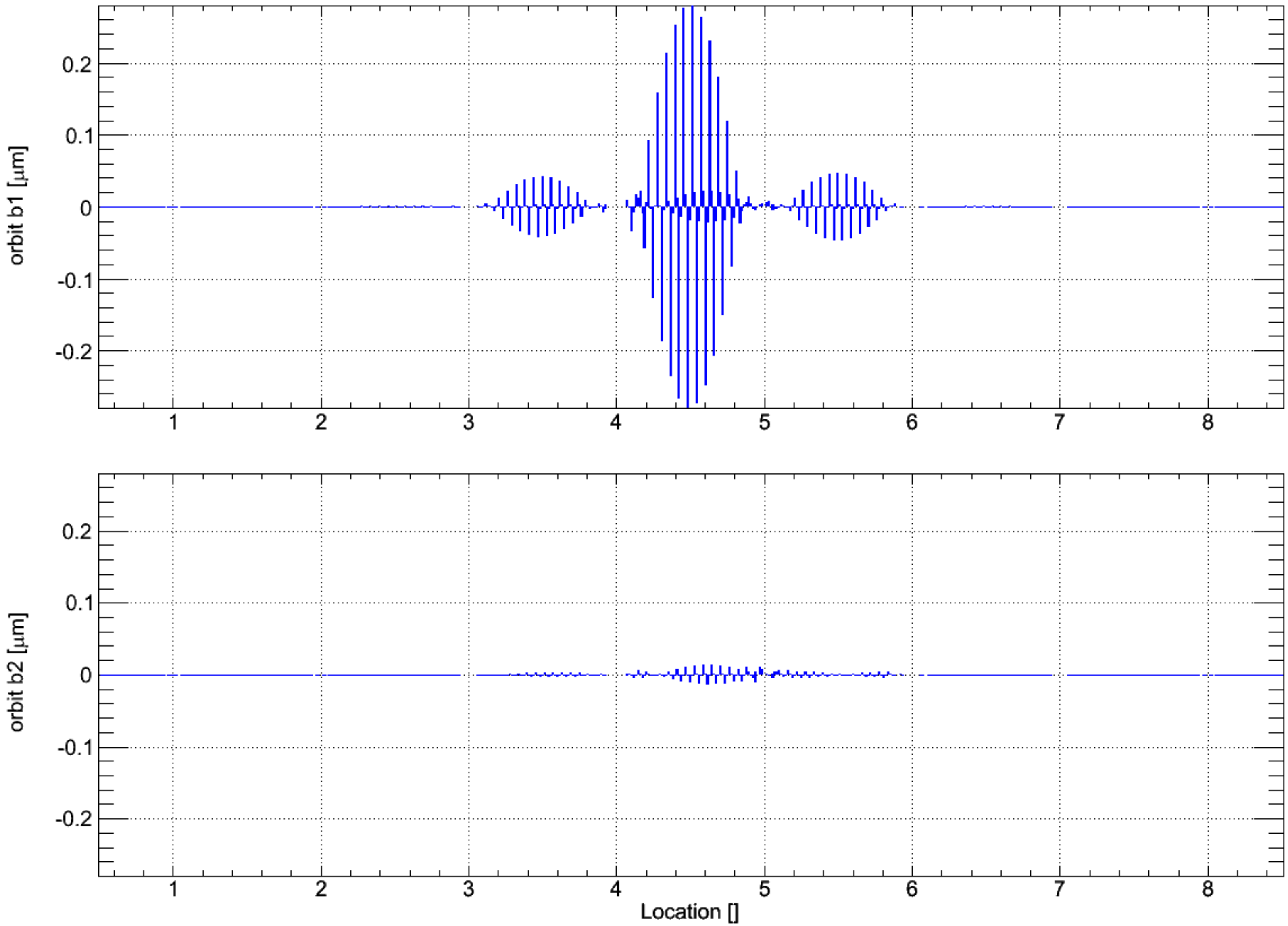
LHC example: BPM eigenvector #100 $\lambda_{100} = 3.38 \cdot 10^2$



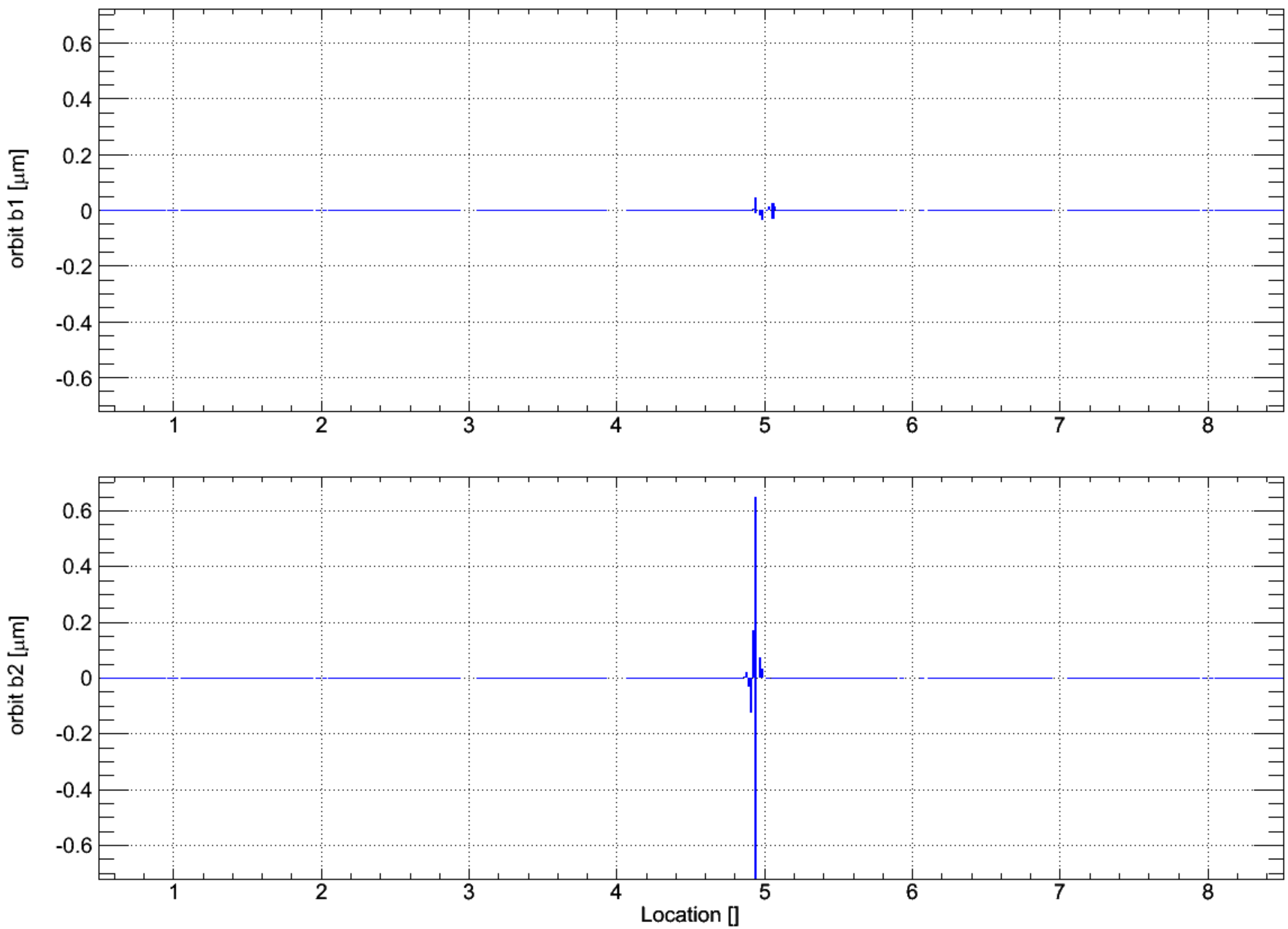
LHC example: BPM eigenvector #291 $\lambda_{291} = 2.13 \cdot 10^2$



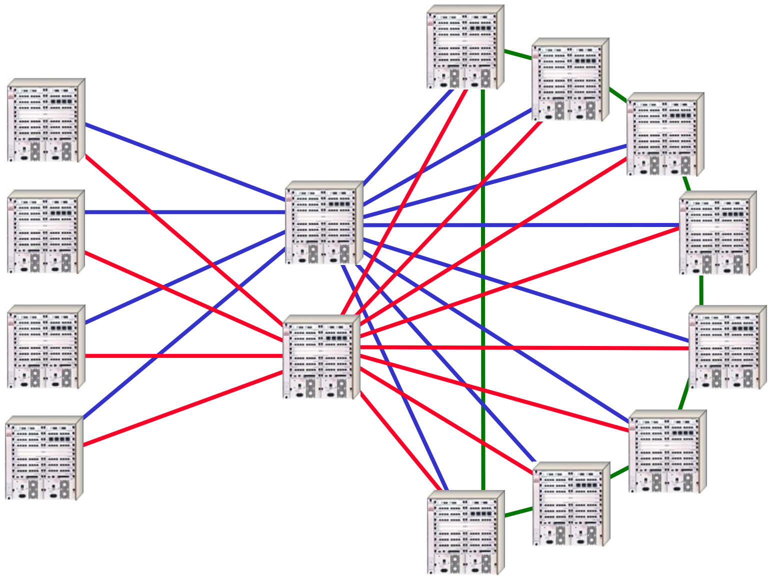
LHC example: BPM eigenvector #449 $\lambda_{449} = 8.17 \cdot 10^{1}$



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



- CERN's Technical Network as backbone
  - Switched network
    - no data collisions
    - no data loss
  - double (triple) redundancy
- Core: "Enterasys X-Pedition 8600 Routers"
  - 32 Gbits/s non-blocking, $3{\cdot}10^7$ packets/s
  - 400 000 h MTBF
  - hardware QoS
    - One queue dedicated to real-time feedback
    - ~ private network for the orbit feedback

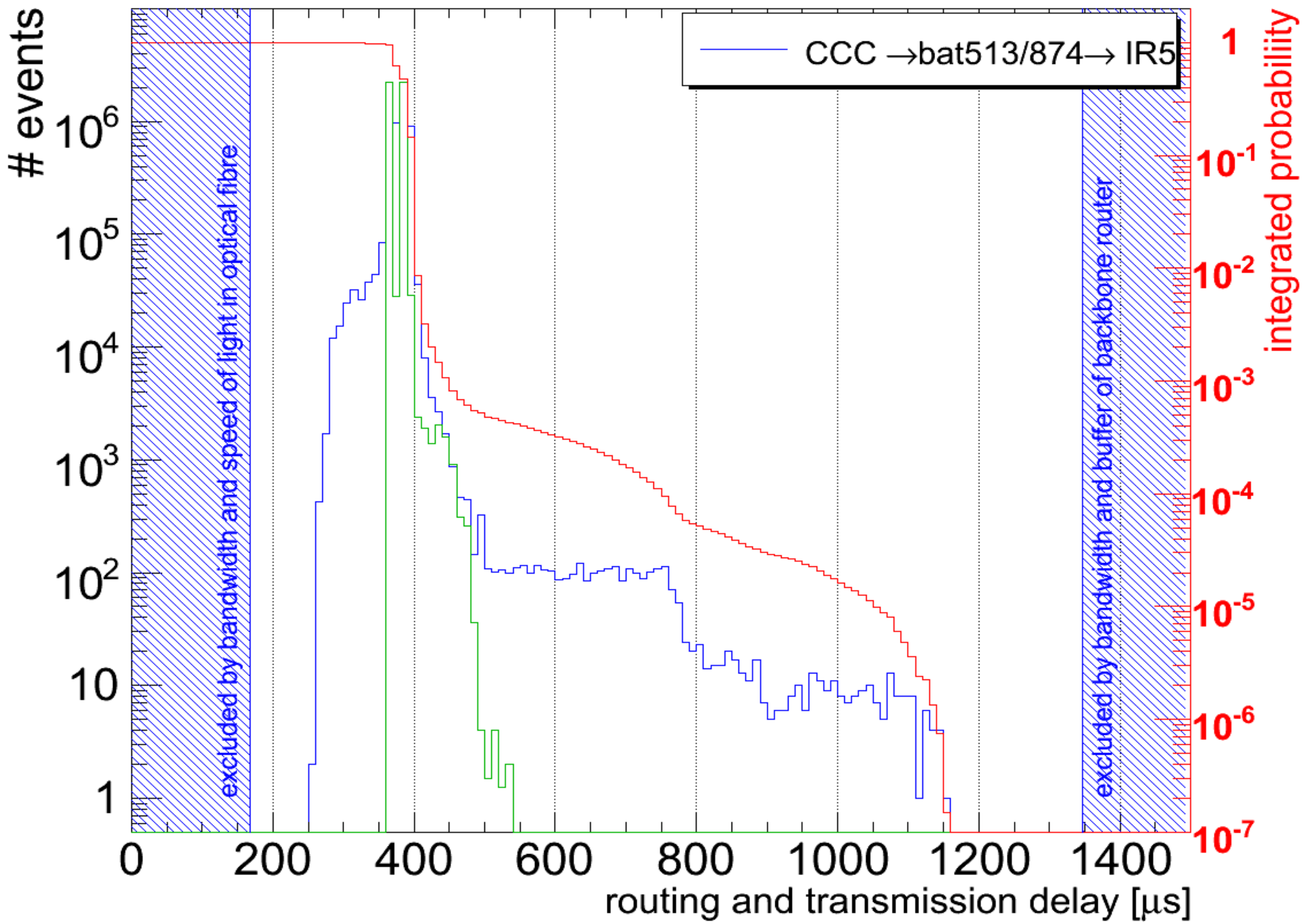


- Routing delay ~ 13 µs
- longest transmission delay (exp. verified) ~ 320 µs

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

Technical Network and Data Communication II/II

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

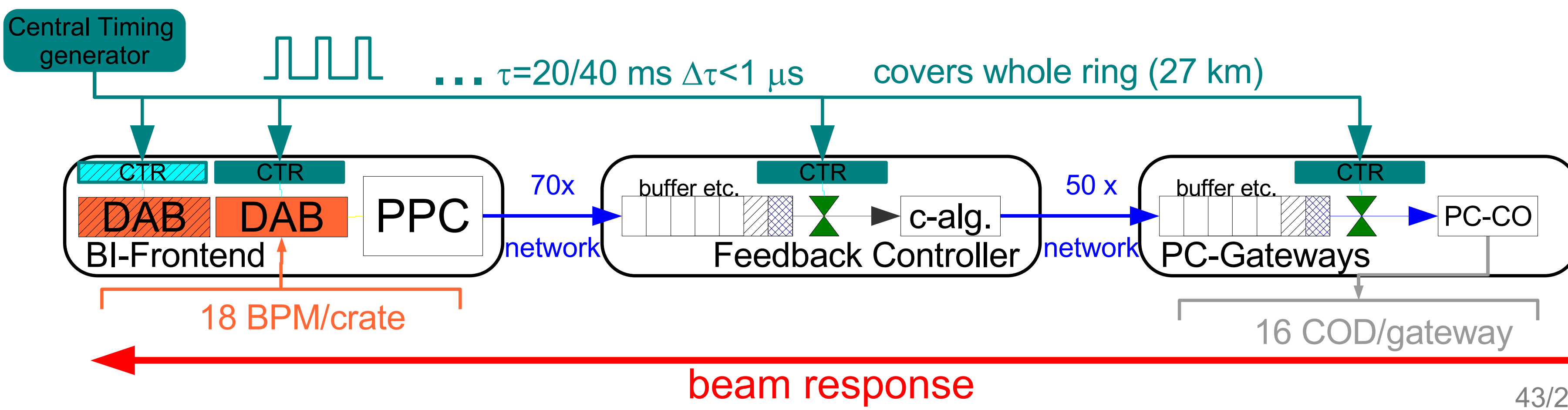


Remaining Jitter Compensation: Fix Max Loop Delay

Two main strategies:

- actual delay measurement and dynamic compensation in SP-branch:
  - high numerical complexity, due to continuously changing branch transfer function
  - only feasible for small systems

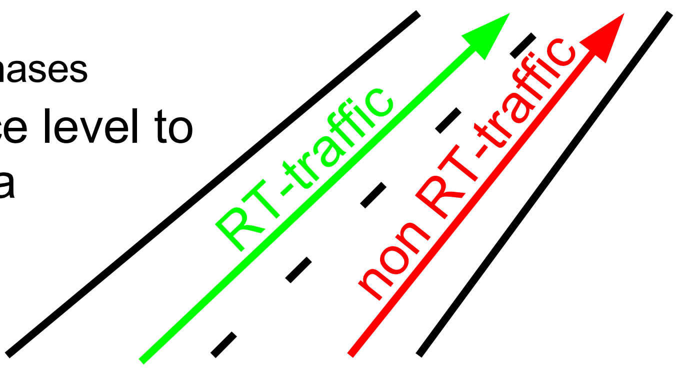
- Jitter compensation using a periodic external signal:
  - CERN wide synchronisation of events on sub ms scale that triggers:
    - Acquisition of BPM system, reading of receive buffers, processing and sending of data, time to apply in the power converter front-ends
  - The total jitter, the sum of 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...



Bottleneck I: Network in the high-level front-ends!

- The front-end network interfaces are presently the bottleneck. e.g. feedback controller @ 50 Hz:
- lots of in-/outbound connections:
  - Two types of loads:
    - Real-Time: BPM and COD control data
      - Avg. bandwidth: ~13 Mbit/s
      - short bursts: full I/O load within few ms
        (100 MBit/s resp. 1GBit/s, burst duration desired to be short in order to minimise the total loop delay)
    - Non-Real-Time:
      - transfer of new settings to OFC (matrix ~30 MB)
      - PID configuration etc.
      - relay of BPM and feedback data (monitoring/logging)
      - ...

  - (Peak) load similar to high-end network servers
    - Nearly constant full load during certain operational phases
- network interface should be scheduled on the device level to provide a Quality of Service (QoS) for real-time data
  - One reserved FIFO queue for feedback data
  - General purpose queue for other data



Bottleneck I: Network in Front-Ends: Data Rates

Hardware:

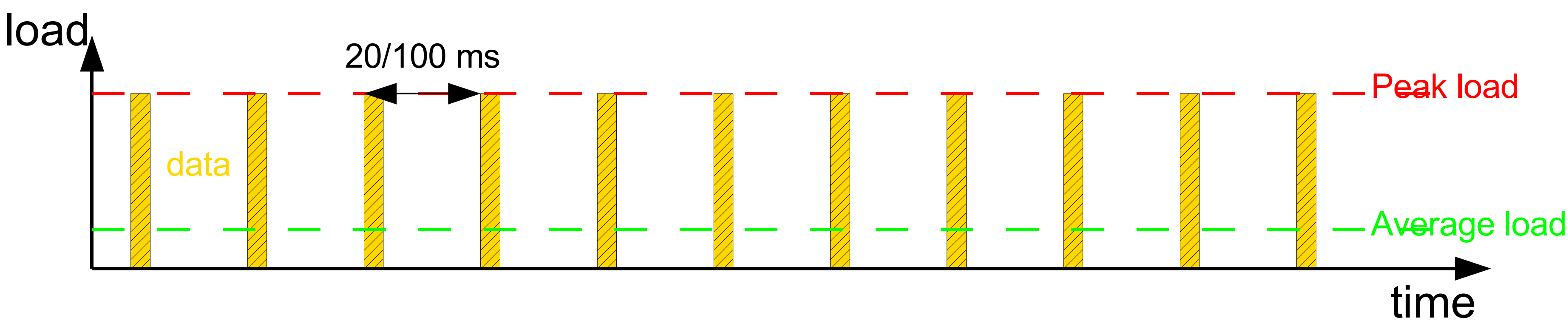
- both rings covered by 1056 BPMs
- Measure both planes (2112 readings)
- Organised in front-end crates (PowerPC/VME) in surface buildings
  - 18 BPMs (hor & vert) ⇔ 36 positions / VME crate
  - 68 crates in total, 6-8 crates /IR

Data streams:

- Average data rates per IR:

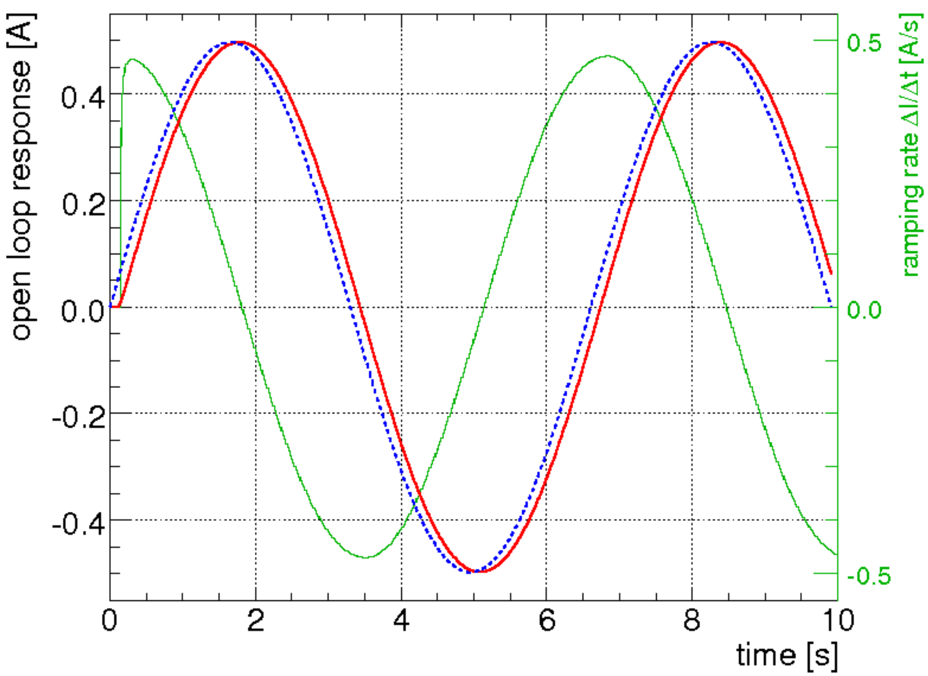
– 18 BPMs x 20 bytes+overhead	~1500	bytes	/ sample / crate
– 1056 BPMs x 20 byte	~ 94	kbytes	/ sample
@ 10 Hz:	~ 7.7	Mbit/s	
@ 50 Hz:	~ 38.4	Mbit/s	

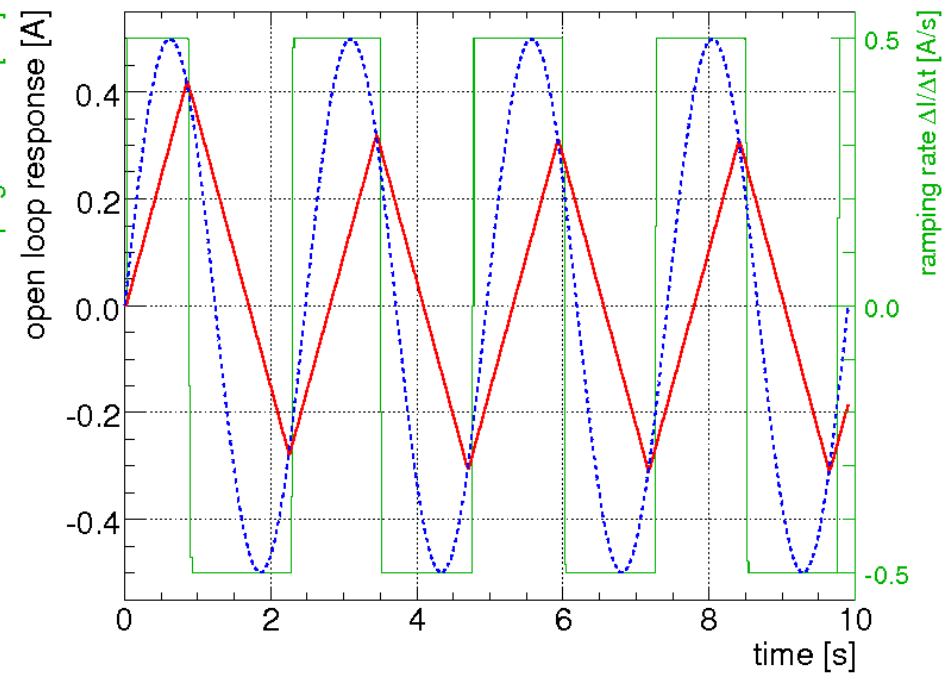
- Peak data rates (bursts): 100Mbit/s resp. 1Gbit/s (depending on Ethernet interface)



Including Non-Linearities in the Controller Design II/III

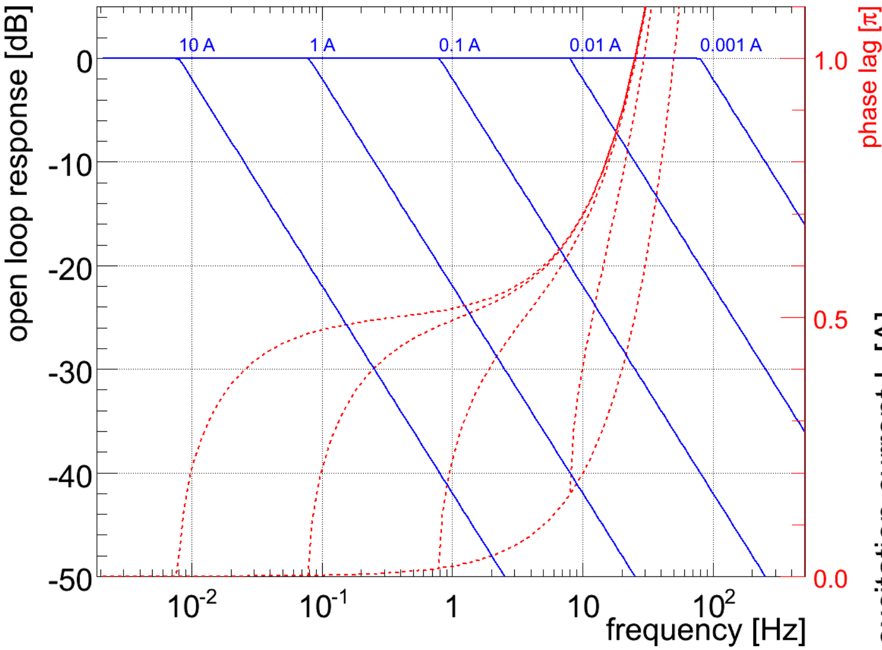
- Two main dynamic contributions
  - Delays: computation, data transmission, etc.
  - Slew rate of the corrector circuits (voltage limitation):
    - ±60A converter: $\Delta I/\Delta t|_{max}$ < 0.5 A/s
    - ±600A converter: $\Delta I/\Delta t|_{max}$ < 10 A/s



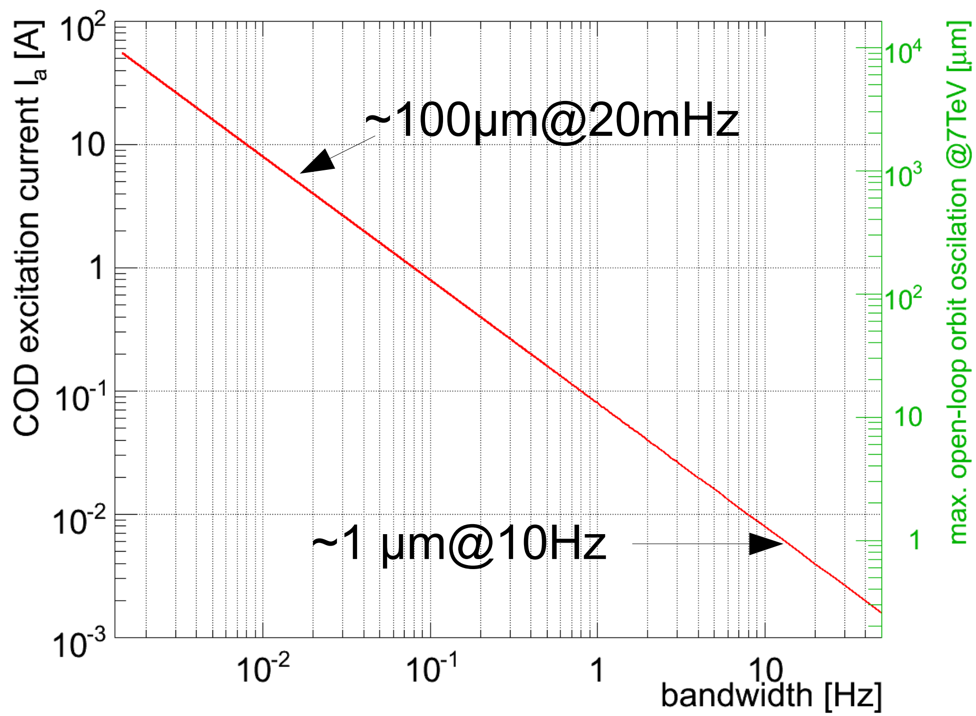


APAC'07, Real-Time Feedback on Beam Parameters, Ralph.Steinhagen@CERN.ch, 2007-01-29

- The open-loop corrector circuit bandwidth depends on the excitation current:
  - non-linear phase once rate limiter is in action



ΔI=0.1A ↔ Δx≈16 μm@β=180m



- Consider ~16μm@1Hz as effective bandwidth @ 7TeV
- Injection: ~15 times faster!