LHC Orbit Stability during β^* Squeeze

Ralph J. Steinhagen

Special thanks to J. Wenninger

Overview

- Summary of orbit stability requirements and dynamic perturbations
- Brief orbit correction/feedback sketch
- Transient orbit in IR3&IR7 during to β^* Squeeze

For details on the feedback design and architecture:
6th LHC Commissioning Working Group Meeting: http://lhccwg.web.cern.ch
http://www.agsrhichome.bnl.gov/LARP/061024_TF_FDR/index.html

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	~ 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 ≈μ)

Perturbation Prediction of Orbit, E, Q, Q', C^-, ...

- ...can be grouped into:
  - Environmental sources:
    (mostly propagated through quadrupoles and their girders)
    - correlated and random ground motion, tides,
    - temperature and pressure changes,
    - cultural noise (human activity), and other effects.
  - Machine inherent sources:
    - decay and snap-back of the main dipoles' multipoles,
    - eddy currents in the magnet and on the vacuum chamber,
    - flow of cooling liquids, vibrations of the ventilation system,
    - changes of the final focus optics — today's focus
  - Machine element failures:
    - particularly orbit correction dipole magnets
      (most other magnets are interlocked and inevitably lead to beam dump)

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	$(9.5 \ldots 16)/^{O}C$	$< 10^{-3}/^{O}C$	-	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

"One-Slide" Orbit Correction Strategy

- Orbit Correction will consist of two steps (which may alternate repetitively):
  - Initial setup: "Find a good orbit" (mostly feedback "off")
    - establish circulating beam
    - compensate for each fill recurring <u>large</u> perturbations:
      - static quadrupole misalignments, dipole field imperfections
      - ...
    - tune for optimal orbit
      - keep aperture limitation
      - rough jaw-orbit alignment in cleaning insertions
      - ...

    → reference orbit
  - During fill: "Stabilise around the reference orbit" (feedback "on"):
    - correct for <u>small</u> and random perturbations Δx
      - environmental effects (ground-motion, girder expansion, ...)
      - compensate for residual decay & snapback, ramp, squeeze
    - optimise orbit stability at collimator jaws/roman pots.

Space-Domain: No "black feedback magic"

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

$$\boxed{\Delta\vec{x}(t) = \underline{R}\cdot\vec{\delta}_{ss}} \quad with \quad R_{ij} = \frac{\sqrt{\beta_i\beta_j}}{2\sin(\pi Q)}\cdot\cos(\Delta\mu_{ij} - \pi Q)$$

matrix multiplication

  - similar for other parameters but different dimension
  - their control consists essentially in inverting these matrices

$$\underline{R}_{orbit}\in\mathbb{R}^{1056\times530} \qquad \underline{R}_{Q}\in\mathbb{R}^{2\times16} \qquad \underline{R}_{Q'}\in\mathbb{R}^{2\times32} \qquad \underline{R}_{C^-}\in\mathbb{R}^{2\times10/12}$$

- Some potential complications:
  - Singularities = over/under-constraint matrices, noise, element failures, spurious BPM offsets, calibrations, ...
  - Time dependence of total control loop
  - Controls: How to receive, process, send data ...

Task in space domain:

Solve linear equation system and/or find (pseudo-) inverse matrix R^{-1}

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

- Singular Value Decomposition (SVD) is the preferred orbit feedback workhorse:
  - standard and proven eigenvalue approach
  - insensitive to COD/BPM faults and their configuration (e.g. spacing)
  - minimises parameter deviations and COD strengths
  - numerical robust:
    - guaranteed solution even if orbit response matrix is (nearly) singular

      (e.g. two CODs have similar orbit response ↔ two rows are (nearly) the same)
    - easy to identify and eliminate singular solutions
  - higher complexity:
    - Gauss(MICADO): $O= \frac{1}{2} mn^2 + 1/6\, n^3$
    - SVD: $O= 2mn^2+4n^3$

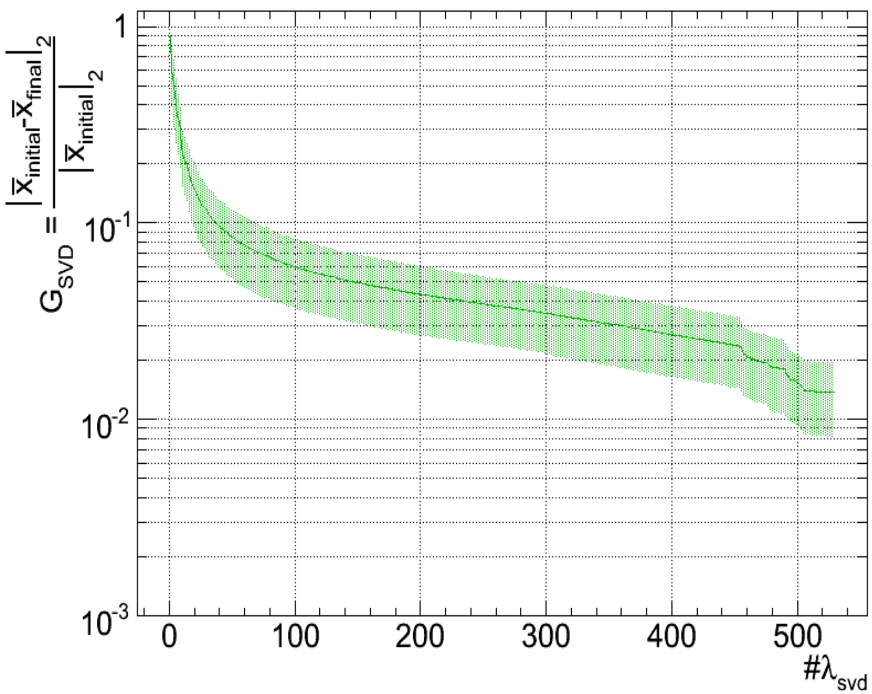
  m=n: SVD is 9 times more expensive, even on high-end CPUs full initial decomposition may take several seconds (LHC: ~15 s/plane), but once decomposed and inverted: simple matrix multiplication ($O(n^2)$) complexity, LHC orbit correction <15ms!)

Example SVD based orbit correction

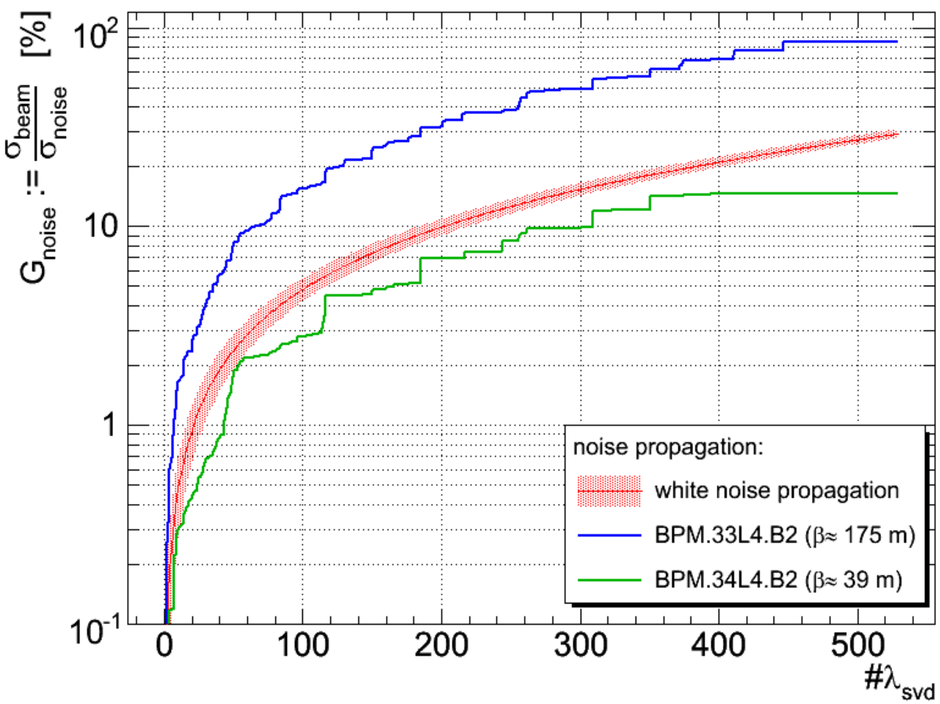
Quick SVD summary:

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

- Orbit attenuation



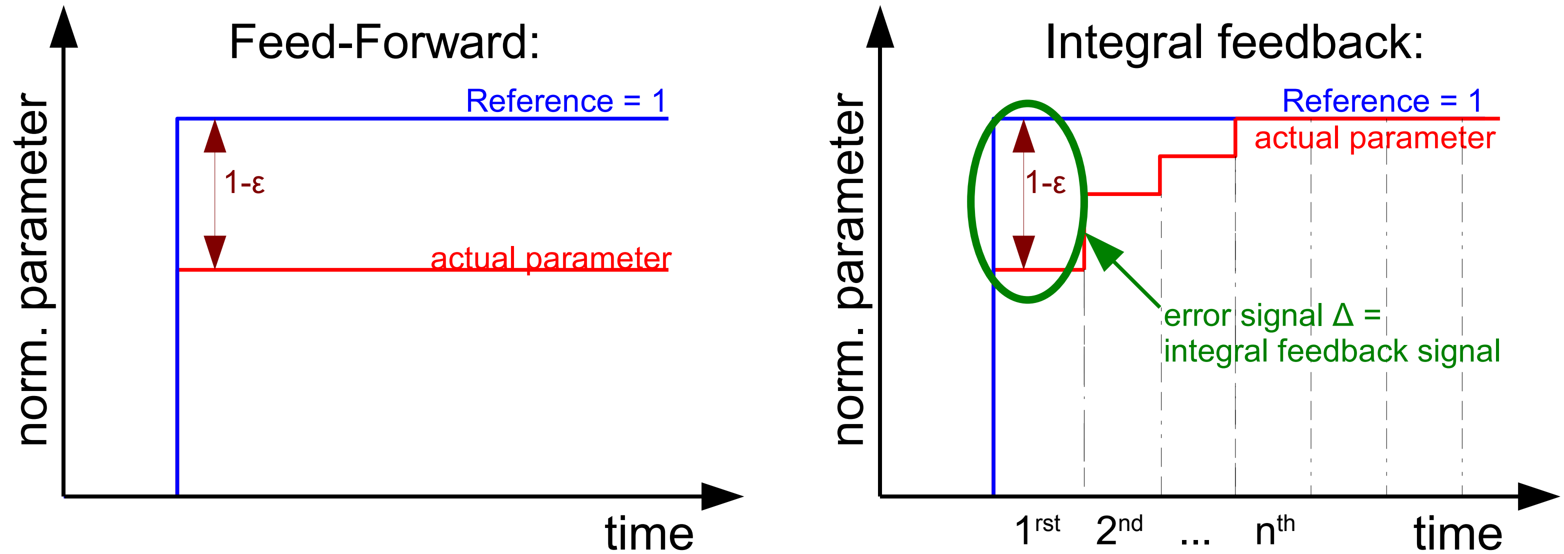
- Sensitivity to BPM noise



Optics and Calibration Uncertainties I/II

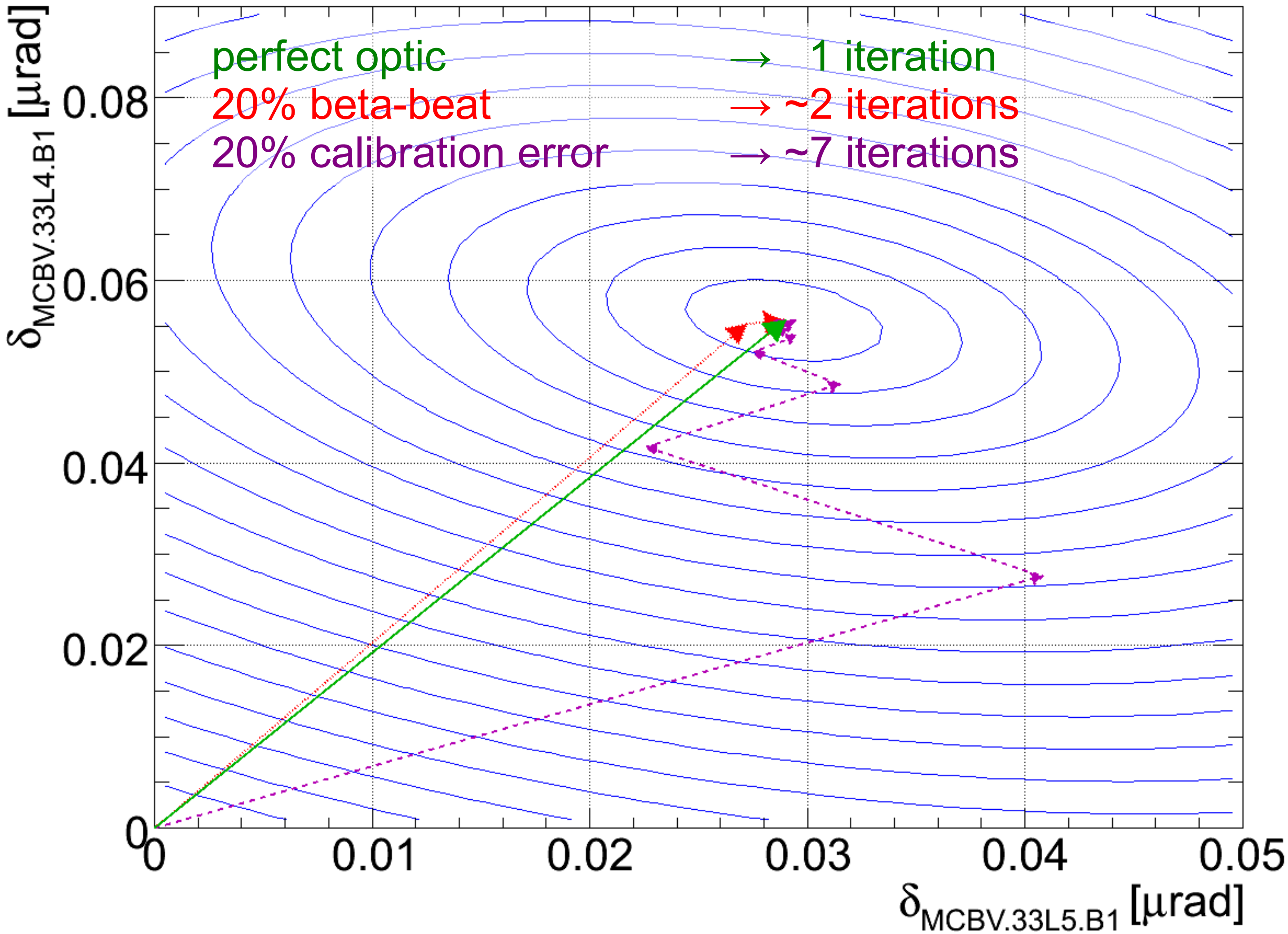
- Machine imperfections (beta-beat, hysteresis....), calibration errors and offsets can be translated into a steady-state ε_{ss} and scale error ε_{scale}:

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

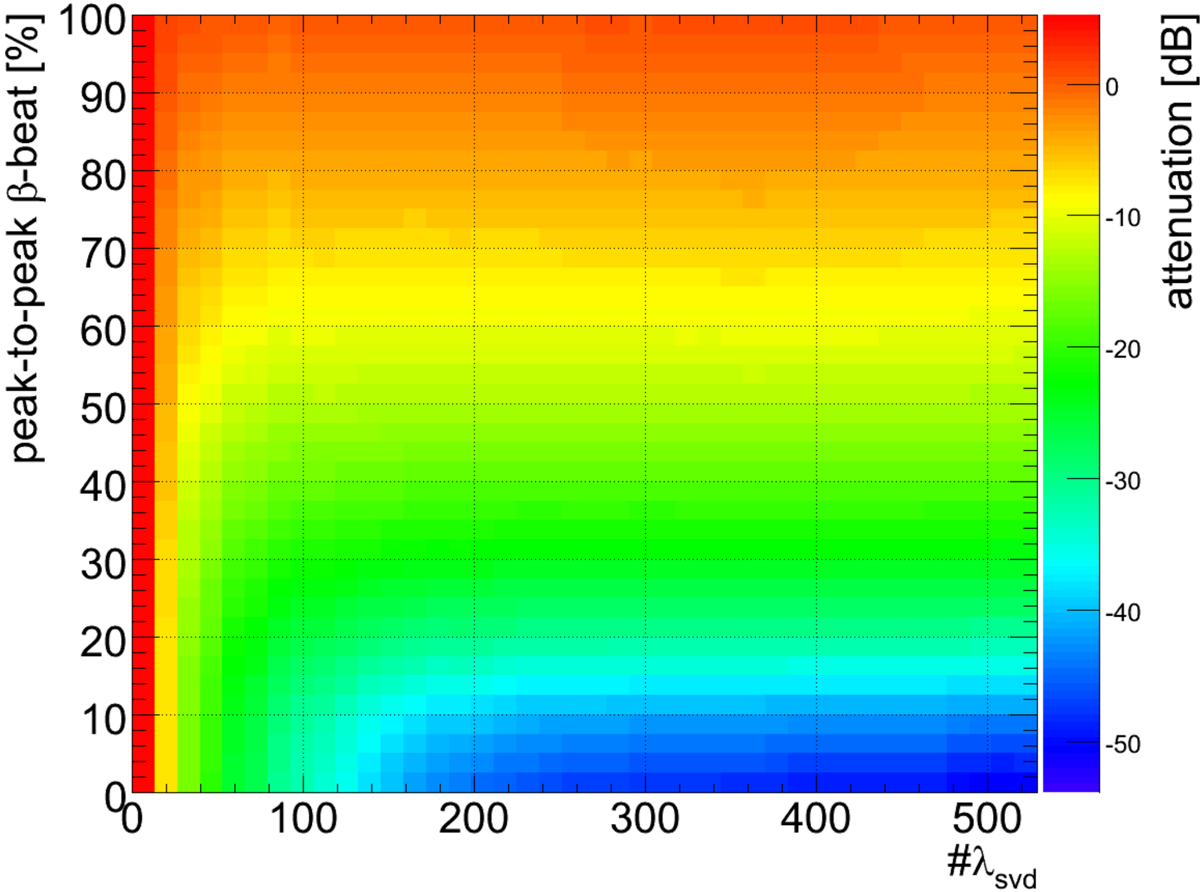


- Uncertainties and scale error of beam response function affects rather the convergence speed (= feedback bandwidth) than achievable stability
- Stability limit: BPM noise and external perturbations w.r.t. FB bandwidth

- Example: 2-dim orbit error surface projection



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



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

attenuation =

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

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

Orbit Transient due to Squeeze

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

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

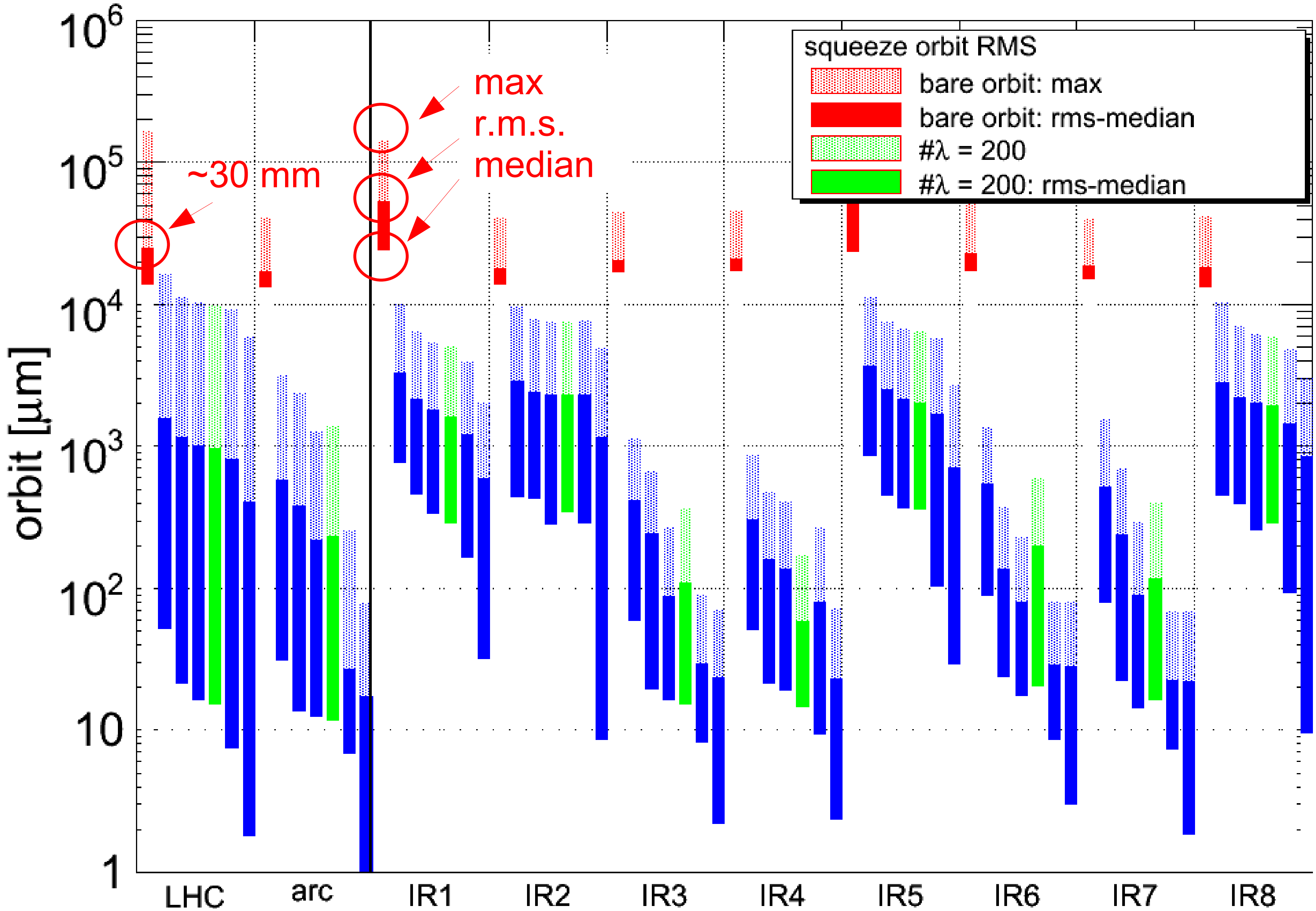
- Working assumption for random quadrupole and BPM misalignment:

  $\Delta x_{quad\text{-}misalignn}$=0.5 mm r.m.s. (worst case scenario)

  – Survey group targets:
    - 0.2 mm r.m.s. globally
    - 0.1 mm r.m.s. as an average over 10 neighbouring magnets.
  – may re-scale results to other alignment assumptions

- Without k-modulation: BPM offsets w.r.t. quadrupole are unknown

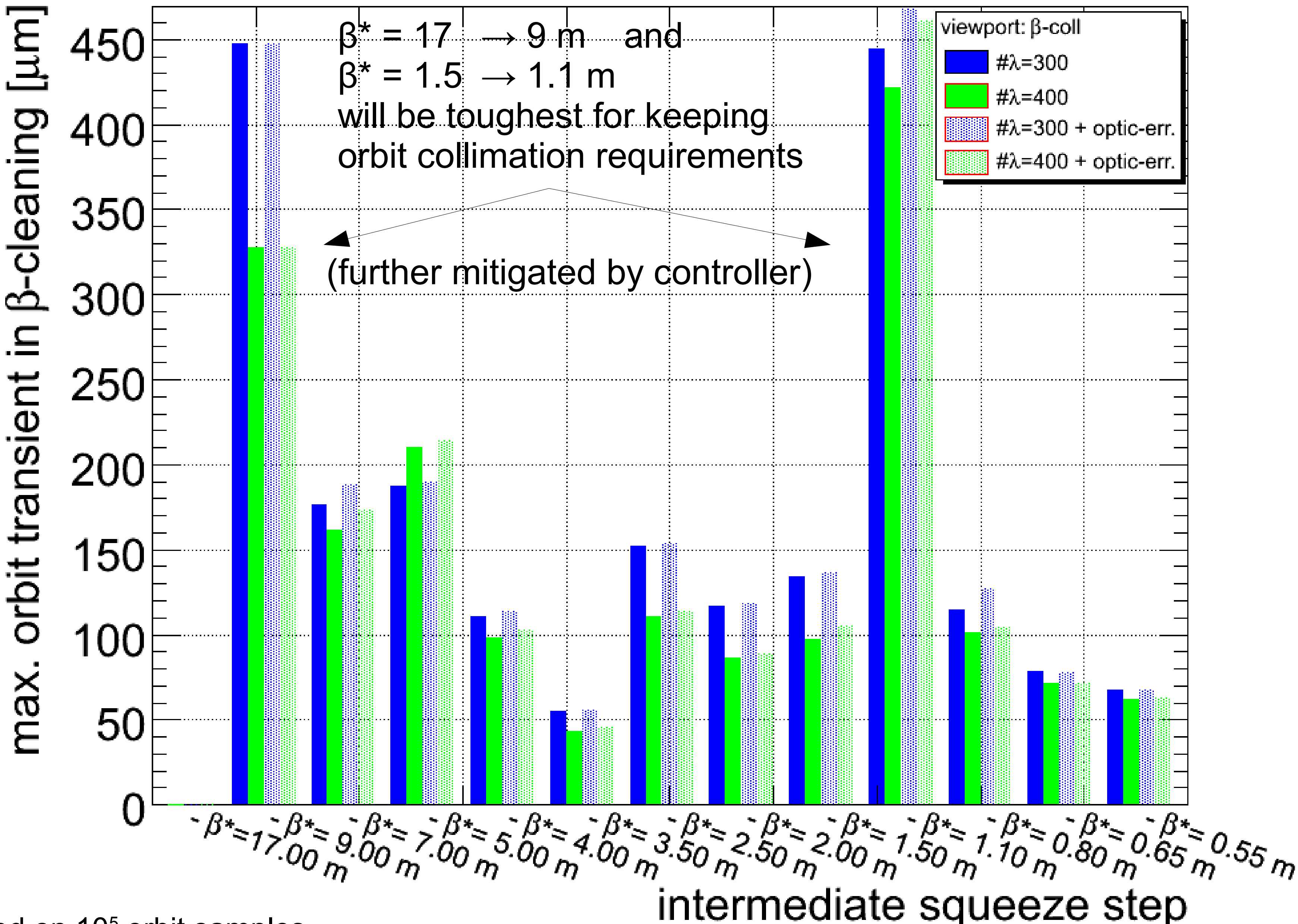
- Transients are an issue w.r.t. beam stability and available current rate limit



based on 10^5 orbit samples

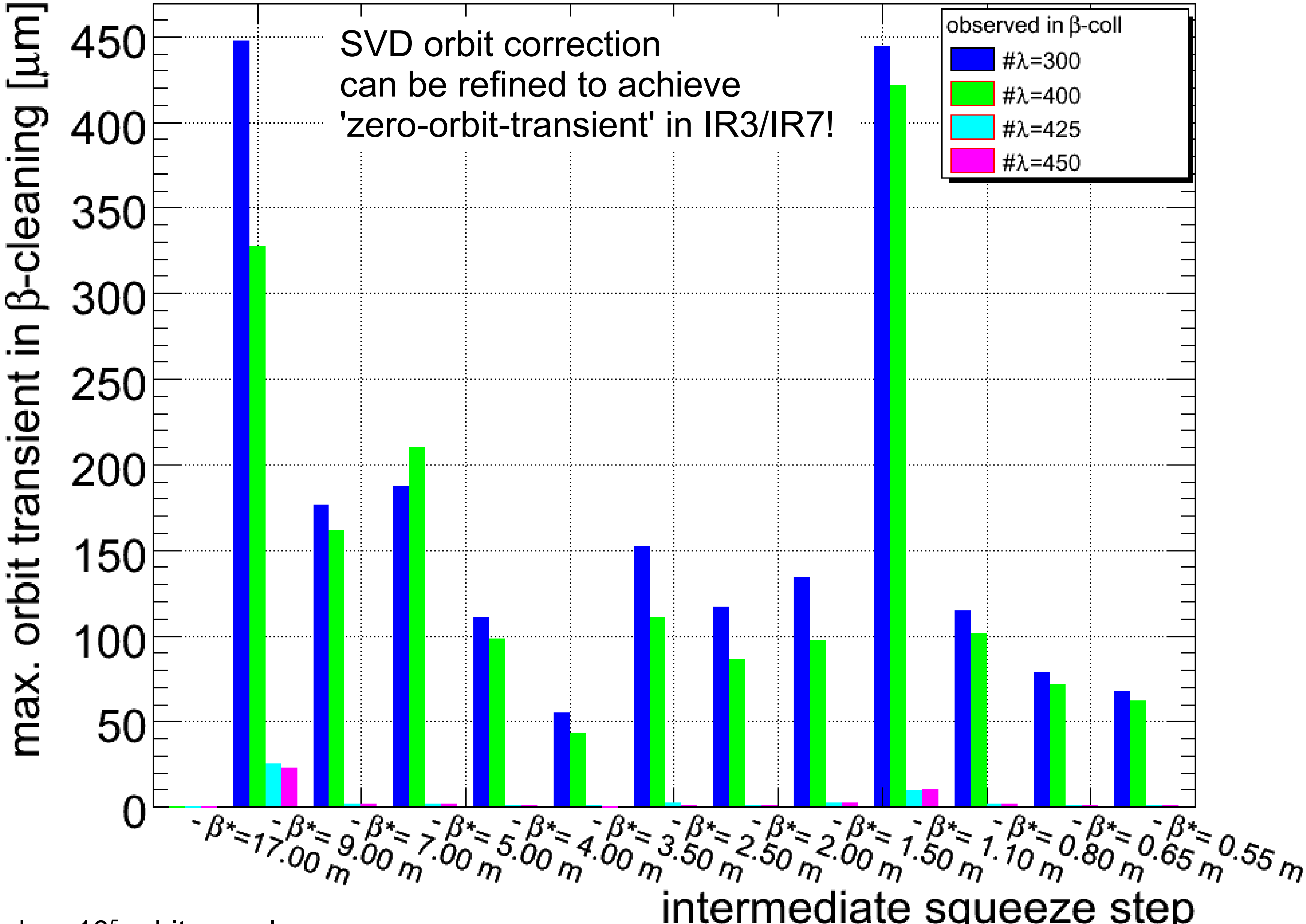
bars: $\#\lambda_{svd}$ = 50, 100, 150, 200, 250, 270 (B1 only)

Transient in Collimation Insertion vs. Squeeze Step - moderate global orbit correction only (commissioning)



based on 10^5 orbit samples

Transient in Collimation Insertion vs. Squeeze Step - refined for 'zero orbit transient'



based on 10^5 orbit samples

Feed-Forward and Squeeze

- In principle: Squeeze is very predictable
  - $\Delta x_{quad\text{-}misalignn} \approx 0.5$ mm r.m.s. → $\Delta x_{orbit} \approx 30$ mm r.m.s. (amplification factor: $k_{squeeze} \approx 60$)
  - for a steady state machine, one could fully compensated this through a feed-forward system (based e.g. on previous β* squeeze with feedback)
  - about 20 minutes of squeeze → $\Delta x/\Delta t|_{max} \leq$ 25 μm/s
  - OK w.r.t. single COD magnet ramping speed: $\Delta x/\Delta t|_{max} \sim$ 81 μm/s
- Expected* thermal & ground motion quadrupole drifts are about $\Delta x_{quad\text{-}ground} \approx$ 5 -10 μm within ~10h
  - $\Delta x_{orbit} = k_{squeeze} \cdot \Delta x_{quad\text{-}ground} \approx$ 300 - 600 μm (w/o orbit feedback)
- If collimation requirement $\Delta x_{orbit} <$ 30 μm → need orbit feedback for squeeze
  - strong dependability, orbit feedback is not a SIL3 system!
  - Possibilities to relax orbit stability requirement?

*see: "Analysis of Ground Motion at SPS and LEP, Implications for the LHC", AB Report CERN-AB-2005-087

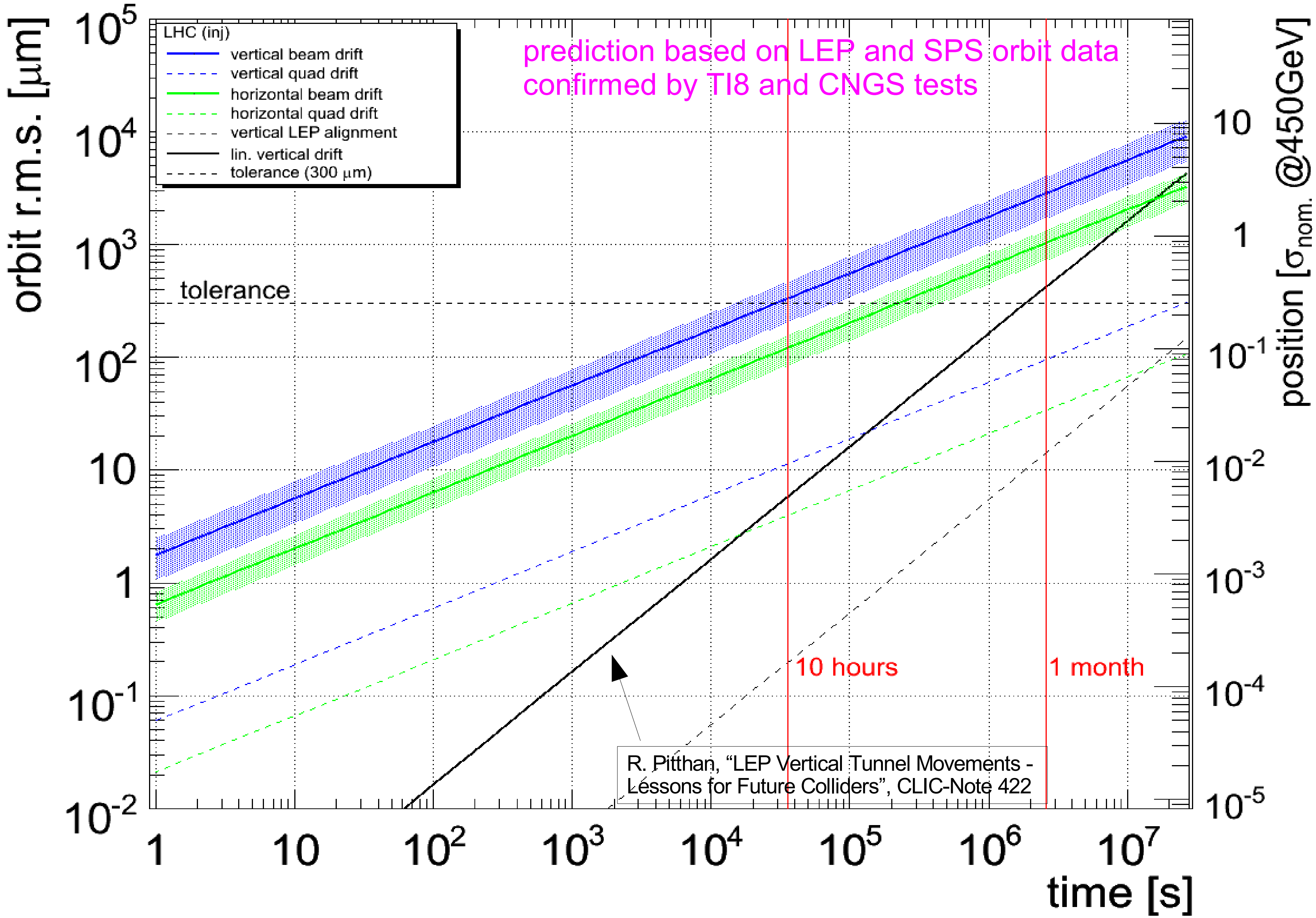
Conclusion

- The effective orbit transient in IR3/7 during squeeze is a superimposition of the expected orbit drifts due to quadrupole feed-down and orbit feedback
- Orbit transients due to squeeze can be large if orbit poorly aligned in IR5/IR1
  - Largest transients expected for: $\beta^* = 17$ m → 9 mm & $\beta^* = 1.5$ m → 1.1 mm
  - Fill-to-fill reproducibility (w/o ofb but including feed-forward): 300-600 µm
- Orbit feedback can be adjusted to fulfill 'zero-orbit-transient'
  - choice of $\#\lambda_{SVD}$ for global type correction
  - Refined through orbit-eigenvector patterns specifically controlling IR3 & IR7
  - Implies trade-off between orbit attenuation and robustness against failures/noise
  - Ultimate stability limited by residual BPM/COD noise
  - Favourable to run with nominal feedback sampling frequency
- Strong dependence of the collimation system on active feedback systems

→ Should spend some time on tuning the orbit inside IR1 and IR5 before squeezing the first time to minimise possible transient and required feedback/COD ramping speed

Reserve Slides

"Analysis of Ground Motion at SPS and LEP, Implications for the LHC", AB Report CERN-AB-2005-087

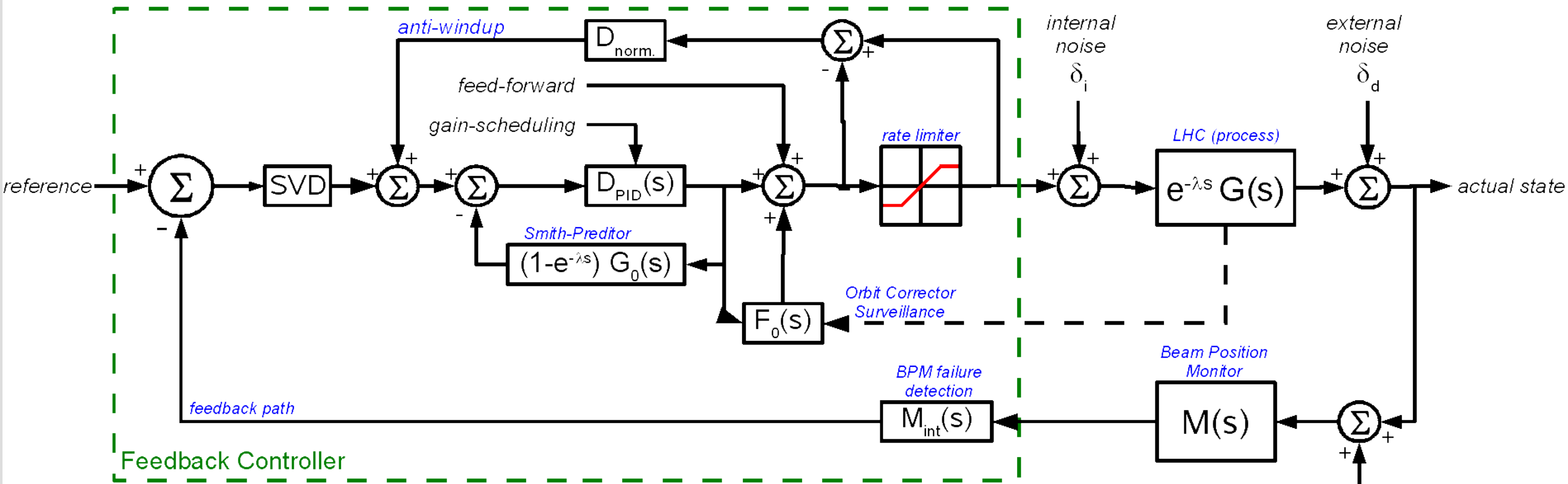


- → closed Orbit drifts after 10 hours ≈ 0.3 -0.5 σ

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

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

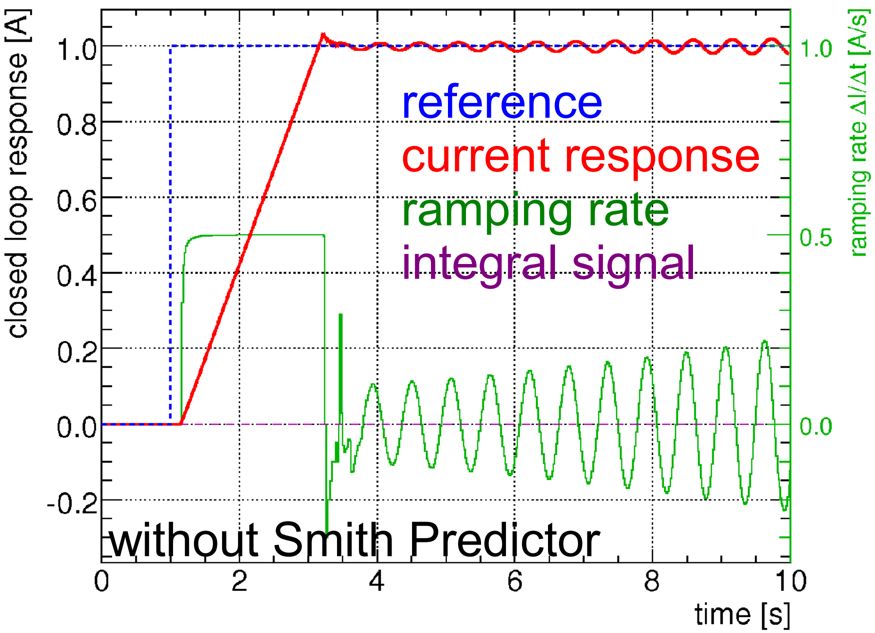
- with τ the power converter time constant, then: $G^i(s)=\frac{\tau s+1}{1}$
- Using (1) and (4) yields $T_0(s)=F_Q(s)\cdot e^{-\lambda s}G_{NL}(s)$
- Inserting in (1) effortlessly yields Smith-Predictor and Anti-Windup schemes:

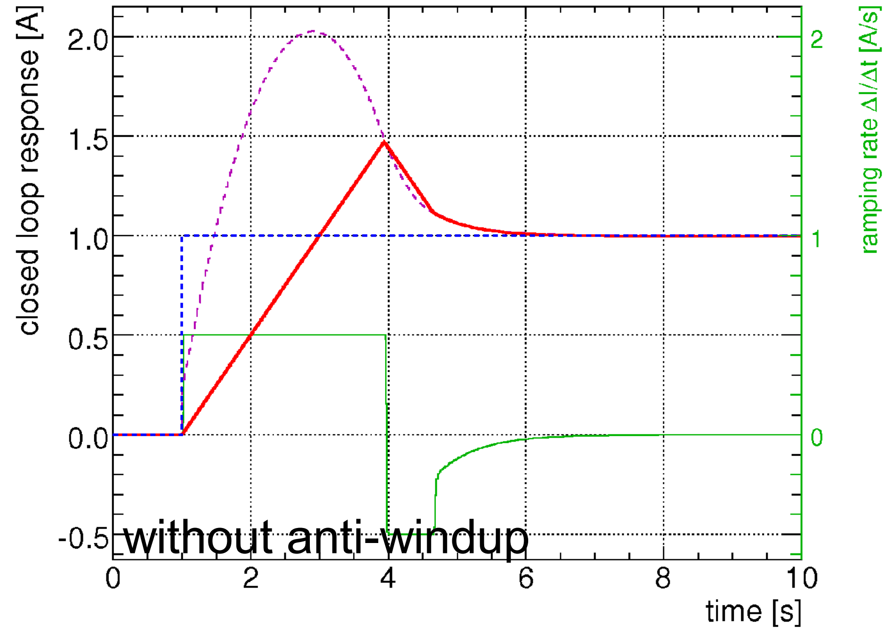


$D_{PID}(s)$ controller gains are independent of the compensator!!

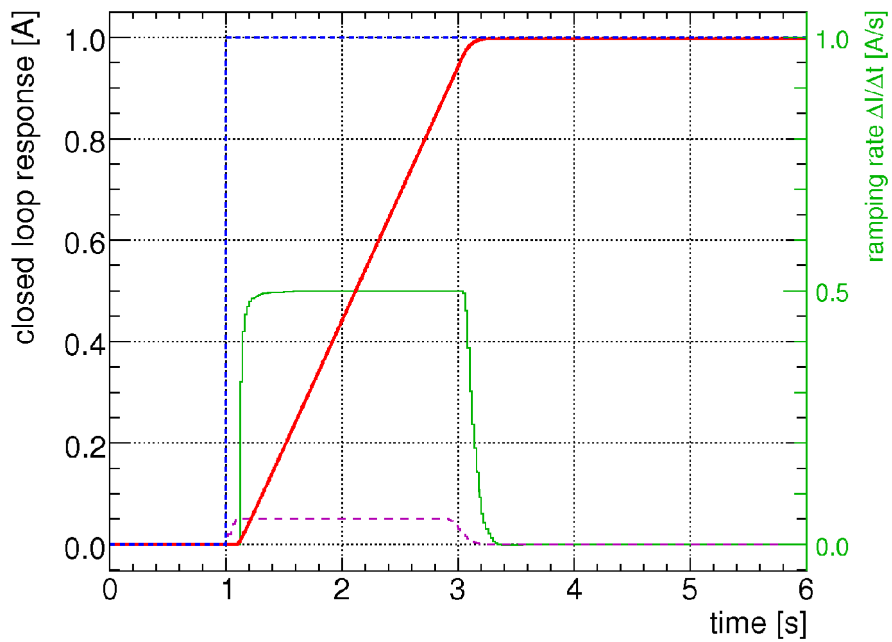
can be adjusted based on the operational scenario

Some Results: Smith-Predictor and Anti-Windup



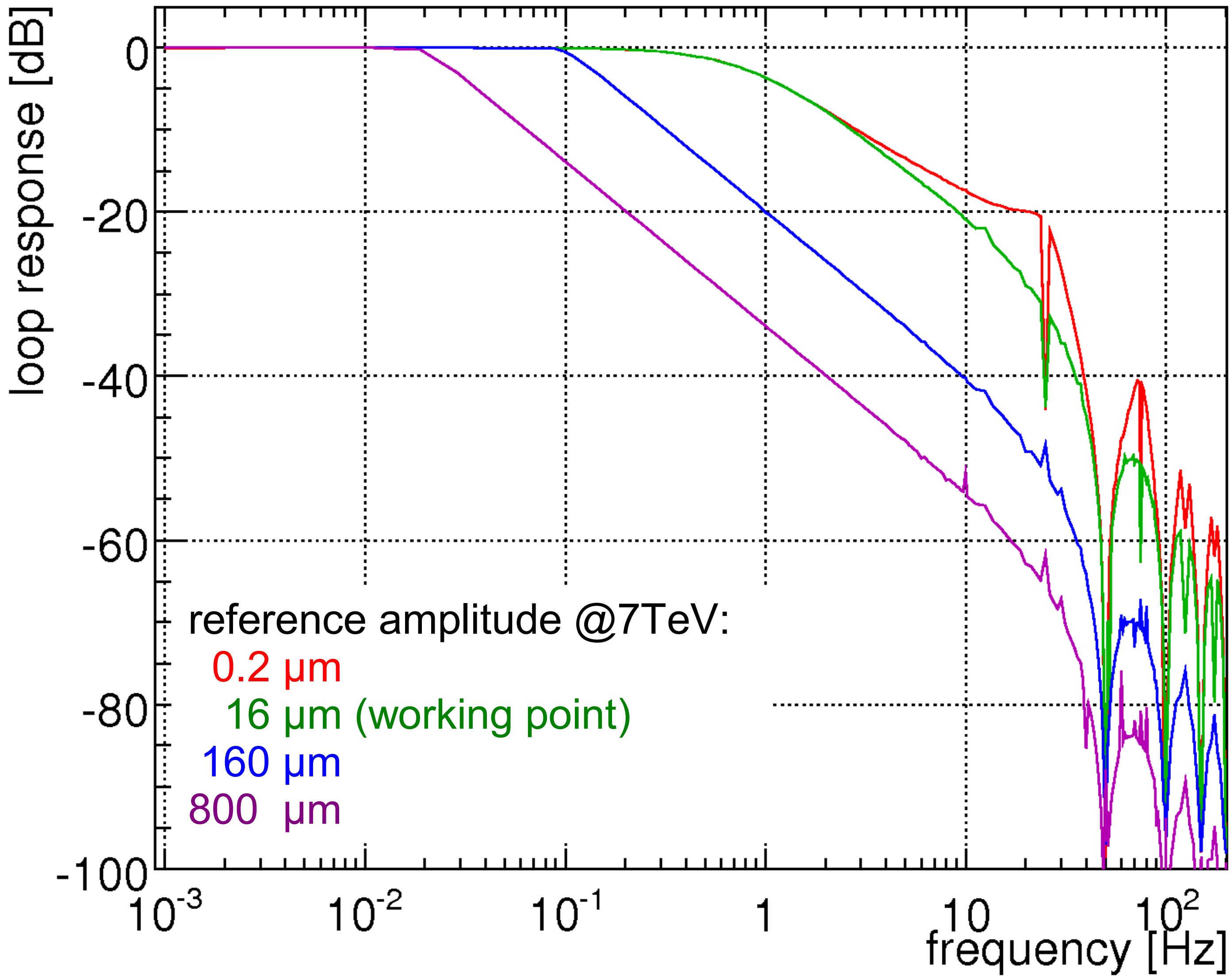


with full delay and windup compensator scheme:



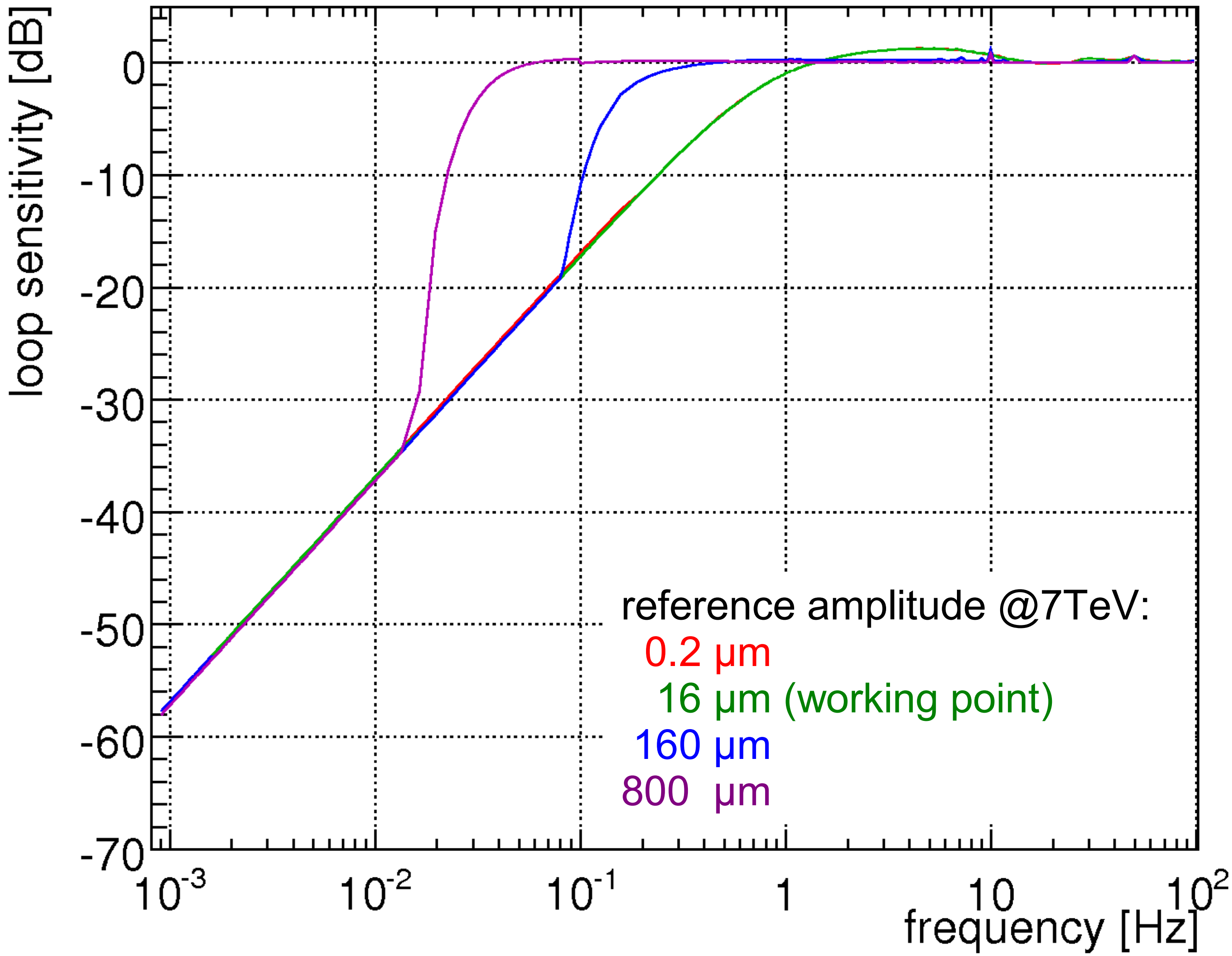
Nominal Feedback Response T_0

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

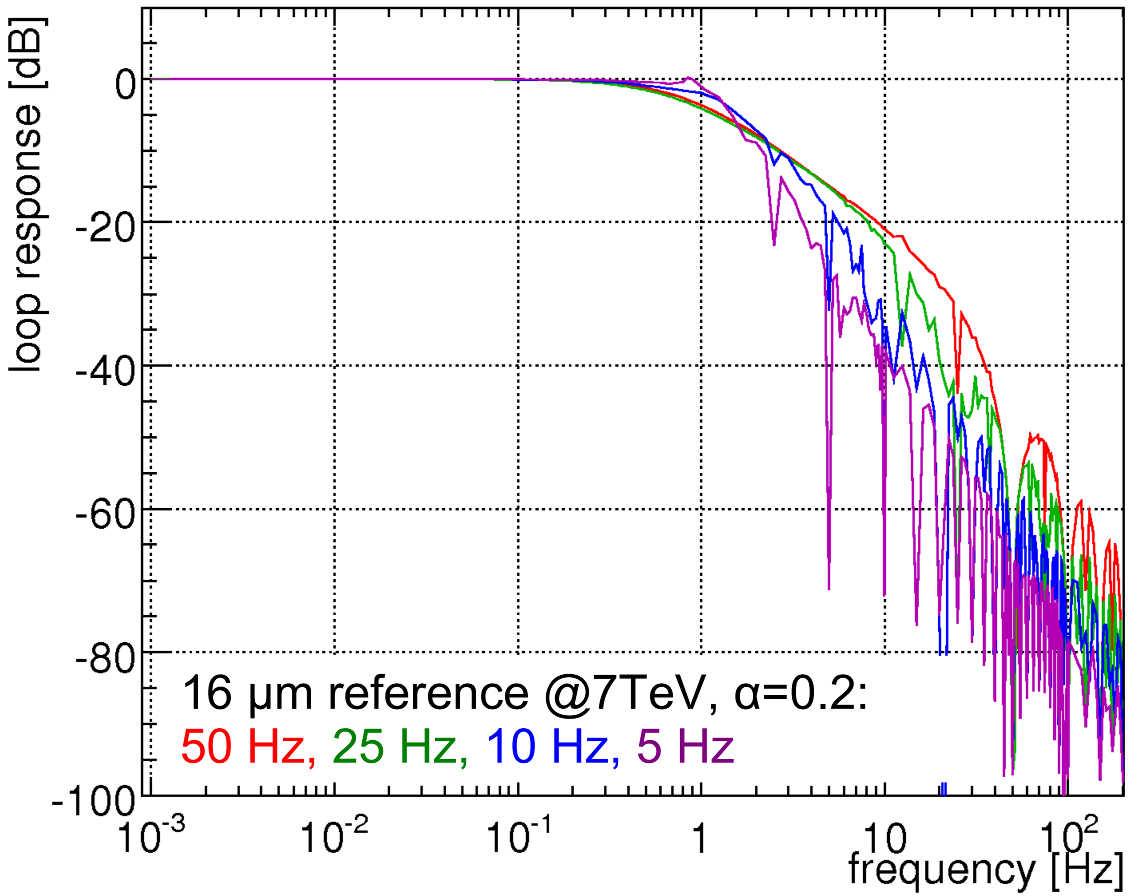


Nominal Feedback Disturbance Rejection S_{d0}

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



- ... sample the position at 10Hz to achieve a closed loop 1Hz bandwidth

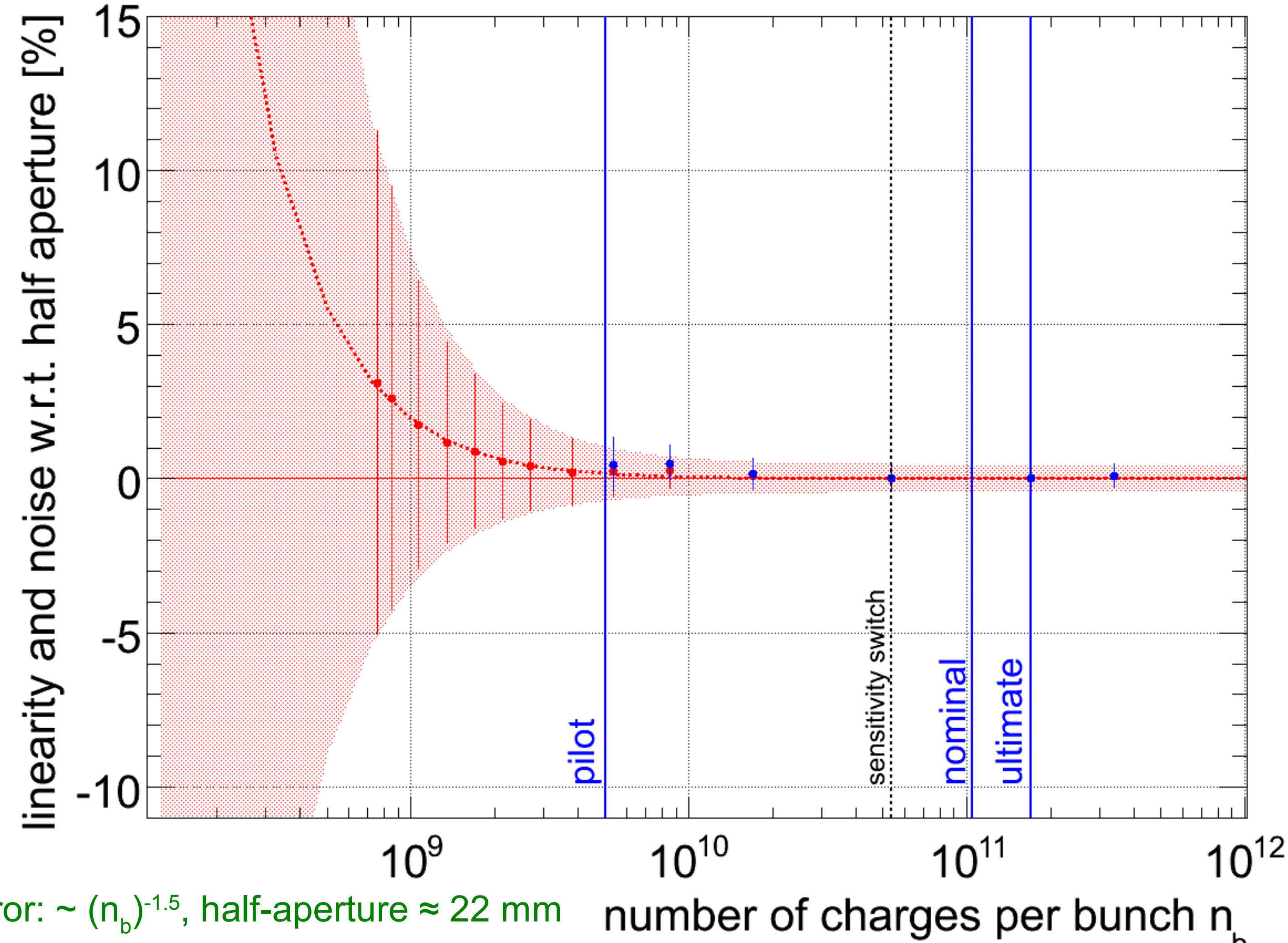


  – ... a theoretic limit assuming a perfect system!
  – common: sampling frequency > 25 ...40 desired closed-loop bandwidth

From threading the first pilot to 43x43 bunches

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

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



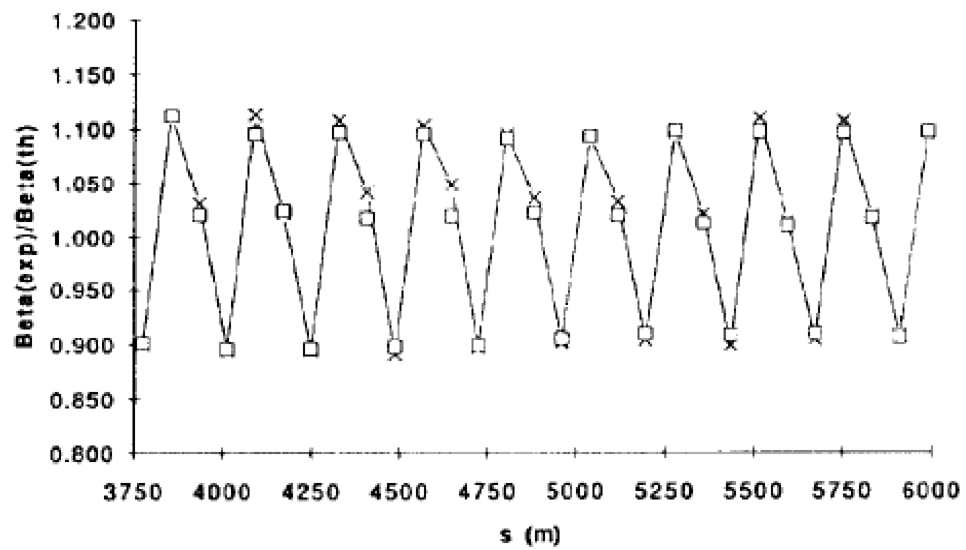
noise/error: ~ $(n_b)^{-1.5}$, half-aperture ≈ 22 mm
switch at: ~$5.3 \cdot 10^{-10}$ protons/bunch

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

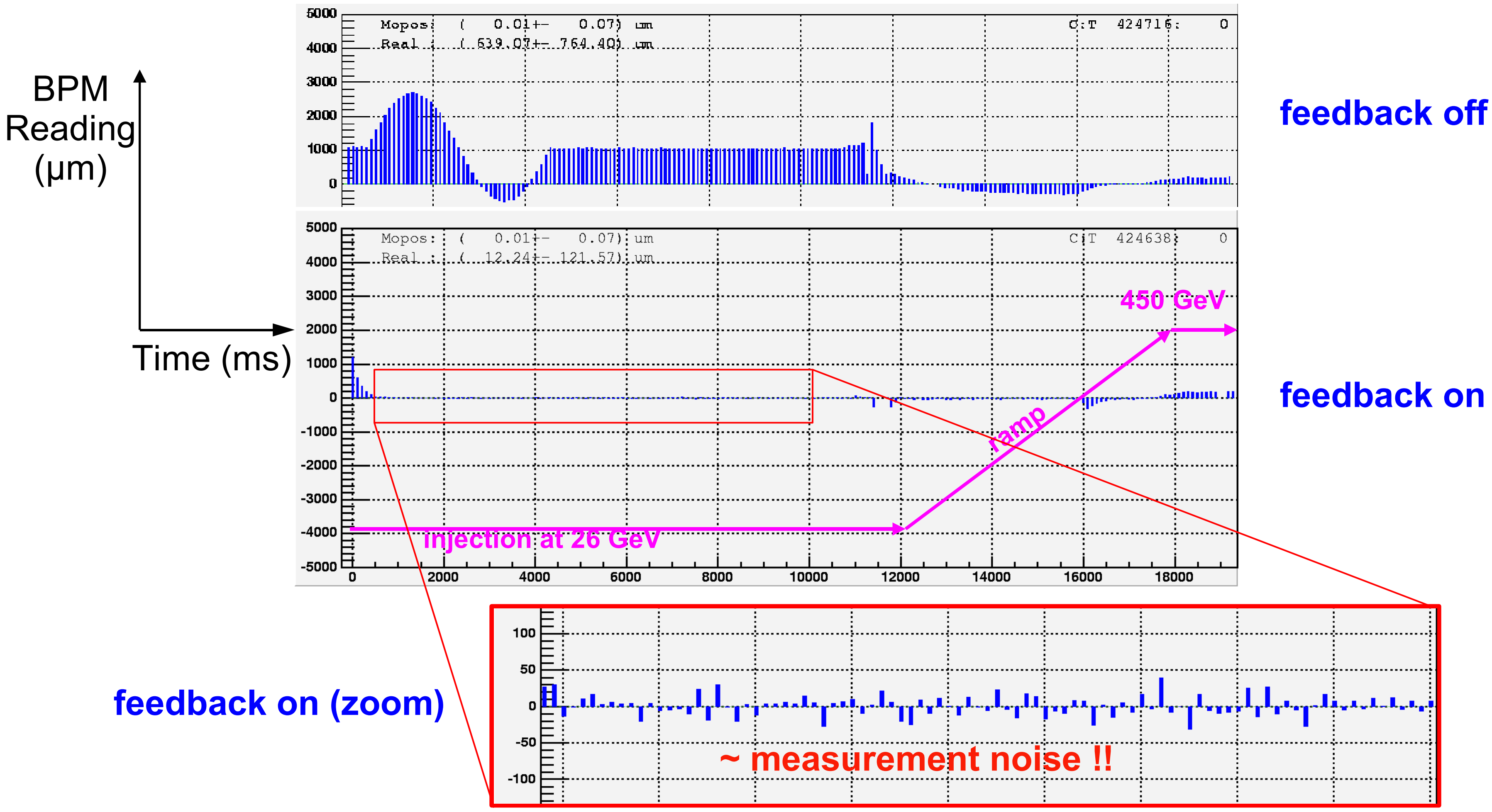
- Optics measurement through phase advance between three adjacent BPMs[1]
  - Design μ_{ij} versus measured (kick+1024 turns) ψ_{ii} phase advance:

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



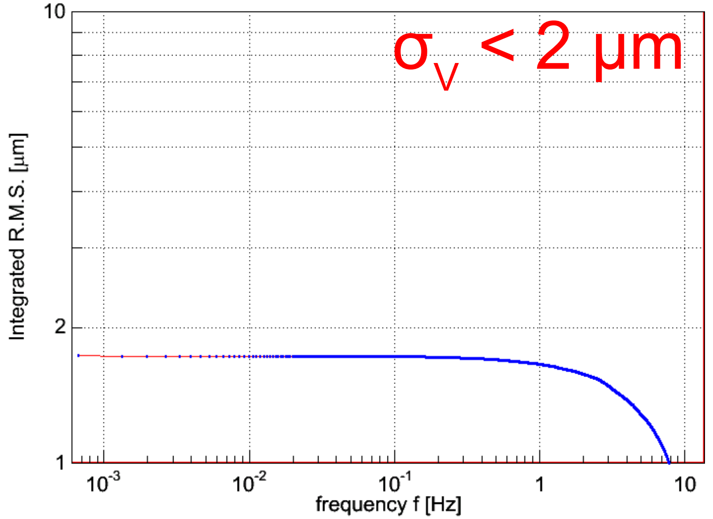
[1]P. Castro, “Betatron function measurements at LEP [..]”, CERN, SL/Note 92-63-BI

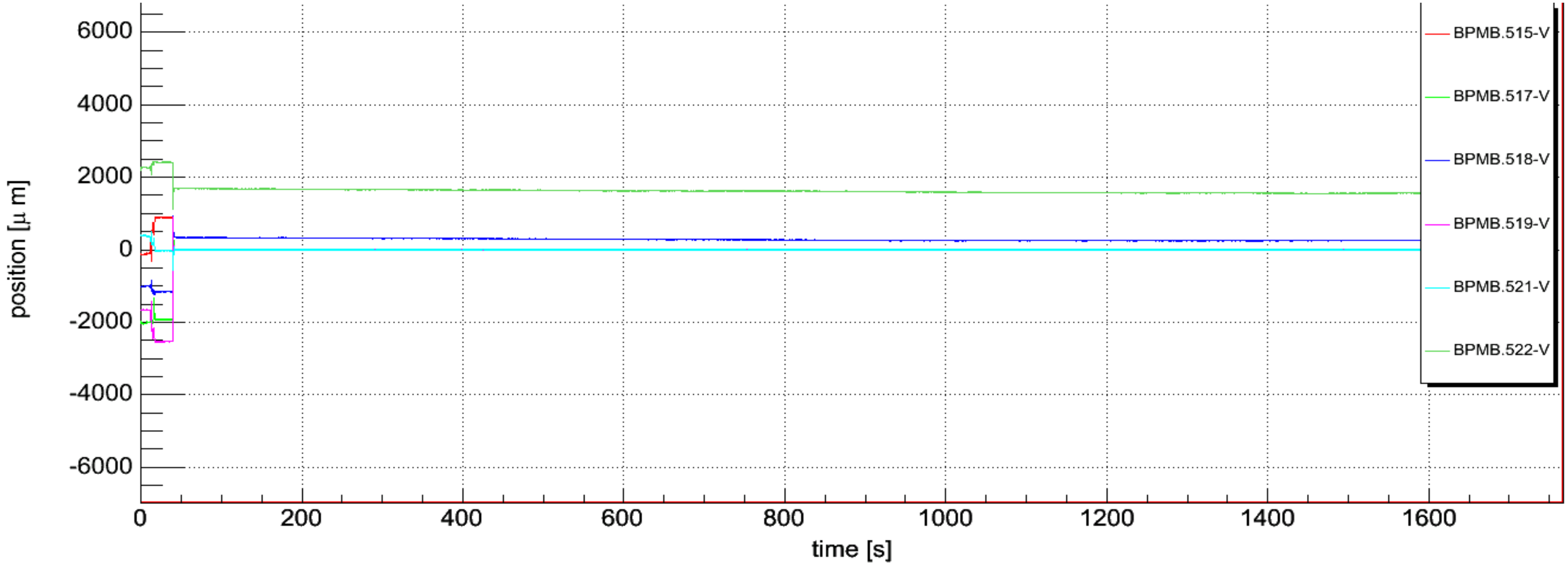
LHC Orbit Feedback Test at the SPS I/II



LHC Orbit Feedback Test at the SPS II/II

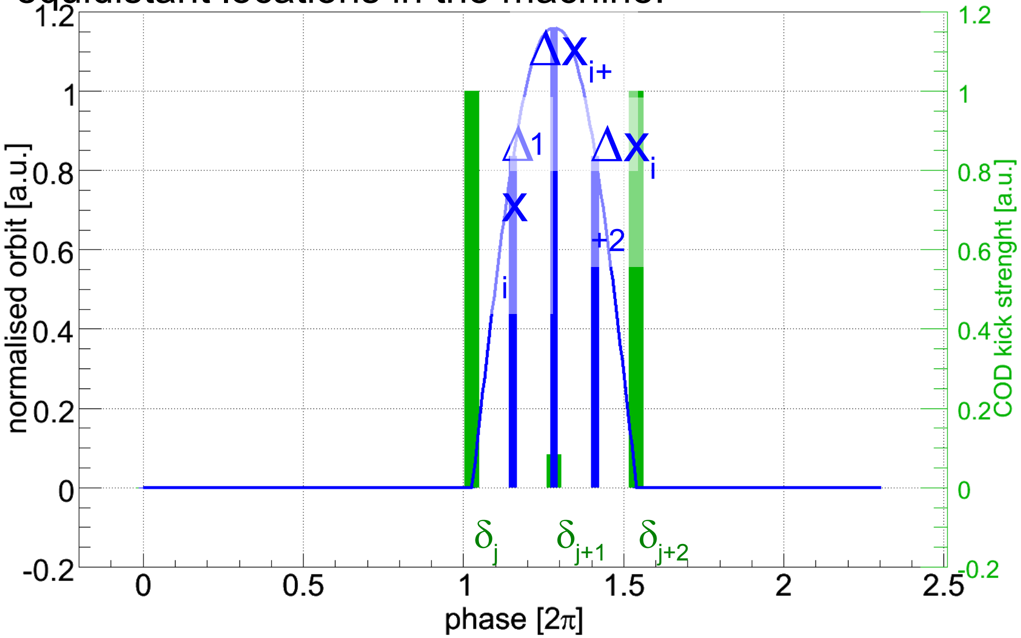
- Stabilisation "record" in the SPS
  - 270 GeV coasting (proton) beam, 72 nom bunches, $\beta_v \approx 100$ m
  - rivals most modern light sources
  - magnitudes better than required
- Target: maintain same longterm stability



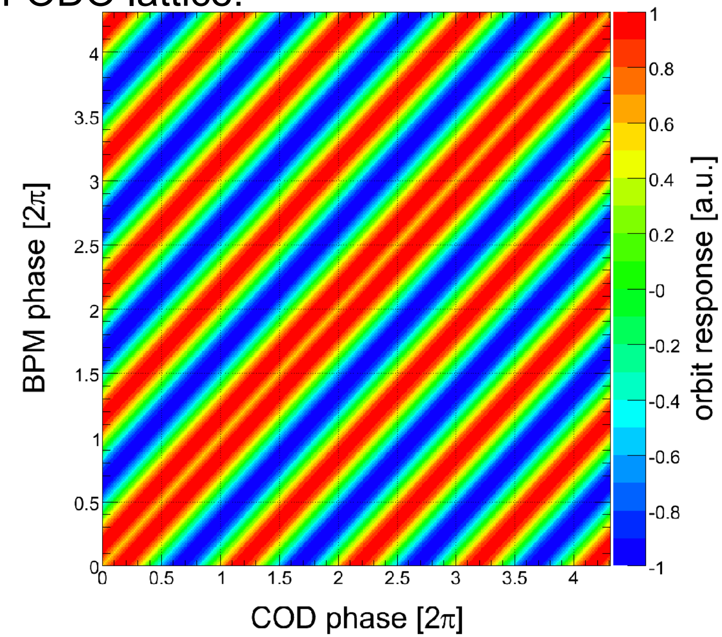


Automated Orbit Correction using Singular Value Decomposition

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

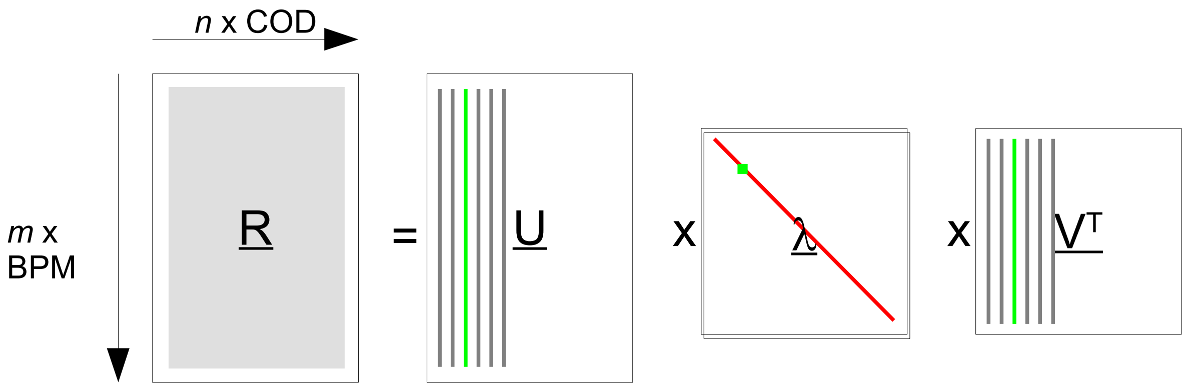
$$\Delta x_i = \sum^{n} R_{ij} \cdot \delta_j \quad with \quad R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi Q)} \cdot \cos(\Delta \mu_{ij} - \pi Q)$$

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

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

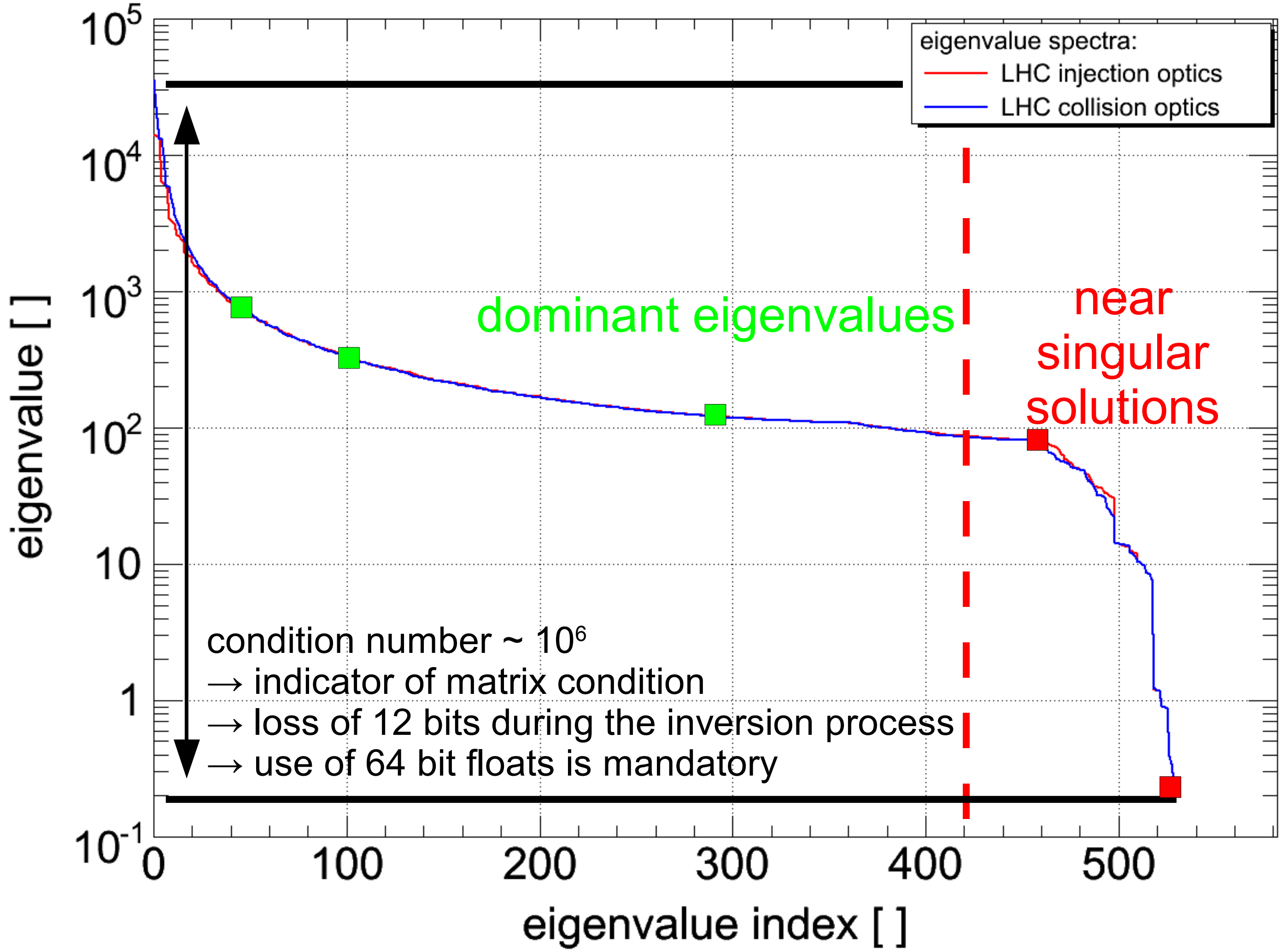
$$\vec{\delta}_{ss} = \tilde{R}^{-1} \cdot \Delta \vec{x} \quad with \quad \tilde{R}^{-1} = \underline{V} \cdot \underline{\lambda}^{-1} \cdot \underline{U}^T \quad \Leftrightarrow \quad \vec{\delta}_{ss} = \sum_{i=0}^{n} \frac{a_i}{\lambda_i} \vec{v}_i \quad with \quad a_i = \vec{u}_i^T \Delta \vec{x}$$

- 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

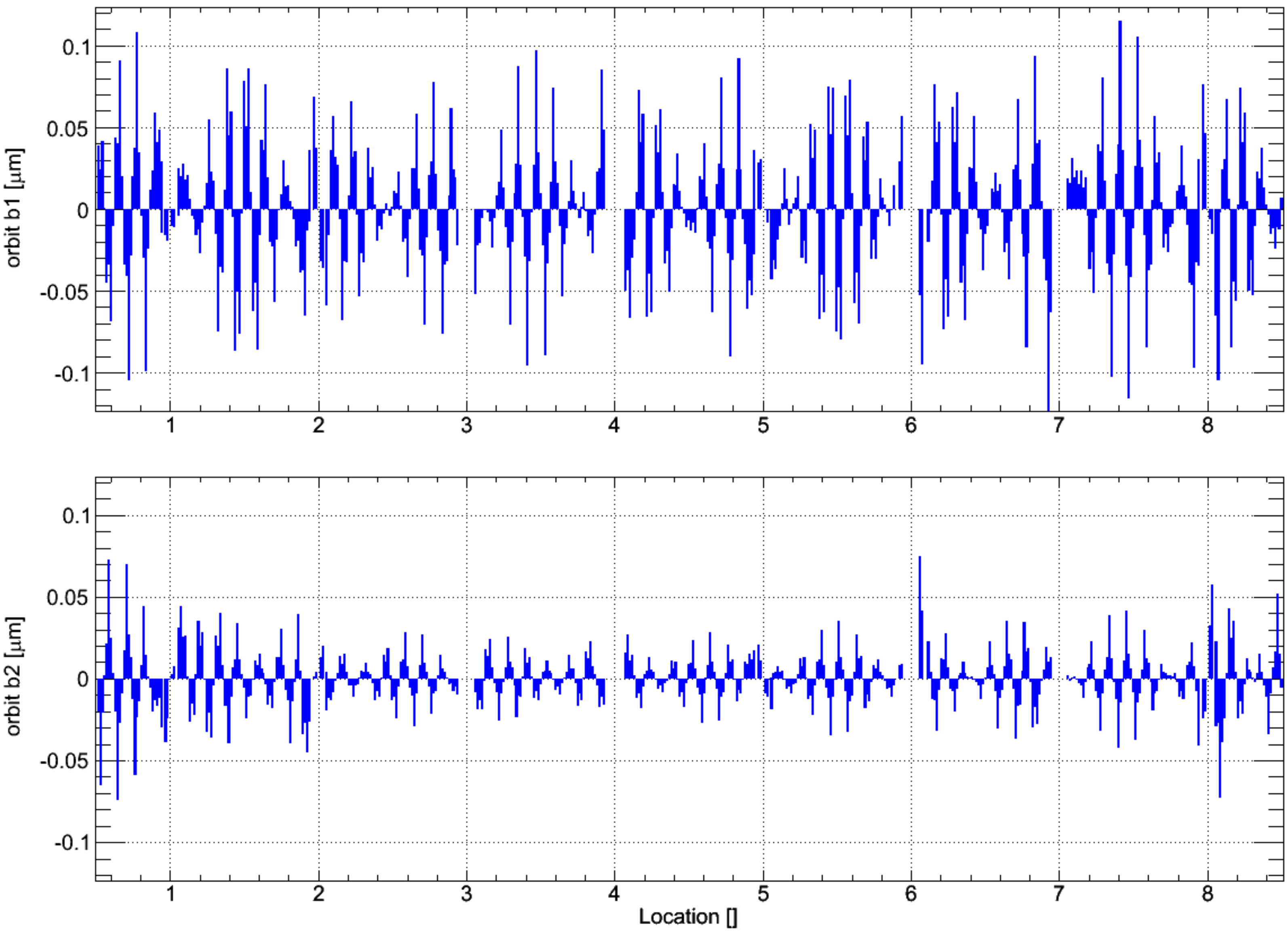
*G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971

SVD example: LHC eigenvalue spectrum

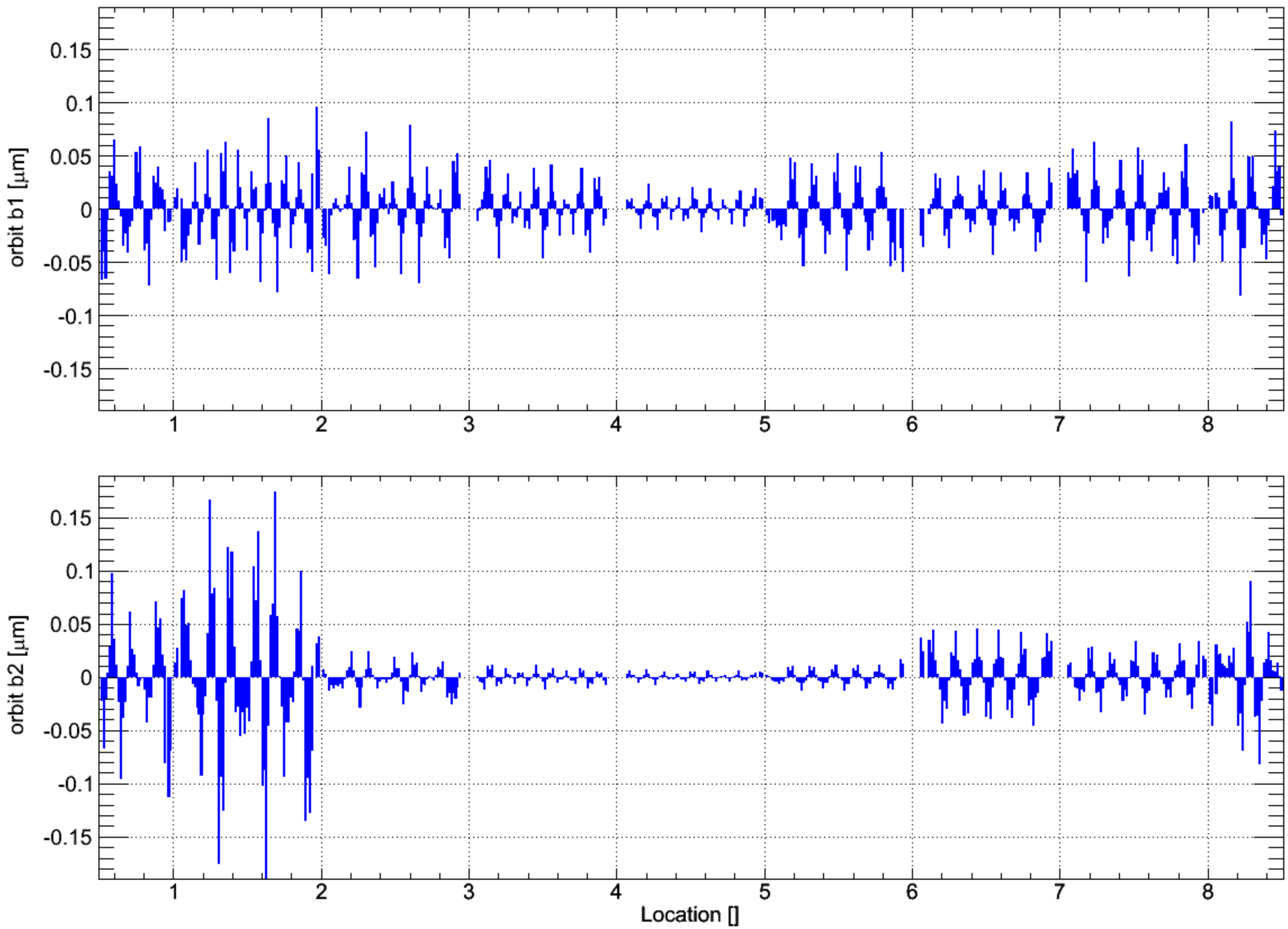
Eigenvalue spectra for vertical LHC response matrix using all BPMs and CODs:



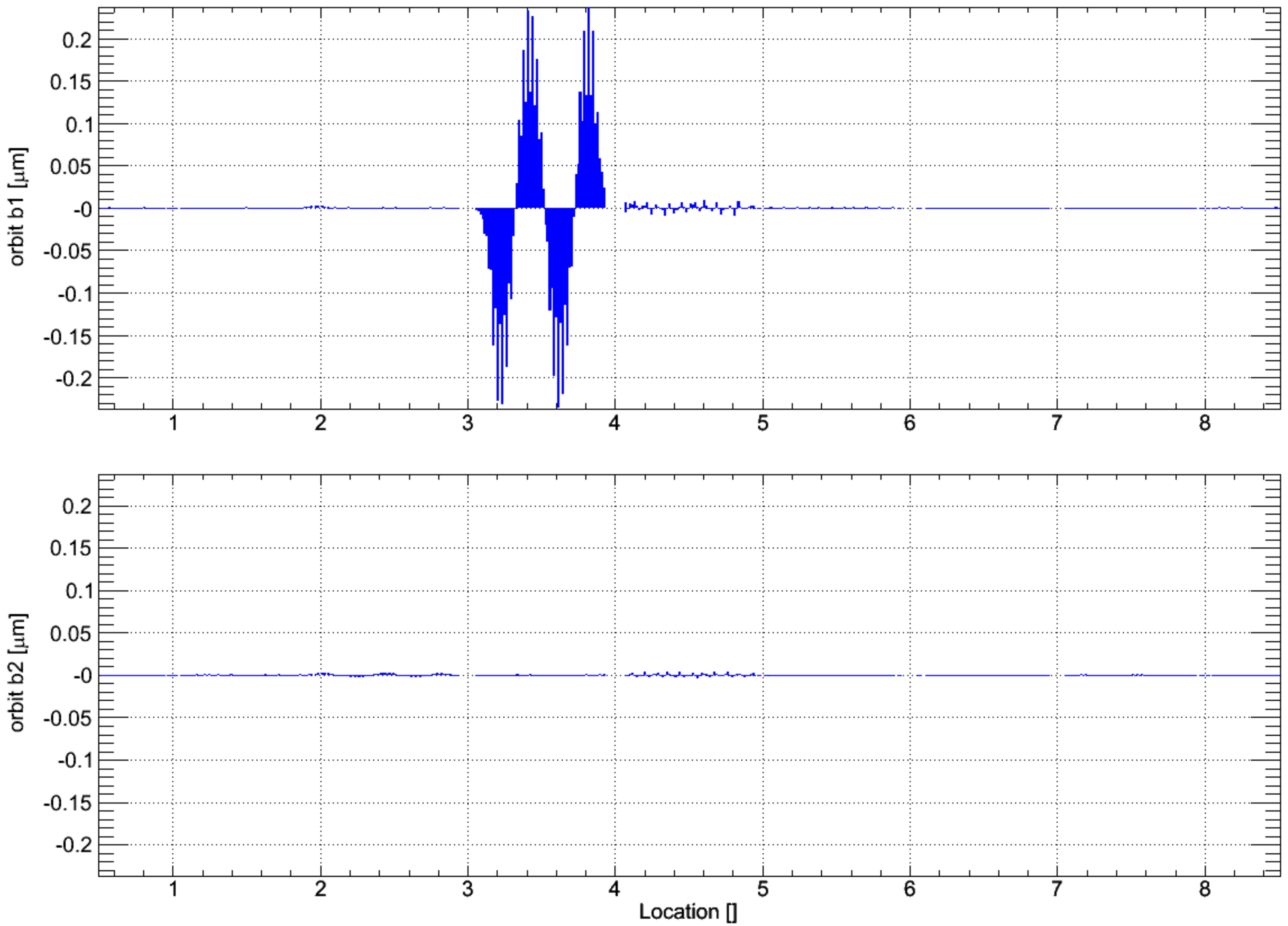
LHC example: BPM eigenvector #50 λ_{50}= 6.69•10²



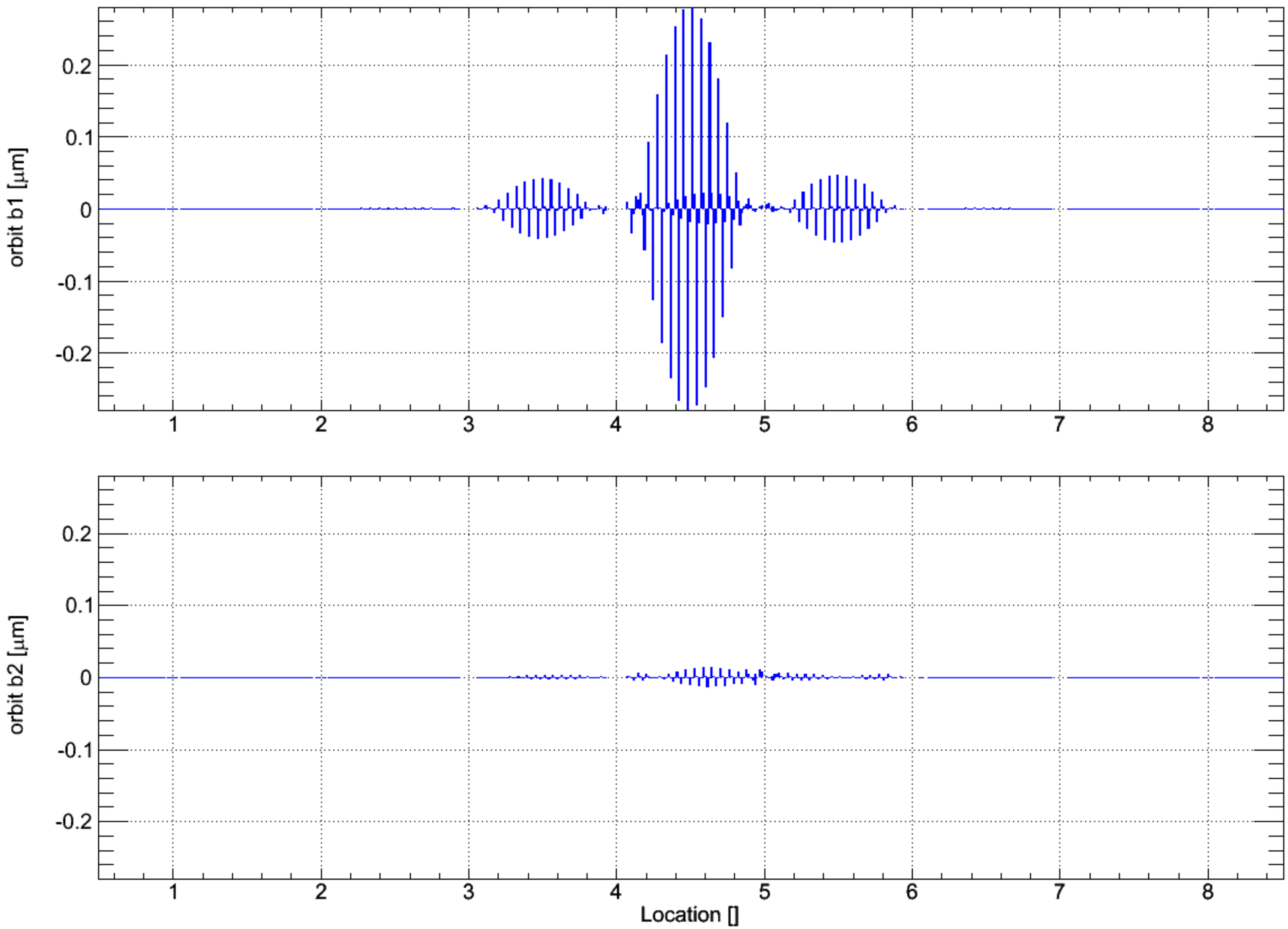
LHC example: BPM eigenvector #100 λ_{100}= 3.38•10^2



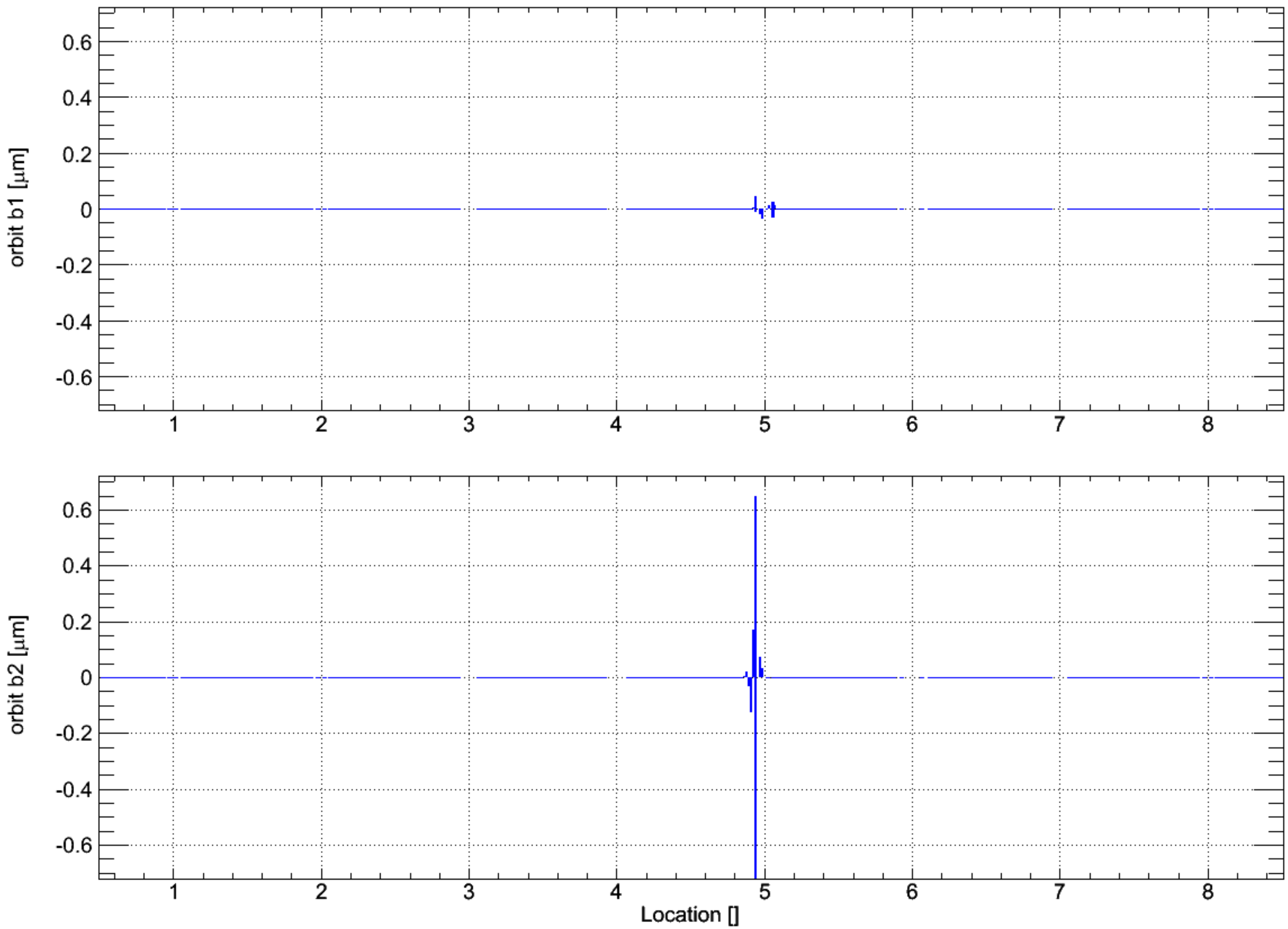
LHC example: BPM eigenvector #291 $\lambda_{291} = 2.13 \cdot 10^2$



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



LHC example: BPM eigenvector #521 λ_{521}= 1.18•10^0



Space Domain: Number of used eigenvalues?

Gretchen Frage: “How many eigenvalues should one use?”

small number of eigenvalues:

- more coarse 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
- ...

large number of eigenvalues:

- 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
- ...

parameter stability requirement

feedback stability requirement

Choice for Q, Q', C^- is much simpler: only two out of *n* non-vanishing eigenvalues!

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)

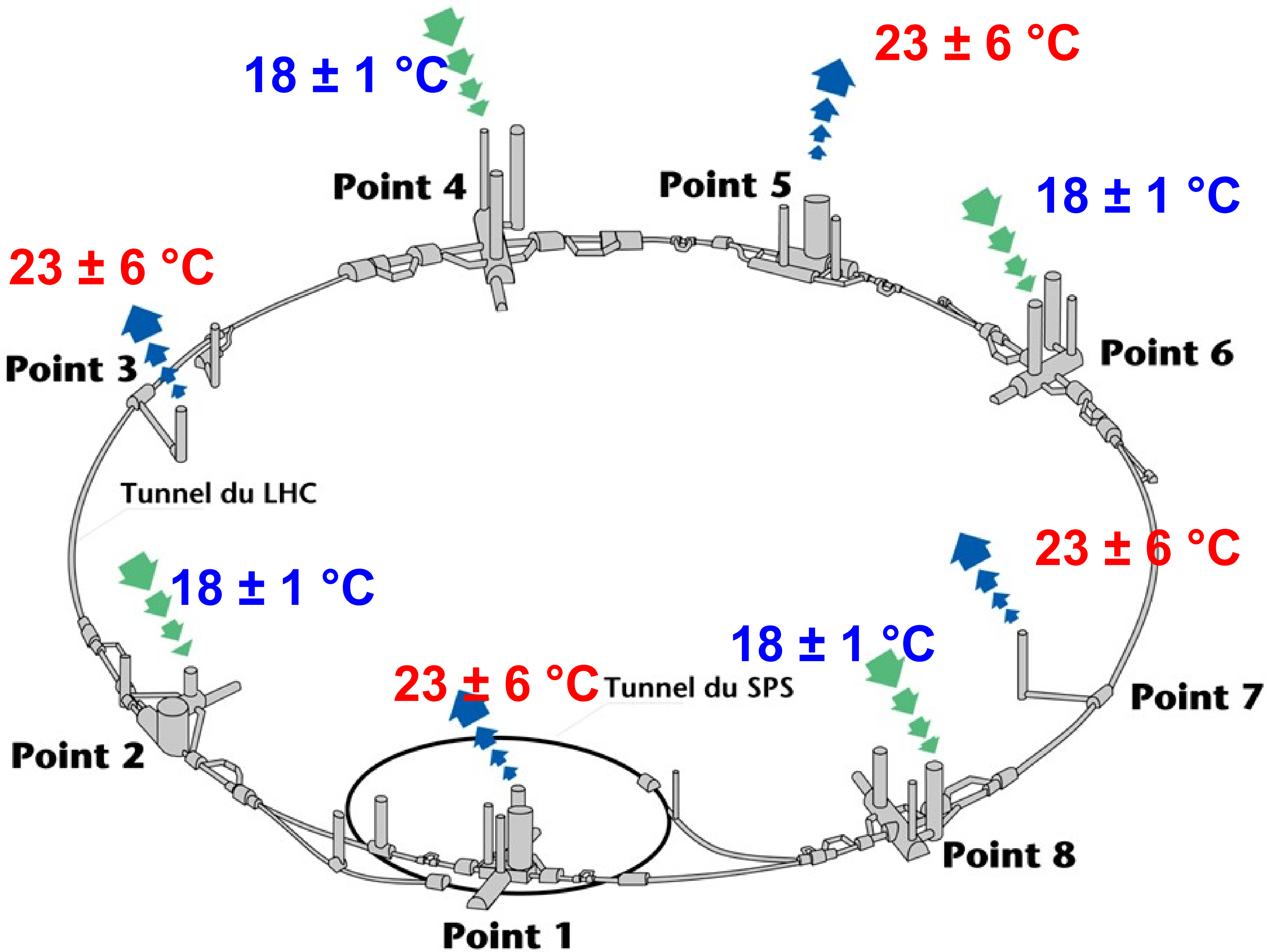
disadvantage:
- total number of to be used eigenvalues less obvious
- Matrix inversion may become instable

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

Micron Stability of the LHC Collimators in the Presence of Thermal Drifts

Thermal Expansion of Girders

Ventilation du tunnel LEP/LHC



back

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):

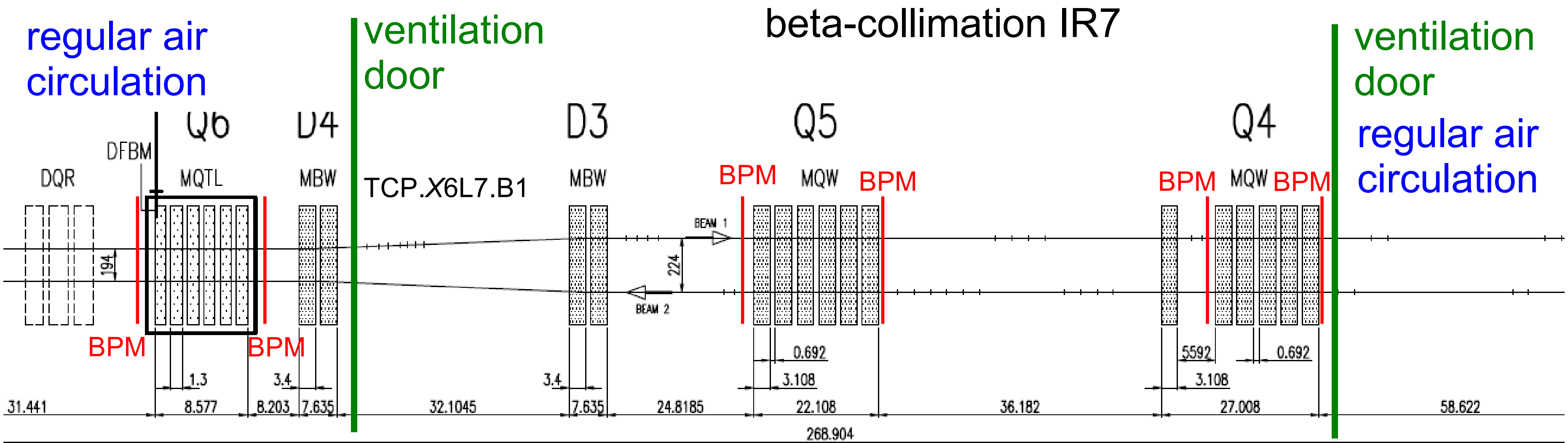
$$\Delta x = x_0 \cdot \alpha \cdot \Delta T$$

- 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 → $\Delta x \approx 3.4 - 5.8$ µm/°C
  - Warm equipment: $x_0 \approx 950$ mm → $\Delta x \approx 9.5 – 16$ µm/°C
- The inlet temperature is stabilised to about ±1°C
  - temperature changes shouldn't pose a problem for even IRs

back

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