LHC Orbit-FB Bandwidth

– Margins, Limits and Caveats –

Ralph J. Steinhagen,

Maxim Andersen, J. Wenninger

Some references:

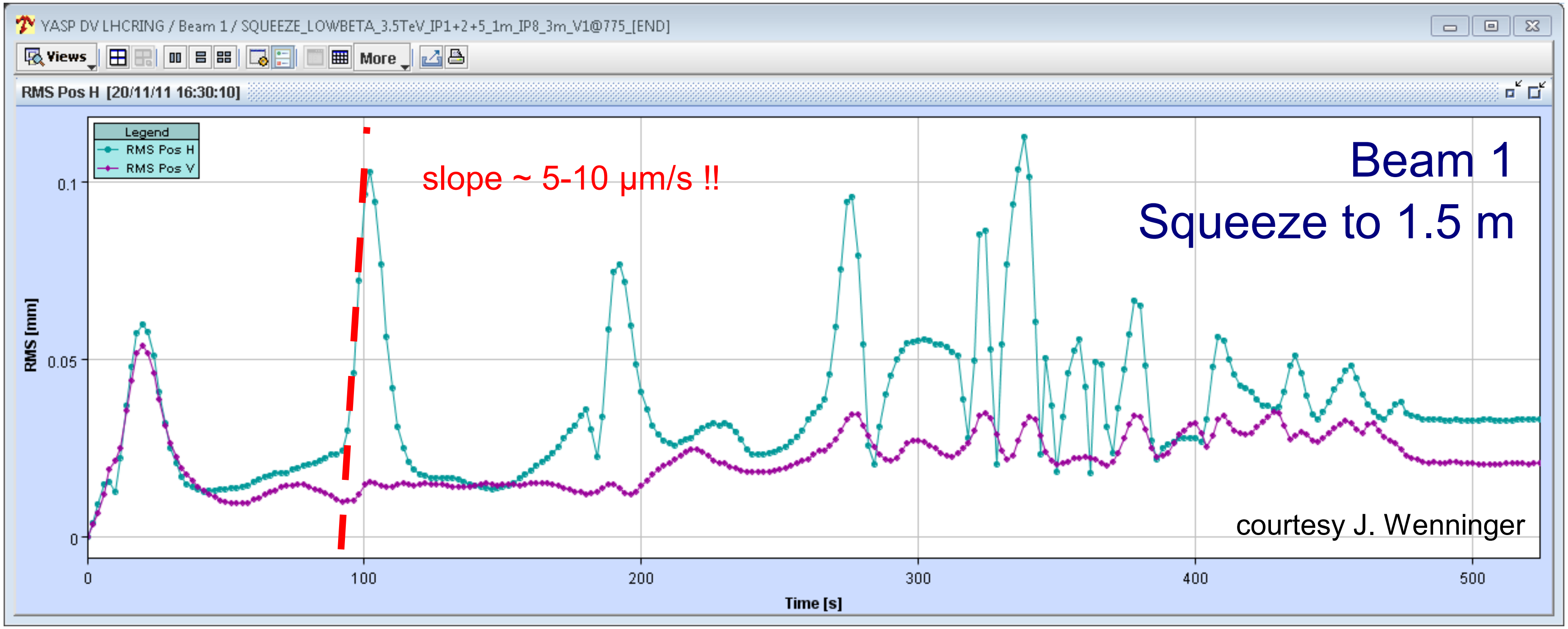
http://cern.ch/AB-seminar/talks/AB.Seminar.rst.pdf (CERN-AB-2007-049)

http://lhccwg.web.cern.ch/lhccwg/Meetings/2007/2007.10.23/2007-10-23_LHCCWG-FAULTY_BPM.pdf

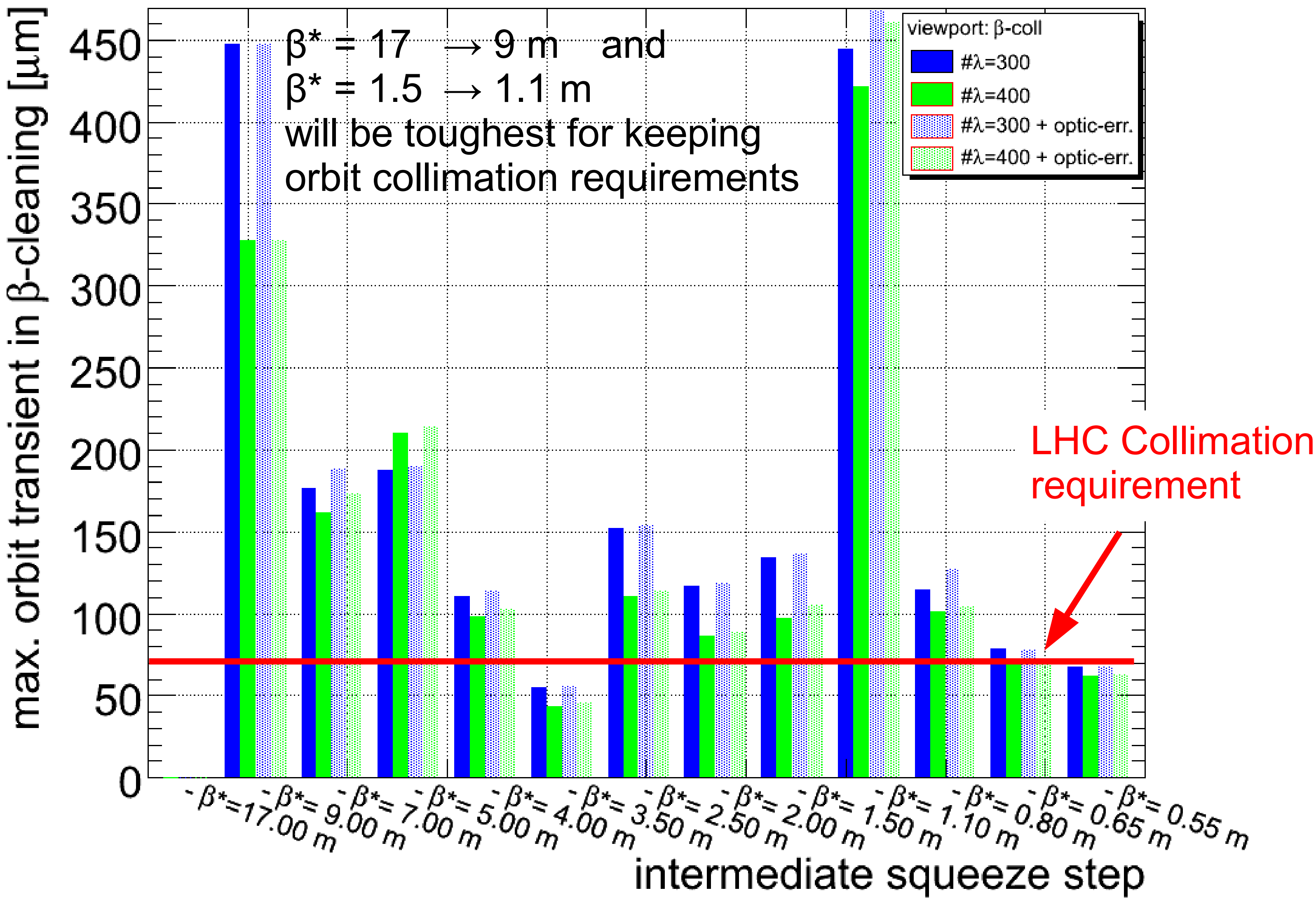
LHC-BPM-ES-0004 rev. 2.0, EDMS #327557, 2002,

Monday: Orbit FB test using a fill for a test dump

- Orbit transients at the 'matched points' (where we pass a matched optics) – issue for tight collimators.
  - Transients are due to mismatch of the Xing and separation bumps due to optics interpolation between matched points.
  - LHCb Xing bump of 250 urad is driving source !
- Simplest cure: faster orbit FB for better damping…
  - … but needed proof-of-feasibility prior to counting on this for 2012!

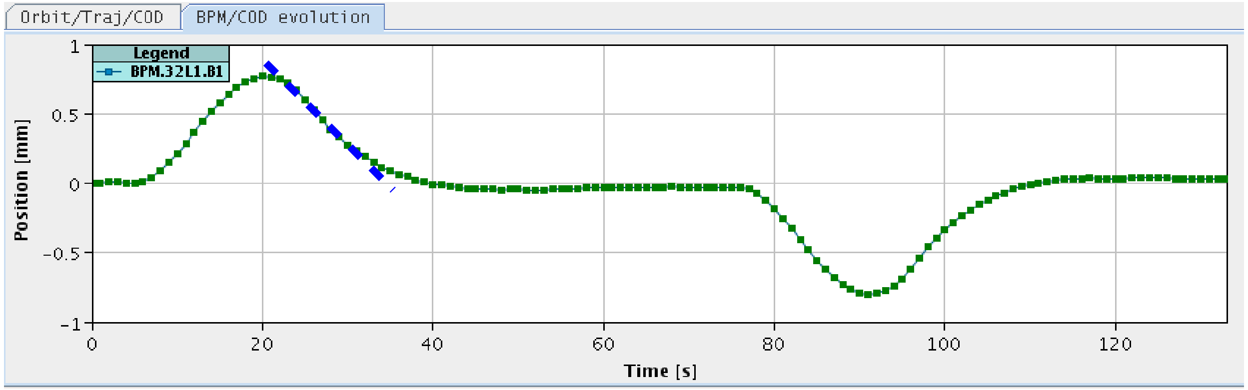


Not a new Effect – has been studied before: Transient in Collimation Insertion vs. Squeeze Step



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

OFB Bandwidth – Pre-Flight Checks @ 3.5 TeV
Response to a kick



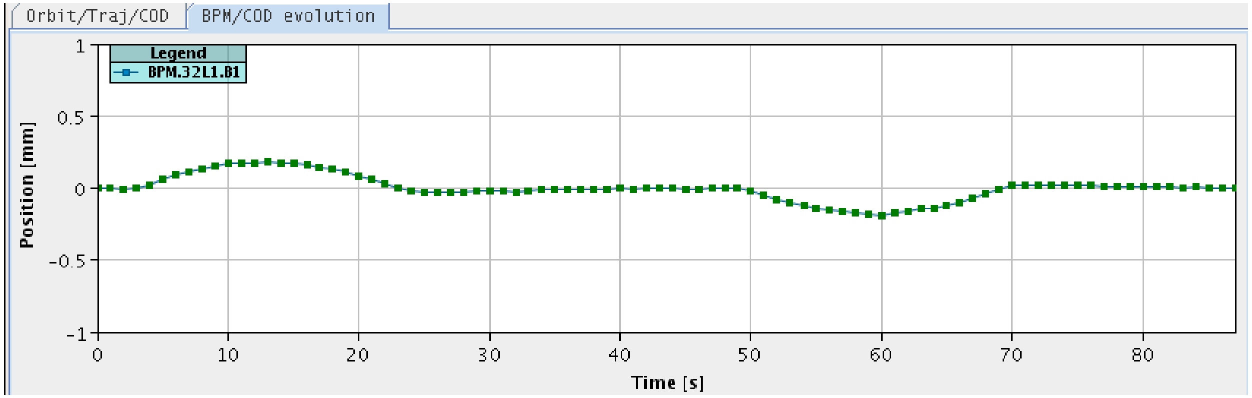
Default Bandwidth:

Setup: OL BW = 10 Hz @ 5μm/s

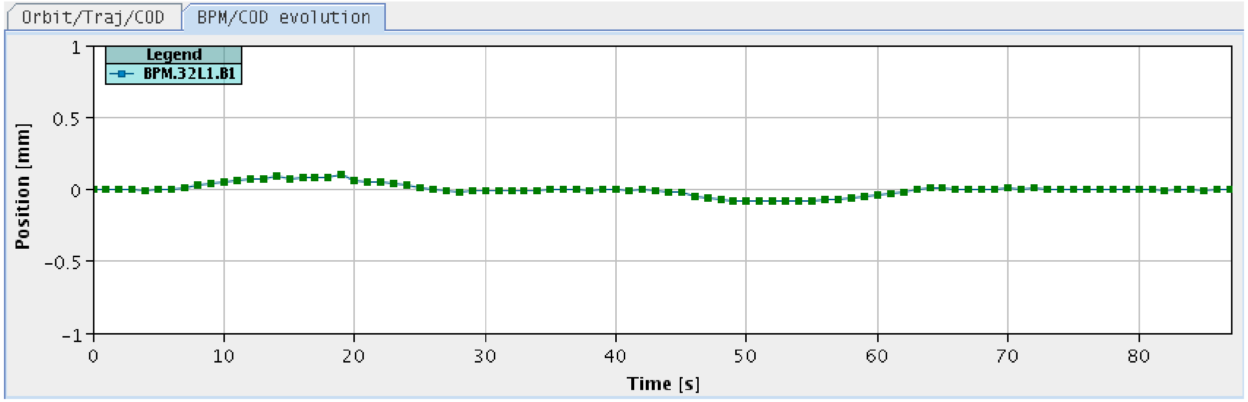
→ CL BW = 0.025 Hz@3.5 TeV

Measured:

$tr_{10\text{-}90\%} \approx 15s \leftrightarrow BW \approx 0.023$ Hz



CL <u>Bandwidth</u> x 5

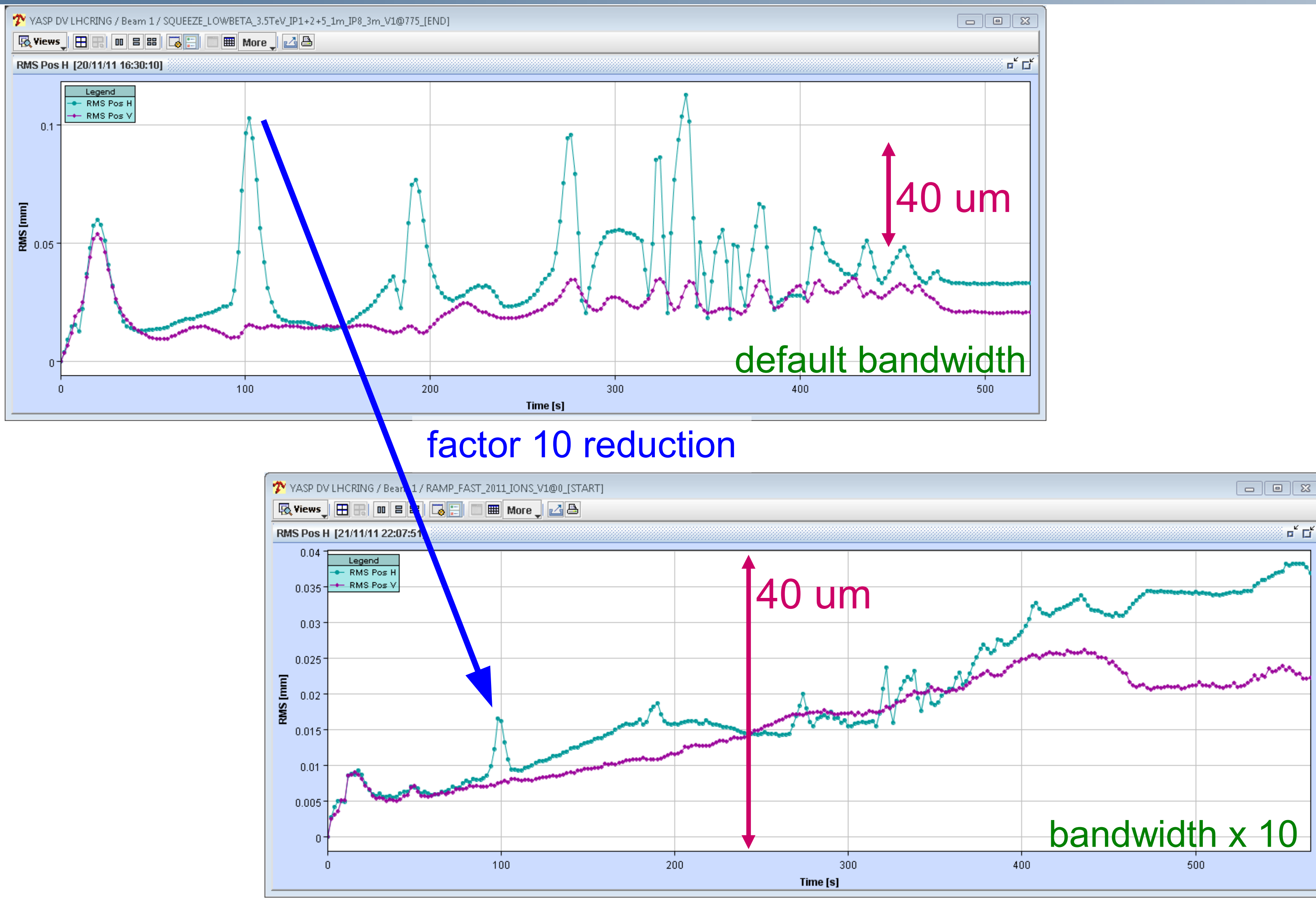


CL <u>Bandwidth</u> x 10

+ linear increase
+ no sign of ringing
→ there is some margin!!

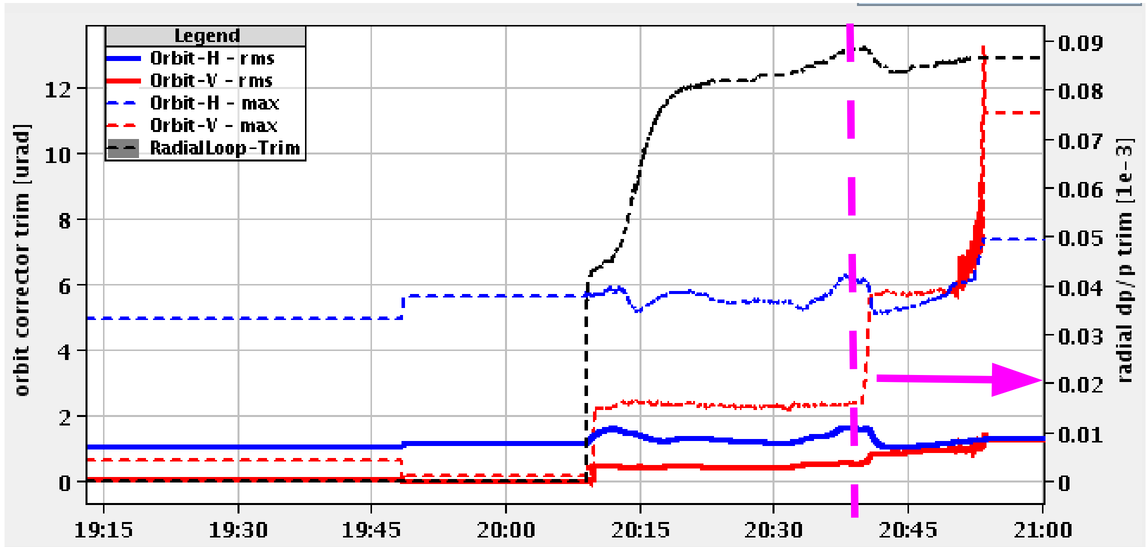
N.B. IR 1+5 @1m, IR 8 @ 3 m

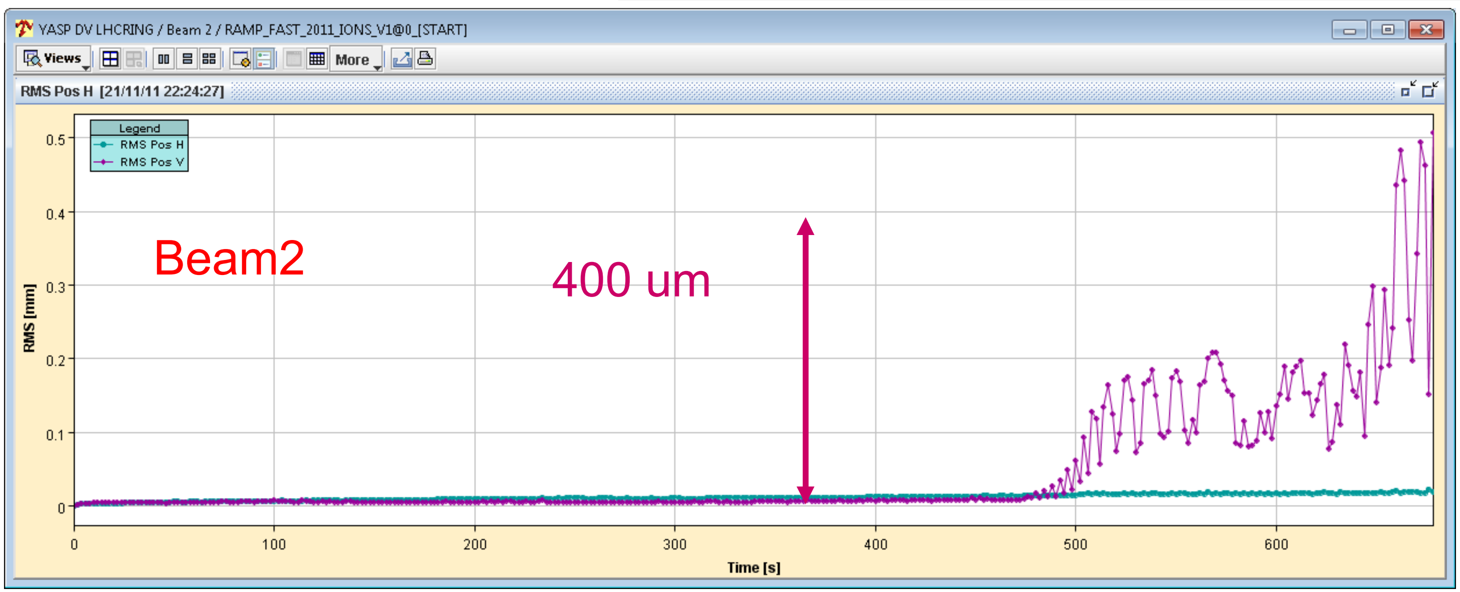
Difference of Bandwidth – The Good...



- Great <u>linear/design</u> performance…*don't count chicken until they are hatched!*

Difference of Bandwidth – The Bad …
Squeeze in IP2 $\beta^* = 3\ m \rightarrow 1\ m$



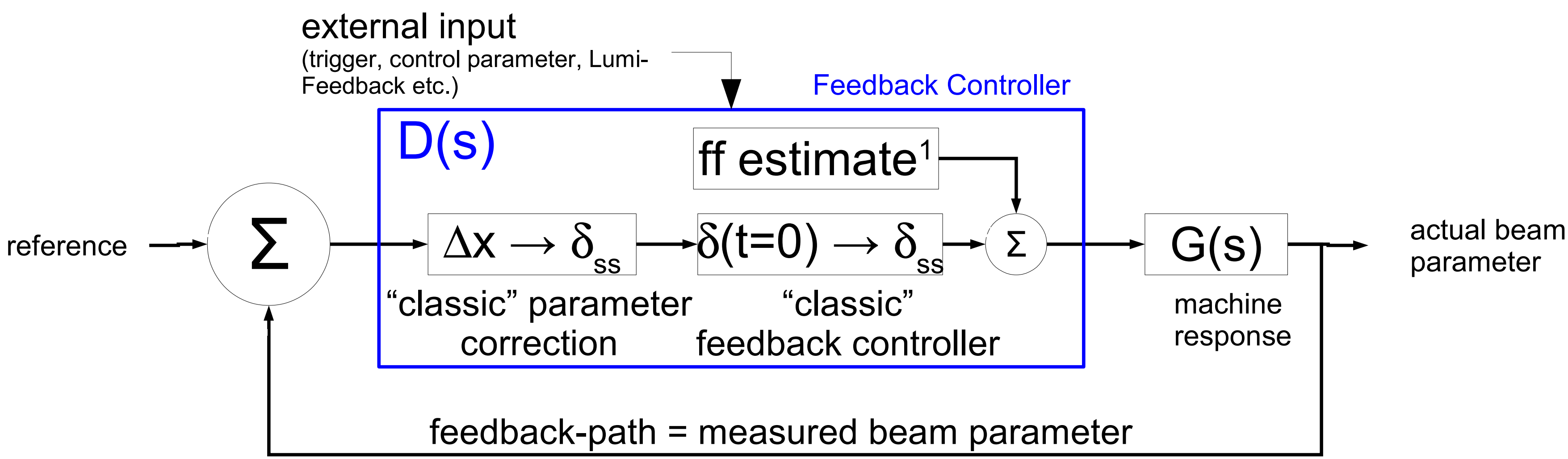


What happened?

- '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 $t \rightarrow \infty$.
  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

space domain (1)

time domain (2, 3)



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

Space Domain: - No "black feedback magic"

- 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:

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

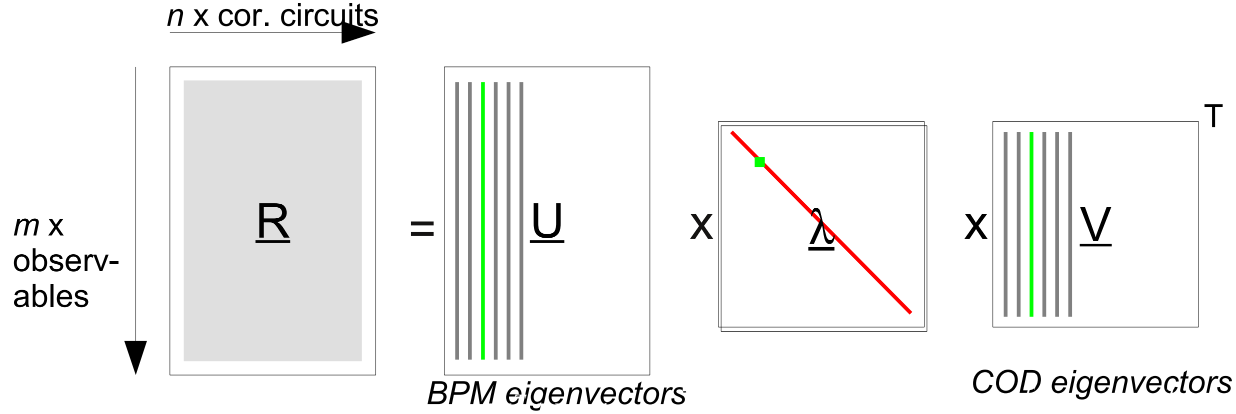
  - control consists essentially in inverting these matrices:

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

- 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:

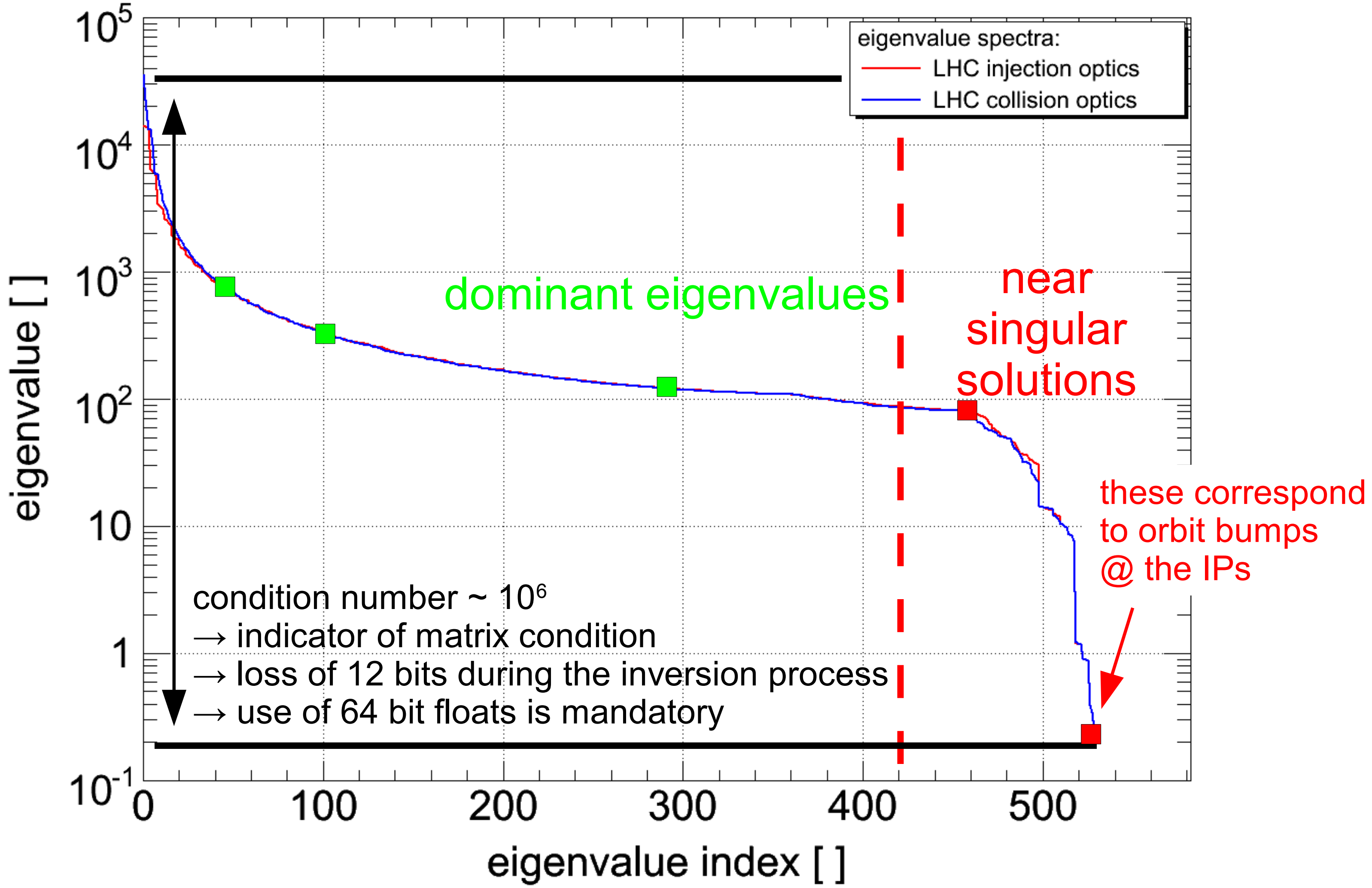
$$\boxed{\vec{\delta}_{ss} = \tilde{R}^{-1}\cdot\Delta\vec{x} \quad with \quad \tilde{R}^{-1} = \underline{V}\cdot\underline{\lambda}^{-1}\cdot\underline{U}^T} \Leftrightarrow \vec{\delta}_{ss} = \sum_{i=0}^{n}\frac{a_i}{\lambda_i}\vec{v}_i \quad with \quad a_i = \vec{u}_i^T\Delta\vec{x}$$

- numerical robust, minimises parameter deviations Δx <u>and</u> circuit strengths δ
- Easy removal of singularities, (nearly) singular eigen-solutions have λ_i~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

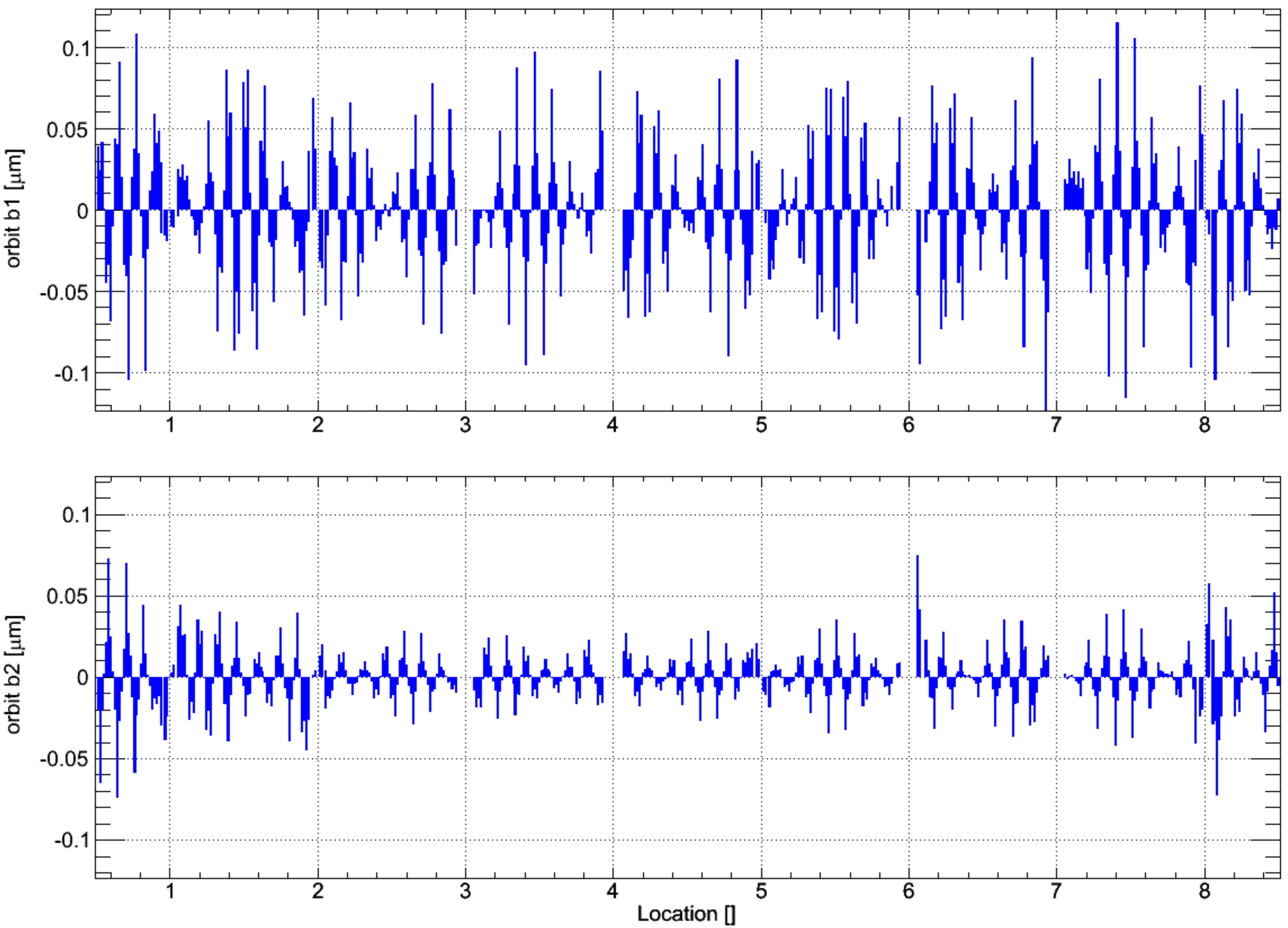
*G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971

Space-Domain:
SVD example: LHC eigenvalue spectrum

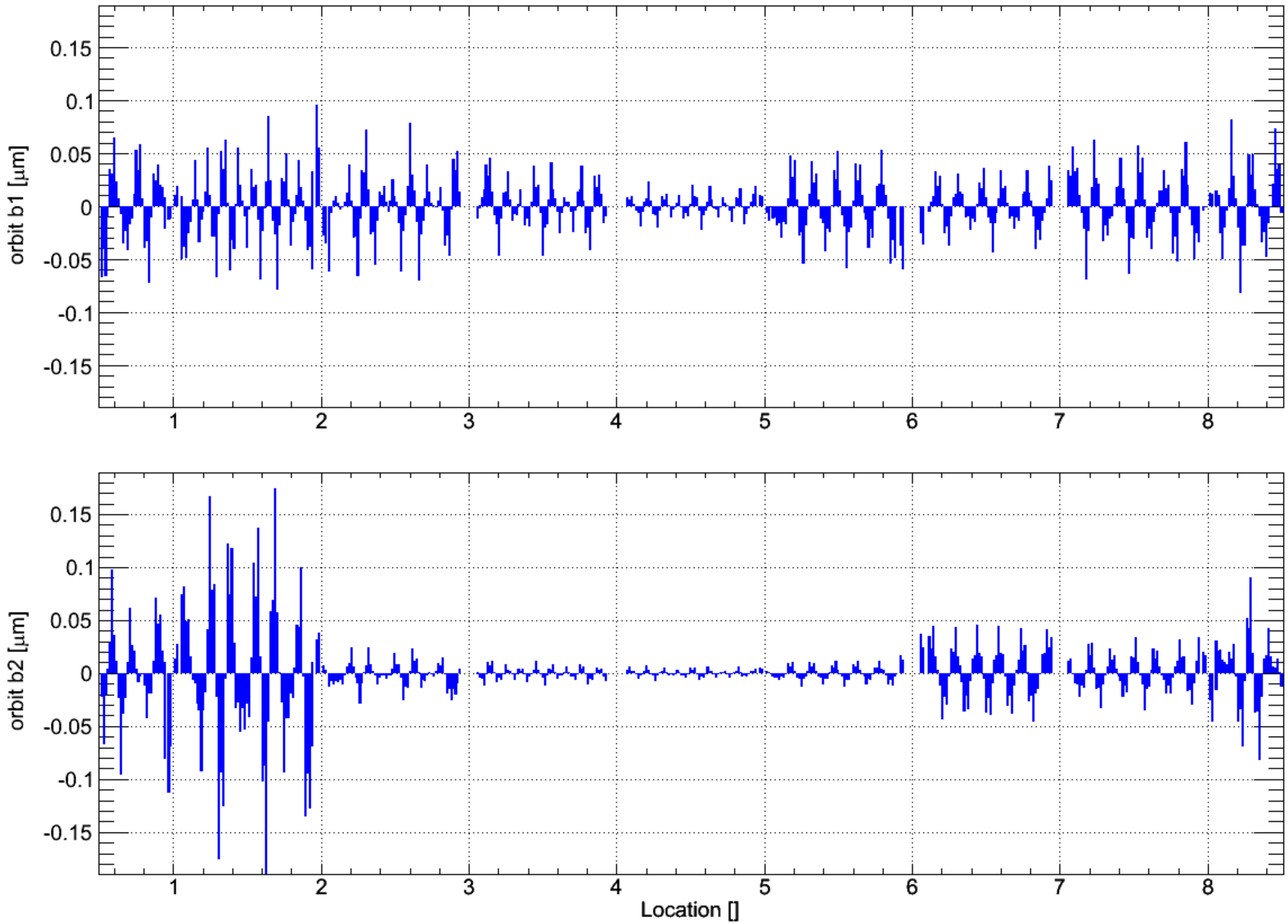
Eigenvalue spectra for vertical LHC response matrix using all BPMs and CODs:



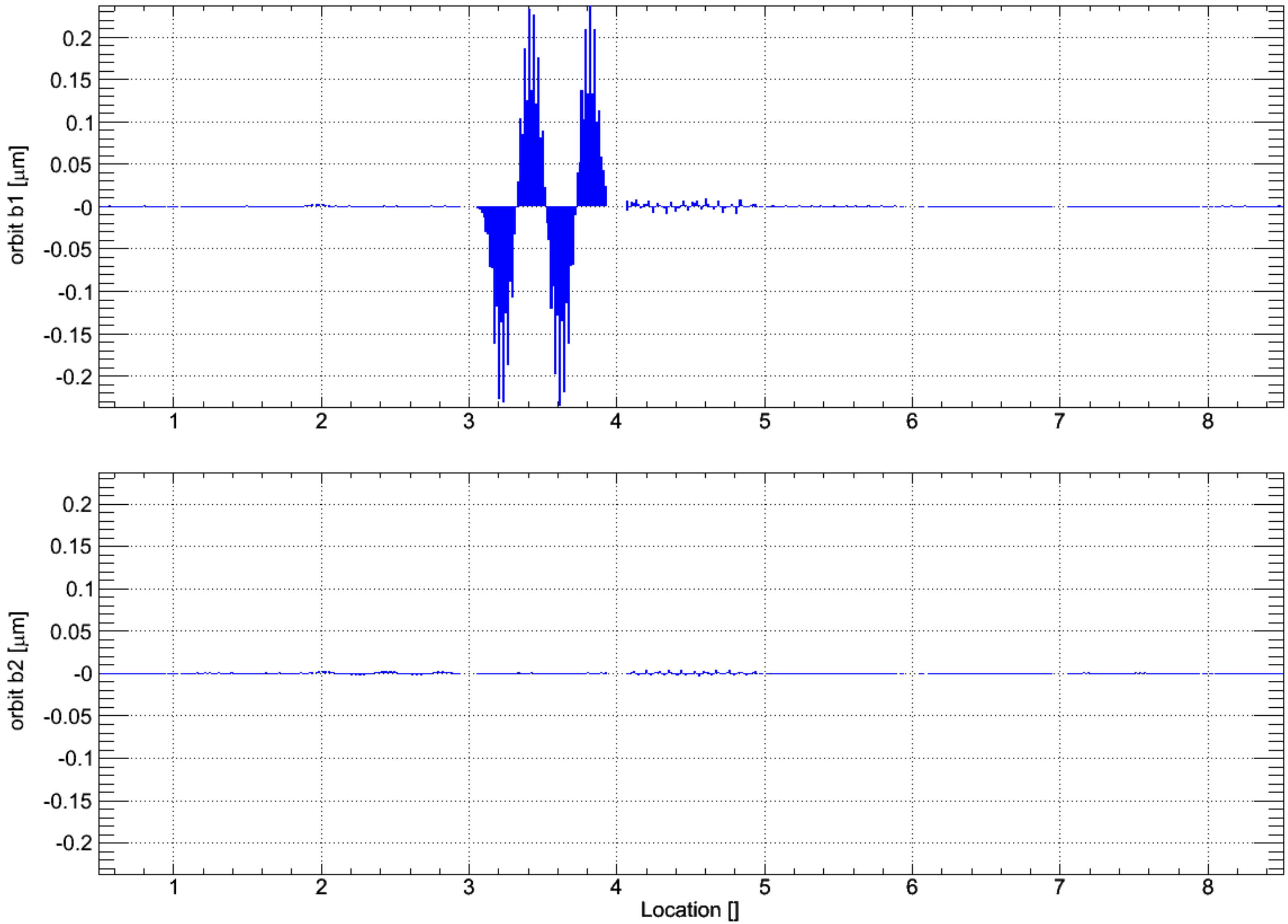
Space Domain: LHC BPM eigenvector #50 $\lambda_{50} = 6.69 \bullet 10^2$



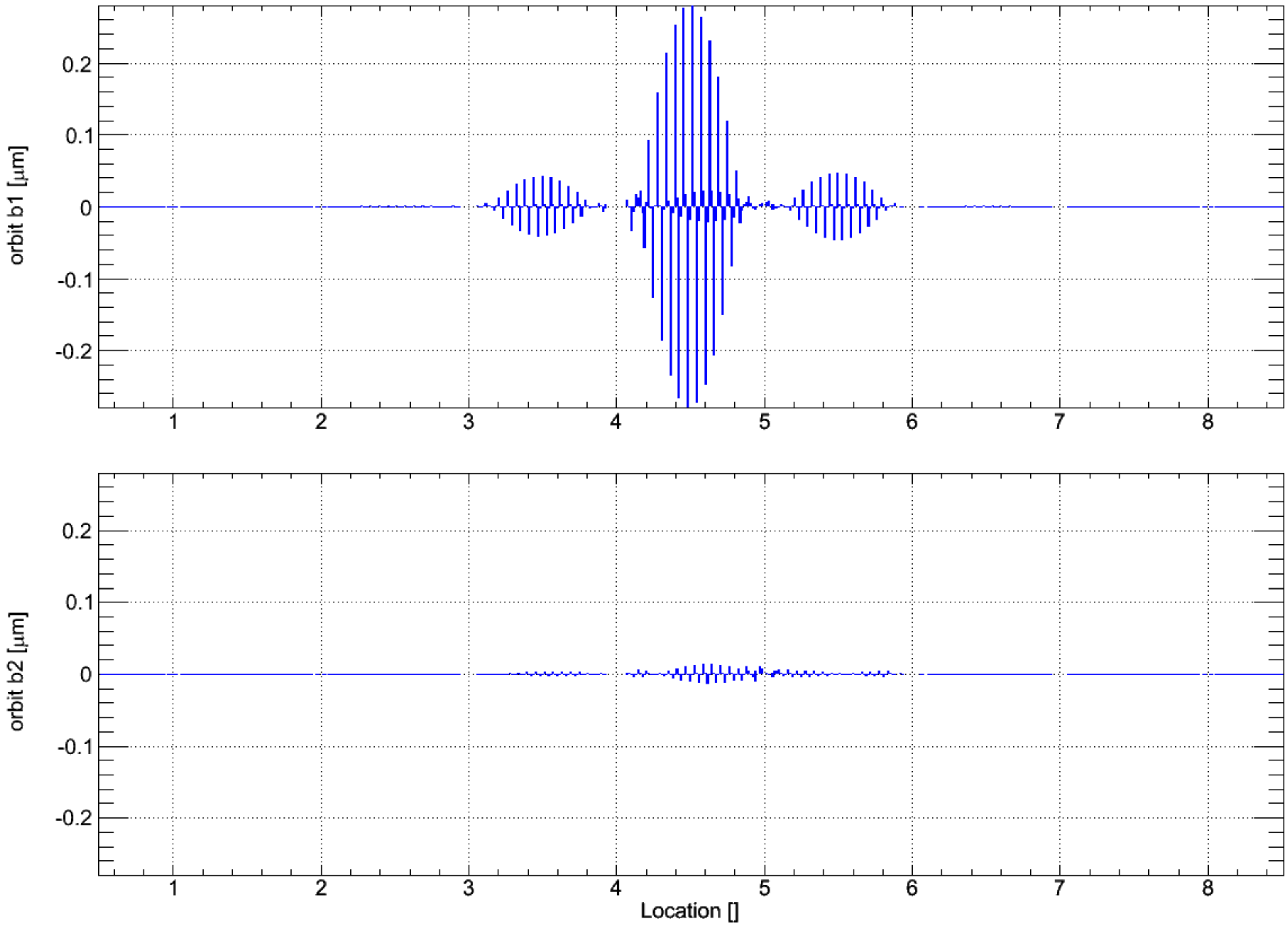
Space Domain:
LHC BPM eigenvector #100 $\lambda_{100} = 3.38 \cdot 10^2$



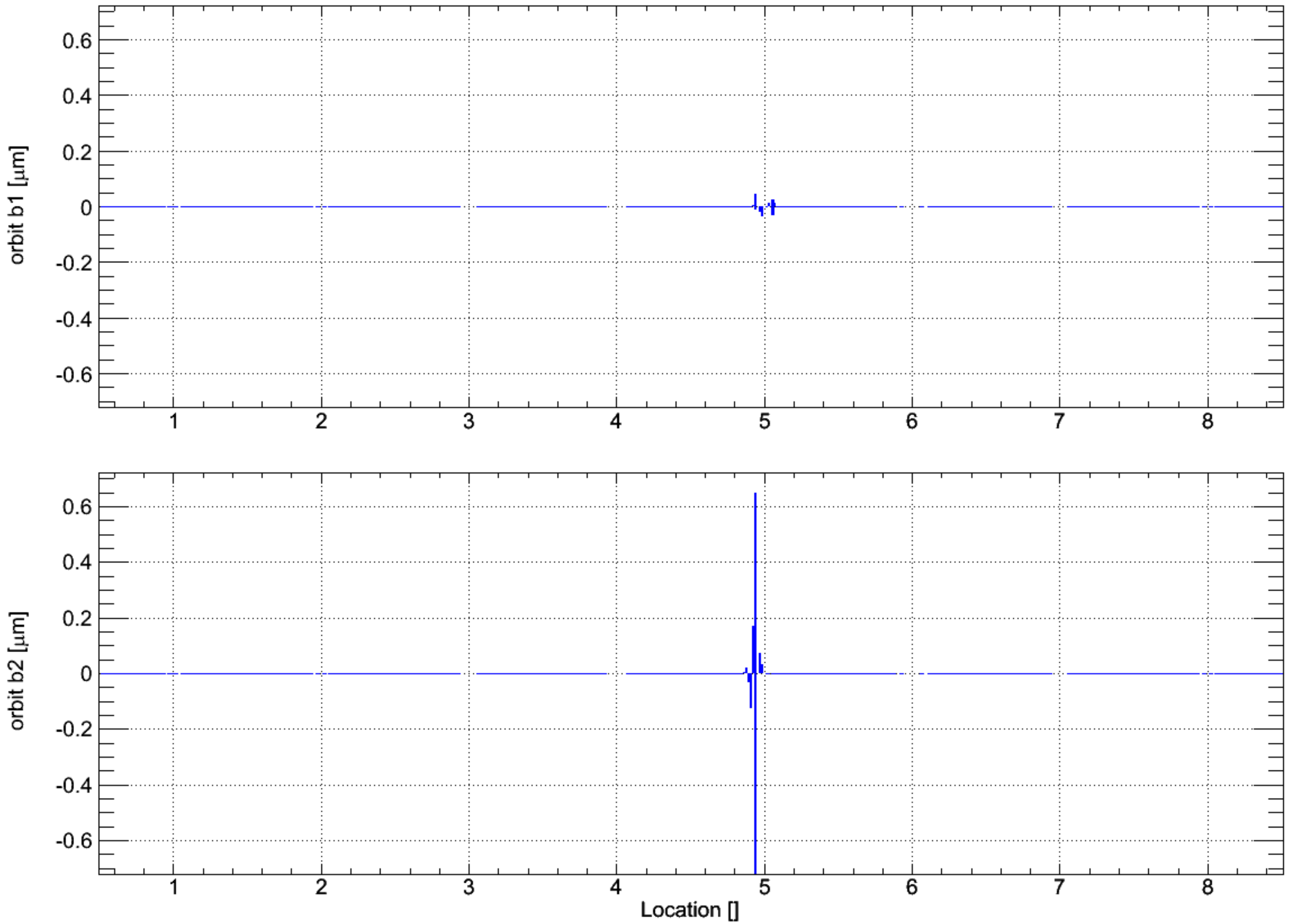
Space Domain: LHC BPM eigenvector #291 $\lambda_{291} = 2.13 \cdot 10^2$



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



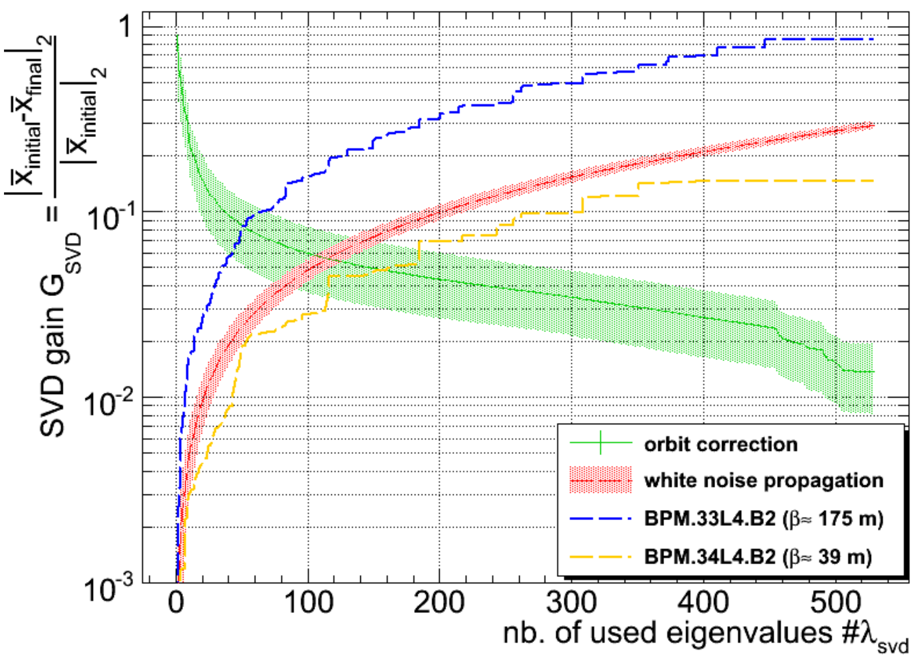
Space Domain:
LHC BPM eigenvector #521 $\lambda_{521}= 1.18 \cdot 10^0$

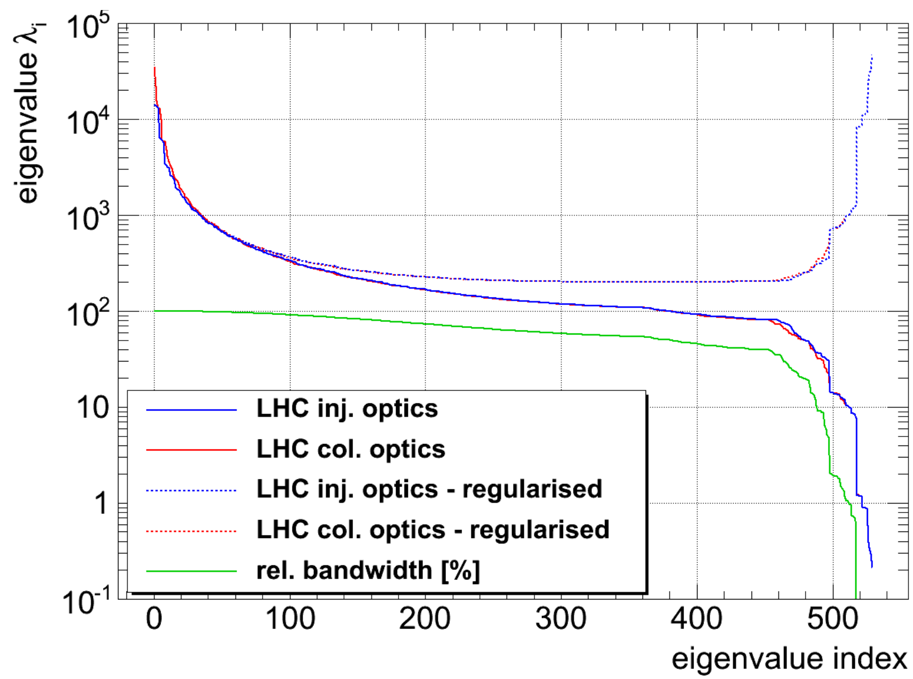


Standard Singular-Value-Decomposition based Orbit Correction

- Initially: Truncated-SVD (set $\lambda_i^{-1}:= 0$, for i>N)
  - not without issues: removed λ_i allowed local bumps creeping in (e.g. collimation)

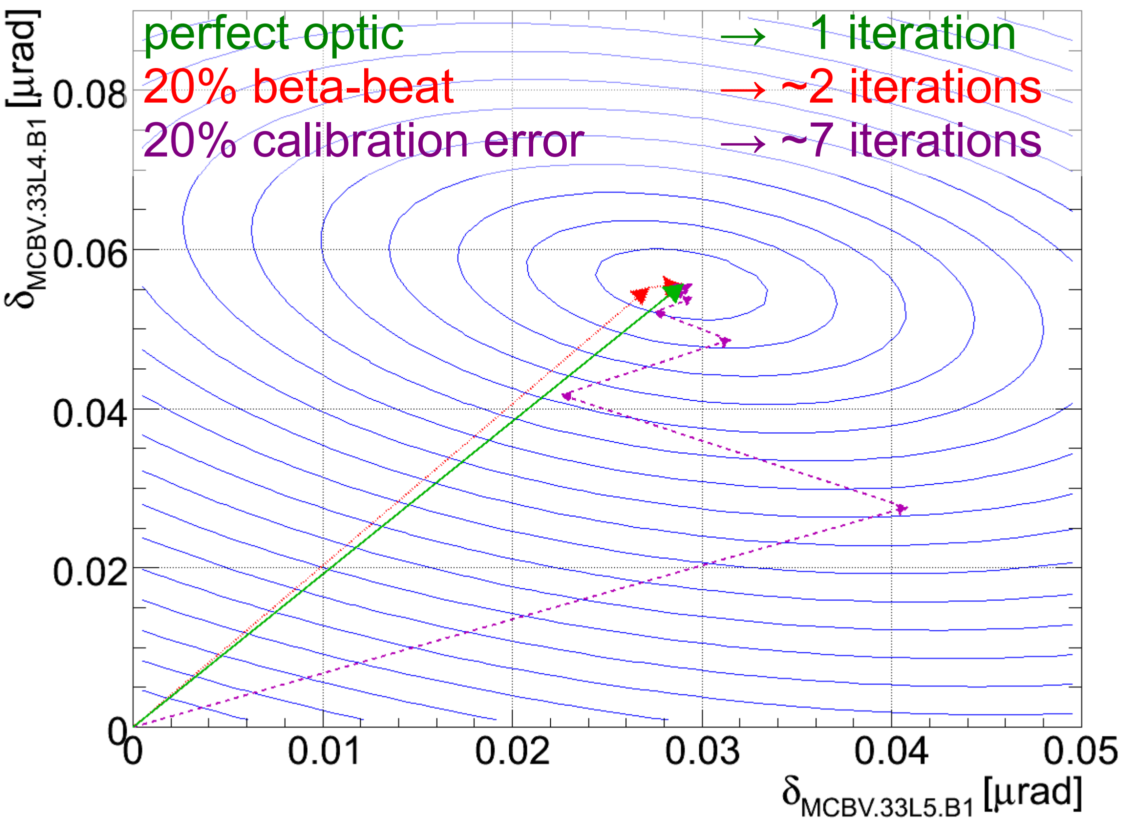
- Regularised-SVD (Tikhonov/opt. Wiener filter with $\lambda_i^{-1}:= \lambda_i/(\lambda_i^2 + \mu)$, $\mu>0$)
  - more robust w.r.t. optics errors and mitigation of BPM noise/errors
    → allowed re-using same ORM for injection, ramp and 10+ squeeze steps





Optics and Calibration Uncertainties → Gradient Search Based Fitting

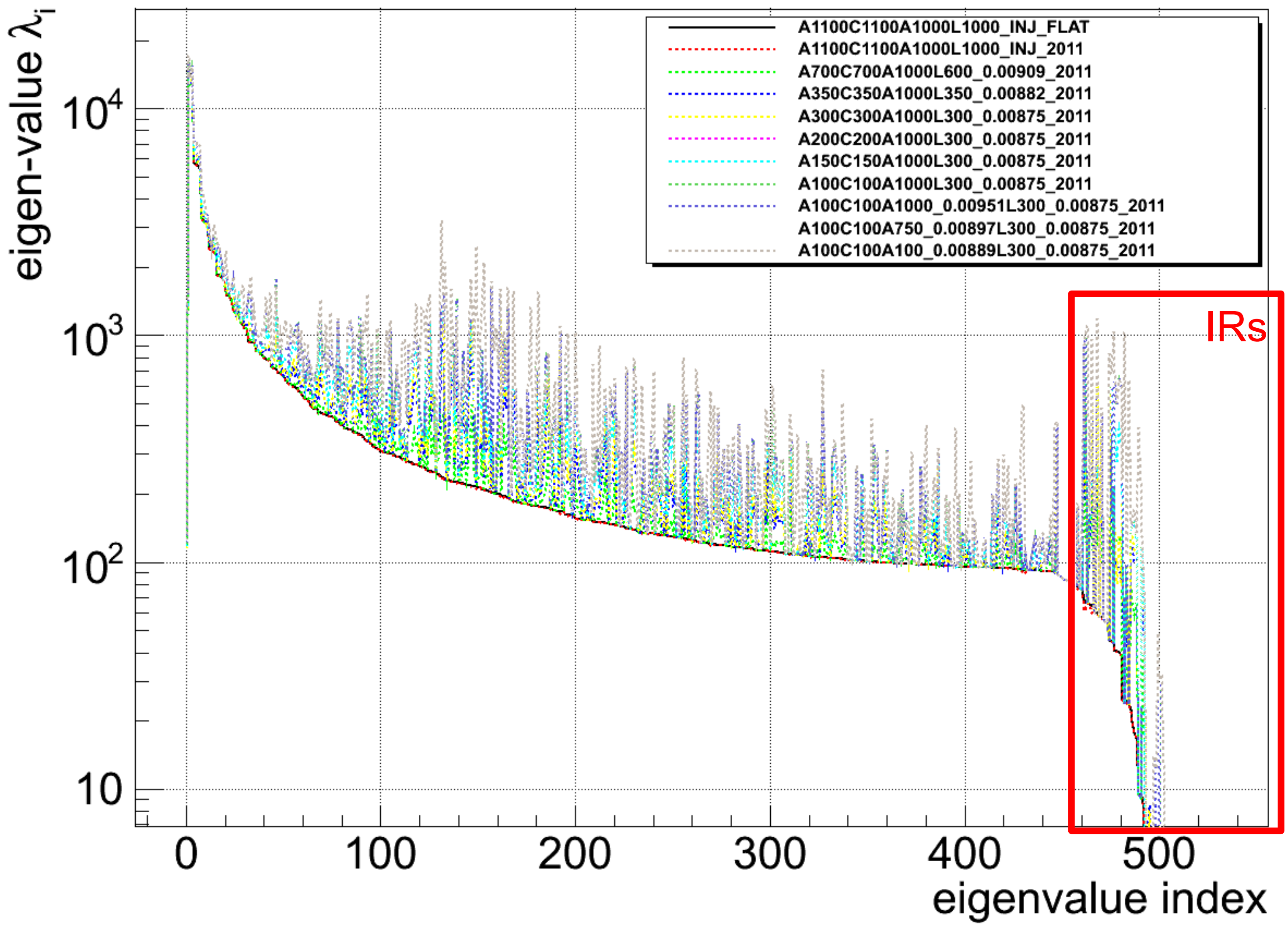
- Optics imperfections may deteriorate the convergence speed but do not affect absolute convergence (response functions are 'monotonic'):
  - for introduction: http://en.wikipedia.org/wiki/Gradient_descent
- Example: 2-dim orbit error surface projection



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

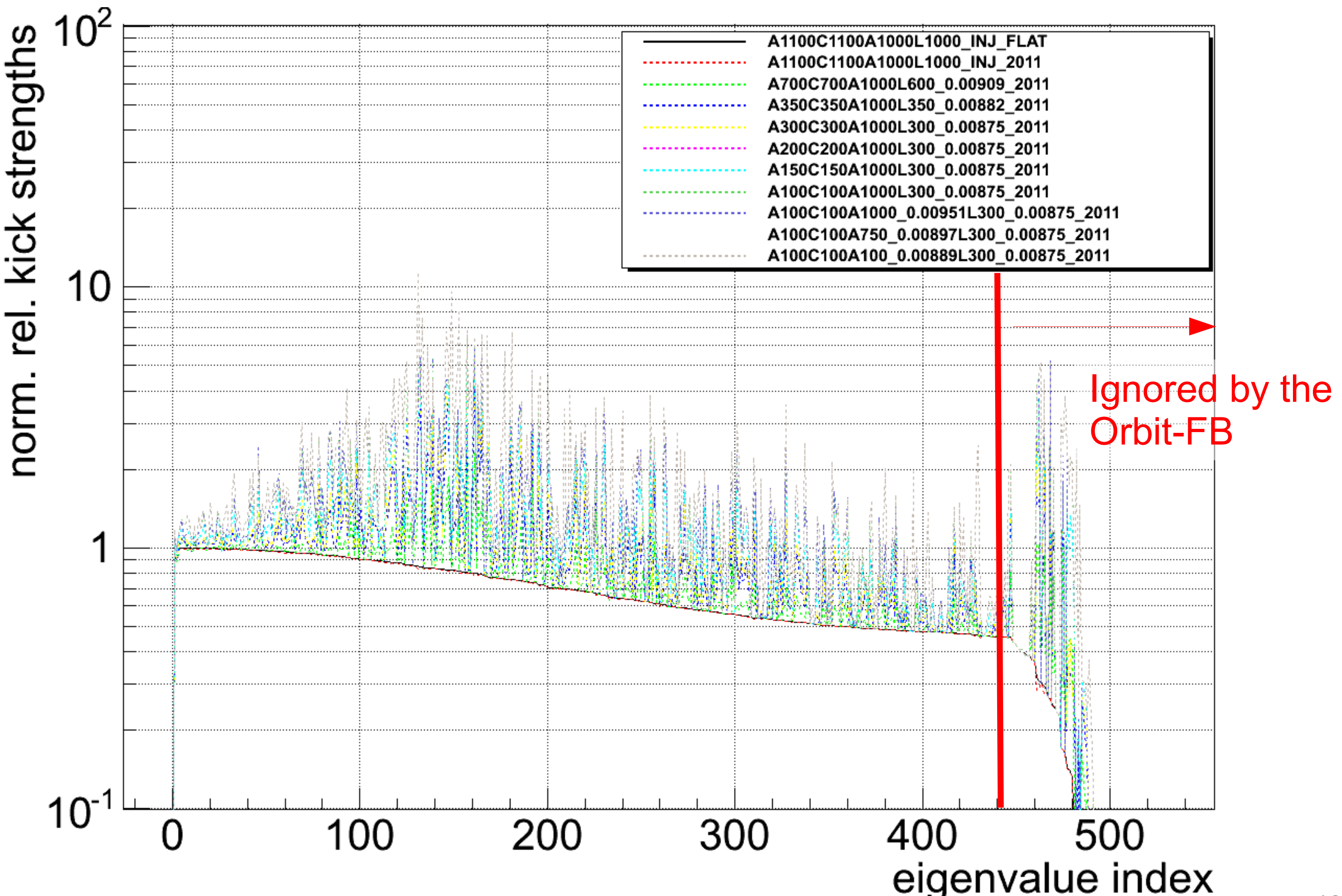
LBOC Orbit-FB Bandwidth, Ralph.Steinhagen@CERN.ch, 2011-11-29

- Eigenvalue spectrum w.r.t. the same injection base 'V':
  - Errors are creeping in, particular for patterns around IRs



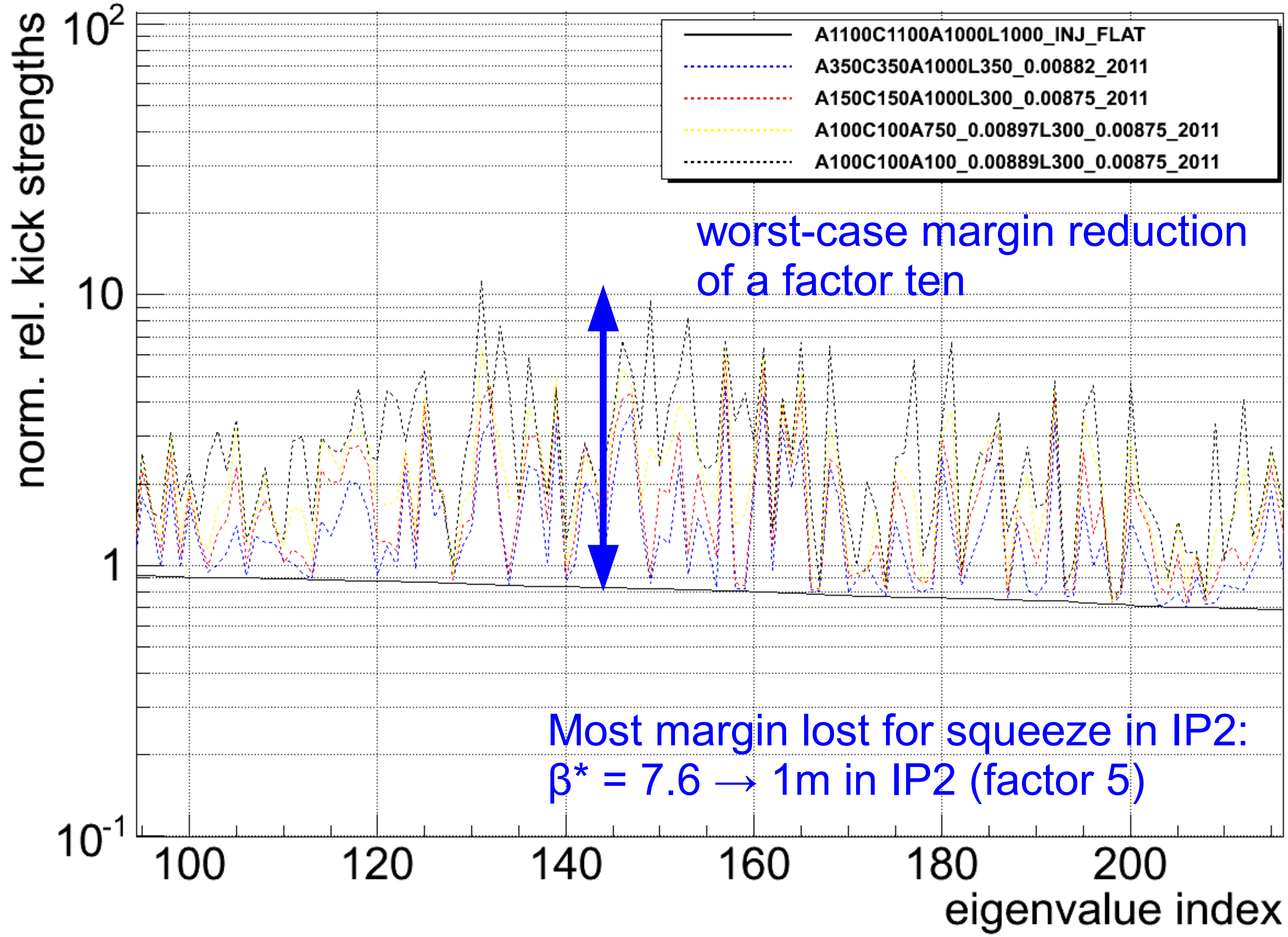
Correction with imperfect Injection Optics II/IV

- Bandwidth modifier w.r.t. eigenvalue index



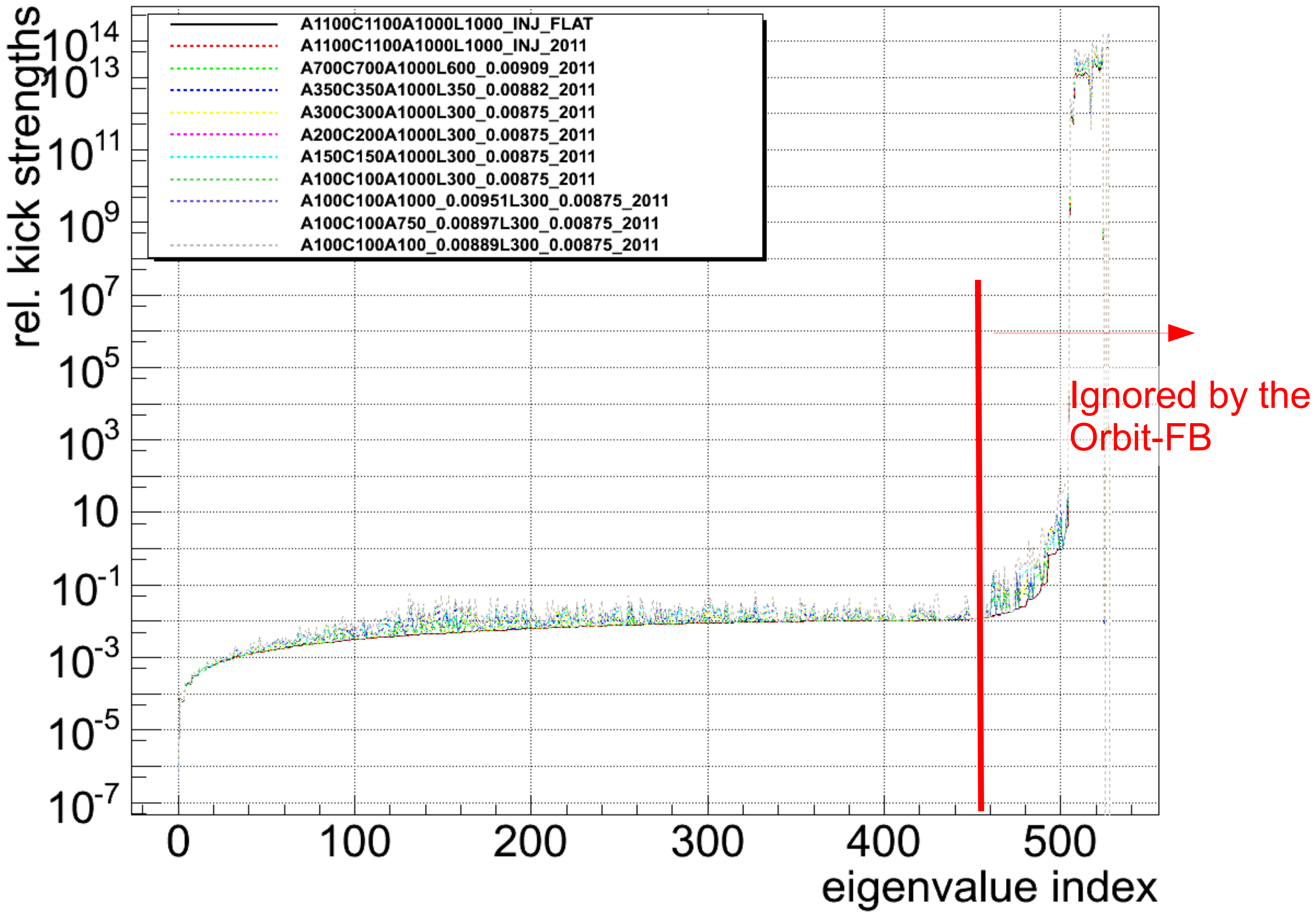
Correction with imperfect Injection Optics III/IV

- Bandwidth modifier w.r.t. eigenvalue index – ZOOM

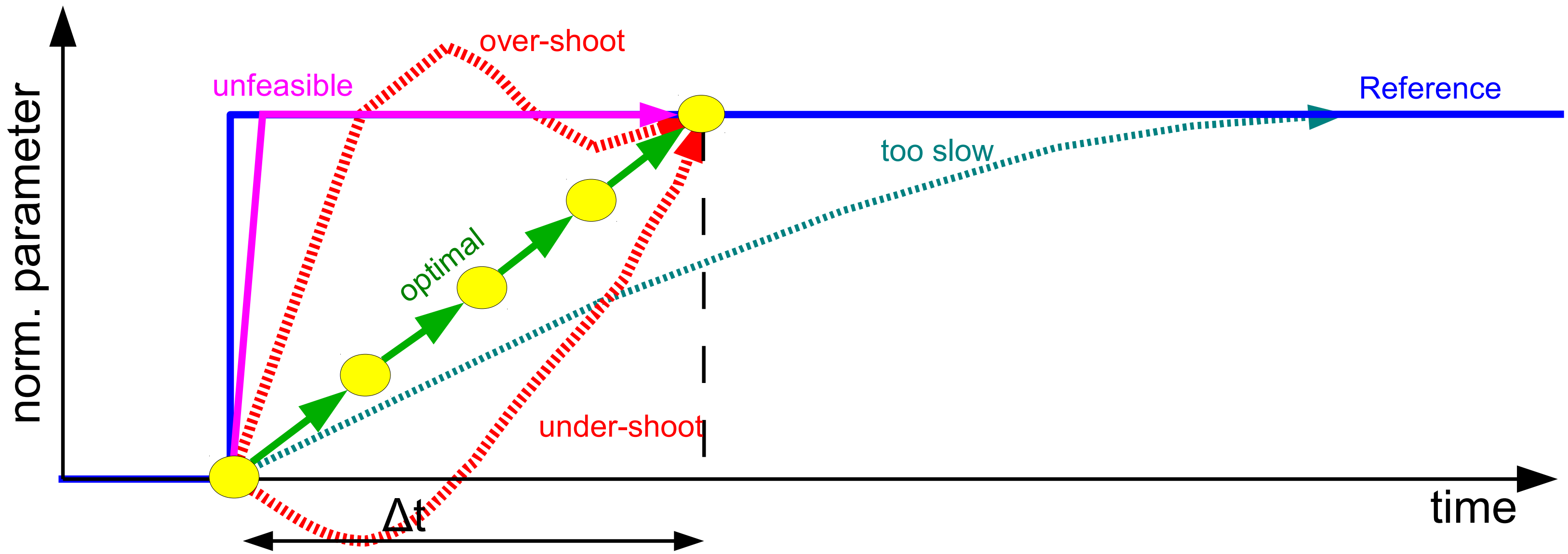


- However, Orbit-FB does not act on a sample-by-sample basis
  → Closed-Loop Bandwidth « Sampling Frequency!!

- Kick strength profile:



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: $T_0(s)=\frac{D(s)G(s)}{1+D(s)G(s)}$ → "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:

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

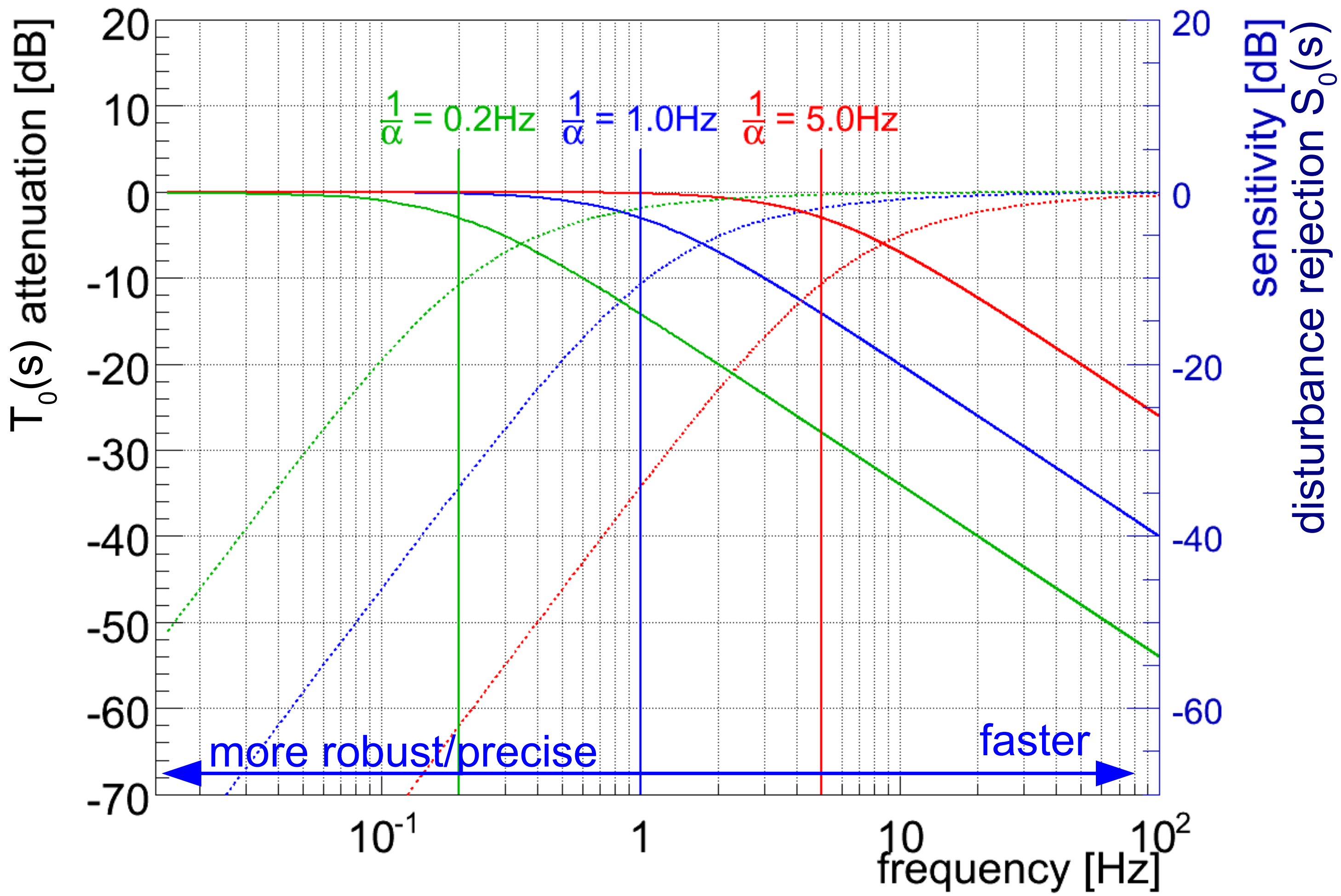
[1]D. C. Youla et al., *"Modern Wiener-Hopf Design of Optimal Controllers"*, IEEE Trans. on Automatic Control,1976, vol. 21-1,pp. 3-13 & 319-338

Example: PLL Closed Loop Controller - Bandwidth

- $\alpha > \tau \ldots \infty$ facilitates the trade-off between speed and robustness

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

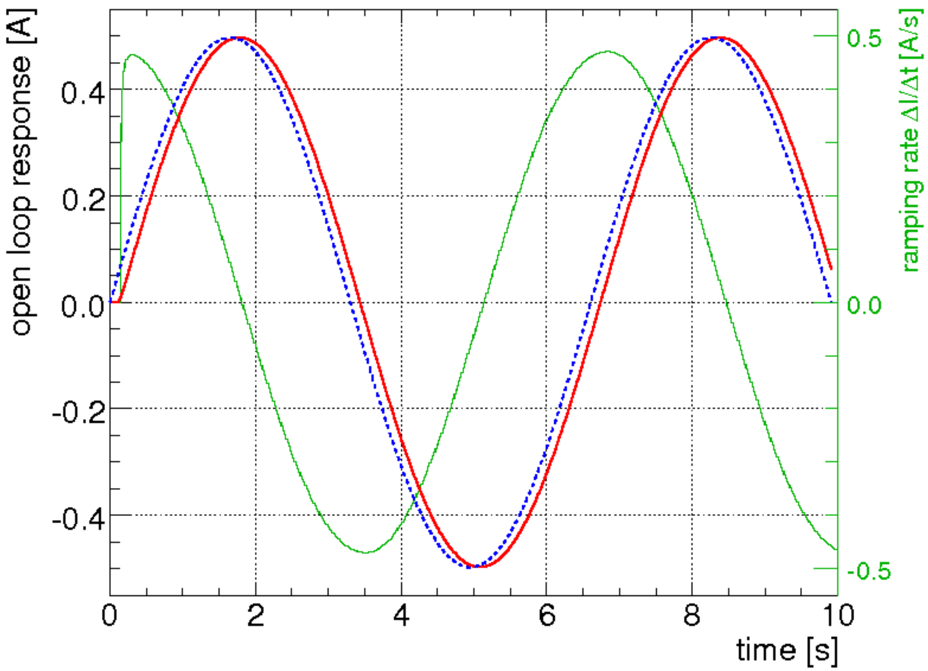
  - operator has to deal with one parameter → enables simple adaptive gain-scheduling based on the operational scenario!



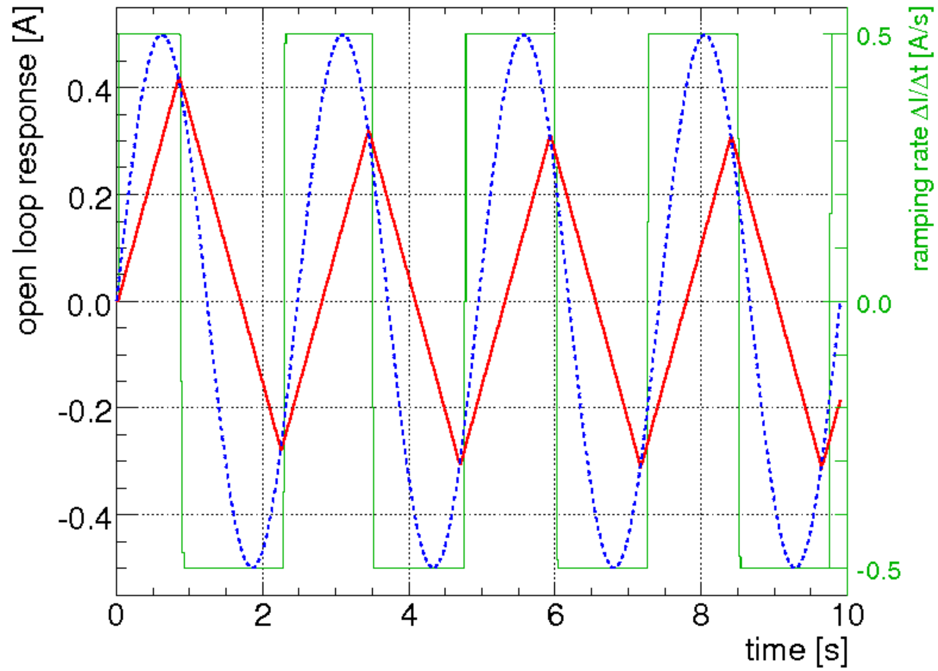
Two common non-linear effects in accelerators:

- 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

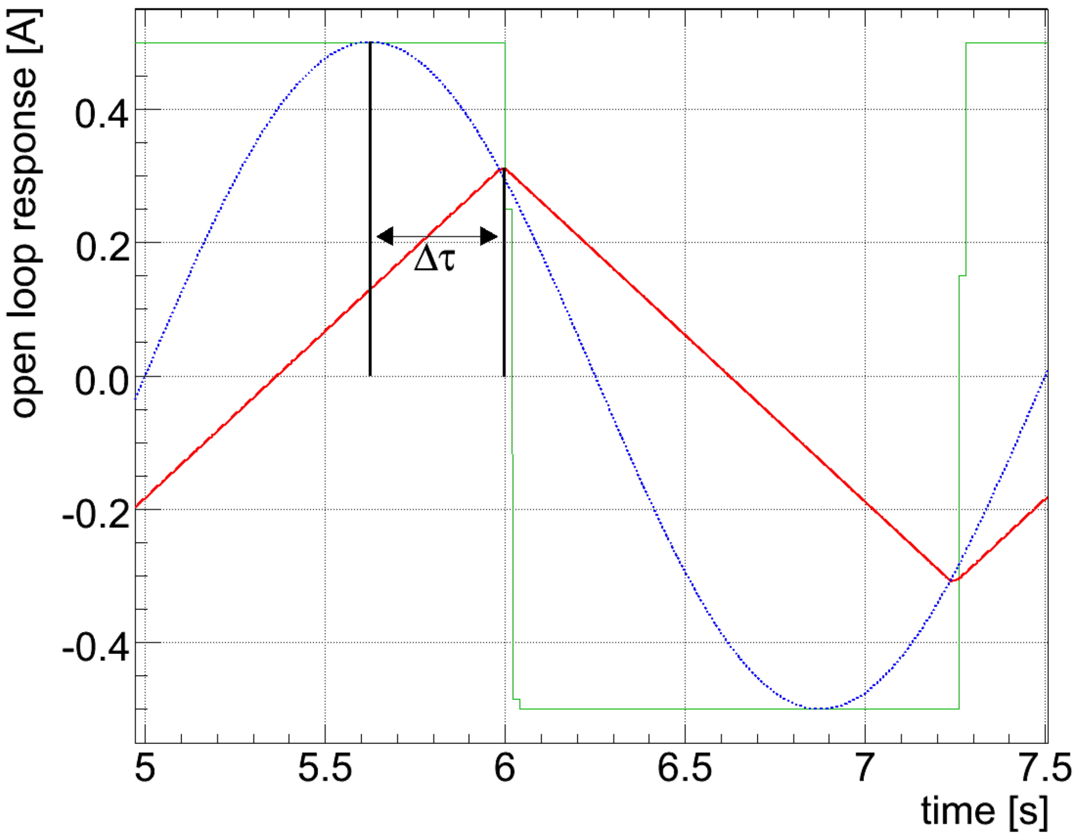
slow perturbation: perfect tracking



fast perturbation: saw-tooth



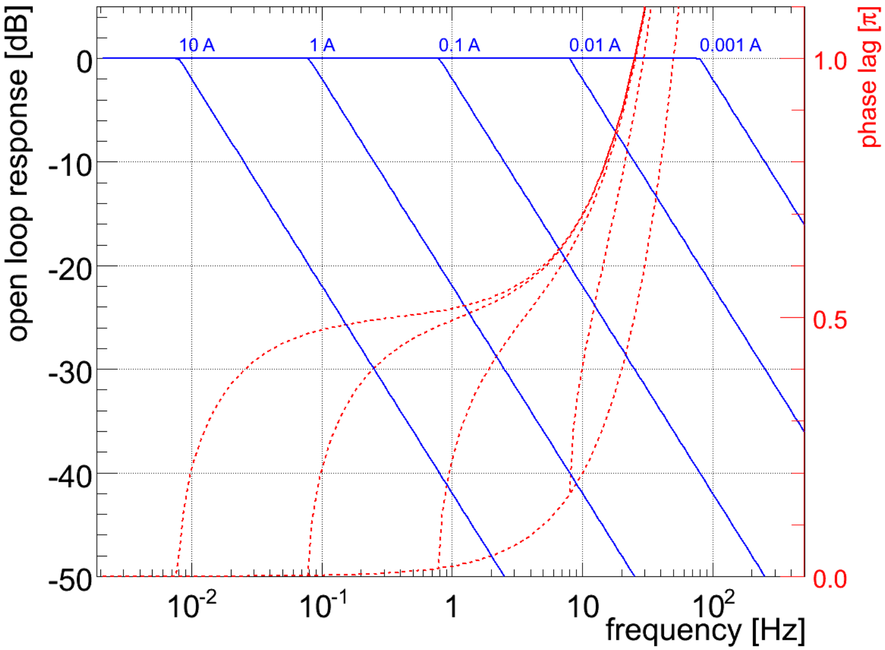
- Rate-limiter in a nut-shell:
  - additional time-delay $\Delta\tau$ that depends on the signal/noise amplitude
  - (secondary: introduces harmonic distortions)



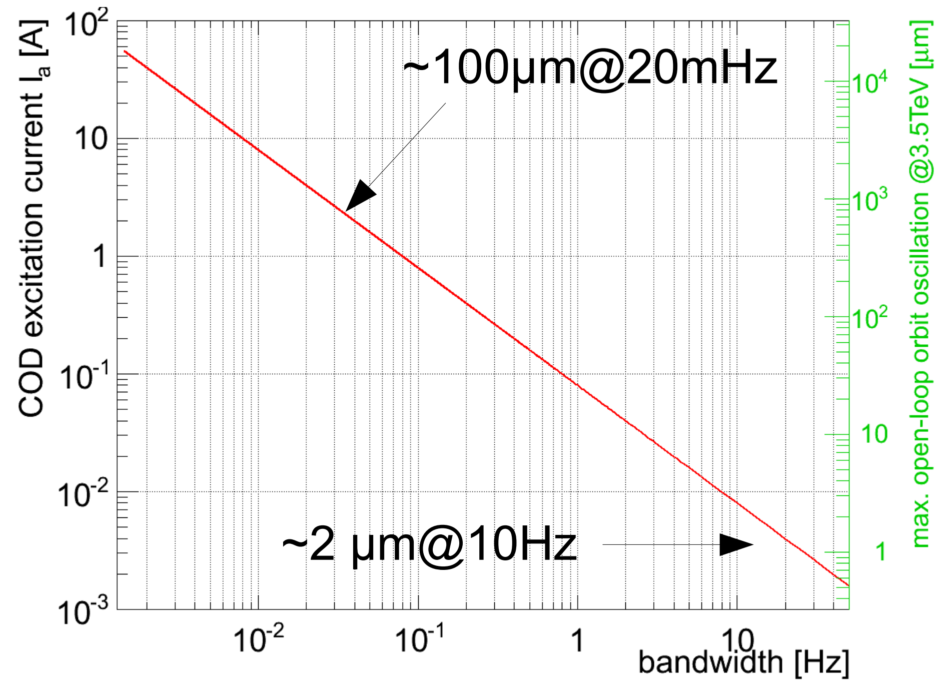
  - N.B. Orbit-FB only knows about strength/rate change of RT trims
    - no info on rate-limits underlying LSA feed-forward functions

Time-Domain: Non-Linearities III/IV

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



ΔI=0.1A ↔ Δx≈32 μm@β=180m



- Consider ~32μm@1Hz as effective bandwidth @ 3.5TeV

Unstable Zeros/non-linearities and delays

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

- ... 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 $G_{NL}(s)$

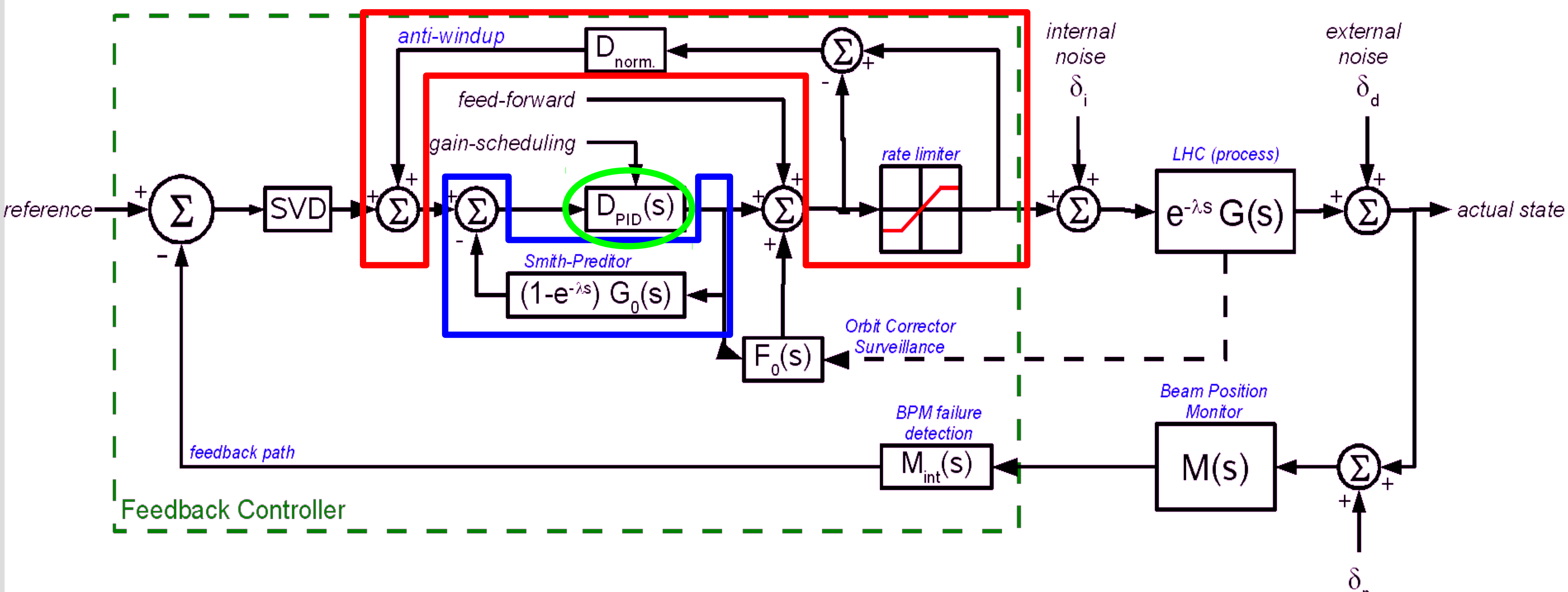
$$G(s)=\frac{e^{-\lambda s}}{\tau s+1}G_{NL}(s)$$

- with τ the power converter time constant and

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

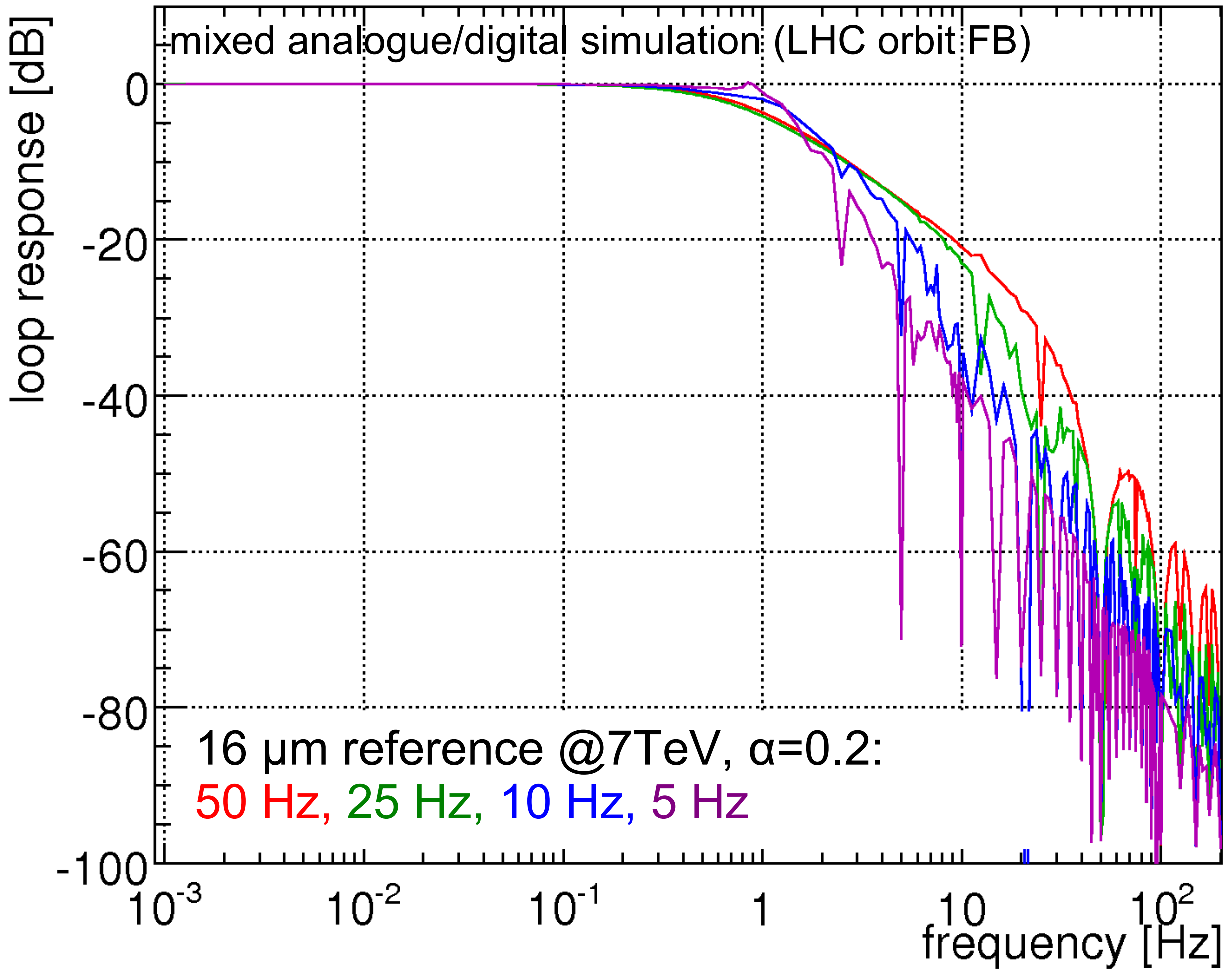
- yields Smith-Predictor and Anti-Windup paths:

$$T(s)=F_{Q}(s)\cdot e^{-\lambda s}G_{NL}(s)$$



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

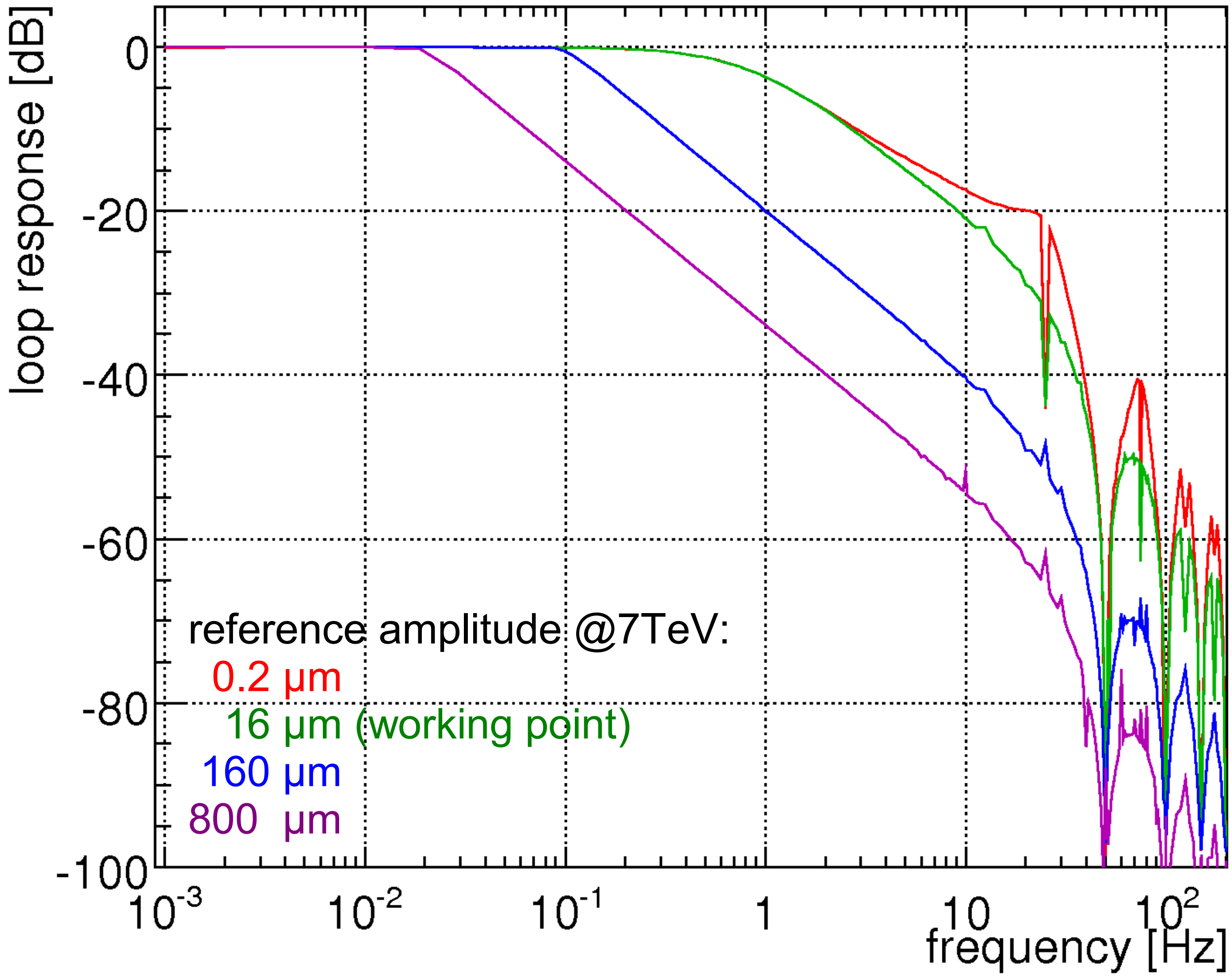
Loop Bandwidth ≠ Sampling Frequency



- ... 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}

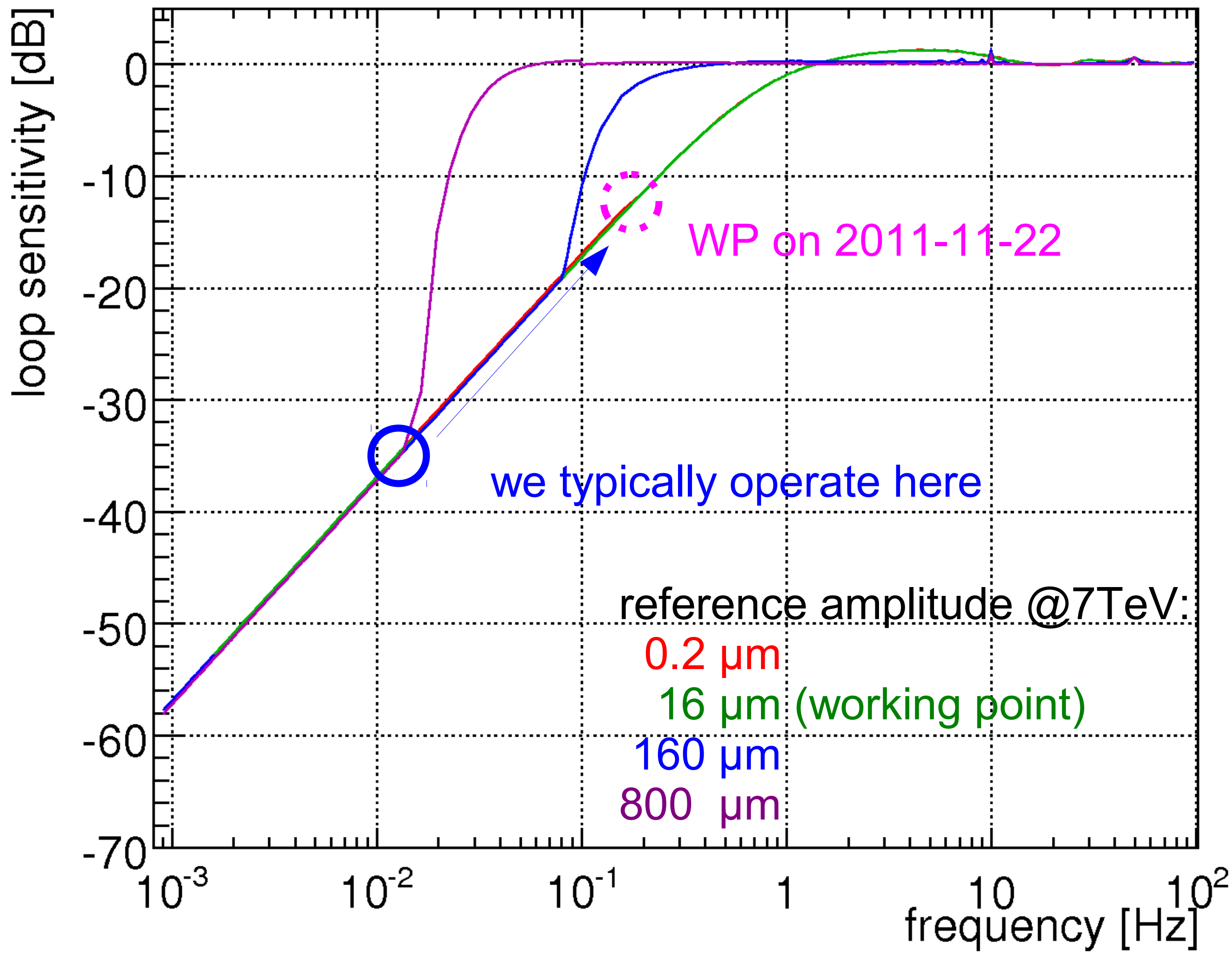
Nominal Feedback Response T_0

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



Nominal Feedback Disturbance Rejection S_{d0}

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



- Factor 10 margin but radically lost if encountering rate-limit or delays → should be validated early-on in 2012!

Conclusion

- Feedback bandwidth can certainly be increased during dedicated special periods such as MDs, setup of new ramps, squeezes, etc.

- However, need to respect intrinsic trade-offs of increasing bandwidth
  - more BPM noise propagated onto the beam
  - limited by CODs and delays → non-linearities become important

- Using the right optics during the squeeze is not mandatory but certainly improves the bandwidth and stability margin
  → should investigate and test the impact of using half- or fully squozen optic

- Specific Orbit-FB wish list for re-commissioning next year:
  - we should aim at verifying the actual orbit feedback stability margin during every/most new squeeze steps → need proper allocated time
  - Perform feed-forward more often/sooner (start of run?)

- e.g. RPLB.UA27.RCBCVS5.R2B2 at 0.1 A/s

- Last squeeze: