LHC Commissioning Working Group:

Overview of foreseen Feedbacks and implications for commissioning

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with input from:
J. Wenninger, R. Jones and others

Will cover ...

- Summary of requirements and expected dynamic perturbations
- Feedback architecture and 'test-bed'
- Some comments on getting them going

Disclaimer:

- Already covered in earlier meetings:
  - Beam Instrumentation and their commissioning → R. Jones, recent LHCCWG talk
  - Corrector circuits and optics: polarities, mapping, rough calibration, ...
- Will evolve most issues around orbit feedback system
  - largest multi-input-multi-output system, largest complexity
  - issues are similar for other FBs

Preliminary Remark:

- Traditional requirements on beam stability (in particular orbit)...

... to keep the beam in the pipe!

- LHC: Requirements/time-line of key beam parameters control depend on:
  1. Capability to control level/ tolerances of particle losses in the machine
     - Machine protection & Collimation
     - Quench prevention
  2. Commissioning and operational efficiency

- Example: Collimation System, Phase I: 43x43 → $N_{max} \approx 5 \cdot 10^{12}$ protons/beam

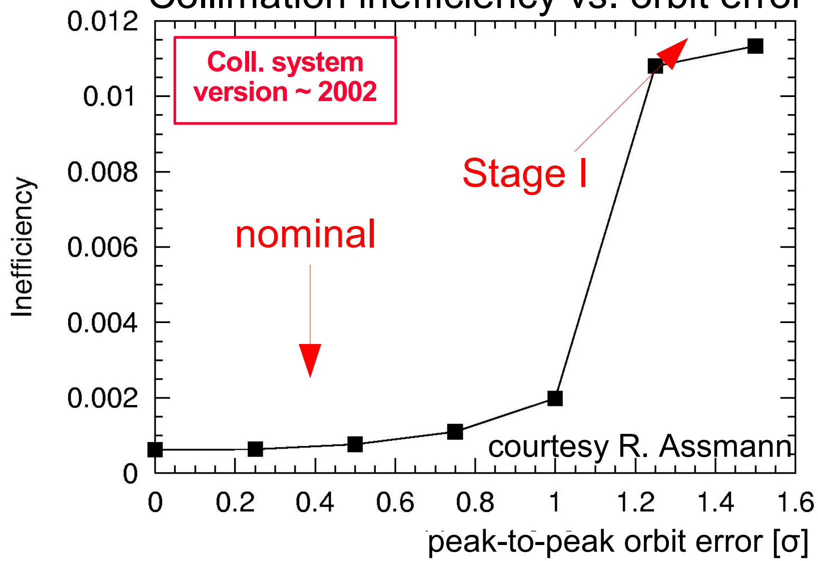
  – required collimation inefficiency[1,2]:

$$\eta = \frac{\tau_{min} \cdot R_q \cdot L_{dil.}}{N_{max}}$$

  – Min. accept. lifetime: $T_{min} \approx 10$ min.
  – Dilution length: $L_{dil} \approx 50$ m
  – Quench level (@7 TeV) R_q: $R_q \approx 7.6 \cdot 10^6$ prot./m/s

→ η < 0.05 (≈ single stage system)

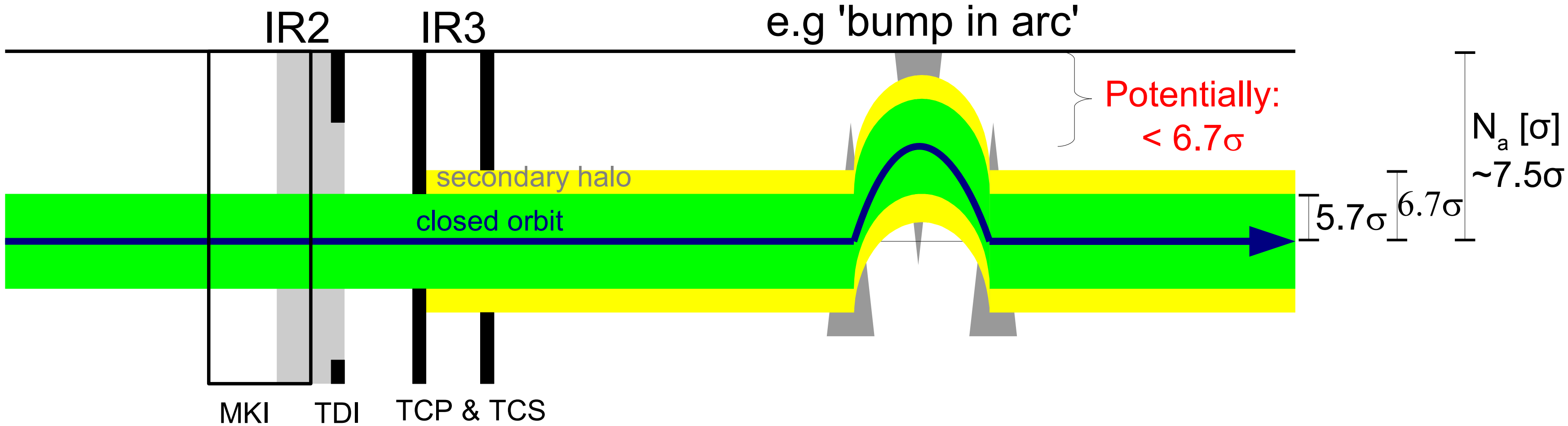
Collimation inefficiency vs. orbit error[1]



- Orbit stability of < 1 σ seem to be sufficient for ≤ 43 bunches
- Nominal: ≈ 0.3 σ locally (collimation) and ~ 0.3 σ globally

[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 proposal[1]: regularly check aperture → see link

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

Nominal Requirements on Orbit

▪ LHC cleaning System:	< 0.3 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.: (estimated arc aperture 7.5 σ vs. Sec. Coll. @ 6.7 σ)	< 0.3-0.5 σ (??)	global
▪ 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!

- Energy matching between of SPS → LHC
  - use horizontal orbit corrector magnets adjust LHC energy (easiest and cleanest!)

- A priori not urgently required for low intensity beams, but
  - may keep capture losses below an acceptable limit
  - minimises abort gap population & feed-down of higher multipoles

$$\Delta Q = Q'_{nat} \cdot \frac{\Delta p}{p} \qquad \mu(b_1) = 1\, unit \rightarrow \Delta Q \approx -0.014$$

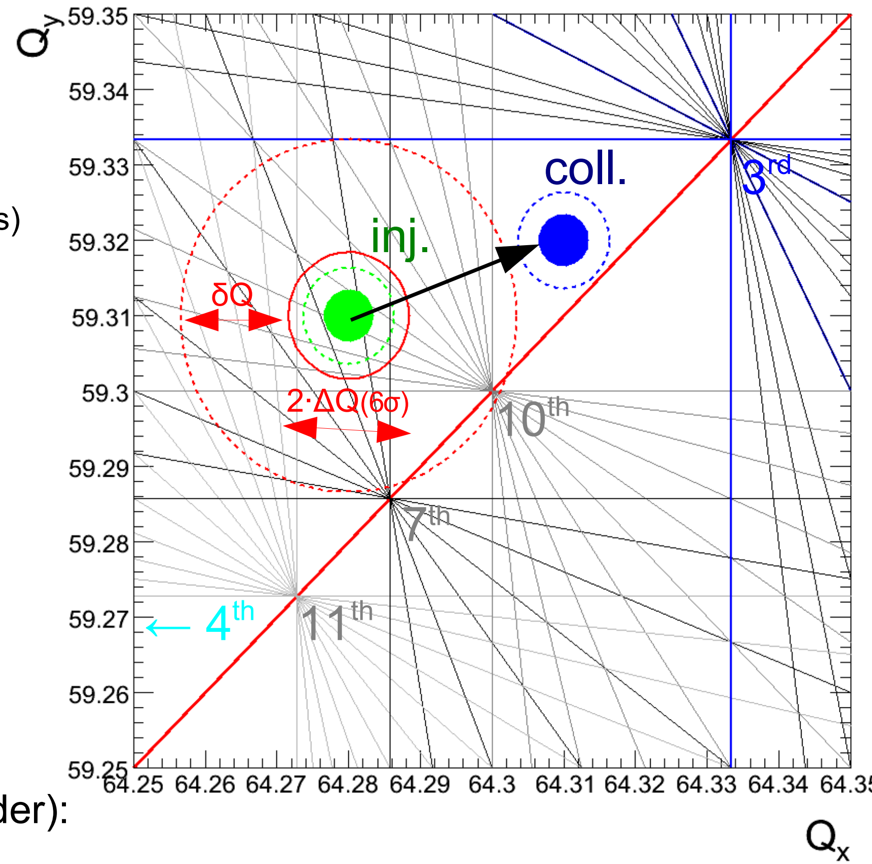
→ favourable once running with high intensity

- Required[1] initial momentum stability: $\Delta p/p < 10^{-4}$ = nominal
  - Simplifies setup of nominal beam after commissioning pilot

[1] E. Chapochnikova, private communications
[2] E. Shaposhnikova, "Abort Gap Cleaning and the RF System", Chamonix XII, 2003
[3] T. Linnecar, "RF Capture and Synchronisation", Chamonix XII, 2003

- Tune spread $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$
  - fixed by available space in Q-diagram
  - Working assumption: (first order:
    no non-linear effects, avoid 3rd and 4th order resonances)

    $\delta Q \leq 0.015 \rightarrow 0.003$
    (early commissioning → 43x43)
  - Nominal[1,2]: $\Delta Q \leq 0.003$ (inj.) $\delta Q \leq 0.001$ (coll)



- Chromaticity
  - SPS: $\Delta p/p$: $2.8 \cdot 10^{-4}$
    (actual $\Delta p/p$ given by SPS → LHC inj.)

  → allowed max lin. chromaticity (5-6 σ, first order):

$$Q'_{max} \propto \frac{\Delta Q_{av}}{\Delta p / p} \quad \rightarrow Q'_{max} \approx 10 \;\&\; Q' > 0\,!$$

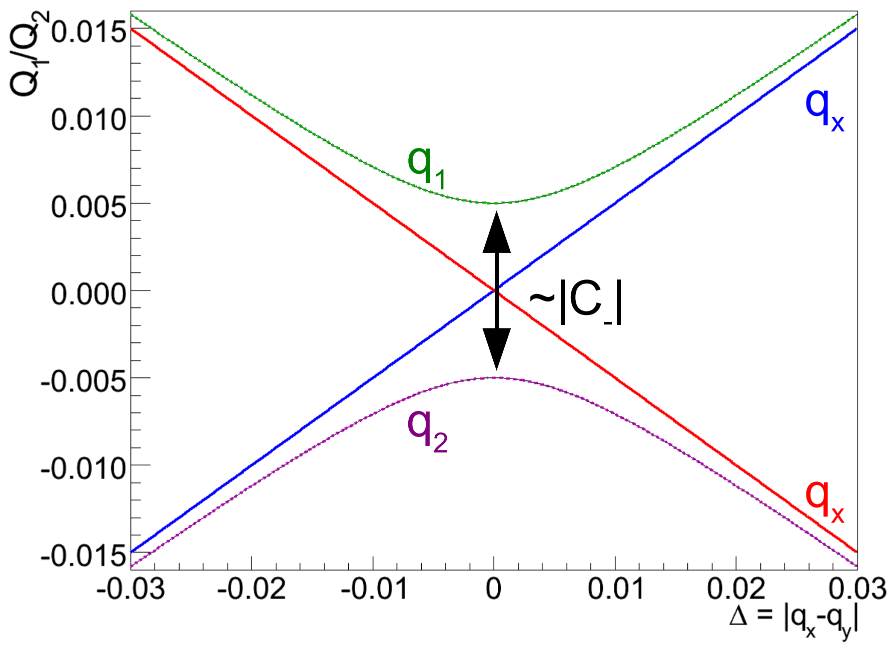
  - Nominal[1,2]: $Q'_{max} \approx 2 \pm 1$

"Numbers are estimates, other more/less strict choices are of course possible – commissioning will clarify real requirements!"

[1] S. Fartoukh, O. Brüning, "Field Quality Specification for the LHC Main Dipole Magnets", LHC Project Report 501
[2] S. Fartoukh, J.P. Koutchouk, "On the Measurement of the Tunes, [..] in LHC", LHC-B-ES-0009, EDMS# 463763

Requirements on Coupling

- Minimum distance Δ_- between tunes given by coupling c_-
  - LHC injection: $\Delta_-=|q_x-q_y|=0.03$, collision: $\Delta_-=0.01$



  - Closest tune approach → $c_-«0.03$ and $c_-«0.01$ respectively
- Requirement for other feedbacks that rely on decoupled planes
- Proposal for alternate higher tune split[1]: $\Delta_-=0.1$ ($q_x=0.285$,$q_y=0.385$)

[1]S. Fartoukh, "Commissioning tunes to bootstrap the LHC", LCC #31, 2002-10-23

Expected Dynamic Perturbations vs. Requirements

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

	Orbit [σ]	Tune $[0.5\cdot f_{rev}]$	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

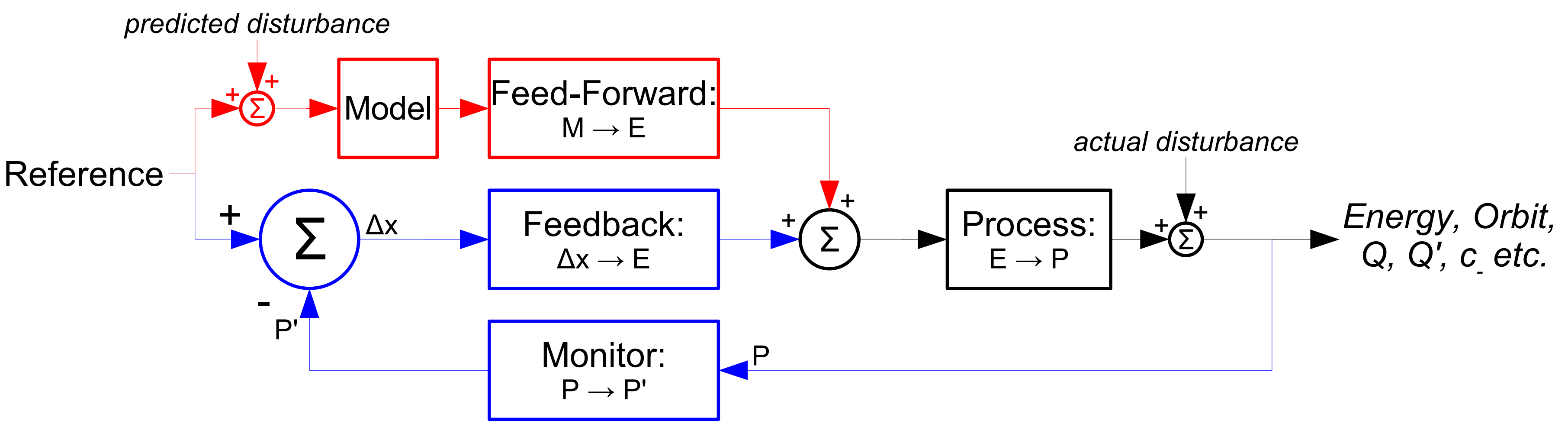
- Feedback priority list: Coupling/Tune → Chromaticity → Orbit → Energy
- Feedback list of "what's easiest to commission":
  - 1rd: Orbit → functional BPM system → OK
  - 1½: Energy → consequence of 100k turn acquisition → OK
  - 2nd: Coupling/Tune → functional Q-meter (-PLL) → Day I-N
  - 3rd: Chromaticity → functional Q-meter and Δf/f modulation → ??
- Foresee time to commission feedbacks at an early stage
  - Most instruments are commissioned parasitically with first circulating beam

* 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 <u>rough</u> process model and measurement of parameter
  - Two types: within-cycle (repetition Δt<<10 hours) or cycle-to-cycle (Δt>10 hours)

preferred choice!



- From the steering point of view: → All control schemes possible
- For the full block diagram → click <u>here</u>
- Choice of Feedback vs. Feed-forward
  - depends on available robust beam parameter measurements

No “black feedback magic”

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

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

matrix multiplication

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

- 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 ...

"One-Slide" Orbit Correction Strategy

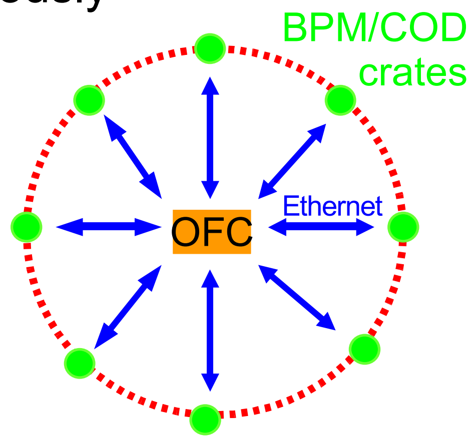
- Orbit Correction will consist of two steps (which may alternate repetitively):
  - Initial setup: "Find a good orbit" (mostly feedback "off")
    - establish circulating beam
    - compensate for each fill recurring large perturbations:
      - static quadrupole misalignments, dipole field imperfections
      - ...
    - 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 small 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.

back

LHC orbit feedback system

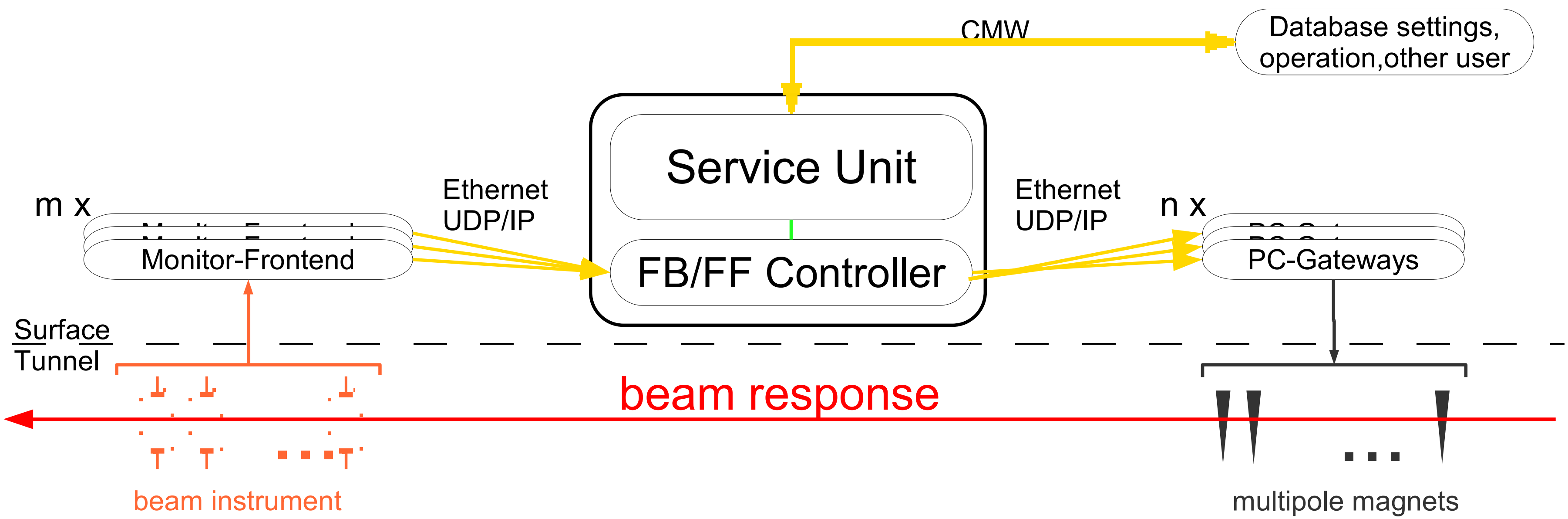
- Small perturbations around the reference orbit will be continuously compensated using beam-based alignment through a central global orbit feedback with local constraints:
  - 1056 beam position monitors
    - BPM spacing: $\Delta\mu_{BPM} \approx 45°$ (oversampling → robustness!)
    - Measure in both planes: > 2112 readings!
  - One Central Orbit Feedback Controller (OFC)
    - Gathers all BPM measurements, computes and sends currents through Ethernet to the PC-Gateways to move beam to its reference position:
      - high numerical and network load on controller front-end computer
      - a rough machine model is sufficient for steering (insensitive to noise and errors)
      - most flexible (especially when the correction scheme has to be changed quickly)
      - easier to commission and debug
  - 530 correction dipole magnets/plane (71% are of type MCBH/V)
    - Bandwidth (for small signals): $f_{bw} \approx$ 1-2 Hz (defines total feedback limit)



more than 3000 actively involved elements!

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

- Service Unit: Interface to users/software control system
- Orbit Feedback Controller: actual orbit/feedback logic
  - Simple streaming task for all feed-forwards/feedbacks: (Monitor → Network $)_{FB}$→ Data-processing → Network → PC-Gateways
  - Can run auto-triggered (no timing necessarily required)
  - Hardware and functional specifications already available



LHC orbit feedback system III/III

- SVD* based global correction scheme in space-domain and Proportional-Integral-Derivative (PID) controll (+ Smith Pred.) in time-domain
  - Uses pseudo-inverse orbit response matrix:
    - Orbit correction = simple matrix multiplication
  - Can easily eliminate near-singular solutions
    (= solutions that may potentially drive the loop instable)
    - Uses all (selected) CODs with rather small correction strengths
    - Less sensitive to single BPM errors, BPM noise and COD failures[1,2]
  - intrinsically minimise uncertainties and unknown effects, due to “integral” part of PID controller
    - Classic, well studied and understood controller
    - Does not require an accurate process model
    - Linearises non-linear systems
  - does not correct for dispersion orbit → minimises cross-talk with E-FB

→ see additional slides on SVD correction

→ All light sources go in this direction!

* SVD: G. Golub and C. Reinsch, “*Handbook for automatic computation II, Linear Algebra*”, Springer, NY, 1971

[1] R. Steinhagen, “Can the LHC Orbit Feedback save the beam in case of a closed orbit dipole failure?”, MPWG #46, 2005-06-01

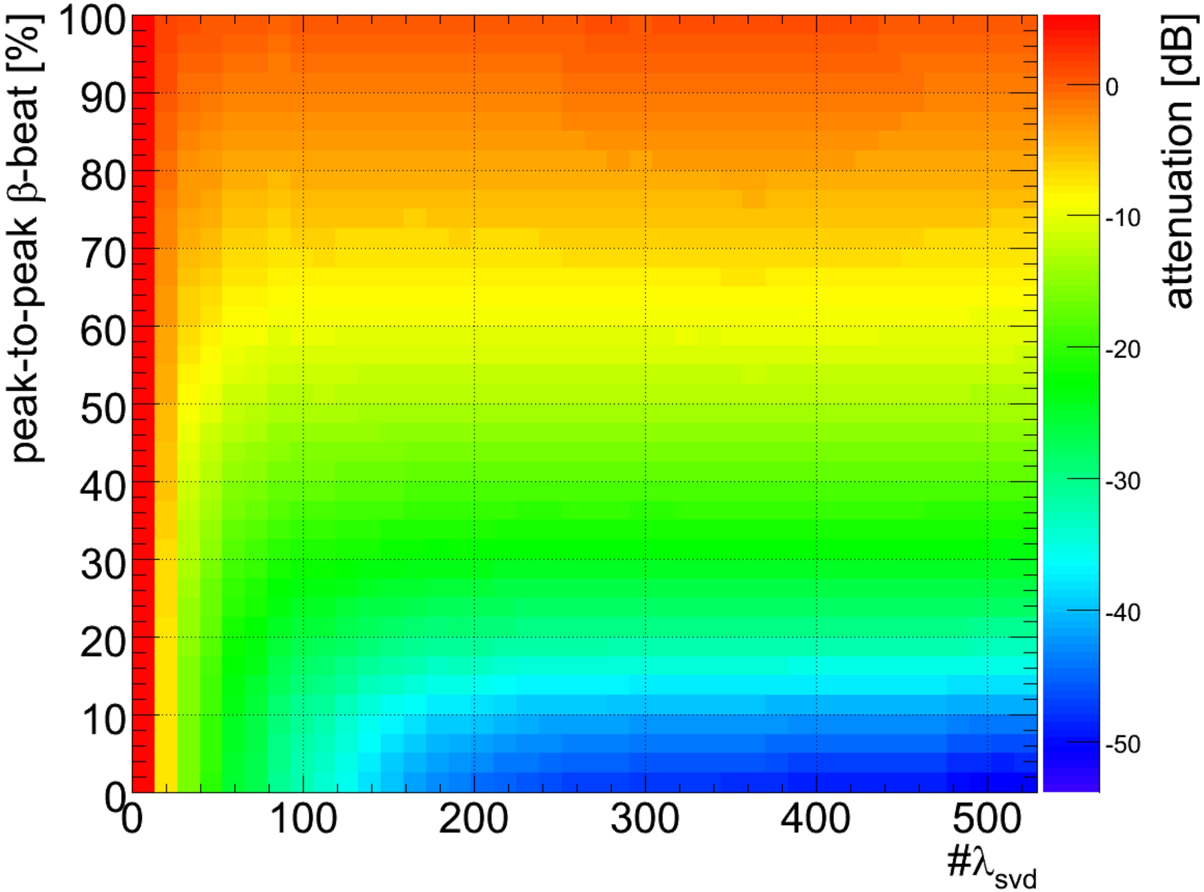
[2] R. Steinhagen, “Closed Orbit and Protection”, MPWG #53, 2005-12-16

Feedback Design Targets:

- Feedback loops are designed to be robust against:
  - optics and calibration uncertainties (through using SVD)
    - "number of used eigenvalues" $\#\lambda_{svd}$ controls robustness vs. precision
  - measurement noise and failing monitors: → see additional slides
    - very likely failure during operation
    - expect up 20% (worst case) and more dis-functional BPMs during operation with beam
  - Failure of orbit corrector circuits: → see additional slides
    - Present estimate: about one failure every 5 days during operation with beam
  - Failures and unavailability of controls infrastructure:
    - network, front-ends, timing etc.

Example: Sensitivity to beta-beat

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



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

attenuation =

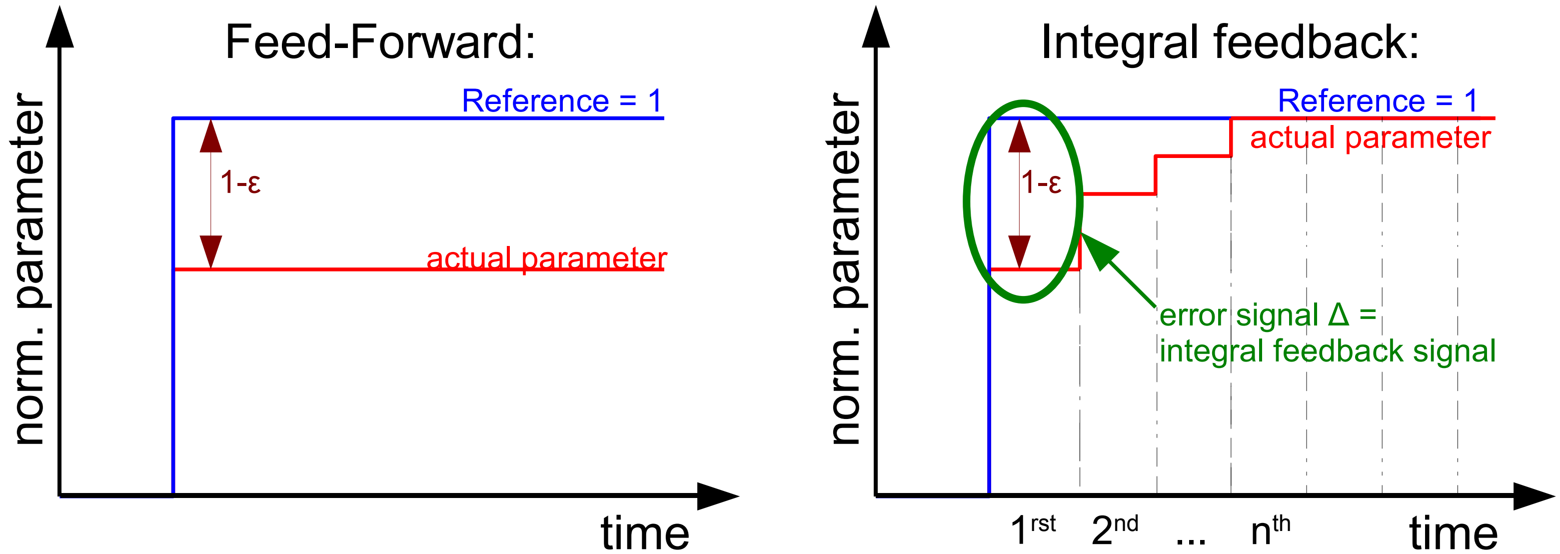
$$20 \cdot \log \left| \frac{orbit\ r.m.s.\ after}{orbit\ r.m.s.\ before} \right|_{ref}$$

- Robust Control: OFB can cope with up to about 100% β-beat!
  - Available aperture and collimation inefficiency w.r.t. β-beat is clearly more an issue

Virtue of PID Controller: Integral Action example

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

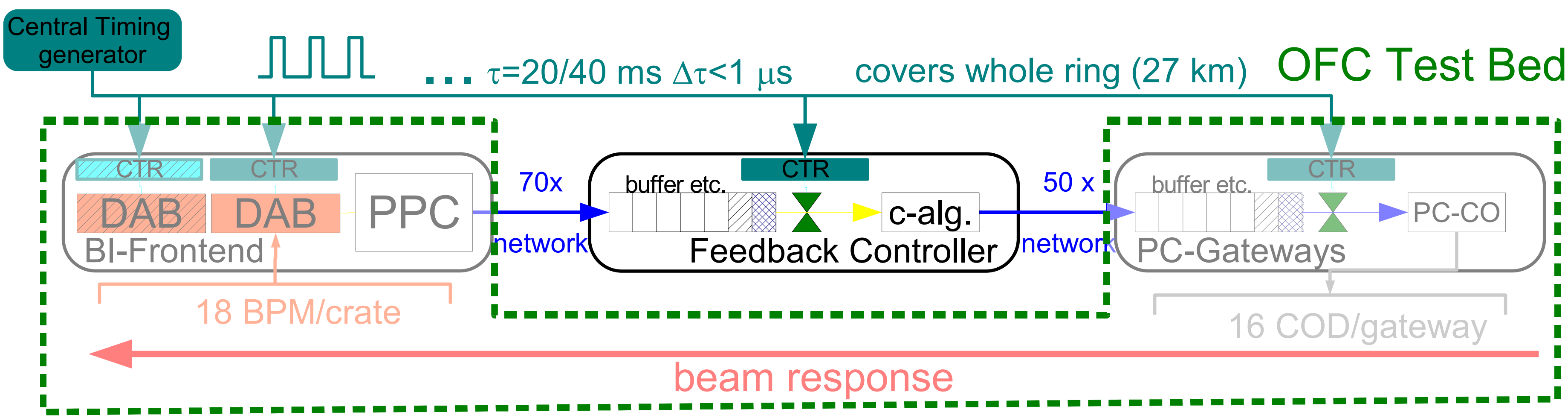
$$\Delta x(s)=R_i(s)\cdot\delta_i \;\rightarrow\; \Delta x(s)=R_i(s)\cdot(\epsilon_{ss}+(1+\epsilon_{scale})\cdot\delta_i)$$



- Uncertainties and scale error of beam response function affects rather the convergence speed (= feedback bandwidth) than achievable stability
- A 4% error of the orbit transfer function has in first order a similar effect as 4% beta-beat on the quadrupole magnets.
- Stability limit: BPM noise and external perturbations w.r.t. FB bandwidth

Orbit Feedback Controller – Test Bed

- Test bed complementary to Feedback Controllers:
  - Simulates the open loop and orbit response of COD→BEAM→BPM
    - Decay/Snap-back, ramp, squeeze, ground motion simulations, ...
    - Keeps/can test real-time constraints up to 1 kHz
  - Same data delivery mechanism and timing as the front-ends
    - transparent for the FB controller
    - same code for real and simulated machine:
      - possible and meaningful "offline" debugging for the FB controller



Commissioning of Feedbacks without Beam

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

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

Commissioning of Feedbacks with Beam

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

  } partially done while threading the first beam!

- It is possible to run feedbacks already after above procedures:
  - e.g. auto-triggered at 0.1 – 1 Hz
  - low integral gain ($K_p=K_d=0$)

Requirements for nominal Feedback Performance

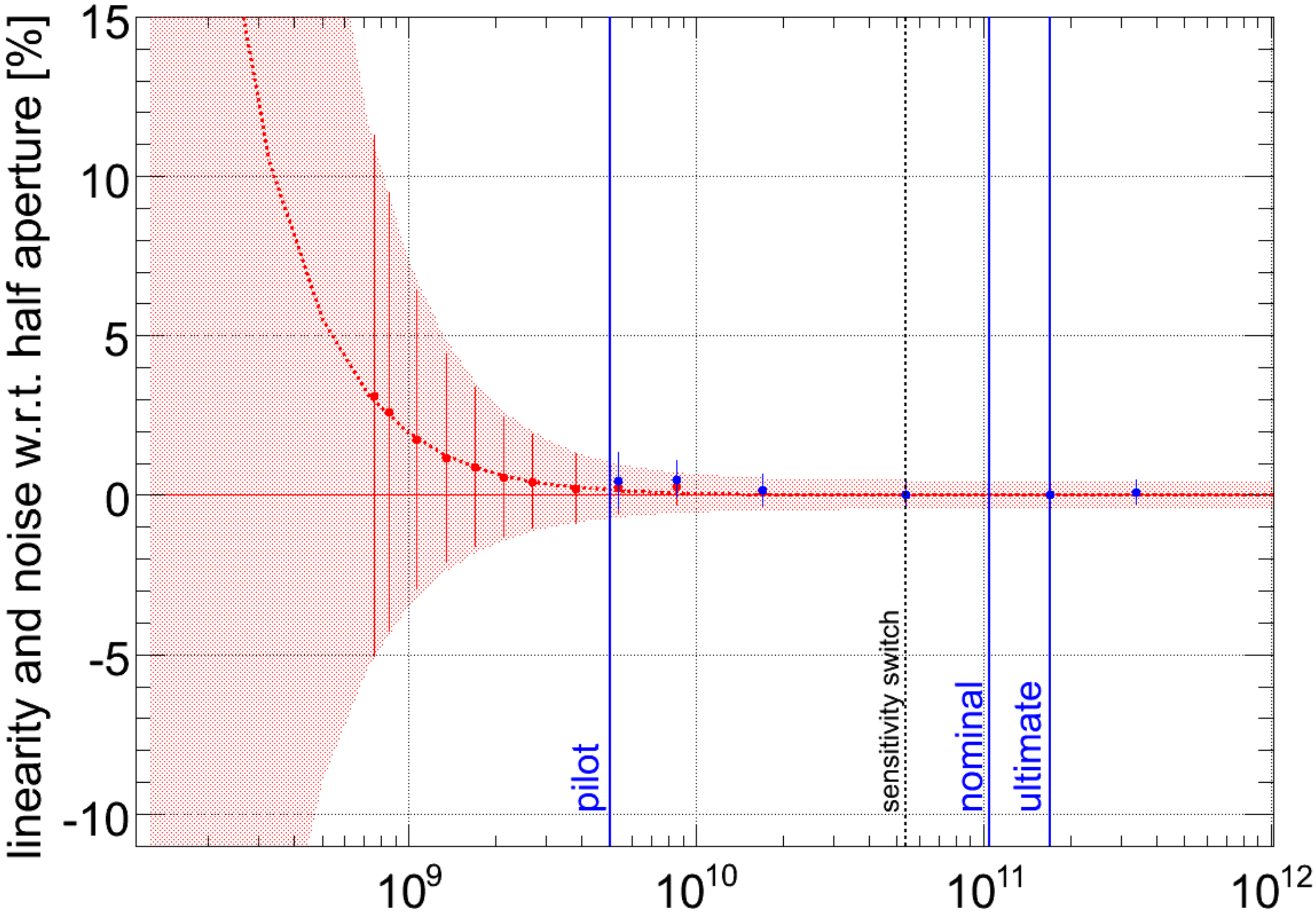
- If we want to run at nominal feedback performance: Favourable to have
  - Beta-beat of about 20% or less
    - e.g. measurement of orbit response matrix:
      - excitation of all CODs and measuring the BPM response
        - » not all CODs were necessarily used for threading (polarity checks)
      - requires about ~10 s per COD → 4h: one shift
      - intrinsically gives a coherent COD/BPM calibration
  - BPM vs. COD calibration within 20%
  - Total feedback loop delay and optimisation of PID gains

(
  - Test of automated feedback procedure for BPM intensity settings change
    - can be omitted, since it seems to be intended to always use low intensity bunches for operation up to 43x43 bunches
    - BBQ is insensitive to bunch/beam intensitiy

)

- 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

Commissioning of Feedbacks: nominal performance

- The possible parameter stability is essentially determined by:
  - feedback bandwidth
  - noise and stability of beam measurements

- Example:
  - BPM orbit resolution: pilot $\Delta x_{turn} \approx 200\ \mu m \rightarrow$ orbit: $\Delta x \approx$ 13-20 μm
  - BBQ (Q,Q' & C^-): $\Delta Q \approx \sim 10^{-4}$, avg. over 10 s

- Actual stability depends on whether we (want to) steer to these limits
  - Filtering is of course possible (e.g. low integral gain K_i)
  - Robustness and availability of instruments is an issue
    - more pronounced for the BPMs
    - Q,Q',Coupling: essentially only one instrument per beam

Conclusions

- Feedback architecture, strategies and algorithms are well established
  - Orbit FB: stability better than about 200 μm should not pose a problem
  - Tune FB: $\Delta Q<0.003$ seems possible, if BBQ works
- Biggest problem so far for LHC feedbacks:
  - Human resources to implement the FB controller, service unit, GUIs, ...
- Commissioning of feedbacks:
  - Most of the requirements for a minimum workable feedback systems are already fulfilled after threading and establishing circulating beam.
  - Redo the optics measurements and calibration with higher accuracies for nominal performance.
- Feedbacks are most useful when used at an early stage
  - RHIC: it is possible to commissioning a new ramp in one go
  - Possibility to use feedback signals as feed-forward for next cycles

Reserve Slides

How to determine the actual aperture?

or:

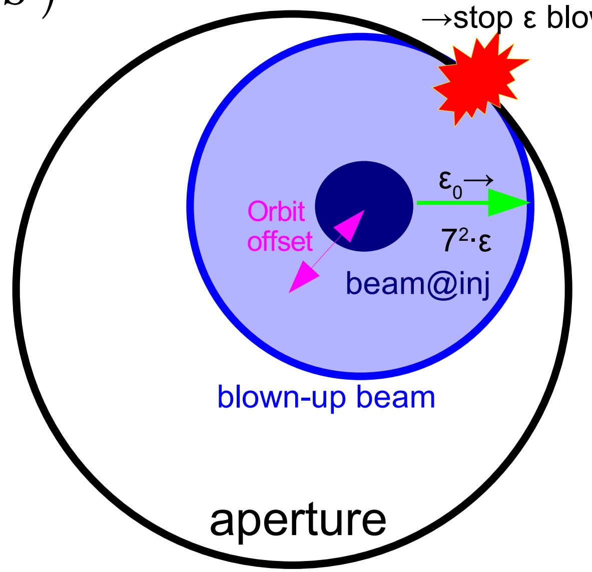
How do we now that we established a good/safe orbit?

back

Aperture measurement proposals:

Two methods to test whether the closed orbit is within 6.7σ of the available mechanical or dynamic aperture:

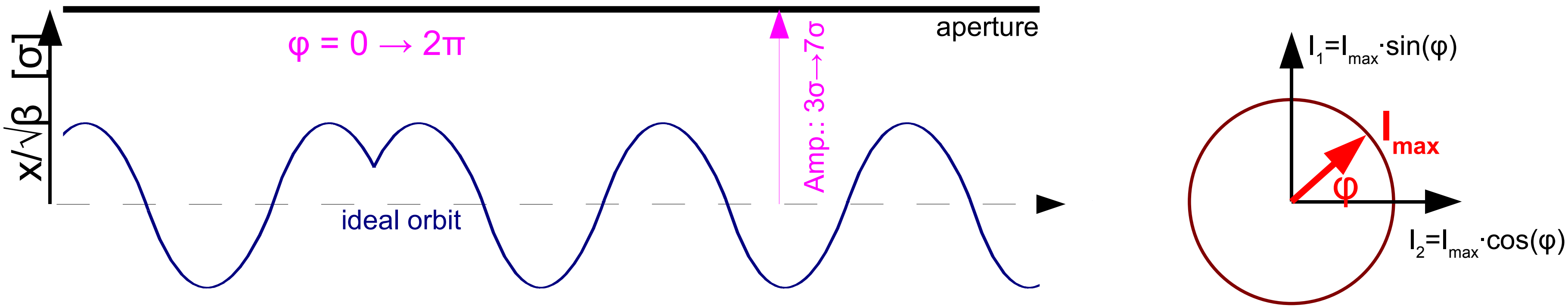
- Scan using emittance blow-up: $\sigma(s)=\sqrt{\varepsilon\,\beta(s)}$
  - Increase beam size in a controlled way while measuring the beam size.
    (e.g. using transverse damper and wire scanner)
  - Once particle loss above given threshold:
    → store last beam size measurement



  - "Is beam size ≥ 6.7 σ_0 ?" (σ_0: beam size at injection)
    - Yes: → mechanical aperture ≥ 6.7 σ → orbit is safe
    - No: → mechanical aperture ≤ 6.7 σ → orbit is un-safe
      - rework orbit reference (compare with old reference....)

back

- Scan using two COD magnets (currents: I_1 & I_2) with π phase advance:



  - Scan I_{max}/φ:
    - $\varphi = 0 \rightarrow 2\pi$ (takes ~25 second @ 7σ, due to COD power converter speed)
  - Increase amplitude (COD currents) till orbit shift corresponds to 6.7σ
  - Loss does not exceed predefined BLM threshold if COD settings@ 6.7σ:
    - Yes: → mechanical aperture ≥ 6.7 σ → orbit is safe
    - No: → mechanical aperture ≤ 6.7 σ → orbit is un-safe
  - additional feature: compare measured with reference BPM step response (x_{co}= 0-3σ)

    → rough optics check (phase advance and beta-functions)

back

Mechanical Aperture Scan through...

Controlled emittance blow-up:

- may check both planes at the same time
- relatively fast measurement
- reliability/robustness of beam size measurement/blow-up is an issue
- no information on injection optics
- tests only one phase
- Tests rather dynamic than mechanical aperture if $a_{dyn} < a_{mech}$
- Destructive measurement
  - beam has to be dumped after scan
  - cannot be used for collimator setup
  - increased beam loss during extraction

Betatron oscillation scan:

- non-destructive measurement
  (could be done to check during each injection)
- rough information on injection optic
- Independent information on planes
- checks only one plane at a time
- What to do if on COD is down?
  - spares: longer measurement
- requires ~30 s for a scan at 7σ
- Required:
  - inhibit injection during scan
  - COD setting reset after scan

- Both methods:
  - Determine the available aperture
  - should be performed with low-intensity beams
  - need time and exclusive control of the machine

- in order to minimise the need for too frequent aperture scans:
  → perform above checks only when exceed given window

back

Indicators whether Aperture Scan is required:

Beam Position Monitors:

- Procedure:

A: Initial check whether Orbit is safe:

- aperture scan (ε blow-up, betatron-oscillation)
  - Potential bump scans to determine location of aperture
- save "safe BPM reference" current settings → x_{ref} = "SAFE SETTING"

B: Check: $\text{if} (|x_{meas.} - x_{ref}| < \Delta x_{tol}) \{...\}$

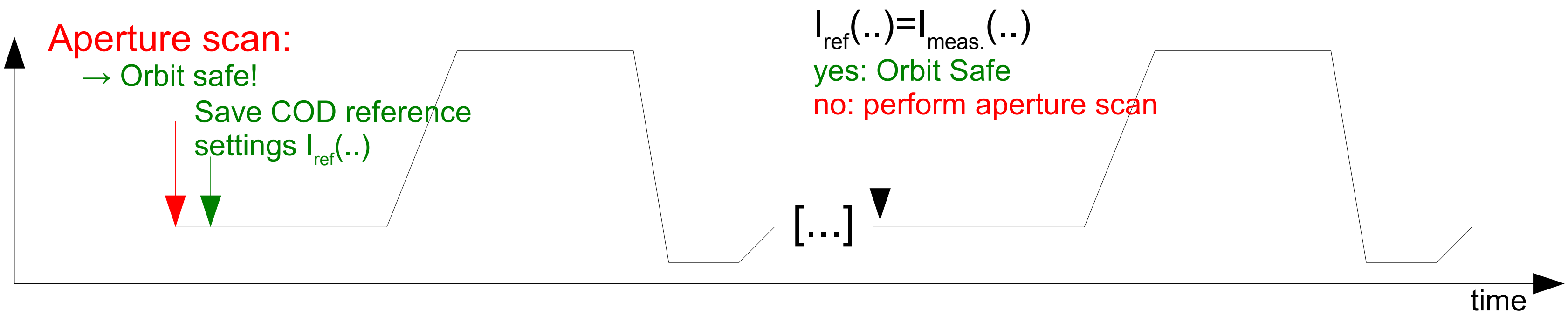
- FALSE: potential orbit bump detected — no
- TRUE: Orbit is safe — yes

– Pro's:
  - Easy to check with circulating beam
  - Less dependent on machine optics
  - Sensitive to most orbit manipulations

– Con's:
  - erroneous BPMs
  - No information before injection
  - Bunch intensity systematics (gain settings) and change of BPM calibration
  - Potential cross-talk with orbit feedback

back

Magnet Current Surveillance I/II



- Proposed Procedure:

A: Initial check whether Orbit is safe:

- aperture scan (ε blow-up, betatron-oscillation)
  - Potential bump scans to determine location of aperture
- Save "safe COD reference" current settings → $I_{ref}(...)$ = "SAFE SETTING"

B: Each cycle:

- Compare with actual current reference $I_{meas}(..)$:

$$\text{if } (|I_{meas}(..) - I_{ref}(...)| < \Delta I_{tolerances}) \{...\}$$

- FALSE: Orbit may contain potential bumps → State A (no)
- TRUE: Orbit can be considered to be safe → State B (yes)

back

Magnet Current Surveillance II/II

- Current Surveillance:
  - Pro's
    - Can be used to check even before first injection
    - Can run continuously with orbit feedback in operation
  - Con's
    - Less sensitive to complicated orbit bumps
    - No precise&simple '$\Delta I \rightarrow \Delta x$' transfer function available
      - depends on machine optic, energy
      - CODs create not only bumps but compensate
        - » ground motion,
        - » decay & snap-back,
        - » multipole field errors,
        - » squeeze induced effects, ...

→ Current tolerance level $\Delta I_{tolerances}$ (“SAFE SETTINGS”) should include margin for

- orbit feedback operation
- expected compensation of closed orbit uncertainties = “natural effects”

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Expected Perturbations of Orbit, Energy, Tune, Chromaticity, Coupling

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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
  - Machine element failures:
    - particularly orbit correction dipole magnets
      (most other magnets are interlocked and inevitably lead to beam dump)
    - → summary

back

Environmental Sources

Perturbations due to

correlated and random ground motion, tides

and thermal expansion of girders

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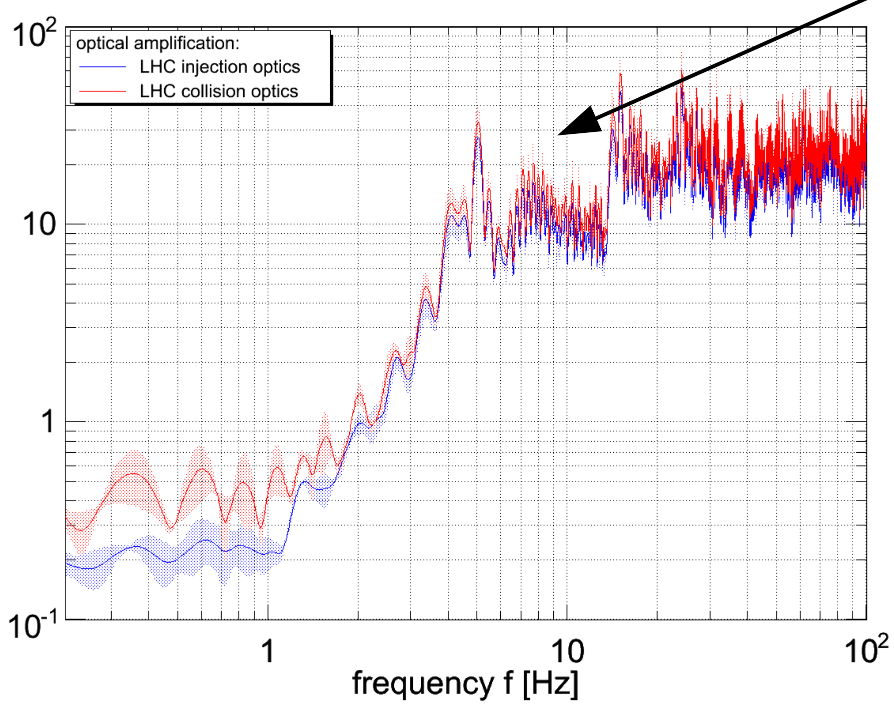
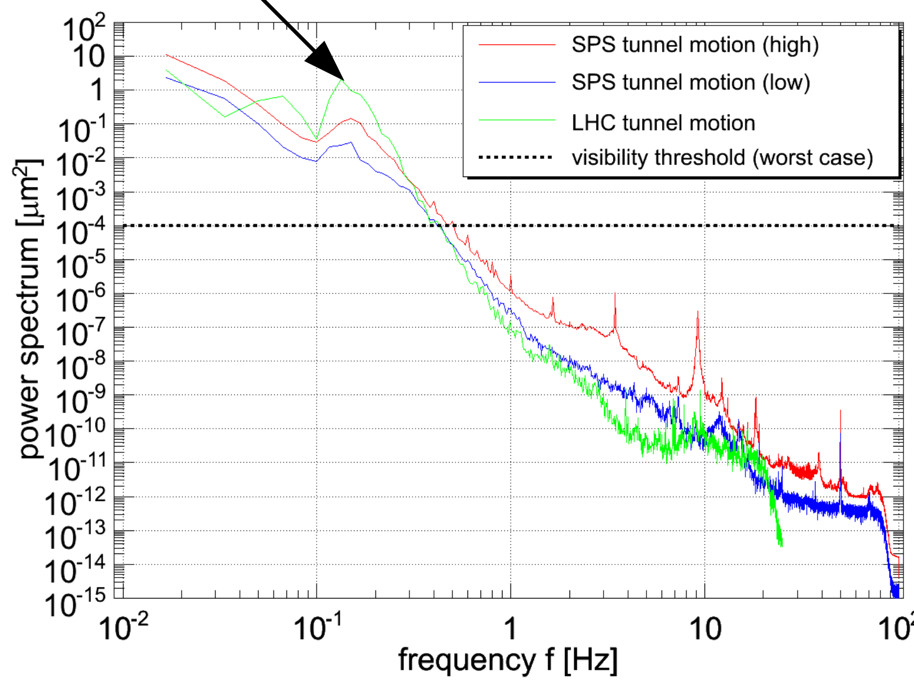
Correlated vs. Random Ground Motion I/II

Two classes of ground motion (see CERN-AB-2005-087):

- Correlated ground motion waves: 'Cultural Noise', ocean swelling, tidal waves, ...
  - Assuming visibility threshold of 1 μm and κ≈1000
    → coherent ground motion negligible above 1 Hz (beware of cryogenics!)

$$\sigma_{beam}[\mu m] = \kappa(f) \cdot \sigma_{ground}[\mu m]$$





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Correlated vs. Random Ground Motion II/II

- Random ground motion (Brownian motion):
  - amplitudes increases with ~√t
    - LEP and SPS based measurements:

$$\sigma_{ground}[\mu m] \approx 5-6\cdot 10^{-2}\left[\frac{\mu m}{\sqrt{s}}\right]\cdot\sqrt{t}$$

  - Propagation of random ground motion onto orbit r.m.s. σ_{beam}:

$$\boxed{\sigma_{beam}[\mu m] = \kappa\cdot\sigma_{ground}[\mu m]}$$

    - LHC injection optics:

κ_H=30.5±11.5 and κ_V=29.6±9.0

    - LHC collision optics:

κ_H=63.3±32.5 and κ_V=62.1±25.5

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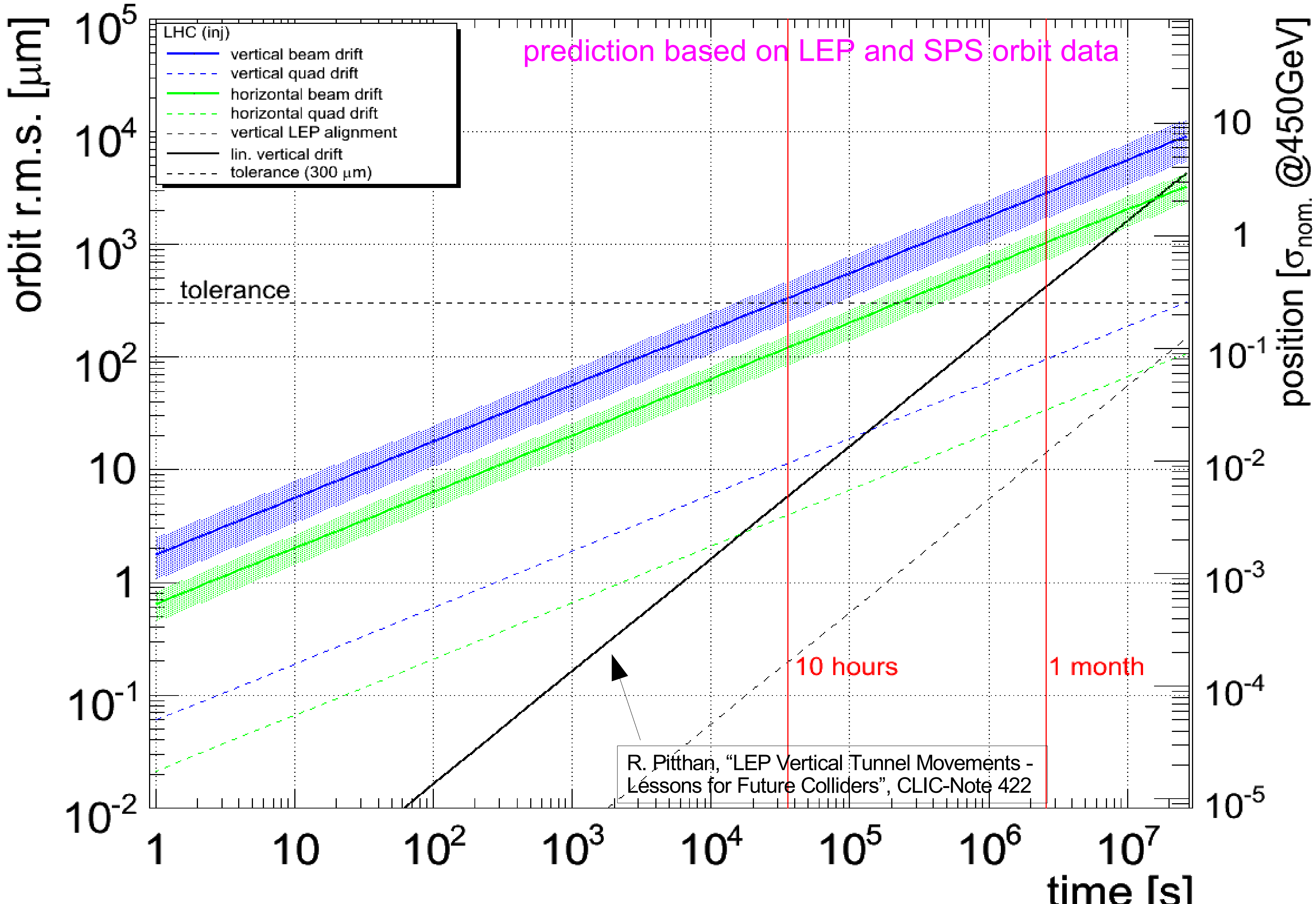
"Analysis of Ground Motion at SPS and LEP, Implications for the LHC", AB Report CERN-AB-2005-087



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

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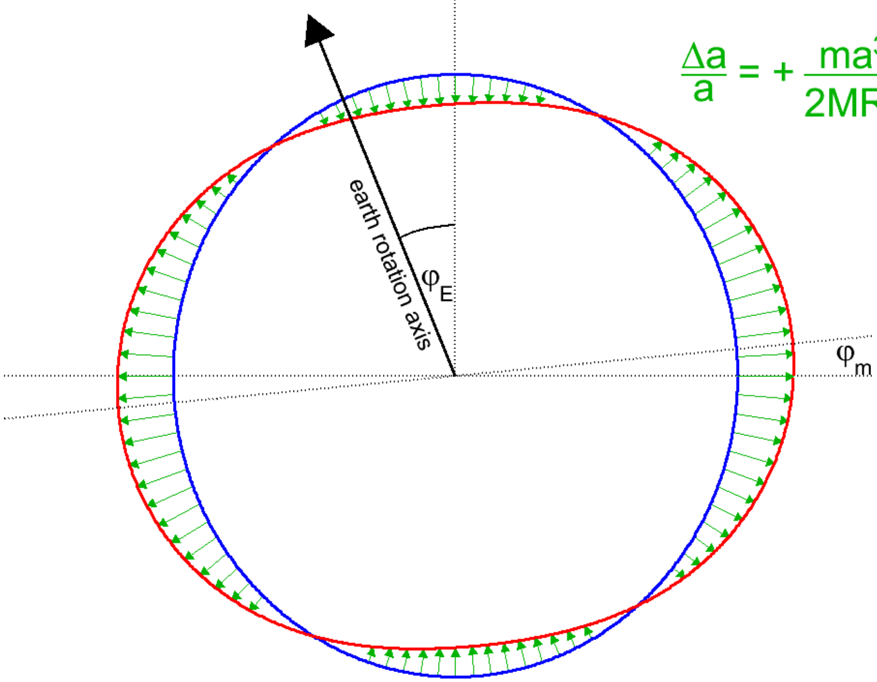
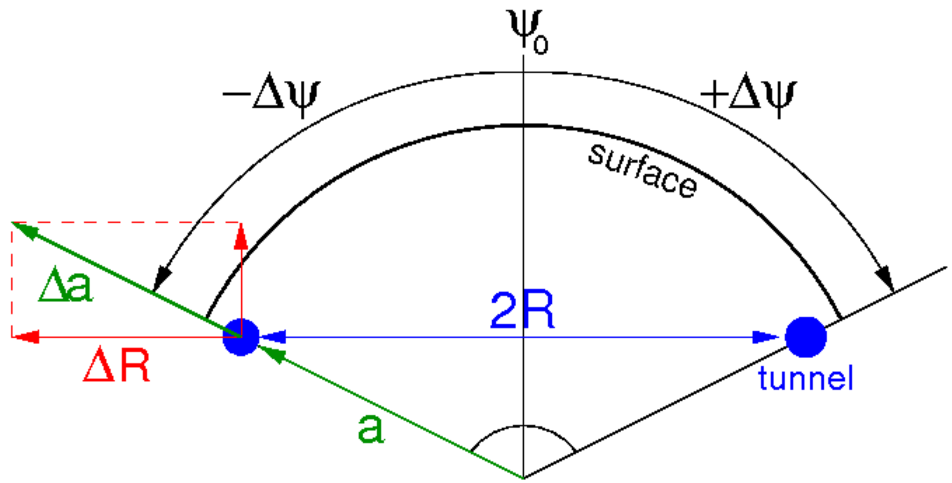
Lunar and Solar Tides

- Moon/sun tides change the geometric circumference of the machine:



$$\frac{\Delta a}{a} = + \frac{m a^3}{2 M R^3}\left(3\cos^2\psi - 1\right)$$



  – well tested at LEP
    → J. Wenninger: CERN-SL-99-025-OP

$$\frac{\Delta p}{p} = -\frac{1}{\alpha_p} \cdot \frac{\Delta C}{C}$$

  – LHC: $\Delta C \approx \pm 0.5$ mm, momentum compaction factor $\alpha_p = 3.2 \cdot 10^{-4}$
    - $\Delta p/p \approx 5.8 \cdot 10^{-5}$ → $2\Delta x = 2 \cdot D_{max} \cdot \Delta p/p \cdot = 326\ \mu m \approx 0.29\ \sigma$

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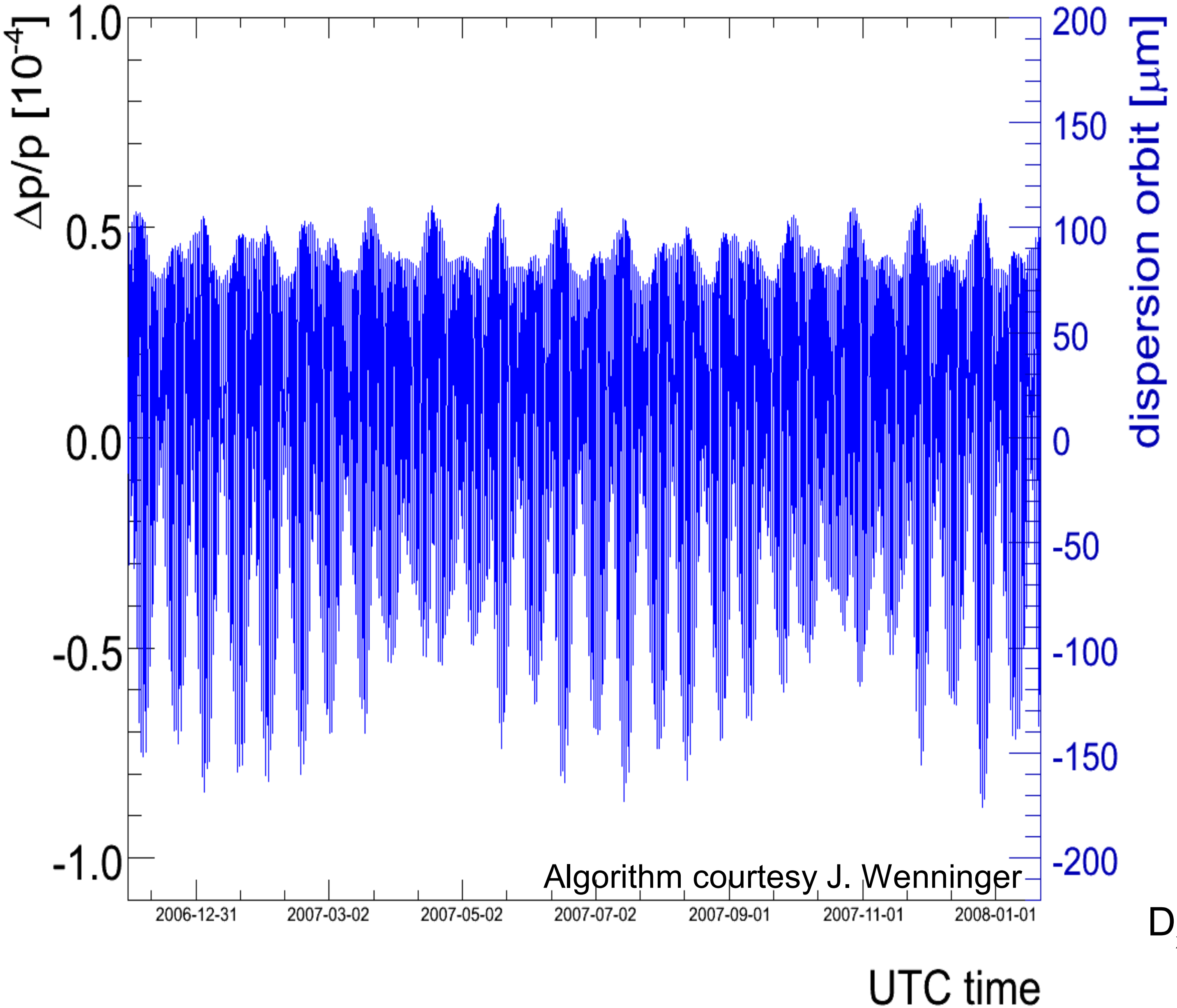
Solar/Lunar Tides prediction for 2007



$D_x := 2$ m

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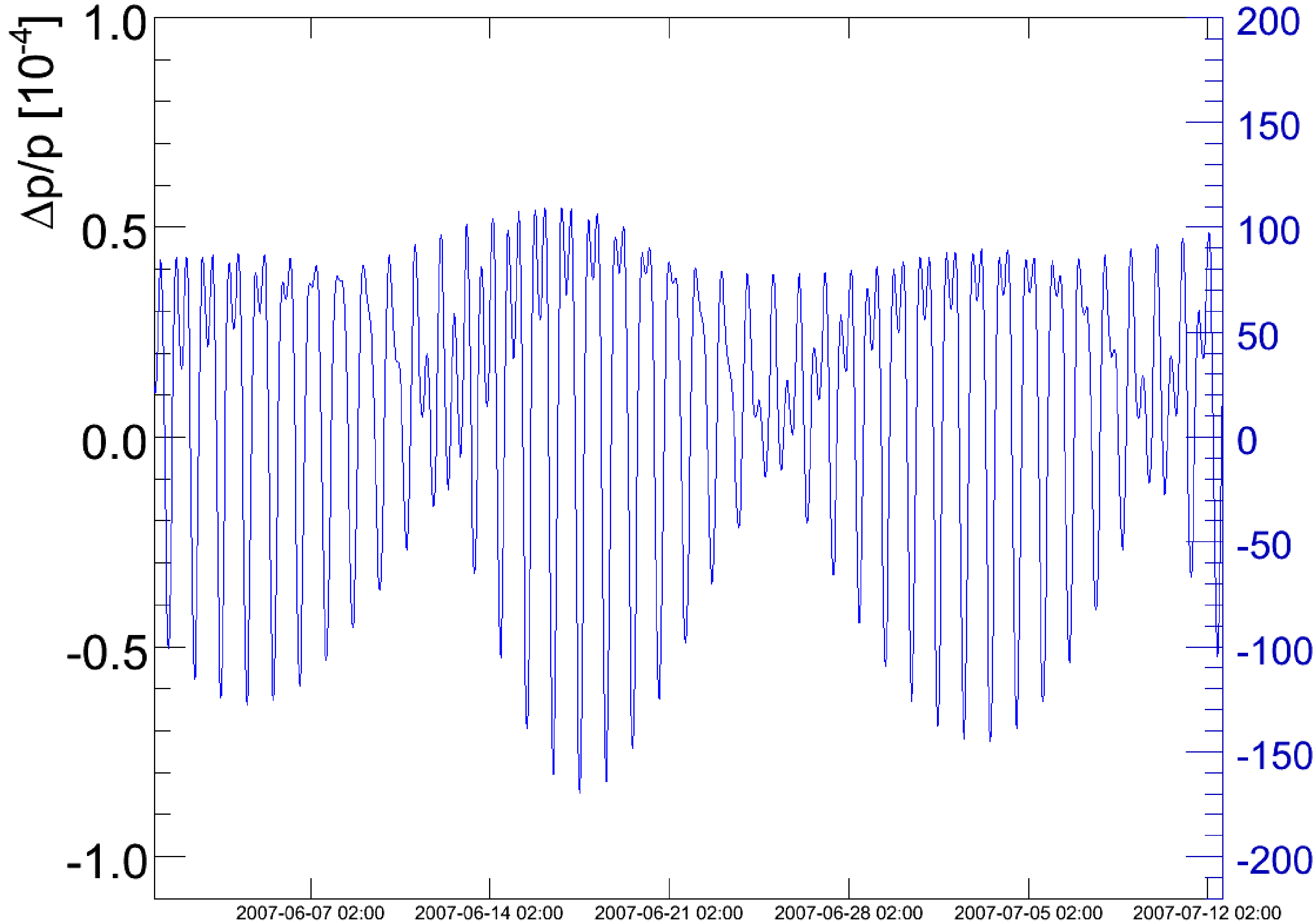
Solar/Lunar Tides prediction for June 2007



$D_x := 2$ m

UTC time

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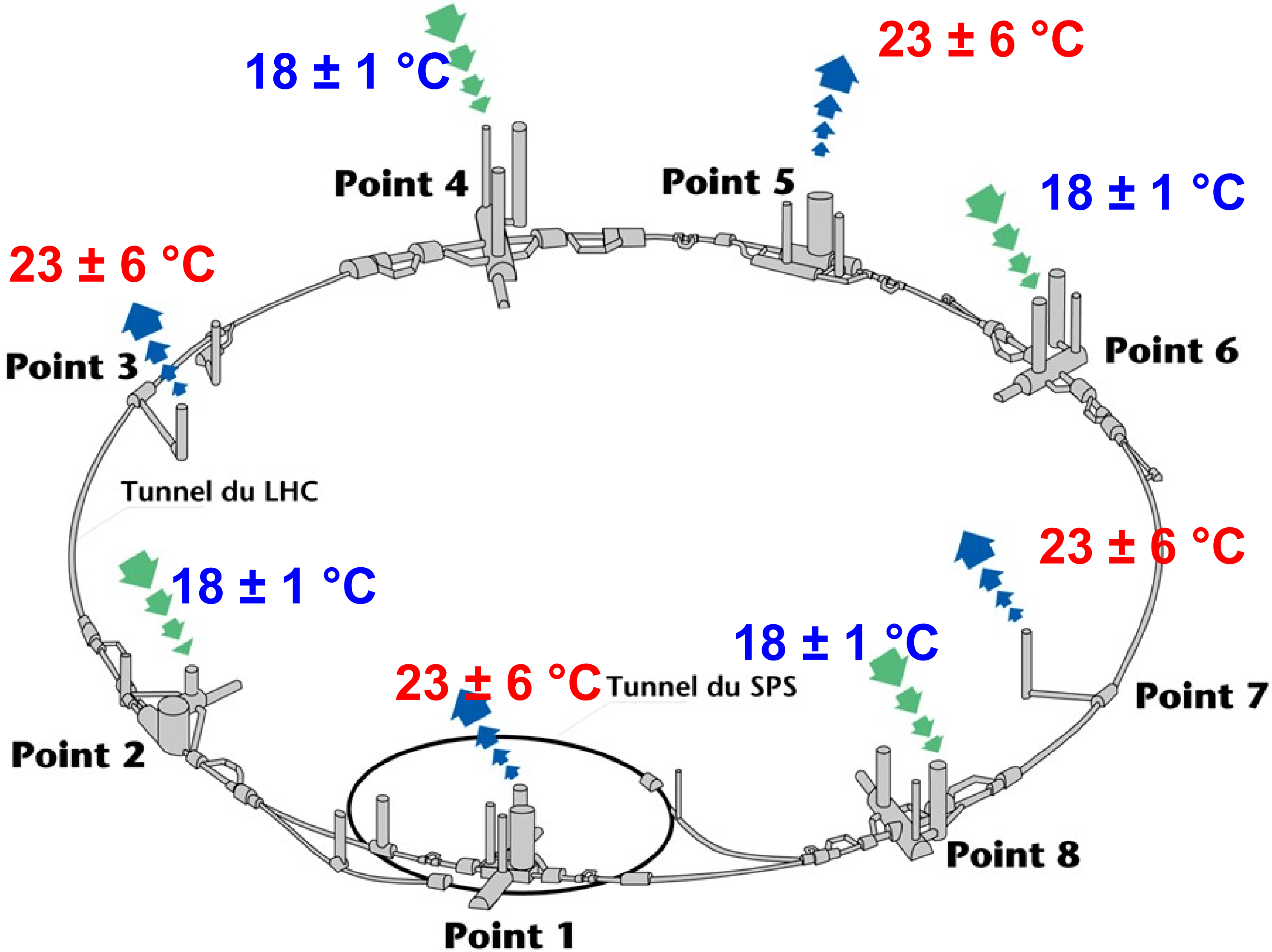
Ventilation du tunnel LEP/LHC



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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

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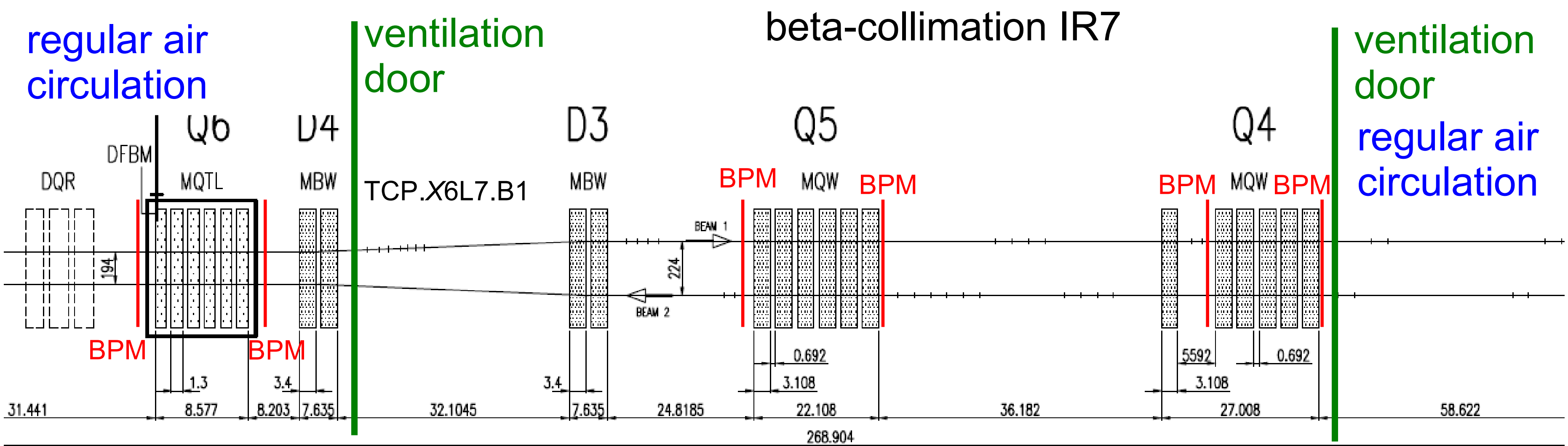
Thermal Expansion of Girders

- 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 ΔT = ± 2°C → Δx ≈ ± 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

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Perturbations due to Multipole Field Errors of main dipoles and quadrupoles

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Expected Dynamic Perturbations

- Current decay in main bends[1,2] (b_1 & b_3) and lattice quadrupoles (b_2):

	Main Dipoles				MQ
	Δb_1	Δa_1	Δa_2	Δb_3	Δb_2
Decay/Snap-back	0.78 ± 0.72	-0.75 ± 2.61	-0.01 ± 0.22	1.64 ± 0.42	1.68 ± 0.56
Ramp	1.5 ± ??	??	-0.06 ± 0.2	0.03 ± 0.19	
Persistent	-2.5 ± 1.4	-0.7 ± 2.96	-0.07 ± 0.41	-7.4 ± 0.34	

  – ...LHC injection optics (v6.5, MAD-X) — snapback:
    - Orbit (H/V): $\Delta x \approx (0.68 \pm 0.23)$ mm/unit $\cdot \Delta b_1(R) \rightarrow \Delta x(y) \sim 0.44 \pm 0.17\ \sigma$
    - Energy: $\Delta p/p \approx 10^{-4} \cdot \Delta b_1(S) \rightarrow \Delta p/p \sim 0.78 \cdot 10^{-4}$
    - Tune: $\Delta Q_{x(y)} \approx Q'_{nat} \cdot 10^{-4} \cdot \Delta b_1(S) \rightarrow \Delta Q \sim -0.011$
    - Tune(MQ): $\Delta Q_{x(y)} \approx 80 \cdot 10^{-4} \cdot \Delta b_2(S) \rightarrow \Delta Q \sim 0.014$
    - Chromaticity: $\Delta Q'_{x(y)} \approx 44(-39) \cdot \Delta b_3(S) \rightarrow \Delta Q' \sim 62 - 70$
    - Coupling $\Delta c_- \approx 0.46 \cdot \Delta a_2(S) \rightarrow \Delta c_- \sim 0.005$
    - Coupling $\Delta c_- \approx 0.014 \cdot \Delta a_2(R) \rightarrow \Delta c_- \sim 0.003$

  – + feed-downs due to orbit ... depends on operational conditions
    - Coupling[4] $\Delta c_- \approx 0.1$ (worst case)

- Machine intrinsic effects: Squeeze (raw uncorrected orbit drift ~ 30 mm)
- Environmental sources & machine element failures (ground motion, girder, cryogenics, ...)

[1] L. Bottura, “Cold Test Results: Field Aspects”, Proceedings of Chamonix XII, 2003
[2] L. Bottura, “Superconducting Magnets on Day I”, Proceedings of Chamonix XI, 2001
[4] S. Fartoukh, “Commissioning tunes to bootstrap the LHC”, LCC #31, 2002-10-23

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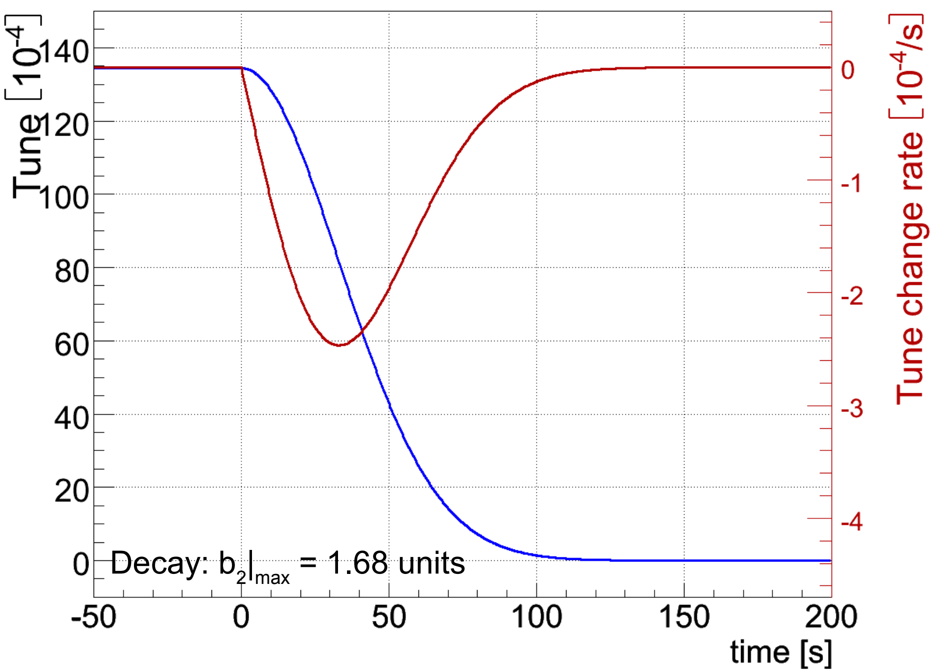
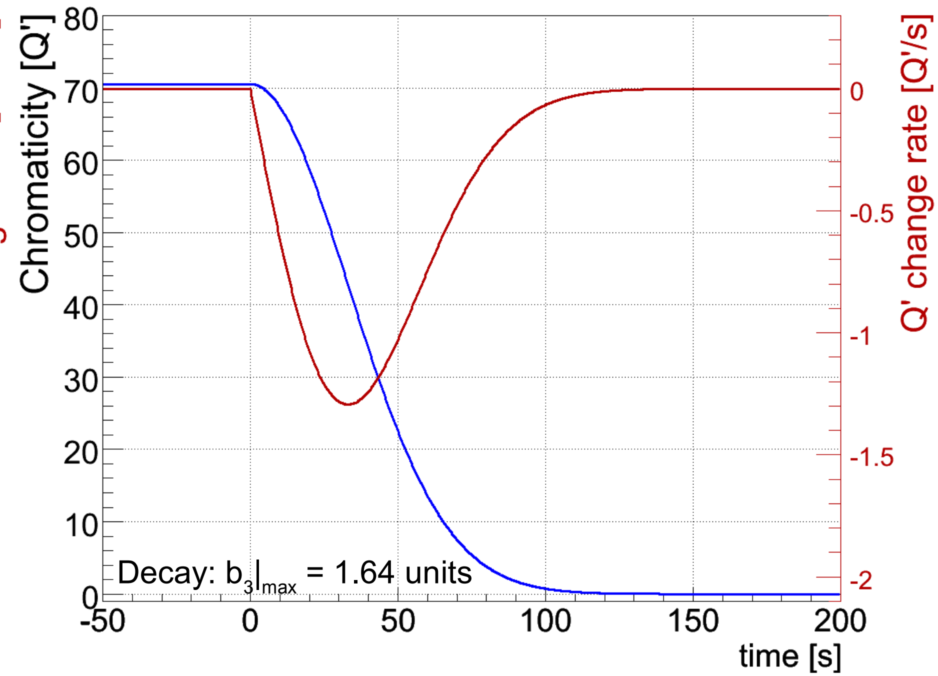
Expected Time-Scales of Perturbations

- Orbit & Energy:
  - Injection (ground-motion, Δb_1): ~ 0.4 σ/10 h → Control @1 Hz sufficient
  - Snap-back: 0.3 σ/100 s → Control @1-10 Hz ??
  - β^*-Squeeze: 0.1 σ/s → Control @10++ Hz OK





- $(\Delta Q'/\Delta t)_{max}$ < 1.3 units/s & $(\Delta Q')_{max}$ < ~ 10 units
  → (measure &) control chromaticity every ≈ 10 seconds (or faster)

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Orbit Transient due to Squeeze

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

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

- Assume Δx=0.5 mm r.m.s. random quadrupole and BPM misalignment (= hopefully, this is the worst case scenario for LHC!)
  - Survey group targets:
    - 0.2 mm r.m.s. globally
    - 0.1 mm r.m.s. as an average over 10 neighbouring magnets.
  - Feed-down are linear: Results can easily be scaled down to your favourable alignment assumption
- Without k-modulation: BPM offsets w.r.t. quadrupole are unknown
- Transient is an issue w.r.t. beam stability and available current rate limit (0.5 A/s)

→ Likely/hopefully 'preaching to the choir': We should spend some time and tune the orbit inside IR1 and IR2 before squeezing the first time.

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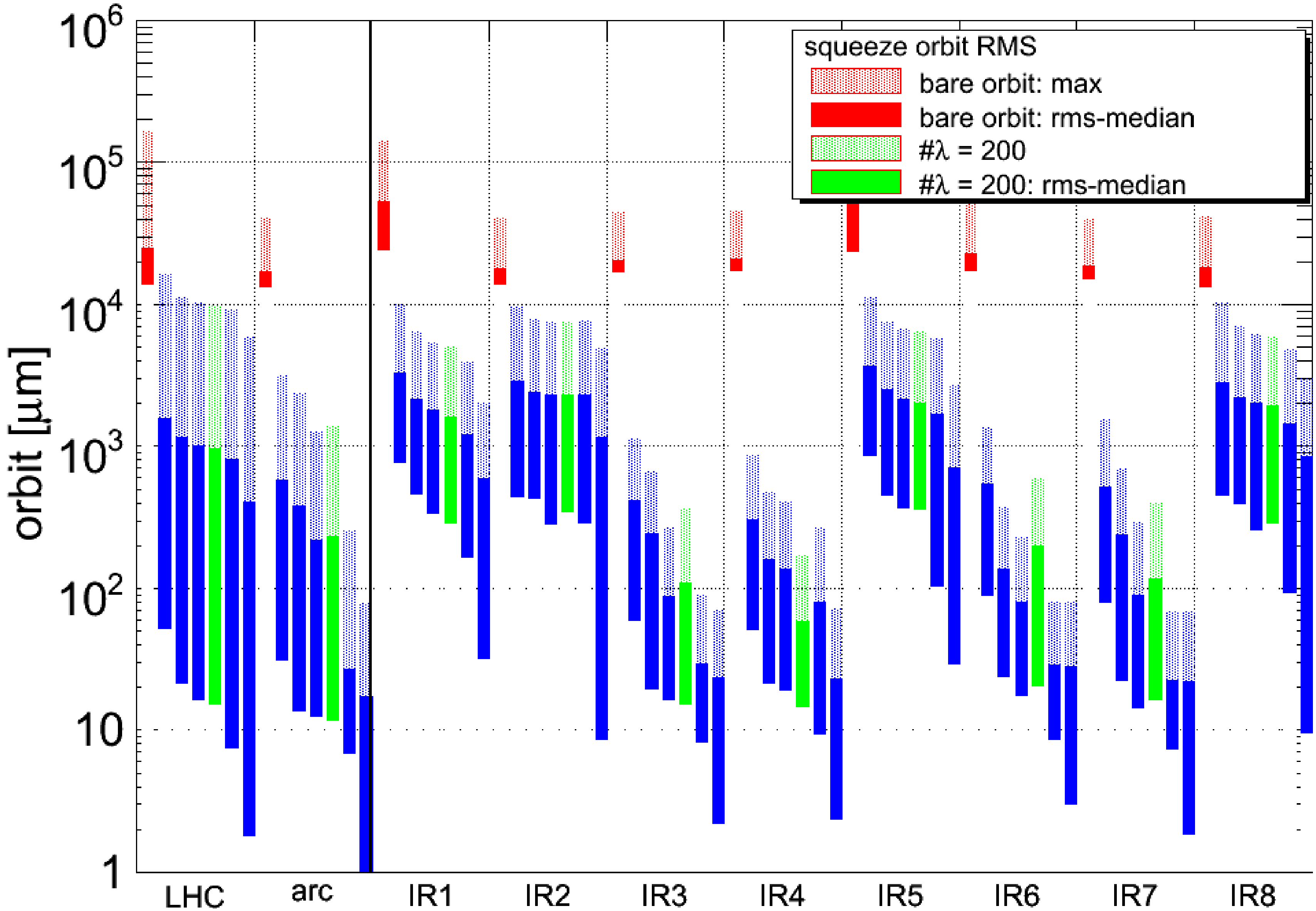
Transient due to low beta Squeeze: Overview LHC



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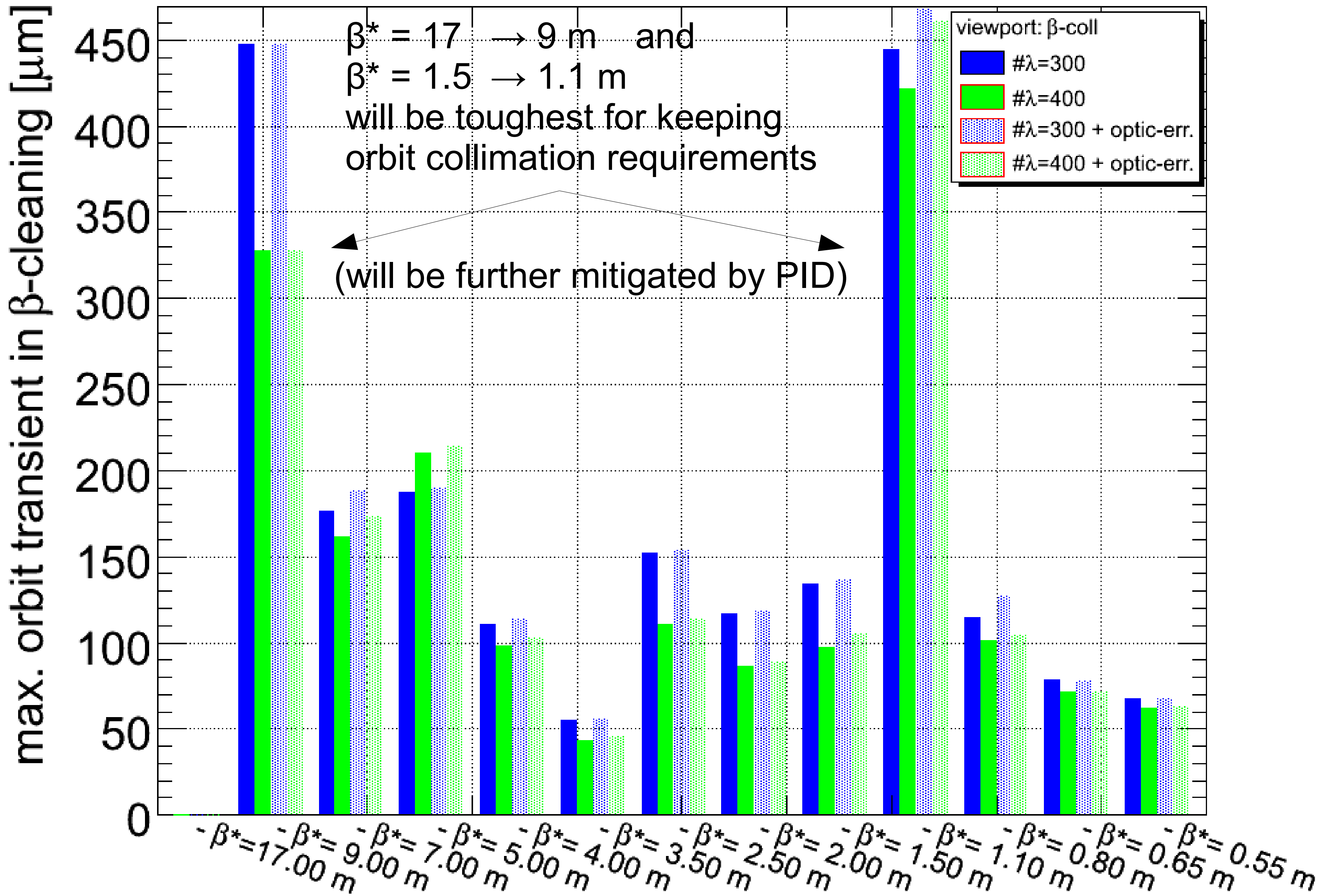
Transient in Collimation insertion vs. squeeze step



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Dynamic Perturbations vs. Requirements Summary

Exp. Perturbations:		Orbit [σ]	Tune [$0.5 \cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	tau
Inj. Energy mismatch		0.25	0.001	~ 1.3	1.0E-4	sev. days
Moon/Sun Tides [1]		0.14	0.0005	~ 1.2	5.0E-5	~ 10 hours
Random Ground Motion [2]		0.3 – 0.5	-	-	-	~ 10 hours
Decay/Snapback [3]	$b_1 \approx 0.75$	0.42	0.011		7.5E-5	~ 1200/100 s
	b_2 & b_3	0.03	-	~ 70 – 140	-	
	MQ: b2≈1.7		0.014			
Ramp induced [3]	$b_1 \approx 1.50$	< 0.8	-0.021	~ 8	1.5E-4	Start of ramp
MCB Hysteresis [4]		0.01	-	-	Xx	
MCB/PC stability [5]	±7mA/60A GeV	0.01	-	-		
β* Squeeze	0.5 mm misalign.	~ 30 mm	??	??	-	~ 1200 s

Requirements: [6]

Pilot	$N_p \approx 5e9$	± 1-2 mm	± 0.1	± 5	-
Stage I (43x43)	$N_p > 5e10$	± 1.8 σ / 1 σ	± 0.015	± 1-5 ??	± 1e-4
Nominal (43^2...2808^2)	$N_p \approx 1.15e11$	± 0.5 mm/0.2 σ	± 0.003(/1)	± 1	± 5e-5

1: J. Wenninger: "Observation of Radial Ring Deformation using Closed Orbits at LEP"
2: RST, "Analysis of Ground Motion at SPS and LEP, implications for the LHC", CERN-AB-2005-087
3: M. Haverkamp, "Decay and Snapback in Superconducting Accelerator Magnets", CERN-THESIS-2003-030
L. Bottura, "Cold Test Results: Field Aspects", Proceedings of Chamonix XII
L. Bottura, "Superconducting Magnets on Day 1", Proceedings of Chamonix XI
FQWG-Homepage: http://fqwg.web.cern.ch/fqwg/

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Perturbations due to failing orbit corrector magnets

(other failures are issue to MP and in most cases result in an immediate beam dump)

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Main MCB Circuit Parameter

Total 1060 orbit corrector dipole (COD) magnets in the LHC.

- Focus on 752 MCBH(V) magnets since they have the same design, parameter and powering: (other: insertion CODs (triplets..), warm, different powering ...)
  - Part of arc SSS: half-cells 11R'*x*' ≤ location_{MCB} ≤ half-cell 11L'*x+1*'
  - Individually powered by a ±8V, ±60A converter, rate limit: 0.5 A/s
  - inductance L: 5.92 H @ 1kHz resp. 5.48 H @ 120 Hz

    (measured: LHC-MSCB-FR-0001, courtesy Mikko Karpinnen)
  - resistance R: 64.5 ... 91.3 mΩ

    (including intrinsic magnet, cable and current lead resistance)

- Maximum kick δ_{max} (↔55 A) on beam: 1260 μrad @ 450 GeV

  81 μrad @ 7 TeV

- Maximum kick amplitude : 144 mm @ 450 GeV and 9 mm @ 7 TeV)

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MCB Optics Parameter

- Arc lattice is similar for injection and collision optics. Maximum orbit response in arc (β = 170 m)
  - $\Delta x_{BPM} \approx$ 100-110 μm/μrad $\cdot \delta_{COD}$
  - resulting orbit change: ~ 1.2 mm/0.5 A @ 450 GeV
    ~ 75 μm /0.5 A @ 7 TeV

- expected average/max kick: 8/30 μrad

  (compensation of random 0.4 mm r.m.s. quadrupole misalignment)
  - Corresponding current in COD circuit:
    - ~ 0.4 / 1.3 A @ 450 Gev
    - ~ 5.5 / 20 A @ 7 TeV
    -

- one COD failure corresponds to an average/max orbit change of (β = 170 m)

  ~ 0.9 / 2.9 mm per COD failure

  breaks collimation tolerances by order of magnitude!

  - Online compensation is favourable in order to increase the beam availability but not required for protection!

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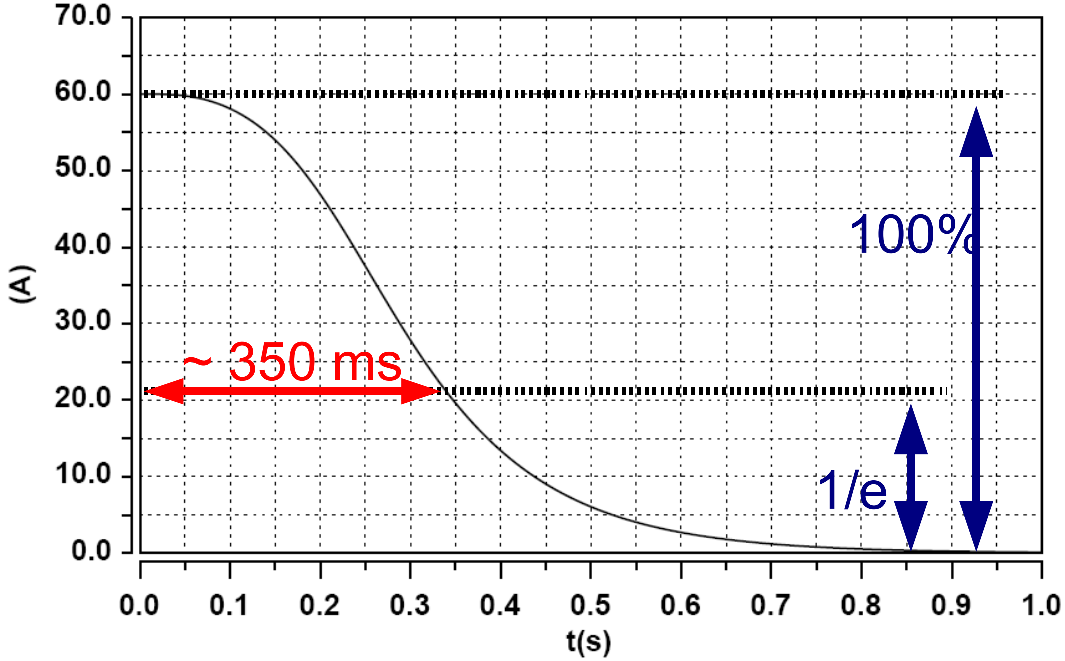
Case I: quenching MCBH/V, current decay



data courtesy to Felix Rodriguez Mateos

very fast current decay:

- decay time: τ ~ 0.35 s ↔ ΔI/Δt ~ 16 (58) A/s @ 7 TeV
- after 1 s the current is practically 0 A
- MCB quenches are expected to be rare

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Case II: 60A/8V Power Converter MTBF

- There are 19 documented and in db logged causes for PC failure
- Mean-Time-Between-Failures (MTBF) expected to be ≈ 10^5 hours

$$P_{failure}/h = 10^{-5}\frac{failures}{hour} \Leftrightarrow \overline{P}_{failure}/h = 1-10^{-5}\overline{\frac{failures}{hour}}$$

  – Probability that one of the 752 MCB PC fails during a 10 hour run:

$$P_{failure/10\,h} = 1-\left(\left(\overline{P}_{failure}\right)^{752}\right)^{10} \approx 7\ percent$$

  – Expect one PC/COD failure in 14 cycles ≈ once per week
  (including all CODs: one failure every ~ 10 cycles)
  – Circuit discharges with a decay time: τ ~ 60-80 s
  – This likely leads to an beam dump request due to:
    - increased particle losses e.g. at the collimator.
    - beam position interlock.
- Beware: actual operational experience may show higher/lower MTBF

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Identification and Compensation of

bogus and failing Beam Position Monitors

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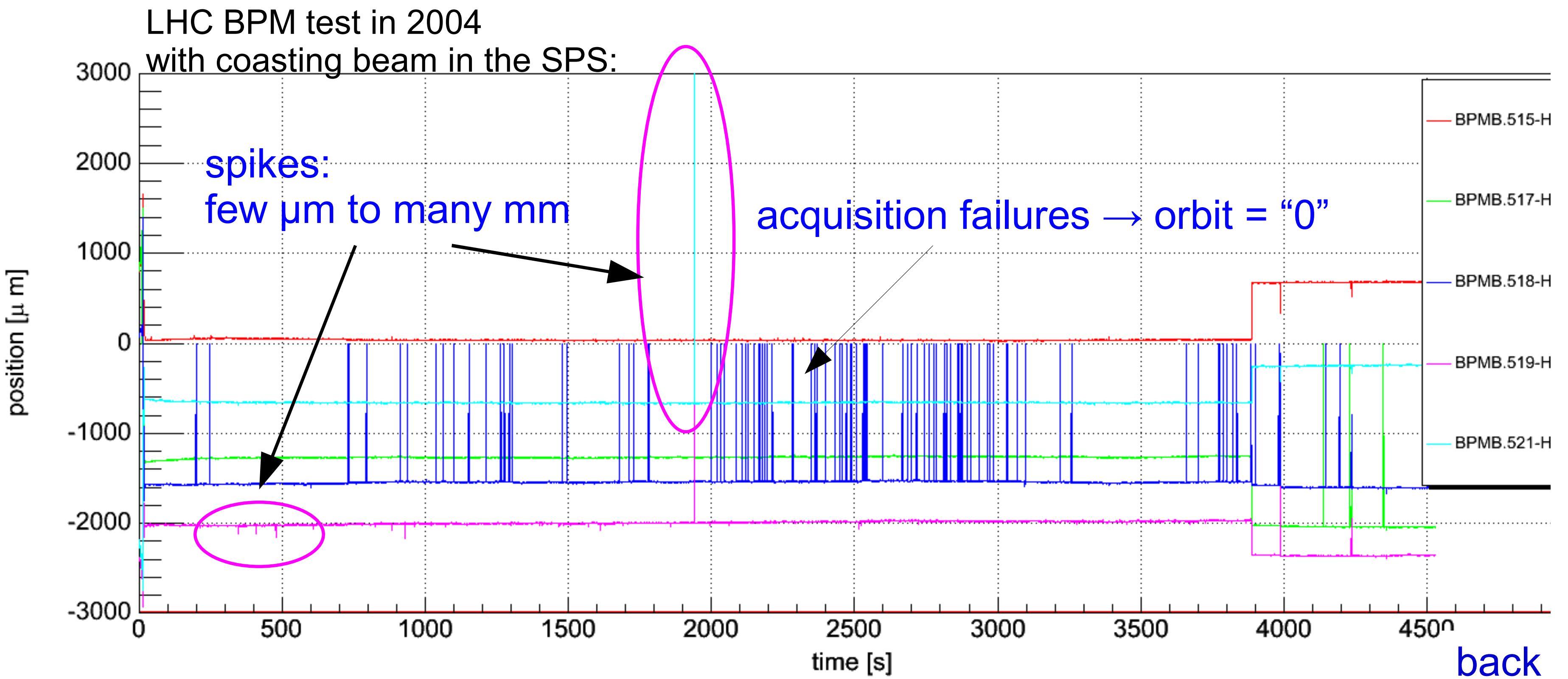
LHC BPM Prototype in the SPS:

- Most common: acquisition failure = no orbit info available and spikes
  - 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
  - within 1% of BPM half aperture ↔ 250 μm (complies with specification)



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Orbit Feedback Robustness against BPM Failures/Errors

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 BPM failures (SPS: mostly spikes)

   ($x_i(n)$=position at i^{th} monitor, n: sampling index; σ_{orbit}= residual orbit r.m.s.)

   - Reject BPM if the following applies:
     - Cuts in Space Domain:
       - (BPMs marked by the front-end itself)
       - $x_i(n)$ > machine aperture
       - $x_i(n) – x_{i,ref} > 3\cdot\sigma_{orbit}$
       - Option: interpolate position from neighbouring BPMs (implemented in APS) → sensitive to quadrupoles/dipoles between BPMs,
     - Cuts in Time Domain (Spike 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

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SVD Robustness: Properties

- Global orbit feedback with local constraints
  - Based on SVD algorithm → see attachment for details
  - Expands orbit using orthogonal “eigen-orbits”

- Important mathematical properties:
    - SVD minimises orbit & deflection strengths
    - Uses rather many CODs with small than few with large kicks
    - Solutions are sorted by their 'effectiveness': large eigenvalues λ_i (solutions) first
    - Local 'bump-like' solutions corresponds to small eigenvalues
  - “number of used eigenvalues” $\#\lambda_{svd}$ controls OFB robustness vs. precision
    - more #eigenvalues → more precise correction (collimation requirement)
    - less #eigenvalues → more robustness against BPM & optic failures
  - discard deliberately solutions with small eigenvalues (=local bumps) → SVD cannot generate (= correct) those bumps
  - However: Will use all (local SVD) eigenvalues regions like collimation. (due to precision requirement)

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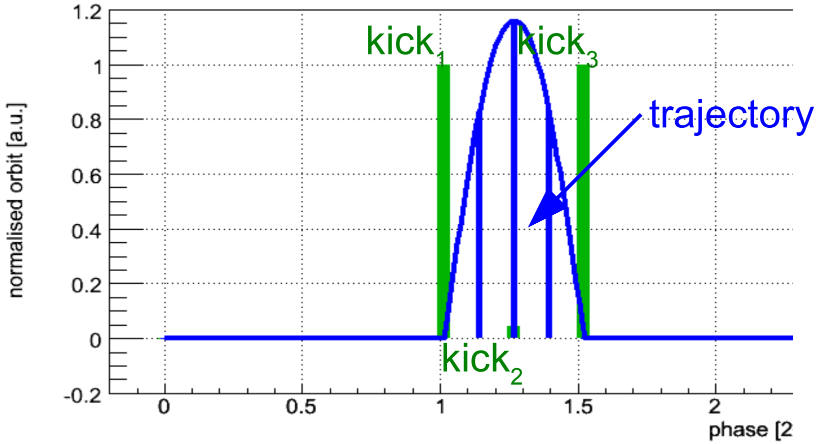
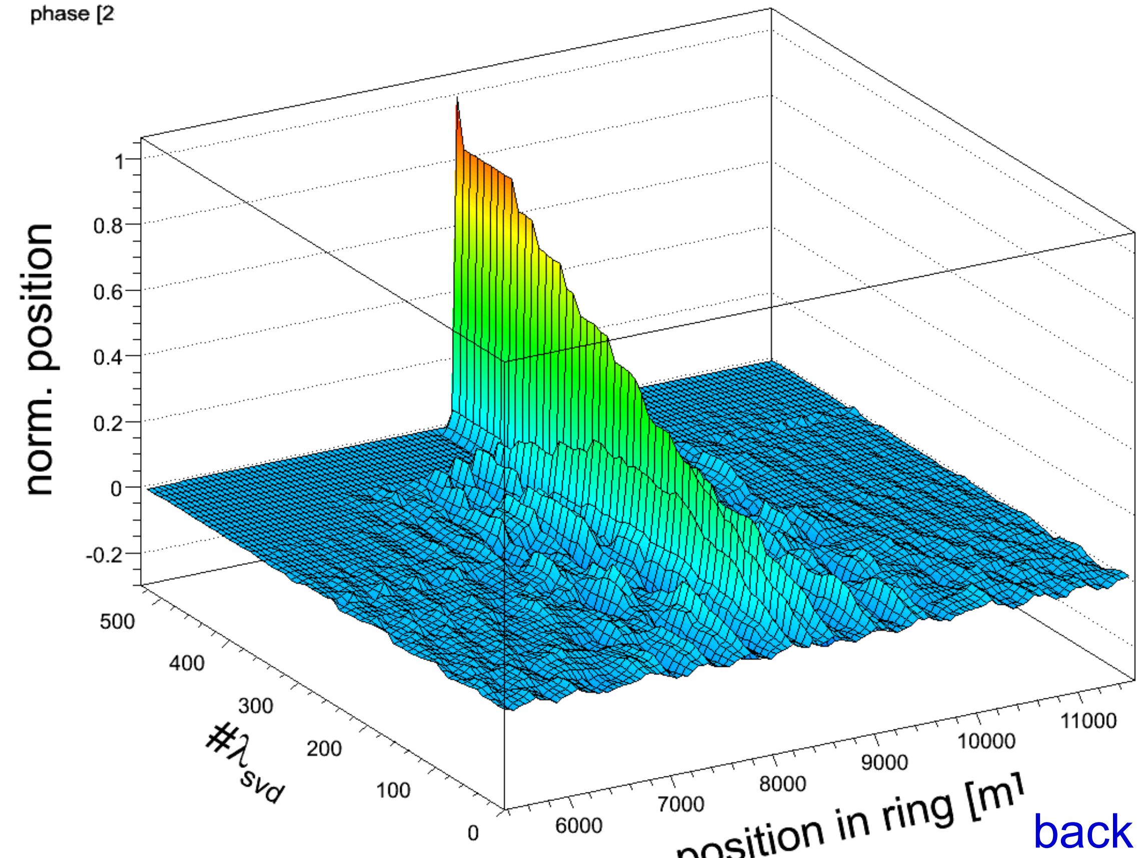
Robustness Examples



- E.g. simplest Three-Corrector-Bump is sampled with at least three BPMs
  - erroneous or noisy BPM has less effect on total correction

Example: Single BPM spike

- perfect orbit (=0)
- BPM.33L4.B2 with spurious offset
- SVD corrects the spurious offset (ridge in surface plot), if a large number of eigenvalues $\#\lambda_{svd}$ is used for the orbit correction
- e.g. $\#\lambda_{svd}$ = 100 → spurious offset propagates to 16 % to the orbit



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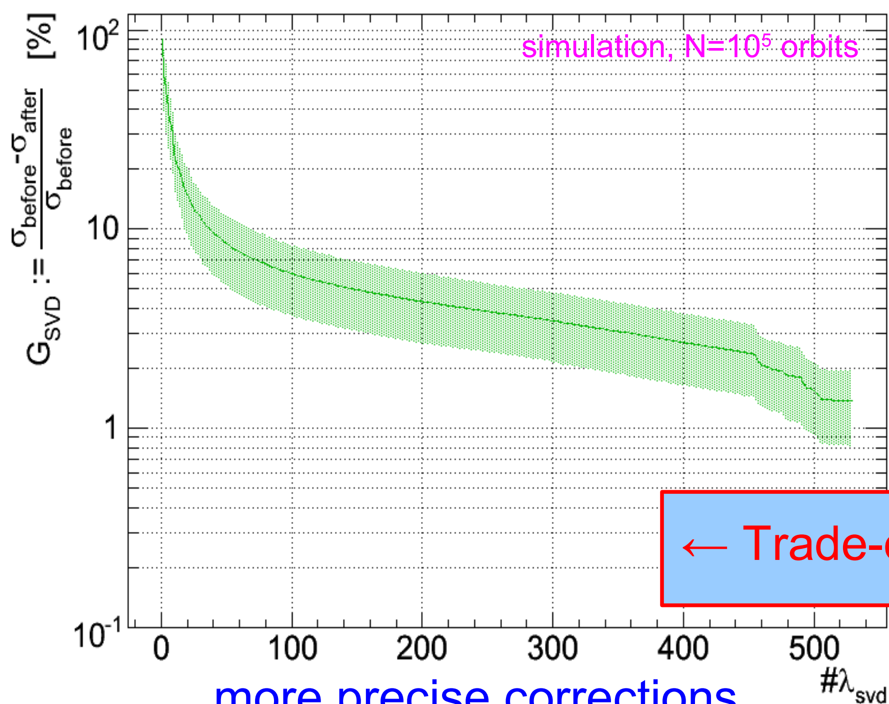
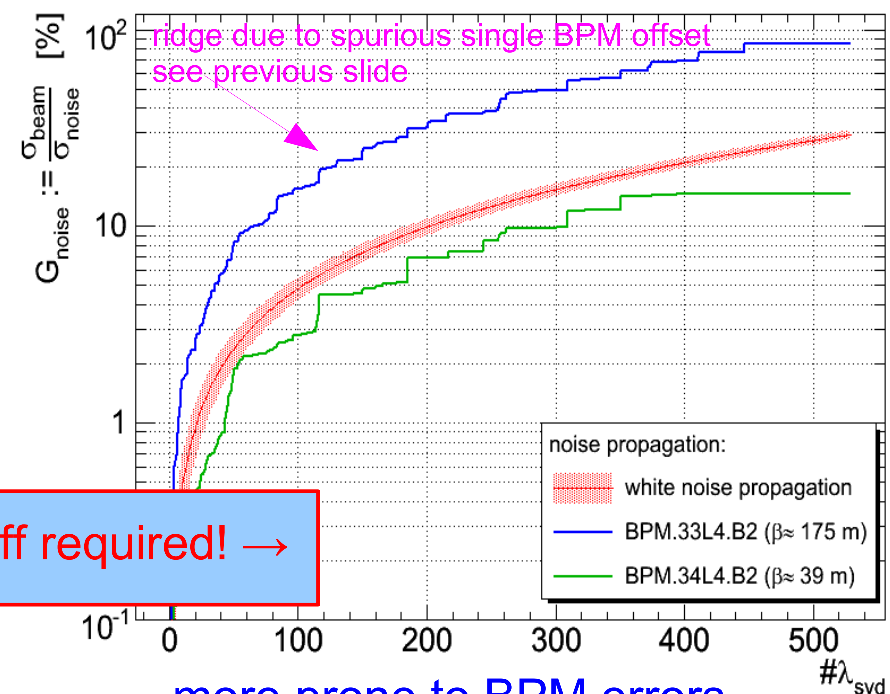
Feedback Sensitivity to BPM Failure

- Propagation of single (arc) BPM failure with $x_i(n) < 3 \cdot \sigma_{orbit} < \sigma_{beam}$
  - #λ≈250: < 40% (β ≈ 175m) resp. < 10% (β ≈ 39 m)
- Propagation of random (white) noise on all BPMs
  - 30% (worst case #λ=529) resp. 10% (OFB operation with #λ≈250)
- BPM induced noise on orbit (single bunch):
  - Single BPM failure: < 0.01 - 0.4 σ
  - White BPM noise: < 0.001 σ (inj) resp. 0.02 σ (coll)





← Trade-off required! →

more precise corrections

more prone to BPM errors

Compensation of failing Closed Orbit Dipole Magnets

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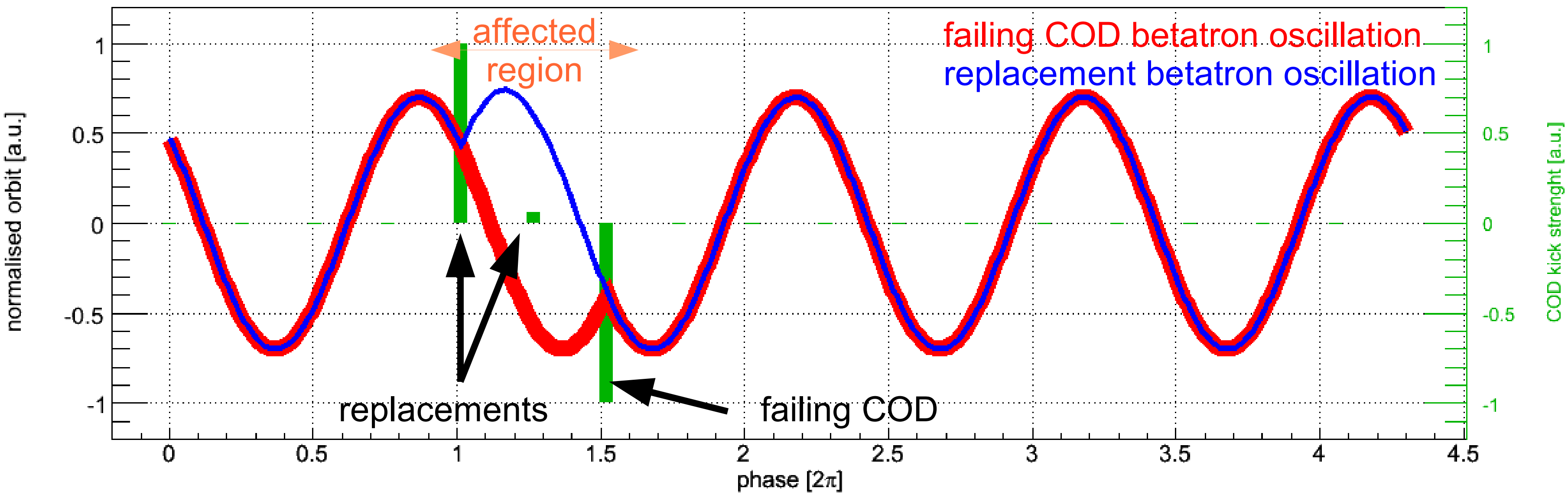
COD/PC failure: Backup Scenario I/IV

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 (total speed determined by time required to reach pattern's largest current)

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COD/PC failure: Backup Scenario II/IV

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

- Controller procedure:
  - If detected: Send the pre-calculated replacement pattern instead of the failing COD's $\Delta I(t)$ through the feed-forward path :
    - Procedure for the first few (milli-) seconds:
      - Mark COD
      - Temporarily disable BPMs (ZOH) in the adjoining region (in order to be insensitive to the spacial transient)
      - Continue normal correction
      - Replace bogus $\Delta I(t)$ with R-pattern only intermediate region affected
    - In parallel:
      - compute new inverse SVD matrix without bogus COD (~ 15s/COD)
      - Swap active matrix once finished recalculation
      - recalculate new anticipatory R-patterns (~ 2 hours/all CODs)
- The feed-forward action is transparent for large spacial distances
- The effectiveness depends on the notify- and feedback-delay.

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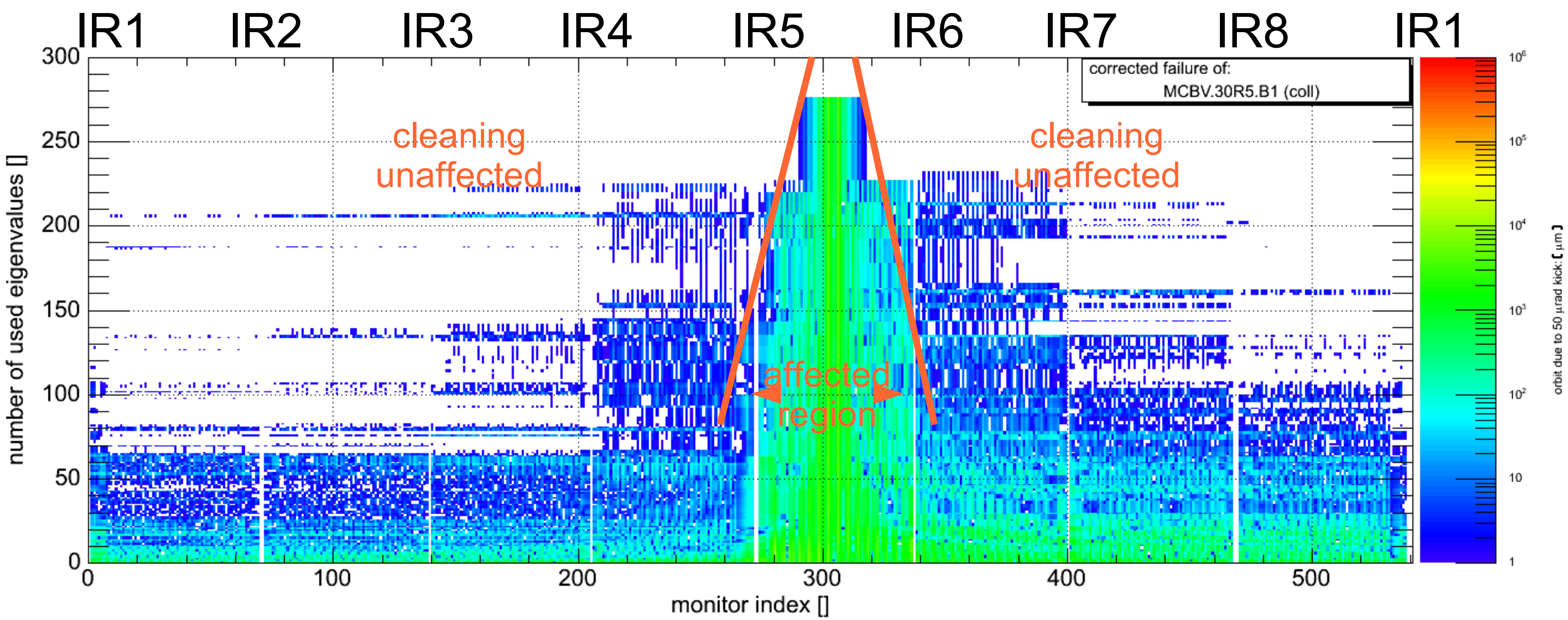
COD/PC failure: Backup Scenario III/IV

- Example: COD MCBV.30R5 failure and compensation (LHC collision optics) plotted: number of used eigenvalues vs. monitor index and residual orbit shift (colour coded: Blue=OK, Red=large transient):



- since number of used eigenvalues and loop stability does not affect the feed-forward one may choose a large number of eigenvalues
  - Apart from transient, cleaning insertion is not affected by failing COD.

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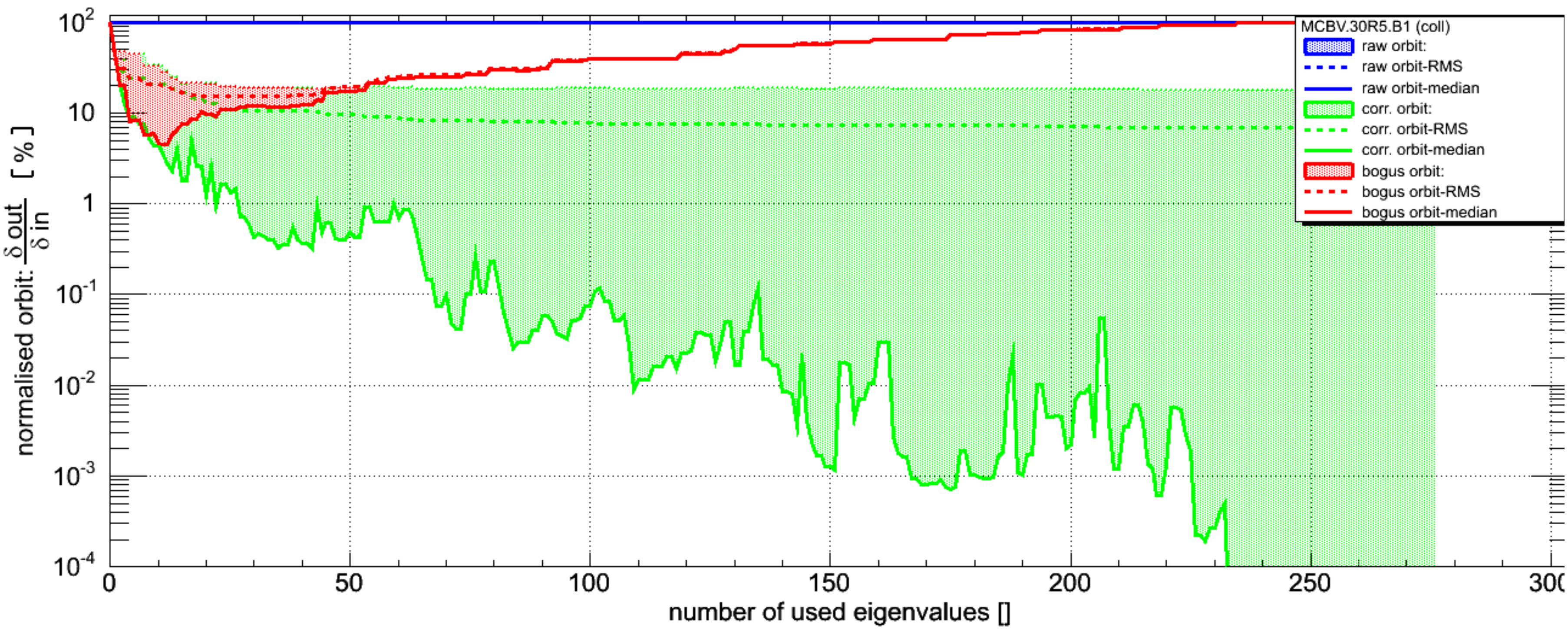
Backup Scenario II – low number of eigenvalues help

- For small $\#\lambda_{SVD}$ the correction is less sensitive to failing or not-reacting CODs
- Plotted: damping with (bold red) and without (bold green) detected COD failure vs. number of used eigenvalues. (damping: ratio between un- to corrected orbit)



- moderate damping without detected failure slows the orbit transient due to the missing deflection.

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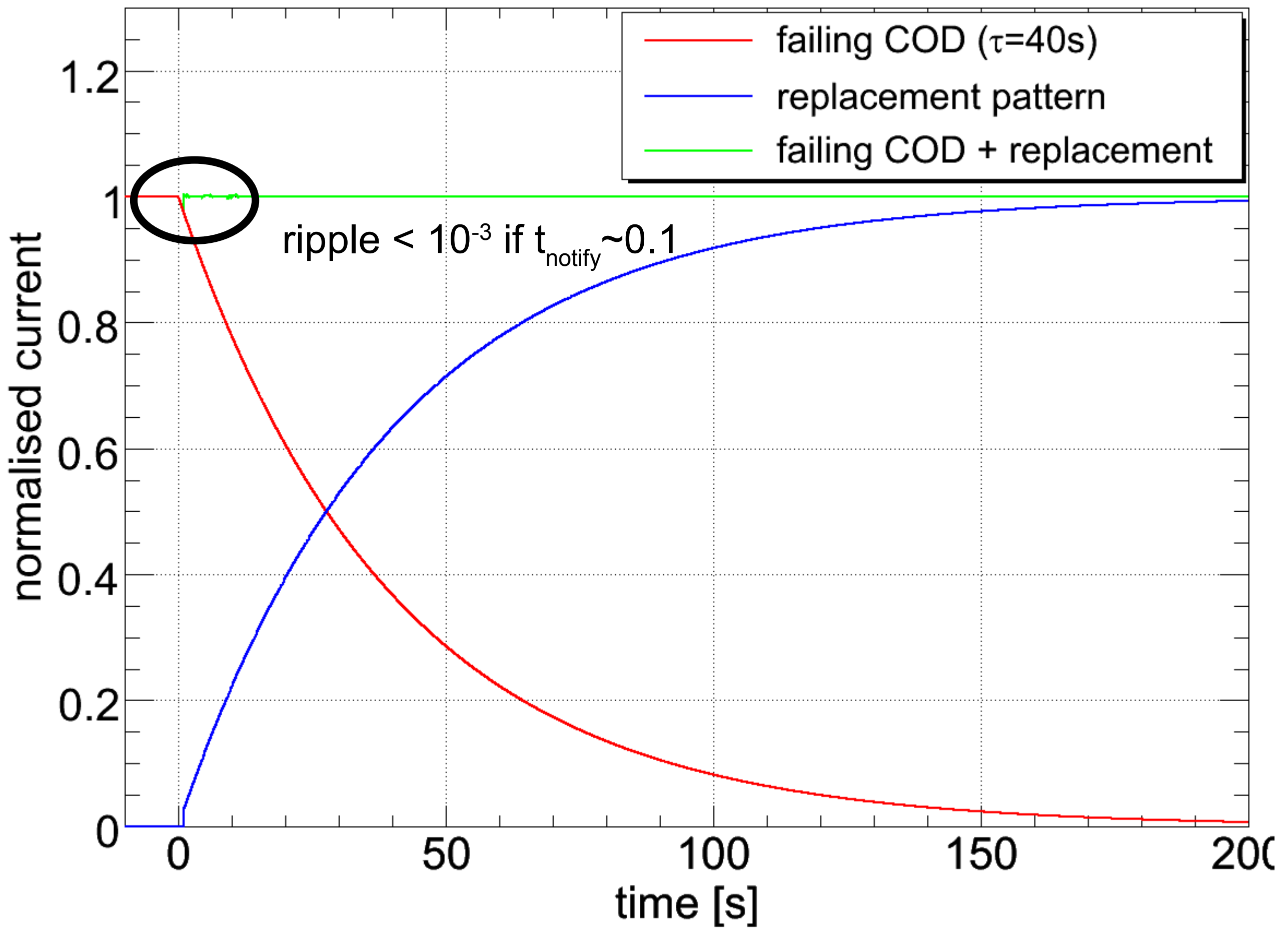
- It is important that the delay t_{notify} till the OFC is notified is short and constant.



- The length of t_{notify} determines the ripple : ~ '1-exp(-t_{notify}/τ)'
- 1 Hz would be OK but will reuse already present 50Hz status feedback channel provided by the power converter gateways (S. Page, AB/PO)

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Automated Orbit Correction using Singular Value Decomposition

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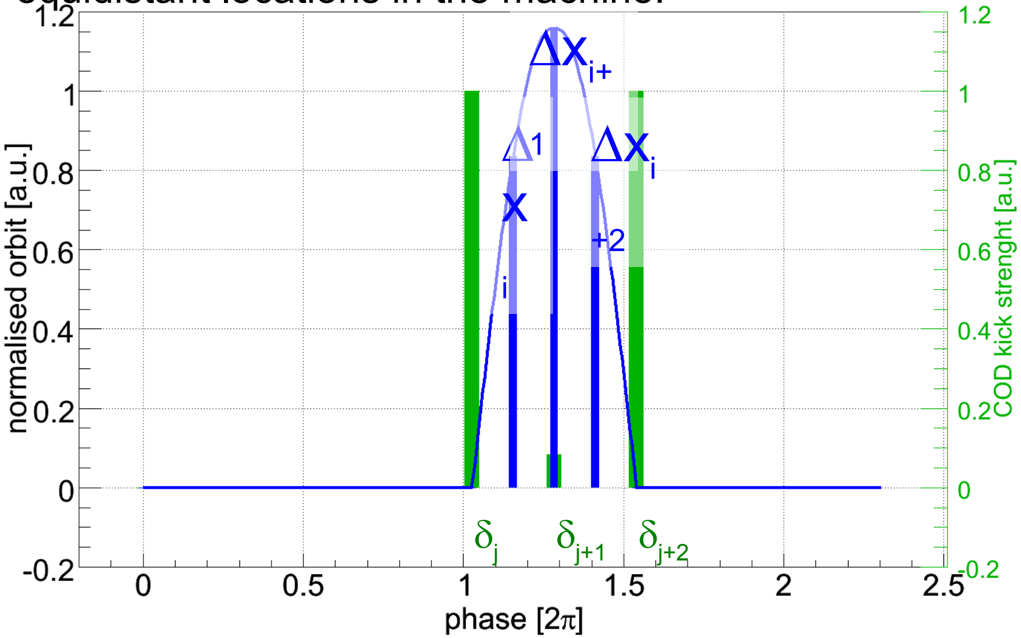
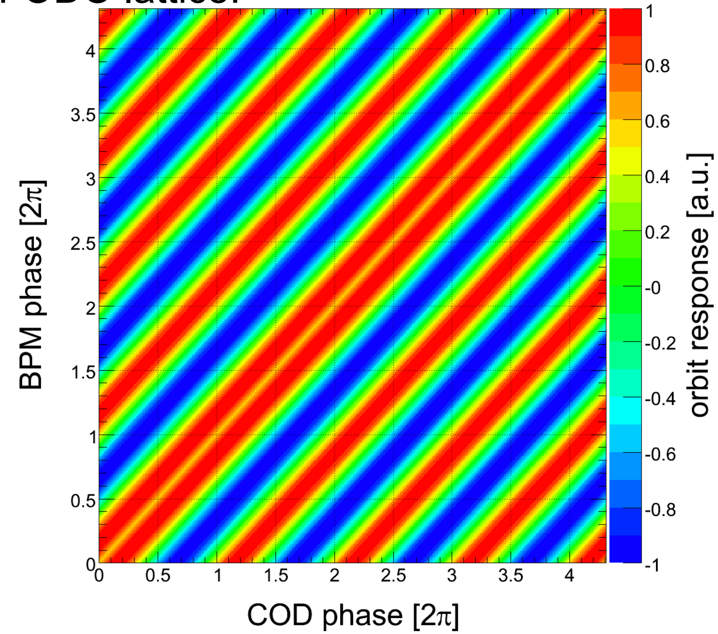
Space Domain: Orbit Response Matrix

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

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

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

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

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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 orbit deviations <u>and</u> 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
  - high 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/plan), but once decomposed and inverted: simple matrix multiplication ($O(n^2)$) complexity, LHC: ~15ms!)

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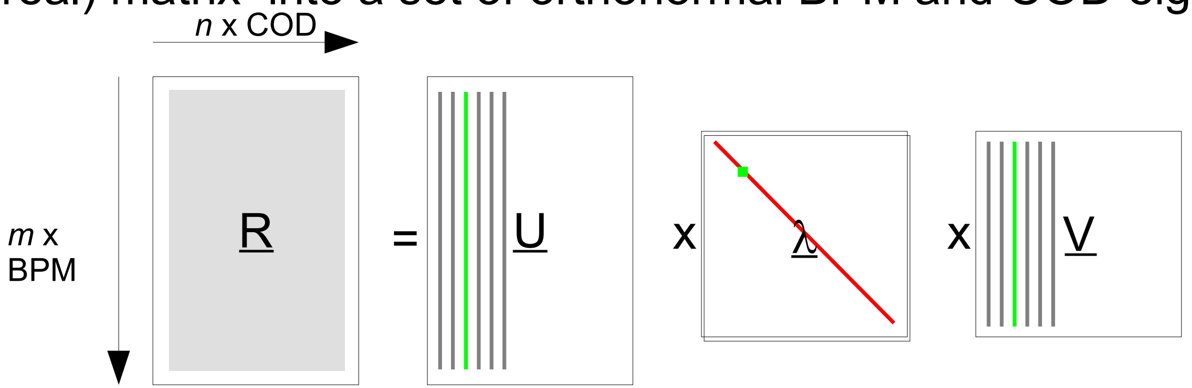
Singular Value Decomposition (SVD) on a slide

Theorem from linear algebra*: “It is always possible to decompose a orbit response (real) matrix into a set of orthonormal BPM and COD eigenvectors”



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

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

- 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 $\lambda_i \rightarrow \infty$ $1/\lambda_i = 0$
- 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

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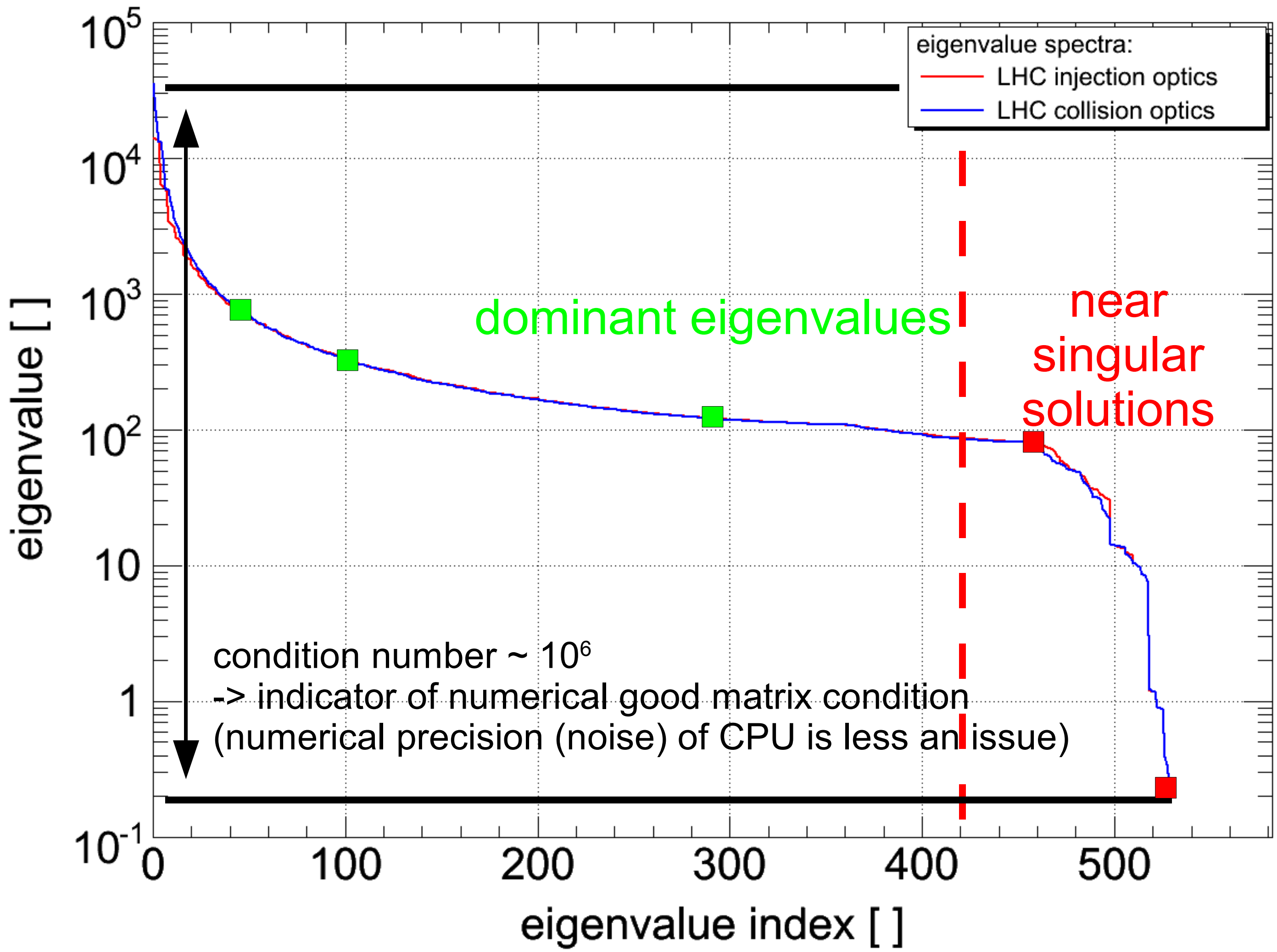
SVD example: LHC eigenvalue spectrum

Eigenvalue spectra for vertical LHC response matrix using all BPM and COD:



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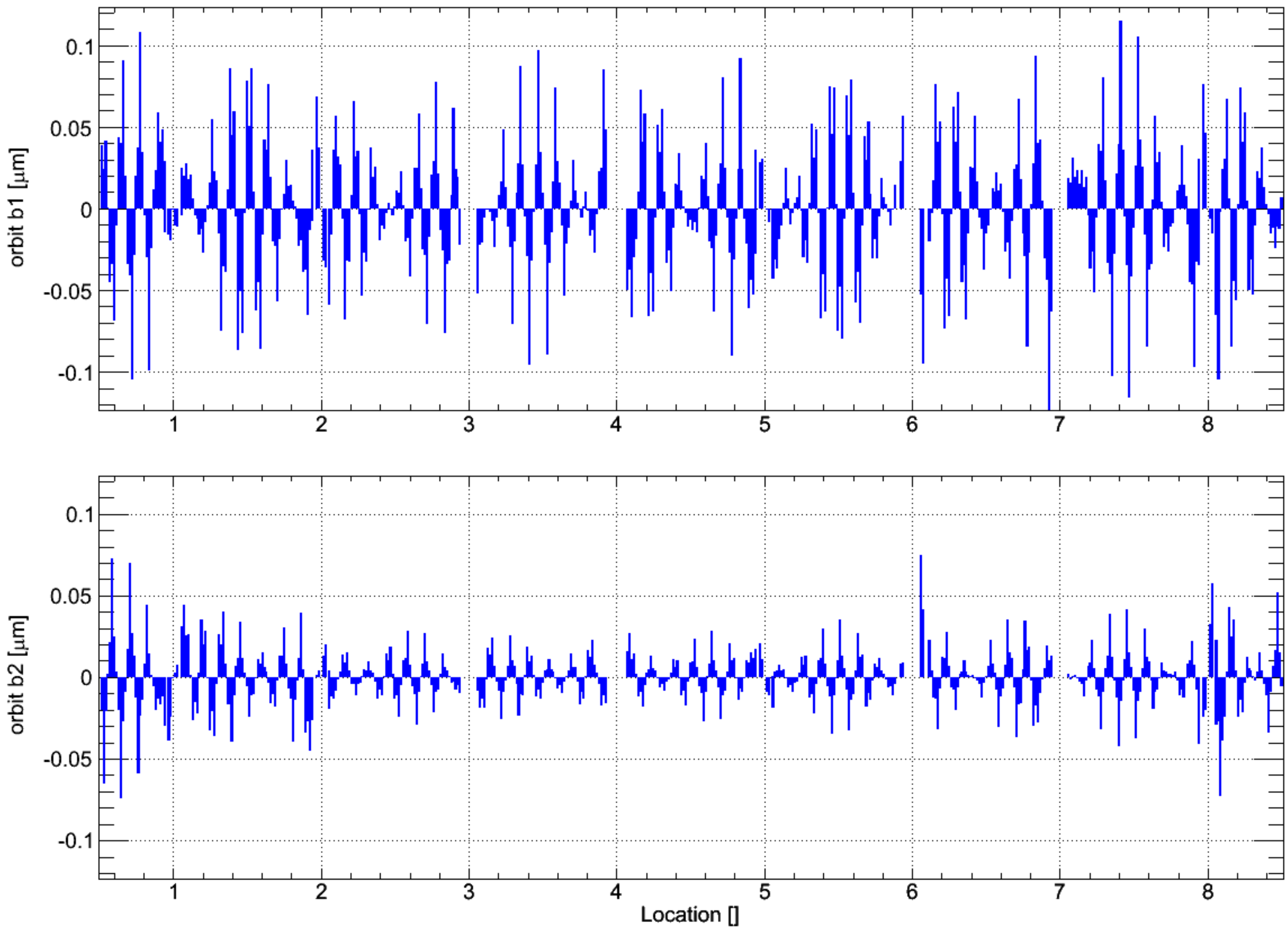
LHC example: BPM eigenvector #50 $\lambda_{50} = 6.69 \cdot 10^2$



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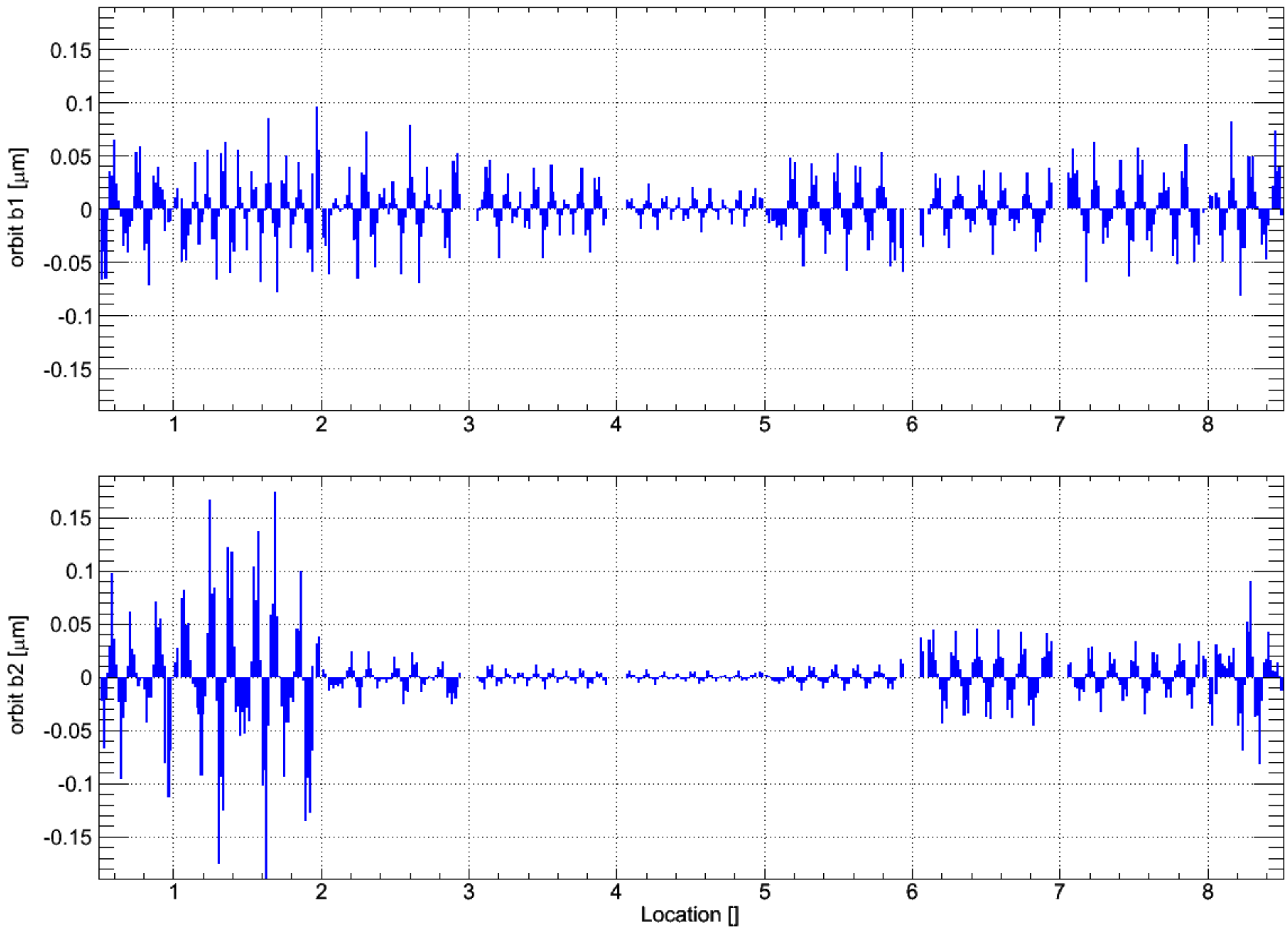
LHC example: BPM eigenvector #100 $\lambda_{100} = 3.38 \cdot 10^2$



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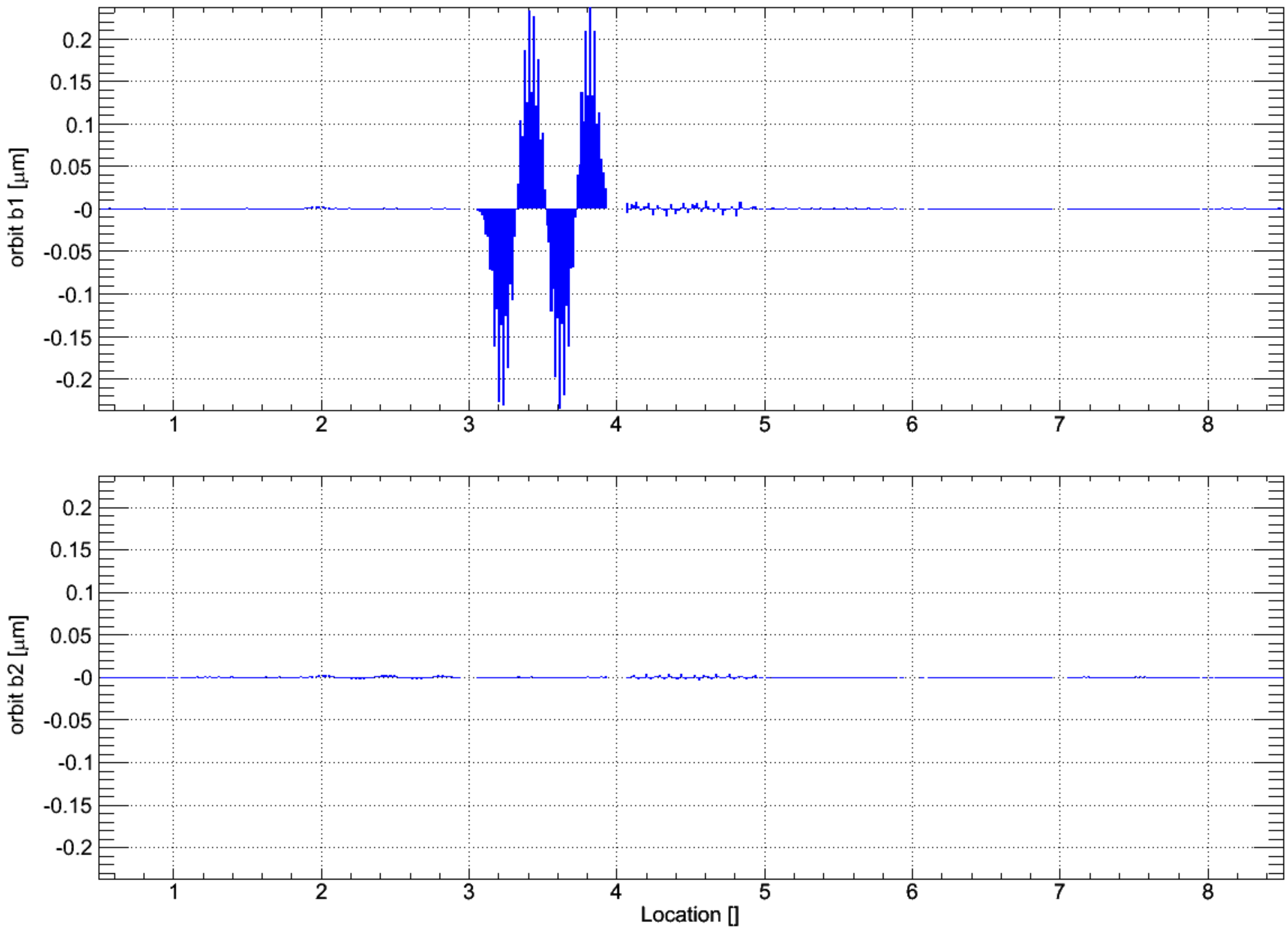
LHC example: BPM eigenvector #291 λ_{291}= 2.13•10²



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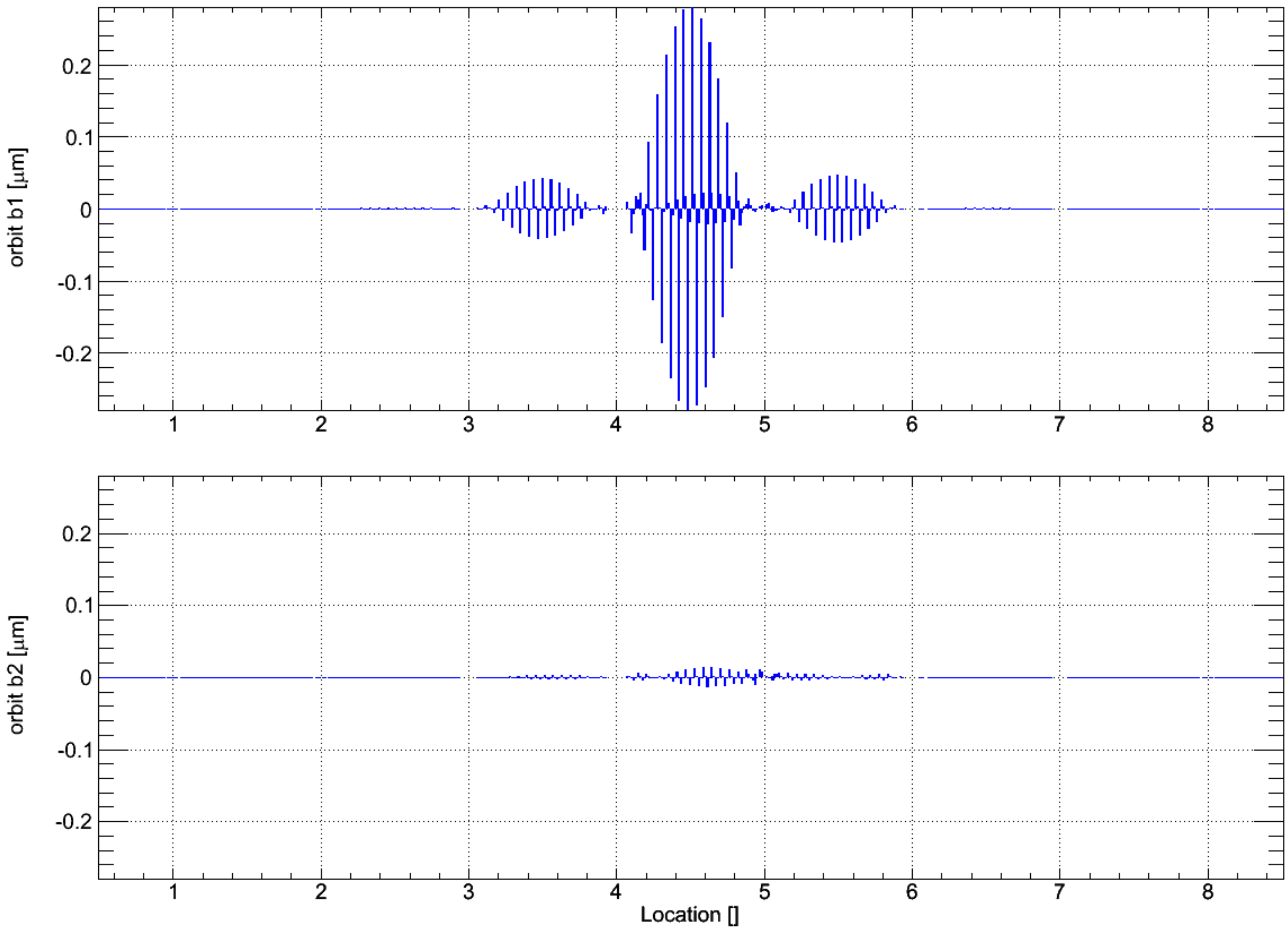
LHC example: BPM eigenvector #449 $\lambda_{449} = 8.17 \cdot 10^1$



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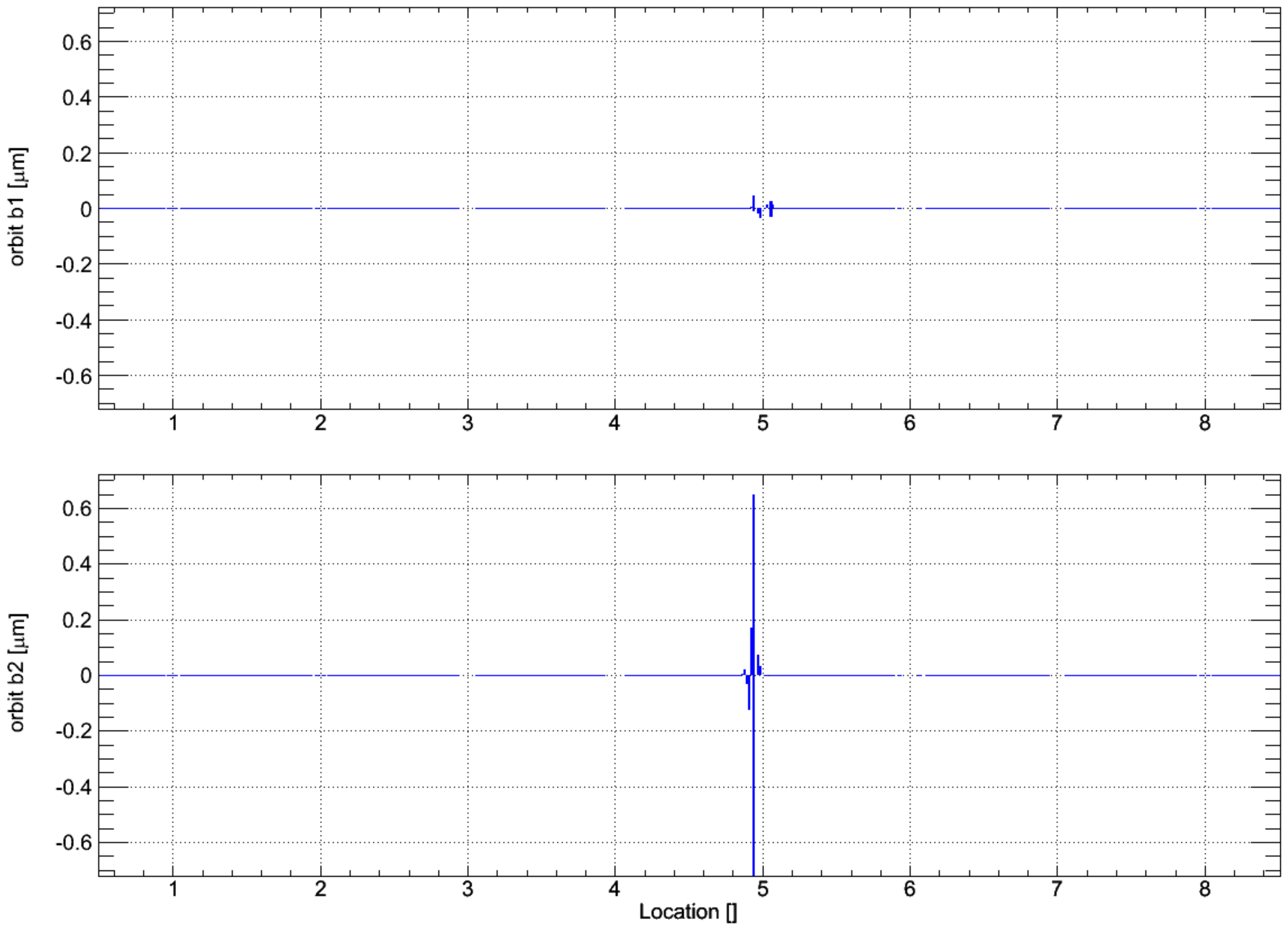
LHC example: BPM eigenvector #521 $\lambda_{521}= 1.18 \cdot 10^0$



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Space Domain: Number of used eigenvalues?

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

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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

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Miscellaneous Slides ahead

Small remark on cross-talk between beams

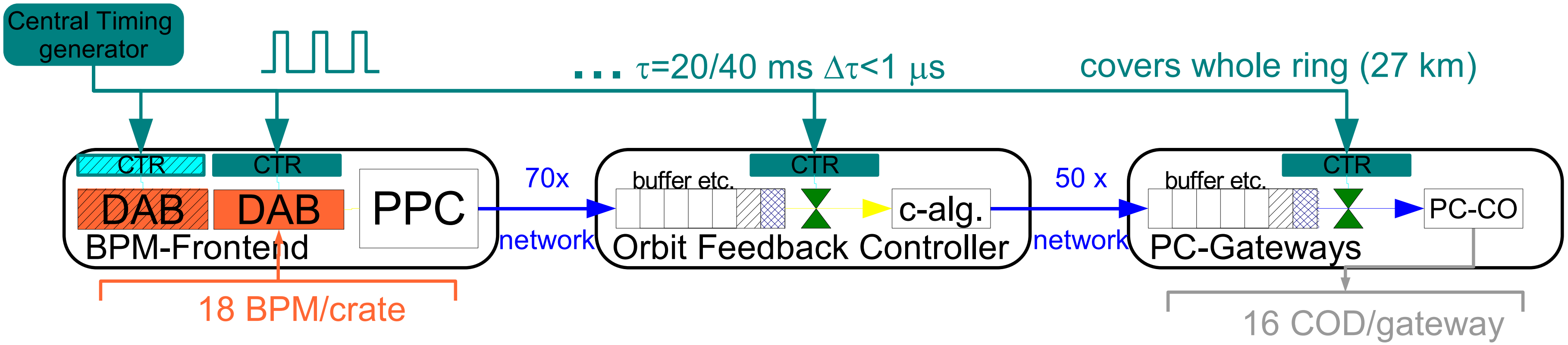
- Energy, Q, Q' and Coupling feedbacks are less affected by cross-talk:
  - Instrumentation and correctors act exclusively on either B1 or B2
- Orbit steering using common elements in beam crossing insertions:
  - Optimisations for 'Beam 1' may have the opposite effect for 'Beam 2'
  - Only use common elements when acting on both circulating beams!
    (exception: one-beam operation)

- Control procedure:
  1. Inject 'Beam 1', correct orbit without insertion CODs
  2. Inject 'Beam 2', correct orbit without insertion CODs
  3. Once having both beams circulating → enable CODs in common regions

Real-Time control requires upper limit on total loop delay

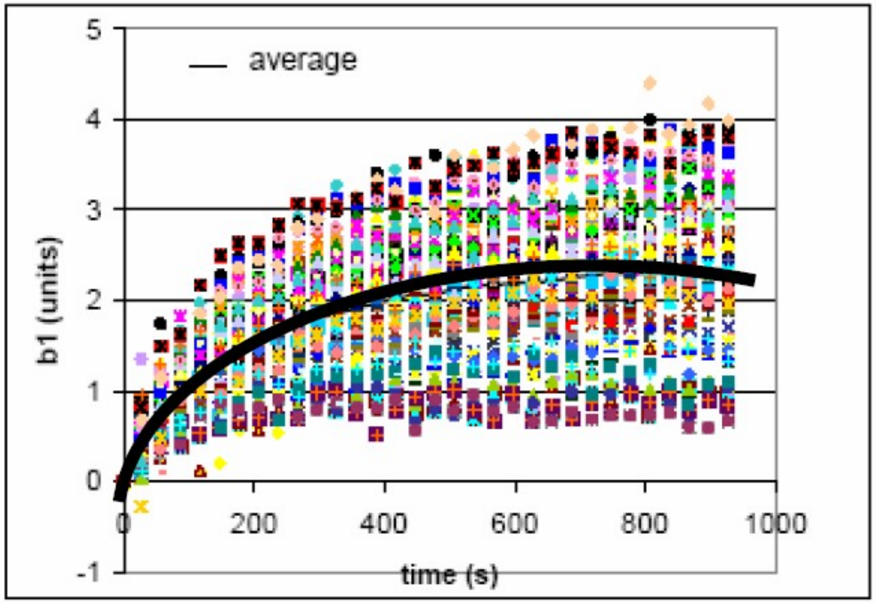
Two main strategies:

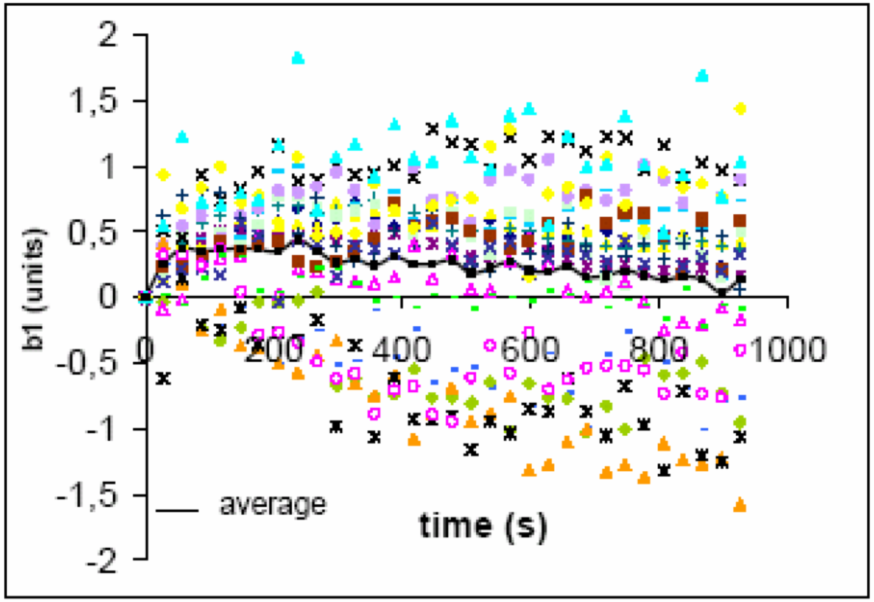
- measurement of actual delay and its dynamic compensation in SP-branch:
  - high numerical complexity, branch transfer function has continuously to be modified
  - only feasible for small systems
- Jitter compensation using a periodic external signal:
  - CERN wide synchronisation of events on sub μs scale that triggers:
    - BPM Acquisition, 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”.
  - feedback loop frequency of 50 Hz feasible for LHC, if required...



FB vs. FF: When is which applicable?

- Border is rather fuzzy.... injection likely won't require RT-feedbacks
- S. Sanfilippo (SM18 Review): “Decay of these magnets not scalable yet.”
  - b_3 & b_1 decay prediction:



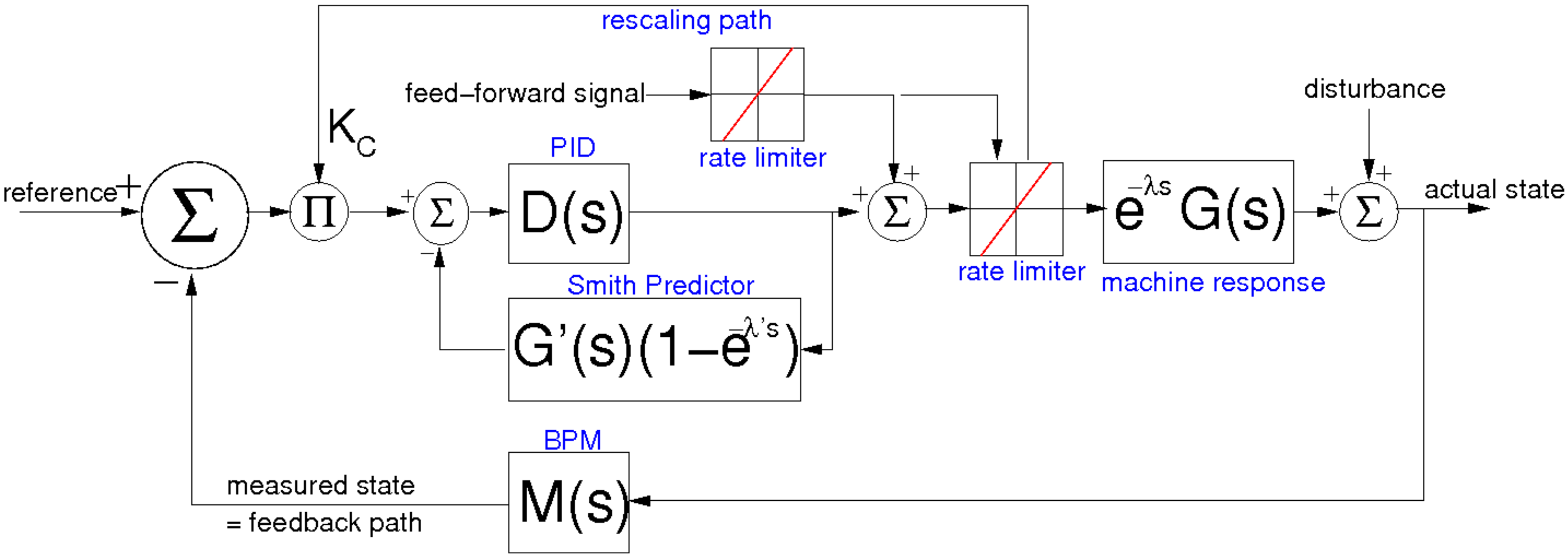


random b_3 → negligible effect
systematic b_3 → seem to be reproducible
→ constant feed-forward function may be established at some point of time

random b_1 → perturbs orbit
systematic b_1 → Δp/p shift
→ both require feedback control for each fill

Example: LHC Orbit Feedback Loop

- Full block diagram:



- D(s): Standard Proportional Integral Derivative (PID) controller
  – Option: Non-linear PID gains based on actual orbit stability/noise
  – 'rescaling part': Counteracts clipping/saturation of CODs
- Internal Smith-Predictor feedback loop:
  – favourable once running at 25/50 Hz
  – provides “cleaner” PID gains which are independent from sampling and other transport lags (simplifies further optimisations)

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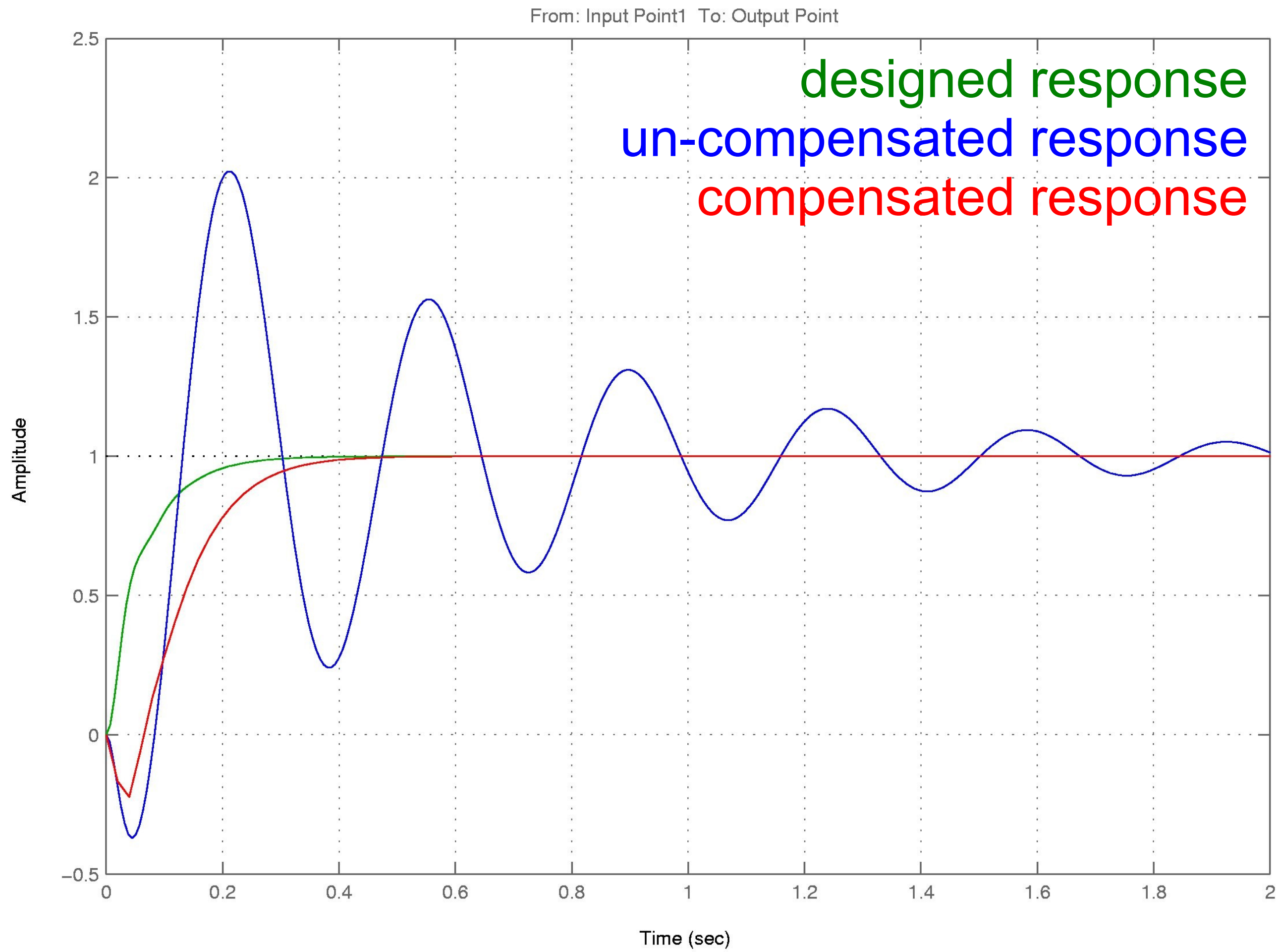
What a Smith-Predictor compensates:

- Classic Smith Predictor compensates only constant delays
- induces an inhibitor signal to to delay the actuator signal by λ



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