

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

- 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

- 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

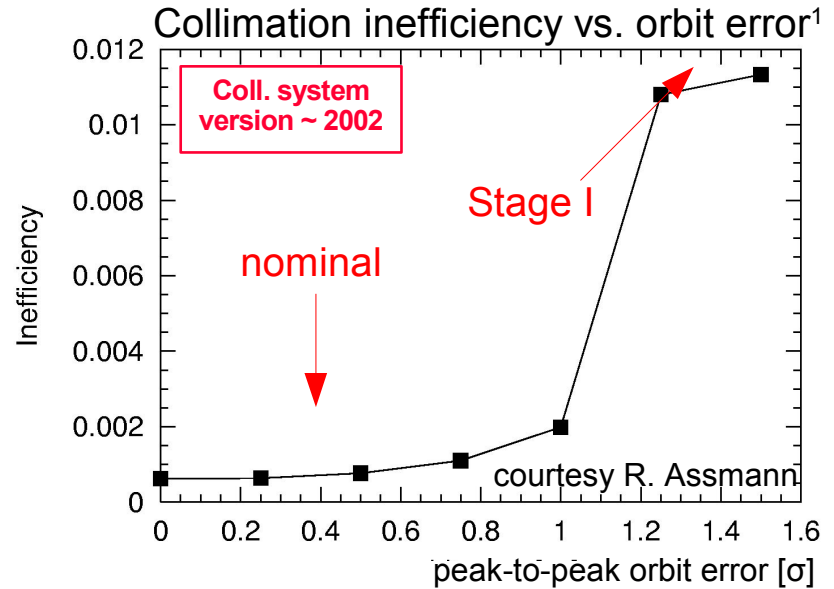
- Example: Collimation System, Phase I: 43x43 → $N_{max} \approx 5 \cdot 10^{12}$ protons/beam

- 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

→ $\eta < 0.05$ (\approx single stage system)



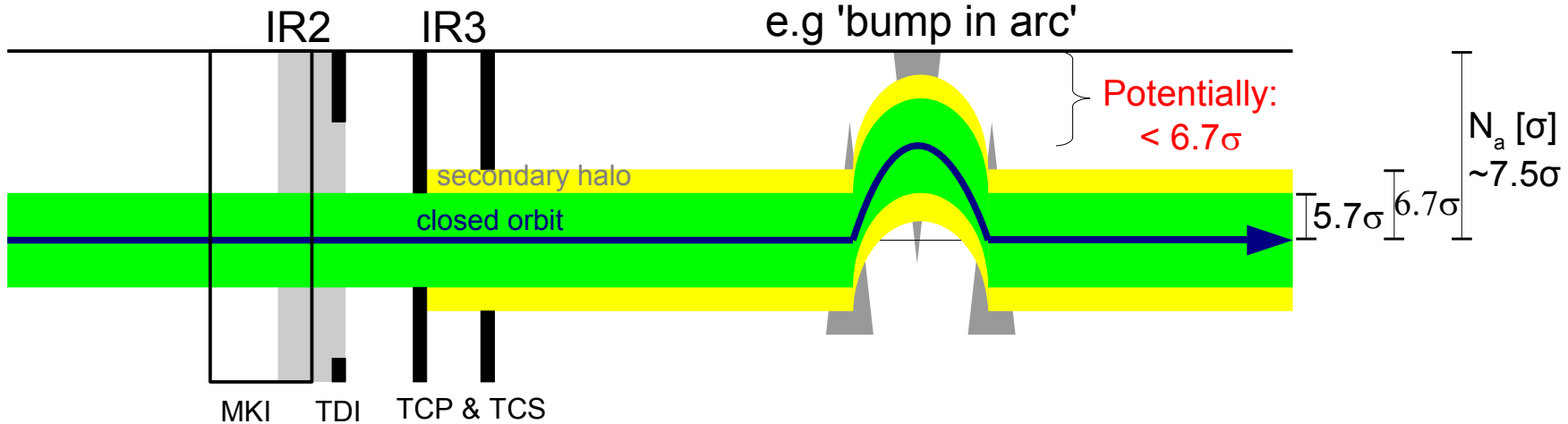
- Orbit stability of $< 1 \sigma$ seem to be sufficient for ≤ 43 bunches
- Nominal: $\approx 0.3 \sigma$ locally (collimation) and $\sim 0.3 \sigma$ globally

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

Requirements on Orbit I/II: machine protection

- Combined failure¹: 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 proposal¹: regularly check aperture → [see link](#)

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

■ LHC cleaning System:	< 0.3 σ	IR3,IR7
■ Machine protection & Absorbers:		
– TCDQ (prot. asynchronous beam dumps)	< 0.5 σ	IR6
– Injection collimators & absorbers	\sim 0.3 σ	IR2,IR8
– Tertiary collimators for collisions	\sim 0.2 σ	IR1,IR5
• absolute numbers are in the range: \sim 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	\sim 200 μm	IR4
– Interlock BPM	\sim 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	\sim 0.5 σ	global
– Maintain beam on clean surface (e-cloud)	\sim 1 σ ??	global

... requirements are similar \rightarrow 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**

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

→ favourable once running with high intensity

- **Required¹ 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

Requirements on Tune and Chromaticity

- 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 $\rightarrow 43 \times 43$)

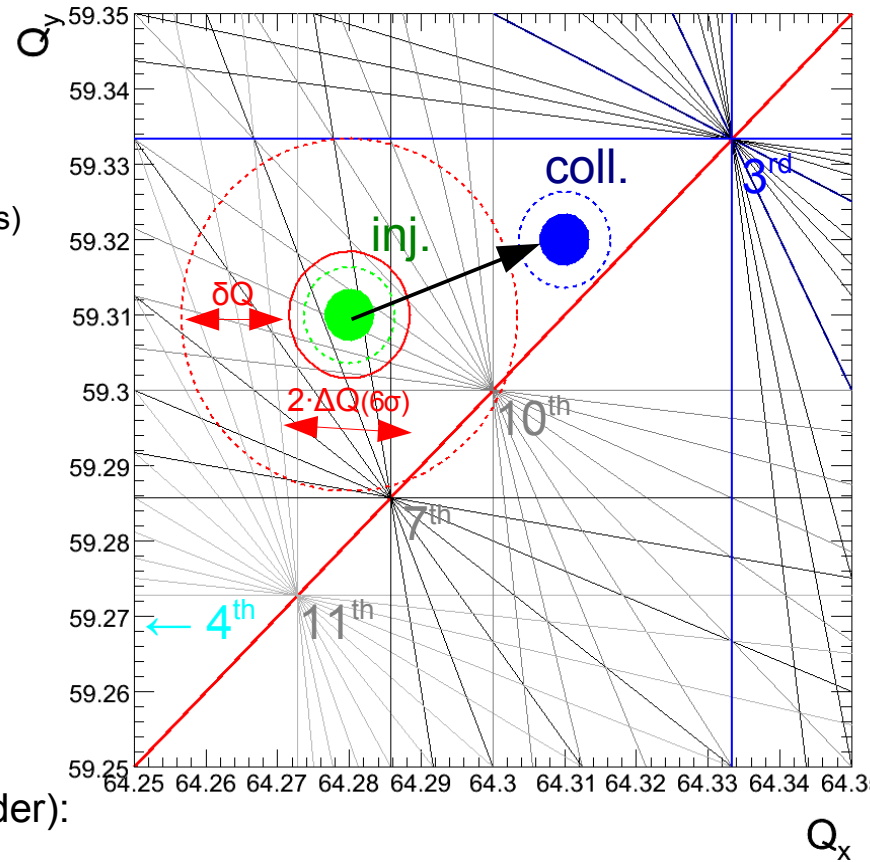
- Nominal^{1,2}: $\Delta Q \leq 0.003$ (inj.) $\delta Q \leq 0.001$ (coll.)

Chromaticity

- SPS: $\Delta p/p: 2.8 \cdot 10^{-4}$
(actual $\Delta p/p$ given by SPS \rightarrow LHC inj.)
- \rightarrow allowed max lin. chromaticity (5-6 σ , first order):

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

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

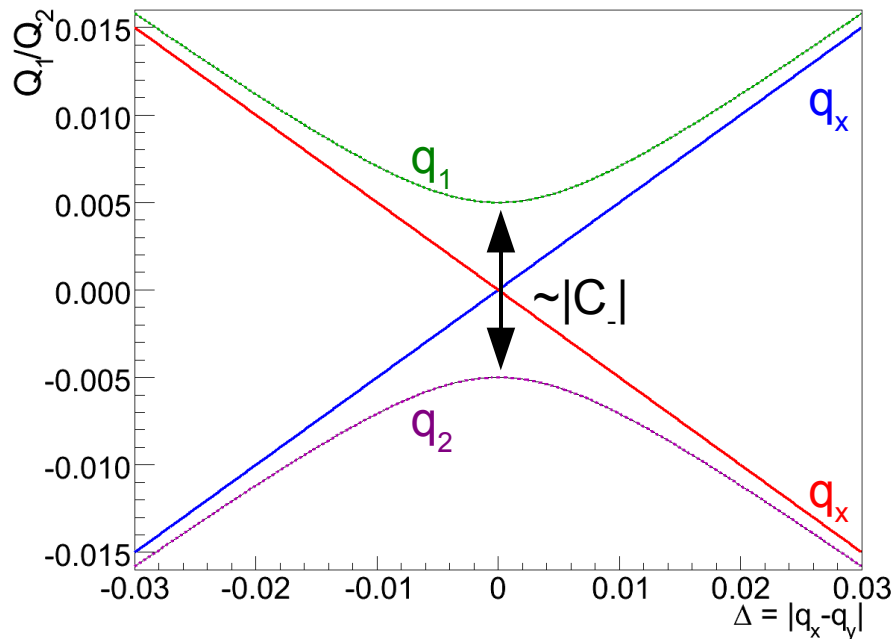


"Numbers are estimates, other more/less strict choices are of course possible – commissioning will clarify real requirements!"

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

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



- Closest tune approach $\rightarrow c_{\perp} \ll 0.03$ and $c_{\perp} \ll 0.01$ respectively
- Requirement for other feedbacks that rely on decoupled planes
- Proposal for alternate higher tune split¹: $\Delta_{\perp} = 0.1$ ($q_x = 0.285$, $q_y = 0.385$)

¹S. 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·frev]	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

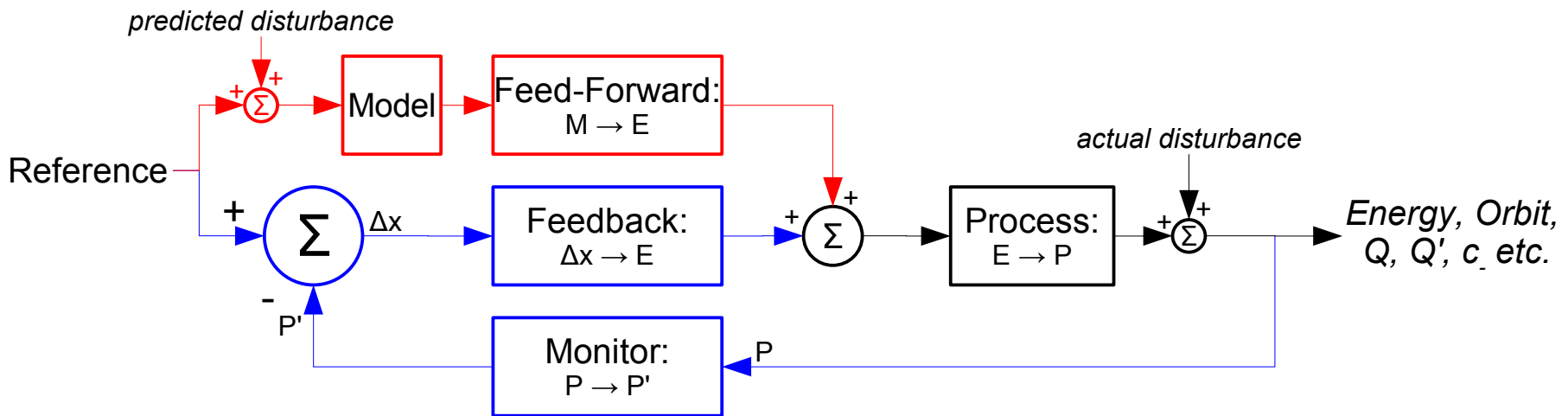
- Feedback priority list: Coupling/Tune → Chromaticity → Orbit → Energy
- Feedback list of “what's easiest to commission”:
 - 1st: Orbit → functional BPM system → OK
 - 1½: Energy → consequence of 100k turn acquisition → OK
 - 2nd: Coupling/Tune → functional Q-meter (-PLL) → Day I-N
 - 3rd: Chromaticity → 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 rough process model and measurement of parameter
 - Two types: within-cycle (repetition $\Delta t \ll 10$ hours) or cycle-to-cycle ($\Delta t > 10$ hours)

preferred choice!



- From the steering point of view: → All control schemes possible
- For the full block diagram → [click here](#)
- Choice of Feedback vs. Feed-forward
 - depends on available robust beam parameter measurements

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

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

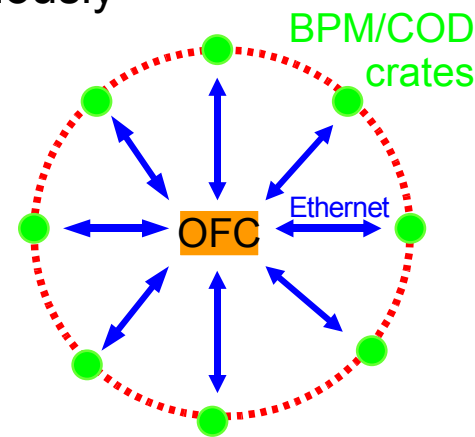
matrix multiplication

- 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 ...

- 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.

- 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: $\Delta\mu_{\text{BPM}} \approx 45^\circ$ (oversampling \rightarrow 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): $f_{\text{bw}} \approx 1\text{-}2$ Hz (defines total feedback limit)

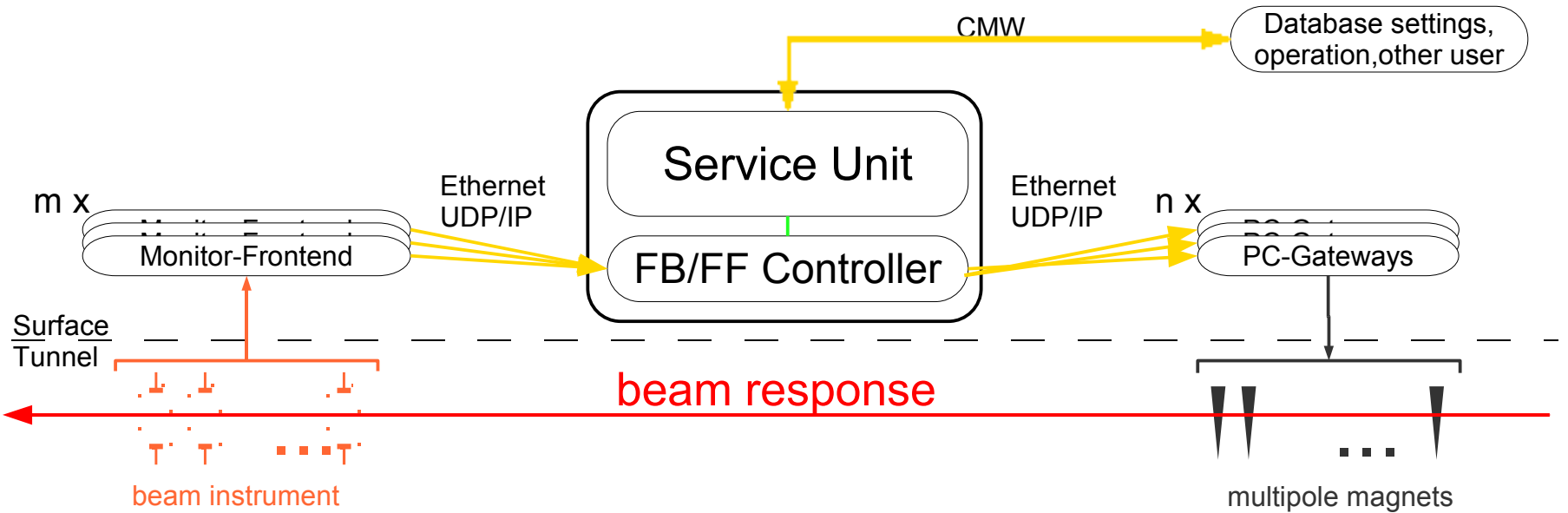


more than 3000 actively involved elements!

Common Feedback/Feed-forward Control Layout

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 \rightarrow Network)_{FB} \rightarrow Data-processing \rightarrow Network \rightarrow PC-Gateways
 - Can run auto-triggered (no timing necessarily required)
 - Hardware and functional specifications already available



- SVD* based global correction scheme in space-domain and Proportional-Integral-Derivative (PID) control (+ 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

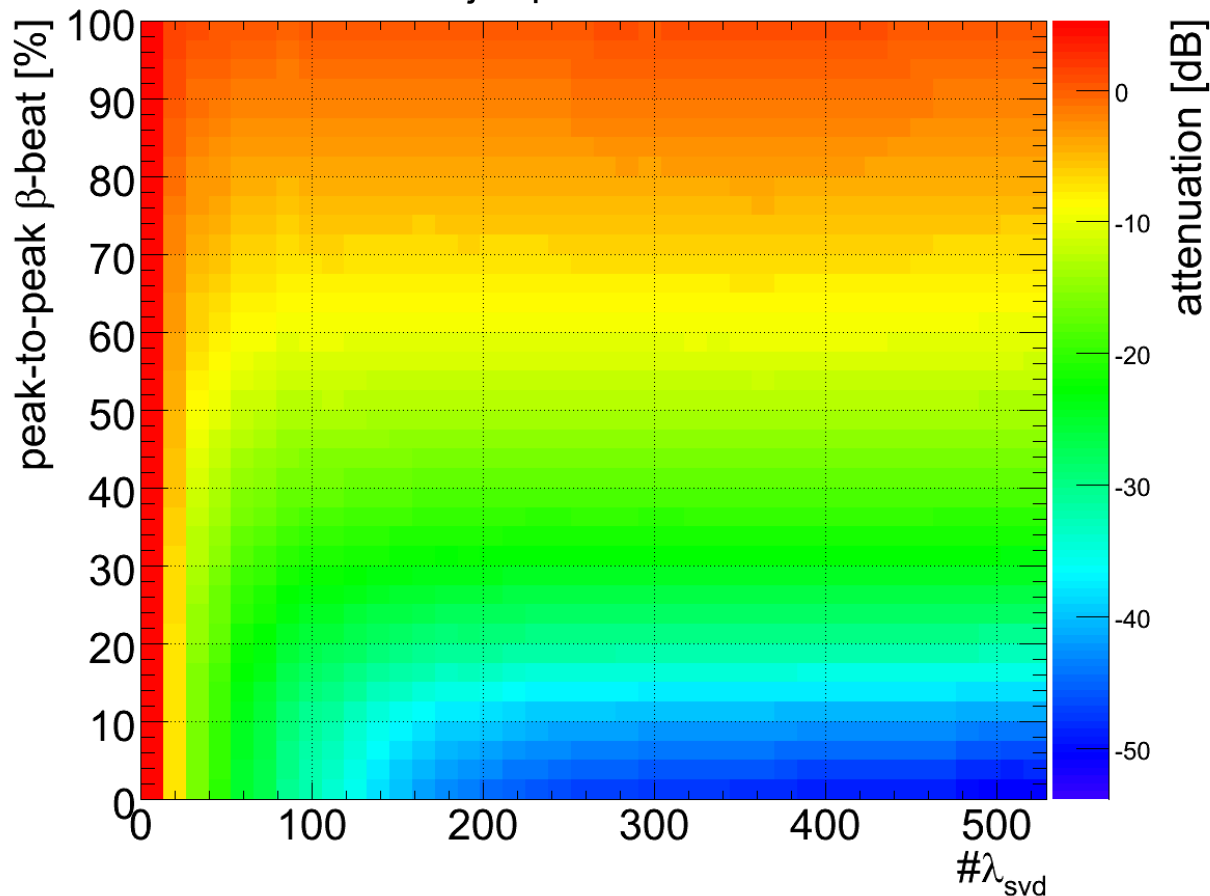
² R. Steinhagen, “Closed Orbit and Protection”, MPWG #53, 2005-12-16

- Feedback loops are designed to be robust against:
 - optics and calibration uncertainties (through using SVD)
 - “number of used eigenvalues” $\#\lambda_{\text{svd}}$ 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



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

attenuation =

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

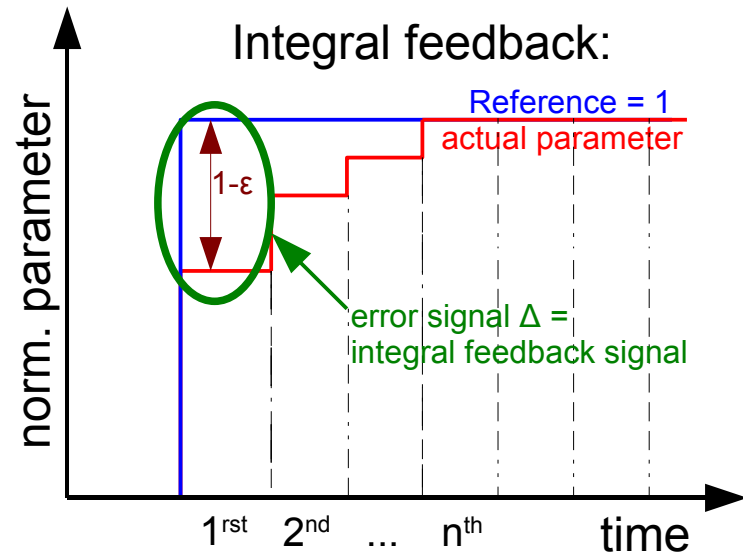
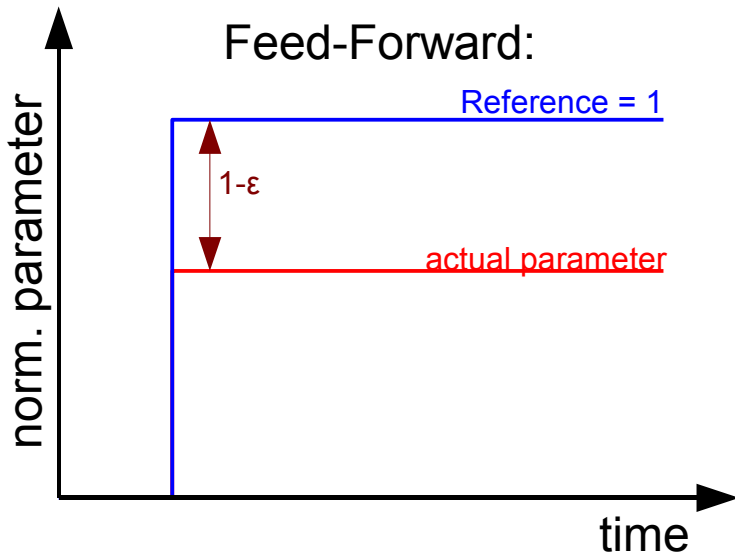
- Robust Control: OFB can cope with up to about 100% β -beat!

- Available aperture and collimation inefficiency w.r.t. β -beat is clearly more an issue

Virtue of PID Controller: Integral Action example

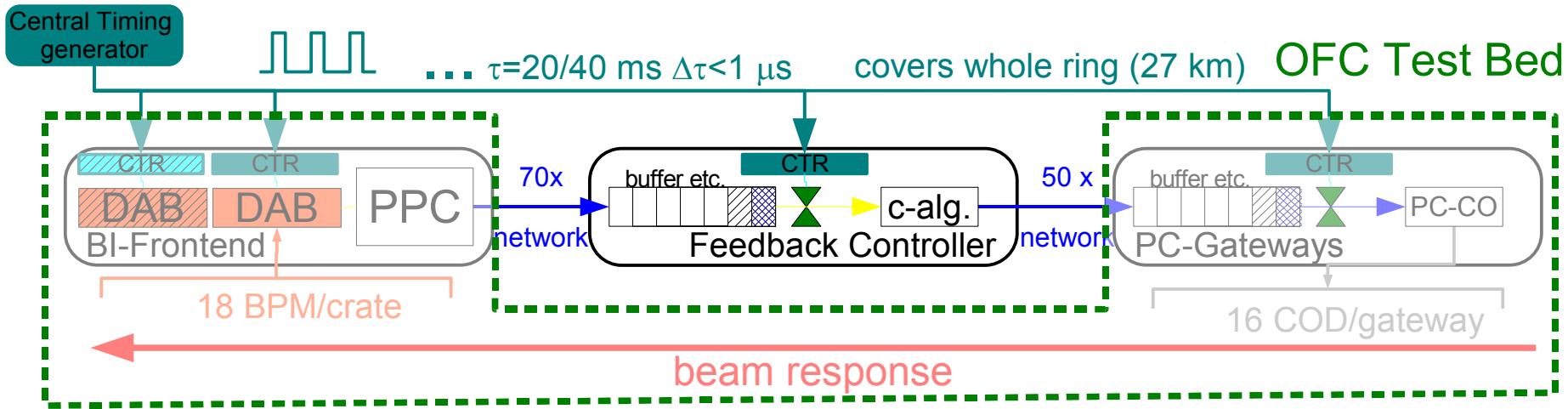
- Machine imperfections (beta-beat, hysteresis....), calibration errors and offsets can be translated into a steady-state ϵ_{ss} and scale error ϵ_{scale} :

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



- 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

- **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



- 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:

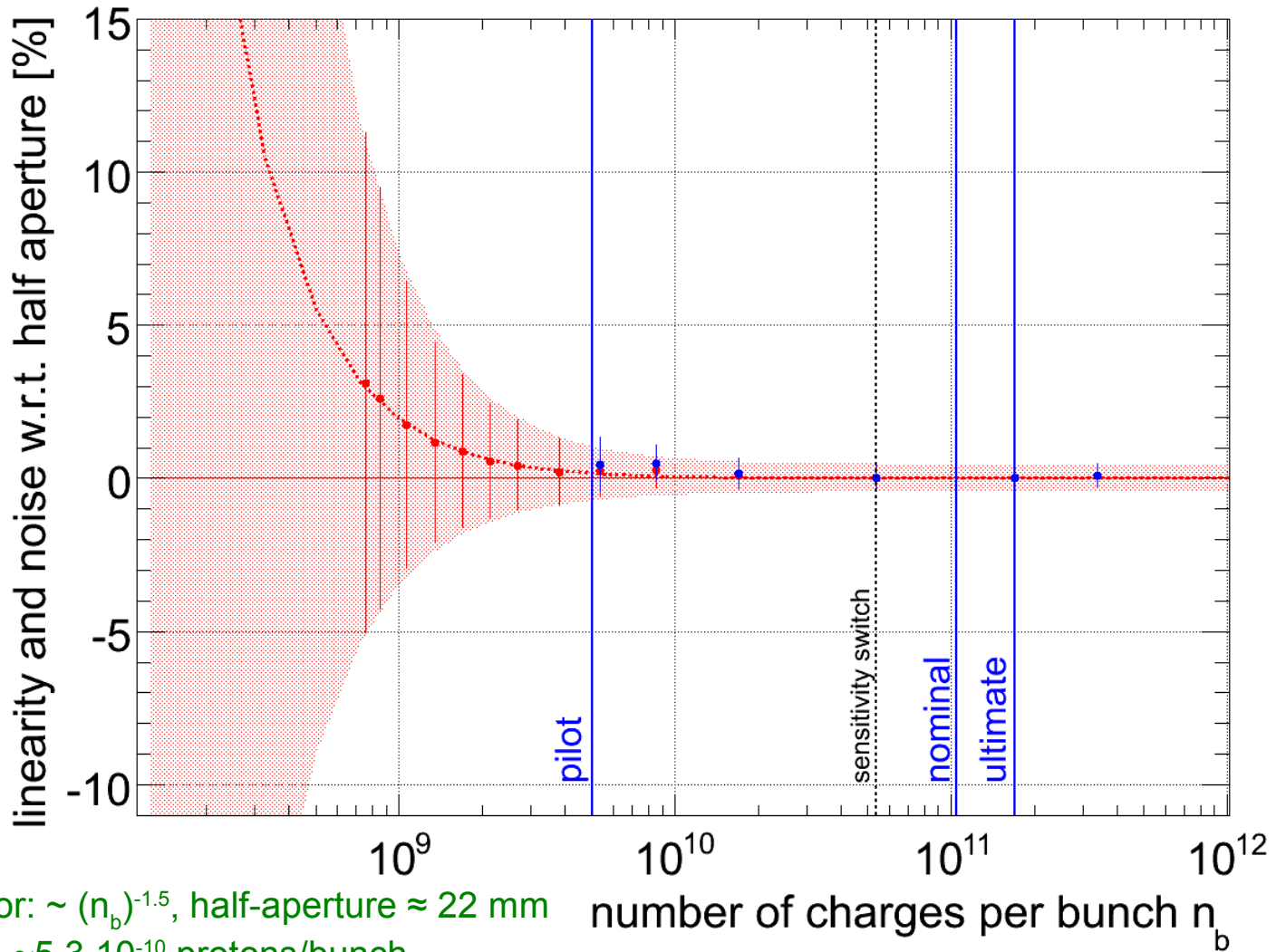
- e.g. auto-triggered at 0.1 – 1 Hz
- low integral gain ($K_p=K_d=0$)

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 intensity

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



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 $\Delta x_{\text{turn}} \approx 200 \mu\text{m} \rightarrow$ orbit: $\Delta x \approx 13\text{-}20 \mu\text{m}$
 - 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

- 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?

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:

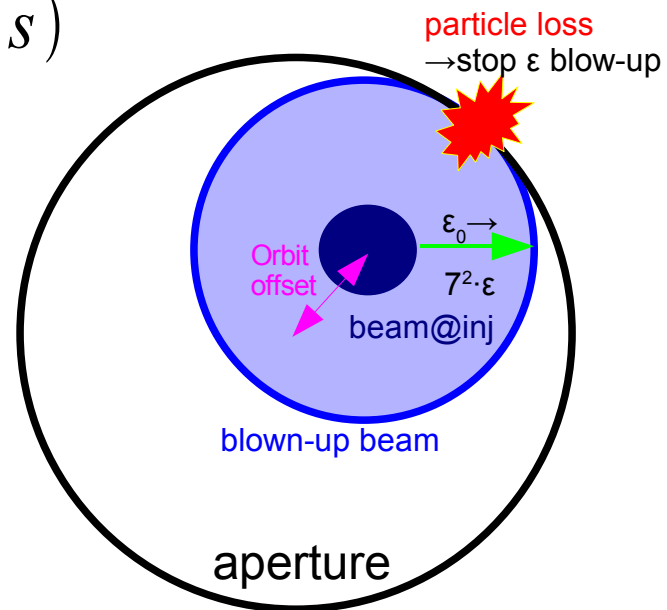
→ store last beam size measurement

- “Is beam size $\geq 6.7 \sigma_0$?” (σ_0 : beam size at injection)

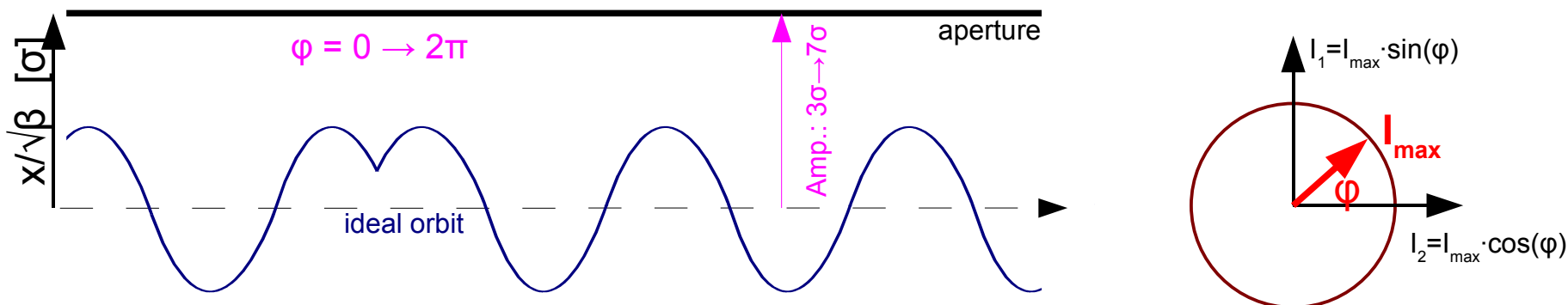
- Yes: → mechanical aperture $\geq 6.7 \sigma$ → orbit is safe

- No: → mechanical aperture $\leq 6.7 \sigma$ → orbit is un-safe

- rework orbit reference (compare with old reference....)



- 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 $\geq 6.7 \sigma$ → orbit is safe
 - **No:** → mechanical aperture $\leq 6.7 \sigma$ → orbit is un-safe

(– additional feature: compare measured with reference BPM step response ($x_{co} = 0-3\sigma$)
 → rough optics check (phase advance and beta-functions))

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 $a_{\text{dyn}} < a_{\text{mech}}$
- **Destructive measurement**
 - beam has to be dumped after scan
 - **cannot be used for collimator setup**
 - increased beam loss during extraction

■ 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**

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

Indicators whether Aperture Scan is required:

Beam Position Monitors:

■ Procedure:

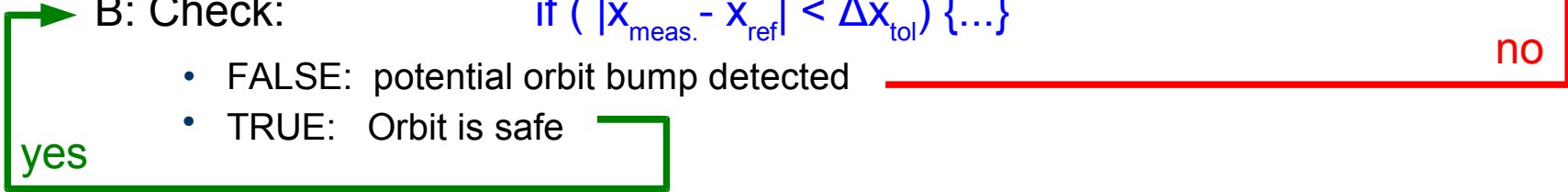
A: Initial check whether Orbit is safe:

- aperture scan (ϵ blow-up, betatron-oscillation)
 - Potential bump scans to determine location of aperture
- save “safe BPM reference” current settings $\rightarrow x_{\text{ref}} = \text{“SAFE SETTING”}$

B: Check:

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

- FALSE: potential orbit bump detected
- TRUE: Orbit is safe

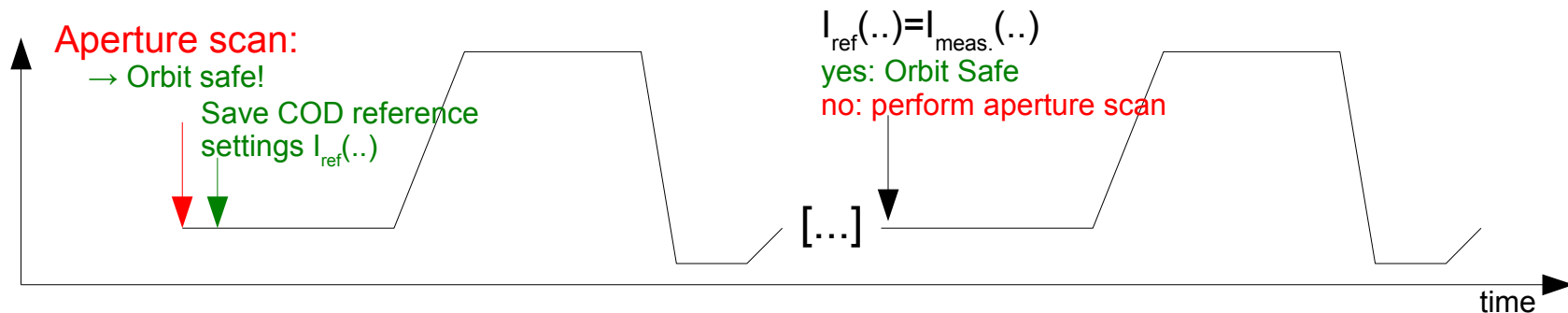


– Pro's:

- 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



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 $\rightarrow I_{ref}(\dots) = \text{“SAFE SETTING”}$

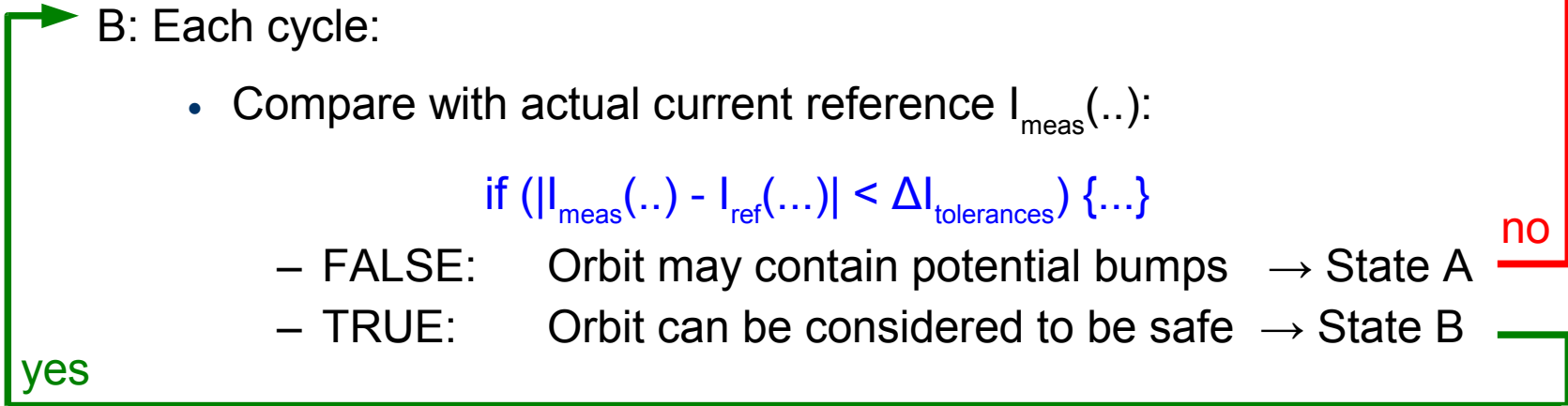
B: Each cycle:

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

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

– FALSE: Orbit may contain potential bumps \rightarrow State A

– TRUE: Orbit can be considered to be safe \rightarrow State B



- 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 $\Delta I_{\text{tolerances}}$ (“SAFE SETTINGS”) should include margin for
- orbit feedback operation
 - expected compensation of closed orbit uncertainties = “natural effects”

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

- ...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

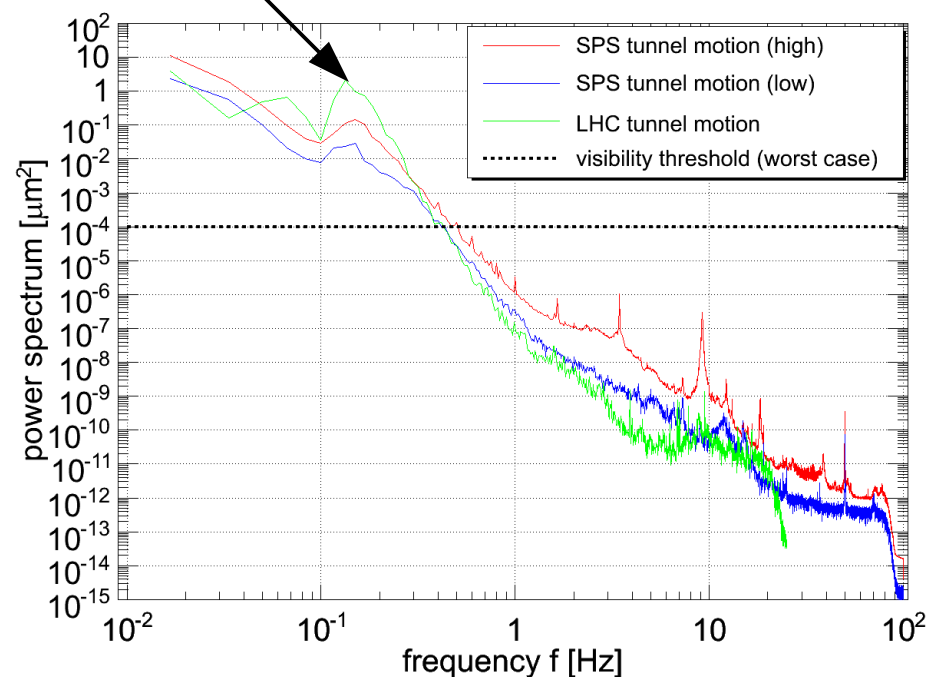
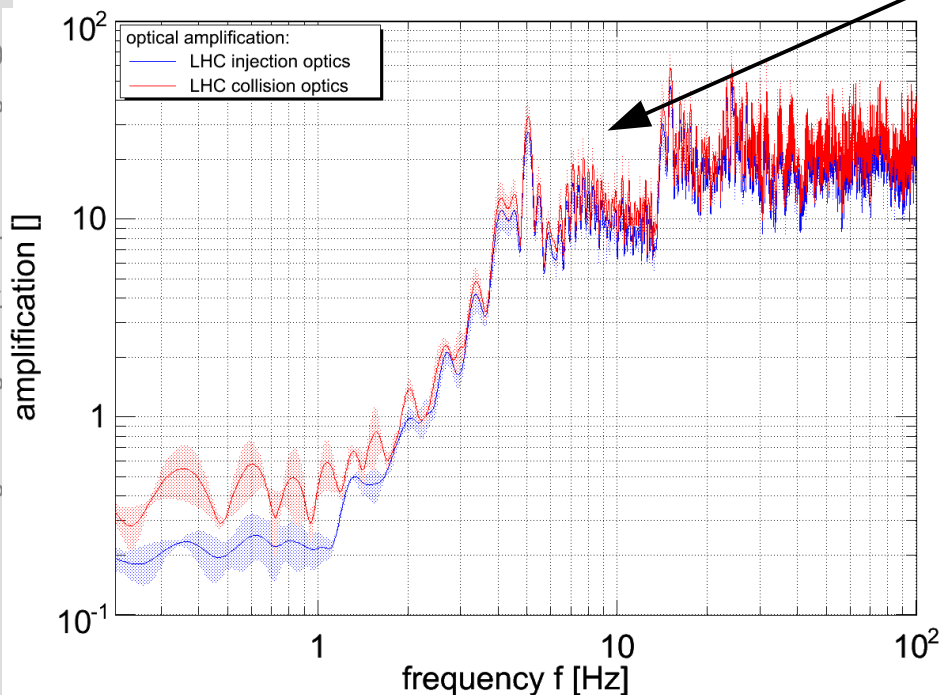


Perturbations due to
correlated and random ground motion, tides
and thermal expansion of girders

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 $\kappa \approx 1000$
 - coherent ground motion negligible above 1 Hz (beware of cryogenics!)

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



- Random ground motion (Brownian motion):

- amplitudes increases with $\sim\sqrt{t}$

- 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} :

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

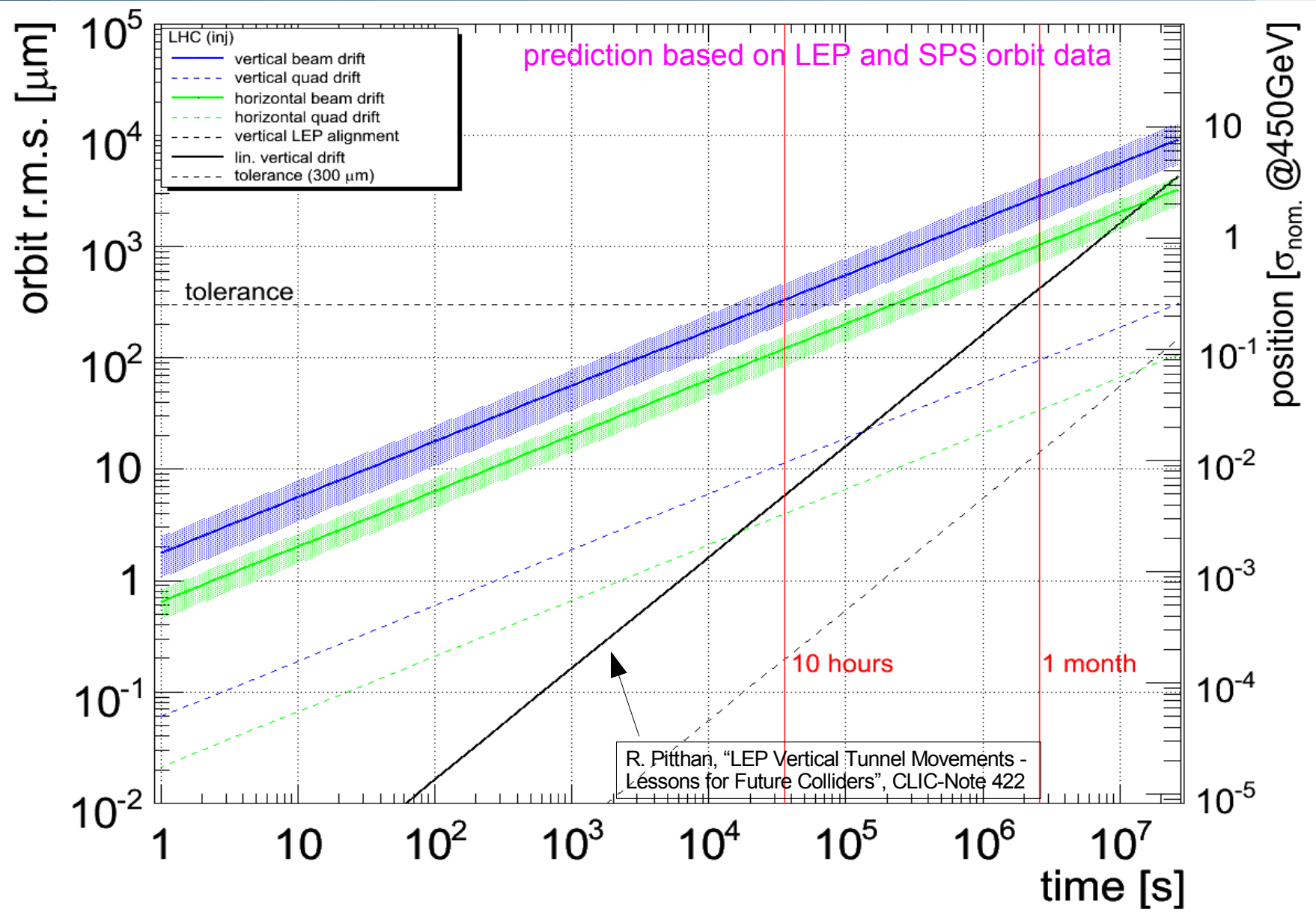
- LHC injection optics:

$$\kappa_H = 30.5 \pm 11.5 \quad \text{and} \quad \kappa_V = 29.6 \pm 9.0$$

- LHC collision optics:

$$\kappa_H = 63.3 \pm 32.5 \quad \text{and} \quad \kappa_V = 62.1 \pm 25.5$$

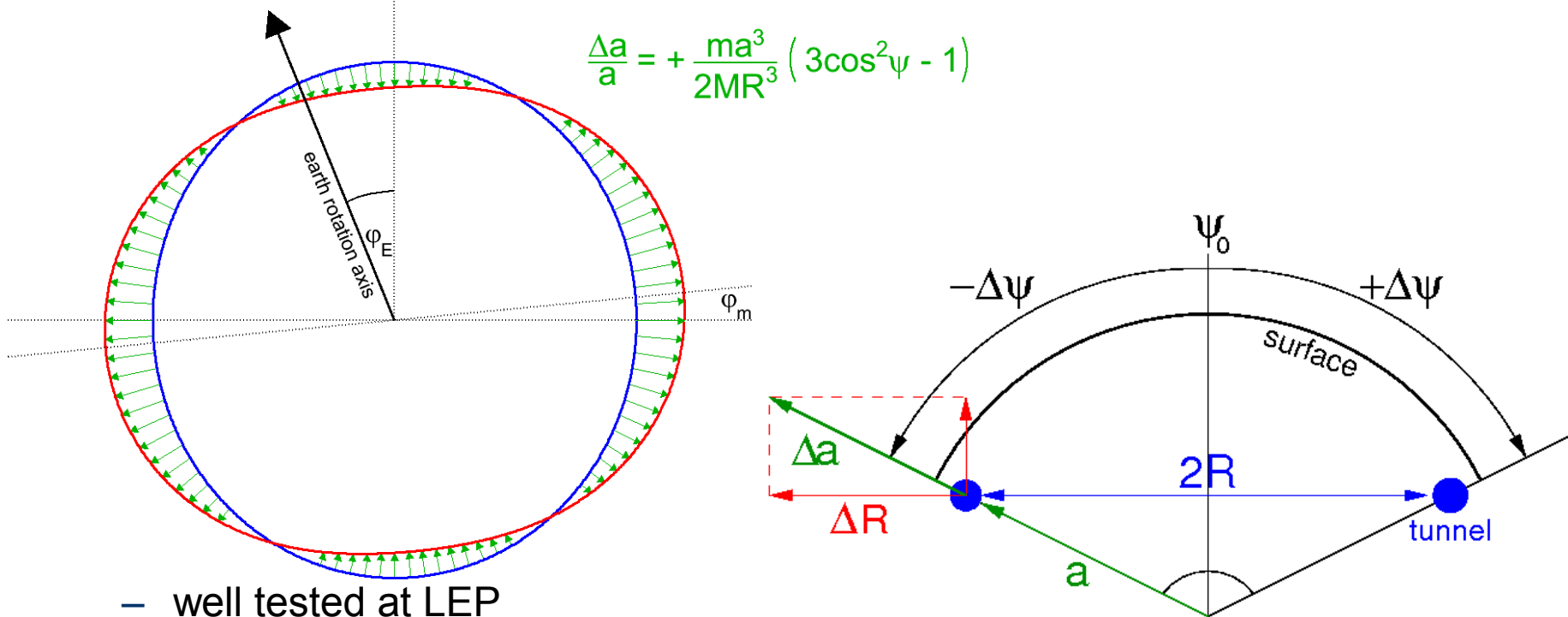
“Analysis of Ground Motion at SPS and LEP, Implications for the LHC”, AB Report CERN-AB-2005-087



→ closed Orbit drifts after 10 hours $\approx 0.3 - 0.5 \sigma$

Lunar and Solar Tides

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



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

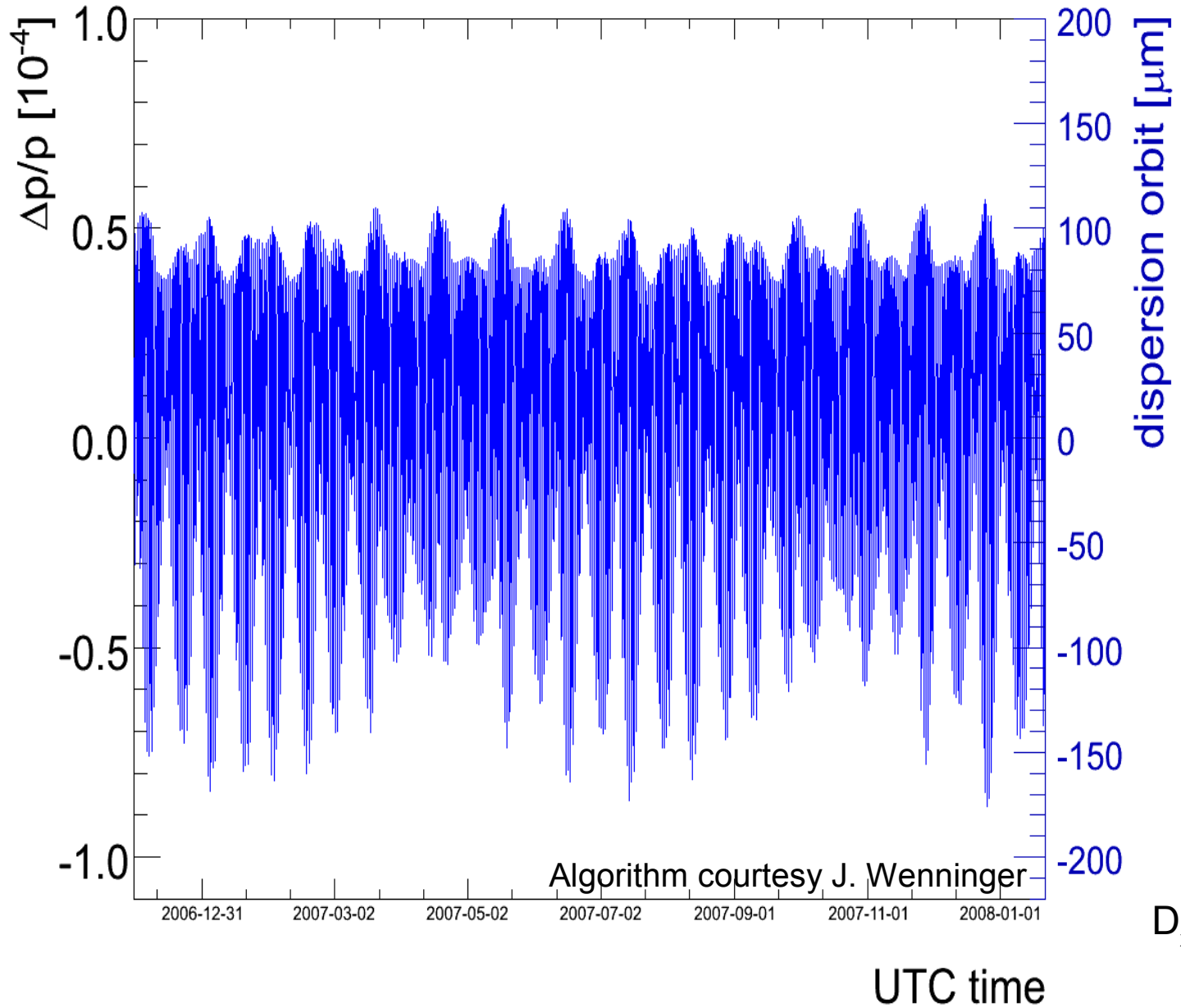
$$\frac{\Delta p}{p} = -\frac{1}{\alpha_p} \cdot \frac{\Delta C}{C}$$

- LHC: $\Delta C \approx \pm 0.5 \text{ mm}$, momentum compaction factor $\alpha_p = 3.2 \cdot 10^{-4}$

- $\Delta p/p \approx 5.8 \cdot 10^{-5} \rightarrow 2\Delta x = 2 \cdot D_{\max} \cdot \Delta p/p = 326 \mu\text{m} \approx 0.29 \sigma$

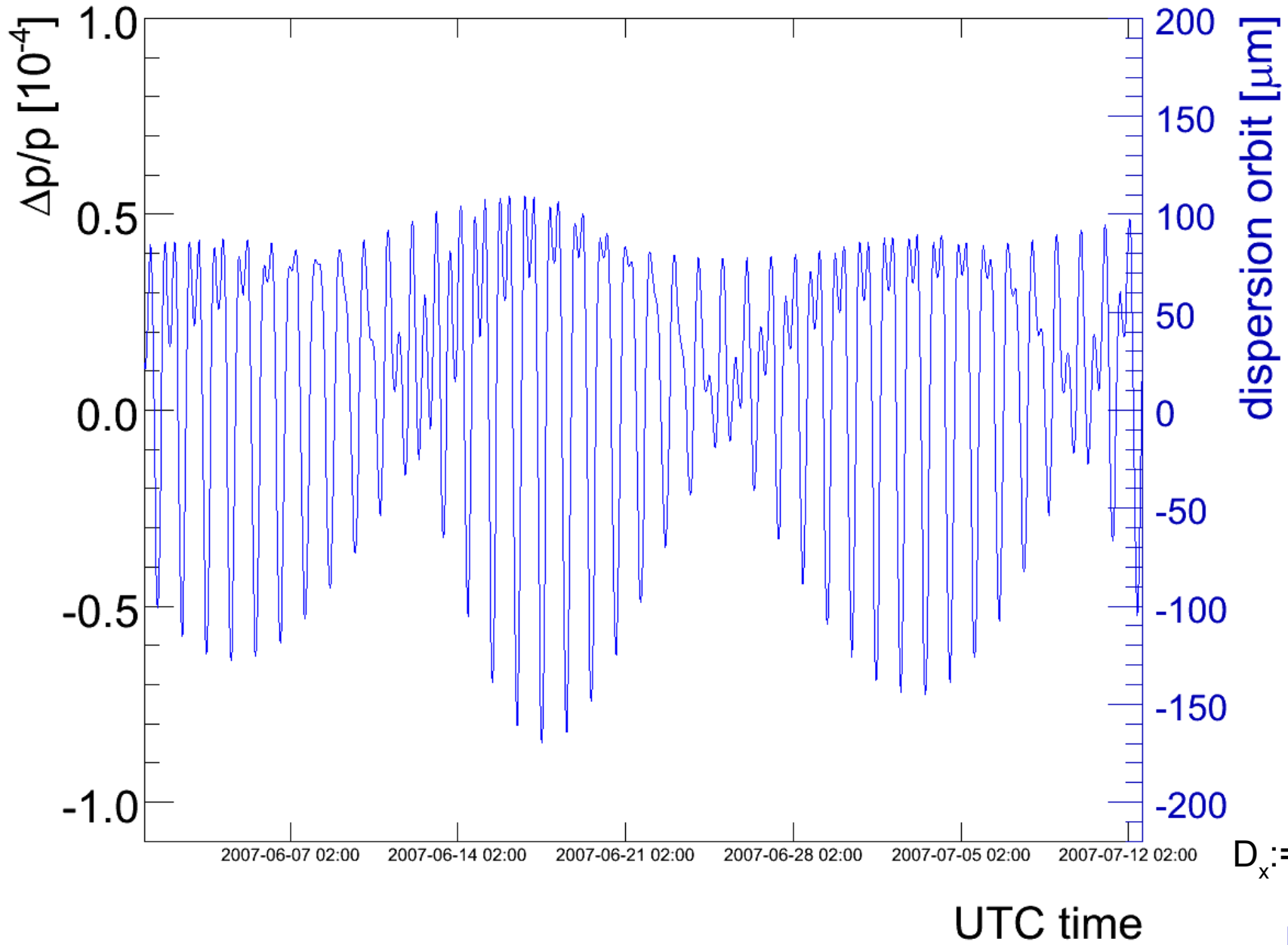


Solar/Lunar Tides prediction for 2007

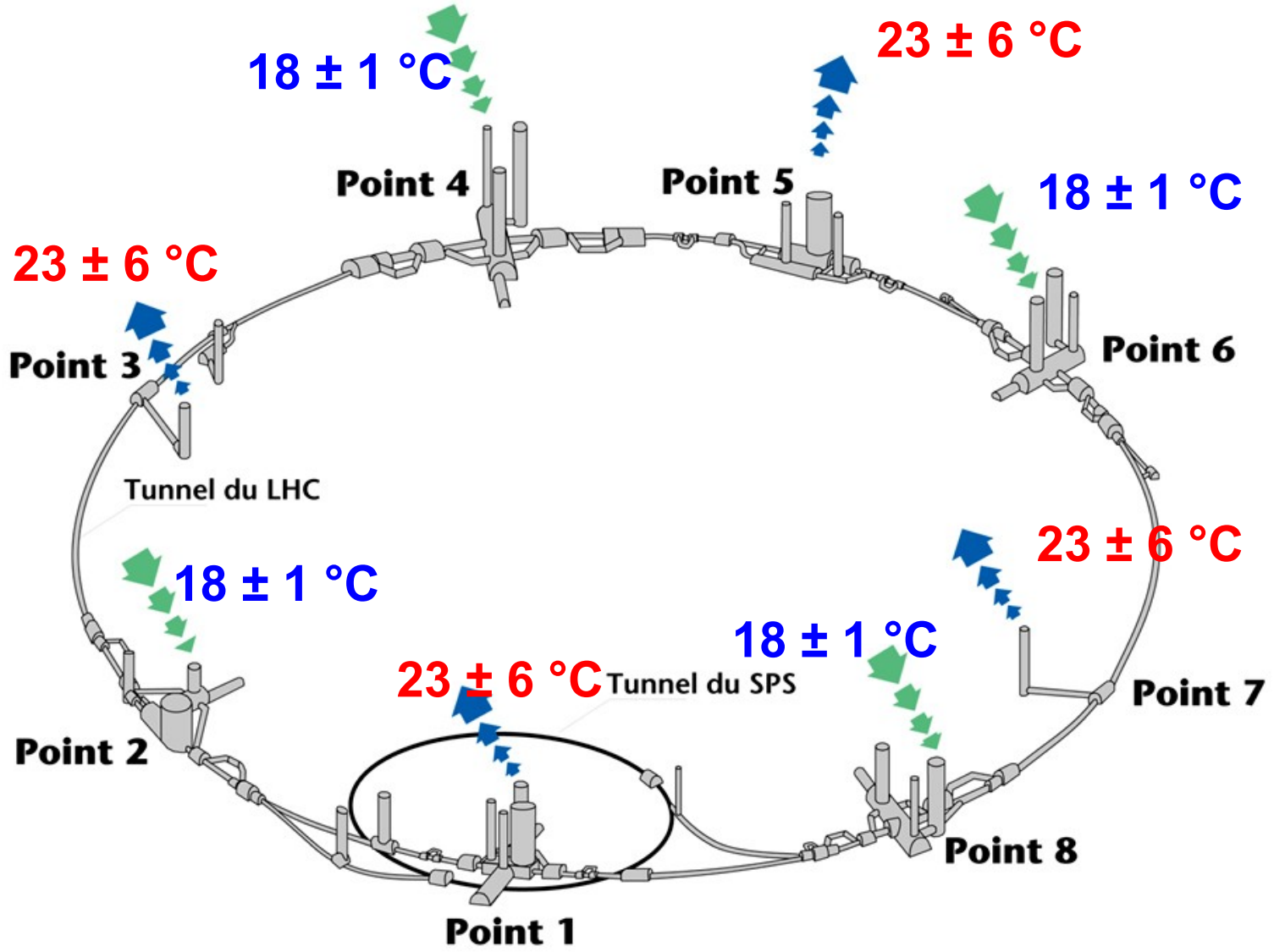




Solar/Lunar Tides prediction for June 2007



Ventilation du tunnel LEP/LHC



Thermal Expansion of Girders

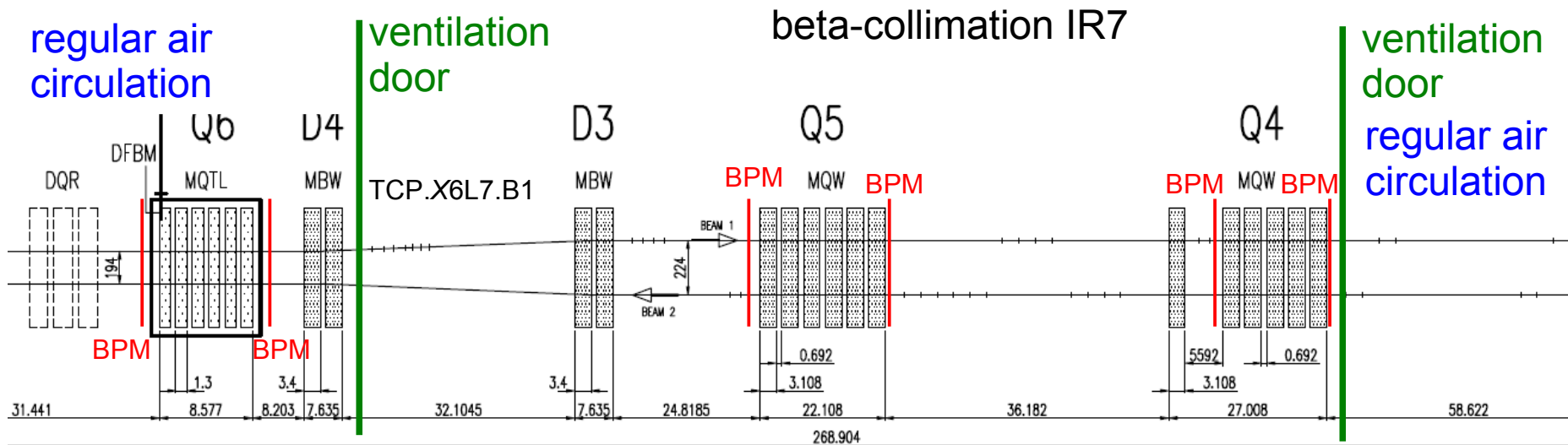
- Mechanism: Orbit feedback intrinsically aligns with respect to the BPMs that are either attached to the quadrupoles or have similar girders
- Thermal expansion, steel $\alpha_{\text{steel}} \approx 10\text{-}17 \cdot 10^{-6} \text{ K}^{-1}$ (BS:970, DIN18800):

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

- Systematic shift of beam reference system with respect to non-moving external reference (e.g. potentially collimators):
 - Cryo-Magnets: $x_0 \geq (340 \pm 20) \text{ mm}$ $\rightarrow \Delta x \approx 3.4 - 5.8 \text{ } \mu\text{m}/^\circ\text{C}$
 - Warm equipment: $x_0 \approx 950 \text{ mm}$ $\rightarrow \Delta x \approx 9.5 - 16 \text{ } \mu\text{m}/^\circ\text{C}$
- The inlet temperature is stabilised to about $\pm 1^\circ\text{C}$
 - temperature changes shouldn't pose a problem for even IRs

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 $\Delta T = \pm 2^\circ\text{C} \rightarrow \Delta x \approx \pm 20 \mu\text{m}$, Collimation: $\pm 50 \mu\text{m}$ might be tolerable (TOTEM 10 μm requirements – a midnight summer dream?)
- CNGS/Ti8: Estimates where $\approx 10^\circ\text{C}$ off (measured 25°C vs. estimated 35°C)
- Wait for LHC commissioning with beam and real temperature experience



Perturbations due to Multipole Field Errors of main dipoles and quadrupoles

- 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	$1.5 \pm ??$??	-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)

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

– + feed-downs due to orbit ... depends on operational conditions

- Coupling⁴ $\Delta c_- \approx 0.1$ (worst case)

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

¹L. Bottura, "Cold Test Results: Field Aspects", Proceedings of Chamonix XII, 2003

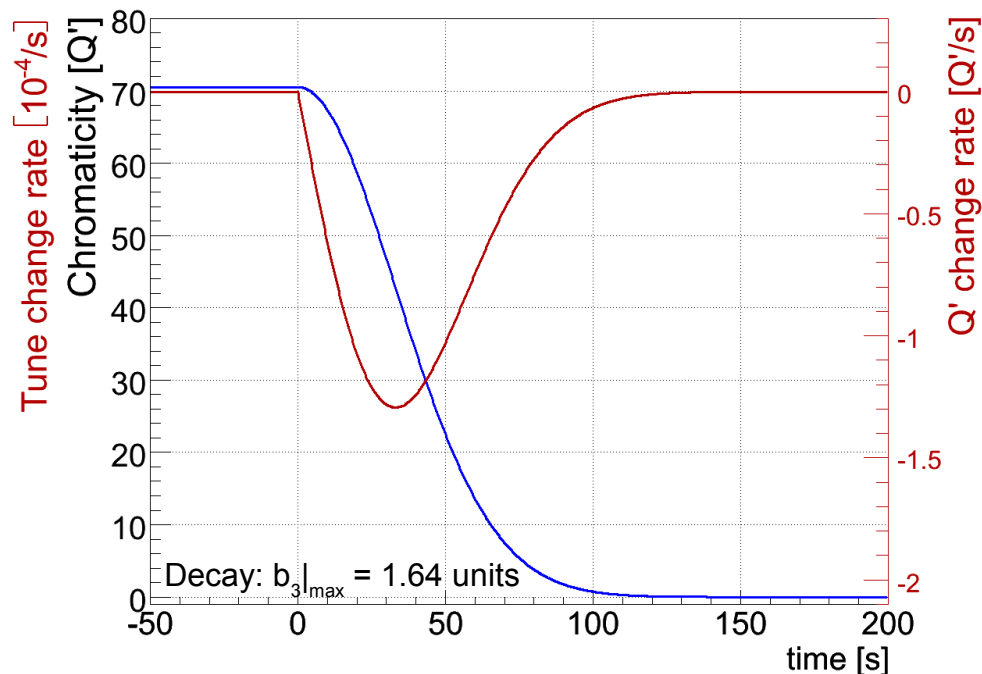
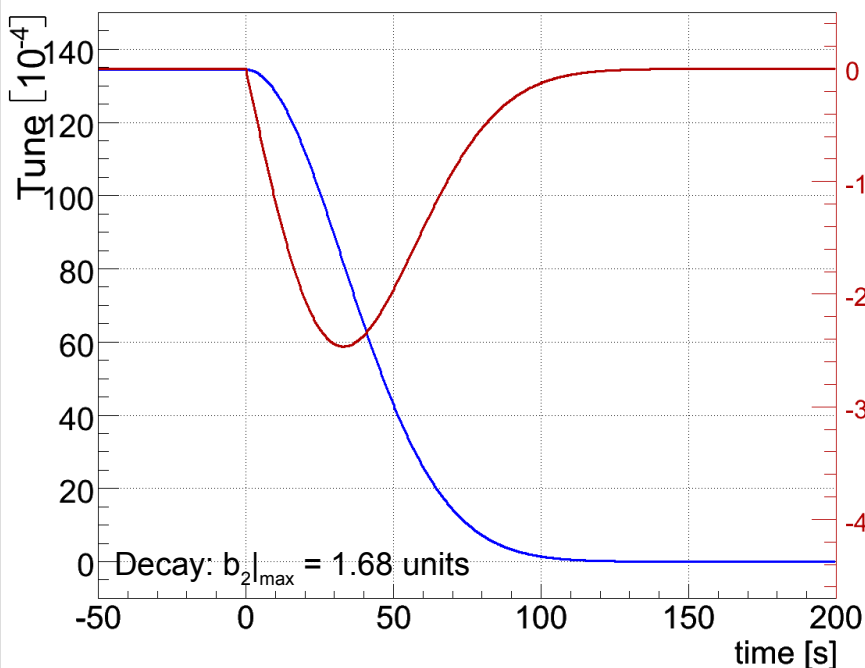
²L. Bottura, "Superconducting Magnets on Day I", Proceedings of Chamonix XI, 2001

⁴S. Fartoukh, "Commissioning tunes to bootstrap the LHC", LCC #31, 2002-10-23

Expected Time-Scales of Perturbations

Orbit & Energy:

- Injection (ground-motion, Δb_1): $\sim 0.4 \sigma/10 \text{ h}$ \rightarrow Control @1 Hz sufficient
- Snap-back: $0.3 \sigma/100 \text{ s}$ \rightarrow Control @1-10 Hz ??
- β^* -Squeeze: $0.1 \sigma/s$ \rightarrow Control @10++ Hz OK



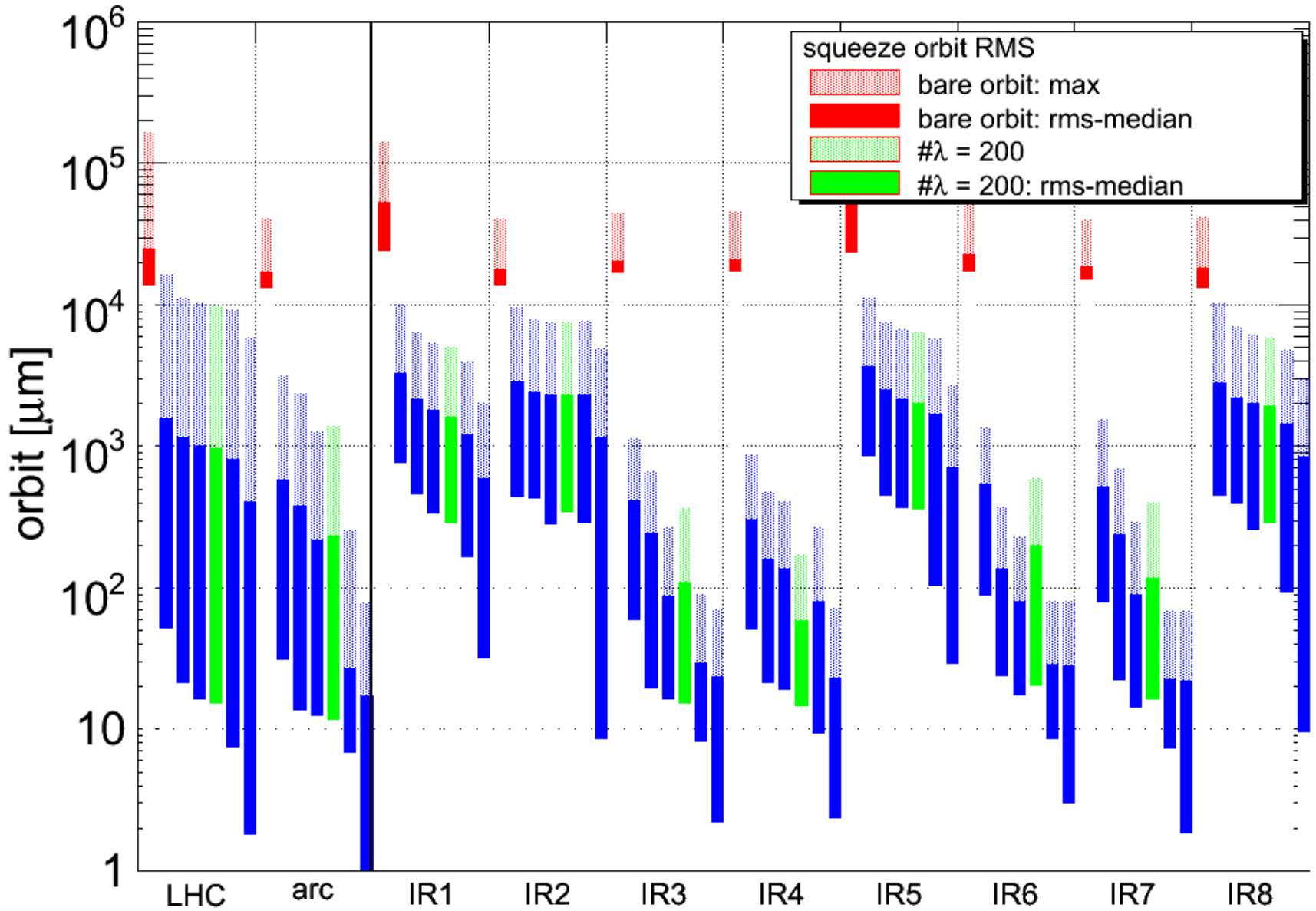
- $(\Delta Q'/\Delta t)_{\max} < 1.3 \text{ units/s}$ & $(\Delta Q')_{\max} < \sim 10 \text{ units}$
 \rightarrow (measure &) control chromaticity every $\approx 10 \text{ seconds}$ (or faster)

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

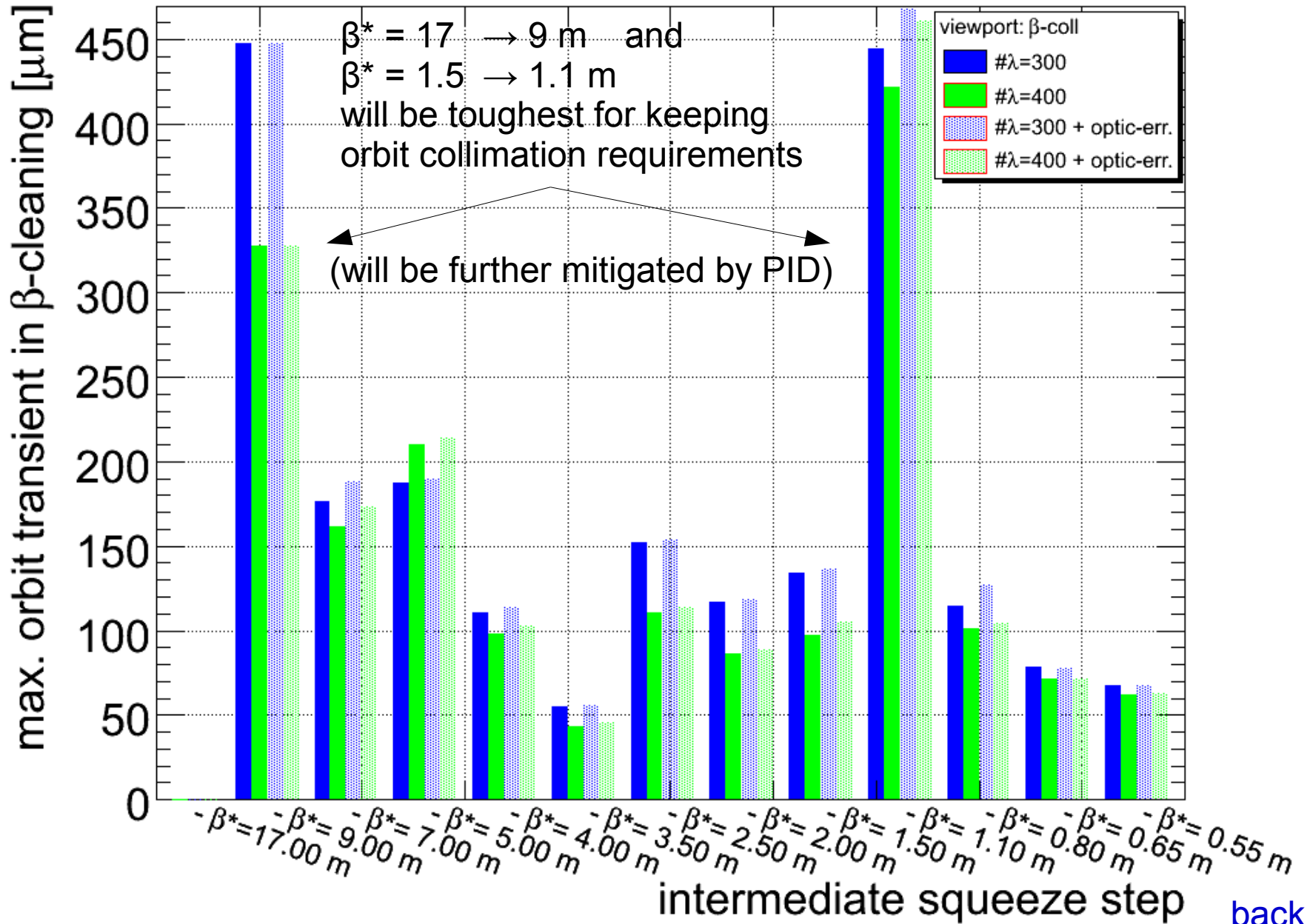
$$\delta_{kick} = (k + \Delta k_{squeeze}) l_{mag} \cdot \Delta x_{quad. - misalign.}$$

- Assume $\Delta x = 0.5$ 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.

Transient due to low beta Squeeze: Overview LHC



Transient in Collimation insertion vs. squeeze step





Dynamic Perturbations vs. Requirements Summary

Exp. Perturbations:		Orbit [σ]	Tune [$0.5 \cdot f_{rev}$]	Chroma. [units]	Energy [$\Delta p/p$]	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	$\sim 1200/100$ s
	b_2 & b_3	0.03	-	$\sim 70 - 140$	-	
	MQ: $b_2 \approx 1.7$		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	± 7 mA/60 A GeV	0.01	-	-		
β^* Squeeze	0.5 mm misalign.	~ 30 mm	??	??	-	~ 1200 s

Requirements: ⁶

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

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/>

Perturbations due to failing orbit corrector magnets

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

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 $11R'x' \leq \text{location}_{\text{MCB}} \leq \text{half-cell } 11L'x+1'$
 - Individually powered by a $\pm 8V$, $\pm 60A$ 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 m Ω
(including intrinsic magnet, cable and current lead resistance)
- Maximum kick δ_{max} ($\leftrightarrow 55$ A) on beam: **1260 μrad @ 450 GeV**
81 μrad @ 7 TeV
- Maximum kick amplitude : 144 mm @ 450 GeV and 9 mm @ 7 TeV)

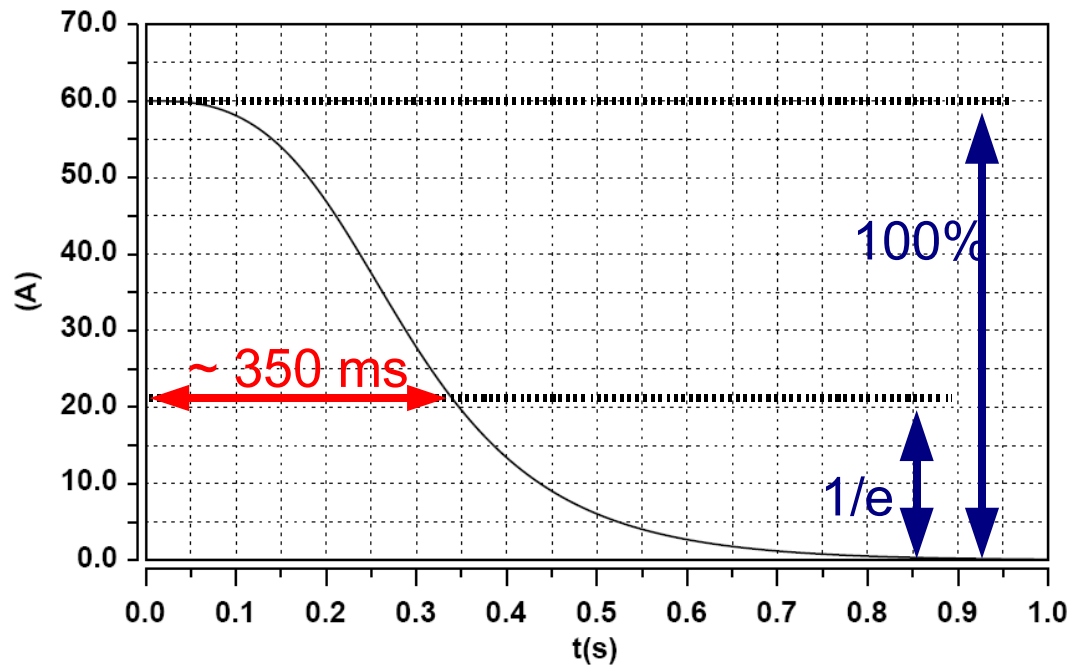
- Arc lattice is similar for injection and collision optics. Maximum orbit response in arc ($\beta = 170$ m)
 - $\Delta x_{\text{BPM}} \approx 100\text{-}110 \mu\text{m}/\mu\text{rad} \cdot \delta_{\text{COD}}$
 - resulting orbit change:
 - ~ 1.2 mm/0.5 A @ 450 GeV
 - ~ 75 μm /0.5 A @ 7 TeV

- 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 ($\beta = 170$ 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!



data courtesy to Felix Rodriguez Mateos

very fast current decay:

- decay time: $\tau \sim 0.35 \text{ s} \leftrightarrow \Delta I / \Delta t \sim 16 \text{ (58) A/s @ 7 TeV}$
- after 1 s the current is practically 0 A
- MCB quenches are expected to be rare

- There are 19 documented and in db logged causes for PC failure

- Mean-Time-Between-Failures (MTBF) expected to be $\approx 10^5$ hours

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

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

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

- Expect one PC/COD failure in 14 cycles \approx once per week (including all CODs: one failure every ~ 10 cycles)

- Circuit discharges with a decay time: $\tau \sim 60\text{-}80$ s

- This likely leads to an beam dump request due to:
 - increased particle losses e.g. at the collimator.
 - beam position interlock.

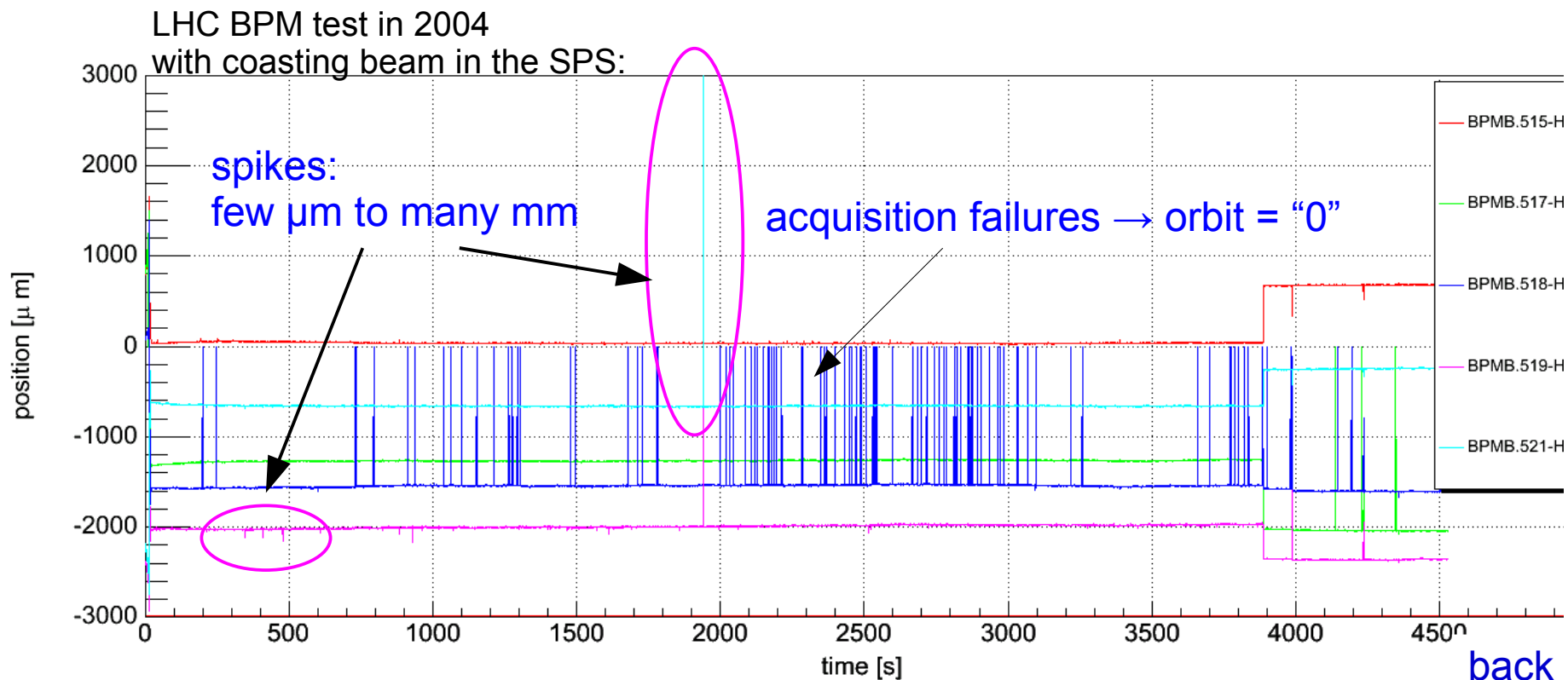
- Beware: actual operational experience may show higher/lower MTBF



Identification and Compensation of bogus and failing Beam Position Monitors

LHC BPM Prototype in the SPS:

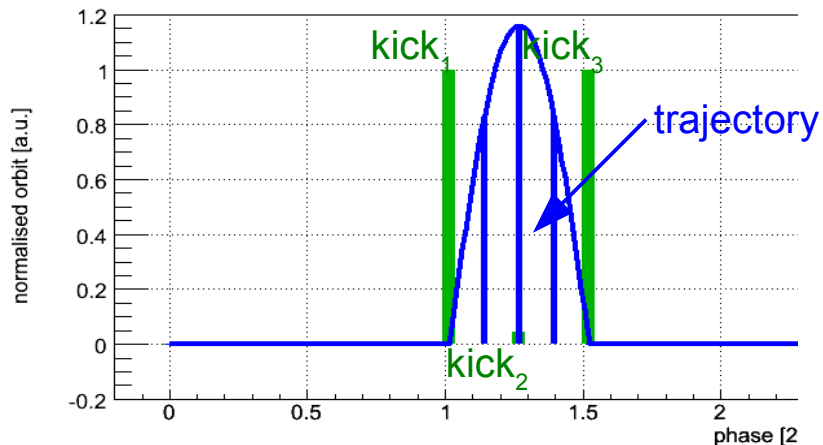
- **Most common: acquisition failure = no orbit info available and spikes**
 - Short term (few ms-s): Zero Order Holder (ZOH)
 - Long term: Disable BPM in feedback and recalculate SVD pseudo-inverse matrix
- **Only a few drifts observed: systematic on bunch length & bunch intensity**
 - within 1% of BPM half aperture \leftrightarrow 250 μm (complies with specification)



1. BPM phase advance of $\sim\pi/4$:
 - 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)
 - $x_i(n) > \text{machine aperture}$
 - $x_i(n) - x_{i,\text{ref}} > 3 \cdot \sigma_{\text{orbit}}$
 - Option: interpolate position from neighbouring BPMs (implemented in APS)
→ sensitive to quadrupoles/dipoles between BPMs,
 - Cuts in Time Domain (Spike detection!):
 - $\Delta x_i(n) = x_i(n) - x_i(n-1) > 3 \cdot \Delta x_{\text{rms}}(n \rightarrow n-m)$ (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

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

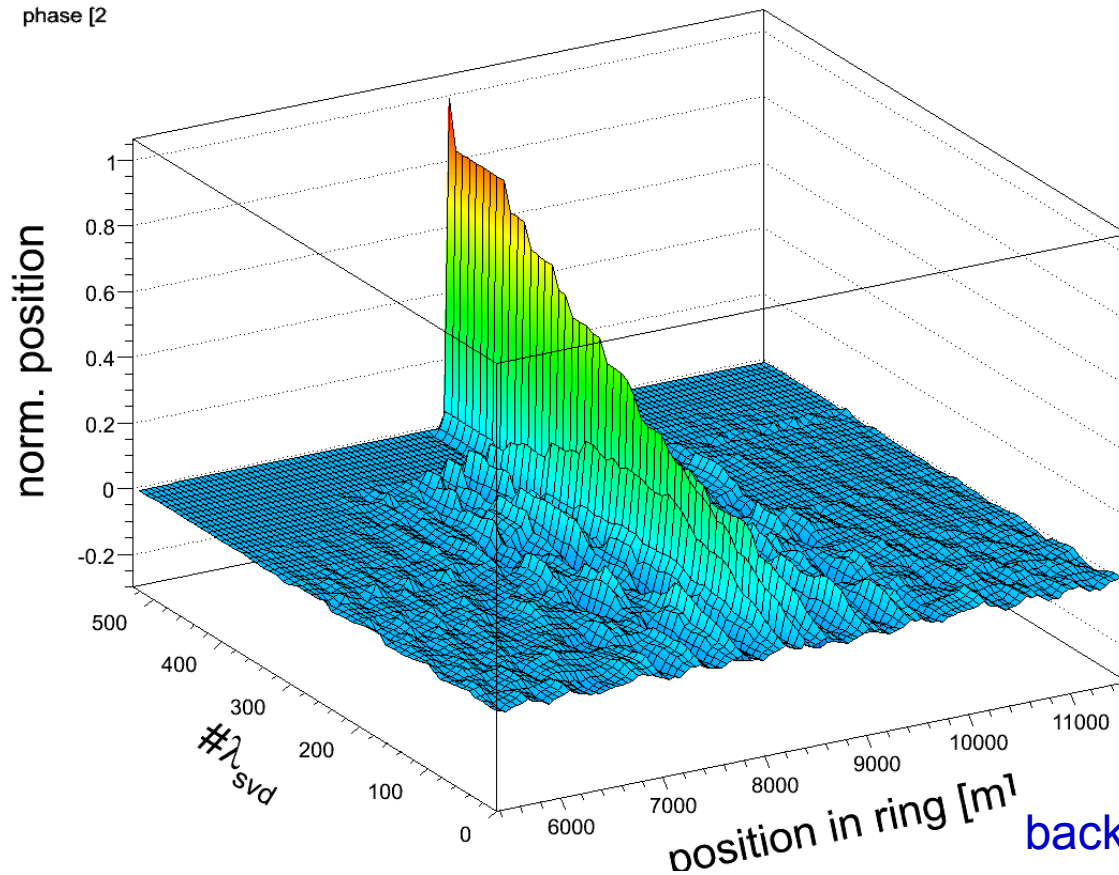
 - Important mathematical properties:
 - SVD minimises orbit & deflection strengths
 - Uses rather many CODs with small than few with large kicks
 - Solutions are sorted by their 'effectiveness': large eigenvalues λ_i (solutions) first
 - Local 'bump-like' solutions corresponds to small eigenvalues
 - “number of used eigenvalues” $\# \lambda_{\text{svd}}$ 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)



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

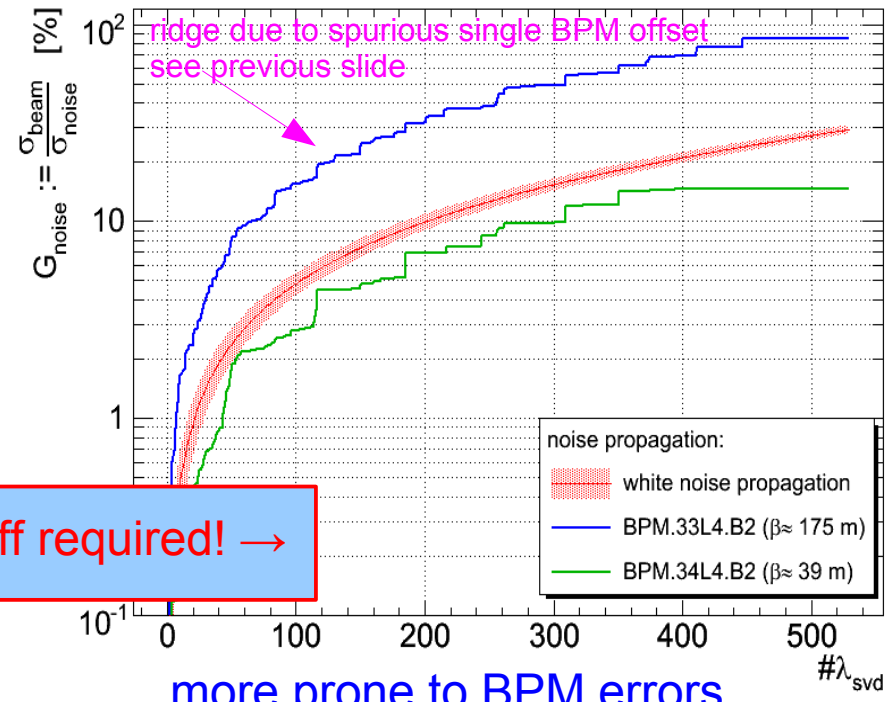
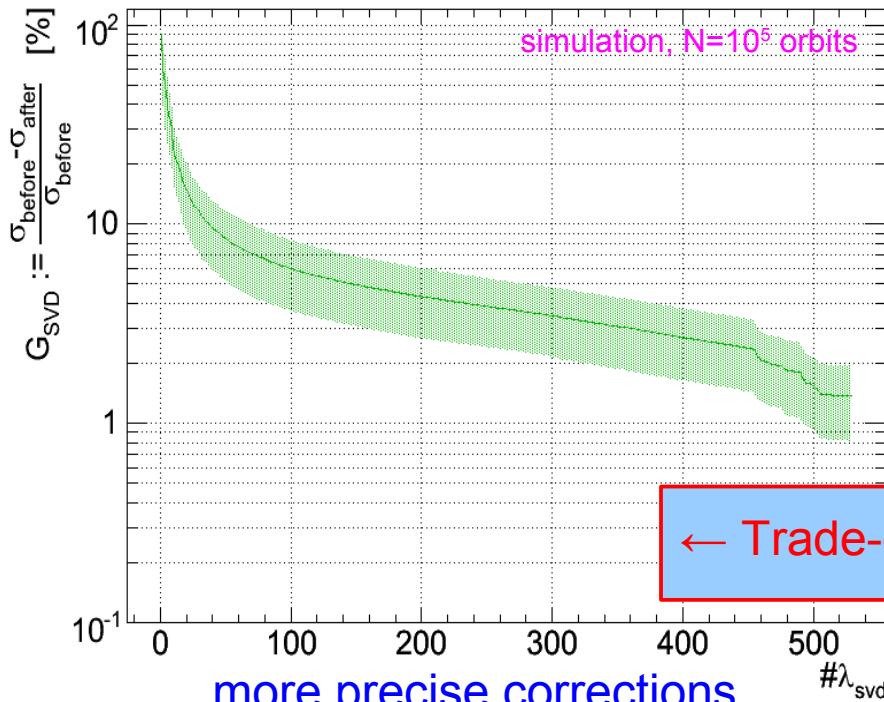
Example: Single BPM spike

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



Feedback Sensitivity to BPM Failure

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



← Trade-off required! →

more precise corrections →

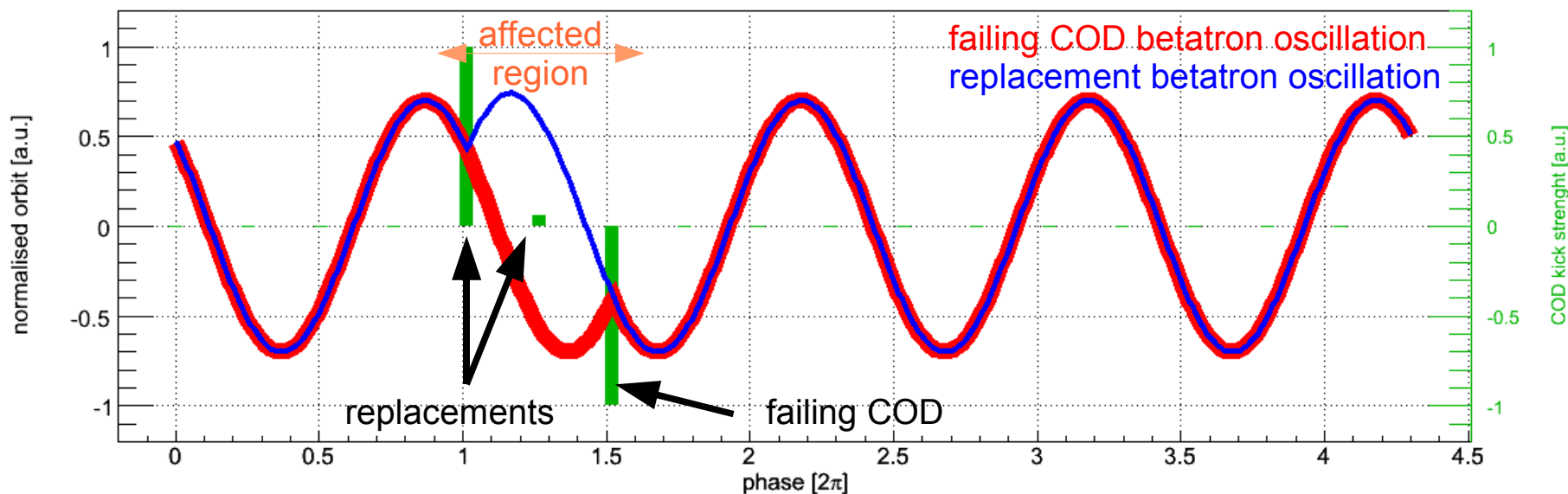
→ more prone to BPM errors



Compensation of failing Closed Orbit Dipole Magnets

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:

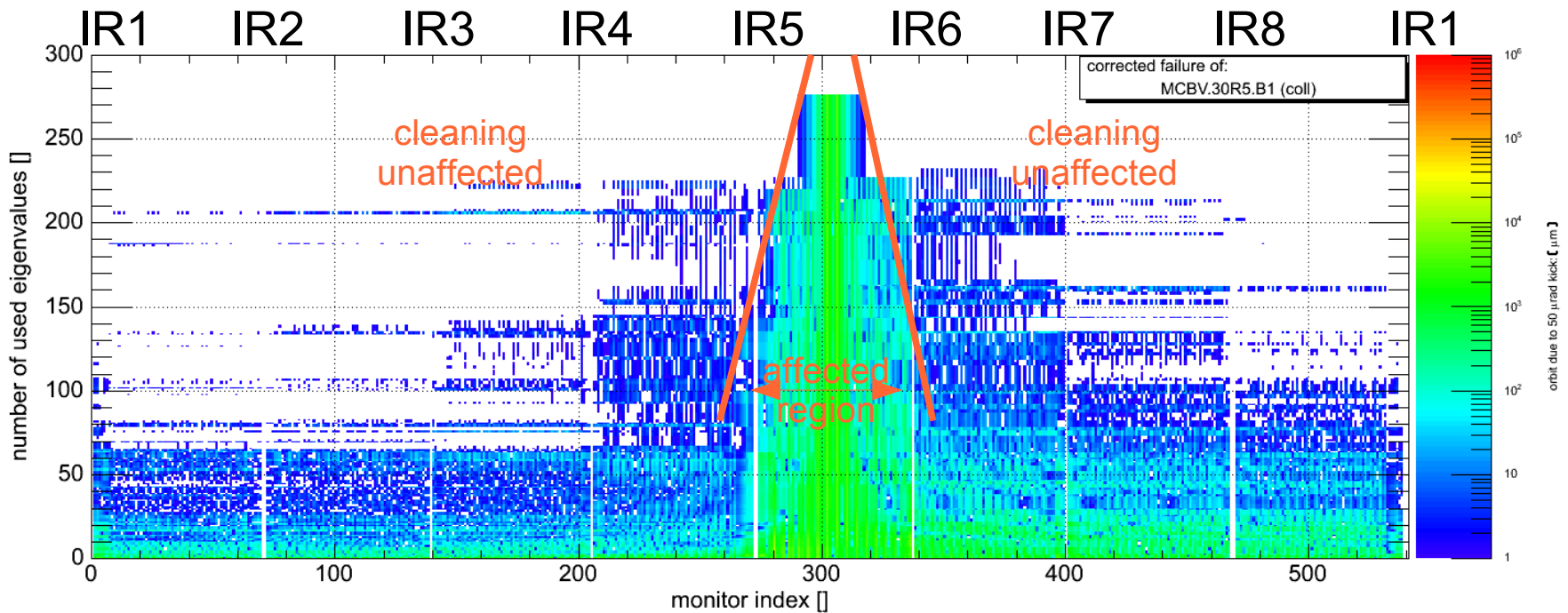


- Though a minimum two correctors are required, it is **favourable to spread replacement pattern over more CODs** (e.g. use intrinsic SVD property):
 - smaller maximum currents in the pattern
 - avoid hitting individual COD's maximum current
 - single COD failure becomes less critical
 - **faster reaction time since $\max \Delta I / \Delta t = n \cdot 0.5 \text{ A/s}$**
(total speed determined by time required to reach pattern's largest current)

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

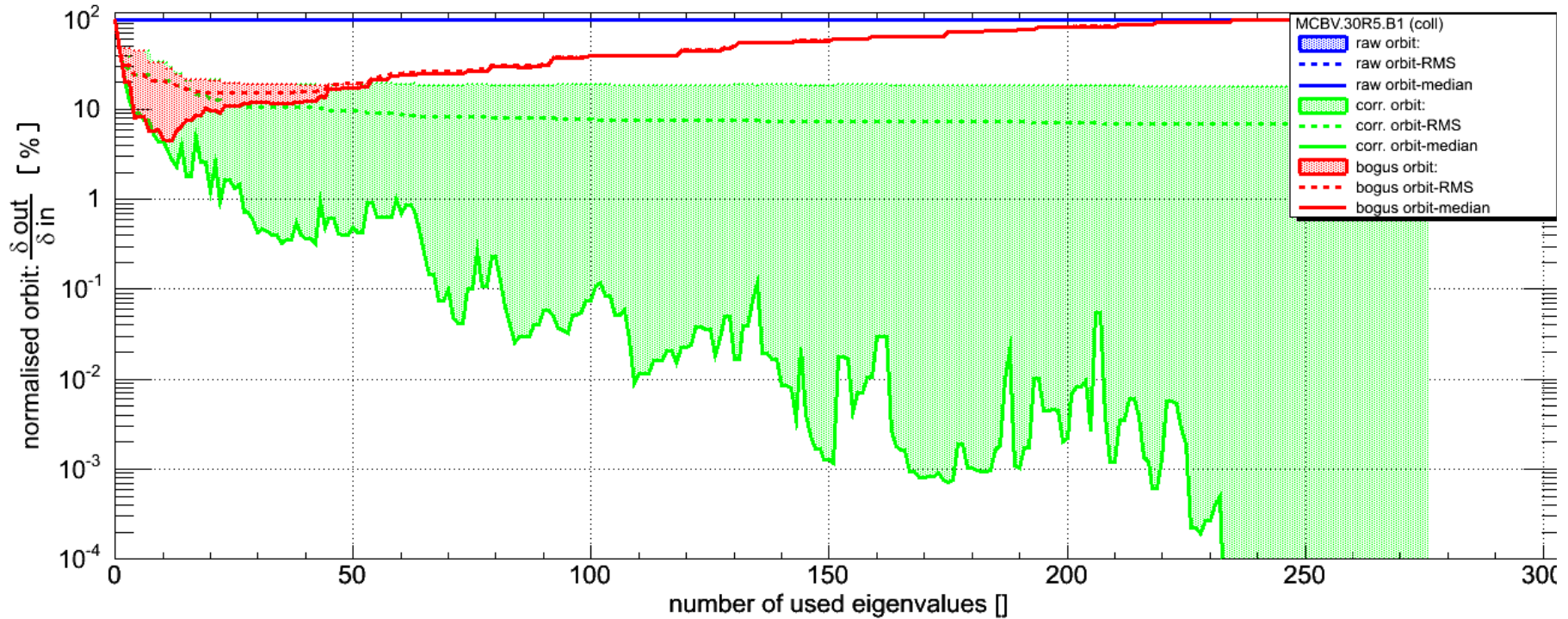
- Controller procedure:
 - If detected: Send the pre-calculated replacement pattern instead of the failing COD's $\Delta I(t)$ through the feed-forward path :
 - Procedure for the first few (milli-) seconds:
 - Mark COD
 - Temporarily disable BPMs (ZOH) in the adjoining region
(in order to be insensitive 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 ($\sim 15s/COD$)
 - 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.

- 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):



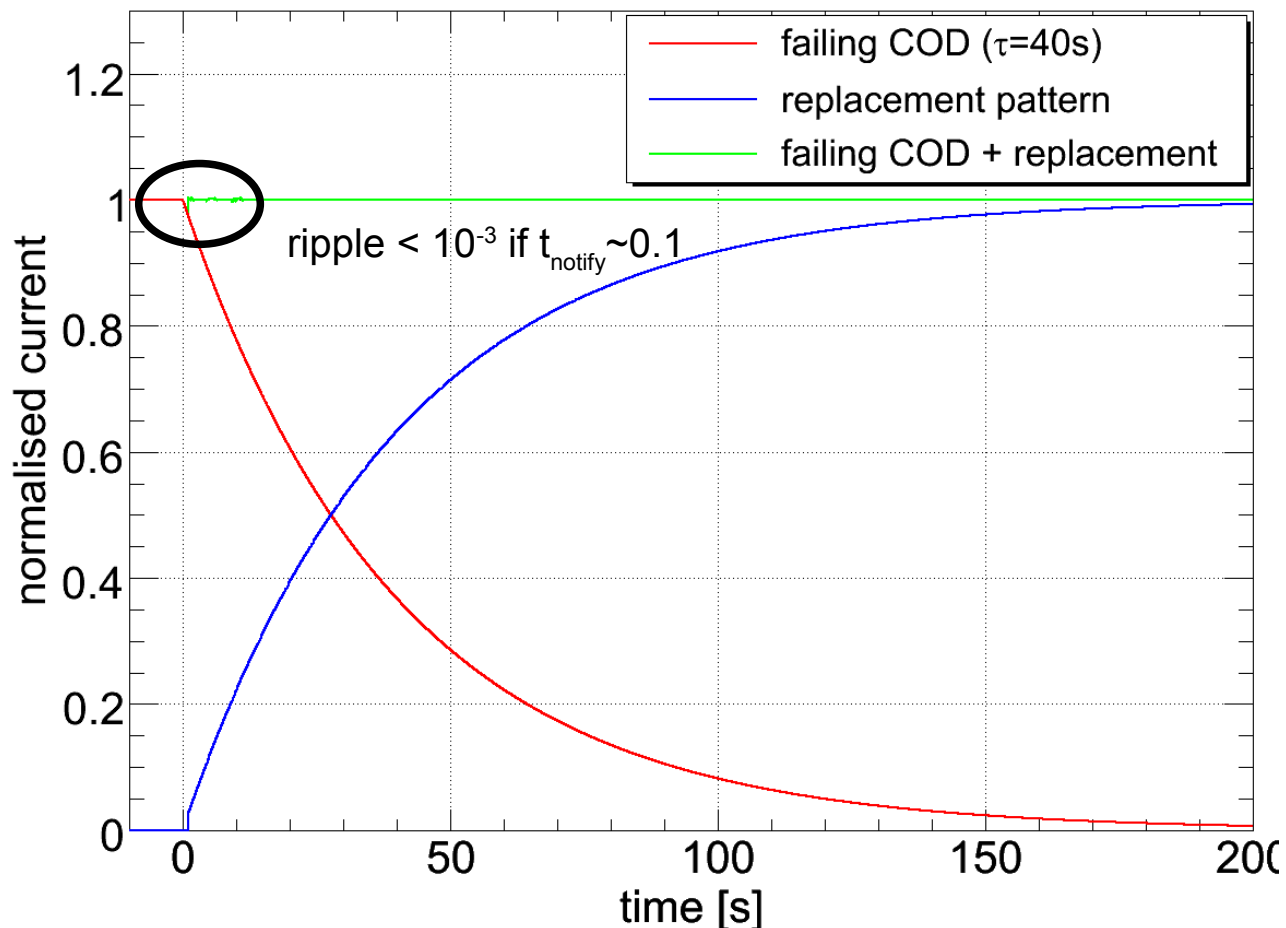
- since number of used eigenvalues and loop stability does not affect the feed-forward one may choose a large number of eigenvalues
 - Apart from transient, cleaning insertion is not affected by failing COD.

- For small $\#\lambda_{\text{SVD}}$ 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.

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

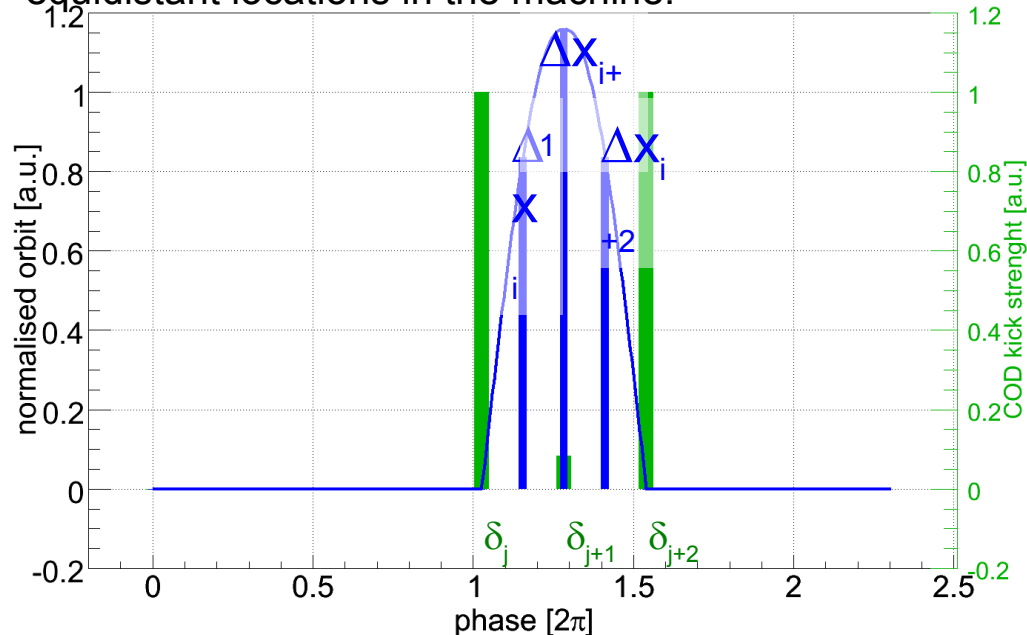


- The length of t_{notify} determines the ripple : $\sim '1-\exp(-t_{\text{notify}}/\tau)'$
- 1 Hz would be OK but will reuse already present 50Hz status feedback channel provided by the power converter gateways (S. Page, AB/PO)

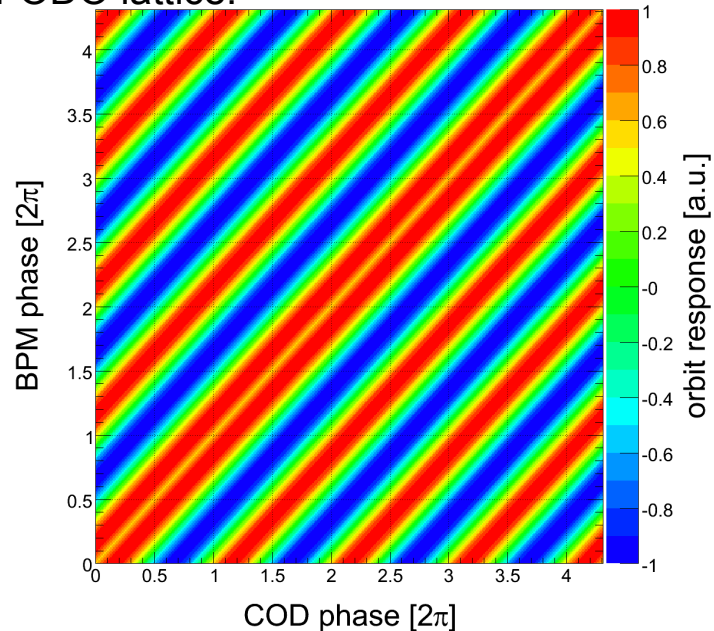


Automated Orbit Correction using Singular Value Decomposition

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 \underline{R} . It can be written as

$$\Delta x_i = \sum_{j=0}^n R_{ij} \cdot \delta_j \quad \text{with} \quad R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin(\pi Q)} \cdot \cos(\Delta \mu_{ij} - \pi Q)$$

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

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

Task in space domain:

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

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

• Singular Value Decomposition (SVD) is the preferred orbit feedback workhorse:

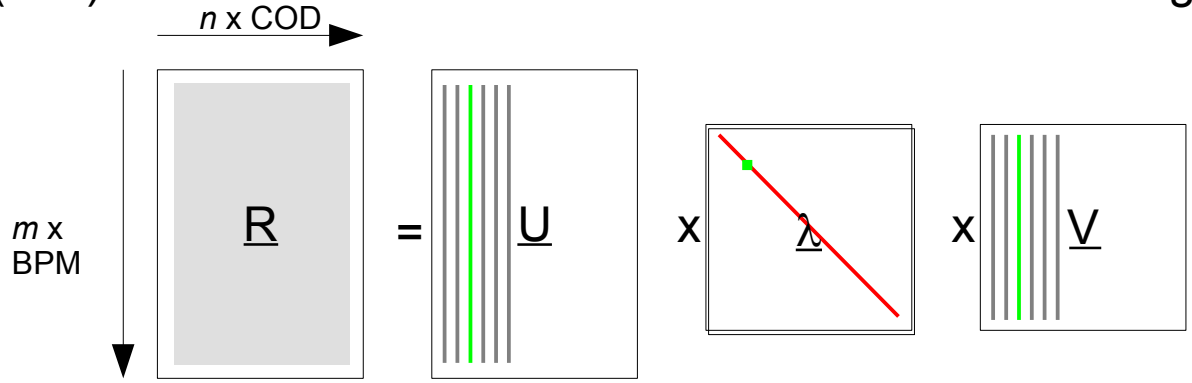
- standard and proven eigenvalue approach
- insensitive to COD/BPM faults and their configuration (e.g. spacing)
- minimises orbit deviations and COD strengths
- numerical robust:
 - guaranteed solution even if orbit response matrix is (nearly) singular (e.g. two CODs have similar orbit response \leftrightarrow two rows are (nearly) the same)
 - easy to identify and eliminate singular solutions

• high complexity:

- Gauss(MICADO): $O = \frac{1}{2} mn^2 + \frac{1}{6} n^3$
- 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: ~ 15 ms!)

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:

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

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

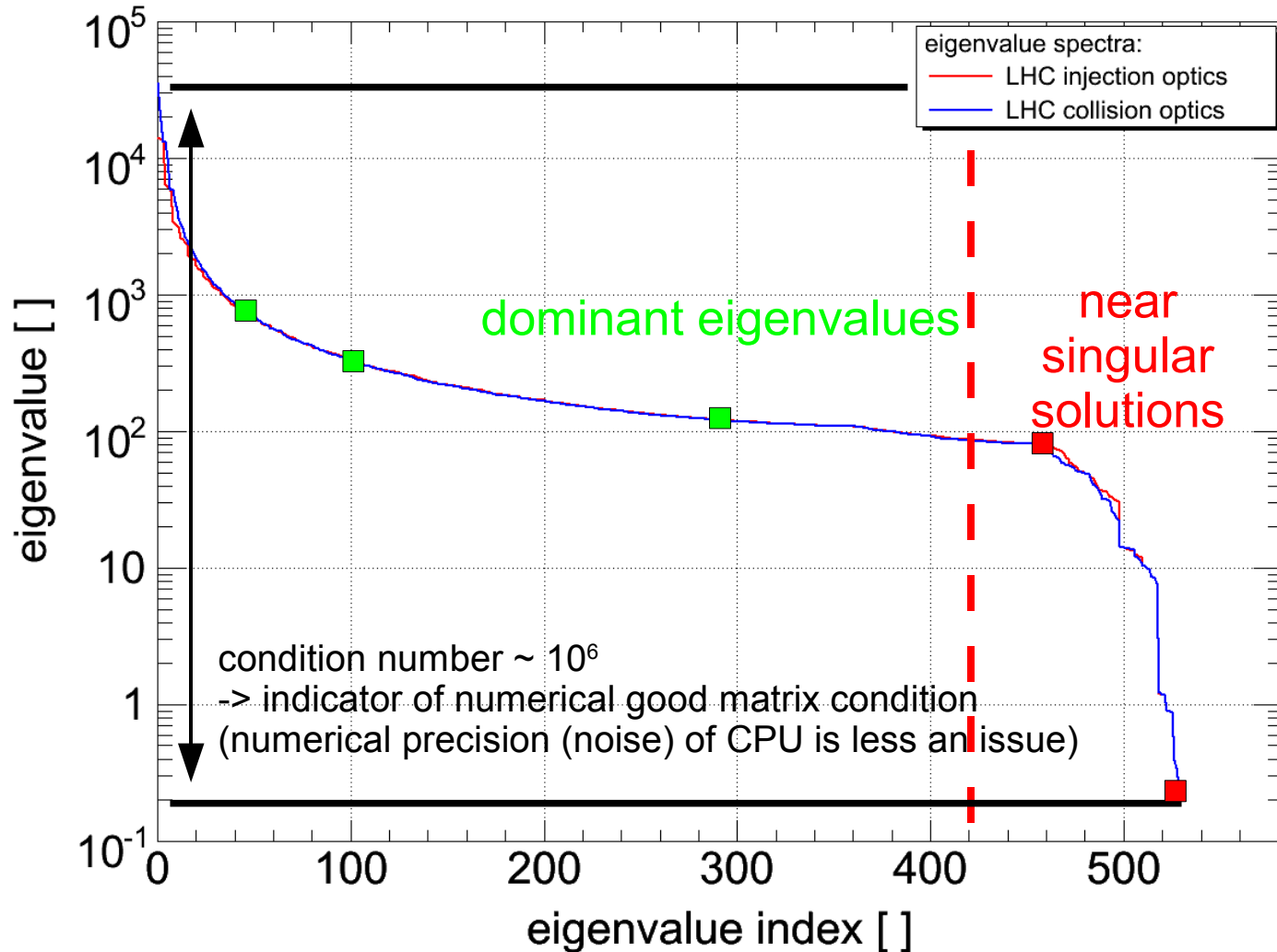
- final correction is a simple matrix multiplication
- large eigenvalues \leftrightarrow bumps with small COD strengths but large effect on orbit

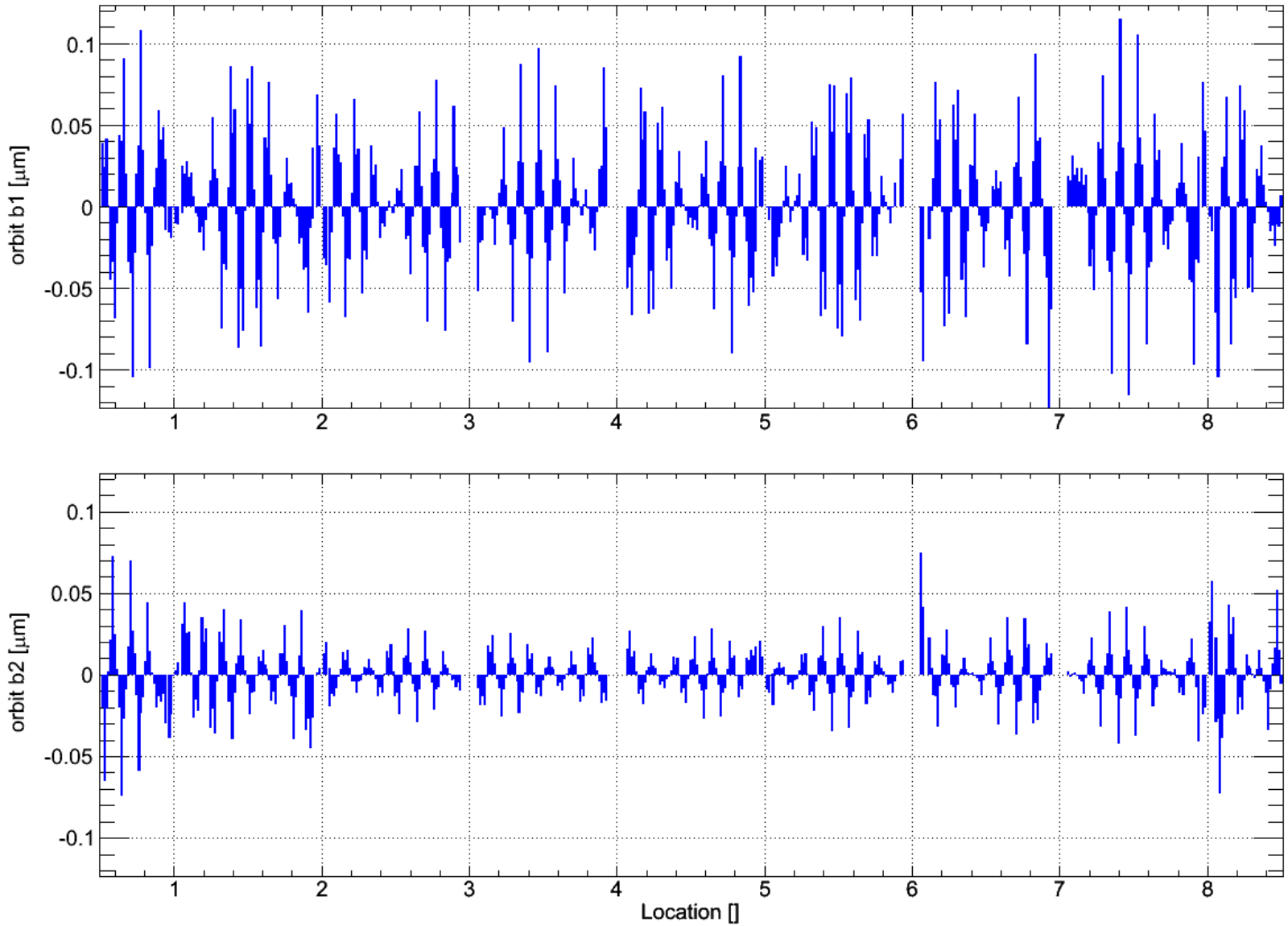
$$\delta_{ss} = \tilde{R}^{-1} \cdot \Delta \vec{x} \quad \text{with} \quad \tilde{R}^{-1} = \underline{V} \cdot \underline{\Lambda}^{-1} \cdot \underline{U}^T \quad \Leftrightarrow \quad \delta_{ss} = \sum_{i=0}^n \frac{a_i}{\lambda_i} \vec{v}_i \quad \text{with} \quad a_i = \vec{u}_i^T \Delta \vec{x}$$

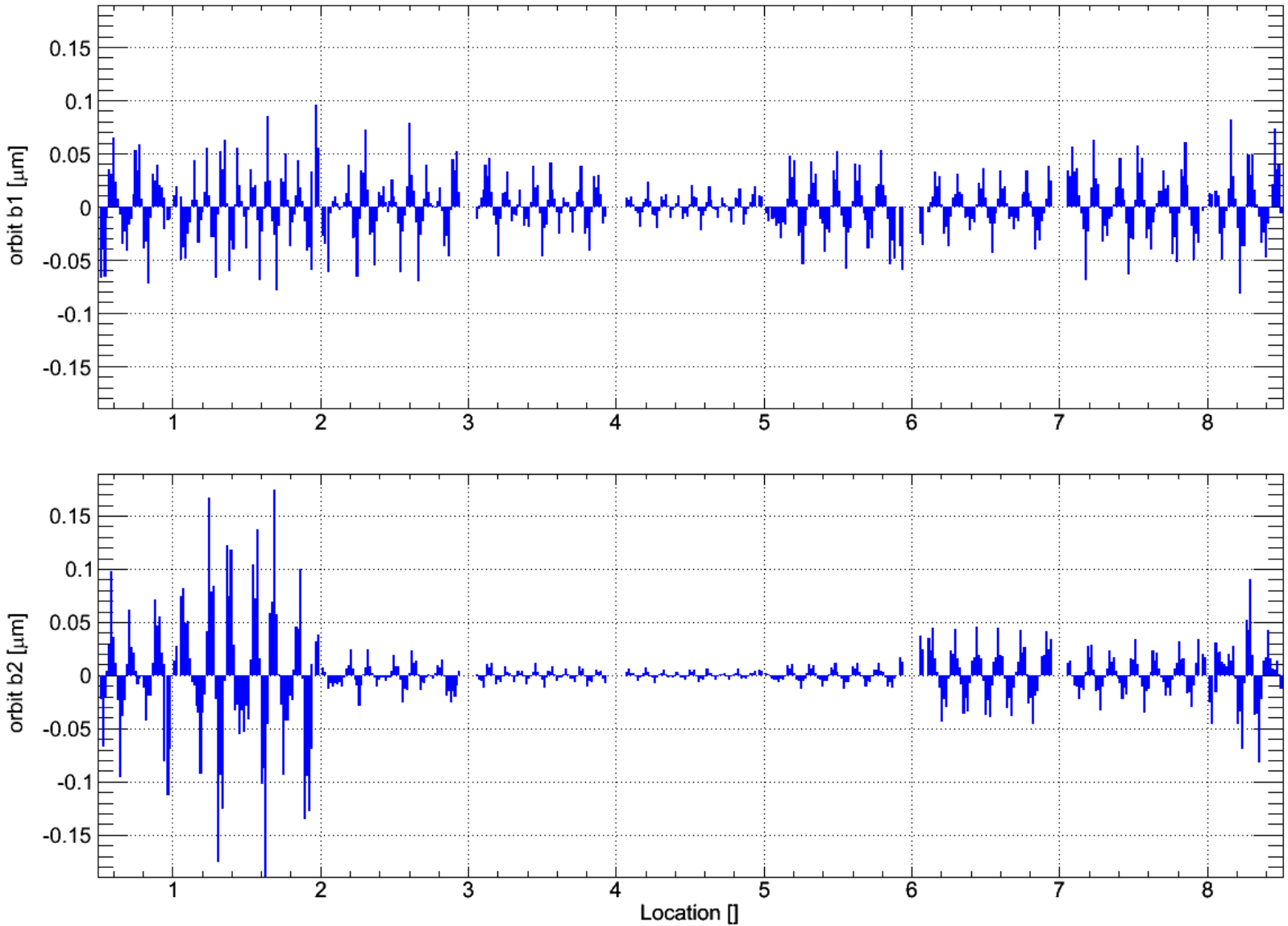
- Easy removal of singular (=undesired, large corrector strengths) eigen-values/solutions:
 - near singular eigen-solutions have $\lambda_i \sim 0$ or $\lambda_i = 0$
 - to remove those solution: $\lim_{\lambda_i \rightarrow \infty} 1/\lambda_i = 0$
- **discarded eigenvalues corresponds to bumps that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

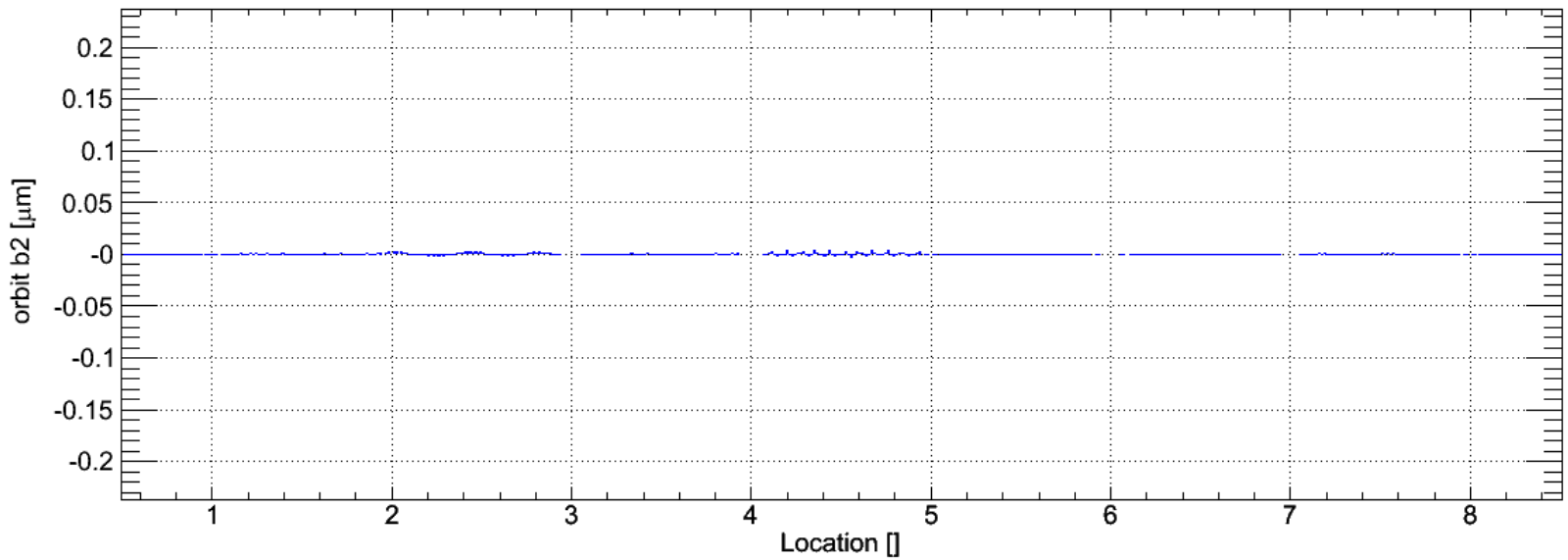
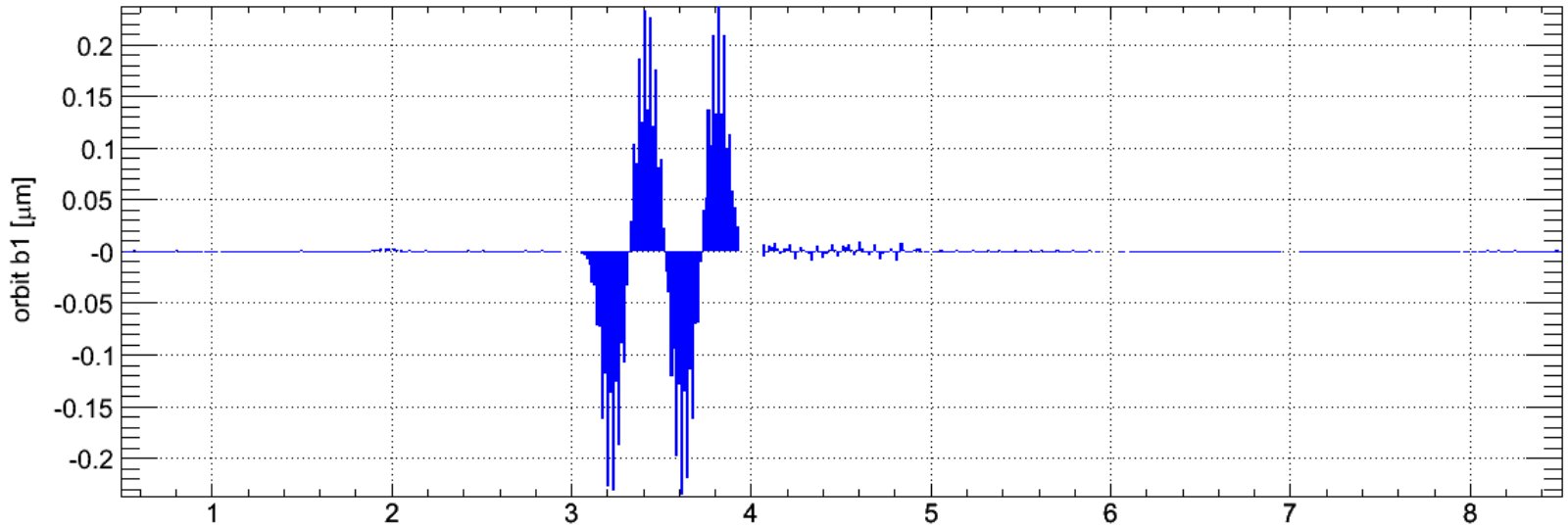
*G. Golub and C. Reinsch, “Handbook for automatic computation II, Linear Algebra”, Springer, NY, 1971

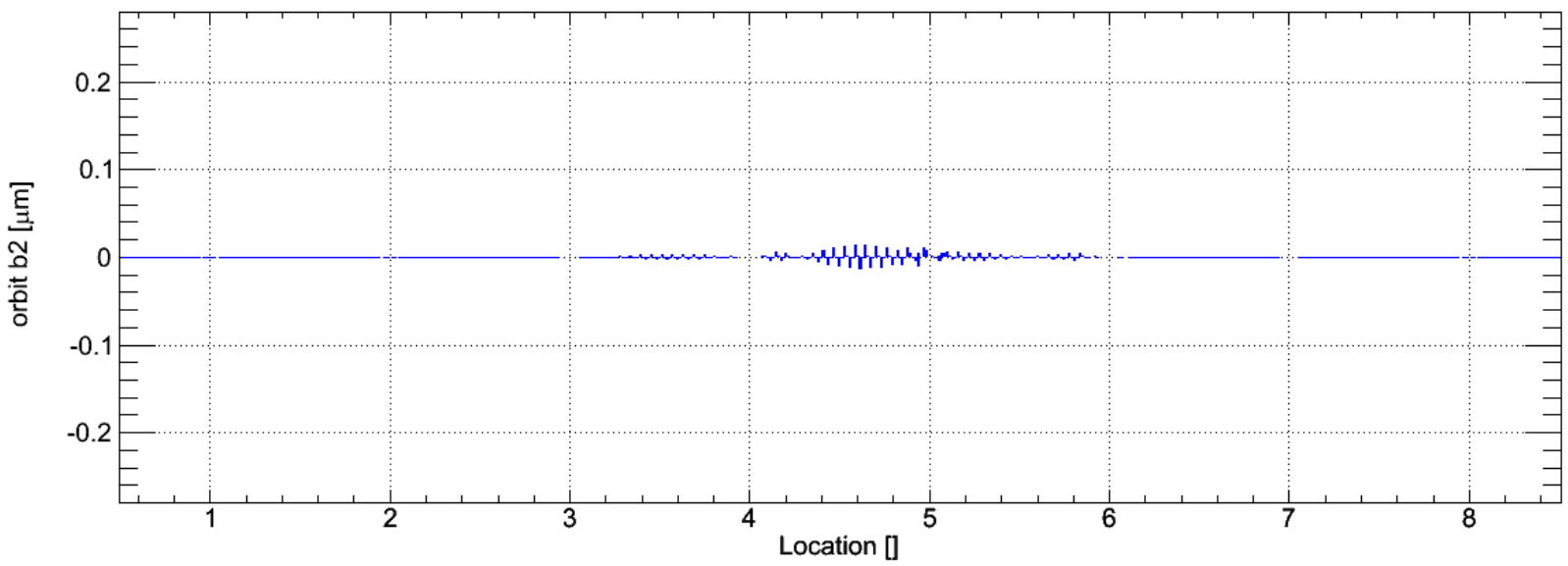
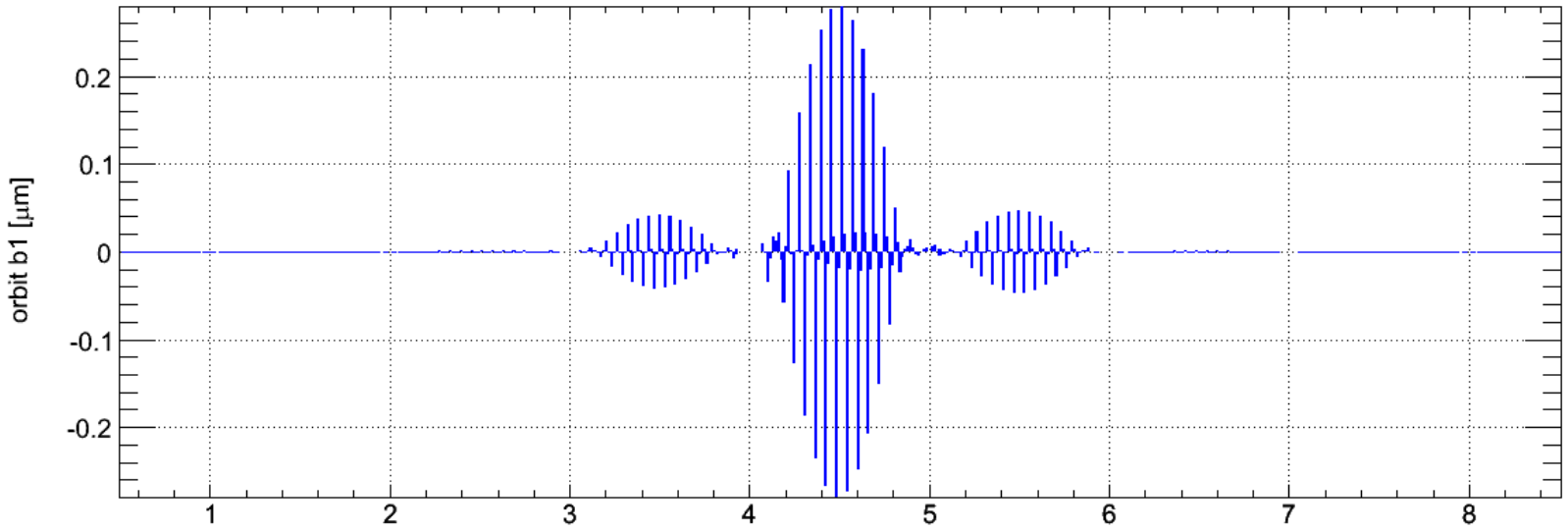
Eigenvalue spectra for vertical LHC response matrix using all BPM and COD:

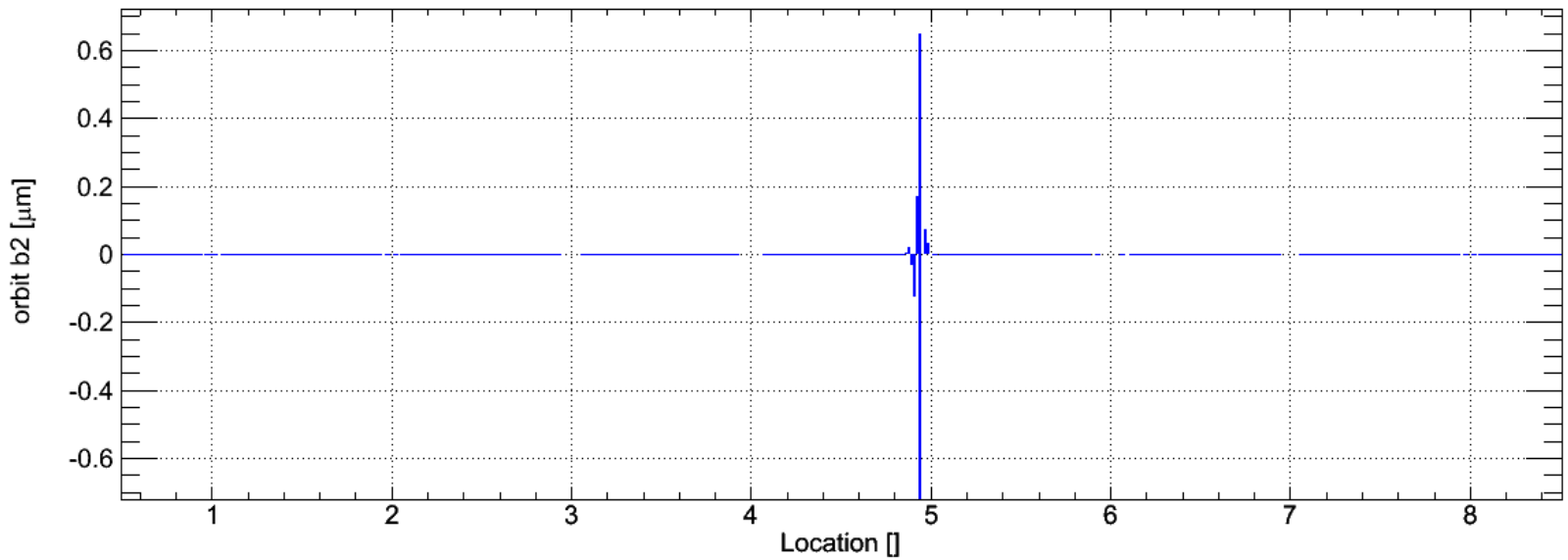
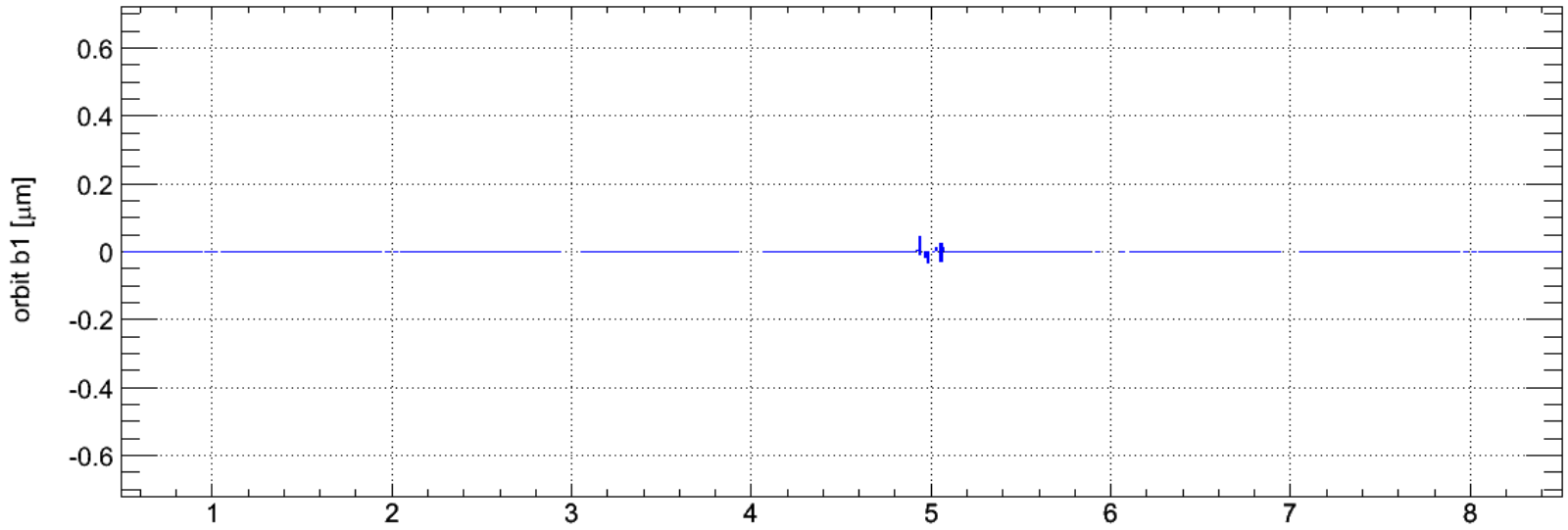












Gretchen Frage: "How many eigenvalues should one use?"

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

- 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 ($\omega = 1 \dots 10$)

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



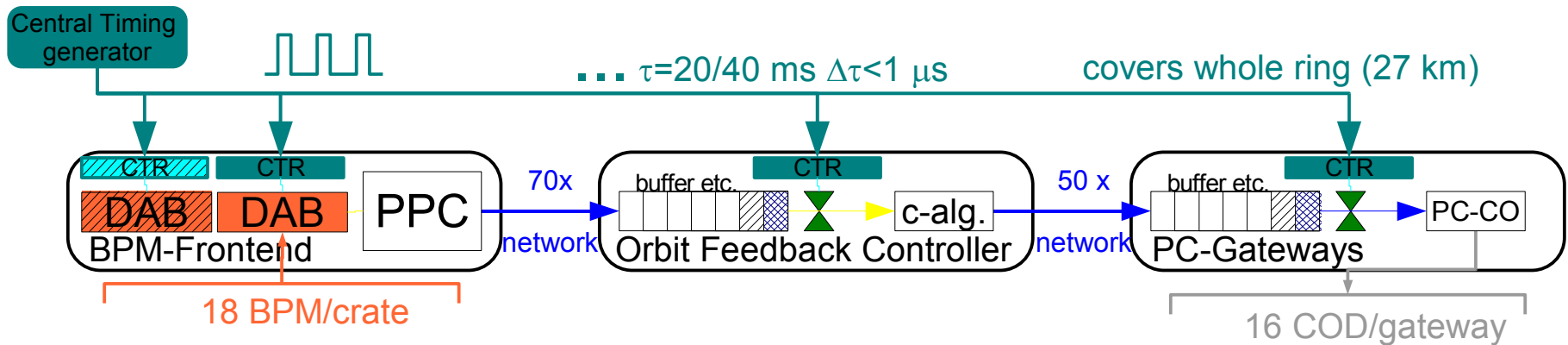
free orbit manipulation (within limits) while still globally correcting the orbit

Miscellaneous Slides ahead

- 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

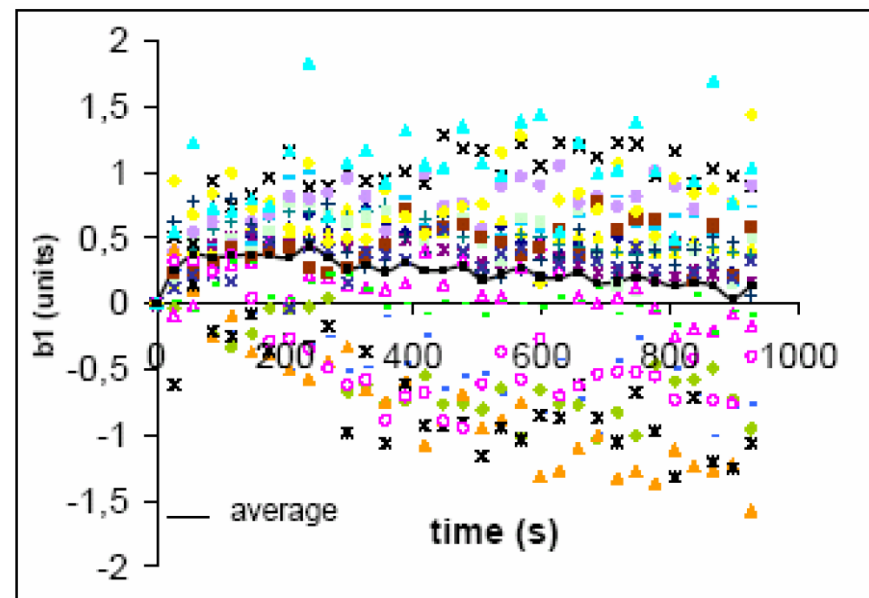
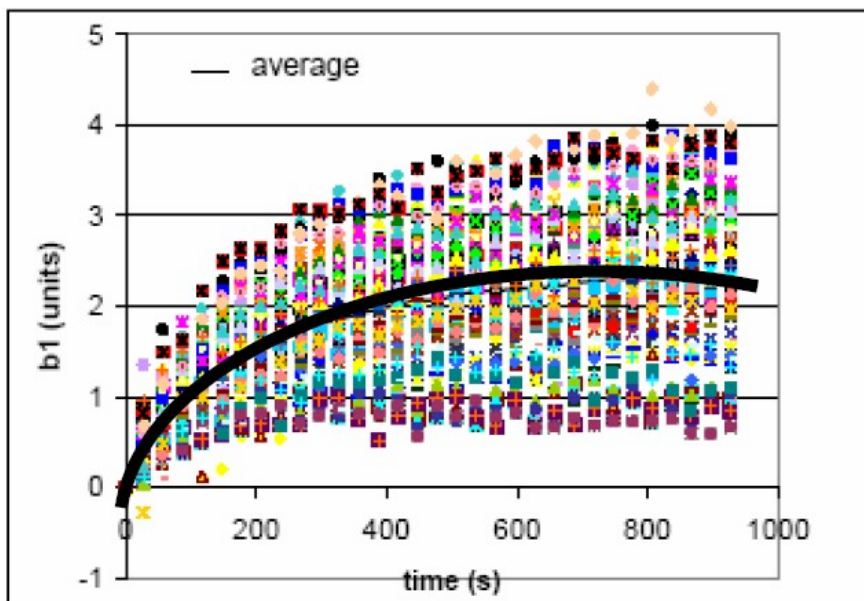
Two main strategies:

- 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:

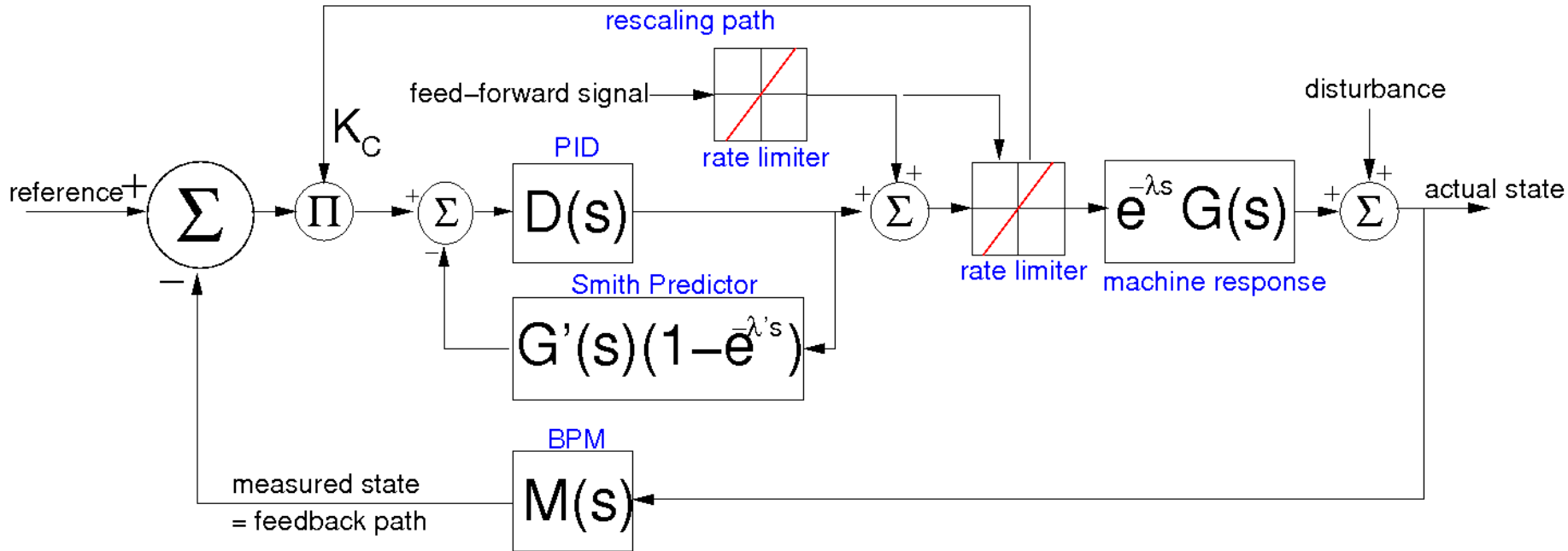


random b_3 → negligible effect
 systematic b_3 → seem to be reproducible
 → constant feed-forward function may be established at some point of time

random b_1 → perturbs orbit
 systematic b_1 → $\Delta p/p$ 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)

What a Smith-Predictor compensates:

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

