Beam-Based Feedbacks and Machine Protection

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for the BI-QP team:
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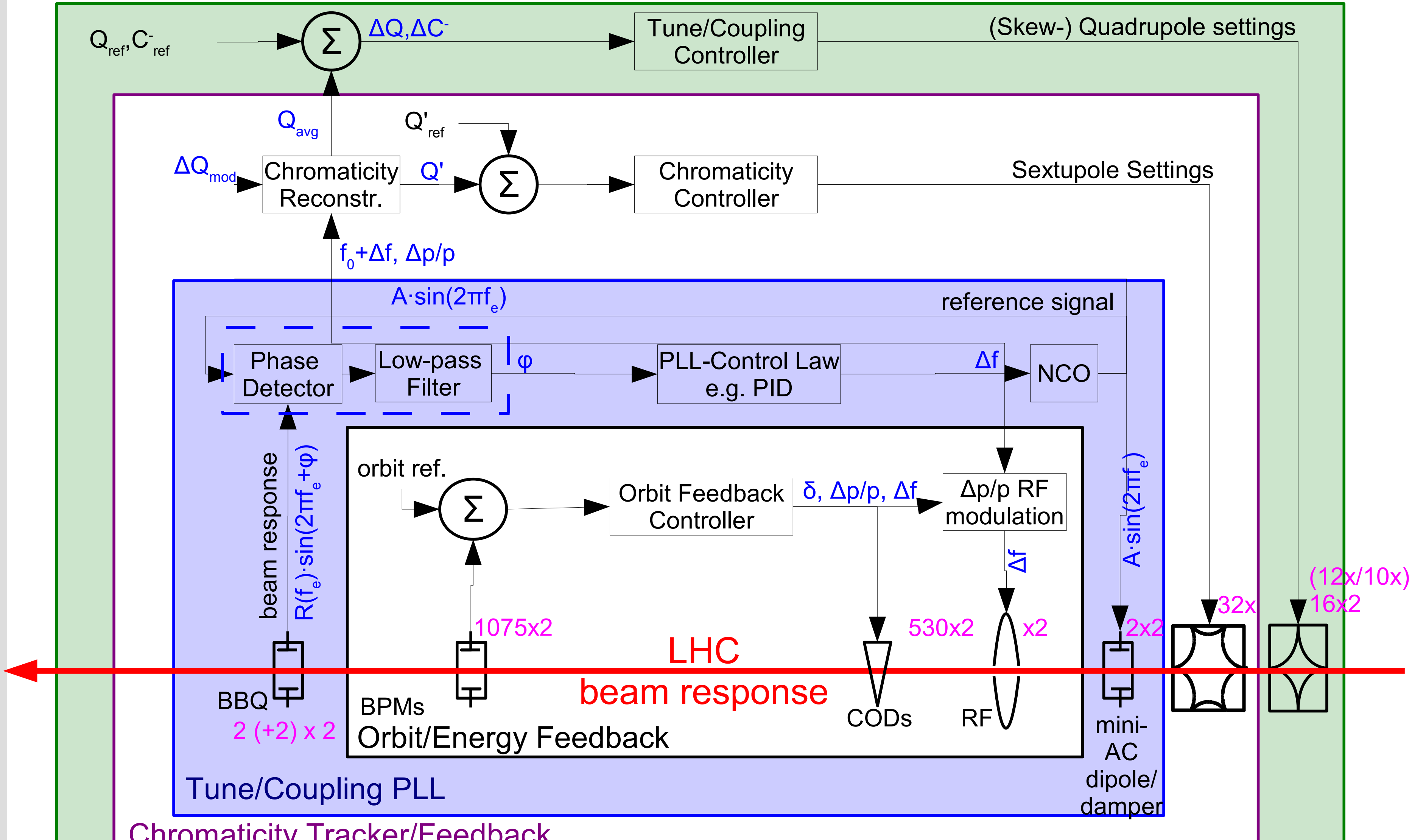
Outline

- Brief System Overview and Dependence
- Internal vs. External Feedback Failures
- Some comments on orbit correction
- BPM 'errors' and 'faults'/'failures' and identification of these
  - pre-checks without beam before every run
  - pre-checks with Pilot beam at the start of every run
  - continuous monitoring during LHC Orbit Feedback operation

Full LHC Beam-Based Control Scheme – The Beast



further: $f_{BW}(PLL) \gg f_{BW}(Q') \geq f_{BW}(Q, C^-)$

Feedbacks and System Reliability I/V

- Beam-based feedbacks are not single entities but involves more than 3300 devices/sub-systems:
  - Most of them are BPMs and BBQ-based systems (>3400 inputs),
  - Corrector circuits, RF cavities, ADT (>1300 outputs), and
  - Feedback controller (OFC) and it's service unit (OFSU ≈ “CMW proxy”)

- Total system performance and reliability is only as good as its weakest link
  - any non-intercepted single device failure can lead to an immediate feedback system failure → losses, compromised machine protection
  - FB controller intercepts some errors but is not responsible for all its inputs
  - “similarities” with B. Todd's MPS-related credo: reliability of interlock system vs. user inputs

- In terms of relative reliability OFC itself is very stable:
  - much less than 1 crash/month (last: 2nd of May)
  - last critical failure: Nov.'09 (rogue RT packets)
  - Last corrected combined failure-mode: B2 dispersion orbit & Q' measurement

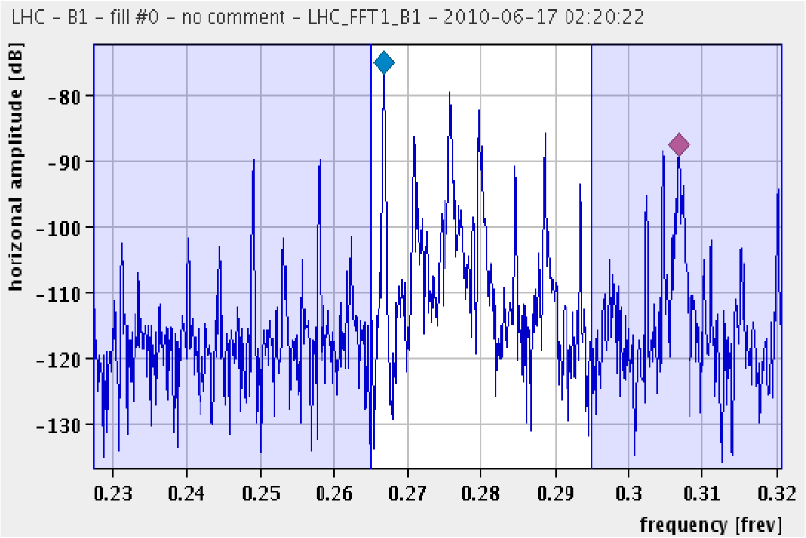
Feedback System Reliability II/V
Impact of Beam Instrumentation

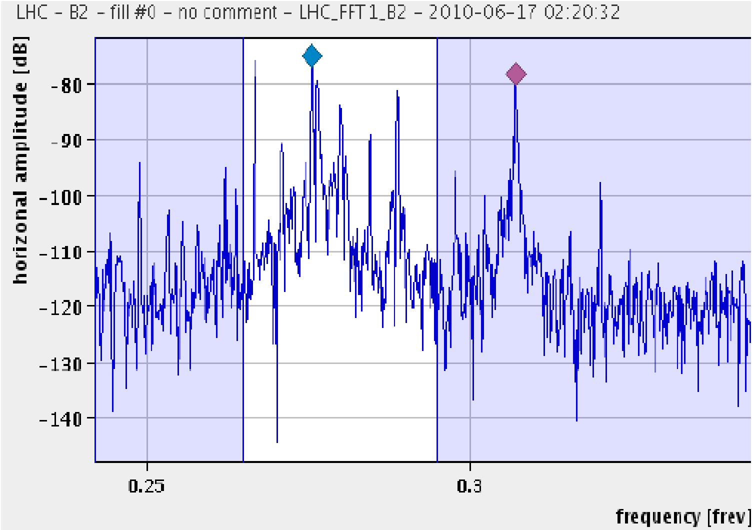
- Most BI equipments were designed having in mind that they shall
  - improve operational efficiency but not as machine safety critical elements
    - notable exception: beam loss monitors
  - Underlying design hypothesis:
    - “measure and correct large(r) errors during machine setup periods”
    - “monitor the performance during regular operation”

- However, even non-safety devices became de-facto safety critical elements
  - Beam position monitors (via OFB and interlocks), Q/Q' diagnostics, …
    - Interdependency issue: same BPMs used for steering and Interlocks
  - Issue: hard to test since signals are not simple voltage or current signals
    - complex/require a substantial amount of numerical post-processing
    - only available with beam and strongly dependent on machine cond.
  - Safety critical elements now rely on feedbacks, e.g.
    - Collimation on orbit
    - Transverse damper on tune
      (becomes anti-damper if tune/noise is outside its filter window)

Feedback System Reliability III/V
Example: Q/Q' Diagnostics Input to the Tune-FB

- BBQ provides enormous state-of-the art signal-to-noise ratio, enabling Q/Q' diagnostics using only passive beam oscillations
  - generally considered as “robust” → the good (times (95 % of the times)
  - However, e.g. Mirko this night: “Tune is horrible for both beams in H...”

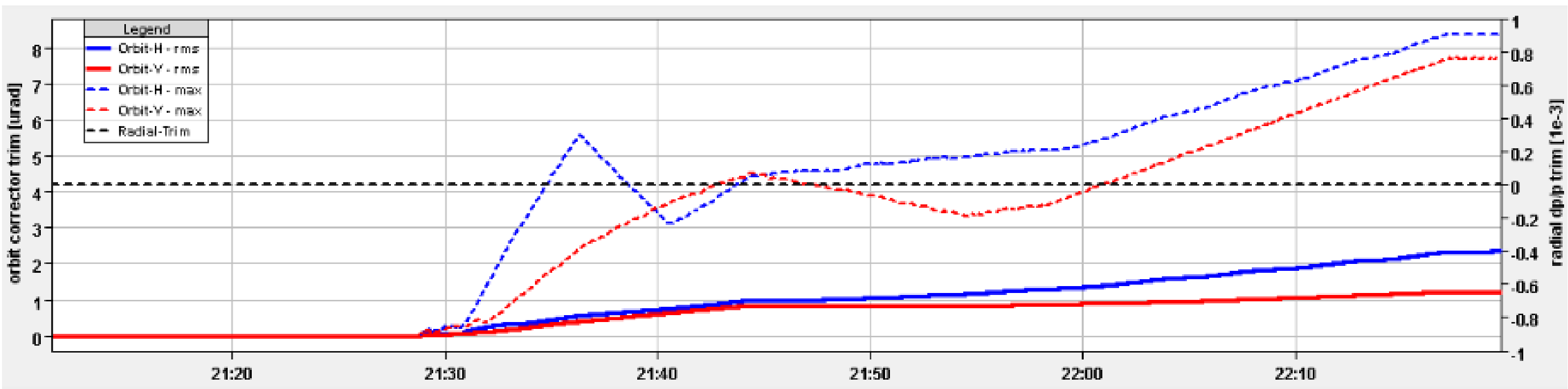




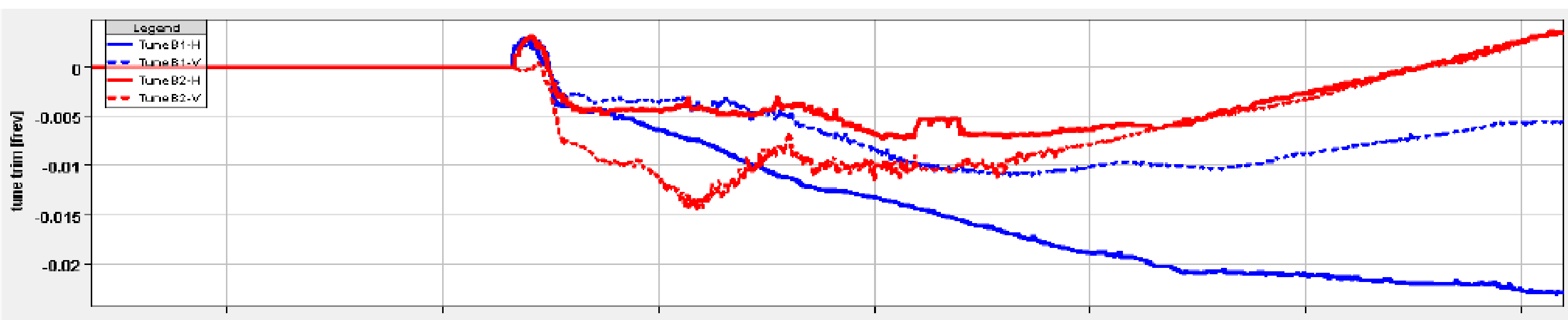
- Obviously, we are constantly improving the situation (e.g. new tune fitter)
- Still, there is no performance or reliability guarantee
  - ability to measure Q/Q' without exciting the beam
  - dependence on many external factors: operators, RF system, general beam operation, ...

Feedback System Reliability IV/IV
Example: Operation and MPS dependence on Feedbacks

- Design hypothesis violated by machine operation de-facto relying/depending on feedbacks on a day-to-day basis to meet machine stability targets
  - Without: beam losses/lost during ramp with pilot/nominal bunch intensities
- Example: Orbit-FB corrected peak orbit of ~ 1 mm (≈ 10x collimator requirements)



- Example: Tune-FB trims exceed required stability ten-fold



- Surprisingly: Q' seems to fairly reproducible and (now) well under control...

Feedback System Reliability V/V

Two categories of failures:

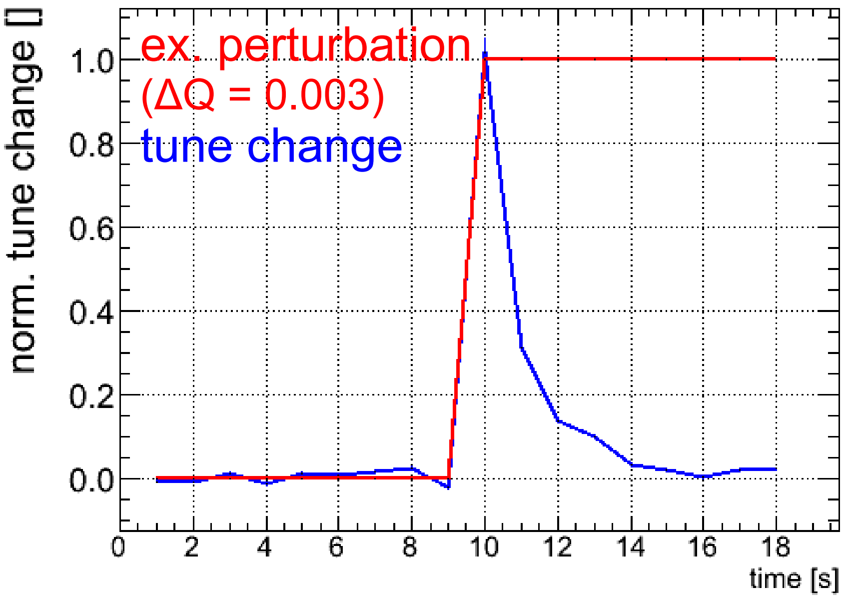
- Internal feedback controller failures, e.g.
  - feedback logic, correction algorithm, configuration/reference errors, etc.
  - easily tested via closed loop transfer function:
    - stable closed-loop ↔ internal logic is OK
    - only a few 'if-else' conditions

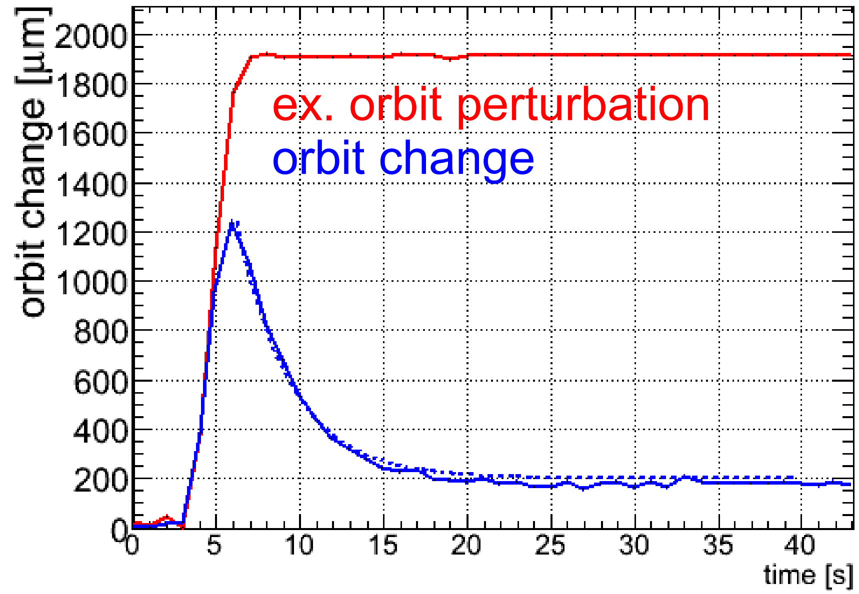
  → checks done for every new OFC and optics release

- External errors and faults of input and/or output sub-systems, e.g.
  - Timing information distribution errors (software libraries, FESA, …)
    - beam energy, beam-presence flag, machine mode
  - Circuit errors (rare)
    - Non-notified/disabled RT trims and circuits
    - QPS: false-positive interpretation of real-time trims as “quench”
  - 'Bad' BPMs, incorrect Q/Q' (beam spectrum issues)
  - Not respected or incorrect operational procedures

Checks of Internal Feedback Controller Failures - Example

- Operational check to test feedback functionality

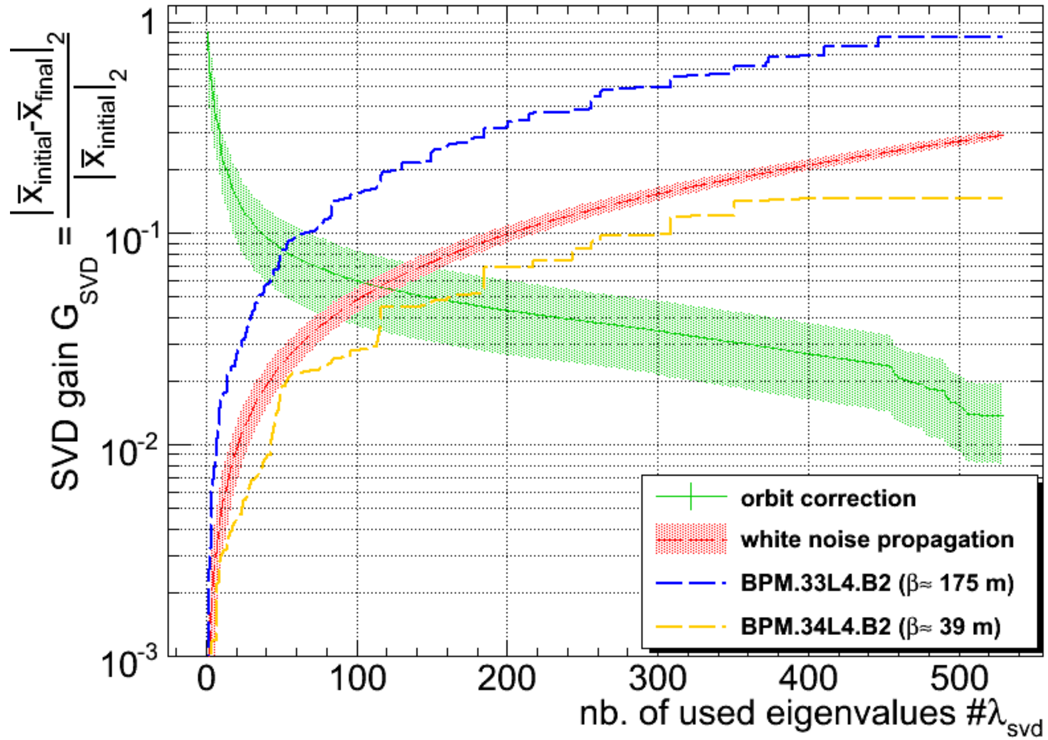




- FB response 1/e - time constants:
  – Tune: 1..2 s ↔ ~ 0.1..0.3 Hz BW (depending on fitting limits)
  – Orbit-FB & Radial-loop: 3.3 s ↔ 0.1 Hz BW
    - 200 um steady-state error due to using only 400/520 eigenvalues
    - Error detected: fixed dispersion orbit compensation that was not working for B2
- Stable closed-loop ↔ internal feedback logic is OK

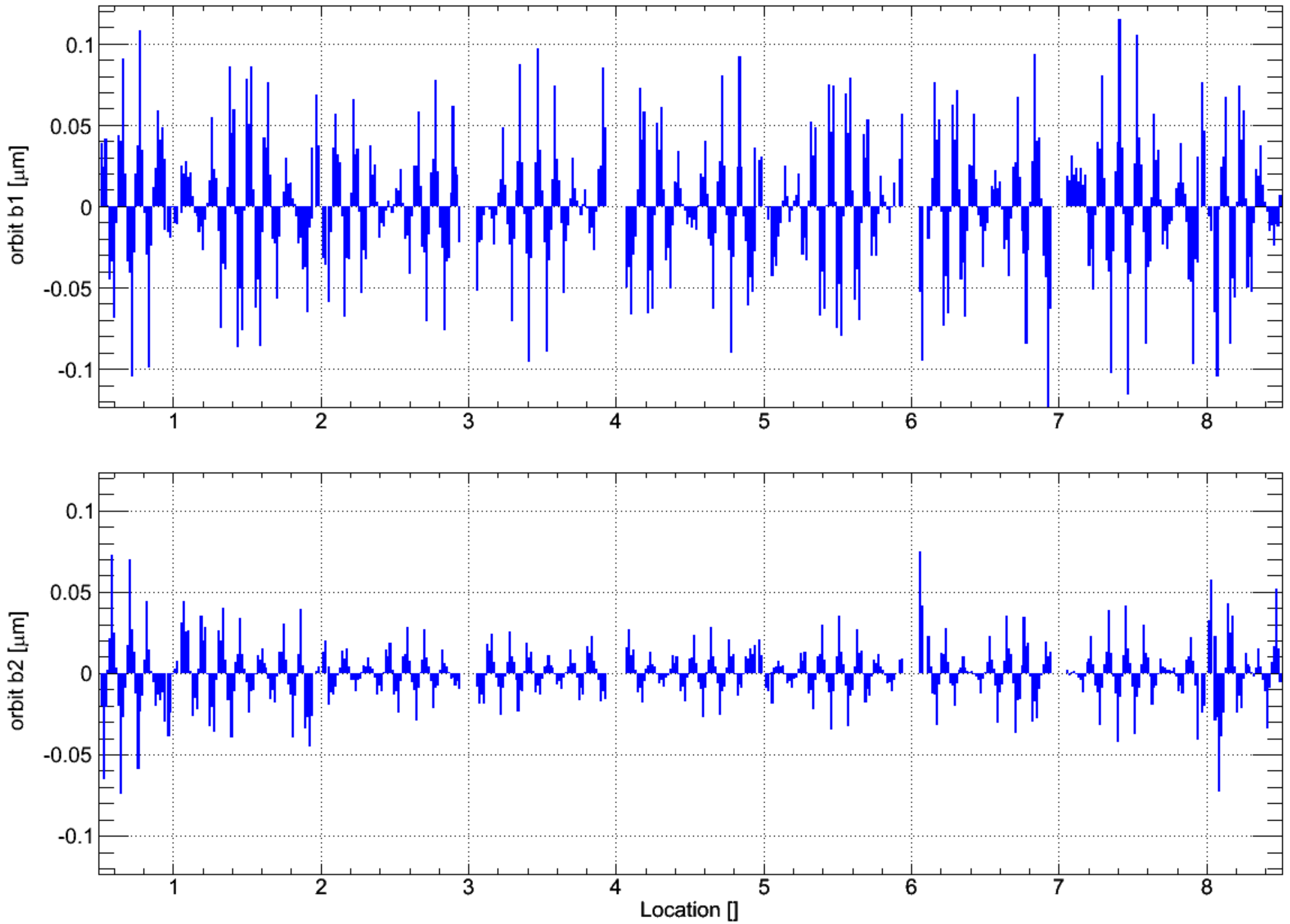
Orbit Attenuation Performance vs. Noise Propagation

- Orbit attenuation vs. sensitivity to BPM failures:



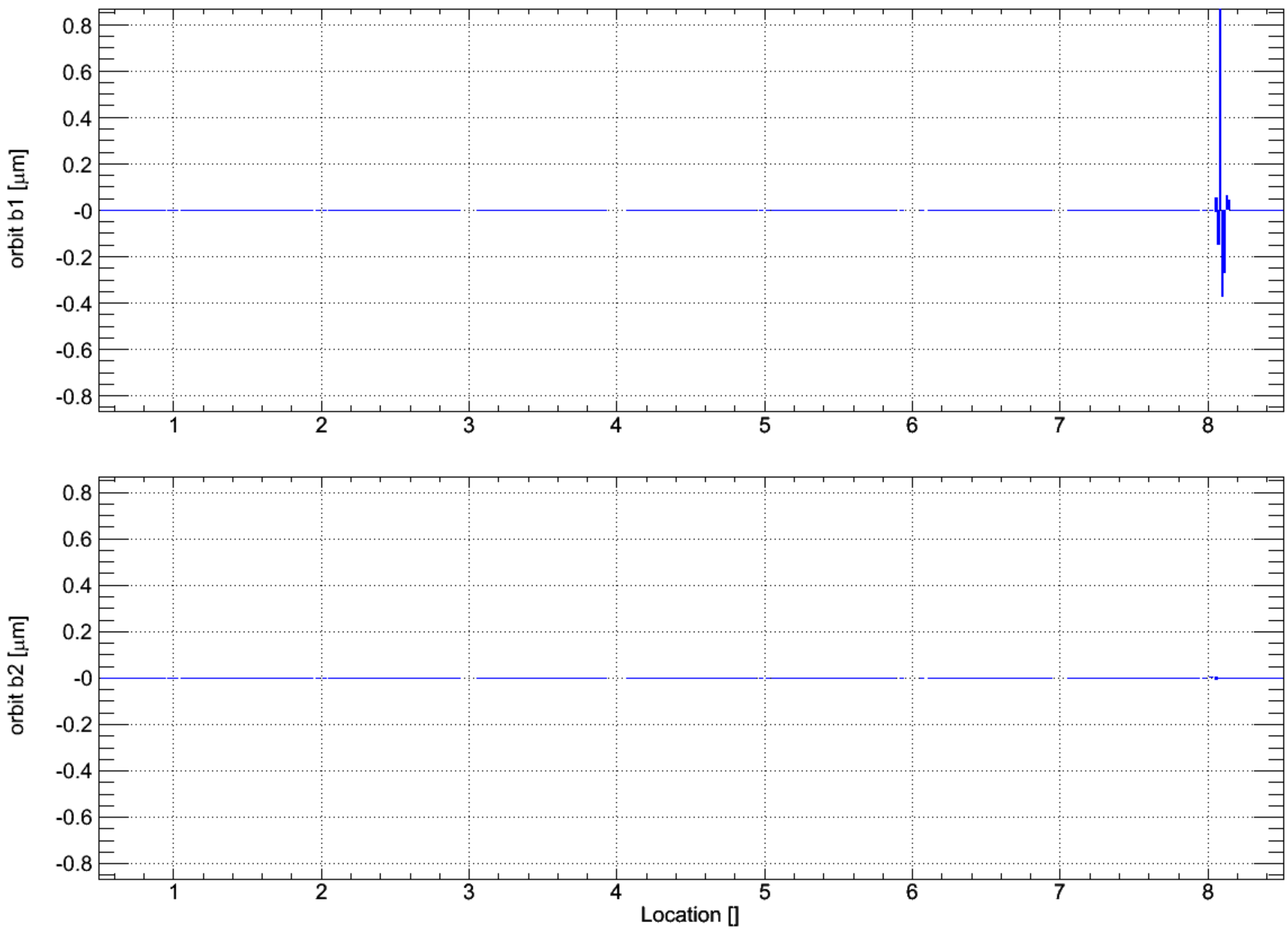
- $\#\lambda_{SVD}$ steers locality versus robustness of orbit correction algorithm
  - soft global requirements but also strong local requirements (collimation)
- Discarded eigenvalues relate to orbit patterns that are not corrected by the FB
- Issue: choice of number of eigenvalues is less obvious:
  - Want a robust but also local correction ↔ choice affects protection
    → $\#\lambda_{SVD}$ is not a free choice or operational play parameter!

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



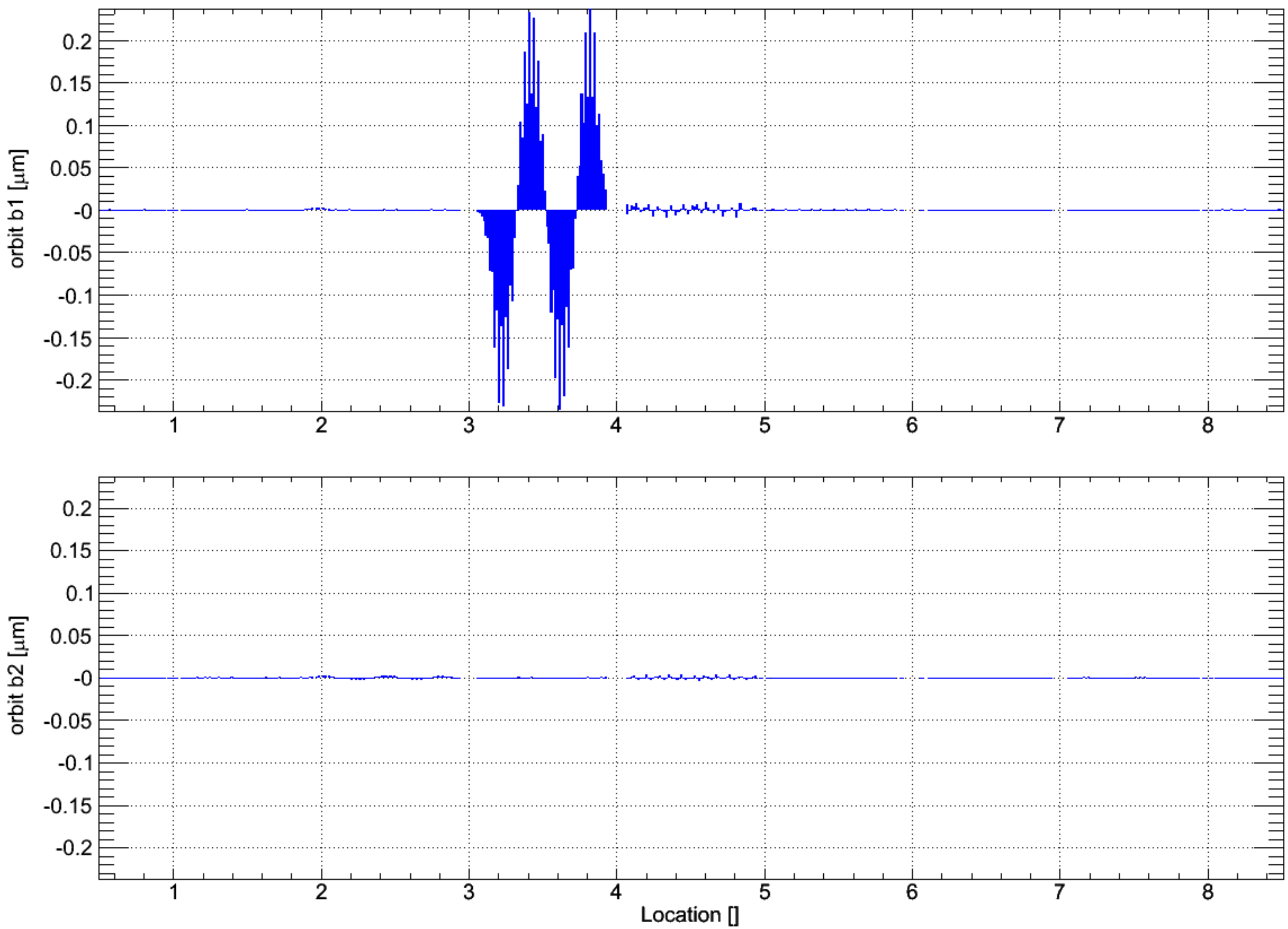
Of course, we do want to use this pattern/eigenvector!!

Feedback Response
LHC BPM eigenvector #529 λ_{529}= 21



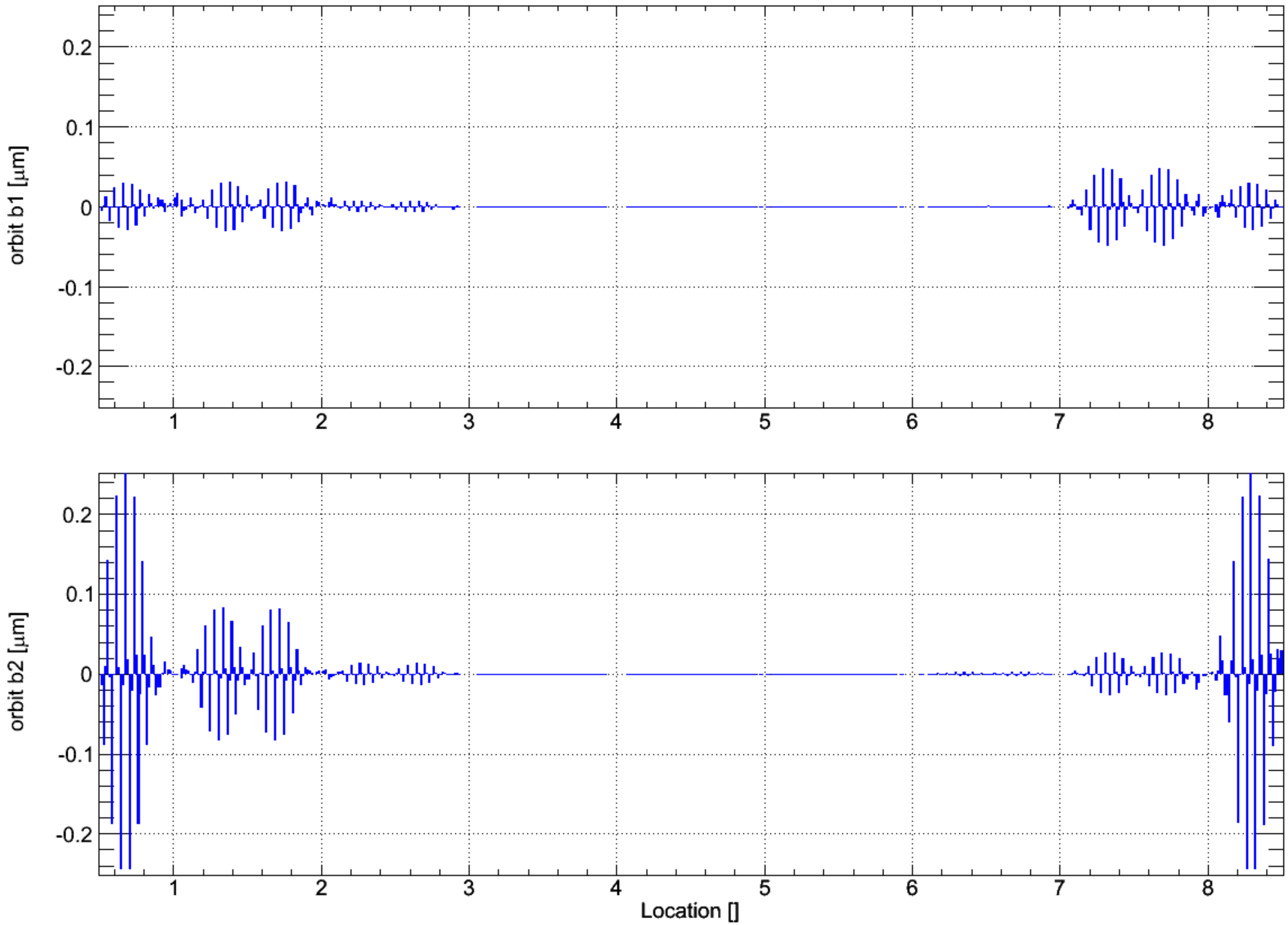
Of course, we do not want to correct for this eigenvector!!

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



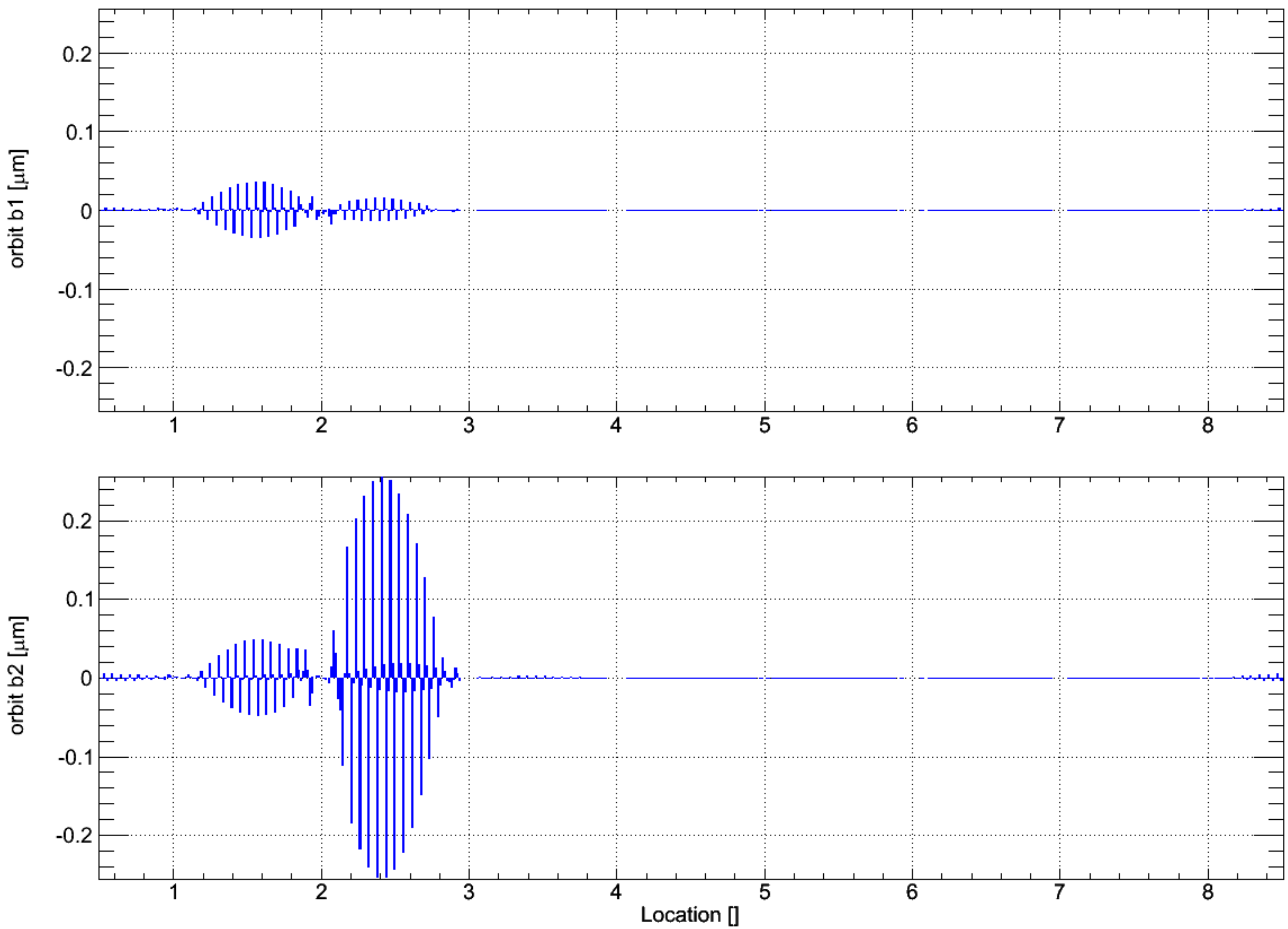
Looks a bit strange .... maybe not...

Feedback Response
LHC BPM eigenvector #439 λ_{439}= 83



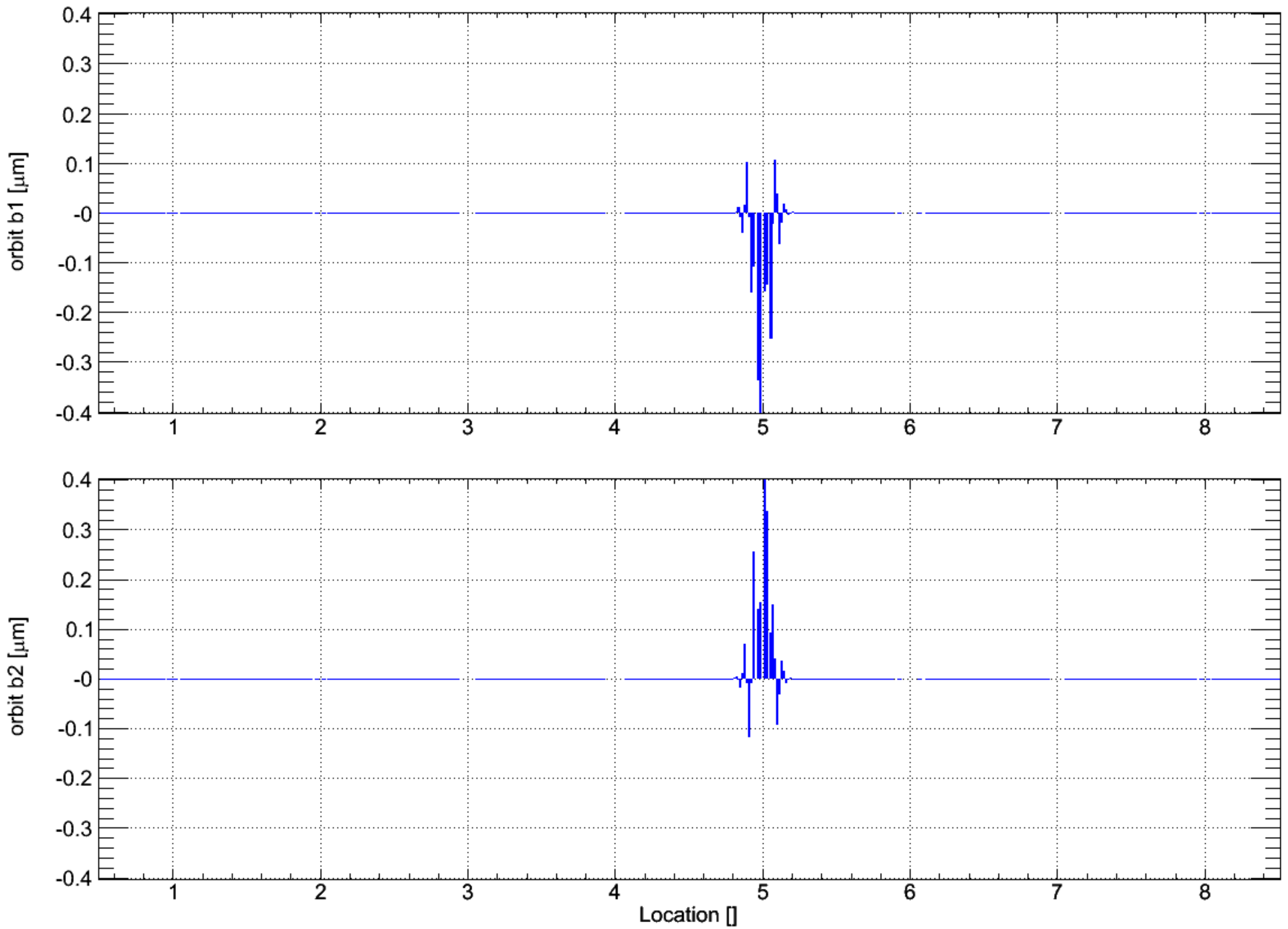
Sure why not...

LHC BPM eigenvector #457 $\lambda_{457} = 81.4$



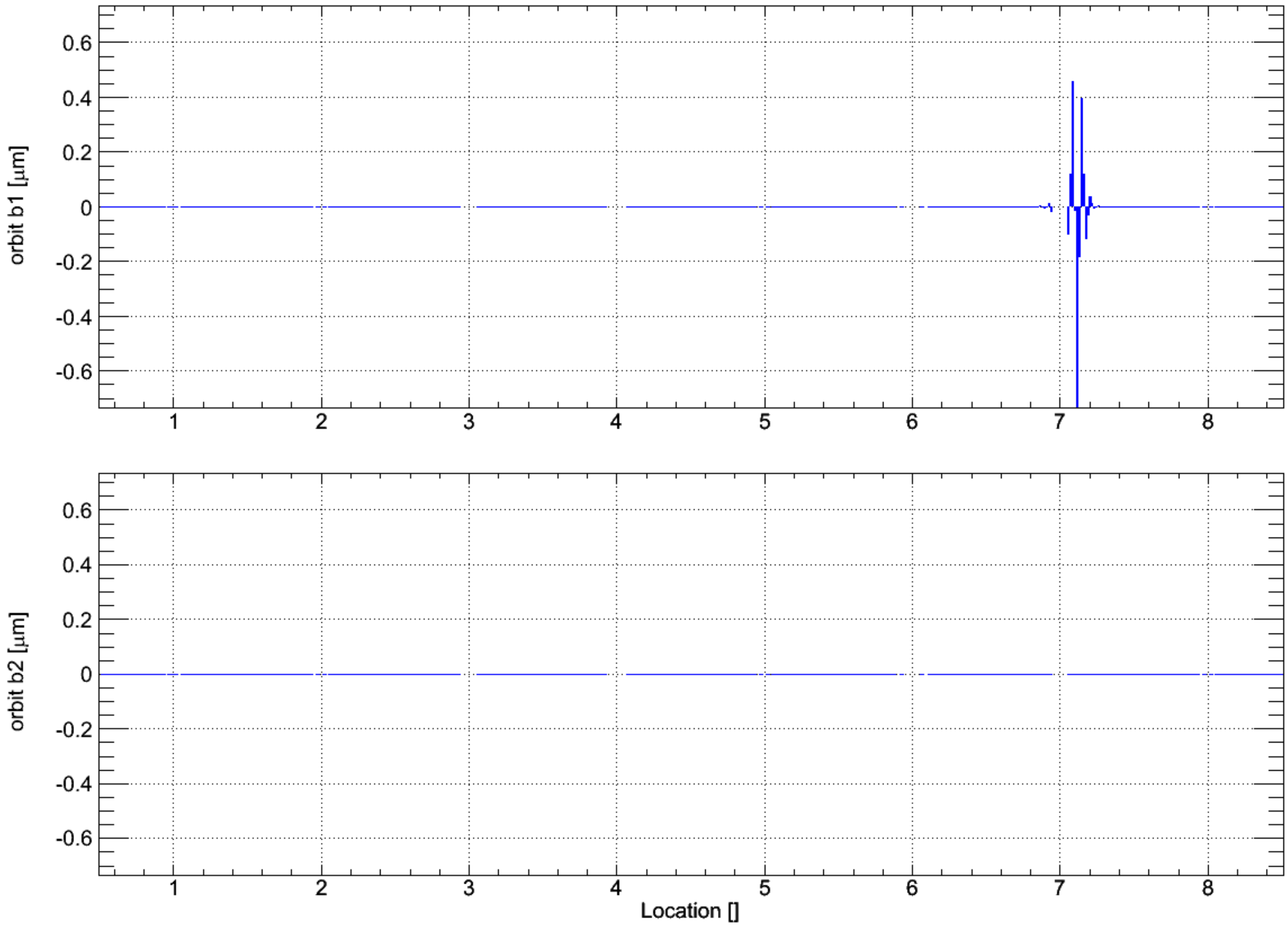
We have seen this pattern creeping slowly into the arcs, haven't we...

Feedback Response
LHC BPM eigenvector #494 λ_{291}= 2.13•10^2



This one would correct/keep the B1/B2 beam separation...

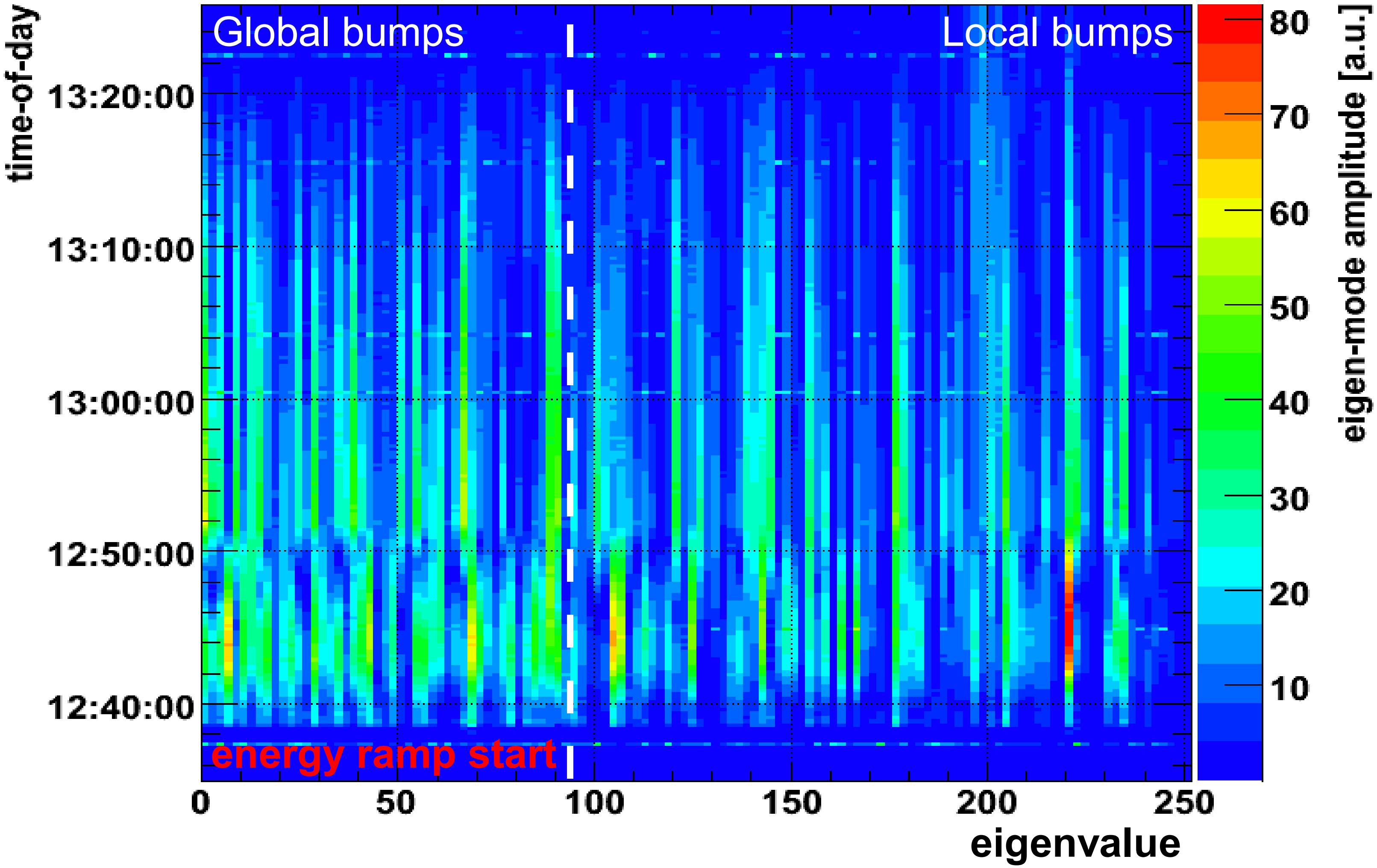
Feedback Response
LHC BPM eigenvector #486 λ_{486}= 40.3



This one would correct/keep the orbit at the secondary collimators...

SVD Decomposition of Orbit Perturbation Sources – or – How the Orbit-FB sees the Energy Ramp

- global bumps ↔ small eigenvalue vs. local bumps ↔ large eigenvalue indices:

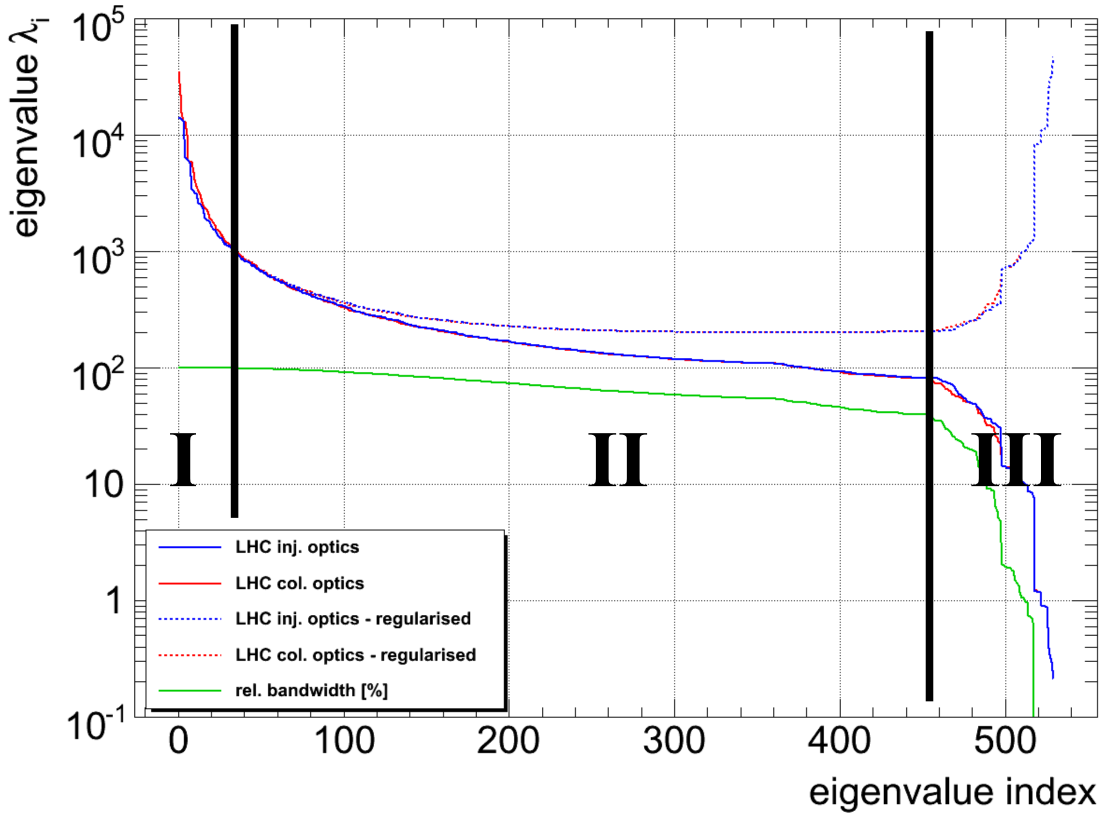


- Some global perturbations but also significant local ones
  → need to use more eigenvalues to allow better local compensation

Feedback Response
Orbit Attenuation Performance vs. Noise Propagation II/II

Mitigation of BPM noise via using a regularised SVD

- large eigenvalue ↔ large bandwidth (fast correction)
- small eigenvalue ↔ small bandwidth (noise-reduced local correction)



- Uncertainties in the beam response matrix reduced the effective control/feedback bandwidth but does not affect the steady-state precision
- Regularised SVD requires only one response matrix during squeeze
  - Demonstrated with separated and colliding beam

Orbit Feedback and Bumps

- General orbit correction strategy:
  - Initial setup: "Find a good golden reference" (mostly feedback "off")
    - establish circulating beam
    - compensate for each fill recurring large perturbations:
      - static quadrupole misalignments, dipole field imperfections, etc.
    - Establish reference orbit (aka "golden orbit")
      - keep aperture limitation, beam life-time
      - rough jaw-orbit alignment in cleaning insertions, ...
  - During fill: "Stabilise around the reference working point" (feedback "on"):
    - correct for small and random perturbations Δx
      - environmental effects (ground-motion, girder expansion, ...)
      - compensate for residual decay & snapback, ramp, squeeze
  - above step may alternate repetitively
- Feedback by itself does not and cannot create local orbit bumps
- However, alternating between these two steps may, creeping in of offset errors
  - E.g. Via correction of spurious temperature drifts and offsets
  - BPMs are not only used by the OFB but also general steering & interlocks
  - Some bumps are systematic due to correction strategy (MICADO)
  - The BPM offsets need to regularly checked w.r.t. available aperture

Feedback System Reliability V/V – REVISITED

Two categories of failures:

- Internal feedback controller failures, e.g.
  - feedback logic, correction algorithm, configuration/reference errors, etc.
  - easily tested via closed loop transfer function:
    - stable closed-loop ↔ internal logic is OK
    - only a few 'if-else' conditions

  → checks done for every new OFC and optics release

- External errors and faults of input and/or output sub-systems, e.g.
  - Timing information distribution errors (software libraries, FESA, …)
    - beam energy, beam-presence flag, machine mode
  - Circuit errors (rare)
    - Non-notified/disabled RT trims and circuits
    - QPS: false-positive interpretation of real-time trims as “quench”
  - 'Bad' BPMs, incorrect Q/Q' (beam spectrum issues)

→ weakest link that need to be enforced to improve overall feedback reliability
→ Need to tackle source of problems not their symptoms!

Now some preaching to the choir...

- Machine Protection System:
  - allows to mask certain interlocks to improve machine availability and operational efficiency while driving beam commissioning or during less safety critical operational periods
  - However: in-built policy of automatically re-enabling disabled interlocks that may be crucial for operation with high stored beam energies
    - IMHO: Setup-Beam-Flag is a great concept!!
- Why a different philosophy for feedbacks?
  - We do lot's of masking/disabling of checks that are never removed later...
  - Some masked issues may hit us later when we least expect/want them!

Tackling the Source vs. Symptoms of Problems II/III
Past Examples

- Spurious QPS trips of special orbit correctors acting on B1 & B2
  → disabled these correctors presently for feedback use, however:
  - limits ability to correct the orbit in the interaction region

- Spurious QPS trips of trim quadrupoles → disabling of Tune-FB, however:
  - beams later lost due to Q/|C^-| excursions during the squeeze

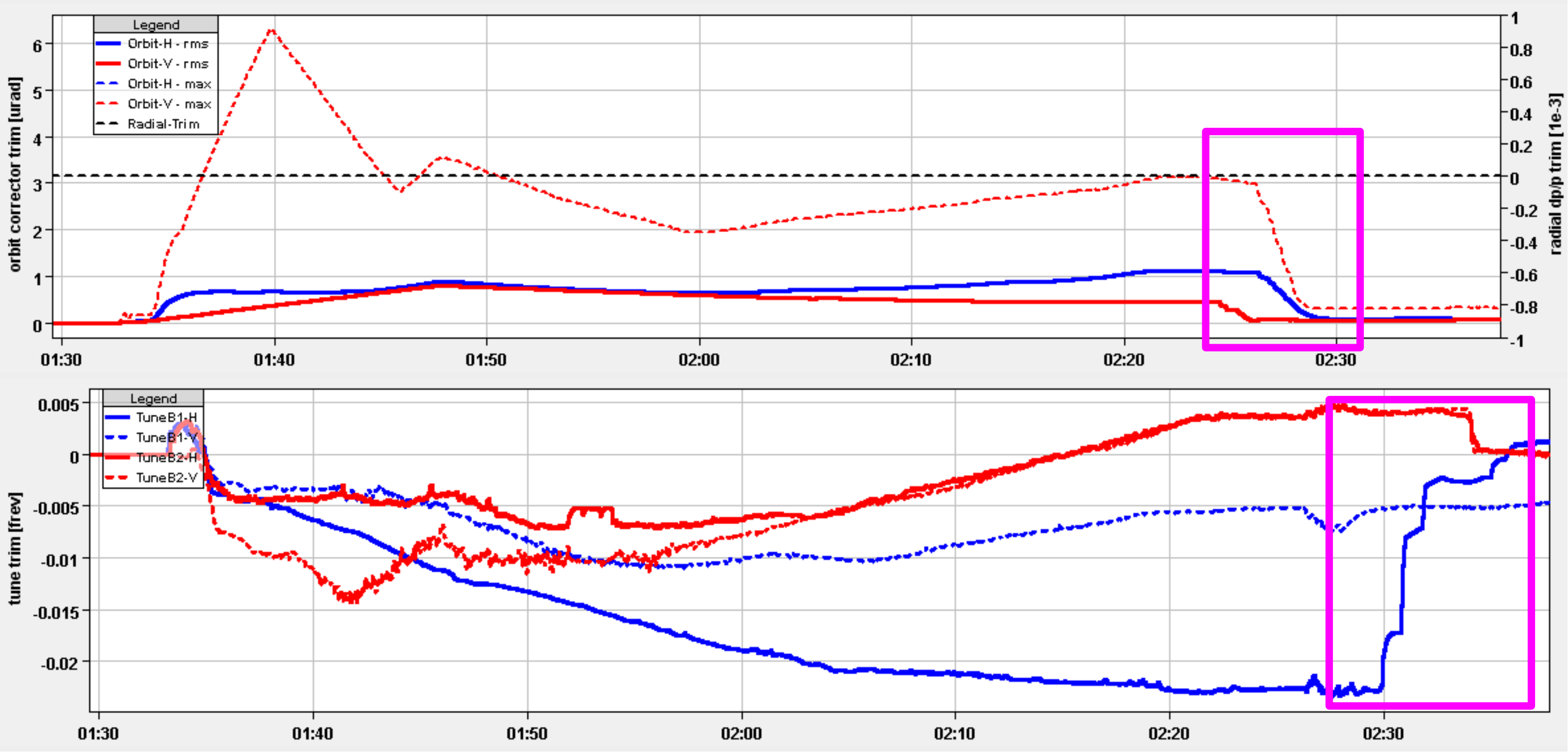
- Trips during coast because of error energy scaling
  → disabling of RT trims at the FGC level which fixed visible effect, however:
  - Problem of error in timing telegram reception still remains
    - Introduces new more difficult to analyse problems
    - Next problem: beam presence flag, machine mode, …

- BPM transient exceeding the 500 um excursion limit and switching OFB 'off'
  → increased on request to 3 mm (de-facto disabling this safety features)
  - orig. problem remains: BPM was/is still noisy and propagated to the orbit
  - Similar: BPM stable at inj. but got a systematic offset during the ramp...

→ Operational efficiency has been improved but underlying problem stayed!
We need to also fix the error sources and dependencies!

In the mean time:

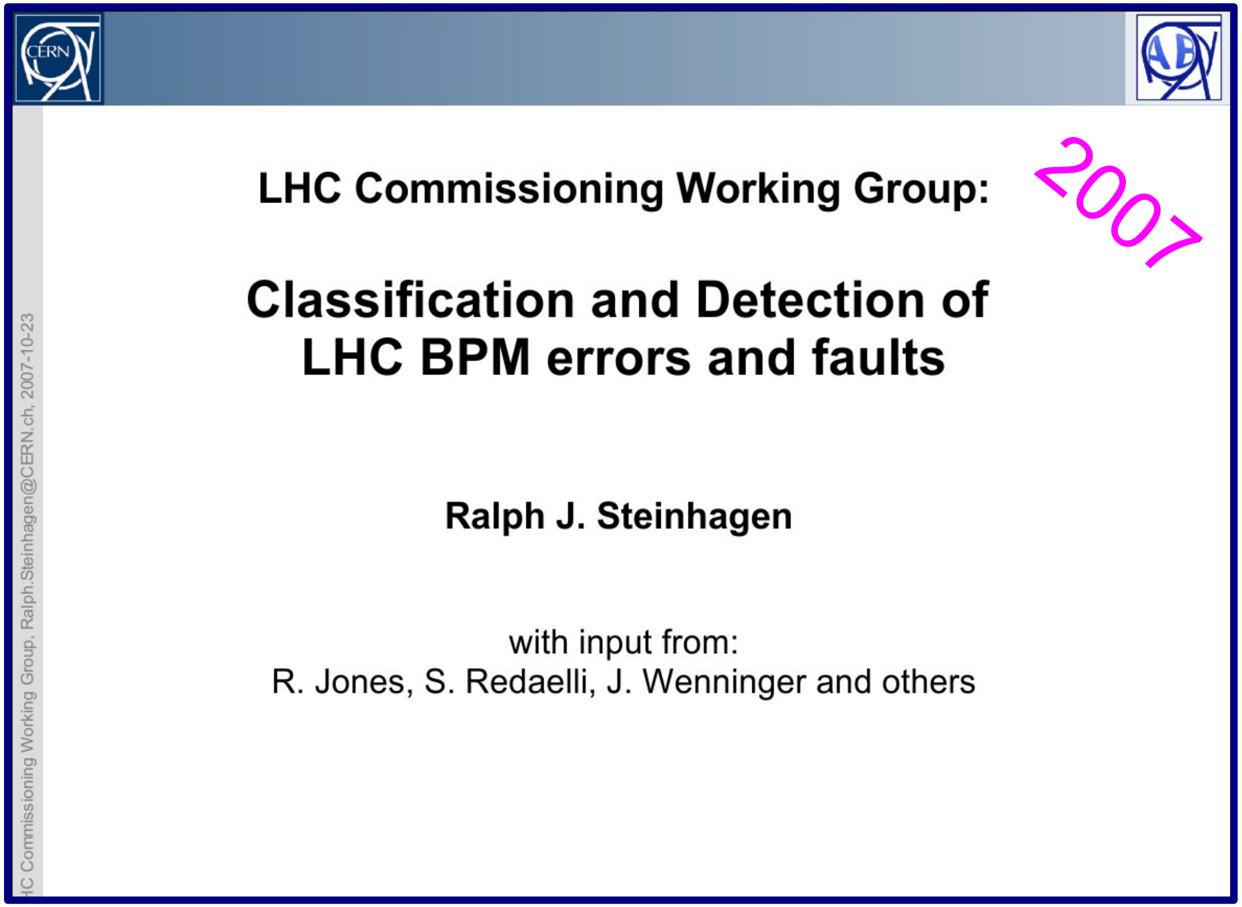
- Reduces effectively dependence on feedbacks and the risk of combined failures that may become critical for machine protection



- Reduces FB dependence and thus safety → needs to be more systematic (e.g. after ramp, before & after squeeze, during collisions when needed, ...)
  – Systematic feed-forward of the FB corrections during the ramp is needed!

Tackling the Source vs. Symptoms of Problems
BPM Errors and Faults: Once upon a time....

- Not a new topic.... LHC Beam Commissioning Meeting in 2007



- “Closed Orbit and Protection”, MPWG Meeting #53, 2005

Some Definition

A more formal definition of “Bad”: Distinguish between beam position monitor...

- *Error*: inconsistency between measured and true beam position
  - minimised by calibration or re-alignment
  - can lead to a a 'Fault' if exceeds pre-defined limits

  → Rhodri's presentation!

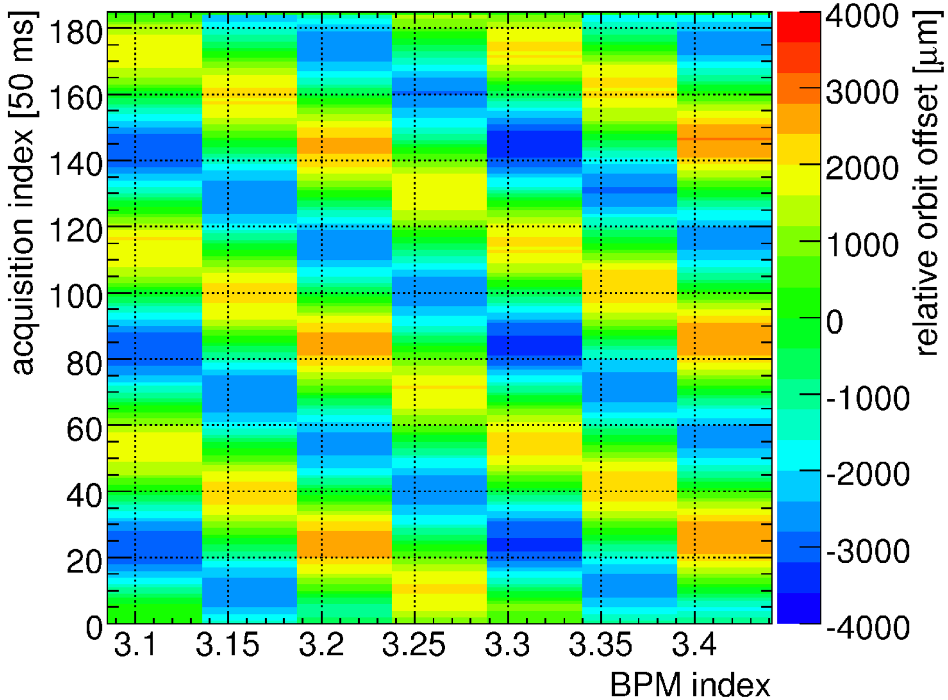
- *Fault* or *Failure*:
  - an error exceeding specified limits or
  - the unavailability of the measurement

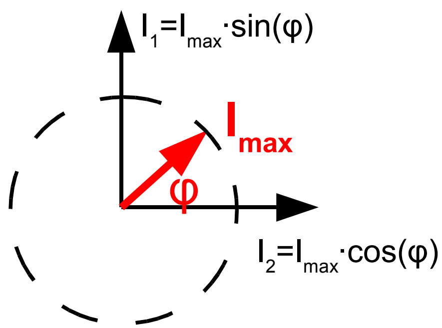
N.B.

'*accuracy*' := maximum measurement error ≠ *resolution*

'*resolution*' := minimum measurable position change

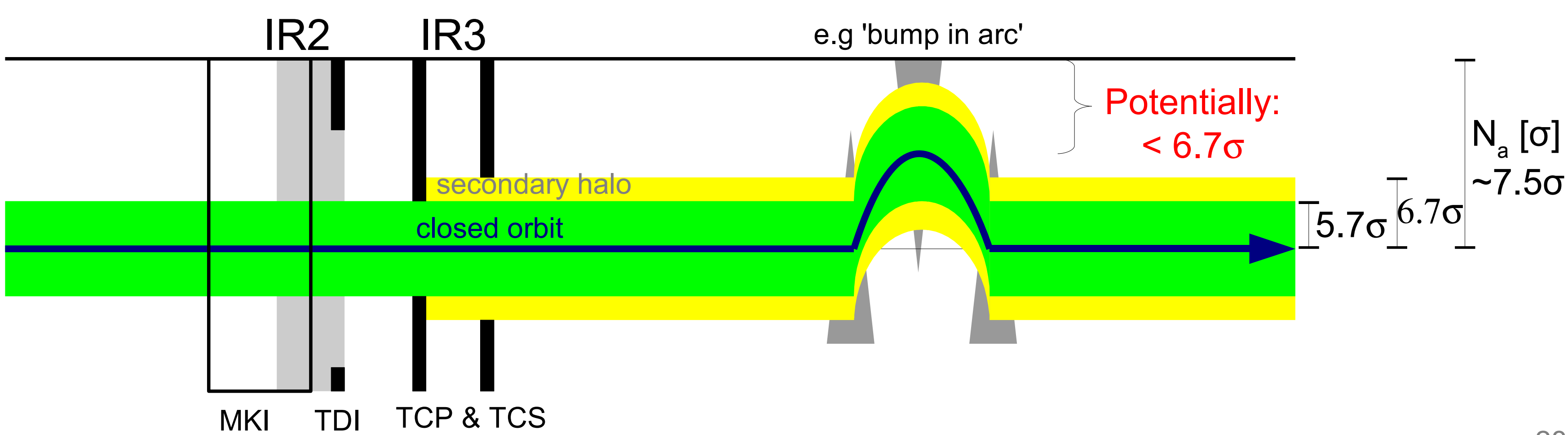
- Three main lines of defence against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
     - eliminates open/closed circuits, dead BPMs, red. temperature effects
  2. Pre-checks with Pilot and Intermediate beams
     - Idea: “Every non-moving position reading indicates a dead BPM”
       → forced slow COD-driven betatron oscillation with rotating phase





     - Tests also calibration factors and/or rough optics estimate
  3. Continuous data quality monitoring through Orbit Feedback
     - detects spikes, steps and BPMs that are under verge of failing

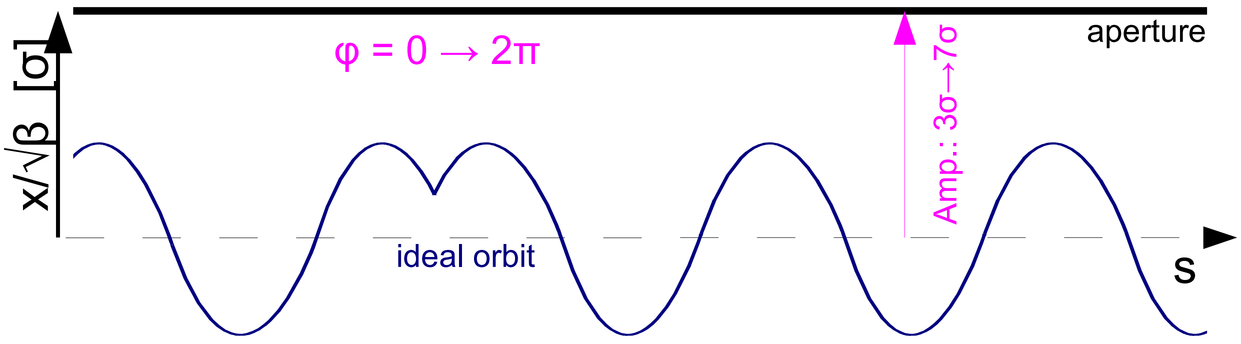
- Two simple functional tests to check whether BPMs are working.
  Idea: "Every non-moving position reading indicates a dead BPM".
  1. free betatron oscillation with rotating phase
     - non-moving BPM readings → faulty BPM
     - tests calibration factor and/or optics
  2. aperture scan to checks abs. BPM offsets and insures proper machine protection functionality: → Bumps may compromise collimation function[1]
     - To guarantee (two stage) cleaning efficiency/machine protection:
       – TCP (TCS) defines the global primary (secondary) aperture
     - 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.)*

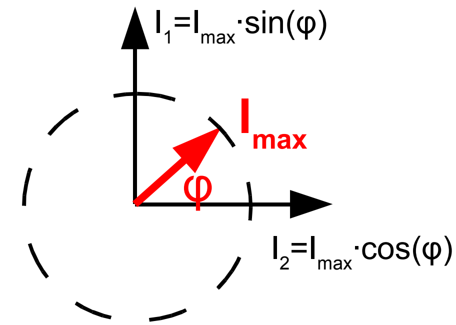


[1] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

2.Pre-checks with Pilot and Intermediate beams II/II

- Scan using two COD magnets (currents: I_1 & I_2) with π/2 phase advance:





- Scan (assuming global aperture of ~ 7.5σ):
  - φ = 0→2π requires ~25 seconds @7σ, per transverse angle
  - propose to measure at: 0^o, 45^o, 90^o, 125^o
- Increase amplitude (COD currents) till orbit shift ≈ 6.7σ
- Loss does not exceed predefined BLM threshold if COD settings@ 6.7σ:
  - Yes: → mechanical aperture ≥ 6.7 s → orbit is safe
  - No: → mechanical aperture ≤ 6.7 s → 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)

3.Continuous BPM data quality checks through LHC OFB I/II

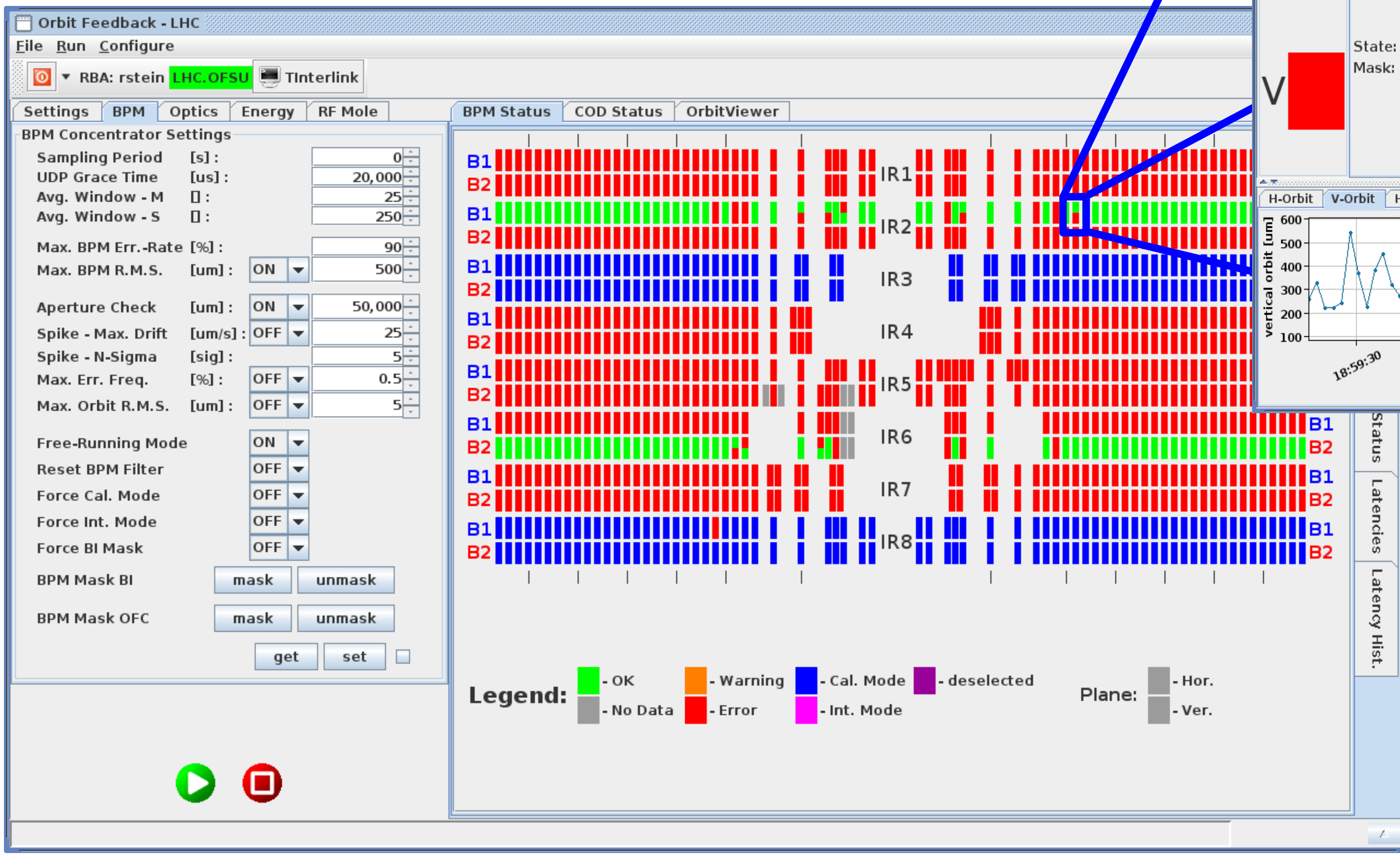
1. BPM phase advance of ~π/4:
   - Twice the sampling than minimum required to detect β-oscillation
   - Distribution of consecutive BPMs on different front-ends
2. Detection of erroneous BPM failures

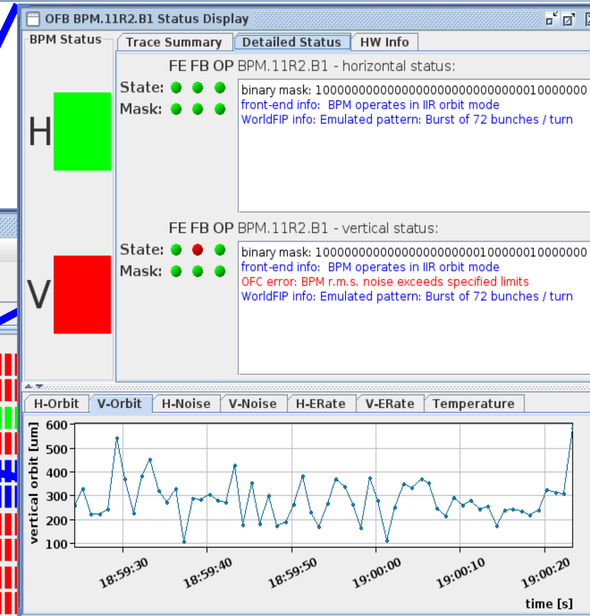
   ($x_i(n)$=position at i^{th} monitor, n: sampling index; σ_{orbit}= residual orbit r.m.s.)
   - Reject BPM if the following applies:
     - Cuts in Space Domain:
       - (BPMs marked by the front-end itself)
       - $x_i(n)$ > machine aperture
       - $x_i(n) - x_{i,ref} > 3 \cdot \sigma_{orbit}$
       - Option: interpolate position from neighbouring BPMs (as done in APS)
     - Cuts in Time Domain (Spike/Step 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.Continuous BPM data quality checks through LHC OFB II/II

- Most likely errors: spikes and static outliers
  - Low-level BPM/COD filter stages tested
  - Majority voting on error-count most efficient filter





- Present situation: most of these checks are disabled!
  - Need to time with various beam types to adjust and enable these filters!
  - Diagnostic is there but rarely consulted in case of problems.

Conclusions

- The feedback systems as a whole are only as safe/reliable as its weakest link
  - Some known and frequent errors are intercepted by the OFC
  - However: general input errors especially if they are not specific for Fbs need to be addressed at the source!
- Feedbacks are/must not be machine protection system elements
  - Monitoring and incorporation of feedback trims is necessary
- Three main lines of defence against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
  2. Pre-checks with Pilot and Intermediate beams (aperture scans)
  3. Continuous data quality monitoring through Orbit Feedback

→ missing, need to be put in place as operational procedure!

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

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

no

yes

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

– Con's:
  - erroneous BPMs → but: gives indication which BPMs are not working.
  - No information before injection
  - Bunch intensity systematics (gain settings) and change of BPM calibration