Proposed Commissioning of Beam-Based Feedback Systems

Ralph J. Steinhagen, BE-BI

for and special thanks to the (in-)vincible Gauls:

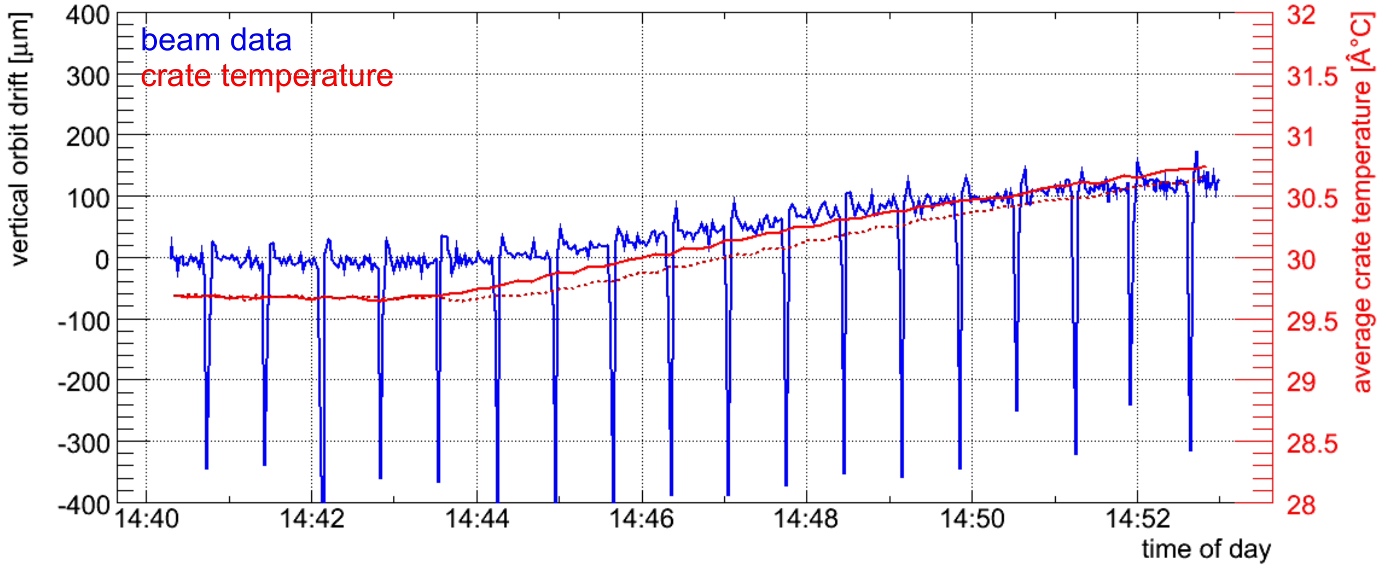
S. Bart Pedersen, A. Boccardi, L. Bottura, A. Butterworth, P. Cameron, E. Calvo Giraldo, K. Fuchsberger, M. Gasior, J. L. Gonzalez, S. Jackson, L. Jensen, O.R. Jones, Q. King, G. Kruk, S. Page, G. Sivatskiy, R. J. Steinhagen, J. Tückmantel and J. Wenninger

Reminder: Beam Stability Requirements

- Reminder: stability requirements summary (Chamonix'06):

	Orbit [σ]	Tune [0.5·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

- ... "FBs are most beneficial and (likely) required before the very first ramp!"
- Change of 7 TeV → 5 TeV → 1.1 TeV operation (L. Bottura et al.):
  - Snapback effects expected to scale linearly down with a factor ~ 6 (or more)
- Effects such as β*-squeeze and PC transients, girder drifts remain:



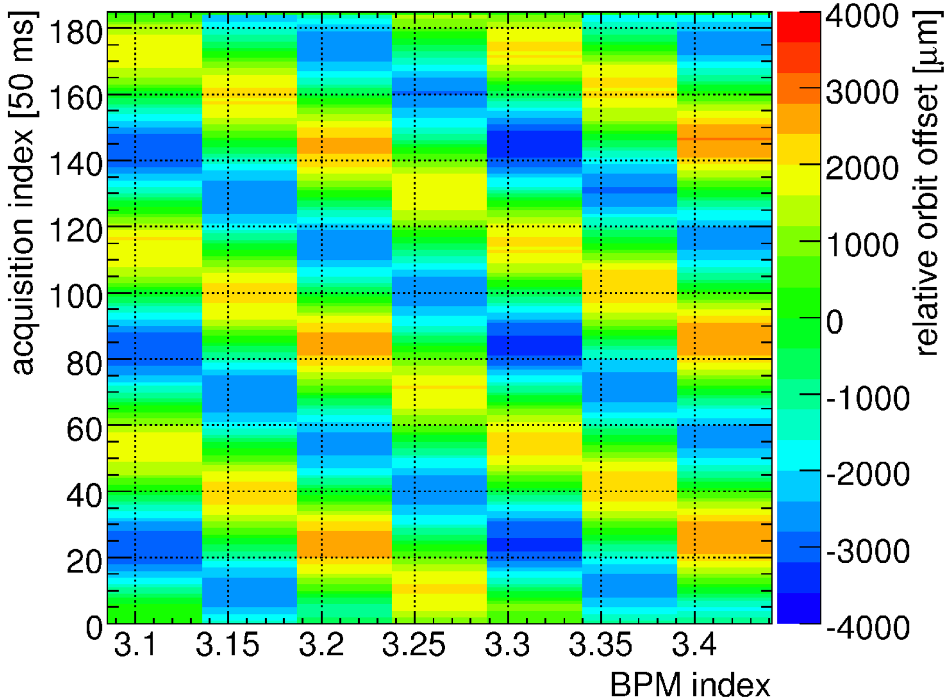
Proposed Commissioning Strategy

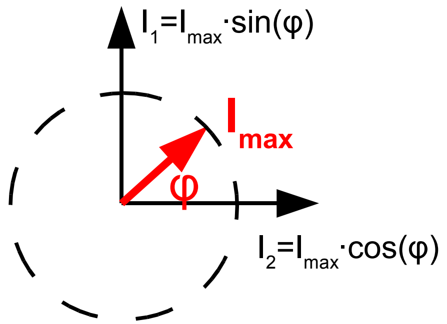
- Commissioning strategy: one step at a time
  1) Input concentration and sanity checks
     - BPMs: polarities, calibration, filters, dp/p est.
       → (partially) sector tests, first circulating beams
     - $Q^{(')}$-PLL: BTF scan ↔ PLL-Lock, re-tuning
       → discussed last LHC-CWG meeting
  2) Output mapping/fan-out tests and sanity checks
     - OFC ↔ FGC mapping, polarities, calibrations
       – Follow-up of inconsistencies!
     - Test feed-forward (= open-loop) channel
       – circuit response using RT channel
         ↔ compare with model

     → (partically) cold-checkout, first circulating beams
  3) Feedback response
     - Dealing with the obvious or the "unknown factor"
       → one shift or up to a year!?!

- Proposed sequence: 'Radial Loop' → Orbit FB → Q-PLL → Q'-PLL → Q'-FB → Q-FB

- 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
  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

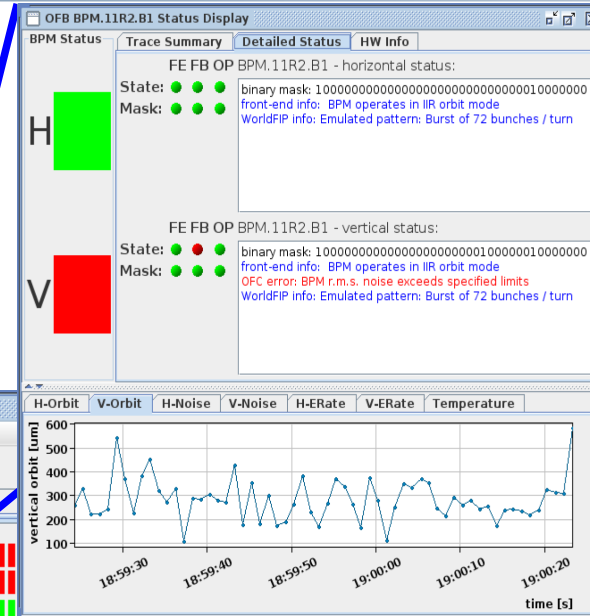


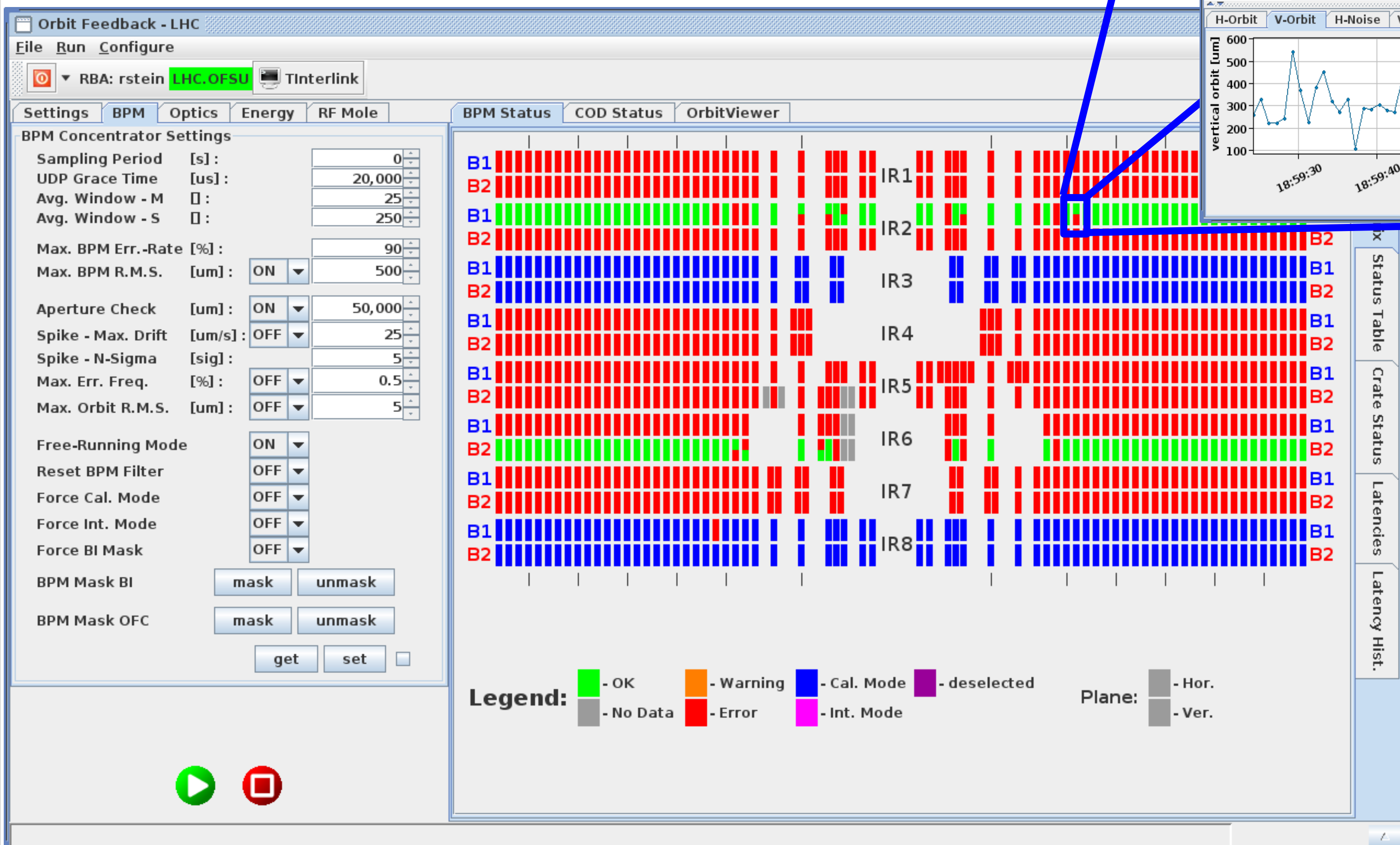


     - Tests also calibration factors and/or rough optics estimate
  3. Continuous data quality monitoring through Orbit Feedback
     - detects spikes, steps and BPMs that are under verge of failing

Input Concentration and Sanity Checks II
Status Monitoring

- Most likely errors: spikes and static outliers
  - Low-level BPM/COD filter stages tested
  - Majority voting on error-count most efficient filter
- Republishing of WorldFIP BPM concentrator settings
- DAB Temperature logging
- Filter/Test stages accessible/configurable via GUI

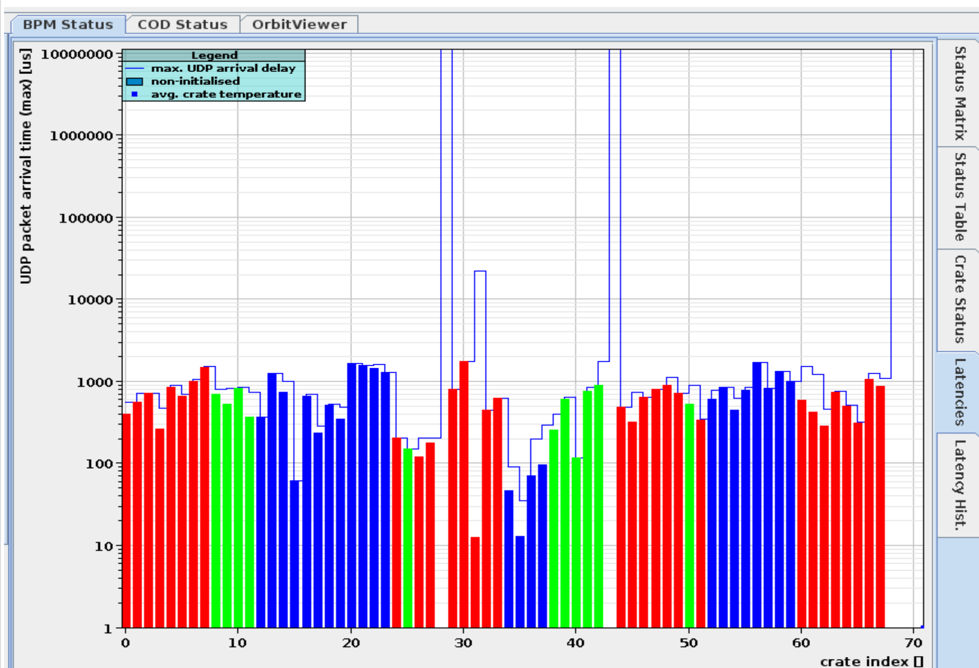


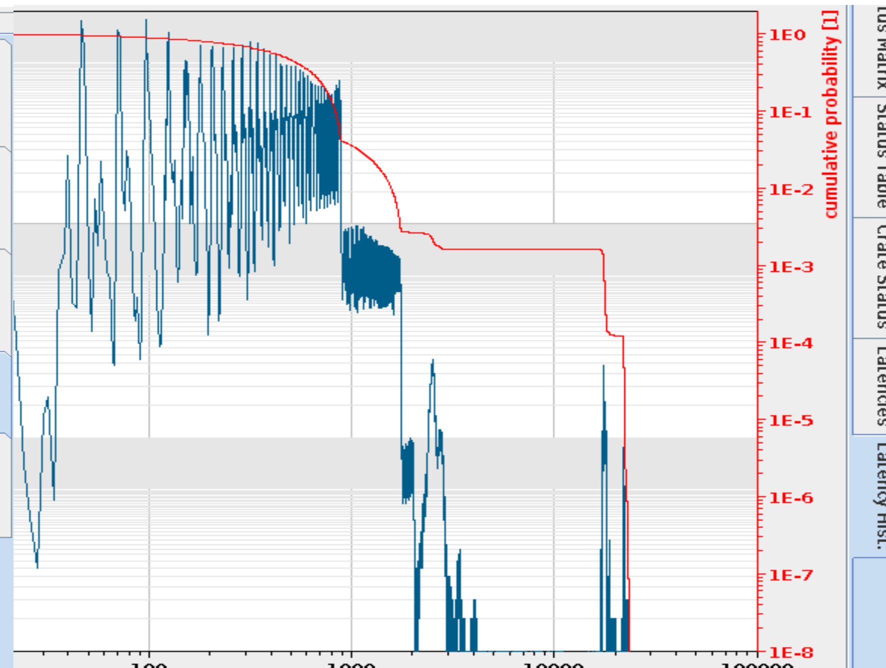


Input Concentration and Sanity Checks III
Data Concentration @ 25 Hz Performance

- 'Real-Time' Feedback Performance:
  - Depends on the correct numerical result and the latency it has been applied.
  - Does <u>not</u> mean that the feedback has to run very fast!

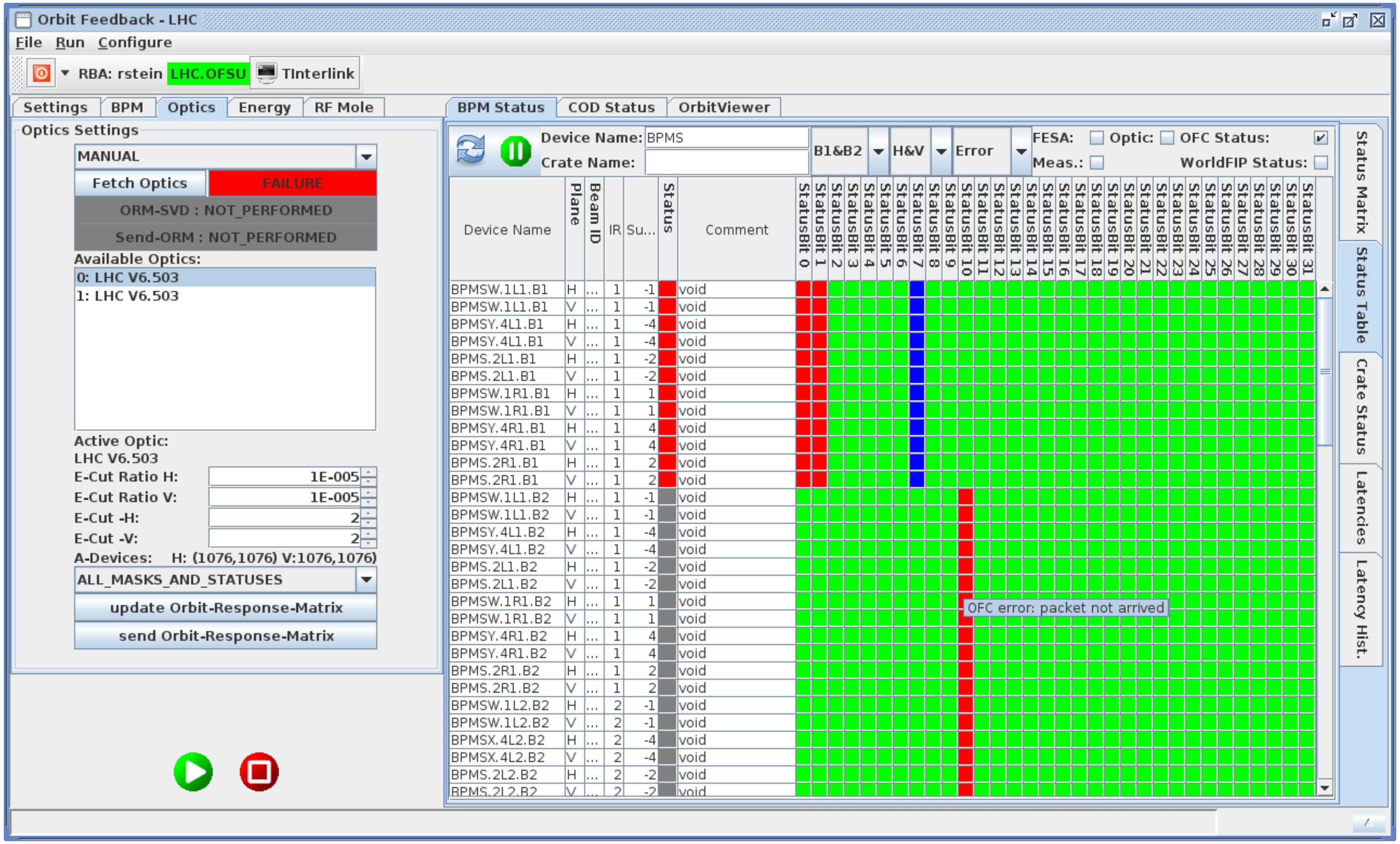
- General status: very good
  - Little effect of 100k turn BPM capture on the orbit acquisition
  - A few rare outliers (special interlock BPMs)





Input Concentration and Sanity Checks IV
Status Monitoring

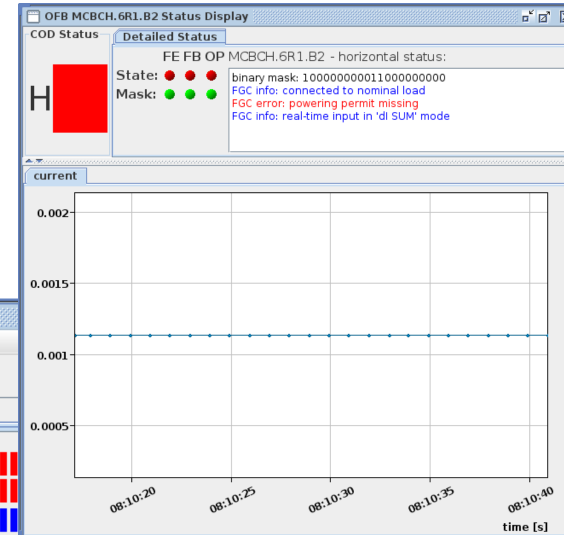
- Some convenience function to produce simple status reports
- GUI access to more frequently used functions (Optic, FB gains, ,,,)
  – Most buttons/icons have Tool-Tips
- Expert low-level interface to cover the rest (→ 'Tinterlink')

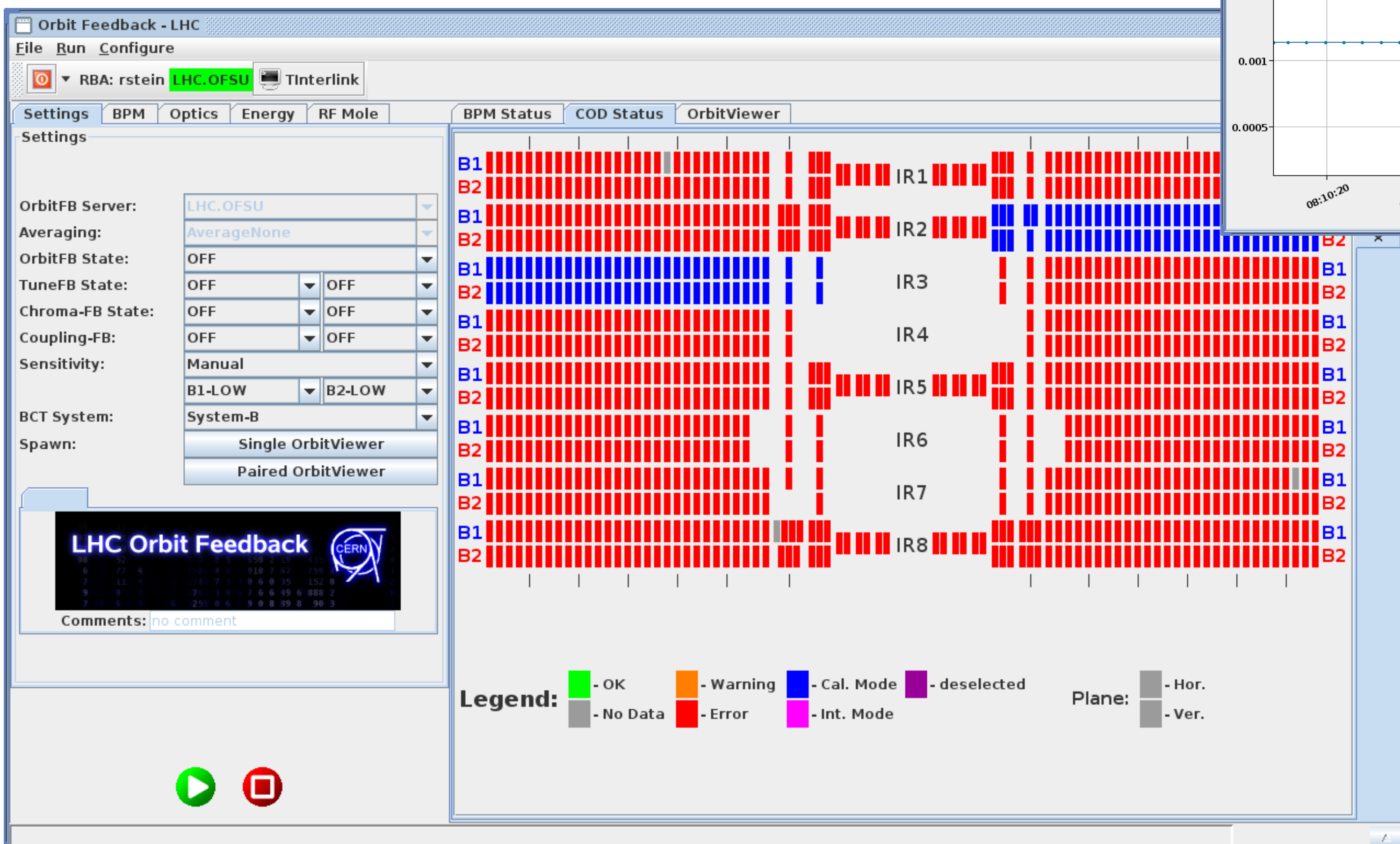


→ Comments, suggestions and requests are welcome

Output mapping/fan-out and Sanity Checks I

- Similar synopsis and tool chain for the corrector circuits
  - Essentially re-publishing of the FGC state from an OFC point of view, RT Monitoring of currents, etc.



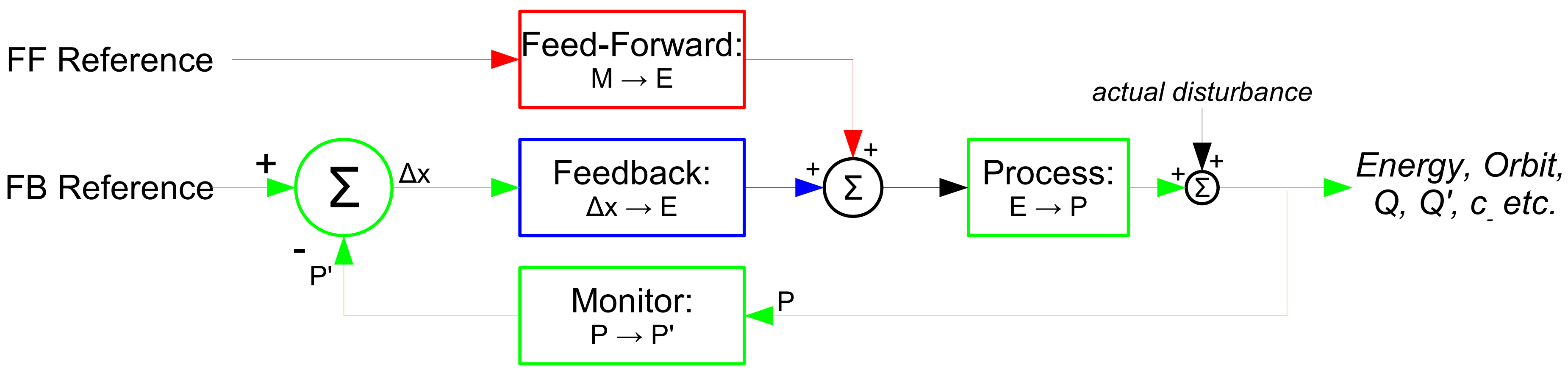


Output mapping/fan-out and Sanity Checks II
OFC ↔ FGC interface tests

- FGC data concentration, polarity and calibration checks
  - checked during HWC, injector tests, first circulating beams

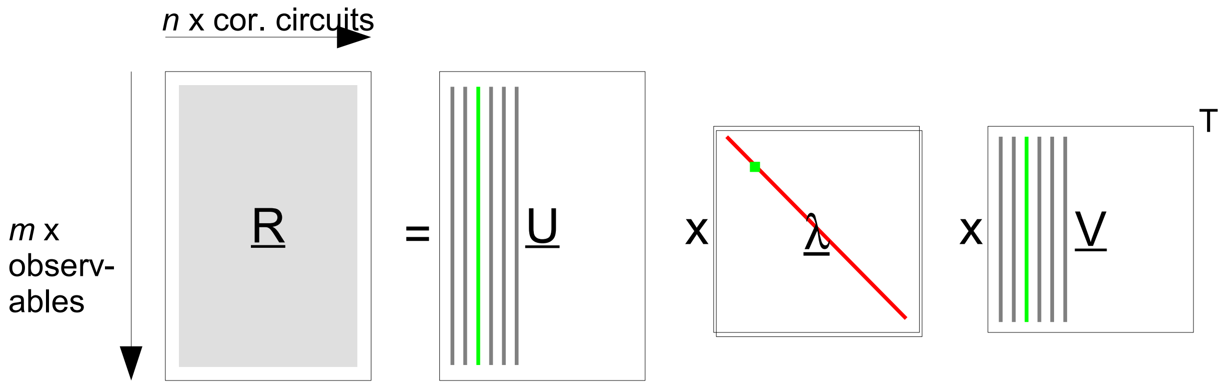
- FGC data fan-out mapping (N.B. 1300++ devices)
  - has never been done for all CODs/corrector circuits
    → this Thursday (partially), cold check-out and first circulating beam
  - Pattern to check mappings of all CODs at the same time based on their associated beam ID, IR and cell location

- Feed-Forward check: apply known RT trim and verify with LSA/measurement
  - For Q/Q'-FB based on copy of the corresponding LSA knobs (courtesy G. Kruk)
  - Final check of mappings and power converter ramping limits



Feedback Response
Singular Value Decomposition (SVD) on a slide

Linear algebra theorem*:



eigen-vector relation:

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

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

- though decomposition is numerically more complex final correction is a simple vector-matrix multiplication:

(default) SVD

$$\vec{\delta}_{ss} = \tilde{R}^{-1} \cdot \Delta \vec{x} \quad \text{with} \quad \tilde{R}^{-1} = \underline{V} \cdot \underline{\lambda}^{-1} \cdot \underline{U}^T$$

$\Leftrightarrow$

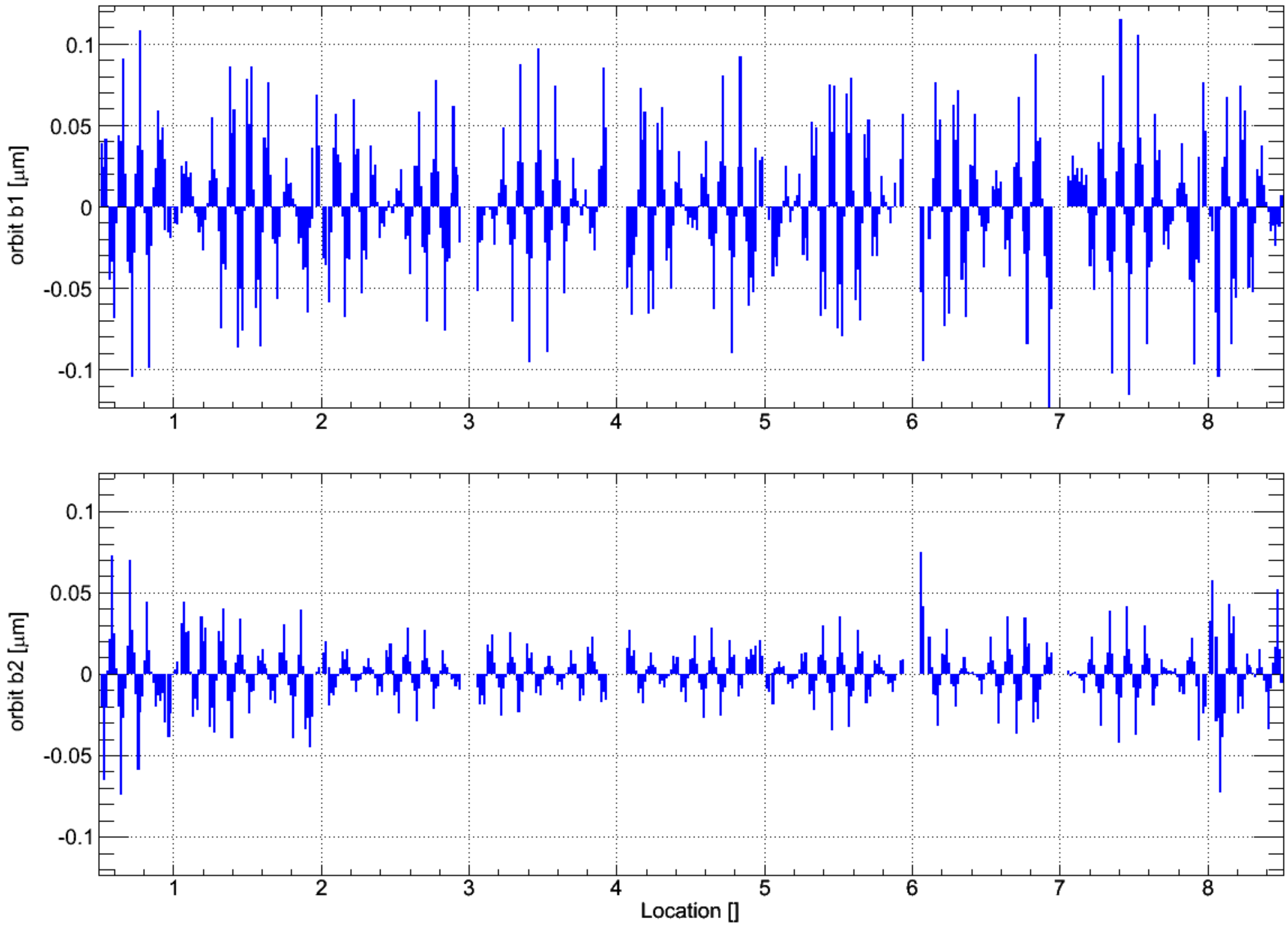
SVD++

$$\vec{\delta}_{ss} = \sum_{i=0}^{n} \frac{a_i}{\lambda_i} \vec{v}_i \quad \text{with} \quad a_i = \vec{u}_i^T \Delta \vec{x}$$

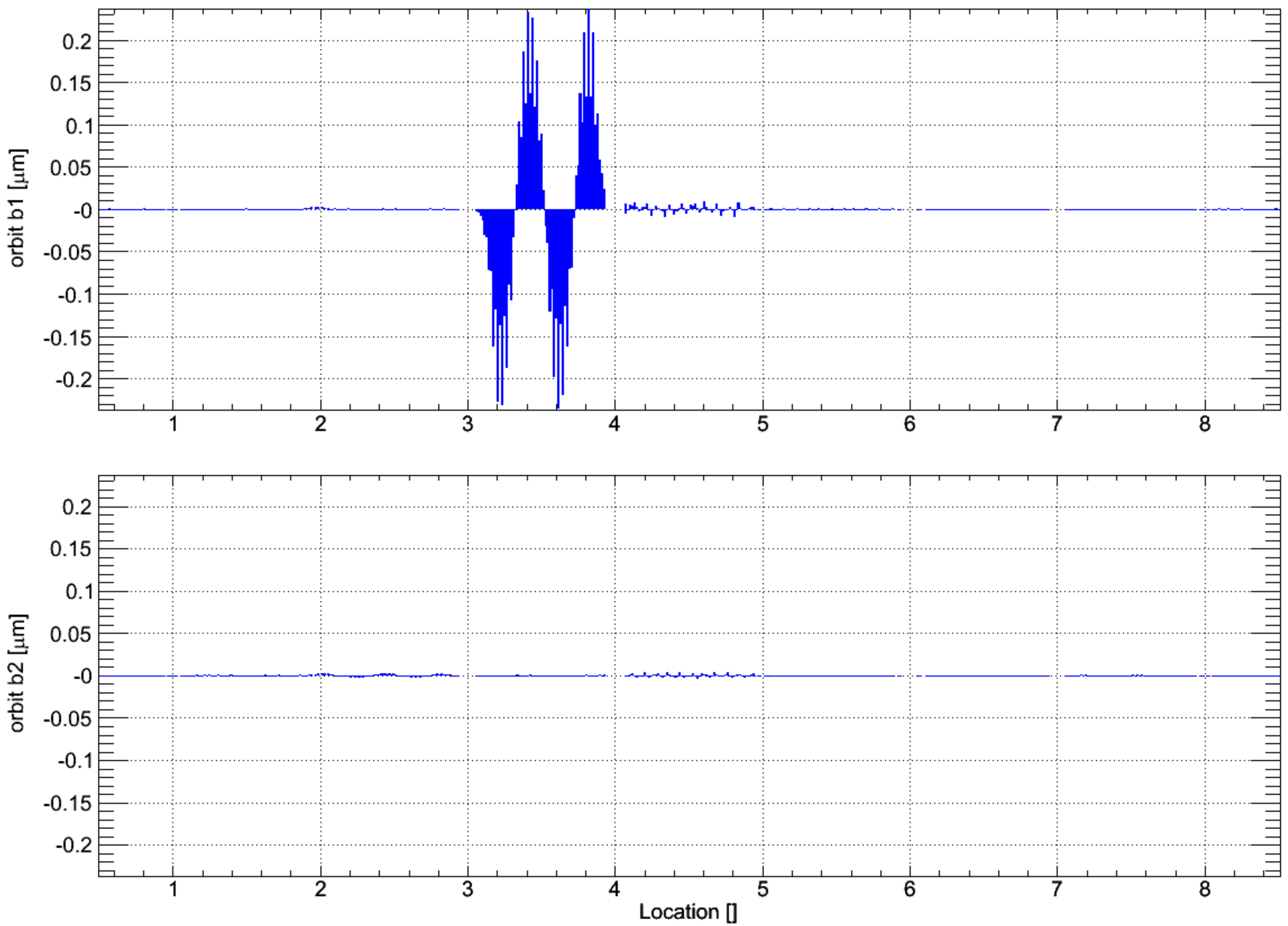
- numerical robust, minimises parameter deviations Δx <u>and</u> circuit strengths δ
- Easy removal of singularities, (nearly) singular eigen-solutions have $\lambda_i \sim 0$
  - to remove those solution: if $\lambda_i \approx 0 \rightarrow$ '$1/\lambda_i$:= 0'
  - discarded eigenvalues relate to patterns that are not corrected by the FB

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

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

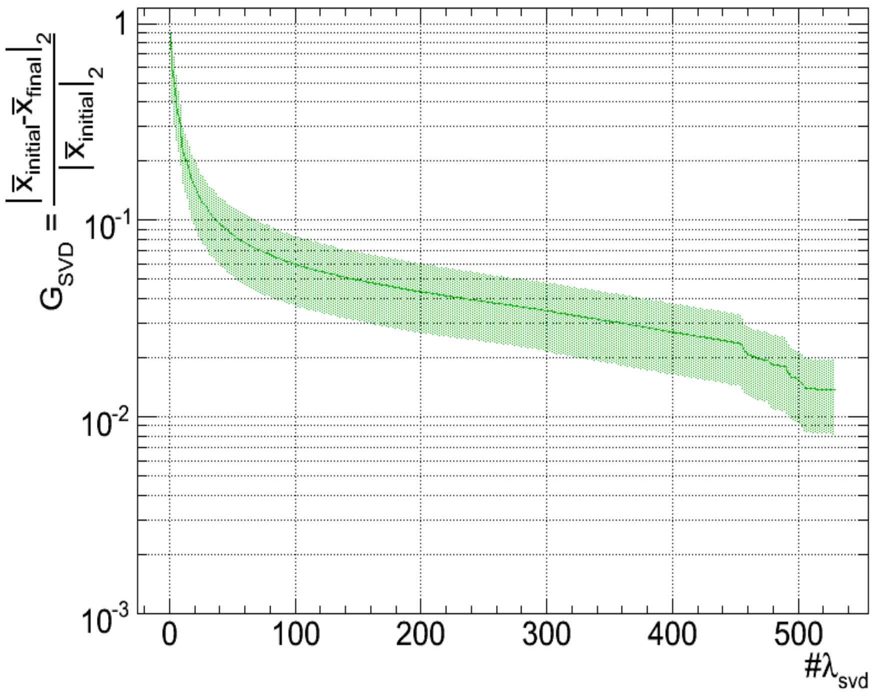


Feedback Response
LHC BPM eigenvector #291 $\lambda_{291} = 2.13 \cdot 10^2$

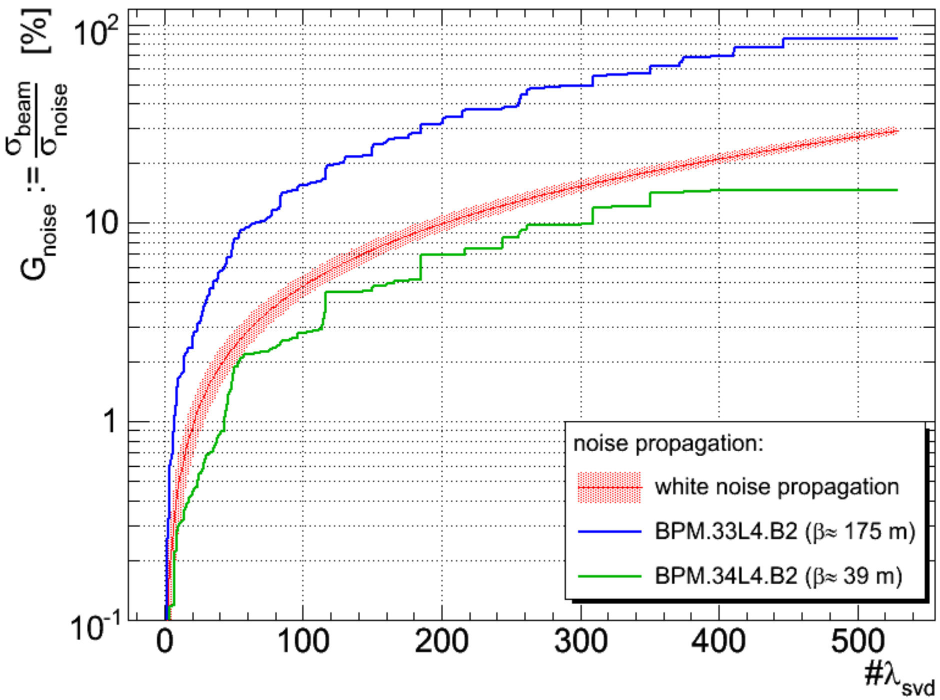


Feedback Response
Orbit Attenuation Performance vs. Noise Propagation

- Orbit attenuation



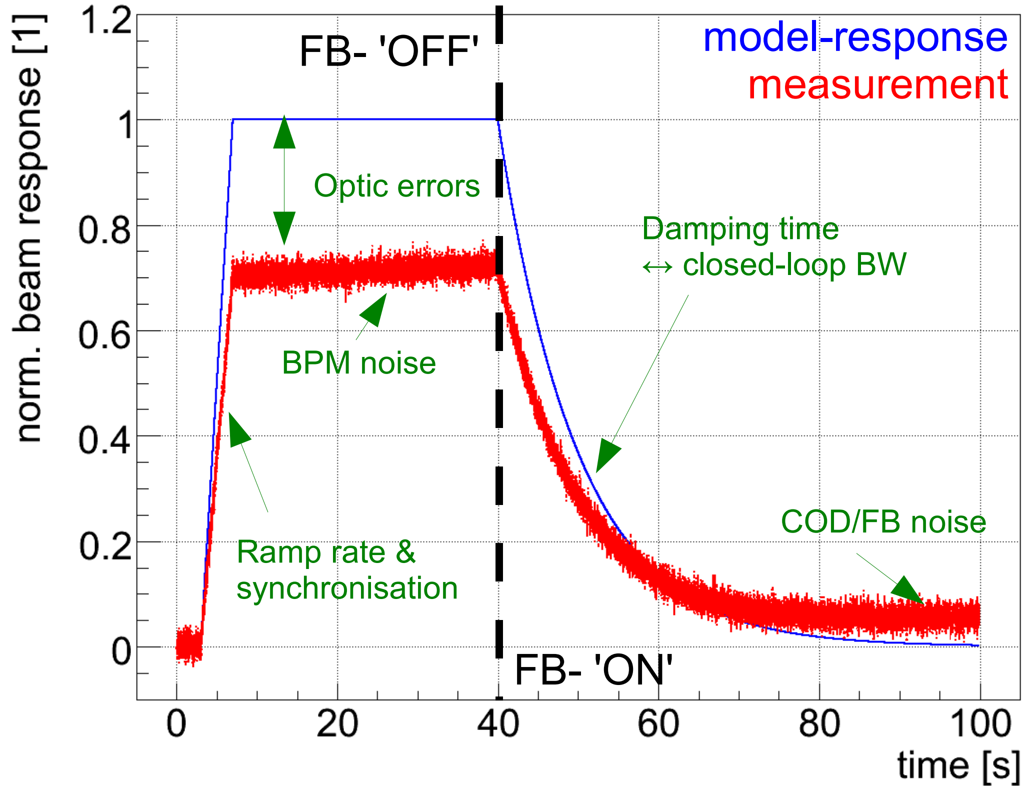
- Sensitivity to BPM noise



- “Regular” SVD:
  – Number of for the inversion used eigenvalues steers accuracy versus robustness of correction algorithm → however, no robust local control
- Extended SVD (SVD++): Feedback bandwidth depending on eigenvalue
  – large eigenvalue ↔ large bandwidth (fast correction)
  – small eigenvalue ↔ small bandwidth (noise-reduced local correction)

Feedback Response

- Open → Closed-Loop Response (automated ROOT-based script):
  – using e.g. orbit eigenvector or single COD/parameter



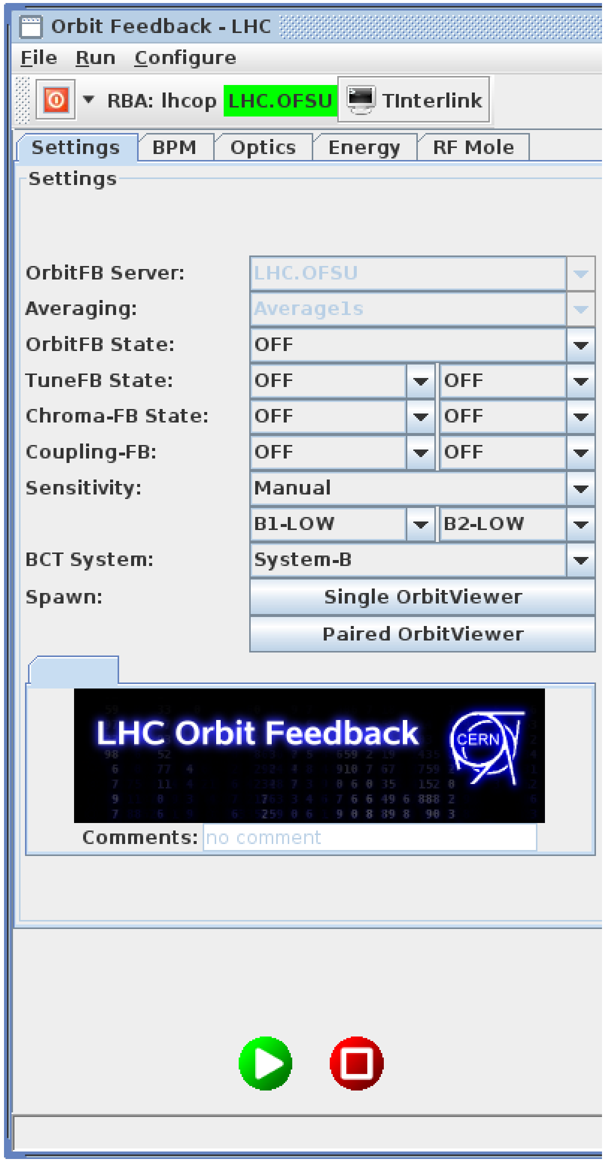
N.B. LHC circuits are first-order systems!!

  – expected vs. measured open-loop response:
    - Verification of optic and calibration errors
    - allows re-tuning of design vs. meas. Response

- Default OFC gains → closed-loop bandwidth of ~ 0.1 Hz
  – can be follow (or abort) the FB action semi-manually

Initial Feedback Operation '09

- Provided preceding steps are successful
  - We could run OFB with:
    - 0.1 Hz Bandwidth
    - Ref. orbit taken at 'on'→'off' transition
- Need time to re-commission and re-tune:
  - for higher than ~0.5-1 Hz FB-bandwidths
    - delay compensation (Smith-Predictor)
  - If operation shows a high rate of BPM and/or COD failures
  - prior to first β*-squeeze
    - optics changes, bandwidth retuning
  - nominal collimation operation
    - Fill-to-fill BPM offset re-calibration
    - Reference orbit management



Conclusion

- Feedbacks are most useful when used at an early stage:
  - feedback signals can provide feed-forward information for next fills

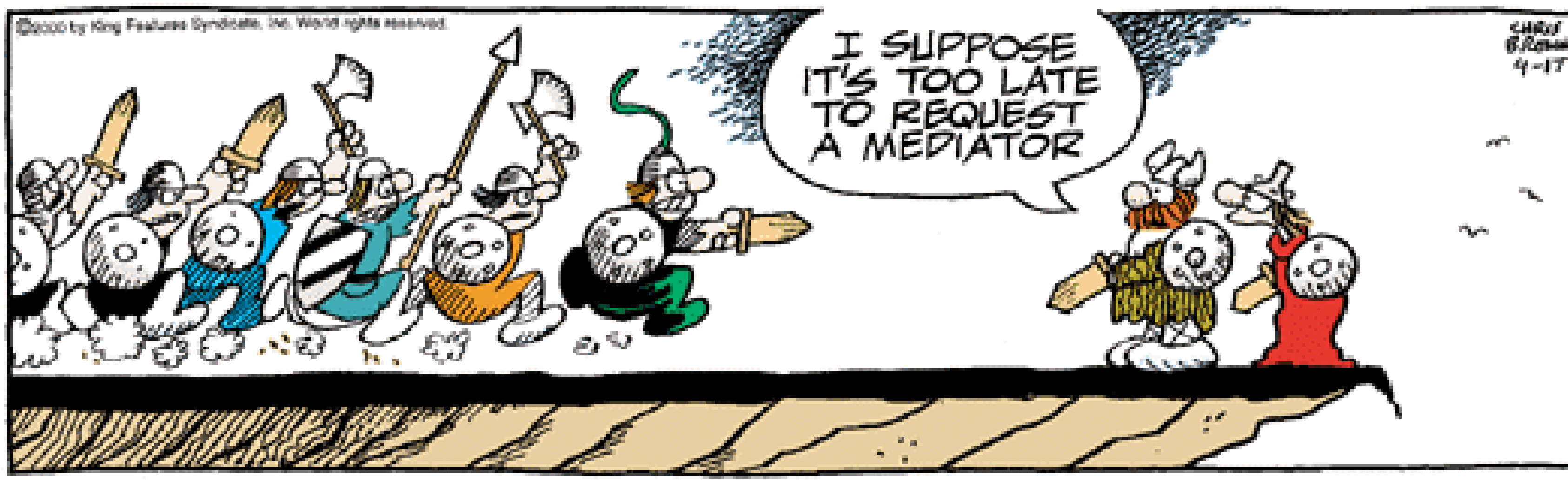
- Feedback commissioning is divided into three components
  - Beam Instrumentation checks
  - Corrector circuit checks

  } Partially done during HWC and with first circulating beam as pre-requisite of general beam control

  - Feedback Setup – the main (and only?) feedback specific part
    - Open- vs. closed-loop response
      - The good case: not much to commission → on/off switch
      - The bad case: 'RT' bug fixes → 1-2 shifts up to a week
      - The ugly case: discover a non-anticipated effect that is beyond the present FB design → anybodies guess

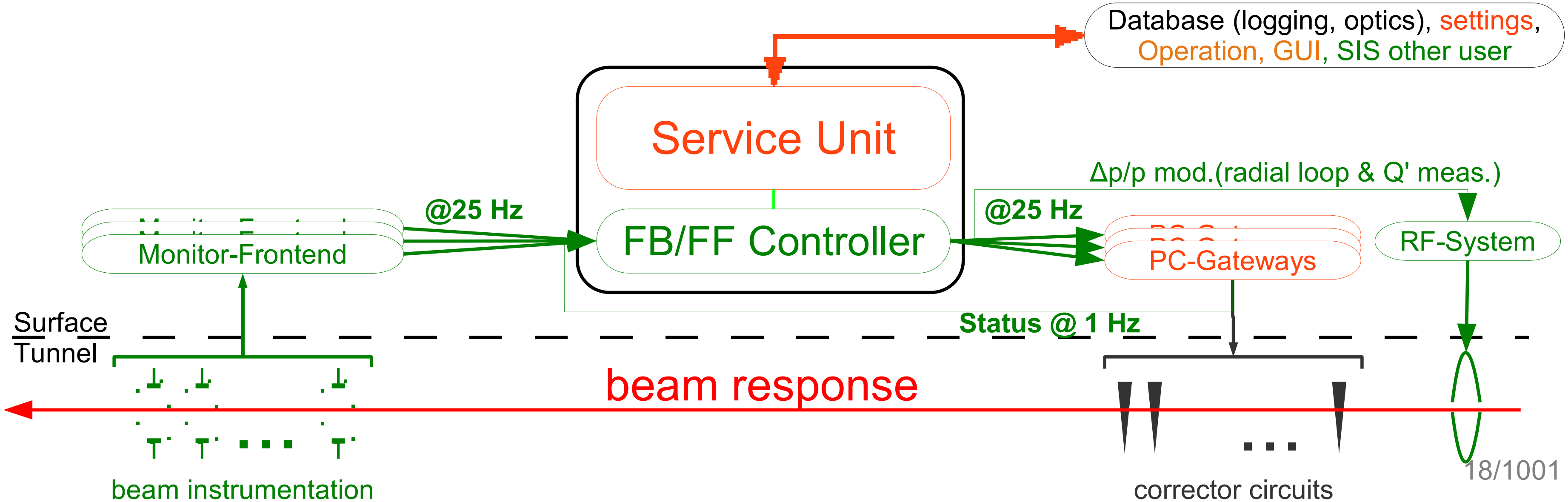
- LHC is not the first machine with a BBQ, Q/Q' PLL system or beam-based feedback system, however: there is no guarantee for 'no surprises' or perfect commissioning prior to real LHC operation!
  - We are prepared but some things need to be tested with real beam!

Additional Supporting Slides

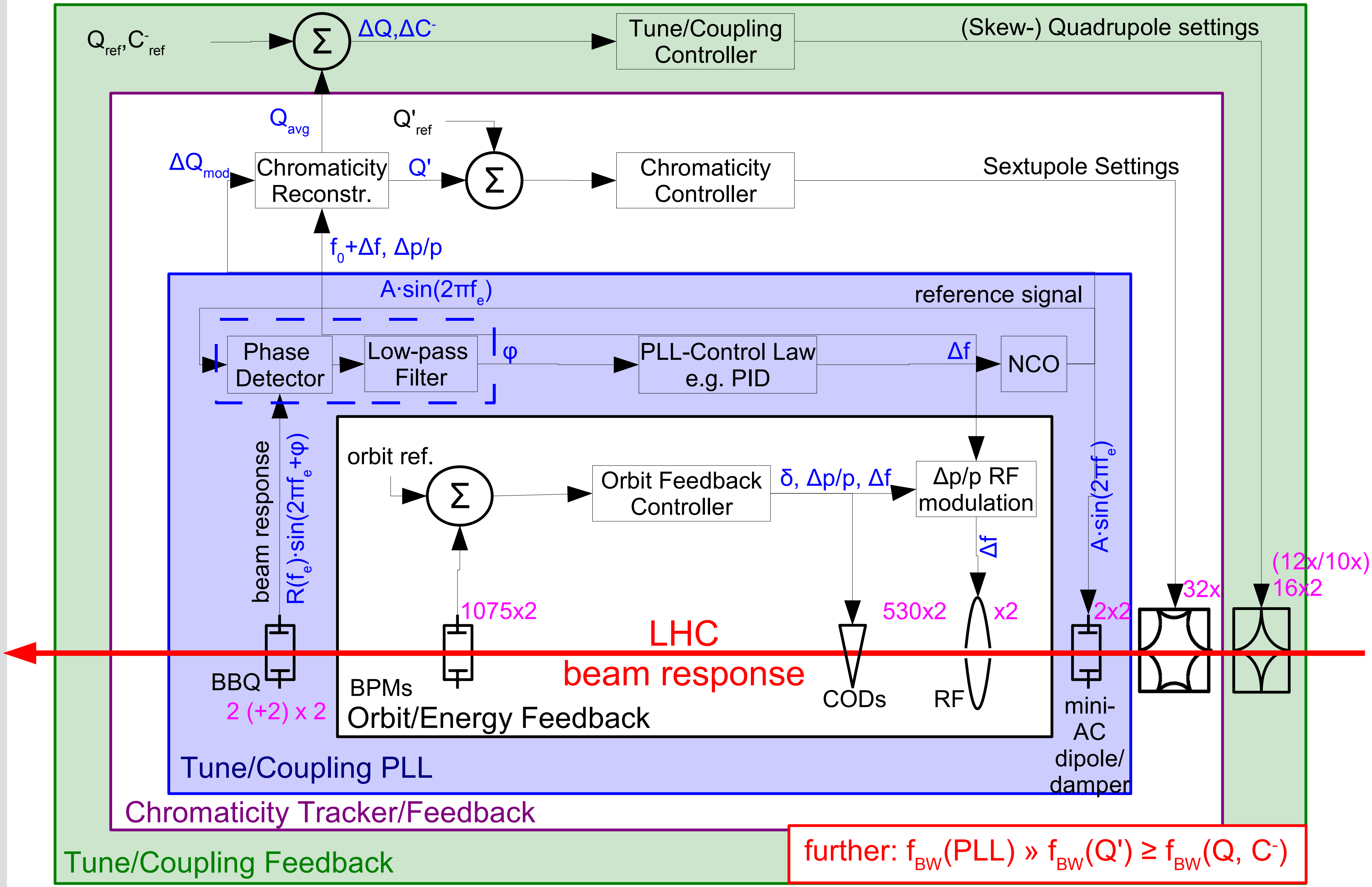


Status Overview

- BPM'08 & COD'09 data concentration
  - BPM/COD filter/sanity checks, bit masks
  - Orbit, Q/Q' republishing/logging pending
- FB/FF Controller – technical infrastructure in place → OK 'til first squeeze
  - OFSU-OFC energy update, Orbit/Q/Q' correction (LSA copy)
  - OFC-OFSU mapping on its way to completion → "operational comfort"
    - LSA mechanism prepared → sequencer automation
    - ROOT-based expert scripts are available to cover the difference
- RT device mapping/polarity checks missing: has never been done for all CODs
- Need operation experience for oper. sanity checks, dealing with 'what if ...' cases



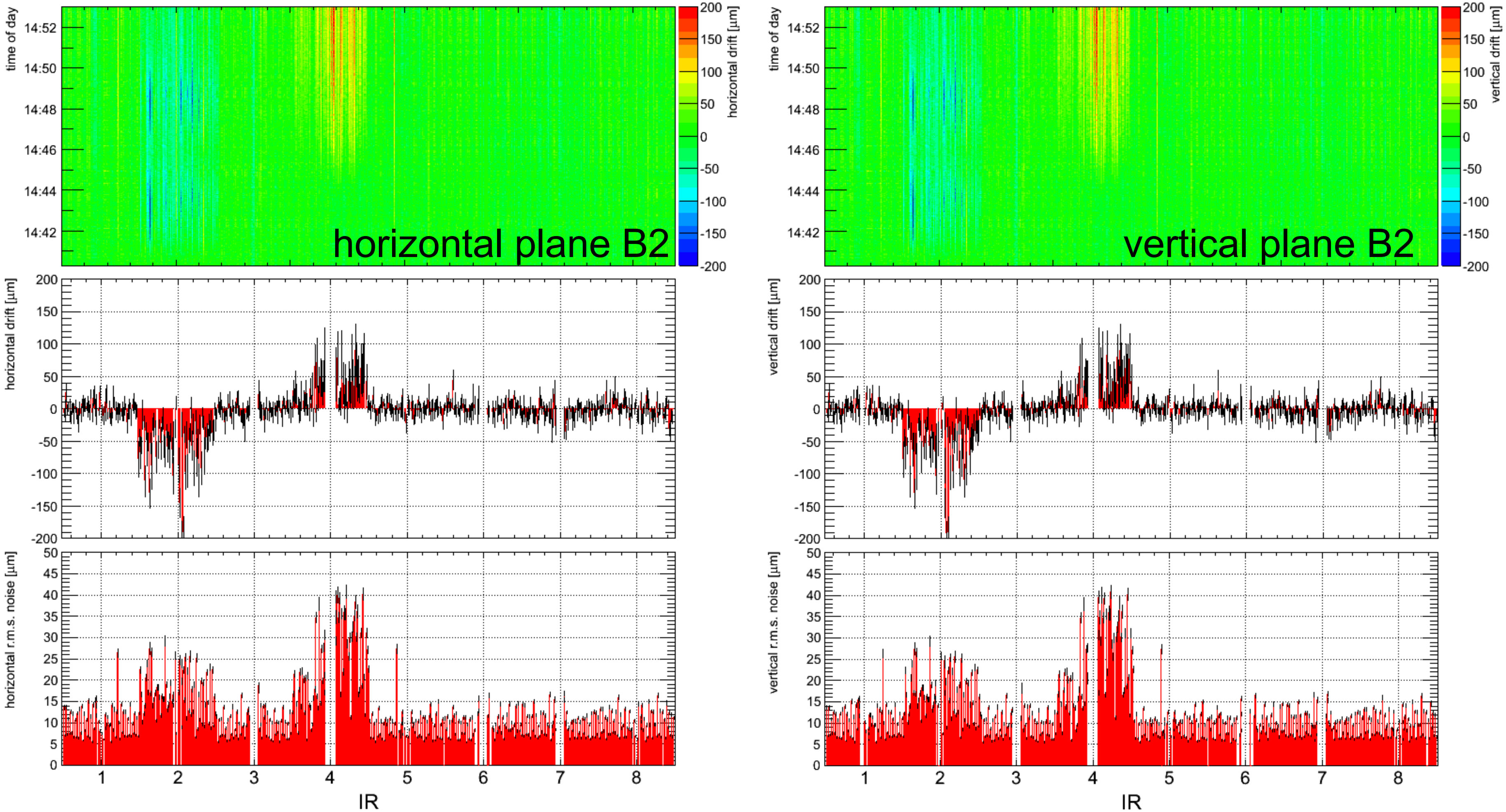
Full LHC Beam-Based Control Scheme – The Beast



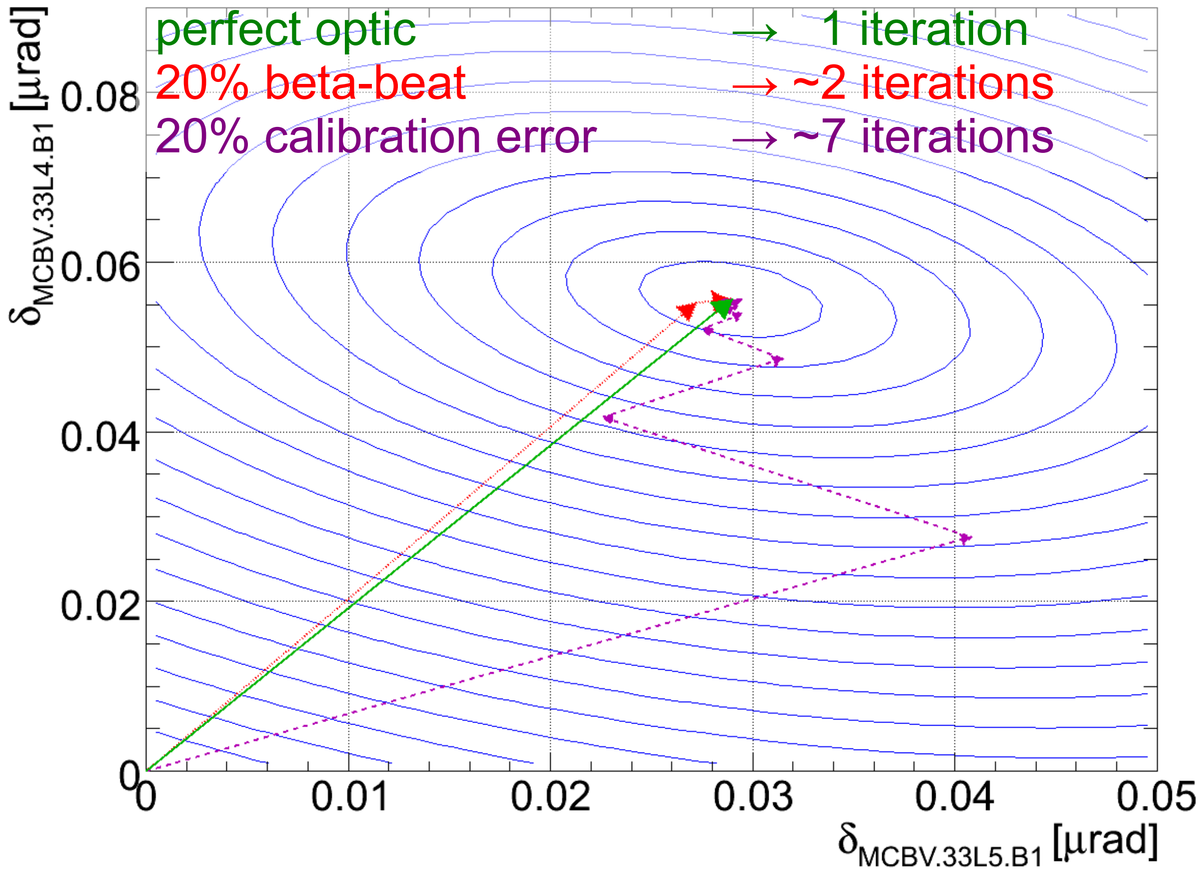
LHC FBs: 2158 input devices, 1300+ output devices → total: ~3300 devices!

LHC Beam Position Monitor – Orbit Stability B2 – LHC Day 1

- Residual injection orbit stability (orbit feedback/radial loop off)



- Optics imperfections may deteriorate the convergence speed but do not affect absolute convergence (response functions are 'monotonic'):
- Example: 2-dim orbit error surface projection

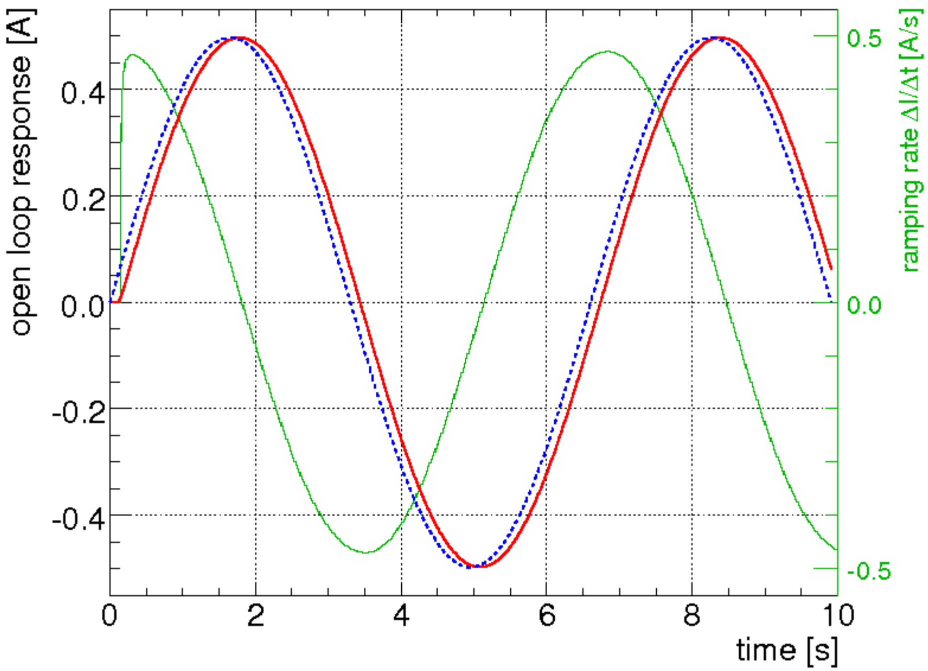


- LHC feedbacks are practically insensitive to optics (= beta-beat) errors
  - However, pickup and corrector magnet polarities are crucial

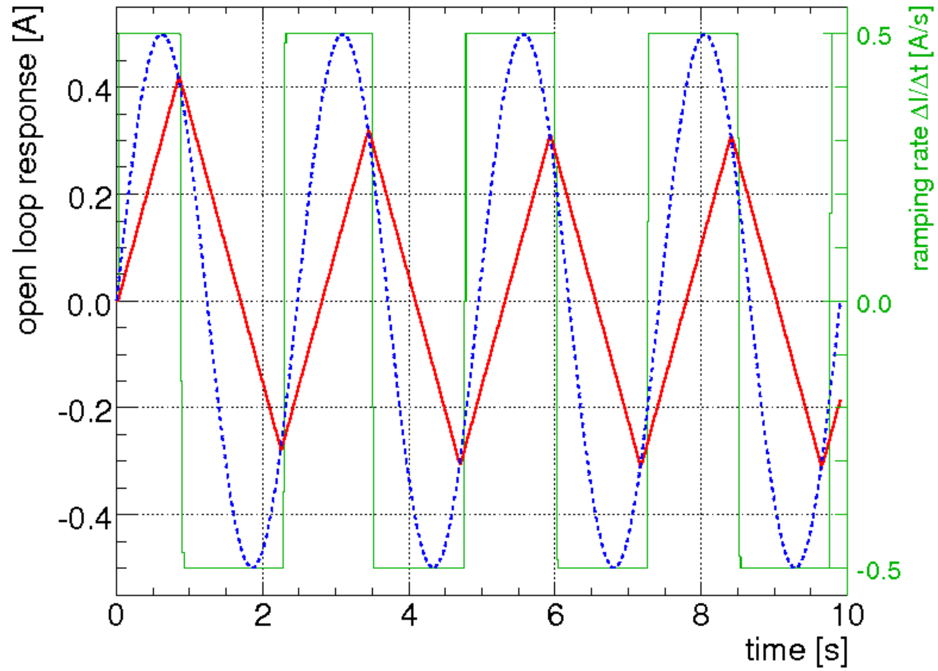
Two common non-linear effects in accelerators:

- Delays: computation, data transmission, dead-time, etc.
- Rate-Limiter: limited slew rate of corrector circuits (due to voltage limitations)
  - e.g. LHC: ±60A converter: $\Delta I/\Delta t|_{max}$ < 0.5 A/s

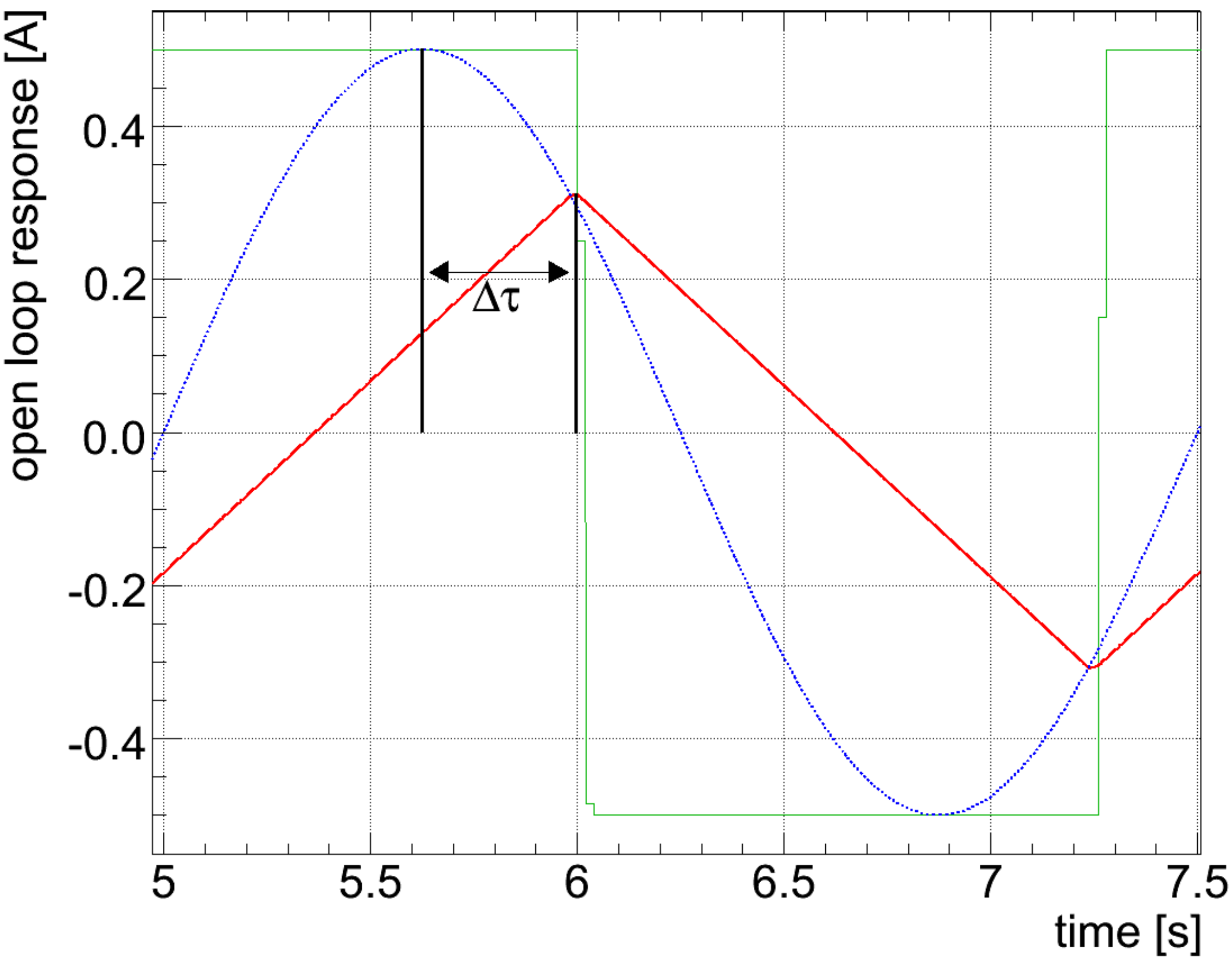
slow perturbation: perfect tracking



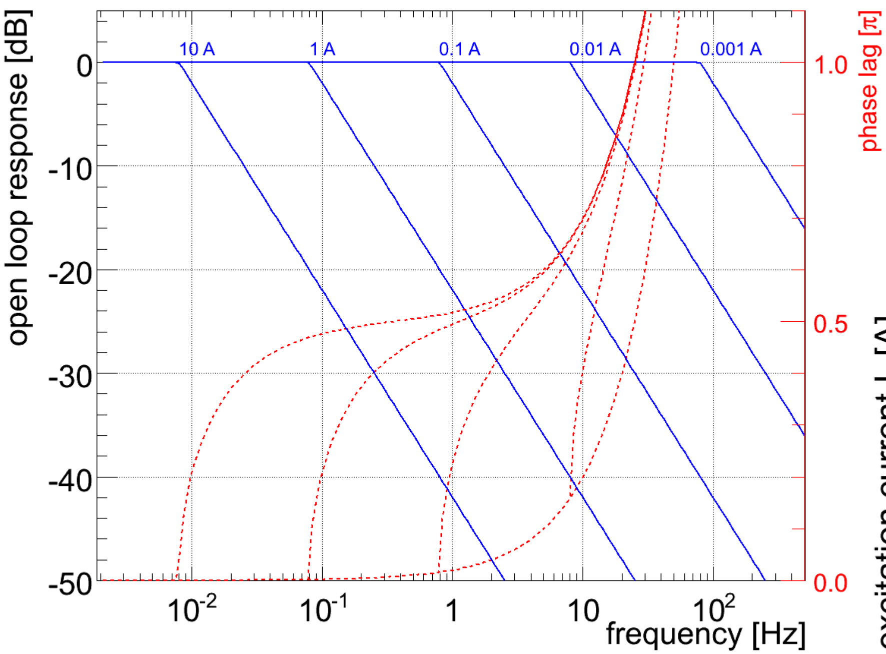
fast perturbation: saw-tooth



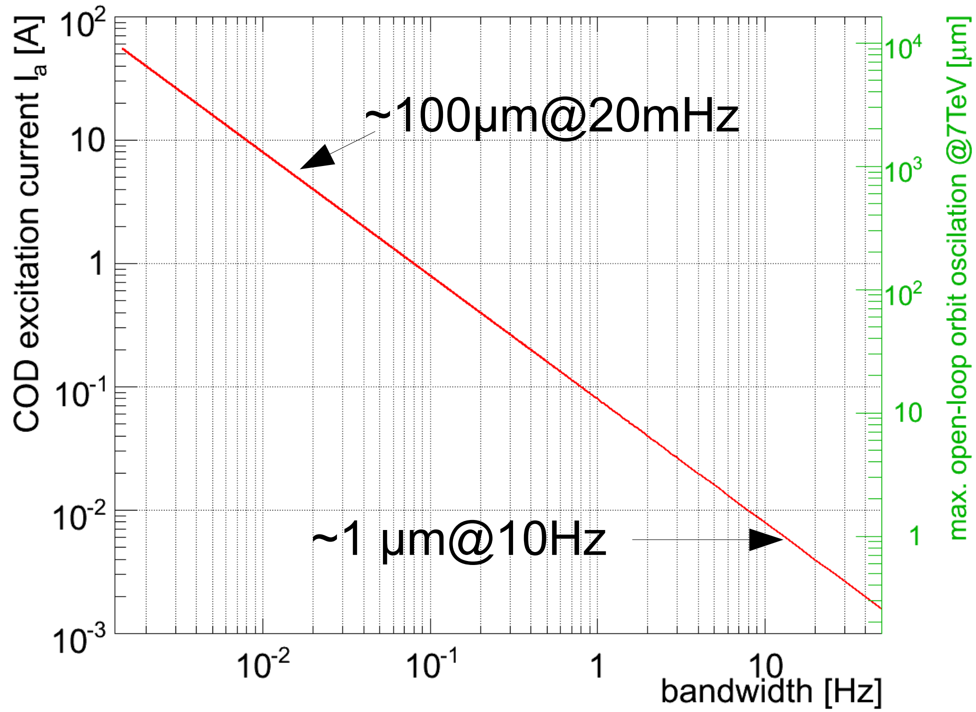
- Rate-limiter in a nut-shell:
  - additional time-delay Δτ that depends on the signal/noise amplitude
  - (secondary: introduces harmonic distortions)



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



ΔI=0.1A ↔ Δx≈16 μm@β=180m



- Consider ~16μm@1Hz as effective bandwidth @ 7TeV