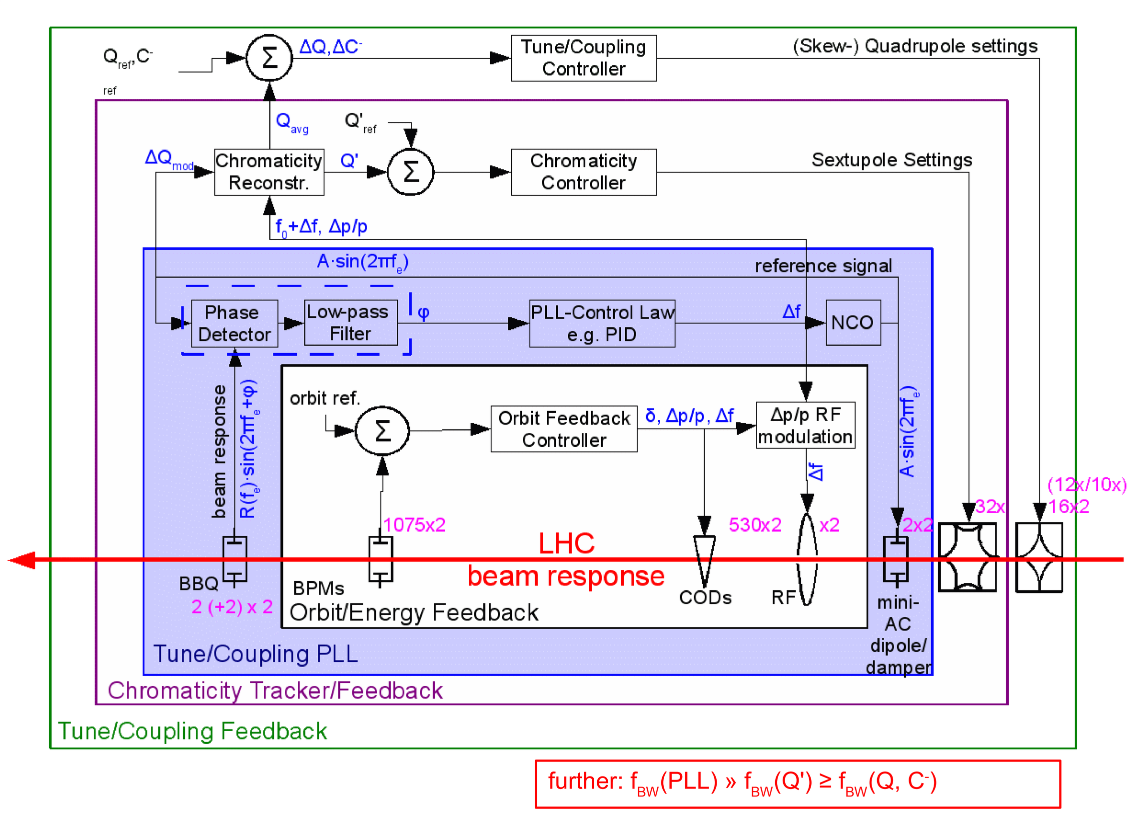
Commissioning and Initial Performance of the LHC Beam-Based Feedback Systems

R. J. Steinhagen, A. Boccardi, A. Butterworth, E. Calvo Giraldo, R. Denz, M. Gasior, J.L. Gonzalez, S. Jackson, L. K. Jensen, O. R. Jones, Q. King, G. Kruk, M. Lamont, S. Page, J. Wenninger (CERN, Switzerland)

Abstract

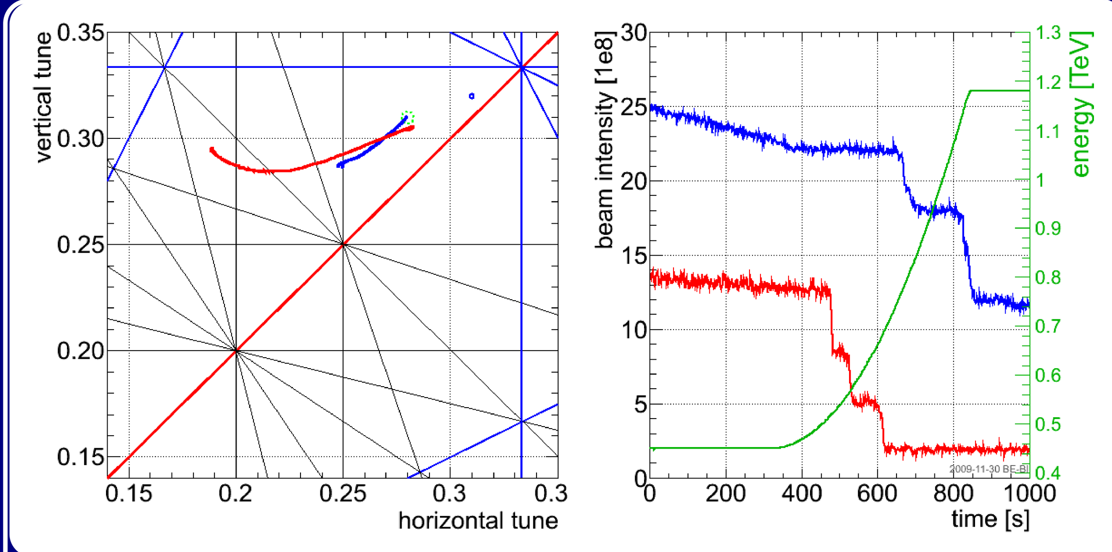
The LHC deploys a comprehensive suite of beam-based feedbacks for safe and reliable machine operation. This contribution summarises the commissioning and early results of the LHC feedback control systems on orbit, tune, chromaticity, and energy. Their performance -- strongly linked to the associated beam instrumentation, external beam perturbation sources and optics uncertainties -- is evaluated and compared with the initial feedback design assumptions.

LHC Feedback-Architecture



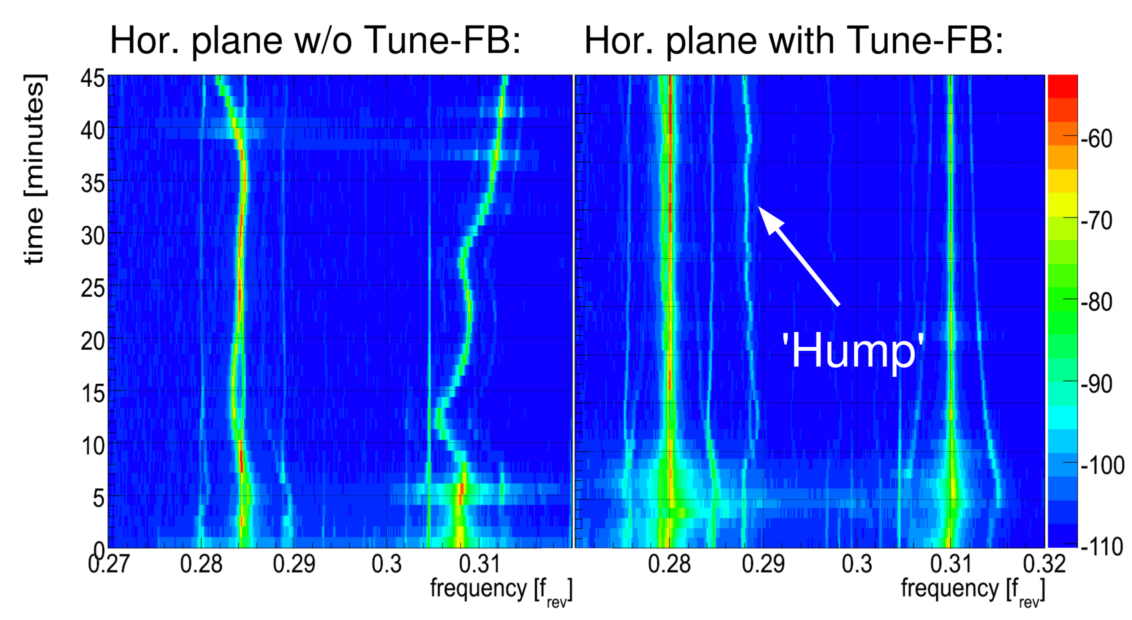
- more than a dozen beam-based feedback loops
- 2158 input devices, 1136 output devices
  → total: ~3300 devices
  → half the LHC is controlled by FBs
- minimisation of inter-loop cross-talk is mandatory!
- Most feedback functionality is dedicated to the detection and mitigation of element errors and failures

Initial Ramp Commissioning:



- Base-Band-Tune (BBQ) Meter was work horse from LHC Day-I!!
- No hardware, minimal software and only a few beam related issues
- most measurements were done with residual beam excitation → FFT based analysis
- Early beams lost due to large tune drifts while ramping → commissioning programme shifted
  - from: Orbit-FB → Q'-FB → … → Tune-FB
  - to: Tune-FB → Q'-FB → … → Orbit-FB

Q during Ramp without and with Feedback:



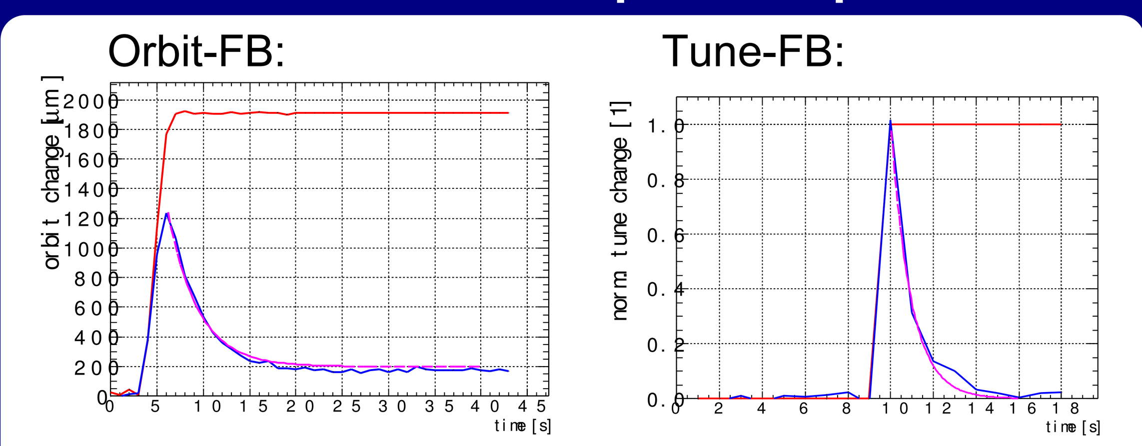
- For perfect pre-cycled machine the uncorrected fill-to-fill tune stability is typ. ~$3\cdot10^{-3}$ but often reaches up to ±0.02

Situation confused with de-facto 3 pre-cycles:

- 'Rampdown Combo': MB/MQ down from 6 kA at 2 A/s,
- 'Precycle' (after access etc.): MB/MQ to 2 kA at 2 A/s, &
- (unfortunately) a mixture of the two (many fills do not end with a 'programmed dump'...)

→ Tune-FB routinely used during (almost) every ramp to compensate these effects!

Time-Domain Closed-Loop FB Responses:

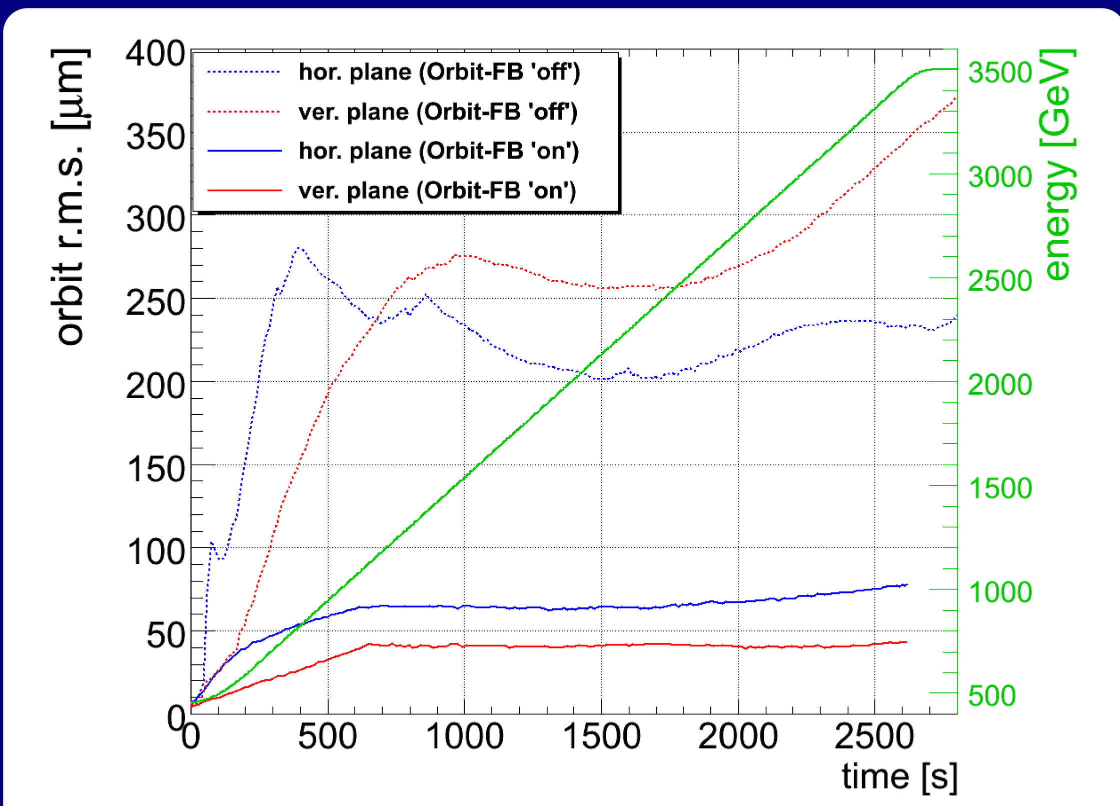


FB response 1/e - time constants:

- Tune: 1..2 s ↔ ~ 0.1..0.3 Hz BW
  - Achieved peak-to-peak tune stability 10^{-3}
  - from Q-FB point-of-view: choice between FFT vs. PLL is transparent
- Orbit-FB & Radial-loop: 3.3 s ↔ 0.1 Hz BW
  - 200 um steady-state error due to using only 400/520 eigenvalues

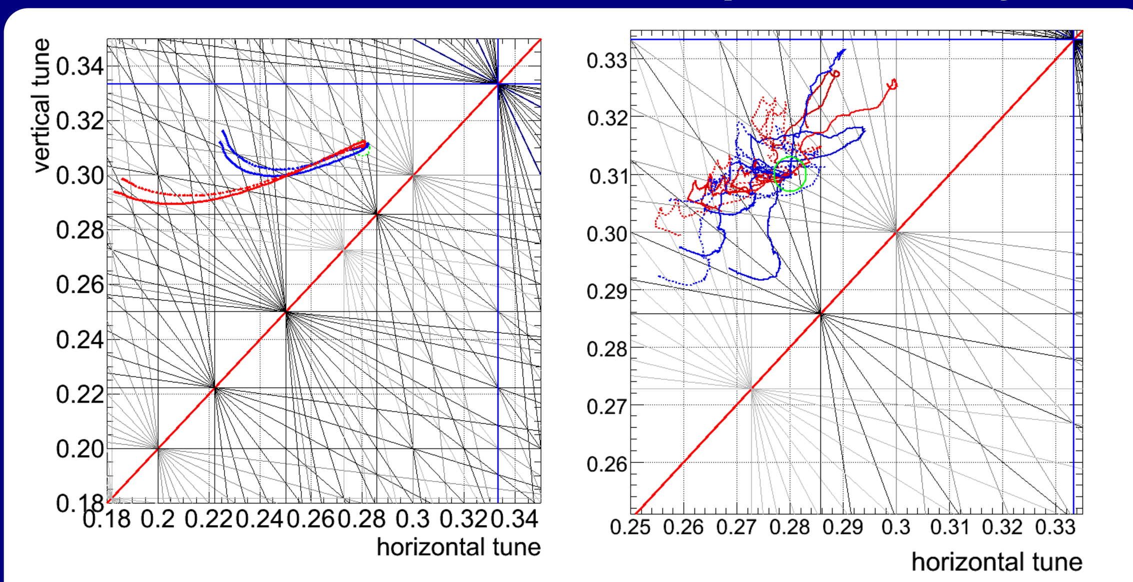
→ In good agreement with model! → going to 0.5 or 1 Hz BW should not pose (big) problems

Orbit-FB Performance:



- Residual error corresponds to local bumps that were not corrected by the Orbit-FB (limited number of used eigenvalues of 280 vs. 530 total)
- Short-term BPM stability < 1 μm however important long-term dependencies on intensity and electronics temperature causing drifts up to 300 μm.

"Bare" Tune- and Tune-FB Reproducibility



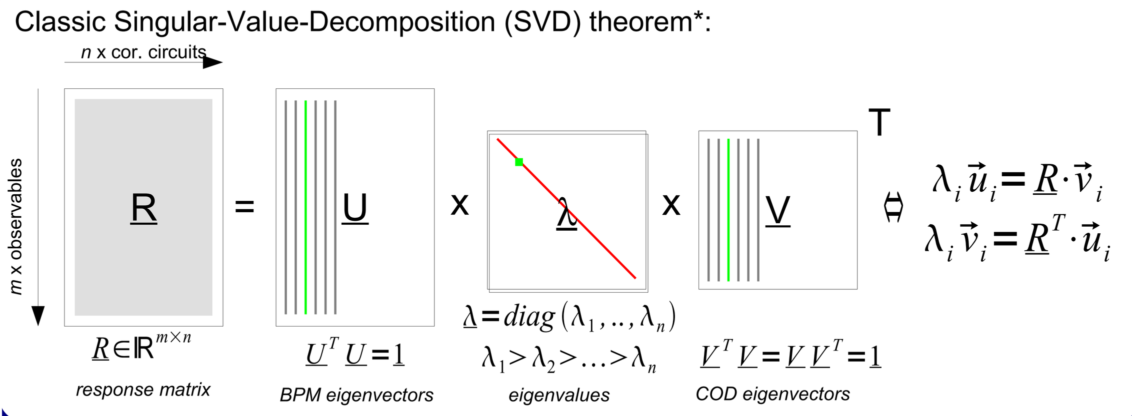
Comparison of two "perfect" ramps to 1.2 TeV with Q-FB

Ramps to 3.5 TeV with Q-FB & Feed-Forward corrections and various pre-cycle histories

- "Bare" tunes – the tunes in the absence of feed-back corrections – as assessment of the fill-to-fill stability:
  - After perfect pre-cycle: $\Delta Q < 2\text{-}3\cdot10^{-3}$
  - Non-standard pre-cycle: $\Delta Q < 0.3$!!

Alternate SVD Orbit-FB Algorithm

Classic Singular-Value-Decomposition (SVD) theorem*:



Standard corr. using pseudo-inverse response matrix:

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

static matrix-vector multiplication O(n²)

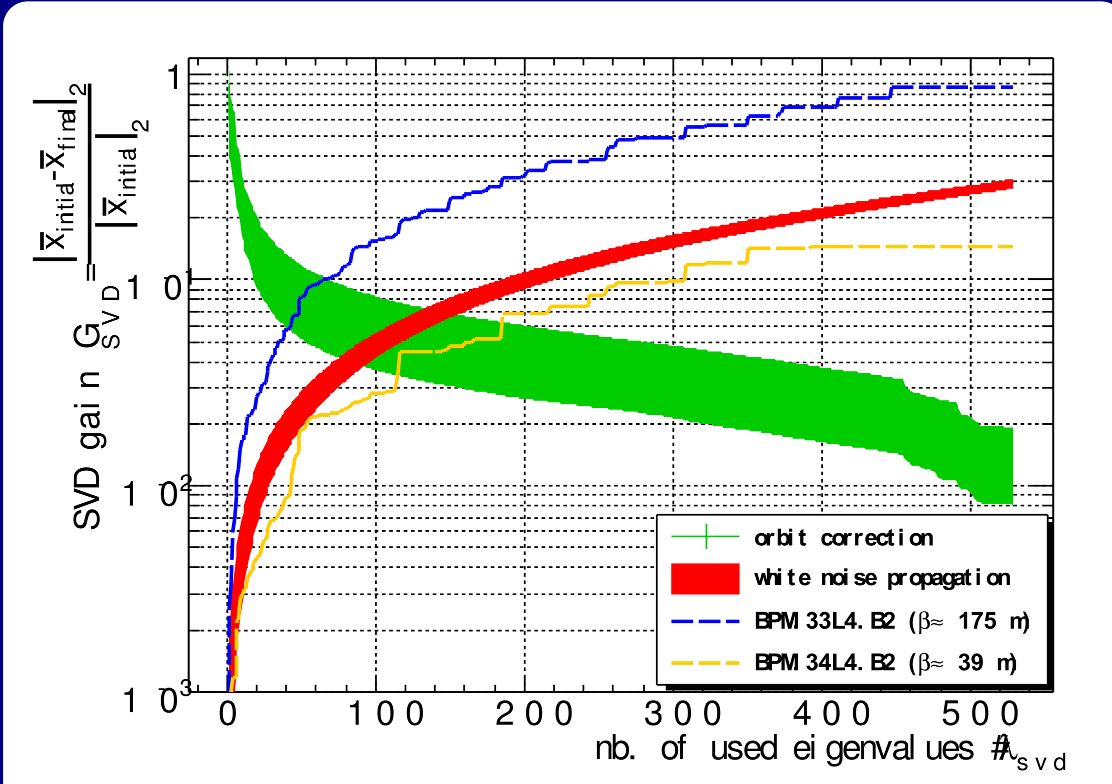
Alternate "SVD++" Correction:

$$\Leftrightarrow\quad \vec{\delta}_{ss}=\sum_{i=0}^{n} D\left(\frac{a_i}{\lambda_i}\vec{v}_i, t\right)\quad with\quad a_i=\vec{u}_i^{T}\Delta\vec{x}$$

One FB controller D(x,t) for each eigenvalue O(2n²):

- allows quick online re-configuration and different bandwidth for local/global orbit correction

Locality of Orbit-FB vs. Sensitivity to Noise



Deliberate de-selection of eigenvalues allows a trade-off between orbit correction precision and sensitivity to measurement noise and failures.

Initial OFB commissioning: 280, now 370 eigenvalues

Encountered Issues& Ongoing Commissioning:

- Real-time corrector trims caused spurious trips of the magnet's quench protection system
  - Now filtered for tune corrector circuits
  - Solution for sextupoles and skew-quad. Pending
- Q-PLL commissioning but was found to be limited by residual strong um-level tune oscillations:
  - Could be fixed by larger excitation possible but considered impractical (ε-blow-up, …)
  - Pot. cross-talk with transverse feedback
  - However, residual tune oscillations allowed the reliable operation of passive Q/Q' tracking using a Fourier-based analysis approach → back-bone of day-to-day operation.
- Long-term Orbit-FB stability limited only be systematic BPM dependencies on bunch intensities and electronics temperatures
  - temperature stabilisation in preparation
  - Intensity dependence under evaluation

Conclusion

The commissioning of the beam-based feedbacks and associated diagnostic chains advanced well during the first days with beam and facilitated early-on a fast and reliable LHC operation. In response to tune drift related particle losses during the first ramps, the commissioning of the Q-FB was given priority and and achieved tune stabilities of a few 10^{-4} at injection down to 10^{-4} for energies above 0.8 TeV. The orbit feedback achieved stabilities of 70 um r.m.s. during the first ramps and is currently limited by the chosen locality of the correction. In the long-term however, BPM dependencies on crate temperature and bunch intensity leading to drifts of up to 300 um will have to be addressed.