Results of the LHC Prototype Chromaticity Measurement System Studies in the CERN-SPS

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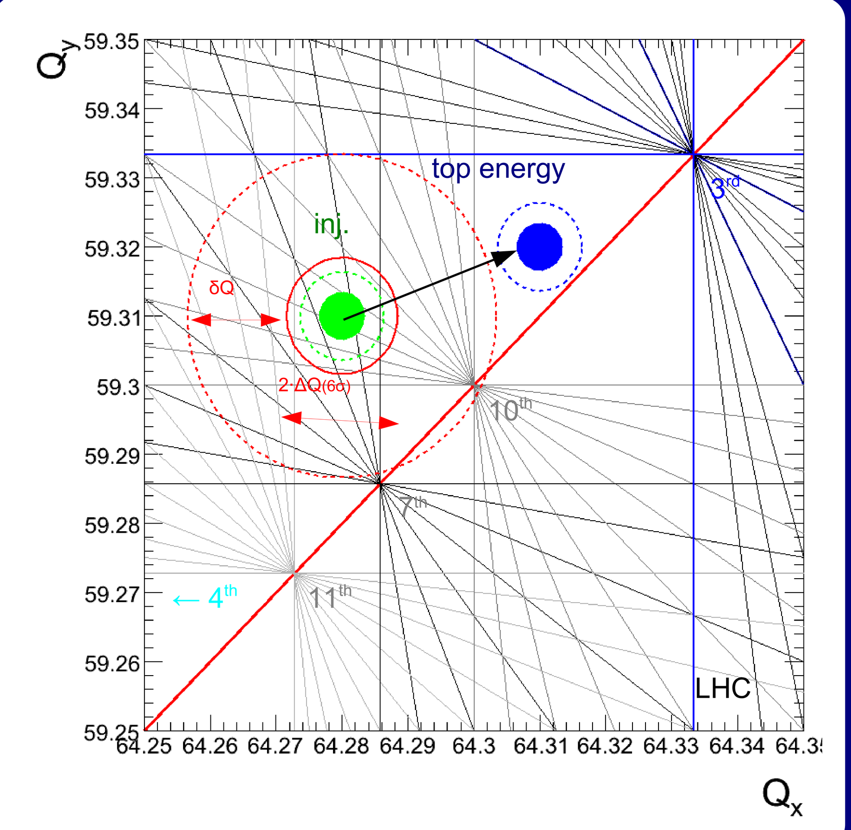
Abstract

Tune and chromaticity control is an integral part of safe and reliable LHC operation. Tight tolerances on the maximum beam excursions allow oscillation amplitudes of less than 30 µm. This leaves only a small margin for transverse beam and momentum excitations, required for measuring tune and chromaticity. This contribution discusses the baseline LHC continuous chromaticity measurement with results from tests at the CERN-SPS. The system is based on continuous tracking of the tune using a Phase-Locked-Loop (PLL) while modulating the beam momentum.

The high PLL tune resolution achieved, made it possible to detect chromaticity changes well below the nominally required 1 unit for relative momentum modulations of only $2\cdot10^{-5}$. The sensitive tune measurement front-end employed allowed the PLL excitation and radial amplitudes to be kept below a few micrometers. These results show that this type of measurement can be considered as practically non-perturbative, permitting its use even during nominal LHC operation.

Parameter Stability Requirements



Stability requirements on LHC tune and chromaticity are primarily driven by the ability to control particle loss. The lack of synchrotron radiation damping (hadrons) requires up to 12th order resonances to be avoided.

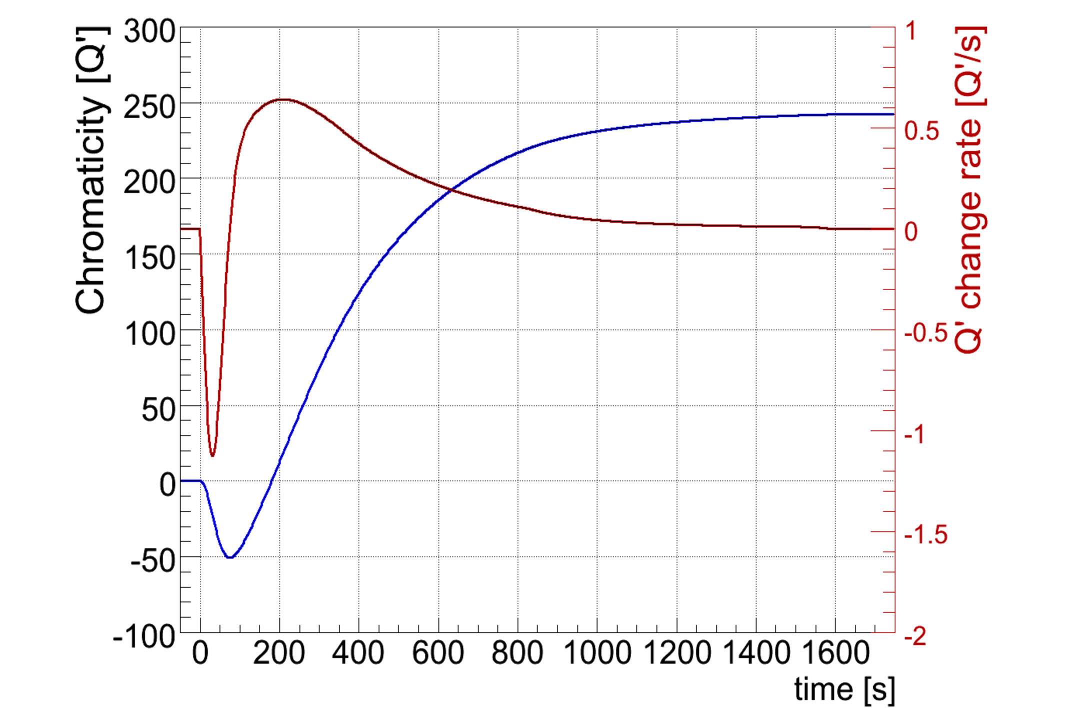
- LHC Cleaning and RF System imposes tight constraints on the orbit/betatron oscillations:

$$\Delta z \leqslant 35\,\mu m \quad \rightarrow \quad \frac{\Delta p}{p} < 10^{-5} \qquad \Delta Q = Q' \frac{\Delta p}{p} \quad (1)$$

- Classic Method: $\Delta p/p > 10^{-3}$ & $\Delta Q_{res} \approx 10^{-3}$ → $\Delta Q'_{res} \sim 1$
- LHC's Q' Tracker 'Gretchen Frage':
  Q' Tracker Feasibility with $\Delta p/p < 10^{-5}$ & $\Delta Q'_{res} \sim 1$
  → $\Delta Q_{res} < 10^{-5}$ → will deploy BBQ-based PLL

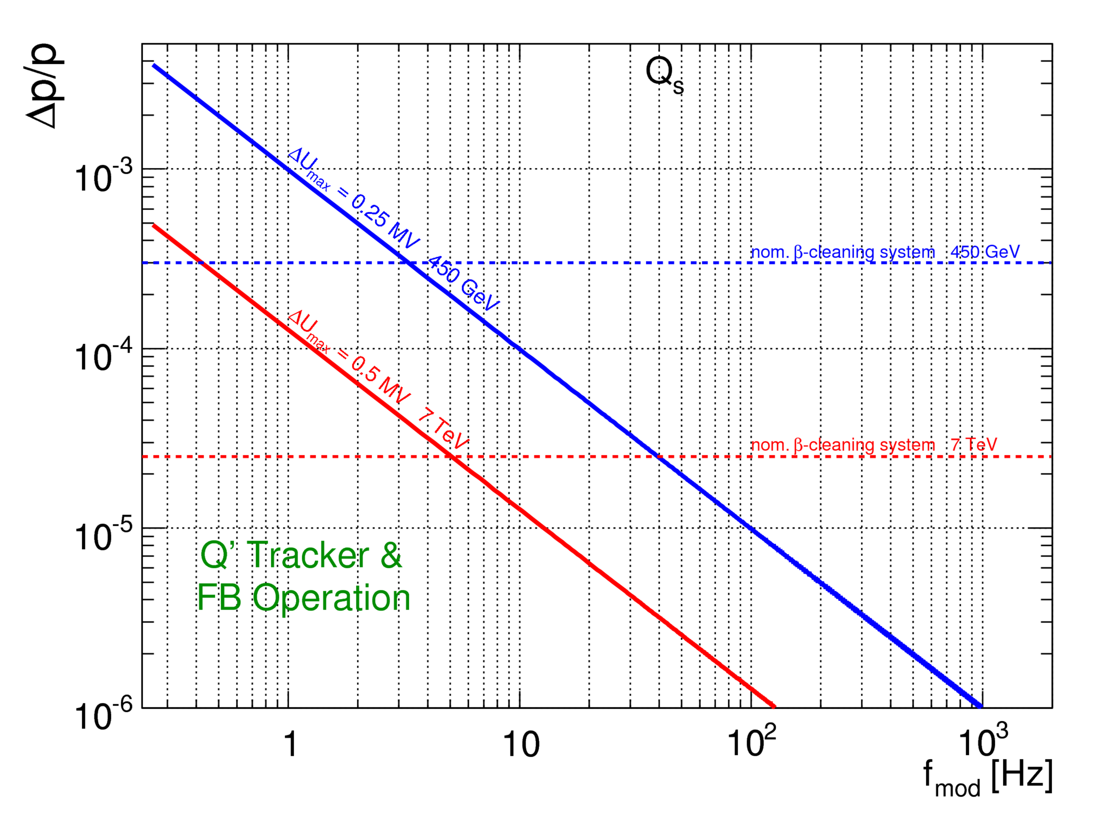
Expected Perturbations vs. Requirements:

- Sources: power supply drifts and ripples, hysteresis, ramp tracking errors, beam-beam, e-cloud, decay & snap-back, persistent currents, ...
- Ramp: max. $\Delta Q' \approx 300$ units @ $\Delta Q'/\Delta t \approx 1.2$ units/s



	Orbit [σ]	Tune [$0.5\cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Perturbations:	~ 1-2 (30 mm)	0.025 (0.06)	~ 70 (300)	± 1.5e-4	~0.01 (0.1)
Max. Drift Rate:	~ 25 µm/s	< 10^{-3} /s	< 1.3 s		
Pilot	-	± 0.1	+ 10 ??	-	-
Commissioning	± ~ 1	±0.015→0.003	> 0 ± 10	± 1e-4	« 0.03
Nominal	± 0.15	±0.003 / ±0.001	2 ± 1	± 1e-4	« 0.01

LHC RF Power Limitation:



- There are multiple but similar detection techniques:
  - **modulation below Q_s** → **classical method**
  - **modulation above Q_s** → **McGinnis'/Brüning's method**
- **LHC RF Power permits only small modulations**

Chromaticity Reconstruction Algorithm:

- For short time-scales, Δp/p-driven tune changes can be approximated by (ω_m: RF modulation frequency):

$$Q(t) = +\beta_0 + \beta_1\cdot\sin(\omega_m t) + \beta_2\cdot\cos(\omega_m t) + \beta_3\cdot t + \beta_4\cdot t^2 + \beta_5\cdot t^3$$

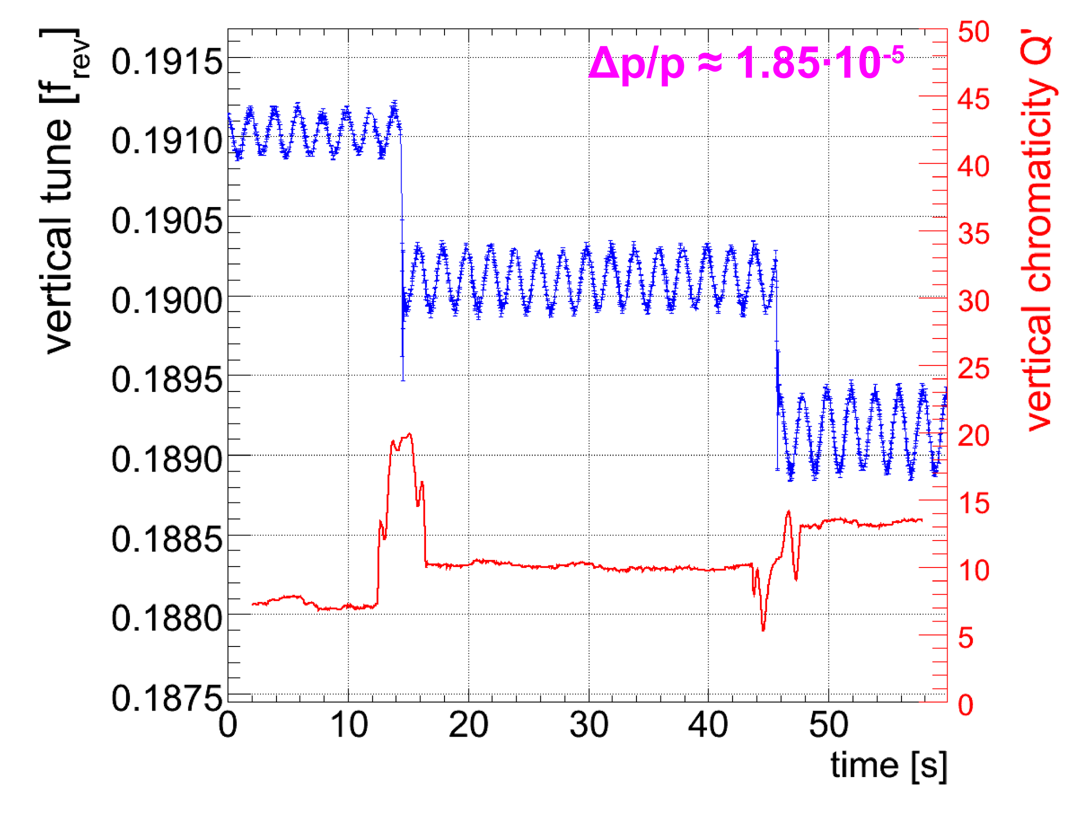
$$\& \quad \Delta Q = \sqrt{\beta_1^2 + \beta_2^2}$$

- Demodulation techniques:
  - **Amplitude demodulation:**
    - fails for systematic non Q'·Δp/p dependent Q drifts
  - **Linear regression:** similar to classic amplitude demodulation but includes systematic offset, quadratic, cubic, ... drift components
    → numerically: simple vector matrix operation:

$$\begin{pmatrix} Q(0\cdot T_s) \\ Q(1\cdot T_s) \\ \vdots \\ Q(N\cdot T_s) \end{pmatrix} = \underline{R} \cdot \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_5 \end{pmatrix} \xrightarrow{SVD} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_5 \end{pmatrix} = \underline{R}^{-1} \cdot \begin{pmatrix} Q(0\cdot T_s) \\ Q(1\cdot T_s) \\ \vdots \\ Q(N\cdot T_s) \end{pmatrix}$$

  - **Chi-square-fit:** most robust, most flexible but also most complex technique (numeric sense)
    - same result as linear regression for constant ω_m.

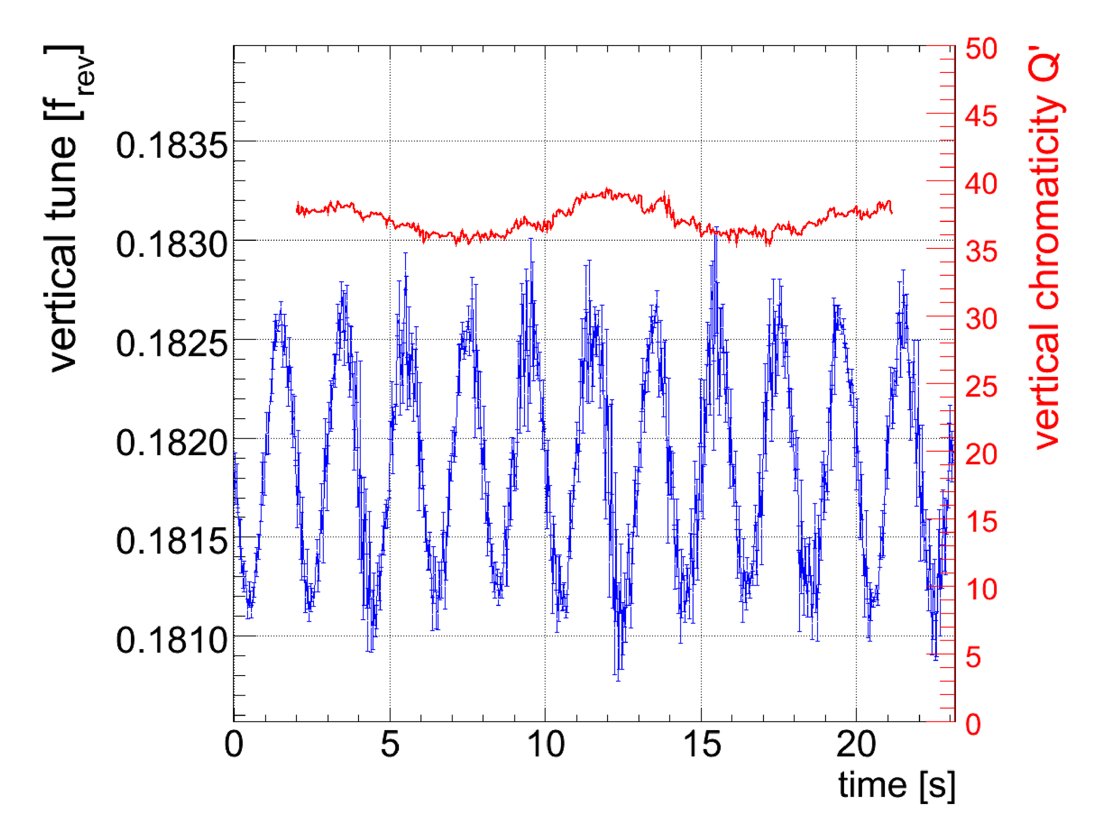
LHC Q' Tracking Tests in the CERN-SPS:



- **Unprecedented *Q'* resolution better than 1 unit**
  - **here: use 2 ω_m periods for linear regression**
  - **radial momentum modulation ($\Delta p/p \approx 1.85\cdot10^{-5}$).**
  - **Excitation amplitudes in the few µm range**

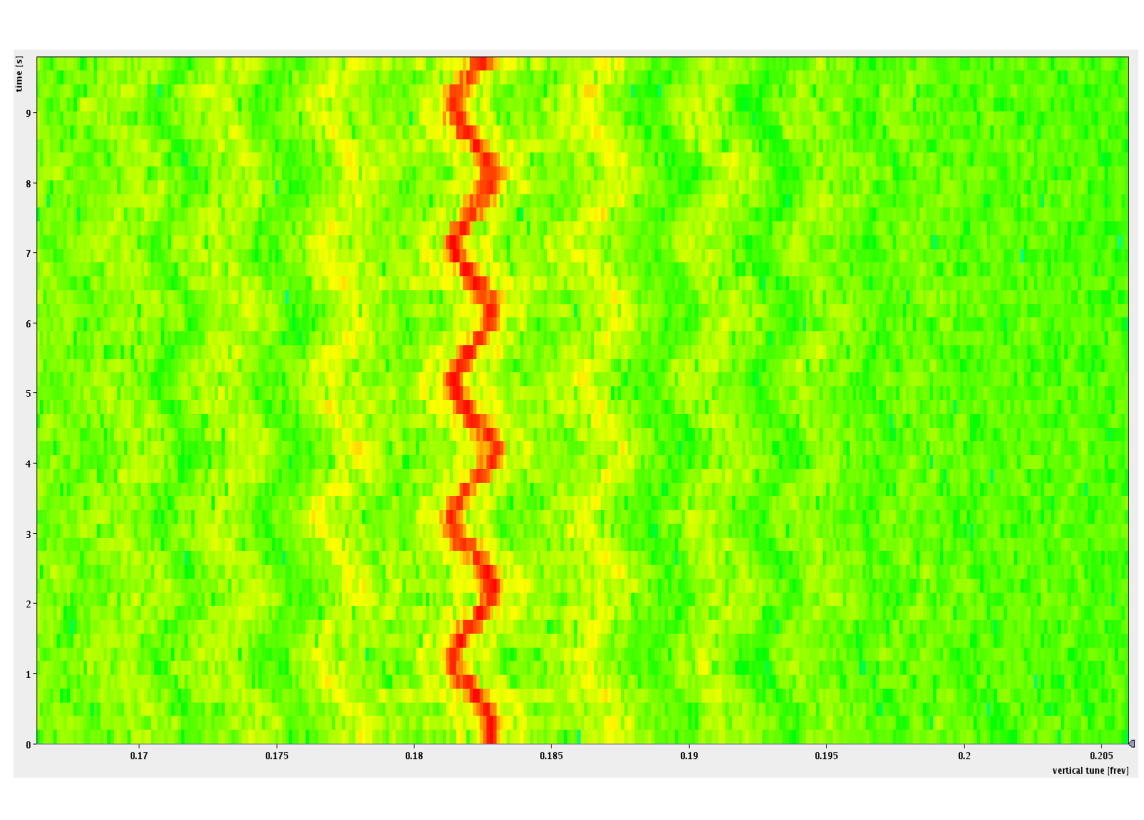
N.B. tracking transients: ΔQ' feed-down on ΔQ (off-centre orbit in sextupoles)

Q' Tracking Tests Large Chromaticities I/II



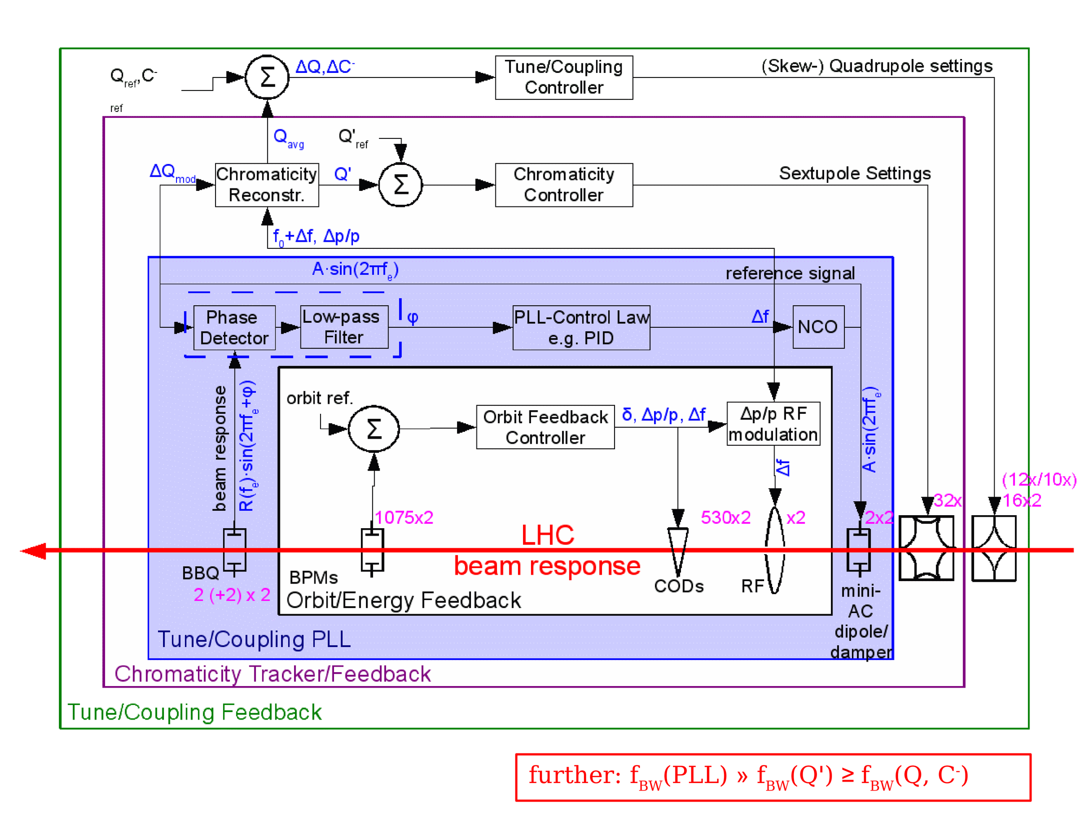
- Scans to assess the maximum useful range yield showed that this method can cope with values of chromaticities up to at least 34 units
  - most Fourier based method fail in this regime due to de-coherence of transverse oscillations due to Landau-Damping (*Q'*, amplitude detuning, ...)

Q' Tracking Tests Large Chromaticities II/II



- Momentum driven ΔQ modulation are visible in the FFT spectrum for very large chromaticities (*Q'* » 10)
- LHC Base-Band-Tune (BBQ) System = Direct-Diode-Detection:
  - exploitation: LHC Q Phase-Locked-Loop (PLL)
  - excitation amplitudes can be kept within a few µm

LHC Q' Tracker Feedback Integration



- LHC Feedbacks:
  - more than a dozen beam-based feedback loops running during nearly all operational phases
  - 2158 input devices, 1136 output devices → total: ~3300 devices → half the LHC is controlled by FBs
  - minimisation of cross-talk is mandatory!

Conclusion

The LHC requires a continuous, automatic control of orbit, tune, chromaticity, betatron coupling and energy for safe and reliable machine operation. The LHC Cleaning and Machine Protection systems impose tight constraints on the allowed transverse beam oscillations, traditionally required to measure *Q* and *Q'*. These constraints have led to the development of the high sensitivity direct diode detection technique, further exploited through a *Q* tracking PLL. Combining this detection technique with small momentum modulation has allowed a tracking of *Q'* with unprecedented accuracy using minimal excitation in the µm range. Based on tests at the CERN-SPS, the performance of such a system has been shown to be compatible with nominal LHC requirements during regular operation.