Advancements in the Base-Band-Tune and Chromaticity Instrumentation and Diagnostics Systems during LHC's First Year of Operation

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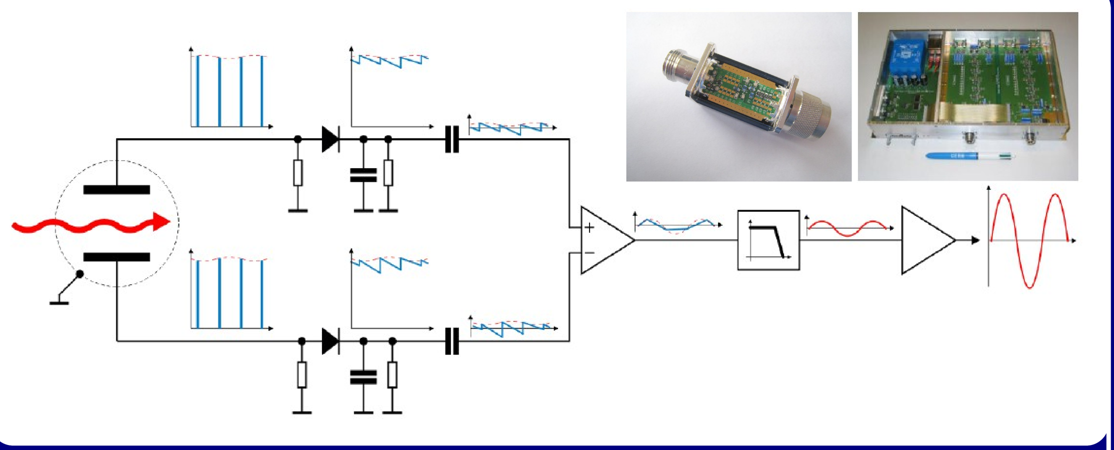
Abstract

The Base-Band-Tune (BBQ) system is an integral part of day-to-day LHC operation, driving tune and chromaticity diagnostics and feedbacks. This contribution summarises the system's overall performance and documents the various improvements of the analogue front-end circuitry, digital post-processing and integration that were necessary in response to issues arising during high-intensity physics operation since its first introduction in 2005.

1 Direct-Diode-Detection BBQ



Basic principle: AC-coupled peak detector
- no saturation, self-triggered, no gain changes
- intrinsically down samples spectra:
  ...a few GHz → 1kHz ... f_{rev}
- Base-band: very high sensitivity/resolution ADC available
- Measured resolution estimate: < 30 nm
  → ε blow-up is a non-issue

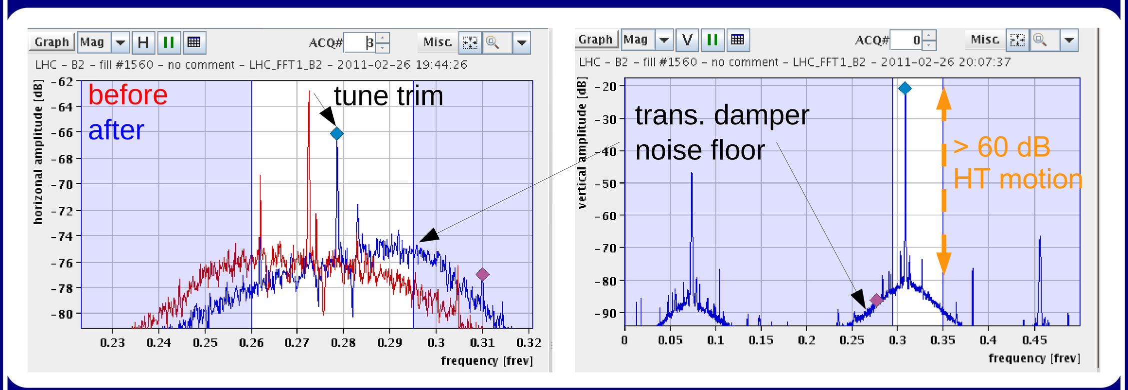
Noteworthy second-order effects:
For small number of bunches: Peak → Average Q detector
- finite charge-up time of storage capacitor due to bunch-length τ << revolution period T_{rev}

From the charge balance equation (first order):

$$\frac{V_0}{V_I} = \left(1 + \frac{r}{R}\cdot\frac{T_{rev}}{\tau}\cdot\frac{1}{n}\right)^{-1}$$

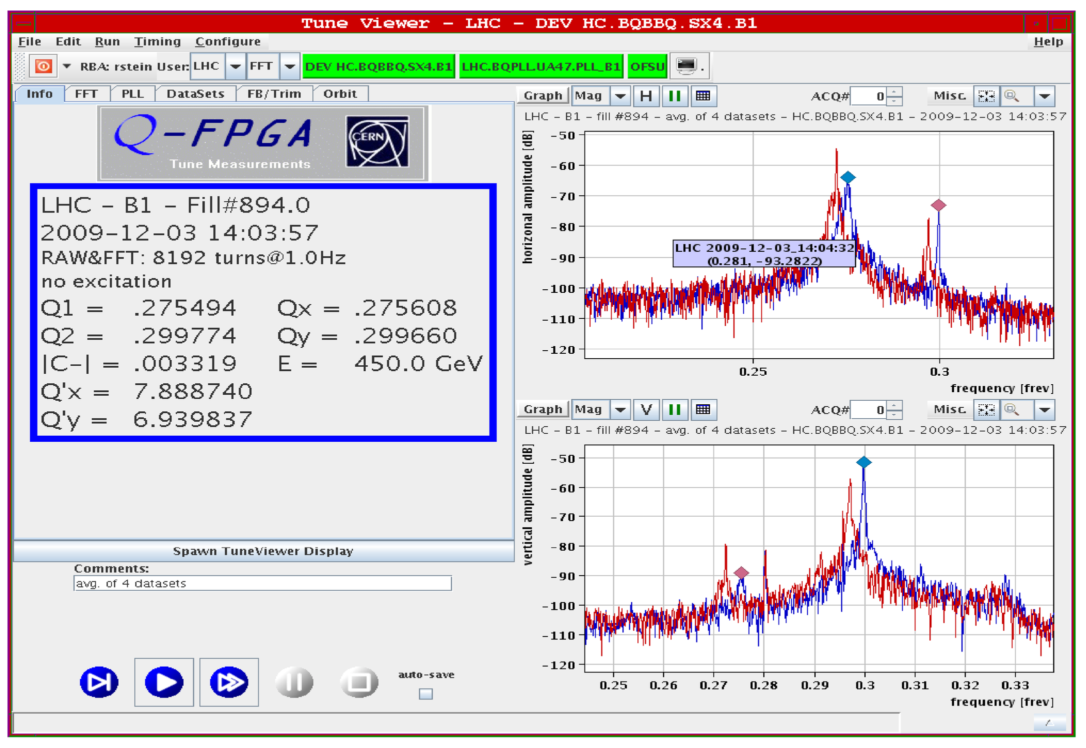
(n: number of bunches, r: approx. diode series resistance, R: discharge resistance)

For large number of bunches:



BBQ is sensitive to GHz-range head-tail motion!

2 The Good...



Initial design assumption: no residual tune signatures on the beam (0 dB S/N)

→ Anticipated constant driving of the beam and – to limit the required excitation levels – the highly-sensitive BBQ system was developed.

Blessing/Curse after start-up:

1) BBQ turn-by-turn resolution of better than 30 nm
   more sensitive than other LHC systems (ADT: 1µm, BPM: 50 µm)

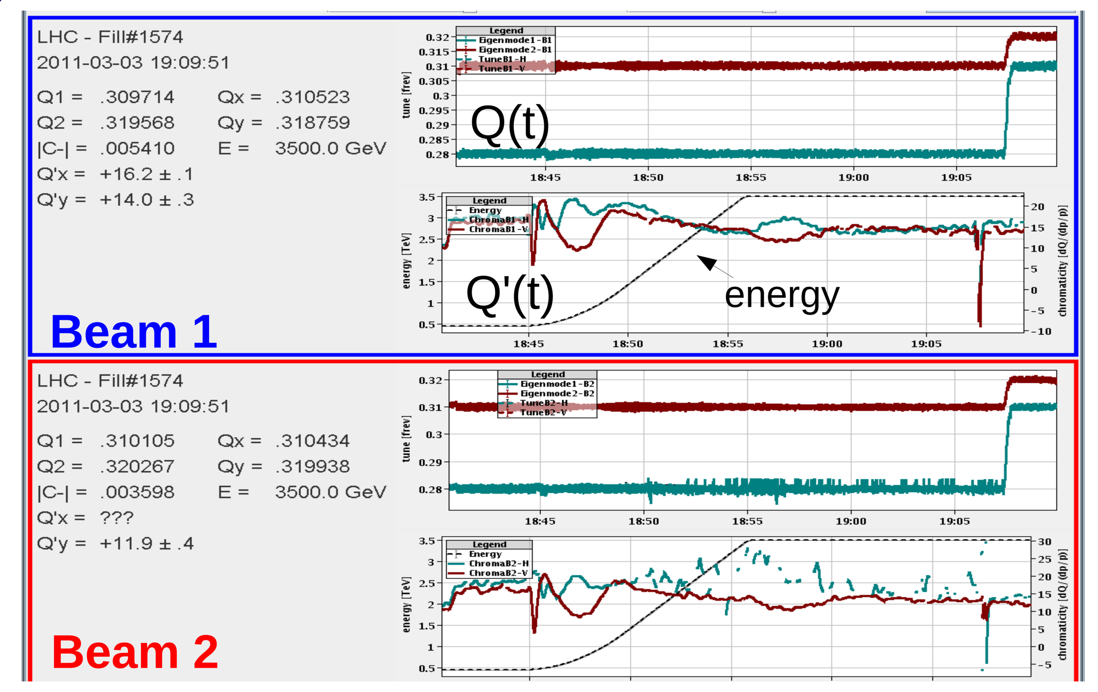
2) Ever-present Q oscillations up to µm level

Luxurious 30-40 dB S/N ratios enabled the passive monitoring, tracking and feedbacks without any additional excitation,

However, µm-level oscillations are incoherent "noise" from a Tune-PLL point of view

- Need to excite ~30 dB above this "noise" to recover the same performance as with a "passive-only" FFT system
  → 10...100 µm oscillations vs. collimators <200 µm
- Driving the beam with the present ample signals seemed to be inefficient/less robust

The Long-Term BBQ/FB Performance



Out of 191 ramps in 2010:

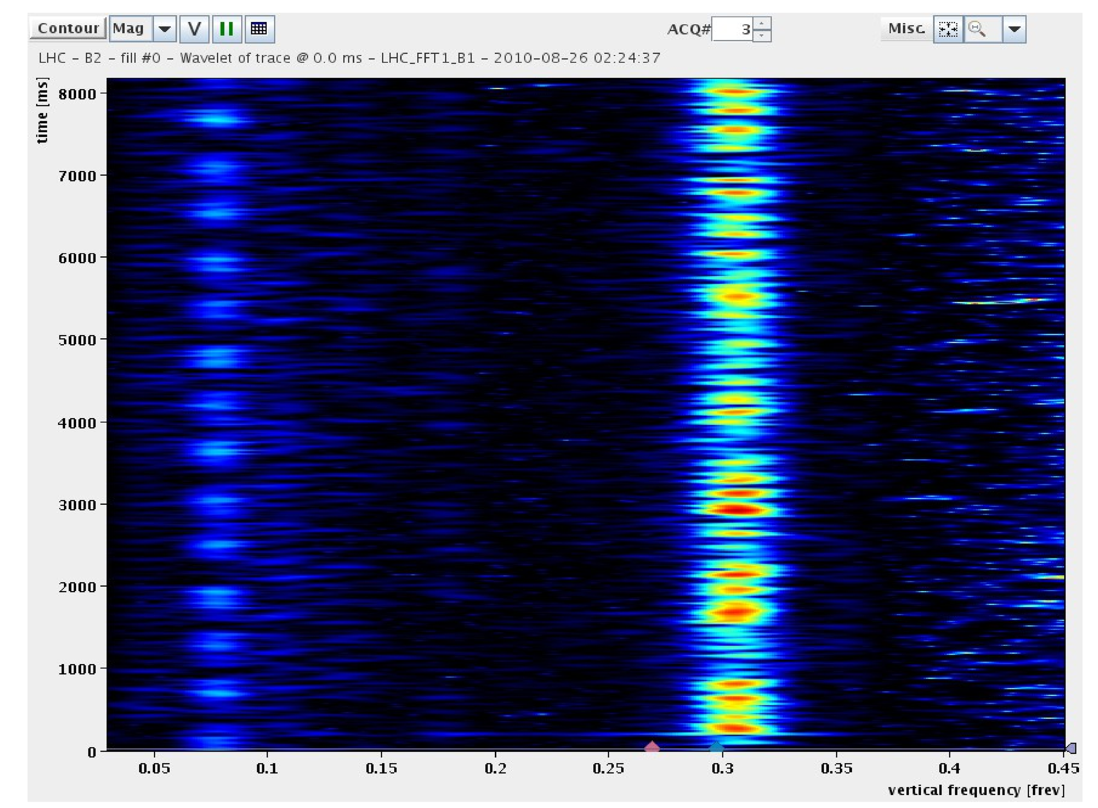
... 155 ramps with > 99% transmission,
178 ramps with > 97% transmission

... only 12 ramps lost with beam (6 with Tune-FB during initial commission.)

... "if without FBs": 83 crossings of 3rd, 4th or C- resonance,
157 exceeded |ΔQ|>0.01

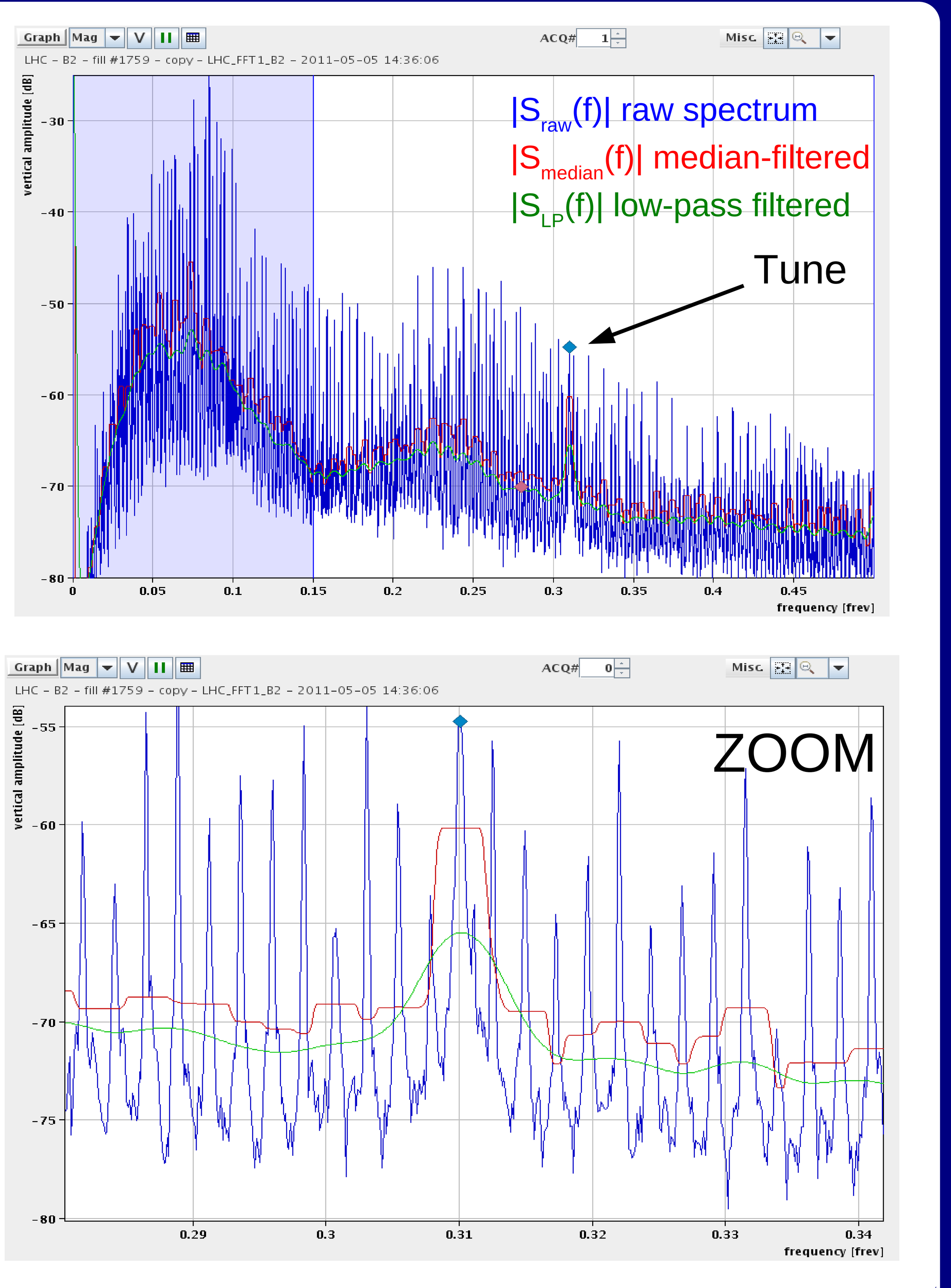
Impressive performance for a first year of operation

Source of Tune-Oscillations...



...remains unknown but is rather a burst-like instabilities than due to coherent perturbation.

3 The Bad...



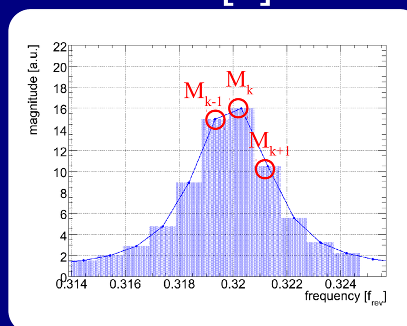
"Forest" of Q_s lines due to longitudinal bunch phase and shape oscillations (machine development)

Remedy → Refined Q-Tracker Algorithm

Idea: Q resonances are wider than mains harmonic and Q_s interference lines:

1) calculate of the *n*-turn based raw-spectra $S_{raw}(f)$,
2) compute (averaged) magnitude spectra $|S_{raw}(f)|$,
3) apply n_{median}-wide median-filter → $|S_{median}(f)|$,
4) apply $\pm n_{LP}$-wide average-filter → $|S_{LP}(f)|$,
5) find highest peak $Q_{est.}$ in $|S_{LP}(f)|$ with $f_{min} \leq Q_{est.} \leq f_{max}$,
6) re-search highest peak Q_{raw} in $|S_{raw}(f)|$ around the previous estimate '$Q_{est.}\cdot n/2 \pm n_{median}/2$',
7) re-fine binning-limited Q_{raw} estimate by fitting the tune resonance to a Gaussian distribution [5]:

$$Q \approx Q_{raw} + \frac{\frac{1}{2}\log(M_{k+1}/M_{k-1})}{\log(M_k^2/(M_{k-1}M_{k+1}))}$$

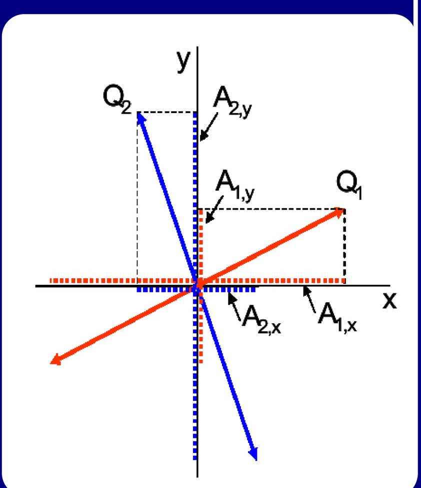


8) derive the coupling and unperturbed tunes [6]:

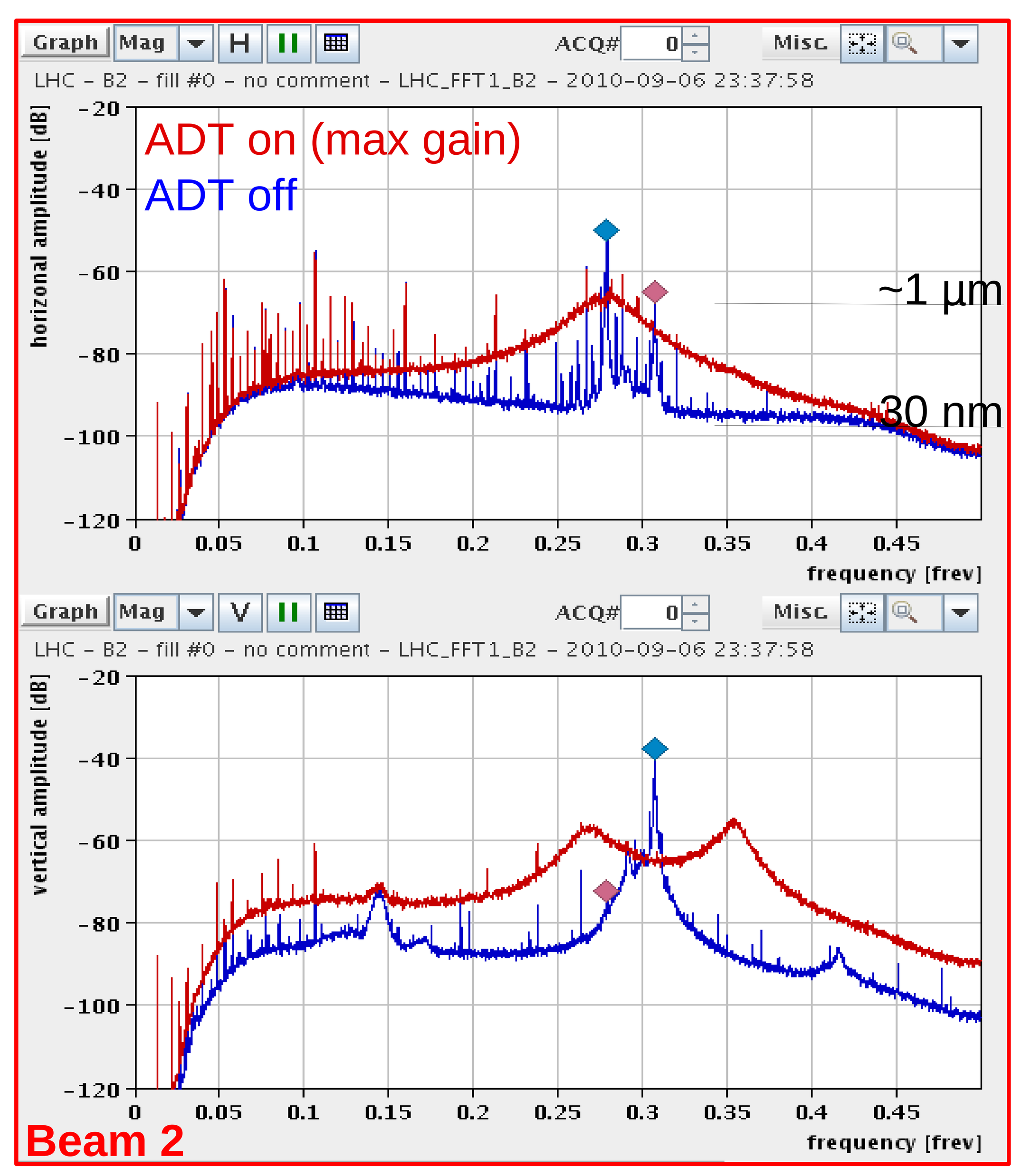
$$r_1 = \frac{A_{1,y}}{A_{1,x}} \quad \wedge \quad r_2 = \frac{A_{2,x}}{A_{2,y}}$$

$$\Rightarrow \quad |C^-| = |Q_1 - Q_2|\cdot\frac{2\sqrt{r_1 r_2}}{(1+r_1 r_2)}$$

$$\wedge \quad \Delta = |Q_1 - Q_2|\cdot\frac{(1-r_1 r_2)}{(1+r_1 r_2)}$$



4 The U...ndetectable



Higher transverse bunch-by-bunch FB (ADT) gain implies also more measurement noise propagated onto beam → nullifies the higher BBQ sensitivity

The LHC is not yet limited by instabilities, and the ADT is thus operated with reduced gains whenever precise Q/Q' diagnostics or Tune-FB are required.

Conclusion

The BBQ system facilitated a fast and reliable commissioning and operation of the LHC from day one. Ever-present um-level tune oscillations in the LHC provide tune signal-to-noise ratios of 30 dB above the BBQ's nm-level noise floor preluded a change of paradigm of relying on passive monitoring of beam oscillations only and required modifications to the LHC Q and Q' diagnostic algorithm. In response, a multi-stage fitter algorithm has been implemented, efficiently suppressing non-tune related interferences lines by rejecting those lines with bandwidths smaller than the expected minimum tune resonance bandwidth. Beam observations helped with a better understanding of second order effects such as the BBQ measuring the average tune for a low number and becoming increasingly sensitive to intra-bunch head-tail oscillations for a larger number of bunches circulating in the machine.