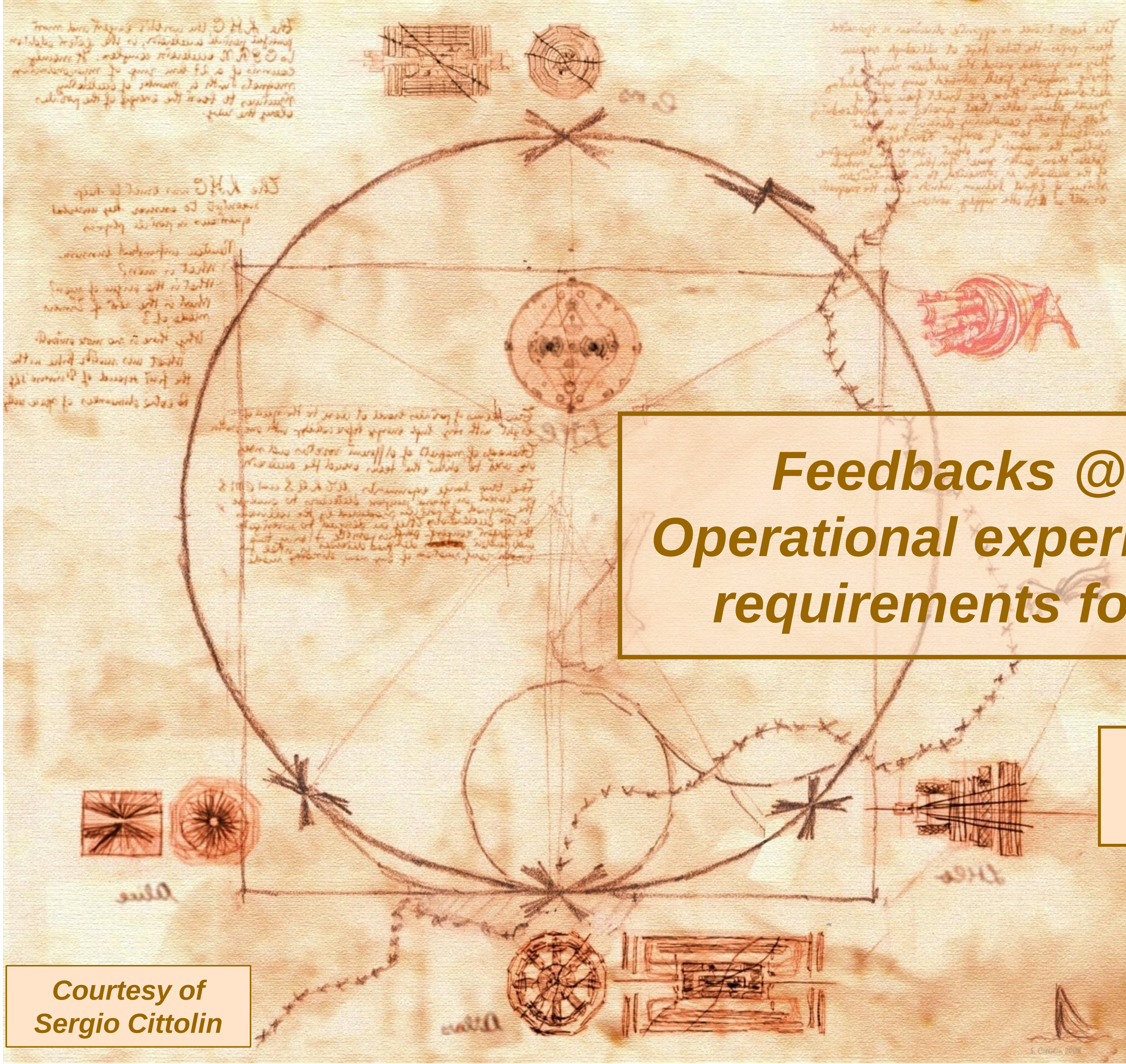


Feedbacks @ LHC Operational experience and requirements for 7 TeV

J. Wenninger
CERN

Courtesy of Sergio Cittolin

Outline

OFB - Initial specifications

OFB - Configuration

OFB - Performance at 3.5/4 TeV

OFB at 7 TeV

QFB - Performance at 3.5/4 TeV

QFB at 7 TeV

Back to the specs…

- The requirements for orbit stabilization were mostly driven by collimation (to preserve the collimator hierarchy).
  - *There was no operational experience of complex multi-stage cleaning systems → made the specs a bit tricky.*
- There were a number of other local requirements, and not too well defined demands from machine protection (for example).
  - *The LHC parameters were so much pushed wrt existing machine that it was not always easy to know what would be really required !!*
- LEP experience + LHC simulations:
  - *RT feedback required for ramp and squeeze.*
  - *In other (stable) phases of the LHC cycle, orbit changes are very slow – uncritical.*

Let's have a quick look at a MAC presentation on orbit FB that I gave in June 2005…

Collimation requirements

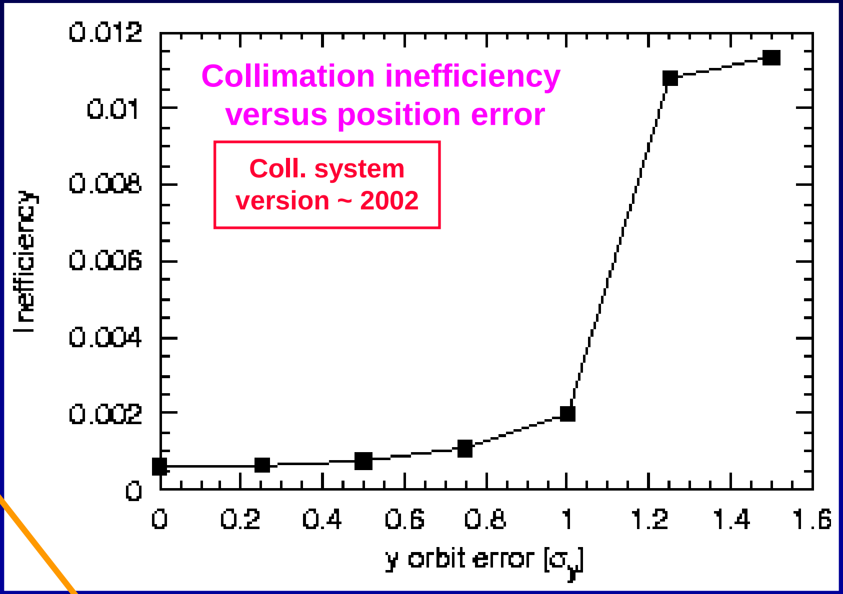
Total tolerance on separation of primary & secondary jaw :

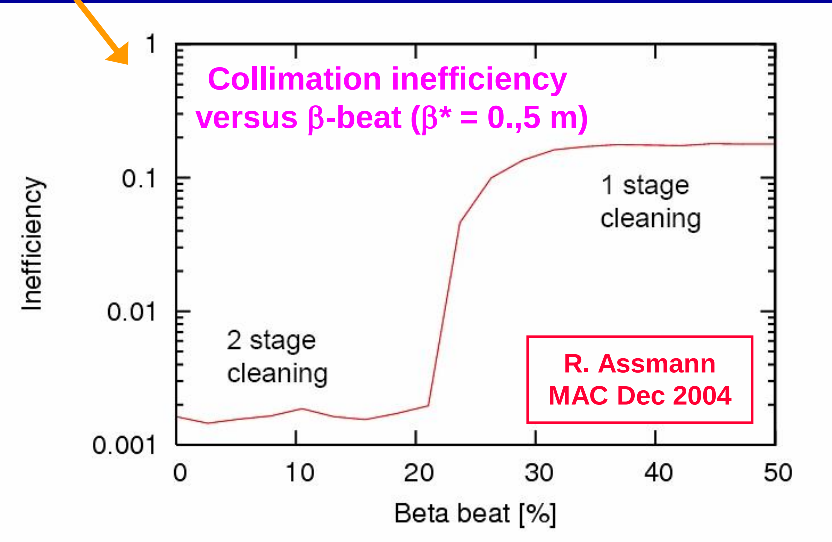
→ 0.6σ from simulation of beta-beat effect.

Split up among :

- Mechanical tolerance of jaws ~ 40 μm.
- Setting up tolerance
- β-beat
- Orbit

} **dynamic ↔ reproducibility (fill-to-fill, inside fill)**





Example of *tolerance sharing* at 7 TeV :

Mech. tol	40 μm
Setup	50 μm
Orbit	50 μm
β-beat	5 %
Total 0.6σ	160 μm (β = 150 m)

'Conservative' : errors added linearly!

Local stability requirements

Absorbers & protection devices :

TCDQ (prot. asynchronous beam dumps)	$<0.5\sigma$	IR6
Injection collimators & absorbers	$\sim 0.3\sigma$	IR2,IR8
Tertiary collimators for collisions	$\sim 0.2\sigma$	IR1,IR5

→ absolute numbers are in the range : ~100-200 μm

We used > 1σ margins (↔ BPMs, experience)

Active systems :

Transverse damper	~200 μm	IR4
Q-meter / PLL BPM	~200 μm	IR4

Performance :

Collision points stability	minimize drifts	IR1,2,5,8
TOTEM / ATLAS Lumi Roman Pots	~20 μm	IR1,IR5

Global stability requirements

Injection protection :

- Arc aperture wrt protection devices — <0.5σ ~ 0.5 mm

Feed-down of multipoles (injection/ snapback) :

- Reduce perturbations from feed-downs — <0.5 mm

Electron cloud :

- Maintain beam on cleaned surface — <1 mm (?)

We used > 2σ margins: took advantage of the larger aperture wrt design (~12σ instead of ~8σ)

In summary :

- Many tight local requirements
- Looser global requirements
- Collimation is the driving constraint behind the feedback system.
- Collimation constraints of ~ 50 μm may become tighter if the β-beat changes are larger than 5% !

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Introduction

From Kajetan…

Beam positions $\vec{u} = \begin{pmatrix} u_1 \\ u_2 \\ \dots \\ u_{N_M} \end{pmatrix}$, COD kicks $\vec{\delta} = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \dots \\ \delta_{N_C} \end{pmatrix}$

$$\Delta\vec{u} = R\,\Delta\vec{\delta} \quad \xrightarrow{\text{SVD}} \quad \Delta\vec{\delta} = R^{-1}\overbrace{(\vec{u} - \vec{u}_{\text{ref}})}^{\Delta\vec{u}}$$

Response Matrix (Calculated from Optics)

Pseudo-Inverse

Reference Orbit (= Desired Orbit)

Two main parameters
(Both change along the cycle)

Architecture and correction

- SVD casts the solution into eigenvector / eigenvalue pairs. The correction can also be put in the form of a matrix multiplication.
  - *Well established numerical algorithm, provides flexible correction.*
- Two steps:
  - *Decomposition of the matrix – takes 20-40 seconds for a LHC matrix (size **1000 x 500**). One decomposition per plane. Planes are independent.*
    - *The decomposition must be re-done whenever a BPM or corrector is added or removed. In good cases only once for a given optics.*
  - *Correction is in the form of Matrix **x** Vector multiplication – **very fast** (~ms). Simplest possible form of correction !!!*

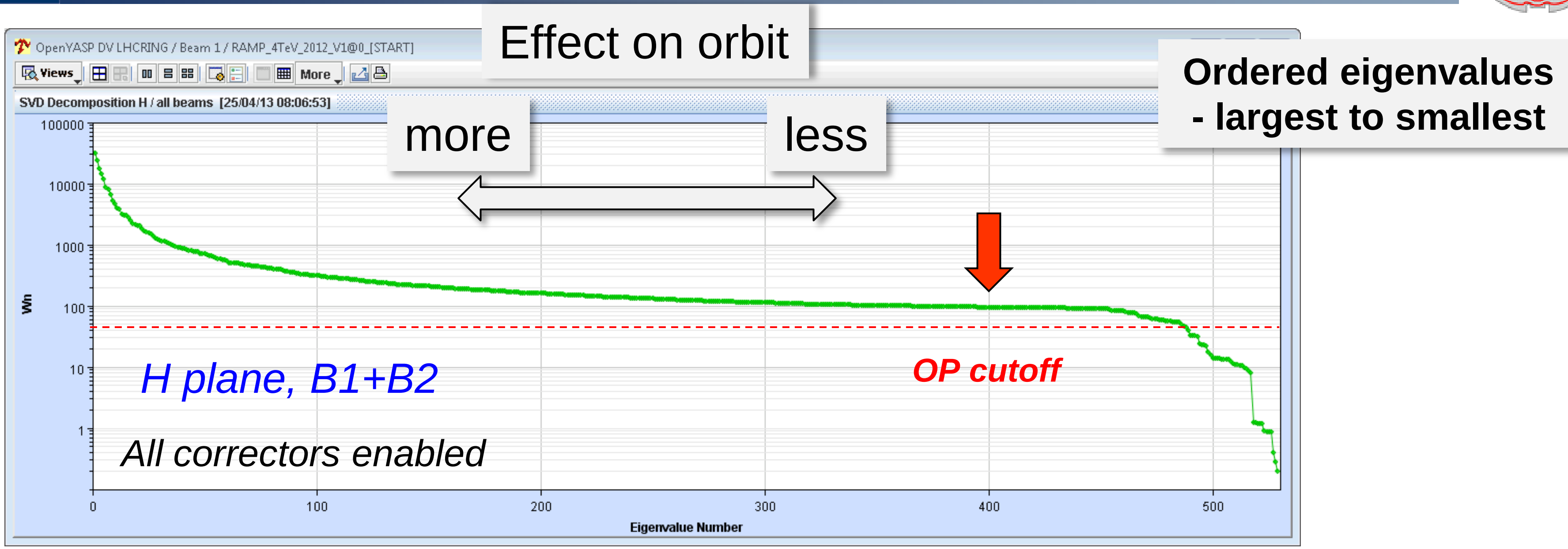
$$\Delta\vec{\theta} = \mathbf{R}^{-1}\,\Delta\vec{u}$$

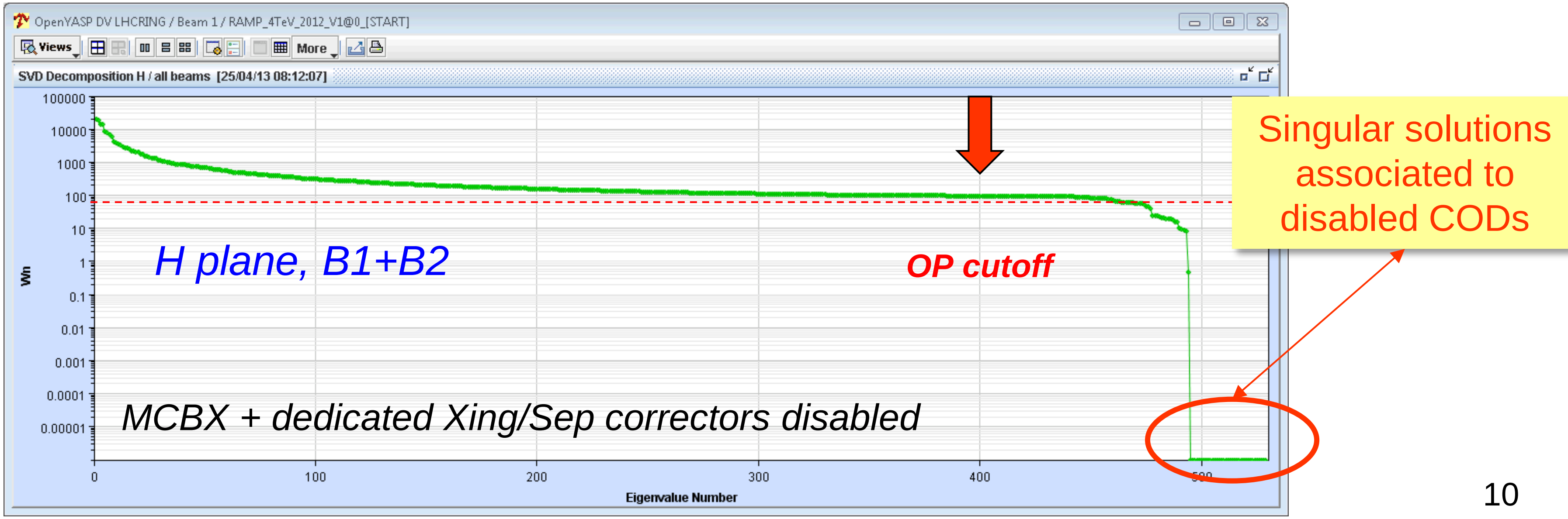
Corrector kicks (increments)
500 elements

SVD 'inverse' matrix
500x1000

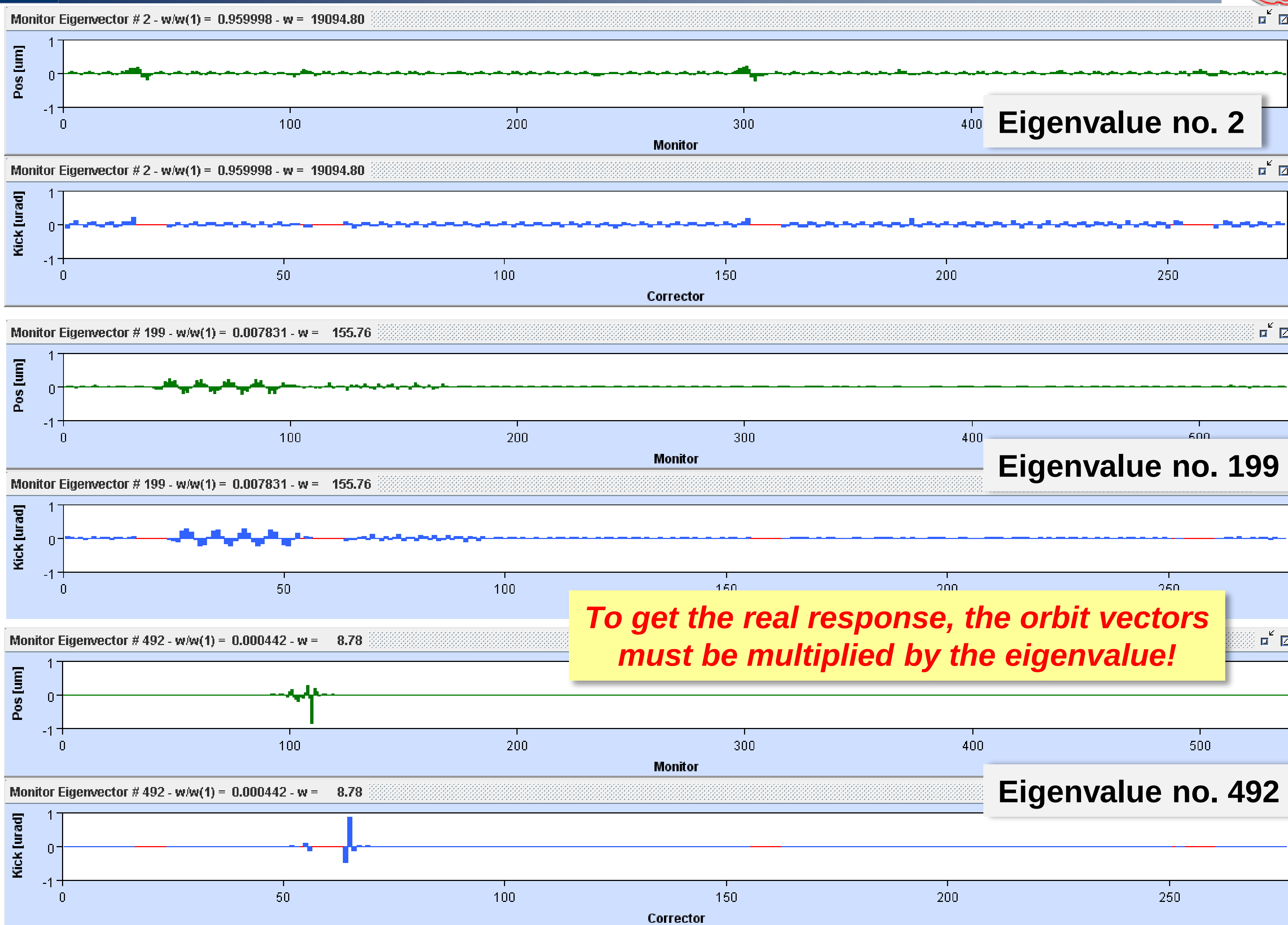
BPM readings (wrt reference)
1000 elements

SVD eigenvalues – physics optics 2012





Eigenvalue examples (B1 part)



Operational configuration

- SVD configuration:
  - *More eigenvalues → better (and more local) correction.*
  - *More eigenvalues → more sensitive to bad BPM readings.*
  - *More eigenvalues → larger corrector kicks.*

  Optimum to be found by experience. Depends on BPM quality !!

  In practice there was little time for tuning !

- Operational settings in 2012:

Parameter	Value	Comment
No. hor. eigenvalues	**400**	Limited by corrector integral run-away.
No. ver. eigenvalues	**440**	
Eigenvalue cutoff	**0.0025**	= eigenv / largest eigenv. Matched to no. eigenvalues. Protection for cases with many disabled correctors

Operation configuration - correctors

- *Corrector magnet selection*: we use **ALL** correctors except the (common) MCBX at Q1-Q3 and some redundant LSS correctors.
- Reasons to exclude the MCBX:
  - *They are proportionally ~3-4 x slower in dI/dt that the other correctors → strong limitation on correction speed / bandwidth.*
  - *They are a factor 10-15 slower in relative acceleration (dI/dt / d^2I/dt^2).*
  - *MCBX are the only correctors with QPS → risk of fake trip. See the issues with the QFB.*
  - *MCBX can easily steer the beams out of collision – critical on BPM quality.*

There was no time (and so far no urgent need) to study the effect and limitations of MCBX in detail.

Operation configuration - BPMs

- By default all BPMs are used.
- Every time a BPM is added or removed → SVD decomposition.
  - *Initially we had no clear idea on how often BPMs would have 'problems'*.
  - *A few isolated missing BPMs can be 'tolerated' without re-running SVD.*
- In practice we observed in the CCC:
  - *BPMs with offsets that appeared at injection.*
    - *De-selected manually as part of the injection process. Re-compute SVD at end of injection – no op problem.*
  - *BPMs with (large) unstable readings, appearing any time in the cycle. Have been occasionally an issue (~ ½ dozen time / year?) → fake bumps.*
    - *OP crews have essentially no chance to intervene on time.*
    - *Automated algorithms can help – never time to test them.*
    - *Worst (rare) cases caught by SIS → dump.*
- We have typically ~20 (oo 500) deselected BPMs / plane and beam.

Optics / response matrix changes

- Optics errors degrade the performance of orbit corrections.
- Rule of thumb for optics errors (beta-beating):
  - *Up to 20% - no problem.*
  - *Up to 50% or so – still good convergence.*
  - *Around 100% - divergence.*

Typical max. β-beating after correction

- When the optics is changing during the squeeze phase, one should update the matrix (→ SVD decomposition).
- Software and timing events (as trigger) were prepared for automated optics changes, but they were never used / fully commissioned.
  - *Issues when computing many SVD decompositions → OFSU crashes.*
  - *Corrections at standard bandwidth converged usually well without change (but optics also unchanged in 90% of the machine).*
    - *Optics had to be changed only for high-beta in 2012.*
  - *Since it worked like this …. No time devoted to commissioning optics and matrix swapping.*

A note on energy

- The length of the LHC beam orbit is defined by the RF frequency.
  - *OFB should never try to steer the average radial position with orbit correctors - this does not work → must be done with RF frequency !!*
  - *By trying to steer the radial position with correctors the only effect is to change the dipole field (→ energy) without affecting the radial position !*
    - *Strong feed-down on the tunes !*
- Due to 'issues' with the subtraction of the mean radial orbit, the OFB tended to make exactly the error described above.
  - *Orbit response matrix is missing this part of the physics.*
- In 2012 an extra FB loop was added ('energy FB') to ensure that the **average hor. kick** by the OFB+energy FB = 0.
  - *Due to issues with the interplay of the two loops and the setup of the energy FB we had to limit the no. of horizontal eigenvalues to **400**.*
  - *One could alternatively use a constraint in the response matrix.*

Reference orbits

- One extra complexity for the OFB is the fact that the orbit reference changes along the cycle.
  - *Changes in crossing angles, beam separation…*
  - *Optics change (→ bump shape changes @ constant angles…).*
  - *References also change in MDs, high-beta operation etc.*

    → Need a flexible reference system.

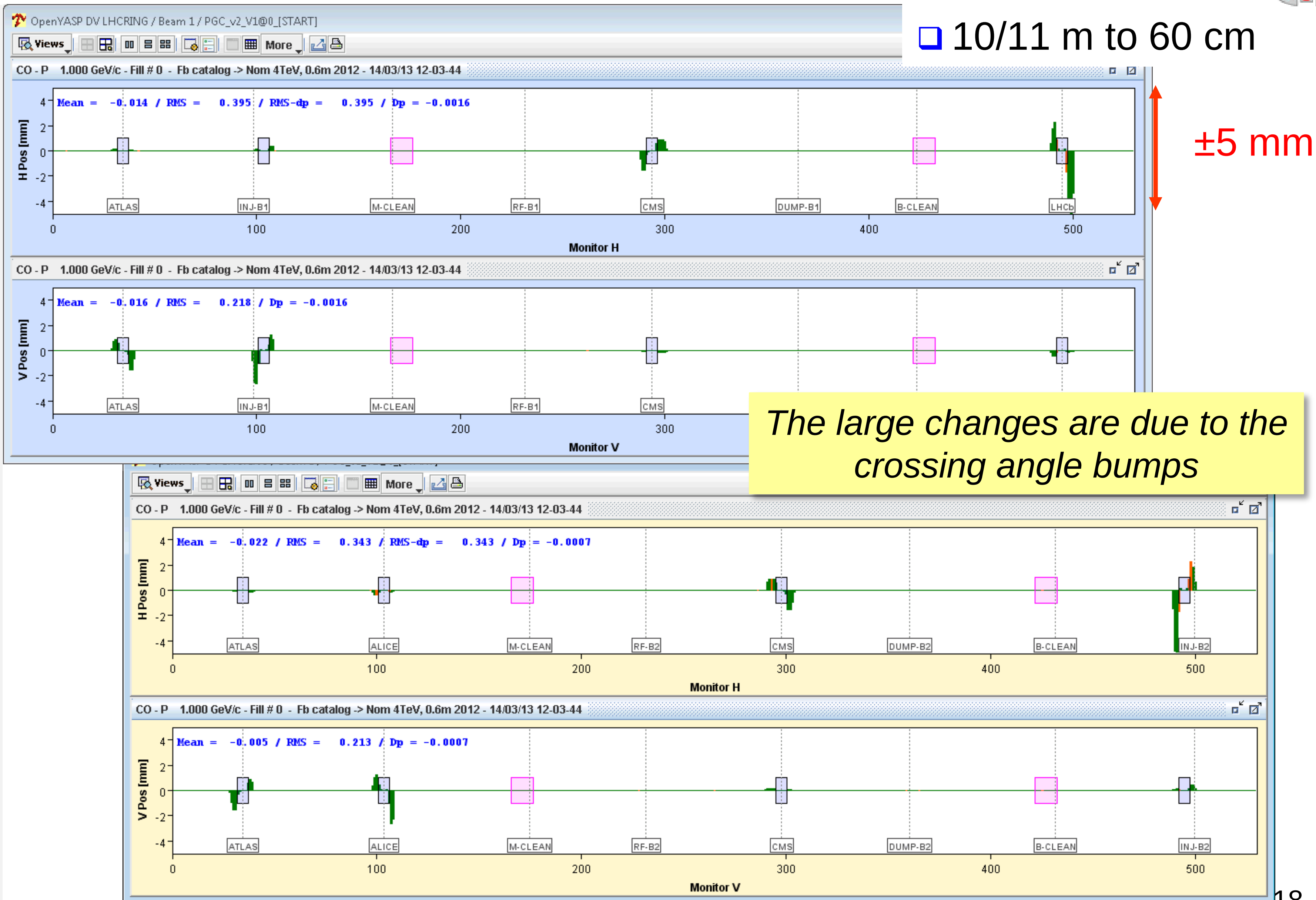
→ Kajetan

- Reference orbits are handled by a dedicated SW tool + LSA DB tables.
  - *A flat BASE orbit (no bumps, no crossings) is defined at the start of the run.*
  - *All orbits consist of BASE + overlaid bumps.*
  - *Organized as points in time, linear change between points. Typically:*
    - *Ramp: one reference at start, another at end.*
    - *Squeeze: up to ~10 reference points. All changes are in LSS1/2/5/8.*

→ Laurette

Example: ref. orbit change in 2012 pp squeeze

- 10/11 m to 60 cm



The large changes are due to the crossing angle bumps

Feed-forward

- To minimize the size of the RT corrections, a feed-forward of the RT corrections into the corrector functions was applied periodically.
  - *Better chance to survive FB outages.*
  - *Strong Machine Protection recommendation (keep RT trims small !!).*
- With FF the typical RT corrections are reduced from around10-12 urad peak to ~2 urad peak and <1 urad rms (short term fill-2-fill reproducibility).
  - *FF is working very well → LHC has a high short term reproducibility.*
    - *But not good enough to maintain 50-100 μm in a squeeze.*
    - *Ramp reproducibility is better than squeeze reproducibility.*
  - *FF valid ~ few weeks. Ground motion limits the validity of settings (probably).*

Radial loop

- The orbit is kept centered radially by feeding back the radial error (wrt reference) on the RF frequency.
  - *Very small trims.*
  - *Compensates for tides etc in ramp and squeeze.*
- This feedback worked smoothly (and it usually had little to do !).
- This RT input into the RF system was also used for Q' measurements by radial modulation.

OFB in the LHC cycle

Injection
- OFB on briefly for correction with probes.
- Repeat with nominal.

Fixed reference

↓

Ramp
- OFB and radial FB on.
- Reference change injection → flat top.

Dynamic reference

↓

Squeeze
- OFB and radial FB on. OFB critical !!
- Reference changes along the squeeze.

Dynamic reference

↓

Collide
- OFB and radial FB off.

↓

Stable Beams
- Very small & slow orbit changes.
- OFB and radial FB off → issue with BPM temperature systematics.
- Manual correction by OP if needed.

→ Laurette

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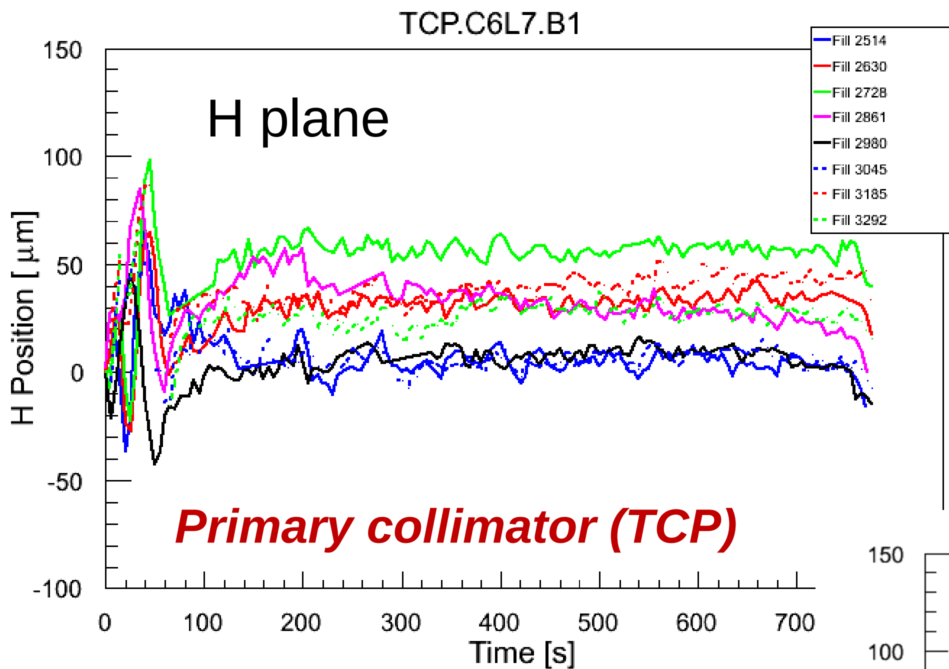
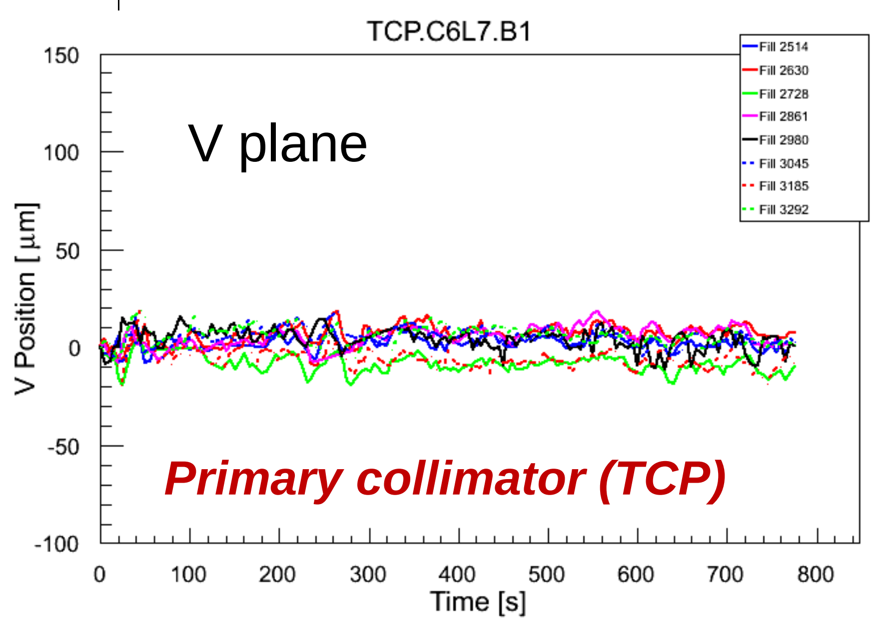
Performance – ramp 2012

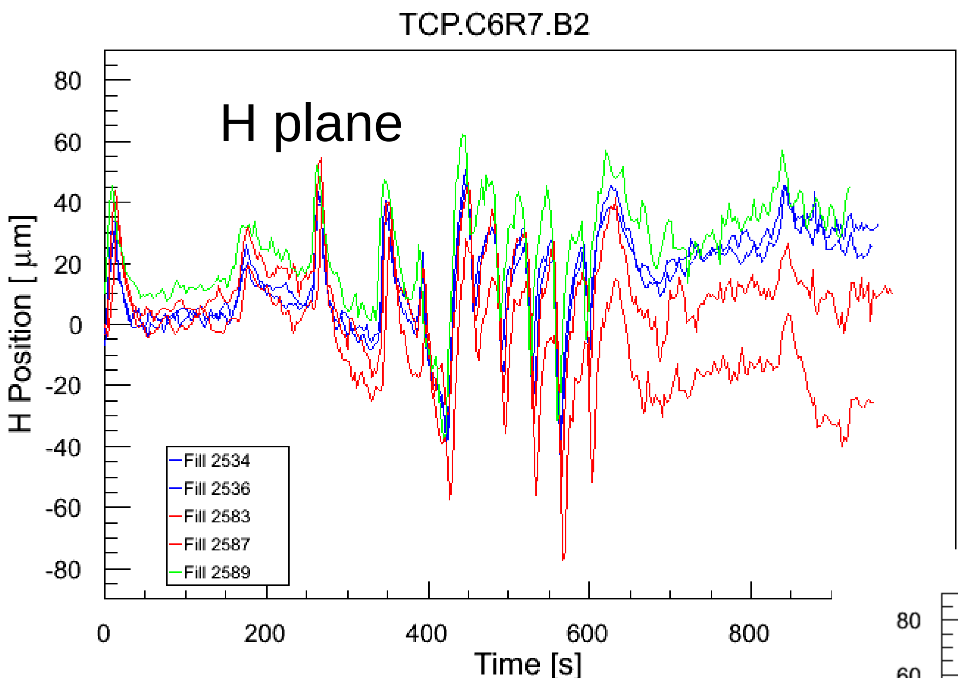


- 8 fills: April to November.
- Excellent performance!
- Some transients in H at start of ramp (snapback) – need a bit more bandwidth?
  - ***But transient less than 0.2σ – non-issue.***

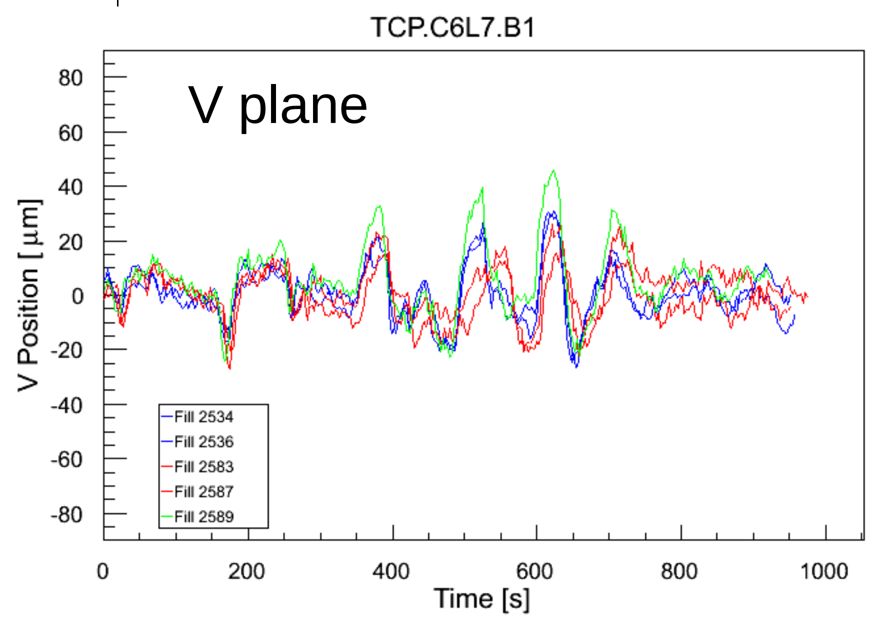


Better than / in specs !

Performance – squeeze 2012



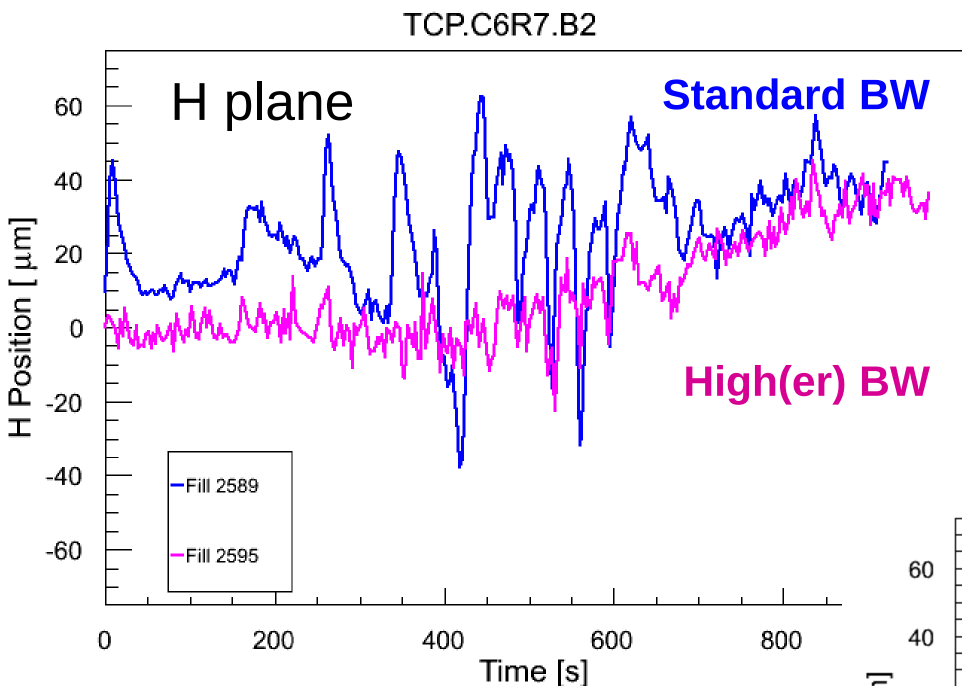
- 5 fills in April/May.
  - ***Good example for the typical F2F reproducibility.***
- Residual spikes at the matched optics points: smoothing in LSA and too coarse optics changes.
- At LEP the squeeze was practically unpredictable !



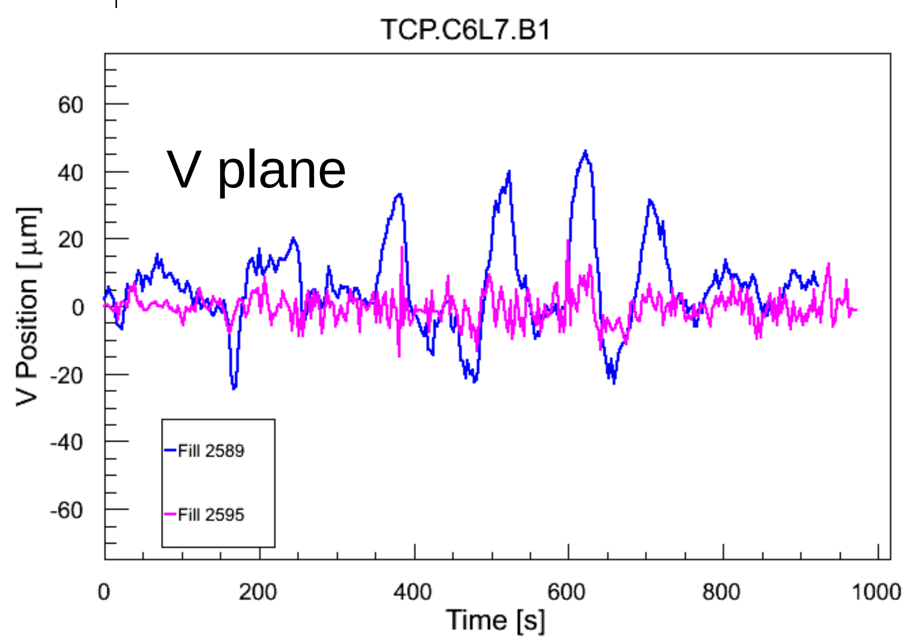
Better than / in specs !

But not good enough with tight collimators…

Performance – squeeze 2012 (2)

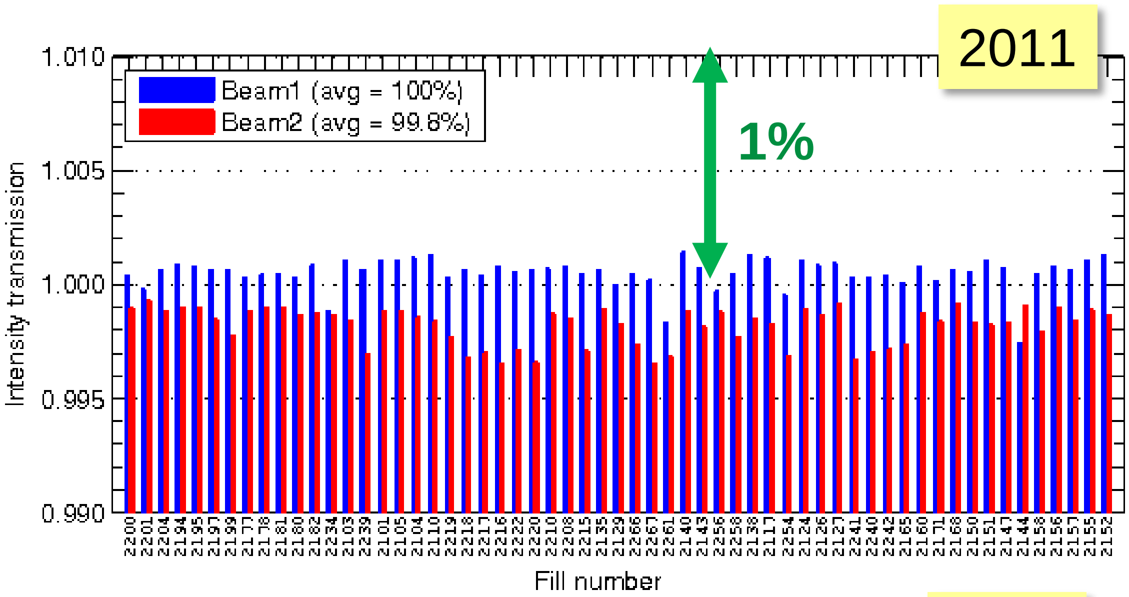


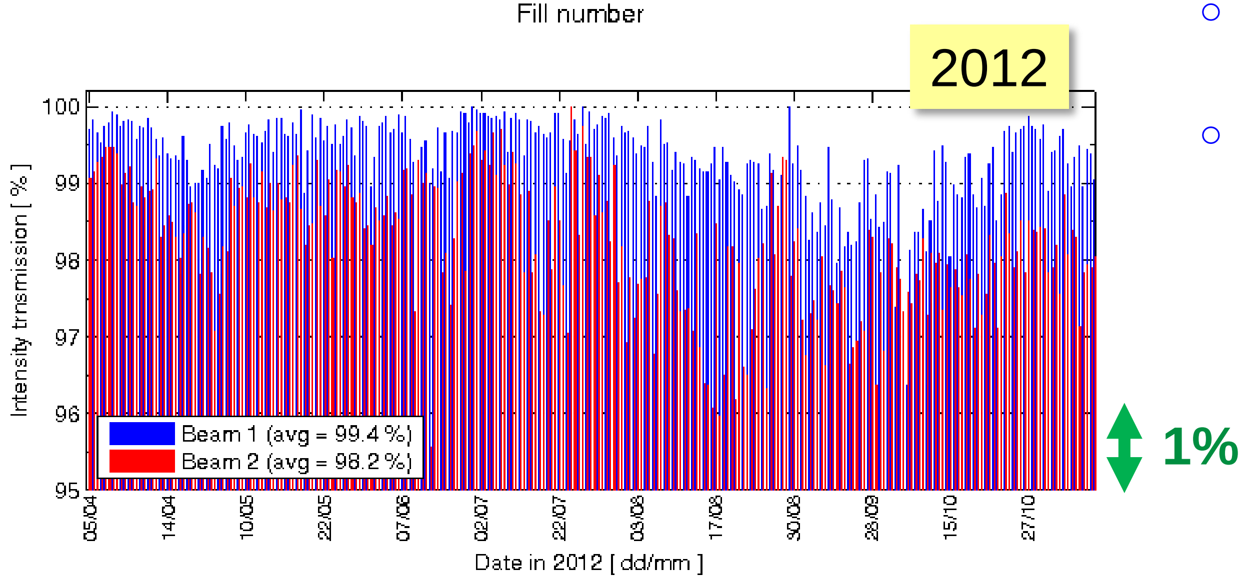
- Test with higher bandwidth to cure residual spikes - makes a difference !
- Feed-forward (FF) of the high bandwidth fills very successful.
  - ***FF preserves quality.***
  - ***After FF back to normal BW.***



Better than the specs !

Squeeze transmission



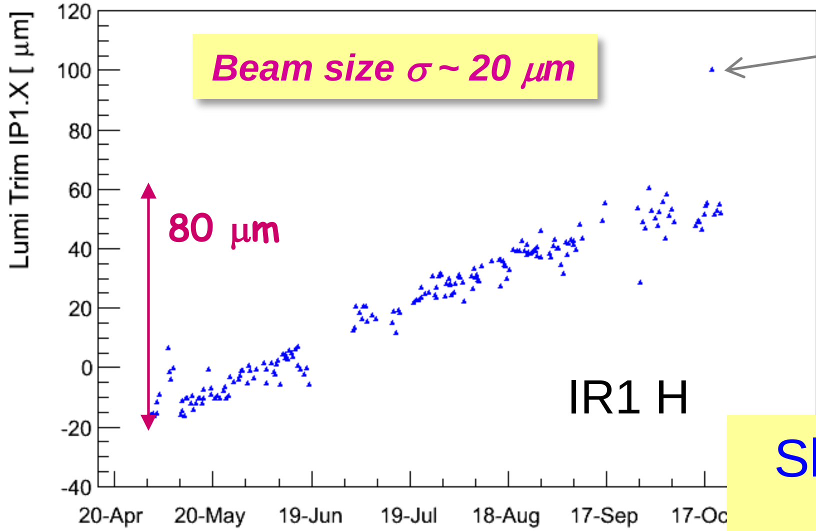


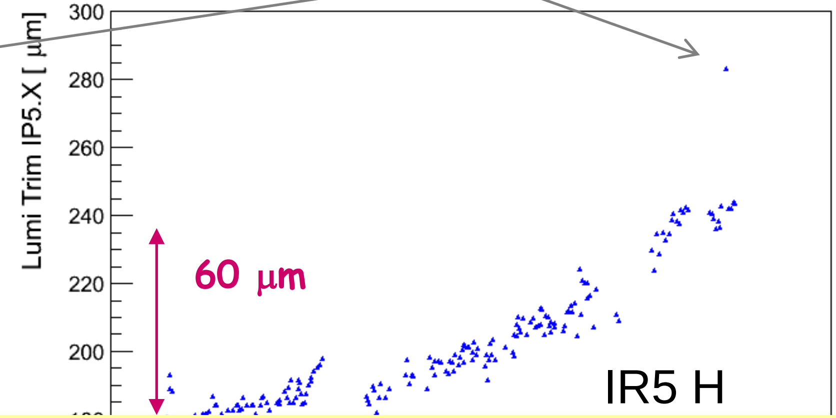
- Squeeze transmission in 2011 ~ perfect – no losses.
- In 2012, despite much better orbit stability, ~2% losses on B2.
  - *It is not just orbit !*
  - *Particles in the tails, and they re-populate !*
  - *Much tighter collimators (5.7 → 4.3 σ) have a large impact.*

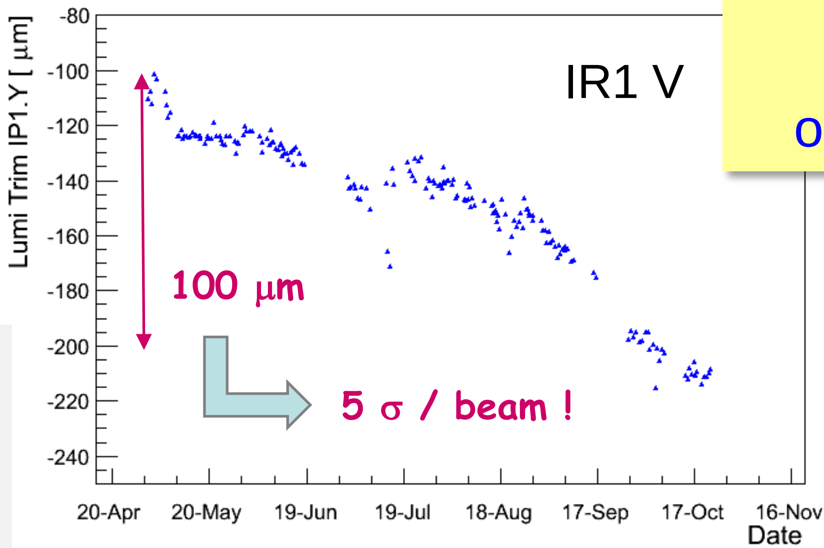
Evolution of L optimization trims in IR1/5

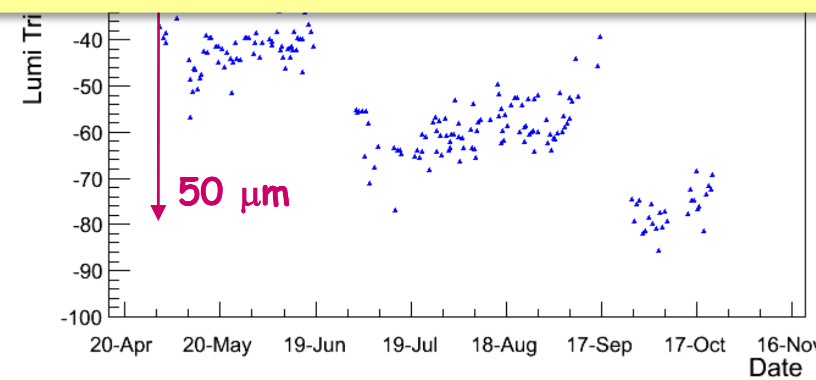
- B1 trims (B2 – opposite sign)

Orbit correction @ injection









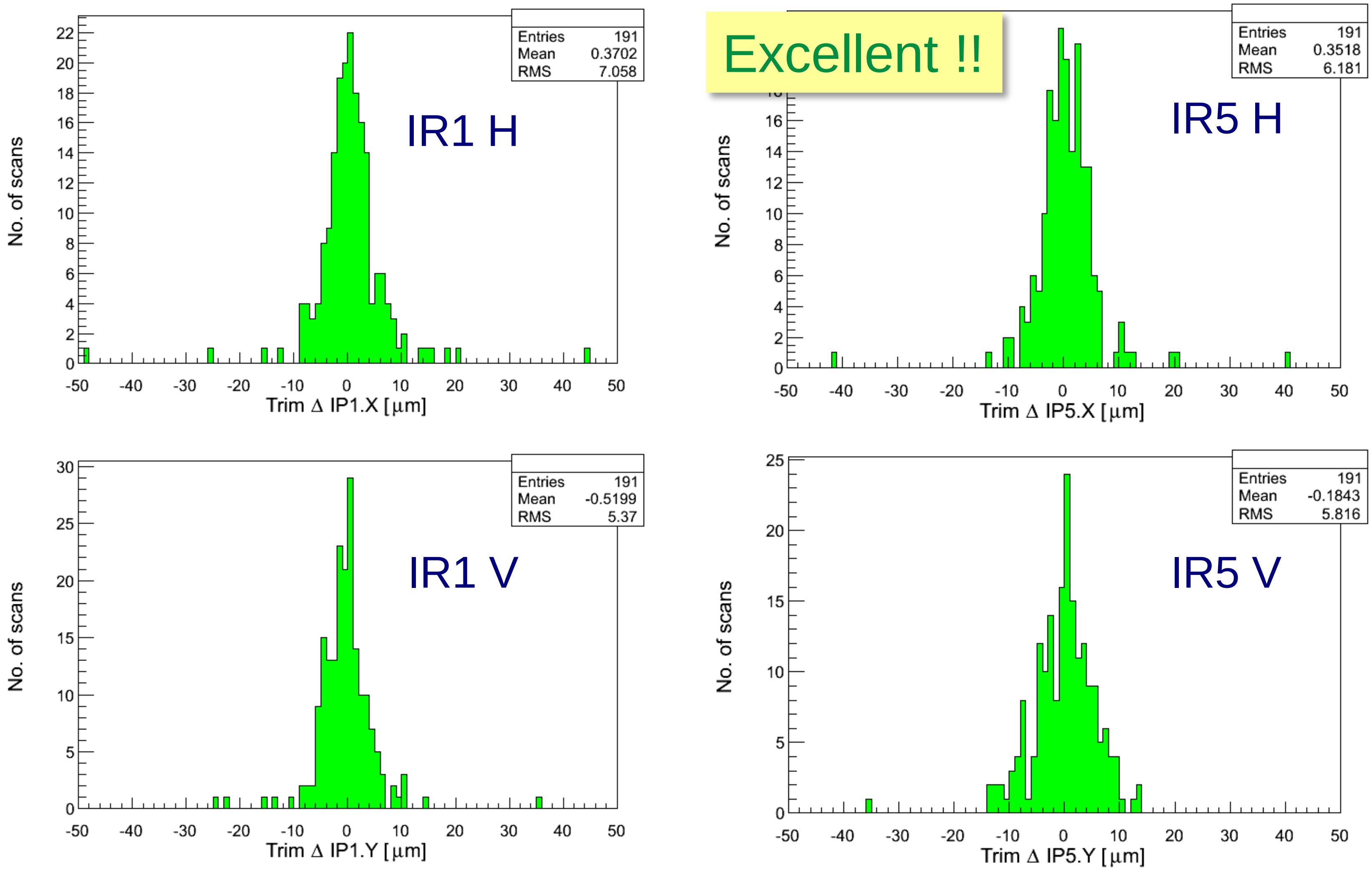
Slow drifts due to local orbit structures that build up with time around the IPs.

→ would require more eigenvalues !

or very precise BPMs and local steering.

Fill-2-fill changes IR1/5

- B1 trim changes from one fill to the next
  - **The large majority of changes are ≤ ½ σ ≈ 10 μm <u>per beam</u>.**



Summary of low energy LHC performance

- The OFB performance in terms of stabilization was excellent – well within specs – often better !
  - *Global orbit stabilized to ~50 μm rms in arcs – limited by BPM reproducibility?*
  - *LSS performance ~100-200 μm peak. Eigenvalue limit or BPMs?*

    → *Detailed analysis will be done during LS1.*

- The quality of the BPMs and the performance of the OFB made it possible to run the LHC with a single collimator setup / year (IR7/3) without noticeable cleaning degradation over 6 months.
  - *TEVATRON aligned the collimators in every fill !*
  - ***Incredible success ! Large positive impact on LHC efficiency !***

    → ***Requires OFB in ramp & squeeze.***

Summary of low energy LHC performance

- A lot of the issues that we encountered were due to communication (FEC-OFC-OFSU-LSA) and ‘testing’ issues (→ difficult to localize bugs).
  - *Absence of realistic testing environment(s).*
  - *Initial success of the LHC (and of the OFB) led to fast intensity ramp up → ‘frozen’ situation → difficult to introduce changes.*

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LHC after LS1

- Some LHC parameters at 6.5+ TeV that are relevant for OFB.

Parameter	Changes	Comment
Beam sizes	Smaller, ~30%	Requires better performance to maintain same stability in σ.
Primary coll. (TCP) gap	No change in mm	Smaller beam size provides larger margin (in σ).
Coll. hierarchy	Tighter, ~30%	Scaling more or less with beam size. Possibly smaller retractions.
IP beam sizes	Smaller, ~40-70%	From emittance (see size) and β^*.

- At first sight we need small improvements / similar performance.
  - *With constant TCP gaps we may be more relaxed wrt 4 TeV / 2012 !*
  - *Perturbations at IPs tend to scale with β^*. Smaller β^* / σ at IP does not necessarily require better OFB performance. More an issue for BPMs.*
  - *Need more PC current for same kick → bandwidth.*

Operation after LS1

- Standard operation should not be an issue for OFB as it stands now.
  - *Improvements in LSA & squeeze re-optimization should also help.*
- New operation modes may appear, the most constraining consists in colliding the beams during squeeze phases.
  - *Code word: colliding squeeze and β* leveling.*
  - *Main constraint is to keep the beams colliding (within ~ ±1 σ) while the optics and orbit references are changing.*
- Impact of squeezing with collisions will be analyzed in a detail during LS1, it will surely have consequences on:
  - *Setup of the squeeze – need more care (and more time) .*
  - *Reference orbit handling.*
  - *Tuning of OFB performance for optimal response.*
  - *Importance of BPM quality around the IRs.*

→ ***Must be open for changes in steering logic.***

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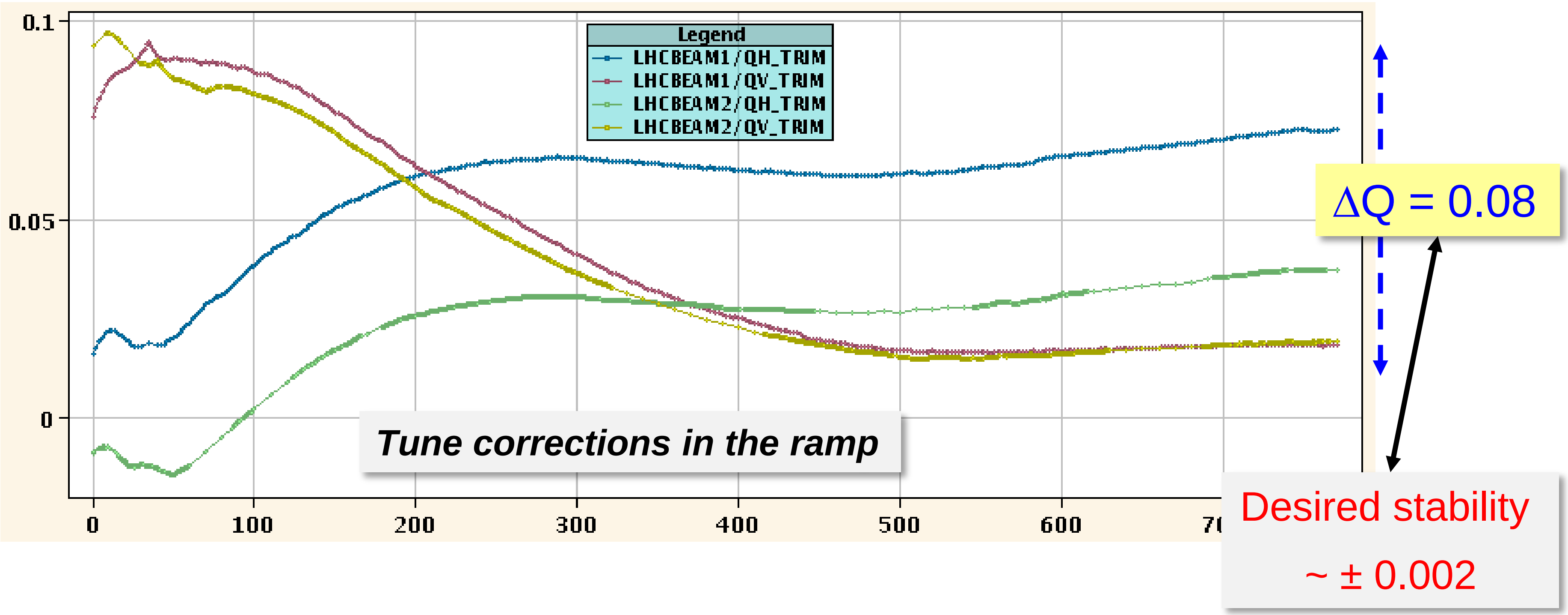
Tune feedback in run 1

- The tune feedback (QFB) performance was 100% correlated to the quality of the tune signal. Most of the time the QFB was limited by signal quality.
  - *We never (rarely) probed the QFB intrinsic performance.*
  - *Discussion of the tune signal is outside the scope of this review.*
- Situation end of 2012:

→ Laurette

  - *QFB was on for all ramps, but frequently switched off temporarily due to signal quality. The corrections were not 100% reliable (→ input signal).*
  - *Bandwidth reduced to avoid shaking the tune (rather than stabilizing it).*
    - *Induced false QPS triggers (until thresholds were raised).*
  - *QFB was always off in the squeeze during regular operation. We relied on the machine reproducibility.*
  - *FF was essential for ramp and squeeze. Low intensity cycles, where QFB could be kept on, were used for the FF.*
    - *Also used for Q' FF.*

Feed-forward of tune corrections

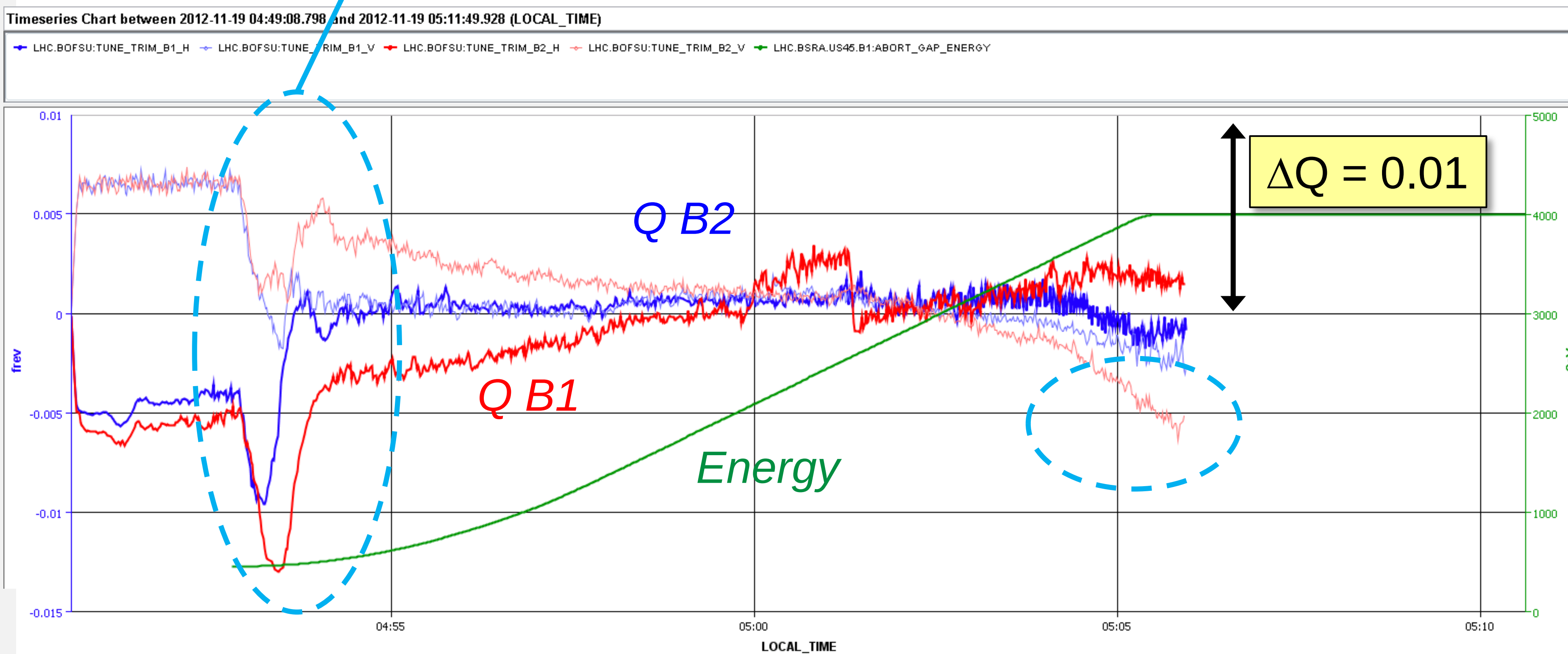


- Feed-forward worked very well (and saved us in the squeeze) thanks to good machine reproducibility.
  - *Only difficult region is the start of ramp / snapback (~first ¼ of the ramp) This will be investigated during LS1.*

QFB in the ramp : example

Snapback:

incorporation of injection trims to be improved?



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After LS1

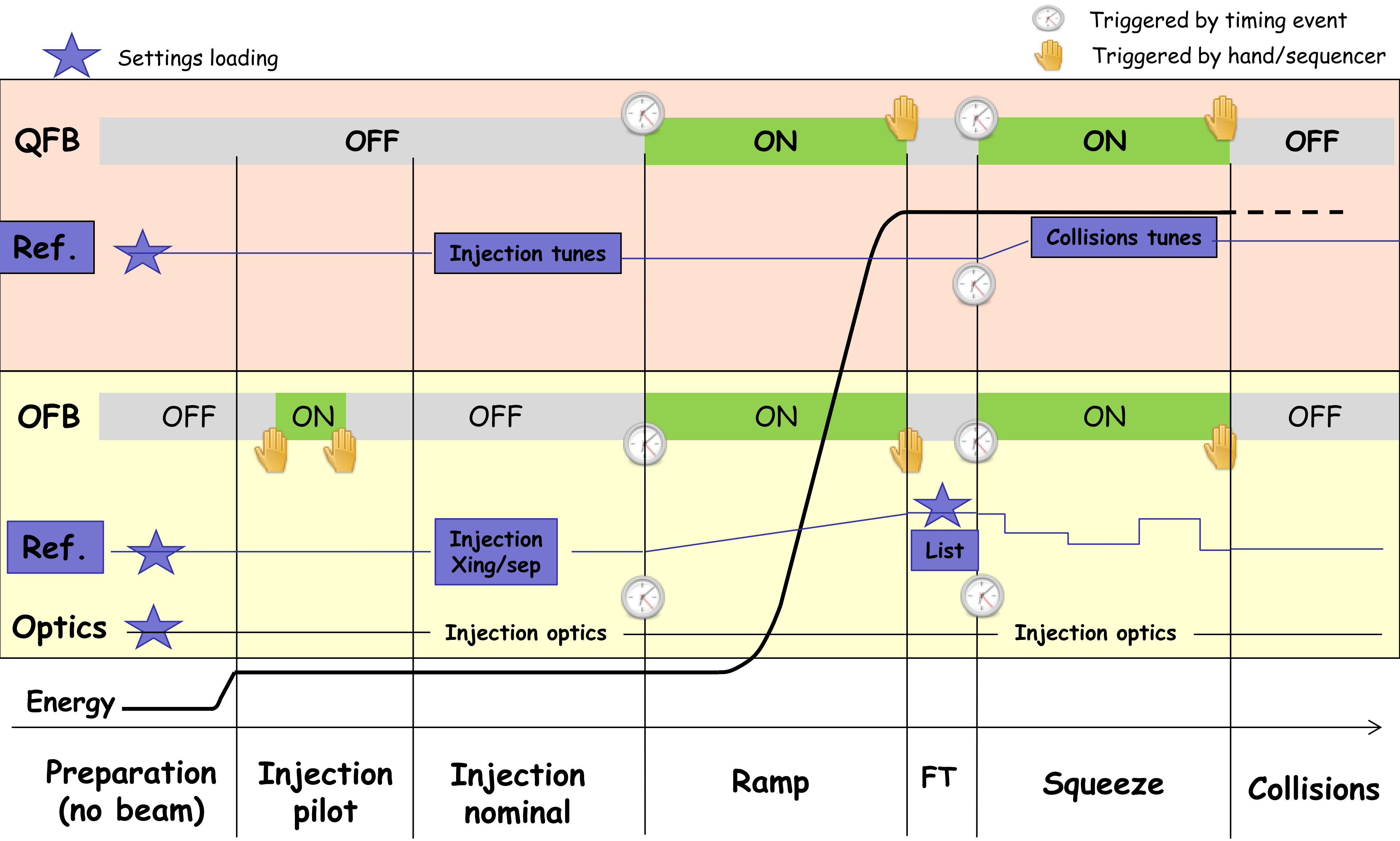
- With a reliable Q signal a tune stability of ±0.001 seems to be easily achievable and sufficient - based on 'good' tests in past years.
  - *After LS1 we may get other potential sources of Q signals (for example from the ADT / damper) → foresee to use them as QFB input?*
- We should also consider the strategy if Q signals do not improve…
- Squeeze with colliding beams and β^* leveling may be a new challenge for Q measurements due to the effect on the Q signal.
- Once the tune is under control, one could consider continuous Q' measurements (radial modulation).
  - *Would be good to have, but looks quite far away (losses, reliability…).*

Overall summary

- OFB performance was excellent. Current performance seems to match 7 TeV requirements given the existing margins.
  - *With beta* leveling & squeeze with collisions, the focus may shift from collimators to the IP.*
- QFB performance limited mainly by Q signal quality. Intrinsically OK for 7 TeV?
- If the current FB concept is maintained, areas of improvements:
  - *Testing environment,*
  - *Reference handling in OFSU/OFC (structure, reliability),*
  - *Optics and SVD management,*
  - *Gain/bandwidth management,*
  - *…*

Appendix

Feedbacks during LHC cycle



Energy and Orbit FB

- Energy feedback (which counteracts the horizontal offset created by the orbit feedback) corrects the average of the effect by using only arc CODs that have a non-negligible dispersion function.
- This Energy-FB correction COD pattern also creates an orbit perturbation. It was initially believed that this is compensated by the Orbit-FB. But due to the limited number of eigenvalues used it is only partially corrected.