Orbit and Feedbacks

J. Wenninger

- **Machine protection and orbit**
- **Feedbacks – orbit and tune**
- **Operational issues with feedbacks**

Acknowledgements: R. Schmidt, S. Redaelli, R. Jones, R. Steinhagen, B. Goddard, V. Kain & many others…

Orbit and machine protection

- Machine protection CANNOT always rely on a perfect orbit:
  - ***Many failures involve a shift of the closed orbit (⇔ dipole kicks).***
- For MP the horizontal plane is more critical than the vertical plane:
  - *Almost all strong dipoles are bending horizontally!*
    - *Exception : ALICE spectrometer and compensators.*
  - ***Asynchronous beam dumps.***
- **Protection strategy:**
  - *Whenever possible detect failures BEFORE the orbit is affected:*

    QPS, FMCM, PIC, WIC – see talk by M. Zerlauth.
  - *Collimators should shadow the aperture as much as possible such that losses occur mostly (first) in IR7 and IR3 if the orbit moves (globally).*
  - *Detect losses with BLMs: depending of the situation, either BLMs in the cleaning region or in cold regions will react first.*

The collimator hierarchy may be violated by the orbit changes!

Failures involving the orbit

Orbit change due to powering failures

- Beam interlocks of PIC, WIC, FMCM and QPS are involved.
  - *So far the interlocks always 'won': beam dump before any orbit shift!*

    see presentation by M. Zerlauth

    …but this may not always be true (to be seen for case of quench).
  - *60 A arc orbit correctors are not covered by Hw interlocks – see later.*

- The orbit change is/would be global, the beam is very likely to provoke loss on collimators, or leakage in SC areas.

  BLM beam interlocks are our next line of defense.

Failures involving the orbit

Orbit changes due to incorrect settings
- concerns essentially orbit correctors (CODs).

- Consequences depend a lot on the details.
  - *The effect may be a global orbit change leading to beam loss (and then to a beam dump) or to an orbit interlock (see later).*
  - *In other cases a local bump may push the beam to the aperture (most likely at injection): BLMs must (and can) catch the failure as the CODs are slow !*
  - *In a 'light' case, the orbit is displaced globally or locally, and beam operation may not be stopped by an interlock. The margin for the displacement depends on intensity and lifetime, can be large for bumps.*

Operation with orbit perturbations

MP issues when operating with a ‘perturbed’ orbit:

- The collimation hierarchy may not be respected.
  - *In case of low lifetime or a failure lasting for a number of turns, BLMs in cleaning regions or elsewhere protect the machine.*
- The most dangerous situations arise **in combination with a single turn failure**:

Particles oscillating around the CO may hit the aperture!

- ***Injection process*** *– so far not a big issue as we inject relatively safe beam – this will change in the coming weeks.*
- ***Asynchronous dump*** *– beam may hit a collimator, or more critical apertures – horizontal plane only. See previous talks.*
- *Aperture kicker – tightly interlocked !*

Orbit and tune control

Orbit stability requirements

Collimation: **(**see also collimation talks)

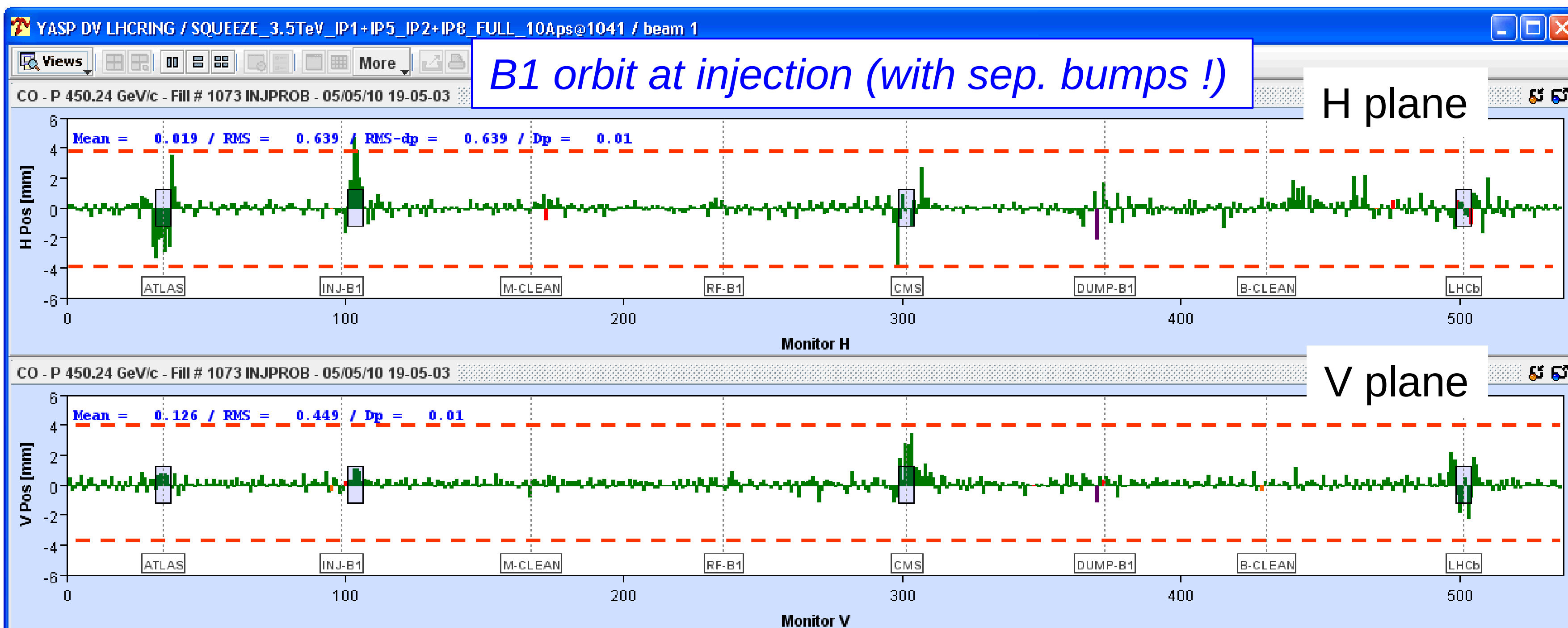
- For nominal cleaning efficiency the collimation hierarchy must be respected.
  - *At nominal β* of 0.55 m, the orbit tolerances are at the level of 0.3σ.*
- If the cleaning hierarchy is not respected:
  - *The lowest acceptable lifetime at which the collimation protects the SC magnets from quenches is increased.*
  - *A secondary or even tertiary collimator may become primary.*
  - *Protection is provided by the BLMs in the and cold regions and at all collimators – does not apply to single turn failures.*

Other systems:

- Injection protection: orbit tolerances are at the level of ≈0.3-1σ.
- Transverse damper and shottky: tolerances ~n×100 μm.
- Crossing angle and separation: tolerances not too well defined ~0.5σ.
- ...

Corrected orbit

- The nominal tolerances for the orbit due to aperture requirements:
  - *±4 mm at injection, ±3 mm at nominal field.*
- The achieved orbit is significantly better:
  - ***±2 mm*** *(in many regions even better)*
    - → *gain for the aperture of ~1.5-2 σ at injection.*



Orbit feedback (OFB)

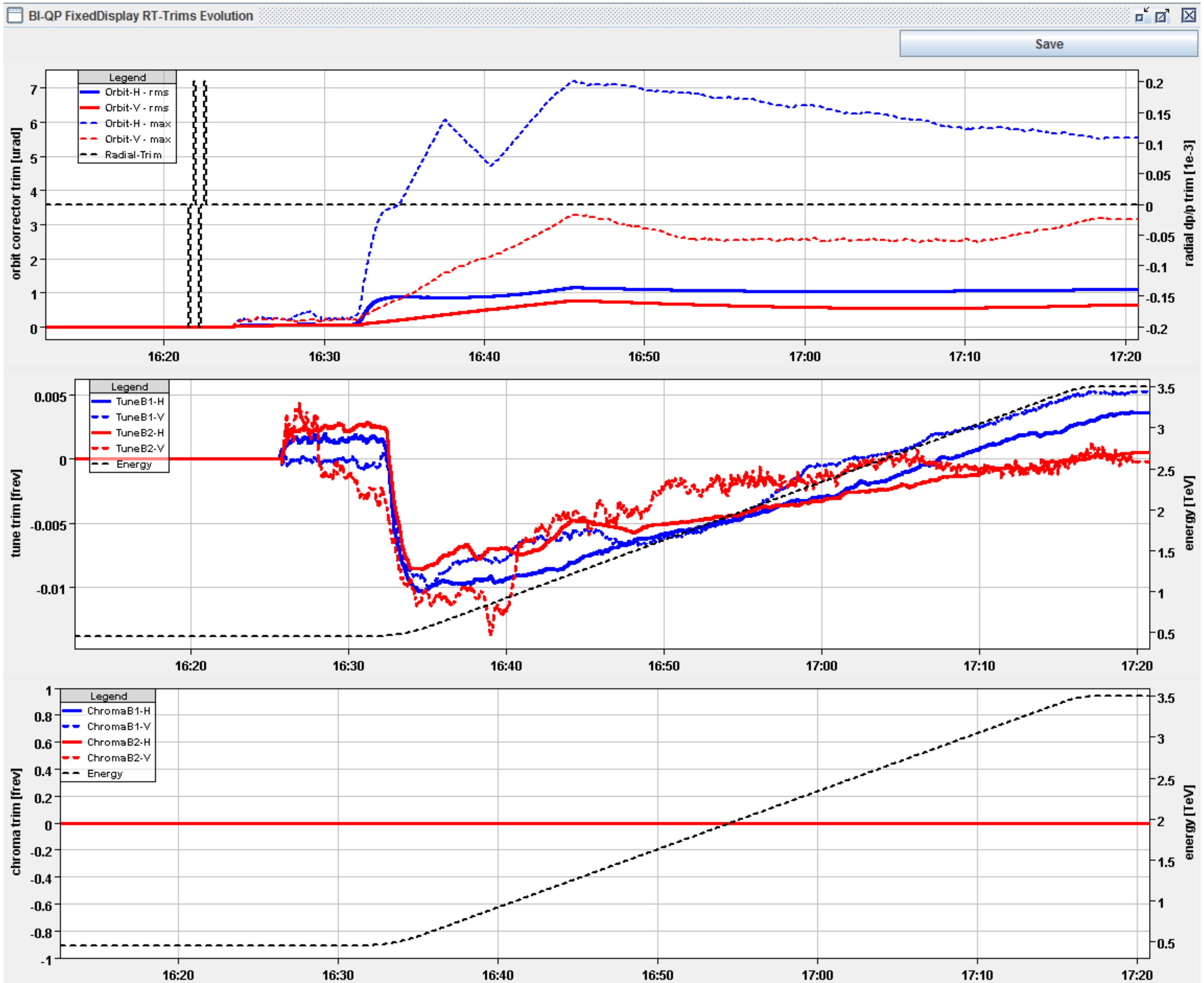
- The orbit at the LHC is controlled by centralized RT orbit feedback system (**OFB**) running on a Linux server in the CCC.
  - *Collects orbit data from 68 BPM FECs at 25 Hz.*
    - ***~1000 BPMs with both H and V information.***
  - *Sends out corrections to the PC FECs at 25 Hz (+ RF frequency).*
    - ***~1100 orbit correctors (CODs).***
  - *Data transfer by UDP packets over the technical network.*
- Correction strategy is based on a global SVD correction of both beams.
  - *Many eigenvalues (390 out of ~500) are used to provide high quality corrections over the entire ring.*
    - *- Side effect: OFB can introduce local bumps…*
  - *Due to issues with the QPS system the orbit correctors in the common vacuum chamber regions (experiments) are not used – de facto 'decouples' the rings for the OFB.*

Tune feedback (QFB)

- Tune control is of course essential in hadron machines, and to ensure good beam lifetimes the LHC has a RT tune feedback (**QFB**).
  - *Collects tune data at 25 Hz (based on FFT spectra) for each beam/plane.*
  - *Sends out corrections to the PC FECs at 2.5 Hz (limitations from QPS !).*
  - *Data transfers by UDP packets over the technical network.*
- QFB and OFB share the same server and exchange information (RF frequency).
- The tune FB system may also provide:
  - *Q' feedback (using a low amplitude RF freq. modulation).*
  - *Coupling feedback.*

Not used for the moment

FBs in action : ramp



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OFB trims (μrad)

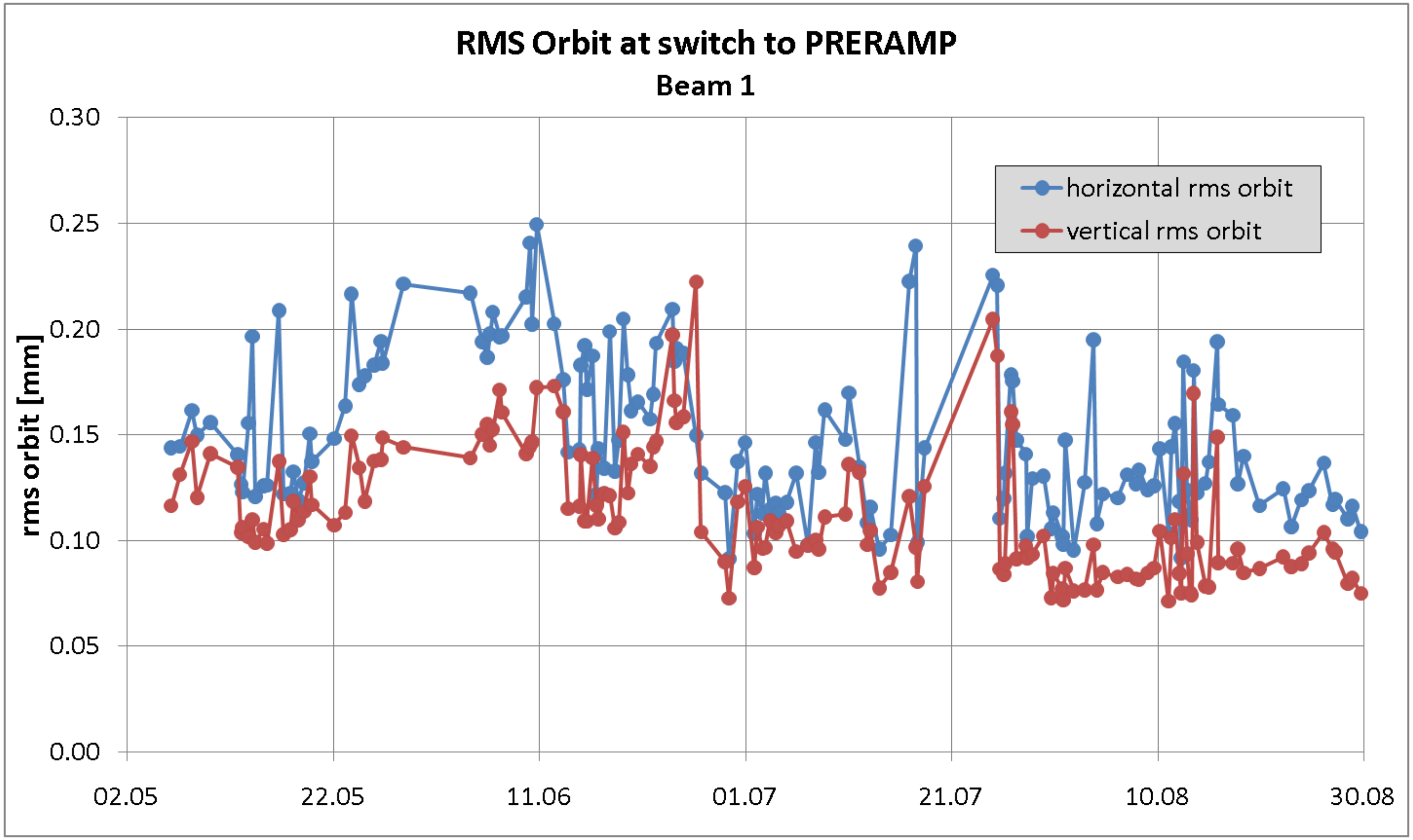
QFB trims

Energy (TeV)

FB usage

- **Injection:**
  - *OP crews correct orbit and tunes back to reference (by hand).*
- **Ramp:**
  - *OFB and QFB switched on at end of filling for the ramp.*
    - *So far OFB corrected towards the orbit measured at time of switch on.*
  - *Both FBs off when reaching flat top.*
- **Squeeze:**
  - *OFB back on.*
  - *QFB off in the fist 30 seconds of squeeze due to reference change (0.27,0.31) to (0.31,0.32), then QFB back on.*
  - *OFB and QFB off at end of squeeze.*
- **(to) Collisions:**
  - *Collapsing of separation bumps and ramping of crossing (temporary) done in ~2 minutes. Functions only, no FBs.*
  - *Manual correction towards physics reference.*
  - *No feedbacks during collisions – RT trims disabled to avoid spurious trims.*

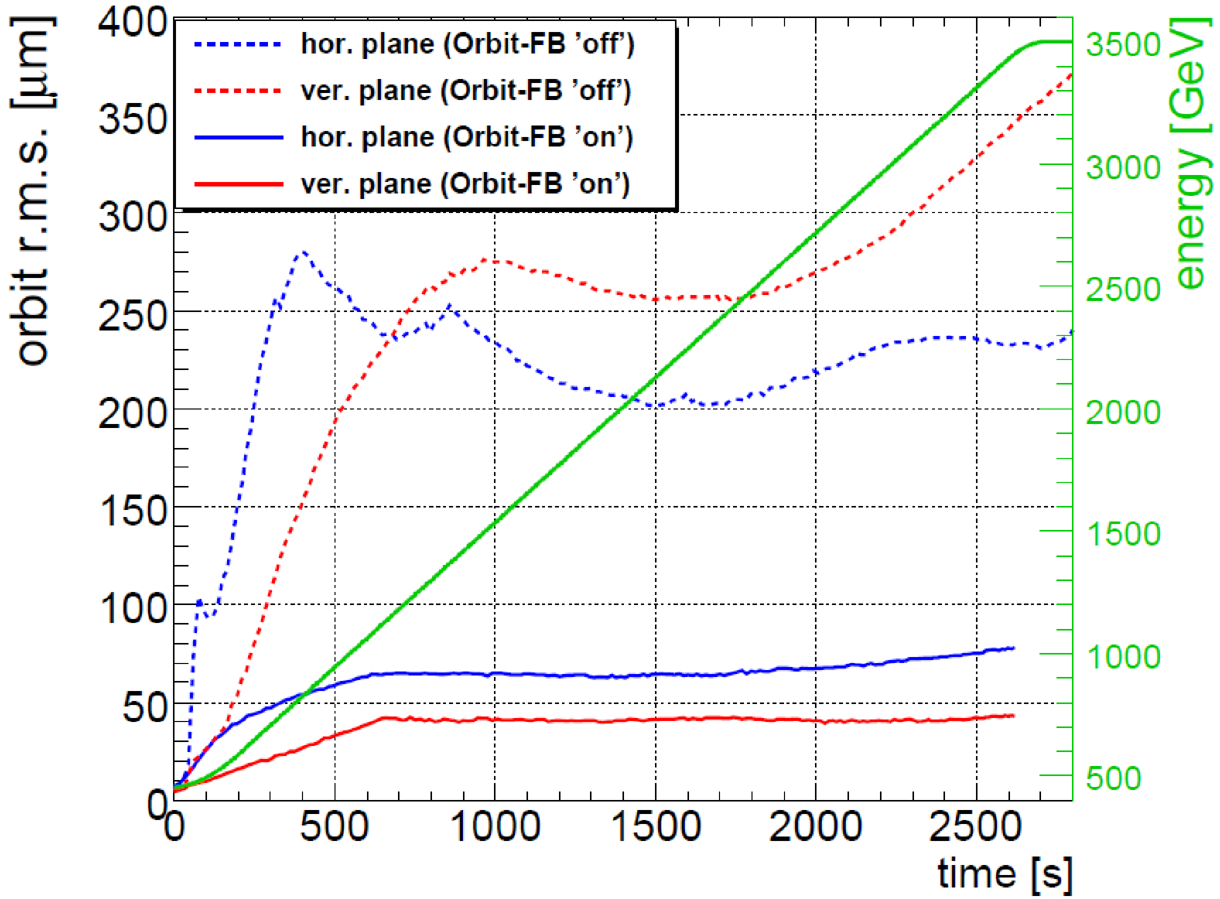
Orbit rms wrt reference orbit (begin May collimation setup) for B1 just before starting the ramp as a function of time.



T. Baer

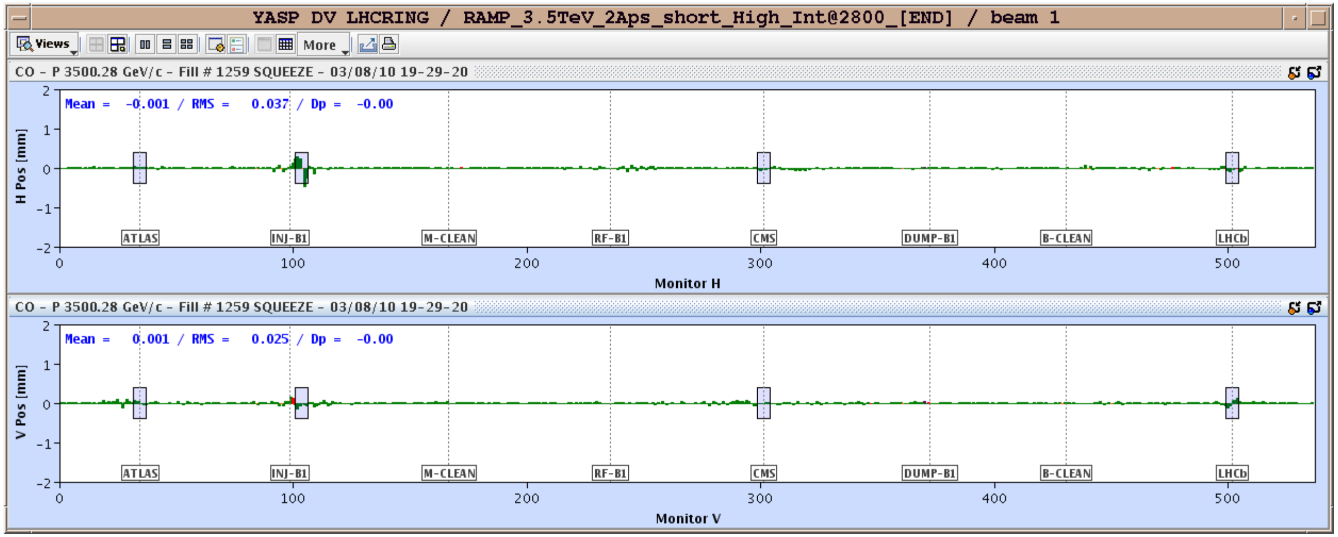
OFB performance : ramp

Orbit stability in the ramp: ≤ 80 μm rms



R. Steinhagen

OFB performance : squeeze



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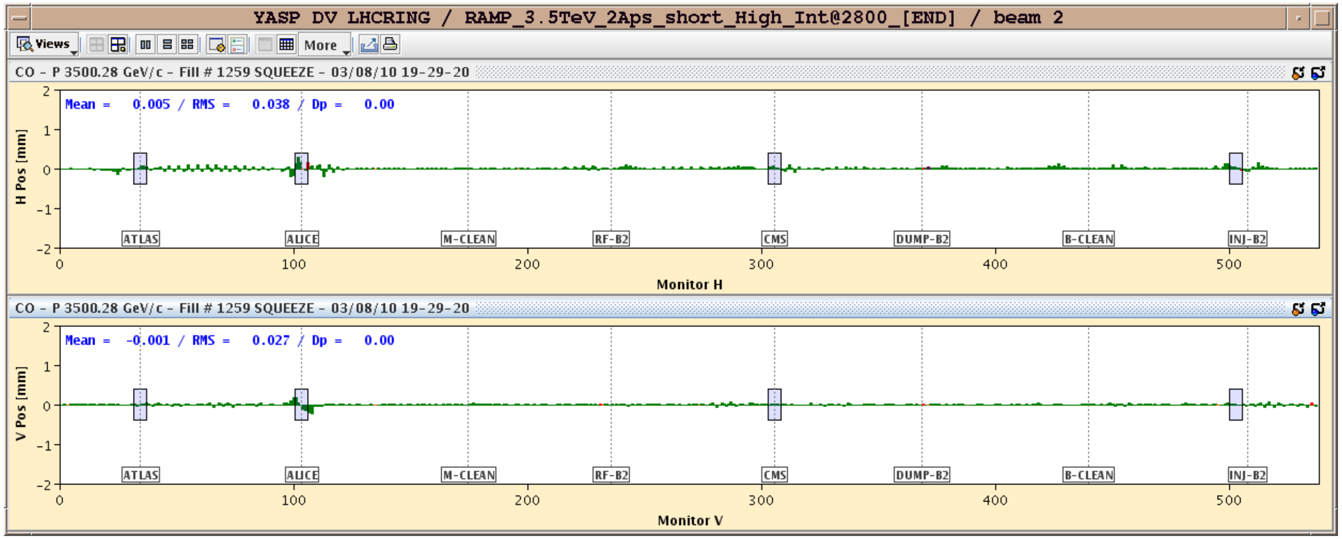
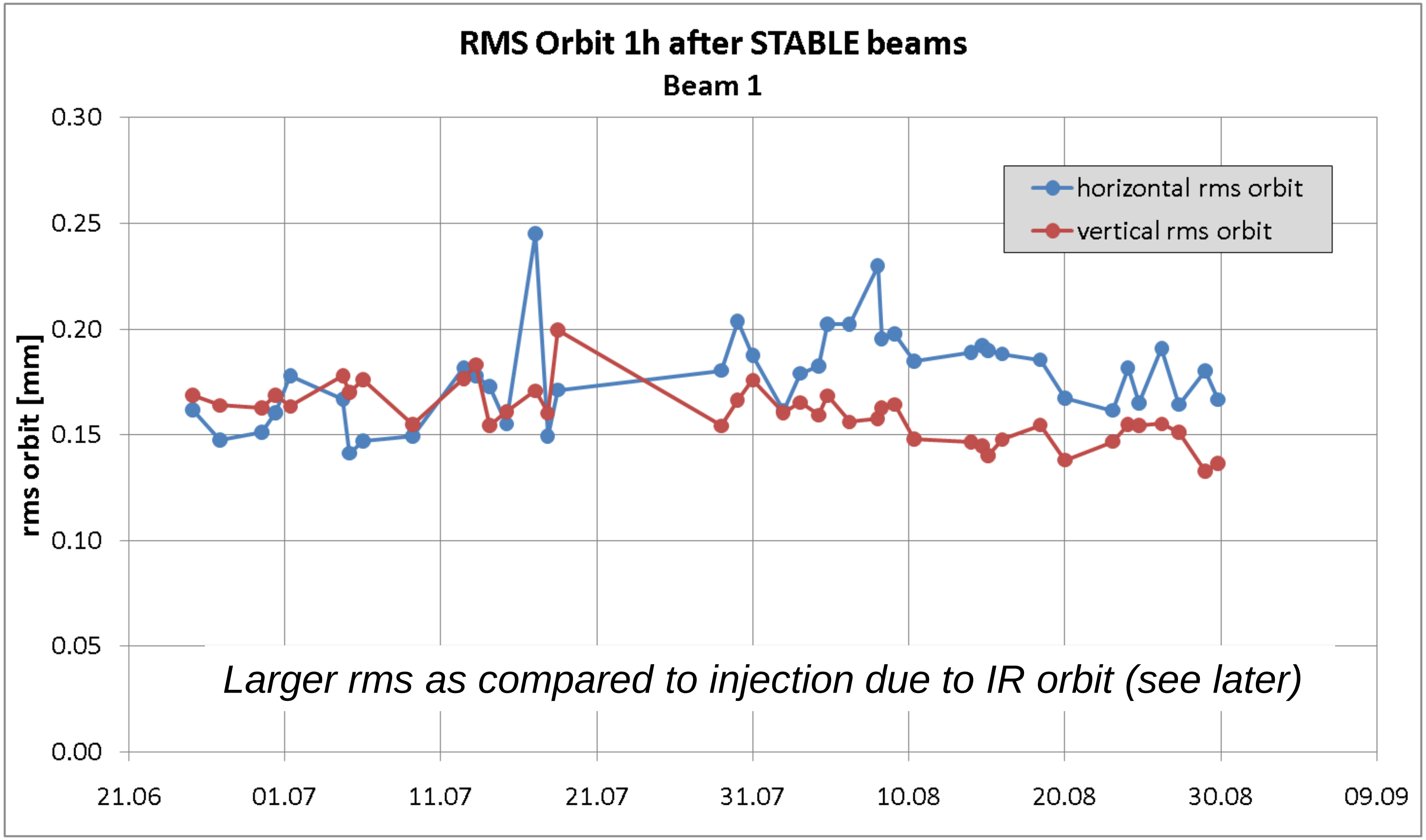
Orbit change
in the squeeze,
β* 10 m to 7m:

~30 μm rms



Orbit in collisions

Orbit rms for B1 wrt reference orbit (end June collimation setup) 1 hour after declaring stable beams.

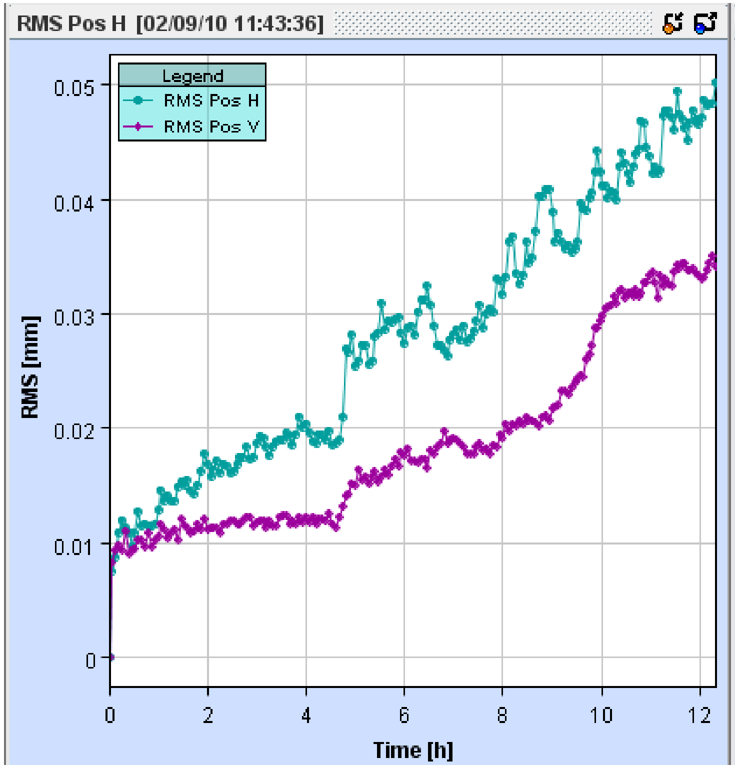


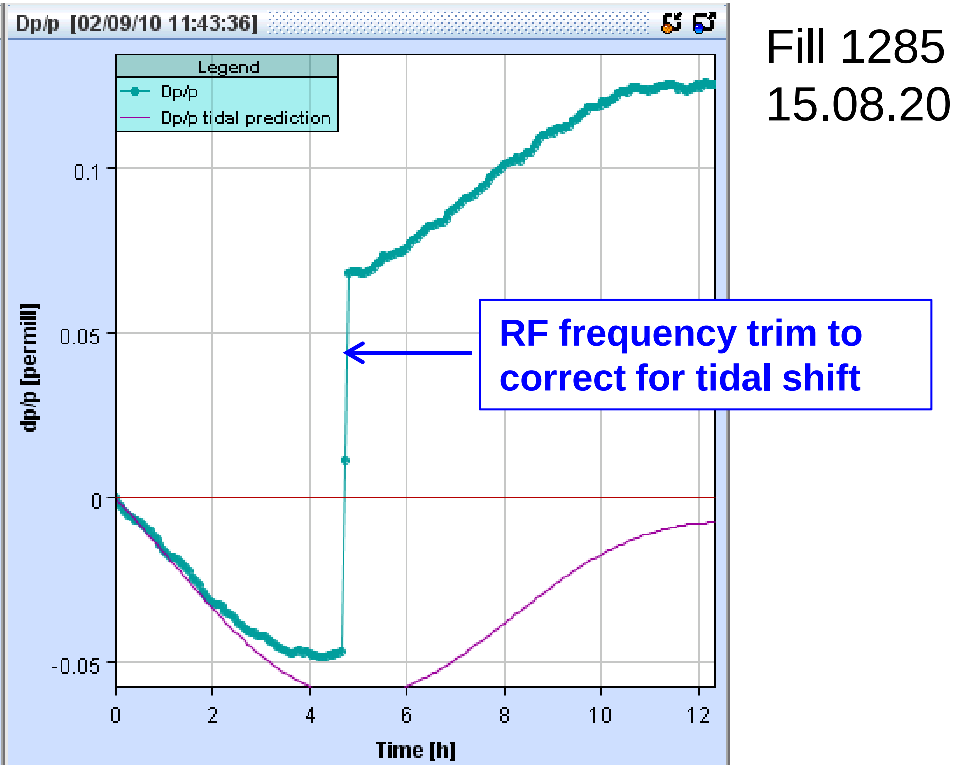
Larger rms as compared to injection due to IR orbit (see later)

T. Baer

Collisions (stable beams)

- Stability in collisions is excellent.
  - *Rms drifts ~20-50 µm over 12 hours.*
  - *No automatic corrections of rms and of dp/p shifts (tides !!) for the moment.*
  - *Automatic correction of tides (± 0.1 permill peak-to-peak) and orbit is being investigated.*





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Time in stable beams(hours)

LHC and FBs

- The performance of the FBs is very good!
- The LHC only operates reliably with both orbit and tune FBs (ramp and squeeze).
  - Ramp and squeeze essentially without losses !!!!

Orbit control issues

FB issues

- The feedbacks (OFB, QFB) are complex systems that can fail in various ways – we must be able to catch failures of the systems with the MPS.

- Dependence on FBs can be reduced with feed-forward of the real-time trims into the PC functions (for next fills).
  - *High(er) survival probability when FBs switch off.*
  - *For the orbit FF works well because drifts are slow.*
  - *For tune FF is more delicate, in particular at the start of the ramp – still quite larger variations (~ 0.01-0.02) from fill to fill.*
  - *We can improve here…*

FB issues

- QFB:
  - *Loosing the peak, coupling too large (automatic off), fake noise peaks…*
    - *A number of ‘events’, either saved by OP crews or caught by the MPS.*
  - *Interference with transverse damper (not enough signal) – work ongoing.*
  - *Interference with QPS system: voltage spikes from trim requests lead to erroneous QPS system triggers.*
    - *All events (many !!) were caught by PIC interlocks.*
    - *Situation was improved by changes within QPS system.*
- OFB:
  - *Spurious trims (reset, RF frequency).*
  - *Issues with enabled/disabled BPMs and CODs.*
  - *Running with injection optics through the squeeze.*
    - *Worked well so far, but far from ideal (software for changing optics ready but not tested).*

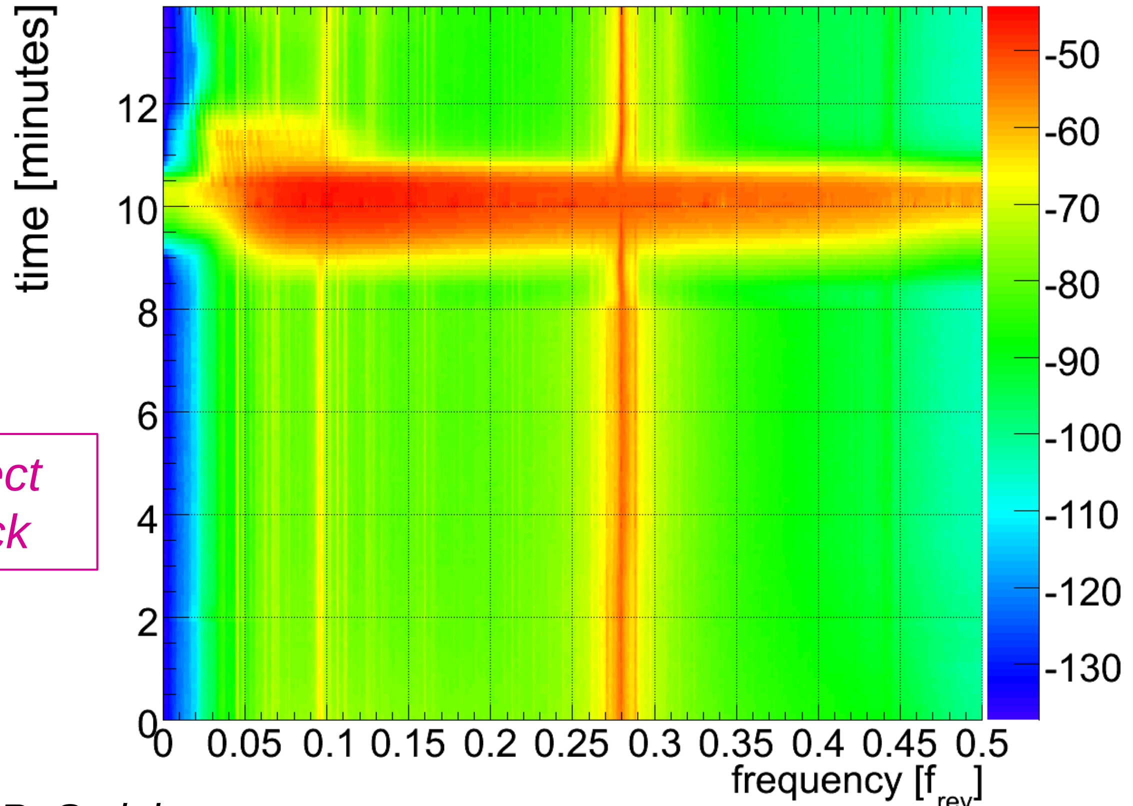
Many feedback control issues have solved in the past month.

Q issues : loosing track…

Example from a recent ramp:

- *Sudden increase of noise (longitudinal), QFB switches OFF.*
- *Situation back to normal after a few seconds.*
- *OP crews switched the QFB back on, beams ramped OK !*

We have to expect this to come back



R. Steinhagen

BPMs : intensity dependence

- LHC BPM system works on bunch to bunch basis
  - *Only depend on bunch intensity*
- BPMs can be used in 2 sensitivity modes
  - ***High sensitivity :*** *from ~1×10^{9} to ~5×10^{10}*
  - ***Low sensitivity :*** *from ~5×10^{10} to ~2×10^{11}*
  - *Only changes threshold for bunch detection -* ***no gains changed.***
    - *Required to make system immune from reflections generated by imperfect cabling, connections & BPMs.*
- Tests have shown that
  - *B2 behaves as expected.*
  - *B1 has a grey zone between 3×10^{10} and 5×10^{10} where neither sensitivity gives required results – related to the special intensity mode*

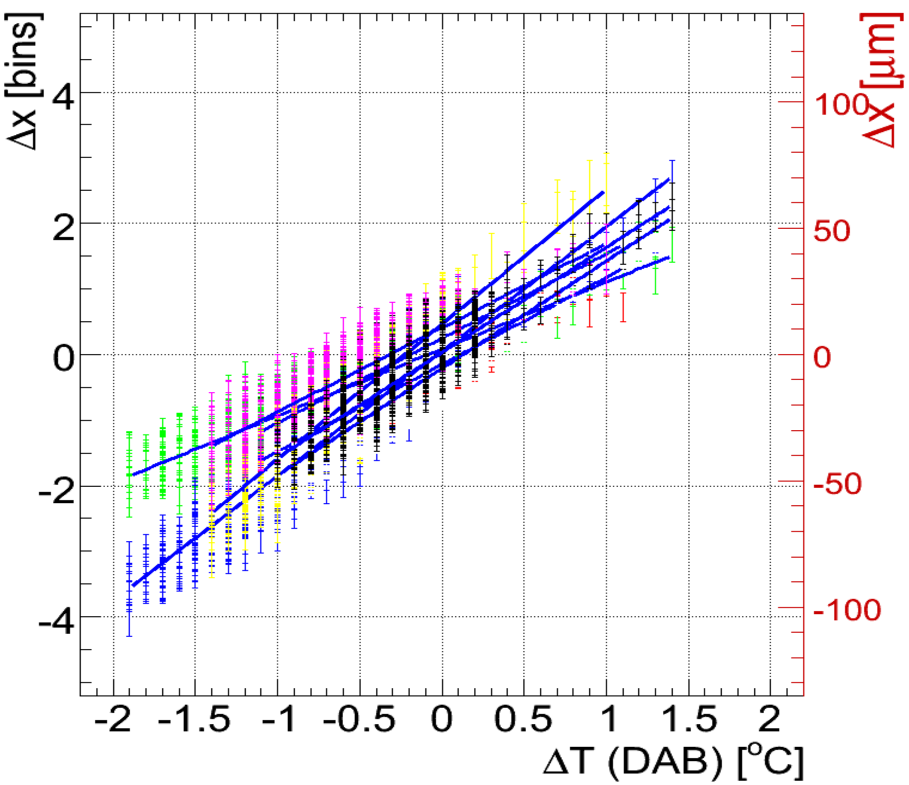
> - Max variation with intensity <200μm from 6×10^{10} to 1×10^{11}.
> - Systematic orbit shifts of similar size between probe bunch of 5-10×10^{9} and a nominal bunch of ~1×10^{11}.

Position dependence on temperature

- BPM electronics component known to suffer temperature dependence is the wide band time normaliser integrator card:
  - *Located on surface*
    - *Prone to relatively large temperature variation*
  - *Position encoded in pulse length 10 ± 1.5ns*
    - *Temperature affects offset & hence integral*
      - *position dependence should be minimal*
  - *Clear correlation between acquisition card temperature and position*

- Systematic position shifts of up to ~0.3 mm, correlated H & V, have been observed until ~June.

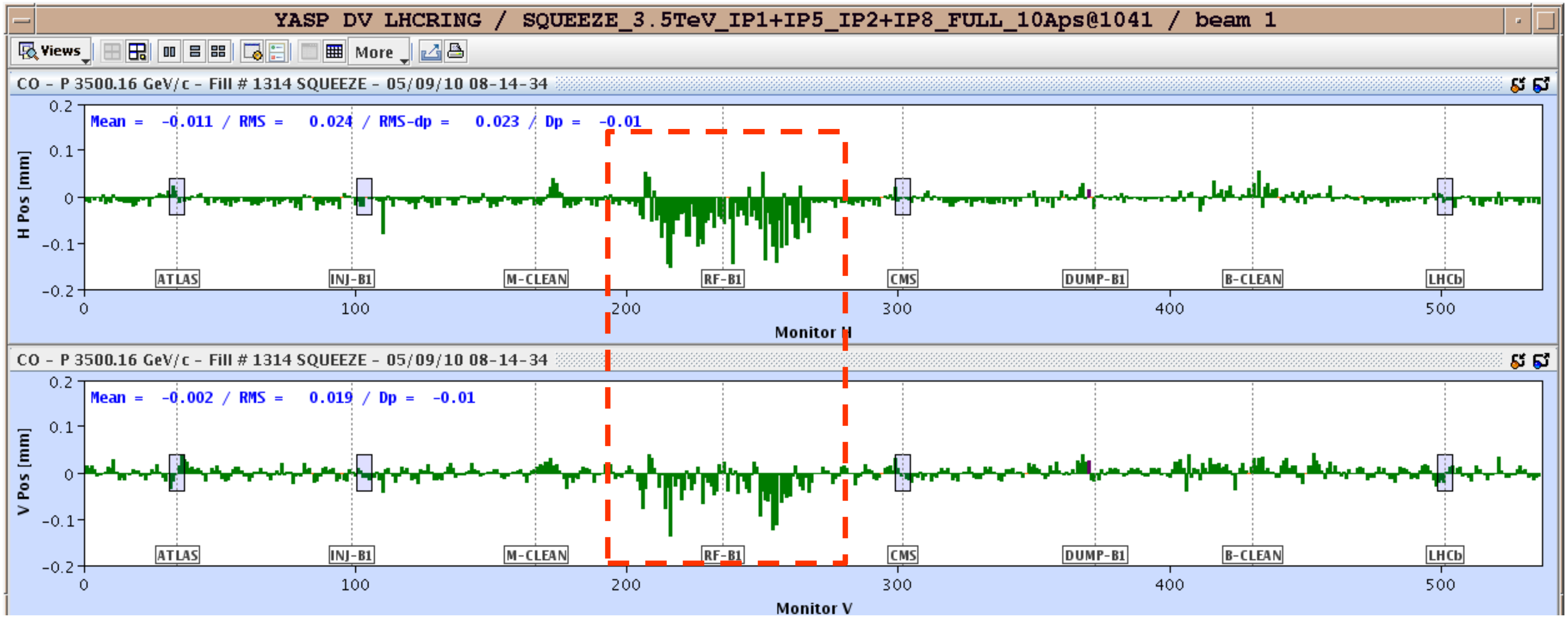
✓ **Situation has improved a lot with an automatic T correction.**



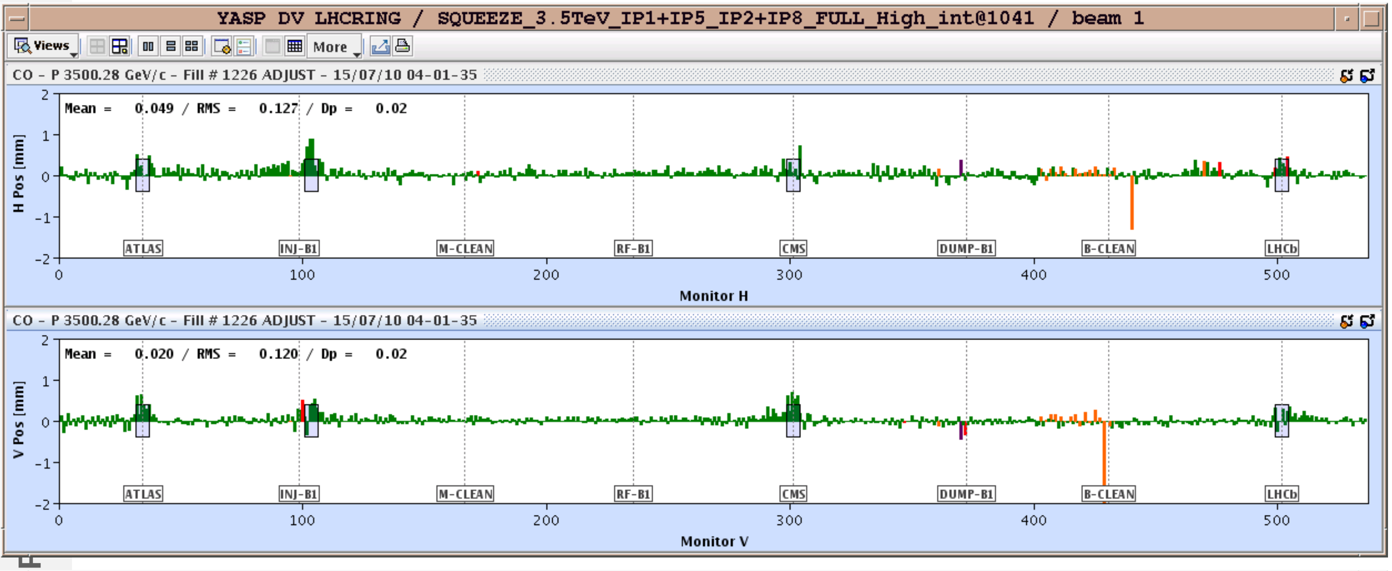
Temperature effect in action

A recent example (last Sunday !) for residual temperature effects.

~ 100-150 μm peak



Flat top orbit : Mid-August versus Mid-June



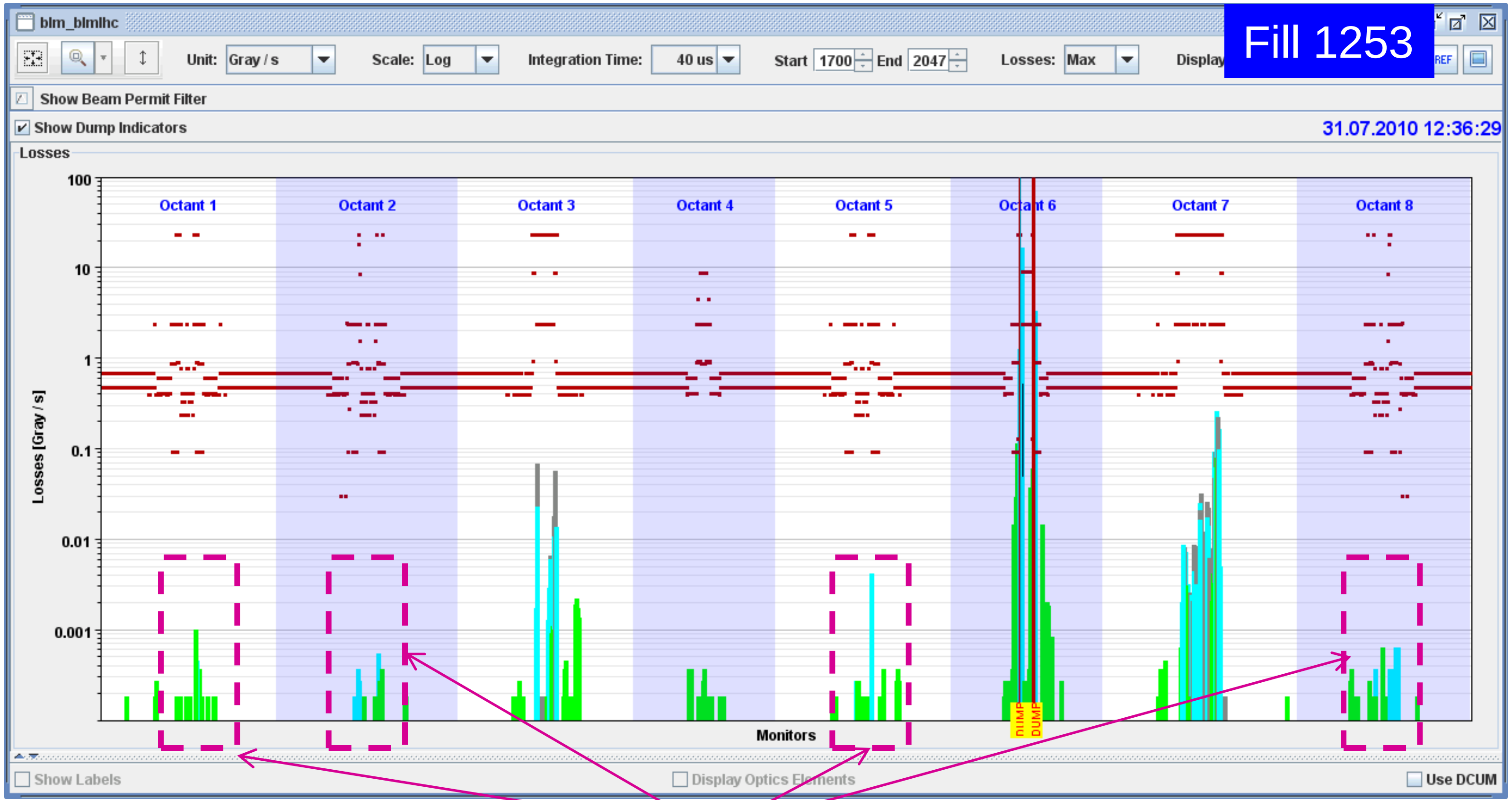
- Large(r) shifts in the experimental IRs:
  - *~1 mm peak*
  - *always > 0*
  - *Not correctable or only with huge deflections…*
- Shifts were stable in August.
- Residual effect of temperature?
  - *reference orbit was established before the T correction.*

Issue because of the TCT collimators!

IR orbits : TCDQ – TCT margin check

- Validated in de-bunched beam tests, and checked with every dump with the PM (we always have some debunched beam) – OK !

  >> does not provide information on the available margin !



IRs : no anomalous losses

BPM effects summary

- Residual intensity dependence (~50 μm rms, 200 μm max) is minimized by operating always with ~nominal bunch intensities.
  - *Automated sensitivity switching at injection (probe → nominal b.) will be tested soon.*
- Temperature effects on the electronics are now under better control.
  - *Residual effects can still be observed at the level of ~100 μm.*
- Bunch length dependence should be ‘small’.
  - *Not yet observed / resolved.*
- IR BPMs. Checks (k-modulation) ongoing…

Orbit interlocks

Orbit interlocks : hardware interlocks (BIS)

❑ Beam excursion interlock in IR6 (dump region):

- *Based on 4 dedicated BPMs per beam (couplers), installed in IR6.*
- *Turn-by-turn reaction, configurable (no. out tol triggers / no. of turns).*
- *Position tolerance is* ***±3.5 m****m around reference orbit.*
- *Interlock is dedicated to dump protection – avoid dumping off-axis.*

❑ RF frequency interlock (IR4):

- *Reaction/measurement time 50 ms (accuracy ±20 Hz).*
- *Frequency tolerance is ±100 Hz ⇔ ±0.08%. Reference frequency deduced from the machine energy information (see SMP system).*
- *Interlock designed for dump protection – avoid off-energy dumps.*
- *Interlock now also protects against large frequency swings (Q' measurement, erroneous trims…) that would drive the beam into the off-momentum collimators.*

Both interlocks are maskable with setup beam.

Software Interlocks on Orbit

- The Software Interlock System (SIS) provides a simple and reliable way to program complex interlocks in a central place, correlating multiple systems/signals.

  see presentation by L. Ponce (next !)

- SIS is used, among other things, for global orbit interlocks.
  - *Complete BPM and COD data available.*
  - *Interlock update rate is 0.5 Hz (2 sec period).*
- The interlocks that will be described in the next slides were initially much looser (tolerances a factor 2-3 looser).
  - *Tolerances were tightened as we improved control/reproducibility.*
  - *Many issues with OFB and correctors that were observed initially would now trigger a beam dump.*

60 A arc CODs interlock (SIS)

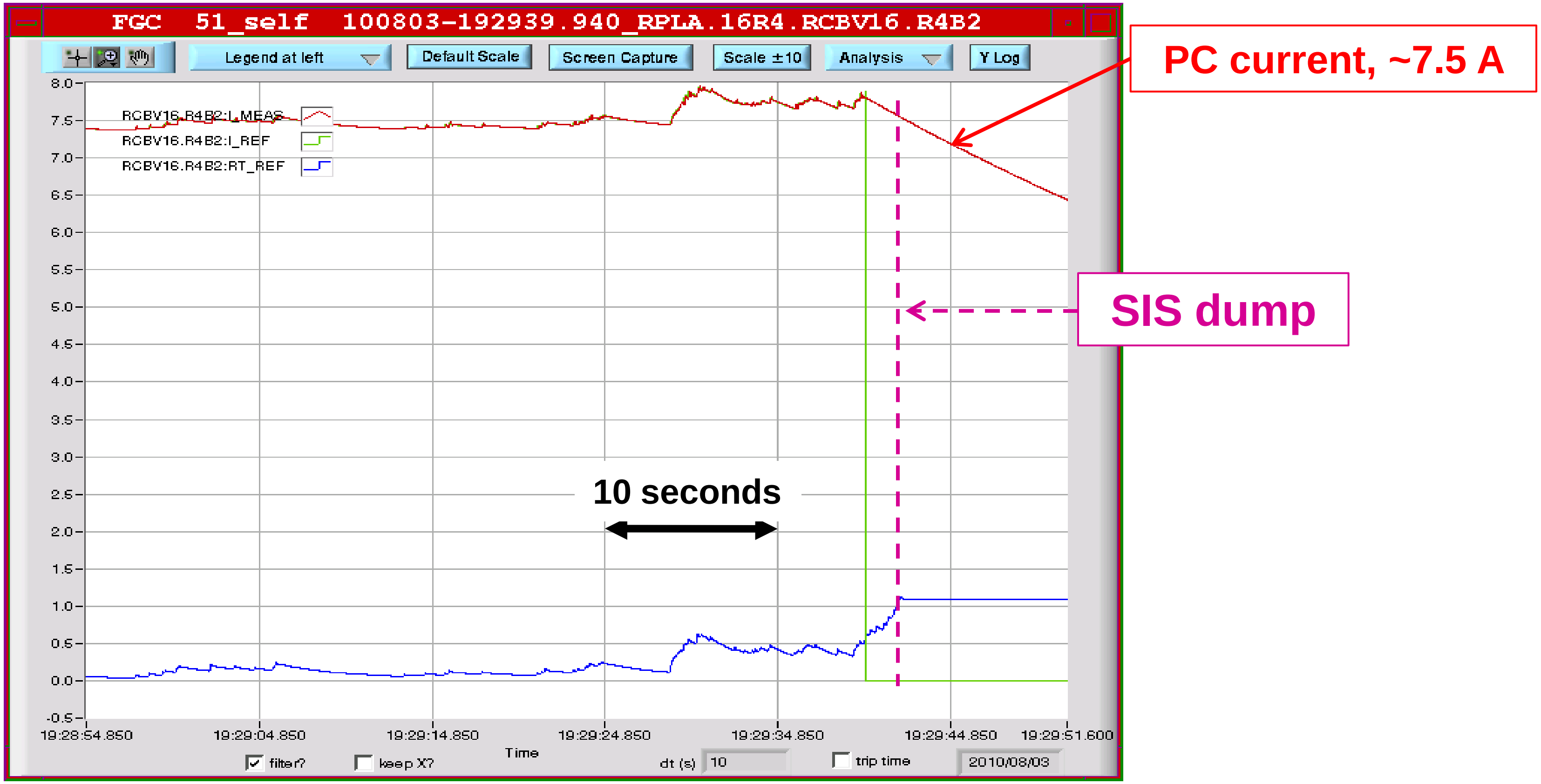
- The 60 A arc COD PCs are installed below the magnets in the tunnel.

  ~ 750 PCs installed in the arcs

- The 60 A arc CODs are not interlocked with PIC (also no QPS).
- To catch powering failures at an early state, the state of those CODs is interlocked by the Software Interlock System (SIS):
  - *Beam dump request as soon as one COD state switches to OFF.*
  - *SIS reaction time ~2 seconds (max), to be compared with a current decay time of ~40 seconds.*
    - *Typical COD kick ~10 μrad, max kick ~25 μrad.*
    - *Perturbation limited to ~1-2 μrad → ~0.1-0.2 mm rms orbit change.*

60 A arc COD trip

- Example of a COD trip (the only trip > 450 GeV in July-August) caught by SIS during a test squeeze.
  - *Beam dump triggered before any significant current and orbit change.*



Orbit interlocks (SIS)

- Global orbit interlock:
  - *<u>Dump if > 10 BPMs out of tolerance</u>, configuration depends on mode.*
  - *Tolerances for non-stable beams have to cover changes in separation and crossing angles → significantly larger tol. Present settings:*

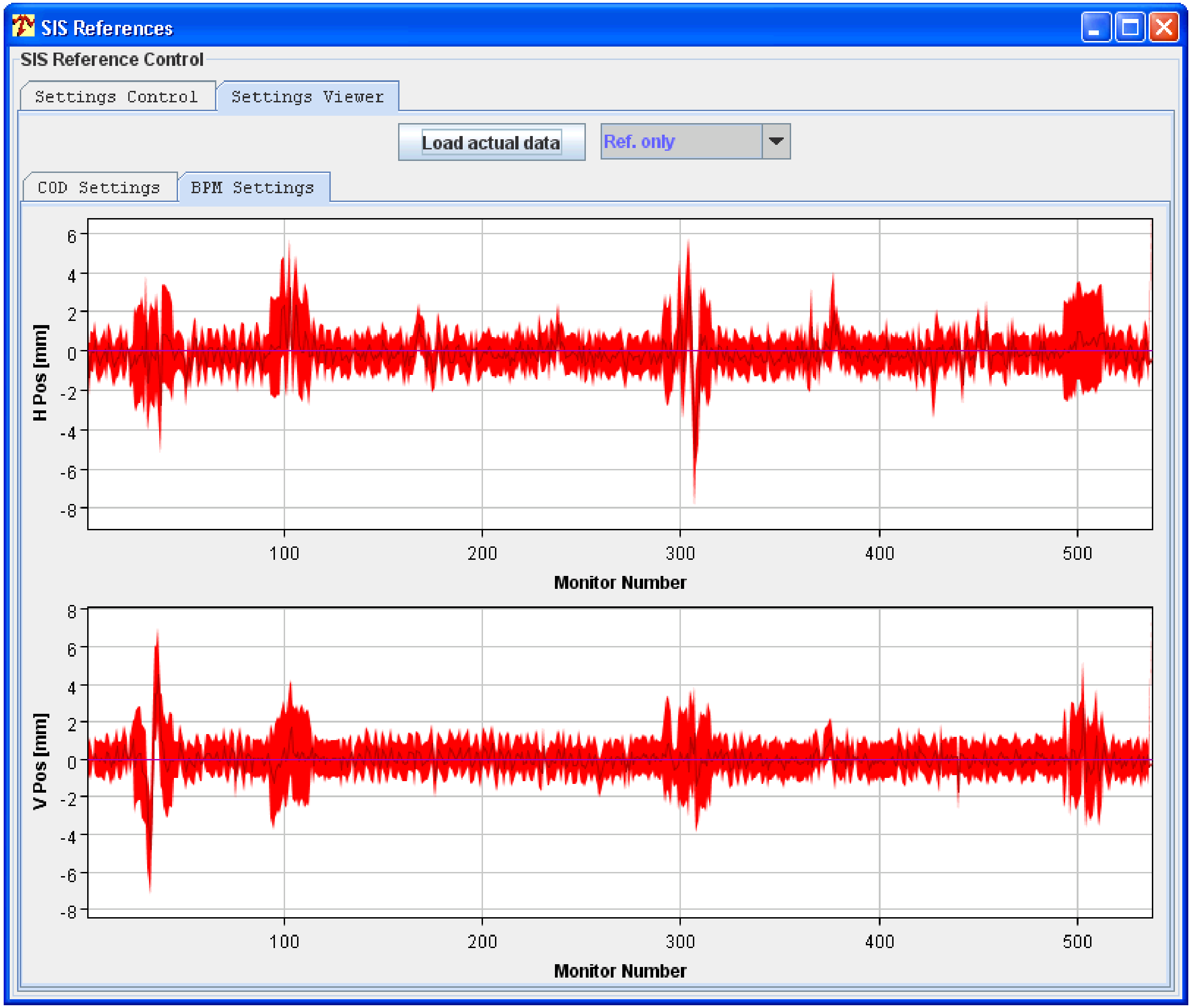
Mode	Arc tolerance	Exp. IR tolerance
Stable beams	±1 mm (⇔dp/p ±0.12%)	±2.5 mm
Other modes	±2 mm (⇔dp/p ±0.25%)	±3.5 to 6 mm

450 GeV: 1σ ≈ 1.2 mm **3.5 TeV: 1σ ≈ 0.4 mm**

  - *This interlock has triggered dumps.*
  - *There is a potential to tighten tolerances, by up to a **<u>factor 2-3</u>**, without triggering to many 'erroneous' dumps with slightly stricter orbit control and finer interlock granularity (injection/ramp/squeeze).*
  - *A tighter interlock acting on INJECTION will be put in place for unsafe injections.*

Orbit interlock example

Orbit interlock reference and tolerance (stable beams) for B2.



COD settings interlock (SIS)

- Bump protection interlock:
  - *Dump if ≥ 2 CODs out of tolerance, configuration depends on mode.*
  - *Very simple interlock to catch large local bumps, no attempt to perform bump reconstruction with optics…*
  - *Tolerances for non-stable beams and IRs have to cover changes in separation, crossing angles and lumi scans → significantly larger.*

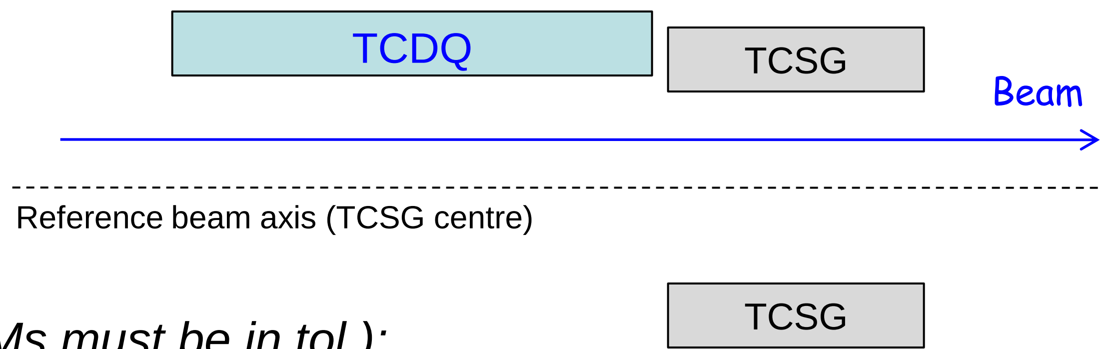
Mode	Arc tolerance	Exp. IRs tolerance
Stable beams	±20 μrad	±30-50 μrad
Other modes	±30 μrad	±30-60 μrad

20 μrad ⇔ 4 mm orbit excursion

  - *There is a potential to tighten tolerances in the arcs, **factor ~2**, but this will require close follow up when a COD fails and is not repaired.*
  - *A tighter interlock acting on INJECTION will be put in place for unsafe injections.*

Orbit at dump protection (SIS)

- Orbit interlock to ensure correct distance of beam to dump protection device (TCDQ). Interlocked:
  - *TCDQ retraction to TCSG too large (also Hw interlock !)*
  - *TCSG gap too large (also Hw interlock !)*
  - *Beam position (**2 BPMs**) deviation from TCSG axis.*



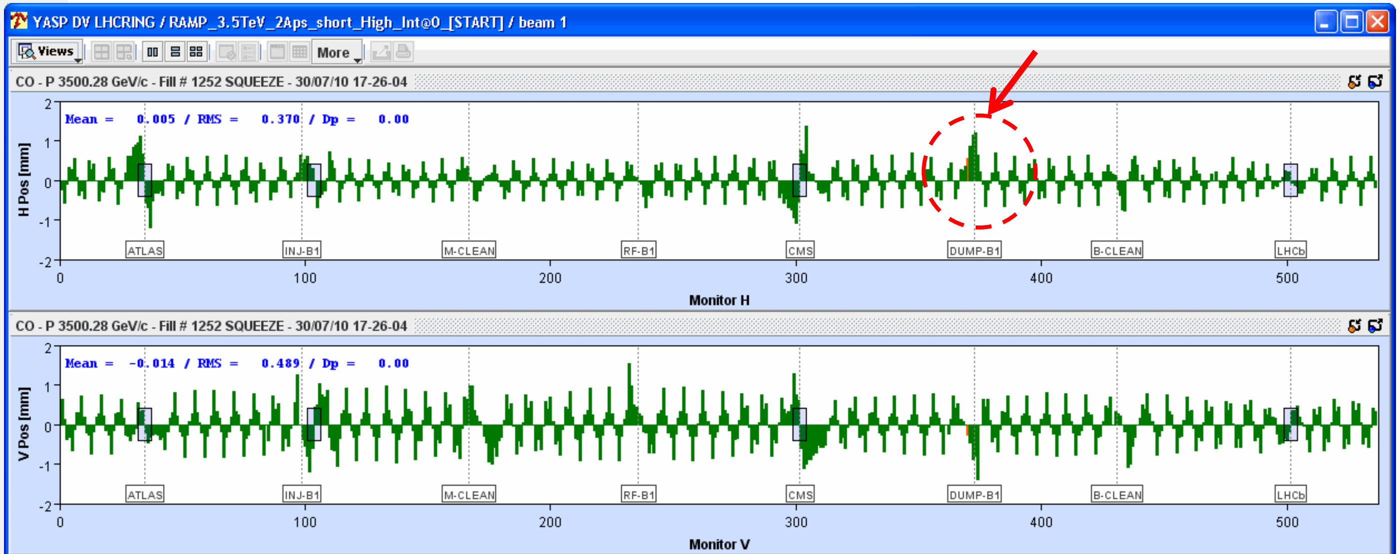
  - *Tolerances (both BPMs must be in tol.):*

    Injection : ***±1 σ (± 1.8 mm) wrt TCSG centre.***

    3.5 TeV : ***±1.7 σ (± 1.2 mm) wrt TCSG centre.***

    For nominal β the required tolerance is ~0.5 σ !*
  - *This interlock has triggered dumps.*

Failure example – procedural error



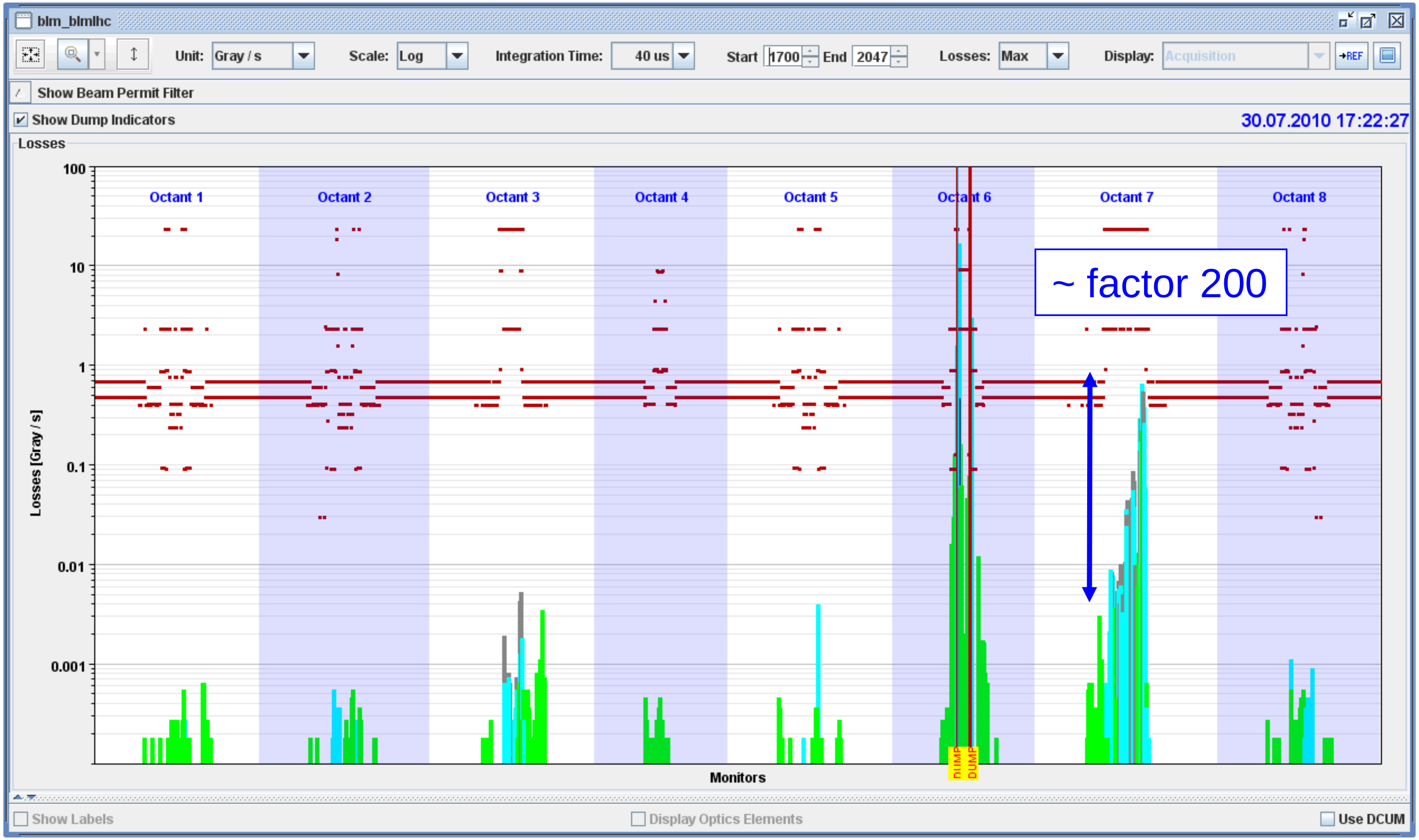
Orbit error due to COD settings problem

Dumped by orbit interlock at TCDQ (losses not sufficient to dump by BLMs at collimators)

Failure example - cleaning with orbit excursion

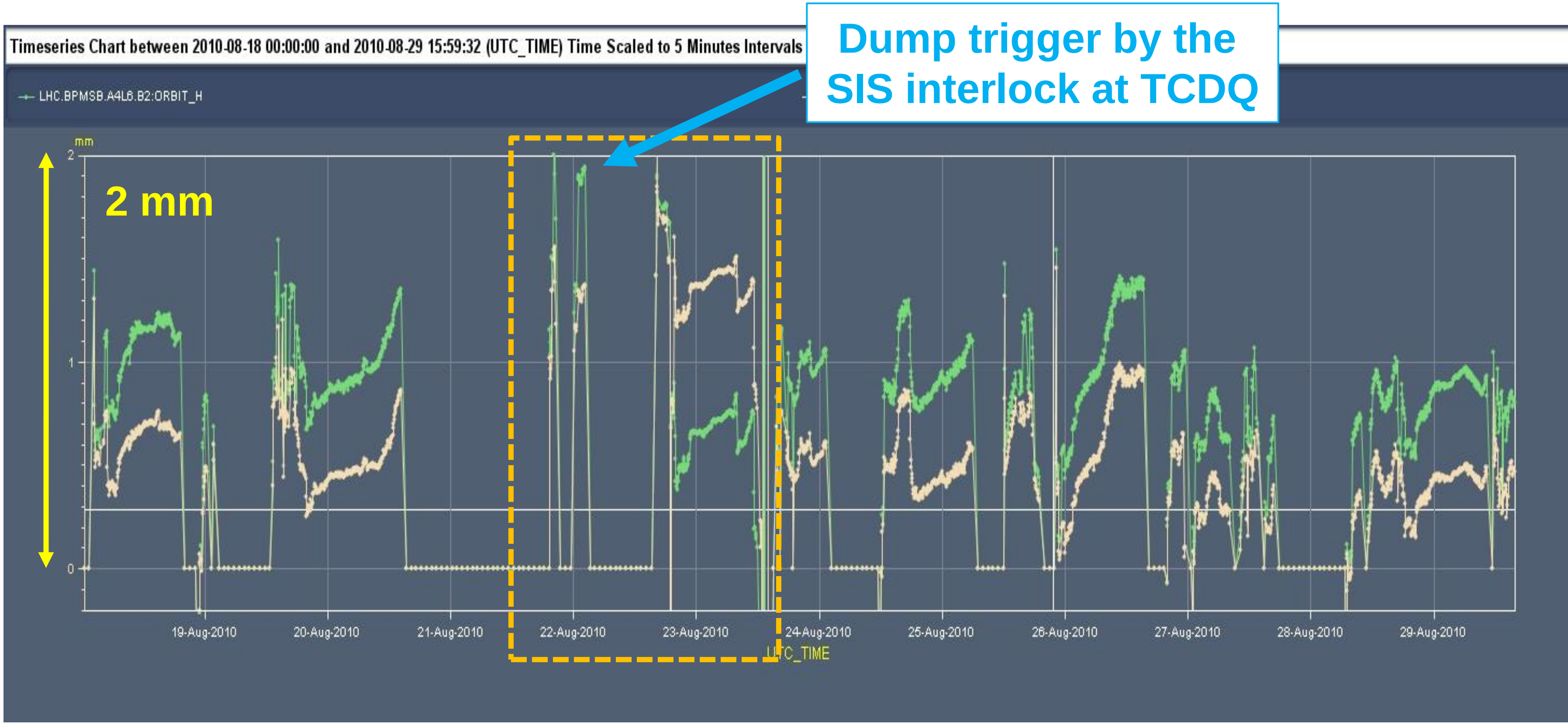
While the orbit was perturbed (see previous slide) the beam cleaning quality reduced:

- leakage to SC part a factor 200 instead of ~5'000-10'000.



BPMs at TCDQ

- The stability of the orbit at the TCDQ is presently around ±0.5-0.7 mm (~±1 sigma) at 3.5 TeV
  - *Could be improved by better orbit control (see later).*
  - *Some issues (worries !!) with systematic jumps at the BPMs !!*



Orbit/tune FB failure coverage

- Tune (feedback) errors (= wrong tune) are very well covered by collimation system.
  - *Regular validation tests of the collimation – see previous talks.*

- Orbit (feedback) errors (=wrong orbit):
  - *Phase space for errors reduced with more and with tighter interlocks.*
  - *With higher intensity beam movements at the collimators will more easily trigger dumps by BLMs (depends on tails too) – provides de-facto limit to orbit changes.*
  - *<u>Residual window for errors</u>:*
    - *~mm scale (global) orbit errors → issue for collimator hierarchy, possibly exposing collimators to asynch. dumps (TCT).*
    - *Local bumps up to ~4-6 mm: injection and asynch. dump.*

    Aiming to close windows…

Operational improvements around FBs

- Orbit (feedback):
  - *Protect against the use of wrong reference orbit. Need to define the best strategy. What about test ramps & squeezes ?*
    - *Some limits from the orbit interlocks…*
  - *OFB operation on a reference orbit and not on a measured orbit. This will ensure consistent correction strategy – coming soon.*
  - *Better filtering of erroneous BPM readings. Software ~ready, testing required.*
  - *FB should not try to use CODs that are OFF…*
- Tune (feedback):
  - *Interference transverse damper – tune measurement.*
  - *Coupling feedback to avoid QFB problems/stops in the squeeze. Requires some commissioning time.*
- Both systems:
  - *Voice alarms when the systems switch off.*
  - *(Better) handling of varying references.*

Outlook

- LHC operation relies on feedbacks and the smoothness of the FB performance is improving (X fingers !).
    - *There are a number of possible improvements.*
- Orbit control is already very good, but not yet 'nominal LHC' grade.
    - *Need more understanding of BPMs in the IRs, temperature etc*
    - *Orbit interlocks can be improved somewhat, but may never cover all risks (in particular for collimators). Regular checks (loss maps) needed.*
- Protection against orbit errors at injection that could lead to a serious issue in coincidence with an injection failure will become an issue.
    - *Injection interlock with tight tolerances (even single BPMs) on orbit and correctors possible – instead of beam dump. Forces to stop (and think) before proceeding. Coming soon.*

Outlook

- Possibilities for end of mission checks as cross-check for orbit errors or suspicious orbit features – 3.5 TeV:
  - *Analysis of loss pattern at dump time can reveal hierarchy problem – already done – to be automated in PM !*
  - *Loss maps – already done – frequency adequate?*
  - *Analysis of loss maps due to lifetime dips etc occurring during regular operation. Less accurate than dedicated loss maps but most likely capable of detecting orbit errors.*
- Longer term:
  - *Dedicated fast BPM hardware interlock for orbit changes (also dx/dt) should be considered. Multiple BPMs could cover most global orbit errors.*
  - *Hw interlock for 60 A CODs?*
  - *Hw interlock for beam position versus TCDQ.*