Orbit & orbit corrector interlocks in SIS
& COD failure mitigation

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Content

- Beam positon interlocks
- Orbit corrector interlocks
- Collimator BPM interlocks
- PC interlock server – CODs and quads
- Orbit correction failure ‘mitigation’ – SUE case
- Summary

SIS interlock references

- The interlock configuration settings for SIS (references, thresholds etc) are stored in:
  - ***One non-multiplexed beam process*** *for interlocks that are completely independent of the machine configuration.*
  - *In **3 beam processes** for injection settings, overall cycle settings and stable beam settings.*
    - One set of 3 beam processes per hypercycle.
- Provides the flexibility to cover different configurations like low beta, ATS, high beta, medium beta etc. Interlock settings are swapped automatically with the hypercycle change (delay of 10-15 mins possible).
- All orbit related interlocks that act on the beam permit are automatically masked out when the **SBF is true**.
  - *Avoid spurious dumps during commissioning, MD etc with 'safe' beams because an interlock mask was forgotten.*
- (most) orbit related interlocks that act on the injection permit are automatically masked out when the **SPS intensity is ≤ 5E11 p**.

Active beam position interlocks in SIS

- The following SIS interlocks are currently active:
  - ***Global orbit*** *interlock at injection → injection permit.*
  - ***Global orbit*** *interlock for the cycle (all modes) → beam permit.*
  - ***Global orbit*** *interlock in stable beams → beam permit.*
  - ***Local orbit*** *interlock around injection points → injection permit.*
  - ***Local orbit*** *interlock in IR6 (TCT/dump protection) → beam permit.*

- The interlocks are further subdivided into beam1 and beam2 interlocks (independent) as well as into vertical and horizontal planes (where applicable).
  - *A beam1 interlock removes only the relevant beam1 permit (injection or beam), and vice-versa for beam2.*

Global orbit interlocks

- The global orbit interlocks are configured per beam & plane.
- Interlock configuration:
  - *A reference position, tolerance window and status (active for interlock) per BPM (and per plane).*
  - *The number of BPMs out of tolerance to trigger a permit removal.*
- For injection and stable beams, all BPMs are active (except faulty ones!). For the cycle interlock, due to the large changes in configuration IR[1,2,5,8] are ~ not interlocked.
- References are trimmed from YASP (steering).

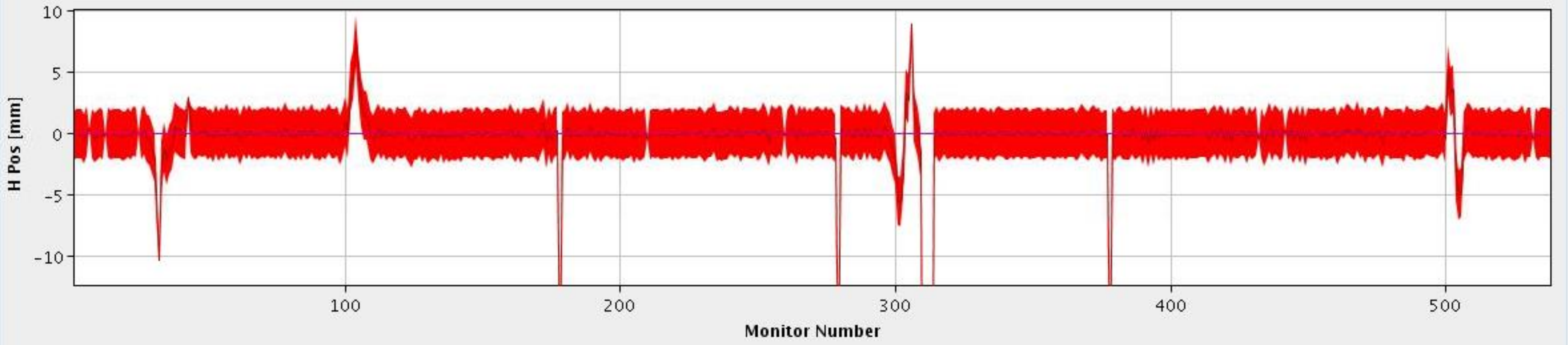
Interlock	# BPMs	Tolerance window [mm]	Comment
Injection	10	±2	All BPMs have the same tolerance
Cycle	10	±1	IR1/2/5/8 BPMs are not interlocked
Stable beams	10	±0.6	Tolerances for IR1/2/5/8 are larger (lumi scans etc) in mm.

Values for cycle & SB may evolve during the year !

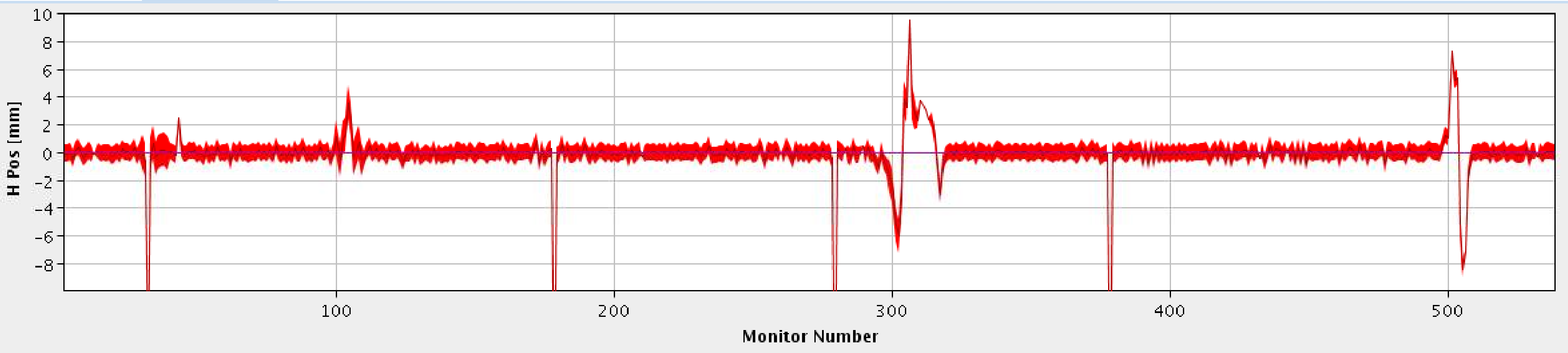
- Example of interlock settings for injection and stable beams.

Large 'outliers' and elements with '0' tolerance are disabled !

B1H - injection



B1H – stable beams



Local orbit interlocks

- Local interlock around the injection regions to ensure orbit is in tolerance based on 4 BPMs around Q4/5.
  - *Reference setting identical to the global orbit.*
  - *Tolerance reduced to ±0.6 mm.*
  - *Interlock if 2 (or more BPMs) out of tolerance → remove injection permit.*

- Local interlock in IR6 to ensure that the beam does not move away from the TCDQ and exposes the TCTs.
  - *Single sided interlock based on the 2 strip-line interlock BPMs (BPMSI).*
  - *Interlocks the offset between BPM readings and TCSP center. Assumes that relative position of TCSP & TCDQ are handled by HW interlocks (position, BETS etc).*
  - *Tolerance 1σ at injection, 2.5σ at 6.5 TeV.*
  - *Interlocks when both BPMs are out of tolerance.*
  - *Should be replaced by an interlock on the collimator BPM on TCSP (already in place, but masked) → should be more accurate and reliable.*

Active COD interlocks in SIS

- The following SIS interlocks are currently active on orbit correctors:
  - ***Global cod*** *interlock at injection → injection permit.*
  - ***Global cod*** *interlock for the cycle (all modes) → beam permit.*
  - ***Global cod*** *interlock in stable beams → beam permit.*
  - ***COD failure (60A)*** *interlock → beam permit.*
  - ***MCBX current*** *interlock → injection permit.*

- The interlocks are further subdivided into beam1 and beam2 interlocks (independent) as well as into vertical and horizontal planes (where applicable).
  - *The global COD interlocks work like the global orbit interlocks.*
  - *A beam1 interlock removes only the relevant beam1 permit (injection or beam), and vice-versa for beam2.*

Global COD interlocks

- The global cod interlocks are configured per beam & plane.
- Interlock configuration:
  - *A reference kick, tolerance window and status (active for interlock) per COD.*
  - *The number of CODs out of tolerance to trigger a permit removal = 2 for all cases → aim to cover 'bumps'.*
- For injection and stable beams, reference and tolerances are defined precisely. For the cycle, due to the large changes in configuration IR[1,2,5,8] are ~ not interlocked – same issue than for BPMs.
- Interlock settings are generated from YASP (steering).

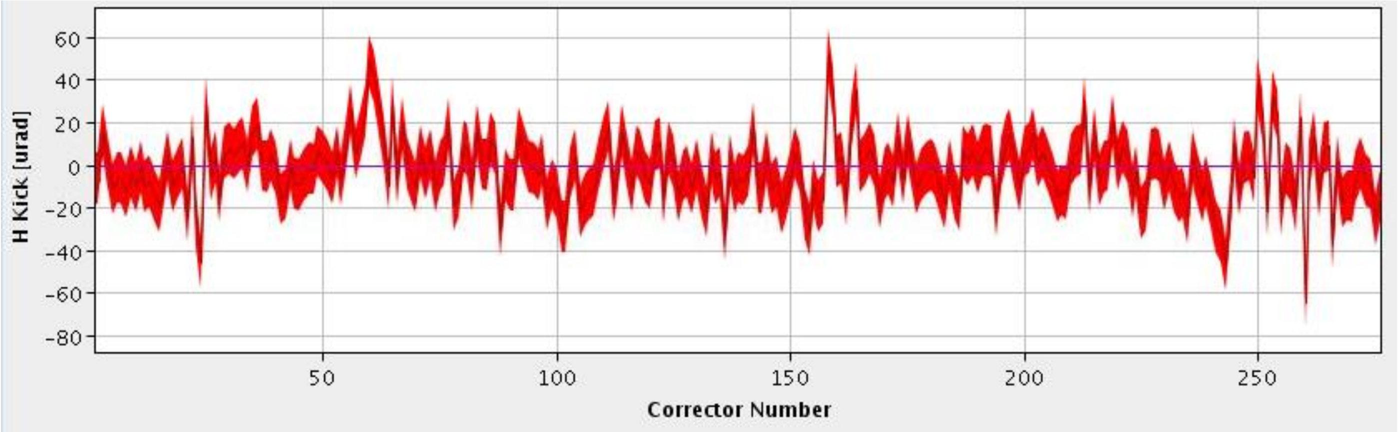
Interlock	**# CODs**	**Tolerance window [μrad]**	**Comment**
Injection	2	±12	All CODs have the same tolerance
Cycle	2	±20	IR1/2/5/8 CODs are not interlocked
Stable beams	2	±12	Tolerances for IR1/2/5/8 are larger (lumi scans etc) and cover the lumi scan envelope of 5-6σ beam separation (+margin)

Values for cycle & SB may evolve during the year !

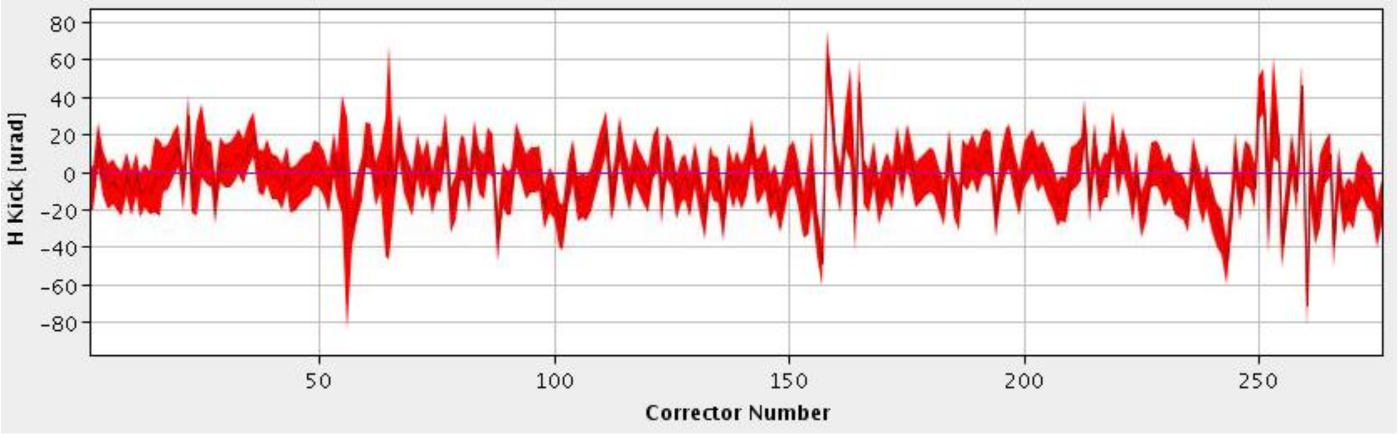
Global cod interlocks

- Example of interlock settings for injection and stable beams.

B1H - injection



B1H – stable beams



MCBX interlocks

- Based on failure studies made for the LHC experiments ~2008, it was recognized that an incorrectly powered MCBX common corrector could send the beam into the experimental vacuum chambers at injection – **can only happen at the first injection into an EMPTY machine**.
  - *Also applies to the D1/D2 separation dipoles that have a similar SIS interlock.*
- As a remedy the current of all MCBX correctors was interlocked to ±50A at injection.
- This interlock is much softer that the other COD interlocks that are in place.
  - *The limit of 50 A corresponds to ~100 μrad tolerance, compared to 12 μrad for the global COD interlock.*
- A left-over of the early days, but since it does not harm, it was just left in place.

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Beam-related machine protection for the CERN Large Hadron Collider experiments

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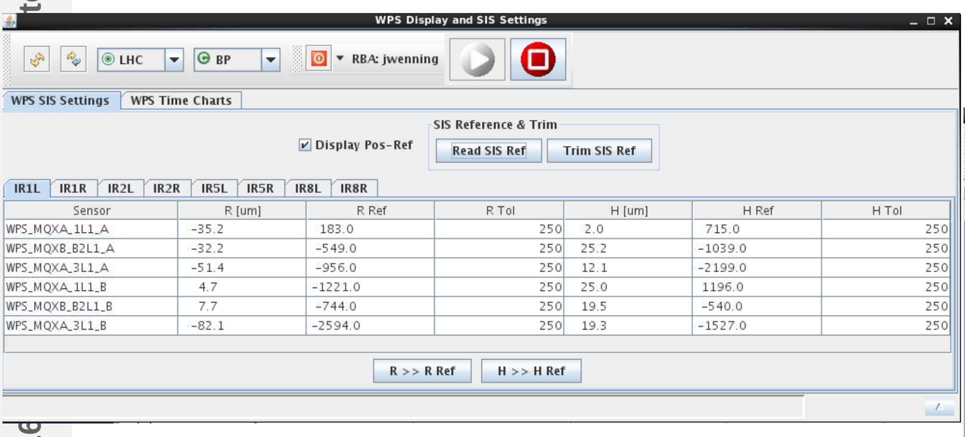
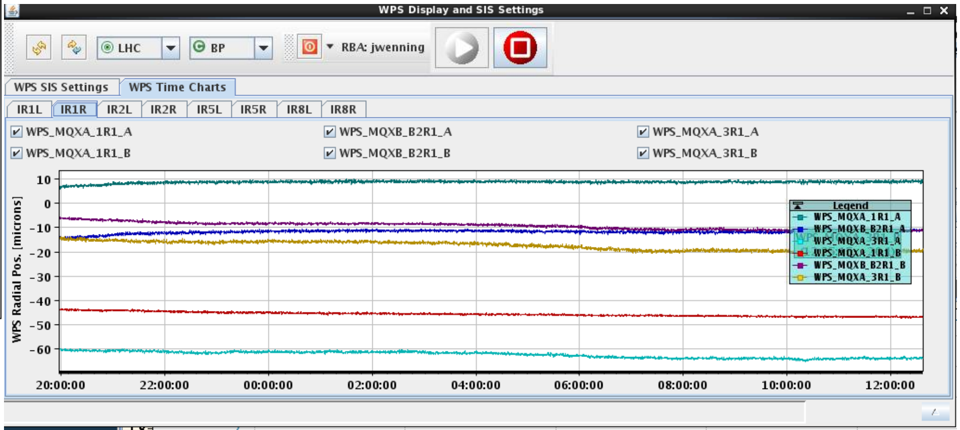
A side step: triplet position monitoring

- Since an incorrect triplet position is equivalent to a MCBX deflection, the triplet positions are also interlocked in SIS.
- The interlock is based on the triplet Wire Position System (WPS) that provides both vertical and radial positions for Q1,Q2 and Q3 (2 points /mag).
  - *Interlock is only applied to injection permit (both beams !).*
  - *Reference settings are established at the start of a run, or whenever SU touches the magnets in a TS.*
  - *Tolerances are ±250 μm – for stable beams we care already at ± 10 μm.*
- Application to check readings, import readings as interlock references and display time evolution. It is very popular in the CCC when the triplets move…



Sensor	R [um]	R Ref	R Tol	H [um]	H Ref	H Tol
WPS_MQXA_1L1_A	-35.2	183.0	250	2.0	715.0	250
WPS_MQXB_B2L1_A	-32.2	-549.0	250	25.2	-1039.0	250
WPS_MQXA_3L1_A	-51.4	-956.0	250	12.1	-2199.0	250
WPS_MQXA_1L1_B	4.7	-1221.0	250	25.0	1196.0	250
WPS_MQXB_B2L1_B	7.7	-744.0	250	19.5	-540.0	250
WPS_MQXA_3L1_B	-82.1	-2594.0	250	19.3	-1527.0	250

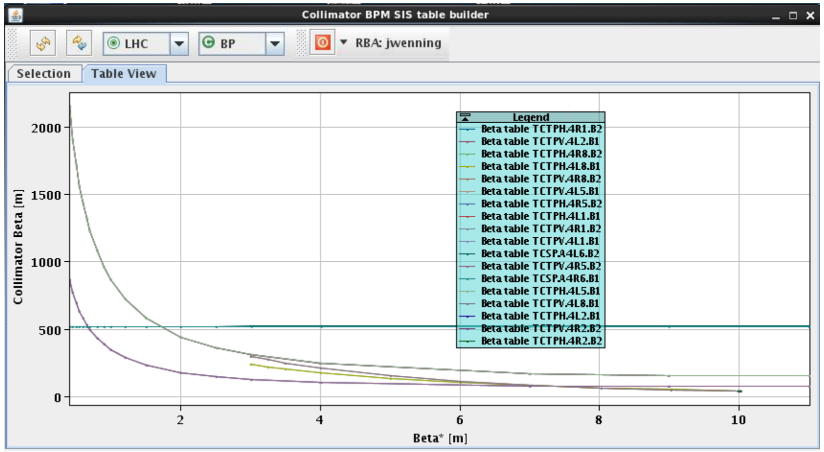


60A COD failure interlock

- The **60A arc orbit correctors (MCBH and MCBV, ~750) are not interlocked by the PIC**. If such a COD fails, no HW interlock is triggered directly.
- The SIS 60A cod failure interlock tries to close that gap by monitoring the 60A state. If a 60A COD fails (state change detected) SIS removes the beam permit (for the corresponding beam) if the kick is > 5 μrad (current setting).
  - *This interlock triggers regularly in stable beams (few times / year).*
- One limitation comes however from the fact that in case of a **SUE**, *no state information is sent by the FGC gateway*, but an **exception is thrown**.
  - *This is very difficult to handle in SIS – need to catch and decode the exception message. The current philosophy is not to react to an exception as this can be just a communication (CMW) issue.*
  - *This implies that currently the SIS interlock triggers only once the PC is back (~1 minute) and seen as faulty. In case of large excursions it is the orbit interlock that will dump first.*

Collimator BPMs

- Interlocks on the collimator BPMs have been put in place with a preliminary logic. The interlock logic has to know the optics (β*) since the tolerances change with the aperture margins.
- The interlock settings consist of:
  - *A table of β* versus collimator β and interlock tolerance in σ.*
  - *A reference emittance (3.5 μm) to define the beam size.*
- SIS logic:
  - *Reads back the appropriate β* and the energy,*
  - *Interpolates the collimator β and tolerance for that β*,*
  - *Calculates the beam size at the BPM,*
  - *Normalizes the two BPM readings by the beam size,*
  - *Finally applies the tolerance → interlock if both BPMs are out of tolerance*
- An auxiliary application is available to construct the reference settings.



Collimator BPMs - status

- All collimator BPM interlocks are running reliably (at least on the SIS side).
- All interlocks are in the interlock tree, but are currently masked.
- The interlock limits are currently set to 4σ except for:
  - ***1σ*** *in IR1 and IR5 at β*= 40 cm,*
  - ***1.5σ*** *in IR6 at β*= 40 cm (linked to IR5 β*),*
  - ***2.5σ*** *in IR8 at β*= 3 m.*

- During this year I would like to replace the local orbit interlock in IR6 by the equivalent based on collimator BPMs.
  - *This would provide the same functionality, but I expect it to be much more reliable, and it may provide room for tighter interlocks if required.*

PC interlock – CODs (server)

- The PC interlock server was designed in ~2012 to improve the COD interlocking in SIS.
  - *Tracks **time dependent interlock functions** across the LHC cycle instead of the 3 ‘static’ references that are internal to SIS (see before).*
    - Based on reference copies of the standard settings beam processes.
  - *Uses time dependent references and tolerances that must be correctly configured.*
- The PC interlock server provides one interlock status (true/false) for all LHC CODs (not split up by beam & plane for the moment).
  - *Currently **masked in SIS**.*
  - *Stable beams settings identical to SIS SB interlock, for the rest of the cycle tolerance of ±15 μrad.*
  - *Like all other interlocks, it will be automatically masked when the SBF is true.*
- The COD part has been around since 2012, but was never reactivated after LS1.
- Since the COD references are now complete for both low beta and medium beta cycles, and everything seems to be running smoothly, I propose **to unmask this input in SIS <u>after TS1</u>**.

PC interlock – Quads (server)

- The interlocking of the quads follows the same principle as for the CODs.
- Separate signal to SIS that summarizes the status of all quads.
  - *Currently **masked out in SIS**.*
  - *Like all other interlocks, automatically masked out when the SBF is true.*
- The interlock tolerances have been tightened progressively since the beginning of May.
  - *Generates an interlocks on the optics correction of the OMC team if they are not included in the reference settings – already a good indication !*
- Even tighter settings (5º phase, triplets) were put in place ~ this week.
- On track…

60A SUE failure mitigation

- With the current interlock logic (SIS and BIS) a SUE of a 60A CODs that has a kick larger than 5 μrad will lead to a beam dump due to:
  - *SIS COD interlock (current and/or state),*
  - *SIS orbit interlock(s):*
    - The overall interlock limits are between 1σ and 2σ.
  - *BLMs at collimators…*

- In order to **rescue** the beams during stable beams after a SUE on a 60A COD with a significant kick we must:
  - *Stop interlocking on the 60A COD state (SIS),*
  - *Correct the orbit actively to cope with the transient orbit change that lasts ~ 1-2 minutes until the current has decayed,*
  - *Possibly open the orbit interlock limits to cope with the transient orbit ecursions – tbc.*

Rescue the beam – ideal case

- An optimum action sequence to rescue the beams corresponds to:
  - *Recognize which is the faulty corrector (!),*
  - *Remove the faulty corrector from the configuration for corrections,*
  - *Recalculate the SVD of the response matrix,*
  - *(re)start correcting the orbit.*
- If one concentrates only on the beam & plane that is affected (assume that such failures appear for a single COD in any XX minute interval) the operation described above can be performed in **2-3 seconds**.
  - *The 60A circuits time constants are in the range 20-60 seconds, a few seconds delay can be tolerated.*
- Unfortunately this logic is not easy to implement in the LHC orbit FB.
  - *It could be done in the steering application 'rather easily' ('just work' & test) but it requires one instance open permanently to be ready for rescue.*
    - Possible limitations due to trim speeds through LSA to be checked.

Rescue tests

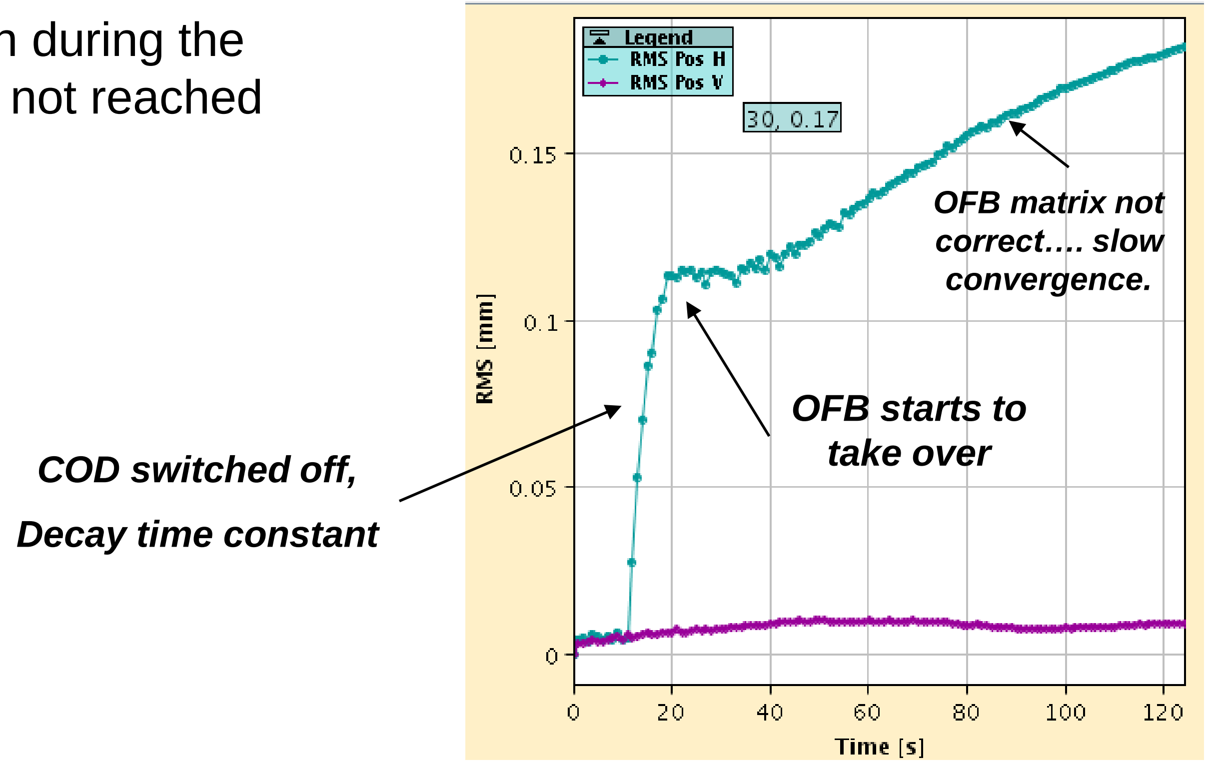
- A few tests were run at **injection** to evaluate what could be done with the orbit feedback <u>without changes to the system</u>.
  - *Not much difference to 6.5 TeV – same time scales and distortions.*

- Those tests are clearly far from the ideal correction case !
  - *Orbit correctors with kicks of ~20 μrad were switched off with the OFB on.*
  - *The OFB continued to correct with a matrix that assumes that the corrector is working (no re-computation as described before).*

SUE Test 1

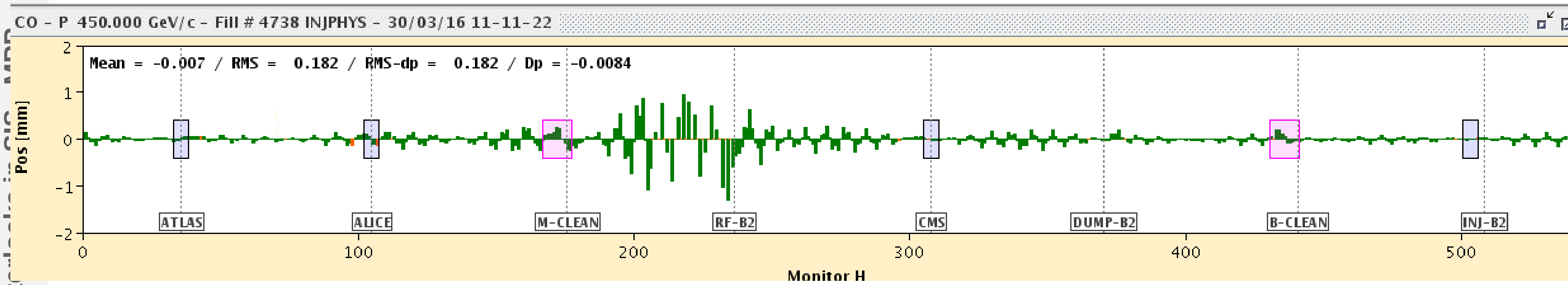
- Test 1: trip of MCBH20.L4B2
- OFB with **40** eigenvalues and high gain (scaled by **2**) – except for the gain that can be switched on the fly, this is the current configuration in stable beams ! This is what you could get in collisions if the beam is not dumped during the process !

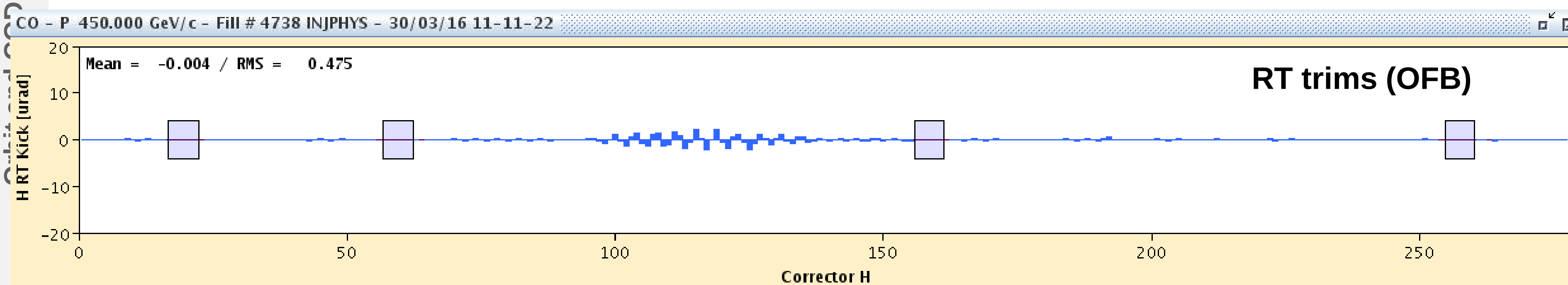
- Rms orbit evolution during the test – steady state not reached after 2 minutes.



SUE Test 1

- Orbit in ~steady state condition for test 1 (difference wrt initial).
  - *Excursion of up to ~ 1.4 mm, excursions around the ring of ~0.2-0.4 mm.*
  - *Correction kicks are very distributed by design of this OFB configuration for stable beams (gentle correction)*

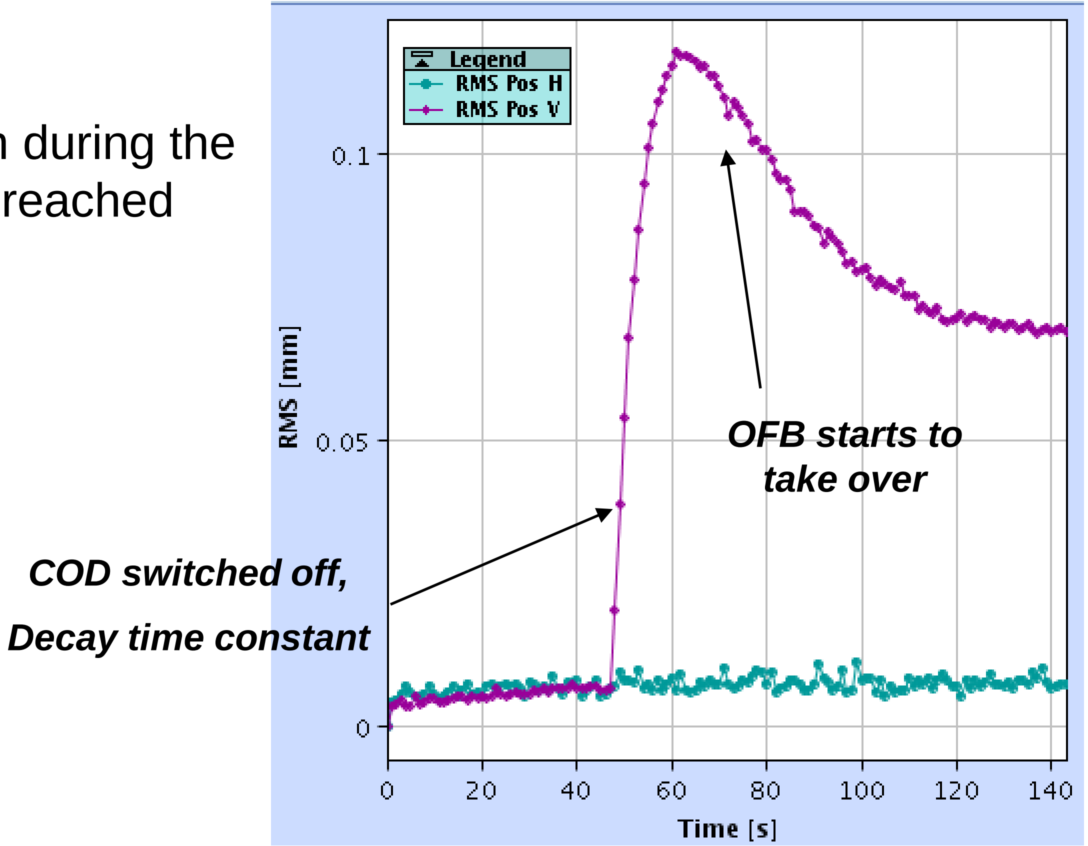




SUE Test 2

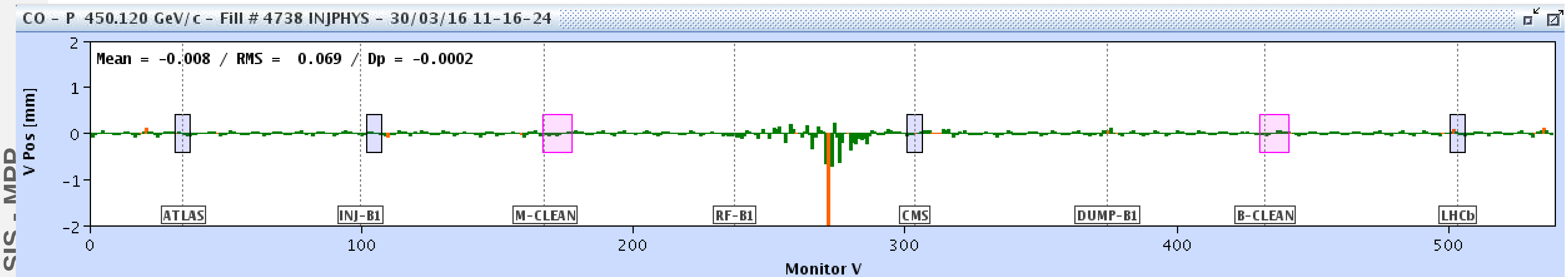
- Test 2: trip of MCBV29.L5B1
- OFB with **300 eigenvalues** and high gain (scaled by **2**) – this is a much more aggressive setup ! Cannot be put in place so easily in stable beams, but not excluded.

- Rms orbit evolution during the test – steady state reached after ~2 minutes.

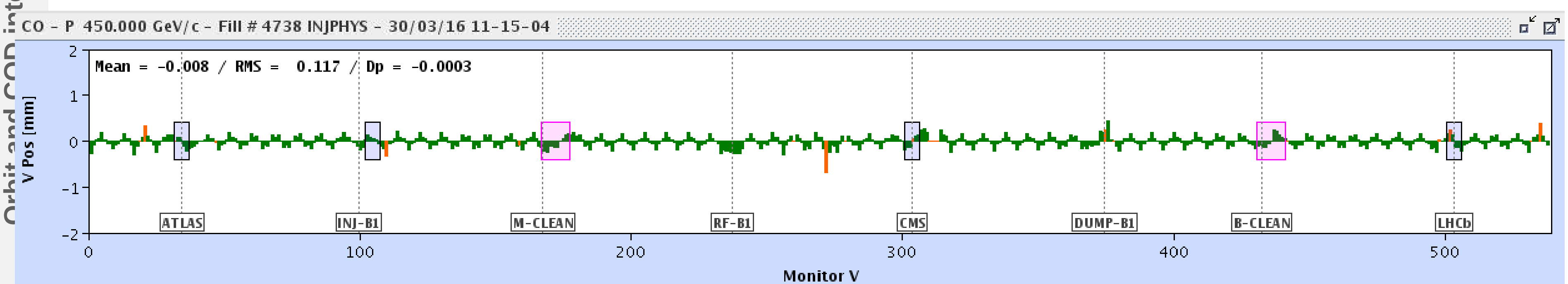


SUE Test 2

- Orbit in steady conditions for test 2 (difference wrt initial).
  - *Excursion below 1 mm – expected due to the larger number eigenvalues (more accurate). Note that it could leak into collimation / IRs !*



- Worst orbit (largest rms).
  - *Excursion of ~ 0.3 mm around the ring, not the largest <u>local</u> excursion !*



This could actually be OK, and could be 'finished' off some time later (min…hour) by a manual correction (OP).

Summary

- A large subset of SIS interlocks is related to orbit interlocks.
- In stable beams the interlock limits correspond to ~1-2σ – depending on the failure scenario.
  - There is some margin to tighten if desired.
- The collimator BPM interlocks are ready to go when we feel confident that the data is of good quality and reliable.
- We have no specific interlocks for roman pots, there is room for significant > 2σ local excursions.
  - Just some vocal warnings exist (not checked in 2016, not for AFP).
- Most SIS COD interlocks will soon be replaced by the PC interlock server.
  - The quadrupole interlocks seems to be in good shape.
- To survive 60A failures, we will have to change the interlock logic (60A), very likely accept larger transients on the orbit (also at BPM collimators). But there is some hope if the rate becomes 'intolerable'.