LHC Commissioning Working Group:

Classification and Detection of LHC BPM errors and faults

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with input from:
R. Jones, S. Redaelli, J. Wenninger and others

Outline

- Formal definition of “Bad” BPM: 'errors' and 'faults'/'failures'
- Examples for common failure modes and measurement errors
- Test procedures to identify faulty or erroneous BPMs
  - pre-checks without beam before every run
  - pre-checks with Pilot beam at the start of every run
  - continuous monitoring during LHC Orbit Feedback operation

Some Definition

A more formal definition of “Bad”: Distinguish between beam position monitor...

- *Error*: inconsistency between measured and true beam position
  - minimised by calibration or re-alignment
  - can lead to a a 'Fault' if exceeds pre-defined limits

- *Fault* or *Failure*:
  - an error exceeding specified limits or
  - the unavailability of the measurement

N.B.

'*accuracy*' := maximum measurement error ≠ *resolution*

'*resolution*' := minimum measurable position change

Sub-Classification of BPM error

- In a linear model, errors can be further decomposed into an 'offset and 'calibration factor':

$$x_{meas} = x_{offset} + a_{cal} \cdot x_{true}$$

  – (some) errors affect either offset or slope only

  – absolute offset often not required (provided it is constant):

    → e.g. beam-based alignment of LHC Collimation

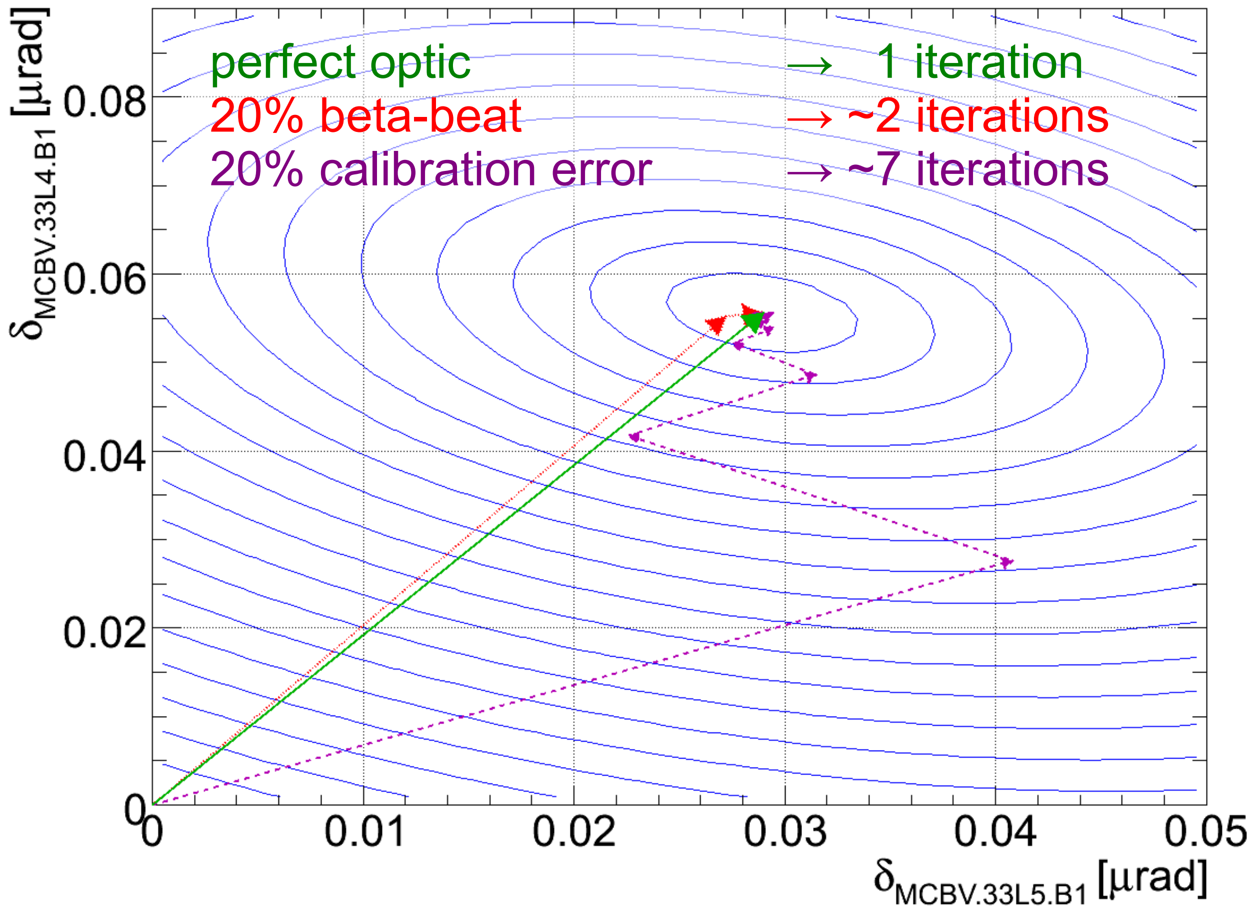
    → e.g. orbit response or equivalent lattice response measurements

  – systematic calibration factor is minimised by beam-based steering

    • LHC OFB Example: Assuming 20% beta-beat or 20% BPM calibration error, FB reaches after 7 iterations the same convergence as after one iteration for a 1% beta-beat/BPM calibration error.

Beam Response Matrix Uncertainties

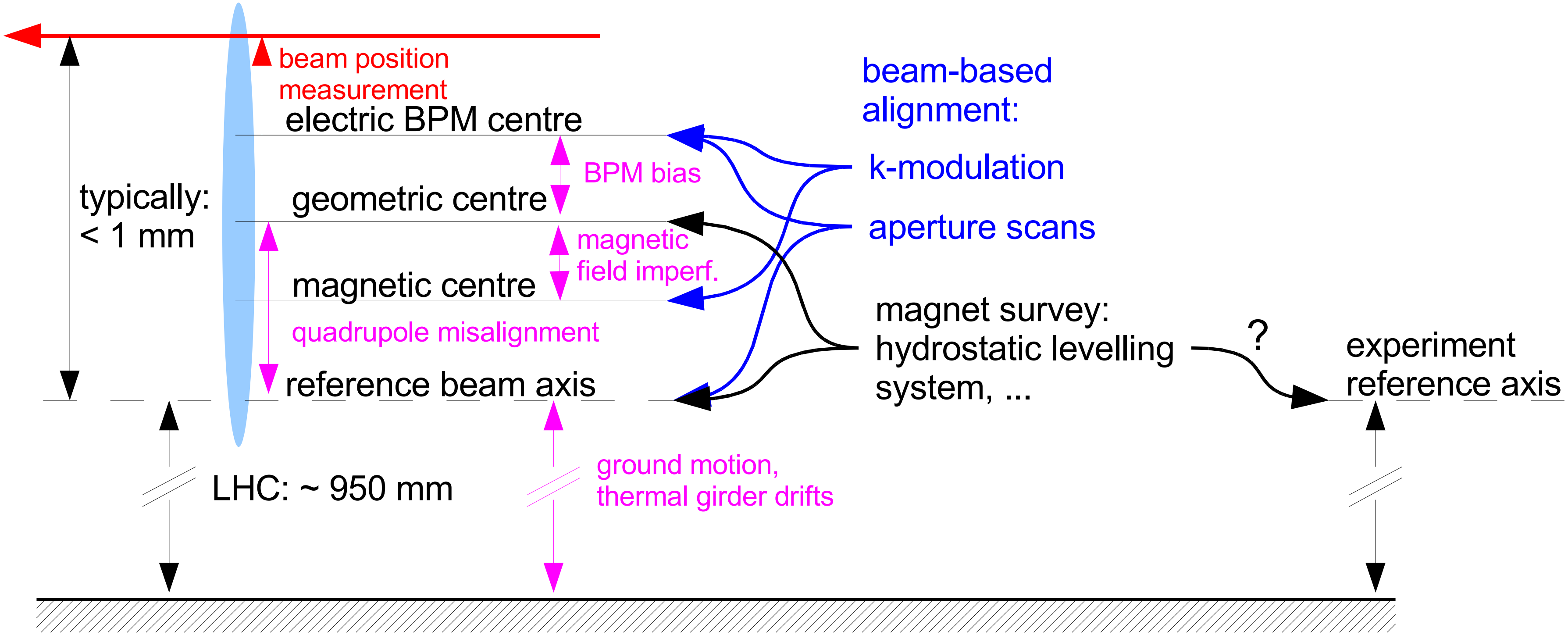
- Uncertainties in the beam response matrix reduced the effective control/feedback bandwidth but does not affect the steady-state precision
- E.g. LHC orbit feedback:



LHC Commissioning Working Group, Ralph.Steinhagen@CERN.ch, 2007-10-23

Known Error Sources: BPM Offset and Alignment I/II

- BPM stability analysis depends on the choice of reference system:
  - magnetic quadrupole centre (minimising feed-down effects)
  - geometric centre of beam screen (maintaining aperture constraints)
  - external reference
- Several reference system definitions possible:
  - LHC's choice: Safety first → beam screen centre as reference



not to scale!

Known Error Sources: BPM Offset and Alignment II/II

- Beam Position Measurement:
  - electrical BPM bias: 100 µm r.m.s.
  - electrical BPM centre w.r.t. geometric BPM centre: 200 µm r.m.s.
  - mech. BPM centre w.r.t. beam screen centre: < “200 µm r.m.s.”
    - after aperture scan: ~ 130 µm
  - electrical BPM centre w.r.t. magnetic quad. centre: 200 µm r.m.s.
    - after k-modulation: < 50 (5?) µm

      (mostly limited to insertion regions)

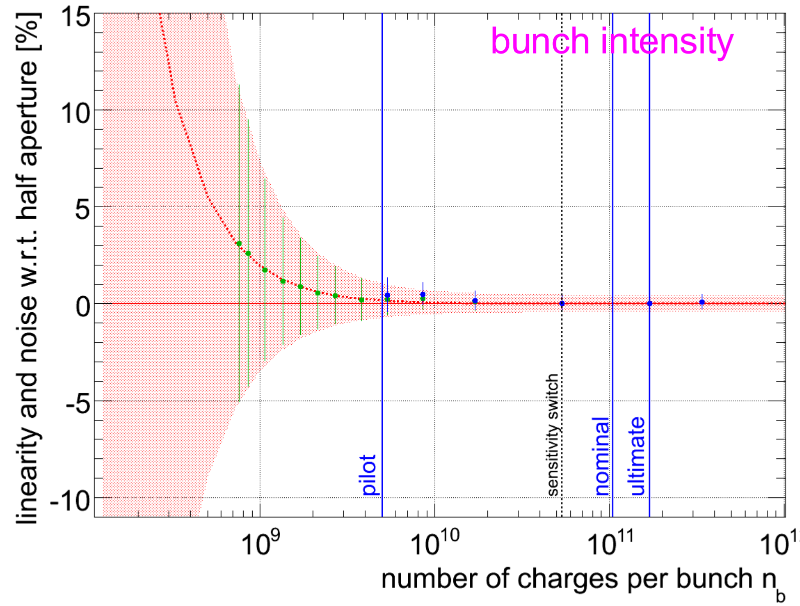
- Survey group targets for magnet alignment:
  - 0.2 mm r.m.s. globally , 0.1 mm r.m.s. as an average over 10 cells
  - N.B. Orbit FB: working assumption: 0.5 mm r.m.s.
  - Watch out: CLIC-Note-422, CERN-THESIS-2001-010
    → final focus stability might be determined by systematic drifts

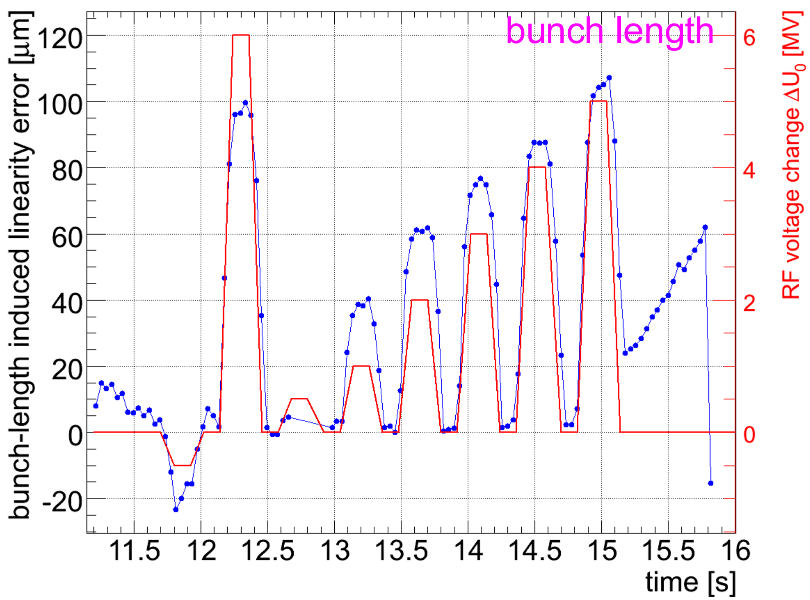
Known Error Sources: BPM dependence on

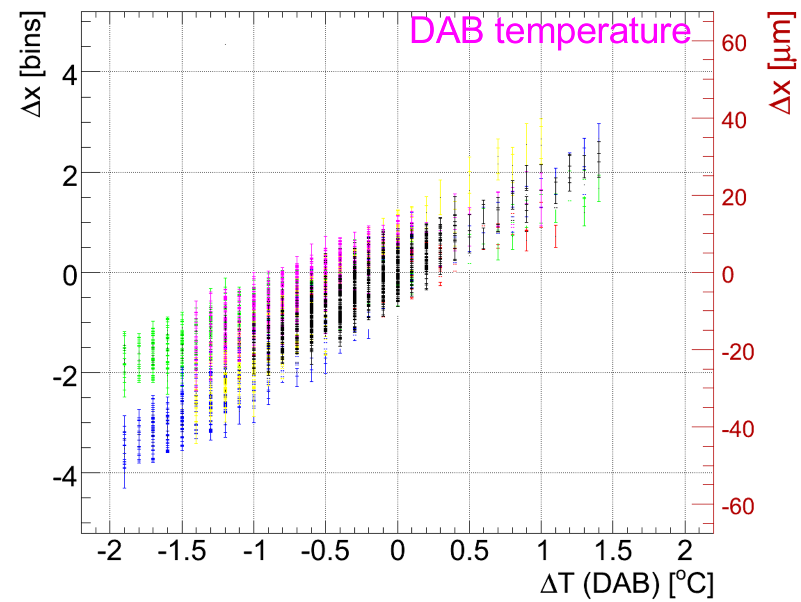
- bunch length σ_b, intensity n_b (σ_f: filter time constant) and integrator temperature changes ΔT, filling pattern, ...:

$$\Delta x_{error} \sim \frac{\sigma_{eff}^3}{n_b^{1.5}} + \approx 15-20\frac{\mu m}{^oC}\cdot \Delta T$$

$$with \quad \sigma_{eff} \approx \sqrt{(\sigma_b^2 + \sigma_f^2)}$$







Some Failure Sources:

- From the point of view that the BPM should measure position...
- The measurement may fail if:
  - open connections, short circuits, broken optical fibre, etc.
    - observable: no beam position related change or reading
  - the Wide-Band-Time-Normaliser card is in 'CALIBRATON' mode
    - observable: no true beam position related change or reading
  - BPM 'POSITION/INTENSITY' switch to 'INTENSITY'
    - observable: no beam position related change or reading
  - BPM is set to 'HIGH-SENSITIVITY' ($n_b < 5 \cdot 10^{10}$) though bunch intensity $n_b \gg 5 \cdot 10^{10}$ (→ 'LOW-SENSITIVITY') and vice versa
    - BPM will trigger on bunch reflection and ghosts, observable: spikes
  - Sensitivity switch not triggered by/synchronised with the orbit feedback
    - observable: steps

...plus lots of other sources which usually cause the absence of orbit acquisitions.

- Three main lines of defence against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
     - eliminates open/closed circuits, dead circuits/element candidates
  2. Pre-checks with Pilot and Intermediate beams
     - verifies calibration offset (guarantee) and slope (golden orbit)
     - verifies/guarantees proper function of machine protection
  3. Continuous data quality monitoring through Orbit Feedback
     - detects spikes, steps and BPMs that are under verge of failing

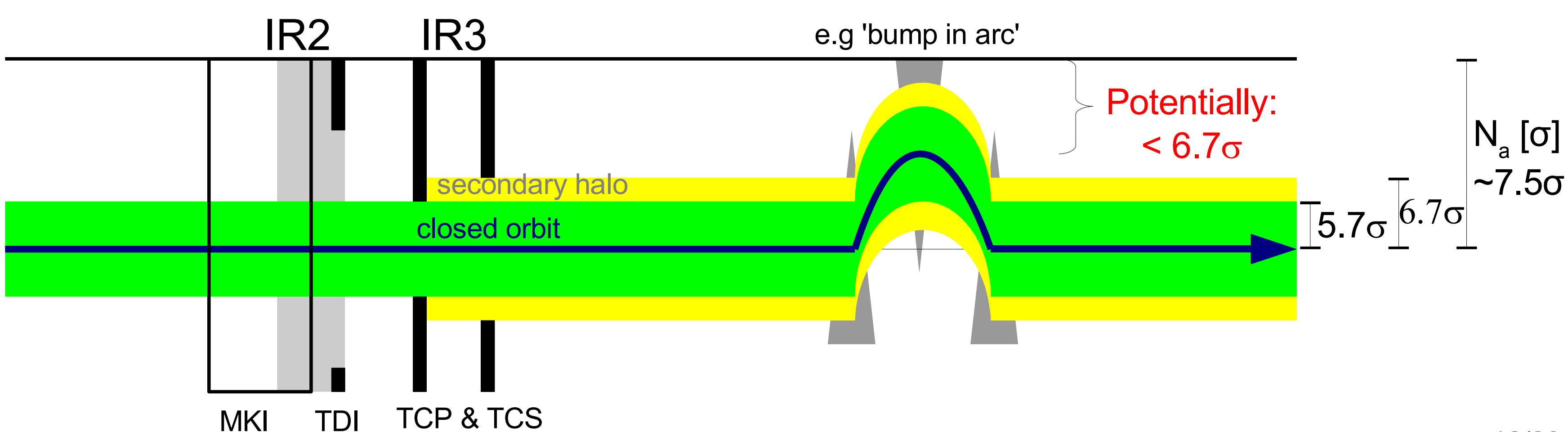
- (k-modulation can for a few (insertion) BPMs provide some additional limited cross-checks for BPM misalignments w.r.t. magnetic quadrupole limits. However: no hard limits!)

1.Pre-checks without beam using the in-built calibration unit

Prior each run:

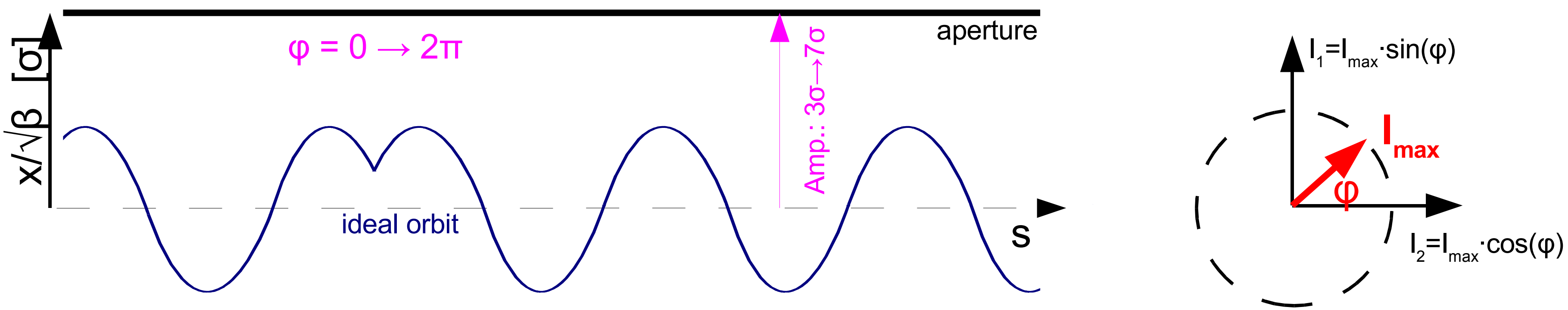
- Each LHC WBTN can be put into an in-situ calibration mode
  - verifies active links/unbroken cabling
  - verifies that WBTN and rest of the acquisition chain is alive
  - verifies/removes drifts of electronic components
- However: With beam, from the beam position measurement point of view, calibration or intensity mode are equivalent to a BPM failure:
  - will/should be monitored through
    - LHC Sequencer/Software Interlock System
    - BPM turn-by-turn data concentrator and/or
    - LHC Orbit Feedback Controller/Service Unit
      - small additional status flag in orbit data
      - ceasing of feedback operation till: ('calibration mode' v 'intensity mode') == false

- Two simple functional tests to check whether BPMs are working.
  Idea: "Every non-moving position reading indicates a dead BPM".
  1. free betatron oscillation with rotating phase
     - non-moving BPM readings → faulty BPM
     - tests calibration factor and/or optics
  2. aperture scan to checks abs. BPM offsets and insures proper machine protection functionality: → Bumps may compromise collimation function[1]
     - To guarantee (two stage) cleaning efficiency/machine protection:
       - TCP (TCS) defines the global primary (secondary) aperture
     - Orbit is not a "play-parameter" for operation, except at low intensity.
       (*'Playing' with the orbit will result in quasi-immediate quench at high intensity.)*



[1] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

- Scan using two COD magnets (currents: I_1 & I_2) with π/2 phase advance:



- Scan (assuming global aperture of ~ 7.5σ):
  - φ = 0→2π requires ~25 seconds @7σ, per transverse angle
  - propose to measure at four transverse angles: 0°, 45°, 90°, 125°
- Increase amplitude (COD currents) till orbit shift ≈ 6.7σ
- Loss does not exceed predefined BLM threshold if COD settings@ 6.7σ:
  - Yes: → mechanical aperture ≥ 6.7 s → orbit is safe
  - No: → mechanical aperture ≤ 6.7 s → orbit is un-safe
- additional feature: compare measured with reference BPM step response (x_{co}= 0-3σ)

  → rough optics check (phase advance and beta-functions)

2.Pre-checks with Pilot and Intermediate beams IIII/III

- After some preliminary discussions with collimation (S. Redaelli):
- Propose to perform two procedural steps for each fill

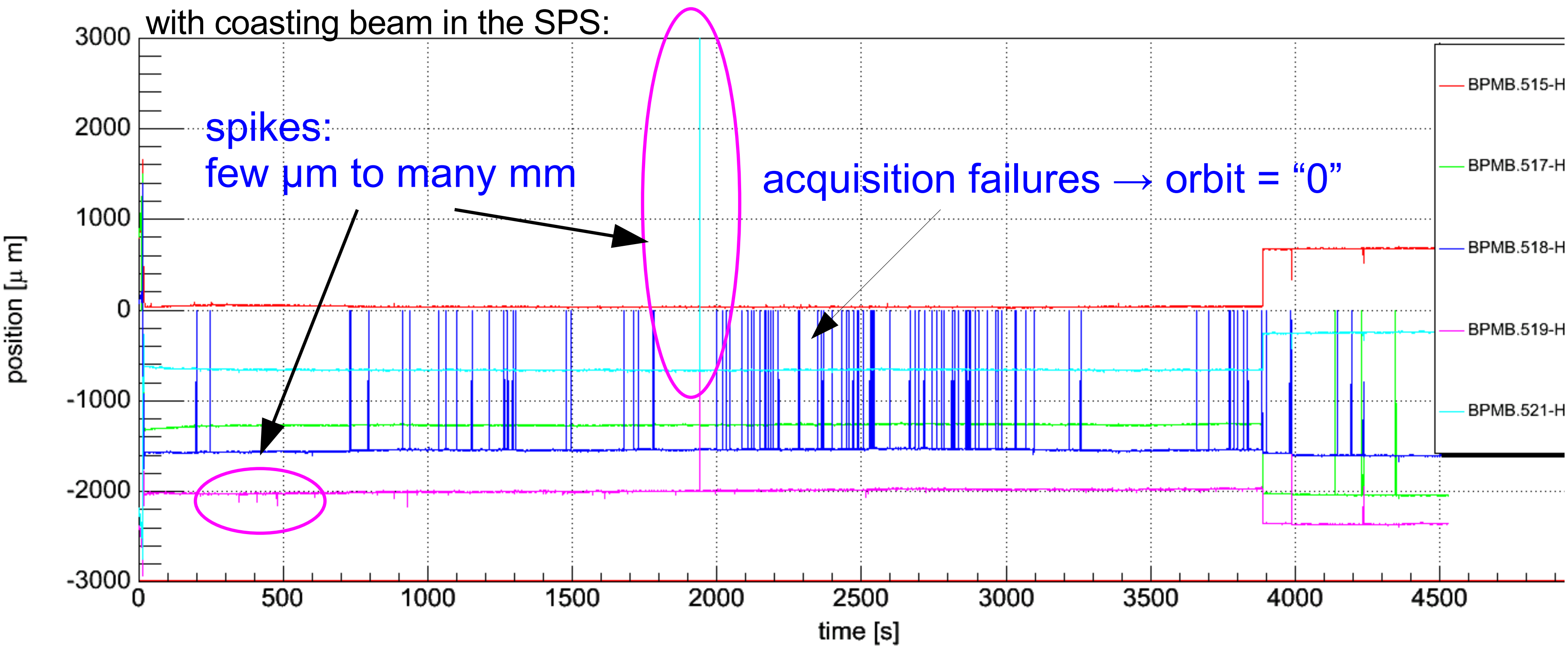
(assume: 'empty LHC' → 'Pilot' → 'Intermediate Beam' → filling of nominal beam → ...)

1. After first Pilot injection: scan aperture <u>with retracted collimators</u> till either the assumed mechanical aperture is reached or beam loss is triggered
   - eliminates “dead” BPMs for 'HIGH-SENSITIVITY' setting
     - also: identifies BPMs that are in calibration/wrong gain mode
   - gives an estimate of the BPM offsets <u>and</u> tests the safe aperture model with and accuracy of better than one r.m.s beam width.
   - further: verifies that either injection optics (orbit response) is within tolerances or that the BPM calibration is correct
2. After injection of intermediate beam: <u>collimators in nominal positions</u> w.r.t. above measured global aperture and scan till a pre-defined beam loss (pattern) is reached
   - eliminates “dead” BPMs for 'LOW-SENSITIVITY' setting
   - verifies that primary collimators/absorbers are set correctly
     → Partial assuarance that we setup the system properly....

LHC BPM Prototype in the SPS:

- Most common failure symptoms: no orbit info available, spikes and steps
  - Short term (few ms-s): Zero Order Holder (ZOH)
  - Long term: Disable BPM in feedback and recalculate SVD pseudo-inverse matrix
- Only a few drifts observed: systematic on bunch length & bunch intensity

LHC BPM test in 2004
with coasting beam in the SPS:



1. BPM phase advance of ~π/4:
   - Twice the sampling than minimum required to detect β-oscillation
   - Distribution of consecutive BPMs on different front-ends (minimise impact of front-end drop outs)

2. Detection of erroneous BPM failures

   ($x_i(n)$=position at i^th monitor, n: sampling index; σ_{orbit}= residual orbit r.m.s.)

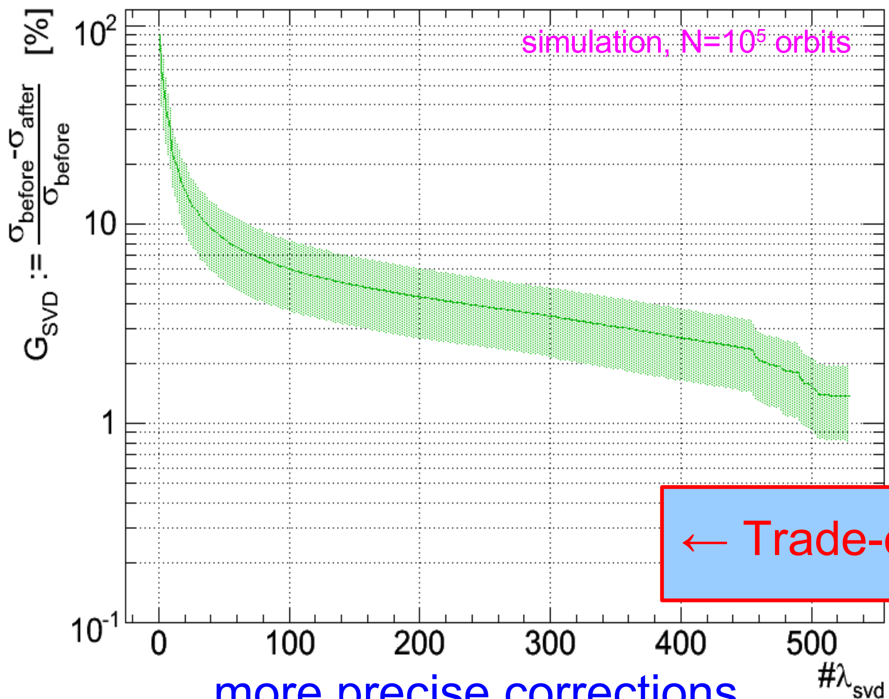
   - Reject BPM if the following applies:
     - Cuts in Space Domain:
       - (BPMs marked by the front-end itself)
       - $x_i(n)$ > machine aperture
       - $x_i(n) - x_{i,ref} > 3 \cdot \sigma_{orbit}$
       - Option: interpolate position from neighbouring BPMs (as done in APS)
     - Cuts in Time Domain (Spike/Step detection!):
       - $\Delta x_i(n)=x_i(n)-x_i(n-1) > 3 \cdot \Delta x_{rms}(n \rightarrow n-m)$ (dynamic r.m.s. of last 'm' samples)
       - filters to reduce noise (e.g. low integrator gain)
       - re-enable BPMs with new reference if dynamic r.m.s. is stable for n seconds
       - ...
   - Difficult to detect coherent, very slow or systematic drifts

     (e.g drift of BPM electronics vs. systematic ground motion, temperature drifts ... etc.)

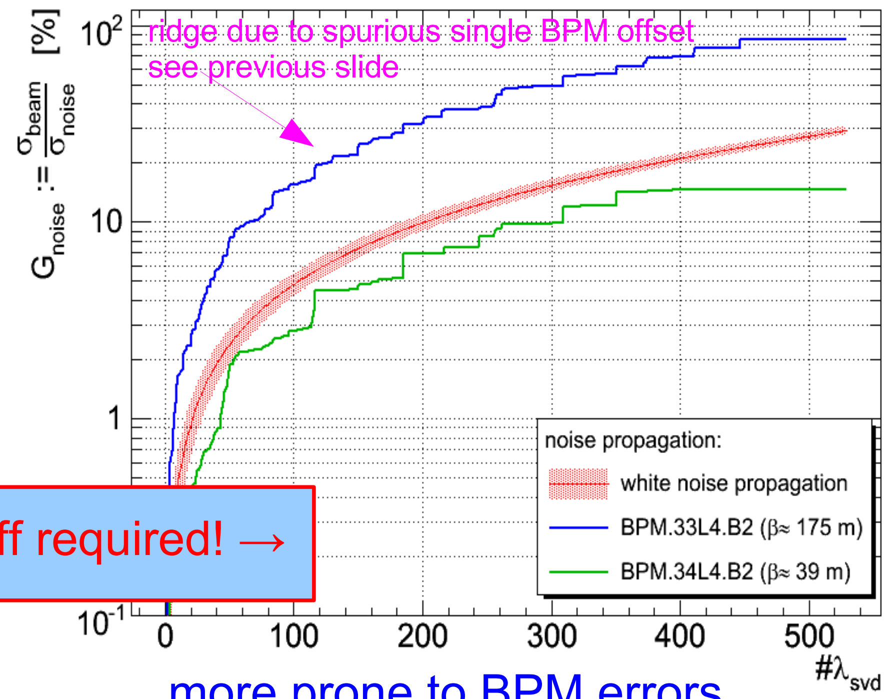
3. Use SVD based correction → less sensitive to BPM errors

3.Continuous BPM data quality checks through LHC OFB Feedback Sensitivity to BPM Failure

- Propagation of single (arc) BPM failure with $x_i(n) < 3\cdot\sigma_{orbit} < \sigma_{beam}$
  - #λ≈250: < 40% (β ≈ 175m) resp. < 10% (β ≈ 39 m)
- Propagation of random (white) noise on all BPMs
  - 30% (worst case #λ=529) resp. 10% (OFB operation with #λ≈250)
- BPM induced noise on orbit (single bunch):
  - Single BPM failure: < 0.01 - 0.4 σ
  - White BPM noise: < 0.001 σ (inj) resp. 0.02 σ (coll)



more precise corrections →

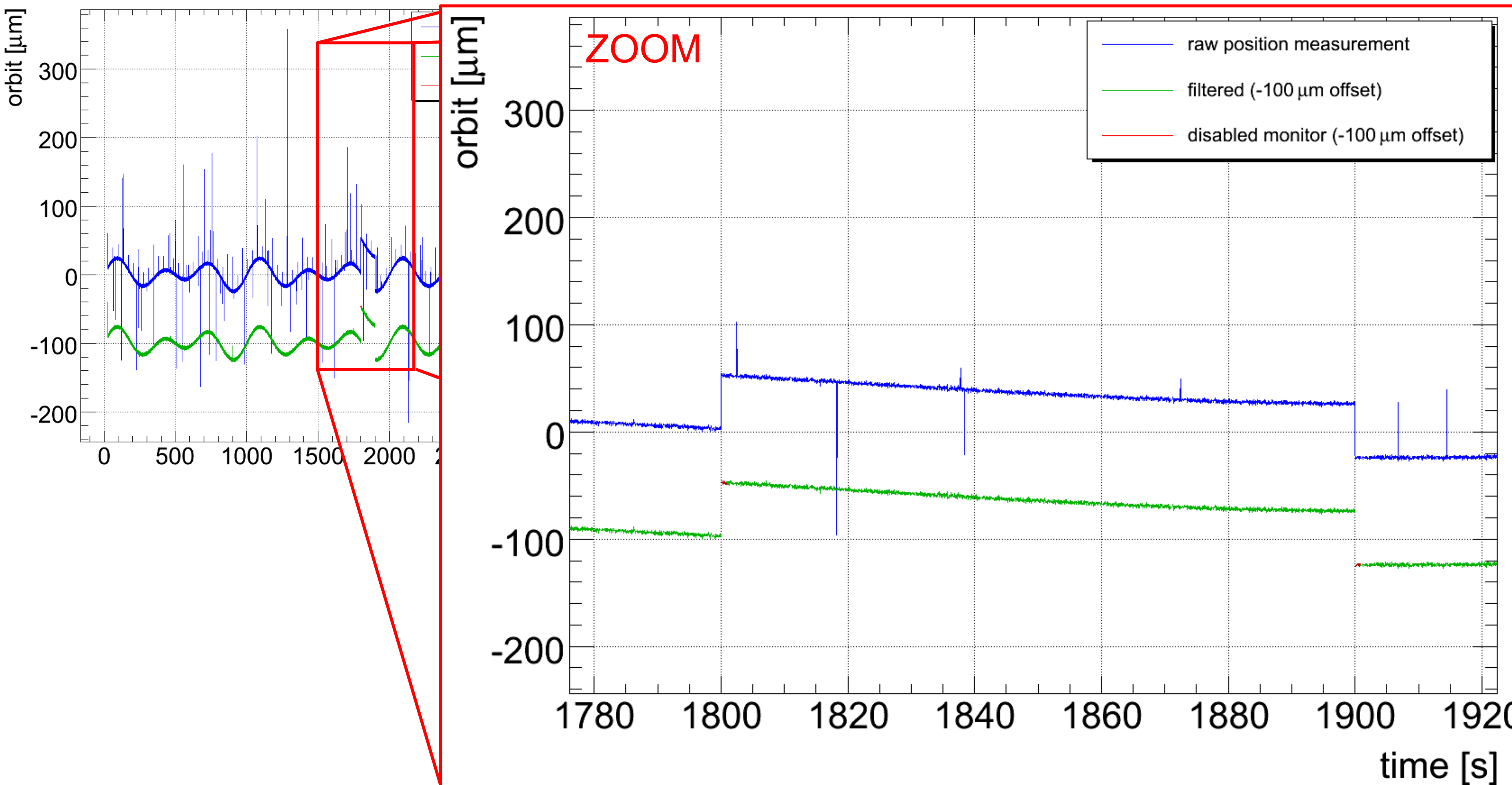


← Trade-off required! →

more prone to BPM errors →

3.Continuous BPM data quality checks through LHC OFB - some implementation examples

- Orbit feedback procedure in case of a
  - spike: fail-safe choice of assuming that orbit is at reference position
  - step: pause feedback, average orbit before and after detected step (used for a-posteriori calibration) and continue from new averaged orbit



Summary of BPM Error and Failures

- Presently, the following errors/failures/states are identified, classified and distributed through OFB Controller/Service Unit (BPM concentrator)

BPM front-end:

- kFRONTEND_NOT_AVAILABLE
- kFRONTEND_SINGLE_ACQ_FAILURE
- kFRONTEND_TOO_HIGH_ERROR_RATE
- kFRONTEND_INTENSITY_MODE_SET
- kFRONTEND_CALIBRATION_MODE_SET
- kFRONTEND_HIGH_INTENSITY_MODE
- kFRONTEND_DAB_TEMPERATURE_ABOVE
- kFRONTEND_DAB_TEMPERATURE_BELOW
- kFRONTEND_DESELECTED_BY_EXPERT

OFB Controller/SU & Operator/GUI

- kOFC_PACKET_NOT_ARRIVED
- kOFC_PACKET_ARRIVED_LATE
- kOFC_DETECTED_SPIKE
- kOFC_DETECTED_STEP
- kOFC_TOO_HIGH_ERROR_RATE
- kOSU_PACKET_NOT_ARRIVED
- kOSU_PACKET_ARRIVED_LATE
- kOSU_DETECTED_SPIKE
- kOSU_DETECTED_STEP
- kOSU_TOO_HIGH_ERROR_RATE
- kFBEXPERT_FAULTY
- kFBEXPERT_TEMPORARILY_DESELECTED
- kOPERATOR_FAULTY
- kOPERATOR_TEMPORARILY_DESELECTED

Conclusions

- Many BPM error and failure sources are understood and anticipated in the orbit steering and feedback procedures
  - Provided they are randomly distributed (and not at critical locations such as collimation, injection/extraction...):
    - OFB can cope with up to20% of erroneous/faulty BPMs

- Three main lines of defence against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
  2. Pre-checks with Pilot and Intermediate beams (aperture scans)
  3. Continuous data quality monitoring through Orbit Feedback

- Something to be kept in mind: To verify and re-check deselected BPMs in order to not end up with "zero" as working tagged BPMs

- More details on BPM error, failures and FB function can be found in:
  "LHC Beam Stability and Feedback Control - Orbit and Energy", CERN-AB-2007-049

additional slides

How to determine the actual aperture?

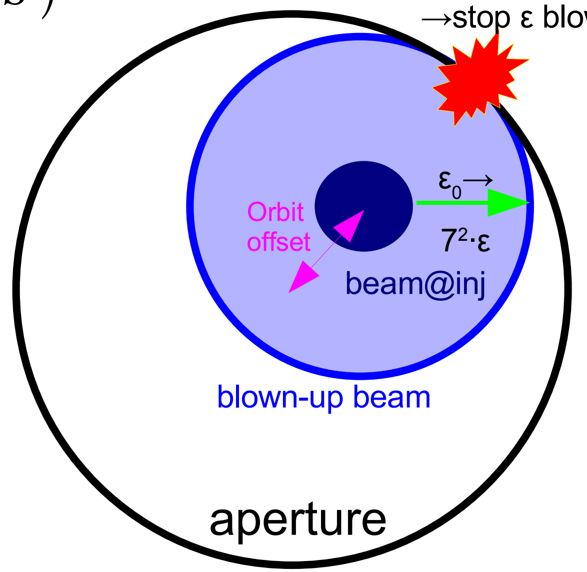
or:

How do we now that we established a good/safe orbit?

Aperture measurement proposals:

Two methods to test whether the closed orbit is within 6.7σ of the available mechanical or dynamic aperture:

- Scan using emittance blow-up: $\sigma(s) = \sqrt{\varepsilon \beta(s)}$
  - Increase beam size in a controlled way while measuring the beam size.
    (e.g. using transverse damper and wire scanner)
  - Once particle loss above given threshold:
    → store last beam size measurement
  - "Is beam size ≥ 6.7 σ_0 ?" (σ_0: beam size at injection)
    - Yes: → mechanical aperture ≥ 6.7 σ → orbit is safe
    - No: → mechanical aperture ≤ 6.7 σ → orbit is un-safe
      - rework orbit reference (compare with old reference....)



Beam Position Monitors:

- Procedure:

A: Initial check whether Orbit is safe:

- aperture scan (ε blow-up, betatron-oscillation)
  - Potential bump scans to determine location of aperture
- save "safe BPM reference" current settings → x_{ref} = "SAFE SETTING"

B: Check: if ($|x_{meas.} - x_{ref}| < \Delta x_{tol}$) {...}

- FALSE: potential orbit bump detected → no (back to A)
- TRUE: Orbit is safe → yes (back to B)

– Pro's:
- Easy to check with circulating beam
- Less dependent on machine optics
- Sensitive to most orbit manipulations

– Con's:
- erroneous BPMs → but: gives indication which BPMs are not working.
- No information before injection
- Bunch intensity systematics (gain settings) and change of BPM calibration

LHC BPM Specification

- LHC-BPM-ES-0004 rev. 2.0, EDMS #327557, 2002, p. 25:

	Measurement	P	Range	Accuracy	Scale error	Offset	Non-linearity	Resolution
				peak	*peak*	*peak*	*peak*	*rms*
Beam threading	TR2	*	R2	±2000µm	+	+	+	+
Close trajectory on itself	TR3	*	R1	±500µm	+	NR	+	+
Position error at injection	TR4	*	R1	±500µm	+	NR	+	+
			R1	±50µm	+	NR	+	+
Momentum mismatch detection at injection	TR5	*	R1	±1500µm	+	NR	+	+
			R1	±250µm	+	NR	+	+
Optics and local Q' checks	TR7/TR8	*	± 1 mm ⊂ R1	±400µm	+	NR	+	+
				±50µm	±4%	NR	+	+
	TR11		R2		NR	NR	±500µm	50µm
Aperture optimisations	CO2	*	R1	±500µm	+	±250µm (±750µm)	+	+
LHC Collimation/Orbit FB	CO3		± 1 mm ⊂ R1	±20µm	NR	NR	NR	+
Orbit at injection elements	CO4		± 1 mm ⊂ R1	±30µm	+	+**	+	+
Position error at injection	CO7		R1			±100µm	±200µm over ±4mm	1000µm
Momentum FB (radial loop)	CO8		R1	±250µm	+	NR	+	+
Dispersion measurements	CO9 IP		± .1 mm ⊂ R1	±15µm	+	NR	+	+
	CO9 other		± 1 mm ⊂ R1	±175µm	+	NR	+	+
b2/a2 to b4/a4 (~TOTEM)	CO14		± .1 mm ⊂ R1	±10µm	+	NR	+	5µm