Can the LHC Orbit Feedback save the Beam in case of a COD failure?

Ralph J. Steinhagen

Thanks a lot for input:
F. Bodry, L. Ceccone, R. Denz,
M. Karppinen, F. Rodriguez Mateos, D. Nisbet,
V. Montabonnet, J. Wenninger, M. Zerlauth,
...

Outline

MCB correction magnet circuits

(special insertion CODs not in the scope of this talk)

- General parameters
- Failure scenarios
  - I. Quenching magnet
  - II. Power converter failures

Orbit Feedback

- Orbit Correction Scheme
- Feedback Controls Layout
- Failsafe & retaliatory action schemes

Main MCB Circuit Parameter

Total 1060 orbit corrector dipole (COD) magnets in the LHC.
Focus on 752 MCBH(V) magnets since they have the same design, parameter and powering: (other: insertion CODs (triplets..), warm, different powering ...)

- Part of arc SSS: half-cells 11R'*x*' ≤ location$_{MCB}$ ≤ half-cell 11L'*x+1*'
- Individually powered by a ±8V, ±60A converter, rate limit: 0.5 A/s

- inductance L:
  - specified as 7 H
    (see LHC-MSCB-C1-0001, EDMS No. 104193)
  - In EDMS 6.02 H
  - measured: 5.92 H @ 1kHz resp. 5.48 H @ 120 Hz
    (LHC-MSCB-FR-0001, courtesy Mikko Karpinnen)

- resistance R: 64.5 ... 91.3 mΩ
  (including intrinsic magnet, cable and current lead resistance)

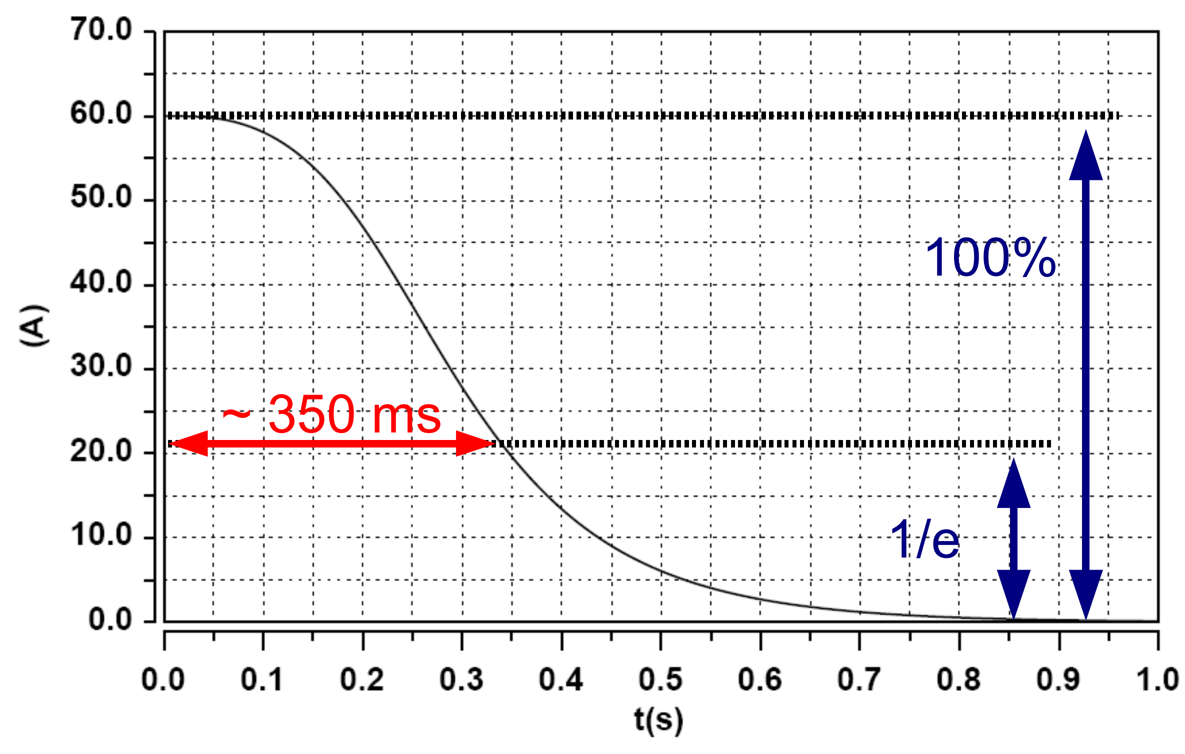
- Maximum kick δ_{max} (↔55 A) on beam: 1260 μrad @ 450 GeV
  81 μrad @ 7 TeV

- Maximum kick amplitude : 144 mm @ 450 GeV and 9 mm @ 7 TeV)

MCB Optics Parameter

- Arc lattice is similar for injection and collision optics. Maximum orbit response in arc (β = 170 m)
  - $\Delta x_{BPM} \approx$ 100 µm/µrad · δ_{COD}
  - resulting orbit change: ~ 1.2 mm/0.5 A @ 450 GeV
    ~ 75 µm /0.5 A @ 7 TeV
- expected average/max kick: 8/30 µrad
  (compensation of random 0.4 mm r.m.s. quadrupole misalignment)
  - Corresponding current in COD circuit:
    - ~ 0.4 / 1.3 A @ 450 Gev
    - ~ 5.5 / 20 A @ 7 TeV
- one COD failure corresponds to an average/max orbit change of (β = 170 m)
  ~ 0.9 / 2.9 mm per COD failure
  - breaks collimation tolerances by order of magnitude!

Case I: quenching MCBH/V, current decay



data courtesy to Felix Rodriguez Mateos

very fast current decay:

- decay time: $\tau \sim 0.35$ s ↔ $\Delta I/\Delta t \sim 16$ (58) A/s @ 7 TeV
- after 1 s the current is practically 0 A
- MCB quenches are expected to be rare

Case II: 60A/8V Power Converter MTBF

- There are 19 documented and in db logged causes for PC failure
- Mean-Time-Between-Failures (MTBF) expected to be ≈ 10^5 hours

$$P_{failure}/h = 10^{-5}\frac{failures}{hour} \Leftrightarrow \overline{P}_{failure}/h = 1 - 10^{-5}\frac{\overline{failures}}{hour}$$

  - Probability that one of the 752 MCB PC fails during a 10 hour run:

$$P_{failure/10\,h} = 1 - \left(\left(\overline{P}_{failure}\right)^{752}\right)^{10} \approx 7\ percent$$

  - One may expect one PC/COD failure in 14 cycles
    (including all CODs: one failure every ~ 10 cycles)
  - This may lead to an beam dump request due to:
    - increased particle losses e.g. at the collimator.
    - beam position interlock.
  - Online compensation is favourable in order to increase the beam availability but not required for protection!

However: actual operational experience may show higher MTBF

Case II: "Initial" assumptions about PC failures

- Initial assumption about Power Converter failures:
  - voltage drops to zero
  - COD circuit "slowly" discharges
  - decay time constant given through: $\tau = L/R$
    - Initial inductance: 7 H
    - total circuit resistance (cable and current lead): ~ 50 mΩ

    –> $\tau \sim 140$ s

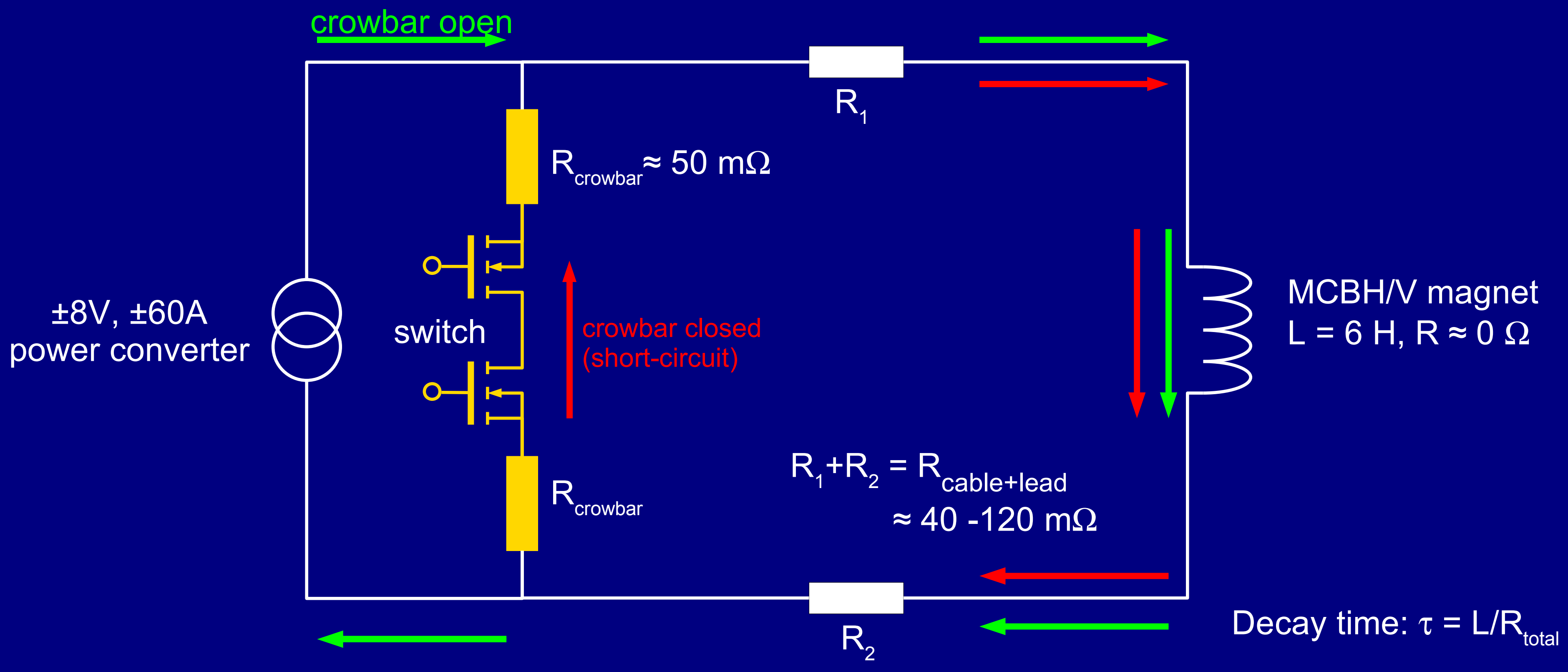
- Actual implementation shows however:
  - decay time
    - Initial inductance: 5.5 H
    - total circuit resistance (same as above + crowbar): ~ 190 mΩ

    –> $\tau \sim 30$ s (factor five change)

Thanks a lot to AB/PO and AT for the clarification!

Case II: Crowbar design and Decay Time Constant

In case of a failure, the power converter circuit is shorted in order to prevent spikes and the circuit slowly discharged through a crowbar:



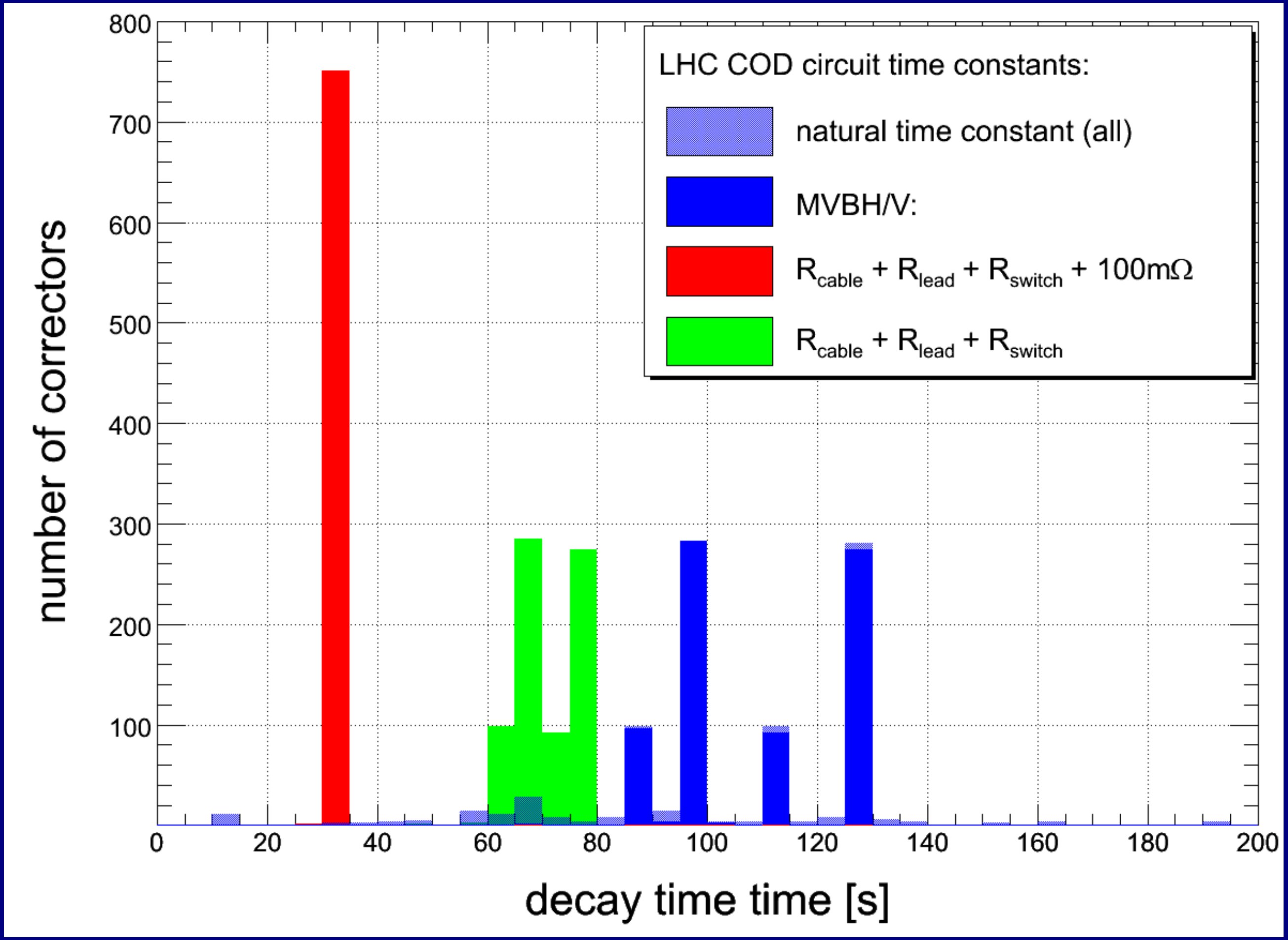
Decay time: $\tau = L/R_{total}$

-> natural decay time:

- with initial crowbar design ($2 \cdot R_{crowbar}$): τ = 30-35 s
- crowbar without additional $R_{crowbar}$: τ = 60-80 s

Failing power converter – decay time distribution

A more detailed view on the decay time distributions of all COD magnets:



data courtesy to Markus Zerlauth

- most CODS are MCBH/V (752 of 1060 total, 997 registered in the cabling database)

Additional Crowbar Resistance

- 100 mΩ removal relaxes requirements on possible fast automated compensation and make even manual interventions (operator) possible should the occasion arise.

- $R_{crowbar}$ not required for:
  - operation
  - protection of magnet
  - protection of power converter
  - protection of or current lead

-> removal procedures (ECR) under way

- MCBH(V) failure time constant:

$$\tau = 60\text{-}80 \text{ s}$$

PC/COD failure summary

- About every 140 hours one of the 752 PC/MCB may fail.

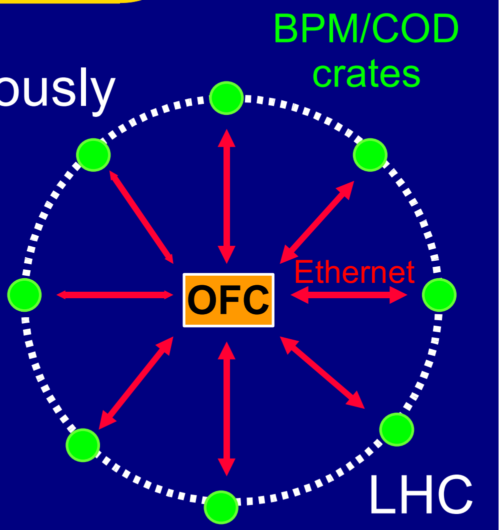
- Average orbit drift due to failure: 0.9 mm (max: 2.9 mm)

- Decay time constants:
  - Quench of MCB: 0.4 s
  - PC failure: 60 - 80 s (after crowbar resistor removal)
  - (normal ramping: ~0.75 s @ 450 GeV resp. ~12 s @ 7 TeV)^

- If uncompensated, a PC/COD failure may result in a beam dump request either due to:
  - increased particle loss e.g. in LHC cleaning insertions,
  - exceeded stability at fast beam position interlock system.

- A compensation of those failures is not required for machine protection but may increase the overall availability of beam in the machine.

LHC orbit feedback system



- Small perturbations around the reference orbit will be continuously compensated using beam-based alignment through a central global orbit feedback system. The system consists of:
  - 1056 beam position monitors
    - BPM spacing: $\Delta\mu_{BPM} \approx 45^\circ$ (oversampling → robustness!)
    - Measure in both planes: > 2112 readings!
  - One Central Orbit Feedback Controller (OFC)
    - Gathers all BPM measurements, computes and sends currents through Ethernet to the PC-Gateways to move beam to its reference position:
      - 🔴 high numerical and network load on controller front-end computer
      - 🟢 a rough machine model is sufficient for steering (insensitive to noise and errors)
      - 🟢 most flexible (especially when the correction scheme has to be changed quickly)
      - 🟢 easier to commission and debug
  - 530 correction dipole magnets/plane (71% are of type MCBH/V)
    - Bandwidth (for small signals): $f_{bw} \approx$ 1-2 Hz (defines total feedback limit)

more than 3000 actively involved elements!

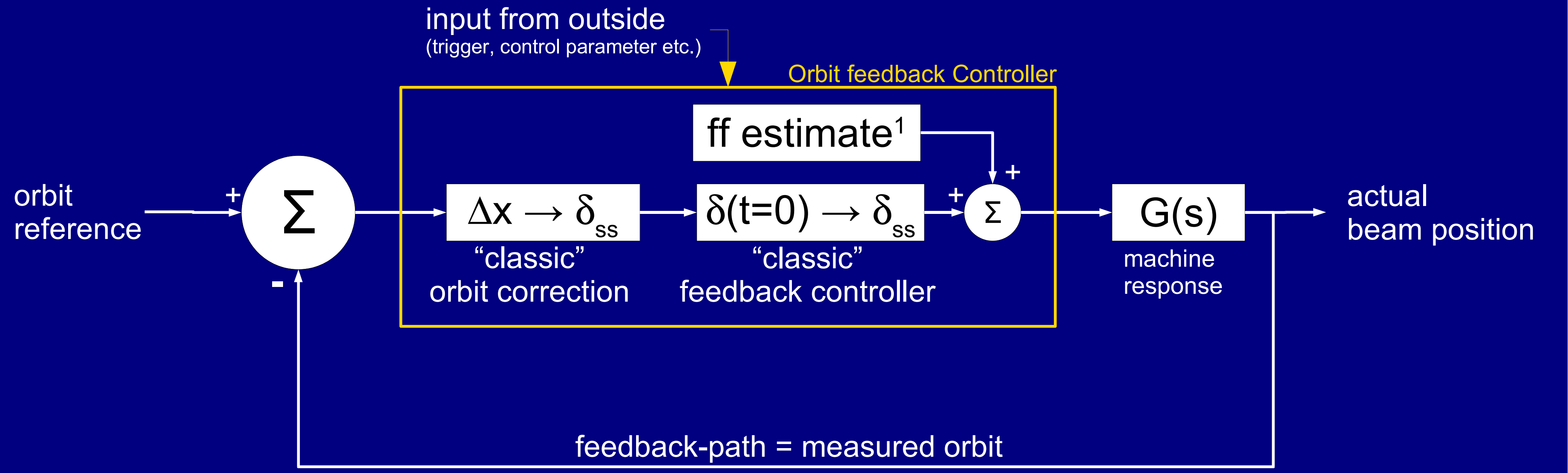
Orbit Feedback/Feed-Forward Control Scheme

The orbit feedback controller consists of three stages:

1. Compute steady-state corrector settings $\vec{\delta}_{ss}=(\delta_1,\ldots,\delta_n)$ based on measured orbit shift $\Delta x=(x_1,\ldots, x_n)$ that will move the beam to its reference position for $t\rightarrow\infty$.
2. Compute a $\vec{\delta}(t)$ that will enhance the transition $\vec{\delta}(t=0)\rightarrow\vec{\delta}_{ss}$
3. Feed-forward: anticipate and add deflections $\vec{\delta}_{ff}$ to compensate changes of well known and properly described[1] sources:

space domain

time domain



input from outside

(trigger, control parameter etc.)

Orbit feedback Controller

ff estimate[1]

orbit reference

$+$

Σ

$-$

$\Delta x \rightarrow \delta_{ss}$

"classic" orbit correction

$\delta(t=0) \rightarrow \delta_{ss}$

"classic" feedback controller

$+$

$+$

Σ

G(s)

machine response

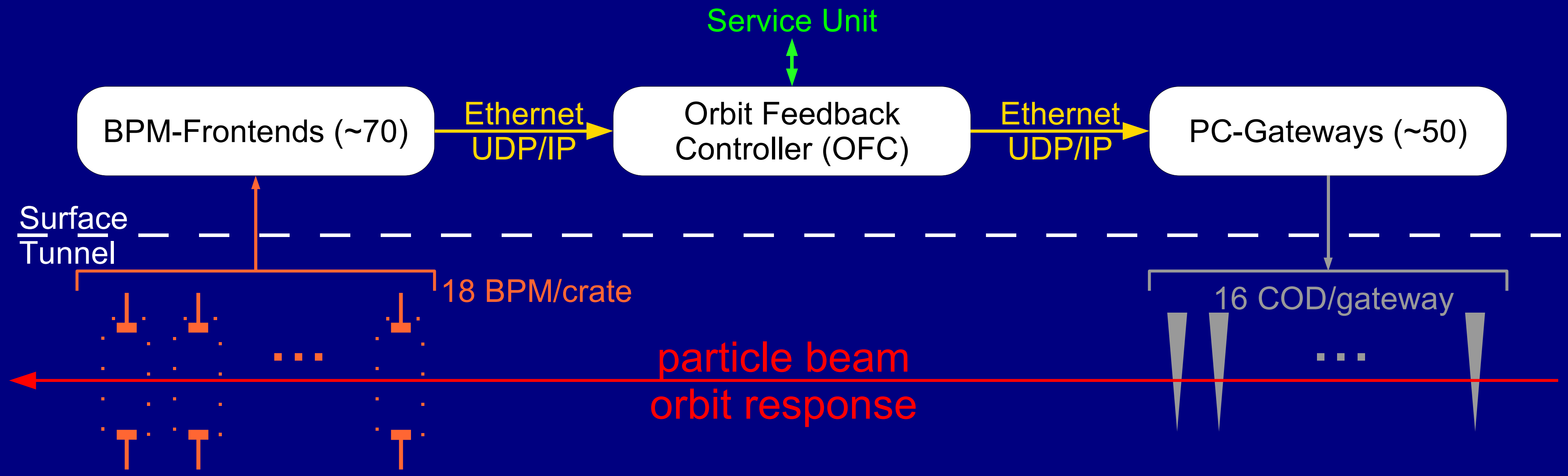
actual beam position

feedback-path = measured orbit

[1] properly described = accurate & fast real-time model of the source

Normal Orbit Feedback Controller (OFC) Operation

1. reception of the BPM data
2. Difference of measured to reference orbit: $\Delta x = (\Delta x_1, \ldots ,\Delta x_m)$
3. Correction in space domain: obtain new steady-state COD deflection $\delta_{ss}=(\delta_1,\ldots,\delta_n)$ through simple matrix multiplication: $\delta_{ss} = R^{-1}\,\Delta x$
   (R^{-1}: SVD inverted orbit response matrix)
4. Conversion of the deflections angles into COD currents
5. Correction in time domain: PID + Smith-Predictor
6. Add feed-forward currents
7. Verify and send the new settings to PC gateways
8. (wait for next external trigger)



Service Unit

BPM-Frontends (~70)

Ethernet UDP/IP

Orbit Feedback Controller (OFC)

Ethernet UDP/IP

PC-Gateways (~50)

Surface

Tunnel

18 BPM/crate

16 COD/gateway

particle beam

orbit response

Anticipated Orbit Feedback Failure Scenarios

- It is nearly guaranteed that one or more of the > 3000 in the feedback involved elements will fail while beam is in the machine.

- Failure scenarios for which retaliatory actions exist:

  - A: Central feedback controller
    - total unavailability → up to now no real hot-spare policy
      (“You'll have to wait till it's rebooted or the controller restarted”)

  - B: BPM failures
    - Case 1: false readings
    - Case 2: partial unavailability
      - spikes, acquisition errors, detected false readings
    - Case 3: total unavailability
      - electronics, power cut, front-end software, lasting 'case 2' failures

  - C: COD failures
    - Case I: quench
    - Case II: power converter failure
    - Case III: power converter gateway failure

Backup Scenario I – Controller Algorithm

- What happens when a BPM or COD becomes temporarily unavailable?

  - If detected: ZOH and on-the-fly recalculation of the SVD matrix:

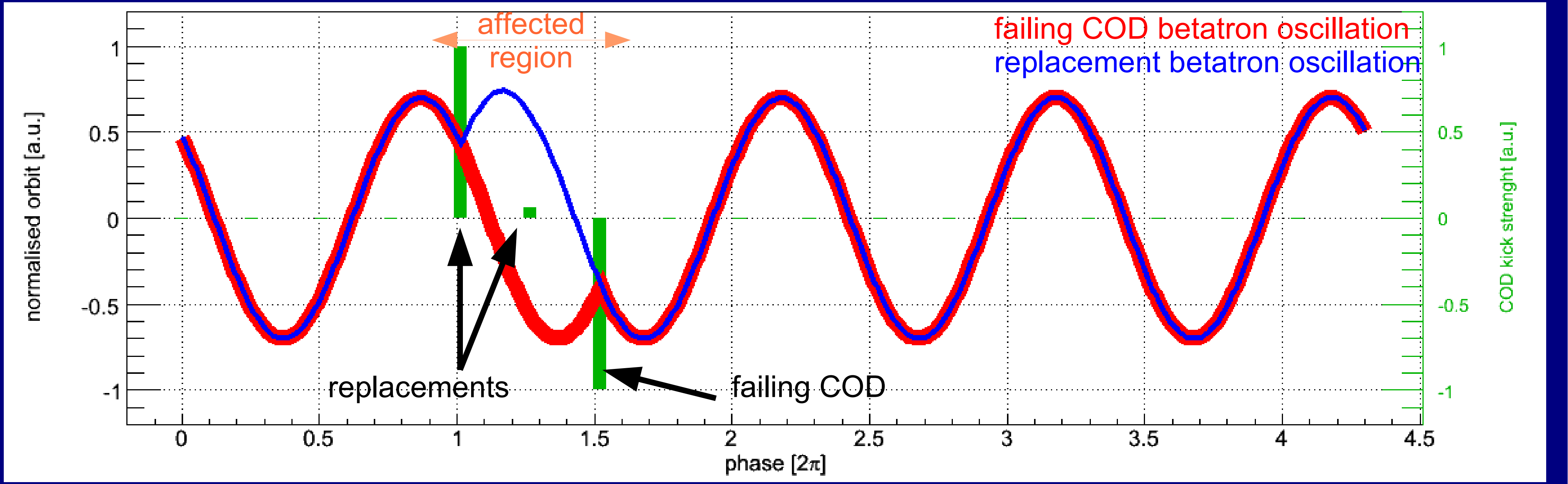
    - Zero-Order-Holder (ZOH) of BPM position and COD current
      - orbit position changes only slightly during most operational phases. anticipated drifts (compatible with most stability requirements):
        - ground motion: « 10 µm/s
        - squeeze « 30 µm/s

    - In parallel:
      - compute new inverse SVD matrix without bogus BPM/COD (~ 15s)
      - Swap active matrix once finished recalculation

  - No need to stop feedback while recalculating the new inverse matrix!
    - Feedback requirements preserved in most parts of the rings
    - Only a small area and likely only one ring is affected

Backup Scenario II – total COD/PC failure

- What can the feedback do in case of a fast COD drop-out?
  - The effect of the failing COD can for sufficiently long (spacial) distances be compensated and replaced through a pattern of correctors:



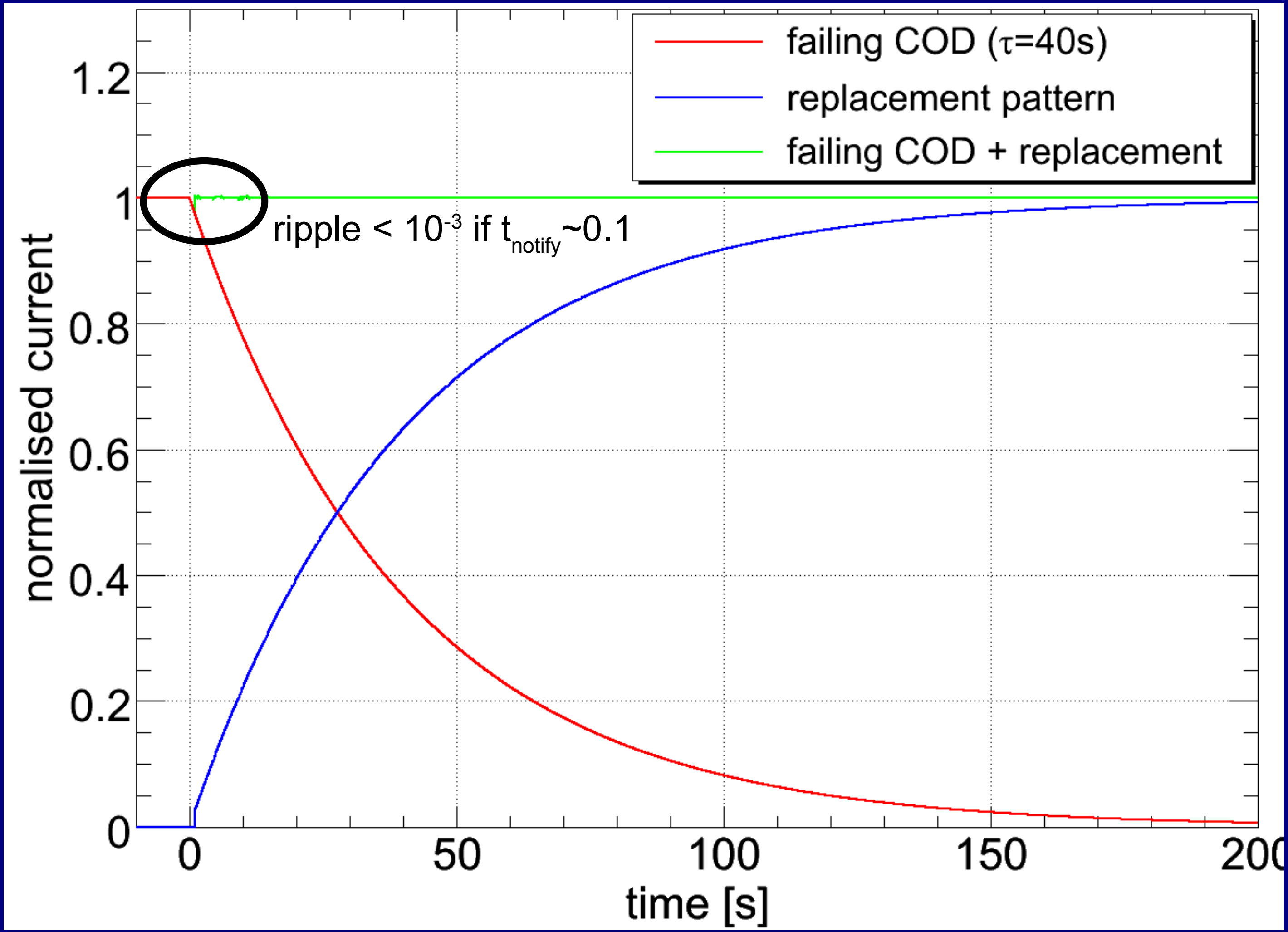
  - Though a minimum two correctors are required, it is favourable to spread replacement pattern over more CODs (e.g. use intrinsic SVD property):
    - smaller maximum currents in the pattern
      - avoid hitting individual COD's maximum current
      - single COD failure becomes less critical
      - faster reaction time since max ΔI/Δt = n · 0.5 A/s
        (total speed determined by time required to reach pattern's largest current)

Backup Scenario II – Controller Procedure

- What can the feedback do in case of a fast COD drop-out?
  - If detected: Send the pre-calculated replacement pattern instead of the failing COD's ΔI(t) through the feed-forward path :
    - Procedure for the first few (milli-) seconds:
      - Mark COD
      - Temporarily disable BPMs (ZOH) in the adjoining region (in order to be insensitive to the spacial transient)
      - Continue normal correction
      - Replace bogus ΔI(t) with R-pattern only intermediate region affected
    - In parallel:
      - compute new inverse SVD matrix without bogus COD (~ 15s/COD)
      - Swap active matrix once finished recalculation
      - recalculate new anticipatory R-patterns (~ 2 hours/all CODs)
  - The feed-forward action is transparent for large spacial distances
  - The effectiveness depends on the notify- and feedback-delay.

Backup Scenario II – timing

- It is important that the delay t_{notify} till the OFC is notified is short and constant.



  - The length of t_{notify} essentially determines the performance and size of the ripple(more than actual feedback frequency)
    - ripple ~ exp($-t_{notify}/\tau$))

Backup Scenario II – Effectiveness

Proposed feed-forward scheme yields good compensation if t_{notify} is short:

- t_{notify} ~ 0.1 s → ripple $< 10^{-3}$
- t_{notify} ~ 1 s → ripple ~ 3%
- (quenching COD compensation seems feasible (@10 Hz) if t_{notify} is sufficiently short)

Small comment on compensation of other CODs (~300/1056 total):

- CODs around the dispersion suppressor :
  - similar to MCB case
  - but: different time constants!

- Compensation of other magnets is rather difficult:
  - common (warm/cold) CODs in insertion:
    - affect both beams!
    - failure causes serious beam separation in IP that barely can be compensated using neighbouring magnets (too few)
  - warm magnets in IR3 and IR5:
    - decay time comparable to quenching cold magnets
    - would require small t_{notify} < 0.1 s delay (feasibility!?)

Conclusions

- About every 140 hours (14th fill) one of the 752 PC/MCB may fail with beam.
- Average (max) orbit drift due to COD failure: 0.9 mm (2.9 mm)
  - Decay time constants:
    - Quench of MCB: 0.4 s
    - PC failure: 60 – 80 s

      (after the two 50 mΩ resistances in crowbar are removed)
- Uncompensated, PC/COD failure may result in a beam dump request.
- The LHC OFC can take actions and save the beam if:
  - active link between PC-Gateways and Controller present
  - notified within the first second of the PC/COD failure
- A capture of those failures is not required for machine protection but may increase the overall availability of beam in the machine.