What is the Impact of Hysteresis on Orbit Correction and Feedback

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Last Chamonix XIV: Magnetic behaviour of correctors[1,2]

- Hysteresis of the corrector magnets:
  - Many field changes due to feedback operation during one run
  - correctors will be in a less precisely known state at the end of each run.

→ Requires pre-cycling before first injection to bring magnets in a well defined state

- open issues from last Chamonix:
  - Does it affect the settings reproducibility?
  - Does it limit the feedback control of orbit, tune or chromaticity?
- Will report on first correctors' hysteresis measurements in 2005
- Focus on 'MCBH(V)' orbit correction magnets
  other correctors → see W. Venturini's talk
  - Hysteresis measurement results of the MCB magnets
  - Implications for orbit control

[1] W. Venturini, “Magnetic Behaviour of LHC correctors: Issues for Machine Operation”, Chamonix XIV

[2] J.P. Koutchouk, S. Sanfilippo: “Magnetic Issues affecting Beam Commissioning”, session summary, Chamonix XIV

MCBH/V magnets

- Zoo of total 1060 corrector dipole (COD) magnets in the LHC

Magnet type	B [T]	L_{mag} [m]	BL_{mag} [Tm]	I_{nom} [A]
MCBH(V)	2.93	0.647	1.90	55
MCBCH(V) @1.9K	3.11	0.904	2.81	100
MCBCH(V) @4.5K	2.33	0.904	2.11	80
MCBYH(V) @1.9K	3.00	0.899	2.70	88
MCBYH(V) @4.5K	2.50	0.899	2.25	72
MCBXH	3.35	0.45	1.51	550
MCBXV	3.26	0.48	1.56	550
MCBWH(V) (warm)	1.1	1.7	1.87	500

← most arc CODs

- Focus on 752 MCBH(V) magnets: same design, parameter and powering
  - Max. integrated field strength $(BL_{mag})|_{max}$: 1.896 Tm
  - Maximum kick δ_{max} (↔55 A) on beam: 1260 µrad @ 450 GeV
    81 µrad @ 7 TeV
  - Maximum kick amplitude (arc): 144 mm @ 450 GeV and 9 mm @ 7 TeV
- Further focus on beam stability at '450 GeV'

Hysteresis Measurements

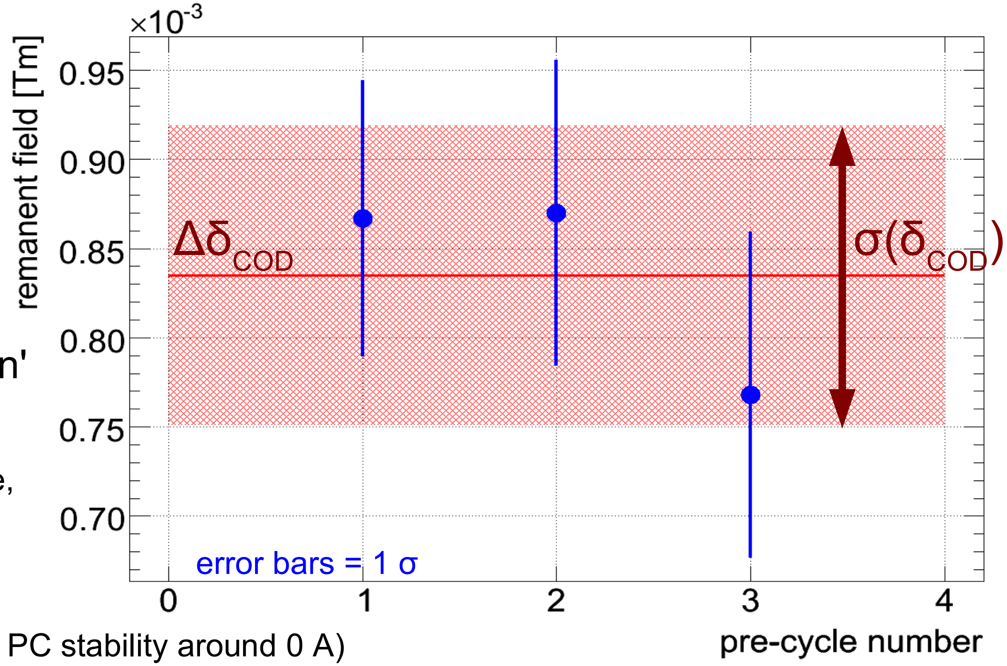
- 2005: MCB orbit corrector magnet hysteresis measurements @1.9 K
  - measurements and data by courtesy of W. Venturini

- Questions to be answered:
  1. What is the reproducibility and deviation after a predefined cycle, e.g. 0 A → 55 A → 0 A or 'De-Gauss' ?
     - Important for:
       - Fill-to-fill injection stability
       - Reproducibility of settings
  2. Is there a minimum required current change in order to change the magnetic field/deflection of the COD?
     - Important for correction convergence
     - May limit the possible correction schemes

- Example: "collision setting → 0 A → I_{nom}= 55 A → 0 A → injection setting: I_{inj}"
  - Magnet goes into full saturation (well defined state)
  - Power converter: $|\Delta I/\Delta t|_{max}$ = 0.5 A/s → pre-cycle duration ~ 5 minutes
  - Can be done in parallel to ramping down the main dipole magnets
- Remanent field after cycling:
  - $BL_{mag} \approx (8.4 \pm 0.8) \cdot 10^{-4}$ Tm
  - ↔ δ_{cod}= (560 ± 53) nrad
  - Low statistics of 'r.m.s. σ deviation' of measured reproducibility!

    (three cycles average ↔ < 1 σ confidence, measurement resolution: ~ $2.5 \cdot 10^{-5}$)
  - Maybe dominated by PC stability

    (used ±600A vs. nominal ±60A converter; PC stability around 0 A)



- However: good estimates fill-to-fill reproducibility to less than ~10^{-4} Tm
- Alternate: De-Gauss cycle - would minimises the mean, more complex and requires more time (pre-tested, but did not have enough time for detailed measurement)

1. Reproducibility after a '0 A → 55 A → 0' A cycle II/II

- Remanent field can be separated into a systematic and random part:
- Systematic remanent field: $\Delta BL_{mag} \approx 8.4 \cdot 10^{-4}$ Tm $\leftrightarrow \Delta\delta_{cod} = 560$ nrad
  - Causes static $\Delta E/E \approx 2 \cdot 10^{-5}$ energy shift and orbit perturbation
  - Small & reproducible from fill-to-fill, can be easily corrected
- Random Fill-to-fill variation: $\sigma(BL_{mag}) = 0.8 \cdot 10^{-4}$ Tm $\leftrightarrow \sigma(\delta_{cod}) \approx 53$ nrad
  - Small relative error: $\sigma(\delta_{cod})/\delta_{max} \approx 4 \cdot 10^{-5}$
  - Numeric simulation of COD orbit lattice response (LHC v. 6.5 inj.):
    - $\sigma_H(\text{orbit}) \approx (\ 966 \pm 245)[\text{m/rad}] \cdot \sigma(\delta_{cod})$
    - $\sigma_V(\text{orbit}) \approx (1004 \pm 275)[\text{m/rad}] \cdot \sigma(\delta_{cod})$

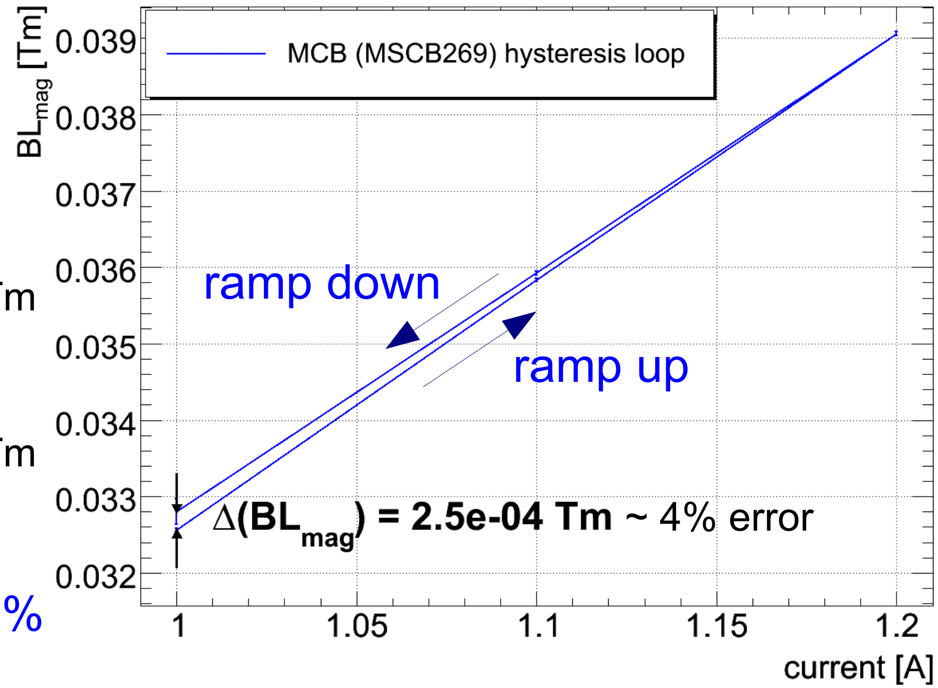
→ Exp. orbit r.m.s. @ inj. due to hysteresis ~50 µm r.m.s. (0.05 σ, σ: beam size)

- Small compared to available aperture (~ 10 mm), collimation requirements (Δx<0.3σ) or expected ground motion contribution[1] (0.3-0.5 σ)
- Undetectable with LHC BPM shot-by-shot resolution of ~100 µm (nom. bunch)
- Poses no problem for reproducibility of injection orbit or threading!

[1] RST: "Analysis of Ground Motion at SPS and LEP, implications for the LHC", CERN-AB-2005-087

2. Small Hysteresis Loops

- Expected orbit correction scale: 0.5 mm ↔ ΔI = 0.2 A @ $\beta \approx$180m
- Width of small hysteresis loop '$I_0 \rightarrow I_0+\Delta I \rightarrow I_0$',
  - 1 A ↔ 1.2 A: $\Delta(BL_{mag}) = 2.5 \cdot 10^{-4}$ Tm ↔ $\Delta\delta_{cod}$= 166.6 nrad
  - 10 A ↔ 1.2 A: $\Delta(BL_{mag}) = 1.1 \cdot 10^{-4}$ Tm ↔ $\Delta\delta_{cod}$= 73.2 nrad
- Error of small hysteresis loop: ~ 4%



Important observation:

- Though requested field change is less due to hysteresis:
  - No quantisation effect observed
  - small ΔI yields a change of magnetic field (deflection) = no "dead-band"!

→ Hysteresis effect that can be compensated by beam-based feedbacks!

- SVD* based global correction scheme in space-domain and Proportional-Integral-Derivative (PID) controller in time-domain
  - Uses pseudo-inverse orbit response matrix:
    - Orbit correction = simple matrix multiplication
  - Can easily eliminate near-singular solutions
    (= solutions that may potentially drive the loop instable)
    - Uses all (selected) CODs with rather small correction strengths
    - Less sensitive to single BPM errors, BPM noise and COD failures[1,2]
  - intrinsically minimise uncertainties and unknown effects, due to "integral" part of PID controller
    - Classic, well studied and understood controller
    - Does not require an accurate process model
    - Linearises non-linear systems

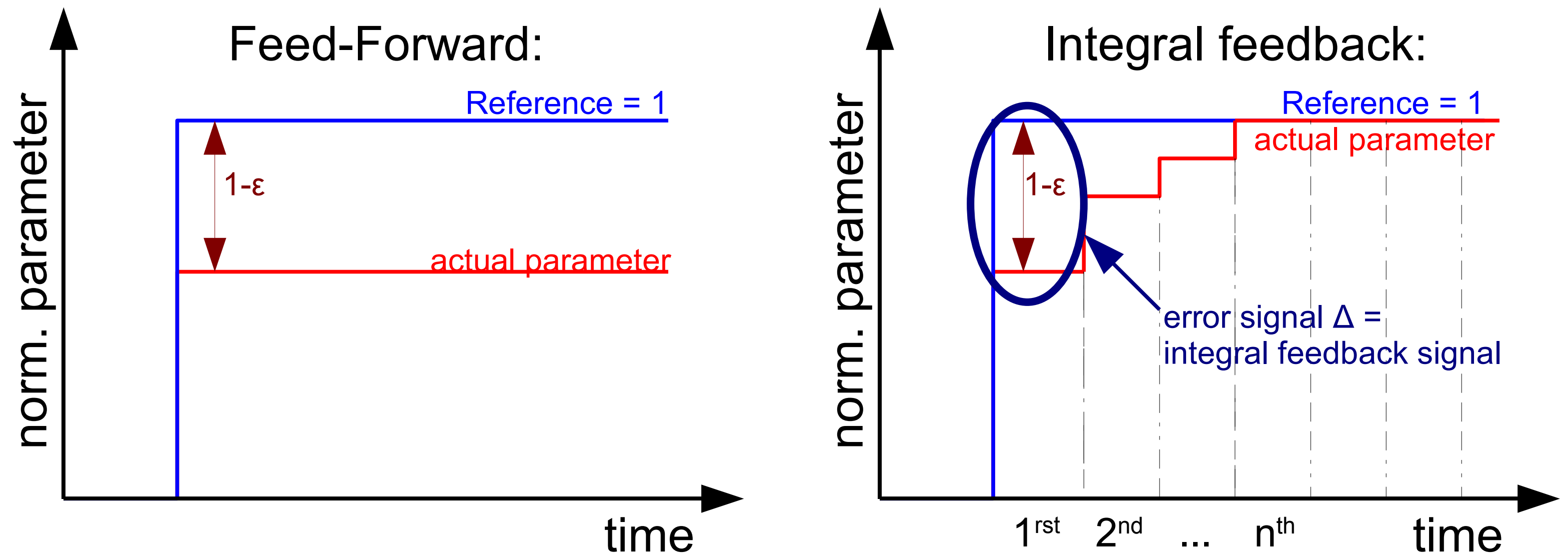
→ All light sources go in this direction!

* SVD = Singular-Value-Decomposition, eigenvalue based approach that can invert near-singular matrices, see:
G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971
[1] R. Steinhagen, "Can the LHC Orbit Feedback save the beam in case of a closed orbit dipole failure?", MPWG #46, 2005-06-01
[2] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

PID Controller: Integral Action example

- Effect of hysteresis can be translated into a scale error ε_{scale}:

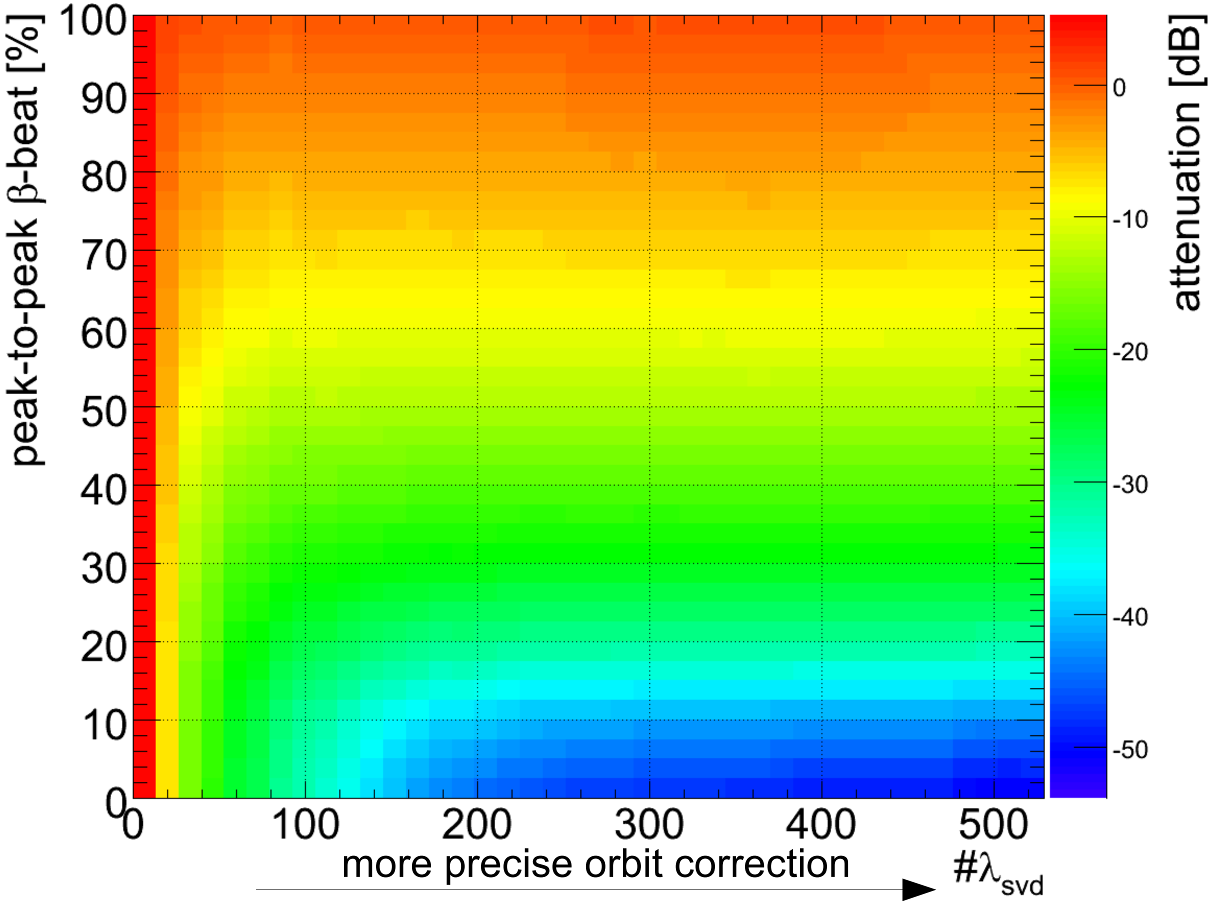
$$\Delta x(s) = \frac{\sqrt{\beta_i \beta(s)}}{2\sin(\pi Q)} \cos(\Delta\mu - \pi Q)\cdot(\delta_i + \delta_{hysteresis}) \rightarrow \Delta x(s) = R_i(s)\cdot\delta_i\cdot(1+\epsilon_{scale})$$



- Hysteresis, uncertainties and scale error of transfer function affects rather the convergence speed (= feedback bandwidth) than achievable stability
- A 4% error of the COD transfer function has in first order a similar effect as 4% beta-beat on the quadrupole magnets.

Example: Orbit Feedback Disturbance Rejection

- Low sensitivity to optics uncertainties = high disturbance rejection:
  - LHC simulation: Inj. Optics B1&B2 corrected



$\#\lambda_{svd}$ controls correction precision

attenuation =

$$20 \cdot \log \left| \frac{\text{orbit r.m.s. after}}{\text{orbit r.m.s. before}} \right|_{ref}$$

- Robust Control: OFB can cope with up to about 100% β-beat!! (we will do better!?!)
  - Collimation inefficiency w.r.t. β-beat is clearly more an issue

Strategy to reach Nominal Beam Conditions

- Machine protection:
  - No nominal beam prior circulating low-intensity beam!
  - Tests correctness of machine optics, parameters, settings etc.

- Use first low-intensity beam to perform beam-based correction of: Energy, Orbit, Tune, Chromaticity, Coupling, ...
  - Integral feedback action: minimises intrinsically uncertainties such as scale error of transfer function, calibration, offsets, hysteresis ...
  - Feedback will run non-stop[1] from first injection till dump

→ Injected first nominal beam finds same conditions as prior optimised low-intensity beam.

[1] short pauses foreseen: parameter adjustment, avoidance of cross-talk between measurements, in case of failures, ...

Comparison with ±8V,±60A Power Converter Stability

- Ultimate beam stability (in the few ten μm range) is limited by:
  - Residual noise floor, quality and errors of BPMs (spikes, systematic drifts etc.)
  - Residual noise floor of COD power supplies
  - Present relevant external perturbations vs. feedback bandwidth

- 2005: 60A converter testing in SM18
  - data by courtesy of V. Montabonnet and A. Cantone

- Stability measurements with MCB load @ 1.6 K (L=6.6 H, R= 12 mΩ)
  - R.M.S. converter stability: $\Delta I/I_{nom} \approx 5 \cdot 10^{-6}$ ↔ $\sigma(\delta)$ = 6.3 nrad r.m.s.
  - LHC orbit response function → predicted orbit uncertainty

    (6 ± 2) μm r.m.s ↔ ~ 0.01 σ stability (σ: beam size)
  - ≈ noise floor of LHC BPM system measuring with single nominal bunch (100 μm shot-to-shot, 255 turn average)

Conclusions

- Hysteresis affects mainly the orbit of the first injected low-intensity beam
- Hysteresis does not significantly affect feedback operation with circulating beam due to the integral part of their PID controller and intrinsically minimise unknown effects and errors due to wrong transfer function scale and hysteresis
- For a good fill-to-fill reproducibility each correction magnet should be cycled after end of each run to return it to a more defined state for the next injection, e.g. by cycling through saturation: → 50 A → 0 A → I_{inj} (~ 5 minutes)
- 2005: MCB cold measurements to estimate of correction dipole hysteresis
  - Reproducibility of the remanent field after a 0A↔50A cycle ~ 10^{-4} Tm
  - Causes injection orbit uncertainty of about 50 µm ↔ small compared to requirements
  - Estimate based on low statistic, rather qualitative order of magnitude than precision
- Stability of the MCB power supplies are likely to define the minimum achievable stability of the orbit after feedback correction to about (6 ± 2) µm r.m.s (0.01 σ)

Reserve Slides

■ LPR501 specification[1]:	
– nom.: $(\Delta p/p)_{max} \approx 10^{-4}$	0.25 σ
– $b_2+b_3\cdot\Delta x$ decay: $(\Delta\beta/\beta)_{3\sigma} \approx 2.5\%$	0.03 σ
■ Moon/sun tides[2] ($\Delta p/p \leq 5.0\cdot10^{-5}$)	0.14 σ
■ Main Bends, random $b_1\approx0.75$ units[3,4] (dipole kick)	0.11 σ
■ Random ground motion[5] (10 hours)	~0.3 – 0.5 σ
■ Systematic ground motion drifts[5,6]:	~?? σ
■ MCB hysteresis[7]	0.01 σ
■ MCB ±8V/±60A PC stability[8] (16bit ADC)	0.01 σ
■ Total (abs):	~0.9 - 1.1 σ

1: M. Giovannozzi: FQWG Meeting on 8th of March 2005
2: J. Wenninger: "Observation of Radial Ring Deformation using Closed Orbits at LEP"
3: M. Haverkamp, "Decay and Snapback in Superconducting Accelerator Magnets", CERN-THESIS-2003-030
4: FQWG-Homepage: http://fqwg.web.cern.ch/fqwg/
5: RST: "Analysis of Ground Motion at SPS and LEP, implications for the LHC", CERN-AB-2005-087
6: R. Pitthan, "LEP Vertical Tunnel Movements - Lessons for Future Colliders", CLIC-Note 422
7: W. Venturini: "Hysteresis measurements of a twin aperture MCB orbit corrector", 19th October 2005
8: V. Montabonnet, Q. King, L. Ceccone: private communications