Hysteresis Compensation in the SPS

IPP MD Days 2025

JAPW'24: https://indico.cern.ch/event/1439972/contributions/6159177/

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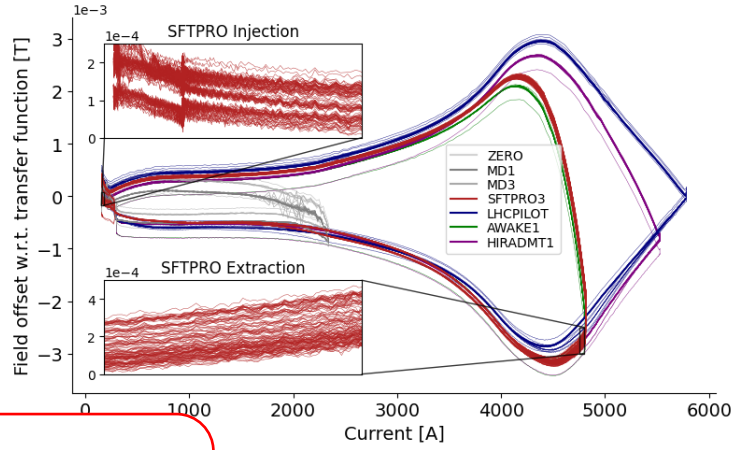
Hysteresis in the SPS main magnets

And the need for reproducible fields

- Cycle-to-cycle differences in magnetic fields are small …
  - Hysteresis effects ± 1 permil, but cycle-to-cycle differences are $\pm$ 100 ppm or less … (in SPS MBIs)
- … But still significant effects on beam
  - 100 ppm ($1 \times 10^{-4}\ T$) tolerance on SFT 400 GeV flat top
  - 10 ppm ($1 \times 10^{-5}\ T$) tolerance on 14 or 26 GeV flat bottom

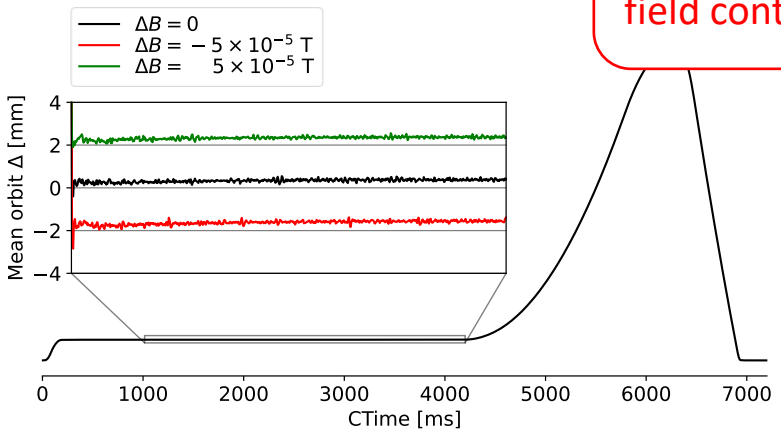
SPS MBI Cycle-to-cycle hysteresis



SPS status quo

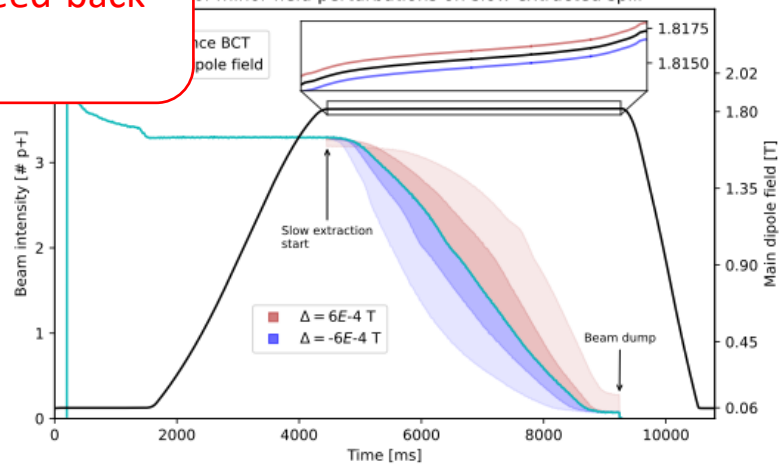
- MD1 quasi-degaussing cycle
- Manual change of SFT beam tune whenever LHC requests beam
- Still beam losses / degradation at injection
- Low flexibility in cycle sequences

Beam orbit perturbation by 50 ppm dipole fie



! N.B. Only PSB and PS dipoles have feed-back field control

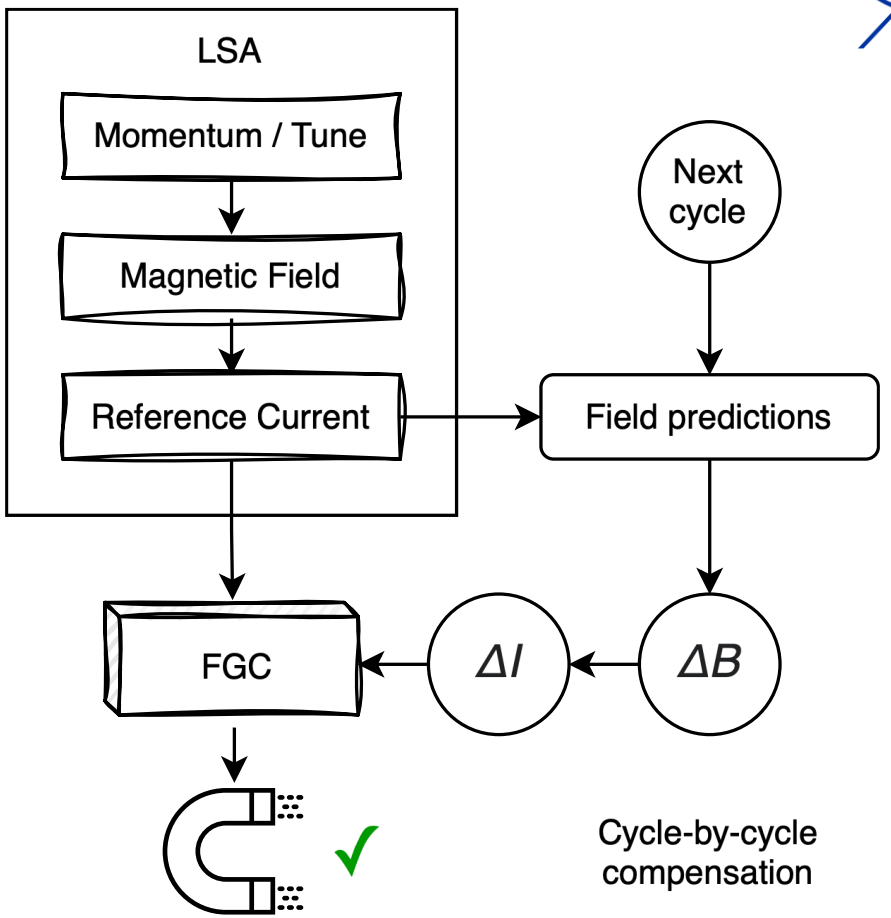
of minor field perturbations on slow extracted spill



What if we could have reproducible fields…

Through feed-forward field compensation

- Most magnetic circuits are controlled in current by translating momentum / tune / correction etc.
  - Control system is agnostic to actual field response in the machine
- Instead: model magnetic field response $I \rightarrow B$ with ML, from measurements
  - Knowing next cycle to be played …
  - … feed-forward correct the field by applying a ΔI for every cycle
  - ⇒ We now can achieve reproducible fields
  - Control paradigm is transparent to set B / Q / K

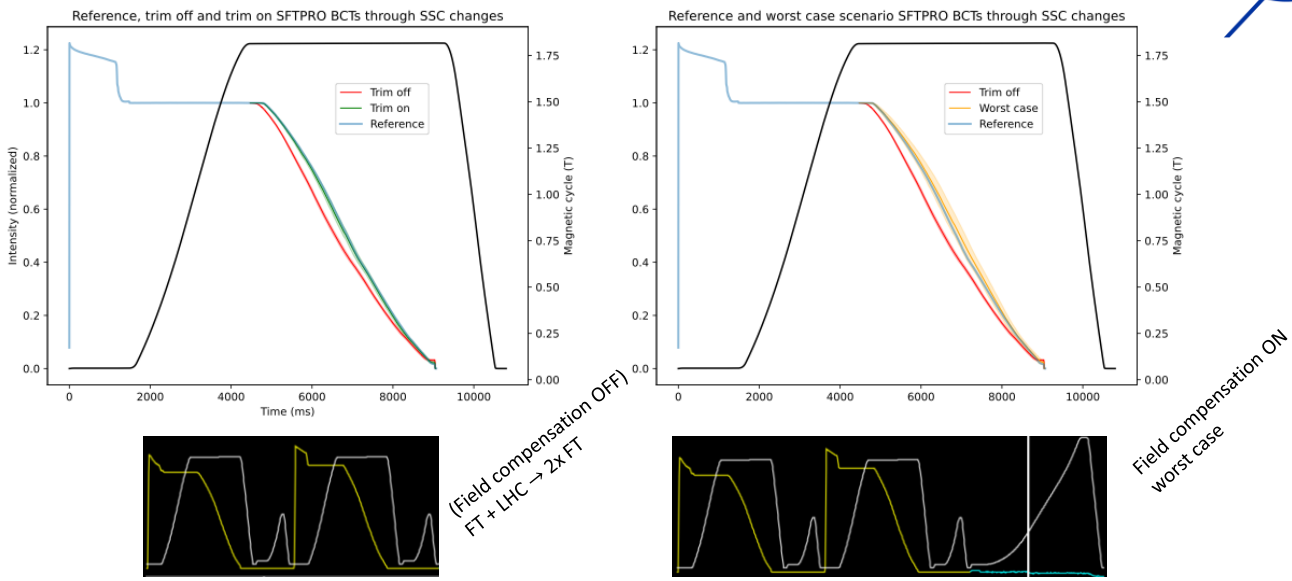


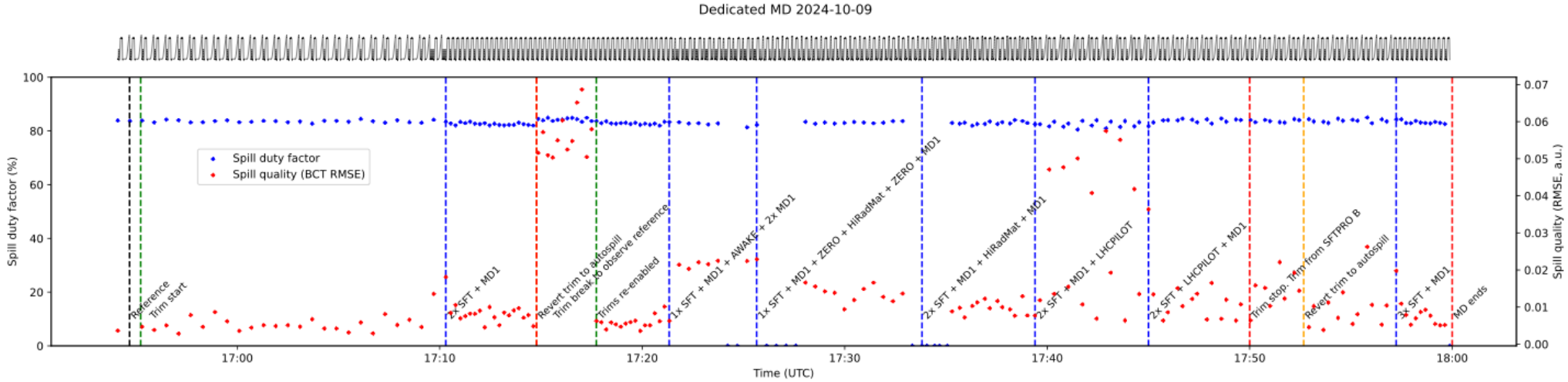
❗ N.B. Assume that all effects can be modeled by measuring field

Significant achievements in 2024 MDs

Operations-ready field compensation at SFT flat top

- Successful SPS MB compensation on SFT FT
  - For common operational conditions
    - Spill macrostructure stable for over 1h
    - … on **every SFT**
    - Field compensation around $\Delta I \approx 0.7$
    - We can “flatten” the MD1 on the MBIs
  - Spill duty factor remains largely unchanged
  - … but RMSE between ref. and measured BCT is significant when field is poorly / uncorrected

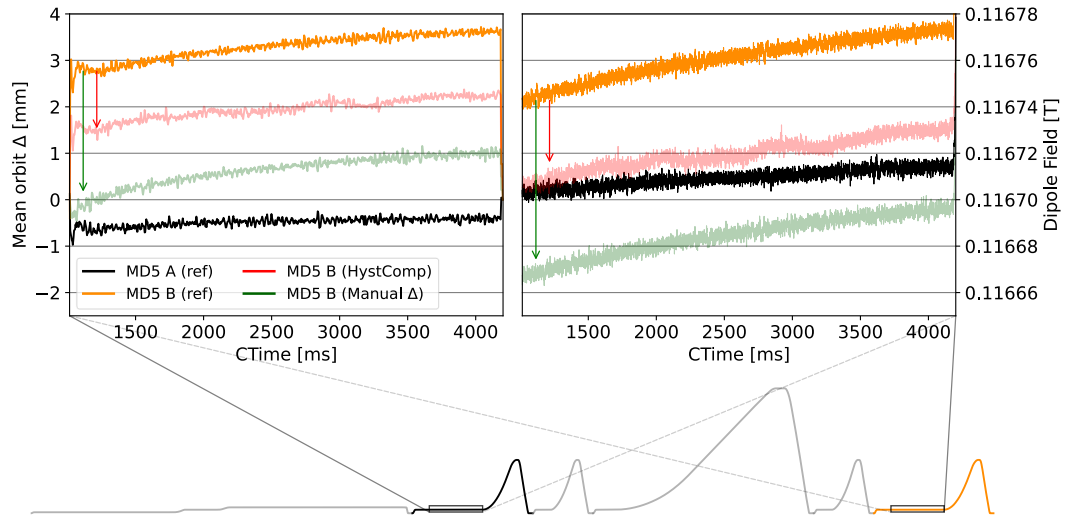




Significant achievements in 2024 MDs

… and challenges

- Only effects from measured field can be compensated by field prediction
  - Field predictions on MBIs satisfy the required accuracy 10 ppm for common supercycles
  - … but some (dynamic) effects on beam still not explained
  - To be investigated in 2025 MDs
    - In the ideal case dynamic effects can be partially decoupled from static effects (hysteresis)
- Insufficient MD time to test other cycles for SPS MBIs
  - 1 of 2 dedicated MDs lost, replaced by 2h spare time, but none of required BCDs were configured
- Field measurements from SPS QF/QD/LOD/LOF still missing
  - Measurements coming this month to enable compensation tests during beam commissioning and MDs



Planned activities in 2025 MDs

Dedicated MDs

- SPS main dipoles
  - Operational tests and SFT MB flat top compensation and operational implementation
  - Comprehensive tests on MB for all (physics) cycles in different combinations and scenarios in first half or year, with full-cycle compensation
  - Parasitic prediction + monitoring (dry run) all year
  - Dynamic effects studies (that are not possible in lab) in controlled supercycles (1-2 MDs)

- SPS main quadrupoles
  - ML-compensation tests on SFT flat top
  - ML-compensation tests on other physics cycles in operational conditions
  - Eddy current compensation studies to follow after MBs, given time

- SPS other magnets
  - Initial studies for autoregressive field compensation on main sextupoles ~~and octupoles~~ in second half of year
  - Timeline dependent on measurements

Planned activities in 2025 MDs

Dedicated & parallel MDs

- Dedicated MDs
  - 12x 3h slots
  - Shorter slots are better for us since setup time is low, but when trained ML models are unsuccessful, we need to re-train, which is difficult to do during the same day as the MD -> better to wait for next slot
  - We need control of the **full supercycle**, and supercycle can change every few minutes, and we will work on every cycle in the supercycle, not only 1 user

- (Long) parallel MDs
  - Same tests as for Dedicated MDs but without full control of supercycle
  - ... But changes to supercycle during parallel MDs are needed to be useful (e.g. add or remove preceding MD1s), or different position of MD cycle in supercycles (asymmetric supercycle)
  - Studies in parallel to physics **for studies on stability** in compensation (on MD cycle)
  - Trim only on MD cycle (as opposed to dedicated MDs)
  - MD cycles can be any type of short MD cycle (SFT-like, 200 GeV MD cycle, AWAKE, etc.)

  - 6x 3h slots through 2025
  - Ideally MDs scheduled in weeks with no dedicated MD
  - Can also be short parallel MDs if, minor changes to supercycle are allowed ($\pm$ MD1)

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MD1)

We are happy to use any compatible machine downtime for short studies