# Data-driven hysteresis compensation

## In the CERN SPS main magnets

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**SUPS32 / WEAN2**

Slides: bit.ly/ipac25-hysteresis

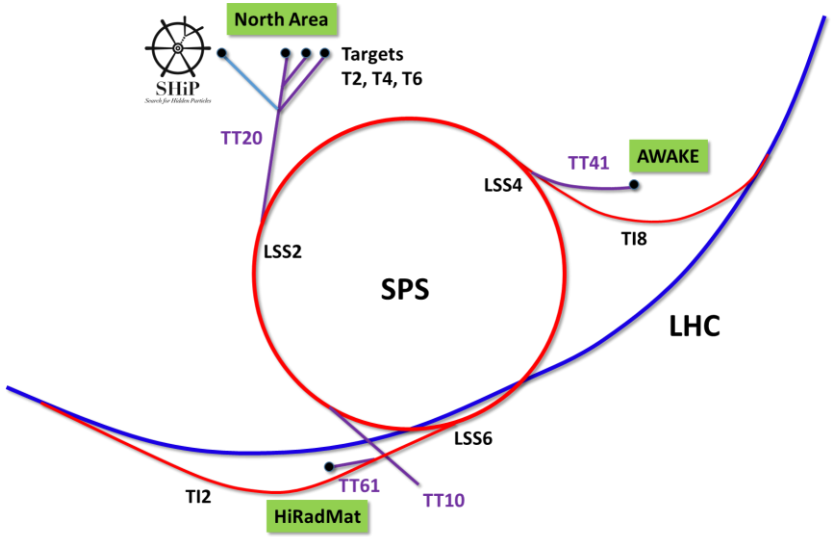
# Contents

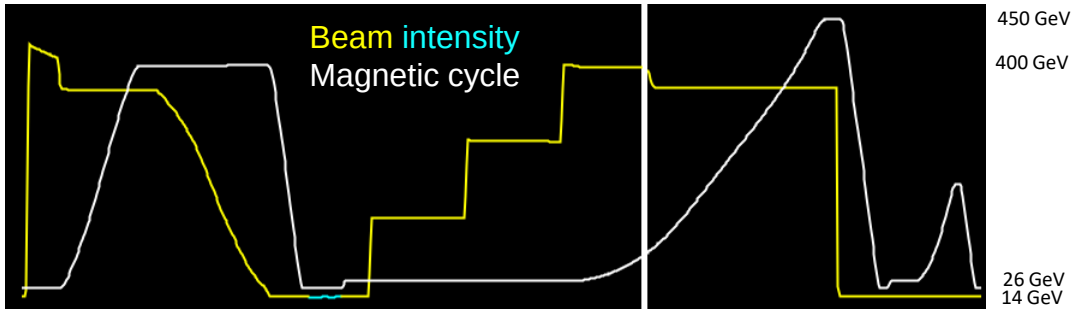
- Overview of the CERN SPS and hysteresis in the main magnets
- Time series forecasting for field prediction
- Cycle-by-cycle field compensation in the main dipoles
- Outlook into higher order SPS magnets
- Limitations in field measurements
- Conclusions


Slides: bit.ly/ipac25-hysteresis

# The CERN Super Proton Synchrotron

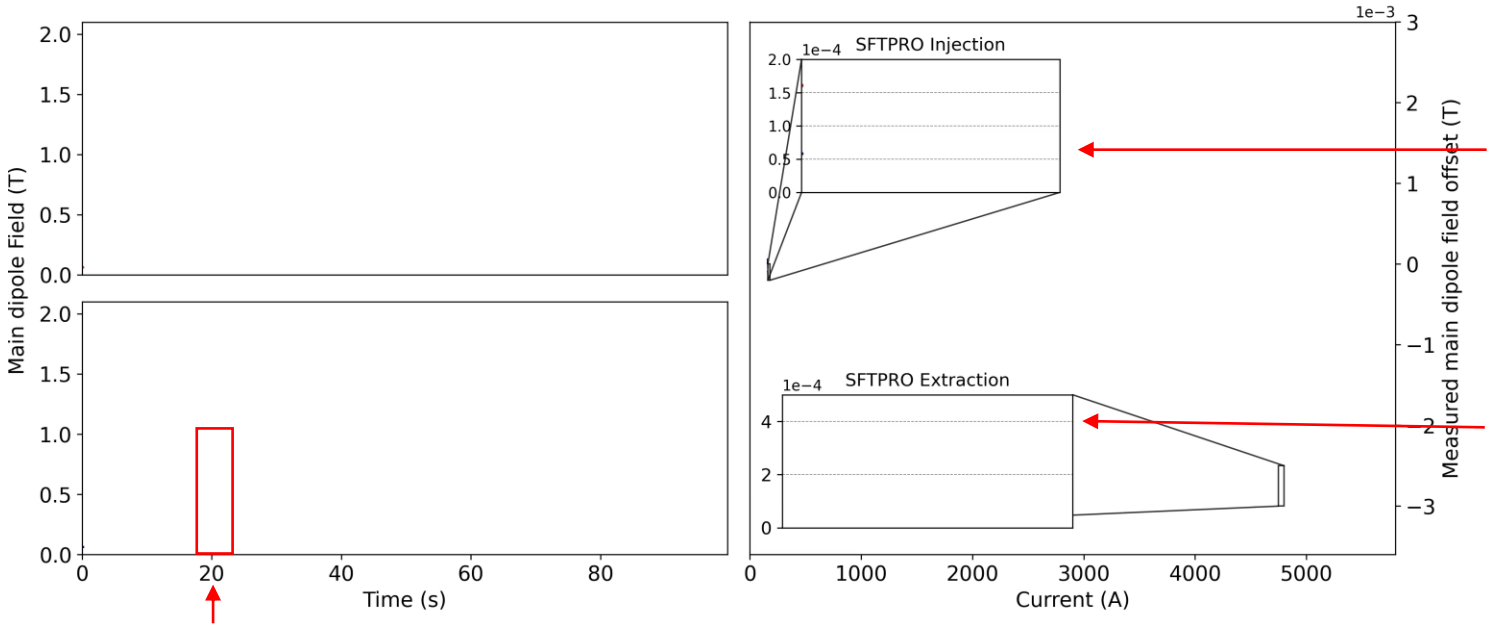
- SPS is a fast multi-cycling synchrotron
  - 14 or 26 GeV → 400 – 450 GeV proton beam
  - 17 GeV → 30 – 300 GeV heavy ion beam
  - Fast extraction to LHC, fixed target experimental areas, **slow extraction** (5 s) to North Area
    - Different beam parameters (including energy) **for each client**
      - Different magnetic sequences for most beams
  - Reduced operational flexibility and efficiency from **hysteresis in main magnets**



# Magnetic hysteresis in multi-cycling synchrotrons

*And limitations on beam operation*




**Injection losses due to**
- Hysteresis
- Eddy current decay

**(Extracted) beam quality degradation**
- Changing SX spill macrostructure

**Waste of energy from precycling**
- 5 kWh every 3.6s cycle
- … for quasi-degauss

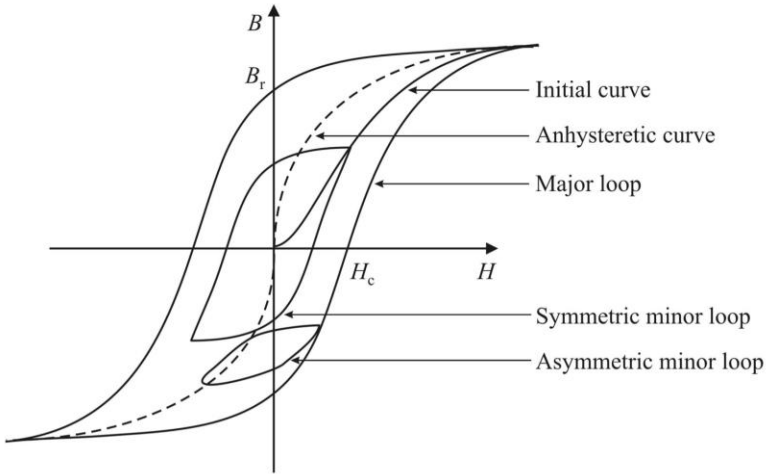
**Main dipole field perturbation**
- 0.6 Gauss ⇔ 1 permil $\Delta p/p$ at 14 GeV injection without precycle
- ≈ 2 Gauss ⇔ 100 ppm $\Delta p/p$ at 400 GeV extraction when magnetic sequence changes

- Beam operation focuses on mitigation of hysteresis effects
  - CERN Injectors: Precycling, constrained cycle sequences and manual parameter adjustments

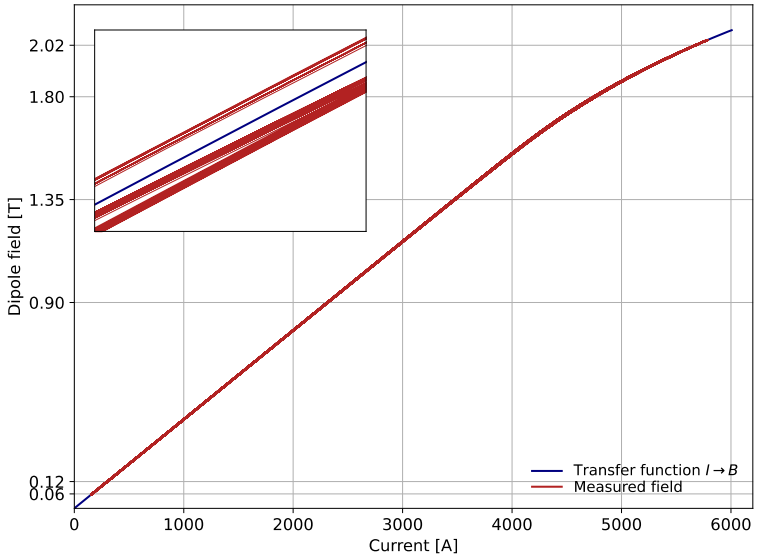
# Hysteresis in the SPS main dipoles

*Online measurements from the SPS*

Expectations



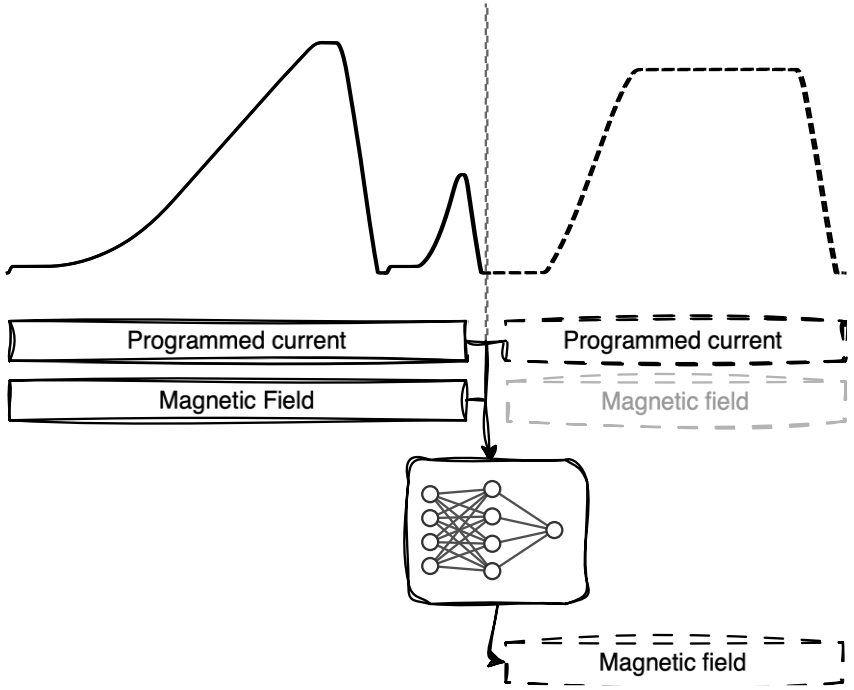

Reality




- Hysteresis and nonlinear effects are orders of magnitude smaller than anhysteretic magnetization
  - But measured field contains a mixture of **hysteresis**, **dynamic effects**, and **measurement artifacts**
  - Phenomenological models are challenging to reach required field accuracy ($< \mathcal{O}(100\ \mathrm{ppm})$)
  - ⇒ fully data driven is the most straightforward way

# High-accuracy field prediction with machine learning

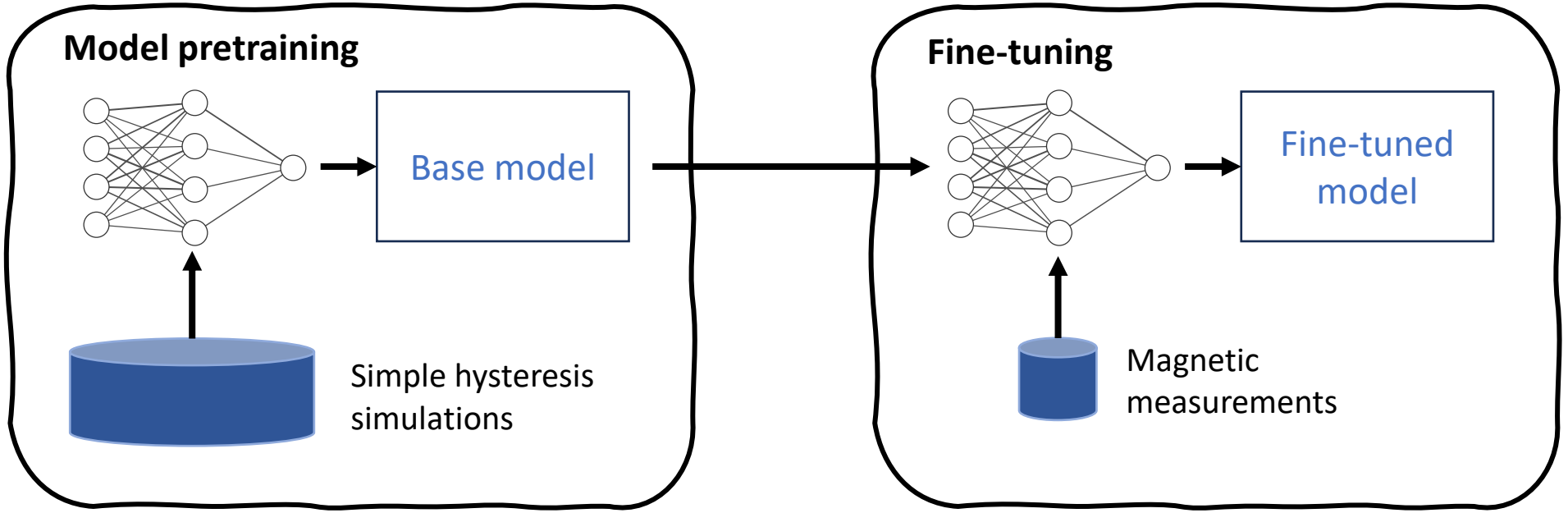
*Time series forecasting for hysteresis prediction*




- Model magnetic field measurements as a time series forecasting task
  - Learn discrete function $B(t, I)$ from measured $\{I, B\}$ datasets, with long prediction horizon ($\approx 1000$)
  - Seq2seq models can be trained to predict every cycle in 1 pass

# State-of-the-art timeseries forecasting with transformers

*Data-driven field prediction*

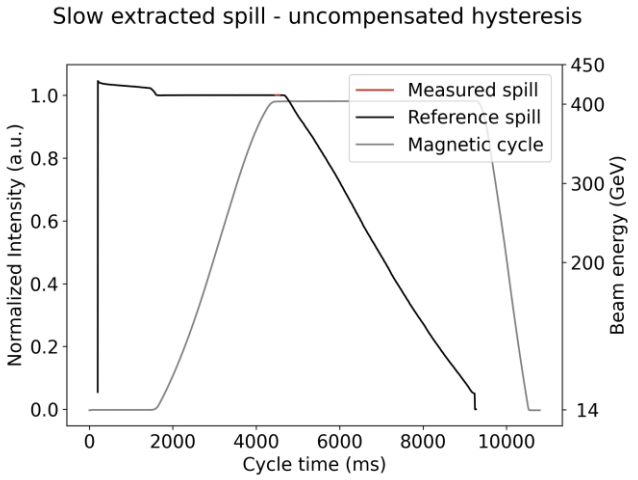


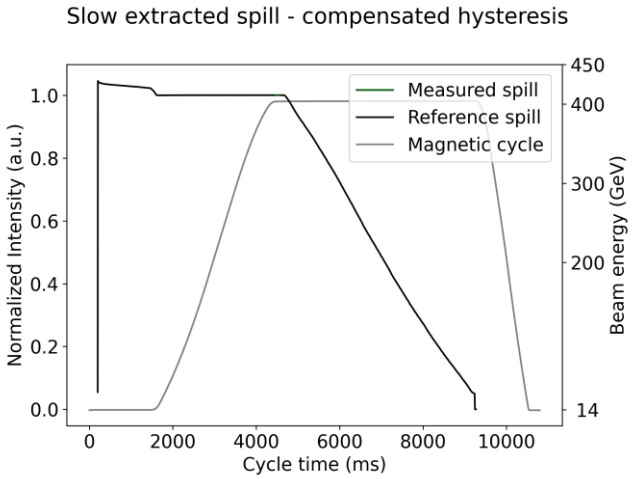

- Attention-based models need plenty of data to train and generalize well
  - **Pre-train** in simulated hysteresis loops (Jiles-Atherton / Preisach) and **fine-tune** on measured data
  - **50 ppm prediction accuracy** on field across operational sequences, at 50 Hz resolution
  - Models can be fine-tuned to other magnets with the same method

# Compensation performance for SPS Fixed Target slow extraction

## Hysteresis Compensation on SPS main dipoles

- 3rd order resonance slow extraction at 400 GeV highly sensitive to tune and orbit
  - 50 ppm main dipole field tolerance (20 ppm on QD/QF)
  - Operational magnetic sequence changes cause up to **150 ppm changes** in the extraction dipole field
    ⇒ spill degradation
- Cycle-by-cycle compensation on dipole field at extraction to **within 20 ppm** ($3 \times 10^{-5}$ T)
  - Not fully reproducible spill - main quadrupoles not yet compensated

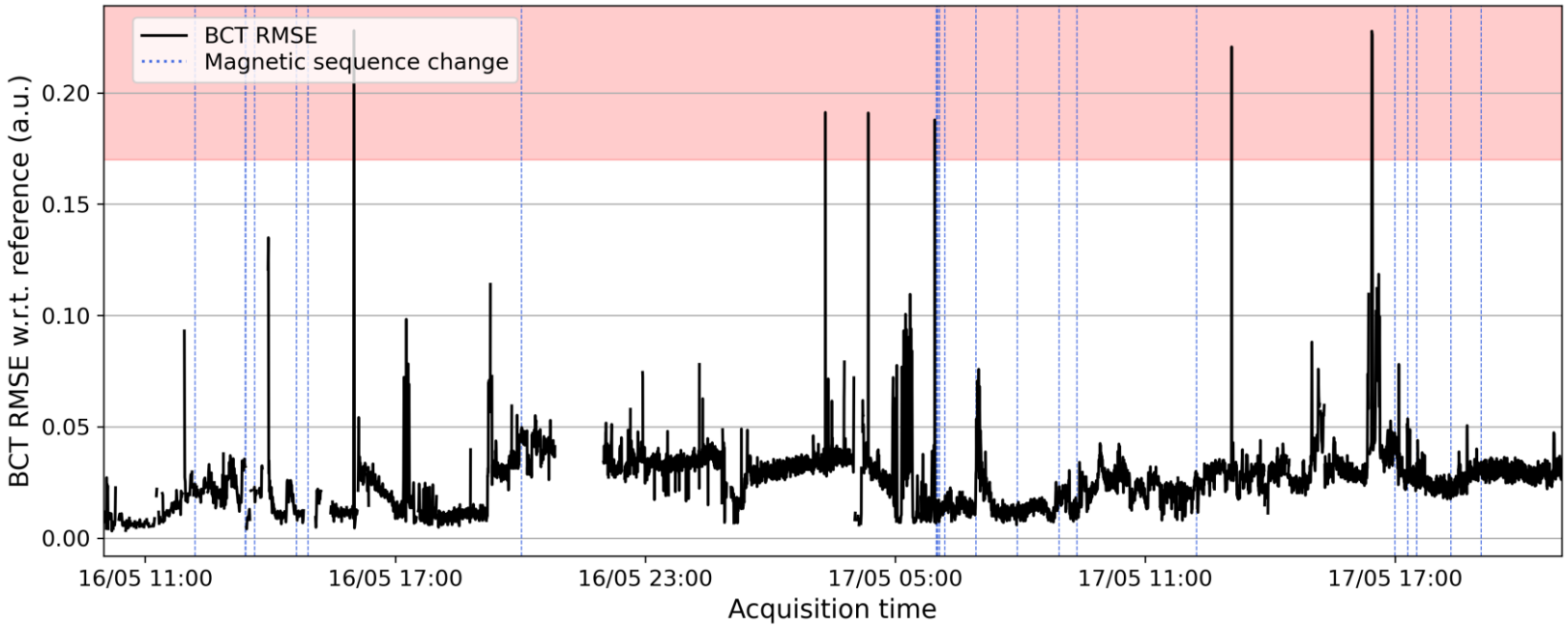


# Continuous control of the SPS main dipoles for slow extraction

## Hysteresis compensation on SPS main dipoles

- Compensation runs reliably for long periods with **past measured field as input**
  - Reproducible beam parameters at SX without intervention from operators **for 36 hours**
  - Spill reproducibility defined as $\mathrm{RMSE}\ (BCT_{\mathrm{ref}}, BCT_{\mathrm{meas}})$
  - Occasionally poor reproducibility – may be hysteresis compensation, or other accelerator systems

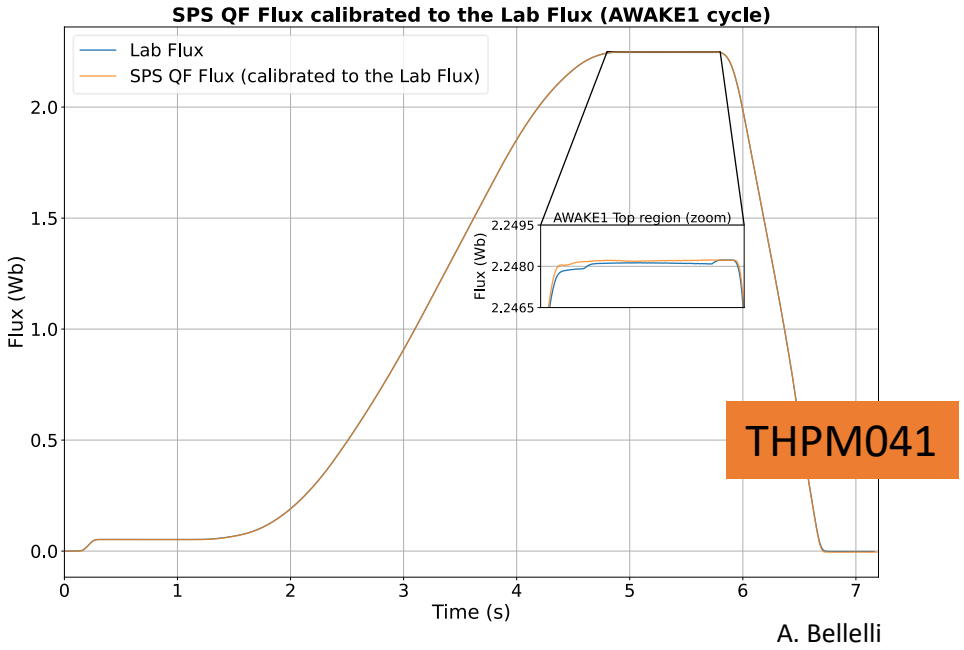



Beam performance when uncompensated (and not manually corrected)

# Hysteresis compensation for higher order magnets

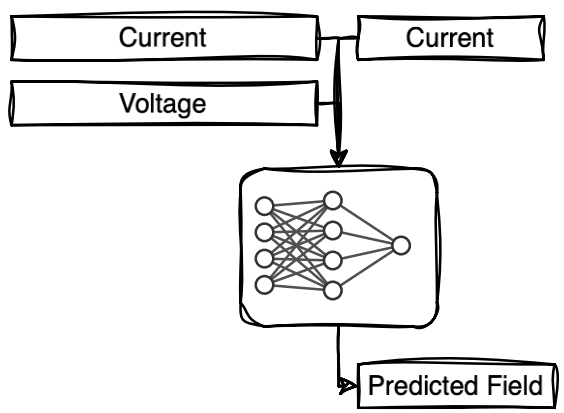
*SPS main quadrupoles and sextupoles*

- Higher order magnets in SPS have no real field measurement system
  - Field compensation can go in open loop control with a **robust magnetic model** and **autoregressive field predictions**
  - First results (1 h continuous control) look promising, but further work and longer studies needs to be done to quantify error propagation
  - Magnet coil voltage can be used **as virtual sensor** if resistive voltage can be reliably isolated from inductive
    - Every magnet is “equipped” with this “instrument”
    - Can be modeled with the same proposed data-driven approach (*TBC*)




THPM041

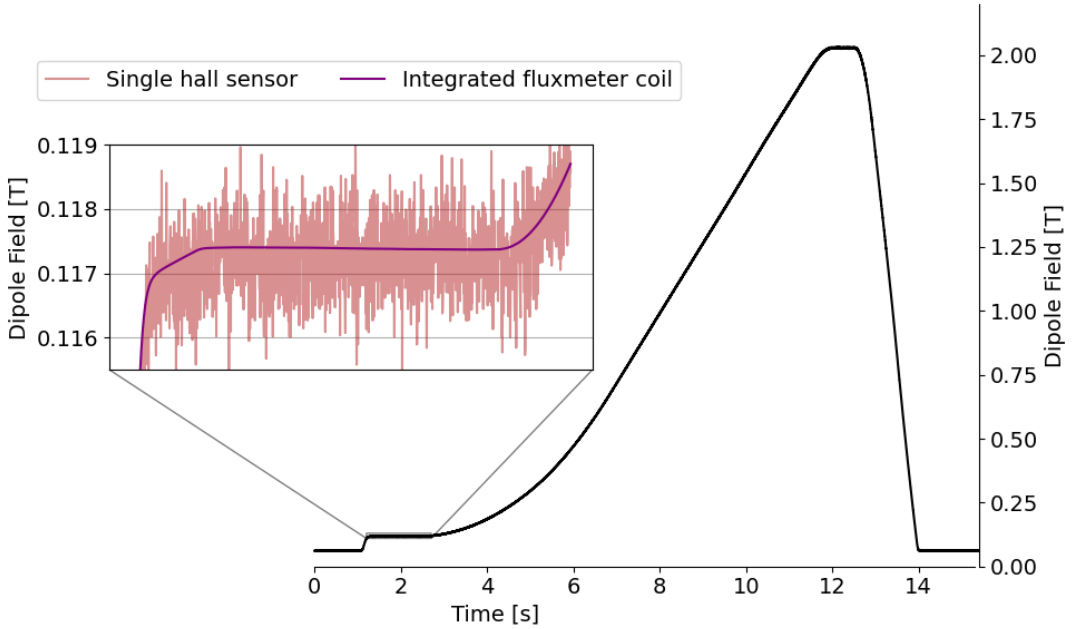
A. Bellelli



# Limitations in field prediction

*High-accuracy magnetic measurements*

- Proposed field compensation paradigm primarily limited by accurate field measurements
  - $< 5 \times 10^{-5}$ T ($\approx 25$ ppm) pulsed field measurements with fluxmeter is difficult due to integration drift
  - But beam is sensitive to 5 ppm…
- Field compensation at injection energy challenging due to low beam rigidity and low SNR in measurements
  - Robust field predictions $< 10$ ppm are required!



# Summary & Conclusions

- Flexible, high-accuracy, purely data-driven magnetic field predictions, from magnetic measurements
  - Fine-tuned neural networks can be transfer-learned to other magnet families and measurements
  - Operationally usable magnetic model and compensation schema for synchrotrons
    - Improved field reproducibility and operational flexibility in CERN SPS
- Online field compensation is being deployed to the SPS main dipoles
  - Potentially significantly increased available beam time without the need for magnet precycling
    - Critical for dynamic beam scheduling and automatic LHC filling at CERN
    - SPS main quadrupoles must be compensated before the full benefit
  - Further extension to the SPS main sextupoles and octupoles is foreseen

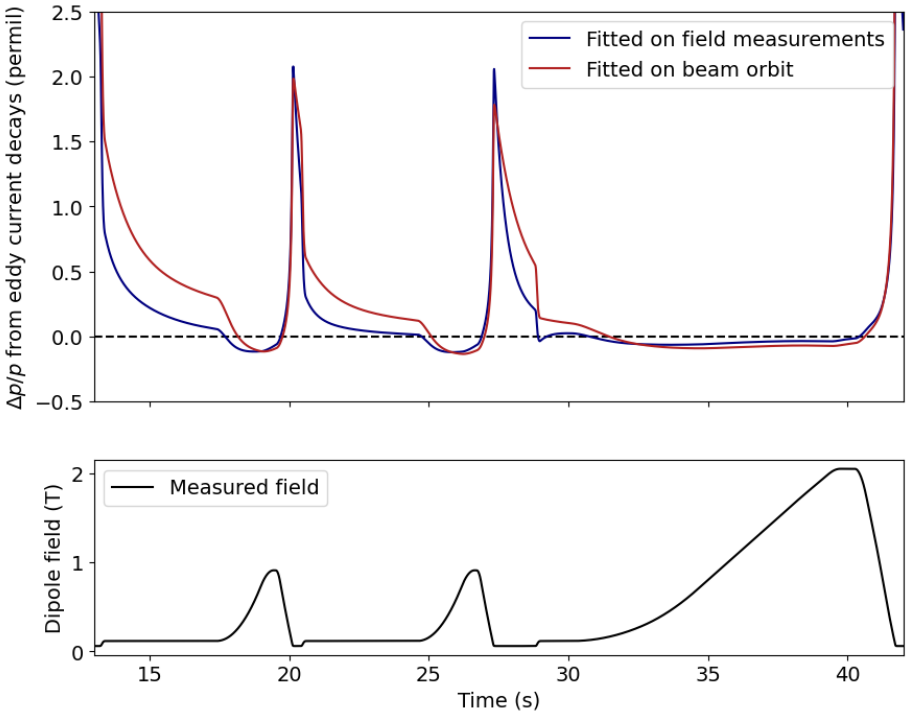
# Thank you

# Extra slides

# A note on eddy current compensation

- Original magnetic field modeling aimed to capture dynamic effects from measurements…
  - … but reference magnet measurements cannot capture eddy current decays in the accelerator
  - Beam experiences dynamic effects that are incompatible with magnet design and field measurements
  - Field contributions from eddy current decays must be fitted from beam data directly (i.e. radial position for main dipoles

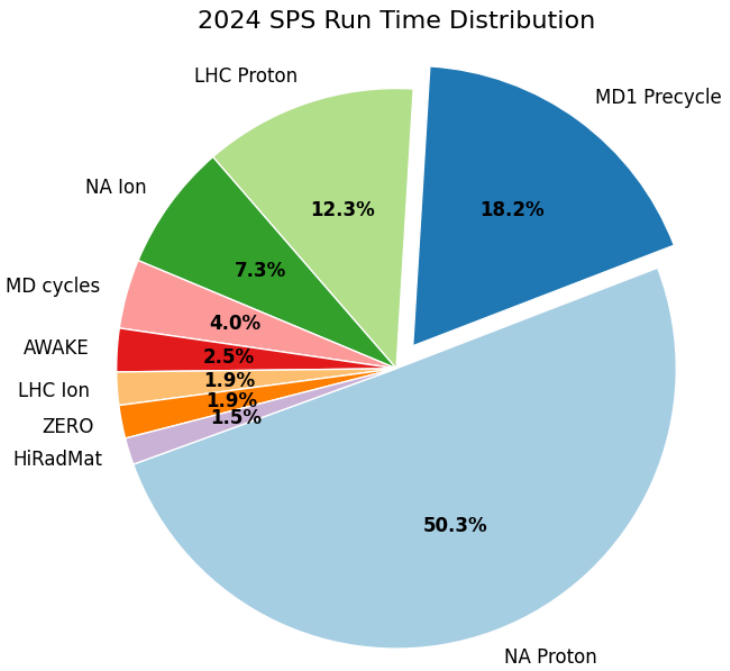
- Eddy current contribution can be added to ML field forecasting for feed-forward compensation



# Towards a particle accelerator without precycling

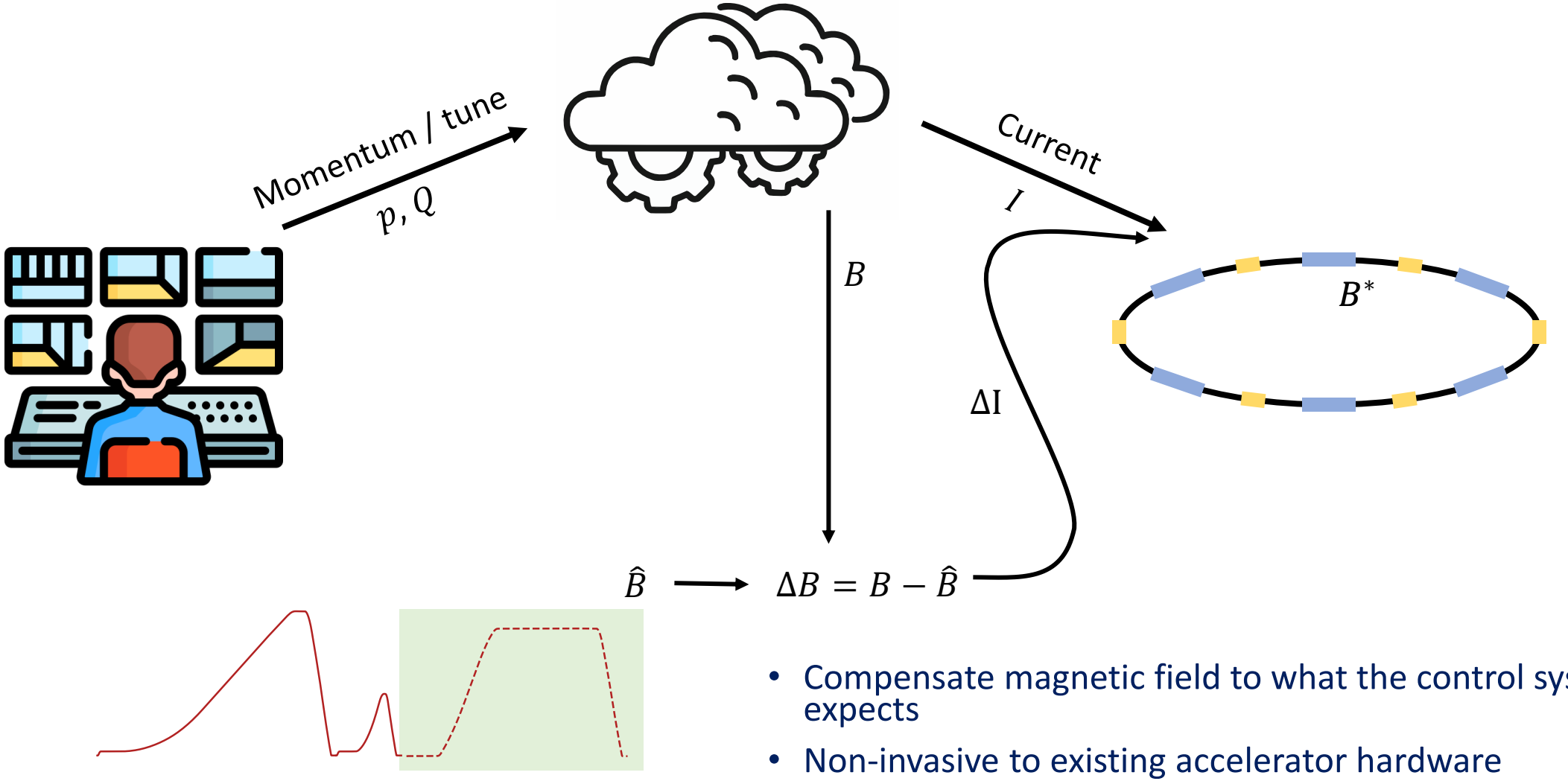
*Potential operational benefits*

- 18 % of the 2024 SPS physics run was spent in precycling
  - 5 GWh of power for precycling only
- Hysteresis compensation facilitates removal of precycle
  - Significant increase in available beam time
  - Improved flexibility for beam operation & cycle scheduling



# Transparent hysteresis compensation

*Through feed-forward field compensation*

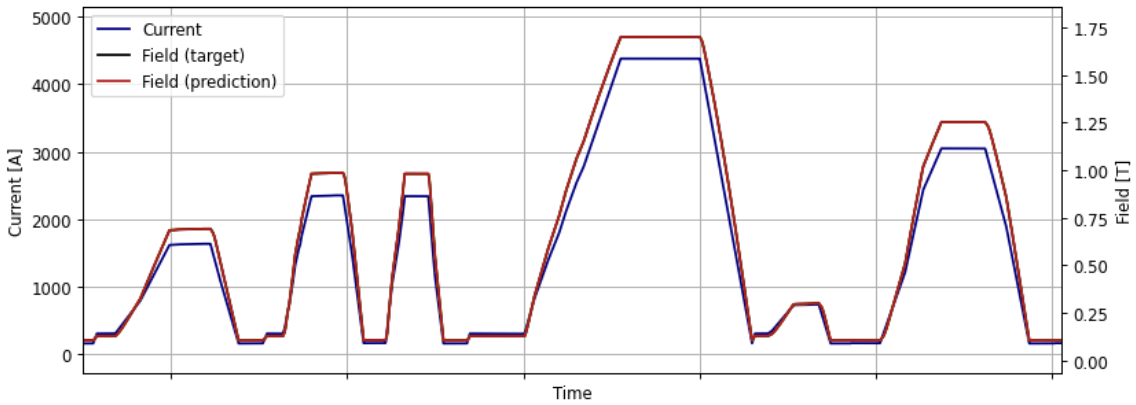



- Compensate magnetic field to what the control system expects
- Non-invasive to existing accelerator hardware

# Fitting transformers on simulated hysteresis

*An interlude…*

- Attention-based models need plenty of data to
  train and generalize well
  - Field measurements from operation can impossibly
    provide sufficient variety in data




- Large amounts of pseudo-realistic, pseudo-random
  waveforms can be generated and then simulated
  - Jiles-Atherton and Flatley ODEs have implementations in Python / MatLab
  - Pre-training learns common waveform shapes and
    generic hysteretic + dynamic behavior

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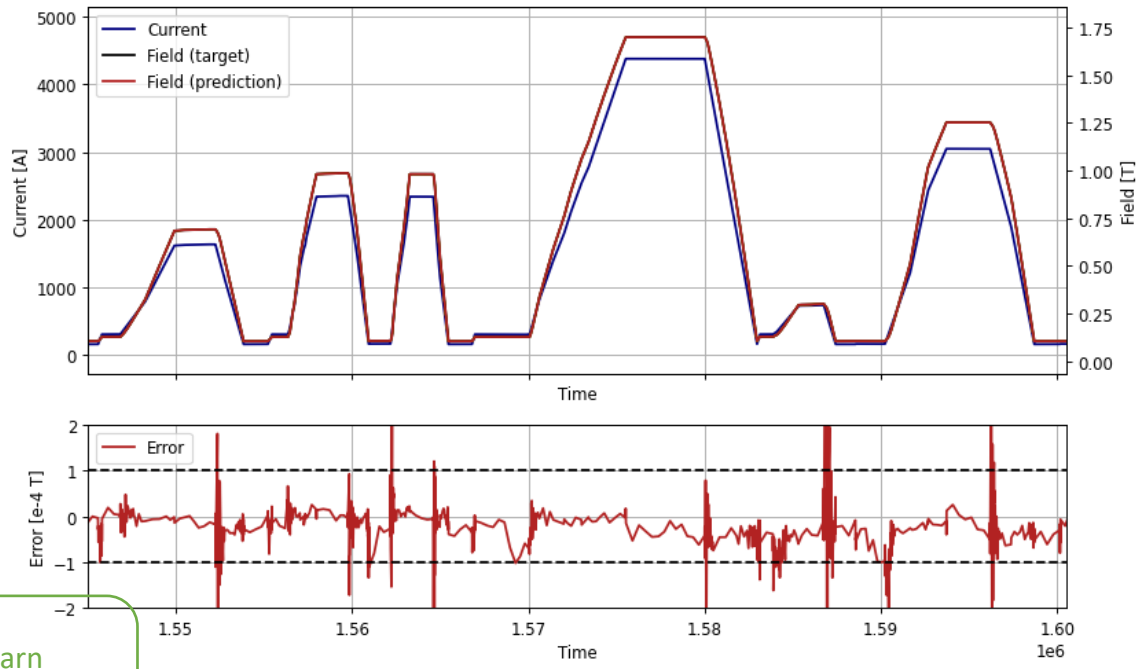


✓We can learn clean hysteretic data sufficiently well!