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FIRST OPERATIONAL EXPERIENCE WITH DATA-DRIVEN HYSTERESIS COMPENSATION FOR THE MAIN DIPOLE MAGNETS OF THE CERN SPS

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Abstract

Magnetic hysteresis, eddy currents, and manufacturing imperfections pose significant challenges for beam operation in multi-cycling synchrotrons. Addressing the dynamic dependency of magnetic fields on cycling history is a current limitation for control room tools using existing models. This paper outlines recent advancements to solve this, presenting the outcome of operational tests utilizing data-driven approaches and an overview of the next steps. Notably, artificial neural networks, including long short-term memory networks, transformers and other time series analysis architectures, are employed to model static and dynamic effects in the main dipole magnets of the CERN SPS. These networks capture hysteresis and eddy current decays based on measured magnetic field and data from the real-time magnetic measurement system of the SPS main dipoles. Cycle-by-cycle feed-forward corrections are implemented through the CERN accelerator controls infrastructure, which propagate corrections of magnetic fields to corresponding adjustments in the current of the power converters feeding the magnets.

INTRODUCTION

The CERN SPS receives proton or ion beams from the PS between energies of 14 GeV to 26 GeV and accelerates them to extraction energies of up to 450 GeV. This corresponds to nominal main bending fields in the SPS dipoles of between 0.06 T and 2.03 T which leaves the linear region of their transfer function (see Fig. 1), leading to hysteresis and saturation.

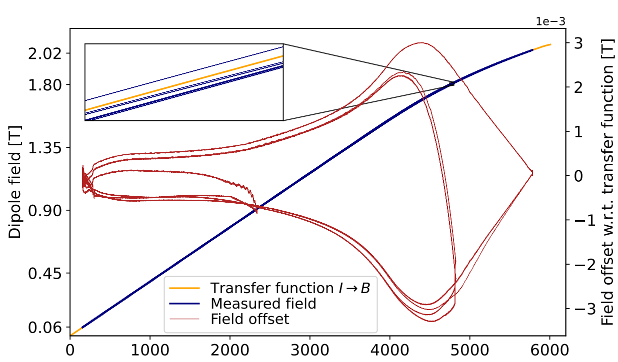

Figure 1: Transfer function mapping excitation current I to magnetic field response B in the SPS main dipoles.

If the sequence of magnetic cycles (so-called supercycle) stays constant, the magnetic field for the different cycles in the sequence is reproducible. However, if the supercycle structure changes, the change in hysteresis will introduce field perturbations for the following cycles (see Fig. 2). Furthermore, induced eddy currents in the magnets create a lagging decay in the magnetic field during and after each ramp, significantly impacting beam quality at the injection plateau following the rapid ramp-down of the previous cycle. The magnetic history is also influenced by the so-called economy mode, whereby the magnets are only ramped halfway, in case the beam is not injected. Due to the perturbing effect of this cycle change, this mode is often disabled, at the cost of over 100 kWh for each 10.8 s fixed target cycle (The fixed target cycle is called "SFTPRO1" in Fig. 2.)

At CERN, all accelerators based on normal conducting magnets are equipped with a system known as the B-Train [1] to measure the magnetic field in real-time in the main bending dipoles. For the CERN PSB and PS, the B-Train is used by the power converters as a feedback to produce the magnetic field requested by the control system [2]. However, the SPS cannot use the current B-Train as input to the main dipole power converters, and it is therefore only used by the RF system and for diagnostics. The methods for mitigating the static and dynamic effects in the SPS magnets across cycles are currently limited to playing a low-energy cycle, called "MD1", to quasi-degauss sextupoles and octupoles and produce reproducible eddy current decays on the injection plateau of the next cycle for the main dipoles and quadrupoles. In the absence of a feedback system for the SPS main dipoles and a lack of real-time field measurement systems for higher-order magnets in all of the synchrotrons at CERN, a hysteresis compensation work package was defined in 2023 as part of the Efficient Particle Accelerators project. This began with a pilot to compensate hysteresis for SPS main dipoles, quadrupoles, sextupoles and octupoles.

This paper presents the first experience of leveraging neural networks to autonomously predict and compensate the fields, cycle-by-cycle, for the SPS main bending magnets, profiting from the abundant magnetic field data measured by the B-Train system. The training data, choice of neural model architecture, parameter selection, and evaluation method will be described. The initial successes of compensating eddy current decay and hysteresis will be presented, and limitations, as well as future steps, will be discussed.

High-Precision Field Control Requirements

With the example of the challenging fixed target cycle with the lowest injection energy of 14 GeV and slow extraction over the 4.8 s flattop, which amplifies perturbations

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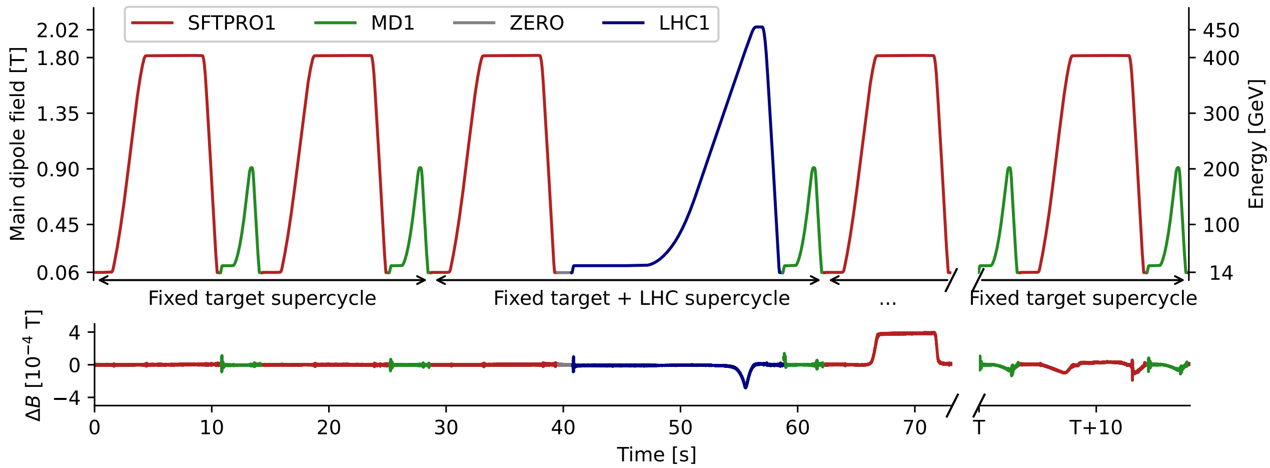

Figure 2: Typical SPS cycle sequence (supercycle) during the physics run. After some time of only fixed target (SFTPRO1) and low-energy machine development (MD1) cycles, a 450 GeV LHC cycle (LHC1) is played. The top plot shows the magnetic cycles with corresponding beam energy; the bottom plot shows the difference in the measured main dipole field for each cycle with respect to an arbitrary reference field from the same cycle type.

of every kind, we introduce the required accuracy of the prediction models developed for hysteresis compensation. The SPS uses chromatic resonant slow extraction [3] for its fixed target program. Slow extraction quality suffers when there is quadrupole hysteresis as it introduces tune working point changes, and also when there is dipole hysteresis as this slightly changes the main field at flattop and thus the radial position and energy offset. Changes in the order of dp/p = 1E-4 are the limit for not perturbing the extraction rate significantly and requiring adjustment. This is equivalent to a dipole field change of 2×10^{-4} T at 1.8 T. As shown in Fig. 2 (bottom), the 4×10^{-4} T change in the main dipole field for the SFTPRO1 flattop caused by a cycle sequence change far exceeds the quality threshold of 2×10^{-4} T. The slow extracted spill therefore has to be adjusted manually to follow these changes.

At the injection plateau of 14 GeV, the remanent field and eddy current decay caused by the preceding cycles cannot be neglected, as even a small change of 2×10^{-5} T, is equivalent to a significant mean radial position change of 1 mm. The accuracy goal for the main dipole field prediction models is currently set to be $\mathcal{O}(10^{-5})$ T, which is challenging, as discussed later.

FEED-FORWARD CORRECTION OF THE MAIN DIPOLE FIELD

With a lack of real-time feedback control for the main dipole fields, we propose a fully autonomous feed-forward compensation strategy. During each cycle, we predict the field for the next cycle, B_{next}, before it starts. This is used to correct the programmed field in the accelerator control system, which propagates the corresponding correction current to the power converters before the next cycle.

We use the state-of-the-art Temporal Fusion Transformer (TFT) neural architecture [4] to learn the history and rate-dependent $I \rightarrow B$ transfer function with a standard quantile loss function. This multivariate time-series prediction model learns to predict the unknown future field B as a function of the knowns, in this case the measured B and I from the past and the programmed I for the future.

We trained the TFT on a two-hour selection of measured current and magnetic field data from the B-Train. This data included diverse operational cycles encompassing dynamic economy mode and standard operation. Additionally, the data incorporated various supercycle changes. The goal was to emphasize the hysteretic behavior typically observed during regular B-Train operations. The data is recorded at 1 kHz, and a moving average filter is applied to smooth and reduce measurement noise before applying a decimation factor of 50 to reach an effective sampling rate of 20 Hz. As the field response predominantly follows a deterministic, nonlinear, magnetization and demagnetization curve, we choose to model only the residual component $B_{\text{res}} = B_{\text{prog}} - B_{\text{meas}}$, as seen in Fig. 1. This transforms the prediction domain from $[0, 2]$ T to $[-4, 4]$ mT, which significantly simplifies achieving the required prediction accuracy.

EDDY CURRENT CORRECTION RESULTS

We tested the trained TFT on a low-energy machine development cycle as shown in Fig. 3, preceded by an SFTPRO1 cycle. The aim was to effectively cancel the eddy current decay in the magnetic field caused by the downramp of the preceding cycle.

For that particular cycle, the beam is injected at 1015 ms at 26 GeV, equivalent to a 0.117 T bending field. Figure 3 shows the effectively constant current input to the dipoles prior to correction, with a slowly ramping field over time caused by eddy current decay corresponding to a change of approximately 3×10^{-5} T over 1985 ms. The field decay results in a radial beam position change over the plateau of

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about 0.4 mm. Following the automatic correction of the field with the proposed compensation algorithm, the programmed current of the main dipoles follows a small ramp down, as opposed to previously staying constant (current change over plateau < 0.1 A). The measured dipole field stays approximately flat, with the beam's radial position staying constant to within 0.1 mm. These results suggest that our method accurately predicts and compensates for these small effects.

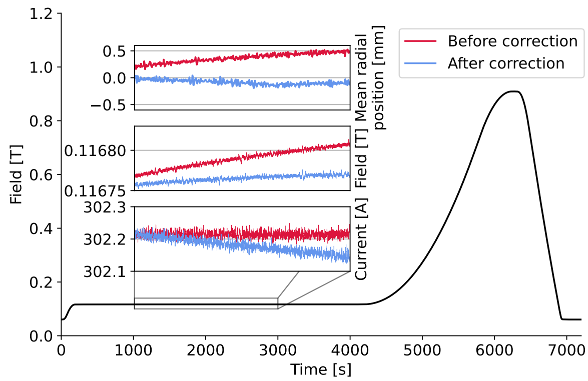

Figure 3: Successful flattening of the injection plateau, where when uncorrected, eddy currents cause a drift in mean orbit of 0.5 mm over a period of 2 s.

HYSTERESIS COMPENSATION AT SLOW EXTRACTION FLATTOP

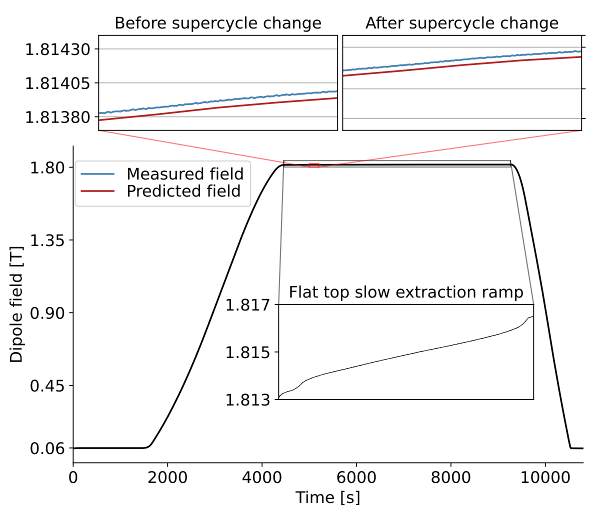

Figure 4: Predicted and measured main dipole field, from 5000 ms to 5500 ms, at the SFTPRO1 slow extraction plateau, before and after an LHC-type cycle is inserted into the supercycle, as seen in Fig. 2.

Further tests were conducted at the fixed target cycle flattop where, during regular operations, effects from hysteresis are most prominent. The SFTPRO1 cycle was played as part of different supercycle compositions, and the measured field at flattop was observed and compared to the TFT predictions. The supercycle was similar to Fig. 2: first with only SFTPRO1 and MD1, and then with an additional LHC-type cycle. The plots in Fig. 4 show the shift in the measured field by 4×10^{-4} T due to hysteresis. In both cases, our transformer model predicts the field with a better than 5×10^{-5} T accuracy, which is below the threshold required for high-quality slow extraction.

LIMITATIONS

As discussed, the goal of the main dipole prediction model is to deliver field prediction accuracies in the order of at least $\mathcal{O}(10^{-5})$ T. However, modeling the accuracy of the measured field is difficult due to integration drift present in the B-Train data when calculating the integral field of the dipole field from the induction coils. The drifts are well outside the required accuracy of 1×10^{-5} T over the duration of the cycle. This can be addressed by conducting ad-hoc measurements of the main dipoles on the test bench instead of using B-Train data. Test bench measurements have the extra advantage of allowing higher flexibility in terms of the supercycle structure used. Ripples in the magnetic field caused by the power converter and measurement noise further complicate the high-precision modeling of the magnetic field response.

Beyond prediction accuracy shortcomings, the SPS power converters require newly programmed current function to be applied 1.7 s before the start of the cycle. This only leaves 800 ms for acquisition, predictions, postprocessing, and sending the new function to the control system. The short time to take action has proven challenging to achieve consistently, and steps to interface directly with the power converters are being explored. Finally, to predict the magnetic fields the proposed architecture requires knowledge of past magnetic fields, which are currently only available for the main dipoles. For higher-order magnets, where no information about past magnetic fields is known, the prediction can only leverage from the predicted field of the previous cycles, and so error accumulation might become problematic. This will be studied in the near future with the dipole data.

CONCLUSION

This paper presents a novel method for high-level feedforward correction of the main dipole fields in the CERN SPS using neural time series prediction. The first successful tests of the model for eddy current compensation at 14 GeV and high-precision prediction of field changes at the 400 GeV slow extraction plateau support the effectiveness of the chosen model and method. However, limitations in prediction accuracy and infrastructural challenges remain.

As the field compensation method is further developed and refined for operations, high-precision lab measurements will take place for the SPS main quadrupoles, sextupoles, and octupoles with improved drift correction methods. In parallel, further hysteresis models are being explored, such as fitting the transfer function with physics-based loss functions in combination with state-of-the-art transformer-based architectures.

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