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EXPERIMENTAL DEMONSTRATION OF MACHINE LEARNING APPLICATION IN LHC OPTICS COMMISSIONING

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Abstract

Recently, we conducted successful studies on the suitability of machine learning (ML) methods for optics measurements and corrections, incorporating novel ML-based methods for local optics corrections and reconstruction of optics functions. After performing extensive verification on simulations and past measurement data, the newly developed techniques became operational in the LHC commissioning 2022. We present the experimental results obtained with the ML-based methods and discuss future improvements. Besides, we also report on improving the Beam Position Monitor (BPM) diagnostics with the help of the anomaly detection technique capable to identify malfunctioning BPMs along with their possible fault causes.

INTRODUCTION

Machine Learning (ML) techniques recently have demonstrated a great potential to improve the optics measurements and corrections in terms of measurements data quality, speed and level of automation [1,2]. Previous works utilized simulations and historical data to verify the performance of developed ML-techniques. The successful restart of the LHC in 2022 made it possible to apply the developed methods during LHC optics commissioning, for the first time, under challenging optics settings where the beams are squeezed to β^*=30 cm [3]. In this paper we summarize the results obtained in operation and discuss future improvements. First, we present the results of turn-by-turn data cleaning, including hardware verification performed by beam instrumentation experts. Second, we compare triplet magnet errors identified by pre-trained ML estimator to local corrections found by traditional techniques. Then, we present another application of supervised learning, namely a virtual diagnostic tool to predict β-functions next to Interaction Points (IPs) and horizontal dispersion, without performing dedicated measurements. Finally, we explore future improvements of presented ML-based methods and potential new applications.

DIAGNOSTICS OF FAULTY BEAM POSITION MONITORS

Turn-by-turn data (TbT) for optics analysis is cleaned by the means of SVD-based algorithm, simple thresholds-based filtering and Isolation Forest (IF) anomaly detection [2]. During the LHC long shutdown, extensive work in collaboration with CERN's beam instrumentation experts allowed to verify the findings of cleaning methods against actual instrumentation issues. Several sets of historical measurements from the past years have been analysed, in order to identify the BPMs marked as faulty in most of the measurements and BPMs which cause unphysical outliers in the optics functions if remaining in TbT-data. In total, out of more than a thousand LHC BPMs, we identified 116 faulty BPMs which are critical for the optics measurements. Remarkably, 50 % of the BPMs reported by combined SVD and IF cleaning, revealed hardware or signal processing issues which otherwise stay hidden. In the commissioning, we applied SVD and IF cleaning with the settings refined on simulations, which demonstrated that cleaning does not affect the measurements in a negative way in terms of false positive classification as shown in Fig. 1. This is important in light of BPM upgrades performed by beam instrumentation experts to solve the identified problems, fewer faulty BPMs are expected to appear in TbT data.

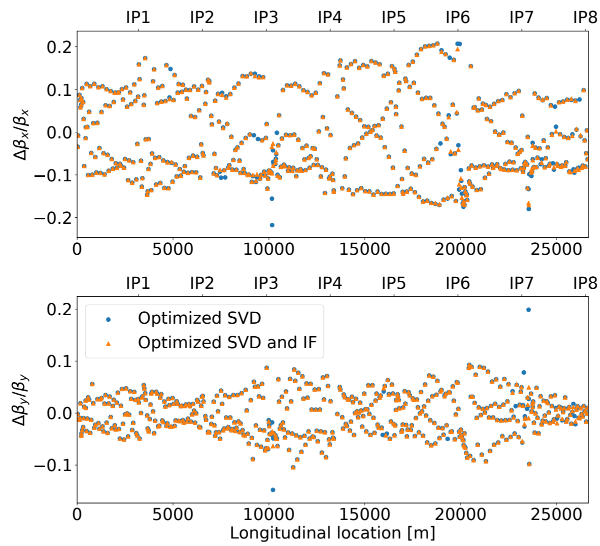

Figure 1: β-beating computed with and without IF-cleaning.

QUADRUPOLE ERRORS PREDICTION

Supervised learning based quadrupole errors prediction allows to reconstruct individual magnet gradient field errors along the whole LHC lattice, correcting the linear optics errors in both beams simultaneously [1]. However, optics corrections using quadrupoles in the arcs are possible only by trimming the circuits, i.e. several quadrupoles powered in series. Therefore, we verify the new concept first for the local corrections in the IRs, since the triplet quadrupoles, whose

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imperfections cause the largest contribution to β-beating can be trimmed individually. We trained a regression model based on the Random Forest (RF) algorithm [4] on a data set built from 60 000 MAD-X simulations where a set of randomly generated quadrupole errors are added to the ideal optics model with $\beta^* = 30$ cm. Each training sample includes 32 output targets corresponding to individual triplet errors and 2215 input features from phase advance differences to the nominal model at every BPM for beam 1 and 2, horizontal and vertical planes. Realistic noise is additionally introduced to the simulated phase advances. The relative RMS error of prediction obtained on a test set is 16%, which is consistent with the previous results, training regression models for different LHC optics settings [5]. Currently, the Segment-by-Segment (SbS) technique is the standard method to correct strong local error sources [6]. It relies on running MAD-X simulations between two BPMs, taking the measured optics functions as start parameters of simulations. The corrections using the quadrupoles inside the segment are then computed by comparing the measured and the simulated phase advances. Matching simulated phase advance errors to the measured ones indicates how well the optics will be corrected by implementing the computed corrections in the LHC. We use the propagation of errors inside a segment implemented as part of the SbS tool to verify the local corrections predicted by the Random Forest model from the measured phase advance-beating. The target is to correct the local errors in IR 1, after reducing the initial peak β-beating of 150% by the means of global coupling and local errors corrections in IR 5 using traditional techniques [7]. Figure 2 demonstrates the great agreement between measured phase advance errors and matching the measurement with predicted triplet errors. ML-based corrections computation required significantly less time compared to traditional techniques and can be computed simultaneously from the phase advances measured in both beams. Further improvements in terms of β-beating reduction are expected by extending the model input with β-functions measured around the IPs.

Table 1: Comparison of ΔK_1 $[10^{-5} m^{-2}]$ corrections for IR 1. Note that APJ used only Q2 and Q3 quadrupoles.

Magnet	APJ	SbS	ML
MQXA1.L1	-	1.23	1.23
MQXA1.R1	-	-1.23	-1.24
MQXB2.L1	1.15	1.22	-0.11
MQXB2.R1	-0.87	-1.22	0.18
MQXA3.L1	1.94	0.41	0.31
MQXA3.R1	-2.88	-0.7	-0.1

We also compare the obtained correcting triplet strength changes (ΔK_1) to the Action-Phase-Jump (APJ) technique [8, 9], that has been applied for the LHC optics corrections for the first time this year and to SbS. While ML-based corrections use only phase advance beating as input, SbS and APJ additionally take into account β from k-modulation. Hence, the corrections from ML-model are weaker as shown in table 1. Nevertheless, the matching results demonstrate that smaller change in Q1 and Q3 still can significantly reduce the phase-beating.

Table 2: Comparison between measured β-function at the IPs and ML-prediction.

Location	K-mod	ML	$\Delta\beta/\beta_{kmod}$
	β_x, β_y[m]	β_x, β_y [m]	x, y [%]
B1, IP1L	1262, 1074	1296, 1223	2.6, 13.8
B1, IP1R	1340, 1051	1268, 1197	5.3, 13.9
B1, IP5L	1388, 1552	1377, 1659	0.8, 6.9
B1, IP5R	1302, 1624	1369, 1642	5.2, 1.1
B2, IP1L	1406, 1773	1435, 1851	2.1, 4.4
B2, IP1R	1366, 1947	1412, 1893	3.4, 2.7
B2, IP5L	1511, 1364	1639, 1315	8.4, 3.6
B2, IP5R	1637, 1377	1632, 1303	0.3, 5.4

VIRTUAL OPTICS MEASUREMENTS

Virtual diagnostics is one of the widest areas of ML application in accelerators. Supervised learning allows to create models capable to predict optics observables without direct measurements. Optics measurements at the LHC can benefit from this concept to reduce the time needed to obtain the data for optics analysis. In this study, we employ the concept of supervised learning in order to build linear regression models for the prediction of normalised dispersion and β-function from the phase advance deviations from nominal design. Phase advances can be easily obtained from harmonic analysis of turn-by-turn data and is a standard first step of optics analysis. The same training data as for quadrupole errors prediction can be used and hence, no additional time for data generation is required.

Reconstructing β Functions in Interaction Regions

Local corrections in the IRs can be improved by including the β-functions at the location of the BPMs next to the IPs into corrections computation. In the LHC, these values are typically obtained with the help of k-modulation technique [10, 11], which also produces the measurement of β^*. However, in order to obtain the β-functions, time consuming quadrupole current modulation has to be performed, followed by semi-automatic cleaning of tune measurements. We trained a Ridge Regression [12] model using samples pairs with the input consisting of phase advance deviations from the nominal model caused by quadrupole errors, and corresponding β-functions around the IPs as output. After the estimator is fitted on the training data, the prediction of β values based on the provided phase advance measurements can be obtained within a few seconds, while k-modulation usually consumes several minutes. Simulations show that the uncertainty of the k-modulation technique for the design $\beta^* = 30$ cm ranges from 1% to 8% depending on the assumed tune measurements resolution and included magnets errors [13]. β-function values at the BPMs left and right

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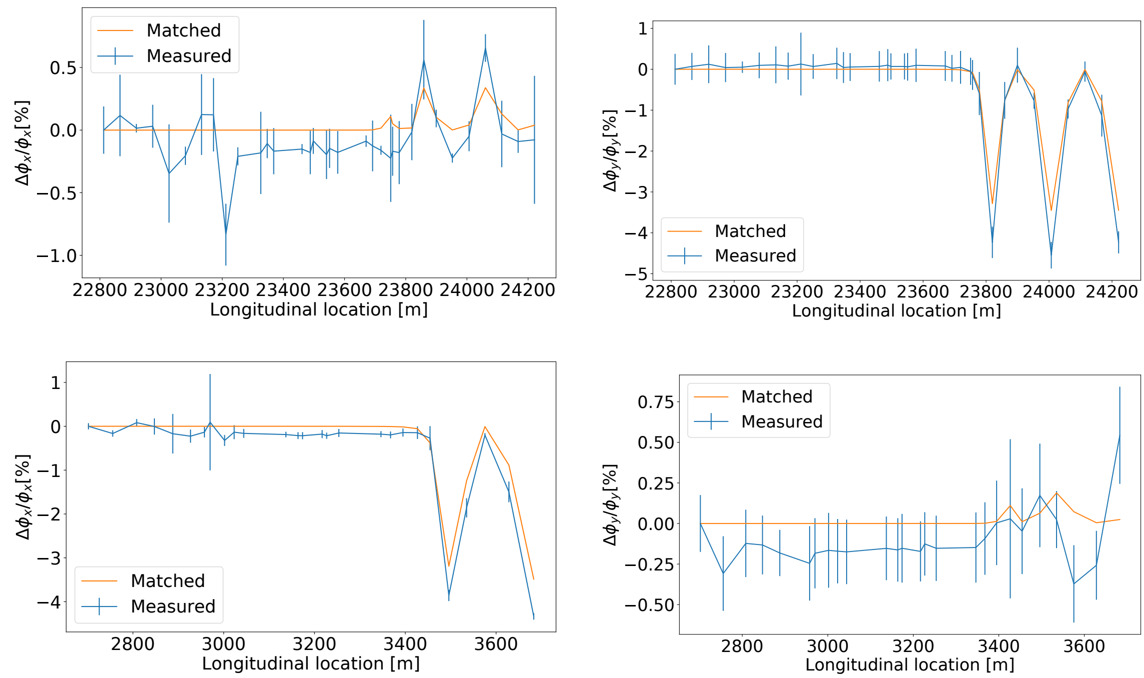

Figure 2: ML-based correction of phase-beating in IR 1, for Beam 1 (upper) and Beam 2 (lower), horizontal and vertical planes left and right respectively.

from IP 1 and 5 obtained from k-modulation and ML prediction are listed in table 2. The measurements are performed with $\beta^* = 30$ cm, demonstrating the average difference between k-modulation and ML prediction of 5%.

Normalised Dispersion Reconstruction

Normalized dispersion is an important optics observable which is independent from BPM calibration and is included into the computation of global corrections. Usually, normalized horizontal dispersion is computed by acquiring turn-by-turn data from several beam excitations, shifting the momentum. As a time-saving alternative, we propose ML-based reconstruction of normalized horizontal dispersion directly from phase advance obtained from a single on-momentum beam excitation. During LHC commissioning, normalized dispersion measurements with $\beta^* = 30$ cm have been performed, together with predicting this observable from phase advance at every BPM location. Simultaneous reconstruction of normalized dispersion in beam 1 and beam 2 using ML requires only a few seconds. The comparison between measured normalized dispersion and its prediction is presented in Fig. 3. The averaged relative error of prediction is 5% and 7% in beam 1 and beam 2, respectively. This result is consistent with the accuracy of the trained estimator on validation data from simulations [14] and demonstrates the potential of the method to save the dedicated measurements time. The accuracy of prediction can be further improved by reducing the noise in the phase advance measurements used as input as previously demonstrated on simulations in [15].

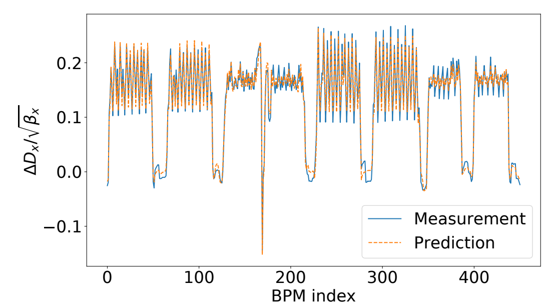

Figure 3: Comparison between measured normalized horizontal dispersion and ML-based reconstruction for beam 2.

CONCLUSIONS

Exploring the results of faulty BPMs detection using the IF algorithm allowed to identify actual hardware and calibration problems, which are being analysed by the experts. For the first time, ML-based local optics corrections have been performed at the LHC during optics commissioning. The predicted triplet errors differ from the correction values obtained with traditional techniques, however these errors correspond well to the measured phase-beating. As next step, we will include the β-function in the IRs into the model in order to obtain even more accurate reconstruction of triplet errors. We also demonstrated an ML-based method to reconstruct β around the IPs and normalized horizontal dispersion, for both beams simultaneously, directly from measured phase advances on-momentum. After these first remarkable achievements, further developments will potentially lead to speed-up machine commissioning for the same performance.

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