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DELIVERABLE REPORT

WP3 – REPORT ON THE SERVICE IMPROVEMENTS FOR MATERIAL TESTING RIs

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Abstract:

The present document reports on the service improvement activities performed for the HiRadMat facility of CERN, which is part of the Work Package 3 of EURO-LABS. In particular, the development of a novel machine learning-based Beam Position Monitor (BPM) calibration method was studied. This method aims to reduce systematic errors in transverse beam position measurements and improve beam delivery in the facility.

D3.5 – WP3 REPORT ON THE SERVICE IMPROVEMENTS FOR MATERIAL TESTING RIS

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For more information on EURO-LABS, its partners and contributors please see <https://web.infn.it/EURO-LABS/>

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Executive summary

The beam delivered at HiRadMat suffers from uncertainty in the beam position measurements, in the experimental area, and in the transfer line upstream. A significant source of position fluctuations stems from the extraction kicker's dependence on the momentum spread and the exact transverse position of the beam when it is extracted from the SPS. The service improvements funded by EURO-LABS involved the development of a novel machine learning-based calibration framework for the Beam Position Monitors (BPMs) of the SPS, aiming to reduce the systematic errors in the position measurements, and subsequently increase the stability and reproducibility of the delivered beams, not only in HiradMat, but in the SPS complex in general.

This document summarizes the status of the work done on this service upgrade of the beam position measurements. It also describes the steps towards full deployment, which is foreseen to start in 2026.

1 INTRODUCTION

EURO-LABS is a network of 33 research and academic institutions (25 beneficiaries and 8 associated partners) from 18 European and non-EU countries, involving 47 Research Infrastructures within the Nuclear physics, Accelerators and Detectors pillars. In this large network, EURO-LABS will ensure diversity and actively support researchers from different nationalities, gender, age, and variety of professional expertise.

Within EURO-LABS, Work Package 3 (WP3) provides Transnational Access (TA) to Research Infrastructures for Accelerator R&D. The facility participating in Task 3.1, HiRadMat, offers a unique high-power pulsed beam irradiation capability for advanced R&D on material testing and the validation of accelerator components for present and future accelerators, but also on novel physics experiments on beam impact on materials.

The Service Improvement (SI) in HiRadMat focuses on developing a system to enhance beam position monitoring and precision, a critical parameter for experiments conducted at the facility.

2 HIRADMAT – CERN

2.1 IMPROVEMENTS

The beam at HiRadMat is quite challenging to produce, control and monitor, given its very high instantaneous power and the high intensities delivered in the facility. Several operational issues have been identified in dedicated studies, including uncertainty in the beam position readings in the experimental area and the upstream transfer line. Accurately identifying the transverse beam position is critical, both for the experiments and the machine itself. A significant source of position fluctuations stems from the extraction kicker's dependence on the momentum spread and the exact transverse position of the beam when it is extracted from the SPS.

The transverse beam position in the SPS accelerator ring and extraction lines is monitored via the ALPS (A Logarithmic Position System) Beam Position Monitoring system. The exact beam position reading during operation is very sensitive to the exact calibration of these devices, that essentially maps the output response of two electrodes to the actual beam position that triggered it. Currently, the calibration of the Beam Position Monitors (BPMs) relies on polynomial fits that are used to map online the response of each device. This calibration method is known to suffer from systematic errors in the position measurements, which increase significantly for off-centred beams. This affects especially the extraction points and the transfer lines, causing position uncertainty that propagates to the facilities and experiments that receive beam from the SPS, such as those at HiRadMat.

A doctoral student working within the CERN SY-BI group, in collaboration with the University of Oxford, has been funded by EURO-LABS to work on the development of a novel machine learning-based calibration method for these BPM devices, with the goal to reduce these systematic errors in the position measurements. In particular for HiRadMat, improved precision of these measurements is critical for the experiments in the facility and something that was a standing issue for long-time. This work will subsequently increase the stability and reproducibility of the delivered beams, not only in HiradMat, but in the SPS complex in general.

The problem to solve was non-trivial. To minimize the position uncertainty, it's important to minimize as much as possible the systematic errors that are inherent in the chosen calibration method. The system at question is susceptible to small variations; even minor errors can be translated to a “fake” change in position. Therefore, it was crucial to map the response of each device separately, which is a complex process in its details. Additionally, each of the ~250 BPM devices in the SPS has a unique response and requires its own calibration parameters. Consequently, the suggested solution needs to be effective in reducing systematic errors, while also being efficient in terms of the number of parameters used and the computational load.

Single Electrode Analysis

The initial stage of the service improvement work has focused on the so-called “single electrode” analysis, using calibration data from individual BPM electrodes obtained off-line. For this part of the analysis, we trained individual neural network models to map the response of each one of the two electrodes of a BPM device, and calculated the residual systematic position errors by combining the individual signals at a subsequent stage. We started by developing and testing neural network models using TensorFlow before migrating to PyTorch, which is a more flexible and widely adopted framework in the accelerator physics community. We conducted extensive tests varying the number of hidden layers, neurons per layer and training parameters, to identify regions of stability in the parameter space, where the model converges reliably and achieves low loss values.

These tests were successful and resulted in identifying a stable area in the parameter space where we could train/test our models and proceed to the next, more advanced steps. In Fig. 1, the results from the single electrode analysis are shown, illustrating model convergence for the appropriate parameters, while the right figure displays one of the unsuccessful trials. This part was essential to narrow down the basic parameters that would be used for the double electrode analysis that followed.

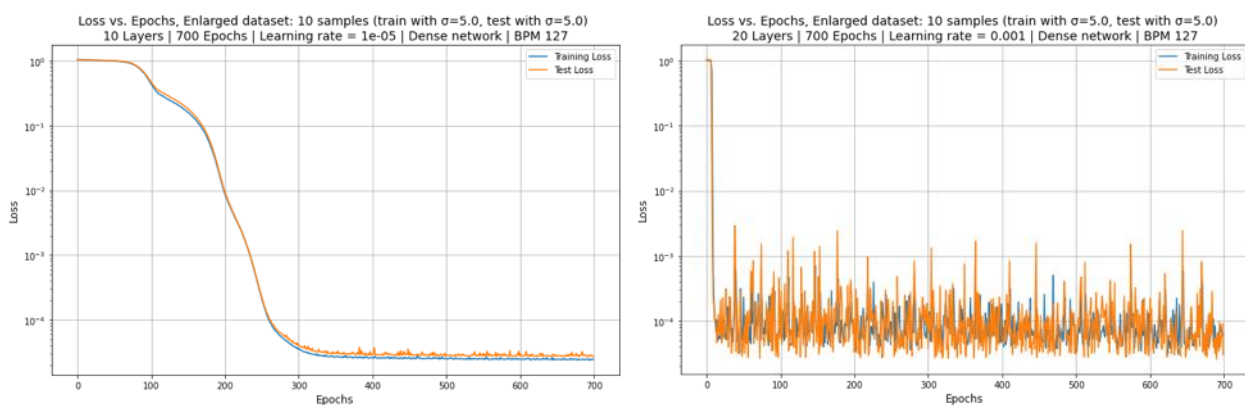


Fig. 1: Single electrode analysis loss plots. On the left, an area of stability has been identified in the parameter space and the model converges. On the right, exploratory trials with different parameters lead to configurations that do not achieve optimal convergence, helping us to identify stable parameter regions for subsequent stages of the analysis.

Double Electrode Analysis

Based on the first part, we expanded to double-electrode analysis, in which the model predicts the position of the beam by directly combining signals from both electrodes. The optimisation and analysis are currently progressing; promising results indicate that the neural network can outperform the polynomial approach in certain operation regimes, which is already a very useful result for

HiRadMat. In parallel to the main workflow, techniques for data augmentation, scaling and robustness against different noise conditions have been studied.

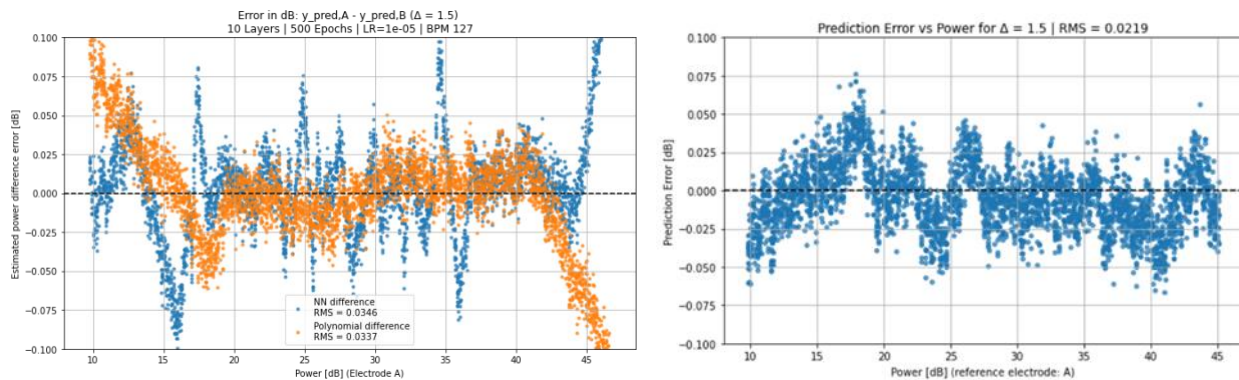


Fig. 2: Position measurement error, expressed as error in power difference between the two electrodes in dB. In these plots, a beam position offset equal to $\Delta = 1.5$ dB has been assumed, which corresponds to a few ~ 100 μm , depending on the device.

- **On the left:** in blue, the position error calculated with the single electrode analysis approach; in orange, the error calculated with the polynomial approach.
- **On the right:** the error calculated with the double electrode analysis approach. Smoother behaviour observed, especially close to the edges of the power range, which can allow for smoother control during beam steering.

2.2 STATUS

The service improvement studies have concluded on the possibility of a neural network-based calibration method that receives as input the digital output of the two electrodes of a BPM device and gives an accurate signal difference between the signal measured by the two electrodes, which corresponds to the measured transverse beam position. For best performance, one model will need to be trained for each one of the SPS BPM devices, with calibration data that has been obtained offline. Further work is planned to fine-tune the neural network parameters, aiming at even lower position errors and/or smoother error curves for the wide range of possible beam position offsets. This will enable more accurate position measurements for certain BPM operation regimes, particularly those involving measurements over multiple turns.

Due to the nature of the system, deployment is foreseen during the long shutdown of the CERN accelerator complex (LS3) in 2026, in line with the CERN accelerator schedule. Until then, EURO-LABS funding ensures steady progress on optimisation in terms of hyperparameters, computational power and defining the exact implementation details. Eight additional months will be funded by CERN for the completion of the thesis and the finalisation of the suggested solution. If time allows, additional comparison between different machine learning regimes will be performed.

2.3 USE OF RESOURCES

The budget profiling from EURO-LABS is approximately 32,000 CHF per year for each of the three years (2024–2025–2026) and will be fully utilized. At the same time, the full cost of this studentship, i.e. 8 additional months, will be complemented by internal CERN funding.

2.4 FEEDBACK FROM OPERATIONS

As described above in Section 2.2, the service improvements are expected to be implemented starting in 2026, to become fully operational when the beams restart after the CERN long shutdown (LS3) in 2029.