15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPS55

SLOW EXTRACTED SPILL RIPPLE CONTROL IN THE CERN SPS USING ADAPTIVE BAYESIAN OPTIMISATION

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Abstract

The CERN Super Proton Synchrotron (SPS) offers slow-extracted, high-intensity proton beams at 400 GeV/c for 3 fixed targets in the CERN North Experimental Area (NA) with a spill length of about 5 seconds. Since first commissioning in the late seventies, the NA has seen a steady increase in users, many of which requiring improved spill quality control. Slow extraction produces effects detrimental to spill quality. While some of these effects have been addressed in recent years, continuous compensation of intensity fluctuations at 50 Hz harmonics originating from power converter ripple has been particularly difficult to solve. In 2023, the deployment of two techniques - "Empty-Bucket Channelling" and active control with Adaptive Bayesian Optimisation – resulted in a significant suppression of these intensity modulations. This paper focuses on using Adaptive Bayesian Optimisation for 50 Hz harmonic control. The chosen algorithm is described, together with details of integration in the CERN control system. The 2023 results are presented and complemented with an overview of the next steps.

MOTIVATION

The third-order resonant extraction at 400 GeV/c from long straight section 2 (LSS2) at the Super Proton Synchrotron (SPS) at CERN serves the fixed target experiments in the SPS North Area (NA). For an ideal spill, the rate of extracted particles dN/dt should remain constant over the 4.8 s long extraction plateau. The macro structure is corrected for that purpose in feed-forward by adjusting the high-level momentum parameter p using *COSE* [1], the 200 MHz from the main SPS RF system is removed by debunching the beam [2], and the fluctuations at 50 Hz and harmonics introduced by the power supplies are controlled by injecting a voltage modulation in the main quadrupole circuit QF at 50 Hz, 100 Hz, and 150 Hz at adjustable phase and amplitude.

As discussed in detail in [3], one of the key requirements for the various feed-forward correction schemes is reproducibility. None of the methods were initially conceived for continuous control. For instance, changes to the set of magnetic cycles played one after the other, the so-called super-cycle, changes the fields of the SPS magnets due to hysteresis and hence the flux of extracted particles during slow extraction. A pilot project for hysteresis modelling and correction is currently underway to address this issue [4]. Amplitude and phase of the $n \times 50$ Hz perturbations also

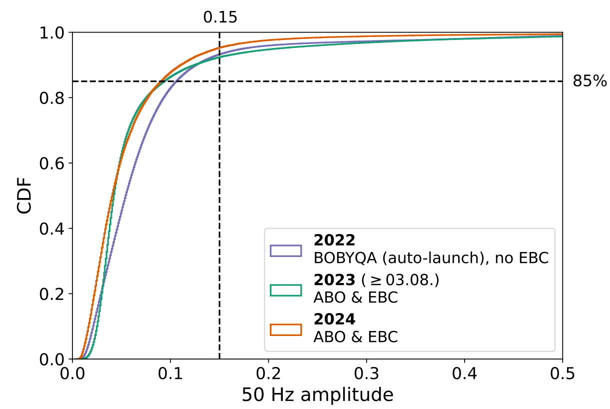

Figure 1: Cumulative distribution function (CDF) for 50 Hz normalised amplitudes in slow extracted spills for 2022, 2023 with operational ABO and EBC, and the 2024 run until 23rd April. The dashed lines indicate the target. Fraction of amplitudes below 0.15: 93.2% [2022], 92.3% [2023], 95.2% [2024].

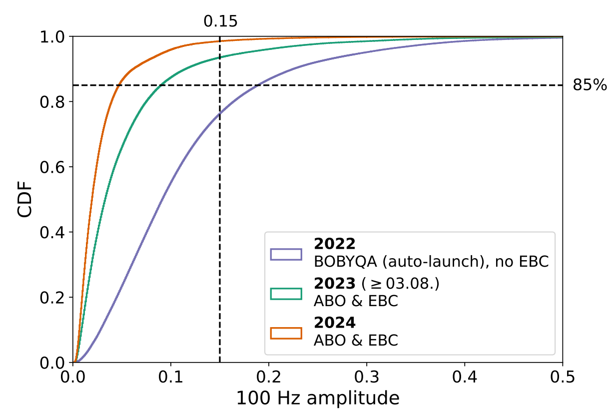

Figure 2: Cumulative distribution function for 100 Hz normalised amplitudes in slow extracted spill for 2022, 2023 with operational ABO and EBC, and the 2024 run until 23rd April. The dashed lines indicate the target. Fraction of amplitudes below 0.15: 76.2% [2022], 93.5% [2023], 98.5% [2024].

change over the course of a day following changes in the electricity supply grid. Furthermore, since the re-start after the Long Shutdown (LS) 2 (2019-2020) and the upgrades of the SPS as part of the LHC Injectors Upgrade (LIU) project [5], the 100 Hz component now needs to be actively controlled in addition to 50 Hz. To date, the origin of the 100 Hz noise has not been understood. No adaptive correction scheme is necessary for 150 Hz.

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This paper discusses the continuous control solution developed for stabilising the $n \times 50$ Hz perturbations of the slow extracted spill over time. It introduces the concepts of Adaptive Bayesian Optimisation (ABO), discusses robustness and limitations from instrumentation as well as the algorithm and shows the results achieved in 2023 and the beginning of the 2024 physics run. In conjunction with the broadband noise reduction scheme *Empty Bucket Channeling* (EBC) [6], ABO fulfils the requirements set by the North Area experiments of remaining below a normalised amplitude of 0.15 for 50 Hz and its harmonics for at least 85 % of the time.

Solving the $n \times 50$ Hz Control Problem

Spill ripple at 50 Hz and harmonics have always been an issue in the SPS. However, since the 2021 run after LS2, the previously infrequent manual adjustments were no longer sufficient. Therefore, in 2022, numerical optimisation (BOBYQA algorithm [7]) in auto-launch mode replaced the manual scans. While the obtained results were satisfying for 50 Hz, suppression of the 100 Hz was far from the requirements of the experiments. In addition, the necessary exploration phase at each launch of the optimiser caused issues for experiment data taking. As a consequence, the continuous control algorithm Adaptive Bayesian Optimisation (ABO) was prepared for the 2023 start-up and continuously improved during the run. For example, to achieve sufficient reactivity the algorithm needed to be run on GPU (on CPU it took up to 7 cycles (7 × 14.4 s) for the next prediction) and to be deployed as a background process using CERN's UCAP framework [8] and the extension package `acc-geoff4ucap`. However, it is only with *Empty Bucket Channeling*, deployed since August 2023, that enough margin was introduced for ABO to continuously follow the phase and amplitude changes to generally remain well below a normalised amplitude of 0.15. Figures 1 and 2 show the results for 50 Hz and 100 Hz for the physics run of 2022, the period in 2023 when both EBC and ABO were operational, and the first part of the physics run in 2024 (with an optimised UCAP configuration and improved EBC settings).

Figures 3 and 4 show the comparison of the amplitude distributions for the 7 days before and after deploying EBC in the SPS while ABO was running continuously. EBC improved the amplitude distribution significantly in the range of interest, especially for 100 Hz.

ADAPTIVE BAYESIAN OPTIMISATION

Bayesian optimisation is a powerful black-box optimisation algorithm, which learns a probabilistic model of the objective function with Gaussian processes (GP) [9]. To make use of the model's uncertainty, the so-called *Acquisition Function* is optimised, rather than the mean $\mu(\mathbf{x})$ of the objective function. In our case, we used the *Upper Confidence Bound Acquisition Function* (UCB):

$$a(\mathbf{x}) = \mu(\mathbf{x}) + \sqrt{\beta}\,\sigma(\mathbf{x}), \quad (1)$$

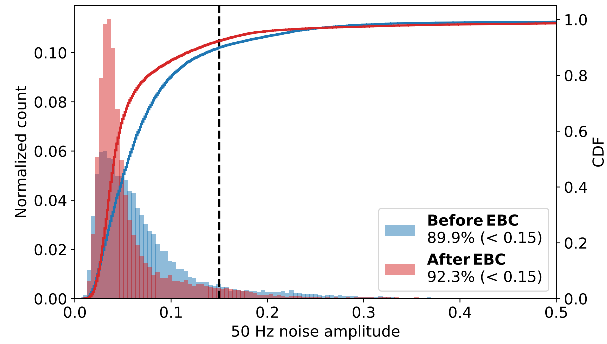

Figure 3: Distribution of 50 Hz normalised amplitudes in slow extracted spills for the 7 days before and after the deployment of *Empty Bucket Channeling* on 3rd August 2023.

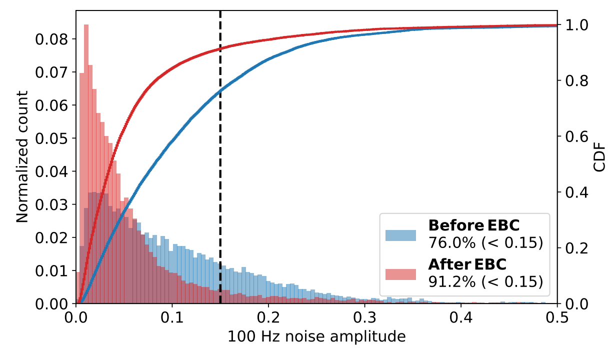

Figure 4: Distribution of 100 Hz normalised amplitudes in slow extracted spills for the 7 days before and after the deployment of *Empty Bucket Chann eling* on 3rd August 2023.

where $\mu(\mathbf{x})$ is the mean of the posterior Gaussian process and $\sigma^2(\mathbf{x})$ the variance. β is a hyperparameter that needs to be tuned for the specific application. It defines the balance between exploration and exploitation during the optimisation process. To use Bayesian optimisation as a continuous control algorithm and make the algorithm adapt to changes, the objective function is not only modelled as a function of the control parameters $\mathbf{x}$ (phase and amplitude in our case), but also as a function of time t. In this sense predicting the optimal next control parameters becomes *forecasting* the next optimum parameters for one time step into the future. In case the system changes, the learned time dependence will tell the model to focus more on the most recent data points. The kernel function of the GP (or prior covariance of the GP) is chosen such that it can represent the correlations in the data well. Following [10] the kernel that we use in ABO is a composite kernel with a *spectral mixture kernel S* for t and the *Matern kernel M* for $\mathbf{x}$:

$$k([t_1, \mathbf{x_1}], [t_2, \mathbf{x_2}]) = \theta_k \times S(t_1, t_2) \times M(\mathbf{x_1}, \mathbf{x_2}), \quad (2)$$

where θ_k is the output scale.

ABO in the CERN Control System

For our use case, ABO was implemented with BoTorch [11] which allows for GPU-accelerated Bayesian optimi-

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sation. The 50 Hz and 100 Hz spill noise compensation controllers are running as background processes on a UCAP node with one NVIDIA A100 Tensor Core GPU. The hyperparameters of ABO as well as the bounds for the allowed phase and amplitude changes are managed through the CERN accelerator settings management system [12] (see Table 1 for the current hyperparameter settings). As such it is integrated like any other system in the SPS. To use ABO for continuous control, the data buffers for conditioning the GP models need to be truncated. The lengths of the buffers were chosen to ensure stability (see Table 1). When ABO is initially launched, it will first collect data with random settings. To avoid the initial data collection phase for subsequent starts, initialisation data is stored every 10 shots for model conditioning at start-up.

Table 1: Hyperparameters for 50 Hz and 100 Hz ABO controllers. The parameters were obtained with initial tuning in simulation and online in 2023. The phase ranges and amplitude ranges in particular for 50 Hz could potentially be further reduced.

ABO	β	**buffer length**	**phase range [degrees]**	**amplitude range [arb. units]**
50 Hz	0.2	250	$[10, 70]$	$[3, 80]$
100 Hz	0.5	180	$[-80, -10]$	$[5, 90]$

LIMITATIONS

In slow extracted beams Secondary Emission Monitors (SEMs) [13] have to be used for beam intensity measurements, and are known as *BSI* monitors in the SPS [14]. The spill BSI acquisition system theoretically delivers data for the entire spill of 4.8 s at a rate of several 10s of kHz, sufficient for correction of power converter ripple at $n \times 50$ Hz [15]. However, a particular issue with these spill monitors is the significant instrumental noise at 50 Hz. The monitor can therefore only be reliably used for ABO above an extracted intensity of about $5{\times}10^{12}$ protons, where approximately 10% of 50 Hz intensity fluctuations are above the monitor noise. This is a factor of 10 above the usual setting-up intensity. The typical extracted intensity for physics is $> 1 \times 10^{13}$ protons. Some of the ABO 50 Hz compensation will therefore also be compensating instrumental noise. A new generation of fast spill monitors is being developed to address this and other issues in view of future experiments in the North Area [16].

Other limitations come from the algorithm itself. Figure 5 shows an example of the data stored in the logging buffer of the 50 Hz controller, showing the evolution of the normalised 50 Hz amplitude as well as the normalised phase and amplitude applied by the controller. The controller manages to keep the amplitudes below 0.15 (red dashed line) for more than 90% of the time in that example. However, when the 50 Hz phase and amplitude of the spill change rapidly, ABO will not react immediately, but only when the GP model has been conditioned with enough new data to have a model better adapted for the new situation. This is the reason why the 50 Hz spill amplitudes are not "flat" as a function of time in Fig. 5. Also, dependent on the hyperparameters and the model quality obtained after fitting (which is currently done for every shot), ABO occasionally predicts non-optimum settings (see the 4 setting spikes in Fig. 5) leading to large 50 Hz spill amplitudes. While these erroneous settings are infrequent enough not to influence the statistics, they could become an issue for future experiments. Studies are currently underway to ensure that only good-quality models are used for inference.

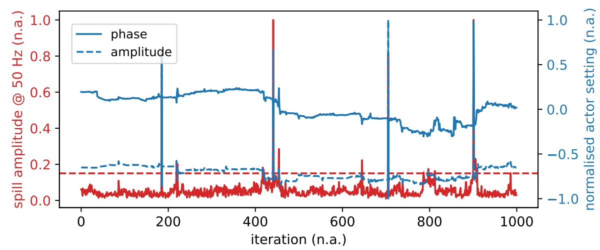

Figure 5: Example ABO logging buffer with 1000 iterations on 15th April, 2024, for 50 Hz. The normalised spill amplitudes as well as applied phase and amplitude actions are shown. The controllers work in normalised action space in the range of [-1,1].

CONCLUSION

The fixed target experiments in the CERN North Area expect constant particle flux during the roughly 5 s slow extraction from the SPS. The intensity fluctuations at 50 Hz and its harmonics have always been an issue, but became particularly difficult to control following upgrades performed during the CERN Long Shutdown 2. The application of a continuous control algorithm using Adaptive Bayesian Optimisation (ABO) in conjunction with *Empty Bucket Channeling* finally managed to stabilise the $n \times 50$ Hz spill ripple well within the targets established by the experiments. The successful implementation of ABO demonstrates not only the potential of machine learning for accelerator control, but also the AI-readiness of the CERN control system that allowed straightforward integration of ABO as a background process. Limitations of the algorithm and, in particular the fast spill monitor, are being worked on in view of future North Area experiments.

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