

A BAYESIAN OPTIMIZATION STUDY OF THE LONGITUDINAL LOCALIZED EXCITATION SLOW EXTRACTION FOR THE XIPAF-UPGRADING SYNCHROTRON*

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Abstract

The longitudinal localized excitation slow extraction method reduces the energy spread of the extracted beam by applying transverse excitation exclusively within specific phase intervals at the edges of the longitudinal phase space of the bunch. For localized square-wave excitation, conventional amplitude modulation formula fails to achieve uniform beam spill. However, the temporal uniformity of the extracted beam is critical for radiotherapy and related physics experiments. The XiPAF-Upgrading Synchrotron, developed from Xi'an 200 MeV Proton Application Facility, serves as a dedicated platform for studying and evaluating single-event effects on aerospace core electronics. In this work, we simulated the localized square-wave excitation slow extraction process using the SynTrack particle tracking code under the parameters of the XiPAF-Upgrading Synchrotron to extract low energy spread beam. Furthermore, a Bayesian optimization method was employed to refine the amplitude modulation curve of the excitation signal, thereby achieving highly uniform beam spill under low energy slow extraction conditions.

INTRODUCTION

RF-Knockout (RF-KO) is a key technique for realizing continuous and stable extracted beam in synchrotron slow extraction. In recent years, with the advancement of application scenarios including proton FLASH radiotherapy [1] and space radiation environment simulation, stricter demands have been imposed on extracted beam parameters, including energy spread, intensity, spill fluctuation and so on. To address these challenges, we proposed the longitudinal localized excitation slow extraction method [2]. Unlike the conventional RF-KO approach, this method applies transverse excitation signal only at the edges of the longitudinal phase space, which not only reduces the energy spread of the extracted beam but also mitigates strong space charge effects and spill fluctuation. The feasibility of this method has been preliminarily verified [2] [3].

The temporal uniformity of the extracted beam is a critical metric in slow extraction. Researchers at HIMAC derived the required amplitude modulation function based on phase

space evolution during RF-KO extraction [4] [5]. However, in the proposed longitudinal localized excitation slow extraction method, the localized excitation signal is limited in both time and longitudinal phase space, rendering the conventional RF-KO amplitude modulation formula inapplicable. Bayesian optimization (BO), with its sample efficiency, robustness to noise, and superior global optimization capability, is particularly well-suited for scenarios involving costly objective function evaluations and complex system behavior. Xu et al. [6] applied BO to optimize the injection process at the KARA storage ring, significantly improving injection efficiency in a nine-dimensional parameter space. Wang [7] used BO to optimize the total extraction efficiency for 10 MeV slow extraction below third-order resonance line, identifying multiple high-efficiency settings within tens of evaluations.

In this study, based on the parameters of the XiPAF-upgrading Synchrotron, we employ Bayesian optimization to modulate the amplitude of the square-wave signal used in longitudinal localized excitation slow extraction.

LONGITUDINAL LOCALIZED EXCITATION SLOW EXTRACTION BASED ON SQUARE WAVE

The longitudinal localized excitation slow extraction method applies transverse excitation precisely to the low density edge region in the longitudinal phase space (Fig.1), effectively reducing energy spread and spill fluctuation of extracted beam while mitigating strong space charge effects. Further details of this method can be found in the Ref. [2].

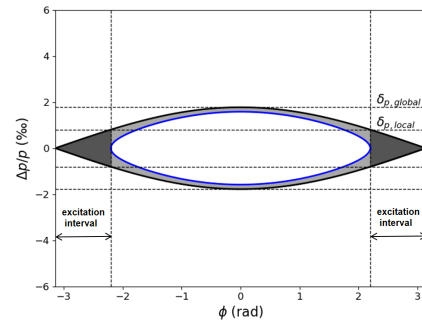


Figure 1: Diagram of longitudinal localized excitation slow extraction method.

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In transverse normalized phase space, by applying the localized square-wave excitation signal once every three turns, particles can be continuously extracted from the upper boundary of the stable triangle. A schematic of the localized square-wave signal and the longitudinal phase space of the bunch is shown in Fig.2.

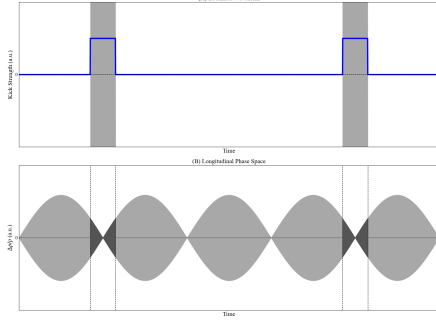


Figure 2: Schematic of localized square-wave excitation.

As particles continuously pass through the excitation interval during their motion in the longitudinal phase space, the number of particles within the interval varies constantly. Therefore, the amplitude of the excitation signal must be properly modulated to obtain a uniformly extracted beam.

APPLICATION OF BAYESIAN OPTIMIZATION ALGORITHM

Bayesian Optimization Principle

Bayesian optimization is a global optimization method tailored for “black-box” problems where the objective function is costly to evaluate and lacks an analytical form. It constructs a surrogate model of the objective and uses an acquisition function to balance exploration and exploitation, enabling efficient global optimization with minimal function evaluations. The iterative process of Bayesian Optimization can be summarized as follows:

Table 1: Bayesian Optimization Process

1. Initialization: A prior distribution is specified for the Gaussian process. Select initial points in the parameter space and evaluate the objective function.
2. For $t = 1, 2, \dots$
 - Update the Gaussian process model based on existing observations.
 - Maximize the acquisition function to determine the next sampling point x_t .
 - Compute the objective value $y_t = f(x_t)$.
 - Add the new sample to the observation dataset and update the surrogate model.

Modeling of Optimization Problems

In this study, Bayesian optimization is used to optimize the amplitude curve of the localized square wave signal, aiming for a temporally uniform extracted beam with sufficient intensity. To enable flexible waveform representation with low-dimensional inputs while ensuring smoothness and feasibility, the kick amplitude curve is parameterized using a Bézier curve defined by 10 control points to be optimized. The objective function is designed to account for extraction uniformity and beam intensity, and is computed as follows:

- **Uniformity Penalty:** Divide the total number of extraction turns into N_{sub} sub-intervals, and denote the number of extracted particles in the i -th interval as c_i . The average number of extracted particles is defined as $\bar{c} = \frac{1}{N_{sub}} \sum_{i=1}^{N_{sub}} c_i$. The uniformity penalty term is given by:

$$J_{uniformity} = \sum_{i=1}^{N_{sub}} \frac{|c_i - \bar{c}|}{\bar{c}} \quad (1)$$

- **Intensity Penalty:** The total number of extracted particles n_{total} directly reflects the extraction efficiency. To encourage higher beam intensity, the intensity penalty term is defined as:

$$J_{intensity} = \frac{\lambda}{n_{total} + \epsilon} \quad (2)$$

where λ is a scaling factor used to balance the magnitudes of the two terms.

Accordingly, the overall objective function can be simply expressed as $J = J_{uniformity} + J_{intensity}$, and the optimization problem in this study is formulated as $\min J(x)$.

Bayesian optimization is employed with the following configuration: the surrogate model is a Gaussian Process using a Matérn kernel with parameter $\nu = 2.5$, which is well-suited to the smoothness of the objective function. The Expected Improvement (EI) acquisition function is used to balance exploration and exploitation. A total of 100 iterations are performed.

SIMULATION RESULTS AND ANALYSIS

The XiPAF-Upgrading Synchrotron with a circumference of 39.96 m is developed from Xi'an 200 MeV Proton Application Facility [8] and serves as a dedicated platform for studying and evaluating single-event effects on aerospace core electronics. We simulated the localized square wave excitation slow extraction using the parameters of XiPAF-Upgrading Synchrotron with SynTrack, a code developed by our research group, whose simulation reliability has been verified in Ref. [9]. Based on the optimization modeling procedure described above, Bayesian optimization was applied to optimize the amplitude modulation curve of the excitation signal. The excitation longitudinal phase interval was fixed as $[-\pi, -0.7\pi] \cup [0.7\pi, \pi]$ in this research. The simulation parameters are listed in Table 2.

Table 2: Parameter Settings of SynTrack Simulation

Items	Parameters
Betatron Tune (horizontal/vertical)	1.6783/2.11
Chromaticity (horizontal/vertical)	0.214/ - 3.303
Extracted Beam Energy	10 MeV
Particle Number	7×10^{10}
Amplitude/Phase of Accelerating Voltage	60 V/0°
Range of extracted turns	20000–25000

As shown in Fig.3 and Fig.4, the objective value decreases rapidly in the initial iterations and converges within fewer than 20 iterations, with the minimum value of 6.36 achieved at the 95th iteration. The fluctuations in Fig.3 reflect the trade-off between exploration and exploitation in BO. This convergence behavior demonstrates that, in a ten-dimensional parameter space, BO can identify an amplitude modulation curve with both high uniformity and high intensity within several tens of evaluations.

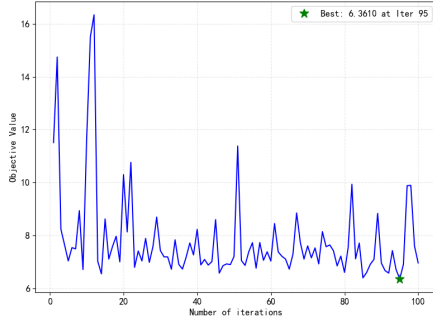


Figure 3: Variation of the objective value.

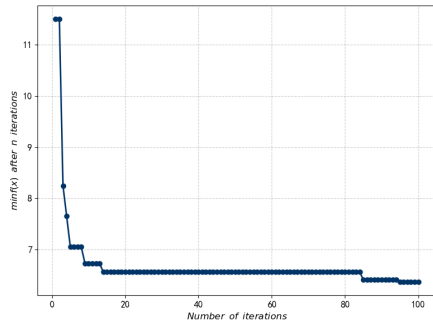


Figure 4: Convergence curve of Bayesian optimization.

The non-uniformity factor R of the extracted beam is defined as $R = \frac{\sigma}{\mu}$, where σ and μ are the standard deviation and the mean value of the extracted beam intensity, respectively. Figure 5 compares the extracted beam intensity under three conditions: the initial state, a state with a relatively high objective value (12th iteration), and the optimal state (95th iteration). If all particles within the excitation range are extracted uniformly, the ideal average current intensity is approximately 70 nA. To clearly observe the trend and

magnitude of beam intensity variation, the curves in Fig.5 have been smoothed. The actual spill fluctuations are shown in the magnified inset. Under the initial parameters, the intensity is relatively uniform but low, while at the 12th iteration, the intensity fluctuates significantly between 10 and 110 nA, with a non-uniformity factor of 0.6. In contrast, the optimal parameters yield a temporally uniform beam with an average intensity of 66 nA and a non-uniformity factor of 0.15, indicating a substantial improvements in both uniformity and intensity. Figure 6 shows the corresponding kick angle curves for these three cases.

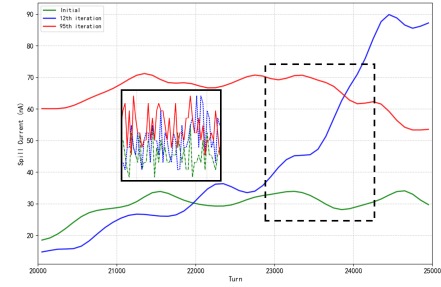


Figure 5: Extracted beam intensity.

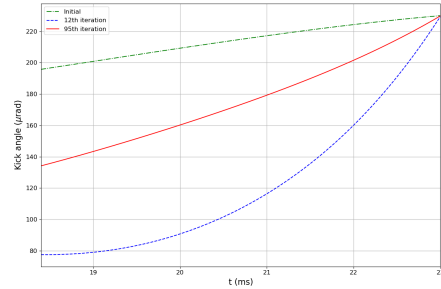


Figure 6: Amplitude curve of the localized excitation signal.

CONCLUSION

In this study, Bayesian optimization is applied to optimize the amplitude modulation curve of the localized square-wave excitation signal in the longitudinal localized excitation slow extraction method. Using the parameters of the XiPAF-Upgrading Synchrotron and the SynTrack code, BO was performed in a ten-dimensional parameter space. Simulation results demonstrate that Bayesian optimization converges within tens of iterations, yielding an extracted beam with an average intensity of 66 nA and a non-uniformity factor of 0.15, achieving significant improvements in both temporal uniformity and beam intensity.

The localized excitation region is kept fixed in this paper. In future work, this region will be gradually expanded to extract the entire bunch, in which case the moving speed of the excitation region will also affect the temporal structure of the extracted beam. This will require further modulation of the excitation amplitude curve using Bayesian optimization, which can also be extended to jointly optimize other performance metrics.

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