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

C. H. Li[1, 2, 3], H. J. Yao[1, 2, 3], Y. Xiong[1, 2, 3], S. X. Zheng[†, 1, 2, 3]
[1]Key Laboratory of Particle & Radiation Imaging (Tsinghua University),
Ministry of Education,Beijing, China
[2]Laboratory for Advanced Radiation Sources and Application, Tsinghua University, Beijing, China
[3]Department of Engineering Physics, Tsinghua University, Beijing, China

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 struggles to achieve uniform beam spill, while the temporal uniformity of the extracted beam is crucial in radiotherapy and related physics experiments. The XiPAF-Upgrading Synchrotron (with a circumference of 39.96 m), developed from Xi'an 200 MeV Proton Application Facility, serves as a dedicated platform for the study and evaluation of single-event effects on core electronics for astronautics. We simulated the localized square-wave excitation slow extraction process using the SynTrack particle tracking code based on the XiPAF-Upgrading Synchrotron's parameters to extract low energy spread beam. Furthermore, a Bayesian optimization method was employed to refine the amplitude modulation curve of the excitation signa, thereby achieving highly uniform beam spill under low-energy slow extraction conditions.

INTRODUCTION

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

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 the phase space evolution during RF-KO extraction [3] [4]. However, in the proposed longitudinal localized excitation slow extraction method, the localized excitation signal exhibits localization 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. [5] applied BO to optimize the injection process at the KARA storage ring, significantly improving injection efficiency in a nine-dimensional parameter space. Wang [6] applied 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 longitudinal low-density edge region (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 Reference [1].

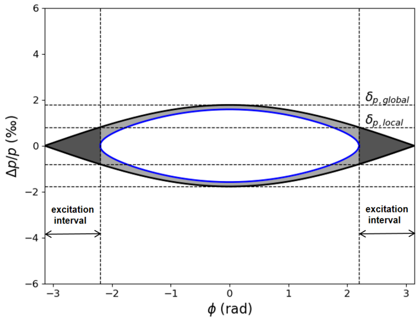

Figure 1: Diagram of longitudinal localized excitation slow extraction method.

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† zhengsx@tsinghua.edu.cn

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

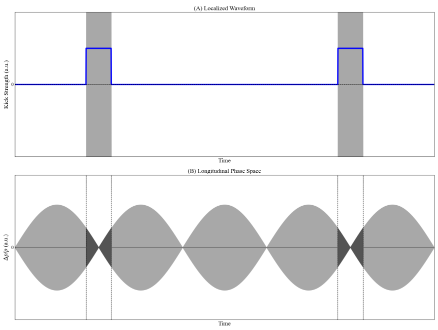

Figure 2: Schematic of localized square-wave excitation.

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 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, …
    - Update the Gaussian process model based on the existing observations.
    - Maximize the acquisition function to determine the next sampling point x_t.
    - Compute the objective value $y_i = f(x_t)$.
    - 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 subject to optimization. The objective function is designed to account for extraction uniformity and beam intensity, and is computed as follows:

- Uniformity Penalty: The total number of extraction turns is divided into N_{sub} sub-intervals, with the extracted particle count in the $i-th$ interval denoted as c_i. The average number of extracted particles is defined as $\overline{c} = \frac{1}{N_{sub}} \sum_{i=1}^{N_{sub}} c_i$ The uniformity penalty term is :

$$J_{uniformity} = \sum_{i=1}^{N_{sub}} \frac{|c_i - \overline{c}|}{\overline{c}} \tag{1}$$

- 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:

$$J_{intensity} = \frac{\lambda}{n_{total} + \varepsilon} \tag{2}$$

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

Therefore, the overall objective function can be simply expressed as $J = J_{uniformity} + J_{intensity}$, and the optimization problem in this study can be 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 to balance exploration and exploitation, and a total of 100 iterations.

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, serving as a dedicated platform for the study and evaluation of single-event effects on core electronics for astronautics. We simulated the localized square wave excitation slow extraction using XiPAF-Upgrading Synchrotron's parameters with SynTrack, which is developed by our research group, and the reliability of its simulation results is verified in Reference [7]. And based on the optimization modeling procedure described above, Bayesian Optimization was applied to 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	1×10^{10}
Amplitude/Phase of Accelerating Voltage	60 V/0°
Range of extracted turns	20000-25000

Figure 3 illustrates the objective value variation, while Fig. 4 shows the convergence curve of Bayesian Optimization. As shown, 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 Bayesian optimization. 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.

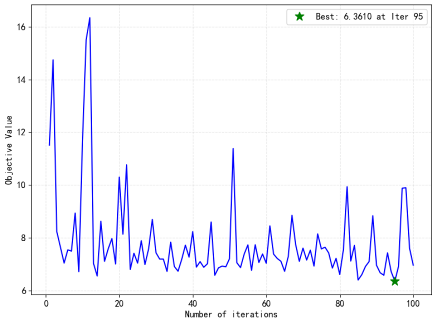

Figure 3: Variation of the objective value.

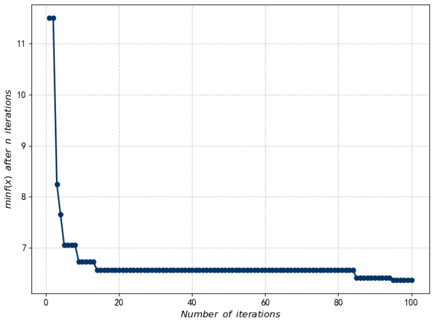

Figure 4: Convergence curve of Bayesian Optimization.

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 uniformly extracted, the ideal average current intensity would be approximately 70 nA. To clearly observe the trend and magnitude of the 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, demonstrating a substantial improvement in both uniformity and intensity. Fig. 6 shows the corresponding kick angle curves for these three cases.

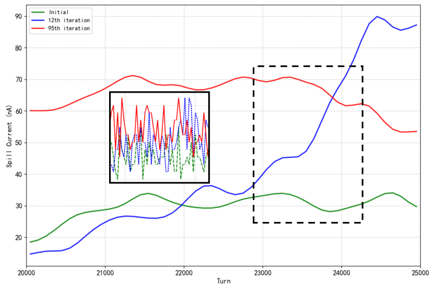

Figure 5: Extracted beam intensity.

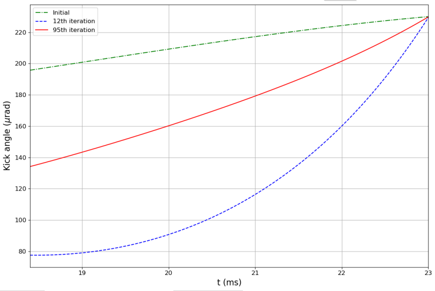

Figure 6: Amplitude curve of the localized excitation signal.

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 is performed in a ten-dimensional parameter space, targeting the uniformity and intensity of the extracted beam. Simulation results demonstrate that BO converges within several tens of iterations, and the optimal parameters significantly improve the temporal uniformity of the extracted beam while maintaining a high average 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 necessitates 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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