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APPLICATION OF BAYESIAN OPTIMIZATION TO BtA INJECTION AT BNL*

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Abstract

Drifting optimal settings and changing working conditions force accelerator operators to keep re-tuning control systems. At BNL, the RHIC injector complex accelerates many different ion species by varying a multitude of control knobs. In this report, we investigate the use of Bayesian optimization (BO) of the Booster-to-AGS (BtA) transfer line to maximize the beam brightness in the AGS. The most suitable magnets were chosen by an investigation of the betatron phase advance to facilitate an efficient BO process, using up to 4 steering magnets and up to 3 quadrupoles. To quantify the beam intensity, we used an integrated current transformer, while the beam emittance was estimated via an Ionization Profile Monitor (IPM). It was demonstrated that the chosen magnets effectively recovered a high intensity beam from a poorly tuned configuration, using an Xopt implementation of BO, without increasing the beam profile. A new electron-collecting IPM is being configured with better systematics and lower noise compared to the current ion-collecting IPM, which can further improve this process.

INTRODUCTION

The Booster to AGS (BtA) transfer line transports beam bunches from the Booster to the AGS and also matches the beam Twiss parameters and dispersion functions to the circulating beam in the AGS at the injection point [1]. The beam is extracted at the F6 extraction septum in the Booster, and injected at the L20 injection septum in the AGS, as shown in Fig. 1.

The BtA line consists of 15 quadrupoles, 5 bends, 2 horizontal correctors, 4 vertical corrector, a stripping foil for operations with heavy ions, and four sets of multi-wire profile monitors [2]. In order to make sure the beam is injected properly at the AGS injection point, beam matching is performed so that the beam parameters at the end of the BtA line matches the circulating beam parameters in the AGS. The transfer line optics do not generate multiples of $\pi/2$ phase advance between correctors or quadrupoles, which makes it nontrivial to uncouple the effects of different correctors and quads on beam alignment and shape, respectively.

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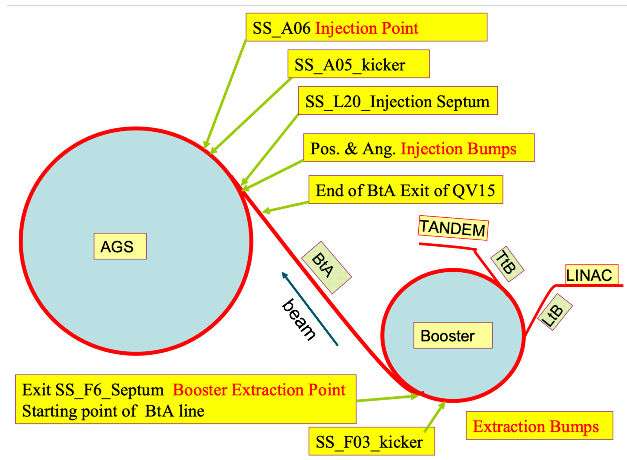

Figure 1: Schematic diagram of the BtA line, and its connections with the Booster and the AGS.

BAYESIAN OPTIMIZATION

Bayesian Optimization (BO) is a powerful and sample-efficient strategy for optimizing objective functions that are expensive to evaluate, noisy, or lack an analytical form. By constructing a probabilistic surrogate model, typically a Gaussian Process (GP), BO balances exploration and exploitation to identify optimal regions of the search space with minimal evaluations. This makes it particularly well-suited for tuning parameters in experimental and simulation-based accelerator physics problems [3].

The Xopt package is an open-source, extensible framework developed to streamline the application of BO in scientific workflows [4]. It supports multiple surrogate models and acquisition strategies, and is designed to interface easily with experimental control systems. Badger, a graphical user interface built on top of Xopt, provides an intuitive platform for configuring optimization problems and monitoring optimization progress in real time. Together, Xopt and Badger enable practical deployment of BO in accelerator operations, facilitating automated tuning and performance improvement across complex, multi-parameter systems.

In our optimizations, we focused on small dimensional parameter spaces $D < 8$ for which BO is a great candidate tool. Due to uncertainties in magnet alignment and the presence of nonlinear magnetic fields, we opted to use a GP surrogate model with radial basis function (RBF) kernel to represent the underlying physical system since the RBF kernel is intrinsically capable of handling nonlinearity. The only caveat of using a GP model is that it is not infinitely trainable, with

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its time complexity growing with the number of samples n as $\mathcal{O}(n^3)$.

We also investigated the use of expected improvement and upper confidence bound acquisition functions, and attempted a trust region BO. We found that UCB without trust region performed best in terms of speed of convergence and avoidance of bad-performance regions which is particularly relevant in terms of operation safety.

AGS INJECTION

The goal of injecting a fast-extracted beam from the Booster into the AGS suffers from some common challenges and from another unique one: the beam circulation in the Booster is opposite to that in the AGS, which causes the periodic dispersion to flip sign. The common challenges include precise kicker timing for energy matching in the absence of an extraction flattop, the proper steering of bunch trajectories notwithstanding the misalignment of quadrupoles, and the matching of bunch phase space distributions to the AGS optics while maintaining proper steering. The last two challenges are an example of a coupled optimization problem which cannot in general be decomposed into two independent problems. In spite of this, it is often the case that one of the two problems yields a greater reward from optimization, and this benefit is further enhanced when the other problem is already near-optimal. In this study we only consider focusing on one objective after the other separately due to time-constrained operations.

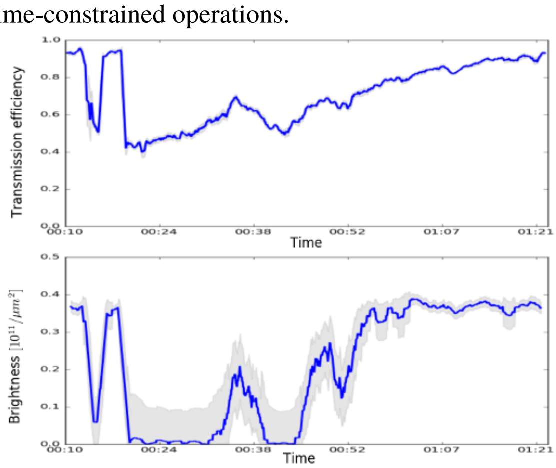

Figure 2: (Top) BO results of the ratio of AGS injection intensity to Booster extraction intensity after spoiling the initial settings, while varying two horizontal and two vertical steering magnets. (Bottom) Beam brightness is a secondary target not included in optimization, but shows strong recovery following spoilage of the settings.

EXPERIMENTAL RESULTS

To test the ability of this approach, we started with a well-tuned beamline that was producing 90%+ proton transmission efficiency and spoiled 4 steering magnets (2 horizontal and 2 vertical). We then launched the Xopt BO toolkit and were capable of recovering the initial transmission efficiency after about 1 hr, as shown in Fig. 2. The reason for the extremely slow convergence in this low-dimensional space is because extra care was taken to obtain clean beam size signals from Ion-Profile Monitors (IPM), to increase the signal-to-noise ratio through averaging over multiple cycles, and to accommodate slow-changing magnets between optimization steps.

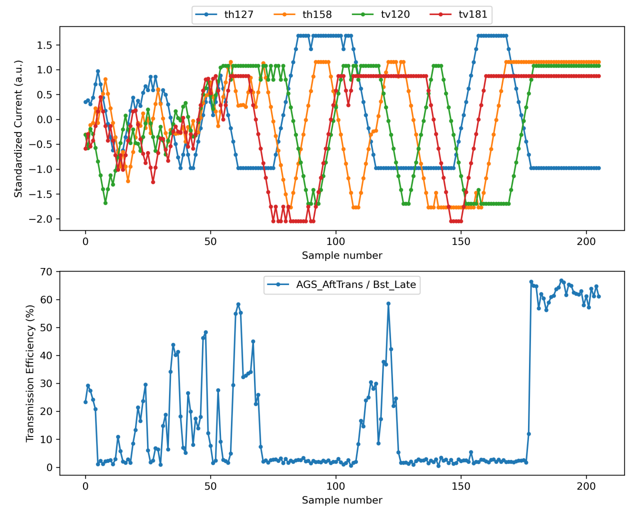

Figure 3: BO results of the ratio of AGS extraction intensity to Booster extraction intensity after spoiling the initial settings, while varying two horizontal and two vertical steering magnets.

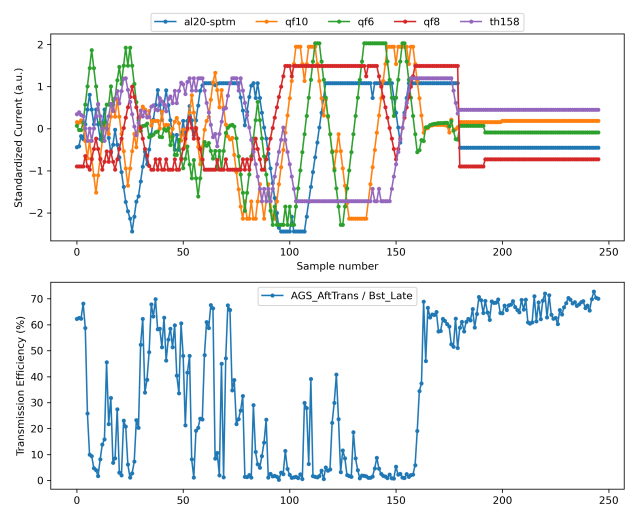

Figure 4: BO results of the ratio of AGS extraction intensity to Booster extraction intensity after spoiling the initial settings, while varying three focusing quadrupoles and two horizontal steering magnets to compensate unintentional quadrupole-induced steering.

We perform another to mimic real-world operations after spoiling the transfer line steering where we did not explicitly average multiple cycles and did not collect IPM data on beam size. Here we optimized the ratio of AGS extraction to Booster extraction intensity (as opposed to AGS injection to Booster extrcation intensity) by varying the 2D steering

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and achieved much faster convergence results in under 20 mins which are shown in Fig. 3.

After aligning the beam with steering magnets, we focused on horizontal optics matching with 3 quadrupoles as well as 2 horizontal steering magnets, without spoiling any quadrupole settings. Again, we focus on the AGS extraction intensity to bypass any consistent and deleterious transient effects. To choose the most suitable quadrupoles, we considered quadrupoles that were as far from π horizontal phase advance from each other as possible in the ideal BtA line model. None of the quadrupoles were close to $\pi/2$ apart as would be desirable, potentially contributing to a weak result. Figure 4 shows that we were only able to achieve a marginal improvement of about 5% in injection performance compared to the prior result with just steering.

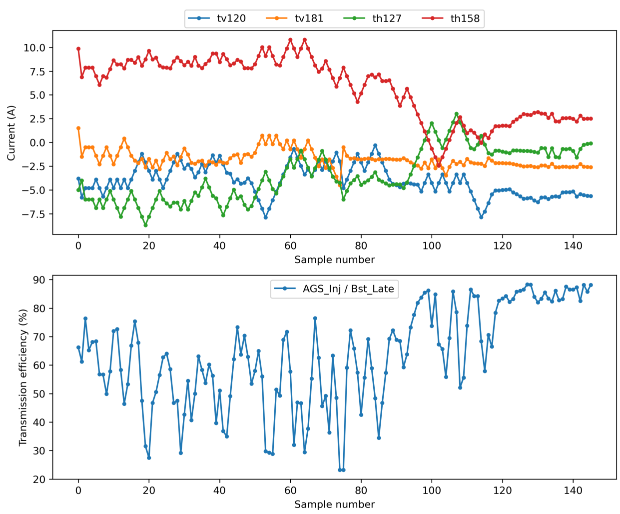

Figure 5: Real-world BO results of the ratio of AGS injection intensity to Booster extraction intensity starting from an untuned machine, while varying two horizontal and two vertical steering magnets.

Finally, in a real-world test of the framework, we launched the optimizer to address the former injection efficiency target at a time when the injection was poorly tuned, starting at an average 65% transmission efficiency, and performed a pure steering optimization in 4D. In this attempt, we again did not explicitly average multiple cycles and did not collect IPM data on beam size due to a poor signal, achieving impressive and much fast convergence results in approximately 15 mins which are shown in Fig. 5.

CONCLUSION

In this project, we deploy Bayesian optimization to autonomously maximize brightness of the circulating AGS beam by manipulating correctors in the Booster-to-AGS transfer line. Even though turn-by-turn monitoring is not available yet, we find that avoiding any explicit averaging of data yields faster and better results compared with explicit averaging of multiple cycles per setpoint, and successfully achieve optimal transmission in a reasonable time while maintaining safety of handling. This work showcases the efficacy of Gaussian Process surrogate models in effectively representing probabilistic data and displays the utility and efficiency of Bayesian Optimization as a tool for autonomous accelerator control.

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