AUTOMATED TUNING TECHNIQUES AT TRIUMF FOR THE ARIEL ERA

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Abstract

Implementing automated tuning techniques has been a priority at TRIUMF, driven by the need to support the significant increase in RIB availability expected with the new Advanced Rare Isotope Laboratory (ARIEL). This efficiency boost will facilitate a broad spectrum of research in nuclear, particle, and astrophysics. This work outlines the shift from manual tuning to an automated approach for optimizing beamline transport. We utilize the predictive digital twin, Model Coupled Accelerator Tuning (MCAT), to compute transport and accelerated beam tunes, while Bayesian Optimization for Ion Steering (BOIS) handles beam orbit correction. BOIS treats steering as a black-box optimization problem, maximizing beam current based solely on direct measurement. By combining MCAT and BOIS, this method offers a more efficient, physics-grounded tuning process, with potential applications for facilities beyond TRIUMF.

INTRODUCTION

Rare Isotope Beam (RIB) facilities are highly complex systems that require frequent retuning for different beam species, energies, and charge-to-mass ratios. At TRIUMF's Isotope Separator and ACcelerator (ISAC) facility [1] which serves about 16 experiments with radioactive beam, beam tuning involves repeated adjustment of beamline optics, corrective steerers, and linear accelerator (linac) parameters. This tuning process places a significant burden on operators, who may be responsible for beam delivery to multiple experiments or, in some cases, may be the only operator on shift. The complexity of the tuning process also makes it more difficult to train new operators and to ensure reproducible and efficient beam delivery.

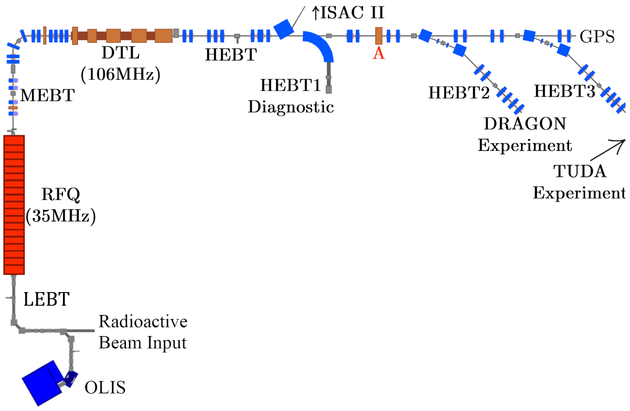

Figure 1: Overview of the ISAC-I RIB postaccelerator, showing major components.

ISAC-I

The Isotope Separator and ACcelerator (ISAC) facility is capable of providing both stable and rare isotope beam to experiments. This facility produces rare isotope beams using proton beam from TRIUMF's 520 MeV cyclotron to bombard production targets, where the resulting isotopes are ionized, extracted, separated [2, 3] and delivered to experiments. Stable beam is provided by the Off-Line Ion Source (OLIS) [4]. The post-accelerator, shown in Fig. 1, is comprised of a Radio-Frequency Quadrupole and a Drift Tube Linac (DTL), the latter of which is a separated function layout [5], where the cavities and bunchers are individually tunable. The post-accelerator is divided into low, medium, and high energy sections by these two linacs: electrostatic ion optics (before the RFQ) define the low energy section, while magnetic optics (after the RFQ) are used in the medium and high energy sections.

ARIEL

The commissioning of the Advanced Rare Isotope Laboratory (ARIEL) [6, 7] will allow for the simultaneous delivery of three RIBs and one stable beam. This expansion includes a new proton beamline from the cyclotron, a superconducting electron linear accelerator (e-linac), and two new target stations, enabling greater coverage of the nuclear chart. With these developments comes a significantly increased operational load and tunable parameters.

To mitigate the future operational load, a change of the tuning paradigm is required, which relies on more automation in the beam delivery process. In this paper, we present an automated tuning approach that decouples the optimization of beamline optics from corrective steering. Optical elements are determined using the digital twin Model Coupled Accelerator Tuning (MCAT) [8], which computes optics (and linac) settings from user-defined constraints. Corrective steerers are then optimized using a previously developed Bayesian optimizer [9].

By combining model-based optics tuning with steering correction, this approach reduces the dimensionality of the tuning problem while providing an easily trainable approach to beam delivery. This technique is compared with a fully Bayesian approach, where both the optics and steerers are tuned using the Bayesian optimizer. Tests were carried out on real beam for several beam species and energies, demonstrating the advantages of the decoupled approach.

AUTOMATED TUNING TECHNIQUES

Driven by the expected completion fo the ARIEL project in 2027, automated tuning techniques have been developed and significantly expanded upon [9–13]. A key aspect of the technique employed at TRIUMF is the decoupling of optics and corrective steerers, which is different from several

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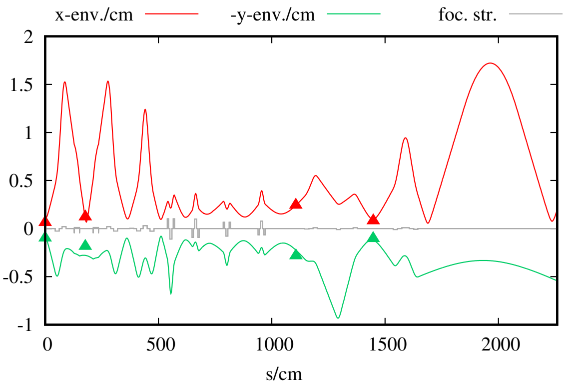

Figure 2: Model-computed x and y 2RMS beam envelopes through the ISAC drift-tube linac (solid lines) compared with RMS beam sizes from profile monitors (markers) for a $^{16}\mathrm{O}^{3+}$ beam. Optics were generated in real time via sequential optimization [11] using an MEBT quadrupole model with fringe-field effects from [14]. The quantity *foc. str.* denotes the quadrupole focal strength. Dataset also used in [14] for model validation, but shown here to illustrate operational use of the parallel-modeling framework.

facilities that treat quadrupoles and steerers as a single black-box optimization problem [15–19].

Optics Modelling

A digital twin of the facility is used in MCAT. A digital twin is defined here as a virtual accelerator that is kept continuously synchronized with the real machine. It reads back live data and computes the beam envelopes of a beamline section to show the current tune. The virtual accelerator is developed in `TRANSOPTR` [20] and continually refined to remain representative of the real machine. The digital twin also has predictive capability based on user-defined constraints. This takes the form of sequential optimization, where the optimization is broken into small segments, and the optimized values of the previous segment are used as the initial conditions for the next segment. With this technique, an end-to-end computation of the envelope can take place in several seconds. Figure 2 shows an example of the beam envelopes from MEBT to HEBT1 as predicted by MCAT, with measured beam sizes from profile monitors. The measured profile-monitor sizes are consistent with the model-computed envelopes, indicating that the model is representative of the machine, and validating the use of the digital twin for online optics prediction.

Bayesian Optimization

`TRANSOPTR` assumes a perfectly aligned beam during transport, and as such any computations are agnostic to beamline misalignments. These misalignments can result from steerer lensing [21,22], stray field effects from OLIS, or other mechanical machine misalignments which have yet to be characterized. The beam orbit correction is then treated as a black-box optimization problem which is solved using Bayesian Optimization.

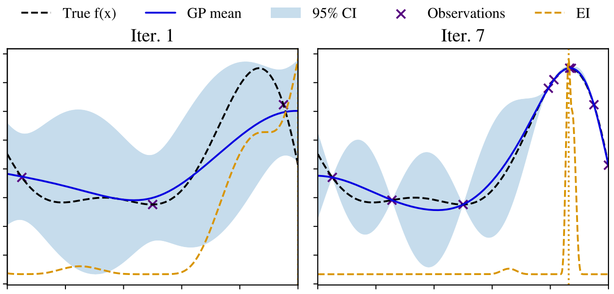

Figure 3: A GP, initialized with 3 random points, is used to model the objective function (black) with sampling guided by the Expected Improvement (EI) acquisition function. The posterior mean is shown in blue, with the shaded band representing the 95% confidence interval. Acquisition function values are plotted in orange. The horizontal and vertical axes represent inputs (x) vs. function values f(x).

Bayesian optimization has become a popular tool for many problems in accelerator physics [23]. Its main advantage is sample efficiency; it can converge on optimal solutions after only a handful of evaluations, making it an ideal choice for online optimization tasks, such as accelerator tuning and real-time beam delivery. This is a probabilistic technique based on Bayesian inference where a surrogate model, typically a Gaussian process (GP) [24], is defined on prior information. The objective is to find the input values that maximize an unknown noisy objective function.

The selection of new evaluation points is determined by the acquisition function (AF), which quantifies the utility of sampling at a given location in the input space, as shown in Fig. 3. Acquisition functions balance exploration (sampling in regions of high uncertainty) against exploitation (sampling near regions with high predicted objective values). Two of the most commonly used AFs are the Upper Confidence Bound (UCB) and the Expected Improvement (EI) [25, 26], defined as:

$$\mathrm{UCB}(\mathbf{x}) = \mu(\mathbf{x}) + \sqrt{\beta}\,\sigma(\mathbf{x}), \tag{1}$$

$$\mathrm{EI}(\mathbf{x}) = \mathbb{E}[\max(f(\mathbf{x}) - f^* - \xi, 0)], \tag{2}$$

where $\mu(\mathbf{x})$ and $\sigma(\mathbf{x})$ are the GP posterior mean and standard deviation, respectively, and f^* is the best observed objective value. The parameters β (for UCB) and ξ (for EI) control the trade-off between exploration and exploitation. Larger β or ξ increase the incentive to explore uncertain regions of the input space, while smaller values bias the search near the current optimum. Striking the right balance is important for reliably locating a global maximum. For this work, UCB held at $\beta = 3$ was found to be the most reliable AF configuration.

At TRIUMF, this has been implemented as Bayesian Optimization for Ion Steering (BOIS). This technique has been extensively tested at the low, medium and high energy beamlines. BOIS provides comparable transmission to operators in a similar time while also allowing for more reproducible beam delivery [9, 13].

RESULTS

Two tuning strategies were evaluated on the MEBT to DTL-injection segment, which contains eight quadrupoles and six steerers. In the decoupled method, the digital twin MCAT with sequential optimization sets the quadrupoles, and BOIS then tunes only the six corrective steerers. In the fully Bayesian method, the optimizer is allowed to vary all fourteen parameters, consistent with practice at other facilities. A stable OLIS beam was delivered for different beam configurations, including ^{16}O^{3+} at 436 keV/u, ^{4}He^{+} at 1.6 MeV/u, and ^{7}Li^{+} at 1.28 MeV/u. For each method, six trials were performed: three using EI and three using UCB.

Figure 4 shows a comparison between the three beam configurations for the different methods. The decoupled approach consistently outperforms the fully Bayesian approach in convergence time and reliability, both between repeated trials and across beam configurations. The fully Bayesian approach showed large variation between the different trials, particularly for the ^{16}O^{3+} test, where the six trials converge toward three distinct transmission regions. The fully Bayesian approach did not produce a high transmission tune for the ^{4}He^{+} beam, possibly due to a larger beam emittance compared to the other isotopes, but an emittance scan is required for confirmation. For the ^{7}Li^{+} test, there was a stripping foil inserted downstream of DTL, leading to an amplified current reading due to the multiple resulting charge states. In this case, transmission was calculated by normalizing to the highest found current across all runs. Together, these results show that the decoupled method is more reliable and efficient for ISAC-linac tuning.

This improvement comes as a result of several factors: 1) Removing the quadrupoles yields a much smaller configuration space from 14 parameters to 6 parameters, making the optimization problem easier. 2) Quadrupoles are more sensitive than steerers, which makes for a much more difficult configuration space to optimize over. This is due to both the strength of the quadrupoles and the hysteresis associated with repeated current changes.

CONCLUSION

In a decoupled tuning technique, Bayesian optimization is applied only to the steering corrections, addressing the beam orbit correction, while setting the optics with a digital twin. Removing the optics from the configuration space avoids the slow convergence and variability seen in fully Bayesian optimization. Tests on the ISAC post-accelerator show that the decoupled method converges in significantly fewer steps compared to a fully Bayesian approach, achieves higher average transmission, and is more robust across species and energies. These results support the decoupled MCAT and BOIS strategy as an efficient operating mode for beam delivery as TRIUMF enters the ARIEL era.

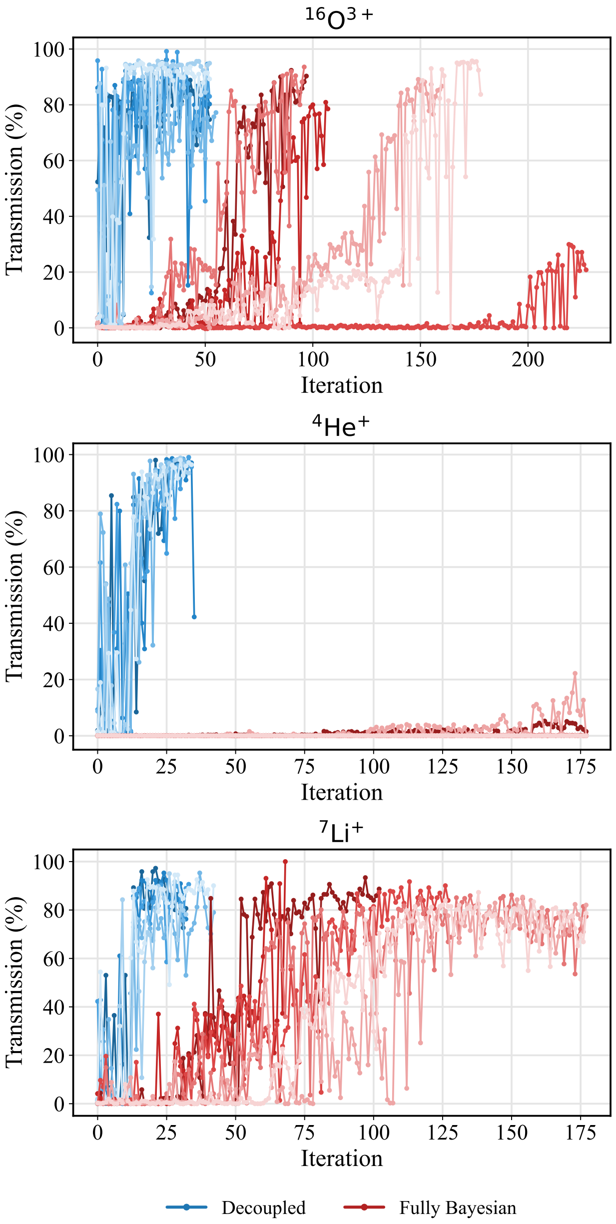

Figure 4: Optimization performance through the DTL for 3 beam configurations, and two optimization methods: decoupled in blue and fully Bayesian in red. The full optimization runs are shown for all six trials of each method, with opacity used to distinguish individual runs.

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