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AUTOMATED OPTIMIZATION OF ACCELERATOR SETTINGS AT GSI

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Abstract

The complexity of the GSI/FAIR accelerator facility demands a high level of automation to maximize the time for physics experiments. Accelerator laboratories worldwide are exploring a large variety of techniques to achieve this, from classical optimization and Bayesian optimization (BO) to reinforcement learning. This paper reports on the first results of using *Geoff* (Generic Optimization Framework & Frontend) at GSI for automatic optimization of various beam manipulations. *Geoff* is an open-source framework that harmonizes access to the automation techniques mentioned above and simplifies the transition towards and between them. It is maintained as part of the EURO-LABS project in cooperation between CERN and GSI. In dedicated beam experiments, the beam loss of the multi-turn injection into the SIS18 synchrotron has been reduced from 40% to 15% in about 15 minutes, where manual adjustment can take up to 2 hours. *Geoff* has also been used successfully at the GSI Fragment Separator (FRS) for beam steering. Further experimental activities include closed-orbit correction for specific broken-symmetry high-transition-energy SIS18 optics with BO in comparison to traditional SVD-based correction.

GEOFF AT GSI

FAIR – the Facility for Antiproton and Ion Research – will constitute an international center of heavy-ion accelerators that will drive the forefront of heavy-ion and antimatter research [1]. The complexity of the FAIR facility requires a high level of automation for future operation [2]. One part of this automation effort is to provide a framework that allows both machine experts and operators to solve certain, focused optimization problems and to make these solutions reusable in an operational context. We call this project the "Generic Optimization Framework and Frontend", or *Geoff* for short [3]. It is based on Python, a programming language that is widely used in scientific research, has a vibrant ecosystem of machine learning algorithms, and is perceived as very beginner-friendly. Both language and framework have proven themselves flexible enough to be quickly adapted to new problems. *Geoff* is already used extensively at CERN, from linacs to SPS and ISOLDE. It is usually embedded into a GUI application, but can also be used in command-line scripting. *Geoff* standardizes interfaces for optimization tasks [4] and provides adapters for various third-party packages, for example: *SciPy, Stable Baselines 3, Scikit-Optimize*. *Geoff* tasks can scale to arbitrary complexity and depend on any Python package; they can use any controls systems and even communicate with external simulation tools, as long as they have Python bindings (see Fig. 1).

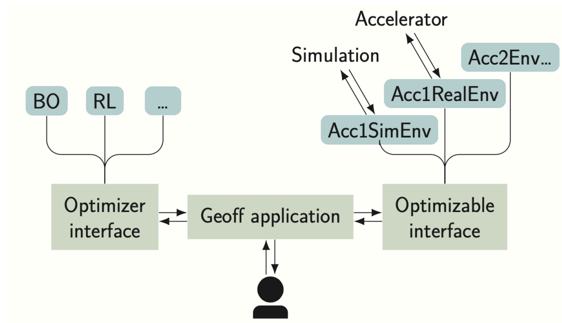

Figure 1: Model of *Geoff* and its components. The optimizer interface includes BOBYQA, Bayesian optimization (BO), and reinforcement learning (RL).

Figure 2 shows an optimization run that used *Geoff* for beam steering in the TK transfer channel at GSI. To shorten the loop between code changes and test runs, we used *Geoff* in a command-line script and ran it inside a terminal window. Custom figures can be shown and updated continuously to monitor the algorithm's progress.

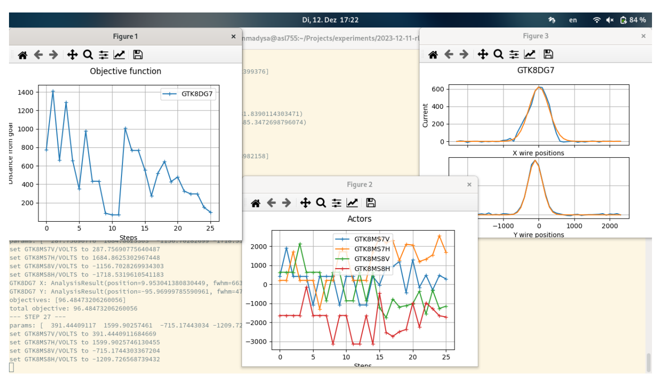

Figure 2: Screenshot of a typical optimization run using *Geoff*. Shown is the usage in a scripting context: the terminal window with logging messages is in the background, live graphs for monitoring in the foreground.

MULTI-TURN INJECTION OPTIMIZATION

Loss-induced vacuum degradation limits the intensity of intermediate-charge-state ion beams and so is a considerable concern for FAIR [5, 6]. To prevent a decrease in the performance of the SIS18 synchrotron due to this degradation, it is crucial to reduce injection losses during the multi-turn injection (MTI) process [7].

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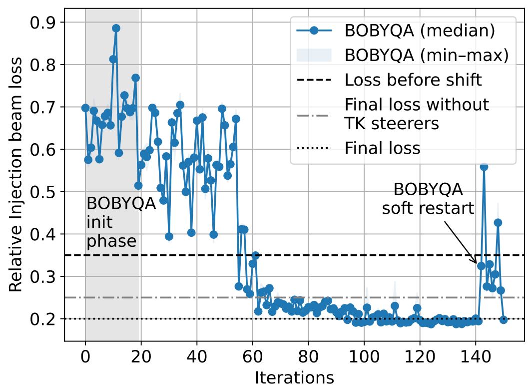

Figure 3: Automatic BOBYQA minimization of beam loss using SIS18 injection parameters and TK steerers. Each point is a measurement, so three points make up one iteration of the algorithm. The gray area marks the initialization phase[1].

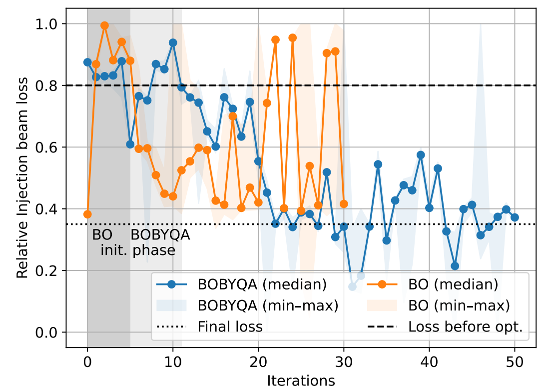

Figure 4: Comparison of BOBYQA and BO for an automatic online optimization of SIS18 injection loss. Each evaluation of the objective function requires three acceleration cycles. The gray areas represent the initialization phases of each algorithm[2].

To work around Liouville's theorem, four bumper magnets create a time-variable closed-orbit bump, such that the injection septum directs each incoming beamlet into an available horizontal phase space close to the previous injected beamlets. MTI losses can occur both at the septum and at the accelerator's acceptance [8].

The objective of our online optimization was to minimize beam loss during injection into SIS18 by adjusting 5 injection parameters and 4 steers in the TK transfer channel. The parameters were randomized before optimization to ensure a sufficiently bad initial state. The loss was estimated by measuring the beam current in the TK, calculating the SIS18 current given perfect injection, and subtracting the measured SIS18 current. To reduce the variance of the objective function, each evaluation took the median of three measurements.

One optimization takes 15–20 min. In one instance, the beam loss was 35% after manual tuning by professional operators; 25% after automatic optimization of only the MTI injection; and 20% after simultaneous optimization of the MTI injection and the beam steering in the TK. (see Fig. 3) In a previous test in November 2023, it was possible to decrease the loss from 45% after manual tuning to 15% [9].

We also compared BOBYQA and BO, presenting the results in Fig. 4. Both algorithms show similar performance within the same number of iterations.

FRAGMENT SEPARATOR OPTIMIZATION

The task of a fragment separator (FRS) is to identify and select the different nuclides in a fragment beam produced in a fixed target. After selection, the nuclides are used for further studies in downstream experiments. At present, setting up the FRS instrument for experiments takes between two to three days at the start of each physics run.

As a first step toward possible full automation, we started with beam steering at a specific point and angle, as measured by two profile grids in front of the target [10]. Because classical optimization operates on scalar functions, these observables have been combined into a single quantity, the sum of the distance between the beam center and a target point ($x = 0\,\mathrm{mm}, y = -3\,\mathrm{mm}$) on both grids. The result of the automatic steering is shown in Fig. 5. While the algorithm ran for 50 iterations, it had already converged after fewer than 20.

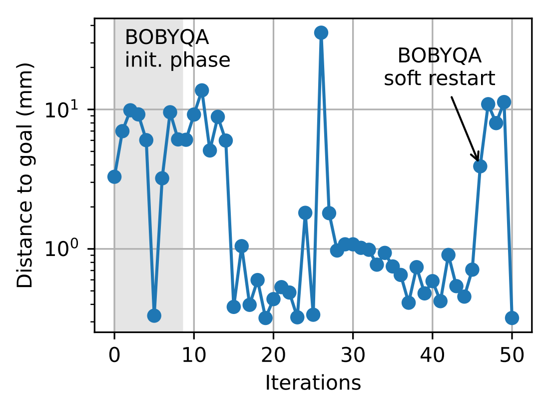

Figure 5: Automatic online steering that uses BOBYQA to minimize the distance between beam center and and the target point on both grids. The gray area marks the initialization phase of the algorithm.

This is not representative because one of the initialization points was already very close to the optimum by chance. Afterward, the algorithm performed soft restarts to escape potential local minima. All in all, the procedure took about 15 minutes. Speedups are limited by measurements being

[1] BOBYQA maintains a quadratic model of the objective function, which must be initialized with $N \geq 2n + 1$ evaluations, where $n = 9$ is the number of optimization parameters.

[2] For BO, the length of the initialization phase is is a free parameter and has here been set to 5.

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bound to the slow-extraction cycle and and by the profile grids requiring multiple cycles to read out both X and Y coordinates due to the limited bandwidth of the multiplexer that they are attached to.

CLOSED ORBIT CORRECTION

Further experimental activities include the exploration of Bayesian Optimization for closed-orbit correction as an advanced approach for optics where the standard correction fails. As optics setting, we chose the particularly challenging *broken-symmetry high-transition-energy SIS18 optics*. This setting shifts the transition energy (γ_t) by modulating the lens strength and reducing the superperiodicity. (For more details, see [11].) The simulated beta functions of the accelerator with this optical setting are illustrated in Fig. 6 and show the reduced superperiodicity of $S = 6$ in the horizontal direction.

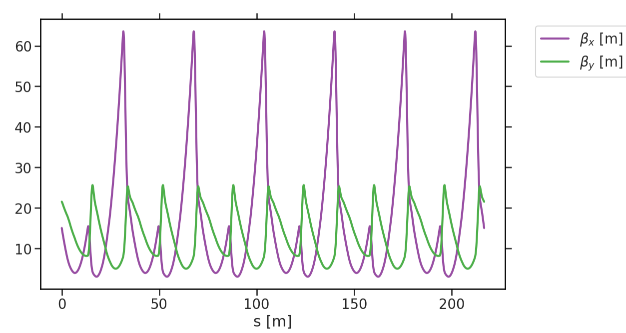

Figure 6: The superperiodicity of $S = 6$ in the horizontal direction is visible in the simulated beta functions.

This design is advantageous for synchrotrons such as the SIS18, as it makes the accelerator more adaptable to its diverse research needs; however, it can cause the traditional, SVD-based correction method to fail. An optimization-based approach should find those corrector magnets setting that minimize the RMS deviation between a target orbit and the orbit measured by the BPMs in presence of noise. Simulations of the influence of noise on the BPMs show that for higher noise levels, BO achieves better results than SVD. In addition, the SVD method's accuracy is decreased by nonlinearities caused by the chromaticity correction with sextupoles.

In the BO-based approach, a Gaussian Process acts as a surrogate model for the machine and in each iteration, the next evaluation point is selected by minimizing the acquisition function, here LCB (Lower Confidence Bound). As Fig. 7 shows, the BO-based correction for the SIS18 converged and found good corrector settings where the SVD-based correction fails. In the standard optics scenario, the BO-based method yields a significantly smaller value than in the challenging case, yet requires more iterations than the SVD method, as illustrated in Fig. 8. Therefore, it is reasonable to utilise the BO method in situations where the SVD method is unsuccessful.

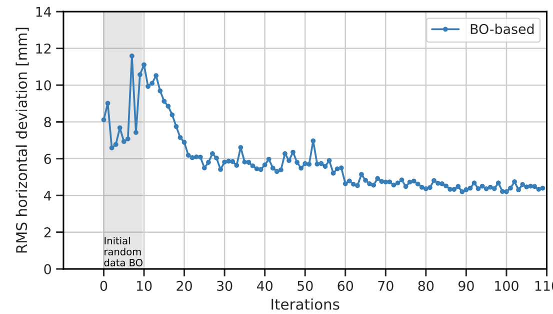

Figure 7: Automatic BO-based correction of closed orbit using the broken-symmetry high-transition-energy SIS18 optics. Each evaluation of the objective function requires three acceleration cycles. The gray area marks the initialization phase of the algorithm.

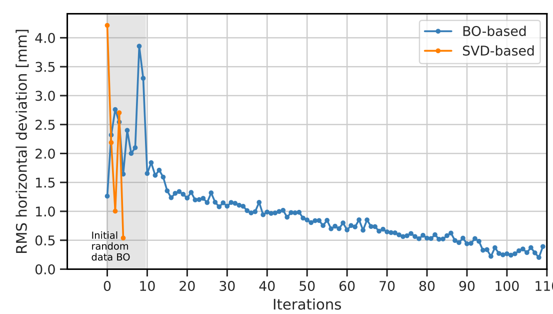

Figure 8: Automatic BO-based correction of closed orbit using the standard SIS18 optics. Each evaluation of the objective function requires three acceleration cycles. The gray area marks the BO initialization phase.

As an additional benefit, the trained surrogate model (including a hyperparameter for noise) can be reused, which speeds up future corrections.

CONCLUSION AND OUTLOOK

We have presented the concept of automation and improvement of crucial beam adjustments at GSI using *Geoff*, a Python-based framework. Furthermore, in the case of unique optics, where the conventional SVD-method fails, the use of BO-based closed orbit correction can be beneficial. *Geoff* offers uniform interfaces for optimization tasks and adapters for various packages, and can operate in a pure scripting environment or as GUI. *Geoff* is maintained as part of the EURO-LABS project in collaboration between CERN and GSI. Developments towards better control room integration at GSI are planned for improved optimization of total SIS18 production cycles.

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