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ONLINE MULTI-OBJECTIVE BAYESIAN OPTIMIZATION OF INJECTION EFFICIENCY AND BEAM LIFETIME WITH SKEW QUADRUPOLES AT NSLS-II*

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Abstract

At NSLS-II, the vertical emittance of electron beam is typically blown up to ~30 pm with a coupling wave to increase beam lifetime during user operation. As more and more insertion devices are added to the storage ring, injection efficiency to the ring drops noticeably in certain machine states, apparently due to degraded dynamic apertures. To help alleviate this issue, we have recently performed online multi-objective Bayesian optimization to increase injection efficiency while maintaining beam lifetime, by adjusting the strengths of 15 skew quadrupoles in non-dispersive sections. We report the results of this optimization effort.

INTRODUCTION

At storage rings like NSLS-II, it is common practice to increase the vertical beam size during beamline user operations to extend the beam lifetime. This mode of operation reduces the frequency of injections needed to maintain a constant beam current in the ring. The main benefits are threefold. First, it minimizes transient orbit disturbances during injections, enhancing orbit stability and enabling high-quality beamline experiments. Second, a longer beam lifetime results in reduced radiation from beam loss. Third, it decreases the load on injection-related equipment, thereby extending the equipment's operational lifespan.

The vertical beam size scales approximately with the square root of the vertical emittance. The two primary sources of vertical emittance are betatron coupling and vertical dispersion [1]. NSLS-II initially used coupling to increase vertical emittance. A coupling wave was introduced into the lattice by powering skew quadrupoles in non-dispersive sections of the ring, which typically raised the vertical emittance to about 30 pm. This method was effective in increasing the beam lifetime, but occasionally reduced injection efficiency, most likely because the large initial horizontal offset from off-axis injection was converted into large vertical oscillations, leading to beam loss at the small apertures of insertion devices (IDs).

To mitigate this issue, a vertical dispersion wave was employed to increase the vertical emittance. This approach has been shown to have a smaller impact on injection efficiency as well as beam lifetime (via the momentum aperture) compared to the coupling method, since it does not significantly affect the vertical oscillations of the injected beam [2, 3]. However, it was later discovered that, in this mode, the horizontally focused X-ray beam at the secondary source of beamline 17-ID-2 became rotated.

The resulting increase in the width of the projected beam at the sample position led to a loss of spatial resolution in certain beamline experiments for macromolecular crystallography, such as data collection from the smallest crystals and highly inhomogeneous crystals [4]. This issue forced us to revert to the coupling wave mode. Since then, we have been seeking ways to improve injection efficiency in this mode.

MULTI-OBJECTIVE BAYESIAN OPTIMIZATION

We recently conducted online multi-objective Bayesian optimization (MOBO) [5] to optimize the harmonic sextupoles at NSLS-II, using the Python package `apsopt` developed by APS-U [6, 7]. The goal was to maximize both injection efficiency and beam lifetime by adjusting the strengths of up to 23 harmonic sextupoles in the ring. This effort resulted in a significant improvement in both metrics within just 50 iterations.

Building on this success, we applied the same optimization technique to address the injection efficiency issue associated with the coupling wave currently used in operation, which had been arbitrarily chosen and never optimized, either online or offline, to reduce its adverse impact on nonlinear beam dynamics. The aim was to improve this wave by maintaining high injection efficiency while preserving, or potentially enhancing, beam lifetime by tuning the strengths of 15 skew quadrupoles (SQH family) located in the non-dispersive sections of the ring.

EXPERIMENTAL SETUP

All the IDs in the storage ring were set to their nominal operation gaps, except for all the in-vacuum undulators, which were set to their minimum gaps to represent the worst case scenario. The linear optics and coupling of the ring were then corrected, resulting in a vertical emittance of approximately 10 pm, as measured by an X-ray pinhole camera. The maximum power supply current limits for the skew quadrupoles are ±18 A, but some of this range is reserved for minimizing

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linear coupling. Therefore, the adjustment range available for optimization was limited to ±8 A ($\pm 3.17 \times 10^{-3}$ m^{-1}).

For the sextupole optimization experiment, beam lifetime was normalized by both beam current and vertical beam size. In contrast, for the current optimization, lifetime was normalized only by beam current. In the former case, it was crucial to exclude the effect of beam size changes, resulting from coupling changes due to off-centered sextupoles, from the lifetime objective, as the primary goal was to enhance lifetime by increasing the momentum aperture, not through beam size increase. In the present case, however, vertical beam size is deliberately increased via coupling, so this effect should be retained in the lifetime objective.

The nominal injection kicker strength was reduced by 20–30% to ensure that the initial injection efficiency (i.e., under minimized coupling conditions) was well below 100%. This allowed observable improvements in injection efficiency as the optimizer tuned the skew quadrupoles. Without this adjustment, efficiency values might be capped at 100%, potentially causing the optimization to converge prematurely to a sub-optimal solution.

In addition to the two main objectives (injection efficiency and normalized beam lifetime), a constraint was imposed to keep the vertical emittance below 40 pm. This guided the optimization toward solutions that increase lifetime without excessively enlarging the beam size. When the constraint was violated, the output of the evaluation was marked as undesired.

Seven random skew quadrupole configurations near the minimum coupling settings were used as the initial dataset for MOBO.

RESULTS

The results of the MOBO optimization for the linear coupling waves are shown in Fig. 1. The initial point (red circle in Fig. 1a) corresponds to the minimal coupling state. The optimization improved both injection efficiency and beam lifetime within 30 iterations. The initial beam lifetime of about 3 hours increased to about 10 hours, with a slight improvement in injection efficiency.

Figure 2 displays the normalized beam lifetime and injection efficiency as functions of the coupling wave amplitude for the operational settings, which were not part of the initial sampling points and therefore are not shown in Fig. 1a. Similar plots for the optimal settings found through MOBO optimization (indicated by the circle that the arrow points to in Fig. 1a) are shown in Fig. 3. The horizontal axis represents the maximum change in power supply currents of the 15 skew quadrupoles relative to the minimum coupling settings; a value of zero corresponds to minimal coupling.

In both cases, the beam lifetime exhibits a symmetric pattern around minimum coupling, as expected. Interestingly, under the optimal settings, injection efficiency increases on the positive side and decreases on the negative side, while it declines rapidly on both sides under the operational settings.

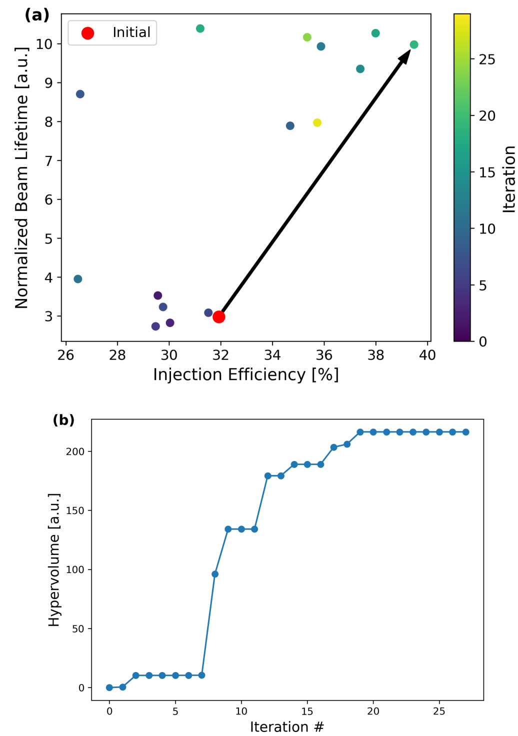

Figure 1: MOBO results for skew coupling wave optimization: (a) Normalized beam lifetime vs. injection efficiency; (b) Hypervolume evolution during optimization (reference point: lifetime = 3, efficiency = 10).

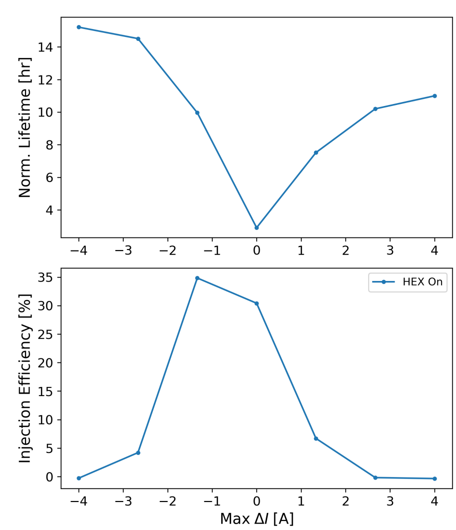

Figure 2: Normalized lifetime and injection efficiency vs. coupling wave amplitude for the current operational settings.

ENFORCEMENT OF SYMMETRIC INJECTION EFFICIENCY CURVES

To enforce symmetry, the evaluation function used by the optimizer was modified. For each setting proposed by MOBO as the next candidate, the evaluator assessed both the setting and its negative counterpart. The objective values from the worse of the two evaluations were then taken as the

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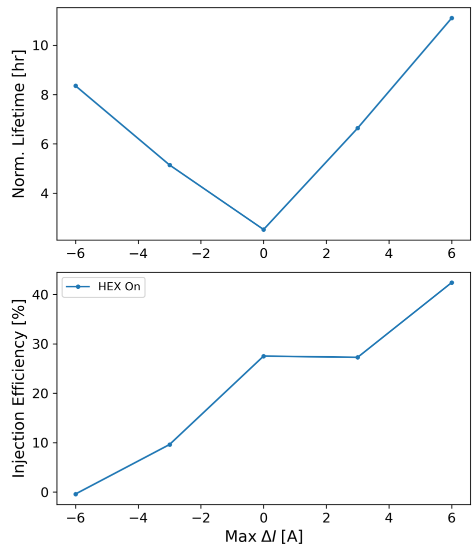

Figure 3: Normalized lifetime and injection efficiency vs. coupling wave amplitude for the optimal skew quadrupole settings identified by MOBO.

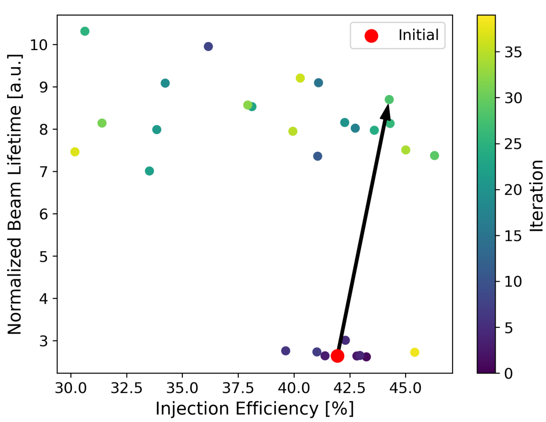

Figure 4: MOBO result for skew coupling wave optimization with symmetry enforcement.

final objectives. This approach prevents the optimizer from favoring previously optimal solution that are not symmetric, effectively forcing it to find a coupling wave with both positive and negative amplitudes that yields better overall performance. As a result, the optimization time roughly doubled, since each iteration had to evaluate two skew quadrupole settings.

The results of this optimization run are shown in Fig. 4. Due to its inherently conservative design, the optimization outcome was not as favorable as in the previous run. Nonetheless, the lifetime improved to ~9 hours from the initial ~3 hours, without sacrificing injection efficiency.

Figure 5 demonstrates that the injection efficiency curve is now more symmetric around the point of minimum coupling, as intended. Compared with the existing operational settings shown in Fig. 2, the range of high injection efficiency has been broadened.

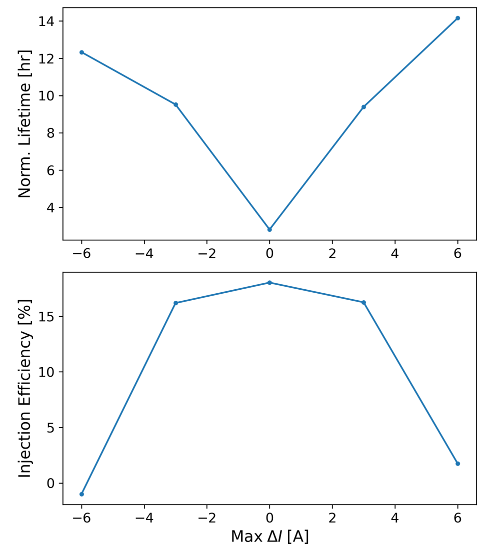

Figure 5: Normalized lifetime and injection efficiency vs. coupling wave amplitude for the optimal skew quadrupole settings identified through symmetry-enforced optimization.

BEAMLINE TESTS

We tested the new coupling wave during several dedicated beam studies in November 2024 to ensure compatibility across all beamlines. The non-symmetric solution was selected for testing, as it offered slightly improved lifetime and injection efficiency. Unfortunately, the rotation issue at the 17-ID beamline persisted with the new coupling wave. As a result, the new configuration has not been adopted for general user operations.

As a next step, we plan to conduct a similar optimization that incorporates the X-ray beam profile metric at the 17-ID beamline as an additional objective or constraint.

In parallel, we are in the process of adding more skew quadrupoles to the ring. With these additional tuning elements, it may become possible to more effectively localize the impact of global coupling or dispersion waves, thereby minimizing their effect on the 17-ID beamline.

CONCLUSION

We applied online multi-objective Bayesian optimization to tune 15 skew quadrupoles in non-dispersive sections at NSLS-II, improving beam lifetime by a factor of three with a slight gain in injection efficiency compared to the minimum coupling state. Despite these improvements, beamline tests revealed persistent beam rotation issues at 17-ID. Future efforts will include optimization with beamline-specific constraints and expanded control using additional skew quadrupoles to better localize coupling effects.

REFERENCES

[1] A. Franchi *et al.*, “Vertical emittance reduction and preservation in electron storage rings via resonance driving terms correction”, *Phys. Rev. ST Accel. Beams* 14, 034002, 2011.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP066

[2] J. Breunlin, S. Leemann, and Å. Andersson, "Improving Touschek lifetime in ultralow-emittance lattices through systematic application of successive closed vertical dispersion bumps", *Phys. Rev. Accel. Beams* vol. 19, p. 060701, 2016. doi:10.1103/PhysRevAccelBeams.19.060701

[3] C. Steier, G. Portmann, D. Robin, J. Safranek, and A. Wolski, "Coupling Correction and Beam Dynamics at Ultralow Vertical Emittance in the ALS", in *Proc. PAC'03*, Portland, OR, USA, May 2003, pp. 3213–3215.

[4] M. Fuchs (private communication)

[5] R. Roussel, A. Hanuka, and A. Edelen, "Multiobjective Bayesian optimization for online accelerator tuning", *Phys. Rev. Accel. Beams* vol. 24, p. 062801, 2021. doi:10.1103/PhysRevAccelBeams.24.062801

[6] N. Kuklev *et al.*, "High efficiency multi-objective Bayesian algorithm for APS-U nonlinear dynamics tuning", presented at *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025. doi:10.18429/JACoW-IPAC25-THPM102

[7] N. Kuklev, "Advanced ML at APS", presented at eeFACT-2025, Tsukuba, Japan, 2025.