ONLINE MINIMIZATION OF VERTICAL BEAM SIZES AT APS*

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Abstract

In this paper, online minimization of vertical beam sizes along the APS (Advanced Photon Source) storage ring is presented. A genetic algorithm (GA) was developed and employed for the online optimization in the APS storage ring. A total of 59 families of skew quadrupole magnets were employed as knobs to adjust the coupling and the vertical dispersion in the APS storage ring. Starting from initially zero current skew quadrupoles, small vertical beam sizes along the APS storage ring were achieved in a short optimization time of one hour. The optimization results from this method are briefly compared with the one from LOCO (Linear Optics from Closed Orbits) response matrix correction.

OVERVIEW

Multi objective optimization techniques are useful tools in finding optimum solutions in many complex systems [1] with many optimization targets and variables/knobs, including applications of genetic algorithms [2,3]. On accelerator and beam-related topics, the genetic algorithm was implemented in 1992 on optimizing sequences of permanent magnet segments of wiggler magnets [4]. Such algorithm was then used for dc-gun photoinjector design optimizations [5], the International Linear Collider damping rings design [6], and electron storage ring nonlinear beam dynamics optimizations based on numerical tracking simulations [7–11].

Recently machine-based online single-objective or multi-objective optimizations were also performed experimentally on operating storage rings, to optimize the dynamic aperture (DA) in SPEAR3 storage ring [12], also to minimize vertical beam sizes along SPEAR3 ring [13]. It was proposed by Tian et al. [13] to employ specific physics quantities that could be measured instantly on an operating accelerator, while it may take a long time to compute such physics quantities in the numerical tracking simulations. For accelerator-based particle colliders, an example of such a physics quantity is the luminosity of two colliding beams [13]. To optimize the photon brightness via reducing average beam sizes at IDs, it is proposed to employ the total beam loss rates [13] as the optimization objective since it is inversely proportional to average beam intensity along the ring. As pointed out by Franchi et al. [14], smaller horizontal-vertical-coupling has three potential advantages: enabling smaller vertical-gap-IDs with higher fields, hence enhancing the photon flux; improving the photon brightness given it is not limited by energy spread; improving injection efficiency for off-axis accumulation schemes. On the other hand, it is also noted [14] that reduced vertical beam sizes may introduce some reductions on Touschek lifetime which may have negative impact on photon users.

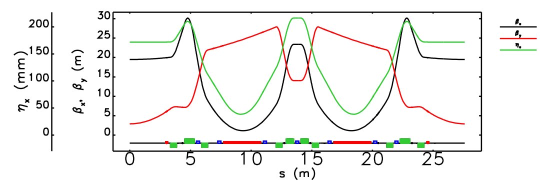

Figure 1: Twiss parameters in one arc section of APS storage ring. Green blocks represent quadrupoles, red blocks represent dipoles, and blue blocks represent sextupoles.

In this paper, online minimization of beam sizes along the APS (Advanced Photon Source) storage ring is presented, which is similar to the study of Tian et al. [13]. The Advanced Photon Source storage ring light source has a circumference of 1104 meters [15] with an effective beam emittance of 3.13 nm [15,16]. The nominal operation mode employs the so-called reduced horizontal beam size (RHB) lattice where horizontal beta function is reduced at one specific insertion device. The linear optics in one of the normal sectors is shown in Figure 1 above. In the following sections, experimental results of beam sizes minimization in APS ring are presented. The bunch fill pattern is 24 or 324 bunches that are evenly distributed in the storage ring.

OPTIMIZATION ALGORITHMS

As the online machine-based optimization method is applied on real accelerators, and uses the real accelerator performances as the optimization targets, it may have an advantage over the nominal simulation based techniques. A total of 59 families of skew quadrupole magnets were employed as knobs to adjust the coupling and vertical dispersions in APS storage ring. A general genetic algorithm was developed and employed for online machine-based optimization studies in the APS storage ring. For the online minimization of beam sizes along the ring, the algorithm could employ one or more of the following evaluation objectives.

- Beam loss rate monitor readings [13]
- Horizontal and vertical beam sizes (measured at sector 35 pinhole location)
- Lifetime calculated using DCCT measurements
- Total beam current measured from DCCT

The following operation bunch modes are available, with some possible advantages and disadvantages listed below.

- 24-bunch mode, with a single bunch current up to 4.1 mA. This bunch mode has a higher beam loss rate and a stronger impact from collective effects.
- 324-bunch mode, single bunch current up to 0.3 mA. Beam loss rates may be more noisy for this mode.

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ONLINE OPTIMIZATION RESULTS

The optimization algorithm could employ either of the following two initial conditions for the 59 families of skew quadrupole magnets, as the starting point.

- Skew quad currents set to zero (turned off).
- APS ring operational skew quad settings.

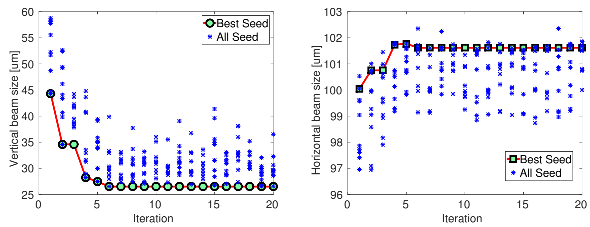

Figure 2: Horizontal (right) and vertical beam size (left) (at sector 35 pinhole location) at each iteration. A total of 20 iterations, and 10 seeds for each iteration. Starting point has skew quads set to zero current.

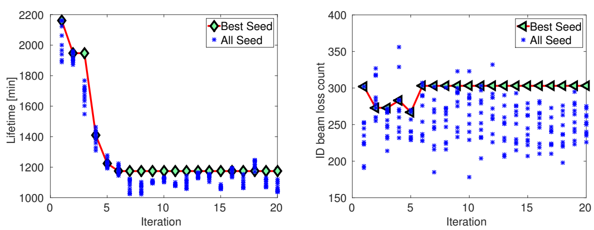

Figure 3: Left: Lifetime (calculated using DCCT current measurements) at each iteration. Right: ID4 beam loss preserved during the studies.

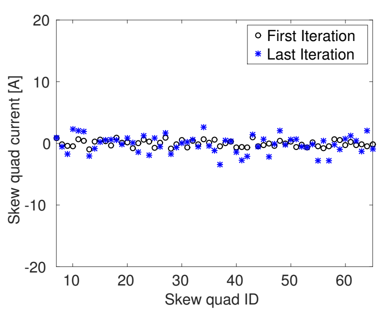

Figure 4: Skew quad strengths (best seed) for the first and last iteration. Starting point is 0 strength skew quads.

Case 1: Starting from 0 Skew Quads

Using 324-bunch mode, a total beam current below 100 mA, and the inital condition of zeros-strength skew quads, the optimization algorithm is able to reduce the vertical beam size and beam lifetime in a short time of 1 hour. The optimization took 20 iterations, each containing 10 random seeds, as shown in Fig. 2 and Fig. 3. Here, an additional objective of ID4 beam loss was introduced to exclude possible impact on the injection efficiency (ID4 has the minimum physical apertures in APS storage ring). It is noted that the injection efficiency usually drops to zero when all skew quads are turned off, from a combined effect of large coupling and large horizontal injection oscillations of off-axis accumulation. The optimized skew quad currents are shown in Figure 4.

Case 2: Starting from Operation Skew Quads

Using 24-bunch mode, a total beam current up to 100 mA, and the inital condition of operational skew quad currents, the optimization algorithm was able to further reduce the vertical beam size, as shown in Fig. 5. The skew quadrupole magnets current (best seed) for the first and last iteration are shown in Fig. 6.

Comparing Fig. 6 with Fig. 4, one observes that the online optimized skew quads were much weaker for Case 1, where the starting point was zero-strength skew quads.

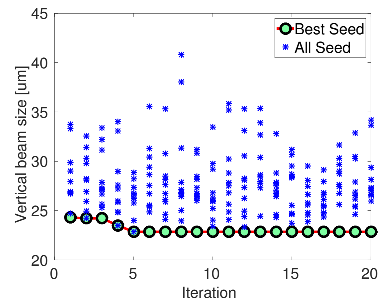

Figure 5: Vertical beam size (at sector 35 pinhole location) at each iteration. A total of 20 iterations, and 10 seeds for each iteration. Starting point was the APS operational skew quad settings.

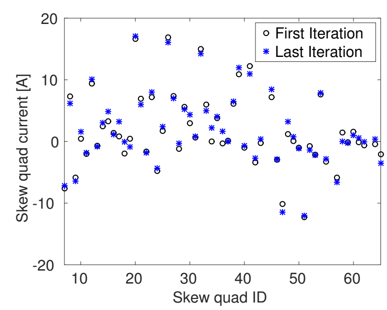

Figure 6: Skew quads strength for the first and last iteration. Starting point was the APS operational skew quad settings.

Case 3: Starting from 0 Skew Quads and Use Total Beam Loss as Sole Objective [13]

As the transverse beam sizes are only measured at one location with pinhole camera (located at sector 35 bending magnet), it may be good to employ the total beam loss rates as the sole optimization target [13]. Such an experiment was performed with 24 bunches and the medium-chromaticity RHB lattice. Figure 7 shows that the sum of all beam loss monitor counts converged quickly, within 10-20 iterations

(0.5 to 1 hour). As shown in Fig. 8, the vertical beam size and lifetime also converge correspondingly, with negative correlations to the total beam loss along the ring.

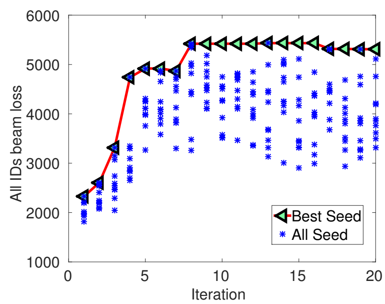

Figure 7: Sum of all beam loss monitor counts at each iteration. A total of 20 iterations, and 10 seeds for each iteration. Starting point is 0 strength skew quads (skew quads all turned off).

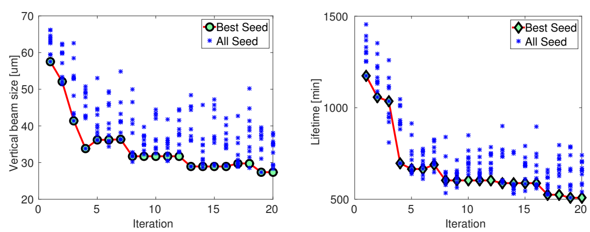

Figure 8: Vertical beam size (at sector 35 pinhole location) (left) and lifetime (right) at each iteration. A total of 20 iterations, and 10 seeds for each iteration. Starting point is 0 strength skew quads.

COMPARISON AND DISCUSSION

The measured horizontal and vertical dispersion functions at the BPMs were compared among the operation lattice (OPER), LOCO based optimization (LOCO) [17–19], and one of the online-optimized lattices (ONLINE), as shown in Fig. 9. The horizontal dispersions are similar, which perhaps indicates negligible changes in linear optics. The vertical disperison of the online-optimized lattice is smaller than that of the operational lattice, and larger than the LOCO based optimization results. It is noted that the operation lattice and the online-optimized lattice share same linear optics, while LOCO based optimization is from 2015 where the linear optics may be different. It is also noted that the operational lattice was not optimized for minimum vertical dispersion; instead, vertical dispersion was deliberately introduced in order to increase the Touschek lifetime.

The online-optimized solution was also preliminarily compared with the LOCO-corrected solution [17–19], in terms of lifetime etc., as shown in Table 1. Although it seems that the online-optimized solution achieves a lower normalized lifetime, one needs to note that the chromaticities are higher for the online-optimized solution which reduces lifetime. The RF voltage is similar. There may be

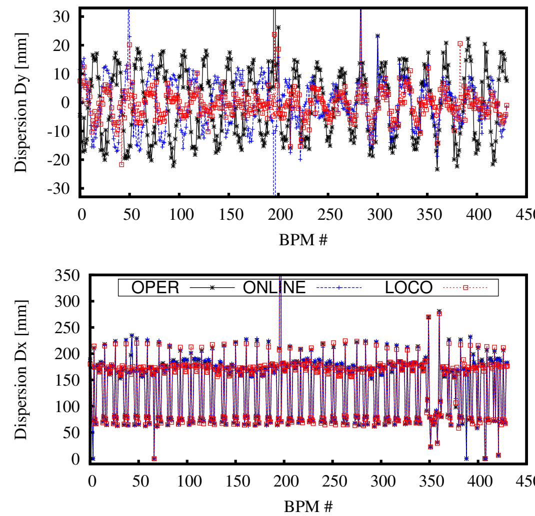

Figure 9: Comparison of measured horizontal (bottom) and vertical dispersions (top) at BPMs. Black: operational lattice; Blue: online-optimized lattice; Red: LOCO based optimization from previous run in 2015 [19].

other machine conditions that are different for these two cases, which may greatly impacts lifetime. Future studies will compare lifetime with same machine conditions.

Table 1: Preliminary Comparison between Online-optimized (MOGA) and LOCO-corrected Solutions [19]

Parameter	MOGA	LOCO
σ_x @s35 pinhole	104.7	103.9
σ_y @s35 pinhole	24.6	22.3
Beam current [mA]	63	95
Lifetime [min]	320	300
ξ_x/ξ_y (measured)	6.34/6.27	4.23/3.28
RF gap voltage [MV]	9.415	9.410

CONCLUSIONS

Online machine-based optimizations of overall vertical beam sizes was demonstrated at APS storage ring. The algorithm converges in a short time within 1 hour. The algorithm may be more efficient if more beam size diagnostics is available along the ring. Possible impact on linear optics and a detailed comparison with LOCO based correction results will be performed in the future, including a true comparison with more conventional methods of minimizing vertical beam sizes along the ring. Lifetime and beam loss rates will be compared under same/similar machine conditions.

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