Multi-objective optimization of storage ring dynamic acceptance and lifetime

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Abstract

As storage ring light sources are pushed to smaller emittances and otherwise modified to meet user requirements, the difficulty of achieving workable injection efficiency and Touschek lifetime increases. Workable injection efficiency requires sufficient dynamic acceptance (DA), while workable Touschek lifetime requires sufficient local momentum acceptance (LMA). We recently developed direct (i.e., tracking-based) single- and multi-objective techniques for tuning linear optics and sextupoles in order to maximize DA and lifetime [1]. We describe the method and several applications to the Advanced Photon Source (APS).

1. Background

APS is a 7 GeV storage ring light source

- 40 double-bend sectors with 5-m-long straight sections.
- Essentially symmetric configuration with independently-powered quadrupoles (400) and sextupoles (280).

APS Upgrade (APS-U) requires lattice changes

- Four 7.7-m-long straights (LSS), created as in Figure 1 [2].
- Special optics insertion for Short Pulse X-ray (SPX [3]) system, which requires special sextupole tuning [4]
- Special optics insertion for Reduced Horizontal Beamsize (RHB), which ideally provides $\sigma_x = 120\mu$m instead of the normal $\sigma_x = 280\mu$m.

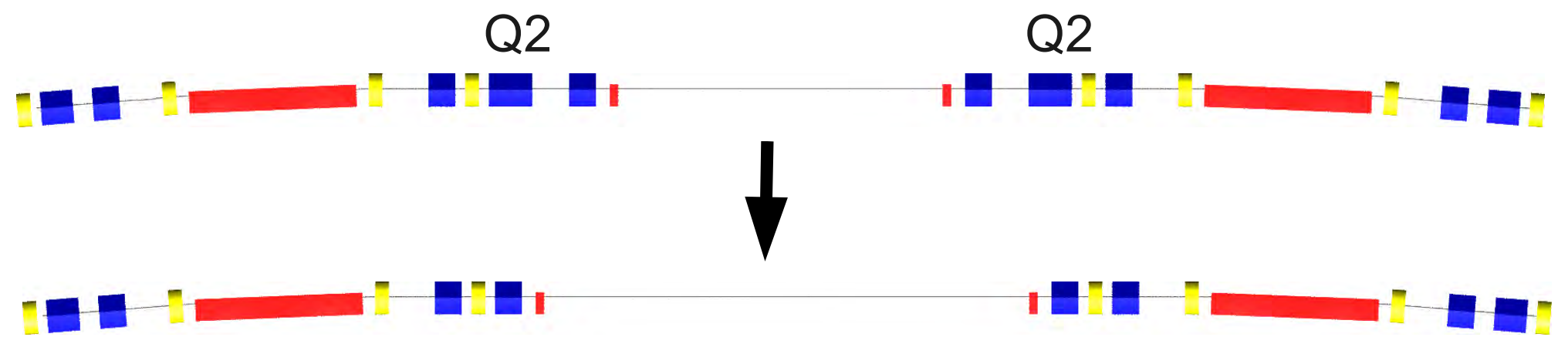

Figure 1: *Concept for making long straight sections (LSSs) in the APS.*

In APS-U, we cannot cannot preserve lattice symmetry. A likely configuration is shown in Figure 2.

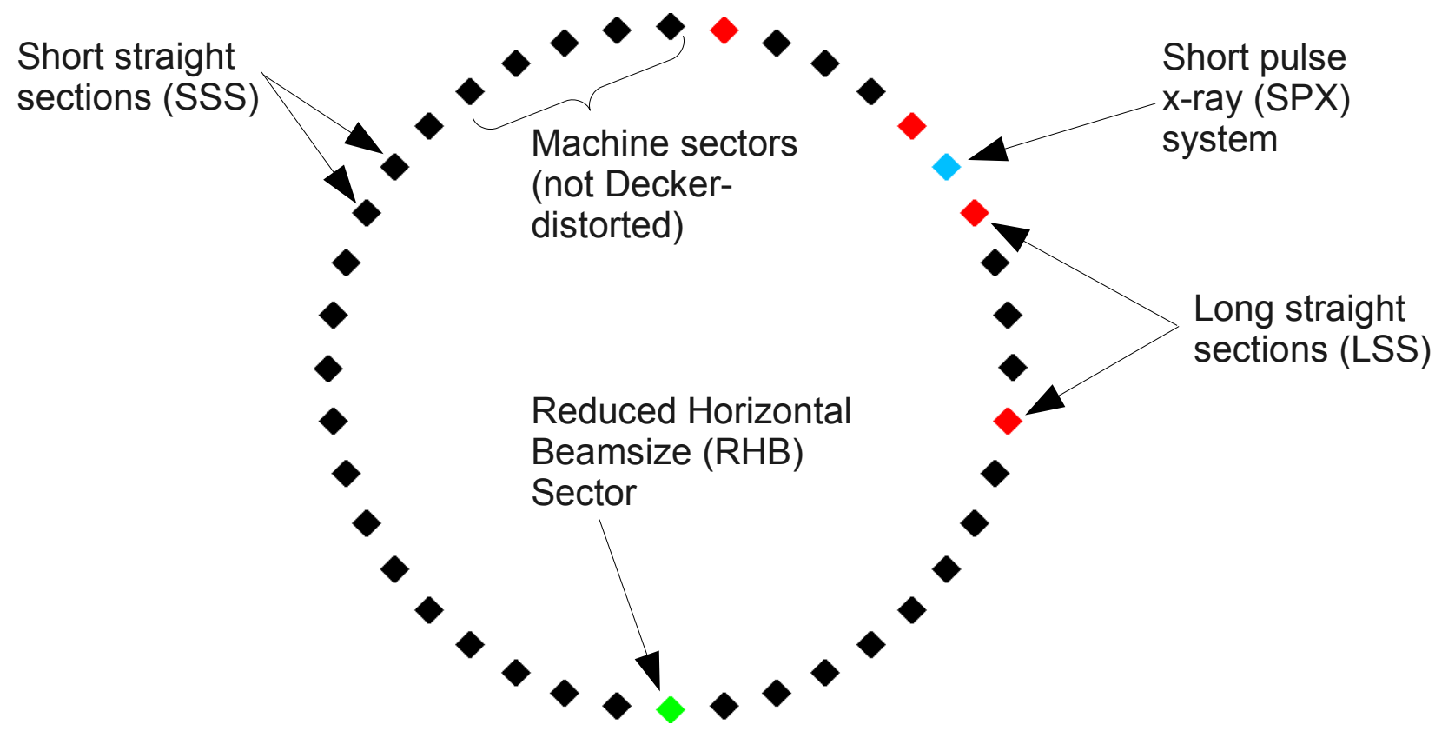

Figure 2: *Likely configuration of straight section types for APS-U.*

Timing-mode fill patterns create an additional difficulty

- APS runs 80% of the time with $>$ 4.25 mA single bunch current
- APS-U will increase this to $>$ 6.4 mA.
- Required chromaticity is high: $8 \leq \xi_x, \xi_y \leq 9$

In low-emittance light sources, sextupoles must be strong to correct chromaticities ξ_x and ξ_y. Sextupoles can drive resonances, so low-symmetry lattices are problematic:

- Poor injection efficiency—determined by dynamic acceptance (DA).
- Poor Touschek lifetime—determined by local momentum acceptance (LMA).

Optimization with a multi-objective genetic algorithm (MOGA) addresses these issues by providing a new way to adjust sextupoles and linear optics.

2. MOGA Method

The MOGA method used here has this form

1. Generate N configurations with randomized parameters
2. Submit configurations for evaluation to obtain corresponding values of M objectives
3. When sufficient number of configurations have been evaluated
   (a) Perform non-dominated sort on M objectives
   (b) “Breed” Rank 1 configurations pair-wise, including randomization of parameters
   (c) Repeat from step 2 until convergence

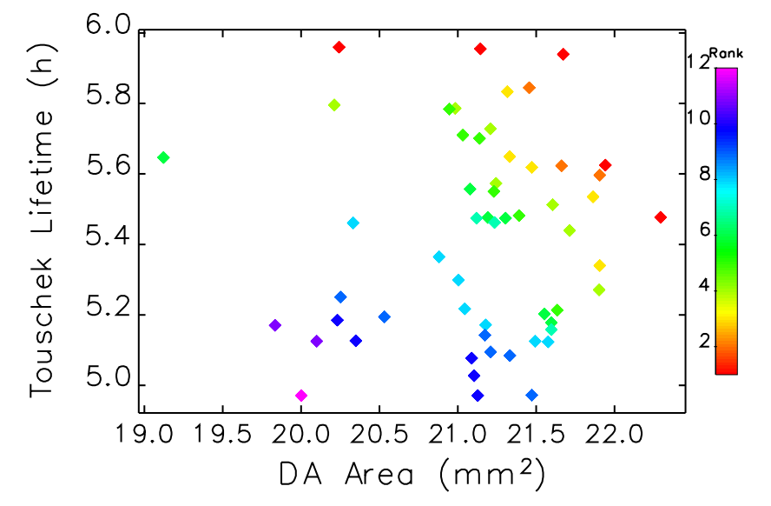

Figure 3: *Example of non-dominated sorting on Touschek lifetime and dynamic acceptance.*

Non-dominated sorting [5] groups points into “ranks.” A point has Rank 1 if no other point dominates it in all performance measures. Removing the Rank 1 points and repeating the analysis allows finding the Rank 2 points, and so on.

3. Application to Storage Ring Optimization

For storage ring optimization, the MOGA algorithm is based on three objectives

- Maximize area of the on-momentum DA
- Maximize Touschek lifetime, which is determined from the LMA
- Minimize chromaticity error (easy)

To optimize these, we allow variation of

- Linear optics, typically just the tunes using a pre-computed grid of solutions
- Sextupole strengths, typically a combination of a few “ganged,” global knobs and several local knobs.

Essential details

- Clipping algorithm [6] used to trim DA prior to area compution
  - Avoids growth of useless DA regions
- Include physical apertures
- Include random strength and tilt errors (identical for all trials)
- Include radiation damping and longitudinal motion
  - May increase or decrease DA/LMA
  - Track enough turns to overlap starting and ending amplitudes

Software tools

- Tcl/SDDS script `geneticOptimizer` implements MOGA.
- `elegant`[7] and `Pelegant`[8] used for
  - Lattice matching
  - Chromaticity and coupling correction
  - SPX sextupole optimization
  - DA and LMA tracking
- `touschekLifetime` [9] is used for Touschek lifetime computation from the LMA, based on Piwinski’s method[10].
- `elegantRingAnalysis` [11] is used for ensemble evaluation

4. Applications to APS Upgrade Optimization

The requirements for APS-U lattice performance are

- Horizontal DA on the inboard side of at least 13 mm, preferrably 15 mm, and at least 7mm on the outboard side.
- Vertical DA of $\geq$ 1 mm.
- Touschek lifetime of $\geq$ 3.8h for 24 bunches in 150 mA with 1.5% coupling. This corresponds to 60s top-up interval.

Two groups of lattices are needed

- “Mock-up” lattices, in which Q1 magnets are turned off to simulate a LSS. Allows testing lattices without hardware changes.
- Production lattices, which require actual hardware changes (removal of magnets).

For each group, several variants are needed

1. Lattices with 4 LSS, but no other features, with $\xi = 9$.
2. Lattices with 4 LSS and RHB, with $\xi = 9$.
3. Lattices with 4 LSS and SPX, with $\xi = 8$.
4. Lattices with 4 LSS, RHB, and SPX, with $\xi = 8$.

In Figures 4 through 7, we show results for 4LSS with $\xi = 9$, using 40 independent sextupoles and the tunes.

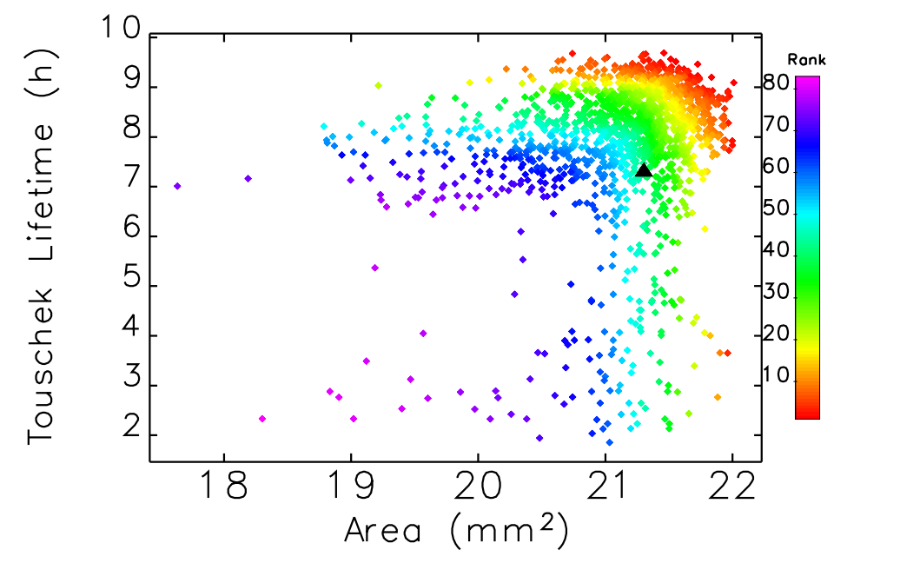

Figure 4: *Final 4LSS configurations ranked by Touschek lifetime (100 mA/24 bunches/1% coupling) and DA area for $\xi = 9$.*

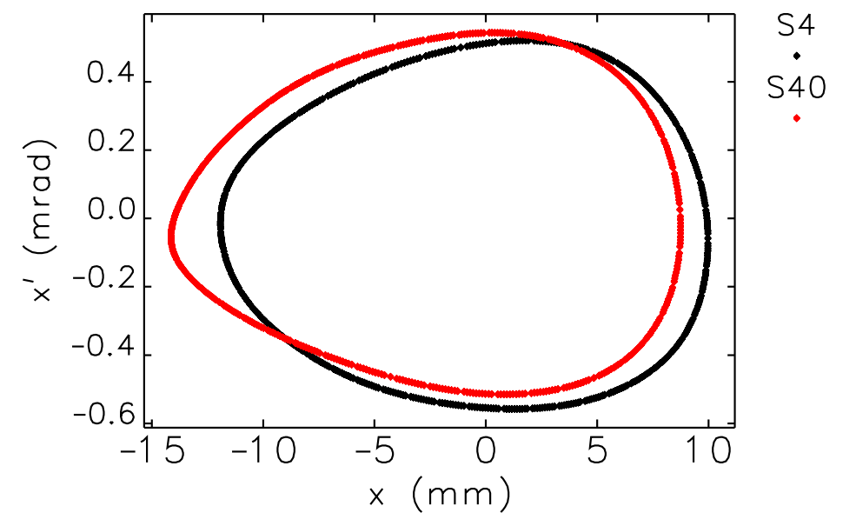

Figure 5: *4LSS lattice with $\xi = 9$ benefits from nonlinear phase space distortion at 15 mm aperture limit.*

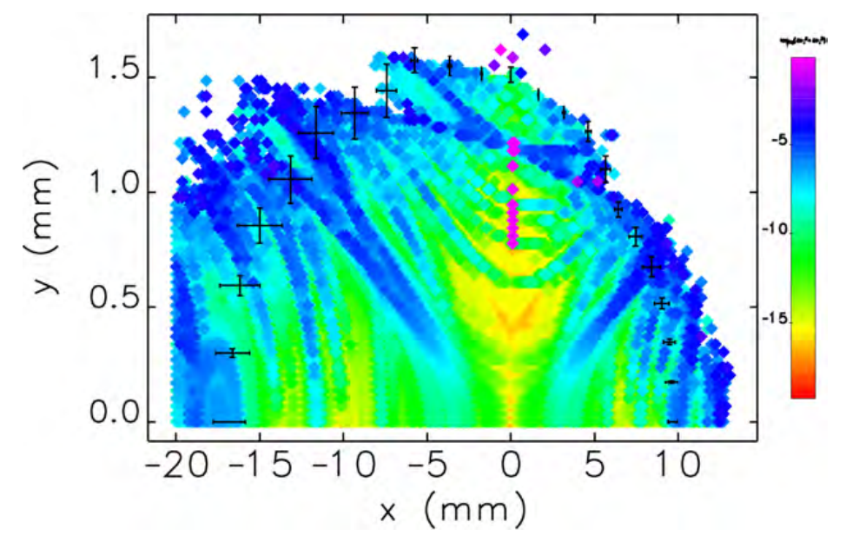

Figure 6: *4LSS dynamic acceptance for 50 ensembles for $\xi = 9$, superimposed on frequency map.*

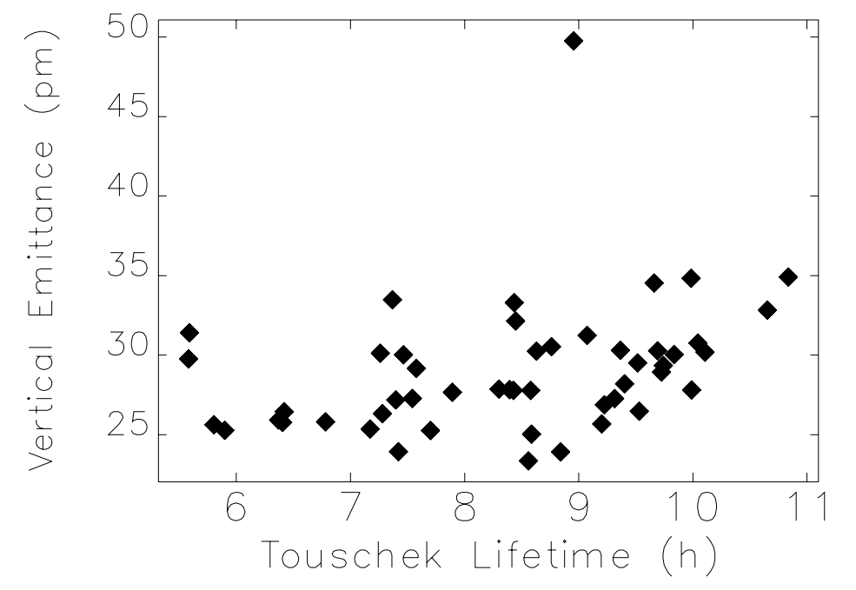

Figure 7: *4LSS lattice lifetime and vertical emittance for 50 ensembles for $\xi = 9$.*

Studies have shown significant experimental verification of this technique:

- Optimization of APS operational lattice increased lifetime by 25% with no reduction in injection efficiency.
- 8LSS mockup with $\xi = 7$ tested, showed excellent performance.
- 8LSS+SPX+RHB mockup with $\xi = 7$ also tested. Results not as good as expected. Suspect sextupole calibration.
- Improvement of Diamond lifetime by 20%

Computer systems used:

- APS Weed Cluster (400 cores)
- ANL Fusion Cluster (3200 cores)
- ALCF Blue Gene P (196k cores)

5. Future Work

Future work will concentrate on continued application of these techniques to the APS upgrade. We are optimizing 4LSS mock-up configurations that will allow testing lattices with four long straight sections and other features prior to making hardware changes.

For the RHB insertion, the results are sensitive to the linear optics, making these very difficult to optimize. We’ve recently incorporated more detailed linear optics optimization for these lattices.

6. Acknowledgements

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