DIRECT METHODS OF OPTIMIZATION OF STORAGE RING DYNAMIC AND MOMENTUM APERTURE *

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Abstract

Optimization of dynamic and momentum aperture is a challenging aspect of storage ring design. For ring-based x-ray sources, large dynamic aperture gives high injection efficiency, which is important for efficient operation and to reduce radiation damage. X-ray sources require large momentum aperture to achieve workable Touschek lifetimes with low-emittance beams. The most widely applied method of optimizing these apertures is to minimize the driving terms of various resonances. This approach is highly successful, but since it is based on perturbation theory, it is not guaranteed to give the best result. In addition, the user must somewhat arbitrarily assign weights to the various terms. We have developed several more direct methods of optimizing dynamic and momentum aperture. These have been successfully applied to operation and design problems related to the Advanced Photon Source and possible upgrades. One surprising discovery is that asymmetric sextupole distributions are very beneficial.

INTRODUCTION

One of the most sought-after characteristics of storage-ring-based x-ray light sources is low emittance. To achieve low emittance, lattice designers employ strong focusing to obtain large horizontal phase advance per cell. With this comes strong chromatic aberrations and thus strong chromaticity correcting sextupoles in order to achieve large momentum aperture. Low emittance means the dispersion function is small, again requiring stronger chromatic sextupoles. These strong sextupoles generally result in small dynamic aperture, making it more difficult to accumulate beam. In extreme cases, the dynamic aperture may be so small that sufficient lifetime is not achieved.

Ring designers add extra families of "geometric" sextupoles to correct the effect of the chromatic sextupoles [1]. The problem facing lattice designers is to adjust the sextupole families to simultaneously maximize both dynamic and momentum aperture. Perhaps the most common way of making these adjustments is to minimize many resonance and tune variation driving terms [2]. However, the method is not without its pitfalls. For example, the designer must carefully choose the weights for these many terms, based on experience and, ultimately, the results of tracking.

In this paper, we present several new methods of simultaneously optimizing dynamic and momentum aperture. These "direct" methods rely on various forms of tracking to directly probe the dynamic and momentum apertures. They are made possible by the advent of relatively inexpensive computing clusters running free software (e.g., GNU/Linux, Sun Grid Engine) on commodity hardware.

Although our methods could use any tracking code, the ability to create fully scripted simulations is essential, since matching and tracking must run without human intervention. Thus, we use the tracking program `elegant` [3], including the parallel version [4], as well as the SDDS Toolkit [5] and `geneticOptimizer` [6].

The APS storage ring has 280 sextupole magnets with individual power supplies. Because of the symmetry of the lattice, these sextupoles are commonly powered in four families. One can more or less arbitrarily choose two sextupole strengths as free parameters, with the other two being used to correct the chromaticity. Because we run in modes with fairly high single-bunch current while lacking a bunch-by-bunch feedback system, we operate with significant non-zero chromaticities $\xi_x = d\nu_x/d\delta$ and $\xi_y = d\nu_y/d\delta$. In 24-bunch, 100-mA mode, we have $\xi_x \approx \xi_y \approx 6$, while for hybrid mode we require $\xi_x \approx \xi_y \approx 10$ to achieve the required 16-mA single-bunch current.

SEXTUPOLE SCAN METHOD

This method was one of the first we developed and has yielded significant improvements for both 24-bunch and hybrid mode. It involves scanning two families of sextupoles in a grid, while using the other two families to obtain the desired chromaticities, with linear optics held fixed. For each grid point, we track a specially designed beam and determine how much of the beam survives N turns, where typically $N > 1000$. Plotting the fraction surviving as a function of the sextupole strengths allows us to choose the optimum sextupole values.

The beam that is tracked is designed to probe both the dynamic and momentum apertures: The beam has a uniform distribution in x, y, and δ, with the extent in each dimension chosen to correspond to the size of the desired aperture. For example, in the APS we ideally would like a horizontal dynamic aperture of ±15mm, a vertical dynamic aperture of ±2mm, and a momentum aperture of 2.25%. Hence we'd create a beam with $x : [-15, 15]$mm, $y : [-2, 2]$mm, and $\delta : [-0.0225, 0.0225]$. Typically, a few thousand particles are needed to get good results.

If we tracked this beam in a lattice with no errors, we'd find that a significant fraction survived for many different sextupole choices, which would not help find a robust solution. Instead, we track with quadrupole and sextupole strength and roll errors. The magnitude of these errors is

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chosen to give lattice function beating and vertical emittance that is several times what is observed after lattice correction [7]. Tracking includes synchrotron motion but no quantum excitation. The rf voltage is artificially increased (about threefold) to increase the synchrotron tune, since this will result in the sweeping several times over various resonances as the tune changes with the changing momentum offset. It also means the beam returns more times to the maximum momentum deviation.

Figure 1 shows results of such a scan. The settings recommended by this scan resulted in a measured lifetime improvement of about 20% and the largest dynamic aperture seen up to that time in our low-emittance lattice.

Although it improved APS operations, this method has several limitations. First, the method is sensitive to the momentum aperture at only a single location and thus only roughly optimizes the Touschek lifetime. Second, the method cannot tell the difference between a dynamic aperture consisting of multiple stable regions and a single, centered region. Third, the method is not practical for more than four sextupoles or variable linear optics.

GENETIC OPTIMIZATION

This method addresses the limitations in the sextupole scan method. The genetic optimization technique, as implemented by the `geneticOptimizer` script, allows any number of optimization variables. The user supplies a pair of scripts, one to run a simulation and another to compute a penalty function from the results of the simulation. Hence, the simulation may be arbitrarily complicated. In some cases, we run `elegant` multiple times, e.g., for complex multi-step matching followed by tracking.

Originally, we used the same tracking idea as used in the sextupole scans. Presently, we directly determine both the dynamic aperture and the position-dependent momentum aperture using `elegant`'s native commands, so we fully address the deficiencies of the previous method.

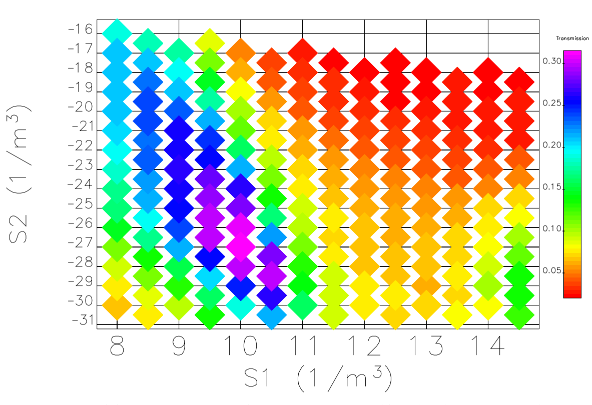

Figure 1: Output from sextupole scan used to optimize APS dynamic and momentum apertures.

We used `elegant`'s "n-line" dynamic aperture search method, which involves searching outward from the origin along several (e.g., 21) lines in x-y space until the stability limit is found. (Although searching from large amplitude toward the origin is faster, one risks being fooled by stable islands.) `elegant` analyses the results of the search to find the dynamic aperture area using an algorithm that detects and compensates for signs of pathological dynamic aperture shape. For example, if the horizontal aperture increases as the vertical coordinate increases, `elegant` clips the horizontal values. This prevents inclusion into the computation of islands or regions that are cut by a resonance.

We included radiation damping and synchrotron oscillations in the dynamic aperture search, and used the dynamic aperture area directly as an input to the penalty function. We typically targeted an area of 30 μm^2, corresponding to a 20mm width and 1.5mm height, for example.

The momentum aperture is determined by tracking particles with increasing positive and negative momentum deviations, starting at several locations [8]. Typically, we determined the momentum aperture at the exit of all the sextupoles in the first four sectors of the APS, which gives a good measure of Touschek lifetime. Again we included radiation damping and synchrotron oscillations. We used the minimum absolute value of the momentum aperture in the penalty function, typically targeting a value of 2.35%.

We now review some applications of this method.

Long Straight Section Lattices

One of the most frequent requests from APS users is for a long straight section (LSS). All existing APS straight sections are the same length and accomodate a total undulator length of 4.8 m. We can increase this to 7.7 m by removing the innermost quadrupole (Q1) of the two triplets and replacing the next quadrupole (Q2) of each triplet with a shorter magnet. We've developed a series of lattices for providing two, four, and eight symmetrically located LSSs.

Because APS has indepenently powered quadrupoles, we are able to mock-up such configurations by turning off selected Q1 magnets, which we did for an 8LSS configuration. The sextupoles in the non-LSS sectors were powered in four families, as now. The 14 sextupoles in the two sectors on either side of the LSS were allowed to vary independently, with no symmetry constraints, which was the key to good results. The lattice was verified in machine studies and exhibited a 25% increase in lifetime compared to the operational lattice, with equally good injection efficiency.

Next, we optimized working points and sextupoles for permanent 2LSS, 4LSS, and 8LSS lattices with asymmetric sextupole configurations. Figure 2 shows the asymmetric sextupole distribution obtained for 8LSS. Figure 3 shows the predicted dynamic aperture for 8LSS, which is more than adequate. The predicted beam lifetime is over nine hours for all the lattices in 24-bunch mode, which is easily accomodated with top-up. There is little doubt that these lattices will work well in practice.

APS Operational Lattice

Inspired by the LSS results, we attempted to further optimize the APS operational lattice, allowing the sextupoles to vary in seven families. We started from the sextupole scan result, but additionally allowed the tunes to vary. The results show a slight improvement in the dynamic aperture, but a dramatic improvement in the momentum aperture (see Figure 4). Shown are the positive and negative momentum aperture values at the exit of all sextupoles for the two configurations. The original optimization shows a rapid oscillation in the momentum aperture through each of the 40 sectors, which is particularly evident in the positive limits. The sextupole scan method did a very good job of optimizing the initial momentum aperture, while the genetic optimization did a better job of increasing the momentum aperture around the ring. The predicted lifetime in 24-bunch mode increases by 25%. The configuration has ∼5% sextupole asymmetry, which may be nonessential.

This lattice was tested in machine studies, yielding some interesting observations. First, we needed to increase the horizontal chromaticity from the design value of 6.0 to 6.7 to stabilize the beam (which is not unusual). Second, we needed to raise the horizontal tune from the predicted optimum value of 36.14 to 36.18 to maximize the lifetime. In the end, the new configuration had 9.4 hour lifetime compared to 7.1 hours in our normal operating lattice (both with 1.25% coupling). The injection efficiency values were 85% and 90%, respectively, with incomplete tune-up having been performed on the new lattice.

CONCLUSION

We have developed several new methods for optimizing the dynamic and momentum aperture of storage ring lattices. Both methods are direct, in that they rely on tracking to determine the performance of the ring. The first method, scanning sextupoles in a grid while tracking a beam that fills the desired dynamic and momentum aperture, was successful in improving our operational lattice. The second method, which uses a genetic optimization technique to directly optimize the dynamic aperture area and the minimum momentum aperture, has given good results for long straight section lattices, which have been confirmed by experiments. We've also used it to re-optimize the APS operational lattice, with a ∼30% increase in lifetime.

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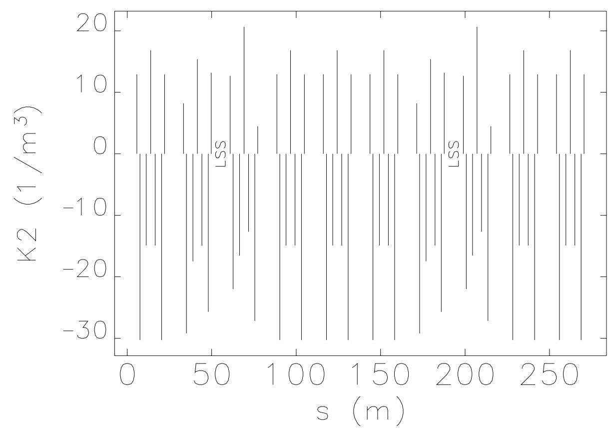

Figure 2: Sextupole distribution for a portion of the optimized 8LSS lattice.

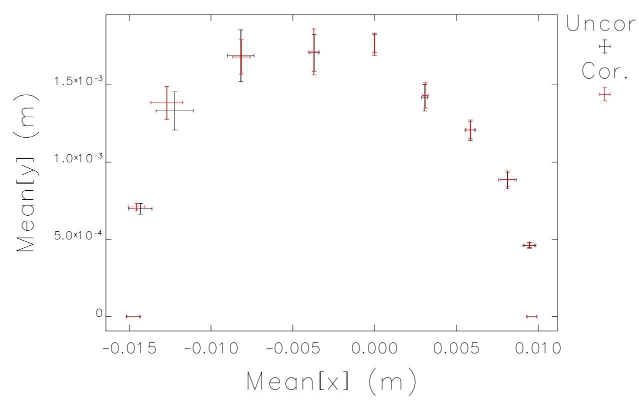

Figure 3: Dynamic aperture of optimized 8LSS lattice for 50 ensembles, with and without coupling correction.

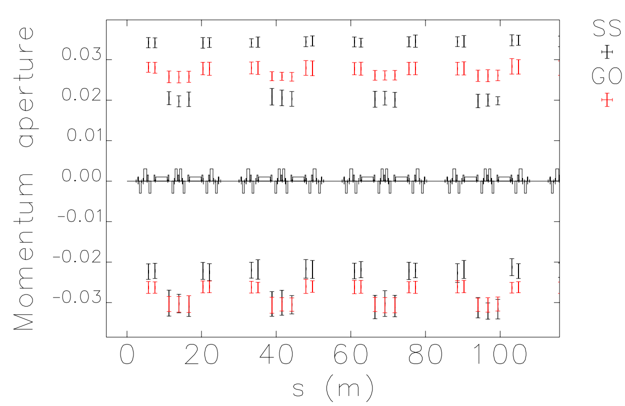

Figure 4: Comparison of momentum aperture for a portion of the lattice from the sextupole scan (SS) and genetic optimization (GO) methods. See text for explanation.