

MULTI-OBJECTIVE OPTIMIZATION OF A LATTICE FOR POTENTIAL UPGRADE OF THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source (APS) is a 7-GeV storage ring light source that has been in operation for over a decade. In the near future, the ring may be upgraded, including changes to the lattice such as provision of several long straight sections (LSSs). Because APS beamlines are nearly fully built out, we have limited freedom to place LSSs in a symmetric fashion. Arbitrarily placed LSSs will drastically reduce the symmetry of the optics and would typically be considered unworkable. We apply a recently developed multi-objective direct optimization technique that relies on particle tracking to compute the dynamic aperture and Touschek lifetime. We show that this technique is able to tune sextupole strengths and select the working point in such a way as to recover the dynamic and momentum acceptances. We also show the results of experimental tests of lattices developed using this technique.

INTRODUCTION

As light source designers strive to achieve ever smaller emittances, the difficulty of achieving workable injection efficiency and Touschek lifetime increases. Achieving workable injection efficiency and lifetime requires sufficiently large dynamic acceptance (DA) and local momentum acceptance (LMA) correspondingly. Emittance minimization requires strong focusing elements to decrease dispersion in dipoles. This leads to higher natural chromaticity, stronger sextupoles, and higher nonlinearities. It makes achieving large DA and LMA difficult. An approach that works best is resonance suppression using lattice symmetry. That is why modern light sources are built in a highly symmetric fashion utilizing many short repeating cells.

The Advanced Photon Source (APS) is a 7-GeV storage ring light source with 40 nearly identical sectors. In the near future, the ring may be upgraded, including introduction of several long straight sections (LSSs). Because APS beamlines are nearly fully built out, we have limited freedom to place LSSs in a symmetric fashion. Arbitrarily placed LSSs will drastically reduce the symmetry of the optics, which would result in collapse of DA and LMA.

Here we discuss a recently developed direct (i.e., tracking-based) multiple-objective optimization technique for tuning sextupoles in order to maximize DA and LMA.

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APS UPGRADE LATTICE

The APS magnetic lattice consists of 40 double-bend sectors. Each sector has ten quadrupoles and seven sextupoles. In anticipation of the need to customize the electron optics, all quadrupoles and sextupoles have independent power supplies. The important part of the upgrade will be provision of long straight sections (LSSs) at (presently) eight sectors. This will be accomplished by removing the long Q2 quadrupoles on either side of the target straight section, then moving other components away from the straight section into the empty locations.

Given that there are 40 straight sections, eight LSSs can be symmetrically placed. However, this would require relocation of beamlines to accommodate the LSS locations, which would be very expensive, would disrupt the beamlines science programs, and is considered unacceptable. Based on recent progress in optimization of the nonlinear properties of lattices [1], we have developed workable non-symmetric configurations incorporating eight LSSs.

OPTIMIZATION TECHNIQUE

Dynamic Acceptance

“Dynamic aperture” is a well-known term that is used to describe nonlinear properties of a lattice. It is the area in horizontal and vertical space with the boundaries defined by particle dynamics only. “Dynamic acceptance” (DA) is similar to dynamic aperture, but includes the effects of physical apertures. The dynamic acceptance is the most relevant quantity for our studies because it defines the injection efficiency. Dynamic acceptance is determined by tracking particles with increasing initial horizontal and vertical amplitudes as is usually done for the dynamic aperture determination, but in the presence of physical apertures.

Local Momentum Acceptance

Momentum acceptance is the maximum momentum displacement for which a particle can survive. This quantity varies as a function of position around the ring, and can also be different for positive and negative displacements. Therefore, we are interested in the local momentum acceptance (LMA) characterized by functions $\delta_n(s)$ and $\delta_p(s)$. These functions determine the Touschek lifetime, which is the main lifetime-limiting process in the APS. The method used to determine $\delta_{n,p}(s)$ is similar to that described in [2]. At different longitudinal positions s , particles are given increasing positive or negative momentum kicks, then tracked for N turns, until the stability limit is found.

Particle Tracking

To determine DA and LMA, tracking must include not only the effects of the magnets, but also longitudinal motion, radiation damping, physical apertures, and errors.

For LMA, including longitudinal motion is essential, since the momentum acceptance may be determined by either transverse dynamics or the rf acceptance.

Radiation damping may increase the DA or LMA by damping the growth of particle motion near the stability boundary. In addition, it gives a large momentum slew that potentially sweeps the particle past many resonances.

Physical apertures are important for determination of the DA. Often, the stable aperture is smaller than the physical aperture, which may lead to the erroneous conclusion that the physical aperture is unimportant. Because of linear and nonlinear coupling, small vertical physical apertures can result in significant reduction of horizontal stable area.

Inclusion of errors is required to excite resonances that would cancel in an ideal machine, and to introduce coupling. Effective methods exist for correcting linear optics and coupling. In the APS, for example, we correct lattice function errors to the 1% rms level and coupling to the 1% level. Instead of modeling realistic errors with correction, we use smaller random errors that give lattice function variations and coupling errors at post-correction levels.

Penalty Functions

Our optimization technique relies solely on tracking. Although any tracking code can be used, the ability to create fully scripted simulations is essential, since lattice matching and tracking must run without human intervention. We use parallel *elegant* [3], the SDDS Toolkit [4] and geneticOptimizer [5]. We use many computers simultaneously to evaluate the DA and LMA for various cases. A genetic algorithm is used to “breed” new configurations based on the best configurations seen so far. For optimization, we use a single fixed ensemble of errors. To guard against choosing an error ensemble that happens to provide atypical results, we evaluate the final optimized configuration with a large number of ensembles.

Any optimization requires one or more penalty functions. We used a multi-objective optimization with objectives derived from the DA and lifetime.

In order to optimize DA, we need one quantity that clearly indicates how good a solution is. Our approach is to use the DA area, but to compute it with certain restrictions that ensure it is useful. We avoid large vertical acceptance by simply not scanning the vertical coordinate beyond the minimum requirement. We also apply a DA clipping algorithm that removes irregular protrusions that enlarge the area but are not useful for injection. Weve found that the DA area A_d is a robust indicator of a good solution.

The Touschek lifetime is computed from the LMA, the Twiss parameters, the beam emittances, and the bunch charge using the program *touschekLifetime* [6], which accepts the Twiss parameters and LMA computed by

Pelegant and applies Piwinski formalism. In order to reduce the computer resource requirements, we compute LMA only at five points per sector in the first six sectors. Then, we assume that the LMA repeats the same pattern in the remaining 34 sectors. (This is checked after optimization when many error ensembles are modeled.)

Tune Variation

Tune variation is important in finding an optimal solution. In the case of complex lattices with many different types of sectors, the most robust way to adjust tunes is to perform matching of the entire ring at once. To save computing time during optimization, we created a grid of lattice solutions with different tunes. The lattices in the grid were created sequentially starting from one point. We can then create new solutions by performing two-dimensional interpolation of quadrupole strengths.

APPLICATION TO APS

Any new lattice must satisfy a set of constraints, which are of course well-satisfied by the present lattice. These constraints include: limit on maximum horizontal and vertical beta functions; horizontal beta functions at the center of ID straights between 15 and 25 m; vertical beta functions at the center of the ID straights within 50% of $\beta_{opt} = L/2$; effective emittance increase below 10% of the present value of 3.1 nm; chromaticity of +8 in both planes (based on experience operating with high single-bunch charge); keeping present power supply limits; and providing sufficient injection efficiency and lifetime for top-up operation.

We optimized a configuration with eight LSSs in initial locations requested by the beamline scientists: straight sections 1, 6, 8, 11, 13, 16, 28, and 33. The linear optics is reflection symmetric for the two sectors on either side of each LSS. Figure 1 (left) shows the linear optics of two consecutive sectors, with short and long straight sections.

Although sextupoles are in symmetric physical locations in the sector, the strengths are allowed to vary without this symmetry constraint. The sextupoles are, however, the same in all sectors with the same sequence of quadrupole strengths (as seen by the beam). Hence, the sextupoles in sectors 1, 6, 8, and so on are identical, as are those in sectors 2, 7, 9, and so on. Since there are seven sextupoles per sector, we have a total of 14 independent sextupole variables for the long-to-short and short-to-long sectors.

In addition to the sectors surrounding the LSSs, we need solutions for ordinary sectors having short straights at each end. Two such solutions are needed due to having two types of regular sectors: Decker distorted and non-Decker distorted. This provides 14 additional sextupole variables. Two of these variables are used to set the chromaticities. This makes the total number of variables for this optimization equal to 28, counting the betatron tunes.

Starting from the nominal, symmetric sextupoles for a symmetric linear solution, we optimized the sextupoles for target chromaticities of $\xi_x = \xi_y = 3$. Once a satisfactory

solution was obtained, we raised the chromaticity in steps to $\xi_x = \xi_y = 8$. Satisfactory dynamic acceptance and lifetime was achieved.

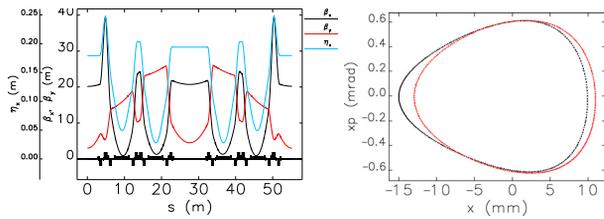


Figure 1: Left: Beta functions of two sectors, first sector is short SS, second sector is long SS. Right: Phase space at ID4 before (black) and after (red) sextupole adjustment.

It is of interest that the dynamic acceptance in this lattice is larger than the nominal limiting physical acceptance, which results from a curious distortion of the phase-space ellipses between the injection point and the location of the minimum aperture that was brought about through adjustment of a significant number of sextupoles between the injection and limiting aperture points.

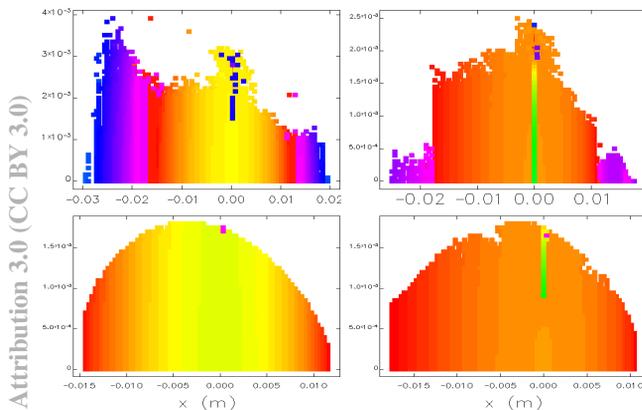


Figure 2: Dynamic aperture simulations for different cases, see description in the text.

Symmetry Breaking to Increase DA

The effect mentioned above can be best illustrated when applied to the present symmetric APS lattice. The smallest aperture in APS is located at sector 4 and has the limit of 15 mm in x from the inside the ring. Adjusting 14 sextupoles on each side of ID4, we can distort the phase space at that location and move particle trajectories away from the aperture limit, as illustrated in Fig. 1 (right).

This sextupole adjustment breaks sextupole symmetry and as expected reduces the dynamic aperture. However, at the same time it increases dynamic acceptance from -15 mm to -18 mm as shown in Figure 2. The top left plot shows dynamic aperture for symmetric sextupoles, the bottom left plot gives the corresponding dynamic acceptance. The acceptance in this case is -15 mm and is equal to the

physical aperture. The top right plot shows dynamic aperture for adjusted (asymmetric) sextupoles. As expected, it is smaller than the dynamic aperture for the symmetric case. The bottom left plot shows the dynamic acceptance for the asymmetric case. It is larger on the negative side compared to the symmetric case and is equal to -18 mm. This increase on the negative side is important for APS because the injected beam comes from the negative side.

EXPERIMENTAL TESTS

Because APS has independent power supplies for all quadrupoles and sextupoles, it is possible to mock up an LSS. This is done by setting to zero the power supplies for the Q1 magnets on either side of the target straight section. After correcting optics and coupling for the 8RLSS mockup, we were able to achieve injection efficiency of 90%, almost as good as for the symmetric APS lattice. The lifetime was 9 hours at the operational values of 1.5% coupling and 100-mA current, which is more than what is required for top-up operation lifetime of 5 hours.

CONCLUSION

We have developed a method for directly optimizing the dynamic acceptance and lifetime of a storage ring lattice using tracking simulations. The method allows adjusting a large number of sextupoles, as well as linear lattice properties such as tunes. Using this method, we've obtained solutions that should permit operating the APS with highly non-symmetric lattices. Breaking the translation and reflection symmetry of the sextupole strengths allows increasing the DA in the presence of non-symmetric optics and physical apertures. Experimental tests of mock-up long straight section configuration have shown good agreement with expectations.

ACKNOWLEDGMENT

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