POTENTIAL TWO-FOLD REDUCTION OF ADVANCED PHOTON SOURCE EMITTANCE USING ORBIT DISPLACEMENT*

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Abstract

The Advanced Photon Source (APS) is a 7-GeV electron storage ring light source that operates with an effective emittance of 3.1 nm using optics with distributed dispersion. Lower emittance is desirable for some x-ray experiments, but is difficult to achieve using conventional optics adjustments because of the required strength of quadrupoles and sextupoles. Changing the damping partition number by changing the rf frequency is another approach, but is incompatible with distributed dispersion because it would require simultaneous realignment of all APS beamlines. In this paper, we evaluate a new approach to changing the damping partition number using a systematic orbit bump in all sectors.

INTRODUCTION

The horizontal emittance in a storage ring is given by [1]

$$\epsilon_0 = \frac{C_q \gamma_0^2 \langle \mathcal{H} h^3 \rangle}{J_x \langle h^2 \rangle}, \tag{1}$$

where $h = 1/\rho$, and all other symbols follow Sands. The important feature of this equation for our purposes is the presence of the damping partition number J_x in the denominator. In a separated-function lattice, we typically have $J_x \approx 1$. In a combined-function lattice, one can have $J_x > 1$. This is evident from the expression $J_x = 1 - \mathcal{D}$, where $\mathcal{D} = \langle \eta h (h^2 + 2K_1) \rangle / \langle h^2 \rangle$. $K_1 = \frac{\partial B}{(B\rho)\partial x}$ is the focusing strength, which affects $\mathcal{D}$ only when ηh is nonzero, i.e., only in a dipole magnet. By making $\mathcal{D}$ negative, we can make J_x larger than 1. This comes at the expense of larger fractional energy spread $\sigma_\delta \propto 1/J_z$, where $J_z = 2 + \mathcal{D}$ is the longitudinal damping partition number.

In an existing storage ring, one cannot easily add a gradient to the dipoles. However, changing the rf frequency produces a systematic orbit in the quadrupole magnets, which results in their behaving like combined function dipoles. This has been done experimentally at APS [2] (and many other facilities) using the original achromatic optics, which has a nominal emittance of 8 nm.

At present we use a low-emittance, distributed dispersion configuration with an effective emittance $\epsilon = \sqrt{\epsilon_0/\beta}\sqrt{\epsilon_0 \beta + \sigma_\delta^2 \eta^2}$ of 3.1 nm. Figure 1 shows a simulation, performed with `elegant` [3], of the emittance as the rf frequency is varied, with the lattice being adjusted to keep the tunes constant. We see that while the raw emittance decreases steadily, the effective emittance reaches a shallow minimum and then begins to increase. This results from the increase in energy spread as the damping partition is changed. The potential effective emittance reduction is only about 15%. An additional difficulty is that if we change the rf frequency, it has the undesirable effect of moving the beam position significantly in all the straight sections. Hence, it is clear that adjusting the rf frequency alone is not a desirable path to lower emittance.

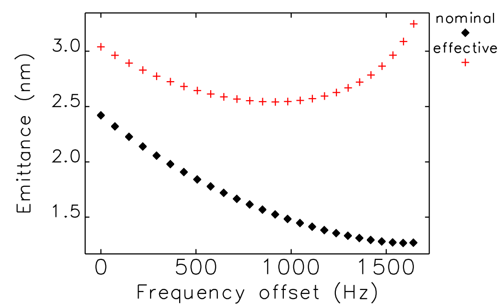

Figure 1: `elegant` simulation of the APS emittance as a function of the rf frequency offset, showing that the effective emittance cannot be greatly reduced by this method.

B. X. Yang suggested another way to take advantage of Eq. 1 without the orbit offset problem: displace the quadrupole magnets transversely. One would of course have to compensate for the orbit deflection using nearby steering magnets to eliminate or reduce the orbit displacement at the straight sections. This idea was tried in simulation and found workable. However, in the course of this work we realized that the same effect could be achieved by using steering elements to systematically move the orbit in the quadrupoles between the dipoles, while keeping the orbit fixed in the straight sections. This has the advantage of not requiring any hardware changes, and is the approach is explored in the present paper.

This approach is not without its challenges. Perhaps the most significant issue is that we will unavoidably have large horizontal orbits in sextupoles. Hence, both quadrupoles and sextupoles become combined-function magnets. It will not be possible to adjust the tune using only quadrupoles (one must simultaneously correct the orbit), or adjust the chromaticities using only sextupoles (one must simultaneously correct the linear optics). Because we will have to power steering correctors in a systematic fashion to produce the needed orbit, and because there is dispersion at all correctors, we'll have to adjust the rf frequency to compensate for rf path-length changes. Since the rf frequency of

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the booster synchrotron is tied to that of the storage ring, the booster will have to operate further off-momentum. (It already operates significantly off-momentum due to frequency changes resulting from the Decker distortion [4].)

LATTICE DEVELOPMENT

Because one cannot indepdently adjust quadrupoles and sextupoles, the development of the lattice is particularly complex. We began by using `elegant`'s internal optimizer, which allows simultaneously optimizing quantities involving orbit, linear optics, chromaticity, damping partition numbers, and emittance. This led to an initial orbit displacement (OD) lattice with the properties listed in Table 1. The sextupoles were adjusted simply to give a chromaticity between 5 and 7, without concern for nonlinear dynamics. As the table shows, the initial lifetime and dynamic acceptance (DA) were not particularly good.

Table 1: Nominal Parameters for Several APS Lattices in 24-Bunch Mode at 100 mA with 1% Coupling

Quantity	Standard	OD Init.	OD MOGA
ν_x	36.14	37.17	37.34
ν_y	19.22	18.26	18.07
$\partial\nu_{x,y}/\partial\delta$	7, 6	5	4, 3
ϵ_0 (nm)	2.51	1.06	0.96
ϵ_{eff} (nm)	3.15	1.48	1.45
σ_δ (%)	0.096	0.171	0.164
J_x	1.00	2.39	2.33
DA (mm^2)	54	15	31
Lifetime (h)	9	1.1	4.4
Rf freq. offset (kHz)	0	1.1	1.1
α_c (10^{-4})	2.8	1.9	1.9

To improve the DA and lifetime, We used a multi-objective genetic algorithm (MOGA) to directly optimize the DA, Touschek lifetime, and chromaticity [5]. This algorithm permits simultaneously adjusting linear optics and sextupoles. The results of the first pass are shown in Figure 2.

The orbit in a single sector is shown in Figure 3, while Figure 4 shows the optical functions. The maximum orbit is just over 10 mm, compared to a vacuum chamber width of ±42 mm. The effective horizontal aperture due to the orbit is still large compared to the horizontal aperture limit of 15 mm in the small-gap insertion device chamber.

Our standard procedure after MOGA optimization of a lattice is to perform ensemble evaluation to ascertain the robustness of the solution. This involves computation of orbit, Twiss parameters, equilibrium beam moments, on-energy dynamic aperture, and local momentum aperture for 50 error ensembles. The error levels are chosen to reflect the typical *post-correction* variation in optics and coupling seen in APS operations. We use 0.02% rms fractional strength errors and 0.5-mrad rms roll errors on quadrupoles

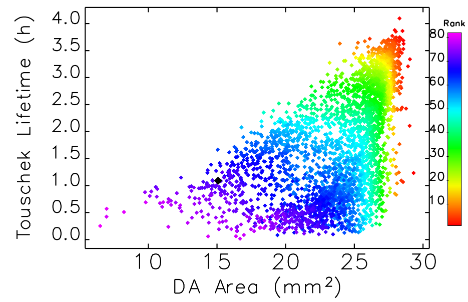

Figure 2: Summary results of first-pass MOGA optimization. The black diamond indicates the starting point.

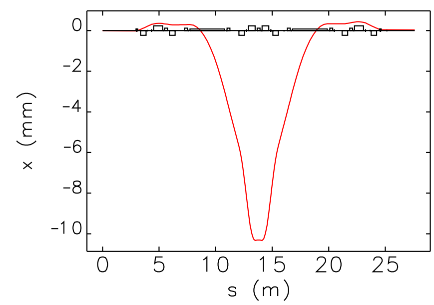

Figure 3: Optimized orbit in a single sector of the APS, produced by steering magnets and dipole trims.

and sextupoles. For ordinary lattice development, this procedure is successful in verifying lattices and providing reasonably close predictions of expected performance [6].

However, with the OD lattice, there are complications. First, strength errors in the quadrupoles and sextupoles result in orbit errors. This is easily dealt with by using `elegant`'s internal orbit correction routine to restore the orbit to the desired pattern (i.e., as shown in Figure 3). Second, roll errors on quadrupoles and sextupoles result in coupling. Normally, we would correct this using the cross-plane response matrix. However, in this lattice the skew quadrupoles are inside the orbit bump, meaning that they affect both the coupling and the orbit. This complicates the correction and needs to be addressed in future work. At present, we side-stepped the issue by reducing the roll errors to 0.25 mrad rms for the quadrupoles.

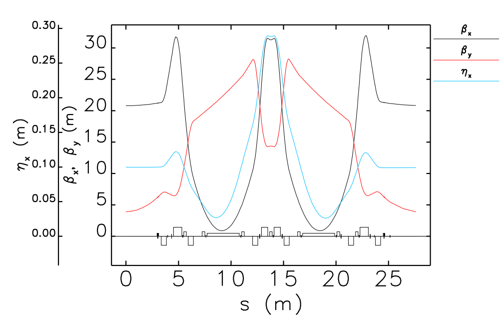

Figure 4: Optimized optical functions for a single sector.

The resultant vertical emittance is somewhat high (70 pm on average, compared to an operational value of about 35 pm). It is likely that the coupling is large enough to adversely impact the beam dynamics. Figure 5 shows the dynamic aperture from the 50 ensembles, along with a comparison to the comparable result for the standard lattice. The dynamic aperture is about 25% smaller on the horizontal inboard size ($x < 0$). The typical residual orbit oscillation for injected and stored beam (using a mismatched bump) is about 7 mm, so the aperture, although small, may be workable. We are also investigating the possible use of a few-millimeter DC bump to address this issue.

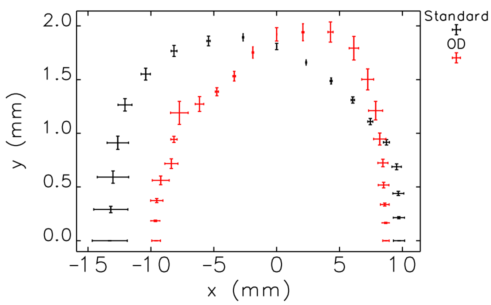

Figure 5: DA from 50 error ensembles for the standard APS lattice and the orbit displacement (OD) lattice.

Figure 6 shows the predicted local momentum aperture for the 50 ensembles, excluding two configurations for which the momentum aperture was zero. In general the momentum aperture is quite good. Indeed it is better than the momentum aperture for the standard APS lattice, owing to the increase in the rf bucket height that results from the reduction in α_c. The median predicted Touschek lifetime for 100 mA in 24 bunches is 8 h. However, this result must be viewed with some skepticism, given that no attempt is made to control the vertical emittance. At this point, we can state that the momentum aperture is large enough that we can reasonably expect good lifetime when the vertical emittance is controlled to normal levels.

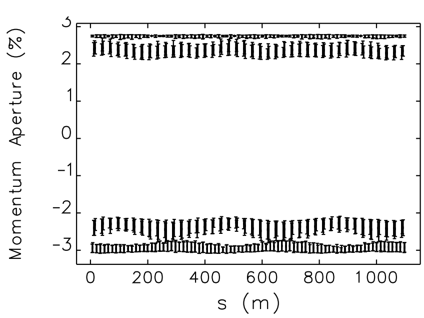

Figure 6: Momentum aperture from 48 of 50 error ensembles for the orbit displacement (OD) lattice.

To verify the emittance results, we used element-by-element synchrotron radiation tracking in Pelegant [7], which gave good agreement with the predictions of radiation integral and beam moments calculations [8] in elegant. We then used the program sddsbrightness to compute brightness tuning curves for a standard APS 2.4-m-long, 3.3-cm-period device. The predicted brightness improvement is about a factor of two, as shown in Figure 7. An additional gain can be made by running with lower vertical coupling, although in truth few users benefit from this.

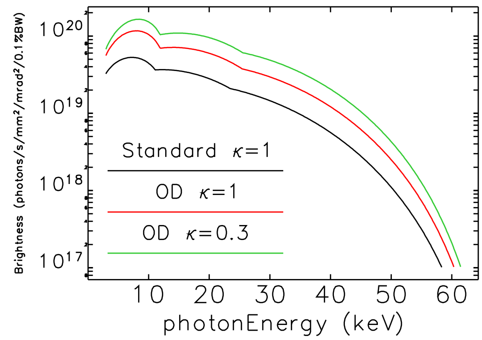

Figure 7: Brightness comparison of the OD lattice to the standard APS lattice.

CONCLUSION

We've shown that we can reduce the effective emittance of the APS by more than a factor of two, to 1.5 nm, using a lattice that incorporates systematic orbit bumps to change the damping partition factors. In simulation, the lattice appears feasible, although the lifetime and dynamic aperture are reduced. This lattice will undoubtably be a challenge to commission. We will probably start with an easier variant, which has the same tunes as used now and delivers an effective emittance of 1.9 nm. This will allow development and testing of tune knobs, chromaticity knobs, and coupling control, all of which will be more complex in these lattices.

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