DYNAMIC APERTURE STUDY AND LIFETIME IMPROVEMENT AT THE ADVANCED PHOTON SOURCE*

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Abstract

Over the past few years, the optics of the Advanced Photon Source storage ring has been optimized to provide lower natural emittance. Presently, the APS operates at 2.5 nm-rad emittance. The optimization was done at the expense of stronger sextupoles and shorter lifetime. Here we present our work on measurement and understanding of the dynamic aperture of the APS in low-emittance mode. We found good agreement between the dynamic aperture measurements and that of the model derived from the response matrix analysis. Based on the model, we were able to increase the lifetime significantly by optimizing sextupoles, correcting optics, moving a working point, and adjusting rf voltage. The higher lifetime allowed us to decrease operating coupling from 2.5% to 1%.

INTRODUCTION

APS is a 7-GeV third-generation light source located at Argonne National Laboratory. As in all light sources, beam lifetime is one of the most important parameters and has a large impact on the stability of the user experiments and the total delivered brightness. To improve on these issues, APS was the first to implement top-up operation, which means that a beam is injected at small time intervals to maintain constant total current. Operation in top-up mode allowed us to decrease natural emittance of the APS lattice from 7.7 nm-rad to 2.5 nm-rad at the expense of lifetime. Top-up operation relaxes the lifetime requirement; however, it does not completely eliminate it. The minimum possible lifetime in top-up mode is defined by injection intervals and injection charge. For APS, with two minutes top-up interval and 3-nC injection charge, the limit is approximately 5.5 hours.

Presently, APS has three operating modes: standard operation mode with 24 equally-spaced bunches and top-up injection; 324-bunch mode with 324 equally spaced bunches and non-top-up injection; and hybrid mode with one 8-mA bunch separated from eight septuplets by half of the ring and top-up injection. Total current is 100 mA in all operation modes. Each operation mode requires a different single-bunch current limit, therefore chromaticity and sextupoles are different in every mode. Most of the measurements and simulations we show here are done for standard mode.

The APS has four families of sextupoles, which are configured such as to provide chromaticity correction and sufficient dynamic aperture. Two families are required for chromaticity correction, and other two families could be used for dynamic aperture optimization.

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DYNAMIC APERTURE STUDY

To measure dynamic aperture of the APS storage ring, we use a fast horizontal kicker. Kicker voltage is scanned and the fraction of the beam surviving after the kick is recorded based on current measurements. The measurement is done with a single bunch and usually with minimized coupling. Single-turn beam position monitors (BPMs) are used to measure kick amplitude. Figure 1 (left) shows measurement results. According to the measurements, the amplitude of 50% beam loss is 10 mm.

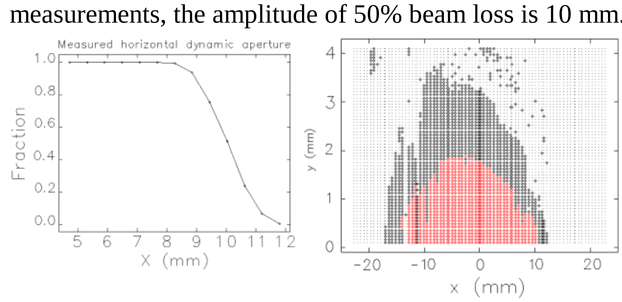

Figure 1: Left – measured horizontal dynamic aperture. Stability limit is 10 mm. Right – dynamic aperture calculation based on tracking. Black symbols are survived particles without aperture limitations, and red symbols are survived particles with aperture limitations included.

For dynamic aperture calculations we used the program `elegant` [1]. To compare calculation results with measurements, an optics model calibrated using a response matrix fit was used [2]. We also included all physical aperture limitations. Figure 1 (right) shows the results of dynamic aperture calculations. Here black dots are all the particles that were tracked, black symbols are surviving particles with no aperture limitations, and red symbols are surviving particles with aperture limitations included. The horizontal calculated dynamic aperture is 10.5 mm, in good agreement with measurements.

Dynamic aperture with coupling

Usually the dynamic aperture measurements are done with minimized coupling of approximately 0.3%. Interesting results were observed when the measurement was performed with 1% coupling. Figure 2 (left) presents measurement of the dynamic aperture with 1% coupling. It shows two curves: one is a full-scale scan, and the other one is a fine scan near the amplitude where we observed the dip.

In order to understand the partial beam loss at intermediate amplitude, we simulated the kick measurement: a bunch of particles was tracked and the fraction of particles that survived after 1000 turns was recorded. We performed simulations with minimized coupling and with operating coupling of 1%. Figure 2 (right) shows the result of simulations. The black curve on the plot corresponds to the simulation with low coupling, and red curve shows the simulations with 1% coupling. The simulation shows the same stability limit as the experiment. It also shows the area with partial beam loss, though the amplitude where it happens is different by 2 mm from the experiment. Presently, we do not fully understand the reason for this difference.

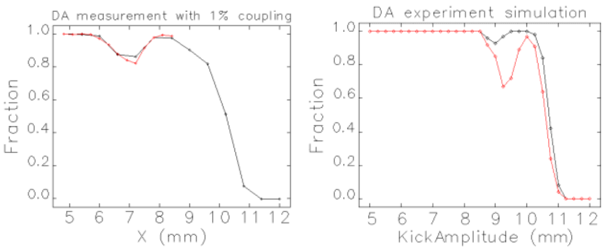

Figure 2: Left: Dynamic aperture measurement with 1% coupling. Red curve is a fine scan around the observed dip. Right: Simulation of the dynamic aperture measurements. Black curve is minimized coupling; red curve is 1% coupling.

To study the source of this partial beam loss, we calculated a frequency map of particles with different horizontal and vertical amplitudes, which is similar to those shown in ref. [3]. This was done with the *elegantRingAnalysis* program [4], which can perform a number of standardized calculations using `elegant`. Figure 3 shows the results of the calculations. We used a lattice with minimized coupling and without aperture limitations. This plot is really a dynamic aperture plot where points represent initial coordinates of stable particles and the colors of the points indicate the betatron tune of each particle. The left plot shows the horizontal tune and the right plot shows the vertical tune. These plots provide a powerful diagnostic tool to visualize the dynamics of the system and understand limitations. On the horizontal tune map (left) we can see that the horizontal tune approaches integer resonance ν_x=36 (red color) along the entire perimeter of the stability area. The vertical tune map (right) shows that at horizontal amplitudes of about +9 mm and –12 mm the vertical tune crosses integer resonance ν_y=19, and that leads to irregularities, unstable islands, and partial beam loss at those amplitudes.

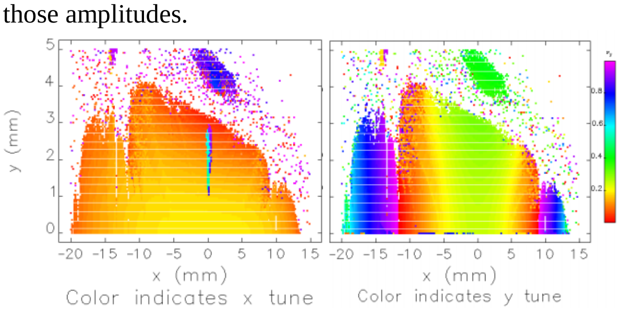

Figure 3: Frequency map with amplitude for present sextupoles. Color indicates horizontal (left) or vertical (right) betatron tunes. Color code is shown on the bar to the right.

Now that we know what resonances limit the dynamic aperture, the strategy to improve it becomes simple – we need to change the amplitude-dependent tune shift to avoid those resonances. Tune shift with amplitude can be expressed by a well-known formula:

$$\delta\nu_x = C_{xx} J_x + C_{xy} J_y + o(J^2)\,,$$

$$\delta\nu_y = C_{xy} J_x + C_{yy} J_y + o(J^2)\,,$$

where J is action and C is a coefficient describing the tune shift. By changing the strength of harmonic sextupoles, we were able to decrease the C_{xy} coefficient. Reduction of C_{xx} was not helpful because it was already small, and overall tune dependence on horizontal aperture has a considerable contribution from higher-order terms. Figure 4 presents a frequency map for new sextupoles. One can see that the irregularities previously attributed to the ν_y=19 resonance are no longer there. Overall, the horizontal dynamic aperture is increased by several millimeters and vertical aperture is decreased by one millimeter. The decrease of the vertical dynamic aperture is not important because of the small physical aperture. Unfortunately, real-life limitations of sextupole strength did not allow us to test the improvement in the experiment because the strength of one sextupole family exceeds power supply limits by 25%.

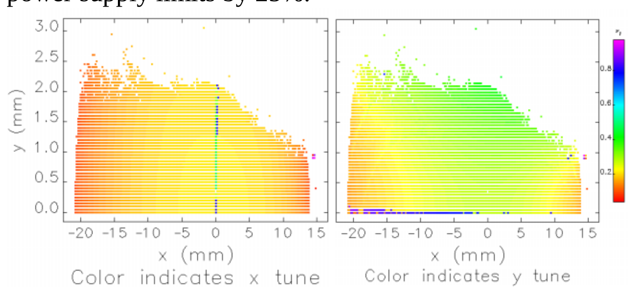

Figure 4: Frequency map with amplitude for optimized sextupoles. Color indicates horizontal (left) or vertical (right) betatron tunes. Color code is shown on the bar to the right.

LIFETIME IMPROVEMENT

Today, about 75% of all scheduled user time is top-up operation. As was mentioned before, top-up injection makes it possible to operate with lower lifetime. Minimum possible lifetime is defined by the injection interval and injection charge. In order to maintain required lifetime in standard operating mode in the lattice with 2.5 nm-rad emittance, we had to run with coupling of 2.5% for some time.

APS has four families of sextupoles, therefore there are two degrees of freedom available for dynamic aperture optimization. Sextupole strength optimization was done for the old 8-nm-rad lattice. An attempt to reoptimize the sextupoles to increase the dynamic aperture did not provide big benefits within power supply limits. Experimental scans to improve lifetime were not successful either. Finally, we have found an easy way to predict lifetime changes and to improve the lifetime in our case.

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The APS has a rather large operating chromaticity: +7 in the horizontal and +6 in the vertical plane in standard mode, in order to provide for high single-bunch current limit. Therefore, Touschek-scattered particles most likely are lost on strong low-order lattice resonances. For our present sextupole scheme, the nearest strong resonance is ν_y=19.5, which is reached at a momentum deviation of +1.6%. By increasing the S2 sextupole family to its maximum, we were able to change the nonlinear chromaticity such that the distance to the resonance increased to a momentum deviation of +1.9%. Figure 5 (left) shows the tune diagram with a footprint of the working point when momentum deviation is scanned from –2% to +2%. Due to this sextupole change, a small rf voltage reduction, and a small betatron tune change, the lifetime was increased from six hours to almost ten hours. As a result, we were able to decrease operating coupling from 2.5% to 1%.

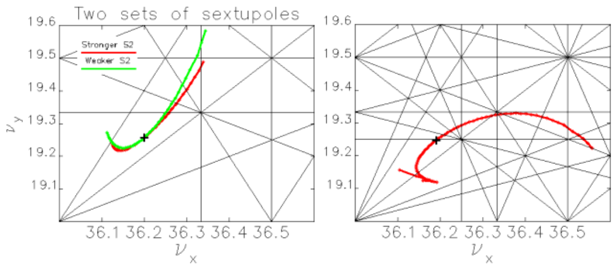

Figure 5: Left: Momentum scans on a tune diagram for two sets of sextupoles. The momentum deviation is scanned from –2% (left side of the curves) to +2% (right side of the curves). Right: Momentum scan with stronger sextupoles, the momentum is scanned from –3.5% to 3.5%. A black cross is the present working point.

Distance to the resonance ν_y=19.5 defines lifetime at the APS storage ring. To illustrate this, we present measurements of momentum acceptance for different operating modes, or actually for different chromaticities. Momentum acceptance is measured by scanning rf voltage while recording the beam lifetime. Because the momentum acceptance increases with rf voltage, one expects the lifetime to increase as well until the rf voltage no longer limits the acceptance due to dynamic effects. At this point the lifetime starts to decline due to bunch length decrease. The point where these two tendencies cross defines the dynamic momentum acceptance. Figure 6 shows three rf voltage scans for different operating modes, and Table 1 summarizes the results of the voltage scans.

At present, further lifetime improvement is limited by achievable sextupole strength. However, calculations show that a simple modification of sextupole design by adding small pole tips could allow us to increase the maximum sextupole gradient by twenty to thirty percent [5]. The momentum scan of the working point with stronger sextupoles is shown in Fig. 5 (right). Changing the sign of higher-order chromaticity completely eliminates resonance ν_y=19.5, and the next limiting resonance would be ν_x=36.5. The momentum deviation limit could be increased to 3.0%, which would lead to significant lifetime increase.

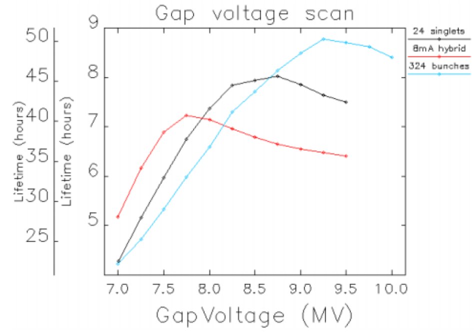

Figure 6: Gap voltage scan for different operating modes. Lifetime is different for all curves due to different current during measurements. Measurements for 324-bunch mode are shown in a different scale due to higher lifetime.

Table 1: Chromaticity and Momentum Deviation at Which the Resonance ν_y=19.5 is Crossed

	ξ_x	ξ_y	dp/p calculated	dp/p measured
24 singlets	7	6	1.9%	2.0%
324 bunches	3	5	2.2%	2.3%
8-mA hybrid	9.5	9	1.6%	1.7%

CONCLUSIONS

We have studied dynamic aperture limitations of the APS with new low-emittance optics. The agreement between measured data and simulation results is good. To achieve this, tracking with a calibrated optics model with coupling and with aperture limitations is required.

We have found that for APS (and probably other machines with high symmetry and high operational chromaticity), the lifetime can be predicted by a momentum deviation scan of the working point. Based on this scan and combined with several minor adjustments, we were able to improve the lifetime by 50%. This allowed us to reduce coupling from 2.5% to 1%, thus increasing on-axis brightness of the beam. We have also found that if it were possible to increase sextupole strength by 25%, the momentum acceptance would increase from 2% to 3%. That would result in further significant increase in lifetime. Design work is underway to modify sextupole poles in order to increase the strength without changing power supplies.

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