NEW LATTICE DESIGN FOR APS STORAGE RING WITH POTENTIAL TRI-FOLD INCREASE OF THE NUMBER OF INSERTION DEVICES*

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Abstract

The Advanced Photon source (APS) recently held a workshop on upgrade options for the APS storage ring. Several options were discussed that included both storage ring and energy recovery linac options. Here we present a storage ring lattice that fits into the APS tunnel and has a number of significant improvements over the existing storage ring. The present APS lattice has 40-fold symmetry with each sector having one 5-m-long straight section for insertion device (ID) placement. Each sector also provides one beamline for radiation from the bending magnet. The upgrade lattice preserves locations of the existing insertion devices but provides for increased ID straight section length to accommodate 8-m-long insertion devices. This lattice also decreases emittance by a factor of two down to 1.6 nm·rad. And last but not least, it provides two additional 2.1-m-long ID straight sections per sector with one of these straight sections being parallel to the existing bending magnet beamline. We also present dynamic aperture optimization, lifetime calculations, and other nonlinear-dynamics-related simulations.

INTRODUCTION

The Advanced Photon Source is a 7-GeV synchrotron light source that has been successfully operating for more than a decade. A now commonly used continuous injection (top-up) was pioneered at APS. Implementation of top-up lowered requirements to the electron beam lifetime and allowed us to operate more complicated lattices. Over the years, effective electron beam emittance was pushed from 8 to 3.1 nm·rad (natural emittance of 2.5 nm·rad) [1]. The single-bunch charge was raised from 15 nQ in standard operation to 60 nC in special "hybrid" mode of operation. At this point we are about to approach improvement limits of the currently installed equipment. Recently, a Machine Advisory Committee (MAC) was convened to discuss possible upgrade options for the APS. The options ranged from storage rings to energy recovery linacs. In this paper, we will describe one of the lattices that was presented to the MAC.

Important boundary conditions were given for the APS upgrade. Any upgrade machine has to use the existing APS tunnel, all ID beamlines must be preserved, and all existing bunch patterns have to be supported after the upgrade. A separate study was performed that concluded that for the present pool of user experiments, the energy of the electron beam must stay at 7 GeV.

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The main goals of the upgrade are the following. The new machine has to provide increased x-ray brightness and improved transverse coherence. It must have capabilities to support time-resolved studies requiring picosecond pulses. It also should provide significantly longer ID straight sections for installation of more sophisticated or multiple devices.

LATTICE

The most important requirement for any upgrade lattice is to keep numerous and expensive user beamlines in place. The present APS lattice has 40-fold symmetry with 35 straight sections available for installation of 5-m-long insertion devices (five remaining straight sections are occupied by rf and injection). Any new lattice has to also provide for 40 long straight sections. An increase in brightness can be achieved (among other thins) by decreasing electron beam emittance and by increasing insertion device lengths.

It is well known that electron beam emittance is proportional to the third power of the bending magnet angle. Since the number of long straight sections (or lattice cells) is fixed, the only way to decrease the bending angle is to increase the number of dipoles per cell. Within the limitations of the lattice cell length and existing magnet technology, the only feasible solution is a triple-bend cell.

Besides ID beamlines, APS also provides for a number of bending-magnet-based beamlines. One easy way to increase brightness for these beamlines is to use undulators as radiators instead of dipoles. It is actually possible in triple-bend cell configuration when bending angles of the middle and side dipoles are chosen such that the straight section after the middle dipole is parallel to the existing bending magnet beamline (see Figure 1). For users who would want to keep their radiation sources bending-magnet-like, three-pole wigglers could be provided.

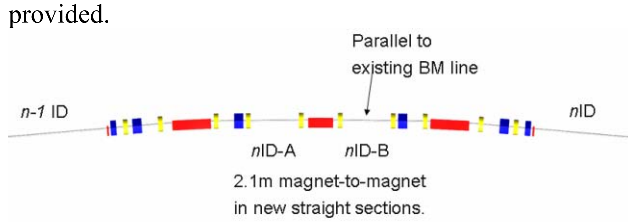

Figure 1: One sector of the APSx3 lattice.

One lattice cell consists of three dipoles, six quadrupoles, and ten sextupoles. The lattice is symmetric around the center of the middle dipole. It has one long straight section for installation of up to 8-m-long undulators and two 2.1-m long straight sections where 1-m-long undulators can be fitted. The second short straight section is parallel to the present bending magnet beamline with a 50-mm offset. The radiation from this source point can still fit into an existing shielding wall penetration, and existing bending magnet beamlines can be realigned to use the radiation from this source. To use radiation from the first short straight section, new shielding wall penetrations and new beamlines have to be built. One-cell beta functions are shown in Figure 2. Main parameters of the lattice are shown in Table 1 in comparison with the present APS.

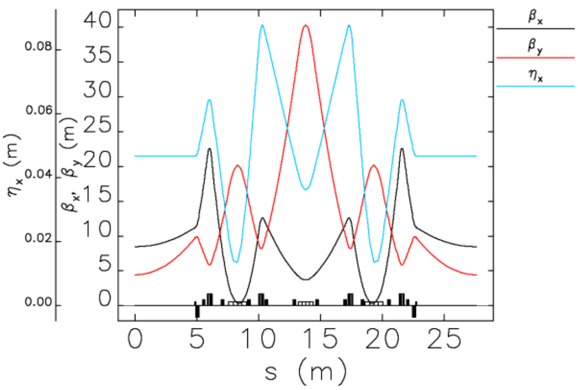

Figure 2: Beta functions of one cell.

Table 1: Main Lattice Parameters

	APSx3	APS
Energy (GeV)	7	7
Emittance (nm·rad)	1.4	2.5
Effective emittance (nm·rad)	1.6	3.1
ν_x, ν_y	50.1, 19.4	36.2, 19.3
Chromaticity X and Y	-129, -65	-92, -42
Energy spread	1.4×10^{-3}	0.96×10^{-3}
Energy loss per turn (MeV)	9.1	5.4
Momentum compaction	1.2×10^{-3}	2.8×10^{-3}

In order to achieve such a small emittance, very strong focusing elements are required. Also to save space for insertion devices, dipoles incorporate field gradients. A preliminary design of magnetic elements was performed using the 2D Poisson program [2]. Required strengths with required quality were achieved except for the strongest gradient dipole. To design pole shape for combined-function dipoles, automated optimization of the pole profile was used [3].

Dynamic Aperture

As always, strong focusing leads to high chromaticity and small dispersion, both of which result in very strong sextupoles. Achieving the required dynamic aperture (DA) is always a challenge for small-emittance lattices. To maximize DA, we plan to use five families of sextupoles instead of the two families required for chromaticity correction.

The required DA is defined by the injection process. Tt has to satisfy the following condition at the injection point:

$$A \geq 5\sigma_s + 3\sigma_i + \Delta d \ ,$$

where σ_s and σ_i are the beam sizes of the stored and injected beam respectively, and Δd is the septum thickness with some margin. For septum thickness of 2.5 *mm* and injected beam with 65 nm·rad (emittance of the present APS booster), the required DA is equal to 7.7 *mm*.

Due to very high sextupole strength, higher-order sextupole terms affect particle dynamics significantly. One of consequences is a very strong tune shift with amplitude that cannot be minimized below some level due to higher-order terms. As a result, particles with even moderate amplitudes cross over the nearest integer resonances. For the ideal lattice, these resonances are suppressed due to high symmetry of the lattice. But they always exist in the real machine; therefore, DA optimization has to be done in the presence of errors.

The optimization process was automated using geneticOptimizer [4] with 6D tracking results supplied by elegant [5]. Three sextupole families were varied as well as the betatron tunes. At each evaluation point, the DA was calculated for a lattice with one fixed set of magnetic errors. The magnitude of errors was chosen such that it represents the typical scale of beta function beating and typical coupling. Figure 3 shows dynamic aperture for the optimized sextupole set calculated for the ideal lattice; colors shows betatron tunes. Figure 4 shows the betatron tune footprint for this dynamic aperture.

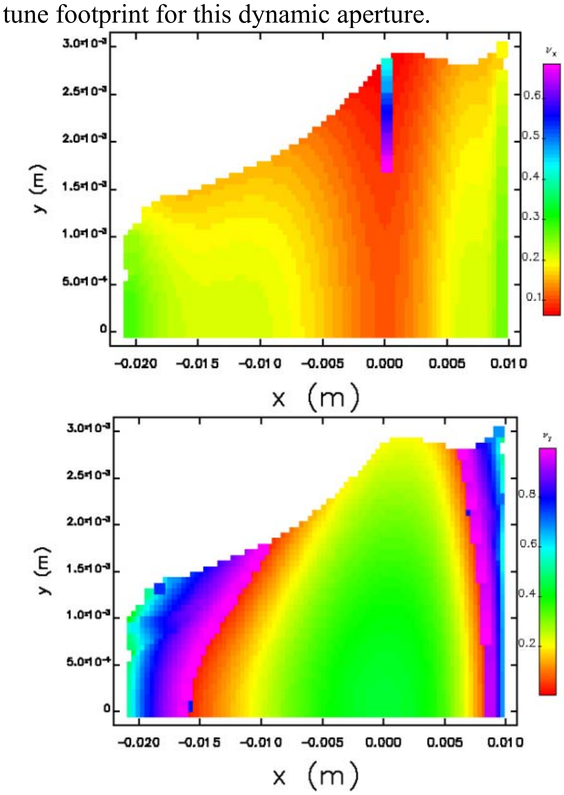

Figure 3: Dynamic aperture of ideal lattice with optimized sextupoles. Colors show betatron tunes, top – horizontal betatron tune, bottom – vertical betatron tune.

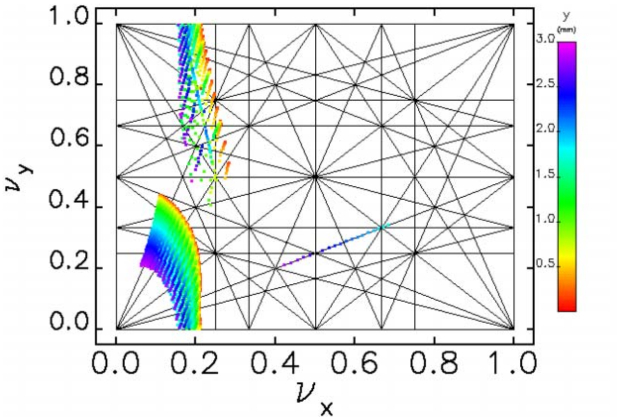

Figure 4: Tune diagram showing tune shift with vertical amplitude for the ideal lattice. Colors show vertical amplitude.

After sextupole optimization was done, dynamic aperture calculations were performed for 100 random seeds of errors. The average dynamic aperture is shown in Figure 5. In general, this DA is enough for injection, considering that the injected beam comes from the negative side.

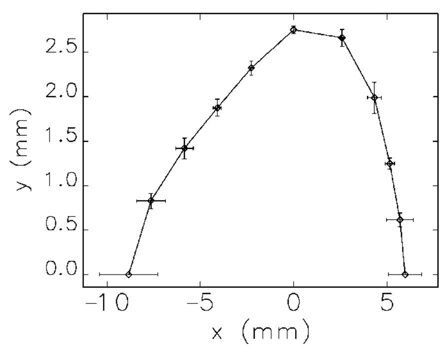

Figure 5: Average dynamic aperture based on 100 random error sets. Error bars show rms variation of results.

To study the injection process more closely, a simulation of injection was performed with realistic a 6D beam. A fraction of surviving particles was recorded for different injection amplitudes. For simplicity, injection was simulated as just an initial deviation of the bunch; no kicker were used. A lattice with one set of errors was used. Particles were tracked for 1000 turns, which covers several synchrotron oscillations. Results are shown in Figure 6 for two different injected beam emittances. According to the simulations, injection efficiency with the existing booster will be limited to about 95%. Assuming some safety margin, a new booster with smaller emittance will be required. For example, a beam with 30-nm·rad emittance can be injected with 100% efficiency, which also has some margin for errors. Recently, a booster lattice with emittance of 10 nm·rad was designed [6].

The momentum aperture of the lattice was also calculated and found to be ±3%. It was calculated using the usual approach when a single particle with momentum deviation is tracked starting from different points along the lattice. For this momentum aperture, the lifetime for the main APS fill pattern with 24 equally spaced bunches was calculated to be 6.5 hours for 200-mA beam with 1% coupling.

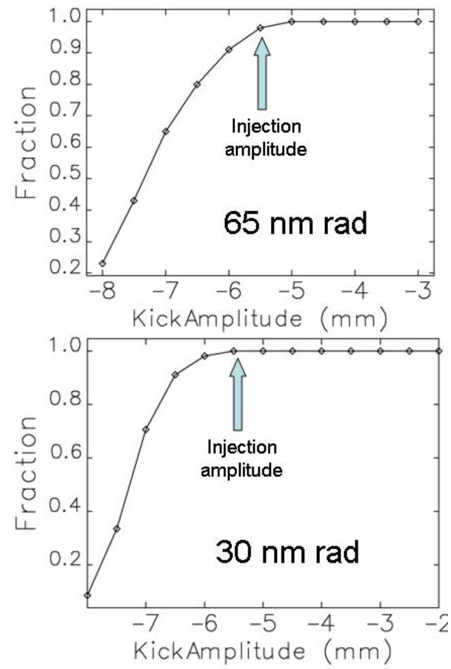

Figure 6: Injection efficiency simulation for two different emittances of the injected beam.

CONCLUSION

We presented a new lattice for the APS upgrade. It can be placed in the existing APS tunnel, it has an emittance that is a factor of two smaller then the existing lattice, and it preserves all ID beamlines. The length available for IDs is increased from 5 m to 8 m, and it provides the opportunity to install additional one-meter-long IDs in the locations of the present bending magnet beamlines. We presented results of dynamic aperture optimization, injection simulations, and lifetime calculations. We have found that dynamic and momentum apertures suitable for injection and lifetime can be achieved.

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