A 1-nm EMITTANCE LATTICE FOR THE ADVANCED PHOTON SOURCE STORAGE RING*

A.Xiao†, M. Borland, V. Sajaev, ANL, Argonne, IL 60439, USA

Abstract

We present a triple-bend lattice design that uses the current APS tunnel. The new lattice has a 1 nm-rad effective emittance at 7 GeV. A forty-period symmetric optics is presented. For the benefit of some X-ray user experiments, an optics with four special straight sections of one-third the beam size of normal sections was investigated as well. The associated nonlinear optical difficulties are addressed and simulation results are presented.

INTRODUCTION

The Advanced Photon Source (APS) has been operating successfully for 11 years. The machine performance has been improved gradually through modification of the lattice, use of top-up, and introduction of optimized undulators [1]. The current APS effective emittance is 3.1 nm, which has been lowered from the original design value of 8 nm. This value is limited by existing hardware. Any further significant improvement will require a replacement of the storage ring.

In order to keep existing expensive beamlines relevant and to serve users with better X-ray beams, several APS upgrade plans have been proposed and investigated [2, 3]. In this paper, we will introduce a triple-bend-based 1-nm lattice design. In this design, the straight sections for insertion devices are also increased from 5 to 10 meters, which allows installation of 8-m undulators.

LATTICE PROPERTY

The spectral brightness of undulator radiation is given by [4]

$$B = \frac{\dot{N}_{ph}}{4\pi^2\sigma_{t,x}\sigma_{t,x'}\sigma_{t,y}\sigma_{t,y'}(d\omega/\omega)}, \quad (1)$$

where $\sigma_{t,x}$, $\sigma_{t,x'}$, $\sigma_{t,y}$ and $\sigma_{t,y'}$ are total effective beam size and beam divergence at the undulator, and $\dot{N}_{ph}$ is the photon flux, which is proportional to the number of periods in the undulator. It is obvious that decreasing the effective emittance and using a longer undulator are ways to obtain higher brightness.

The achievable emittance of different lattice types can be written as [5]

$$\epsilon = F(\nu_x, lattice)\frac{E^2[GeV]}{J_x N_d^3}, \quad (2)$$

where $0 < J_x < 3$ is the partition number, $J_x = 1$ for the separated function bending magnet, N_d is the number of bending magnets, E is the beam energy, and F is related to the focusing strength and lattice type.

Guided by Equation 2, we used `elegant` [6] to design a triple-bend-based lattice. The horizontal tune was increased from the current value of 36.2 to 57.3. To give more space to insertion devices and also to increase J_x, we have used combined-function bending magnets in our design. The basic lattice parameters are given in Table 1. The lattice functions for one cell are shown in Figure 1. The lattice has 40 such cells around the ring. Since some users may want different X-ray properties for their experiment, we have added four low-β, low-η insertions into our symmetry lattice. The beam-size at these “low-β” insertions is one-third of that in the normal sections. With these insertions, the effective emittance for the normal beamlines

Table 1: Basic Parameters of the APS 1-nm Lattice

Energy	E	7 GeV
Betatron tunes	ν_x, ν_y	57.3,21.4
Natural chromaticity	ξ_x, ξ_y	-127.4,-45.1
Natural emittance	ϵ_0	0.5 nm
Effective emittance	ϵ_x	0.89 nm
Horizontal damping time	τ_x	5.87 ms
Vertical damping time	τ_y	7.93 ms
Longitudinal damping time	τ_δ	4.81 ms
Energy loss per turn	U_0	6.5 MV
Energy spread	σ_δ	0.116%
Momentum compaction	α	1.04×10^{-4}
Damping partition	J_x	1.35
Damping partition	J_y	1.0
Damping partition	J_δ	1.65

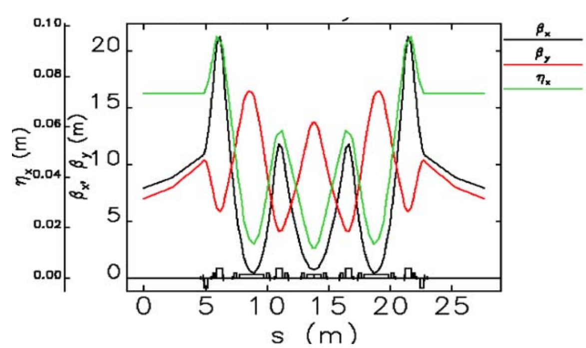

Figure 1: Optical function of APS 1-nm symmetric lattice (one cell).

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† xiaoam@aps.anl.gov

increases to 1 nm. The optical functions around one of the special insertion are shown in Figure 2.

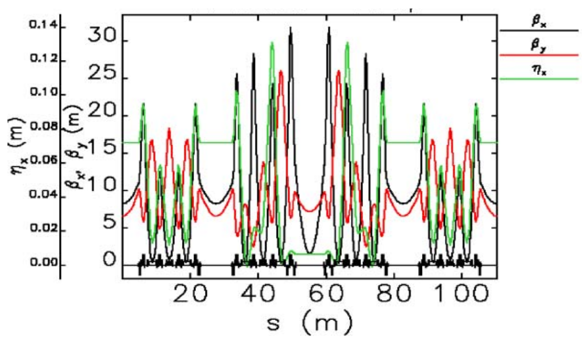

Figure 2: Optical functions of the APS 1-nm low-β lattice (4 cells).

MAGNET REQUIREMENTS

This strong focusing design requires very strong magnets, which poses a difficult challenge for magnet design. The magnet strength requirements are listed in Tables , 3, and 4. A preliminary magnet design using the 2D Poisson code [7] was performed. Using a 20-mm magnet bore radius, we obtained up to $K1 = 2.35\ m^{-2}$ in the quadrupole design and up to $K2 = 175\ m^{-3}$ in the sextupole. The combined-function bending magnet was designed using an automated technique, but the good field region is small and requires more effort. Using a curved magnet would alleviate this issue, but is more expensive.

Table 2: Combined-function Bending Magnet Strength for the APS 1-nm Lattice

			Sym.	Lowβ
Name	L[m]	Angle[rad]	K1[m^{-2}]	K1[m^{-2}]
B0	2	0.061	-0.277	-0.268
B1	1.132	0.035	-0.372	-0.384

Table 3: Quadrupole Strength for the APS 1-nm Lattice

		Sym.	Lowβ		
			Normal	Type-A	Type-B
Name	L [m]	K1 [m^{-2}]	K1 [m^{-2}]	K1 [m^{-2}]	K1 [m^{-2}]
QI1	0.3	-1.185	-1.199	-1.612	-1.023
QI2	0.5	1.413	1.419	1.633	1.463
QDF	0.5	1.698	1.702	1.659	1.675
QI3	0.3	1.698			-1.327

Table 4: Sextupole Strength for the APS 1-nm Lattice

		Sym.	Lowβ		
			Normal	Type-A	Type-B
Name	L [m]	K2 [m^{-3}]	K2 [m^{-3}]	K2 [m^{-3}]	K2 [m^{-3}]
S1	0.2	56.8	71.0	66.5	47.3
S2	0.2	-101.8	-121.2	-93.3	-65.1
SD	0.2	-85.0	-89.4	-84.4	-99.0
SE	0.2	-98.2	-100.1	-51.4	-90.9
SF	0.2	136.8	132.5	87.9	130.0

DYNAMIC APERTURE

Dynamic aperture (DA) optimization is a considerable challenge due to significant nonlinear effects coming from strong focusing and tight lattice structure. The required dynamic aperture is determined by injection and Touschek lifetime requirements. At the injection point, the required transverse dynamic aperture A must satisfy

$$A \geq 5\sigma_s + 6\sigma_i + \Delta d + m, \tag{3}$$

where σ_s and σ_i are the stored and injected beam sizes, respectively, Δd is the septum thickness, and m is a margin. Based on experience with APS, we assumed $\Delta d + m = 3$ mm. With $\beta_x = 7$ m at the injection point, the required dynamic aperture is $A_{min} \approx 5.8$ mm for 22-nm injected beam emittance and $A_{min} \approx 7.5$ mm for 65-nm injected beam emittance (65 nm is the current value for the APS booster).

Dynamic aperture optimization is performed using `elegant` and the `geneticOptimizer` [8] script developed at APS. Figure 3 shows the dynamic aperture for the ideal symmetric lattice. The aperture is larger than ± 10 mm.

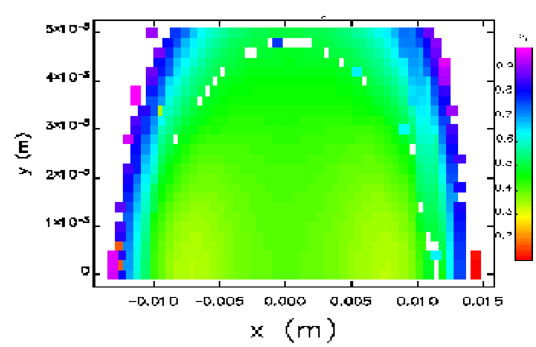

Figure 3: Dynamic aperture of the APS 1-nm symmetric lattice.

Magnet imperfections and misalignments are inevitable in the real machine. APS magnet alignment and field strength tolerances are shown in Table . We included these errors together with multipole errors (using those assumed for the ILC damping ring design [9], see Figure 4). Orbit and tune correction are included in the dynamic aperture

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Table 5: Magnet Strength and Alignment Error Tolerances for the APS [5]

rms tolerances	APS
Quadrupole position [mm]	0.1
Sextupole position [mm]	0.1
Magnet roll [mrad]	0.1
$\Delta B/B[10^{-3}]$	0.1

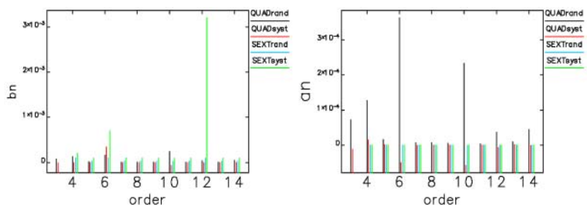
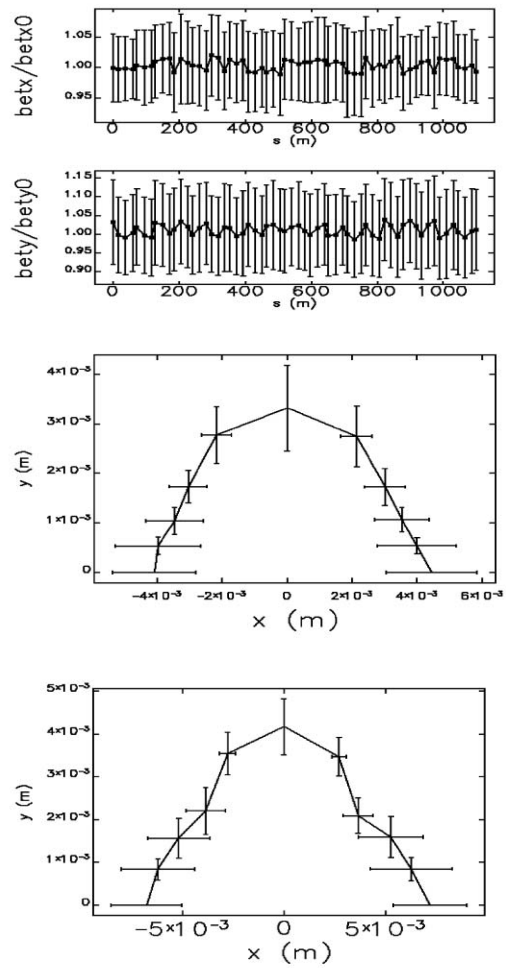


Figure 4: Multiple magnetic errors.

optimization. The results of average and rms values of beta beating, orbit distortion, and dynamic aperture are shown in Figure 5 (50 random seeds). With about 15% beta beating in x and 30% beta beating in y, the average dynamic aperture in x is about 4 mm. This is too small to accumulate booster beam into the ring, but it is enough to store beam and perform lattice correction, which will improve the DA greatly. Using 60% of nominal error levels, we get about ± 7 mm dynamic aperture, similar to that for APS today.

The momentum aperture of this lattice is shown in Figure 6. With about 3% momentum aperture at 12 MV rf voltage, the calculated Touschek beam lifetime is 4.5 hours at 8-mA bunch current, which is acceptable with top-up.



(a)

(b)

(c)

Figure 5: APS 1-nm lattice with errors: (a) Beta beating of full error, (b) dynamic aperture of full error, (c) dynamic aperture of 60% error.

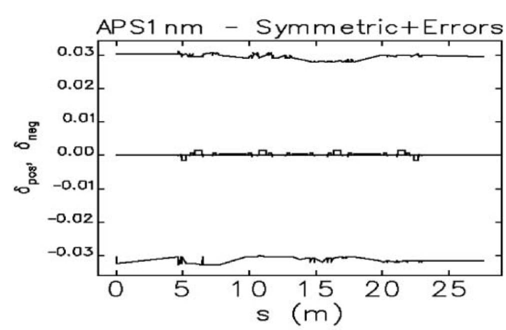


Figure 6: Momentum aperture of the APS 1-nm lattice (with errors).

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