PROGRESS AND PROSPECTS TOWARD BRIGHTNESS IMPROVEMENTS AT THE ADVANCED PHOTON SOURCE*

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Abstract

We report on recent and planned brightness improvements at the Advanced Photon Source storage ring. These involve changes in storage ring optics and recent ideas for insertion devices. The storage ring emittance will decrease from 8 nm-rad to 3.5 nm-rad. The ratio of vertical to horizontal emittances can be made at least as low as 0.5% based on past experience, but 0.25% could probably be achieved in the new lattice. The possibility of increasing the available length for undulators is explored. Brightnesses are calculated for both old and new undulator designs for various lattices.

1 INTRODUCTION

The present 8 nm-rad optics of the Advanced Photon Source (APS) storage ring make the standard undulator A at APS a very bright source of x-ray photons. Lowering the horizontal or vertical emittances of the electron beam and adopting new undulator designs will increase the photon brightness. We will cover recent and potential storage ring optics improvements, describe briefly the undulator designs, and then show the brightness achieved for combinations of lattice improvements and undulators.

2 LATTICE IMPROVEMENTS

The original APS lattice has an equilibrium horizontal emittance (ϵ_x) of 8 nm-rad and zero dispersion (η_x=0) in the straight sections. The equilibrium vertical emittance ϵ_y depends on magnet errors and how well they are compensated. The ratio ϵ_y/ϵ_x is commonly called the coupling, which we will use as an indicator for higher brightness: a lattice with lower coupling will have higher brightness. The original specification for the coupling was 10% or less.

Our present standard lattice differs significantly from the original design by the much smaller ϵ_y/ϵ_x of 1% and a smaller β_y at the undulator (ID). The emittance was slightly reduced because of slightly different β in the dipoles as a result of matching the smaller β_y at the IDs.

A lower ϵ_x optics can be achieved by allowing η_x in the ID straight section to be nonzero. In the past, emittance optimization has consisted of rematching the lattice with specific constraints on η_x in the dipole and in the straight section. Having done this, one evaluates the emittance and iterates. Using the code `elegant` [1], however, we are able to optimize the emittance directly while constraining the beta functions and tunes. Indeed, because the beam size (σ_x) in the straight section in general has contributions from both the emittance and the energy spread (through η_x), we used `elegant` to minimize σ_x rather than ϵ_x. Additional constraints included reasonable $\beta_{x,y}$ values inside the straight sections and in the arcs. We obtained an emittance of 3.5 nm-rad and a beam size of 255 μm rms.

Without correction, the coupling of the low-emittance lattice will be $\sim$ 1%, giving lower ϵ_y than in the standard lattice. We believe that we can push the coupling of the low-emittance lattice to a value of $\sim 0.25\%$, which has been achieved in the standard lattice.

There is an ongoing effort to develop a practical horizontal focusing optics insertion at a particular ID. The converging electron beam at the center of an ID straight section will produce a photon beam of smaller transverse size some distance downstream in the user beamline without the aid of x-ray optics. Such an insertion has been implemented during machine studies with β_x = 60 m for the diagnostic sector and is reported in ref. [2].

Presently about L = 5.0 m is available for installation of undulators in the 5.9-m straight section. Removing the nearest quadrupole magnet from the two adjacent girders allows L = 7.7 m. The ring optics for such an insertion were successfully tested by setting the adjacent quadrupoles to zero. A further increase to L = 10.7 m is possible by shortening the nearest two dipoles and allowing their position to move longitudinally. These special solutions have increased emittance, so we give results for a ring with only one such straight section modification.

The optics parameters of the original and low ϵ_x lattices and their variants are listed in Table 1. The relative energy spread in all cases is 9.6×10^{-4}.

Magnet errors, misaligments, and beam steering for users cause asymmetries in the machine functions, which may increase ϵ_x and ϵ_y. Correction methods have been developed at APS to recover the symmetry of η and β [3]. Because ϵ_y has contributions from η_y in the dipoles and from skew quadrupole errors, the coupling is minimized in two steps. η_y is first minimized using skew quadrupoles in the dispersion-matching sections of the arcs using a matrix method [3]. We then adjust two knobs controlling the main coupling resonance (ν_x-ν_y) harmonic components via the skew quadrupoles in the dispersion-free sections, thus minimizing the measured beam size or beam lifetime. The process is semi-automatic and takes about 30 minutes. In the standard lattice, we were able to reduce the coupling to

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Table 1: APS SR Lattice Parameters

Parameter	Original	Present	Low emittance	Low emittance with L=7.7 m	Low emittance and low coupling with L=7.7 m	Low emittance and low coupling with L=10.7 m
ϵ_x (nm-rad)	8	7.7	3.5	3.6	3.6	3.8
ϵ_y (pm-rad)	800	77	35	36	9	9.5
β_x at ID (m)	14.0	16.1	14.9	16.3	16.3	14.7
β_y at ID (m)	10	4.4	3.7	4.0	4.0	4.4
η_x at ID (m)	0	0	0.12	0.10	0.10	0.02
σ_x at ID (μm)	334	352	255	261	261	237
$\sigma_{x'}$ at ID (μrad)	24	22	15.3	14.9	14.9	16.1
σ_y at ID (μm)	89	18.4	11.4	12.0	6.0	6.5
$\sigma_{y'}$ at ID (μrad)	8.9	4.2	3.1	3.0	1.5	1.5

0.22%. For the low-emittance lattice, the dispersion is nonzero everywhere, so a different correction method will have to be developed to integrate correcting η_y and the main coupling resonance.

Small coupling generally implies a short beam lifetime, especially for our standard fill pattern of 100 mA in 23 bunches. The impact of the shorter lifetime will be reduced when we operate in top-up injection mode, which will be a significant fraction of the time in 2002 [4]. Using more bunches will also improve the lifetime.

3 INSERTION DEVICES

The standard permanent magnet hybrid undulator A has a period length of 3.3 cm. There are presently 21 of these installed on the APS storage ring, with two more scheduled for installation in the next few months. This device has proven to be a good, all-round undulator. Because the minimum gap is fixed (10.5 mm; K_{eff} = 2.78), the lowest accessible energy is 2.9 keV. Some users, however, seek higher brightness, which can be obtained with a shorter-period undulator (which compromises the lowest accessible energy). The total power and on-axis power density will also be higher, for the first harmonic, by a higher ratio than the increase in brightness. But if the user can handle the power loads, the shorter period is a route to higher brightness.

Some users have already opted for shorter-period undulators. One user presently has two undulators with a 2.7-cm period installed, both in the same sector. (This user also opted to increase the brightness by increasing the total length of the undulator.) The minimum gap is 8.5 mm. At that gap, the stronger of the two undulators delivers an effective K of 2.18 for the first harmonic at 5.10 keV. (The other device was designed to operate at smaller gaps and gives an effective K of 1.80 at 8.5 mm.)

A circularly polarizing undulator (CPU) with 12.8-cm period has also been installed at the APS. This device is delivering high-brightness photons at energies below 3 keV, a region that is inaccessible by undulator A. In addition, it provides variable polarization: left circular, right circular, and vertical and horizontal linear, with brightness above 10^{18} in circular mode.

Fig. 1 summarizes the calculated on-axis brightness for the present APS lattice for the 3.3-cm undulator A (also shown is the performance for the APS design lattice), the undulator with 2.7-cm period, and the CPU. All devices are 2.4 m long and the beam current is 100 mA. There is an almost 10-fold increase in brightness from the original design lattice because of the lowered coupling (coupling reduced from 10% to 1%) and the reduced β_y. It should be noted that in the tuning curves for the undulator A and the CPU, the third harmonic curve extends low enough to intersect the first harmonic curve. Thus, there is no brightness gap between the harmonics. Since a smaller vacuum chamber was installed for the 2.7-cm-period undulator, the brightness gap between the harmonics has almost disappeared.

The possibility of further brightness enhancements by using an undulator with an even shorter period, 2.5 cm, is also being considered, and a vacuum chamber with a smaller outside dimension has been designed. This chamber allows a minimum undulator gap of 7.5 mm. A 2.5-cm-period undulator in combination with that vacuum chamber is expected to give a peak field of 9100 G, for a K of 2.12 and a minimum first harmonic energy of 5.7 keV.

Fig. 2 shows the prospect for the low emittance lattice, 0.25% coupling, and a current of 300 mA for devices that are 7.7 m long. (Presently the storage ring front ends can handle the heat load for 100 mA for the undulator A at closed gap.) The peak brightness for the 2.5-cm-period device is now above 10^{21}. Comparison is also made with the standard undulator A, which is only 2.4 m long.

A superconducting undulator is planned for the APS. The user for this device is interested in high brightness for energies above 30 keV, with a wider tunability range than would be achievable with a short-period permanent magnet device. This proposed undulator would have a period length of 1.0 cm and a K_{eff} = 1.0. Its performance is outstanding for the high-photon energies, as shown in Fig. 2. The performance of a 7.7-m-long CPU in combination with the low-emittance lattice is also shown.

The low-emittance lattice with a β_y of 4 m and 0.25% coupling matches the inherent photon beam diffraction-limited source size and divergence in the vertical direc-

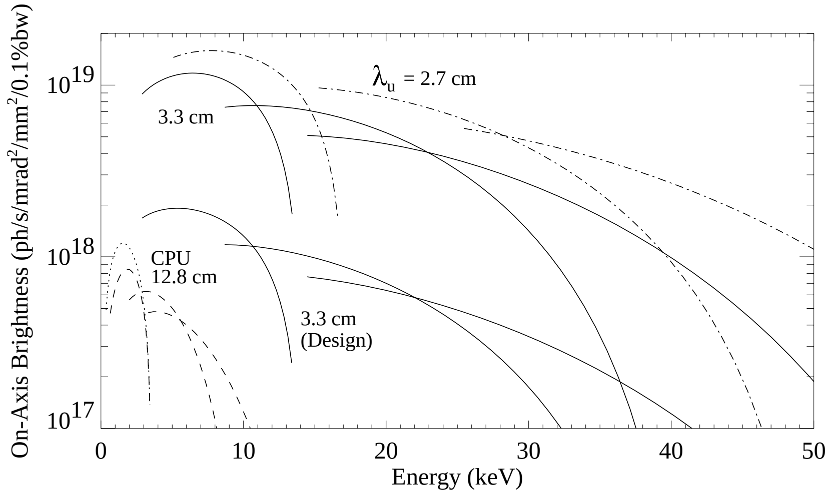

Figure 1: On-axis brightness for the present APS lattice (ϵ_x = 7.7 nm-rad, ϵ_y/ϵ_x = 1.0%) at 7.0 GeV with 100-mA beam current for a standard 3.3-cm-period undulator A (upper set of solid lines) and for a 2.7-cm-period undulator (dot-dashed lines). For the undulator A, the original design performance (ϵ_x/ϵ_y = 10%) is also shown as the lower set of solid lines and for the CPU, both the circular (dots) and linear (dashes) polarization modes are shown.

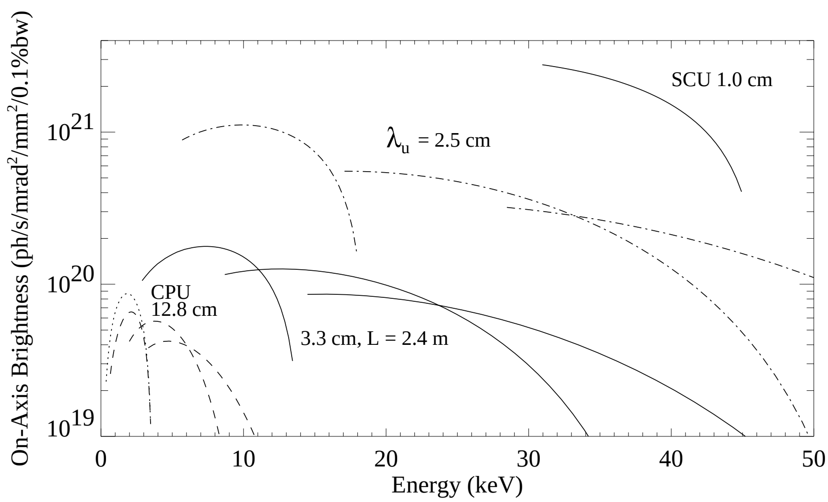

Figure 2: On-axis brightness for a future APS low-ϵ_x (3.6 nm-rad) low-ϵ_y/ϵ_x (0.25%) lattice at 7.0 GeV and 300 mA with 7.7-m-long undulators. For the 3.3-cm-period undulator A the performance is for a 2.4-m-long device. For the CPU, both the circular (dots) and linear (dashes) polarization modes are shown. The SCU is a proposed superconducting undulator.

tion for the long devices. The brightness therefore scales linearly with the length of the undulator and should increase by about 40% when going to the 10.7-m-long devices. A high brightness of 10^{21} can be achieved by reducing the emittance and the coupling, increasing the current, and making the insertion devices longer. Obviously, the power loads will be a challenge, and it may be necessary to limit the tunability range for these devices, such as by operating devices at small K values only.

4 REFERENCES

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