ACCELERATOR ASPECTS OF THE ADVANCED PHOTON SOURCE UPGRADE*

L. Emery†, M. Borland, G. Decker, K. Harkay, L. Moog, A. Nassiri, ANL, Argonne, IL 60439, USA

Abstract

The Advanced Photon Source (APS) is a third-generation storage-ring-based x-ray source that has been operating for more than 13 years and is enjoying a long period of stable, reliable operation. While APS is presently providing state-of-the-art performance to its large user community, we must plan for improvements and upgrades to stay at the forefront scientifically. Significant improvements should be possible through upgrades of beamline optics, detectors, and end-station equipment. In this paper, we discuss the evolutionary changes that are envisioned for the storage ring itself. These include short-pulse x-rays, long straight sections, superconducting undulators, improved beam stability, and higher current. With these and other changes, we anticipate significant improvements in capacity, flux, and brightness, along with the ability to perform unique time-resolved experiments.

INTRODUCTION

The Advanced Photon Source (APS) is a high-brightness 7-GeV storage ring light source in operation since 1996. Although the ring is highly successful, significant accelerator component upgrades are proposed as part of the APS upgrade. Several straight sections will be lengthened from 4.8 m to 7.7 m. The present x-ray pulse duration is on the order of 100 ps FWHM, which may be decreased to about 2 ps for two beamlines. We also anticipate providing new types of insertion devices (IDs) to augment the existing mostly-planar devices; these may include devices for switchable polarization and superconducting undulators (SCU). Presently we operate at a maximum current of 100 mA in top-up mode, which may be increased to 150 or 200 mA. Finally, we are working on improvements to both short- and long-term beam stability.

It is important that each upgrade does not compromise present operating capabilities significantly, such as 1) high reliability, 2) the stability of the 16-mA bunch in a hybrid bunch pattern, 3) beam emittances of the two transverse planes, 4) ability to have reduced horizontal beam size (RHB) in one sector, and 5) good enough beam lifetime so that injector charge is sufficient in top-up operation.

LONG STRAIGHT SECTION

The APS has 40 largely identical sectors with straight sections that accommodate two 2.4-m IDs. Long straight sections (LSS) would provide the ability to use a single, longer device to deliver higher brightness and flux. LSSs can also accommodate special equipment without excessively reducing ID length; for example, crab cavities for producing short-pulse x-rays [1, 2].

We selected the least costly implementation of LSS, that is, by simply removing the Q1 quadrupoles on either side of a straight section and replace the next quadrupoles (0.8-m long) with 0.5-m-long quadrupoles. This allows 7.7 m for IDs, and requires no new magnets.

We could benefit from having many LSSs. Ordinarily, to ensure adequate dynamic and momentum aperture, we would have to arrange any LSSs in a symmetric pattern, which requires that the number of LSS groups be a factor of 40. Given the user request for specific sectors of LSS, which are unsymmetrically placed around the ring, we found that we could substantially restore the original apertures with an optimized set of sextupole gradient settings obtained through a genetic optimizer.

We have developed several lattices using this scheme [3, 4]. Figure 1 shows the lattice functions for a nonsymmetric configuration of 8 LSSs. Tests of similar lattices

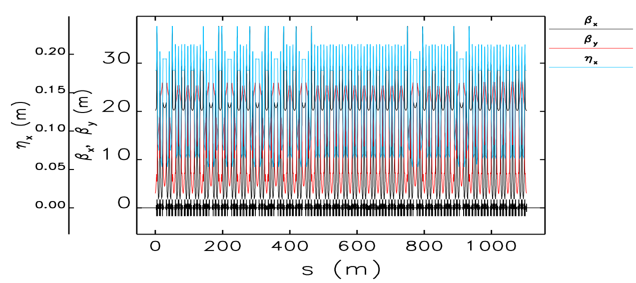

Figure 1: Optics for long straight section lattice for APS.

showed good results [4]. Measured dynamic aperture and lifetime agree with prediction after some effort spent on correcting the coupling. Because of the reduced number of quadrupoles, the dispersion in the LSS is somewhat larger than in the normal straights, giving an increased effective emittance for the LSS of 3.60 nm, compared to 3.36 nm for the normal straights (all straights have 3.1 nm in the APS today). The beamsize and divergence change by less than 10% compared to present values.

The lattice can also be modified to include a straight section with reduced horizontal beamsize (RHB), which involved matching a lower β_x in a straight section. Again, the lower symmetry requires a genetic search of optimum sextupole settings.

The sextupole gradient search is repeated for various chromaticity settings required for different bunch patterns. Our standard 24 bunches, 100 mA pattern requires a chro-

* Work supported by the U.S. Department of Energy,Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

† lemery@aps.anl.gov

maticity of 7 (6) in the horizontal (vertical) planes. The hybrid bunch pattern (with 16 mA in a single bunch) requires chromaticity of 9 in both planes with bunch-by-bunch transverse feedback running. The higher chromaticity reduces the dynamic apertures and lifetime, more so with the addition of RHB (and SPX – see below) optics. Because of the reduced lifetime with these optics, our plan is to only operate the hybrid bunch pattern without the RHB and SPX optics.

A longer straight section will increase the vertical impedance produced by resistive wall and taper transitions at the ends of the straight section vacuum chamber. Longer taper designs for the LSS will restore the impedance.

SHORT-PULSE X-RAYS (SPX)

The Zholents scheme [1] for producing short-pulse x-rays with deflecting cavities is adopted over various others because it is most compatible with normal operations and has the least flux penalty. Two sets of superconducting 2.815-GHz (8^{th} harmonic of main rf frequency) vertical deflecting cavities are to be installed at the downstream ends of sectors 5 and 7, thus creating special source points for straight sections 6 and 7 [2]. The first set of deflecting cavities impose on the particle coordinates of the bunches a correlation (chirp) in vertical momentum and longitudinal position. The bunch is transported through dipole magnets and undulators and finally to the second set of cavities where the correlation is removed. (The vertical phase advance between the two sets of cavities is 2π.) The emitted x-ray photons are also chirped, so that at a far enough distance the x-ray pulse acquires a significant spatial correlation. One then filters spatially with vertical slits to obtain a pulse of the order of 2 ps, albeit at reduced flux.

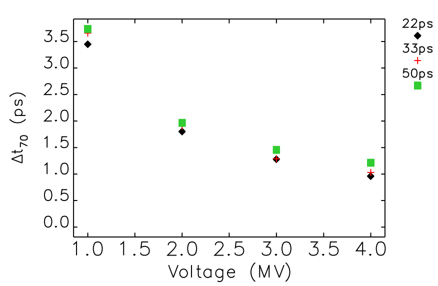

Figure 2: X-ray pulse duration as a function of deflecting voltage for different electron bunch durations.

Nonlinearities, errors, and other details [5] destroy the ideal cancellation of the kicks, resulting in vertical emittance growth. Vertical emittance, together with the natural opening angle of the undulator radiation, smears the chirp, limiting how short a pulse can be produced [6]. As the deflecting voltage is increased, the emittance growth also increases and reduces the anticipated benefit.

As a result, total deflecting voltages above about 4 MV are of little value. In addition, at or below this level we can ensure negligible impact on other users. Figure 2 shows the results of a simulation of the expected short-pulse x-ray (SPX) bunch duration using a vertical slit 30 m from the undulator set to transmit 1% of the incident photons.

Development of the cavity is a collaborative effort of Argonne and Thomas Jefferson national laboratories. The cavities will feature strong dampers for lower-order and higher-order resonant modes, not only to reduce heat load to the cavities but to avoid multi-bunch instabilities.

NEW INSERTION DEVICES (IDS)

There are presently 47 IDs installed at APS, 30 of which are 33-mm-period undulators A (UA) that provide a continuous tuning range above 3.2 keV. To optimize performance, a variety of other period lengths (18, 23, 27, 30, 35, 55, and 128 mm), have been provided. As we move away from multi-purpose beamlines, we can provide many experiments with an order-of-magnitude higher brilliance source, without increased heat load, by replacing UA devices with lower-K undulators optimized for a particular energy range. Longer insertion devices, coupled with increases in stored current, will require upgrades to the front end and certain high-power beamline components (slits, windows, beam stops, etc.).

Revolver IDs have two or more planar hybrid permanent magnetic (HPM) structures of different period lengths on one support. One or the other HPM can be selected while beam is present in the storage ring. Though more complicated mechanically, they are more space efficient than multiple in-line devices, and would obviate the need for LSS in some cases. A Pareto-optimal approach is being applied to selection of revolver periods and will be used to minimize the total number of periods that have to be designed.

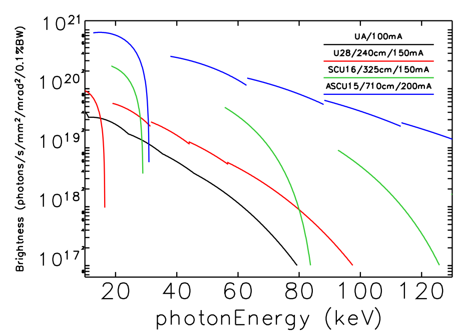

Figure 3: Brightness for standard APS device today, plus two upgrade and one long term possibility (ASCU).

To improve brightness for hard x-rays, APS has an ongoing R&D program [7] to develop a short-period superconducting undulator (SCU) based on NbTi wire, targeting first-harmonic radiation between 20 and 25 keV. Prototype 42-pole cores (0.34 m) of period of 16 mm have met the design goal of 0.61 T (20.5 keV) for 500 A with a phase error of 2 degrees. An in-ring test of this device is planned for 2012, with longer devices to follow. A measurement system is being developed to measure the magnetic structure in the horizontal orientation [8]. Fig. 3 indicates possible brightness improvements for the APS upgrade and beyond.

APS has one electromagnetic ID providing variably polarized radiation [9]. We anticipate adding more polarized devices, including APPLE and electromagnet designs [10]. APPLE undulators provide control of the direction of the polarization vector, the helicity of the polarization, and, in the circularly-polarized mode, also produce mostly first harmonic on axis. By masking off-axis radiation that carries the higher harmonics, one can protect heat-sensitive optical components downstream.

To reduce higher-harmonic contamination seen in the photon beam downstream of the monochromator, quasiperiodicity (see [10] and references therein) will be introduced into selected IDs of different types. The higher harmonics generated by a quasiperiodic undulator are shifted in energy from those that are produced by a periodic device. As a result, the x-ray monochromator will transmit primarily the first harmonic radiation, leading to a substantial improvement in the signal-to-noise ratio for experiments.

HIGHER CURRENT[11]

The accelerator could operate today stably at the upgrade current of 150 mA in all fill modes in the LSS lattices, but thermal limitations in the x-ray front ends (FEs) and beamlines prevent this. We plan to upgrade the FEs and beamlines to 200 mA, and keep an upgrade of the accelerator to 200 mA as an option.

We also know that only 2 klystrons (number used for 100 mA) are needed for 150 mA operation, though they do operate at nearly their 1-MW full rating. To store 200 mA, parallel four-klystrons operation is required. A modest upgrade of controls would be necessary to improve stability for that mode of klystron operation.

We've identified other storage ring components that limit the operational current and have made R&D plans to achieve a stored current of least 200 mA for existing bunch patterns. The limitations are coupled-bunch instabilities (CBI), excessive beam-driven heating, and short lifetime, which can be alleviated as described below.

CBI is caused by higher-order modes (HOM) in rf cavities, which can be suppressed by HOM dampers (HOMD) in individual cavities. We presently have HOMDs in 4 of 16 cavities, permitting stability for all operating bunch patterns at 164 mA or more, and for 324 bunches up to 245 mA. However for general bunch patterns, excessive heating develop in the HOMDs even at low currents. New HOM dampers are currently being designed to alleviate this.

Beam-driven heating is generally bunch-pattern dependent and occurs in rf-cavity couplers and in cavity-like storage ring components, such as beam scrapers. Coupler heating is highest for the 24-bunch pattern, the lowest number of bunches we consider, which limits the current to 164 mA. Rf conditioning may help raise this limit. However, for reliable 200-mA operation, the existing input power couplers will be replaced with a modified design that has shown favorable results.

IMPROVED BEAM STABILITY

Experiments at APS require beam stability across multiple spatial (nanometer to micron) and time (microsecond to day) domains. Increasing the stability of delivered x-ray beams improves the quality of all APS science as it reduces jitter and beam-induced artifacts in experimental data, thus making more challenging experiments possible.

With a goal to increase the short- and long-term beam stability by a factor of two to four, the upgrade plan consists of the following. 1) The obsolete BPM electronics for the narrowband rf (70) and photon BPMs (70) will be replaced with modern systems, providing improved resolution, noise floor and drift characteristics by an expected factor of 2. 2) The existing ID photon BPMs (34) will be replaced with BPMs based on hard x-ray fluorescence [12], providing improved immunity to background radiation and improved long-term drift characteristics by expected factor of 2. 3) The current real-time feedback system will be completely replaced by modern components to improve the bandwidth from approximately 60 Hz to 200 Hz. The number of fast corrector magnets that can be used will be doubled. The expected reduction of AC beam motion is a factor of 4 in the 200 Hz band. 4) Tunnel temperature regulation will be improved by addition of fine-adjustment reheat coils (air), new sensor instrumentation, and increased water flow. 5) 34 ID and 34 rf BPMs will be instrumented with position sensors to allow compensating for temperature-induced motion of the monitors. This will improve long-term drift by factor 2.

The SPX project has the potential to negatively impact beam stability. As a result, specific steps are taken as part of SPX project that include setting tolerances on various errors and providing the diagnostics needed for a control, feedback, and fine tuning.

ACKNOWLEDGMENTS

A large number of people at APS have contributed to this work through discussions, calculation, simulations, and machine studies.

REFERENCES

[1] A. Zholents et al., NIM A, **425**, 385, (1999).
[2] A. Nassiri, these proceedings.
[3] M. Borland et al. Technical Report LS-319, APS, (2010).
[4] V. Sajaev et al., These proceedings.
[5] M. Borland, PRST-AB, **8**(7), 074001, (2005).
[6] M. Borland and V. Sajaev, Proc. 2005 PAC, 3886 (2005).
[7] Y. Ivanyushenkov et al., Proc. 2009 PAC, 313 (2009).
[8] Y. Ivanyushenkov et al., these proceedings.
[9] E. Gluskin et al., AIP Proc. 521, 344-347 (1999).
[10] R. Dejus et al., Proc. 2009 PAC, 307 (2009).
[11] K. C. Harkay et al., these proceedings.
[12] B. Yang et al., these proceedings.