ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

STATUS OF THE APS-U PROJECT*

R. Hettel†, Argonne National Laboratory, Argonne, USA

Abstract

The Advanced Photon Source Upgrade (APS-U) project at the Argonne National Laboratory will replace the existing 7-GeV, 1.1-km circumference double bend storage ring lattice with a new 6-GeV hybrid 7BA lattice that will reduce horizontal electron emittance from 3 nm-rad to 42 pm-rad, including IBS effects for 200-mA operation. With new optimized permanent magnet and superconducting undulators, an increase in spectral brightness of two to three orders of magnitude in the 10-100 keV X-ray energy range will be realized. The project includes nine new high performance beamlines and fifteen enhanced beamlines that will exploit the high brightness and coherence of the new facility. The project is in full swing, more than 50% complete by cost, and is on schedule for first beam sometime in mid-2024, a slip of 10 months from the original schedule due to the impact of COVID-19. Project status, challenges and outstanding issues will be discussed in this article.

INTRODUCTION

The world of storage ring light sources entered a fourth generation with the inception of the 3-GeV, 7-bend achromat lattice MAX-IV storage ring [1] having ~200pm-rad emittance, an order of magnitude less than 3rd generation rings, realizing multi-bend achromat lattice ideas for low emittance light sources explored in the early 1990s [2]. This bold and pioneering step initiated a new wave of 4th generation storage rings (4GSRs) having enhanced brightness and coherence – almost every storage ring light source is studying MBA lattices – and, in some cases, these new designs are actually being built.

High photon brightness and coherence are beneficial for a wide range of X-ray science applications because it enabes beam focusing to very small spot sizes (<10 nm) for pin-point scattering, spectroscopic and imaging applications and it maximizes the performance of various measurement techniques that exploit brightness and coherence. 4GSRs increase brightness and coherence by pushing electron emittance down to values approaching the diffraction-limited photon emittance l/4p for photon wavelength l. The quest has been to reach emittances corresponding to the nanometer and angstrom wavelengths typically used at X-ray light sources. For the 1-Å X-rays that are used to study atomic structure having angstrom length scale, the diffraction-limited emittance is 8 pm-rad, a value that is reached in the vertical plane at 3rd generation storage ring light sources but is hundreds of times smaller than the horizontal emittance for those machines. 4GSR emittances are pushed to the level of 100 pm-rad or, in some cases, to a few 10s of pm-rad, reaching the diffraction limit for sub-nanometer X-rays.

The APS-U Project is the direct result of the advent of 4GSR light source technology and its embrace by the international community. In particular, with 6-GeV MBA machines either built (ESRF-EBS, [3]), in construction (HEPS in China, [4]) or in planning (Spring-8-II [5], PETRA-IV [6]) and possibly others, DOE Basic Energy Sciences determined that the APS-U had to be built for the United States to remain in a competitive and leadership position in the international hard X-ray community. The APS-U will provide users of the Advanced Photon Source with X-rays having twice the spectral flux and from two to three orders of magnitude higher spectral brightness and transverse coherence than the existing facility (Fig. 1). The small horizontal emittance will enable the production of nearly round photon beams, desirable for X-ray focusing optics and many experimental techniques, and, with on-axis swap-out injection [7], will enable the use of insertion devices having small horizontal apertures and small diameter round vacuum chambers. APS-U electron beam properties are summarized in Table 1.

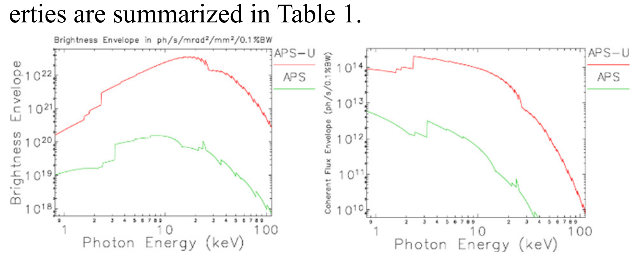

Figure 1: Comparative brightness and coherent flux for the APS and APS-U.

Table 1: Parameters for the APS and APS-U Storage Rings (with IBS)

Quantity	APS	APS-U
Beam Energy	7	6
Beam Current	100	200
Number of Bunches	24/324	48/324
Bunch Duration (ps rms)	34	104
Energy Spread (% rms)	0.095	0.135
Bunch spacing (ns)	153/11.4	77/11.4
Emittance Ratio	0.013	1
Horiz Emittance (pm-rad)	3100	31.9
Horiz Beam Size (μm rms)	275	12.6
Horiz Beam Divergence (μrad rms)	11	2.5
Vert Emittance (pm-rad)	40	31.6
Vert Beam Size (μm rms)	10	7.7
Vert Beam Divergence (μrad rms)	3.5	4.1

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

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

The scope of the APS-U project, including new storage ring, 9 new high performance and 15 enhanced performance X-ray beamlines and new permanent magnet and superconducting undulators is illustrated in Fig. 2.

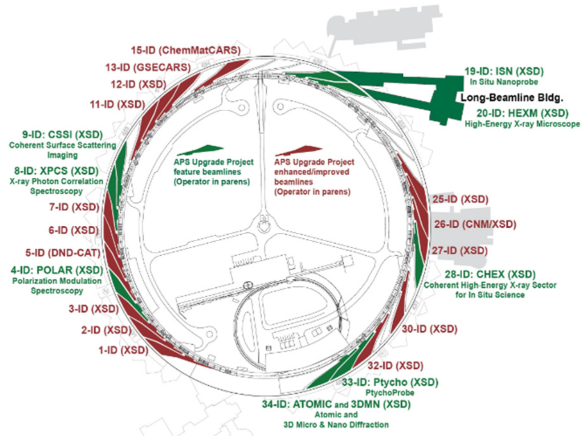

Figure 2: The APS-U project scope includes replacing the storage ring, building 9 "feature beamlines" (green), including 2 in a new long beamline building, enhancing 15 existing beamlines (red), installing new permanent magnet and superconducting insertion devices, and modifying the injector complex for "swap-out" injection.

APS-U LATTICE DESIGN

The design of MBA lattices for 4GSRs has evolved since MAX-IV, including the introduction of the hybrid MBA to reduce sextupole strengths for high energy rings [3], longitudinal gradient dipoles (L-bends) [3, 8], and "reverse bends" in the achromat [9]. The latter two developments enable a reduction of the integrated product of dispersion and horizontal beta functions along the dipole, thereby reducing emittance. The APS-U lattice [10] (Fig. 3) employs all three of these developments to reach an emittance of 42 pm-rad with a ring circumference of ~1.1 km, a beam energy of 6 GeV and a stored beam current of 200 mA. Note that the reverse bends increase the total lattice bending angle from 360 to 435 degrees. Like other 4GSRs, small-diameter (~2 cm) NEG-coated vacuum chambers will be used, primarily in the central FODO sections of the lattice containing high strength gradient dipoles. Stainless steel and aluminum chambers, some having antechambers, will be used elsewhere together with Inconel chambers for fast orbit correctors.

Building any ultralow emittance 4th generation storage ring light source understandably presents many challenges in accelerator physics and technology. Developments in high fidelity lattice simulation, genetic optimization algorithms, particle tracking, impedance, ion trapping and magnetic modeling codes at the APS [10] and elsewhere, together with advances in achieving very tight mechanical and magnetic tolerances have made possible the successful design of such strongly focusing and highly nonlinear lattices. The tracking code has been enhanced recently with the incorporation of realistic 3D magnet models using generalized gradient expansion methods [11]. Some APS-U quadrupoles and sextupoles having strengths of order 100 T/m and 6800 T/m^2 respectively require small bore radii (13-14 mm) and vanadium permendur pole faces. Alignment tolerances between magnets of 30 µm or less, and <100-µm alignment tolerances between magnet support girders is specified.

Collective effects Collective effects have also been extensively studied [12] and steps taken to reach acceptable single- and multi-bunch instability thresholds by reduce vacuum chamber impedance, including a longitudinal (and possibly transverse) multi-bunch feedback system, providing temperature control of the 10 individual main RF cavities that can be used to avoid harmful cavity HOMs from affecting the stored beam, and implementing a superconducting 4th harmonic (1.408 GHz) bunch lengthening cavity [13]. This passive harmonic cavity will enable ~3.5-h mean Touschek lifetime in 48-bunch, 200-mA (16 nC/bumch) timing mode and ~7.5-h mean lifetime in 324-bunch, 200-mA (2.4 nC/bunch) high brightness mode. Symmetric bunch fill patterns are required for stable operation of the bunch lengthening cavity. The cavity introduces a spread in synchrotron frequency, but lowers the average frequency to <1 kHz, within the bandwidth of the orbit feedback system. To operate the longitudinal feedback system together with the bunch lengthening cavity and to decouple it from the orbit feedback system, the longitudinal system will feedback on bunch energy as sensed with a BPM in a high dispersion location. An improved model of ion instability has been developed, supported by experimental studies [14], and the residual orbit instability caused by ground diffusion that cannot be corrected with the

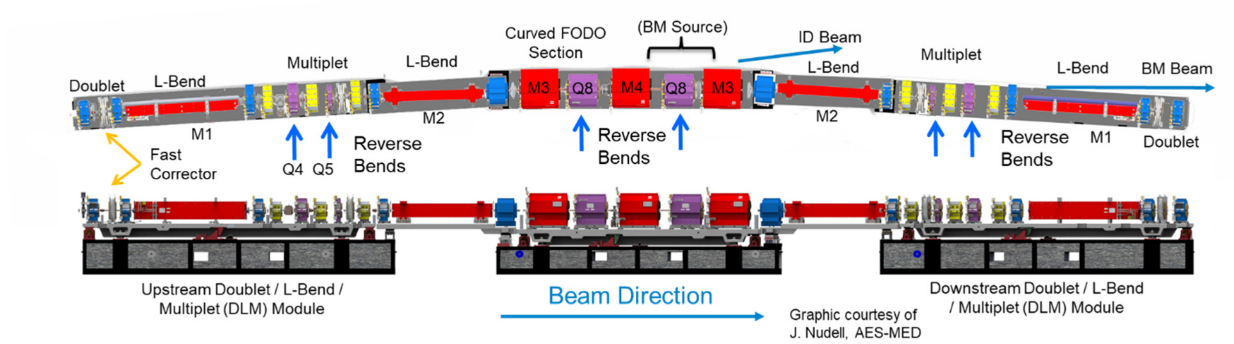

Figure 3: One of 40 7BA sectors for the APS-U.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

electron BPM-based orbit feedback system has been studied [15].

The maximum stable bunch charge for the APS-U will be 16 nC, implying 48 bunches are needed for 200-mA operation. The present 100-mA APS operates with 16-nC bunches in 24 bunches. It is also capable of storing a ~60 nC in a single "camshaft" bunch well separated from other lower charge bunches, a beneficial mode for "timing" users. This mode will disappear with the APS-U, and the separation between bunches will be reduced by a factor of two to 77 ns in 48-bunch mode, somewhat more challenging but tolerable for timing mode users.

INJECTION

The optimized dynamic acceptance for the aggressive APS-U lattice is only ± a couple of millimeters – large compared to the <15-μm horizontal and <8-μm vertical rms beam sizes but too small for conventional off-axis injection and accumulation. Thus APS-U is adopting the on-axis, swap-out injection scheme where an individual stored bunch in the ring is kicked out and replaced with a full-charge fresh bunch on each injection cycle (Fig. 4). The beam will be injected horizontally on-axis using a pulsed 1.4-T septum magnet, 3 horizontal fast kickers and a horizontal-vertical emittance exchange scheme [16, 17] in the booster-to-storage ring (BTS) to reduce horizontal injected beam size for high injection efficiency (Fig. 5).

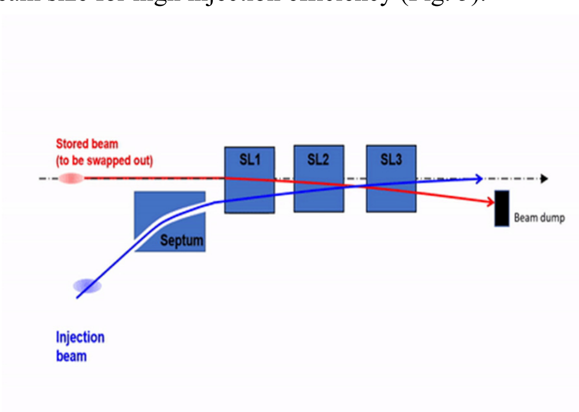

Figure 4: Horizontal swap-out injection.

This injection method implies that the beam injector system must be capable of reliably supplying a ~16-nC bunch on each injection cycle for 48-bunch, 200-mA operation and the injection kicker system must be fast enough to swap out a single stored bunch whose upstream and downstream neighbors are only 11.4 ns away in 324-bunch mode. Work is ongoing to improve the performance of the APS injector chain, which consists of a 450-MeV linac, a 450-MeV particle accumulator ring (PAR), a 6-GeV, 1-Hz booster synchrotron and related transport lines, to meet the high charge objective. Technology is on-hand to produce the +/- ~25-kV (50 kV differential voltage), ~11-ns kicker pulses. We note that the PAR enables the accumulation of the desired single bunch charge for the ring from multiple linac pulses before being accelerated in the booster. The time interval between injection shots to maintain ~1% stored beam current constancy is expected to be ~25 s for 48-bunch, 200-mA mode with ~3.5-h lifetime, and ~7.5 s for 324-bunch, 200-mA mode with ~7.3 h.

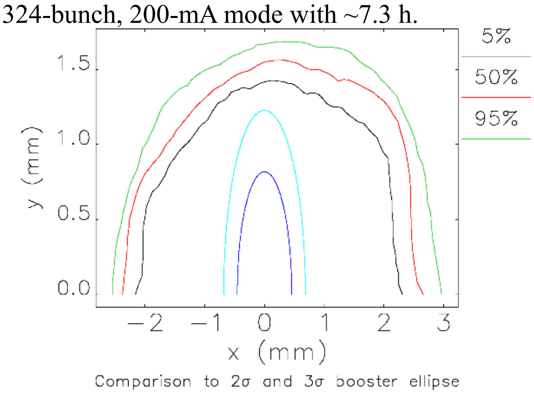

Figure 5: Injected booster beam with emittance exchange fits comfortably in storage ring acceptance.

Due to the higher energy density of the bunch that is being kicked out, it must receive a weak pre-kick to allow it to decohere before striking the swap-out dump to avoid damaging it [18]. Damage is even more of an issue for the dumps that intercept a whole beam dump (all stored bunches) due to an unforeseen RF system trip. While this damage could be mitigated with a vertically movable, refreshable dump surface, a scheme for "fanning out" the stored bunches using a weak, long-pulse beam abort kicker triggered by an RF trip is planned to distribute the deposited energy on the dump to avoid damage [19].

An added complication for injecting into the storage ring is that the path length for the new lattice is ~044 m less than the original ring, which is 3 times the circumference of the booster. The ring RF frequency will therefore be 142 kHz higher than that for the booster. A new frequency-agile injection timing system using direct digital synthesis technology is being devised that will alter the booster frequency during the energy ramp to adjust booster bunch timing to accurately hit a target bucket in the ring [20]. Additional frequency ramping will shift the booster from being on-energy at injection from the upstream injection chain to being off-energy by 0.6-0.8% later in the accelerating ramp to reduce horizontal emittance via a change in horizontal damping partition.

The injected beam bunch will have a much higher emittance than the 42 pm for the stored beam. This will effectively result in a dip in average stored beam brightness at injection of ~2% for 48-bunch mode (1 bunch out of 48 with a large emittance) and ~1% for 324-bunch mode (3 bunches out of 324 since the kicker waveform perturbs the two bunches adjacent to the target bunch to some extent), returning to full brightness in <50 ms (several damping times)

SCOPE AND SCHEDULE

The scope for the APS-U project is summarized in Fig. 6. These systems are described in detail in reference [21].

As of April 2021 the project, which has a total project cost (TPC) of 815 M$ that includes ~32% contingency, is

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

50% complete by cost and 70% by cost and obligations. The project at this stage has good cost and schedule contingency although both of these have been impacted by the COVID-19 situation. The high level project schedule (Fig. 7) was recently adjusted with a shift of 10 months of the 1-year installation darktime from June 2022 to mid-April 2023, and this shift together with higher than anticipated contract costs have taxed the contingency allocation. Meanwhile the schedule shift is benefitting users who will now have an additional 3-month experimental run before the darktime and will have more time to plan funding strategies and how to what actions they will take during the darktime. Many are making arrangements for beam time at other light sources during that period.

Storage Ring	Insertion Devices	Front Ends	Beamlines
1,321 Magnets	11 Phase Shifters/Supports	470 Tables/Supports	36 Enclosures
4,640 Vacuum Components	48 Canted Magnets/Supports	162 Shutters	61 Mirrors
120 Modules	33 Corrector Magnets	108 BPMs	28 Instruments
80 Support Plates	800 Vacuum Components	162 Masks	23 Monochromators
2,245 Power Supplies	68 Power Supplies	116 Collimators	9 Transports
400 Power Supply Controllers	4 Superconducting Undulators*	19 High Heat Load Front Ends	22 Compound Refractive Lens
560 RF BPM Electronics	43 Planar Insertion Devices**	16 Canted Front Ends	13 Enhanced Beamlines
200 Module Assemblies	12 Revolver Devices***	20 Bending Magnets	9 Feature Beamlines

Figure 6: Components required (black) to implement final systems (blue) for the APS-U.

At the end of the darktime it is expected that there will be at least 25 mA of stored beam and many of the X-ray beamlines will begin to open, especially those that were not significantly modified. Close to normal operations with 100 mA or more with several of the recommissioned enhanced and some number of new feature beamlines is expected ~6 months after the 1-year period. More time will be needed to fully commission some of the more technically challenging feature beamlines.

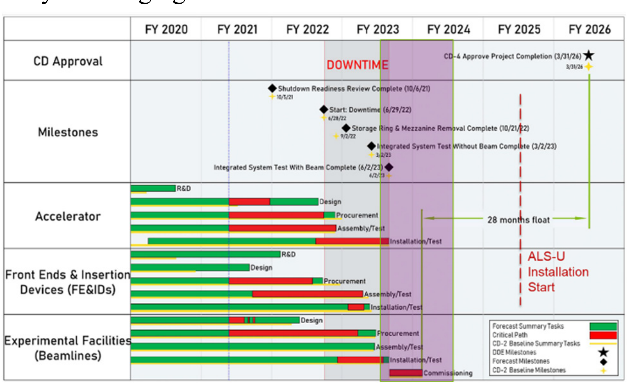

Figure 7: High level APS-U schedule. The 1-year ring installation darktime has been shifted from June 2022 to April 2023 due to COVID-19-related schedule slippages.

IMPLEMENTATION PROGRESS

Recent progress in the implementation and receipt of components for the APS-U is presented in reference [22], with some brief overview below.

Magnets and Supports

Over 900 of the 1321 ring lattice magnets have been received, magnetically measured and accepted to date. In addition, the first massive support plinths (there are 3 per sector as shown in Fig. 3) have been received. The first practice assembly of the DLM-A plinth and magnets (the left-hand plinth in Fig. 3) has been completed (Fig. 8). Magnets were mounted on the precision-machined raft sitting on top of the plinth and the 30-µm rms magnet-magnet alignment tolerance was met without further adjustment. The 120 plinth modules needed for the APS-U 40 sectors will be pre-assembled (in an off-site workspace) and eventually moved into the ring tunnel using Traksporters [23].


Figure 8: DLM-A plinth practice assembly.

Power Supplies

The project has received and accepted 94 of the 1002 unipolar power supplies needed for the storage ring lattice and all of the 1243 fast and slow bipolar supplies needed for orbit correction and magnet trims. 75 more undulator canting magnet supplies have not yet been tested. The unipolar supplies have 10 ppm stability, while the bipolar supplies for orbit feedback have 10-kHz bandwidth. Power supplies under test are shown in Figure 9.


Figure 9: Unipolar power supplies (left) and bipolar supplies with bulk supplies (right) under test.

Controls and Diagnostics

Detailed specification of the complex control system is ongoing. The upgraded controls fiber network is being installed. The "Component Database", which will enable one-stop access to documentation, travellers, specifications, physical location and more for all components is in an advanced stage of development.

All of the 140 4-channel I-Tech Libera Brilliance+ electron BPM processors needed for the 560 BPMs in the ring have been received, although 4 have been returned to the company for repair of some performance issues. In addition, 20 Libera SPARK processors will be used together with high speed RF switches to monitor the first-turn trajectory of the injected bunch [24].

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

Two Bergoz in-flange DCCTs have been ordered and one received.

The Machine Protection System is in advanced stage of design. The system accommodates the fast Beam Position Limit Detector system that aborts stored beam if the electron orbit exceeds millimeter-limits in order to protect the vacuum chamber from mis-steered synchrotron radiation. BNL is collaborating with this implementation.

Vacuum System

The vacuum chamber system for the APS-U is highly complex with hundreds of individual components, the majority of which have been ordered. At the moment delivery and assembly of vacuum chamber compo nents is on the critical path for the project and is one of the contributors to the shift in darktime schedule.

BLS and Feedback Systems

The first cold test of the superconducting Bunch Lengthening System harmonic cavity was successfully completed. The cryogenic system design is complete and some components have been received, including the helium refrigerator.

Transverse and longitudinal feedback systems will both use DIMTEL processors.[25]. Shorter versions of the narrow aperture injection stripline kickers will be used for horizontal and vertical feedback to match the 426-mm half wavelength of the ring RF. Processing electronics has been configured to directly sense bunch energy with a BPM in a high dispersion section for longitudinal feedback to eliminate the long synchrotron oscillation quarter-period delay (a few milliseconds) for applying an energy kick if bunch phase was detected [26]. A model for the longitudinal kicker has been tested.

A prototype implementation of the fast orbit feedback system spanning two of the 40 APS lattice sectors has been tested. The system operates with a 22-kHz sampling frequency and, together with few-kHz correctors, will enable a global closed loop bandwidth of at least 1 kHz that will help to maintain <10% beam size stability [27].

Insertion Devices and Experimental Systems

Forty-nine planar hybrid permanent magnet undulators (HPMUs) will be removed from the existing APS and 23 of them will be rebuilt with new period lengths to optimally match the APS-U 6-GeV operation energy. Nineteen others will receive minor modifications and all 42 will be reinstalled in the APS-U. Permanent magnets and poles are installed in precision-machined "monokeepers" (Fig. 10) that enable reaching phase error tolerances with very little shimming. Eight new and one refurbished 2-headed revolver undulators will be installed along with 9 superconducting undulators (SCUs, Fig. 10) [28] and one electromagnetic variably polarizing undulator. ID beamlines will receive new front ends, many designed for high heat load (21 kW and 620 kW/mrad^2).

Nine new "feature" X-ray beamlines that are intended to exploit the brightness and coherence of the new source are included in the project. They enable state-of-the-art performance using techniques that include in-situ high energy coherent scattering, magnetic spectroscopy, coherent diffraction imaging (CDI), small- and wide-angle X-ray photon correlation spectroscopy (XPCS), ptychography/spectromicroscopy, coherent grazing incidence small angle scattering (GiSAXS) and diffraction microscopy. Two of these beamlines will be very long (180 m and 210 m), extending out beyond the present APS building into end stations housed in a new building. These new beamlines will be equipped with newly designed instruments that use state-of-the art technology to realize their functions. In addition, 15 of the ~60 existing beamlines will be upgraded with new X-ray optics (mirrors, monochromators, focusing elements, etc.) and detectors to enhance their performance. Dozens of other beamlines will receive minor improvements to assure equal or better performance than at present. The contract for shielded enclosures for new beamlines was recently awarded; their installation is expected to extend through the darktime.

Figure 10: HPMU monokeeper (left) and SCU cryomodule. (right).

CONCLUSIONS

The APS-U Project is progressing well with adequate and secure funding, at least at this time. A large number of project components have been received and accepted, and more are being delivered continuously. At the moment delivery of vacuum chamber components is on the critical path; it is expected that first articles will be received this calendar year, enabling practice assembly of the first 3-plinth magnet/chamber sector. Work is ongoing to define the radiation protection system needed for safe top-up injection with open X-ray beamlines. A recent workshop was held to identify gaps in the integration of tasks being carried out by the project and by the APS operations divisions; plans to resolve these gaps are in progress. A task team is working on overall facility readiness for APS-U operation with beam which will be assessed with an Accelerator Readiness Review near the end of the darktime.

The project team is pushing the state-of-the-art in storage ring light source design, making the APS-U Project extremely challenging but very exciting.

ACKNOWLEDGMENTS

The author thanks the APS-U Project team and the APS Operations staff for their input and support. Special thanks to Michael Borland, Glenn Decker, Mohan Ramanathan, Fernando Rafael, Uli Wienands, Kathy Harkay, Weixing Cheng, Jim Kerby and Elmie Peoples-Evans who provided information for this article.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOXA02

REFERENCES

[1] M. Eriksson *et al.*, "The MAX-IV Synchrotron Light Source", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper THPC058, pp. 3026-3028.

[2] D. Einfeld and M. Plesko, "A modified QBA optics for low emittance storage rings", in *Nucl. Instrum. Methods. in Phys. Res. A* vol. 335, no. 3, pp. 402-416, Nov. 1993. doi:10.1016/0168-9002(93)91224-B

[3] L. Farvacque *et al*., "A low emittance lattice for the ESRF", in *Proc. IPAC 2013*, Shanghai, China, May 2013, paper MOPEA008, pp. 79-81.

[4] G. Xu *et al.*, "Progress of Lattice Design and Physics Studies on the High Energy Photon Source", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1375-1378. doi:10.18429/JACoW-IPAC2018-TUPMF052

[5] H. Tanaka *et al*., "SPring-8 upgrade project", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 2867-2870. doi:10.18429/JACoW-IPAC2016-WEPOW019

[6] C. Schroer *et al*., "PETRA-IV: the ultralow emittance source project at DESY", in *Journal of Synchrotron Radiation,* vol. 25, no. 5, pp. 1277-1290, Sep. 2018. doi:10.1107/S1600577518008858

[7] L. Emery and M. Borland, "Possible long-term improvements to the advanced photon source", *in Proc. 20th Particle Accelerator Conf. (PAC'03)*, Portland, OR, USA, May 2003, paper TOPA014, pp. 256-258.

[8] R. Nagaoka and A. Wrulich, "Emittance minimisation with longitudinal dipole field variation", in *Nucl. Instrum. Methods A,* vol. 575, no. 3, pp. 292-304, Jun. 2007. doi:10.1016/j.nima.2007.02.086

[9] A. Streun, "The anti-bend cell for ultralow emittance storage ring lattices", in *Nucl. Instrum. Methods A*, vol. 737, pp. 148-154, Feb. 2014. doi:10.1016/j.nima.2013.11.064

[10] M. Borland *et al*., "The upgrade of the Advanced Photon Source", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, Apr.-May 2018, pp. 2872-2877. doi:10.18429/JACoW-IPAC2018-THXGBD1

[11] M. Borland *et al.*, "Tools for use of generalized gradient expansions in accelerator simulations", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB059, this conference.

[12] R. Lindberg and A. Blednykh, "Instability thresholds for the Advanced Photon Source multi-bend achromat upgrade", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 1822-1824. doi:10.18429/JACoW-IPAC2015-TUPJE077

[13] M. Kelly *et al.*, "Superconducting harmonic cavity for the Advanced Photon Source upgrade", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3267-3269. doi:10.18429/JACoW-IPAC2015-WEPTY008

[14] J. Calvey and M. Borland, "Modeling ion effects for the Argonne Advanced Photon Source Upgrade", in *Phys. Rev. Accel. and Beams*, vol. 22, no.11, p. 114403, Nov. 2019. doi:10.1103/PhysRevAccelBeams.22.114403

[15] V. Sajaev, APS/ANL, private communication, Dec. 2020.

[16] M. Borland, APS/ANL, private communication, Nov. 2020.

[17] P. Kuske and F. Kramer, "Transverse emittance exchange for improved injection efficiency", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 2028-2031. doi:10.18429/JACoW-IPAC2016-WEOAA01

[18] M. Borland *et al.*, "Using decoherence to prevent damage to the swap-out dump for the APS upgrade", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1494-1497. doi:10.18429/JACoW-IPAC2018-TUPMK004

[19] M. Borland, APS/ANL, private communication, June 2020.

[20] U. Wienands *et al.*, "A scheme for asynchronous operation of the APS-U booster synchrotron", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1823-1825. doi:10.18429/JACoW-IPAC2018-WEPAF007

[21] T. E. Fornek, "Advanced Photon Source Upgrade Project preliminary design report", USA, APSU-2.01-RPT-002, Sep. 2017. doi:10.2172/1423830

[22] H. Cease *et al.*, "APS Upgrade Status", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB125, this conference.

[23] Hilman, Inc., https://www.hilmanrollers.com/power-systems/traksporter-move-100-ton-heavy-machinery-without-forklift

[24] W. Cheng, APS/ANL, private communication, Oct. 2020.

[25] Dimtel, Inc., https://www.dimtel.com/products/index

[26] U. Wienands, APS/ANL, private communication, May 2020.

[27] H. Bui *et al.*, "Feedback controller development for the APS-MBA upgrade", in *Proc. 6th Int. Beam Instrumentation Conf. (IBIC'17)*, Grand Rapids, MI, USA, Aug. 2017, pp. 203-205. doi:10.18429/JACoW-IBIC2017-TUPCF04

[28] M. Kasa *et al.*, "Superconducting undulators for the Advanced Photon Source Upgrade", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1884-1886. doi:10.18429/JACoW-IPAC2019-TUPRB095