Argonne NATIONAL LABORATORY

Advanced Photon Source Upgrade

Advanced Photon Source Upgrade Project

Preliminary Design Report

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Chapter 1: Executive Summary

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Acronyms and Abbreviations

APS	Advanced Photon Source
APS-U	Advanced Photon Source Upgrade
Argonne	Argonne National Laboratory
BESAC	Basic Energy Sciences Advisory Committee
CD-n	DOE Critical Decision (n = 0, 1, 2, 3, 4)
DOE	U.S. Department of Energy
ID	Insertion Device
MBA	Multi-Bend Achromat
PDR	Preliminary Design Report
PME	Project Management Executive
SC	Office of Science
TPC	Total Project Cost
UChicago	UChicago Argonne LLC

1 Executive Summary

1-1 Introduction

The tremendous scientific impacts of U.S. world leadership in accelerator-based x-ray light source user facilities over the last 40 years were underscored in the July 2013 *Report of the Basic Energy Sciences Advisory Committee (BESAC) Subcommittee on Future X-ray Light Sources* [1]. The report noted that recent technological advances are driving widespread international interest in developing the next generation of synchrotron light sources, which will enable transformational advances across a wide range of scientific disciplines. Given the rapidly changing global landscape driven by worldwide investments in this technology, the report urged the U.S. Department of Energy (DOE) Office of Basic Energy Sciences to take swift action to establish a world-leading next-generation storage ring in the United States:

- "... The Office of Basic Energy Sciences should ensure that U.S. storage ring x-ray sources reclaim their world leadership position..."
- "The very large, diverse U.S. user population presently utilizing U.S. storage rings represents a major national resource for science and technology. It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments . . . in other countries. "
- "... developments include diffraction-limited storage rings with beamlines, optics and detectors compatible with the 10^2 - 10^3 increase in brightness. . . . "
- "... recommendation for a new U.S. light source facility should not be based on capacity issues, but rather on science-driven needs for new and unavailable photon characteristics that would allow users to carry out previously impossible grand challenge experiments. "

In response to the BESAC report recommendations, Argonne responded by revising the scope of the APS-U project to address the recommendations of the committee report, thus ensuring that APS-U maintains a world leadership position in hard x-ray storage ring capabilities. These changes were significant enough to warrant revisiting CD-1 and seeking a new approval prior to moving forward. On February 4, 2016, the Project Management Executive (PME) approved the revised CD-1 and the revised Acquisition Strategy.

In a December 21, 2015 letter, Director of the DOE Office of Science (SC), Dr. Cherry A. Murray, asked the BESAC to provide an update of its assessment of the proposed upgrades to x-ray scattering facilities (both free electron laser-based sources and ring-based sources) and to the Spallation Neutron Source using the same criteria that were used in prior studies - "the ability of a proposed upgrade or construction project to contribute to world leading science and the readiness of the upgrade or construction project to proceed to construction"- and the same rating system. The June 9, 2016 BESAC report stated, "It should be recognized that the international competition is extremely keen in the area of hard x-ray science. As such the APS-U upgrade is critical. The subcommittee considers the APS-U project as "absolutely central" and "ready to initiate construction, ... The APS-U Project is well on its way. "

Following the 2016 BESAC report, and recognizing the opportunity to reduce overall project risk by using the advanced technical design of certain components as a means to advance the project, CD-3B was approved October 6, 2016.

1-2 Project Capabilities

The APS Upgrade promises a revolutionary increase in brightness and coherent flux that will reach up to three orders of magnitude beyond current APS performance. This technological leap will create an unparalleled x-ray microscope that builds on the APS' exceptional capabilities to offer researchers a scientific tool that will yield breakthrough discoveries for decades to come.

The APS-U design has been motivated by a set of performance goals that deliver on the opportunities outlined by BESAC:

- Achieving an increase in brightness and coherent flux for hard x-rays (>20 keV) of at least two orders of magnitude beyond today's capability;
- Achieving single-bunch brightness for time-resolved experiments of one to two orders of magnitude beyond the APS' current capability;
- Enabling a set of experimental capabilities that ensures leadership in hard x-ray sciences;
- Achieving average flux that is twice as great as today's capability; and
- Exploiting the use of novel insertion devices.

The APS-U's MBA storage ring lattice, insertion devices and front ends, and experimental systems make it possible to meet these performance goals and provides the ability to focus all x-rays down to nanometer-size spots, enabling the transformational science that the BESAC report envisions.

The performance parameters of the APS-U storage ring and the existing APS are compared in Table 1.1. Two APS-U operational modes are described: The timing mode maximizes single-bunch brightness, and the brightness mode maximizes brightness performance. The various figures of merit for electron beam and photon beam performance parameters - brightness, coherent flux and pinhole flux - for the existing APS and APS-U are also shown. The APS-U will increase brightness and coherent flux by a factor of 540 at 20 keV, relative to present-day APS performance. The smaller size of the APS-U's electron beam and horizontal aperture also will enable use of novel insertion devices that could not previously be implemented in a storage ring light source. Ultimately, the science enabled by the APS-U will reflect the combined improvements in the storage ring and in the ID sources, front ends, and beamlines.

1-3 Project Scope

The APS-U's generational leap in performance is based on a preliminary design that includes:

- A new 6 GeV high-brightness MBA storage ring, in the existing tunnel, that reduces emittance by a factor of ~ 70 relative to today's APS storage ring;
- Doubling stored beam current to 200 mA;
- New insertion devices optimized for brightness and flux, including superconducting undulators on selected beamlines that produce significantly higher photon flux at higher energies;
- New and updated front ends with a common design for maximum flexibility;

Table 1.1. APS Upgrade Performance Parameters

	APS-U Timing Mode	APS-U Brightness Mode	APS Now	Units
Electron Beam Energy	6	6	7	GeV
Electron Beam Current	200	200	100	mA
Number of Bunches	48	324	24	
Effective Emittance	32	42	3113	pm
Emittance Ratio	1.0	0.1	0.013	
Horizontal Beam Size (rms)	12.6	14.5	274	μm
Horizontal Divergence (rms)	2.5	2.9	11.3	Rad
Vertical Beam Size (rms)	7.7	2.8	10.8	μm
Vertical Divergence (rms)	4.1	1.5	3.7	Rad
Stability of Beam Position/Angle	<10%	<10%	<10%	
Brightness - 20 keV(**)	154	325	0.6	10^{20} [a]
Pinhole Flux - 20 keV(**)	186	217	20.1	10^{13} [b]
Coherent Flux - 20 keV(**)	148	312	0.6	10^{11} ph/s
Single Bunch brightness - 20 keV	321	100	2.6	10^{18} [a]

[*a*] photons/sec/0.1%BW/mm^2/mrad^2
[*b*] photons/sec/0.1%BW in 0.5mm x 0.5mm pinhole @ 30 m
** Nominal energy based on choice of insertion device. Maximum value for an ID optimized for 20keV

- A suite of feature beamlines designed to fully exploit the high brightness source;
- Improvements to existing beamlines to take advantage of the vastly improved source performance.

The final APS-U project scope will include a refined set of the hardware, instrumentation, and capabilities described in this Preliminary Design Report (PDR), pending development of detailed final designs and accompanying cost estimates. The intent of this PDR is to document a complete and evolved preliminary design that meets the performance goals, including a complete set of feature and enhanced beamlines. The complete project baseline will be set at Critical Decision 2 (CD-2).

1-4 Cost and Schedule

The preliminary cost range of the APS Upgrade Project is $700M to $1,000M, with a current Total Project Cost (TPC) point estimate of $770M. The production phase, from CD-3 to ready for beam commissioning, is estimated at four years in a technically driven schedule. The cost and schedule estimate was developed using a bottom-up approach based upon expert analysis and opinion from engineers, accelerator physicists, scientists, and technicians who have recently constructed and/or fabricated systems similar to those systems and components at the APS. All cost estimates were escalated from FY 2016 base dollars to then-year dollars in the technically driven schedule. Currently the overall contingency is estimated to be 35% of the cost to go.

An initial APS-U Project summary schedule of expected milestones is shown in Table 1.2. The APS Upgrade will be executed with minimal impact on APS operations until the one-year removal and installation period, which in a technically limited schedule is currently anticipated to begin no earlier than 2022. Pending funding decisions for FY 2018 and beyond, the integrated schedule and these associated milestones will be revised as appropriate.

Table 1.2. APS Upgrade proposed Critical Decision milestones

Major Milestone Events	**Preliminary Schedule**
CD-0 (Approve Mission Need)	4/27/2010 (Actual)
CD-1 (Approve Alternative Selection and Cost Range)	2/04/2016 (Actual)
CD-3b (Approve Long-Lead Procurement)	10/06/2016 (Actual)
CD-2 (Approve Performance Baseline)	1st Qtr, FY 2019
CD-3 (Approve Start of Construction)	4th Qtr, FY 2019
CD-4 (Approve Start of Operations)	1st Qtr, FY 2026

1-5 Alternatives Analysis

The following alternatives were considered for meeting the scientific need for a next-generation light source as set out in the July 2013 BESAC report:

1. Take no action and rely on existing domestic and foreign light sources to meet the future scientific needs of U.S. scientists;
2. Equip other U.S. synchrotrons with MBA technology;
3. Design and build a new greenfield synchrotron light source facility somewhere in the United States; or
4. Upgrade the existing APS.

The advantages and disadvantages of each of these alternatives are considered below.

1. **Take no action and rely on existing domestic and foreign lightsources to meet the future scientific needs of U.S. scientists.** The science enabled by APS-U requires high-brightness x-rays with high coherence at high energy. No other existing or planned U.S. x-ray facilities can offer these combined capabilities. Absent a domestic fourth-generation hard x-ray synchrotron light source, U.S. scientists could attempt to utilize upgraded synchrotrons overseas, such as ESRF-II in France or the upgraded SPring-8 in Japan. However, U.S. researchers historically have had difficulty accessing beam time at these facilities, which are oversubscribed and in some cases give preferential access to local researchers. Access likely will be reduced even further as these facilities are upgraded and offer world-leading capabilities. Lack of beam time, coupled with the cost and inconvenience of foreign travel, would dramatically limit U.S. scientists'ability to conduct research at a world-leading facility. This alternative is not credible given the mission capability gap that would remain, and therefore does not satisfy the mission need. This alternative also does not satisfy the recommendations of the July 2013 BESAC report that stated "The Office of Basic Energy Sciences should ensure that U.S. storage ring sources reclaim their world leadership position."
2. **Equip other U.S. synchrotrons with MBA technology.** Although it would be possible to equip other U.S. synchrotrons with MBA technology, the upgraded facilities could not match APS-U's performance, particularly at high x-ray energies (>20 keV). Only an upgrade to the APS positions the United States for world leadership in terms of source capabilities, providing world-leading brightness at all energies above approximately 4 keV. There are no cost-effective alternative strategies to satisfy the mission need by upgrading other U.S. light sources.

3. **Design and build a new greenfield synchrotron light source facility somewhere in the United States.** Constructing a greenfield facility that would meet or exceed APS-U performance would cost substantially more than the APS Upgrade. The estimated cost of a 1.4 km greenfield fourth-generation synchrotron radiation source with equivalent beamlines is $2 - $2.5 billion, compared with the APS-U project cost of $700M to $1,000M (which leverages existing infrastructure, technical systems and beamlines valued at $1 billion to $1.5 billion.) Such a facility could deliver 2-3 times the brightness of an upgraded APS, but at substantially higher cost. APS-U also capitalizes on APS'existing wealth of beamline operations experience. Although concepts exist for even larger ultimate storage rings that would offer greater high-energy x-ray flux, the cost of constructing such an ultimate storage ring would of course be far greater than either APS-U or the 1.4 km greenfield facility described above. No science drivers have been identified that would justify the dramatically increased cost of constructing a new, very large storage ring.
4. **Upgrade the existing APS.** Upgrading the existing APS offers the most practical strategy to meet the mission need and the performance targets described in the BESAC report. As noted above, the APS provides a ready-made foundation that includes a substantial investment in existing facilities. The APS Upgrade improves beamline performance all around the ring, with great improvements for a large number of beamlines. The Upgrade also leverages the intellectual capital of the APS' expert staff and a vibrant, experienced user community. Today, APS hosts the largest user community of any DOE Office of Science User Facility, and we anticipate serving a user community beyond that size in the APS Upgrade era.

The APS-U represents a unique opportunity to achieve global leadership in hard x-ray science capabilities. Without APS-U, however, the orders-of-magnitude performance gap between United States light sources and their competitors overseas will be insurmountable. The full description is in the APS-U Project Acquisition Strategy. [2]

1-6 Acquisition Strategy

The acquisition strategy relies on UChicago Argonne, LLC, the DOE M&O contractor for Argonne National Laboratory, to directly manage the APS-U project acquisition. The design, fabrication, assembly, installation, testing, and commissioning of technical components in the APS-U project will be performed by Argonne and APS scientific and technical staff, along with other national laboratory and industrial partners. This is described in greater detail in the APS-U Project Acquisition Strategy. [2]

References

[1] U.S. Department of Energy. *Report of the BESAC Subcommittee on Future X-ray Light Sources*. U.S. Government, Washington, DC, 2013.

[2] Argonne National Laboratory. APS-U Acquisition Strategy, APSU-1-PLN-002-00, 2016.