Argonne NATIONAL LABORATORY

Advanced Photon Source Upgrade

Advanced Photon Source Upgrade Project

Final Design Report

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Chapter 1: Executive Summary and Project Overview

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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
BOE	Basis of Estimate
CD-n	DOE Critical Decision (n = 0, 1, 2, 3, 4)
DOE	U.S. Department of Energy
ID	Insertion Device
MBA	Multi-Bend Achromat
PME	Project Management Executive
SC	Office of Science
TPC	Total Project Cost
WBS	Work Breakdown Structure

1 Executive Summary and Project Overview

1-1 Introduction

The Advanced Photon Source (APS) at Argonne National Laboratory is a world leading synchrotron source of high energy x-rays, one of five light sources operated under the stewardship of the Department of Energy Office of Science / Office of Basic Energy Science. The APS enables experimental research of thousands of laboratory, university and industrial users each year conducting fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and US national interests in energy, environment, and national security. The APS has operated in this manner for over 20 years.

The research disciplines that light sources support—condensed matter and materials physics, chemistry, geosciences, and aspects of biosciences—touch virtually every important aspect of energy resources, production, conversion, transmission, storage, efficiency, and waste mitigation, providing a knowledge base for achieving a secure and sustainable energy future. The 2018 Basic Energy Sciences Advisory Committee (BESAC) report, "A Remarkable Return on Investment in Fundamental Research", provides key examples of major technological, commercial, and national security impacts directly traceable to BES-supported basic research.

With advances in storage ring design and technologies, the opportunity exists to dramatically increase the performance of the APS facility. The Advanced Photon Source Upgrade (APS-U) project will provide scientists with a storage ring x-ray source possessing world-leading transverse coherence and extreme brightness which will be a unique asset in the U.S. portfolio of scientific user facilities. By building capability on the existing APS facility the APS-U will cost significantly less than a green-field implementation. The magnetic lattice of the APS storage ring will be upgraded to a multi-bend achromat configuration to provide 100-1000 times increased brightness and coherent flux for multi-keV x-rays. The APS-U is a critical and cost-effective next step in the photon science strategy that will keep the U.S. at the forefront of scientific research.

Argonne has developed the scope of the APS-U project to ensure that APS-U maintains a world leadership position in hard x-ray storage ring capabilities. On February 4, 2016, the Project Management Executive (PME) approved the revised CD-1 and the revised Acquisition Strategy.

Later in 2016, in response to the Director of the DOE Office of Science (SC), Dr. Cherry A. Murray, BESAC provided 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 up- grade 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. After further design and development, CD-2 for the APS-U was approved December 13, 2018. At the time of this report, the majority of the CD-3B authority has been obligated, the overall design is well advanced, and the project is seeking full CD-3 approval.

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 x-ray microscope that builds on the current APS's 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 will enable the user community to investigate new regimes of science:

- 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 Multi-bend achromat (MBA) storage ring lattice, insertion devices, 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, together with on-axis "swap-out" injection, will also enable use of novel small-aperture 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 insertion device (ID) sources, front ends, and beamlines.

1-3 Project Scope

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

- new storage ring incorporating a 7-bend Achromat lattice, augmented with longitudinal gra-

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)	12.9	14.7	280	μm
Horizontal Divergence (rms)	2.5	2.8	11.6	μrad
Vertical Beam Size (rms)	8.8	3.2	10.0	μm
Vertical Divergence (rms)	3.7	1.3	3.4	μrad
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 *times* 0.5mm pinhole @ 30 m
** Nominal energy based on choice of insertion device. Maximum value for an ID optimized for 20keV

dient dipoles and reverse-bend magnets to further reduce emittance, in the existing tunnel,
- new insertion devices optimized for brightness and flux, superconducting undulators on selected beamlines,
- new or upgraded front ends with a common design for maximum flexibility and minimized operational cost, and
- a suite of new beamlines and substantial refurbishment of other existing beamlines, along with new optics and detectors that will enable most beamlines to take advantage of the improved accelerator performance.

To successfully deliver on these goals, the Project must deliver Key Performance Parameters as defined in Table 1.2. The threshold values are the minimum required, while the objective values define the technical goals of the project. The final APS-U project scope includes descriptions of the hardware, instrumentation, and capabilities required to deliver on those goals. The intent of this FDR is to document the functional requirements, interfaces, and engineering specifications for the hardware that will realize the project goals. This report accomplishes this by giving an overview of the scope of each system, followed by a table of more detailed documents which provide more detail on sub systems and components. In cases where the design is not yet fully complete, this is acknowledged and risks and mitigations to the project overall have been noted. It is expected that this report is a living document, with timely updates as further documentation is developed.

1-4 Work Breakdown Structure

All required scope for completion of the APS-U project is included in the Work Breakdown Structure (WBS), shown to level 4 in Figure 1.1, beginning with the first year of funding in FY 2010 and continuing through project completion in FY 2026 (CD-4). The early years of funding, FY 2010 to FY 2013, was allocated to pre-MBA scope, labeled U1. Funding for the MBA scope began in

Table 1.2. APS-U Key Performance Parameter

Key Performance Parameter	**Thresholds (Performance Deliverable)**	**Objectives**
Storage Ring Energy	> 5.7 GeV, with systems installed for 6 GeV operation	6 GeV
Beam Current	≥ 25 mA in top-up injection mode with systems installed for 200 mA operation	200 mA in top-up injection mode
Horizontal Emittance	< 130 pm-rad at 25 mA	≤ 42 pm-rad at 200 mA
Brightness @ 20 keV[1]	$> 1 \times 10^{20}$	$> 1 \times 10^{22}$
Brightness @ 60 keV[1]	$> 1 \times 10^{19}$	$> 1 \times 10^{21}$
New APS-U Beamlines Transitioned to Operations	7	≥ 9

FY 2014 and is incorporated in U2. Development of the WBS and WBS dictionary is consistent with the requirements set forth in DOE Order 413.3B [1], *Program and Project Management for the Acquisition of Capital Assets and ANSI/748c, Earned Value Management Systems.*

The organization of the WBS reflects a logical breakdown of the work by major component and system. Each component or system contains progressively lower levels to further define the sub-elements down to the lowest WBS element. Each element of the WBS captures all costs, resources, and activities necessary to complete that particular scope of work with an associated schedule, and the WBS dictionary describes the detailed activities and elements required to design, fabricate, construct, install, and transition to operations the APS-U.

The second- and third-level WBS elements are defined as:

- U.U1 - Includes all actual costs incurred to design, procure, fabricate, install and test aspects of the APS-Upgrade Project through FY 2013, prior to inclusion of the MBA storage ring.
- U.U2 - Includes all phases of design, procurement, fabrication, installation and testing of the MBA storage ring, associated front ends and insertion devices, and new, upgraded and improved beamlines.
- U.U2.01 - Project Management, Planning and Administration: Project Office administrative and management activities that cross the entire project, such as management, regulatory compliance, quality assurance, safety, project controls, etc.
- U.U2.02 - Conceptual Design and Development: Conceptual Design and R&D activities necessary to support delivery of project objectives.
- U.U2.03 - Accelerator: Includes management specific to accelerator scope, and all phases of design, procurement, installation, and testing of the accelerator upgrades.
- U.U2.04 - Experimental Facilities: Includes management specific to experimental facilities scope, and all phases of design, procurement, installation, and testing of new beamlines and upgrades to beamlines.
- U.U2.05 - Front Ends and Insertion Devices: Includes management specific to front end and

insertion devices scope, and all phases of design, procurement, installation, and testing of front ends and insertion devices for beamlines.

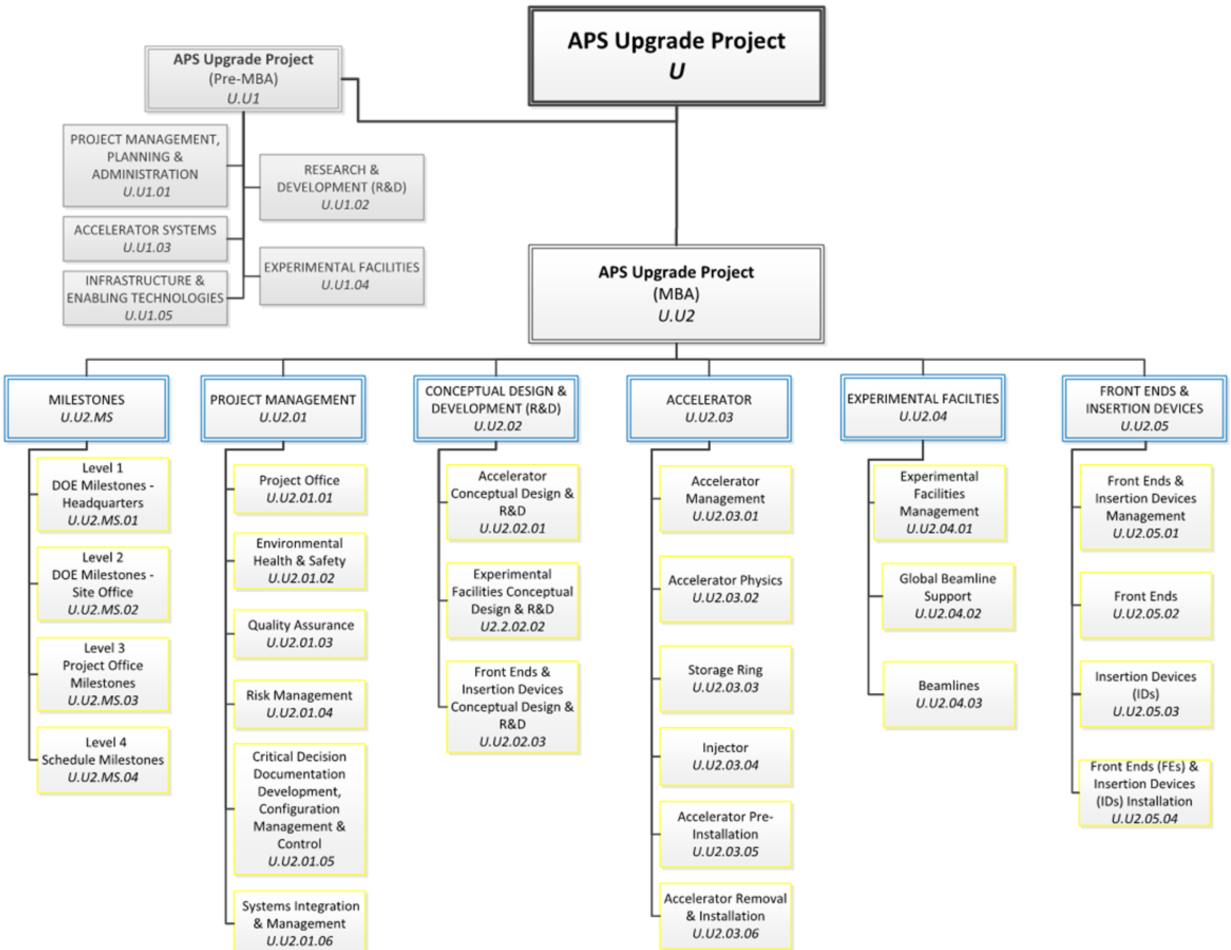

Figure 1.1. Organization of the WBS

1-5 Cost and Schedule

The Total Project Cost (TPC) of the APS Upgrade Project is \$815M. The cost estimate and funding profile are shown in Tables 1.3 and 1.4. The production phase, from CD-3 to ready for beam commissioning, is estimated at four years in a technically driven schedule. Currently the overall contingency is estimated to be 30% of the cost to go.

An initial APS-U Project summary schedule of expected milestones is shown in Table 1.5 and 1.6. 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 June 2022.

Table 1.3. Cost Summary for the APS Upgrade at CD-2.

WBS Element	WBS Description	Total Estimated Cost ($M)ext
	Total EstimatedCost (TEC)	
U1	**APS Upgrade Project – previous scope costs**	**35.4**
U2	**APS Upgrade Project – Multi Bend Achromat**	**610.7**
U2.01	Project Management	57.9
U2.02	Conceptual Design and Development	49.4
U2.03	Accelerator Systems	250.0
U2.04	Experimental Facilities	186.2
U2.05	Front Ends and Insertion Devices	67.2
	Contingency(TEC)	**150.4**
	Sub-total (TEC)	**796.5**
	Other Project Cost (OPC)	
U1	**APS Upgrade Project – previous scope OPC**	**8.5**
U2	**APS Upgrade Project – MBA OPC**	**7.1**
	Contingency (OPC)	**2.9**
	Sub-total (OPC)	**18.5**
	Total Project Cost	**815.0**

Table 1.4. Funding Profile

	Funding (BA) in Millions of Dollars (Then-year Dollars)											
	All Prior Years	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	Total
OPC	8.5									5.0	5.0	18.5
TEC	40.0	20.0	20.0	20.0	42.5	93.0	130.0	150.0	159.8	121.2		796.5
Total	48.5	20.0	20.0	20.0	42.5	93.0	130.0	150.0	159.8	126.2	5.0	815.0

Table 1.5. APS Upgrade 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)	12/13/2018 (Actual)
CD-3 (Approve Start of Construction)	4th Qtr, FY 2019
CD-4 (Approve Start of Operations)	2nd Qtr, FY 2026

Table 1.6. APS Upgrade Production Level 2 Milestones

	Production Level 2 Milestones)	
Activity ID	**Activity Name**	**Schedule Date**
MS-L2-5093	Beamline Selection Process Started	Jan-16(A)
MS-L2-2095	DMM R&D Magnets Ready for Int. Systems R&D	Mar-17(A)
MS-L2-4105	Beamline Insertion Device Selection Complete	Jun-17(A)
MS-L2-2107	FODO Magnets Ready for Integrated System R&D	Jul-18(A)
MS-L2-0021	Magnets Q1-Q6 Contract awarded	Oct-18(A)
MS-L2-2300	28-ID Front End Tested with Beam	Nov-18(A)
MS-L2-0111	Accelerator Component Development Complete	Apr-19
MS-L2-4010	Beneficial Occupancy of FOE for 28-ID-A	Jul-19
MS-L2-0061	Magnets M1-M2 contract awarded	Feb-20
MS-L2-5053	ID Vacuum Chamber Final Design Complete	Apr-20
MS-L2-0031	Magnets Q1-Q6 33% received	May-20
MS-L2-0041	Magnets Q1-Q6 67% received	Dec-20
MS-L2-5082	ID Vacuum Chamber Procurement Complete	Feb-21
MS-L2-0071	Magnets M1-M2 33% received	Apr-21
MS-L2-0051	Magnets Q1-Q6 100% received	Aug-21
MS-L2-0101	Unipolar Power Supplies 50% received	Oct-21
MS-L2-0081	Magnets M1-M2 67% received	Oct-21
MS-L2-1050	Shutdown Readiness Review Complete	Feb-22
MS-L2-3060	Receive All Unipolar Power Supply Controllers Components	Mar-22
MS-L2-0091	Magnets M1-M2 100% received	May-22
MS-L2-3095	Magnets M1 & M2 Complete	Jun-22
MS-L2-5085	Insertion Devices Procurement Complete	Jun-22
MS-L2-3070	Ass'y / Test - Injection / Extraction Systems Complete	Jul-22
MS-L2-3050	Accelerator Procurement Complete	Jul-22
	Installation Level 2 Milestones)	
Activity ID	**Activity Name**	**Schedule Date**
MS-L2-1030	START: Storage Ring & Mezzanine Downtime	Feb-23
MS-L2-1040	Storage Ring and Mezzanine Removal Completed	Apr-23
MS-L2-1080	Storage Ring Testing without Beam Completed	Sep-23
MS-L2-1090	Storage Ring Testing with Beam Completed	Jan-24
MS-L2-2000	Beamline Commissioning Completed	Jun-24

1-6 Risk Assessment and Management

A Risk Management Plan (RMP) for the APS-U project establishes guidelines for risk management and analysis, defines and describes the risk registry, describes the roles and responsibilities of project personnel in performing the risk management functions, and defines the reporting and tracking requirements for risk-related information for updates to the risk registry.

At baseline, a basis of estimates (BOE) and risk-based contingency of 30% across the project as a whole exists. The BOE contingency needs are identified in subsections below; at this stage of the project, the difference between the BOE contingency needs and total available contingency are deemed appropriate to mitigate the risks identified. The major risks currently identified and the mitigations are identified below.

1.6.1 Civil Construction Risks. A categorical exclusion was approved by the DOE NEPA compliance officer on March 7, 2017. The civil construction aspects of the APS-U are small, limited to building extensions to house two long beamlines expected to cost on order $17M. Overall risk to the project is therefore small.

1.6.2 Accelerator Risks. Risks for the accelerator have been identified in the APS-U Risk Registry. In summary, the extended prototype and development program executed over the past years has retired the majority of the technical risks, the major remaining risks are vendor/supplier management, the integration of components into the new storage ring, and finalization of interfaces with the existing APS injector, beam stability, and installation risks. To mitigate the risks, an extensive R&D effort has been completed which established the technical capabilities, produced sector mock-ups, and demonstrated handling and alignment strategies. This development work has fed back into world leading simulations, providing overall confidence in the ability to successfully execute the project. At the time of this writing, remaining technical challenges include the assembly and test of the injection septum magnet, ongoing at a partner laboratory with tests expected in 2020; final determination of local radiation shielding upgrades; completion of a superconducting undulator development program with industry in 2020; beam tests of the RF BPM design and the whole beam dump material, both of which will be complete in 2019; and implementation of a new injection timing and synchronization system to be tested on the existing ring prior to the installation dark time.

8.1.3 Beamline and Other Technical Equipment Risks. The insertion device, front end, and beamline risks are low for this project. The APS-U builds on the extensive experience of the APS in the design, planning, and construction of these components. For insertion devices and front ends, the APS-U directly uses designs and procurement information from recent experience both at APS and other facilities, such as NSLS-II. The major uncertainty is in the scaling from component quantities of one or two to those an order of magnitude more. For the beamlines, an extensive set of scientific and technical reviews has been undertaken with the User community to define the scientific goals and beamline capabilities, and the technologies necessary to execute them. The major risk in the beamlines is in the limited number of vendors for given technical components, and the potential pile up of work during the downtime. Both of these are being mitigated through early procurement of components, and scheduling of work in advance of the shutdown wherever possible.

8.1.4 Cost Risks. In the development of the risk registry, the project has identified cost risks associated with vendor specialization, foreign vendors, and delays in funding. A component of the cost risk will be the time between the collection of technical quotes from vendors and the actual execution of the quote due to past funding profile uncertainties, however to date contract experience has been overall favorable.

8.1.5. Schedule Risks. The largest schedule risks identified at this stage of the APS-U are the removal, installation, and commissioning periods which directly affect the scientific productivity of the community, and vendor delivery risks such as those seen at NSLS-II and other projects. The APS-U has worked to develop a detailed installation schedule, both to better understand the logistics required in the installation period and to understand design changes that make installation easier. With respect to the overall schedule, there are currently 28 months of schedule float to CD-4.

8.1.6. Project Funding Risks. There are significant risks associated with continuing resolutions (CRs) and the overall project funding profile. With respect to CRs, the APS-U currently hold 3 months of carryover each year to mitigate budget risk. As a baselined line item construction project, some of the funding uncertainty has been removed, but the project is always in close contact with the Program Office.

8.1.7. Interface and Integration Risks. There are moderate risks for the APS-U project because the project is being executed alongside and within the on-going APS operations program. Both the APS-U and Operations portions of the facility portfolio must achieve their respective goals for the renewed facility to be ready to thrive in 2025. To manage this, the APS-U works with the PSC Operations Directorate to define interfaces across the facility, and manages an integrated staffing plan for the Directorate as a whole. The Project and Operations will work co-operatively and constructively to deliver the best facility possible at the time of project completion.

References

[1] U.S. Department of Energy. *DOE O 413.3B*. Number Program and Project Management for the Acquisition of Capital Assets. Washington, DC, 2010.