The Advanced Photon Source Strategic Plan

Enabling frontier science in the national interest

October 1, 2019

The Advanced Photon Source is a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

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1. Mission Statement

The mission of the U.S. Department of Energy Office of Science-Basic Energy Science's (DOE-SC-BES's) Advanced Photon Source (APS) at Argonne National Laboratory is to enable internationally leading research and development by operating an outstanding hard x-ray synchrotron radiation user facility accessible to a broad and diverse spectrum of researchers, and to support the scientific and technical directions of the U.S. Department of Energy, including development of new light source technologies, while maintaining a safe, diverse, and environmentally responsible workplace.

2. Vision Statement

Our vision is to operate and develop world-leading hard x-ray user facilities and advance the forefront of x-ray science, transforming exploration of energy, biological and other functional materials, chemistries and complex systems.

3. Executive Summary

The APS at Argonne National Laboratory is a U.S. DOE-SC-BES scientific user facility. The core mission of the APS is to serve a multi-faceted scientific community by providing high-energy x-ray science tools and techniques that allow users to address the most important basic and applied research challenges facing our nation, while maintaining a safe, diverse, and environmentally responsible workplace.

The APS is optimized to provide this nation's highest-brightness hard x-rays (i.e., photon energies above 20 keV). This makes it ideally suited to explore time-dependent structure; elemental distribution; and chemical, magnetic, and electronic states under *in situ* or *operando* environments for a vast array of forefront problems in materials science and condensed matter physics, chemistry, and the life and environmental sciences.

The APS became operational in 1996, and as a mature facility today, the APS will continue to improve beamline performance to take full advantage of its existing source properties, as well as deliver new capabilities required by the large and scientifically diverse APS user community. This includes improving specific beamlines and end stations and continued optimization of the APS beamline portfolio, while maintaining the outstanding reliability and availability of the APS accelerator and storage ring systems. Additionally, research challenges that require vastly brighter hard x-rays or higher coherent flux than the APS currently produces are now within reach because of revolutionary new storage ring lattice designs that dramatically reduce the stored electron beam emittance. The APS Upgrade Project (APS-U) will perform a major upgrade of the APS, implementing a multi-bend achromat (MBA) storage ring magnetic lattice that will increase APS x-ray beam brightness and coherent flux by 100 to 1000 times over current values, depending on photon energy, and building new beamlines to take full advantage of the new source. Combining the penetrating power of the hard x-rays produced by the upgraded APS with the time structure of the electron bunches in the APS storage ring will result in an x-ray light source ideally suited for meeting the global science and energy challenges of the 21st century by providing the time-resolved, three-dimensional microscopy, imaging, scattering, and spectroscopy methods necessary to revolutionize our understanding of hierarchical architectures and beyond-equilibrium matter, and of the critical roles of heterogeneity, interfaces, and disorder.

The APS-U Project received Critical Decision (CD)-1 approval in February 2016, CD-3B approval in October 2016, CD-2 approval in December 2018, and CD-3 approval in July 2019, thus setting the Project firmly on the path of construction activities.

"The Advanced Photon Source Strategic Plan" evolved from the March 2018 "Advanced Photon Source Five-Year Facility Plan." This current plan incorporates changes made since the third revision of the previous plan was published (October 1, 2018).

This plan charts the path over the next five years for the improvements and R&D that will maintain the APS position as a world-leading hard x-ray synchrotron source while simultaneously preparing for the APS-U. The x-ray science strategy is focused on developing and improving high-energy-, high-brightness-, and high-coherence-driven beamlines and techniques, as well as capitalizing on unique timing and high-speed imaging capabilities. Method and technique developments for x-ray science are described holistically where beamline instrumentation is viewed as a tightly integrated unit, spanning from source to optics to sample to detectors, all held together by effective and smart controls, and seamlessly coupled with analyses and visualization.

Accelerator-operations planning will meet the current and future capabilities expected of a world-leading light source while maximizing efficiencies and delivering high beam availability to users. It is currently assumed that the present APS storage ring will pause operation approximately in 2022 and be replaced by the MBA lattice. Thus, this document aligns replacement and upgrade plans for accelerator systems to maintain a very high level of APS performance and reliability, with R&D plans that take into account the long-term transition to an MBA lattice source. This is accomplished in three main areas: accelerator reliability, accelerator improvement, and accelerator R&D to advance new concepts and next-generation light sources.

This plan also describes engineering, maintenance services, and computing infrastructure that directly support and enable world-class performance of the APS accelerator and beamline complex, while ensuring a safe environment for APS users and personnel.

Finally, this plan briefly describes the development of the Interface Portfolio that captures and prioritizes investments in general maintenance and obsolescence projects, in integration with the APS-U, and in the set of projects that will ensure mature operation and high reliability of the accelerator complex after the implementation of the APS-U. In addition, the plan describes improvements for infrastructure and general operations, human capital development, and user processes and scientific access including outreach and training. A critical focus for the coming years is preparing the user community for the approximately one-year dark time associated with the APS-U Project, which is currently planned to span FY22 and FY23.

4. Introduction

The APS is one of five x-ray light sources that are operated as national user facilities by the DOE-SC-BES (there are four storage rings: the APS, the Advanced Light Source [ALS] at Lawrence Berkeley National Laboratory, the Stanford Synchrotron Radiation Lightsource [SSRL] at the SLAC National Accelerator Laboratory, and the National Synchrotron Light Source-II [NSLS-II] at Brookhaven National Laboratory; and one free-electron laser: the Linac Coherent Light Source at the SLAC National Accelerator Laboratory).

Of the four storage rings, the APS operates at the highest electron energy (7 GeV, 100 mA) and has been optimized to be the source of this nation's highest-brightness storage ring-generated hard x-rays (i.e., photon energies above 20 keV). High-brightness hard x-rays can penetrate deeply into materials and can be concentrated efficiently in a small spot. This combination enables *in situ*, real-time studies of internal structures and chemical states in actual environments and under relevant operating conditions.

The APS is also the largest of the DOE light source facilities in the size of its user community. The APS facility comprises an accelerator complex and storage ring, beamlines, and supporting laboratory and office space. There are currently 68 operating x-ray beamlines; of these, 43 are operated directly by the

APS (Appendix 1) including operation of the National Institute of General Medical Sciences and National Cancer Institute (GM/CA-XSD) beamlines funded as a national facility for structural biology by the National Institute of General Medical Sciences and National Cancer Institute of the National Institutes of Health; and the HPCAT-XSD beamlines, which are funded by the National Nuclear Security Administration. As of June 2019, the APS has also assumed operational responsibility for the Structural Biology Center (SBC-XSD) beamlines, which are funded by the DOE Biological and Environmental Research program in the Office of Science.

The Sector 26 Hard X-ray Nanoprobe is operated jointly by the APS and the adjacent BES scientific user facility, Argonne's Center for Nanoscale Materials (CNM). Finally, beamline 6-BM-A,B is operated jointly by the APS and the National Science Foundation-funded Consortium for Materials Properties Research in Earth Sciences.

The 23 beamlines outside of this portfolio of 43 APS and 2 jointly-operated beamlines are operated by the collaborative access teams (CATs). The APS has by far the largest participation of operational partners of any U.S. light source. These very diverse collaborations of industry and academia operate according to a number of different models and, to the benefit of the user community, bring in substantial non-BES funding. The APS provides photons and some minimal direct operations support, with recovery of certain costs, in return for each CAT awarding a fraction of its beam time to general users. This fraction is a minimum of 25%, although several CAT-operated beamlines now serve as national resources and award 100% of their time to general users. The specialized nature of CAT beamlines and end-station instrumentation, including detectors and optics, also allow the APS user community to provide the broadest reach and to build world-leading capabilities in key fields such as high-pressure research, dynamic compression science, and the biological and life sciences.

Access to the APS is obtained via a scientific peer review process, and access is heavily over-subscribed. In FY18, the APS supported 5704 unique users (on-site and remote/mail-in) from 50 U.S. states, the District of Columbia, and 33 nations, who conducted research that spanned the full range of fundamental and applied sciences across fields including materials science, biological and life sciences, geosciences, planetary science, environmental science, engineering, chemistry, and physics. Users of this facility come from academia, industry, and government institutions.

As the APS user program has grown, so has the facility's publication output grown, with 2365 papers recorded in our publications database in calendar year (CY) 2016, 2227 papers in CY 2017, and 2233 papers in CY 2018 reported at the time of this writing (September 2019). Of those, 1989 (CY16), 1966 (CY17) and 2033 (CY18) are peer-reviewed journal articles, with approximately 16% of those in DOE-defined high-impact journals (*Advanced Materials, Angewandte Chemie International Edition, Applied Physics Letters, EMBO Journal, Cell, Environmental Science and Technology, Journal of the American Chemical Society, Nano Letters, Nature Chemical Biology, Nature Chemistry, Nature Geoscience, Nature Materials, Nature Nanotechnology, Nature Photonics, Nature Physics, Nature Structural and Molecular Biology, Nature*, *Physical Review Letters, Proceedings of the National Academy of Sciences of the United States of America,* and *Science*). In addition, macromolecular crystallographers utilizing APS x-ray beams place more protein structures in the Protein Data Bank than do researchers at any other light source in the world.

The APS produced first x-ray light in 1995 and became operational in 1996. Since then, a number of major advances have occurred in accelerator, storage ring, and beamline technologies and techniques. Combined, these advances have dramatically altered the landscape for x-ray science. In particular, research challenges that require vastly brighter hard x-rays or a higher coherent flux than the APS currently produces are now within reach because of new storage ring lattice designs that dramatically reduce the stored electron beam emittance. Therefore, the APS has developed plans to install an MBA magnetic lattice into the existing storage ring tunnel that will increase x-ray beam brightness and coherent flux by approximately 130 times at 20 keV over current values. This upgrade of the storage ring is a cost-effective approach to a "fourth-generation" storage ring as it will reuse much of the existing accelerator and beamline infrastructure.

While the detailed science case and technical design for this upgrade are presented in other documents, the brightness and coherence increase from the APS-U in the hard x-ray region of the spectrum will revolutionize imaging, microscopy and nanobeam science, high-energy methods, and high-wavenumber scattering techniques. The penetrating x-ray probes produced by the upgraded APS will transform *in situ* real-time studies of internal structure during synthesis and of materials functions in actual environments and under relevant operating conditions across a hierarchy of length scales from the atomic to the macroscopic. They will also enable time-resolved studies of dynamics over a wide range of time scales from many seconds to less than a nanosecond, allowing observation of the relationships between structure and function. This upgrade will help maintain the APS world-leading position in the hard x-ray community for decades to come.

With a targeted implementation of the APS-U years in the future (2023), beamline performance at the APS must continue to increase in order to take full advantage of the existing source in the interim. Additionally, the APS will continue to deliver new capabilities to the user community while meeting the scientific needs embodied in our nation's future challenges and the DOE mission—which are inextricably entwined—as well as providing the highest level of support to APS users. This includes improvements to specific beamlines and end stations, as well as continued optimization of the APS beamline portfolio, while maintaining the excellent reliability and availability of the APS accelerator and storage ring systems.

"The Advanced Photon Source Strategic Plan" is driven by the above responsibilities. The document comprises an outline of improvements and R&D to be undertaken by APS Operations during the next five years, employing a two-pronged approach: keeping the APS a world-leading hard x-ray synchrotron source while simultaneously preparing for the upgrade.

To achieve these goals, the APS will invest in improving aging accelerator and beamline infrastructure while developing innovative capabilities and continuing to drive efficient mission execution. By creating a synergy between today's improvements and tomorrow's needs, the APS will enable operational capabilities for the next five years and continue to grow a scalable, forefront science program that will smoothly transition to take advantage of an upgraded accelerator source.

To summarize, goals described in this strategic plan are comprehensive and have gone through a full facility-wide strategic prioritization process for resource allocation. However, for beamline investments, prioritization is a continuing process based on user needs and trends, and will necessarily involve ongoing, deep engagement with the APS user community and other stakeholders.

Finally, it is also important to note that the APS Divisions maintain more detailed strategic plans that are updated annually. See:

APS Engineering Support (AES) Strategic Plans

Accelerator Systems Division (ASD) Strategic Plan

X-ray Science Division Strategic Plans

5. Strategic Focus

5.1. X-ray Operations and Improvements, and Research and Development on X-ray Techniques, Optics, Detectors, and Data Sciences

The APS operates a suite of cutting-edge beamlines that address problems across a wide range of disciplines relevant to the needs of the U.S. scientific community. Modern scientific and technological challenges not only require the ability to gain insight about the properties of matter, but must do so with spatial resolution down to a few nanometers, temporal resolutions reaching nanoseconds, and under *operando* or extreme conditions. To address this need, the APS long-term strategy includes building a new, low-emittance MBA x-ray source; developing beamlines and the ancillary capabilities needed to fully exploit this source; and fostering a broad-based and vibrant hard x-ray science community that provides international leadership in science enabled by this source.

Targeted research and development activities by APS staff lay the foundation for taking full advantage of the upgraded source, as well as delivering new capabilities that make more effective use of the existing facility. A key component of this strategy is leveraging the high-performance computing capabilities and expertise both within Argonne and across the DOE complex for comprehensive and timely analysis of large, complex, and multi-modal data sets. Furthermore, Argonne capabilities in nanofabrication, engineering, and computing play a central role in the development of hardware and software essential to fully utilizing the APS-U source characteristics, including high-stability/high-precision instrumentation, state-of-the art x-ray optics (e.g., wave-front-preserving optics, zone plates, and x-ray micro-mirror microelectromechanical systems devices), advanced energy-resolving detectors, and methods in data management and computational x-ray science. The APS staff play a quintessential role in this effort by continuing to advance x-ray instrumentation, algorithms, methods, and techniques.

Keeping the APS at the forefront of scientific research requires the continued evolution of the beamline portfolio; the hiring, development, and retention of talented scientists, engineers, and technical professionals; and expansion of the depth and breadth of our user community. Investments must be made in beamlines, staff, and R&D to continue improving and expanding APS capabilities, and to preserve APS leadership positions in the hard x-ray sciences. These directions and investments are aligned with the four specific priority areas for the APS given below.

5.1.1. Priorities

Brightness- and Coherence-Driven Beamlines and Techniques

The APS source after the MBA upgrade will provide world-leading beam coherence and brightness at high energies (> 20 keV). These beam characteristics will greatly enhance experiments in the areas of x-ray photon correlation spectroscopy (XPCS), imaging, and microscopy (including coherent diffractive imaging), which will make possible completely new measurements not feasible today (see, e.g., the "Early Science at the Upgraded APS" document,). For example, the increased coherence at higher energies delivered by the APS-U will provide a 4- to-6-order-of-magnitude increase in the time resolution of XPCS, revolutionizing the ability to probe the dynamics of systems in attenuating sample environments, such as electrochemical cells with applications to energy storage. With lens-less imaging approaches it will be possible to achieve high resolution in a large three-dimensional (3-D) field of view (e.g., 10-nm, 3-D resolution in a 1-mm^3 volume). Likewise, the high-intensity, focused APS x-ray beams will provide the ability to study nanometer-size voxels with chemical specificity in complex chemical environments. Beamline improvements, staffing, and related technical developments that enhance these areas will be given the highest priority. The APS will work to develop, establish, and refine methods and techniques that take full advantage of the greatly increased brilliance and coherence that an upgraded APS will provide. For example, fast XPCS is being advanced using pixel-array detectors developed in collaboration with commercial vendors. These detectors provide time sensitivity far shorter than the circulation time of an electron bunch in the storage ring (see Figure 1).

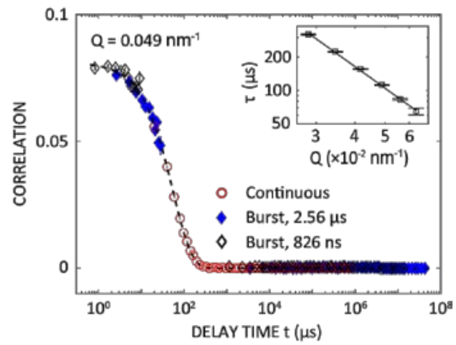


Figure 1. XPCS autocorrelation function measured from silica nanoparticles demonstration sub-microsecond delay time resolution. Figure courtesy of A. Sandy (Argonne).

High-Energy Beamlines and Techniques

The APS is unique among current U.S. light sources in providing highly brilliant x-ray beams at high energies (>20 keV) enabling deep penetration into matter, complex sample environments for *in situ* and *operando* experiments, minimizing radiation damage, and providing precise structural information. Developments at the APS in superconducting undulator technology, high-energy focusing optics, and new detection schemes have further pushed the spatial and temporal resolution limits achievable with high-energy x-ray methods. The APS staff have exploited these unique high-energy strengths to develop a number of world-leading x-ray characterization tools for addressing problems in materials science, chemistry, extreme conditions, etc. After the upgrade, the APS will have significantly increased degrees of coherence and enhanced flux densities at high energies. This will make it feasible to extend many coherence-based x-ray techniques much further into the high-energy regime, particularly in areas such as imaging, microscopy, XPCS,

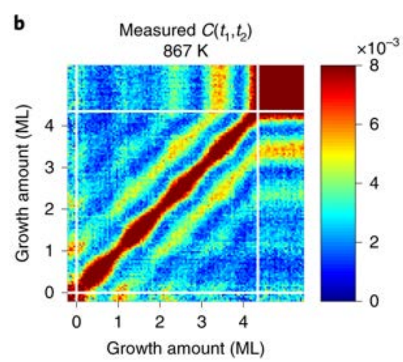


Figure 2. Two-time correlation functions measured from two-dimension islands before, during, and after growth using a pink x-ray beam at 25 keV at the 12-ID-D beamline. Such work will increasingly be enabled by the high coherent flux at higher x-ray energies provided by the APS-U. G. Ju *et al*., Nat. Phys. **15**, 589 (2019). ©2019 Springer Nature Publishing AG

surface diffraction, etc. Staff of the APS and their Argonne colleagues are developing the experimental and analysis tools that are required to apply such coherent methods at higher energies for applications such as strain-mapping of individual grains within polycrystalline matrix using coherent diffraction imaging or understanding atomic mobility during layer-by-layer growth using crystal truncation rod XPCS (see Figure 2). The APS will continue to emphasize and invest in expanding such novel high-energy methods.

Timing and High-Speed Imaging Capabilities

The current APS bunch pattern, with a routine operating mode employing a large intra-bunch separation, is unique among third-generation synchrotron sources. This led to the development of a number of ultra-fast x-ray scattering and spectroscopy capabilities at the APS for probing dynamic phenomena on 100-ps to microsecond time scales. Further, high-speed imaging of single-event processes such as dynamic compression or additive manufacturing (see Figure 3), has gained increasing user interest. To retain the existing APS strength in timing measurements, the upgraded source will support a 48-bunch pattern with a similar large, intra-bunch spacing. The ability to focus the full x-ray beam flux onto sub-micron spots will enable new types of time-dependent studies in more-complex environments and on nanoscale heterogeneous systems, such as those involved in energy conversion processes. In addition, the increased coherence will significantly improve phase contrast in transmission imaging, and enable high-flux projection microscopy that closes the gap between high-speed imaging with low spatial resolution and x-ray microscopy with poor time resolution. Further, the timing mode coupled with a high coherent flux and advances in high-speed detectors could push the limits of XPCS measurements to pulse-by-pulse framing, accessing entirely new timing regimes. Time-resolved coherent scattering is being developed as a technique for examining the dynamics of structural transitions involved in energy conversion, and computational methods such as multivariate analysis are being investigated to improve on the achievable time resolution. Time-resolved techniques will play a key role in an upgraded APS, and the APS will continue to invest in timing and high-speed imaging, particularly where they are coupled with new approaches that leverage brightness, coherence, and/or high energies.

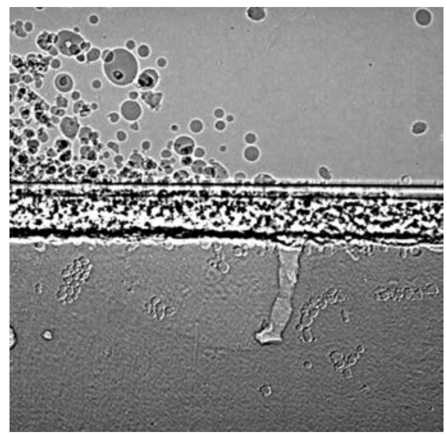


Figure 3. Ultra-fast x-ray radiography of *in operando* metal powder bed additive manufacturing process. R. Cunningham *et al*., Science **363**, 849 (2019). ©2019 American Association for the Advancement of Science. All rights reserved.

Beamline Operations and Development

The APS serves a large number of users across many diverse scientific fields who benefit greatly from excellent beamline capabilities and outstanding staff expertise. The availability of numerous x-ray characterization capabilities is essential for understanding the structure, morphology, elemental distribution, and chemical state of complex hierarchical systems, providing a key component in finding new functionalities. The APS will continue to optimize and invest in sought-after programs and facilities, including but not limited to highly automated approaches for enabling multidimensional inquiries such as investigations of structural changes during battery cycling (see Figure 4). Machine learning and artificial intelligence approaches will be incorporated into data collection and analysis in collaboration with Argonne and other collaborative programs. Specialized support labs will be expanded or developed for on-site sample preparation in dedicated environments for the highest level *in situ* and *operando* research (e.g., the electrochemistry lab to support battery-related experiments) or for extreme-conditions research (e.g., high-pressure infrastructure). The APS will continue to work with the scientific user community to identify and respond to future requirements, including training and developing the user base as well as disseminating information through workshops, seminars, schools, etc.

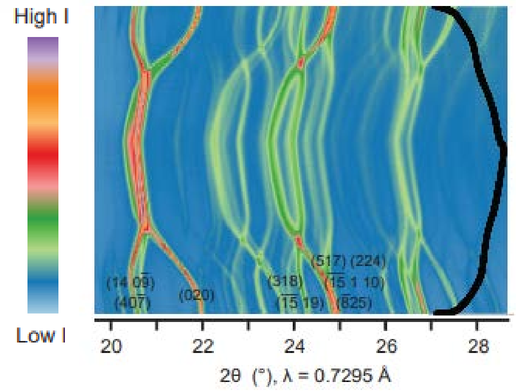


Figure 4. Structural evolution of Nb-W-W battery electrode during in operando electrochemical cycling. K. Griffith *et al.*, Nature **559**, 556 (2018). ©2019 Springer Nature Publishing AG

5.1.2. Implementation

To accomplish the goals outlined above, the APS will continue to develop instrumentation and techniques for advancing x-ray science. Further, the APS will maintain the productivity of the current beamline suite while simultaneously transitioning toward a portfolio of beamlines and instruments that will fully exploit the unique characteristics of the upgraded APS. Accomplishing this transition requires directing investments toward beamlines and technologies aligned with the APS-U. Where possible, these efforts will be leveraged through cooperation with collaborative access teams, Argonne Divisions, and other light sources within the DOE complex.

As the APS beamline portfolio evolves toward increased nanobeam- and coherence-based techniques, much more stringent demands will be placed on the speed, stability, precision, frame rate, etc. required from beamline instruments. Likewise, while the increased data rates enabled by the APS-U will permit carrying out experiments that are impossible today, they necessitate exploring new methods for managing, analyzing, and visualizing extremely large data volumes. This forces the adoption of a holistic approach in instrument design, where instruments are less as an assortment of individual components, but rather a tightly integrated system spanning from source to optics to sample to detectors to computation and visualization, held together by effective and smart controls, and seamlessly coupled with analyses and visualization. New analysis methods suggest innovative ways of performing experiments with flexibility, speed, and capabilities that were not possible only a decade ago. For example, four-dimensional imaging and video-rate scanning-probe microscopy is becoming a reality and will be substantially enhanced at the APS by the incorporation of the MBA lattice. The APS-U will dramatically improve coherence- and high-energy-based techniques such as hard x-ray nanoprobes, x-ray photon correlation spectroscopy, coherent diffractive imaging and ptychography, and nanoscale high-energy diffraction and scattering. Advances in x-ray methods are required to optimally use these capabilities in the APS-U era.

To realize this vision, the APS is developing new instrumentation platforms and infrastructure that are capable of such fast data acquisition. For example, the Velociprobe instrument (see Figure 5) is designed and built for very rapid forward-scattering ptychography measurements. The low-vibration, rapid scanning, integrated positional feedback design of this instrument is being utilized to test new methodologies for data acquisition (e.g., arbitrary trajectory scanning) and to inform decisions for the instrument design of new APS-U beamlines. Similarly, novel concepts for rapid data acquisition, analysis, feedback, and autonomous experiment control are being pursued in the project MONA (Monitoring, Optimization, Navigation, and Analysis). This project, a collaboration between the Argonne, Lawrence Berkley, and Brookhaven national laboratories, is seeking to weave real-time experimental control using the Brookhaven-developed Bluesky package, real-time streaming-data analysis from APS beamlines using Argonne Leadership Computing Facility (ALCF) high-performance computing resources, and on-line visualization employing tools developed by the CAMERA center at Lawrence Berkeley National Laboratory. A recent example of applying this approach to tomography is shown in Figure 6. The eventual goal of the project is to incorporate advanced analysis algorithms that will drive measurements to identified regions of interest. Taken together, this set of thrusts will enable innovative x-ray techniques and scientific approaches that are orders of magnitude faster and more sensitive than those available today.

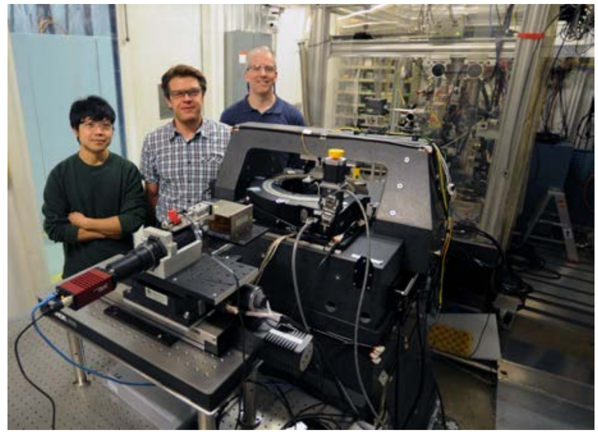


Figure 5. The Velociprobe: A prototype instrument for rapid forward-scattering ptychography measurements developed using novel mechatronic engineering approaches and recently installed at 2-ID-D.

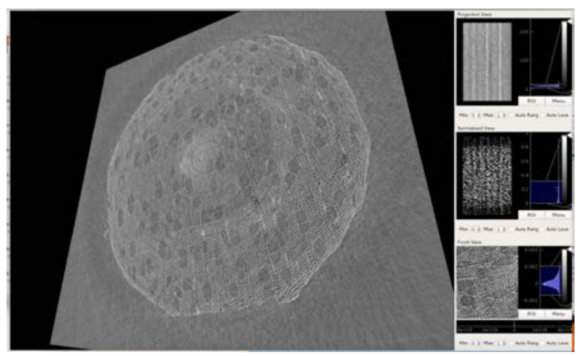


Figure 6. Real-time tomographic reconstructions obtained from data streamed from a beamline to a high-performance computing cluster at the ALCF.

The APS is invested in collaborative efforts in the data and computing space. As a part of the BES-funded Data Solutions Task Force Pilot Project, the APS is collaborating with the ALS and CAMERA, the NSLS-II, and the LCLS and the SSRL to share common software tools. This project focuses on integrating and deploying common XPCS data collection and processing software, including Bluesky from Brookhaven, XPCS-Eigen from Argonne, PyDM from SLAC, and Xi-CAM from Lawrence Berkeley, at XPCS instruments at each of the five BES light sources. The APS is leading the Light Sources and Computing and Networking Facilities Data Working Group. This working group, comprising representatives from the five BES light sources, the four DOE Advanced Scientific Computing Research computing and networking facilities, the BES neutron sources, and the BES nanoscience research centers aims to establish the framework for developing collaborations in the computing space between the BES experimental facilities and Advanced Scientific Computing Research facilities and researchers, to help solve the anticipated computational challenges the facilities will face over the next decade. The APS is also investing in advanced optics and detectors that will enable full use of the beam characteristics of the upgraded APS source. The optics strategy concentrates on the development of high-performance nano-focusing optics, such as high-efficiency zone plates, graded multilayer mirrors, and other diffractive optics; and of wave-front-preserving optics, including novel crystals and mirrors. On-going collaborations with the SLAC and Brookhaven national laboratories have been pursing adaptive optics mechanisms for correcting wave-front distortions; similar approaches are now being applied to enable controllable beam sizes at the sample position. Development of beamline advanced optics simulation and optimization software and of optical/at-wavelength characterization techniques are also a crucial component for improving optics performance.

The detector development strategy focuses on cutting-edge detectors that are unlikely to be commercially available, leveraging key partnerships with detector groups across the country and making use of unique Argonne resources. The APS detector R&D efforts comprise three areas: pixel array detectors, high-energy sensors, and emission detection. Current projects in each of these areas are: the MM-PAD detector (Cornell University); germanium strip detectors for high-energy spectroscopic applications (Brookhaven National Laboratory); and transition-edge sensors for high-energy-resolution emission detection applications for hard x-ray research (NIST). The APS will be the first synchrotron source to deploy a hard x-ray transition-edge sensor detector at the beamlines.

The innovative instrument approaches described above, coupled with advances in detectors and x-ray optics, will afford scientists at the upgraded APS a clear opportunity for direct imaging at spatial resolutions of 5 nm and below, and at the 1-nm length scale utilizing ptychography, approaching single-atom sensitivity. It will also allow unprecedented fidelity in imaging extended 3-D volumes. For example, the APS-U Project will deliver the coherent hard x-ray flux enabling the imaging of samples 1-mm^3 in size at 3-D resolutions of 10 nm, corresponding to 10^{15}(!) voxels, in less than one day. Significant resources will be needed to develop mechanisms for handling, moving, and storing such large data sets, and providing meaningful reconstructions on time scales suitable to drive experiment decisions.

X-ray Science Division goals for FY 2020 include:

- maintaining active and productive user programs on APS beamlines and developing innovative instrumentation that advances beamline capabilities particularly in the areas of high energy, coherence, and nano-focusing;
- supporting the APS-U Project in completing construction and commissioning the APS-U IDEA R&D test beamline, implementing a long-range R&D plan for optics and instrument testing on the IDEA beamline, initiating construction of advanced spectroscopy and LERIX beamlines, and continued work on guiding the development of the APS-U feature beamlines and enhancements;
- completing the major beamline development project of canting of the 2-ID beamline (brilliance), and beginning the user program at the X-TIP branch beamline at 4-ID (Lab partnership with the Center for Nanoscale Materials);
- demonstrating the use of computational methods and data handling approaches integrated into the experimental workflow, including Bluesky, APS data management system, streaming data analysis, machine learning, and transparent use of high-performance computing resources;
- commissioning the first transition-edge-sensor energy-dispersive multi-pixel detector, implementing adaptive optics schemes for adjustable beam-size at sample position, upgrading metrology capabilities to be APS-U ready, and applying the modular deposition system for fabrication of high-energy multilayer optics;
- addressing on-going obsolescence issues at the beamlines through a coordinated multi-year plan to replace key components, and implementing this plan in close coordination with the APS-U to identity clear responsibilities for particular sub-systems.

5.1.3 X-ray Science Developments by Collaborative Access Teams

This plan is primarily focused on the APS-operated, BES-funded beamlines. However, over the years, the APS has built very strong partnerships with members of CATs. The funding sources for these CAT beamlines are diverse and vary from federal sources (National Science Foundation, National Institutes of Health, DOE Biological and Environmental Research, DOE National Nuclear Security Administration) and consortia of universities and/or industry. The collective operating budgets of over $30 M per year make significant additional resources and expertise available to users in a wide variety of disciplines including the life sciences, pharmaceutical research, the geological and environmental sciences, high-pressure studies, and shock physics to name a few. Key developments for beamlines built and operated by the CATs also must be considered as these beamlines function as complementary assets to the BES program at the APS. While CAT developments, with the exception of macromolecular x-ray crystallography, will not be covered in detail in this plan, the APS will actively monitor and support proposed CAT upgrades. The APS-U will provide unique opportunities for these beamlines as well.

Most of the life sciences beamlines at the APS are dedicated to macromolecular x-ray crystallography, although other bio-related techniques are well represented around the experiment hall including small-angle x-ray scattering, imaging, and bioXAS (x-ray absorption spectroscopy). Almost every CAT-operated beamline at the APS caters to some biological and life sciences users, and collectively have invested ~ $150 M in capital equipment. The APS-U will provide a unique opportunity for the biological and life sciences. Imaging experiments will benefit significantly from the improved spatial resolution, providing unprecedented details of cellular machinery. The reduction in data collection times will allow imaging of much larger fields of view. Growing crystals of sufficient size and quality for “single-crystal” data collection is still a major bottleneck in structural biology. Synchrotron-based serial crystallography, which is in a nascent stage of development, overcomes this bottleneck by using many (100s to 100,000s) of micrometer-sized crystals to construct a full dataset. The combination of the MBA source and improved optics will provide at least a 1000-fold increase (two orders of magnitude in source improvement combined with an order of magnitude in focusing efficiency) in intensity in micrometer-sized x-ray beams compared to today’s beams, allowing atomic resolution and structure determination of macromolecular complexes from crystals as small as 500 nm. Recently, the first pink-beam, serial-crystallography experiments were performed at the APS. The increased bandwidth and intensity, compared to monochromatic beam allowed data of sufficient quality to be recorded from a series of single-crystal, 100-ps exposures analogous to data collection at the Linac Coherent Light Source. The increased bandwidth allowed full reflections to be recorded rather than the partials that are observed with monochromatic x-rays. This resulted in a 100-fold reduction in the number of crystals, and more importantly, a reduction in the amount of precious protein required for structure determination.

Near-term goals in the macromolecular x-ray crystallography arena include:

- upgrade of the x-ray optics in order to ensure beamlines can fully exploit the new MBA source,
- continued development of pink-beam serial crystallography methods, and
- implementation of injector and fixed-target sample delivery systems across multiple beamlines.

5.2. Accelerator Operations and Improvements, and Research and Development on New Concepts and Next-Generation Light-Source Technologies

5.2.1. Introduction

The APS accelerator complex is the backbone of the APS scientific program. It includes a 7-GeV, 1.1-km storage ring operating with a 100-mA electron beam; a full-energy booster synchrotron; a 450-MeV particle accumulator ring; a 500-MeV pulsed linac; and an S-band radio-frequency (rf) thermionic electron gun. The APS has the largest installed 352-MHz CW rf power system in the U.S. and the second largest installed pulsed S-band rf power system. The APS uses more than 1500 power supplies for various magnets, supports more than 45 insertion devices (IDs), and utilizes numerous precision diagnostic devices to maintain beam quality.

Maintaining the high reliability of APS accelerator operations presents significant challenges. The accelerator systems continually undergo improvements directed at meeting new needs of the scientific program. As noted above, the APS has developed a technical design for a new storage ring employing an MBA lattice. Replacing the existing storage ring with a new ring is currently planned to start in 2022 and be completed in 12 months. The result will be a dramatic 2-to-3 orders-of-magnitude increase in x-ray brightness. Careful provisions have been made in the ASD strategic plan to align current accelerator improvements and upgrades with the needs of a new ring, thus balancing requirements of current and future APS operations.

The ASD strategic plan is based on the following goals:

- Continue to operate the APS with excellent availability and beam quality
- Prepare the APS accelerator systems and staff for the APS Upgrade
- Pursue research in accelerator science and technology to benefit x-ray science

5.2.2. Accelerator Reliability

The APS accelerator complex has been in operation for more than two decades. One of the challenges facing the ASD is maintaining reliable operation of the complex while preparing for the APS-U. Although the APS-U provides a new storage ring, the injector systems are undergoing relatively minor upgrades of individual components. By the time the APS-U is operational, much of the injector system will be over 25 years old, and in several cases using outdated technologies. The ASD will implement a plan to update as much of these systems as possible before the Upgrade without impacting operational reliability. The APS staff and management will ensure that this is done in the most cost-effective and efficient manner. Through dedication to timely upgrades and rigorous maintenance protocols, the APS has become one of the world leaders in accelerator reliability with beam availability routinely above 97%. This requires continuous communication between technical staff and management to assess risks to reliable operation and to prioritize activities targeting high-risk issues.

For example, the APS linac, typically operated between 400-500 MeV, has much of the original control system developed in the early 1990s. It is becoming increasingly difficult to identify spares and replacement components for these parts. A linac rf test stand is being installed in an auxiliary building that will allow us to independently process rf components such as linac structures, waveguide windows, and SLAC energy doublers, and test new rf sources without impacting APS linac operations. This will also support development and commissioning of a modern linac controls system.

5.2.3. Accelerator Improvements

5.2.3.1. Magnetic Devices

The Magnetic Devices Group within the ASD is responsible for all APS magnetic systems, including over 45 undulator IDs, and is the world leader in superconducting undulator (SCU) development. The ASD continues to improve undulator performance, meeting challenges for the APS and other light sources in the DOE complex. Future work is focused on development of three-way-position revolver undulators, improving construction efficacy of hybrid IDs to meet technical and construction goals for the APS and the APS-U, development of automated ID magnetic tuning procedures, and development of a novel ID mechanical system that will allow faster gap change and better control of “strongback” deformations.

In preparation for mass production of hybrid IDs for the APS-U, special attention is being given to development of U.S. industrial partners to handle the majority of ID assembly external to the APS. The ASD continues to improve planar SCUs and is building a 3.5-m-long SCU with an extended “good field region" using NbTi wire and a thin vacuum chamber. A significant leap in SCU development will include the completion of NbTi SCU technology, and transfer of that technology to an industrial partner for SCU fabrication outside of the APS. The ASD is also designing SCUs using Nb_3Sn wire that provide even broader x-ray tuning ranges, and a high-temperature superconductor for a new generation of SCUs.

The ASD continues to advance the development of SCUs for polarization control. The next generation of polarizable sources is the Super Conducting Arbitrary Polarizing Emitter (SCAPE). (Figure 7). The SCAPE consists of horizontal and vertical undulators offset by a half period. By powering the coils in various configurations, the SCAPE can produce linear and elliptically polarized beams. One of the goals is to be able to switch helical polarizations at a rate greater than 10 Hz.

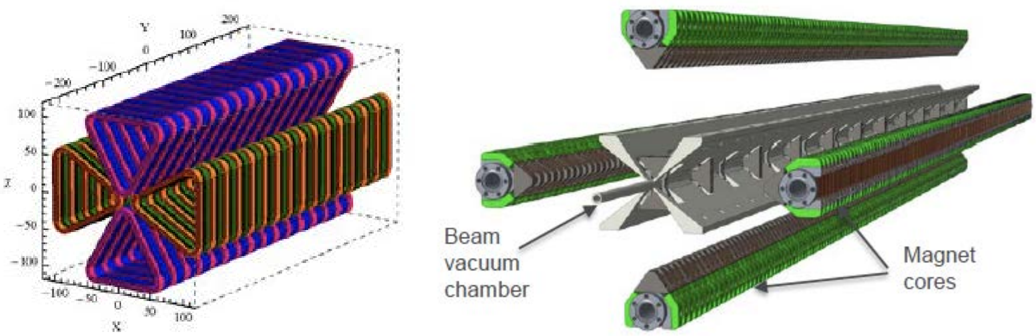


Figure 7. (Left) The Radia Model for the SCAPE SCU magnets. Horizontal and vertical fields are shifted by a half period and can be powered arbitrarily, allowing variable polarization. (Right) A mechanical drawing of the SCAPE assembly. The x-wing vacuum chamber allows extraction of heat generated by the beam.

5.2.3.2. Radio-Frequency Systems

The RF Group within the ASD maintains and improves the rf system reliability and lifetime for all of the APS accelerator systems by addressing aging, obsolescence, and performance issues, thus allowing the existing hardware to provide reliable performance up to the installation of the APS Upgrade and beyond. Specific attention is given to identifying and replacing weak and aging components, and to proactive maintenance of the 352-MHz storage ring rf systems.

One of the primary strategies for addressing obsolescence of the storage ring rf system is to transition from high-power klystron tubes to solid-state technology with the potential to provide higher efficiency, longer lifetime, and lower maintenance and ownership costs than traditional klystron power amplifiers. Laboratory Directed Research and Development-funded research led to a successful in-house 8 kW prototype. Efforts have advanced to an industry 30-kW prototype that will allow testing of a final combiner configuration (Figure 8). If successful, the next step will be to work with industry to build a full-scale 200-kW rf station for installation and testing in the APS storage ring before the APS-U dark time. To ensure an adequate supply of 352-MHz klystrons during the transition to solid-state amplifiers, an effort is under way to secure a second klystron vendor (Figure 9).

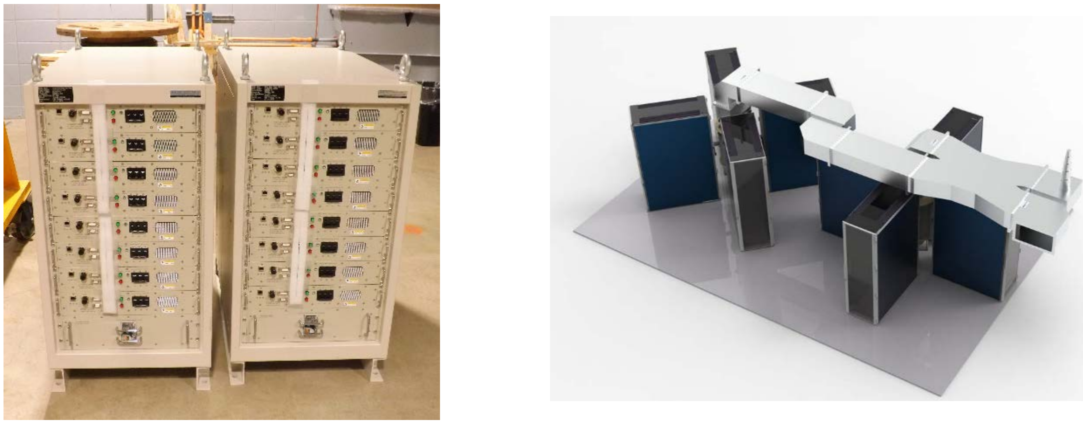


Figure 8. (Left) The photo shows the first 32-kW prototype solid-state amplifier received from R&K. (Right) The rendering shows the concept for a 200-kW amplifier. Each rack contains 15 2-kW amplifiers that are combined in the combiner cavity hidden below the waveguide. The first prototype amplifier was tested on the combiner cavity later in 2019.

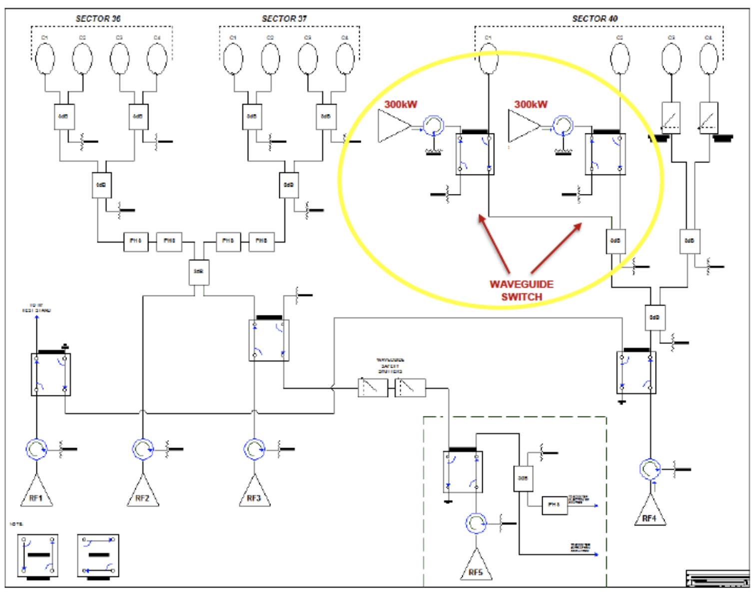


Figure 9. The transition plan to solid-state rf amplifiers will occur over approximately five years beginning from 2021. The schematic above shows the planned hybrid configuration of the rf system in 2023, following the APS-U installation.

Another area of emphasis is addressing obsolescence issues in the various rf systems in the APS storage ring and injectors. For example, the low-level rf controls will be upgraded to a modern digital system using a common platform. The ASD also maintains several rf test stands for testing components and developing new concepts. A 352-MHz rf test stand is utilized on a routine basis to condition and test new "green" tuners, couplers, and dampers in order to maintain a stock of conditioned and verified spare parts for the 352-MHz rf cavities. In addition, ASD is initiating procurement of the first new S-band 50-MW klystron/modulator system for the linac. The plan is to replace/modernize all linac rf stations over the next five years.

5.2.3.3. Power Supplies

The ASD will continue to identify and replace aging power supply hardware before it impacts operations. This will be achieved by continuing proactive maintenance, continuing the thermal imaging program to identify any overheating parts and electrical connections and repair them before an actual failure, and thoroughly testing all power supplies including stress tests during machine start-up before each user run to ensure reliability for operations. The ASD will continue to closely monitor the condition of power supply equipment during operations, and schedule repair and replacement during machine interventions for equipment that has shown signs of elevated temperatures, voltage ripples, and/or communication issues. Examples are rising temperatures of the aluminum electrolytic capacitors in power converters, and communication issues with power supply controllers caused by increased voltage ripples from the low-level-control power supplies. Obsolescence of a large number of components is a long-standing issue. Next in line is replacing the programmable logic controllers, the GESPAC power-supply controllers, and digital signal-processing controllers. Many commercial power supplies utilized in the injectors (particularly in the linac) are close to 30 years old. The ASD will replace those power supplies that are not supported by vendors. New commercial power supplies will not be 100% compatible with the original ones, so in-house solutions will be developed, in particular for many kicker power supply systems.

5.2.3.4. Beam Diagnostics

The ASD Diagnostics Group maintains and upgrades existing storage ring and injector diagnostics systems addressing aging, obsolescence, and performance issues that allow the hardware to provide reliable performance up to the APS-U “dark” (storage ring installation) period and beyond. More specifically, booster beam position monitors (BPMs) have been migrated to a field-programmable gate array-based system and particle accumulator ring BPMs with Libera SPARC electronics have been upgraded, as have obsolete BPMs and current monitors in the linac, transport lines, and linac extension area.

5.2.3.5. Accelerator Operations and Physics

The Accelerator Operations and Physics (AOP) Group is the main source of accelerator physics theory and simulation in order to understand and improve the APS electron beams. Formerly, managing reliable operation of the APS accelerator complex was part of the AOP mission, but now it is the responsibility of the separate Main Control Room group within the ASD. The AOP stresses thorough automation of machine operation and analysis, since these are the keys to high reliability. For example, the AOP has improved real-time detection and monitoring of malfunctioning power supplies and BPM electronics to further enhance orbit stability by removing the malfunctioning devices quickly from the orbit feedback system in order to facilitate repairs. Other automation improvements include beam-dump analysis, injection optimization, and lattice and filling pattern switching. Other activities include improving operation of the bunch-by-bunch feedback system targeting via a reduced chromaticity in order to improve beam lifetime, in particular in a non-top-up, 324-bunch filling pattern where variation on the synchrotron radiation intensity with the decreasing current affects pointing stability in the users’ beamlines.

One of the important issues to resolve in preparations for the APS Upgrade is the effect of the impact of the APS-U beam on the various collimators that will be added to the vacuum system that protects the chamber. Thermal analyses of a beam strike on a collimator have shown that the beam power density is sufficiently high to melt the collimator and essentially drill through the material. In a recent experiment jointly conducted by the AOP and the Diagnostics groups the electron beam was focused to a smaller transverse size and directed onto a test collimator that was inserted into the beam. The collimator was externally imaged in real time to observe the effect of beam impacts on either aluminum or titanium portions of the collimator. The setup is illustrated in Figure 10 (upper left) where the beam has a glancing impact on the edge of the collimator. Figure 10 upper right is a frame of the video recording corresponding to the beam impact. The glowing line is the light emitted from the glowing metal. Small ejecta are observed in the image. Figure 10 lower left is a postmortem cross-sectional image of a strike on the aluminum portion, and (lower right) on the titanium portion of the collimator. The image clearly shows plastic flow of the metal after heating from the beam. Experiments and analysis continue in order to understand this effect in detail.

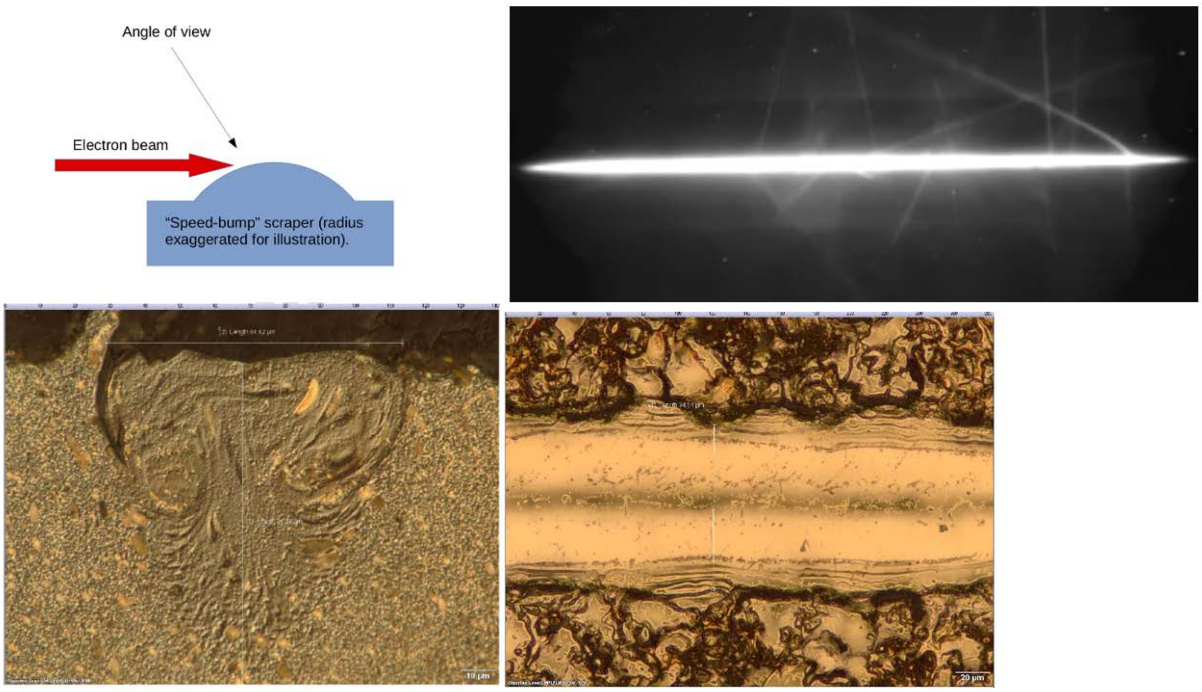


Figure 10. Shown upper left is a schematic layout of the collimator beam strike experiment. The upper right panel is an image of the test collimator during a beam strike. Ejecta are observed as small flares from the molten metal. The image at the lower left shows a postmortem metallurgical analysis revealing the cross section of a beam strike region for the aluminum portion of the collimator. The image at lower right shows a top view of the beam strike "trough" formed on the titanium portion of the collimator.

The ASD is a world-leader in modeling storage ring light sources with the continued development of the **`elegant`** code and a related suite of tools. The AOP continues improving and enhancing high-performance computing accelerator simulations while making these state-of-the-art codes available to the entire accelerator community, benefiting many accelerator facilities and projects beyond the APS and APS-U. Specific plans include increasing parallelization in simulation codes and SDDS tools; further development of a graphics processing, unit-based version of **`elegant`**; and continued benchmarking of single-particle and collective effects.

5.2.4.Accelerator R&D to Advance New Concepts and Next-Generation Light Sources

The APS has an earned reputation for staying on the cutting edge of accelerator science and technology that is beneficial for Argonne and the other DOE light source facilities. A suite of accelerator R&D programs focused on a versatile, cost effective, and energy efficient future light source ensures that the U.S. and the APS continue to maintain this competitive edge.

The APS core strategy is to perform high-impact accelerator research by concentrating on several key areas that maximize key APS strengths: sophisticated, high-fidelity simulation; development of advanced insertion devices; and innovative ideas for improved accelerator performance. While the main path forward focuses on an MBA lattice, opportunities also exist to explore whether the APS can supplement that with additional capabilities for use by specific user groups and for activities beyond the APS Upgrade.

Another component of the ASD strategic plan is innovative accelerator R&D advancing cutting-edge accelerator science and technology in the area of synchrotron light sources and other accelerator research areas beneficial for the greater accelerator community. The ASD has established leadership in several areas of interest to future light sources, including:

- Nb_3Sn superconducting undulators: The Accelerator Systems Division is developing the first full-scale device based on Nb_3Sn wire with a promise of 30% higher field vs NbTi SCUs. Testing of a 0.5-m prototype is under way with the goal of installing a 5.2-m cryostat containing dual 2.x-m SCUs prior to the APS-U dark time.
- Cavity-based x-ray free-electron lasers: With the advent of the high repetition rate x-ray free-electron lasers such as the Linac Coherent Light Source (LCLS)-II, several schemes for improving the longitudinal coherence of the x-rays have appeared, which depend on resonating the x-rays in an optical cavity based on high-purity diamond mirrors. A collaboration between Argonne and SLAC has formed with the three-year goal of building an optical cavity and demonstrating it on the LCLS-I, and anticipated use on LCLS-II when available.
- High average brightness photoinjectors: Argonne is adopting the superconducting rf gun originally developed at the University of Wisconsin-Madison, and completing the demonstration and characterization of this gun.

5.3. Infrastructure, General Operations, Engineering Support, and Other Miscellaneous Improvements

The APS continues to reinforce a vision for safe and predictable operations. Safety incidents are addressed promptly by Photon Sciences Directorate (PSC) management through a variety of Argonne-wide initiatives, such as the creation of an Electrical Safety Manual and revised Qualified Electrical Worker (QEW) training. These were followed by initiatives in FY19 of the creation of a Work Planning & Control (WPC) Manual and Controlling Hazardous Energy Manual. Local PSC Directorate safety augmentations include increased observation/conversations, SMART-card targeted observations rolled out across the PSC directorate, continuing use of the pre-job brief, and high-risk work reviews supported by a register to capture and communicate high-risk work (later adopted by Argonne). Improvements to work planning and control were implemented in FY18 with an overhaul of the governing policy/procedure in order to match with fundamental Integrated Safety Management tenets and inclusion of CATs in rollout of the revised process steps. A document management system completed and implemented APS-wide in FY18 generates consistent identification and metadata for all types of documentation produced at the APS, regardless of the originating Group, Division, or project.

The bulk of responsibility for general infrastructure, operations, and engineering support falls to the AES Division. The Division provides engineering, electro-mechanical, vacuum and water maintenance services, as well as computing infrastructure in direct support of enabling world-class performance of the APS accelerator and beamline complex, while ensuring a safe environment for APS users and personnel.

The AES Division also acts as the *de facto* liaison to many of the Argonne service directorates. In FY18, a large effort was undertaken in concert with the Argonne Infrastructure Services Directorate to contract with an independent architectural/engineering firm for a complete characterization and assessment of all infrastructure related to the APS, commonly referred to as the 400-series of buildings that comprise the bulk of the APS. This included, but was not limited to building foundations, superstructures, roofing, interior construction, mechanical systems, electrical systems, specialty systems, and associated utilities not included in a prior Argonne-wide utility master plan.

The result was a comprehensive needs assessment prioritized by urgency, and reviewed and endorsed by both APS Operations and the APS Upgrade Project to yield a framework order by which infrastructure needs can be addressed leading up to, during, and after the downtime associated with APS-U Project implementation [the “Advanced Photon Source (APS) Infrastructure Master Plan Volume 1,” Figure 11]. These are further characterized by recommended funding source, dependent on scope, magnitude, and funding level estimated by the architectural/engineering firm and reviewed by the Infrastructure Services Directorate. The listing provides a clear picture of near-term site demands as well as long-term improvements to promote reliable operation of the APS up to and after APS-U Project implementation.

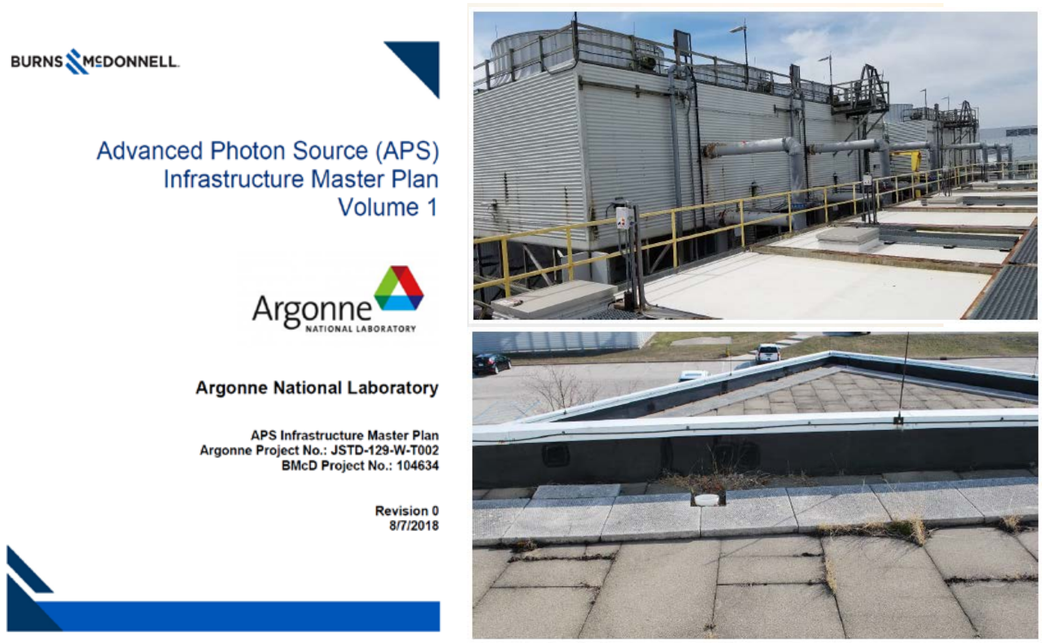


Figure 11. Shown at left is the cover of the “Advanced Photon Source (APS) Infrastructure Master Plan Volume 1,” with (at right) examples of repair/replacement projects such as the APS cooling tower bank (upper right) and storage ring roof (lower right).

Progress has been significant on execution of the APS master plan-prioritized projects. The replacement of the APS experiment hall roof, as part of a campus-wide Argonne roof replacement program, began in July 2019 and will be completed over the course of three fiscal years. The cooling tower replacement and upgrade effort selected the final two candidate designs for manufactured cooling tower upgrade as well as specified the design of a redundant cooling tower. Improved chilled water filtration and chemical treatment contracts were awarded to a vendor in August 2019 for implementation thereafter, to be followed by a proposal to address tower-water filtration and treatment. Total conversion of experiment hall lighting to LED will be completed in FY20. The local substation providing 13-kV power to the portion of the Argonne site that includes the APS (Substation 549A) has had one bus completely upgraded during the April/May 2019 APS maintenance shutdown without issue, and the second bus will be upgraded in the August/September shutdown. The front plaza of the APS central lab/office building (Bldg. 401) has been completely refurbished and redesigned, including safety enhancements to the staircase, lighting, and hand railings.

The PSC Directorate also continues to reduce storage space footprint as an additional initiative to control and reduce levied space charges. For example, Divisions within the PSC Directorate currently occupy approximately 23,780 sq ft identified as storage space in 10 facilities in the 300-series buildings on the Argonne campus. Another 11,241 sq ft of storage is added when including 14 buildings in the 400-series complex that house the APS including lab/office modules. The PSC Directorate has performed a systematic evaluation with PSC Divisions to identify, tag, remove, and ultimately dispose of material from these buildings, including adhering to the removal criteria in the Technical Basis Document for clearance of potentially activated material.

With a target of at least a 20% reduction of storage space in the 300-series buildings, which accounts for the bulk of the (non-high bay) storage space, the PSC Directorate realized a 26% net reduction (approximately 9,535 sq ft) after a concerted effort by PSC personnel that completed in March 2019. This is estimated to yield an annual gross lease cost savings of about $228,000.

Data network upgrades are a focus in looking ahead to APS-U data demands. In the last two years, the AES Information Technology Group has performed a number of upgrades and fulfilled large support requests including but not limited to these initiatives:

- The redundant XRAY network core switches providing higher redundancy, resiliency and performance now have active/active uplinks doubling their bandwidth. The XRAY core switch now supports 100-GB uplinks with a 19.2-Tbps switching capacity with up to 7.142 billion packets per second for data throughput.
- A new APS tier-2 firewall with 40-GB uplinks on every interface has been added, with advanced traffic inspection and evasion prevention along with clustering for load balancing and high availability.
- The accelerator wireless network has been upgraded with Aruba 2 x 7210 WLAN controllers and over 50 AP-300 series access points.
- The main accelerator server has been upgraded to a FAS8200 with a SATA+SSD hybrid storage solution to improve performance and reduce latency for the accelerator control applications.
- The XSD beamline data storage space has been more than doubled from 350 TB to 760 TB, including 15 TB of solid-state storage

  More than a dozen Data Management virtual servers have been added; these coordinate moving data from beamline stations to the high-performance computing cluster, the Voyager DDN storage system, and APS users' home institutions via Grid FTP.
- Servers were created to support beamline operations at sectors 25 and 28 for the APS Upgrade.
- Work was carried out with Sector 16 to support experiments with proprietary data requirements.
- The storage cluster Voyager was put into production in late FY18. Voyager is a Data Direct Network system running their GRIDScalar product (embedded GPFS) with an initial capacity of 800 TB. The system is accessed via the XSD-developed Data Management software. The capacity was increased to 4 PB in January 2019 with 1 PB currently in use. To facilitate access, six data transfer nodes (DTNs) support file transfer services for XSD, CAT, and external users.
- The Voyager DTN was installed for the Argonne Leadership Computing Facility. A team of Argonne Leadership Computing Facility computational scientists used it to develop and deploy data analysis work-flow software.
- The APS on-demand data analysis cluster Orthros had 200 TB of new storage added. This replaced 72 TB of obsolete disk storage and increased system capacity. Orthros also has a DTN on the ESNet ScienceDMZ Network. APS users are employing the ScienceDMZ to transfer data to NERSC for additional reprocessing.
- The Orthros home filesystem was upgraded to solid-state drives to improve analysis speeds. Some users write progress logs to their home directory while the analysis is running. Along with the solid-state drives, a new home directory server and fallback server were installed. These are currently being used by XSD computational scientists and the APS-U to run simulation software.

Addressing obsolescence in accelerator and beamline systems, as well as upgrades in engineering toolsets, continues in earnest across the PSC Directorate. This effort, referred to as the development of the Interface Portfolio, is assembling the prioritized list of projects required to be completed prior to the APS Upgrade dark time starting in FY22 (for more details see Section 5.4). Divisional Groups have long had an implied mandate to modernize legacy hardware and software systems due to obsolescence or increased operating parameters, but the Interface Portfolio has become the focal project list for APS mission readiness.

A long-term effort devoted to upgrading all ion pumps and controllers in the linac/particle accumulator ring/booster and klystron galleries has been completed. Personnel safety systems have been given complete upgrades to programmable logic controller hardware, building upon reliable operation and addressing vendor obsolescence. Front-end equipment protection system upgrades began in the August/September 2018 shutdown period for insertion device and bending magnet beamlines, moving to an Allen-Bradley ControlLogix programmable logic controller platform for enhanced capabilities and diagnostics. All bending magnet front-end protection system upgrades were completed by the end of the August/September 2019 shutdown.

State-of-the-art technical component design and rendering tools continue to be implemented at the APS. The AES Design and Drafting Group now utilizes advanced 3-D model builds, including a low-memory-consumption system build heavily utilized by the APS Upgrade Project. Some recent examples of three-dimensional modelling are shown in Figure 12. This Group maintains a handheld, reverse-engineering scanner that has seen widespread use for APS Operations facility and beamline applications as well as for the APS Upgrade. The demand from the facility and operations for 3-D printed components has increased dramatically in the last three years, and regularly approaches almost 800 individual ticket requests for a 3-D printed component on one of the three machines maintained by the Group. Future installations support the concept of a small production cell, to drastically reduce conventional supply chain durations, and include purchase of a metal 3-D printer as well as a small water-jet cutting machine. The AES Mechanical Engineering and Design Group continues to advance the state of the art in design of novel sample holders with the acoustic levitation on 2- and 3-axis sample holder Laboratory Directed Research and Development project and, through a Small Business Innovation Research project, development of an advanced COMSOL multi-physics simulation predictive capability for next-generation synchrotron light source compact vacuum chambers.

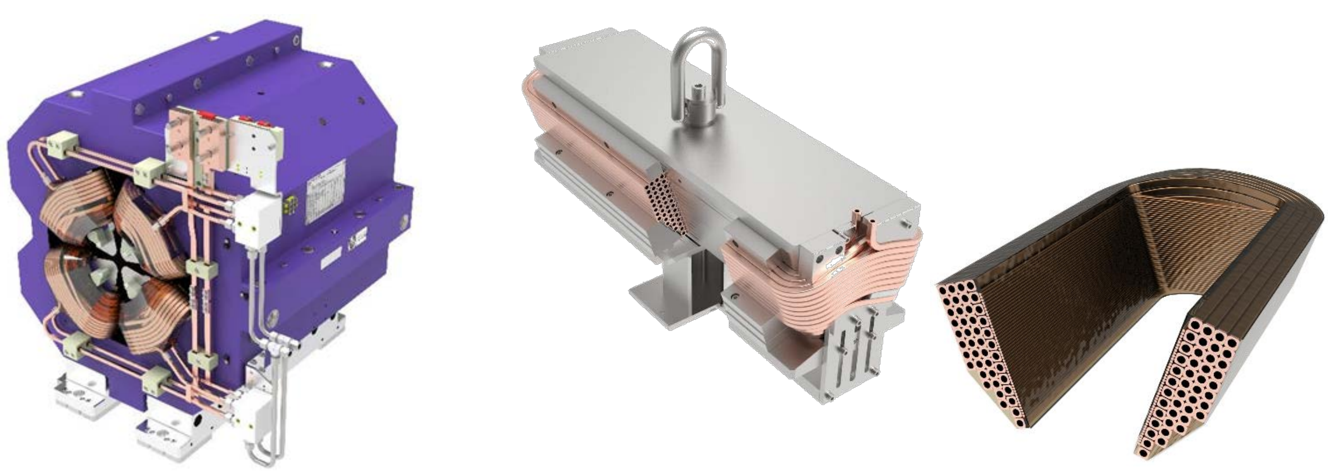


Figure 12. Three-dimensional virtual model of an APS Upgrade Q8 magnet (left), and M4 magnet coil design and fixture (right).

The APS has also provided a significant fraction of effort and design expertise in support of Strategic Partnership Projects, specifically to the design and construction of the LCLS-II at the SLAC National Accelerator Laboratory. From design and supply of the horizontal-gap vertically polarizing undulator to the final shipment of hard and soft x-ray undulator vacuum chambers in August 2018, the APS has been a valuable partner over four years in support of this significant DOE project.

5.4. Mission Readiness and Obsolescence – Interface Portfolio

Mission readiness, as defined for the APS facility, is the development of projects that anticipate and mitigate risks associated with beamline and accelerator equipment reliability, end-of-life failure, and obsolescence. This approach is applied to all work that is not included in the scope of the APS Upgrade Project, but that is required for the long-term reliable operation of the APS.

Significant progress occurred in the development of mission readiness projects in FY19.

First, in October 2018, APS Operations and the APS Upgrade signed a Memorandum of Understanding (MOU) ahead of the DOE CD-2 Review. The MOU framed agreed-upon responsibilities and interfaces between Operations and the APS-U. Broadly, Operations is responsible for maintaining and incrementally improving all existing APS systems in a manner consistent with current operating levels, while the APS-U is responsible for upgrading those systems if they are required to perform at levels beyond those currently achieved (e.g., incremental improvements to the injector system to support high-charge operation).

Second, CD-2 was granted in December 2018 and performance of the APS-U was baselined. The MOU became the defining document that has guided the further refinement of mission readiness projects, appropriately renamed as the Interface Portfolio. The Interface Portfolio incorporates priorities in readying the facility for implementing the APS-U scope in the next three years. Beyond that, it prioritizes projects within the Portfolio that are aimed to mitigate risk and deliver mature and long-term reliable operation in the future.

The methodology for developing the Portfolio consisted of analyzing machine-by-machine and system-by-system needs largely following the Operations Work Breakdown Structure (WBS). Outcome of the analysis was a comprehensive portfolio of projects, each with a WBS classification, identified sponsor and project manager, urgency/priority rating, business case, and estimated resource needs to be executed by Operations in order to meet facility goals of:

- maintaining user operations with excellent beam availability and quality up to the time of APS-U installation;
- meeting or exceeding the performance specifications for machines and systems, which (1) are not part of the APS-U scope and (2) are required for successful commissioning of the new MBA lattice source; and
- proactively addressing obsolescence, maintenance, and improvements so that the APS can reach optimal performance of the new source as quickly as possible following commissioning and handoff from the APS-U Project to operations.

The Interface Portfolio, which rolls up the Gap Analysis projects with mission readiness-related projects from the PSC Divisions strategic plans, comprises of 150-plus projects ranging in cost from \$30K to \$4M, and effort from a few days to ~8,000 hours for projects that require coordinated teams and specialized facility expertise.

The PSC Directorate has recently chartered a Portfolio Management Office to develop and manage the mission-readiness projects with the explicit objective of delivering an integrated multi-year plan that includes resource allocation, risks, and dependencies coordinated both within the portfolio and with the APS-U project management P6 system. The approach to developing this plan includes:

- using the Operations WBS to organize projects around machines (linac, particle accumulator ring, etc.) and systems (water, interlocks, etc.);
- meeting with the responsible project managers, group leaders, and machine managers to discover and refine the scope;
- identifying groups of projects that are related by common deliverables, then forming an integrated team of subject experts to oversee execution of these projects in coordination with the APS-U;
- continuously reviewing and updating the portfolio, taking into consideration changes in Divisional priorities and APS-U P6 milestones;
- presenting the portfolio to the PSC Senior Management Team for final approval to start detailed planning of projects identified for execution in FY19-FY22; and
- building out detailed plans (scope, schedule, resources, risks) for each project identified for execution, and executing planned projects upon authorization by the Senior Management Team.

For example, the portfolio includes 27 information technology projects spanning the facility, accelerator, and beamline areas of the Operations WBS. During the first discovery meeting, which included the Information Technology, Controls, and Safety Interlocks groups, and the APS-U Control Account Managers for Feature Beamlines, 11 of the 27 information technology projects were identified as related to a facility-wide network upgrade that included significant APS-U scope. The Program Management Office worked with the ASD, AES, and XSD Divisions and the APS Upgrade Project to charter a Network Installation Team (Figure 13), whose sole purpose is to ensure successful installation of the network upgrades.

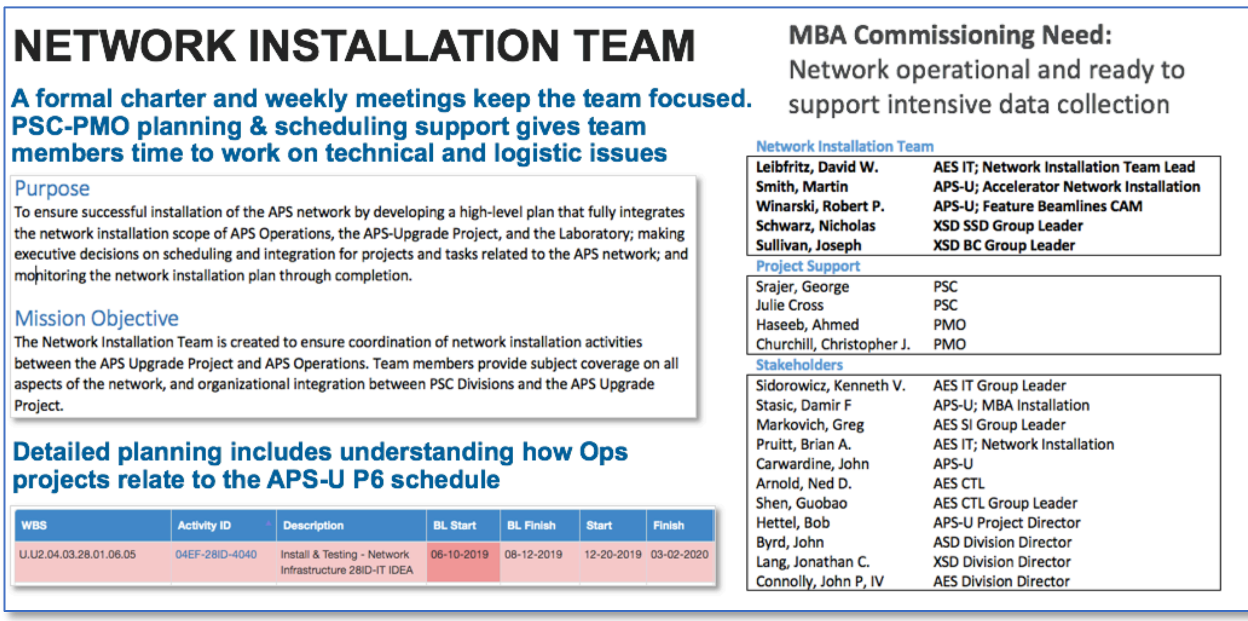


Figure 13. Network installation team charter describing the scope of the project and its stakeholders. The charter is used as a framework for developing a detailed, resource-loaded plan.

Plans for FY20 include integration of the linac, particle accumulator ring, booster, and timing system projects.

The portfolio is maintained in an enterprise Project Portfolio Management suite on the Laboratory’s ServiceNow platform. The web-accessible database increases the portfolio’s visibility and allows a more agile approach to long-term planning and scheduling as urgent issues arise or priorities change.

5.5. User Processes and Scientific Access

The APS continues to support more users than any other DOE light source facility, as noted in the Introduction. The APS user program includes an integrated, comprehensive suite of outreach, administrative, support, and educational activities to facilitate quick and easy access to the beamlines and to fill the future R&D pipeline with both users and scientific staff. Below are highlights of the user program and delineated enhancements planned for the next five years that will provide even better services to APS users.

A crucial aspect of APS planning will be preparing the user community for the APS-U dark time of approximately one year spanning parts of FY22 and FY23. The BES light sources have documented complex-wide beamline capabilities that will be available starting now and going into the APS-U dark period in order to provide APS users clear options for alternate beamlines that will be available while the APS is off line. A major focus in FY20 will be to work with the user community and the CATs to communicate information about the APS-U dark time, and to solicit ideas from the community about how to minimize the very significant disruption that the dark time represents. Discussions continue with other BES light sources and with sponsors to identify mechanisms to enhance user throughput at other light sources during the dark time.

5.5.1. Outreach to Users

The APS fosters and promotes scientific communication and collaboration through the organization and support of a diverse array of conferences, workshops, schools, and short courses as well as hands-on training opportunities encompassing the use of x-ray techniques, software, and data collection systems designed to familiarize APS users with the ever-evolving technology and research foci at the APS and to expand the user base.

As the APS Upgrade Project moves forward, more communication is required to keep APS users abreast of activities and engaged in the new science opportunities.

In-house and online lectures explain the technical parameters of the APS-U in order to assist APS staff and resident users in best aligning their plans for near- and long-term detectors and optics purchases, thus maximizing the benefits they will derive from the improved source.

Conferences and workshops focus on diffraction-limited light sources, techniques, and science areas in the “sweet spot” provided by an MBA source. These events expose current and future users to the capabilities and scientific opportunities of the APS Upgrade.

Input from these activities and from other mechanisms is being utilized to align the selection of upgraded beamlines and accelerator source parameters with user needs and the most transformative science opportunities. In addition, outreach to CAT funding agencies and organizations helps the CATs sustain their operations and implement capital improvements to their facilities. The FY19 activities are listed below:

- Serving the Future of Structural Biology: New Technologies for MX Beamlines (February 13, 2019)
- 2019 APS/CNM Annual User Meeting (May 6-10, 2019) included workshops that focused on the APS-U era:
    - Driving Scientific Discovery with Artificial Intelligence, Advanced Data Analysis, and Data Management in the APS-U Era
    - RIX after the APS Upgrade: Science Opportunities
    - *In Situ* and Multimodal Microscopy for APS-U

Future workshops include:

- Time-Resolved Chemistry and the APS Upgrade (October 1-2, 2019)
- Catalysis Research, X-rays, and the APS Upgrade (October 3-4, 2019)

Additionally, the User Program Office continues to develop a consolidated voice for those engaged in supporting and/or interested in research conducted by users of America's national user facilities. This is accomplished via professional communities and research networks, and by promoting awareness about the benefits and significance of user facility research.

5.5.2. User Support/Access

The APS provides both administrative and scientific-access support for users. User-related systems are being expanded, streamlined, and integrated, resulting in better service for users, better data collection for future planning, and cost savings.

In 2018, the User Program Office began a multi-year, comprehensive review of all of its online systems, including registration, proposals, scheduling, user portal, and experiment safety as well as all related user communications in an effort to streamline and better integrate all of these systems. Efforts in 2019 have resulted in:

- a multi-laboratory, multi-facility project to develop a universal proposal system that could potentially accommodate the needs of all light source user facilities in the DOE complex;
- an APS User Program Office-championed Argonne "Improving How We Work (IHWW)" team to make improvements to the current user on-boarding systems, and to investigate and develop a new common registration platform and procedure that would work for users of all user facilities at Argonne; and
- preliminary work to incorporate ORCID into the APS user platforms. This technology will be included into the future registration system that will be adopted at Argonne.

Accomplishments and ongoing efforts include:

- The APS User Program Office is the team lead for a universal proposal process for synchrotron facilities in the DOE complex. The team's accomplishments include a review of the NSLS-II PASS system, a request-for-information call for potential system development vendors, a review of 15 ServiceNow vendors, and a two-day demonstration by the top four ServiceNow vendors. A statement of work, a technical specifications document, and a governance plan will be drafted by the end of the CY19.
- The full integration between the APS user database and the Argonne FAVOR system has been completed. This has eliminated nearly all of the manual and repetitive steps previously required to process site access requests for non-U.S. citizens.
- My APS Portal was enhanced to include an electronic user agreement acknowledgement form, which has eliminated the previous paper system.
- The requirement to collect CVs from non-U.S. citizens was implemented into the APS user and visitor registration forms.
- Enhanced programming to identify proprietary work at the proposal stage in order to ensure that appropriate financial resources are in-house prior to the commencement of an experiment was completed.

Goals for FY20:

- Fully implement ORCID into the APS platforms to allow for future development such as sharing proposals and training records with other synchrotron facilities across the DOE complex.
- Develop a robust use of application programming interfaces to develop user-friendly dashboards, generate reports, and allow sharing of information with other facilities.
- Eliminate the manual process of creating Federal Access Central Tracking System addendums to update hosts. This will be accomplished by integrating data held in the APS experiments database with the Argonne FAVOR system.
- Release a detailed request for proposal for a universal proposal process, choose a vendor, and begin work on the project.
- Continue efforts on the Argonne IHWW-team initiative.
- The User Program Office and Argonne Environment, Safety and Health Division personnel will begin work on developing a new experimental safety authorization process to include real-time applications and iPad technology on each beamline after the MBA storage ring installation period.

5.5.3. User Training

Most required user training is now available on the web and can be taken by users online before arrival at the APS, saving time and enhancing the safety profile of the community. Individual user training expiration dates are included in both the My APS Portal and the Experiment Safety Assessment Form to ensure that users participating in hands-on work are up to date with all required training before an experiment begins. The IHWW team will be championing an effort to eliminate the need for the APS to “mirror” Argonne’s user training courses and enable the APS to directly utilize Argonne’s training management system.

5.5.4. Proposal Review Process

The APS User Program Office plans to run its current proposal submission and review process in parallel with the new (not yet defined) proposal process prior to the MBA storage ring installation period to ensure that the new system meets all necessary requirements. A credible and transparent user-proposal review process is critical to a successful user program. The APS Proposal Review Panels (PRPs) are composed to provide the best possible peer review for beam-time proposals, whether organized by technique- or science-driven expertise. The APS uses 15 PRPs to evaluate general user proposals. The number and make-up of the PRPs have evolved and will continue to evolve in order to best support the changing scientific landscape at the APS.

Discussions with the APS Users Organization, Partner User Council, and Scientific Advisory Committee members have been initiated to assess how the proposal submission and review processes will function as the facility comes out of the dark period.

5.5.5. Training the Future Science Generation

Staff of the APS are and will continue to be strong and active advocates for training graduate students to more effectively and efficiently use U.S. national x-ray facilities. The APS is continually looking for new ways to expand networking and education programs. More than 40% of the experiments at the APS involve participation by undergraduate or graduate students who are generally part of a larger, university-based research team led by an experienced researcher. This hands-on experience helps students learn to formulate new scientific ideas, prepare successful research proposals, plan and conduct experiments, and analyze and interpret data. Postdoctoral scholars, often as principal investigators, participate in over 20% of experiments performed at the APS.

In FY18, several schools were held at the APS including:

- NRS 2018: Nuclear Resonant Inelastic Scattering and Data Analysis (November 2-4, 2018)
- BioSAXS 4: Getting started in biological small-angle x-ray solution scattering (November 7-8, 2018)
- CCP4/APS School in Macromolecular Crystallography: From Data Collection to Structure Refinement (June 17-24, 2019)

The flagship school is the National School on Neutron and X-ray Scattering. For the last 21 years, the APS has co-hosted the school (originally with the former Intense Pulsed Neutron Source at Argonne, now in partnership with the Spallation Neutron Source at Oak Ridge National Laboratory). This program has educated more than 1000 graduate students; some of these former students are now sending their own students to this summer program. School organizers are expanding the curriculum to train potential users of the next generation of high-brightness sources, such as the APS-U.

The APS is continually looking for new ways to expand networking and education programs. In 2019, several hands-on training courses were held in conjunction with the APS annual users meeting including:

- SAXS Software Packages Irena and Nika
- XANES and High-energy Resolution Fluorescence Detection (HERFD) XANES
- X-ray Absorption Spectroscopy Simulations Using FDMNES

The APS staff and resident users at the CAT sectors continue to participate in Argonne's growing Exemplary Student Research Program (organized by the Argonne Educational Programs and Outreach Division) for high school students. Teams of students work closely with APS and CAT beamline staff member to learn about careers in x-ray science and conduct experiments. The APS is always seeking ways to expand this program by leveraging beamlines that have outreach components in their funding profiles.

5.6. Human Capital and Workforce Development

The most important resource of the PSC Directorate is its people; they are the essence of a very dynamic organizational culture. The PSC Directorate, which comprises the three APS operating Divisions (ASD, AES, and XSD) and the APS Upgrade Project, prides itself on a workforce that includes a diverse collection of outstanding scientists, professionals, and support personnel dedicated to scientific discovery and to finding solutions to intractable problems of national and international importance. Attracting and retaining world-class community of talent is essential to maintaining the PSC Directorate's reputation and record of performance.

Identifying, implementing, and integrating workforce strategies throughout the Directorate is a high-priority issue for the PSC leadership. To be successful, the PSC must contend with the many variables that affect the organization's ability to successfully attain its strategic objectives and achieve its mission outcomes. In order to achieve this, the PSC Directorate is strongly committed to talent management approaches that efficiently and effectively attract, engage, and retain the human capital.

To be effective, the PSC Directorate focuses on five key areas:

- Workforce planning
- Organizational capability assessment
- Professional development, career advancement, and succession planning

- Diversity and inclusion
- Change management

In addition to professional development via traditional enrichment paths such as technical conference attendance and participation, Employee Resource Groups (ERGs) at Argonne further personal and professional development, promote diversity within Argonne, and strengthen networking opportunities within the community. Argonne is committed to a diverse and inclusive environment that celebrates the uniqueness of every individual.

The PSC Directorate utilizes a dedicated Diversity and Inclusion Working Group to assist the organization in fostering diversity in its workforce practices and environment, including execution of an annual diversity and inclusion action plan with specific goals and metrics. The PSC Directorate is committed to the highest standards in recruiting, hiring, mentoring, recognizing, rewarding, and providing professional advancement opportunities for all staff members.

The PSC is strongly committed to a talent management strategy to attain its strategic objectives and achieve its mission outcomes. To have an effective talent management strategy the PSC must focus on the following talent management areas over the next five years, with yearly reviews.

5.6.1. Workforce Planning

A process is in place to review Divisional workforce plans routinely throughout the year. This allows PSC management to identify staffing requirements before they become challenges. The PSC Directorate is committed to an annual, comprehensive review of talent capability for both accelerator and beamline operations by using APS and APS-U staffing prerequisites. With this kind of insight, the PSC line managers can direct recruitment, employee development, and retention and recognition resources accordingly, in real time, as issues and needs arise.

5.6.2. Organization Capability Assessment (Talent Discussions)

The PSC Directorate is compelled to better understand its organizational capability, collective skills, expertise, and alignment of people resources. To achieve this, management conducts talent discussions once a year that:

- provides the Directorate executive team with an opportunity to build a shared model of the strengths and weaknesses of its people resources,
- allows the Directorate executive team to prioritize performance improvements from his or her respective areas, and
- provides an opportunity for the Directorate executive team to shape and convey to staff the Directorate performance goals and expectations for each person.

5.6.3. Professional Development and Career Advancement

The PSC Directorate is committed to the professional development of staff member’s knowledge, skills, and abilities required for career advancement. This includes all types of facilitated learning opportunities, ranging from formal coursework to specific conferences and informal learning opportunities. The PSC Directorate uses a variety of approaches to professional development, including coaching, consultation, communities of practice, mentoring, lesson study, reflective supervision, and technical learning.

Frequent and open communication with employees reveals those personal and career development goals that align with the Directorate’s strategic goals. Finding the commonalities means finding a mutual goal and a supportive relationship between the Directorate and employee for achieving it.

5.6.4 Core Values

Argonne's core values help define and create the culture required for the PSC Directorate: a safe, welcoming, and inclusive environment where all can thrive. As the APS continues to expand into new scientific frontiers, Argonne's core values guide us in maintaining a safe and inclusive environment in which our employees and partners can thrive:

Impact: We think creatively, pursue innovative ideas, and deliver excellence to positively change our community, nation, and world.

Safety: We take personal responsibility for the safety, security, and well-being of ourselves, those around us, and our environment.

Respect: We embrace diversity, value the perspectives and contributions of others, and act professionally toward all.

Integrity: We are honest, keep our commitments, and take responsibility for our actions and outcomes.

Teamwork: We include and inspire others, share and communicate openly, and celebrate success as one Argonne team.

These values serve as guideposts as the PSC community comes together to create a safe, inclusive and welcoming environment.

5.6.5. Diversity and Inclusion

The PSC Directorate is committed to working with the PSC Diversity and Inclusion Working Advisory Group, the Argonne Diversity and Inclusion Office, internal ERGs, and other Argonne resources. The PSC Directorate diversity and inclusion activities are organized into four goals delineated in the Argonne diversity and inclusion strategy, and assessed with items from the Argonne 2017 Climate Survey.

- Goal 1 – "Engage," focused on visibility and leadership of diversity and inclusion
- Goal 2 – "Enlist," focused primarily on professional development
- Goal 3 – "Educate," focused on resources, training, and networking to promote diversity and inclusion awareness
- Goal 4 – "Empower," focused on processes and support for diverse recruitment and engagement efforts

"As we strive for excellence in all we do, we need to make sure that we are recruiting, hiring and retaining the very best people — a diverse group of smart, talented and capable men and women who are committed to our mission of delivering new discoveries and innovations that address our nation's most pressing needs in energy, sustainability and security." (Source: www.anl.gov/hr/diversity-and-inclusion)

5.6.6. Change Management

The PSC Directorate is committed to a year-over-year:

- alignment of the organizational structure to strategy (Laboratory/Directorate/Division);
- reduction of complexity of the organizational construct (one important principle kept in mind is not making the roles of the leadership team too confusing or complex);
- focus on better Divisional proficiencies;

- identification of those places where organizational complexity is an issue, where complexity caused by factors such as a lack of role clarity or poor processes is a problem, and what is the responsible course of action; and
- PSC leadership weighing of the work to be done against the load on line managers and staff.
    - Often it is impossible for some managers to focus on leadership tasks because of expected output requirements, so it is important to balance:
        a) staff, directly supervised and managed;
        b) the ability of the staff to do work without any supervision; and
        c) the amount of work that managers must do to stay on top of their responsibilities.

5.6.7. Summary

The PSC Directorate talent management strategy flows from the Directorate mission, vision, values, and goals. This enables every employee to see where she or he fits within the PSC organization.

Within the next decade, the PSC Directorate can expect to see:

- a growing number of retirements from a predominantly mature workforce,
- increased competition for highly skilled employees, and
- a continuing need to balance competing priorities in a fiscally responsible manner.

Developing the PSC workforce take time, energy, and financial investment. So while there are benefits for employees, it is also important to focus on developing those skills, attitudes, knowledge, and behaviors that will influence PSC mission outcomes. Frequent and open communication with employees reveals those personal and career development goals that align with the PSC Directorate strategic goals. Change is the only constant, so change is inevitable.

6. Summary and Outlook

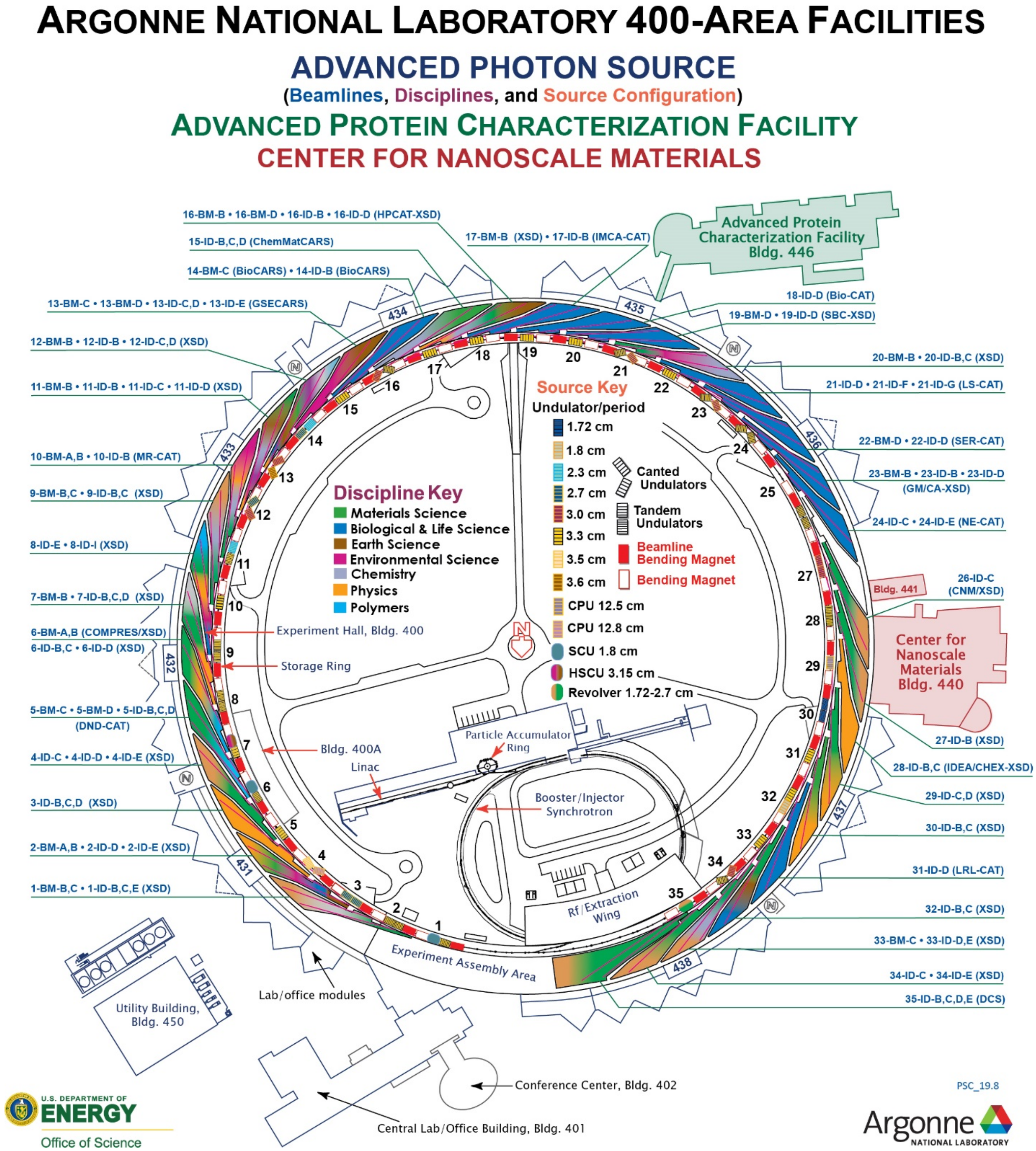
The APS is moving forward to implement a major upgrade that includes installation of an MBA magnetic lattice into the existing storage ring tunnel to increase x-ray beam brightness and coherent flux 100 to 1,000 times. Together with the construction of new beamlines that are optimized for the new source, these upgrades will transform the APS into a fourth-generation storage ring that will revolutionize imaging, microscopy, and nanobeam science as well as high-energy x-ray techniques. The CD-3 approval in July 2019 authorized the APS Upgrade to proceed with procurements needed to build the nation's brightest energy, storage-ring based x-ray source. June 2022 is the target date for starting major installations, which includes replacing the existing storage ring. The PSC has been already preparing the facility for this generational transition for several years by now, but in FY19, the coordination between Operations and the APS-U has reached a mature state and an elevated level of purpose, which resulted in the development of the Interface Portfolio.

Following the implementation of APS-U, APS accelerator and beamline performance, user support, and infrastructure systems will remain world-class. Concurrently, the PSC Directorate will continue to develop its human capital, improve the user experience, and train the future generation of users. To fulfill the APS mission, "The Advanced Photon Source Strategic Plan" serves as a baseline guide that captures these goals over the next five years.

Input to “The Advanced Photon Source Strategic Plan” was achieved through many channels, including discussions with and/or review by DOE sponsors, the APS user community, sister facilities, resident users, APS staff, Argonne leadership, and the broader scientific community. Review was carried out by direct request for input to this specific document. Discussions (both specific to this document and on a broader basis) occurred at regular meetings and reviews (e.g., the APS Scientific Advisory Committee; the APS User Organization; the APS Partner User Council; DOE reviews of APS Operations and the APS Upgrade Project; and the UChicago Argonne, LLC, Board of Governors reviews of the APS), regular international meetings and workshops of the synchrotron and general scientific community, and special workshops that considered future strategic plans for the APS and similar facilities.

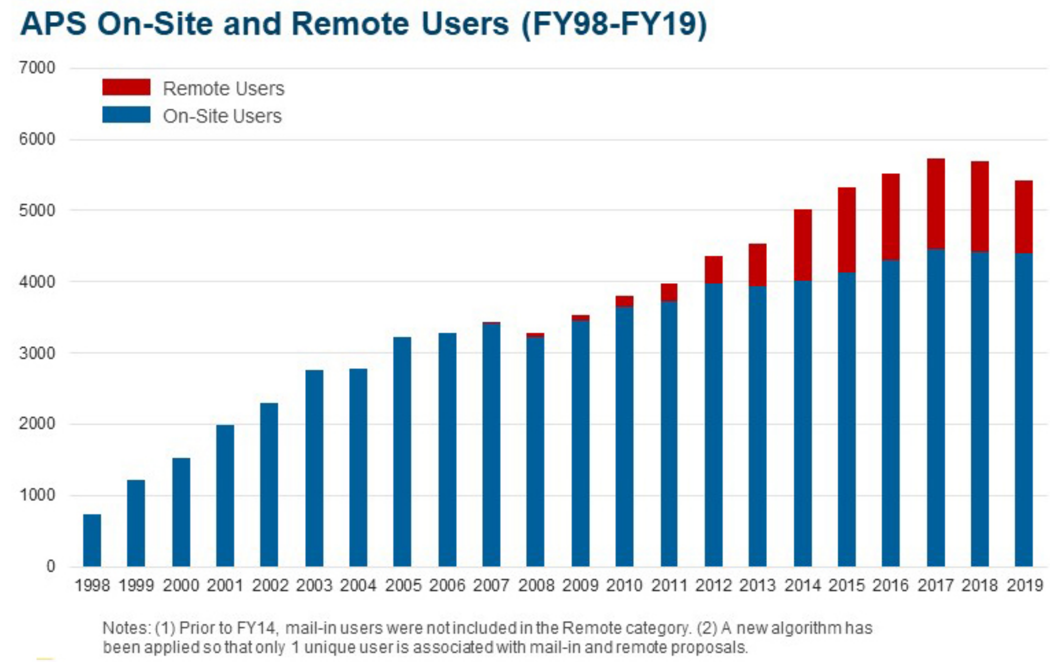
This plan will be reviewed annually and revised on a rolling basis. Updates as needed will accommodate significant changes in funding, shifts in the priorities of DOE, or new research avenues and opportunities.

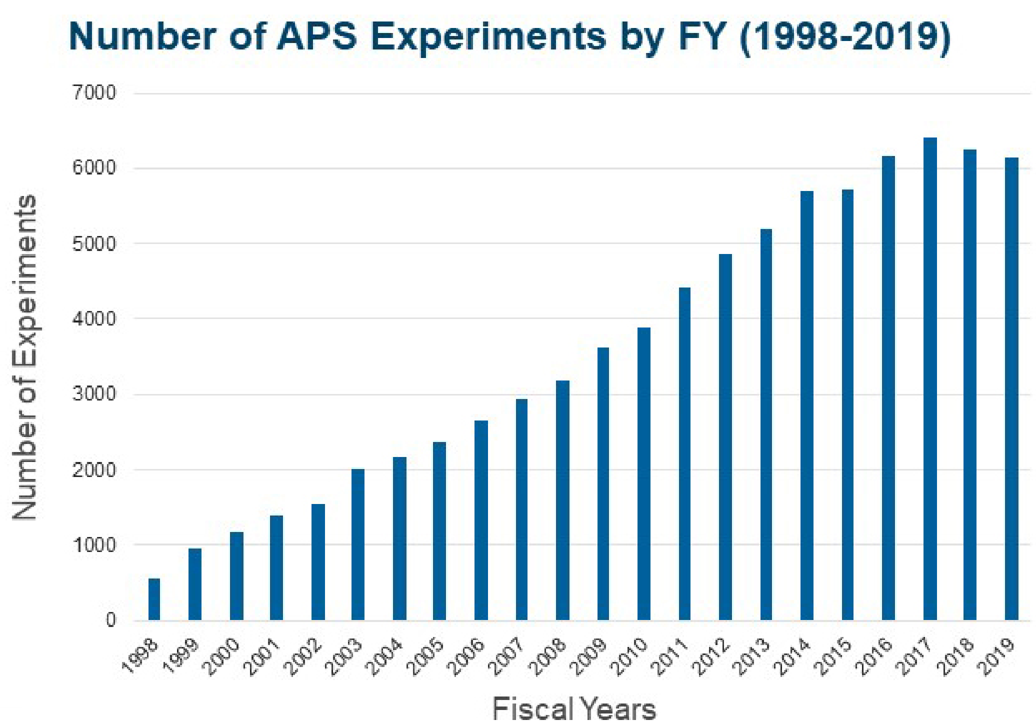
Appendix 1: Beamlines at the APS



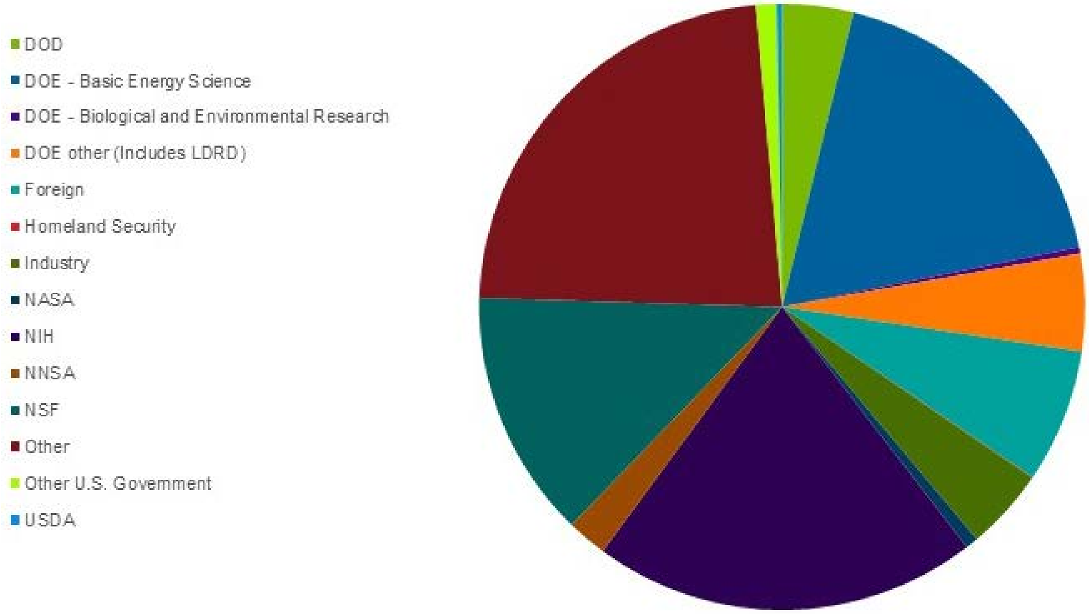
Map of APS beamlines, disciplines, and x-ray sources. There are 68 simultaneously operating beamlines at the APS divided into 47 insertion device and 21 bending magnet beamlines. XSD is currently responsible for a total of 43 beamlines. In addition, the APS is a partner in two additional beamlines: the Dynamic Compression Sector (35-ID) and the CNM Nanoprobe (CNM/XSD, 26-ID). The other 23 beamlines are fully operated by the collaborative access teams.

Appendix 2: User Data



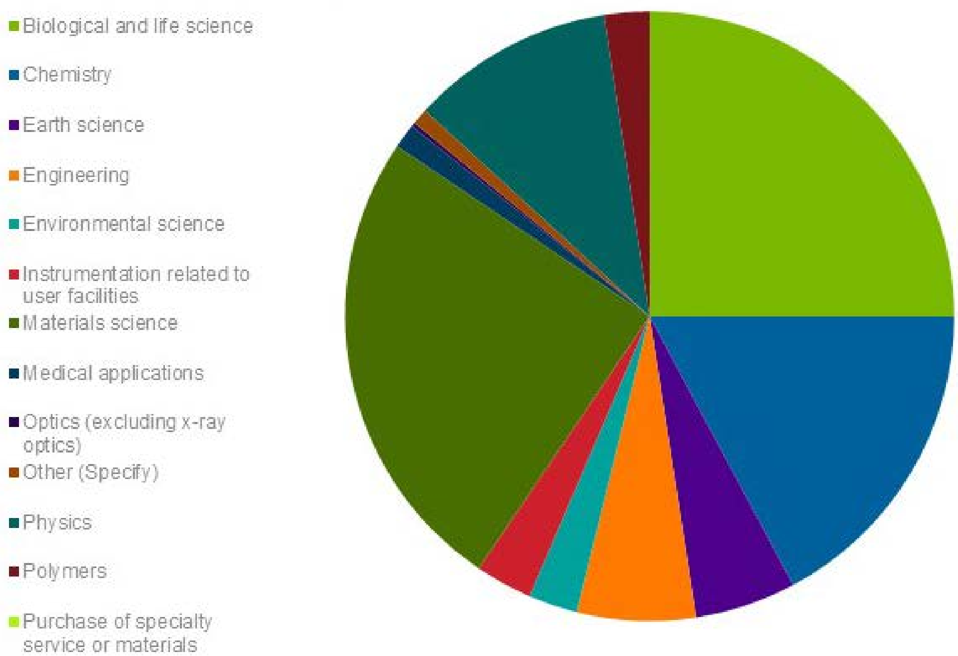


APS Users by Source of Support FY2019



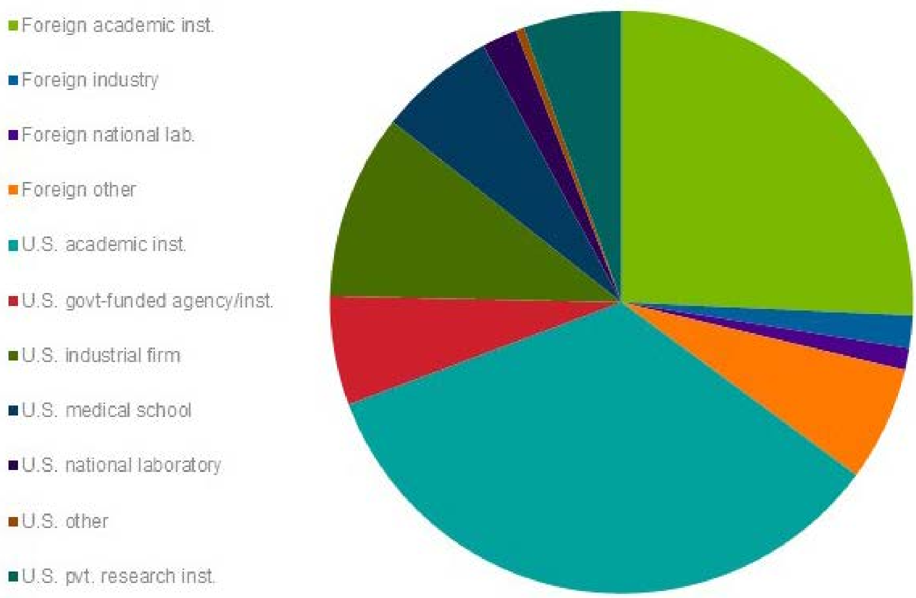
Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.

APS Users by Experiment Subject FY2019



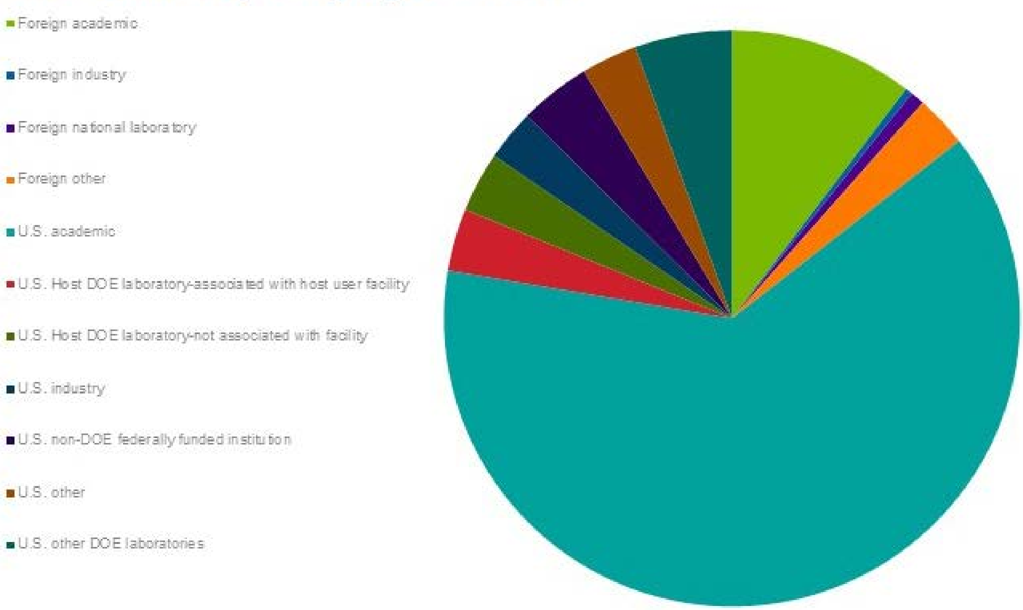
Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.

APS User Institutions by Institution Type FY2019



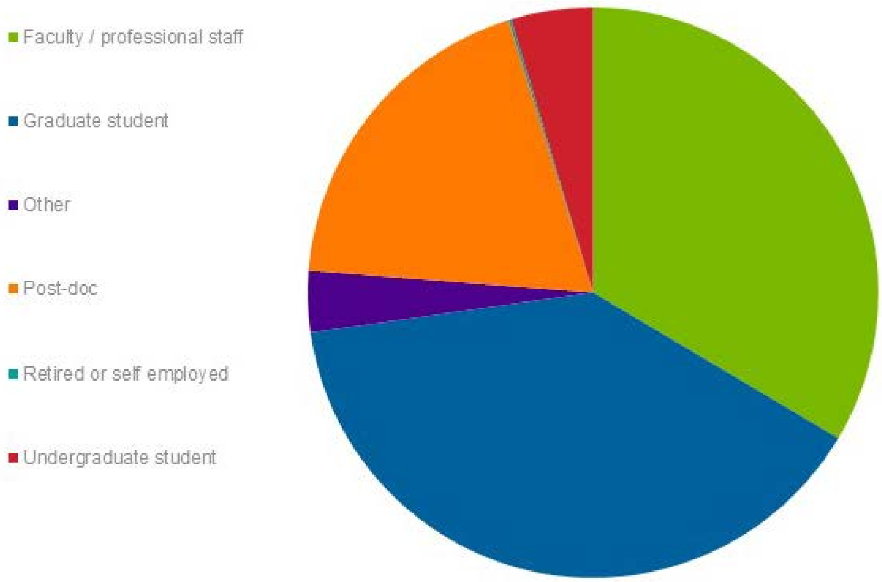
Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.

APS Users by Employer FY2019



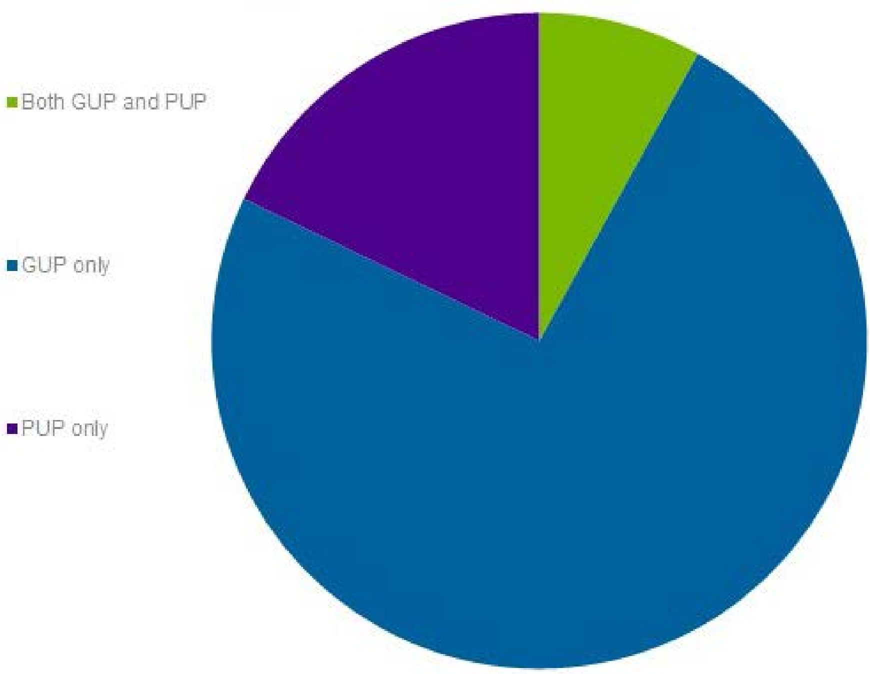
Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.

APS Users by Employment Level FY2019



Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.

APS Users by User Type FY2019



Note: A new algorithm has been applied so that only 1 unique user is associated with mail-in and remote proposals.