The Advanced Photon Source Strategic Plan

Enabling frontier science in the national interest

October 1, 2020

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

The APS 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 *in 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, and has set 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 fourth revision of the previous plan was published (October 1, 2019).

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 mid-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 incorporate 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 an update of the Operations (formerly called Interface) Portfolio that was developed to capture and prioritize APS Operations-funded investments in general maintenance and obsolescence projects, in close coordination with the APS-U. The Operations Portfolio captures 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 of no user beam associated with the installation period of the MBA lattice, which is currently planned to last from June 2022 to June 2023.

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 [LBNL], 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 [BNL]; and one free-electron laser (FEL): the Linac Coherent Light Source [LCLS] 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 two 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 (GM/CA-XSD); two Structural Biology Center (SBC-XSD) beamlines, which are funded by the DOE Biological and Environmental Research program in the Office of Science; and four HPCAT-XSD beamlines, which are funded by the National Nuclear Security Administration.

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 currently 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.

Most of the access to the APS is obtained via a scientific peer review process. In fiscal year (FY)19, the APS supported 5426 unique users (on-site and remote/mail-in) from 48 U.S. states, the District of Columbia, Puerto Rico, and 29 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 2353 papers recorded in The APS Publications Database in calendar year (CY) 2017, 2486 papers in CY 2018, and 2285 papers in CY 2019 reported at the time of this writing (September 2020). Of those, 2033 (CY17), 1966 2193 (CY18) and 2026 (CY19) are peer-reviewed journal articles, with approximately 12% of those years combined in DOE-defined high-impact peer-reviewed 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 is executing a plan to install an MBA magnetic lattice into the existing storage ring tunnel that will increase x-ray beam brightness and coherent flux over current values by approximately 130 times at 20 keV. This upgrade of the storage ring is a cost-effective approach to a "fourth-generation" storage ring as it will reuse a significant portion of the existing accelerator and much of the 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 and beyond), 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 (XSD) Strategic Plans

5. Strategic Focus

5.1. X-ray Operations Improvements and X-ray Techniques Research and Development

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 *in 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 the APS 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. 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 lensless 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

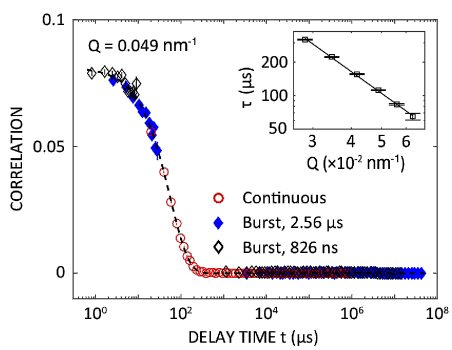


Figure 1. XPCS autocorrelation function measured from gold-silica nanoparticle colloids demonstrating sub-microsecond delay-time resolution. Q. Zhang et al., J. Synch. Rad. **25**, 1408 (2018).

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).

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 *in 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, 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.

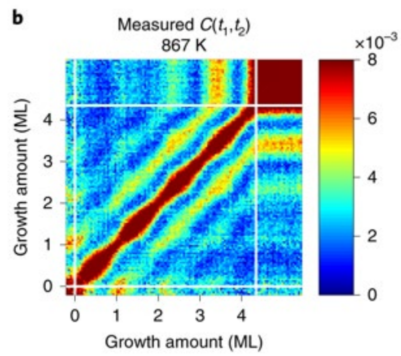


Figure 2. Two-time correlation functions measured from two-dimension islands before, during, and after growth using a pink x-ray beam at 25 keV at the 12-ID-D beamline. Such work will increasingly be enabled by the high coherent flux at higher x-ray energies provided by the APS-U. G. Ju et al., Nat.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

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, spectroscopy, and imaging 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, and is developing advanced software and detection methods to enable spectroscopic timing experiments in 324-bunch mode. 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.

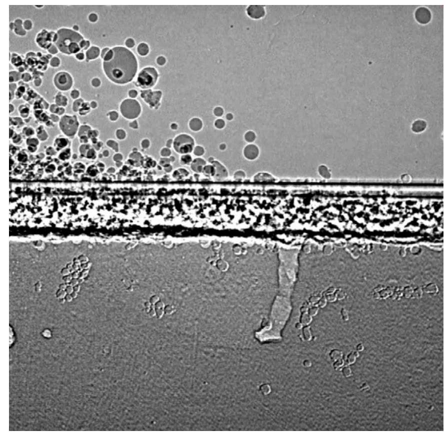


Figure 3. Ultra-fast x-ray radiography of *in operando* metal powder bed additive manufacturing process. R. Cunningham et al., Science **363**, 849 (2019).

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 multimodal inquiries into mission-critical scientific questions such as investigations of structural changes during battery cycling (see Figure 4). Machine learning and artificial intelligence approaches will accelerate data collection and analysis in collaboration with the Argonne Computing, Environment, and Life Sciences (CELS) Directorate and other Argonne Divisions. Specialized support labs will be expanded or developed for on-site sample preparation in dedicated environments for the highest level *in situ* and *in 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.

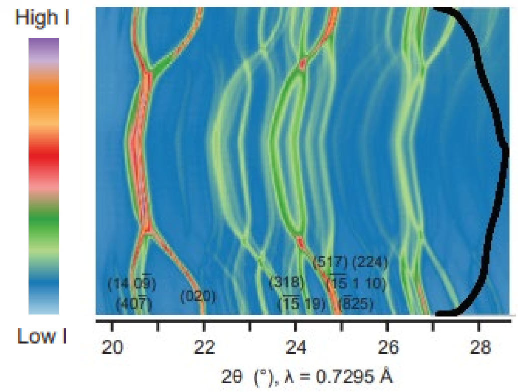


Figure 4. Structural evolution of Nb-W-W battery electrode during *in operando* electrochemical cycling. K. Griffith et al., Nature **559**, 556 (2018). ©2019 Springer Nature Publishing AG

5.1.2. Implementation

To accomplish the goals outlined above, the APS will continue to develop instrumentation and techniques for advancing x-ray science. Furthermore, 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, inverting, 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.

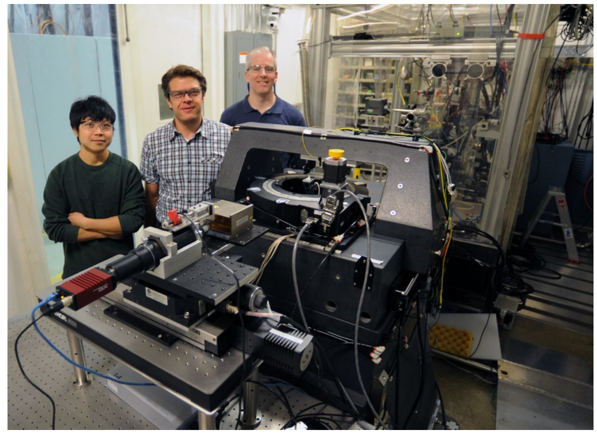


Figure 5. The Velociprobe: A prototype instrument for rapid forward-scattering ptychography measurements developed using novel mechatronic engineering approaches and recently installed at beamline 2-ID-D. J. Deng et al., *Rev. Sci. Instrum*. **90**, 083701 (2019).

To advance data analysis, the APS is pursuing novel applications of artificial intelligence/machine learning (AI/ML) for autonomous experimental control and large-scale data inversion, reduction, and abstraction. For example, the PtychoNN (Neural Networks) approach shown in Figure 6 has the potential to replace the time-consuming conventional iterative ptychographic processes with deep neural networks. This approach has been shown to be up to 300 times faster than conventional methods and may require five times less data, speeding up not only reconstruction, but also data acquisition. Effective AI/ML implementation will require a tight integration with leadership computing facilities (LCFs). Figure 7 shows how the APS leveraged LCFs to generate real-time interactive tomographic reconstructions. This work won the "Top Recognition for an Exemplary Blend of Networking, Computing and Storage" award at the SCinet Technology Challenge, Supercomputing Conference (SC'19). Further advances in these areas will be driven through a mix of operations initiatives, Laboratory Directed Research and Development awards, and submissions in response to DOE funding opportunity announcements.

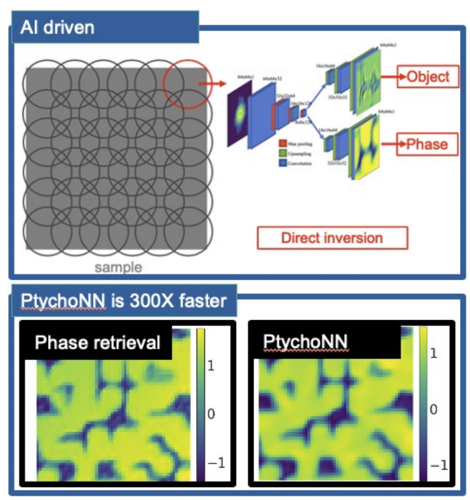


Figure 6. The PtychoNN machine learning approach for ptychography data reduction, and comparison of results to the conventional iterative phase retrieval approach. M. Cherukara et al., *Appl. Phys. Lett*. **117**, 044103 (2020).

The APS has also begun systematically deploying the Brookhaven-developed Bluesky experiment control package at APS instruments. One of the key advantages of Bluesky is its built-in ability to tag measurements with comprehensive metadata that is necessary for the effective application of AI and ML. Bluesky also facilitates adaptive control, so this feature, combined with data streaming to LCFs and AI/ML, will allow experiments to execute advanced analysis that will autonomously identify the most significant volumes in a sample and drive instruments to those regions in real-time. Together, these thrusts will enable innovative x-ray techniques and scientific approaches that are orders-of-magnitude faster, more dose efficient, and more sensitive than those available today.

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 the Center for Advanced Mathematics for Energy Research Applications, the NSLS-II, the LCLS, and the SSRL to develop and employ common software tools. The first deliverable for this project is focused on integrating and deploying a common XPCS software suite—Bluesky from Brookhaven, XPCS-Eigen from Argonne, PyDM from SLAC, and Xi-CAM from Lawrence Berkeley—at all the BES light-source XPCS instruments, with tomography and ptychography to be examined next. Collaborative strategic directions are developed and promulgated through APS leadership of the Light Source Data and Computing Steering Committee and the Light Sources and Computing and Networking Facilities Data Working Group.

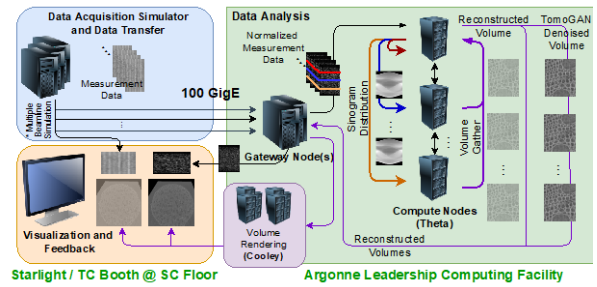


Figure 7. Utilization of the ALCF Theta supercomputer for tomography reconstruction at SC19. Tomography data acquisition is simulated at Denver (conference site), transferred to and processed on-the-fly at ALCF; reconstructed data volumes are visualized on the conference floor.

In parallel to the longer-term computing objectives described above, the ongoing COVID-19 pandemic has placed an emphasis on the rapid deployment of remote experimental control mechanisms for users. During the latter half of FY20, the APS began implementation of a remote access mechanism using the NOMACHINE NX software suite to allow users to view and control beamline instruments and run experiments remotely. Additional software tools have been developed to allow APS beamline staff to manage user access to beamline resources compatible with the operational environment of the beamline and consistent with overall access approval coordinated by the APS User Program Office. To date, the APS has deployed this solution to ~50 beamline workstations; during the coming fiscal year, this will be deployed to the full suite of XSD beamlines and augment the management system to fully meet needs identified by the beamline staff.

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. Effort is also being directed toward the production of multilayer optics suitable for high x-ray energies. An additional focus is updating tools such as the long-trace profiler (LTP) and interferometer systems to be ready to characterize state-of-the-art mirrors for the APS-U and beyond. Figure 8 is a model of the upgraded LTP that will be able to measure APS-U-quality mirrors and beyond in a variety of orientations with vastly improved control and processing software than is available today. Another thrust is further development of advanced beamline optics simulation and optimization software that include the ability to simulate heat loads and their effect on x-ray optical-system performance. These tools, coupled with planned further enhancements in optical/at-wavelength characterization techniques are critical tools for improving optics and, ultimately, beamline performance.

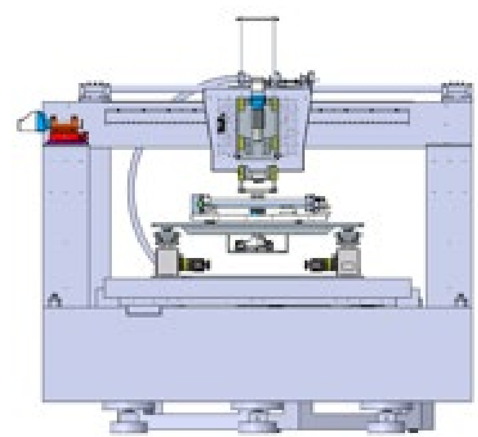


Figure 8. Design for an upgraded LTP capable of measuring APS-U-quality mirrors in their holders and in a variety of orientations, i.e., horizontal and vertical (upwards and downwards facing.)

Considerable APS work in x-ray optics is performed in collaboration with other light sources. A goal in many of these collaborations is testing and developing optics concepts relevant to diffraction-limited light sources. A recently concluded project demonstrated adaptive correction of a mirror profile based on interferometer measurements, while a new DOE-BES-funded collaboration with LBNL, SLAC, and BNL will investigate the applicability of cryogenically cooled mirrors for such sources. Because of the novel properties of silicon near liquid-nitrogen temperatures, such mirrors promise enhanced brilliance-preserving performance under high power densities, but mitigating the vibration issues associated with the flow of cryogens is a long-standing challenge that this research program seeks to address. Another collaborative goal is research to inform the possible next generations of light sources. Specifically, the APS and SLAC are executing a project to perform proof-of-principle demonstrations of a cavity-based x-ray free-electron laser (CB-XFEL) that could ultimately be capable of producing fully coherent x-ray pulses. X-ray Science Division work in this area is focused on obtaining and characterizing essentially perfect diamond crystals (Bragg reflectors), micron-level relative positioning and control over large distances (10–100s of meters), and performance testing of suitable beam position monitors (BPMs).

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 these areas are the mixed-mode pixel array detector (MM-PAD) in collaboration with Cornell University; evaluation of germanium, cadmium zinc telluride, and perovskite high-Z sensors in collaboration with BNL, Cornell University, Northwestern University, and SLAC; and transition-edge sensors for high-energy-resolution emission detection applications for hard x-ray research in collaboration with the National Institute of Standards and Technology.

Current x-ray experiments are often detector-limited rather than source-limited, with available detectors unable to take full advantage of the bright, high-energy x-ray beams produced by modern synchrotrons. The mixed-mode pixel array detector (MM-PAD) is a collaborative project between the APS and Cornell University that seeks to address these shortcomings by producing an instrument that addresses this gap in four ways: 1) high dynamic range per frame; 2) low noise over the full dynamic range; 3) high frame rate (> 1 kHz); and 4) high stopping power for hard x-rays.

The continued desire for x-ray pixel detectors with higher frame rates will stress the ability of detector designers to provide sufficient off-chip bandwidth to reach continuous frame rates in the 1-MHz regime. Moving in a linear approach from 10 kHz (~ current maximum detector frame rates) to the ~1-MHz frame rates desired by many APS-U beamlines would require an unsustainable number of power-hungry, high-speed transceivers at the edge of a detector chip. Instead, in collaboration with staff at Argonne's Mathematics and Computer Science (MCS) Division, new strategies are being developed to make the most efficient use of off-chip bandwidth by utilizing data compression schemes for photon-counting and charge-integrating pixel detectors. Recently, two compression schemes have been implemented that increase the effective off-chip bandwidth by a factor of 6×, 10×, and 12× for high-energy x-ray diffraction, ptychography, and XPCS. Additional compression algorithms that can still better exploit statistical redundancy in space and time will be explored to further improve compression ratios.

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 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 2021 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;
- expanding remote operation and automation capabilities of beamline instruments;
- supporting the APS-U Project in completing construction, and commissioning the APS-U Instrumentation, Development, Evaluation & Analysis (IDEA) and Advanced Spectroscopy and LERIX (Lower Energy Resolution Inelastic X-ray Scattering) beamlines, implementing a long-range R&D plan for optics and instrument testing on the IDEA beamline, initiating construction of the Polarization Modulation Spectroscopy beamline, and continuing to work developing the full suite of APS-U feature beamlines and enhancements;
- completing the canting of the 2-ID beamline to enhance brilliance-driven capabilities, and beginning the user program for the high-throughput high-energy diffraction microscopy instrument at 6-ID-D (a National Science Foundation-funded partnership led by Carnegie Mellon University) to provide expanded high-energy capabilities;
- further deploying computational methods and data handling approaches integrated into the experimental workflow, including Bluesky, the APS data management system, streaming data analysis, and machine learning, and exploring the applicability of edge computing to augment real-time data reduction;
- completing the deployment of the hard x-ray transition-edge sensor, energy-dispersive, multi-pixel detector; deploying the MM-PAD v2.1 with silicon and cadmium telluride sensors; and continuing the development of on-chip compression methods;
- upgrading metrology capabilities to be APS-U ready, applying the modular deposition system for fabrication of high-energy multilayer optics, and investigating the applicability of cryo-cooled mirrors for high power density applications at next-generation light sources; and
- addressing on-going obsolescence issues at the beamlines through a coordinated multi-year plan to replace key components, such as monochromator cryopumps, 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 the 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 those 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.

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 linear accelerator (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 or obsolete technologies. The ASD is currently implementing a plan to update as much of these systems as possible before the MBA 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 MeV to 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 for independent processing of rf components such as linac structures, waveguide windows, and SLAC energy doublers, and testing of 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 3.8-m-long SCU using superconducting NbTi wire and a thin-wall 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 9). 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. A scheme is being worked on for switching polarizations for a user beamline from two devices by varying the beam orbit.

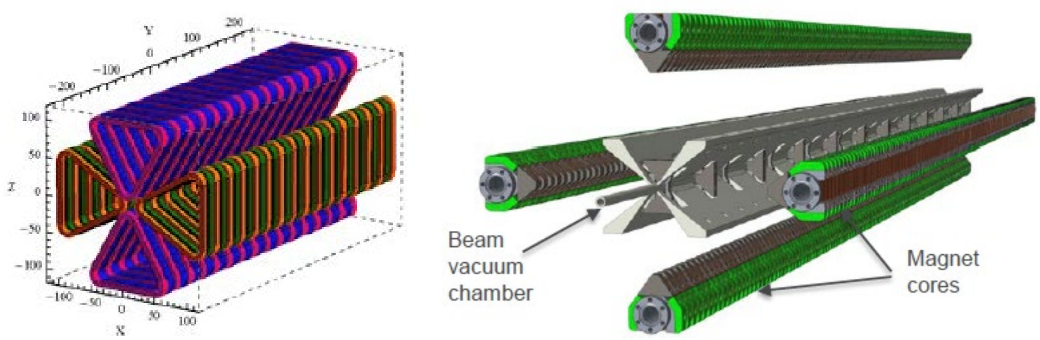


Figure 9. (Left) The Radia Model for the SCAPE SCU magnets. Horizontal and vertical fields are shifted by a half period and can be powered arbitrarily, allowing variable polarization. (Right) A mechanical drawing of the SCAPE assembly. The x-wing vacuum chamber allows extraction of heat generated by 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.

The strategy 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 has led to a design consisting of a combined network of individual 2-kW amplifiers with a total power of up to 200 kW. These efforts have included purchase of a 30-kW prototype from industry that passed a series of tests over the past year with flying colors. In addition, both cavity and waveguide combiner networks were tested using a 30-kW amplifier and a klystron in a "back-feed" mode where 200-kW power was fed into the output of the combiner network. All tests performed within expectations. The cavity combiner configuration (Figure 10) has been selected and the first 200-kW unit has been fully specified and is currently out for bid from industry. The next step will be to prepare the APS infrastructure for installation and testing of this unit in the APS storage ring before the APS-U installation period. A nominal plan has been developed for procurement of two solid-state units per year following the storage ring demonstration that will allow for replacement of the current klystron-based system before the stock of klystrons is depleted.

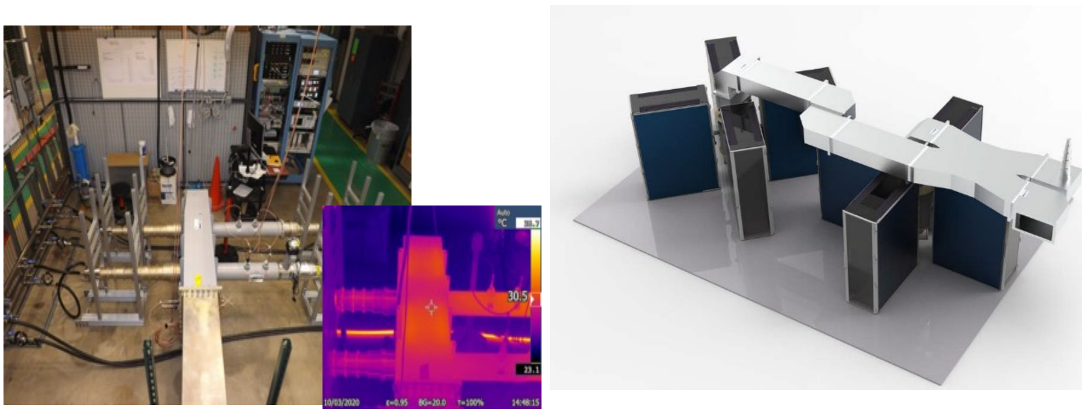


Figure 10. (Left) The photo shows the "backfeed" test of the waveguide combiner. The inset shows an infrared photo indicating rf heating of the network. Results were in excellent agreement with modeling. (Right) The rendering shows the concept for a 200-kW amplifier. Each rack contains 15 2-kW amplifiers that are combined in the combiner cavity hidden below the waveguide. The first prototype amplifier was tested on the combiner cavity late in 2019.

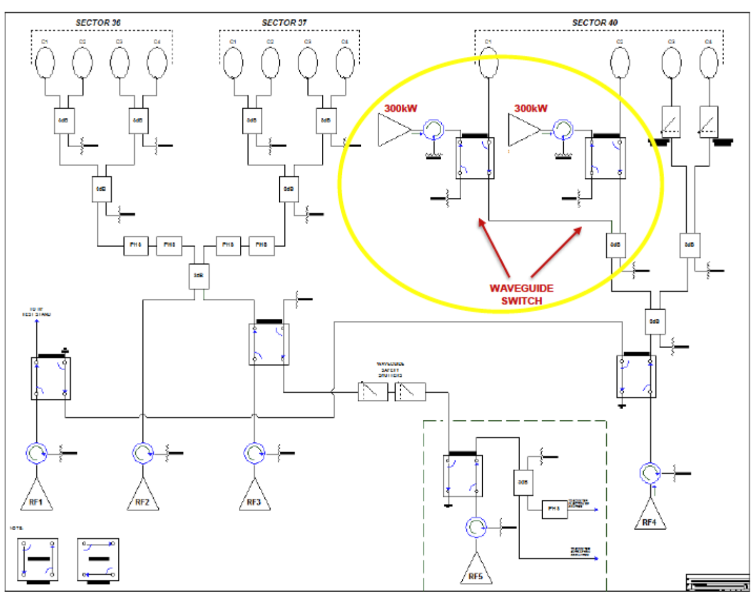


Figure 11. The transition plan to solid-state rf amplifiers will occur over the decade beginning from 2021. The schematic above shows the planned hybrid configuration of the rf system in 2023, following the APS-U installation.

Another area of emphasis is addressing obsolescence issues in the various rf systems in the APS storage ring and injectors. A number of improvements to the particle accumulator ring harmonic rf system are being implemented that will enable the higher stored bunch needed for APS-U operation. An initiative to upgrade the APS linac rf systems has also begun. These improvements include:

- gradual replacement of the aging, home-built, pulsed high-voltage modulators with commercial modulators;
- gradual replacement of the current linac klystrons with higher peak-power klystrons;
- upgrade of the obsolete linac hybrid, analog, low-level rf controls with modern digital controls;
- upgrade of the obsolete timing controls to a system more compatible with the upgraded APS-U timing system;
- general replacement of other obsolete linac systems including power supplies and some diagnostics as needed; and
- set-up of a linac rf test stand to allow testing and conditioning of rf components without potential interruption to APS operations.

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.

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. The Group's primary Operations goal is to provide reliable performance of diagnostic instrumentation up to the APS-U installation period and beyond. For the APS-U, the focus is on completing the final design for all systems including BPMs and BPM electronics, orbit and multi-bunch feedback systems, beam-size monitors, current monitors, and APS-U-specific injector upgrades including the booster-to-storage ring transport line redesign. Through the APS-U installation and commissioning periods, it is also planned for Operations-related injector upgrades to address various instrumentation obsolescence and reliability issues. Part of these upgrades will include new BPMs and current-monitoring electronics for the linac, particle accumulator ring, booster, and transport lines; new linac beam-rf phase detectors for linac phase feedback; and the current monitor interlock as part of the radiation safety system. Finally, the plan is to leverage injector instrumentation upgrades to support the Linac Extension Area such as using the new BPM and current monitor systems developed for the linac and transport lines.

5.2.3.5. Accelerator Operations and Physics

The Accelerator Operations and Physics Group (AOP) 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 Group mission, but now it is the responsibility of the separate Main Control Room Group within the ASD. The AOP Group stresses thorough automation of machine operation and analysis, since these are the keys to high reliability. For example, the AOP Group 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.

In preparation for APS-U operation, the AOP Group and other Groups in ASD are using the existing APS to simulate APS-U conditions in several key areas. One of the important issues to better understand 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 vacuum chambers. Thermal analyses of beam strikes on a collimator have shown that the beam power density is sufficiently high to melt the collimator and essentially drill through the material. Over the past two years, a series of experiments were jointly conducted by the AOP Group and the ASD Diagnostics Group, where 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. Figure 12 (left) shows 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 12 (right) is a picture of the test collimator after an extended study following beam strikes at varying current levels. This section is under metallurgical analysis. Experiments and analysis continue in order to understand this effect in detail.

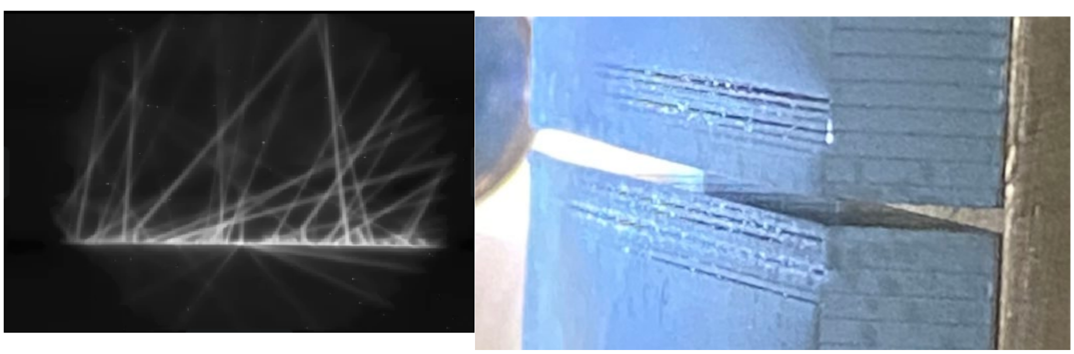


Figure 12. (Left) The test collimator during a beam strike captured from a frame of the recorded video. Beam moves from left to right. Ejecta are observed as small flares from the molten metal. (Right) A picture of the test collimator after an extended study following beam strikes at varying current levels. This section is under metallurgical analysis.

Another area of focus in preparation for the APS-U is the subject of beam-ion instabilities. In this instability, ionized gas molecules resonate in the electric fields of the electron beam, causing electron beam motion and eventual emittance growth. Simulations of this effect (see below) show that the beam-ion instability could be a problem for the nominal 324-bunch fill pattern for the APS-U. One proposed solution that appears to solve the problem is to modify the fill pattern with small gaps to disrupt the ion motion and “guard” bunches (i.e., larger bunches at the edges of the gap) to mediate the beam loading transients induced by the gaps. Although this solution is effective in simulations, the aim was to demonstrate the effect experimentally using the existing APS storage ring. In the experiment, an intentional gas leak of N_2 gas was added to the storage ring in the Sector 25 straight section to raise the local pressure by two to three orders of magnitude. Strong vacuum pumping on either side of the straight section limits the pressure “bump” locally. A schematic of the experimental setup is shown in Figure 13. This setup allows injection of nitrogen gas and creates a condition where a beam-ion instability can occur. One of the signatures of the instability, which typically first occurs in the vertical plane, is the electron beam oscillating at the characteristic ion frequency. Shown also in Figure 13 (right) is a plot of the vertical betatron sidebands during an ion instability, with the peak of the spectrum near 3 MHz to 4 MHz. This measurement was done at a range of currents up to 200 mA. A test of the guard bunch fill pattern for the same conditions shows no instability, providing strong support for the proposed mediation plan for the APS-U. Further studies will continue with the goal of further characterizing the beam-ion instability.

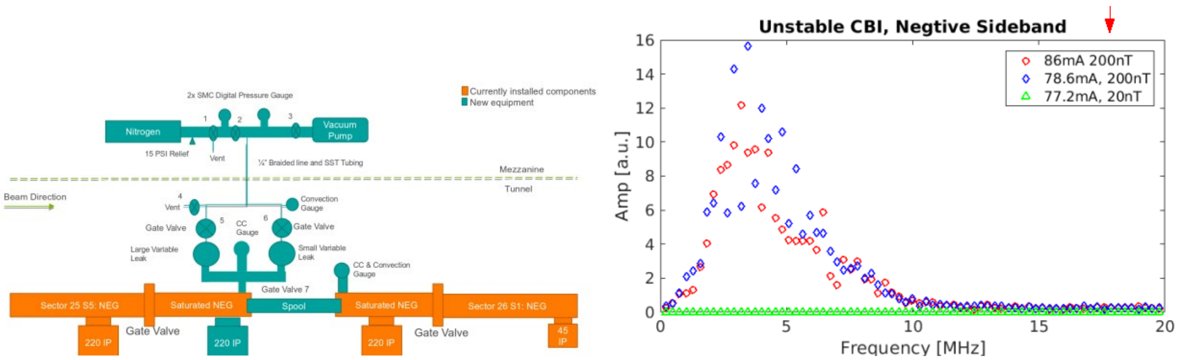


Figure 13. (Left) A schematic of the gas injection setup for a controlled leak in Sector 25 of the storage ring. Strong vacuum pumping on either side of the injection limits the vacuum “bump” to a small region. (Right) The spectrum of unstable vertical sidebands at increased vacuum pressure. The peak between 3 MHz to 4 MHz corresponds to the expected ion frequency for these beam conditions.

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 Group 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 the APS-U. One of the highlights over the past year has been the addition of a new module, **ioneffects**, that includes the creation and motion of ionized gas species for the modeling of beam-ion instabilities described above. This module includes the detailed vacuum profile of the accelerator as determined from other codes such as MolFlow. Specific future plans for **elegant** include adding electron beam polarization tracking and 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.

5.2.3.6. Main Control Room Operations

The Main Control Room (MCR) operations staff serves on the front line of the operations of the APS accelerator systems and are responsible for operation of the entire accelerator complex. Over the past year, the MCR operations staff was moved to its own Group in order to improve its visibility within the ASD and the APS in general. The MCR staff maintains beam stability and stored beam injected current. It operates all of the injection system (linac, particle accumulator ring, and booster) and the main storage ring. The MCR is primarily tasked with prompt recovery of beam upon a loss as well as general communication of beam status with users, but also is responsible for:

- user steering and beam optimization,
- group Lockout-Tagout (LOTO) and operation of the Access Control Interlock System to prevent personnel exposure to ionizing radiation,
- approval and coordination of work performed on the accelerators,

- coordination between various technical groups,
- reviewing and authoring dozens of procedures for operation of the various technical groups, and
- implementing policies and operating standards as set forth by the machine managers.

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. Each of these are highlighted in the sections below.

5.2.4.1. 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. Nb_3Sn superconductor has an excellent record of development in high-field magnets for applications in high-energy physics. For this reason, the Division has partnered with Fermilab for this program; this sister DOE lab provides expertise for heat treatment of the wound SCU cores. Testing of a 0.5-m prototype is under way with the goal of beam test in the APS by installing a 1.2-m device in place of an existing SCU prior to the APS-U long shutdown. Shown in Figure 14 is a recent photo of the treated SCU core. Extra care has been taken to treat the core with an insulating material (the white coating) and for extra fine machining to avoid any damage to the sensitive Nb3Sn wire.

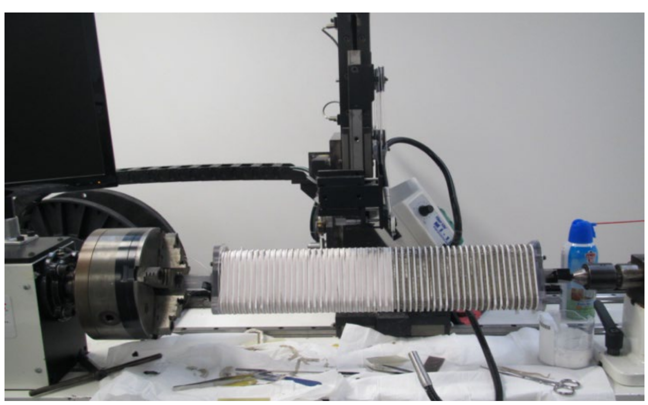


Figure 14. Shown here is a magnet with mica insulations, during winding.

5.2.4.2. Cavity-based, x-ray free-electron lasers

With the advent of the high-repetition-rate x-ray FEL lasers such as the 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-II Hard X-ray Research (HXR) FEL, and using it with the high-repetition-rate superconducting linac when available.

A detailed schematic of the proposed cavity-based x-ray free-electron laser (CBXFEL) scheme is shown in Figure 15. The electron beam passes through an undulator. Some of the lasing x-rays created resonate in the optical cavity with a path length corresponding to the distance between electron bunches. As the optical cavity fills, the interaction of the x-rays with the electron beam improves the longitudinal coherence of the x-rays, similar to an optical laser. The challenge is that, to fill the cavity, diamond mirrors of extremely high quality are required; challenging as well are the mechanical tunability and stability of the mirrors. As an initial test, the plan is to operate the LCLS copper linac with two bunches in a pulse with a separation equal to the cavity path length.

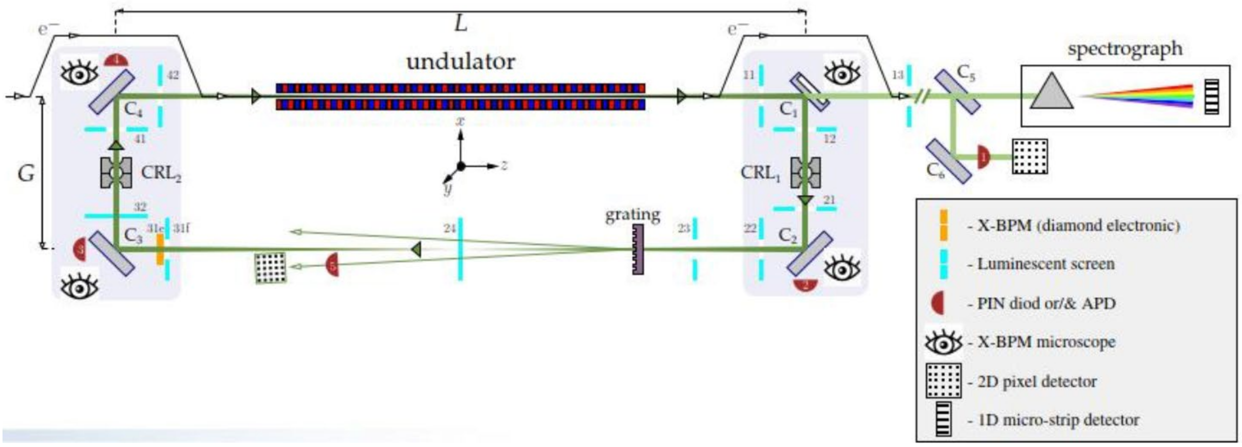


Figure 15. A schematic diagram of the CBXFEL setup planned in the LCLS HXR FEL line. Small chicanes bring the electron beam around the diamond mirrors into the optical cavity. The path length of the cavity is adjusted to be the distance between electron bunches. Each of the mirrors is mounted on nanopositioning actuators to allow tuning of the cavity. The cavity is fully instrumented to diagnose the performance.

5.2.4.3. High average brightness photoinjectors

Argonne has adopted the superconducting rf gun originally developed at the University of Wisconsin-Madison as part of a BES-funded R&D project with the goal of using the existing cryoplant in the Argonne Physics Division Accelerator Development and Test Facility (ADTF) to complete the demonstration and characterization of this gun. The gun was shipped to Argonne in December 2019 and is undergoing modifications to allow connection to the ADTF cryoplant and preparation for first cool-down by the end of 2020. Shown in Figure 16 is a cross-section schematic of the gun and cryostat along with a photo of the gun in the Physics Division clean room undergoing preparation.

The first phase of studies will focus on characterizing the maximum accelerating gradient in the structure, understanding the thermal load of the cathode and supporting stalk, and operation in closed-loop refrigeration. When complete, preparations will begin for beam studies to characterize the electron beam emittance and energy gain from the gun using components from the beam transport equipment that came with the gun.

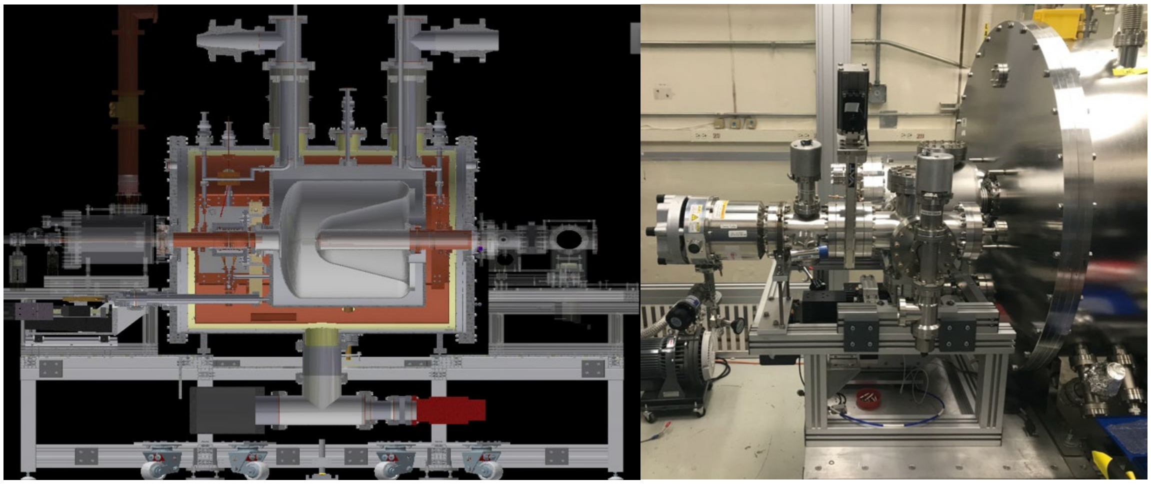


Figure 16. (Left) A rendering of the University of Wisconsin-Madison FEL gun. (Right) A photo of the gun under preparation in the Physics Division clean-room facilities.

5.2.4.4. Compact Accelerators for Future Light Sources

There has been tremendous progress in compact acceleration schemes over the past decade with concepts ranging from laser and beam-driven plasmas to dielectric and corrugated wakefield acceleration. The vision at Argonne has been focused on high-gradient compact accelerators that provide high energy transfer efficiency, relatively low fabrication cost, and sufficient beam quality for lasing in an FEL with a path towards high repetition rates of tens of kHz and the eventual goal of a lower cost, multi-user x-ray FEL facility that can address the most pressing problems in science. The concept, funded by Laboratory Directed Research and Development awards, is to use a high-frequency (180-GHz) collinear wakefield accelerating (CWA) structure based on a corrugated circular waveguide. A large drive bunch creates a wake that accelerates the trailing witness bunch. A schematic of the concept is shown in Figure 17. A high-repetition-rate electron gun creates a drive and witness beam, which is accelerated to 1 GeV in a superconducting rf (SRF) linac. However, from there the beam is switched into an array of compact CWAs where it is accelerated to higher energy and fed into individual FELs. A photo of a sample corrugated CWA structure is shown in Figure 17 (right).

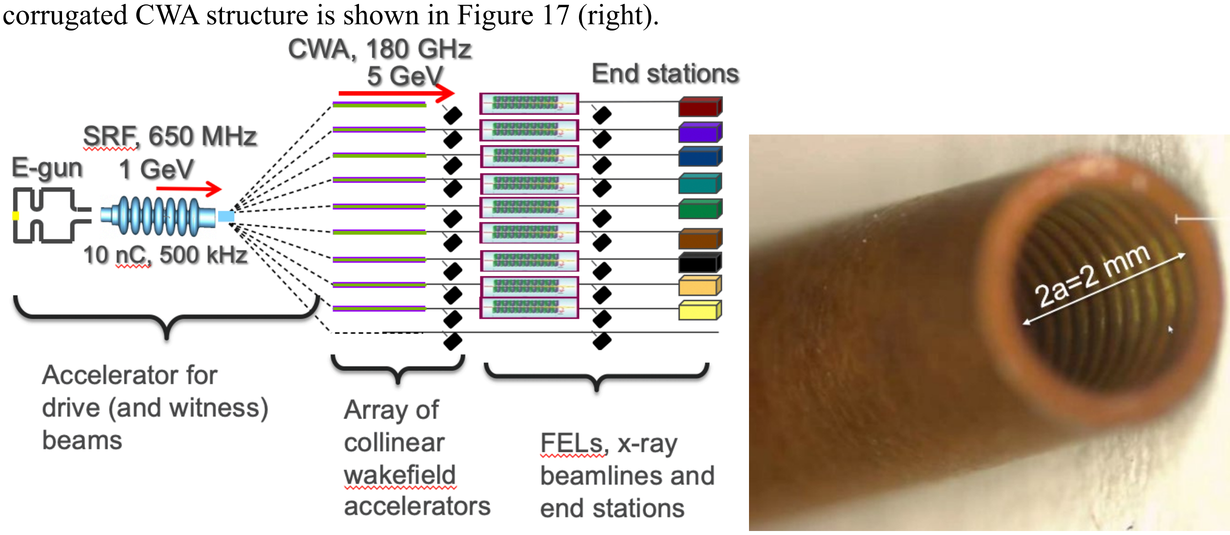


Figure 17. (Left) A schematic view of the vision for a compact multi-user FEL facility. (Right) Photo of the corrugated accelerating structure fabricated using electroforming techniques.

Recent work has focused on the fabrication and characterization of this structure. Each accelerating module is envisioned to be a 0.5-m length of corrugated waveguide made with electroforming techniques. Each structure is attached to water cooled copper fan-blocks, which is then embedded in a quadrupole wiggler (QW.) The QW is critical since it provide a periodic FODO array that stabilizes the drive beam from beam breakup instabilities. Each module is being designed to provide about 50 MeV of acceleration. Engineering drawings of each of these pieces are shown in Figure 18. Each 0.5-m accelerating section is connected with a transition section that serves to provide beam position measurements and extract higher-order-mode power from the beam, as well as mechanical bellows.

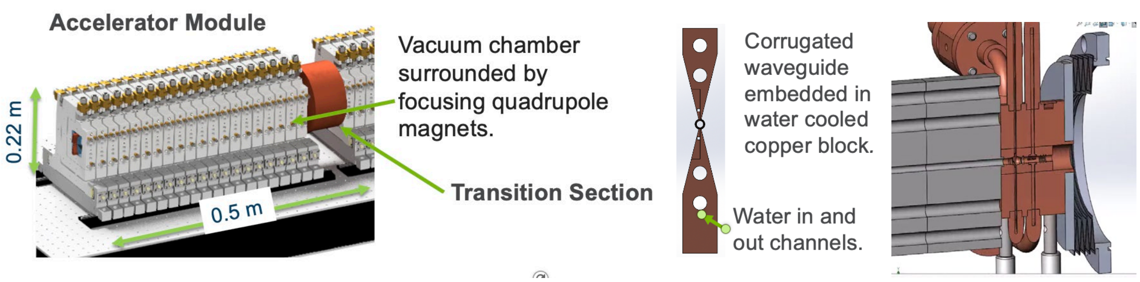


Figure 18. (Left) An engineering computer-aided design drawing of a 0.5-m accelerating section. The vacuum chamber is surrounded by the periodic array of miniature quadrupoles (the quadrupole wiggler). (Middle) The 2-mm-diameter CWA is embedded in a water-cooled copper block that allows operation at higher bunch repetition rate. (Right) Each accelerating section is connected via a transition section that provides higher-order-mode damping and beam position measurement.

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 PSC management through a variety of Argonne-wide initiatives, such as the creation of an Electrical Safety Manual and revised Qualified Electrical Worker training in FY18. These were followed by initiatives in FY19 that saw the creation of a Work Planning & Control Manual and a Controlling Hazardous Energy Manual.

Local PSC Directorate safety augmentations include increased observation/conversations; SMART-card targeted observations rolled out across the directorate; continuing use of the pre-job brief; and high-risk work reviews supported by a register to capture and communicate high-risk work, which was adopted by Argonne as the High-Risk Work Register and is now known as the Management Awareness Tool. Improvements to work planning and control were implemented in FY18 with an overhaul of the governing policy/procedure in order to match fundamental Integrated Safety Management tenets and inclusion of the 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, operation, 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 19].

The projects identified by the needs assessment 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.

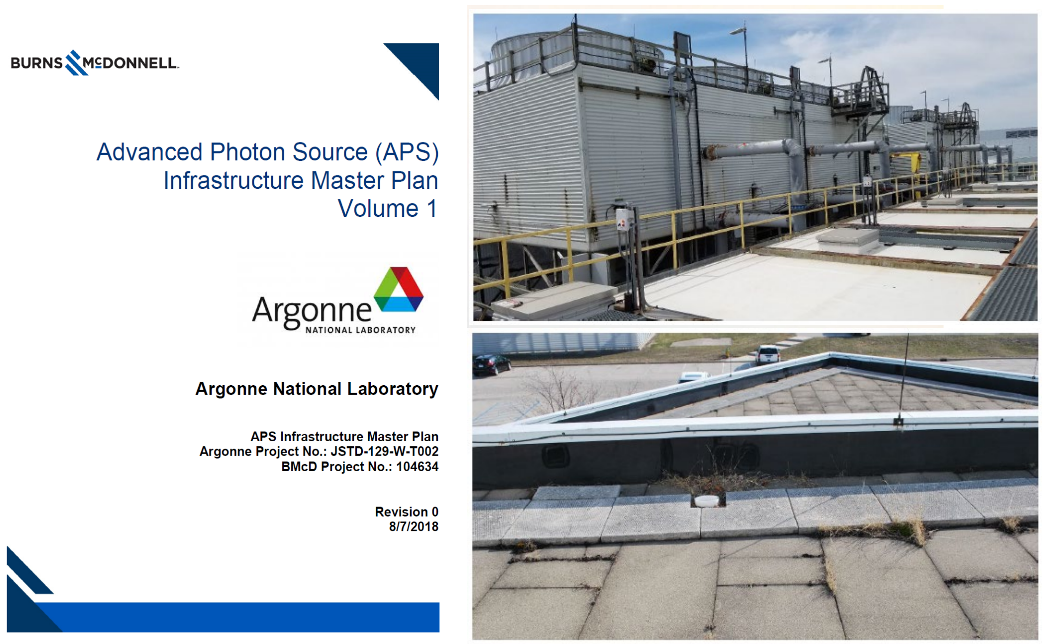


Figure 19. (Left) The cover of the "Advanced Photon Source (APS) Infrastructure Master Plan Volume 1." (Right) Examples of repair/replacement projects such as the APS cooling tower bank (upper right) and storage ring roof (lower right).

Significant progress has been made 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 at the time of this writing is approximately 70% complete, with a target completion in FY21.

The cooling tower replacement and upgrade effort has started in earnest with the installation of a redundant cooling tower bank in FY20, the first of three major replacements.

Improved chilled water filtration and chemical treatment contracts were awarded to a vendor in August 2019 and completed in FY20. Total conversion of experiment hall lighting to LED was completed in FY20 and was expanded to include the retrofit of the storage ring mechanical-mezzanine lighting to LED by the end of FY20.

The PSC Directorate also continues to reduce the storage space footprint as an additional initiative to control and reduce levied space charges. In FY19, a significant and concerted effort was expended to realize a 26% net reduction (approximately 9565 square feet) in storage space in the 300-series buildings.

In FY20, a significant effort was completed to create storage space in Building 378 for klystrons and other equipment that required relocation from Building 400A, so that a mezzanine could be constructed for an APS-U Project material receipt and specialized testing footprint (Figure 20).

Figure 20. Shown at left is Building 400A in February 2020, used primarily for testing. The center image shows the same space after all material was consolidated and relocated in Building 378 in June 2020. The right image shows the mezzanine construction for the APS-U as of late July 2020.

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

- The APS is upgrading its fiber optic complex in preparation for APS-U-era networking needs. Networking to each laboratory/office module (LOM), to which beamline networks are connected, is being upgraded to 4 x 48 strands of single-mode fiber. The LOMs 435-438 have been upgraded and LOMs 431-434 will be upgraded in FY21.
- Multiple beamlines had local networks upgraded to provide numerous 10-Gbps host connections and 2 x 40-Gbps active redundant uplinks to the core switch. For new and upgraded beamlines, additional network switches were added to hutches to provide improved data separation and a more efficient network topology.
- The IT Group now supports 34 DM virtual servers (VMs) for XSD, and has started working with the XSD Scientific Software and Data Management Group deploying DM VMs for CAT sectors. These VMs coordinate moving data from beamline stations to the Voyager high-performance file system.
- With the onset of the COVID-19 pandemic, IT Group resources were re-deployed to focus on XSD beamline remote access conversion, including domain account access, user account configuration, experimental safety assessment form programming, and set-up of the beamline portal starting with sectors 4, 7, 8, 11, 12, 16, 30, 32, and 34.
- The IT Group assisted with the new network buildout, installation, and configuration of servers and storage for Sector 20 (Southeast Regional CAT) due to the impending construction of the APS-U Long Beamline Building.

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 (which started in the August/September 2018 shutdown period) for insertion device beamlines are approximately 60% complete prior to the August/September 2020 shutdown. These upgrades include 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. 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-U.

The demand from the facility and operations for 3-D printed components has increased dramatically in the last three years, and regularly approaches almost 900 individual ticket requests and nearly 2500 individual components printed on three machines maintained by the Group. A vision of a small production cell was realized in FY20, dedicating laboratory space to house all 3-D printers (plastic- and metal-capable) as well as a small water-jet cutting machine, to drastically reduce conventional supply chain durations.

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 a 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.

5.4. Mission Readiness – PSC Operations Portfolio

The PSC Directorate chartered a Portfolio Management Office (PSC-PMO) in 2019 to develop and maintain a portfolio of mission-readiness projects to further execution of the PSC Strategic Plan. The PSC-PMO is responsible for managing an integrated multi-year project execution plan that includes the scope, schedule, effort, and cost for Operations projects requiring more than 300 hours/year effort or $50K/year for materials and services.

The Operations Portfolio is currently organized into three programs:

1. Readiness for the APS-U Project
2. Maintenance and obsolescence mitigation to ensure reliable x-ray beam delivery and mature accelerator operation
3. The PSC long-term strategy for continued science excellence at the APS

Development of the Operations Portfolio has in part been guided by the Memorandum of Understanding (MOU) between PSC Operations and the APS-U Project. The MOU frames agreed-upon responsibilities, activities, and interfaces between the two parties. Broadly, PSC Operations is responsible for maintaining and incrementally improving all existing APS systems in a manner consistent with current operating levels, while the APS-U Project is responsible for upgrading any systems that will be required to perform at levels beyond those currently achieved, e.g., incremental improvements to the injector system to support high-charge operation.

The PSC-PMO is in a continuous process of assessing gaps between the current state of the facility and the envisioned future state, identifying risks and opportunities, aligning the projects with the PSC strategic goals, and determining the order of execution. While the Operations Portfolio projects are outside of the APS-U Project scope, the multi-year execution plan takes into consideration APS-U Project installation and commissioning schedule and effort needs.

The portfolio resides in an enterprise Project Portfolio Management suite on the ServiceNow platform maintained by Argonne. 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. Proposals may be submitted by individuals, Group Leaders, or Division Directors, and PSC-PMO takes care to (1) assign proposals to the correct area in the Operations Work Breakdown Structure (WBS) and (2) evaluate proposals across Divisions and Groups to identify related projects/proposals that fall into different WBS areas. For example, the portfolio includes 27 information technology activities (6 projects, 21 proposals) that impact the business, accelerator, and beamline areas of the Operations WBS.

During the discovery meeting, which included the Information Technology, Controls, and Safety Interlocks Groups, and the APS-U Control Account Manager for Feature Beamlines, 11 IT projects were identified as part of a facility-wide network infrastructure upgrade that included significant APS-U scope. The PSC-PMO worked with the ASD, AES, and XSD Divisions and the APS-U Project to develop the schedule for an integrated network installation that includes Operations and APS-U scope (Figure 21) to meet Operations needs and APS-U milestones.

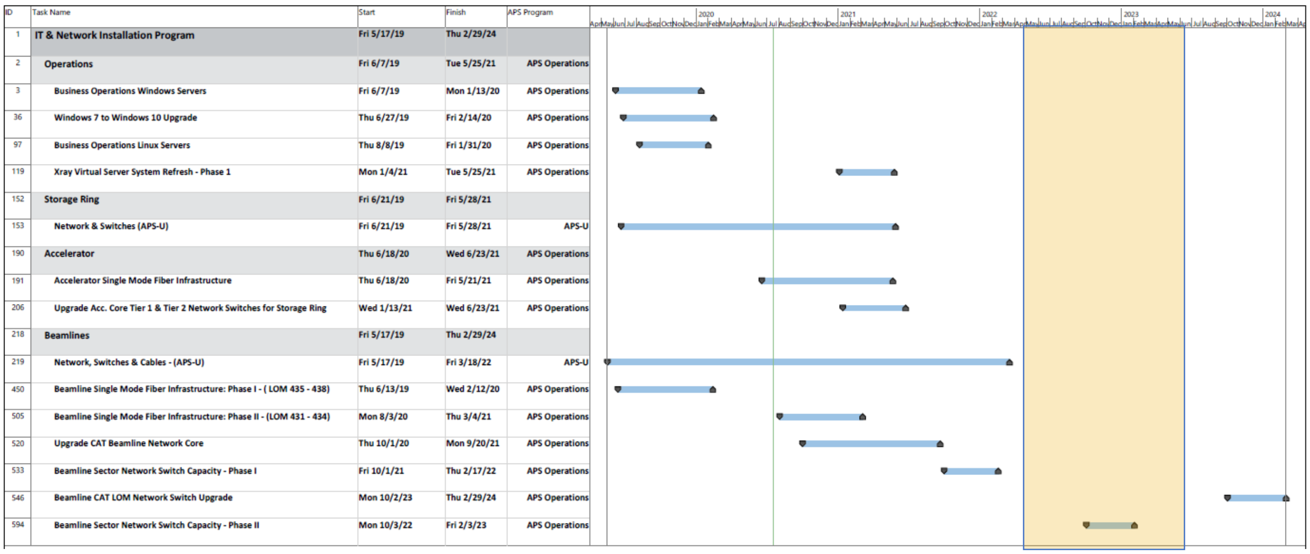


Figure 21. The integrated network and IT infrastructure installation schedule is shown above. Most IT and Network upgrade projects will be completed prior to the APS-U installation period indicated by the shaded area.

5.4.1. FY21 Project Execution Plan

Major FY21 activities include developing resource-loaded plans to:

- install a first-article, 200-kW, solid state amplifier unit for the storage ring;
- install a first 50-MW klystron, modulator, and digital low-level controls for the linac;
- upgrade the accelerator core tier 1 & tier 2 network switches for the storage ring;
- improve temperature stability in the storage ring;
- upgrade the CAT beamline network core; and
- implement the access control interlock system upgrade.

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 to this document. 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 installation period of approximately one year spanning parts of FY22 and FY23 (tentative due to the potential impact of COVID-19). The BES light sources have documented complex-wide beamline capabilities that will be available starting now and going into the APS-U installation period in order to provide APS users with clear options for alternate beamlines that will be available while the APS is off line. A major focus in FY21 will be to work with the user community and the CATs to communicate information about the APS-U installation period, and to solicit ideas from the community about how to minimize the significant disruption to scientific access that the installation period represents. Discussions continue with other BES light sources and with sponsors to identify mechanisms to enhance user throughput at other light sources during the installation period.

5.5.1. Outreach to Users

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. 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. These activities also serve to expand the user base.

In-house and online lectures explain the technical parameters of the APS-U in order to assist APS staff and resident beamline staff 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 a MBA source. These events expose current and future users to the capabilities and scientific opportunities of the APS Upgrade. Workshops held in fiscal year 2020 are listed in Section 1.1.5 below.

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.

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. The pandemic led to improved communications at various levels with the resident beamline staff and users, which includes: formal announcements via MailChimp; the website Ask the APS User Organization; and The Beamline Info Broadcast, an internal communication tool to inform beamline staff about items such as new user tools, enhancements, or changes to existing user platforms, notifications of procedural changes and their impact, announcements, and more.

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.

The User Program Office continues its comprehensive review of all of its online systems, including registration, proposals, scheduling, user portal, experiment safety, and registration as well as all related user communications in an effort to streamline and better integrate all of these systems. An update on this effort and other accomplishments completed in 2020 are below:

- The writing, release, and review of a request-for-proposal for a universal proposal process for light sources in the DOE complex. A final report was submitted to light source directors.
- The APS-led "Improving How We Work (IHWW)" team on improving user experience completed 11 system improvements in FY2020; 8 are still in process. Some of the more complex improvements, like collecting USCIS documents (PII) within the registration process and eliminating the mirroring of training records at the APS are nearing completion. When completed, Argonne will begin Phase 2 of the improvement plan: a common registration process for Argonne.
- The implementation of ORCID into the APS/CNM registration process will be completed by the end of FY 2020.
- The automation of host addendums to the DOE FACTS (foreign access central tracking system) was completed. This eliminated the e-mail/manual generation of thousands of addendums per year by Argonne FVA staff.
- In response to COVID and the minimum staffing available, an on-line system was developed that allows beamline staff to report the end of an experiment, eliminating human contact.
- The APS has also developed a reporting tool to identify COVID research being conducted at the facility.

Goals for FY21 include:

- moving to the next phases of utilizing ORCIDIDs, which include the automated collection of user research publications, upload beam time and service awards to user records, and identify equipment usage at the APS and CNM;
- developing an improved scheduling platform that supports drag-and-drop technology that will integrate the long-range scheduling process with the general user proposal scheduling process;
- developing user-friendly dashboards that will generate reports and allow sharing of information;
- playing a leading role in Argonne's initiative to develop a common registration platform for Argonne;
- working with Argonne's Environment, Safety, Health, and Quality Division personnel to investigate enhancements to the APS experimental safety authorization process to include real-time applications and iPad technology on each beamline after the MBA storage ring installation period;
- developing a YouTube orientation video to incorporate into the registration approval process; and
- beginning the process of planning for the APS General User Program post-dark time.

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 Experimental 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 complete the project under way that will 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

Upon determination of a chosen proposal platform by the light source directors, the APS User Program Office will initiate procurement and work with the vendor to begin development of a new proposal system.

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 striving to expand its networking and education programs. Nearly 44% 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 19% of experiments performed at the APS.

In FY20, schools and other offerings held at the APS included:

- APS Upgrade Workshop: Time-Resolved Chemistry and the APS Upgrade **(**October 1-2, 2019)
- APS Upgrade Workshop: Catalysis, x-rays and the APS-U **(**October 3-4, 2019)
- APS Upgrade Workshop: APS-U Metrology Workshop (December 9-10, 2019)
- APS Upgrade Workshop: Second OASYS School (December 11-12, 2019)
- 2020 National School on Neutron and X-ray Scattering (held virtually June 13-27)
- Virtual Workshops from the 2020 APS/CNM Users Meeting (held virtually August 24-September 4)

The flagship school is the National School on Neutron and X-ray Scattering. For more than two decades, 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. Due to the COVID-19 pandemic, in FY20 the school was held virtually. Although this approach did not allow for hands-on experiments, it did permit an expanded number of students to participate (over 200 students this year rather than the usual 60 students per year previously).

The APS staff and resident beamline staff 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. Fiscal year 2020 was the ninth year of the program. Teams of students work closely with APS and CAT beamline staff members 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 a 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 realize this, the PSC Directorate is strongly committed to talent management approaches that efficiently and effectively attract, engage, and retain 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, equity, 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, Equity, and Inclusion Working Group to assist the organization in fostering diversity in its workforce practices and environment, including execution of an annual diversity, equity, 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 Directorate is strongly committed to a talent management strategy for attaining strategic objectives and achieving mission outcomes. To have an effective talent management strategy, the PSC Directorate will focus on the following talent management areas over the next five years, with yearly reviews.

Beginning in March 2020, challenges facing the PSC Directorate accelerated dramatically with the advent of the global COVID-19 pandemic and by the far-reaching impact of this unprecedented event. As required by the DOE and Argonne, PSC staff, along with the rest of the Laboratory, transitioned to a largely telecommuting, minimum safe operations mode. Following federal, state, and local guidelines, the Lab transitioned to a less-restrictive limited operations phase in June.

While PSC Human Resources maintained a minimal presence on-site during these phases, the interactions required for carrying out day-to-day functions and responsibilities were moved on-line. The pace of recruitment and on-boarding of new hires, particularly for the APS-U, continued almost without interruption thanks to the planning and support by, and coordination with Argonne Human Resources. As a result, in the period from March 1, 2020, through July 30, 2020, PSC Human Resources virtually on-boarded a total of 23 new employees.

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:

- provide the Directorate executive team with an opportunity to build a shared model of the strengths and weaknesses of its people resources,
- allow the Directorate executive team to prioritize performance improvements from his or her respective areas, and
- provide 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 members' 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 Directorate and employee for achieving it. Like all PSC functions, this critical initiative has continued remotely even in the face of obstacles imposed by the COVID-19 pandemic.

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 the PSC Directorate in maintaining a safe and inclusive environment in which PSC 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. The COVID-19 pandemic has broadened the scope of this critical core value to include multi-level, reinforced guidance for best practices to guard against coronavirus infection/transmission.

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, Equity, and Inclusion*

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

- Goal 1 – "Engage," focused on visibility and leadership of diversity, equity, and inclusion
- Goal 2 – "Enlist," focused primarily on professional development
- Goal 3 – "Educate," focused on resources, training, and networking to promote diversity, equity, 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.

Change management took on a new meaning in the face of COVID-19. The PSC Directorate, like the rest of Argonne, was required to be agile in altering the way an enormous array of job responsibilities are carried out in order to meet the requirements of Argonne's operations modes.

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. 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.

The hope is that the organizational requirements imposed by the COVID-19 pandemic will soon be a thing of the past. But the lessons learned in this time about responding to crises and maintaining a viable, safe, and effective workforce will be a valuable resource for PSC management and staff far into the future.

6. Summary and Outlook

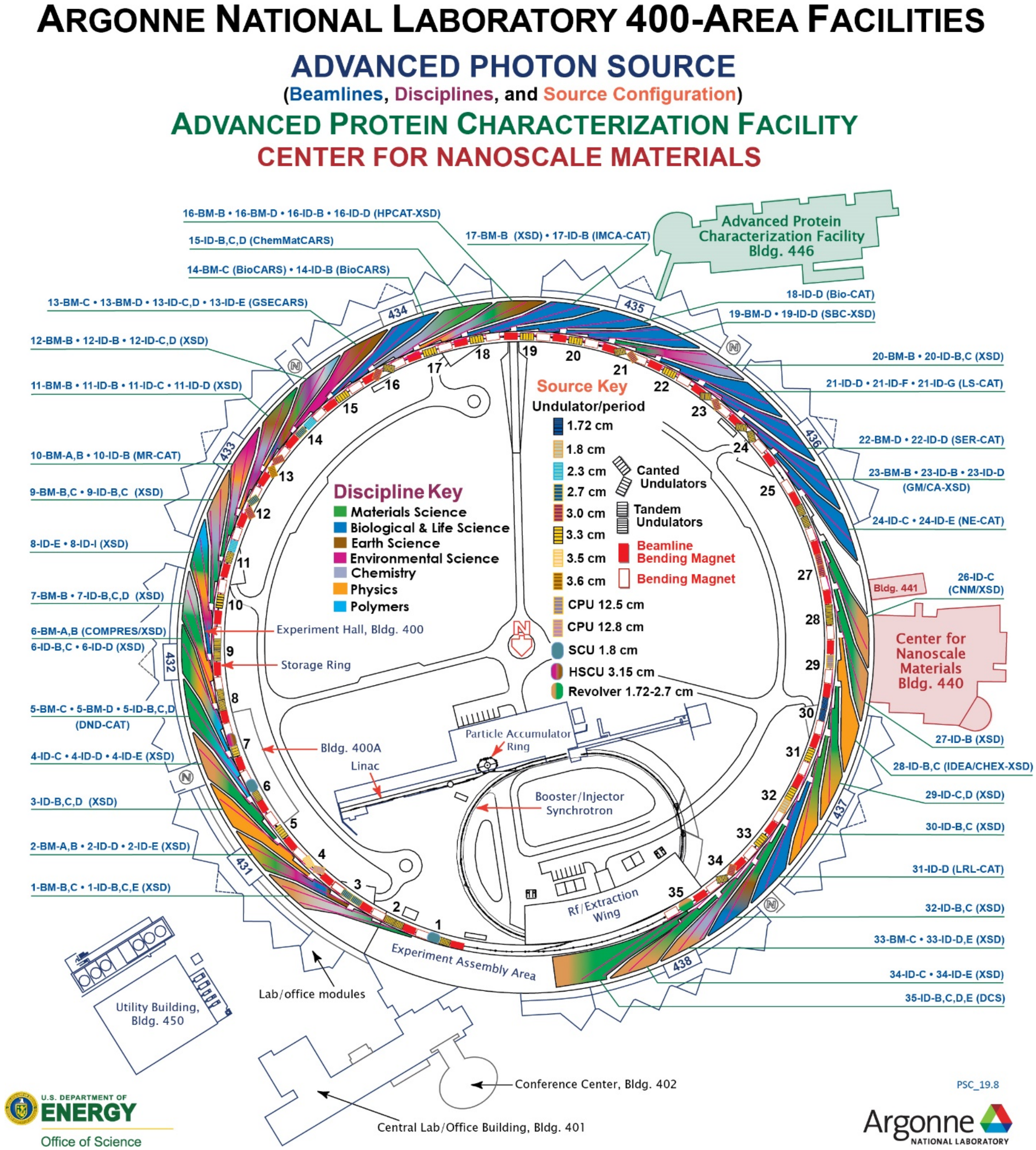
The APS is moving forward to implement a major upgrade that includes installation of a MBA magnetic lattice into the existing storage ring tunnel to increase x-ray beam brightness and coherent flux 100 to 1000 times. Together with the construction of new beamlines that are optimized for the new source, 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. Fiscal year 2020 was very productive for the APS-U Project. Numerous technical components were received, assembled, and tested. As of June 2020, almost 50% of the APS-U is complete by cost and commitments. June 2022 is the target date for starting major installations, which includes replacing the existing storage ring. The PSC has been 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 the 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.

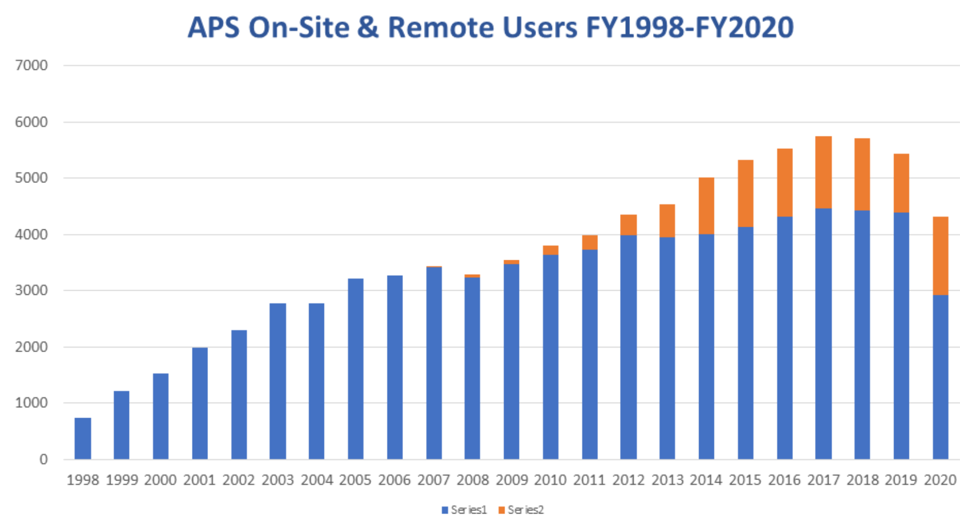
This plan will be reviewed annually and revised on a rolling basis. Updates as needed will accommodate significant changes in funding, shifts in the priorities of DOE, or new research avenues and opportunities.

Appendix 1: Beamlines at the APS

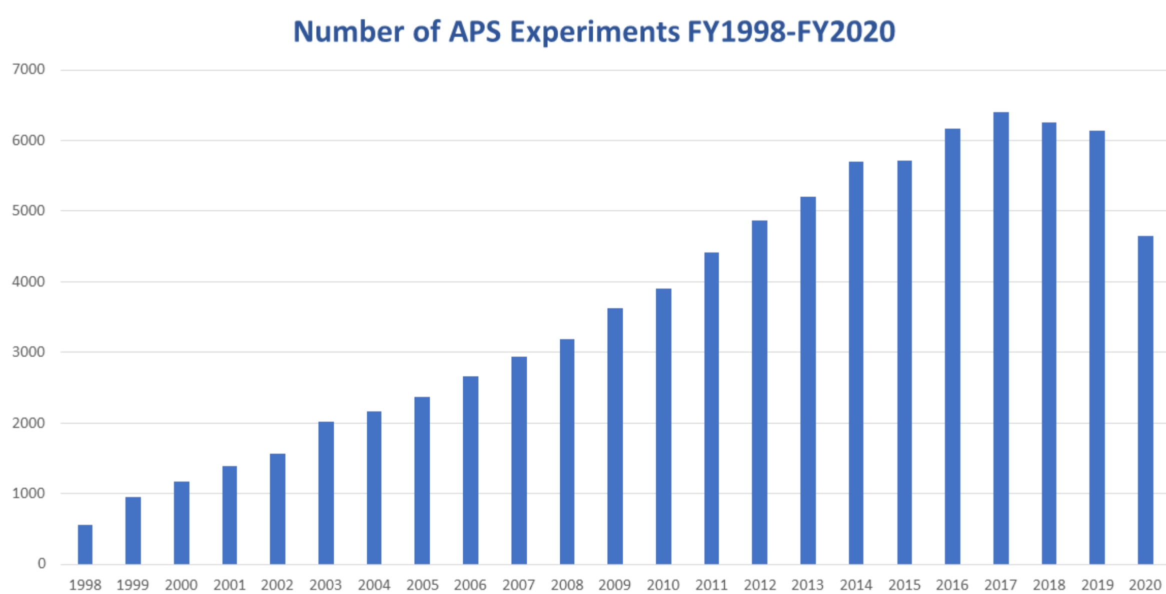


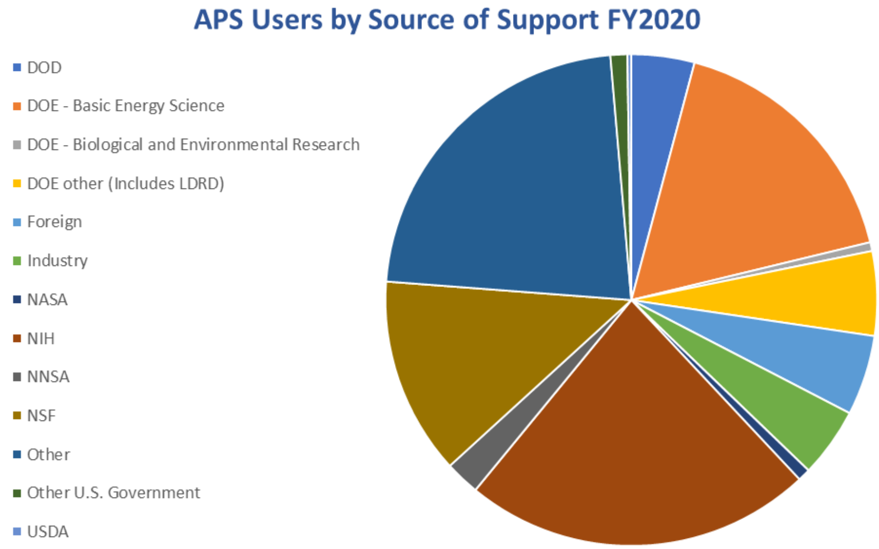
Schematic of APS beamlines, disciplines, and x-ray sources. There are 68 simultaneously operating beamlines at the APS divided into 47 insertion device and 21 bending magnet beamlines. The XSD is currently responsible for a total of 43 beamlines. In addition, the APS is a partner in two additional beamlines: 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.

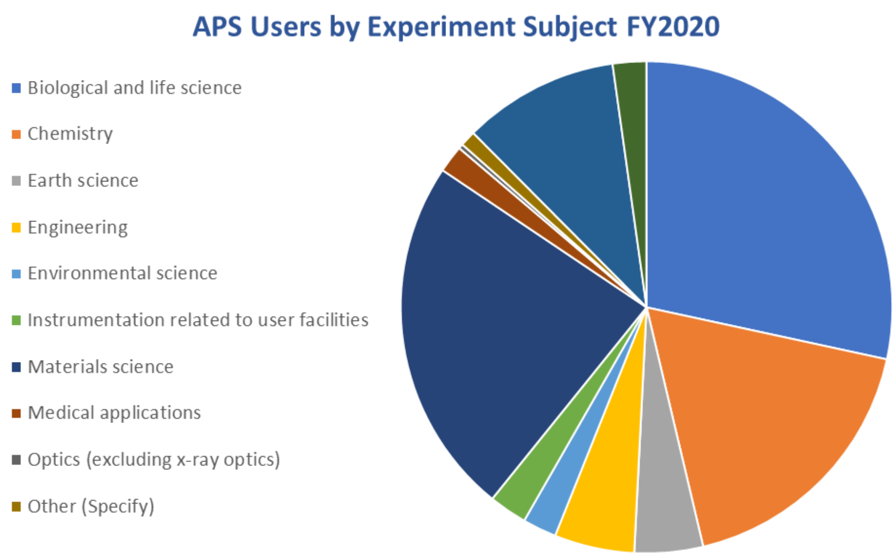
Appendix 2: User Data

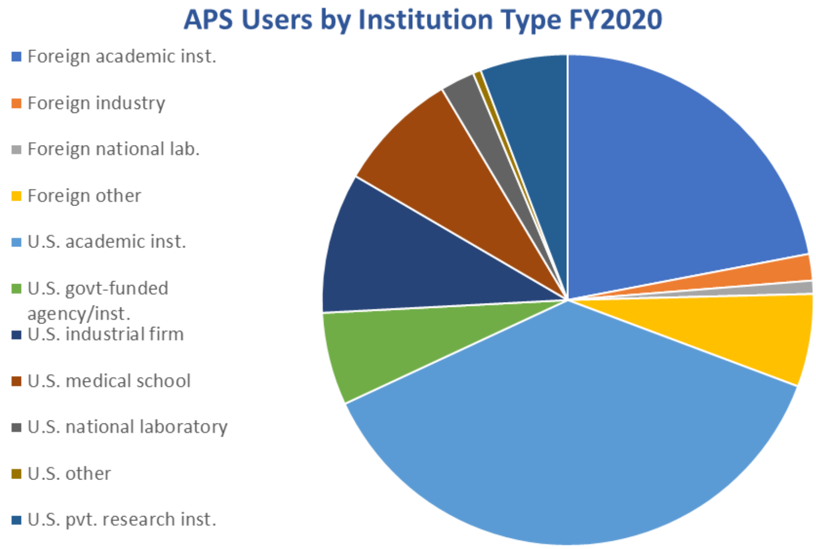


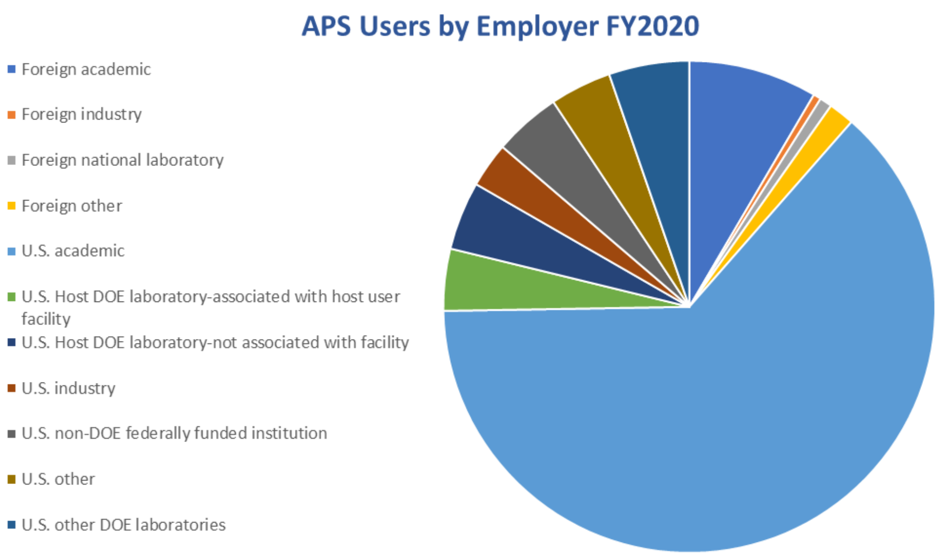
Notes:
1). Prior to FY14, mail-in users were not included in the Remote category.
2). FY20, new BES user counting policy has been applied so that only 1 unique user is associated with mail-in experiments and the user is only counted once in the whole population.

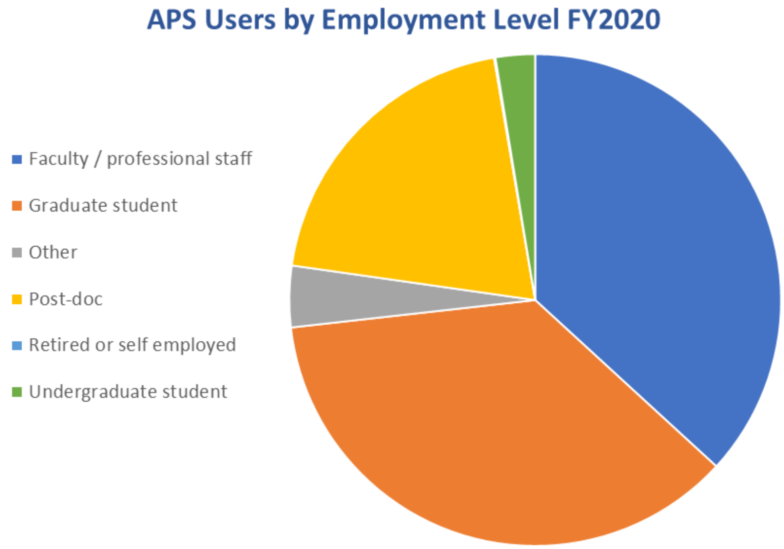


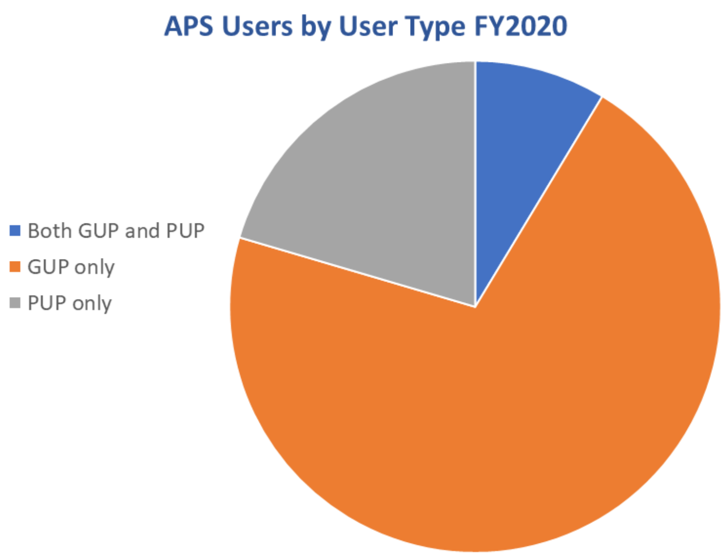

APS Users by Source of Support FY2020
DOD
DOE - Basic Energy Science
DOE - Biological and Environmental Research
DOE other (Includes LDRD)
Foreign
Industry
NASA
NIH
NNSA
NSF
Other
Other U.S. Government
USDA


APS Users by Experiment Subject FY2020
Biological and life science
Chemistry
Earth science
Engineering
Environmental science
Instrumentation related to user facilities
Materials science
Medical applications
Optics (excluding x-ray optics)
Other (Specify)


APS Users by Institution Type FY2020
Foreign academic inst.
Foreign industry
Foreign national lab.
Foreign other
U.S. academic inst.
U.S. govt-funded agency/inst.
U.S. industrial firm
U.S. medical school
U.S. national laboratory
U.S. other
U.S. pvt. research inst.


APS Users by Employer FY2020
Foreign academic
Foreign industry
Foreign national laboratory
Foreign other
U.S. academic
U.S. Host DOE laboratory-associated with host user facility
U.S. Host DOE laboratory-not associated with facility
U.S. industry
U.S. non-DOE federally funded institution
U.S. other
U.S. other DOE laboratories


APS Users by Employment Level FY2020
Faculty / professional staff
Graduate student
Other
Post-doc
Retired or self employed
Undergraduate student


APS Users by User Type FY2020
Both GUP and PUP
GUP only
PUP only