1.1. The 2020 Accelerator Systems Division Strategic Plan

1.1.1. Introduction

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

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

The ASD strategic plan is based on the following goals:

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

1.1.2. 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By the time the APS-U is operational, much of the injector system will be over 25 years old, and in several cases using outdated or obsolete technologies.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 Upgrade without impacting operational reliability. The APS staff and management will ensure that this is done in the most cost-effective and efficient manner. Through dedication to timely upgrades and rigorous maintenance protocols, the APS has become one of the world leaders in accelerator reliability with beam availability routinely above 97%. This requires continuous communication between technical staff and management to assess risks to reliable operation and to prioritize activities targeting high-risk issues.

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

1.1.3. Division Organization

The ASD is organized and staffed to address the goals provided above. The ASD currently has about 120 scientists, engineers, technicians, safety and administrative staff distributed in eight groups. One of the major changes in 2019 was the transfer of the Controls group from AES to ASD. This transfer allows a tighter coupling of the other technical groups in ASD to the Accelerator Controls. A second Associate Division Director was also added to assist with the management of the staff and the increase in projects to modernize the accelerator complex. Shown in Fig. 1 is the current organization of the ASD with the entire staff for each group listed as of 1 July 2020. Staff members matrixed to the APS-U division are indicated with parentheses.

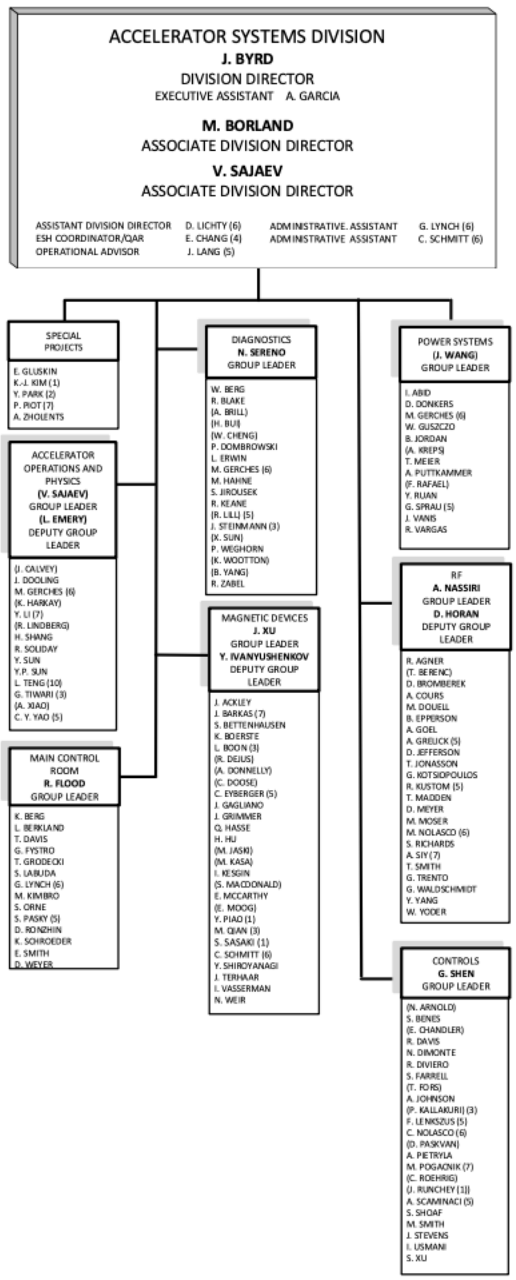

Figure 1. ASD Organizational Chart as of 1 July 2020.

1.1.4. *Accelerator Improvements*

1.1.4.1. *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 2). 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. We currently are working on a scheme for switching polarizations for a user beamline from two devices by varying the beam orbit.

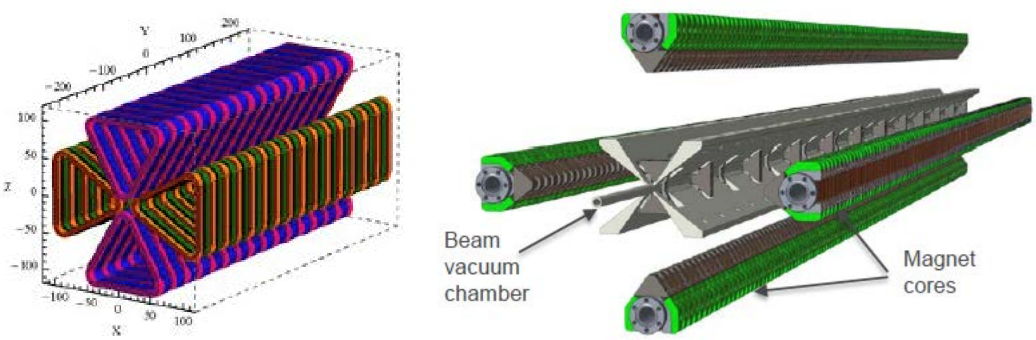

Figure 2. (Left) The Radia Model for the SCAPE SCU magnets. Horizontal and vertical fields are shifted by a half period and can be powered arbitrarily, allowing variable polarization. (Right) A mechanical drawing of the SCAPE assembly. The x-wing vacuum chamber allows extraction of heat generated by the beam.

1.1.4.2. *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 an industry 30-kW prototype that passed a series of tests over the past year with flying colors. In addition, both cavity and waveguide combiner networks were tested using 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. We have selected the cavity combiner configuration (Figure 3) and have fully specified the first 200 kW which 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 dark time. The configuration is illustrated in Figure 4 where a single cavity will be driven by the first solid-state amplifier in a switchable configuration. 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.

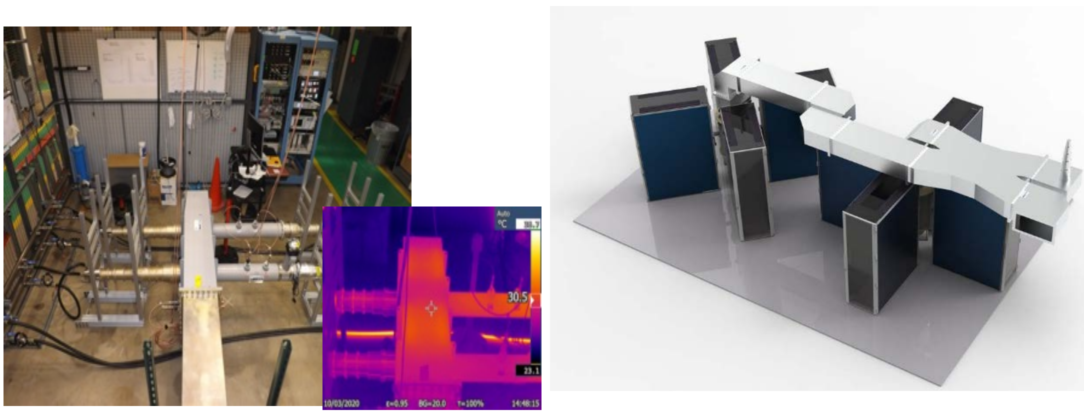

Figure 3. (Left) The photo shows a photo of the “backfeed” test of the waveguide combiner. The inset shows an infrared photo indicating RF heating of the network. Results were in excellent agreement with modeling. (Right) The rendering shows the concept for a 200-kW amplifier. Each rack contains 15 2-kW amplifiers that are combined in the combiner cavity hidden below the waveguide. The first prototype amplifier was tested on the combiner cavity later in 2019.

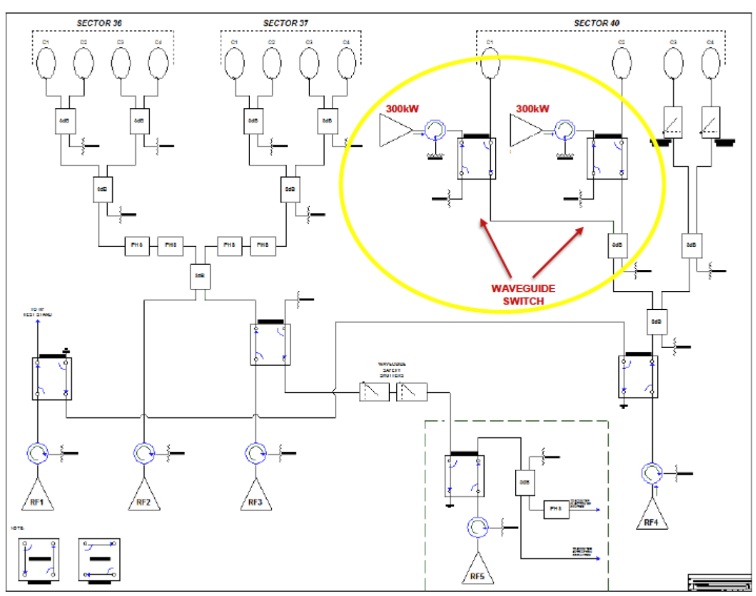

Figure 4. The transition plan to solid-state rf amplifiers will occur over the decade beginning from 2021. The schematic above shows the planned hybrid configuration of the rf system in 2023, following the APS-U installation.

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 PAR harmonic RF system are being implemented that will enable higher stored bunch needed for APS-U operation. We have also initiated an initiative to upgrade the APS linac RF systems. These improvements include:

- Gradual replacement of the aging home-built pulsed HV 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 APSU timing system
- General replacement of other obsolete linac systems including power supplies and some diagnostics as needed.
- Setup 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.

1.1.4.3. 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.

1.1.4.4. Beam Diagnostics

The ASD Diagnostics Group maintains and upgrades existing storage ring and injector diagnostics systems addressing aging, obsolescence, and performance issues. Our primary operations goal is to provide reliable performance of diagnostic instrumentation up to the APS-U "dark" period and beyond. For APS-U, we are focussing on completing final design for all systems including beam position monitors (BPMs) and BPM electronics, orbit and multibunch 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 dark and commissioning periods, we are also planning for operations related injector upgrades to address various instrumentation obsolescence and reliability issues. Part of these upgrades will include new BPMs and current monitor electronics for Linac, PAR, 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, we plan on leveraging injector instrumentation upgrades to support the Linac Extension Area (LEA) such as using the new BPM and current monitor systems developed for the linac and transport lines.

1.1.4.5. Accelerator Operations and Physics

The Accelerator Operations and Physics (AOP) Group is the main source of accelerator physics theory and simulation in order to understand and improve the APS electron beams. Formerly, managing reliable operation of the APS accelerator complex was part of the AOP mission, but now it is the responsibility of the separate Main Control Room group within the ASD. The AOP stresses thorough automation of machine operation and analysis, since these are the keys to high reliability. For example, the AOP has improved real-time detection and monitoring of malfunctioning power supplies and BPM electronics to further enhance orbit stability by removing the malfunctioning devices quickly from the orbit feedback system in order to facilitate repairs. Other automation improvements include beam-dump analysis, injection optimization, and lattice and filling pattern switching.

In preparation for the APS-U operation, the AOP 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 chamber. Thermal analyses of a beam strike on a collimator have shown that the beam power density is sufficiently high to melt the collimator and essentially drill through the material. Over the past two years, a series of experiments jointly conducted by the AOP and the Diagnostics groups 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 5 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 10 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.

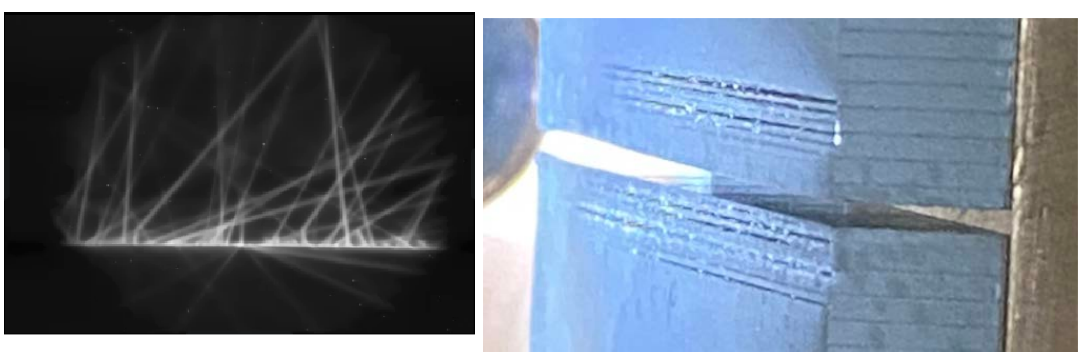

Figure 5. The left image is the test collimator during a beam strike captured from a frame of the recorded video. Beam moves from left to right. Ejecta are observed as small flares from the molten metal. The image at the right shows a picture of the test collimator after an extended study following beam 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, we wanted to demonstrate the effect experimentally using the existing APS ring. In the experiment, an intentional gas leak of N_2 gas was added to the storage ring in Sector 25 straight section that would raise the local pressure by two to three orders of magnitude. Strong vacuum pumping on either side of the straight limits the pressure "bump" locally. A schematic of the experimental setup is shown in Figure 6. 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 Fig. 6 right is a plot of the vertical betatron sidebands during an ion instability, with the peak of the spectrum near 3-4 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 APS-U. Further studies will continue with the goal of further characterizing the beam-ion instability.

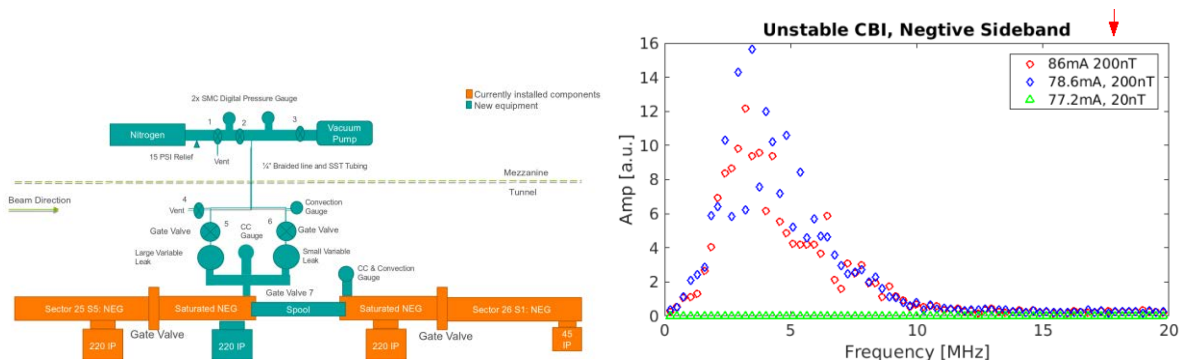

Figure 6. The left panel shows a schematic of the gas injection setup for a controlled leak in Sector 25 of the storage ring. Strong vacuum pumping on either side of the injection limits the vacuum "bump" to a small region. The right panel shows the spectrum of unstable vertical sidebands at increased vacuum pressure. The peak between 3-4 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 continues improving and enhancing high-performance computing accelerator simulations while making these state-of-the-art codes available to the entire accelerator community, benefiting many accelerator facilities and projects beyond the APS and APS-U. 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.

1.1.4.6. 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, we have moved the Main Control Room (MCR) operations staff 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
- Implementing policies and operating standards as set forth by the machine managers.

1.1.5. 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.

1.1.5.1. 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, we have partnered with Fermilab for this program, who 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 1.2m device in place of an existing SCU prior to the APS-U long shutdown. Shown in Figure 7 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.

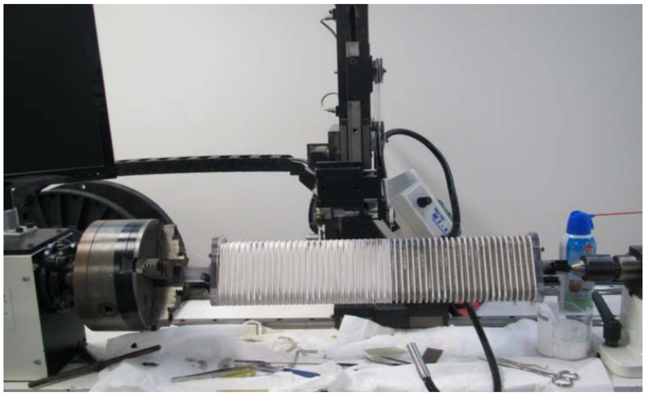

Figure 7. Magnet with mica insulations during winding.

1.1.5.2. Cavity-based x-ray free-electron lasers (CBXFEL)

With the advent of the high repetition rate x-ray free-electron lasers such as the Linac Coherent Light Source (LCLS)-II, several schemes for improving the longitudinal coherence of the x-rays have appeared, which depend on resonating the x-rays in an optical cavity based on high-purity diamond mirrors. A collaboration between Argonne and SLAC has formed with the three-year goal of building an optical cavity and demonstrating it on the LCLS-II HXR FEL, and anticipated use on with the high repetition rate superconducting linac when available.

A detailed schematic of the proposed CBXFEL scheme is shown in Figure 8. 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 with extremely high quality are required as well as mechanical tuneability and stability of the mirrors. As an initial test, the plan is the operate the LCLS Cu linac with two bunches in a pulse with a separation equal to the cavity path length.

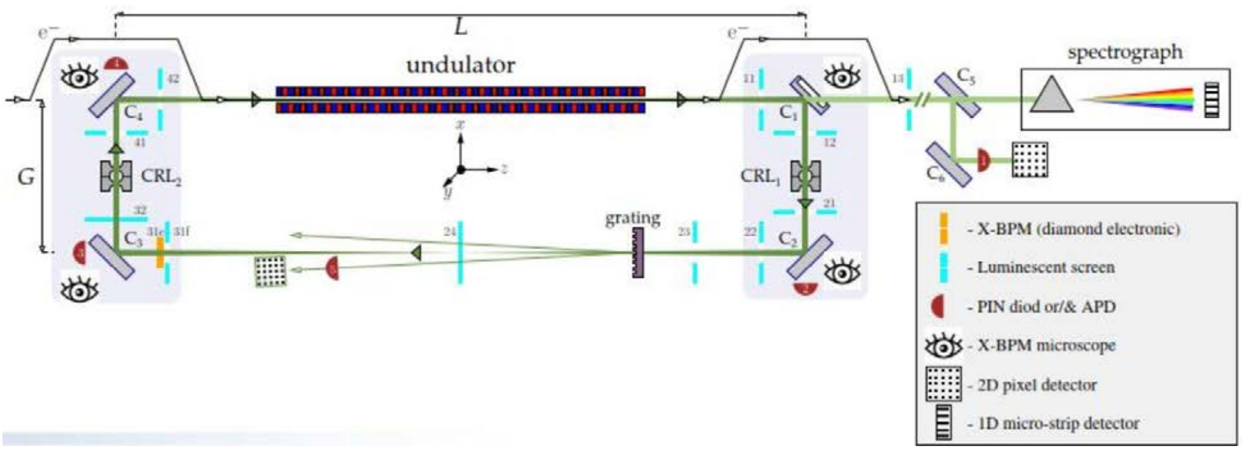

Figure 8. A schematic diagram of the CBXFEL setup planned in the LCLS HXR FEL line. Small chicanes bring the electron beam around the diamond mirrors into the optical cavity. The path length of the cavity is adjusted to be the distance between electron bunches. Each of the mirrors is mounted on nanopositioning actuators to allow tuning of the cavity. The cavity is fully instrumented to diagnose the performance.

1.1.5.3. 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 cooldown by the end of 2020. Shown in Figure 9 is a cross-section schematic of the gun and cryostat along with a photo of the gun in Physics 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, we will prepare 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.

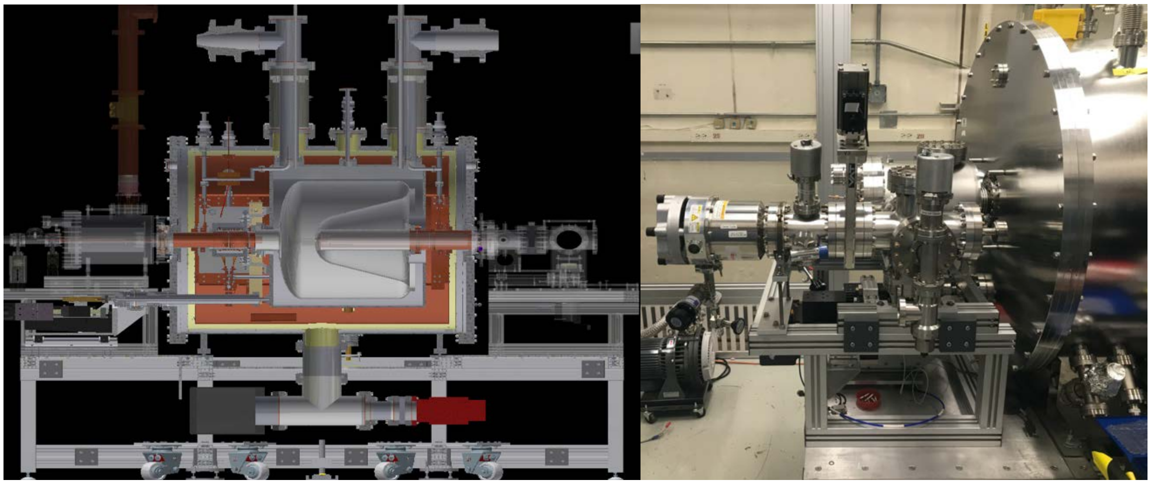

Figure 9. Right) A schematic view of the Wisconsin FEL (WiFEL) gun. A photo of the gun under preparation in the Physics clean room facilities.

1.1.5.4. 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. Our vision at Argonne, led by Sasha Zholents, 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 LDRD, 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 10. A high repetition rate electron gun creates a drive and witness beam which is accelerated to 1 GeV in an 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. An photo of a sample corrugated CWA structure is shown in right of Figure 10.

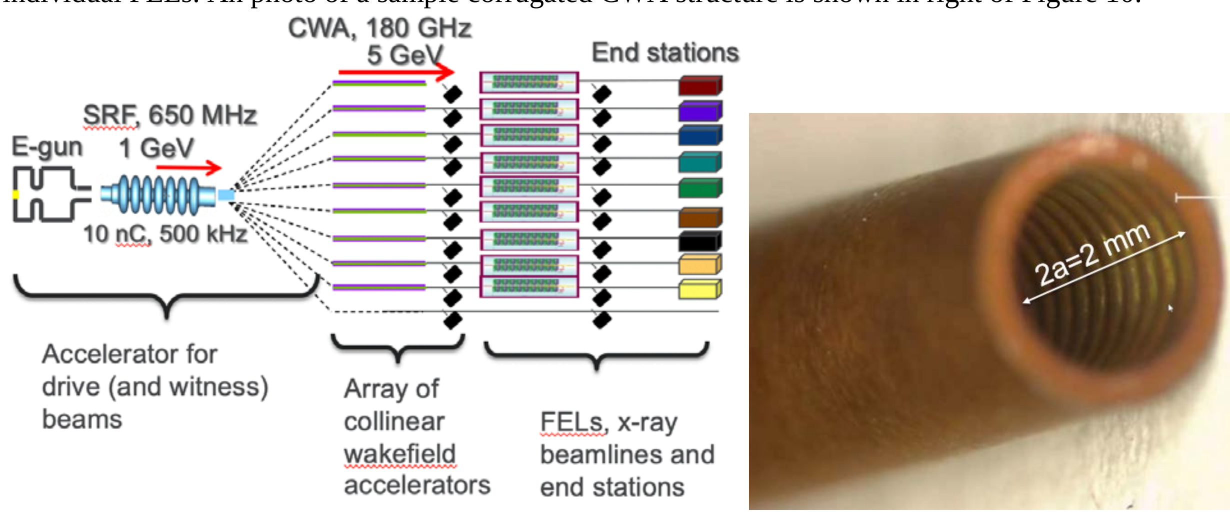

Figure 10. Left) A schematic view of the vision for a compact concept for a multi-user FEL facility. Right) Photo of the corrugated accelerating structure fabricated using electroforming techniques. .

Recent work has focused on the fabrication and characterization of this structure. Each accelerating module is envisioned to be 0.5 meter length of corrugated waveguide of 0.5 m made with electroforming techniques. Each structure is attached to water cooled copper fanblocks 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 11. 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.

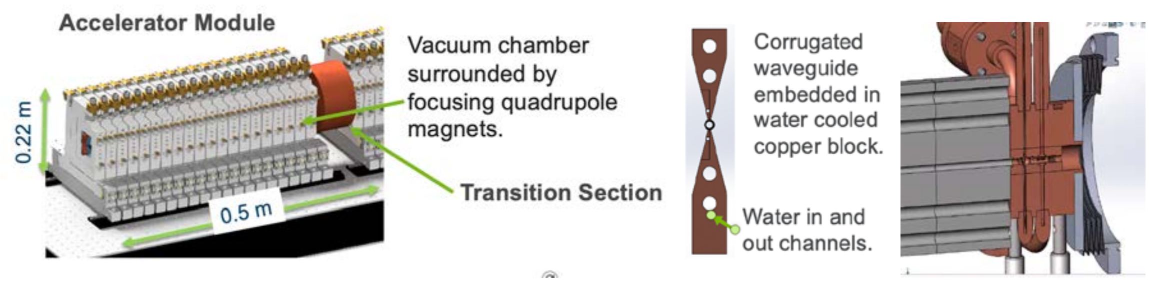

Figure 11. Left) An engineering CAD drawing of a 0.5. m accelerating section. The vacuum chamber is surrounded by the periodic array of miniature quadrupoles (the quadrupole wiggler). Middle) The 2 mm diameter CWA is embedded is a water-cooled copper block that allows operation at higher bunch repetition rate. Right) Each accelerating section is connected via a transition section that provide HOM damping and beam position measurement.