New Initiatives

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The APS provides its users with the brightest hard x-ray beams in the Western Hemisphere. This national research facility, which is funded by the U.S. Department of Energy, Office of Basic Energy Science, has been operating for user experimentation since 1996. The APS has proven to be a highly reliable source of brilliant x-ray beams for an ever-growing user population. It is APS management's responsibility to assure that this facility in particular, and x-ray science in general, continue to evolve to meet the needs of current and future users, who will bring synchrotron-technique science to new realms of scientific discovery.

Twenty Years on: A Vision for the Future of the APS

Over the past three decades, the brilliance of synchrotron x-ray sources has doubled every 10 months. Use of coherent flux, which is directly proportional to beam brilliance, has had major unforeseen benefits for work in the physical sciences, life sciences, and engineering. But improved performance will permit new uses of existing sources such as the APS.

Over the next 20 years, new and exciting x-ray sources are expected to appear on the x-ray science horizon. These sources will not be simple enhancements of existing third-generation sources. They will be a new breed of sources with new properties and the potential for new applications. Even as these new sources come into existence, the APS must remain at the cutting edge of third-generation synchrotron radiation technology, where the demand for x-rays will not decrease for the next 20 years or more. At the request of DOE, a 20-year upgrade plan for the APS has been developed. It is organized into four temporally overlapping phases:

• Phase I. Complete beamline installations on the remainder of the storage ring and maximize operations at existing beamlines. This phase, which has already begun, is expected to extend over the next eight years.

• Phase II. Optimize source characteristics. This phase will overlap Phase I and focus on upgrading of insertion devices and accelerator characteristics. It too, has already begun and will continue for a decade or more.

• Phase III. Develop the next-generation user facility by improving the efficiency and performance of beamlines and taking advantage of advanced detectors, robotics, and automation. This phase will start in full in approximately eight to ten years.

• Phase IV. Implement a major upgrade of the accelerator complex to develop a "super storage ring." Work on this final phase will begin about 10 years from now and will last for approximately 10 years.

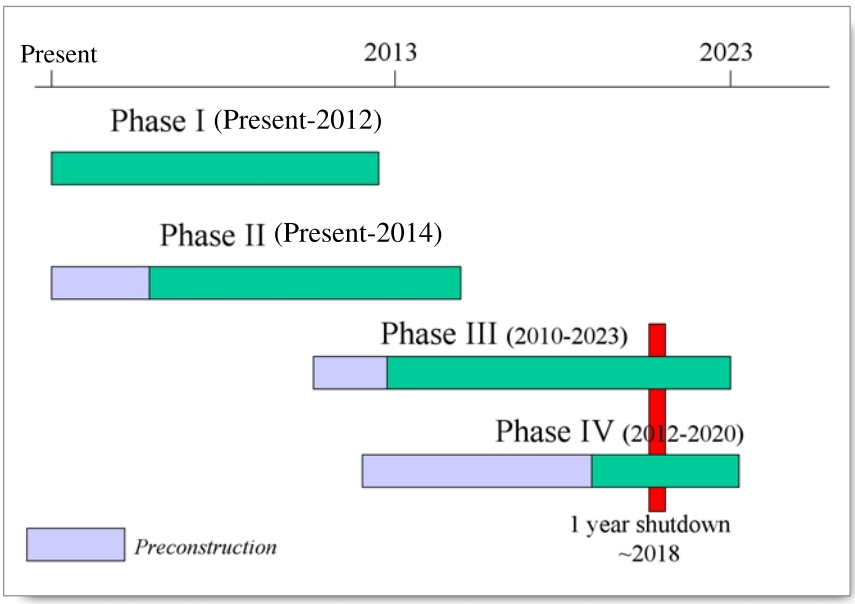


Fig. 1. Timeline for implementation of Phases I-IV.

Phase I

The appropriate focus for the first phase of a 20-year plan for APS upgrade (Fig. 1) is full utilization of the storage ring. It is expected that construction of approximately 10 new APS beamlines will occur from the present through FY 2012. This new construction will encompass the four remaining insertion device beamlines and the installation of several new bending magnet beamlines. These 10 new beamlines will not include three sectors dedicated to macromolecular crystallography, where construction has begun or is about to begin (General Medicine and Cancer Institutes Collaborative Access Team [CAT]), Northeastern CAT and Life Science CAT); the insertion device beamlines for two exciting proposals whose construction has been partially funded by DOE-BES (the inelastic x-ray scattering beamline and the nanoprobe beamline to be associated with the CNM); and a powder diffraction beamline on a bending magnet line, also funded (Fig. 2) by the Department of Energy's Office of Basic Energy Sciences.

Construction of the remaining available APS sectors is expected to continue through the next decade. In parallel with construction of new beamlines, we must contend with the aging of our existing beamlines. Ten years have passed since several APS beamlines were first designed, and they are in need of major refurbishments to take advantage of recent advances in optics and instrumentation. Development of state-of-the-art detectors is perhaps most urgent. In many cases, better detectors are already on the critical path to achieving faster data collection. Construction and refurbishment of some aging beamlines will be the responsibility of the APS, either alone or in collaboration with partner users. The proposed science to be performed at those beamlines will drive the new construction and upgrades.

The APS will rely heavily on guidance from its Scientific Advisory Committee in determining which beamlines will be built and upgraded. Future beamlines are expected to fall into two major categories: those used for "routine data collection," which need to be provided as "turn key" facilities (such as the powder diffraction line currently under construction); and cutting-edge beamlines optimized for "experiments," where constant innovation and tweaking are necessary for scientific success. The highly specialized beamlines in the second category are being designed for radiation properties optimized to particular types of research, such as inelastic x-ray scattering, high-energy x-ray scattering, or nanoprobe applications. Therefore, concurrent with development of new beamlines under Phase I, the aggressive source development specified in Phase II is also needed.

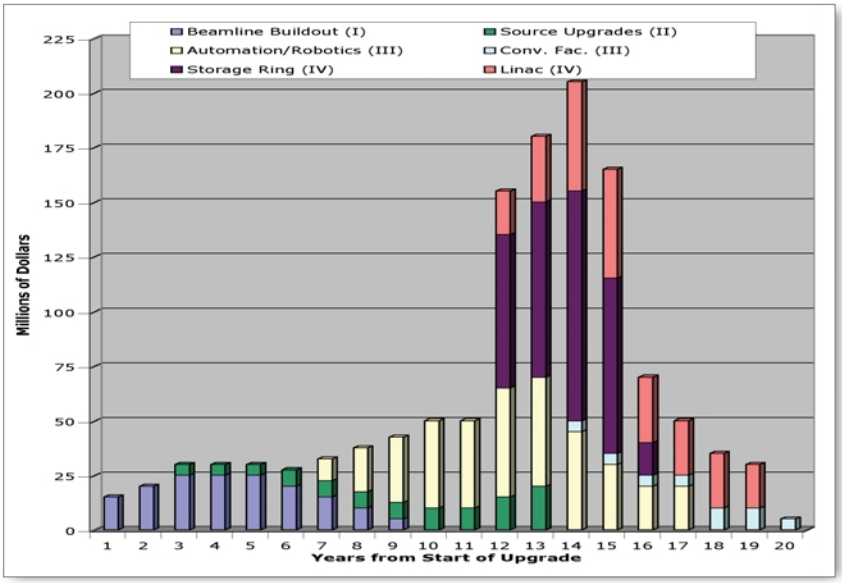
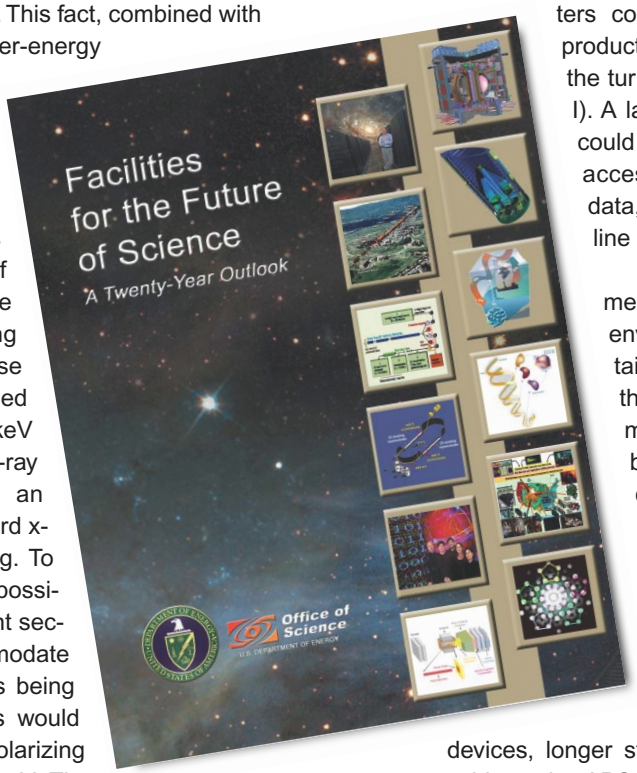


Fig. 2. Budget profile for Phases I-IV.

Phase II

Given the limitations imposed by the current magnetic lattice of the APS storage ring, further reductions in the natural emittance (presently better than the original design specification by a factor of almost three) can be only incremental. Therefore, without major reconstruction of the storage ring, significant increases in beam brilliance must come through the development of optimized insertion devices or increases in circulating beam current, as well as compatible front ends and optical components. These enhancements could improve effective brilliance by more than an order of magnitude.

Despite the common idea that high-energy, third-generation storage rings are associated with the production of hard x-rays, 6-8 GeV is, in fact, an ideal stored-beam energy for generating elliptically polarized soft x-rays. This fact, combined with the inherently superior stability of higher-energy beams, means that high-energy storage rings have considerable advantage in generating high-quality polarized soft x-ray beams. Insertion device development will push toward increased brightness at high energies with shorter-period devices capable of higher energies (20-45 keV) with the first harmonic. The most promising approach to this development will use superconducting undulators. Increased brilliance at high photon energies (25 keV and above) will improve inelastic x-ray scattering capabilities and provide an unequaled source of high-brilliance hard x-rays for high-energy elastic scattering. To improve beam brilliance further, the possibility of increasing the length of straight sections in the storage ring to accommodate longer or multiple insertion devices is being investigated. Longer straight sections would also allow installation of elliptically polarizing undulators optimized from 0.5 to 3 keV. The beam brilliance from these devices would result in a world-class beamline for photoemission and a photoemission electron microscope capable of spatial resolutions of a few nanometers, well suited to studying the magnetic properties of materials.



In addition to superconducting and polarizing undulators, Phase II work will also focus on solenoid-driven undulators. Insertion devices based on solenoids can have variable periods and variable fields (in contrast to present-day devices with fixed periods and variable fields), making them valuable for a host of scientific applications requiring optimization in several different energy ranges. As noted above, substantial reduction in the natural emittance of the APS is unlikely with its present lattice. However, the effective emittance delivered to users can be improved via enhanced beam stability. Phase II will continue the focus on this effort. Phase II will also focus on reducing the size and duration of perturbations of the stored beam during the top-up process, which will further enhance beam quality.

Phases III and IV

To adequately accommodate the estimated 10,000 researchers who will use the APS during the coming decade, Phase III enhancements will improve ease of access for users, beamline performance, and data-collection speed. Automation and robotics for sample alignment have already been implemented on some macromolecular crystallography beamlines at the APS and elsewhere. Many physical science beamlines could benefit from similar techniques. For instance, integration of automated sample changers into powder diffraction beamlines and small-angle-scattering beamlines seems to be a straightforward extension of the sample changers used for macromolecular crystallography. Moreover, automated alignment of optical components and diffractometers could substantially increase scientific productivity of some beamlines (particularly the turn key beamlines proposed for Phase I). A large class of experiments exists that could be performed effectively via remote access, if real-time communication of data, experimental conditions, and beamline control are achieved.

In Phase IV, significant improvements in the accelerator system are envisioned. As indicated above, maintaining the existing 40-fold symmetry of the storage ring implies that only incremental improvements in particle beam brilliance can be expected. Phase IV calls for a radical change in the storage ring magnetic lattice, from 40-fold symmetry to 80-fold, which will reduce beam emittance by a factor of eight. This 8-fold increase in beam brilliance— n combination with the increased brilliance achieved through optimized insertion devices, longer straight sections, and increased current—would put the APS near the limit of brilliance attainable with a storage ring of its dimensions and energy. The resulting super storage ring would significantly benefit the many important brilliance-related techniques. The obvious advantage of the Phase IV approach to a super storage ring is its use of existing beamlines. The novel concepts proposed would create new capabilities that would be qualitatively and quantitatively different, and considerable R&D would be required to verify the feasibility of the proposed alterations of the storage ring. Modification of the APS storage ring for reduced emittance would not be implemented until very late in the 20-year plan.

While Phases I and II, which were strongly supported by the BES Advisory Committee, will, in all likelihood, be funded through increased operational support, we are happy to report that our plans for Phases III and IV were strongly supported by DOE and the APS Upgrade (i.e., Phases III and IV) was recently included in DOE's 20-year plan, *Facilities for the Future of Science, A Twenty-Year Outlook*. ❍

The Argonne Linear Free-Electron Laser

APS accelerator physicists have developed a high-gain free-electron laser (FEL) using the injector linear accelerator (linac) and the 20-m undulator in the low-energy undulator test line (LEUTL) tunnel. This is the first self-amplified spontaneous-emission (SASE) FEL to reach saturation at visible and ultraviolet wavelengths. (See *APS Science 2002*.) The LEUTL FEL allows experimental techniques hitherto not feasible in this wavelength region. Scientists at Argonne's Materials Science Division have installed a state-of-the-art spectrometer called SPIRIT (Single-Photon Ionization Resonant Ionization to Threshold) at the LEUTL end station to take advantage of the unique characteristics of the LEUTL FEL. An example is the first measurement of a nucleobase adduct by vacuum ultraviolet photoionization. Here, guanine was sputtered with an ion beam from a cinnamic acid matrix. The superior sensitivity of the LEUTL-SPIRIT combination over other methods in detecting adducts can be seen clearly in Fig. 1 (at least a factor of 100 in the case of the guanine-phenyl adduct). The result has important implications for measuring carcinogens and understanding the mechanisms by which they cause cancer.

The basic limitation of the LEUTL FEL is the severe lack of beam time available for experiments because the linac is normally exclusively used for running the APS in top-up mode. Even when the linac is available, it is shared by other activities.

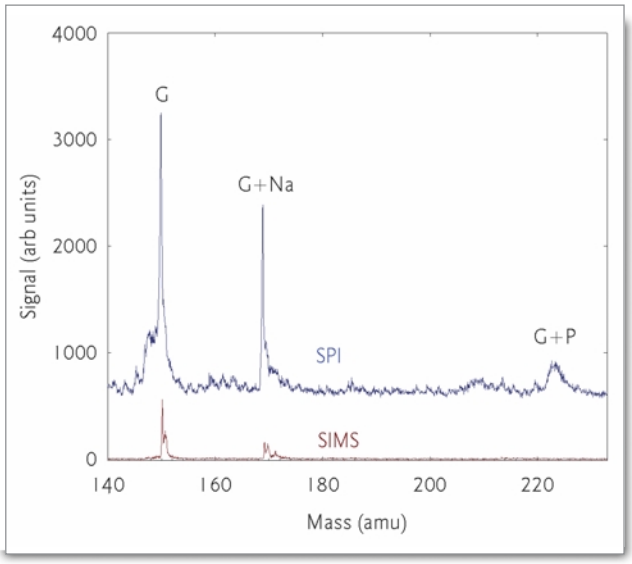


Fig. 1. Single photon ionization (SPI, blue) time-of-flight mass spectrum of guanine (G) with sodium (G+Na) and phenyl (G+P) adducts. The guanine was desorbed with an ion beam and photoionized with the LEUTL beam tuned near 157 nm. Notice the prominent G+P peak with SPI-LEUTL (in blue) compared to the barely visible corresponding peak with secondary ion mass spectrometry (SIMS, red). The SPI spectrum has been offset for clarity.

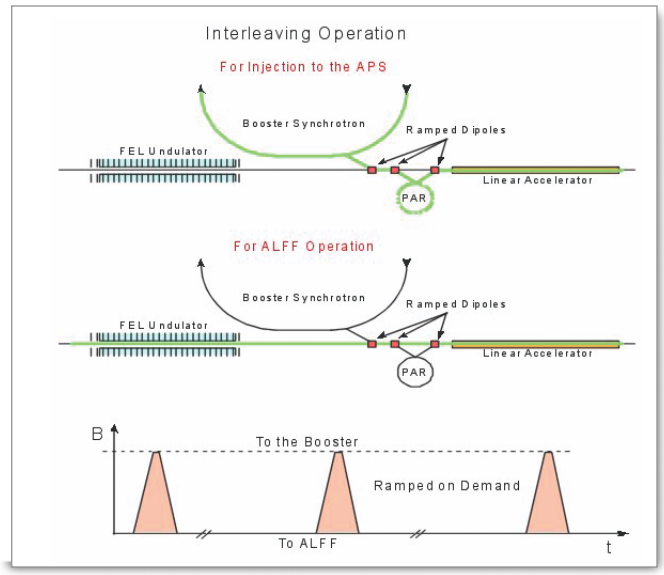


Fig. 2. Top: Electron beam path, shown in green, for injection into the booster synchrotron and APS storage ring. Middle: Beam path for ALF operations. Bottom: Timing diagram for the ramped dipoles used for interleaving.

Recently, APS submitted a proposal to the Department of Energy that would turn this one-of-a-kind FEL into a beamline capable of serving as a serious experimental program, which would be known as the Argonne Linear Free-Electron Laser, or ALF. The main improvements that need to be made for the ALF conversion are an upgrade of the linac and gun components for the interleaving operation and greater pulse stability. Interleaving, illustrated in Fig. 2, involves dynamically sharing the linac beams between top-up of the APS storage ring and servicing ALF; this will dramatically increase the availability of the FEL to 96%, compared to the current 3%. The operating wavelength region will be reoptimized by tuning the undulator gaps. The improvement project will take three years and cost about $5M.

Three scientific grand challenges are delineated in the ALF proposal: diagnosing the initial stages of cancer, evolution of our sun, and selective bond breaking. For a broader view on the potential scientific uses of the ALF, a workshop was held at Argonne on October 30-31, 2003. Over 60 scientists participated in four working groups: AMO (atomic, molecular, and optical sciences) and chemical physics, cosmochemistry and geosciences, material science, and biology and environmental science. The workshop confirmed that there is strong user interest the unique capabilities, not available from other sources, of the ALF beams in the combination of pulse energy (100 microjoules), duration (300 femtoseconds), and broad tunability. *(Contact K.-J. Kim, kwangje@aps.anl.gov)* ❍

There are a number of possible developments that may be attractive to new scientific users, including seeding to increase the temporal coherence, and related experiments with electron beams produced by the APS guns under development. They include ultrafast diffraction and microscopy. Given sufficient scientific interest, it is envisaged that the ALF and related activities can be incorporated as part of a new strategic initiative at Argonne.

Undulators for the Linac Coherent Light Source

The Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center (SLAC) will be the world's first x-ray free-electron laser (FEL). Compared to the APS, the peak brightness of the LCLS will be more than 9 orders of magnitude larger and the pulse length will be at least a factor of 500 shorter. These extreme properties will enable a broad range of new science and technologies.

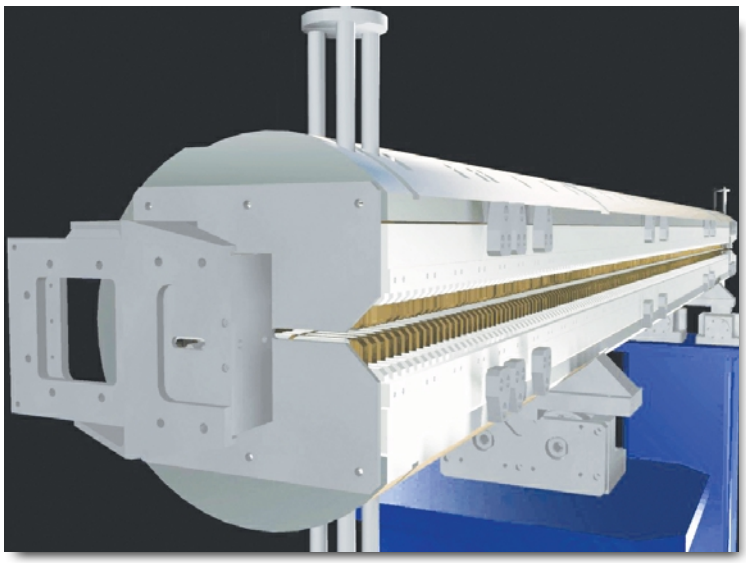


Fig. 1. A three-dimensional model of one of the 33 permanent magnet, fixed-gap, 3.4-m-long LCLS undulators.

The LCLS is scheduled to begin operation in 2009. Formal construction begins in fiscal year (FY) 2006, but a significant amount of construction will take place in FY05. Completion of LCLS construction is scheduled for the end of 2007, with commissioning to occur during 2008.

The x-ray FEL at the LCLS will initially operate much like the FEL at the APS (known as the LEUTL, for Low-Energy Undulator Test Line). A high-brightness electron beam will be accelerated by a linear accelerator. This beam will then be guided through a long, precision undulator magnet system. As the electron beam passes through the undulator magnetic field, the resulting light will generate x-rays, and these x-rays will interact back on the electron bunch. This process will conspire to create microbunching within the electron bunch, which will, in turn, radiate coherently and intensely at the resonant wavelength. An exponential runaway feedback process will develop and continue until the process reaches saturation. This self-amplified spontaneous emission FEL process generates an x-ray pulse that is transversely coherent and has a very high degree of temporal coherence. It is laser-like at x-ray wavelengths.

Much like the Spallation Neutron Source at Oak Ridge National Laboratory, the LCLS is a multilaboratory collaboration, the principal laboratory being SLAC, where the LCLS will be. Both the Argonne and Lawrence Livermore national laboratories are major collaboration participants.

Capitalizing on the precision undulator systems expertise at the APS, Argonne is responsible for the delivery of the approximately 130-m-long LCLS undulator system. This component includes the 33 permanent-magnet, fixed-gap undulators; the 33 focusing quadrupoles; all associated diagnostics, vacuum systems, and controls systems; and most supports. Advanced Photon Source scientists and engineers will also consult on the construction of a magnet measurement facility at SLAC.

For the LCLS contingent at APS, the year 2003 was a period of final transition from an R&D effort to the project engineering and design phase. In January 2003, Stephen Milton (milton@aps.anl.gov) was appointed ANL LCLS Project Director. An important LCLS milestone was achieved in May 2003 when the Department of Energy granted LCLS a Critical Decision 2a, giving approval to the request for long-lead procurements in FY05.

Throughout 2003, the ANL LCLS team concentrated on additional engineering and design issues and on completing tests on the first full-length undulator prototype magnet. This magnet, built in 2002, must achieve very exacting and critical tolerances. In particular, the normalized average field strength for this magnet must be correct to within 1.5×10^{-4}. This tolerance translates into an undulator gap constant to within 1 μm. The solution to this technical requirement came from an idea generated during the review of the undulator prototype in November 2003 and utilizes a "canted" pole concept: poles shimmed and tipped by 3 mrad relative to one another.

A complete work breakdown structure and an integrated cost and schedule for the ANL component of the LCLS project have been completed. These will be reviewed in May 2004 by an external, independent review committee, at which time formal baselines will be set for LCLS costs and schedules. ❍