CONF-961229--1

ANL/ASD/CP--91834

FEB 20 1997
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Status of the Advanced Photon Source*

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General Information

The Advanced Photon Source (APS) is a synchrotron radiation source[1] located at Argonne National Laboratory in Illinois in the USA. Its purpose is to provide very intense x-rays in the energy range from 3 to 50 keV for research in materials science, biology, environmental science, and medicine. Construction of the APS was funded by the U.S. Department of Energy at a cost of $468 million.

The APS is one of three similar facilities in the world. The European Synchrotron Radiation Facility, a 6-GeV electron storage ring in Grenoble, France, has been in operation since 1992. The SPring-8 facility, an 8-GeV electron storage ring in Harima Science Garden City, Hyogo Prefecture, Japan is scheduled to begin operation in October 1997. There are over 50 storage ring synchrotron radiation sources in operation worldwide, including 10 in Japan. They vary in size and in wavelength of delivered light, spanning the spectrum from infrared to hard x-rays. The variety of phenomena studied at these facilities is equally broad, ranging from molecular excitations and adsorption processes to x-ray crystallography of proteins. Well-known characteristics of the interaction of synchrotron radiation with matter are being developed into techniques which reach beyond materials science and molecular biology and into everyday life. X-ray microscopy, x-ray angiography, x-ray lithography and microfabrication of semiconductor devices and nanomachines are some examples of such techniques. This is reflected in the population of synchrotron radiation researchers which has grown from its core of physicists and chemists to include biologists, medical researchers, geologists, environmental scientists, pharmaceutical researchers, and engineers.

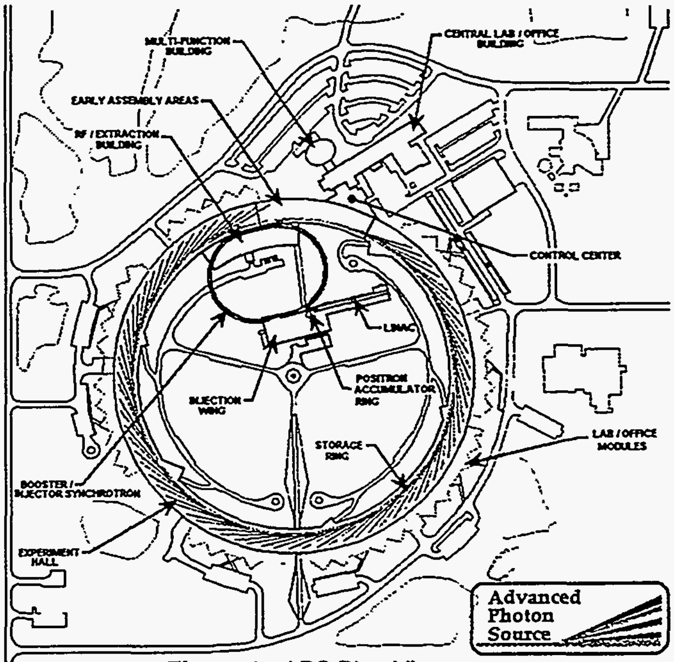

Figure 1. APS Plan View

The scope of the APS project may be broken into three categories: accelerator systems, experimental facilities, and conventional facilities. The accelerator systems consist of the 7-GeV APS positron storage ring and a 7-GeV positron injector. The experimental facilities include 20 undulator radiation sources and the x-ray beamline components necessary to transport their extraordinarily intense x-ray beams outside the accelerator enclosure. Also included are x-ray beamline

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* Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-31.

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components for 20 bending magnet radiation sources. The conventional facilities (see Fig. 1) consist of the accelerator enclosures, a 35,300 m^2 experiment hall to house the x-ray beamlines, an office building for the APS staff and lab/office facilities for the research groups which will construct and operate the first 40 beamlines. Project funding began in 1989, and construction of the buildings began in June 1990. The facility produced its first x-ray beams in 1995. The storage ring can accommodate 14 more undulator radiation sources and an equal number of bending magnet sources, to be funded and constructed sometime in the future.

Description of APS Users

Completion of the x-ray beamlines is the responsibility of 15 groups of researchers called collaborative access teams (CATs) whose proposals were approved by APS. The CATs have secured the additional funds for beamline completion from various sources, including the U.S. Departments of Energy and Agriculture, the National Science Foundation, the National Institutes of Health, the States of Illinois and Florida, the Canadian National Science Engineering Research Council, and the Australian Nuclear Science and Technology Organization, as well as industry and private research foundations. Each CAT will operate two to six beamlines to carry out its proposed experimental programs. In addition, the CATs will make their experimental facilities available to independent researchers up to 25% of the available operating time. The CAT membership includes 640 scientists from 104 universities, 16 national research laboratories, and over 24 industrial research labs. Lists of the APS CATs and their industrial participants are contained in Tables 1 and 2.

Table 1. Collaborative Access Teams (CATs) at the Advanced Photon Source

Basic Energy Sciences Synchrotron Radiation Center (BESSRC-CAT)	Materials science, chemical science, atomic physics
Biophysics CAT (BIO-CAT)	Structure and dynamics of biological and related systems at the molecular level; membranes, fibers, solutions
Consortium for Advanced Radiation Sources CAT (CARS-CAT)	Structural biology, geoscience, chemical sciences, materials science, soil/environmental sciences
Complex Materials Consortium CAT (CMC-CAT)	Structural characterization of complex materials (including complex fluids, self-assembling systems, surfaces and interfaces, and heterogeneous materials)
Du Pont - Northwestern - Dow CAT (DND-CAT)	Surface and interface science, polymer science and technology, materials science
Industrial Macromolecular Crystallography Association CAT (IMCA-CAT)	Structural biology, macromolecular crystallography
IBM-MIT-McGill CAT (IMM-CAT)	Dynamic phenomena in materials science and physics
Center for Real-Time X-ray Studies CAT (MHATT-CAT)	Physics, real-time structural studies of materials, chemical sciences
MICRO-CAT	Microprobe analysis of material structure, biological, and environmental samples
Materials Research CAT (MR-CAT)	Materials, time resolved scattering and spectroscopy, in-situ measurements
Midwest Universities CAT (μ-CAT)	Materials science
Pacific Northwest Consortium CAT (PNC-CAT)	Environmental analysis, materials research, macromolecular crystallography
Structural Biology Center CAT (SBC-CAT)	Macromolecular crystallography
Synchrotron Radiation Instrumentation CAT (SRI-CAT)	X-ray physics and novel synchrotron radiation instrumentation
UNI-CAT	Materials science, structural crystallography, condensed matter physics, time-resolved studies

Table 2. Industrial Participants in APS CATs

Abbott Laboratories	Grant Institute	Pharmacie & Upjohn, Inc.
Amoco Corporation	Holleb & Coff	Procter & Gamble Pharmaceut.
Applied Physics Technologies Corp.	IBM	Schering-Plough Res. Institute
BIOSYM Technologies, Inc.	Kraft Food Technology Center	Searle Research & Development
Bristol-Myers Squibb	Lucent Technologies	SmithKline Beecham Pharmaceut.
DuPont Merck Pharmaceut. Co.	Massachusetts General Hospital	The Dow Chemical Co.
E.C. Slater Institute	Merck & Co., Inc.	The Procter & Gamble Co.
E.I. DuPont de Nemours & Co.	Miles Inc.	The Upjohn Company
Eli Lilly and Co.	Mobil R&D Corp.	UOP Research Center
Exxon Research & Engineering Co.	Monsanto/Searle	Warner-Lambert Co.
Genentech Inc.	Neslab Instruments, Inc.	X-Ray Analytics, Ltd.
Glaxo, Inc.	Parke-Davis Pharmaceut. Res.	

Properties of Synchrotron Radiation

Synchrotron radiation is nothing more than electromagnetic radiation, like radio waves and light[2]. All electromagnetic radiation is produced by the *acceleration* of electric charges. Synchrotron radiation is produced when a beam of electrons or positrons is deflected by magnets in a particle accelerator. Magnets apply a force to the particles which is perpendicular to the direction in which the particles are moving. The abrupt change in direction of the particle beam is the "acceleration" which produces synchrotron radiation. When the energy of the particles in the beam becomes much larger than the rest-mass energy of the particles (i.e., the beam is highly relativistic), the synchrotron radiation develops special properties:

1. Much of the synchrotron radiation power is strongly collimated into a narrow cone centered on the velocity vector of the beam. The opening angle of the radiation power is

   $$\Theta_{rms} = 1/\gamma \,, \tag{1}$$

   where γ is the ratio of total energy to rest mass energy of the particle. For the 7-GeV APS storage ring, γ is approximately (7,000 MeV)/(0.511 MeV) = 13,699, so the radiation is concentrated within 73 microradians of the velocity vector of the emitting particle.

2. Synchrotron radiation from more energetic particles is shifted to short wavelengths. This may be inferred from the fact that the radiation is highly collimated. Imagine a positron travelling on a curved trajectory with radius R. An observer some distance from the electron will be illuminated by the narrow cone of synchrotron radiation as it sweeps past the observer. The cone scans across the observer in a time

   $$\Delta t = \Theta_{rms}\frac{R}{v} \,, \tag{2}$$

   where v is the velocity of the positron. If the electron is highly relativistic, its speed is very near to the speed of light c:

   $$\frac{v}{c} = \frac{\sqrt{E^2 - m^2c^4}}{E} \,. \tag{3}$$

Therefore the physical length of the radiation pulse is just the distance by which the light races ahead of the positron during the period of illumination (see Fig. 2):

$$\ell = (c - v)\Delta t = c(1 - v/c)\Delta t \cong \frac{R}{2\gamma^3}. \tag{4}$$

The characteristic wavelength of the synchrotron radiation must be comparable to this very short pulse length. The formula commonly used to define the "critical wavelength" of synchrotron radiation from a bending magnet is

$$\lambda_c \text{ (in angstroms)} = 5.589 \text{ R (in meters)} / [\text{E (in GeV)}]^3 . \tag{5}$$

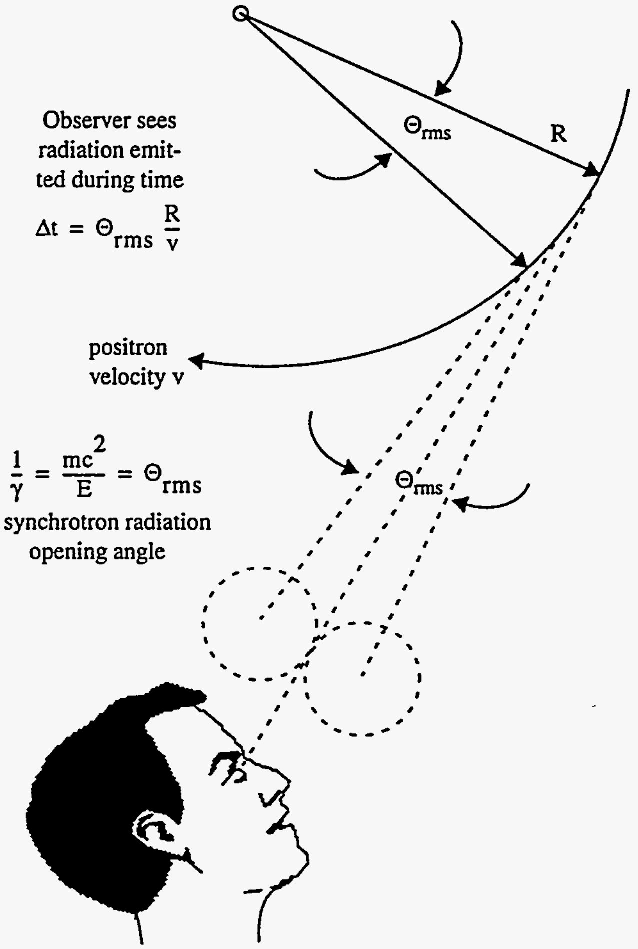


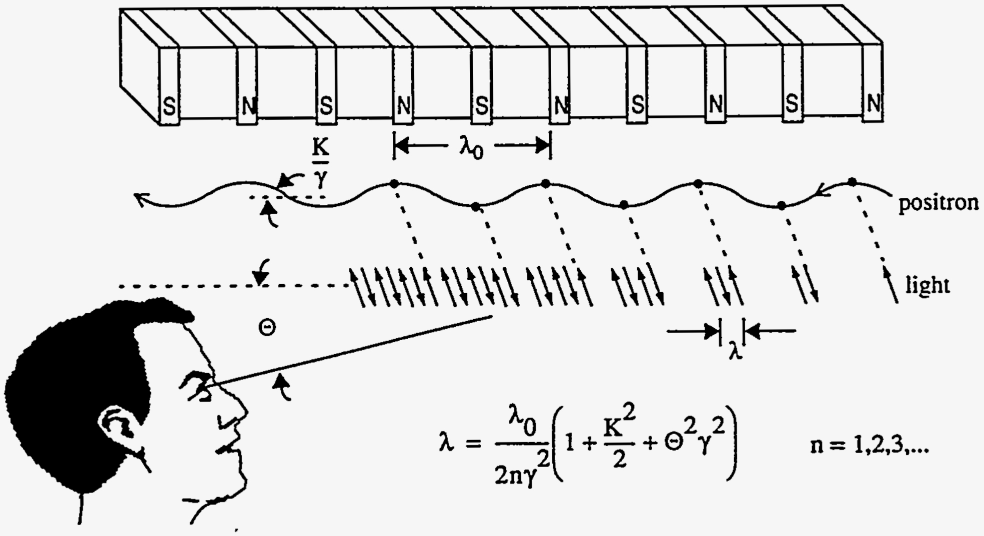
Figure 2. Bending Magnet Radiation. During time Δt, light outraces positron by distance $\ell = \Delta t(c - v) \cong \frac{R}{2\gamma^3}$.

The bending radius of the positron beam in the APS is R = 38.96 meters, so the critical wavelength is 0.63 angstroms.

The most important sources of photons in a modern synchrotron radiation facility are the undulator magnets. Undulator magnets are nothing more than a sequence of magnets which cause a particle to move approximately sinusoidally as it passes through. An undulator is distinguished from a bending magnet (or a series of closely spaced bending magnets called a "wiggler") by the fact that it deflects the particle through a small angle, comparable to the opening angle of the bending magnet synchrotron radiation, $1/\gamma$.

This means that the observer is illuminated by synchrotron radiation from the entire trajectory of the positron in the undulator. The wavelength of the radiation from an undulator is determined by the Doppler effect. As the electron progresses through the undulator from one north pole to the next (a distance of λ_0), the radiation races ahead of the positron by

$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) , \tag{6}$$



$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}+\Theta^2\gamma^2\right) \qquad n = 1,2,3,....$$

Figure 3. Undulator Radiation.

where K/γ is the angle through which the particle is deflected by a single pole of the undulator, and θ is the angle between the observer's line of sight and the forward progress of the particle in the undulator (see Fig. 3). The factor ($1+ K^2/2$) accounts for the fact that the length of the undulating particle path exceeds λ_0. This increased path length means the Doppler effect is less and the wavelength of the radiation is greater. The factor n=1,2,3,... represents the fact that undulator radiation contains several harmonically related wavelengths. The APS undulators have λ_0 - 3.3 cm. It is possible to vary K from nearly 0 to 2.6 by adjusting the undulator gap, and since useful radiation is produced up to n = 5 or so, the APS undulators cover the range of photon energies from 3 to 50 keV.

3. Synchrotron radiation is mostly polarized with electric field in the plane of the particle deflection. Special undulators can be designed to produce circularly polarized radiation, and the APS has such an undulator installed.

4. Synchrotron radiation is very intense. The intensity is often expressed in terms of brightness, the number of photons in a 0.1% wavelength range, per square millimeter, per square milliradian of opening angle. The APS undulators deliver brightnesses of over 10^{18} (see Fig. 4). High brightness allows the experimenter to perform measurements on very small samples, search for very low concentrations of specific elements, or collect data very quickly to understand rapid changes in a substance. However, high brightness brings with it some formidable engineering problems. With 100 mA in the APS storage ring, the total power emitted as synchrotron radiation by the dipole magnets is 0.545 MW. The undulators produce about 4 kW each, concentrated into highly collimated beams with 150 W per mm^2 or more, as much as the power density on the surface of a meteor entering the Earth's atmosphere.

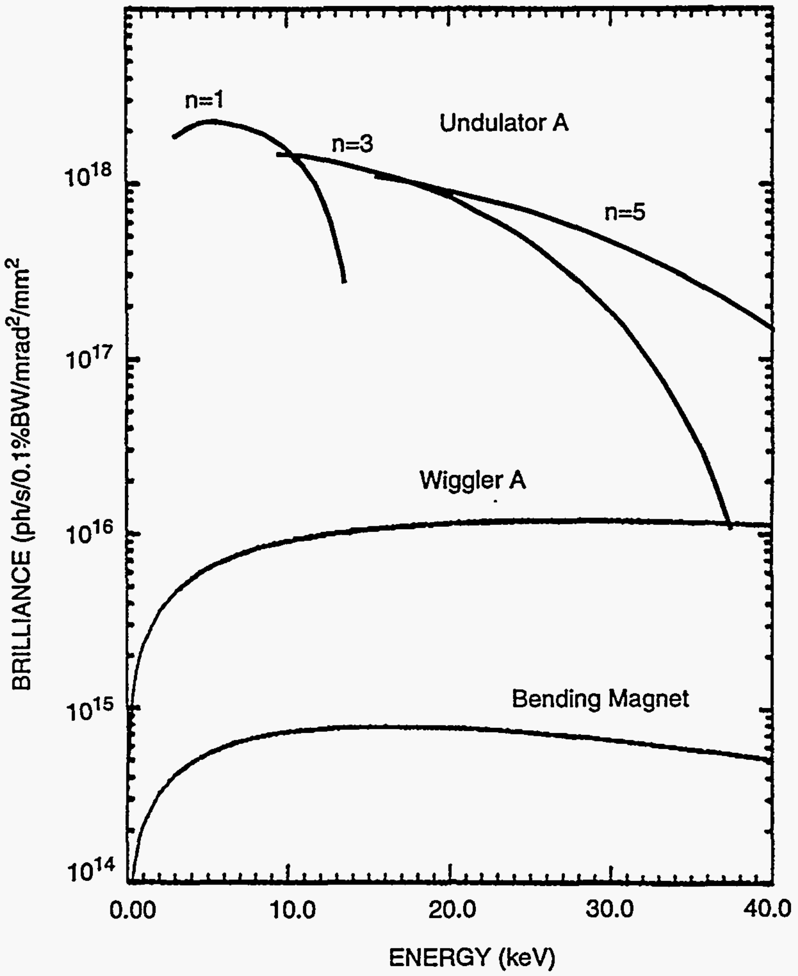


Figure 4. Brilliance of the APS Undulator A, Wiggler A, and Bending Magnet Sources.

Description of the APS

The APS accelerator systems[3] are made up of a 250-MeV electron linear accelerator, a 450-MeV positron linear accelerator[4], a positron accumulator ring (PAR)[5], a 7-GeV booster synchrotron[6], and the storage ring[7] (see Tables 3, 4, and 5). The linear accelerators operate at a repetition rate of 60 Hz. The 250-MeV electrons are focused on a tungsten target to produce positrons which are accelerated to 450 MeV and stored in the PAR. Up to 24 pulses of positrons are collected in the PAR during the acceleration cycle of the booster. Twice every second, positrons from the PAR are transferred to the booster, accelerated to 7 GeV, and injected to the storage ring.

The APS storage ring is designed to make the transverse dimensions of the positron beam as small as possible, so as to produce the brightest possible x-ray beams. The storage ring circumference is divided into 40 sectors, each of which contains a 5-meter straight section. Thirty-five of

Table 3. APS Linac Performance to Date

	Design Goal	Achieved
Electron Linac		
Current on target	1.7 A, 30 ns	2.6 A, 30 ns
Energy on target	200 MeV	235 MeV
Spot size on target	≤ 3 mm dia.	≤ 5 mm dia.
Emittance (95%)	≤ 1.2 mm-mrad	≤ 1.2 mm-mrad
Energy spread $\Delta E/E$	≤ 8 %	≤ 8 %
Bunch length (90%)	≤ 15 °	13 ° ± 3° @ 51 mA
Positron Linac		
Emittance (95%)	6.6 mm-mrad	
Energy spread	≤ 1 %	≤ 1.6 %
Current	8 mA, 30 ns	9 mA, 30 ns
Energy	450 MeV	452 MeV e^+ 655 MeV e^-

Table 4. APS Positron Accumulator Ring Performance to Date

	Operating Goal	Achieved
Energy	450 MeV	450 MeV
Max charge	3.6 nC	4 nC
(current)	(35 mA)	(191 mA)
Bunch length	280 ps rms	500 ps rms (meas. 9.4 kV h=12) < 300 ps (inferred, 25 kV)
Accumulation efficiency	60 %	60 % (10 Hz)

Table 5. APS Booster Performance to Date

	Design Goal	Achieved
Energy	450-7700 MeV	375-7000 MeV
Accelerated charge	6 nC/0.5 s	6 nC/0.5 s
Accumulation efficiency	90 %	~ 95 %
Repetition rate	2 Hz	2 Hz

these straight sections can accommodate undulator magnets, four are reserved for rf cavities, and one contains the special magnets necessary to inject positrons into the ring. Figure 5 is a plan view of 1/40 of the ring. It shows the arrangement of magnets as well as the location of vacuum pumps and beam position monitors. The following is a description of the basic subsystems of the storage ring.

The storage ring magnets include 80 dipole bending magnets, 400 quadrupole focusing magnets, 280 sextupole magnets, 318 vertical/horizontal steering corrector magnets, and 40 skew quadrupole magnets. All magnets have iron yokes and water-cooled copper coils. Their assembly tolerances are of the order of 50 microns, and the magnets were placed around the ring with a precision of 90 microns.

The magnets are powered by over 1,356 individual switching current regulators. They regulate magnet currents with a precision of 100 parts per million.

The storage ring vacuum system is fabricated from aluminum extrusions with aluminum ultrahigh vacuum seals. The shape of the chamber cross section is specially designed to simultaneously incorporate vacuum pumping, confinement of the intense microwave fields around the positron

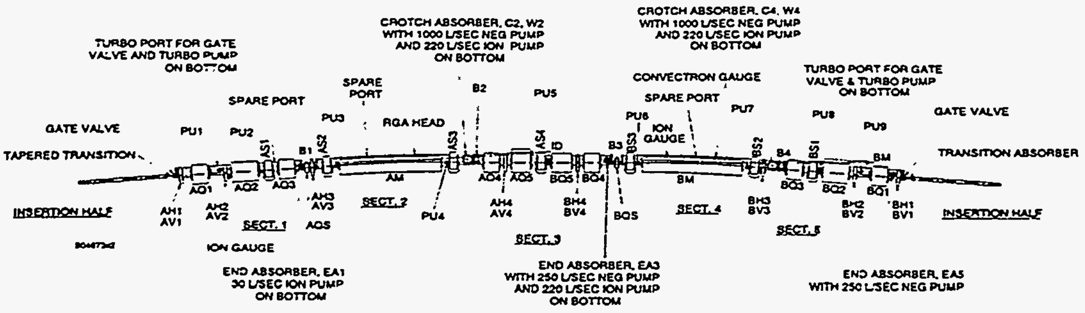


Figure 5. One Sector of the APS Storage Ring.

beam, provision for bakeout of the chamber to 150°C, and Glidcop synchrotron radiation absorbers. Base pressure in the ring is less than 0.1 nanotorr. The synchrotron radiation from the beam causes photodesorption from the chamber walls so the pressure rises to 2 nanotorr when the ring is in operation. The ring is pumped with 251 ion pumps, as well as non-evaporable getter strips distributed continuously around the ring.

The rf systems consist of four 1-MW, 352-MHz radiotransmitters, connected to 16 rf cavities. The rf systems create a 9-MV accelerating field to replace the 6-MeV energy loss by the positrons as they produce synchrotron radiation.

The most important diagnostics devices are the 360 rf beam position monitors (RFBPMs)[8]. Each RFBPM compares the strength of four small radio antennae (actually capacitor plates built into the vacuum chamber) to determine the position of the positron beam to a precision of 5 microns. Other diagnostic devices include beam profile monitors that verify the transverse dimensions of the beam, radiation monitors to identify points at which the injected beam is lost, and a streak camera used to measure the length of the circulating bunches of positrons (66 to 170 picoseconds full width at half maximum intensity).

The computer controls system consists of input-output controllers (IOCs), which are VME computers with a real-time operating system. They communicate with Unix workstations using the TCP/IP networking protocol. The system monitors and controls about 100,000 parameters that are important to the accelerator. The controls system software, called EPICS, was developed by Los Alamos National Laboratory and Argonne. It has been adopted by many scientific facilities around the world.

The undulator magnets are the most important sources of synchrotron radiation in the storage ring. A single undulator design ("undulator A") has been selected by almost all CATs. It is 2.4 meters long, with a period λ_0 of 33 mm. Because it can be closed to a gap of less than 11 mm, it produces high x-ray intensity from 3.6 to 45 keV. Within the undulators is a fixed-gap aluminum vacuum chamber with 1-mm wall thickness and 8-mm vertical aperture for the positron beam. The success in producing this chamber with precisely controlled dimensions made possible the small minimum gap of the undulator and thus the wide spectral range of the standard APS undulator.

The APS storage ring has attained or exceeded essentially all its original design performance specifications (see Table 6). The facility has maintained a schedule of three weeks running followed by three weeks of maintenance and beamline installation since January 1996. The x-ray beamlines are at various stages of construction and commissioning. The first experiments are already yielding significant results, including new crystallographic data on human proteins.

The APS staff is actively involved in both basic and applied research using the storage ring. Miniature linear accelerator structures have been micromachined by APS staff using LIGA tech-

Table 6. APS Storage Ring Design Specifications

	Design Goal	Achieved
Current	100 mA	162 mA
	5 mA (single bunch)	18.3 mA (single bunch)
Lifetime	10 hours @ 100 mA	14 hours @ 100 mA
Emittances	8 nm-radian horizontal	8 nm-radian horizontal
	< 0.8 nm-radian vertical	0.25 nm-radian vertical

niques, and promising results have been obtained in tests of x-ray welding of metal matrix composite materials such as aluminum/aluminum oxide.

Plans for future development of the APS place primary emphasis on construction of x-ray beamlines in the remaining 14 sectors of the facility and on "top-up" operation of the storage ring. Top-up operation means continuous injection while all x-ray beamlines are actively taking data. A 20-ms interruption in collecting the data may be necessary every minute or so during the injection process. Top-up operation will keep the stored current nearly constant. This means that the heat load on x-ray optics and other accelerator components will not vary, and thermal distortions of the optics will not introduce systematic errors in collected data. A constant current in the storage ring will also mean that data rates are always at maximum and the effect of nonlinearities in beam detectors is minimized. Finally, top-up operation may make possible the installation of undulators with extremely small gaps that would make the positron beam lifetime unacceptably short without continuous injection.

In addition, studies will be carried out to raise the stored current to 300 mA and to reduce the horizontal emittance by a factor of 2 and the vertical emittance by a factor of 20. Combined, these changes will increase the brightness of APS undulators by a factor of 1,000 relative to the original design specification.

Other possibilities presently under consideration include development of a slow positron source and a 100-nanometer free-electron laser using the APS linac.

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