ANL ASD/CP-92214

CONF-970503--

PERFORMANCE OF THE ADVANCED PHOTON SOURCE

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Abstract

The Advanced Photon Source (APS) positron storage ring is a 100-mA, 7-GeV, third-generation x-ray synchrotron radiation source which began operation in March 1995. Since that time, significant progress on beamline construction and commissioning has taken place, with many of the x-ray user beamlines in operation. Operational design goals which have been met or exceeded include < 8.2-nm-rad emittance, > 10-hour lifetime, > 90% availability, > 100-mA average current, > 5-mA single-bunch current, < 10% uncorrected coupling, 8-mm full vertical apertures for insertion devices, and ultra-stable orbit (< 4.5 μm rms vertically, 17 μm horizontally). Progress beyond these design goals and a report on development plans, including top-up operation (injection with x-ray beamline shutters open), are presented.

1 INTRODUCTION

The APS storage ring achieved first stored beam with extracted light on March 26, 1995 and was formally dedicated on May 1 of that year. The ring was officially declared operational for user beam by the Department of Energy on August 8, 1996. Ten insertion device (ID) and six bending magnet (BM) beamlines are now operational with six additional beamlines undergoing commissioning. Eighteen of the planned twenty-one insertion devices are now in place. Table 1 lists the relevant APS storage ring characteristics. The APS storage ring lattice, shown in Figure 1, is a double bend achromat Chasman-Green design.

Table 1: APS Storage Ring Characteristics

Energy (GeV)	7.0
Number of superperiods	40
Circumference (m)	1104
Harmonic number	1296
RF frequency (MHz)	351.93
Critical energy (keV)	19.5
Energy loss/turn (MeV)	6.9
Vertical full aperture (mm)	8
Horizontal tune	35.2
Vertical tune	14.3
Synchrotron tune	0.0072
Horiz. beam size at insertion device source point (μm rms)	325
Vertical beam size at insertion device source point (μm rms)	86
Straight sections available for IDs	35
Straight Section Length for IDs (m)	5.2

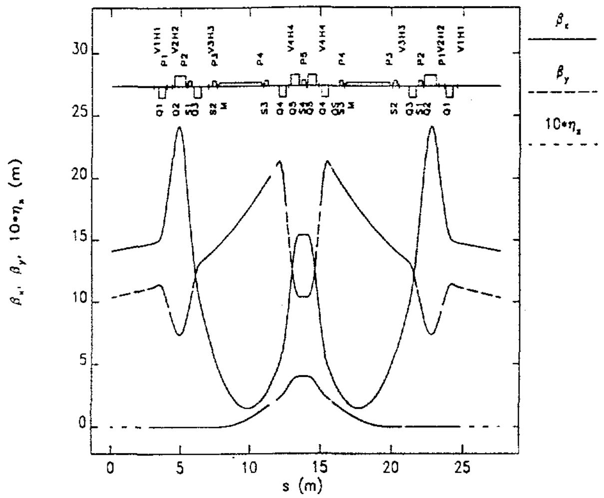

Figure 1: Lattice drawing for the APS storage ring.

2 PERFORMANCE SUMMARY

Table 2 contains APS performance parameters, indicating both design values and best performance to date.

Table 2: Summary of APS Storage Ring Performance

	Design	Achieved
Total current (mA)	100	164
Single bunch current (mA)	5	18.1
Stored beam lifetime (Hr)	> 10	> 30
Emittance (nm-mrad)	8.2	7.6 ± 0.8
Horiz. - vert. coupling	< 10%	< 3%
Natural bunch length (ps rms)	17.6	< 29
Bunch length @5 mA (ps rms)	52	52
Vertical beam stability (μm rms 1-50 Hz)	< 4.5	< 4.0
Horizontal beam stability (μm rms 1-50 Hz)	< 17.	< 17.
User x-ray beam availability	> 90%	87%
Avg. vacuum at 100 mA (nT)	< 1.0	0.8

3 OPERATIONS

Regular user runs began in late 1995. Since that time, operation has normally consisted of 3-week user runs interleaved with 3-week-long maintenance periods used mostly for completion of beamline front-end hardware. With the imminent completion of in-tunnel hardware, the relative proportion of user time to maintenance is expected to increase. Shown in Table 3 are availability data for the last six operational periods. At the APS availability does

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not include injection and orbit correction time at the beginning of each fill.

Table 3: APS Operations Statistics

Run Number	Scheduled User Time (Hours)	X-ray Availability	Amp-Hours
96-5	250.0	65.9%	12.7
96-6a	255.3	69.1%	14.2
96-6b	268.6	83.2%	16.9
96-7	250.0	58.8%	8.6
97-1	342.9	74.0%	18.8
97-2	236.7	79.7%	15.1

The availability over the course of a run has been observed in general to increase with time, so that the second half of a 3-week run contains significantly fewer unplanned beam dump events. This result is perhaps to be expected and provides an argument for longer runs, which will be pursued following completion of front-end installation work. Also, it should be noted that the "best" availability quoted in Table 2 is for the second half of run 97-2, in comparison to Table 3 which gives the run averages. The largest contributor to unplanned beam dumps in 1997 have been rf system interlock trips, and efforts are focusing on this area in particular, with reliability and availability budgets defined in general for all hardware systems.

4 BEAM CURRENT AND LIFETIME

Operationally, the storage ring is filled to just over 100 mA on a routine basis. While the accelerator components are generally designed from an engineering standpoint to withstand up to 300 mA, the ID front-end photon shutters presently limit operation to 100 mA. Because the insertion device gaps can be closed to 10.5 mm, the APS undulator A, for example, is capable of generating a peak heat flux in excess of 150 W/mm^2, 30 meters from the source point. Further engineering upgrades are under consideration to facilitate operation above 100 mA.

During a studies period in July 1996, a maximum 164 mA was stored in the storage ring with insertion device gaps open. The limitation was essentially due to the fact that only three of the four 4-cavity rf stations were operational at the time. Poor vacuum was evidenced near pulsed magnet ceramic vacuum chambers, which has since been traced to a poor conductive interior coating that resulted in heating in the presence of large peak current [1]. These chambers have since been replaced. During the same time frame, a single-bunch current of 18.1 mA was achieved, making use of large positive chromaticity. These studies were performed using electrons. During the maintenance period which followed, the facility was changed over to positrons, with no impact on operation; however, these efforts have not been repeated since that time due to increased focus on reliability and beam stability work.

The APS injector supplies single bunches to the storage ring at 7 GeV. Given the large harmonic number, a large variety of fill patterns is possible, with an associated variation in beam lifetime. As few as 42 bunches provide lifetime in excess of the 10 hour/100 mA design goal, but this can be increased by more than a factor of three by going to a 206-bunch fill pattern. Due to the small emittance, the machine is Touschek limited for bunch currents in excess of about 1 mA, below which the Touschek lifetime becomes comparable with the gas scattering lifetime. The Touschek effect becomes even stronger when considering a reduction in the vertical/horizontal coupling; the ring typically runs uncorrected, with coupling in the 3 to 4% range.

The limitation on gas scattering lifetime comes from ring vacuum, specified to be less than 1 nTorr at 100 mA. As can be seen from the average ring ion gauge data shown in Figure 2, the ring has cleaned up nicely in the past year from natural photodesorption [2].

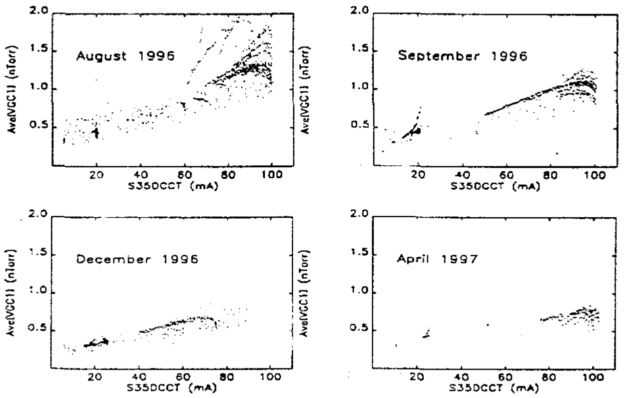

Figure 2: Vacuum vs. beam current and time.

5 EMITTANCE

In early 1996, the first comprehensive study of emittance using insertion device light was conducted on beamline 1-ID [3]. Measurements of beam size and angular divergence resulted in a horizontal emittance value of 7.6 ± 0.8 nm-rad, consistent with the design value of 8.2 nm-rad total emittance and 3% coupling.

Dedicated x-ray imaging capability for the purpose of particle beam diagnostics is available via an x-ray pinhole camera on beamline 35-BM, and is used during operations, with beam size and position process variables logged routinely. This system presently has 1:1 magnification and 60 micron (H) by 40 micron (V) resolutions, with a beamline extension planned to increase magnification by a factor of four. This beamline additionally provides information on beam energy spread due to dispersion at the source point.

A high-resolution imaging station received first light in March of 1997 on beamline 35-ID and is also dedicated to particle beam diagnostics. A special-purpose undulator with 198 periods of 1.8-cm length has a radiation cone angle of only 2.6 μrad in the fundamental, which is less than the positron beam divergences. Initial divergence measurements ($\sigma_{x'} = 21$ μrad and $\sigma_{y'} = 4.9$ μrad) performed at 65 mA stored beam current in May 1997 indicate a vertical coupling of 3.7 ± 0.4% and an emittance of 6.6 ± 0.6 nm-rad (using the theoretical β_x, β_y in the straight; see Table 4 in Ref. 4).

6 BUNCH LENGTH

Associated with the beamline 35-BM is a split ultraviolet / visible light pick-off mirror and optical transport line which can be used both for low-resolution imaging and streak camera bunch-length measurements [5]. In addition to bunch lengthening (Fig. 3), this diagnostic has been used to observe the head-tail instability under reduced chromaticity conditions. Analysis of longitudinal loss factor and transverse impedance can be found in Ref. 6.

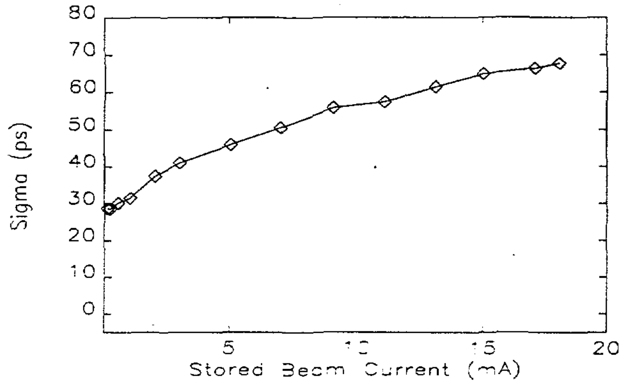

Figure 3: Bunch length vs. current, single bunch.

7 ORBIT STABILITY AND CONTROL

The specification for orbit stability at the APS is that the beam's rms centroid motion should not exceed 5% of its size at beamline source points. For insertion devices, this amounts to 4.5 microns rms vertically and 17 microns rms horizontally in position, and 0.45 microradians rms vertically and 1.2 microradians rms horizontally in angle.

It should be noted that the design 10% coupling is used in deriving these stability criteria. Even though it is possible to reduce the vertical beam size significantly by decoupling the machine, full advantage of the resultant increase in brightness cannot be realized until submicron beam stability can be achieved. Additionally, the reduced Touschek lifetime becomes another limitation on small coupling operation.

It should also be noted that the above stability criteria have been stated without reference to frequency bandwidth. Typically the band of interest to x-ray users extends from very low frequency, i.e., daily variations, up to about 10 Hz, depending on the type of experiment being performed. For many experiments, motions faster than this mimic an increased emittance with associated reduced x-ray flux.

Beam position is measured at 360 stations around the ring circumference using capacitive pickup electrodes. Turn-by-turn position information is collected using amplitude-to-phase conversion rf receivers at each station. Hardware and software averaging is used to obtain submicron resolution readbacks. Orbit correction is effected using up to 317 combined-function horizontal/vertical steering corrector magnets. Of these, 38 have thin wall chambers in their bore, providing correction bandwidth capability above 100 Hz.

Orbit correction software uses a severely under-determined singular value decomposition (SVD) algorithm, using 40 of 317 possible correctors [7, 8], but a maximum number of beam position monitors (BPMs). A unique "despiking" algorithm is used, which replaces BPM readbacks having unphysical offset shifts by the average of neighboring units. The effect of this is that the algorithm focuses on long spatial wavelength (i.e., physical) orbit motions, ignoring to a large extent the unit-to-unit systematic errors in the BPM electronics. Corrections are written to the corrector magnets every 5 to 10 seconds. Local beamline steering is generally performed at user request only.

A major difficulty in assessing long-term orbit stability is the absence of an absolute reference. At the APS, the most accurately believed beam position measurement is derived from x-ray beam position monitors located at bending magnet beamline front-ends, which are sensitive to vertical beam motions. At the 5-micron scale, the long-term (several hour) beam motion characteristics as seen by the x-ray monitors have significant variations compared to the rf beam position monitors. Intensity-dependent offsets in the rf electronics are typically of order 20 microns over a 10-hour fill. Even after compensating for this, examples of what appears to be real beam motion on the rf BPMs at bending magnet source points are not seen on the x-ray monitors. A 7-micron peak-to-peak half-hour period motion read back on the rf BPMs in sector 1 that is correlated with air temperature variations is not present on either of the bending magnet x-ray BPMs in that sector. One possible explanation is that the vacuum chamber is moving locally in response to tunnel temperature changes, but the correction algorithm is insensitive to this owing to the great statistical advantage of using large numbers of BPMs to correct only long spatial wavelength motions. The x-ray BPMs are mounted on specially designed thermally isolated and vibration damped supports, whereas the rf pick-up electrodes are mounted on chambers supported from the magnet girders but mechanically isolated from the magnets themselves. Determining the systematics associated with both the rf and x-ray beam position monitors at the few-micron scale is a major effort in the coming year.

In addition to the "slow" software orbit feedback, a real-time closed orbit feedback system is being commissioned during studies periods and will be released for user operation sometime this summer [9]. This system has access to 320 of the 360 beam position monitors and makes use of the 38 high-bandwidth correction magnets in its global implementation, writing to them at a 1-kHz rate.

A summary of the status of APS orbit stability, over nearly ten decades of frequency, from 3×10^{-5} Hz to 135 kHz, is shown in Figs. 4 and 5. Displayed is the power spectral density averaged over 40 beam position monitors located at insertion device source points. The effect of the real-time closed orbit feedback system is clearly shown. The slow orbit feedback and BPM offset compensation was active for all of the data sets shown and is responsible for the spectral lines located near 0.1 Hz.

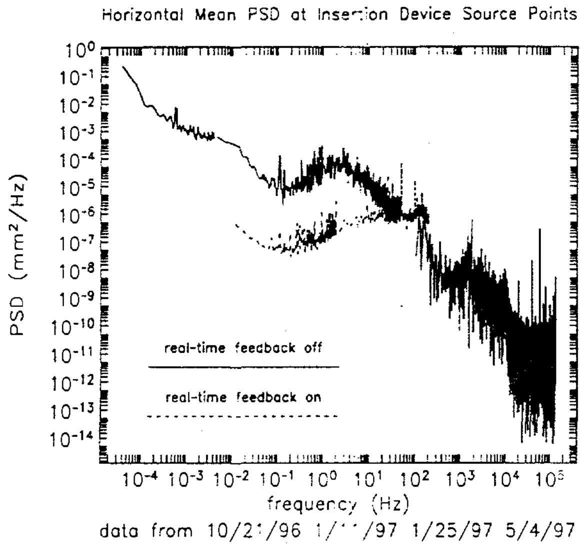

Figure 4: Horizontal spectrum with and without feedback.

Also visible in Fig. 4 are spectral lines at 5.5×10^{-4} Hz (air temperature variations), 25, 50, and 100 Hz (traced to a malfunctioning quadrupole power supply, since repaired), and approximately 1.7 kHz, the synchrotron tune. Lines at 20, 40, and 60 kHz are associated with the pulse-width-modulated power supplies used on nearly all storage ring magnets. Similarly, in Fig. 5 can be seen the 2 Hz injector repetition rate in addition to the 5.5×10^{-4} Hz line.

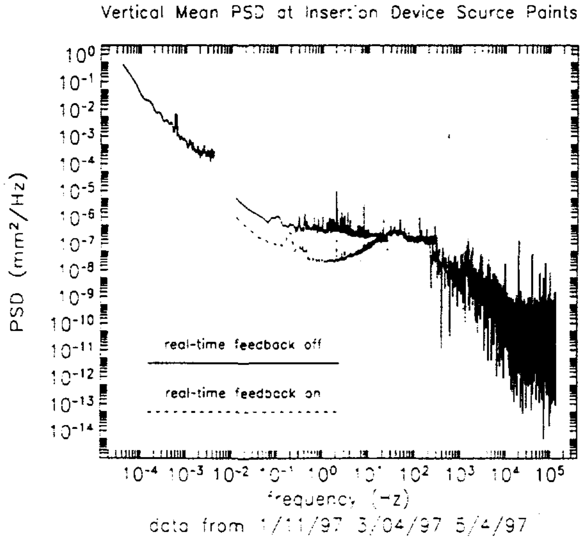

Figure 5: Vertical spectrum with and without feedback.

As stated in Table 2, the orbit stability specifications are met without correction in the band from 1 to 50 Hz. Unfortunately, a very significant contribution to beam motion lies outside this band. The real-time feedback system, when configured to correct dynamic effects only, eliminates the horizontal broadband peak between 0.1 and 10 Hz, extending the band where specification is met down to 10 mHz on the low end. The slow feedback system allows stability criteria to be met at frequencies below this.

In addition to improving orbit stability, the fast feedback system provides an extremely powerful tool for identifying noise sources. By analyzing spectra of the setpoints being written to correction elements, it is in principle possible to localize noise sources to within the spacing of the correctors or better. This type of analysis has occurred before using off-line techniques, and in fact was used to locate a sextupole power supply which was oscillating at 6.5 Hz using EPICS for real-time data acquisition. The possibility of performing this type of analysis in real time up to 500 Hz, and perhaps even generating an alarm when a noise source arises, is an exciting prospect indeed. Early indications are that this will be realizable.

The unique requirements of a synchrotron light source, in particular the extreme emphasis on orbit stability and control, has made possible some unique observations. Shown in Figure 6 is a plot of horizontal beam position averaged over the 40 high dispersion points around the ring. A 25-micron peak-to-peak diurnal variation is clearly seen. This effect was first observed at LEP [10] using polarimeter-based beam energy measurements, and is in fact a geometric effect associated with earth tides. Owing to the small momentum compaction and tight measurement resolution at APS, one can directly observe variations in the ring's orbit circumference resulting from astronomical phenomena.

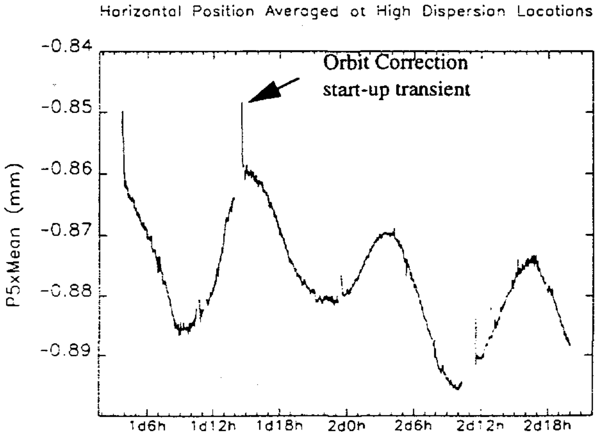

Figure 6: Data showing diurnal ring circumference change.

8 STORAGE RING DEVELOPMENT PLANS

Primary areas where improvements or upgrades are planned in the near future at APS are reliability and availability, orbit stability, and top-up operation. Reliability is a measure of the probability that the ring will be available for a specified time after a user walks in the door and is typically measured in terms of the mean time to an unscheduled beam dump. Availability, on the other hand, is simply the ratio of actual up time to scheduled up time. Both hardware and software upgrades are underway to improve both availability and reliability. Improved electronics cooling, re-design of key machine protection system interlock components, and an rf waveguide switching upgrade [11, 12, 13] are underway on the hardware front, and more sophisticated software alarming and improved software procedures [14] are rapidly becoming available.

Improvements in beam stability are similarly tied to both hardware and software upgrades. The insertion device vacuum chambers have integral to their design two dedicated sets of increased-sensitivity capacitive pick-up electrodes at each end. When these chambers were installed, electronics from neighboring stations were simply relocated to the insertion device pickups. An ongoing upgrade is the procurement of narrow-band switched-receiver electronics [15] for the insertion devices and the relocation of electronics back to their original configuration. While they have nowhere near the bandwidth of the existing electronics as exhibited in Figures 4 and 5, the new receivers should facilitate greatly enhanced long-term stability characteristics at the ID source points. These new electronics will be tied to the real-time orbit feedback system. The software for both real-time and long-term orbit correction is continuously being evaluated for improved characteristics. When submicron beam stability is achieved, a subsequent increase in brightness through lattice modifications and reduced coupling will follow.

Given that the APS has its own dedicated on-energy injector, one special operating mode being actively investigated is called "top-up." This can be simply understood as injection with user x-ray shutters open, for the purpose of regulating stored beam current. This user beam mode has the advantage of alleviating beam-intensity-related systematic errors affecting user experiments. Using existing hardware, it appears feasible to regulate stored beam down to the 0.1% level (i.e., 0.1 mA out of 100 mA total). Improvements in the injector portion of the facility, injection efficiency in general, and beam diagnostics should make it possible to push this to the 0.01% level.

A key safety element necessary for top-up is a modification to the ring access control interlock system used for personnel safety. The worst-case scenario occurs if a storage ring main dipole magnet were to short out during injection with shutters open. This could conceivably direct the injected charged particle beam down a user beamline. If, however, one insists on the presence of stored beam prior to enabling injection in top-up mode, it can be shown that it is impossible for this failure scenario to occur. A reliable top-up beam current monitor for inclusion in this logic is under development.

To gauge the effects of injection beam losses during top-up operation, radiation measurements have been performed on the experiment hall floor while missteering the beam to scrape on the 8-mm-aperture insertion device chambers with safety shutters both open and closed. Preliminary results look promising.

9 CONCLUSIONS

In its first year of operation, the Advanced Photon Source has met all of its design performance goals and is well on the way to providing reliable, ultra-stable beam for its user community. Planned upgrades in brightness, including top-up operation, together with improvements in beam stabilization and injection efficiency will provide state-of-the-art x-ray beams into the next century.

10 ACKNOWLEDGMENTS

This work is a culmination of the efforts of virtually all members of the APS Accelerator Systems Division together with the assistance and support of key members of its sister division, Experimental Facilities.

Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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