Performance of the Advanced Light Source

A. Jackson for the ALS Accelerator Group
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720 USA

Abstract

The Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory (LBL) is the first of the lower energy (1–2 GeV) third-generation synchrotron radiation facilities to come into operation. Designed with very small electron beam emittances to operate with long insertion devices producing very high brightness beams of synchrotron radiation in the VUV and soft x-ray regions of the spectrum, these facilities are complementary to the higher energy (6–9 GeV) facilities [1] designed for harder x-radiation. The ALS storage ring began operation in October 1993. In this paper, we will review the operational performance of the ALS, including the effects of the 4.5 m long undulators (period 5 cm), and discuss the overall performance of the facility.

1. Introduction

The ALS came into full operation as a user facility in October 1993. By December, a regular schedule had been established. Operations are from Monday to Friday, broken into eight-hour shifts for maintenance and installation, accelerator development (which is often in direct support of enhanced capabilities for users), and user shifts. Each week, there are typically two shifts for installation and start-up, three for accelerator physics, and nine for users. During the first seven months of operation the accelerator efficiency has been exceptionally high. Records from January through the end of April show an average uptime of 92%, with regular improvement resulting in 95% during April. Starting currents for experimental runs are at the design level of 400 mA, unless smaller currents for special experiments are requested. With beam lifetimes of around 14 hours, refills are requested by users at six–eight hour intervals.

Three beamlines have been operational since the beginning of the year, one bend-magnet beamline and two beamlines associated with undulators. In May 1994, the ALS closed down for scheduled installation of the third undulator, front end and beamline components for five new beamlines, and a longitudinal kicker to be used for suppression of multi-bunch instabilities.

Accelerator studies have successfully characterized all the major storage ring parameters and the effects of the two undulators. In general, the behavior is in good agreement with that predicted by our modelling codes, with the exception of the multi-bunch beam lifetime, which is anomalously high! These studies, including a probable explanation for the long beam lifetimes, are the main subjects of this report.

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2. Storage ring accelerator studies

The ALS storage ring has twelve-fold symmetry, with long straight sections separated by "three-bend" achromatic arcs. The lattice functions through one super-period are shown in Figure 1. In the sections that follow, we present analysis of closed-orbit correction and chromaticity compensation, measurement of the lattice functions, betatron coupling, emittance, beam lifetime, beam reproducibility and stability, and the effects of undulators. Both transverse and longitudinal multi-bunch instabilities have been observed, and demonstration experiments [2], [3] to damp the coherent motion have been carried out.

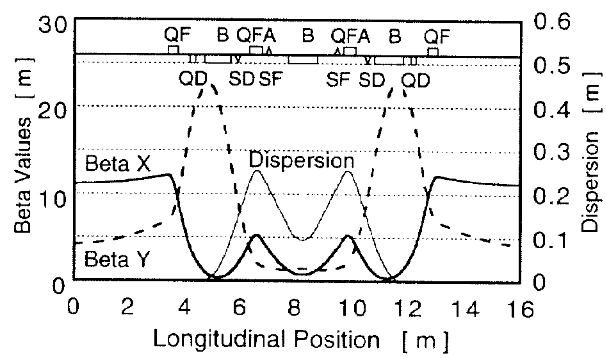

Figure 1. Lattice structure and functions through one unit cell of the Storage Ring.

2.1 Closed Orbit

The uncorrected closed-orbit distortion (COD) in the storage ring, as measured at the positions of the beam position monitors (BPMs), is 1.0 mm RMS and 3.1 mm peak in the horizontal plane, and 1.3 mm RMS and 3.9 mm peak in the vertical plane. This alone is testimony to the excellent construction and alignment of the lattice magnets. Initially, correction was accomplished using the overlapping-bump correction algorithm which successfully reduced the RMS error to less than 0.5 mm in both planes. However, the corrector strengths generated by this method were unexpectedly high, so we tried a new algorithm based on singular-value decomposition of the measured correction matrix. By selectively choosing those eigenvectors with higher corrector sensitivity it was possible to correct the orbit using less than 10% of the maximum corrector strengths to a level of 0.3 mm RMS. This method, which produces a very smooth local orbit, also indicated that some of the BPMs have offsets (either mechanical or electrical) of up to 2 mm. Beam-based measurement of the centers of 48 of the 96 BPMs, with respect to the centers of the individually variable quadrupoles (labeled QF and QD in Figure 1), shows good correlation between this method and the COD offsets. We are now confident that the COD can be reduced to better than 0.1 mm RMS using the measured BPM centers.

2.2 Chromaticity Compensation

The natural chromaticity of the ALS is very high due to the large horizontal focusing forces required to produce low emittance: $\xi_x = -24.5$, $\xi_y = -28.3$. These values are set to zero (first order), by two families of sextupoles, in order to combat the head-tail instability. Because of the strong sextupole fields required, SF = 22.6 m^{-2} and SD = -17.1 m^{-2}, there is a significant second-order variation which, is seen in Figure 2.

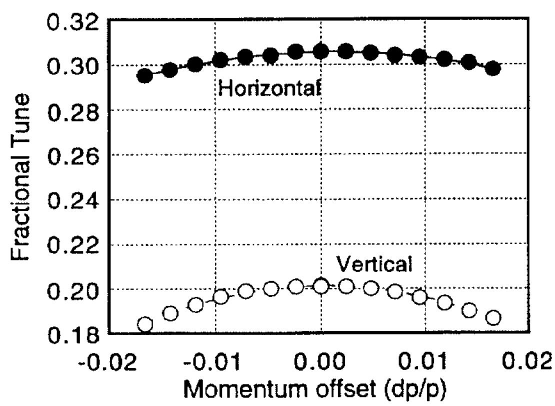

Figure 2. Variation of betatron tune with momentum.

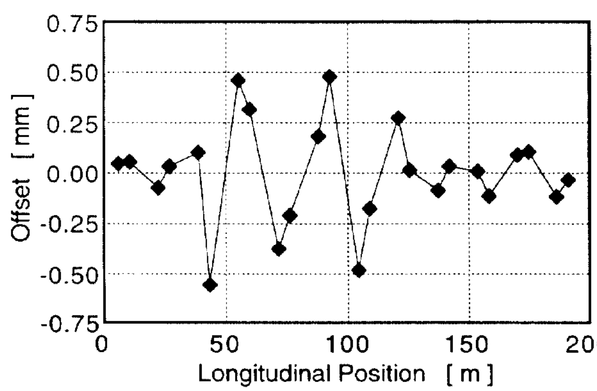

Figure 3. Horizontal offsets in SD sextupoles required to produce the β–beat shown in Figure 4.

2.3 β–function

The horizontal and vertical β–functions around the circumference have been measured using three independent techniques: (1) the betatron tune variation as a function of quadrupole strength, (2) the effect of individual steering magnets on the closed orbit, and (3) the phase of a free betatron oscillation at each BPM. All three methods give consistent results that show a 10% β–beat around the circumference. Our model indicates that the β–beat could be produced by a horizontal COD of less than 0.5 mm in the sextupoles, as shown in Figure 3. Figure 4 shows the β–functions at one family of quadrupoles and the simulation when the closed-orbit offsets in Figure 3 are introduced. From this work, we conclude that the beat should be reduced as the closed orbit is further improved.

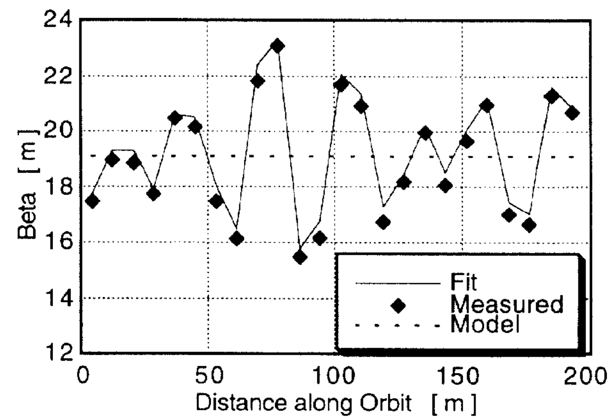

Figure 4. Fit to the measured β–function data when orbit is displaced in sextupoles.

2.4 Dispersion Function

The dispersion function is set to zero in the long straight sections by the QFA family of quadrupoles. It is measured by observing the change in the COD as a function of RF frequency. The data for the horizontal plane are in good agreement with the models, again at the 10% error level, and we have measurements that indicate that the residual dispersion beat is a strong function of the residual COD. Therefore, we again expect the agreement between measurement and model to improve as we improve the closed orbit. A sizable nonlinear component in the dispersion function has also been measured. In the vertical plane, the dispersion is small but finite, and we believe that this small dispersion is responsible for the observed vertical emittance of the beam (see 2.6).

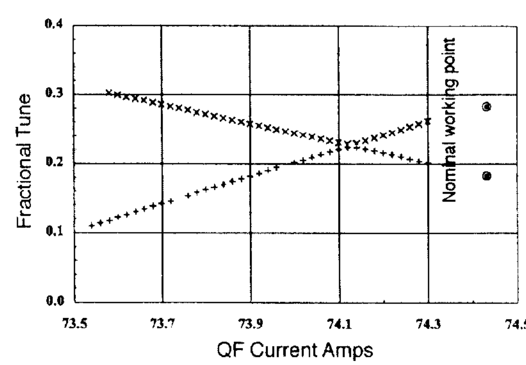

Figure 5. Tune variation observed through the coupling resonance.

2.5 Betatron Coupling

Coupling of energy between the horizontal and vertical planes was measured by observing the difference in betatron frequencies as the coupling resonance is crossed. The smallest difference was $\Delta\nu \approx 0.003$ (see Figure 5), indicating an emittance coupling $\varepsilon_y/\varepsilon_x$(coupling) at the nominal working point ($\nu_x \approx 14.3$, $\nu_y \approx 8.2$), of 0.1%.

2.6 Electron Beam Emittance

The electron beam emittances in both planes have been measured at low current by analyzing the cone width of off-axis radiation from the undulator [4]. This could only be done at low current ($\approx$ 0.5 mA) because the experiment employed a transmission grating that was exposed to the full undulator radiation. The results gave a horizontal emittance of 5 nm-rad, and a vertical emittance of < 0.2 nm-rad. The theoretical natural horizontal emittance is 3.6 nm-rad, which indicates an emittance ratio of $\varepsilon_y/\varepsilon_x \approx 5\%$. Since the contribution from betatron coupling (see 2.5) is much smaller than this value, we conclude that the main contribution to the vertical emittance arises due to the finite vertical dispersion.

2.7 Beam Lifetime

Beam lifetime in the ALS, with the parameters described above and with the present operating RF acceptance of 2.4%, is expected to be dominated by the Touschek effect. That this is the case is verified by measurement of the single-bunch lifetime ($\tau \approx 3$ hr at 1 mA), and by the observation that the lifetime increases significantly when the working point is moved to the coupling resonance. However, in multibunch operation the observed lifetimes are much longer than predicted by the Touschek effect. For example, with 320 mA in 320 bunches (again 1 mA/bunch) the beam lifetime is 13 hr. It is postulated that this anomaly is due to a dilution of the charge density in the bunches arising from multibunch instabilities. Indeed, in multibunch mode we have measured a broadening of the widths of the undulator spectral harmonics consistent with a beam energy spread of up to 0.7% RMS, compared with an expected value of 0.07%. We have also carried out a demonstration experiment to show that damping the longitudinal oscillations narrows the undulator spectral line widths. This will be pursued further in the coming months after the longitudinal feedback system is brought into full operation.

The residual gas pressure around the circumference is found by measuring beam lifetime as a function of aperture, and fitting the expected quadratic dependence at small aperture. At 60 mA this gives a nitrogen equivalent value of 0.5 nTorr, in reasonable agreement with the measured values in the vacuum envelope's antechamber.

2.8 Beam Reproducibility and Stability

The fill-to-fill and week-to-week reproducibility of the main storage ring parameters are assured by rigorously following a prescribed start-up sequence that includes conditioning of all magnets at start-up or after a failure that shuts down a power supply. In the control room the reproducibility is checked by measuring the betatron tunes which are sensitive to both magnet settings and, because of the effect of transverse offsets in the strong sextupoles, to the COD. Investigations of the effects of different magnet cycling scenarios have shown small, but significant, changes in the field distribution in the storage ring magnets, which all have an open back-leg on the outboard side. The effects of these fields on beam behavior are currently under investigation.

The electron beam stability in the vertical plane has been measured with two photon beam position monitors in beamline 7.0, one of the undulator lines. These indicate a beam stability, without any feedback, of better than 4 μm RMS at low and acoustic frequencies. Longer-term stability as measured by these devices is better than 30 μm, but it is not clear whether this is due to beam or beamline motion. The specifications for beam stability are 20 μm RMS horizontally, and 4 μm RMS vertically, corresponding to about one-tenth of the electron beam sizes.

2.9 The Effects of the Undulators

The first two undulators installed in the ALS are each 5-cm-period devices with 89 full periods. With their gaps limited to 23 mm, the peak field achievable is 0.55 T, corresponding to a K-value of 2.6. With the gap fully closed the vertical tune is expected to change by $\Delta\nu_y \approx 0.01$. The measured value was 0.006. Perhaps more important were the changes in COD ($\approx$ 0.4 mm) caused by small error fields in the undulators that vary as the undulator gap is changed. The changes in the error fields are very small, amounting to less than 1.8 G-m. Both undulators caused orbit shifts that affect other users, so an application was developed, using a lookup table, to compensate for the error fields utilizing the local correction magnets. It was found that asymmetric correction was required in both planes, indicating non uniform error fields along the undulator itself. With the steering application running during operations both user groups have been able to manipulate their undulators without any observable effects on the COD, or on other users.

3. Summary

After just seven months of operation, the ALS storage ring can be characterized as a well understood accelerator system with an excellent operational record. The main challenges for the future lie in refining the closed-orbit correction, which we believe will bring the optical functions closer to the ideal twelve-fold symmetry; in learning to deal with multibunch instabilities and their effects on the spectral output of the undulators; and in compensating for the effects of the next round of undulators, which, being more powerful, are expected to require both steering and focusing compensation.

5. References

[1] A. Ropert, "The Status of the ESRF," pp 35-39 Proc. Third European Particle Accelerator Conference, 1992.

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[3] J. Fox, et al., "Operation and Performance of a Longitudinal Damping System Using Parallel Digital Signal Processing," this conference.

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