ACCELERATOR PHYSICS

For researchers at the ALS, 1996/97 was a period of achieving new milestones in resolution. A major factor in this progress was the work of the Accelerator Physics Group, which advanced the properties of the electron beam to the theoretically expected levels and sent higher-quality photon beams down the beamlines. Each step forward in performance, however, has side effects that influence the behavior of the electron beam and introduce new challenges. In meeting each challenge, we build up our understanding of the way the accelerators behave. As our fund of knowledge accrues, so does our ability to carry out our mission of ensuring reliable, ever-improving performance for users.

Among our activities in 1996/97, three characterize the scope of our work. The first improved the operational capabilities of the ALS. The second enhanced the measurement-based modeling tools being used to improve accelerator performance. The third led to unambiguous identification of the "fast-ion instability," a previously unproven effect associated with ions interacting with the electron beam. This research pushed the boundaries of accelerator physics toward the domain of next-generation storage rings, which will be more susceptible to such ion effects.

The Challenge of a Better Beam

One of our major achievements was to bring the multibunch feedback systems (commissioned in 1995) into routine operation. These systems monitor the longitudinal, horizontal, and vertical motion of each electron bunch in the storage ring and feed back correction signals to minimize the motion. As a result of this work, the natural emittance and energy spread of the beam reached their theoretically predicted values of 4 nm-rad and 0.08%, respectively. Furthermore, we achieved an extraordinarily low vertical emittance of less than 0.1 nm-rad at 1.5-GeV beam energy—a particularly successful outcome. However, this step forward in performance posed more challenges for the accelerator physicists.

With such low emittance, the lifetime of the densely packed electron bunches is severely reduced because of the Touschek effect (collisions of electrons within the bunches that transfer transverse momentum to the longitudinal direction). To accommodate our user community, we made the compromise of accepting a slightly larger vertical emittance in return for a longer beam lifetime. We increased the vertical emittance by using skew quadrupole fields (a capability designed into the storage ring's sextupole magnets) to redirect some of the energy of the oscillating electrons from the horizontal to the vertical transverse plane. This transfer of energy is termed "betatron coupling."

Having exploited betatron coupling to improve the beam's lifetime, we then had to determine the most effective way of controlling this phenomenon, since it is highly sensitive to changes in the betatron tune (or number of oscillations by the electrons in one turn around the storage ring). Without such control, the beam size would fluctuate whenever users change an undulator gap, a routine operation that alters the betatron tune. We successfully identified magnet settings at which vertical-focusing changes caused by the undulators have an insignificant effect on electron-beam size.

Another consequence of our progress became evident when users began to take advantage of the better resolution they could attain with the higher-quality electron beam. To fulfill their higher expectations, it was necessary to improve the the beam's positional stability. We achieved a satisfactory state of stability without resorting to the usual practice of global orbit feedback (see "The Quest to Improve Orbit Stability," p. 34).

Machine Modeling Pays Off

One phenomenon that the accerator physicists constantly battle is beta beat or irregularity in the storage ring's beta function, a parameter that is a determinant of the size of the electron beam. Beta beat causes serious problems such as variations in the dimensions of the beam from point to point around the ring, decreased injection efficiency, and reduced beam lifetime. Our major weapon in this battle is a model of the storage ring, which enables us to measure the effects of beta beat and compensate for them. Initiated before the ALS started operations, this "machine model" evolved over the years as an increasingly valuable tool.

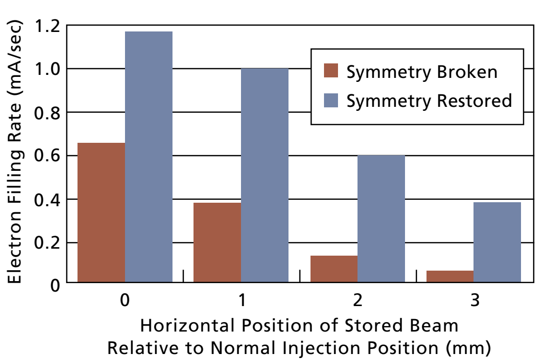
The current version was built by fitting measurement such as betatron tune, chromaticity, dispersion function, and the orbit response matrix. [An orbit response matrix consists of changes in the orbit, as measured at the beam-position monitors (BPMs), resulting from changes in the strength of the steering magnets.] In order to fit the response matrix data (over 15,000 data points), we vary more than 500 parameters in the storage-ring model and thereby achieve a more accurate model. Using this,

In the ALS control room, members of the Accelerator Physics and Electrical Engineering Groups examine plots depicting the variation in the size of the electron beam with changes in the betatron tunes. These plots indicate the outcome of restoring the twelvefold symmetry of the storage ring's magnetic lattice. Focusing errors result in broken symmetry, allowing resonances to become excited, an effect that increases the beam size at certain tunes (as demonstrated in the upper plot on the screen to the right). A model of the storage ring's magnetic lattice allows these scientists to predict quadrupole magnet settings that will restore symmetry. Resonance excitation is thereby reduced, and the betatron tune can be varied with little change in beam size. The lower plot on the right-hand screen demonstrates the effects of restored symmetry. The plot on the left-hand screen shows a scan over a larger area of the lattice with restored symmetry.

we can then predict which parameters should be changed to improve the ring's performance. Throughout 1996/97, we continued to refine the model and improved our measurement technique by increasing the sensitivity of the BPM system.

Our efforts led to better injection efficiency, a measure of the number of electrons actually captured in orbit when injected into the storage ring. It was known that focusing errors (related to the quadrupole magnets around the storage ring) perturb the ring's symmetry, and this condition gives rise to stronger excitation of resonances, which may lead to high electron losses, especially of freshly injected electrons. We used our machine model to conduct studies demonstrating the relation between broken symmetry and injection efficiency. Moreover, fitting the model enabled us to measure the focusing errors and to predict the corrections to the quadrupole field strengths needed to restore symmetry.

Our model also proved its worth by helping us to overcome a focusing effect caused by the 2-tesla wiggler, which was installed in Sector 5 in April 1996. Whenever the wiggler gap was closed, we observed beta beat that resulted in an unacceptable variation in beam size. Although we knew that a solution lay in adjusting the power supplies of the quadrupole magnets, we had to identify the most efficient quadrupoles and determine power supply settings that would correct the focusing over a range of gap widths. The machine model enabled us to select the target magnets and obtain set values that corrected the problem.



Comparison of injection efficiency at various injection-offset distances with symmetry broken (lower efficiency) and with symmetry restored (higher efficiency).

Getting the Jump on Future Challenges

Because of its small transverse beam size, the ALS is one of the first storage rings in the world to be in a position to study the transient regime of ion instabilities. These arise when the electron beam interacts with ions generated by collisions of the electrons with gas molecules. The ions are known to have several deleterious effects, including a reduction in beam lifetime. Such effects become more noticeable with advanced operating conditions—higher beam current, a greater number of electron bunches, and smaller beam dimensions.

One effect, the "fast-ion instability," was first proposed to explain growth in beam emittance observed at Japan's Photon Factory; however, experiments there failed to show any of the predicted parameter-dependent effects. At the ALS, we collaborated with accelerator physicists from Stanford Linear Accelerator Center in conducting a well-controlled series of experiments that unambiguously identified the instability for the first time. Our success has taken us one step ahead in meeting challenges that will inevitably arise from advanced operating conditions at storage rings of the next generation.

Ongoing Initiatives in Accelerator Physics
Refinement of the "machine model"—an interactive computer simulation code for demonstrating the behavior of the ALS storage ring. Application of the model to solve problems, for example, to find sources of beta beat or to create local bumps (offsets) in the beam to test our monitoring system.
Improvement of the feed-forward system, which functions proactively to minimize electron-beam movement as insertion-device gaps are closed.
Further compensation for beta beat in the storage ring, especially when new insertion devices (e.g., the elliptically polarizing undulator) are installed.
Semi-automatic generation of ramping tables for lattice magnets and correctors. (These are tables of settings for raising and lowering the storage ring energy without beam loss or orbit changes.)
Indexing of beam-position monitors to the magnetic centers of quadrupole magnets.
Investigation of readout anomalies from the beam-position monitors in the arc sectors of the storage ring.
Investigation of the relation between electron-beam size and lifetime. (The lifetime of the beam becomes shorter as its dimensions grow smaller.) Our goal is to be able to adjust the degree of trade-off in response to users' needs.
Elimination of parasitic electron bunches when the ALS runs in two-bunch fill mode.
Investigation of the advantages to be gained through a 1.5-gigahertz (third-harmonic) rf cavity—lengthening of the electron bunches in the storage ring with a concomitant increase in the Touschek lifetime.
Investigation of the use of straight sections in which a reduced vertical beta function (i.e., smaller vertical beam dimension) permits the vertical dimension of the vacuum aperture to be reduced, thereby allowing smaller-gap, shorter-period undulators.

THE QUEST TO IMPROVE ORBIT STABILITY

Routine operation of our transverse and longitudinal multibunch feedback systems reduced the electron beam to smaller dimensions than we have ever before achieved for ALS production runs. This feat gave promise of higher-than-ever spectral and spatial resolution for experimental results; but before researchers could capitalize on this promise, the stability of the beam's orbit had to be restored to design specifications. Our design tolerance for deviations in the orbit is stringent, 10% of the nominal beam size. Thus, as the beam grows smaller, so must the distance it is allowed to wander.

Starting in mid-1996, we installed new, highly sensitive beam-position monitors (BPMs) in eleven of the twelve straight sections of the storage ring. Because these BPMs are much more reliable than their predecessors, we began the continuous display of their signals covering a 12-hour period. From these displays, we gained improved insight into distortions of the beam's orbit and were able to recognize systematic trends.

To overcome these distortions, we reconvened an interdisciplinary task force that, in 1995, had successfully identified and eradicated a beam perturbation caused by oscillations in the temperature of the ALS's low-conductivity water supply. This time, the task force was given the mission to bring the orbit's stability to design specifications in the shortest time possible. Time and serious technical constraints precluded working on a closed-orbit feedback system, the standard solution, so we decided to attack the causes of beam motion at their sources.

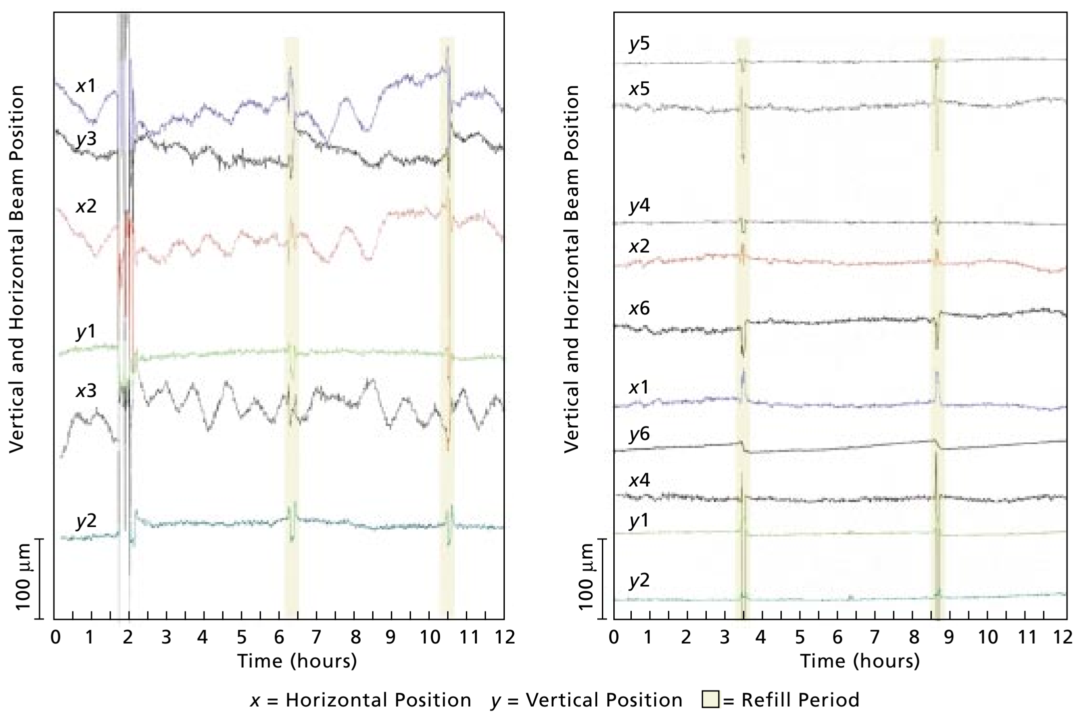
Since the construction of the storage ring, we have been aware that deviations of a few degrees centigrade in the ambient air temperature cause changes in the shape of the storage-ring girders. As a result, the lattice magnets mounted on the girders become misaligned. For this reason, the ALS building had been air-conditioned to a precision of 1°C. The task force reviewed this effect by applying our machine modeling code and by conducting experiments with the storage ring itself. We discovered that changes in the girder temperature of only 0.2°C were enough to cause magnet misalignments of about 50 μm and, consequently, 300-μm orbit deviations; therefore, more stringent temperature stabilization appeared to be a good solution to improving orbit stability. After two months of testing and analyzing, we established a scenario that led to a dramatic improvement. Our correction strategies included keeping the temperature in the storage ring tunnel lower than that of the ALS building, moving the nine temperature-controlling sensors within the accelerator enclosures away from the air outlets, using the average of the sensor readings around the tunnel as the basis for temperature control, and placing four large fans around the storage ring to move the air in the tunnel in a spiral fashion. The new temperature-stabilization scenario reduced the typical peak-to-peak perturbations in the orbit to 20 μm horizontally and 5 μm vertically—well under the design specifications.

One of the last remaining thermal effects we observed was the "10 o'clock hump," an offset of the orbit that began daily around 10 A.M. and lasted for several hours. We determined its cause to be cross talk between the specialized system for cooling the storage ring and the temperature-control system serving the building. Before 10 A.M., the storage ring relied for cooling on chilled water from the specialized system; however, at that hour, the building system would switch from heating or neutral mode to cooling mode and mix its not-yet-chilled water with that of the storage ring system. The increased water temperature caused the shape of the girders to change and brought on the hump. This effect reversed itself once all the water was sufficiently chilled; thus, our solution was to maintain the water in both systems at an appropriately cool temperature.

Besides the temperature-related perturbations, the task force analyzed and controlled others from two different sources. One anticipated perturbation occurs whenever the gap of an undulator or wiggler is changed. The problem is due to small imbalances in the magnetic fields of these devices. We are compensating for this effect by applying steerer fields proactively (in a feed-forward mode) and by restoring the gap to its previous width when we start operations after a refill of the storage ring.

Another perturbation had a more surprising cause. It was discovered by researchers who noticed abrupt changes in the intensity of their photon beam when one of the two large cranes in the ALS building was moved past their beamline. A subsequent study demonstrated that any change in the cranes' position from their normal parking places, but not the actual motion of the cranes, was responsible for the perturbation. The obvious solution was adminstrative—to avoid moving the cranes while researchers are using their beamlines.

Our solutions for controlling these perturbations proved to be highly effective. BPM plots taken in early 1997, after the solutions were implemented, indicate a highly satisfactory state of beam stability in contrast to plots taken in mid-1996.



Signals taken over 12-hour periods from beam-position monitors (BPMs) located in the straight sections of the storage ring upstream or downstream from an insertion device. The plots on the left (from three BPMs) were recorded in August 1996. They show strong excursions in the second hour marking an event that would be typical of a crane movement. Most of the plots on the left also show major oscillations with a one-hour period, which proved to be related to variations in the air temperature in the storage ring tunnel. The plots on the right, taken from five BPMs in April 1997, show a dramatic improvement in the stability of the orbit compared with the earlier plots.