

ORBIT CONTROL AT SYNCHROTRON LIGHT SOURCES

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Abstract

Modern synchrotron light sources are pushing the limits of storage ring performance. Precise control of the electron beam orbit is critical for achieving design goals in these machines. A review of closed orbit control will be given, including an overview of the sources of orbit motion, a description of closed orbit correction and feedback algorithms, and a discussion of the pitfalls and limitations of orbit control. Illustrative examples from light sources worldwide will be included.

1 INTRODUCTION

Synchrotron light storage rings are designed to achieve very small electron beam sizes. The small beam sizes maximize the brightness of the synchrotron radiation. Realizing the benefits of these small beam sizes requires tight tolerances on the electron beam stability. Achieving such stability is not at all easy, so closed orbit control is important in the design and operation of light sources.

Electron orbit jitter effectively increases the electron beam size and degrades the brightness of the photon beam, while slower orbit drift necessitates frequent realignment of the experiments at the ends of the photon beam lines. Orbit stability tolerances are usually specified as 5 to 10% of the electron beam transverse dimensions both in position and angle. For example, the vertical rms beam size in the Swiss Light Source will be $10 \mu\text{m}$, so the vertical orbit stability requirement is $1 \mu\text{m}$ - quite a challenging specification.

The problem must be attacked on two fronts: sources of motion must be identified and reduced, and orbit correction and feedback must mitigate any remaining orbit motion. In section 2 steering techniques used for orbit correction and feedback will be reviewed, and section 3 will review the many possible sources of orbit motion. Section 4 will address the challenges that limit orbit feedback performance.

2 ORBIT STEERING ALGORITHMS

2.1 Local Steering

Two types of steering are used for orbit correction and feedback: local steering and global steering. In a local orbit feedback, 3 or 4 steering magnets are powered to bump to closed orbit of the electron beam in order to lock the orbit at one or two beam position monitors (BPMs) as illustrated in figure 1. The correction is local, so the orbit outside the bump is unaffected.

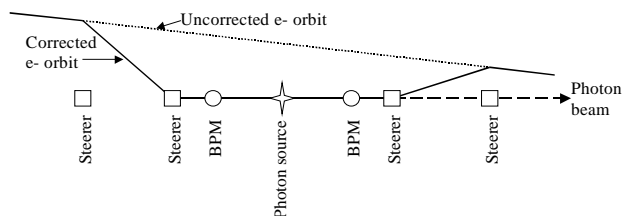


Figure 1: Local orbit feedback.

In figure 1 the orbit is stabilized on two electron BPMs. Alternatively, the bump can be powered to stabilize the beam on photon BPMs down the photon beamline, closer to the experiment. The first orbit feedbacks used photon BPMs [1], and such feedbacks are still common. For example at the Advanced Photon Source, a feedback was recently commissioned that combines a photon BPM with electron BPMs, which takes advantage of the long lever-arm of the beamline. They measured an angular stability of a fraction of a μrad over the course of a week.

2.2 Global Steering

When a single steering magnet is changed, the resulting orbit shift oscillates throughout the storage ring. As far as closed orbit shifts are concerned, storage rings are quite linear. Orbit shifts add up linearly, so the orbit shift, $\Delta\vec{y}$, from multiple steering magnets changes, $\Delta\vec{\theta}$, can be written in matrix form:

$$\Delta\vec{y} = M \Delta\vec{\theta}, \quad (1)$$

This defines the orbit response matrix, M . The response matrix can be calculated theoretically, but it is usually more accurate to measure it. For global orbit correction, the orbit response matrix is simply inverted to find the steering magnet changes required for any desired change in orbit.

A common problem is that the response matrix is singular or close to singular, so it has no well-defined inverse. Of the various algorithms that have been developed to deal with this problem, singular value decomposition (SVD) has emerged as the most popular. Any matrix can be represented with SVD as follows (see, for example [2]):

$$M = \sum_{k=1}^n \vec{u}_k w_k \vec{v}_k^T, \quad (2)$$

where \vec{v}_k is a set of orthonormal steering magnet vectors, \vec{u}_k is a corresponding set of orthonormal BPM vectors, and w_k are the singular values of the matrix M .

Given the SVD of a matrix, the matrix inverse is

$$M^{-1} = \sum \vec{v}_k \frac{1}{w_k} \vec{u}_k^T, \quad (3)$$

which follows from the orthonormality of the two vector sets. It is immediately apparent from the singular value decomposition if the response matrix is singular - one or more of singular values, w_k , are zero. Physically, a zero w_k implies that there is some combination of steering magnet changes, \vec{v}_k , which gives no measurable change in orbit. The orbit shift from this \vec{v}_k is zero at all the BPMs. Removing the terms with zero w_k from the sum in equation 3 produces a pseudoinverse for orbit correction which generates no changes in the steering magnet strengths along the corresponding eigenvectors \vec{v}_k .

Often, in addition to removing the zero w_k , those terms with the small, but nonzero w_k are also removed. The terms with small w_k generate large steering magnet strength changes with little improvement in orbit correction. Also removing the small w_k tends to filter out erroneous BPM data. The orbit shifts from magnetic field errors look much like orbit shifts from steering magnets, so magnetic field errors tend to make orbit shifts that can be represented accurately by the \vec{v}_k with large w_k . Erroneous BPM data gives a larger contribution to the \vec{v}_k with small w_k .

With some storage rings, two global orbit feedback systems are run simultaneously - one operating at low frequency to correct slow orbit drift, and another just correcting the higher frequency orbit jitter. This division has advantages. The slow orbit drift is usually the most difficult to correct. The slow orbit feedback can use most or all of the steering magnets and BPMs. A smaller number of steerers and BPMs are used in the fast feedback to reduce cost and complexity while maximizing speed. The slower correction rate of the slow feedback permits more complicated computations such as algorithms for finding and removing erroneous BPM readings due to noise spikes.[3]

2.3 RF Frequency Correction

Steering magnets are effective for correcting orbit shifts caused by magnet strength and alignment variations, but cannot effectively compensate for variations in the circumference of a storage ring. As will be seen in section 3, such circumference changes do occur. The total length of the electron single-turn trajectory is determined by the rf frequency. If the rf frequency remains unchanged as the circumference varies, an orbit distortion proportional to the dispersion develops in order to keep the single-turn trajectory length constant. This dispersion-like orbit shift can be removed with a feedback that varies the rf frequency.[4]

2.4 Beam-based Alignment

With beam-based alignment one tries to steer through the magnetic centers of the quadrupoles, rather than through the centers of the BPMs.[5] This is desirable for two reasons. First, the magnetic centers of quadrupoles are usu-

ally better aligned than the electrical centers of BPMs, so steering through the centers of the quadrupoles brings the electron orbit closer to the design trajectory. Second, steering to the centers of the quadrupoles minimizes closed orbit variations associated with quadrupole power supply ripple.

The method for determining the offset of the orbit from the center of a quadrupole is simple. If the integrated strength of a quadrupole is changed by $\Delta K L$, the closed orbit is perturbed with an angular kick

$$\theta = x \Delta K L, \quad (4)$$

where x is the initial closed orbit at the quadrupole. Minimizing the shift in orbit from varying a quadrupole strength minimizes x . Often beam-based alignment is used to calibrate the offset between a BPM and an adjacent quadrupole.

3 SOURCES OF ORBIT MOTION

The following survey includes examples of some of the more important and interesting sources of orbit motion from slow ground settlement to orbit variations at hundreds of Hz.

3.1 Ground Settlement

Ground settlement is the dominant source of motion over periods of weeks to years. Initially, the magnets can be aligned to a precision of about 0.1 mm in transverse position and 0.2 mrad in roll angle. Storage rings are usually constructed with a series of girders, with several magnets mounted on each girder. The magnet to magnet alignment on each girder stays relatively constant over time, but the girders move with respect to each other.

Orbit steering magnets can usually compensate for girder to girder motions of a few hundred microns. Larger motions must be corrected by realigning the girders. The frequency of realignment in synchrotron light sources is typically every 2 years,[6] however it varies with local ground stability.

ESRF has an advanced alignment capability in which each girder has remote vertical adjustment, and the vertical alignment is measured with a hydrostatic leveling system. With this system the ring can be aligned vertically in a few hours without ever dumping the stored beam. The SLS is planning a similar system.

An interesting example of ground motion is earth tides.[7] Due to the gravitational attraction of the moon and sun, the earth's surface moves up and down by about 25 cm twice per day. Because the earth's surface is curved, the vertical movement creates a variation in the circumference of storage rings. Figure 2 shows a measurement of this periodic variation in the diameter of ESRF.[4] In addition to the periodic variation, the slower measured variations are due to such things as temperature changes or ground water concentration changes.

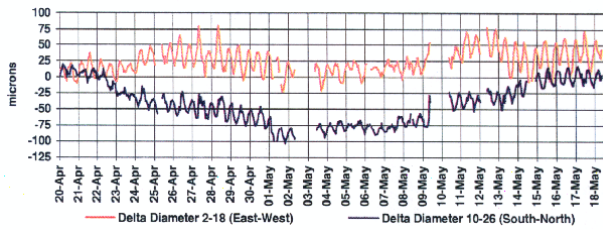


Figure 2: Measured variation in the diameter of ESRF. (Provided courtesy L. Farvacque.)

3.2 Thermal Drift

Often the most difficult challenges in achieving stability specifications are associated with thermal drifts.[4, 8, 9] Orbit motion arises from variations in the temperature of cooling water for the magnets and the vacuum chamber, variations in air temperature, and varying thermal loads associated with synchrotron radiation and ramping of magnets. Air and cooling water temperatures must be regulated to about $\pm 0.2^\circ\text{C}$ to obtain the stability required in a modern synchrotron light source.[10, 11]

At many synchrotron light sources, the problem of varying thermal load in the magnets is solved with full-energy injection, so the currents in the quadrupoles and dipoles remain constant. At SPRING-8 the magnets are not even powered down during short shutdowns.[6]

Top-up injection is a promising method of operation in which the thermal load from synchrotron radiation is held nearly constant by keeping the stored current nearly constant with frequent small injections. APS is actively pioneering the implementation of top-up operation.

3.3 Ground Vibrations

Ground vibrations can lead to orbit motion in the 1 to 50 Hz range. Figure 3 shows a survey of measured ground vibrations at various accelerator laboratories compared to the *new low noise model* (NLNM), which is a minimum of measured motion worldwide.[12]

The peak in the spectrum at around 0.14 Hz is found worldwide and is a result of the surf pounding the coastlines once every 7 seconds. This motion is not a problem, because the wavelength of ground motion at 0.14 Hz is about 30 km - much larger than the dimensions of a light source. The whole lab moves up and down as a unit.

Another important feature to note in Fig. 3 is that the PSD decreases with increasing frequency. Actually, this feature is somewhat masked by plotting in units of velocity instead of position. The PSD in position drops off faster by a factor of f^{-2} .

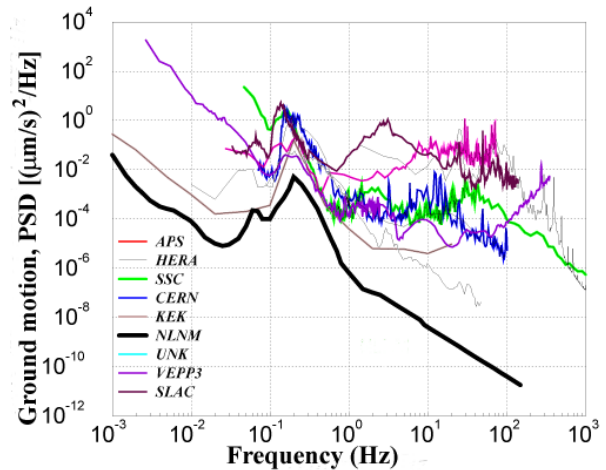


Figure 3: Power spectral density of ground motion at various laboratories. (Provided courtesy V.D. Shiltsev.)

The drop-off of ground motion with frequency is an important consideration when designing storage ring magnet girders. All girders have a set of mechanical resonant frequencies. Girders should be stiff with high resonant frequencies, because there is less ground motion at high frequency. Existing storage rings usually have the first resonant mode in the range of 5 to 20 Hz. Future machines such as SLS and SOLEIL will have girder frequencies about 45 Hz or higher.[6]

A serious girder oscillation occurred at APS.[13] In this case the girder resonance was driven by vibrations in the magnet cooling water system. The vibrations were effectively attenuated by retrofitting the girder supports with damping pads.

3.4 Power Supply Stability

The supplies powering magnets must be well regulated. For example, insufficient rejection of line voltage variations can cause orbit motion. Accelerator laboratories tend to require substantial and varying electrical power levels, which lead to line voltage variations.

Figure 4 illustrates such a problem at SLAC.[14] The spectral lines at the first few harmonics of 10 Hz are orbit motion at SSRL resulting from running the SLAC linac with a 10 Hz repetition rate. (The 5 Hz line is from girder vibrations.) Both the 5 Hz and 10 Hz motion were reduced to acceptable levels with an orbit feedback system. Figure 4 also shows significant orbit motion at harmonics of 60 Hz, illustrating the importance 60 Hz rejection in the power supplies.

An aluminum vacuum chamber has the advantage of significantly attenuating field errors at 60 Hz harmonics and higher frequencies. This rejection results from eddy currents in the aluminum. A stainless steel chamber, in contrast, passes frequencies up to several kHz. Of course, with the steering magnets used for orbit feedback, one *would* like to be able to make fast field changes. For this reason, APS built stainless steel spool pieces for 40 steering

magnets in a fast orbit feedback, while the rest of the APS chamber is aluminum.

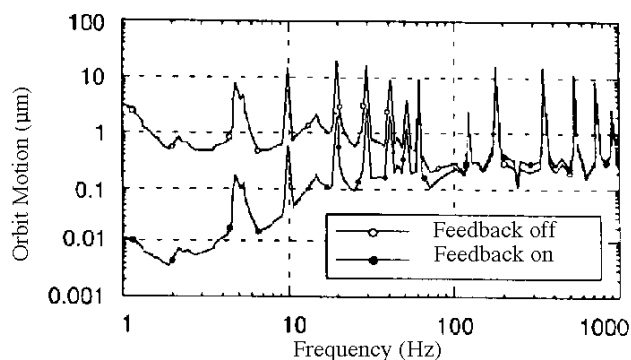


Figure 4: 10 Hz harmonics in SSRL orbit from SLAC linac. (Provided courtesy R. Hettel.)

4 CHALLENGES AND LIMITATIONS OF ORBIT FEEDBACK

4.1 BPM Movement

The degree to which an orbit feedback system can stabilize the beam is limited by BPM errors. As discussed in Sec. 3.2, temperature variations can lead to both magnet field and position variations as well as vacuum chamber motion. The magnet field and position variations lead to orbit motion that can be corrected with orbit feedback. The vacuum chamber motion, however, can move the electron BPMs. An orbit feedback will do its best to move the electron orbit along with the BPM. This problem defines the limit of long term orbit stability in many light sources.

Figure 5 shows the measured horizontal motion with respect to the concrete floor of a particularly bad BPM at the NSLS X-Ray Ring for the first two hours of a fill.[9] The BPM moves hundreds of microns. At NSLS and most first and second generation light sources, dipole synchrotron radiation hits the wall of the water-cooled vacuum chamber, causing chamber motion. In third generation machines the synchrotron radiation usually hits discrete photon absorbers. No light directly hits the vacuum chamber. Nonetheless, some fraction of the power hitting the photon absorbers is reradiated and can hit and heat the vacuum chamber.

Additional techniques used to stabilize the BPMs include decoupling them from the rest of the vacuum chamber with bellows and mounting them on rigid supports with low thermal expansion coefficients. BPMs at third generation machines still move on the order of ten microns. This limits the accuracy with which an electron BPM based orbit feedback can stabilize the photon beams.

This limit can be circumvented to some degree with global orbit feedback using singular value decomposition, which filters out the nonphysical orbit shifts associated with BPM motion. Figure 6 illustrates this at ESRF.[4] The beam motion measured by a photon BPM on an inser-

tion device beamline is plotted for 10 days of operations. The spikes in the data occur at fills and should be ignored. Global orbit feedback using electron BPMs is active for the entire period. For the first half, a local feedback is used to pin the orbit on the electron BPMs just upstream and downstream of the insertion device. For the second half, the local feedback is turned off. The photon beam is considerably more stable with the local feedback off. The local feedback was dragging the beam with the moving BPMs, while the global feedback filters out this nonphysical motion. For this reason, ESRF uses only the global feedback.

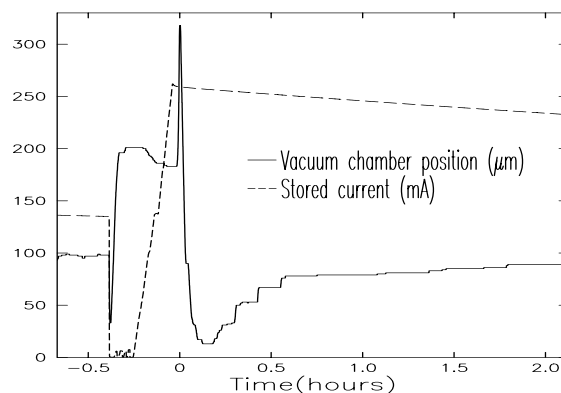


Figure 5: BPM movement in NSLS X-Ray Ring from synchrotron radiation heating.

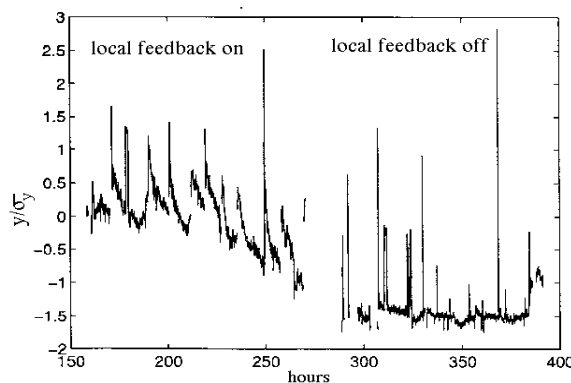


Figure 6: Due to electron BPM motion, photon stability is worse at ESRF when running local orbit feedback. (Provided courtesy L. Farvacque.)

Another approach to the BPM motion problem is to measure it and compensate for it in the feedback.[4, 15, 9, 16] The challenge is to reliably measure the vacuum chamber motion relative to the experimental floor with an accuracy of microns. Any stand holding a measuring device is itself subject to its own stability limits.

Yet another approach is to feedback using photon BPMs instead of electron BPMs. This solution is effective with dipole and wiggler beamlines, but problematic with undulator beamlines for the reason illustrated in Fig. 7 from ESRF.[4] The radiation from the dipole magnet downstream of the undulator is superimposed on the undulator radiation at the photon BPM. This causes an error in

the photon BPM reading. At APS, this problem has been circumvented in one straight by changing the strengths of the upstream and downstream dipoles, and using steering magnets next to the undulator to make up for the angular difference. This removes the dipole synchrotron radiation from the photon monitor. At ELETTRA, work is ongoing to solve this problem by developing energy sensitive photon monitors that respond to the narrow band undulator radiation and filter out the broad band dipole radiation.

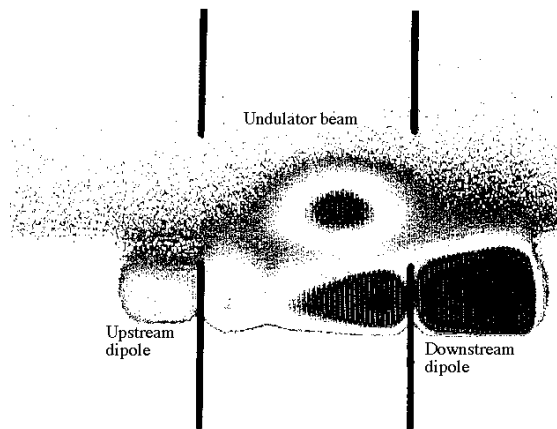


Figure 7: Photon BPM blades see dipole radiation in addition to undulator radiation. (Provided courtesy L. Farvacque.)

4.2 BPM Intensity Dependence

Dependence of BPM electronics on stored beam current and fill pattern can degrade the performance of an orbit feedback.[4, 3] Alternatively, the BPM intensity dependence can be included in the BPM calibration. Precisely reproducing the BPM signals seen in the storage ring can be difficult, so calibration on the bench can be problematic. At APS, they have developed an electron beam based method to calibrate the BPM intensity dependence.[3]

4.3 BPM and Steering Magnet Resolution

The resolution of the BPMs and steering magnets must be sufficient to ensure the feedback does not add noise to the orbit.[17] For example, take a local orbit feedback system using two electron BPMs, one a distance l upstream of the photon source point, and one l downstream. With the feedback active, a noise level, Δy , on the BPMs will inject a noise level in angle and position at the source point of

$$y_{rms} = \frac{\Delta y}{\sqrt{2}} \quad y'_{rms} = \frac{\Delta y}{\sqrt{2}l}. \quad (5)$$

Δy should be small enough that y_{rms} and y'_{rms} are small compared to size and angular divergence of the photon beam at the source point.

For digitally controlled steering magnets, the minimum digital step size must be small. For example, a global feedback with a digital step size of θ_{dig} creates rms orbit motion

of

$$y_{rms} = \frac{\sqrt{n\beta\beta_{st}}}{4\sqrt{6}\sin\pi\nu} \theta_{dig}, \quad (6)$$

where n is the number of steering magnets, β_{st} is the β -function at the steering magnets, β is at the photon source point, and ν is the tune. Again, y_{rms} must be small compared to the source size. Digital resolution as high as 18 or 20 bits can be required.

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