

**BEAM STABILITY IN SYNCHROTRON LIGHT SOURCES\***

Glenn Decker

Advanced Photon Source, Argonne National Laboratory

Argonne, IL 60439, USA

*Abstract*

Numerous third-generation light sources are now in a mature phase of operation, and several new sources are under construction. Submicron beam stability is being achieved routinely at many of these light sources in terms of both AC (rms 0.1 - 200 Hz) and DC (one week drift) motion. This level of stability is a necessary condition for the success of x-ray free-electron lasers such as the Linac Coherent Light Source (LCLS) at Stanford or the European XFEL project. The different methods for addressing this problem at different laboratories— involving various combinations of passive noise identification and suppression, feedback, and feedforward— together with accomplishments to date will be discussed.

indications of what will be expected for future light sources such as x-ray free-electron lasers and energy recycling linacs.

Shown in Table 1 are a set of high-level parameters for the world's operational third-generation light sources (as of June, 2005), defined to be dedicated storage rings having natural emittance below 20 nm-rad. The essential things to notice are that the particle beam tends to be flat, with horizontal beam size  $\sigma_x$  in the range of a few hundred microns, but with vertical beam size  $\sigma_y$  below ten microns in many cases. Since beam stability requirements are typically stated as a fraction like 5 or 10 percent of beam size in a given frequency band, it is clear that submicron stability is a common requirement. The vertical angular divergence of these particle beams is at

Table 1: Properties of Operational Third-Generation Synchrotron Light Sources.

	Energy (GeV)	Horizontal Emittance (nm-rad)	Vertical Emittance (pm-rad)	$\sigma_x$ (mm)	$\sigma_y$ (mm)	Top-up
SPring-8	8	6	14	390	7.5	yes
APS	7	2.5	25	271	9.7	yes
ESRF	6	4.0	30	380	14	planned
SPEAR-3	3	12 / 18	60 / 90	350 / 430	25 / 31	planned
CLS	2.9	15	200	326	30	planned
Pohang LS	2.0 / 2.5	12.1 / 18.9	12 / 19	350 / 434	22 / 27	no
SLS	2.4	5	40	86	6	yes
ELETTRA	2 / 2.4	7 / 9.7	< 70 / 97	241 / 283	15 / 16	planned
ALS	1.5 / 1.9	4.2 / 6.75	200 / 150	240 / 310	27 / 23	planned
BESSY-II	1.72	6	180-240	290 / 76	27 / 17	planned

**INTRODUCTION**

In the past ten years, there has been a remarkable increase in the number of accelerator facilities dedicated to the generation of synchrotron radiation. An indicator of this is the recent launch of the web site [lightsources.org](http://lightsources.org) [1], where 59 separate synchrotron radiation facilities around the world are now listed. The light source beam stabilization field is similarly reaching a mature phase, as evidenced recently by a series of international workshops on beam orbit stabilization [2,3]. Numerous excellent articles have been written on the subject of beam stability in synchrotron light sources [4,5]. The emphasis here will be on trends in third-generation light sources, with

the few microradian level, approaching the diffraction limit for many of these machines. At the Advanced Photon Source (APS), the goal for vertical pointing stability is to limit beam motion to less than 220 nanoradians rms in a frequency band ranging from 0.016 Hz (i.e., one minute) to 200 Hz, while the long-range pointing stability goal is 0.5 microradians p-p, for time scales extending from one minute to one week.

Beam stabilization efforts in general must account for motions in all six phase-space dimensions, on time scales ranging from the bunch repetition rate up to months. Not only beam centroid motion, but also beam size and even higher-order moments of the phase-space particle distribution must be considered. While historically beam stabilization has been defined in terms of the source, i.e., the particle beam properties, it is becoming clear that many properties of the photon beam cannot be directly controlled using particle beam diagnostics alone. As a

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

result, new photon beam diagnostics have been developed and are increasingly being included in accelerator feedback systems. While a stable source is imperative, many experiments require stability beyond what is possible using traditional particle beam diagnostics and closed-orbit feedback systems. Taken to the logical limit, stability requirements depend in detail on the beamline design and experimental arrangement, which can only be properly studied using detailed ray tracing extending from the source through all beamline optics to the sample [6].

Top-up operation, defined to be operation using injection with beamline shutters open to regulate stored beam current at the level of approximately 1% or better, is also indicated in Table 1. This operating mode is very desirable to synchrotron radiation users since it stabilizes the heating effects on beamline components such as mirrors and monochromator crystals. From the machine side, a similar stabilization of vacuum chamber components exposed to synchrotron light is realized. This technique was pioneered at the APS and first put into operation in the year 2000. Since that time, most existing and planned third-generation light sources use or are planning to incorporate top-up into machine operation. A strong secondary motivation for top-up is that it allows the use of extreme lattices and / or bunch fill patterns with very poor lifetime.

A list of light sources presently under construction is shown in Table 2, including the two hard x-ray free-electron laser projects, which will be moving to a new level of beam stabilization technology. Many new ring-based projects are planned with energies near 3 GeV, which take advantage of new high-quality insertion device technology in order to deliver hard x-rays.

Table 2: Light Sources Under Construction

	<b>Energy (GeV)</b>	<b>Horizontal Emittance (nm-rad)</b>
Petra III	6	1
SSRF (Shanghai)	3.5	4
Diamond	3	2.74
Soleil	2.75	3.74
Australian	3	7
LCLS	13.6	0.045
XFEL	20	0.036

## SOURCE IDENTIFICATION

Listed in Table 3 are the types of disturbances that every synchrotron light source is subject to, along with approximate time and length scales where they are most pertinent. Ground settlement can be quite large, up to fractions of a millimeter; however, it is primarily short-range differential settlement that impacts photon beam alignment. This is most easily compensated by extending instrumentation out along the beamline, since position monitoring near the source is insensitive to motion of the beamline relative to the accelerator. The effects of earth

tides are significant, even for small machines such as the Swiss Light Source (SLS), which must adjust the rf frequency to compensate for variations in the ring circumference.

Table 3: Sources of Beam Motion

<b>Source</b>	<b>Time Scale</b>	<b>Length Scale</b>
Ground Settlement	weeks to months	10s to 100s of $\mu\text{m}$ / year
Earth Tides	hours	$\sim 30 \mu\text{m}$ / km
Air / Water Temperature	minutes to days	$\sim 10 \mu\text{m}$ / degree C
Beam-induced Heating	minutes to hours	10s of $\mu\text{m}$ / fill from zero
Insertion Device Parameter Changes	10s of ms to 10s of seconds	10s of Gauss-cm
Stray Fields	0.1 seconds to hours	Variable
Magnet Power Supply Noise	10s of $\mu\text{s}$ to 10s of ms	Design- dependent
Ground Vibration	10 ms to 1 second	10s of nm
Magnet Vibration (from resonance)	10 ms to 1 second	100s of nm
RF System	$\mu\text{s}$ to minutes	10s of $\mu\text{m}$
Impedances / Wakefields	ns to $\mu\text{s}$	10s of $\mu\text{m}$

Regulation of water and air temperature at the level of a fraction of a degree C is becoming common and almost mandatory to assure mechanical component stability at the submicron level, since the thermal expansion coefficient of most materials is on the order of  $10^{-5}$  / degree C. In order to reduce susceptibility to small temperature changes, critical component positions can be carefully monitored using detectors placed on stable supports. At ELETTRA, capacitive sensors placed on carbon fiber pillars are used to monitor the position of high-sensitivity small-gap beam position monitor pickup electrodes [7], which are mounted separately. A similar technique is planned for the Diamond machine in the UK.

Synchrotron radiation heating and wakefields account for a very significant potential source of thermally driven component motion. Extensive instrumentation on the girders at the SLS show direct correlations between the amount of stored beam current and beam position monitor location relative to an adjacent quadrupole magnet at the few-micron scale [4]. This effect was eliminated with the advent of top-up operation when the total stored beam current was regulated at the level of  $\pm 0.15\%$ .

User-variable insertion devices not only produce steering, but in addition are responsible for an edge focusing effect, which disrupts the periodicity of the lattice, causing undesirable beam size changes. Two approaches are generally taken to address the variable bulk properties of insertion devices, and frequently some combination is used. Since these effects are generally

reproducible, feedforward algorithms are used to power nearby steering correctors and / or quadrupole magnets in response to insertion device parameter changes [8]. Extreme care is required in the generation of lookup tables, since systematic errors such as beam position monitor noise can cause problems. The second approach is the use of closed-orbit feedback. Slightly different approaches are required, depending on the time scale of the parameter change. For mechanical variables such as undulator gap changes using motor drives, orbit correction algorithms operating with update rates as low as a few Hz are generally sufficient to compensate for steering effects. Higher-frequency excitations, arising from switched electromagnetic devices for example, require fast feedforward in addition to high-frequency (few-kHz update rate) closed-orbit feedback [9].

In addition to affecting global machine properties such as the closed-orbit and lattice functions, insertion devices produce a local, internal steering effect, which places a fundamental limit on the pointing stability possible using charged particle beam position monitors alone. Shown in Figure 1 are particle beam trajectories derived from numerically integrating Hall probe magnetic field maps of one particular APS insertion device. Data corresponding to four different magnetic field strengths, determined by the device gap, are shown. In each case, the entrance angle (at the left-hand side of the plots) was numerically adjusted to constrain the average slope through the bulk of the device to remain parallel to the horizontal axis. The net result of this is that the angle and displacement of the beam at the exit vary considerably as the gap is varied. What this means is that the photon beam generated by the undulations interior to the device are not colinear with the particle beam trajectory *as determined by rf beam position monitors located external to the device*. Quantitatively, careful fabrication of insertion devices can limit internal trajectory errors at the few-micron / few-microradian level; however, detection of the insertion device photons directly is necessary if one is interested in gap-independent submicroradian-level pointing stability.

The primary sources of stray magnetic fields affecting the beam are magnet power supplies with time variable outputs. Periodic ramping of injector machines produces on-orbit fields in the main storage ring, which are usually difficult to control without orbit feedback. The pulsed injection magnets together with the details of the injection process play a significant role during top-up operation, causing beam size and centroid transients. Careful magnet design and fast feedforward schemes are generally employed to reduce these effects [10,11]. Power supply ripple at harmonics of the mains frequency is generally addressed with special harmonic suppression algorithms built into a fast orbit feedback system [12].

Human-made sources of ground motion generally occur in the frequency range from a fraction of a Hz up to 50 or 100 Hz maximum. These motions have rms amplitudes typically on the order of some 10s of nanometers [13]. An apparently stiff girder assembly can have a vibrational resonance at quite low frequency (7 Hz at ESRF, 10-12

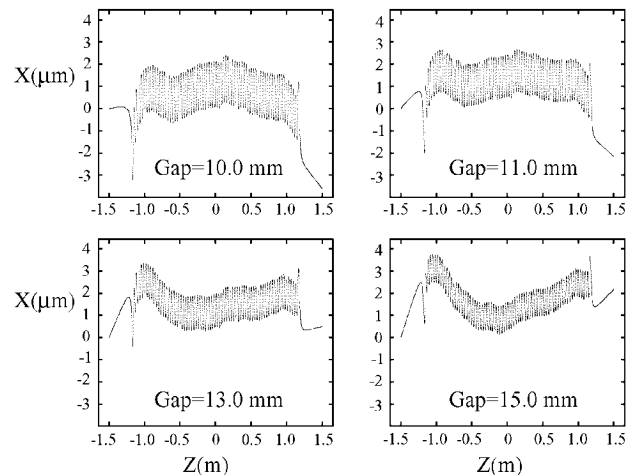


Figure 1: Particle beam centroid trajectory through an undulator as the gap is varied (APS undulator A).

Hz at APS). The effect of this is to amplify ground motion, in some cases by a factor of ten or more. Further aggravating the situation, vibrating quadrupole magnets can result in an additional order of magnitude of particle beam motion, a consequence of the very strong focusing needed for these low-emittance machines. While girder resonances cannot be completely eliminated, the lowest mode frequency can be increased significantly with careful mechanical engineering. Since the spectrum of ground motion generally falls off sharply with increasing frequency, it is expected that raising the lowest mode frequency will reduce particle beam motion accordingly. For the new sources Soleil and Diamond, the lowest mode frequencies have been moved to above 27 Hz [2].

## BEAM POSITION MONITORING

Processing electronics for beam position monitoring were advanced significantly by the advent of the Bittner / Biscardi multiplexed receiver in the late 1980s [14]. This design was further developed by J. Hinkson at ALS and K. Unser with Bergoz Instrumentation, from whom a refined version of the design is commercially available [15]. Recent advances in fast sampling and FPGAs have led to systems with micron-scale resolution on a turn-by-turn and even bunch-by-bunch basis [16]. Long-term stability of the electronics is now rivaling and often surpassing the overall mechanical stability of pickup electrode assemblies [17].

Small-aperture capacitive button pickup electrodes are most commonly used for beam position monitoring near the insertion device source points. These are generally placed on stable support structures, sometimes with mechanical position diagnostics added. The “rotated button geometry,” shown schematically in Figure 2, is used to maximize signal strength while at the same time providing maximum position sensitivity, albeit with increased nonlinearity in the horizontal response [18]. APS, ESRF, and ELETTRA use this geometry. Inductive matching networks are also sometimes placed at the

button, converting it into a resonant tank circuit to further boost signal strength and reduce reflections [19].

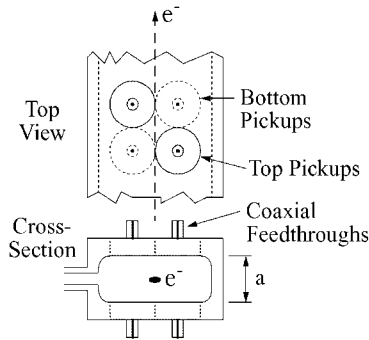


Figure 2: Rotated-button pickup electrode geometry.

For ultrahigh resolution, a cavity BPM based on the excitation of dipole modes will be used for the LCLS x-ray free-electron laser project. This technology, originally developed for linear colliders, should allow submicron resolution and repeatability on a single-pulse basis [20]. Shown in Figure 3 is a cross-sectional view of a recent LCLS design of this type. One of the main advantages of this design is that the signal transmitted through the waveguide is directly proportional to the product of position and intensity, relaxing the need for careful matching of receiver channels, as is commonly required for conventional BPMs based on buttons.

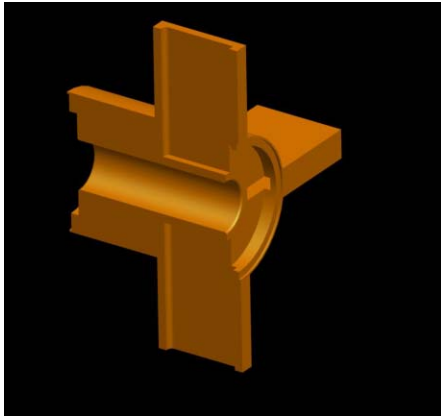


Figure 3: Cavity BPM prototype for the LCLS.

Shown in Figure 4 is a “staggered pair” photoemission-based beam position monitor for detecting bending magnet radiation at BESSY II [21]. Given the top / bottom symmetry of bending magnet radiation, this type of monitor is ideal for high-resolution measurements of the photon beam’s vertical position. When placed far from the source point, it provides the best diagnostic to stabilize the vertical beam pointing angle, useful for time scales extending from fractions of a millisecond to weeks.

For insertion device beams, the use of this type of monitor is complicated by several factors, the most important being the presence of stray radiation background signals together with the variable nature of the insertion device radiation due to user-commanded gap changes, for example. The stray radiation background itself can also be variable, because the steering correctors used for orbit correction produce ultraviolet radiation,

which can be directed down the insertion device beamline. Small orbit changes through quadrupole and sextupole magnets also contribute.

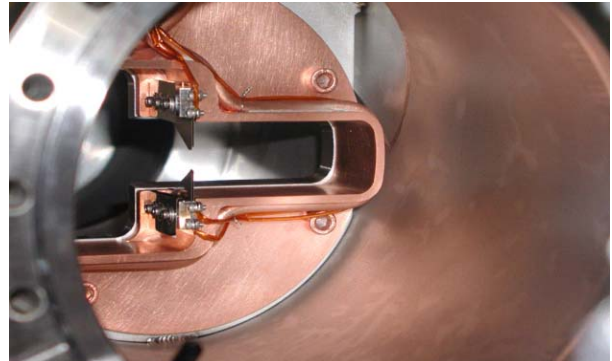


Figure 4: Bending magnet photon BPM (BESSY II).

A number of creative solutions have been implemented for dealing with this problem. One idea employs a relatively complex electron spectrometer-based device to enhance sensitivity to the undulator spectral peaks [22]. For larger machines, a realignment of accelerator components can be used to direct the unwanted stray radiation away from the photon BPM’s field of view [23]. This idea has been fully implemented at the APS and is also under investigation for the 6-GeV PETRA-III project at DESY. Use of these monitors allows sub-microradian p-p stability over one-week time scales for fixed-gap operation, limited to several microradians for variable gaps, due to the internal ID steering effect.

## ORBIT CORRECTION ALGORITHMS

It is generally recognized that singular value decomposition (SVD), if used correctly, is the best method for dealing with orbit correction for relatively large machines. For a square response matrix with an equal number of monitors and correctors, an “exact” correction is possible, forcing all of the monitor readbacks to be constant. If any of the monitors malfunction, the square matrix technique can actually provide a false sense of security. In this case, only careful study of the amount of activity seen on the steering correctors can be used to diagnose problems with the BPM system. It is generally a good design philosophy to use reliable monitors that are not used by the correction algorithm to validate system performance.

A more common situation occurs when the number of monitors differs from the number of steering correctors. If there are more monitors than correctors, SVD provides a solution that minimizes the rms BPM errors around the ring. If the matrix is poorly behaved, however, it may require very large steering corrector variations to achieve this. By ignoring the most inefficient eigenmodes, i.e., those requiring large effort for little gain, the system can be tuned for best performance. The selection of how many eigenmodes to retain is the essence of the SVD method. If there are more correctors than beam position monitors, SVD can provide a solution that “exactly” corrects the orbit, while at the same time minimizing the

required amount of rms corrector variation around the ring. One is still faced with the question of discerning whether or not any particular BPM is lying when using any “exact” correction scheme.

Singular value decomposition provides a solution to the spatial aspect of orbit correction. For the temporal aspect, an all-digital future is nearly here. Modern closed-orbit feedback systems will involve ultrafast BPM sampling; high-speed data networks; and a combination of local signal processing, centralized algorithm coordination, and the distribution of high-speed correction signals to local power-supply controllers with their own digital regulators. In the past, signal processing and data distribution speed limitations have dictated the construction of two or even three separate feedback systems to deal with different frequency bands. Most facilities employ a “slow” workstation software-based feedback system that uses all available BPMs and correctors, with the full response matrix and a lot of error handling capability. These DC feedback systems are generally limited in operation to have update rates of a few Hz. In addition to the DC system, a “fast” system is often operated in parallel, with an update rate of several kHz [24]. Due to processing limitations, the response matrix for these fast systems is generally much smaller than for the DC correction. Feedforward schemes have been used to prevent the fast and slow systems from interacting with each other, generating unstable performance in the overlapping frequency band [25,26]. The ideal situation is to have one unified system, operating from DC to the full available bandwidth of the steering corrector magnets, with access to all monitors and correctors. Such a system will certainly be seen in the next generation of light sources.

## CONCLUSIONS

It is an exciting time to work in the field of light source stability. New facilities with submicron / submicroradian beam stability specifications will likely succeed, given recent experiences at the Swiss Light Source and SPEAR-3. Radio-frequency beam position monitoring electronics has reached a very sophisticated level, with many commercially available options. Photon beam position monitoring is becoming more important due to the advantages of sensing more directly what the experimenter is seeing.

The author would like to thank Hitoshi Tanaka (Spring-8) and Michael Böge (SLS) for initiating and continuing the excellent series of international workshops on beam stability, from which much of the material presented here was taken.

## REFERENCES

- [1] <http://www.lightsources.org>
- [2] Proceedings of the Third International Workshop on Beam Orbit Stabilization – IWBS 2004, December 6-10, 2004, Grindelwald, Switzerland, <http://iwbs2004.web.psi.ch>.
- [3] M. Green, Transcript of SRI 2001 Beam Stability Workshop, Madison WI (2001), <http://src.wisc.edu/meetings/SRI2001/workshops.html>.
- [4] M. Böge, “Achieving Sub-micron Stability in Light Sources,” EPAC '04, Lucerne, Switzerland, July 2004, p. 211.
- [5] R.O. Hettel, “Beam Stability at Light Sources,” Rev. Sci. Instrum. **73** (2002) 1396.
- [6] Michael A. Green et al., “Beam stability: ray tracing requirements and implementations,” SRI 2003, AIP Conference Proceedings 705 (2003) 601-604.
- [7] D. Bulfone et al., “Exploiting Low-Gap Position Monitors in Orbit Stabilization Feedback and Feed-Forward Systems at ELETTRA”, J. Japan. Soc. Syn. Rad. Res. **16** (2003) 4.
- [8] T. Nakatani et al., “Scheme for Precise Correction of Orbit Variation Caused by Dipole Error-field of Insertion Device,” Rev. Sci. Instrum. **76** (2005) 055105.
- [9] O. Singh and S. Krinsky, “Orbit Compensation for the Time-varying Elliptically Polarised Wiggler Operating at 100 Hz,” Nucl. Instrum. Methods A418 (1998) 249.
- [10] L. Emery, M. Borland, “Top-up Operation Experience at the Advanced Photon Source,” PAC '99, New York, NY, March 1999, p. 200.
- [11] H. Tanaka et al., “Top-up Operation at Spring-8 – Towards Maximizing the Potential of a 3<sup>rd</sup> Generation Light Source,” EPAC '04, Lucerne, Switzerland, July 2004, p. 222.
- [12] D. Bulfone, et al., “Fast Orbit Feedback Developments at ELETTRA,” EPAC '04, Lucerne, Switzerland, July 2004, p. 2604.
- [13] V. Shiltsev, “Alignment and Stability of Future Machines,” EPAC '96, Sitges, Spain, 1996, p. 32.
- [14] R. Biscardi, J.W. Bittner, “Switched Detector for Beam Position Monitor,” PAC '89, Chicago, IL, March 1989, p. 1516.
- [15] Bergoz Instrumentation, <http://www.bergoz.com>.
- [16] A. Kosicek, “LIBERA Electron Beam Position Processor,” PAC '05, Knoxville, TN, to be published.
- [17] V. Schlott et al., “Performance of the Digital BPM System for the Swiss Light Source,” DIPAC '01, Grenoble, France, May 2001, p. 69.
- [18] S. Kim, “Optimization of Four-Button BPM Configuration for Small-Gap Beam Chambers,” BIW '98, AIP Conference Proceedings 451 (1998) 310-317.
- [19] E. Plouviez, F. Uberto, “A Fast Local Feedback System to Correct the Beam Position Deviation in the ESRF Storage Ring,” EPAC '96, Sitges, Spain, 1996, p. 1872.
- [20] R. Johnson, Z. Li et al., “An X-band Cavity for a High Precision Beam Position Monitor,” DIPAC '03, Mainz, Germany, May 2003, p. 196.
- [21] K. Holdack et al., “Review of Emittance and Stability Monitoring using Synchrotron Radiation Monitors,” DIPAC '01, Grenoble, France, May 2001, p. 16.
- [22] A. Galimberti et al., “The Next Generation of Photon Beam Position Monitors for Undulator Beamlines,” PAC '01, Chicago, IL, June 2001, p. 544.
- [23] G. Decker, O. Singh, “Method of Reducing X-ray Background Signals from Insertion Device X-ray Beam Position Monitors,” Phys. Rev. ST. Accel. Beams **2** (1999) 112801.
- [24] E. Plouviez, “Upgrade of the Global Feedback of the ESRF Storage Ring,” these proceedings.
- [25] C. Schwartz, L. Emery, “Compensating the Frequency Deadband of the APS Real-time and DC Transverse Orbit Correction Systems,” PAC '01, Chicago, IL, June 2001, p. 1234.
- [26] C. Steier, “Operational Experience Integrating Slow and Fast Orbit Feedbacks at the ALS,” EPAC '04, Lucerne, Switzerland, July 2004, p. 2786.