ACHIEVING SUB-MICRON STABILITY IN LIGHT SOURCES

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Abstract

One of the major goals for present and future light sources is to achieve sub-micron orbit stability of the electron beam at the photon beam source points over a large frequency range. This puts tight constraints on the design of the various accelerator components including girders, magnets, power supplies and diagnostic hardware. Fast orbit feedback systems based on high performance RF- and X-BPMs become essential to suppress residual orbit distortions. Furthermore, the "top-up" operation mode which guarantees a constant electron beam current and thus a constant heat load in 3rd generation light sources is one of the key ingredients to reach sub-micron stability.

BEAM STABILITY REQUIREMENTS

Specific requirements for beam stability for synchrotron radiation experiments vary considerably, depending on the sensitivity of photon-sample interaction and experimental setup to beam parameter fluctuations. This sensitivity is a function of the beam line component configuration, detector and measurement method, sample characteristics and photon beam properties. Nevertheless generic stability specifications can be estimated from stability criteria for measurement parameters common to a majority of experiments (see Table 1). As a result the electron beam motion has to be stabilized in its 6-dimensional phase space such that the above stability requirements for the photon beam parameters are met.

Table 1: Typical stability requirements for selected measurement parameters common to a majority of experiments (adapted from [1])

Measurement parameter	**Stability requirement**
Intensity variation $\Delta I/I$	<0.1 % of normalized I
Position and angle accuracy	<1 % of beam σ and σ'
Energy resolution $\Delta E/E$	<0.01 %
Timing jitter	<10 % of critical t scale
Data acquisition rate	$\approx 10^{-3}$-10^5 Hz
Stability period	$10^{-2(3)}$-10^5 sec

Experiment sensitivity to electron beam instability can be characterized in phase space where the photon beam is represented by a spectral flux density distribution (flux per unit of photon frequency bandwidth). The beam line and experimental sample are represented as a system of apertures forming an acceptance volume within this space [2]. If the measurement signal is defined as the total flux within the acceptance volume, then measurement noise is caused by fluctuations of the beam density distribution in this volume. Figure 1 depicts the displacement of the photon beam with emittance ϵ_0 by centroid motion resulting in $\epsilon_{\rm cm}$ projected to the vertical phase space at an aperture located at a certain distance from the source point. The effect of beam instability on flux transmitted through a phase space aperture depends on the time scale of the fluctuation relative to the detector sampling and data integration times. For fluctuation frequencies much larger than sampling and integration rates, the beam distribution is effectively "smeared out" in phase space, increasing its area but not introducing any new noise. The effective beam emittance is thus given by $\epsilon_{\rm eff} = \epsilon_0 + \epsilon_{\rm cm}$. Centroid motion of ≈30 % of the beam size σ and divergence σ' causes only a 10 % increase in $\epsilon_{\rm eff}$ ignoring possible aliasing effects. Fluctuation frequencies in the range of or less than data integration rates are more harmful. In this case, the beam can move relative to the aperture on a sample-by-sample or scan-by-scan basis, introducing new measurement noise and $\epsilon_{\rm eff}$ is represented by the envelope of emittance ellipse displacements $\epsilon_{\rm eff} \approx \epsilon_0 + 2\sqrt{\epsilon_0\epsilon_{\rm cm}} + \epsilon_{\rm cm}$ [1] as shown in Figure 1. Centroid motion of ≈5 % causes a 10 % increase in $\epsilon_{\rm eff}$. Beam motion occurring over periods much longer than measurement times may have no effect on data quality since the beam is essentially stable. This is especially true if the experiment can be realigned or recalibrated between measurements. The most demanding beam stability requirements arise for a fluctuation frequency interval approximately bounded at the high end by data sampling rates and at the low end by data integration and sample scan times, so that beam noise is not averaged out. Noise spikes or infrequent jumps that do not contribute significantly to the RMS noise floor can be harmful for experiments, particularly those employing difference measurements.

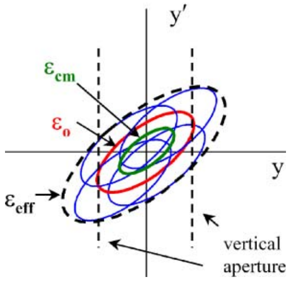

Figure 1: Emittance growth caused by centroid motion [1].

Since most 3rd generation light sources feature low beta (≈1 m) straights in order to allow for low gap (<10 mm) insertion devices (IDs), and operate at very small emittance coupling (<1 %) values with horizontal design emittances of just a few nm·rad, the requirements compiled in Table 1 lead to sub-micron tolerances for the vertical positional and angular stability of the electron beam at the ID source points ($\sigma_{\rm cm} < 1\mu$m, $\sigma'_{\rm cm} < 1\mu$rad) over a large frequency range 10^{-5}-$10^{2(3)}$ Hz.

NOISE SOURCES

In the following an attempt is made to categorize important noise sources discussed throughout the paper on different time scales:

- **Short term (<1 hour):** Ground vibration induced by human activities, mechanical devices like compressors and cranes or external sources like road traffic potentially attenuated by concrete slabs, amplified by girder resonances and spatial frequency dependent orbit responses, ID changes (fast polarization switching IDs <100 Hz), cooling water circuits, power supply (PS) noise, electrical stray fields, booster operation, slow changes of ID settings. Sources of beam motion associated with synchrotron oscillations and single- and coupled bunch instabilities are not considered [1].
- **Medium term (<1 week):** Movement of the vacuum chamber (or even magnets) due to changes of the synchrotron radiation induced heat load especially in decaying beam operation, water cooling, tunnel and hall temperature variations, day/night variations, gravitational sun/moon earth tide cycle.
- **Long term (>1 week):** Ground settlement and seasonal effects (temperature, rain fall) resulting in alignment changes of accelerator components including girders and magnets.

SHORT TERM STABILITY

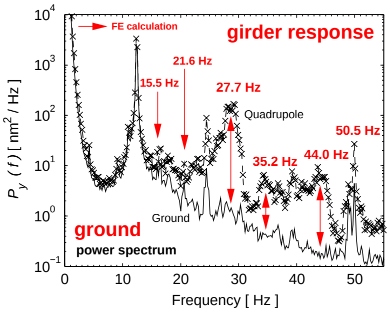

Figure 2: Vertical PSDs simultaneously measured on the slab and a girder mounted quadrupole at the SLS [3].

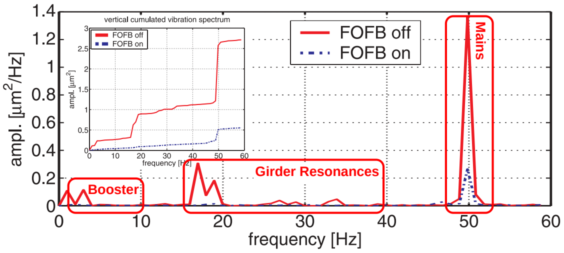

Figure 3: Vertical orbit PSD and cumulated spectrum without(red) and with(blue) orbit feedback measured by a BPM (β_y=18 m) at the SLS [5].

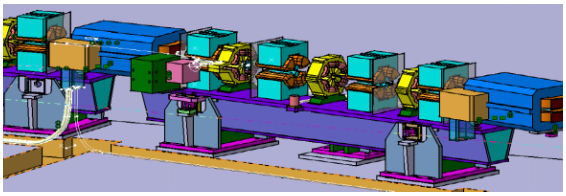

Figure 4: Example of a SOLEIL girder assembly. Quadrupoles, sextupoles and BPMs are rigidly mounted on girders. Bending magnets are bridging adjacent girders [6].

Figure 2 depicts the vertical power spectral densities (PSDs) simultaneously measured on the 40 cm thick concrete slab and a girder mounted quadrupole at the SLS for the spectral range 1-55 Hz. The relatively quiet noise floor on the slab with an integrated amplitude of ≈20 nm for frequencies >4 Hz gets significantly amplified (≈10 times) by magnet girder resonances in the range from 15-50 Hz. On the other hand a pronounced peak at 12.4 Hz induced by a nearby helium-refrigerator is not amplified by the girder [3]. Furthermore the orbit motion is not particularly excited by planar waves at spatial frequencies <15 Hz. At higher frequencies horizontal (vertical) orbit response factors of 8(5) at 30 Hz and 25(5) at 60 Hz have been estimated [4] amplifying especially the girder resonances. Consequently these resonances are clearly visible in the orbit PSD measured by an rf beam position monitor (BPM) (β_y=18 m) for the spectral range 1-60 Hz as shown in Figure 3. The integrated vertical RMS motion without orbit feedback (red curve) is calculated to be ≈1.7 μm. The stray fields of the booster which is mounted to the inner wall of the storage ring tunnel are responsible for a weak 3 Hz component in the PSD which is otherwise dominated by the contribution of the mains at 50 Hz. The situation described is typical for modern light sources. Girders are designed to allow grouping and very precise (≈10-20 μm) pre-alignment of individual magnets. The overall orbit amplification is reduced since the orbit motion is most sensitive to quadrupole-to-quadrupole movement which is strongly suppressed by the rigid girder assembly. In case of SOLEIL [6] the orbit amplification factors are reduced from 30(10) to 16(3) in the horizontal (vertical) plane. Nevertheless mechanical resonances of the girder arrangement can significantly amplify ground motion which is especially dangerous at low frequencies (<20 Hz) where the excitation through the ground and the slab tends to be large. At the SOLEIL site a pronounced 2.5 Hz component with an amplitude of ≈300 nm was measured. It could be partially traced back to heavy trucks on the nearby roads featuring suspension resonance frequencies close to 2.5 Hz. Figure 4 depicts the present SOLEIL girder assembly. Quadrupoles, sextupoles and BPMs are rigidly mounted on girders, while bending magnets are bridging adjacent girders. Careful design involving an additional central jack allowed to push the first dangerous eigenmodes of the assembly to frequencies >40 Hz. Remotely controlled girder movers which give the option to perform beam-based girder alignment as in the SLS case [7, 8] are not foreseen. This suggests that a proper mechanical design can assure short term orbit stability on the micron or even sub-micron level. Thus the operation of the installed IDs becomes the dominant contribution to the short term noise. Since most of the disturbances are of systematic nature and therefore reproducible, feed-forward correction tables can help to minimize the perturbation. Nevertheless the remaining noise is significant and needs to be attenuated by orbit feedback systems featuring large correction bandwidths >100 Hz.

Orbit Feedbacks

Orbit feedbacks can be divided in two classes:

- **Global feedbacks** compensate for perturbations generated by all IDs based on global orbit and/or photon beam positions by means of global correction.
- **Local feedbacks** compensate for perturbations generated by individual IDs based on local orbit and/or photon beam positions by means of local correction in the vicinity of the IDs.

In both cases a certain global reference orbit often referred to as the "golden orbit" needs to be established. Preferably this orbit is going through the centers of quadrupoles and sextupoles in order to minimize optics distortions which lead to spurious vertical dispersion and betatron coupling and thus an increased emittance coupling. Usually some extra steering in the vicinity of the IDs is added. In order to find this orbit "beam-based calibration" techniques [9] need to be employed which determine the offset of the BPM zero reading with respect to the magnetic center of the adjacent quadrupole. This offset is determined by altering the focusing $k + \Delta k$ of individual quadrupoles and measuring the resulting RMS orbit change which is determined by the product of the known Δk and the initial orbit excursion at the location of the modulated quadrupole. A comparison with the corresponding reading of the adjacent BPM reveals the offset. Even for well aligned machines these offsets can be of the order of a few 100 μm [10] since they represent a convolution of mechanical and electronical properties of the BPMs. As a result the remaining DC RMS corrector strength is usually significantly reduced when correcting to the "golden orbit".

The correlation between correctors and BPMs is established by superimposing the BPM pattern for the excitation of every single corrector. Very often the horizontal and vertical plane are treated independently assuming a small betatron coupling. The coefficients of the two resulting correlation matrices also called response matrices can be derived analytically from the machine model or from orbit measurements. To turn this into a correction algorithm it is necessary to "invert" the matrices in order to get the corrector pattern as a function of a given BPM pattern. If the correlation matrix is a square nxn matrix and has n independent eigenvectors and is not ill-conditioned this is easy to accomplish and one gets a unique solution for the problem by matrix inversion. In reality the number of correctors and BPMs can be already different by design or due to BPM failures and magnet saturations. As a result the matrix is non-square and the solution is no longer unique. A very flexible way to handle these scenarios is offered by the SVD algorithm [11]. This numerically very robust method minimizes the RMS orbit and the proposed RMS corrector strength changes at the same time if the number of correctors is larger than the number of BPMs whilst the RMS orbit is minimized in the reverse case. By introducing cutoffs in the eigenvalue spectrum for small eigenvalues only the most effective corrector combinations are selected and the correction gets less sensitive to BPM errors [12]. Thus this technique makes "Most Effective Corrector" and "MICADO" like long range correction schemes superfluous. Since modern light sources are built with very tight alignment tolerances and BPMs are well calibrated with respect to adjacent quadrupoles, orbit correction by matrix inversion in the nxn case which is equivalent to an SVD employing all eigenvalues has become an option since the resulting RMS corrector strength is still moderate (typically ≈100 μrad), BPMs are reliable and their noise is small (no BPM averaging is performed which is similar to a local feedback scenario). This allows to establish any desired "golden orbit" within the limitations of the available corrector strength and the residual corrector/BPM noise.

For the horizontal orbit correction it is crucial to take into account path-length effects due to circumference or rf frequency changes by correcting the corresponding dispersion orbits by means of the rf frequency. A gradual build-up of a dispersion related corrector pattern with a nonzero mean must be avoided since this leads together with an rf frequency change to a corrected orbit at a different beam energy. Thus it is desirable to subtract the pattern from the actual corrector settings before orbit correction in order to remove this ambiguity.

In order to implement a global orbit feedback based on the described algorithm which stabilizes the electron beam with respect to the established "golden orbit" up to frequencies ≈100 Hz BPM data acquisition rates of at least ≈1-2 kHz are needed. If sub-micron in-loop orbit stability is required the integrated noise contribution from the BPM electronics must not exceed a few hundred nanometers which is achieved with modern digital four channel (parallel) BPM [13] as well as analog multiplexed systems [14]. A fast network needs to be established which distributes the acquired BPM data around the ring or to a central point in order to be able to determine the individual correction values which in general depend on all BPM readings. Since the necessary matrix multiplications with the BPM vector can be parallelized a distribution on several CPU units handling groups of correctors is a natural solution. Furthermore the "inverted" matrix can be sparse depending on the BPM/corrector layout such that most of the off-diagonal coefficients are zero. In these cases only a small subset of all BPM readings in the vicinity of the individual correctors determines their correction values. At the SLS where all 72 BPMs have adjacent correctors in both planes and the phase advance between correctors is $<180^\circ$ the structure of the inverted 72x72 matrix resembles a correction with interleaved closed orbit bumps made up from three successive correctors [15]. The feedback loop is usually closed by means of a PID controller function optimizing gain, bandwidth and stability of the loop (see Figure 5). Notch filters allow to add additional "harmonic suppression" [16, 17] of particularly strong lines in the noise spectrum. The effect of the minimum applicable correction strength which is defined by the PS resolution for a given current range must be within the BPM noise and is typically of the order ≈10 nrad corresponding to ≈18 bit (≈4 ppm) resolution for a PS with ±1 mrad maximum strength. Modern PS with digital control have reached noise figures of <1 ppm providing kHz small-signal bandwidth [18] which opens the possibility to use the same correctors for DC and fast correction. Eddy currents induced in the vacuum chamber should not significantly attenuate or change the phase of the effective corrector field up to the data acquisition rate. Since eddy currents are proportional to the thickness and electrical conductivity of materials, only thin laminations (≤1 mm thickness) or air coils should be used for correctors and low conductive materials preferred for vacuum chambers. Eddy currents in vacuum chambers usually impose the most critical bandwidth limitation on the feedback loop. Global fast orbit feedbacks are operational or have been proposed for a large number of light sources, see Table 2. ALS [14], APS [20], ESRF [21], NSLS [17], SLS [5] and Super-ACO [22] (operated <12/03) have running configurations in user operation. BESSY [23], DELTA [24], SPEAR3 [25] and SPring-8 [26] have proposals, some of them [24, 26] test setups. The upcoming machines DIAMOND [27] and SOLEIL [6] have proposals for fast global orbit feedbacks. Local fast orbit feedbacks (see Table 2) stabilize orbit position and angle at ID centers locally without effecting the orbit elsewhere which is accomplished by a superposition of symmetric and asymmetric closed orbit bumps consisting of ≥4 correctors per plane around the ID. Photon BPMs (X-BPMs) which are located in the beam line frontends measuring photon beam positions provide very precise information about orbit fluctuations at the ID source point at a typical bandwidth of ≈2 kHz. With two X-BPMs position and angle fluctuations can be disentangled. Unfortunately the reading depends on the photon beam profile and thus on the individual ID settings. APS is operating X-BPM based feedbacks on their dipole and ID X-BPMs at fixed gap [20]. BESSY has the prototype for an X-BPM based feedback on an APPLE II ID [23]. ELETTRA implemented a feedback for an electromagnetic elliptical wiggler (EEW) based on a new type of digital "low gap" BPM [16]. If several global and/or local feedbacks are operated they need to be decoupled. Either they are well separated in frequency which evidently leads to correction dead bands [20] or they run in a cascaded master-slave configuration [28, 20, 14, 5].

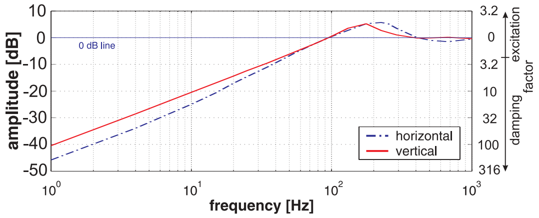

Figure 5: Fast orbit feedback closed loop transfer functions in the horizontal (blue) and vertical (red) plane at the SLS. Damping is achieved up to ≳100 Hz [5].

Table 2: Compilation of **operational global**, proposed global and *operational local* fast orbit feedback systems at light sources (adapted from [19])

SR Facility	BPM Type	max. BW	Stability
ALS	RF-BPMs	<50 Hz	<1 μm
APS	RF&X-BPMs	50 Hz	<1 μm
ESRF	RF-BPMs	100 Hz	<0.6 μm
NSLS	RF&X-BPMs	<200 Hz	1.5 μm
SLS	RF&X-BPMs	100 Hz	<0.3 μm
Super-ACO	RF-BPMs	<150 Hz	<5 μm
BESSY	RF-BPMs	<100 Hz	<1 μm
DELTA	RF-BPMs	<150 Hz	<2 μm
DIAMOND	RF-BPMs	150 Hz	0.2 μm
SOLEIL	RF-BPMs	150 Hz	0.2 μm
SPEAR3	RF-BPMs	100 Hz	<3 μm
SPring-8	RF-BPMs	100 Hz	<1 μm
APS	X-BPMs	50 Hz	<1 μm
BESSY	X-BPMs	50 Hz	<1 μm
ELETTRA	RF-BPMs	80 Hz	0.2 μm

MEDIUM AND LONG TERM STABILITY

In this regime high mechanical stability is needed to achieve stability on the sub-micron level:

- Stabilization of tunnel, cooling water temperature and digital BPM electronics [5] to ≈ ±0.1°and the experimental hall to ≈ ±1.0°.
- Minimization of thermal gradients by discrete photon absorbers and water-cooled vacuum chambers.
- Mechanical decoupling of BPMs with bellows, stiff BPM supports with low temperature coefficients (Invar [6], Carbon Fiber [16]) and/or monitoring of BPM positions [13].
- Monitoring of girder positions [7].
- Full energy injection and stabilization of the beam current to ≈0.1 % ("top-up" operation).

"Top-up" operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant [5]. Figure 6 depicts the horizontal mechanical offset of a BPM located in an arc of the SLS storage ring with respect to the adjacent quadrupole in the case of beam accumulation, "top-up" and decaying beam operation at 2.4 GeV. During accumulation and decaying beam operation BPM movements of up to 5 μm are observed. The position does not change during "top-up" operation at 200 mA after the thermal equilibrium is reached (≈1.5 h). APS [29], SLS [30] and very recently SPring-8 [31] are

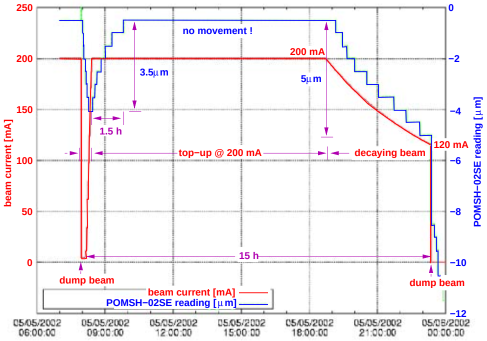

Figure 6: Horizontal mechanical offset of a BPM located in an arc of the SLS storage ring with respect to the adjacent quadrupole in the case of beam accumulation, “top-up” and decaying beam operation [30].

running “top-up” as preferred mode during user operation. It is a difficult task to guarantee sub-micron long-term stability. But since beam lines can be realigned or recalibrated between measurements campaigns which require short and medium term sub-micron stability this seems acceptable.

CONCLUSIONS

It has been shown that short and medium term sub-micron orbit stability can be achieved in 3rd generation light sources. Fast orbit feedback systems and “top-up” operation are key ingredients to reach this level of stability. The stability of beam line components apart from X-BPMs has not been discussed. But it is evident that the achieved stability needs to be maintained throughout the beam line. To this end fast feedbacks on monochromators and other optical components have the potential to improve the stability of the beam line optics considerably [23].

The author would specifically like to thank Boris Keil, Thomas Schilcher, Volker Schlott and Andreas Streun for many fruitful discussions. The author gratefully acknowledges contributions from many other colleagues.

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