GLOBAL POSITION FEEDBACK IN SR SOURCES

V. Schlott, PSI, Villigen, Switzerland

Abstract

Beam stability and orbit control represent key issues for SR sources as user facilities. The continuous reduction of emittance and coupling as well as the increasing sophistication of experiments lead to more and more stringent requirements for beam stability and reproducibility of "golden orbits" down to a micrometer or even sub-micrometer level. Most SR sources have therefore implemented local or global position feedback systems covering a frequency range from DC to 200 Hz.

Key elements of position feedback systems such as pick-ups, correctors, electronics and processing hardware as well as correction algorithms and techniques are presented. Their properties and suitability regarding the character of orbit disturbances, user requirements and feedback loop characteristics are analyzed. Examples and achievements of (global) position feedback systems in various SR facilities are presented.

1 BEAM STABILITY REQUIREMENTS

Third generation SR sources are user facilities, which are committed to deliver high brightness photon beams under extremely stable and reproducible conditions to a large number of experimental stations at the same time. The quest for even higher brightness leads to a continual optimization of storage ring lattices for low emittances (< 10 nmrad) and small vertical beta functions at the locations of the radiation source points. Improved understanding and control of storage ring optics through precise beta function measurements results in low beam coupling (< 1 %) and achievement of vertical beam sizes in the order of 10 microns or less [1,2]. On the experimental side energy resolutions of monochromators have reached values of 10^{-4} to 10^{-5}, while typical intensity modulations to be measured are in the order of 1-10 % [3,4]. For an effective use of such resolving power and the achievement of sufficient signal-to-noise ratios, it is desirable that fluctuations caused by electron beam motions are at least one order of magnitude lower. Angular stability of the radiation source directly influences the photon energy resolution behind the monochromator. Application of Bragg's law to Si_{111} as a monochromator crystal ($\Theta_{Bragg} = 10°$ @ $E_{ph} = 10$ keV) results in angular stability requirements of the electron beam along an insertion device (ID) straight section of well below 5 µrad horizontally and 1 µrad vertically. Fluctuations of electron beam positions on the other hand affect predominantly the intensity stability respectively the signal-to-noise ratio on the detector. High steering accuracy represents for example a critical parameter for full field imaging microscopy, where sample sizes are often comparable to or even smaller than electron beam sizes. New types of IDs, which permit rapid switching of photon beam polarization [5], allow the combination of photoemission electron spectroscopy, with dichroism spectroscopy by applying subtractive processing of signals with switched polarization. Such advanced data analysis techniques require highly stable intensities up to frequencies of the polarization changes. For gaussian beam distributions, position changes of only a few percent σ are tolerable, translating into beam motions of less than 1 µm for third generation SR sources.

2 SOURCES OF ORBIT DISTURBANCES

Sources of orbit disturbances in SR facilities can best be divided in terms of time periods or bandwidth. Figure 1 gives an almost complete overview of the power spectral density of beam noise at SR facilities. It has been taken at the APS and ranges from weeks to microseconds, showing that amplitudes of beam motions decrease from millimeters to micrometers with increasing frequency.

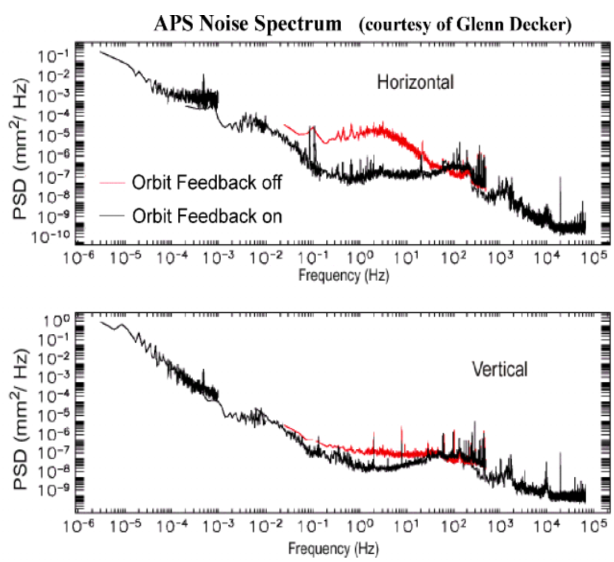

Figure 1: Power spectral density of noise sources at APS.

Ground settling and seasonal changes last over periods of months and years and impair the initial alignment of accelerator magnets. With amplitudes of up to a few millimeters such long-term effects concern mainly the reproducibility of "golden orbits". Usually, such orbit disturbances are not considered to be corrected by feedback systems. Still, dynamic alignment can be performed, if measuring systems like hydrostatic leveling and monitoring of horizontal girder respectively magnet positions are available and motorized girder or magnet movers are applied as correctors [6].

A large variety of predominantly thermal effects cause medium term orbit motions, which last from weeks over days until minutes and reach amplitudes of up to a few hundred micron. Ambient temperature changes in storage ring tunnels and technical galleries affect the stability of mechanical and electronic equipment. Heat load changes due to beam current variations lead to vacuum chamber, beam position monitor (BPM) and even magnet movements as well as to drifts of optical components along the beamlines. In addition, intensity and filling pattern dependence of BPM electronics pretend unphysical orbit motions. Stabilization of the beam current in the storage ring through "top-up" injection or frequent refills seems to be a cure for most of these medium term thermal effects but may introduce additional (high frequency) noise, if injection cycles are not fully transparent. User control of ID settings is a typical medium term source of global closed orbit distortion in SR sources. Local compensation of residual quadrupole field components through the application of feed forwards and look-up tables may minimize this effect, but remaining field errors of the IDs still lead to unclosed local bumps around the straight sections and therefore to closed orbit motions up to 100 µm.

Fast-switched-polarization IDs transfer this kind of orbit disturbances to a higher frequency range of up to 100 Hz. Normally, in this regime orbit motions of less than 10 microns are driven by ground vibrations, which are amplified by eigenmodes of mechanical components like magnets and support girders. Cooling water circuits, electrical stray fields and cycling booster operation can also be identified as sources for beam noise in this spectral regime. Great efforts in improvement of mechanical and electrical designs have been made to reduce such effects to a level of only a few microns rms beam motion, which is - as indicated before – still not sufficient for the increasing sophistication of experiments.

The impact of orbit disturbances on the users is also strongly depending on the detection bandwidth of their experiments. The majority still has comparatively long data acquisition times in the order of 1 to 100 seconds. They are most sensitive to medium term beam motions, which cause intensity as well as energy fluctuations of the photon beam on their samples. Higher frequency disturbances do not represent additional noise to them, but generate an increase of the effective emittance ε_{eff} of the source by quadratically adding the beam centroid movement in phase space to the natural emittance ε_0. There is however an increasing number of experiments, which apply fast scanning methods in the millisecond range [7], demanding sub-micron orbit stabilization with a much higher bandwidth (up to a few hundred Hz). A global position feedback as treated in this context deals with the correction of such orbit disturbances from about 0.001 Hz to about 200 Hz. Higher frequency effects have to be addressed by multi-bunch feedback systems [8], while long term motions are removed through re-alignment or dynamic re-positioning of accelerator components.

3 FEEDBACK ARCHITECTURE

The block diagram in figure 2 shows the typical structure of a global position feedback system.

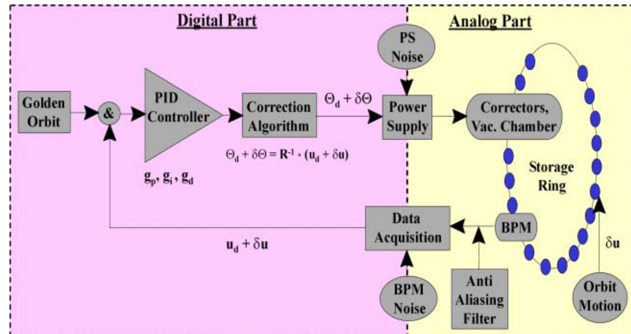

Figure 2: Block diagram of global orbit feedback.

The feedback key components are:

- A sufficient number of BPMs, which measure the actual electron (or photon) beam positions in the storage ring.
- A dedicated network, which is transferring the position information to a (central) processing unit and spreading out the calculated corrector settings.
- A correction algorithm, which compares the measured beam positions to the desired "golden orbit" and predicts orbit corrections based on the known correlation between BPMs and corrector magnets.
- A controller function (e.g. PID), which is optimizing the gain, bandwidth and stability of the closed feedback loop, depending on the transfer functions of the feedback key components.
- A set of corrector magnets, which apply the correction kicks to the electron beam.

3.1 Correction Scheme

Global position corrections in SR (user) facilities should always be performed in reference to the desired "golden orbit" $\mathbf{u_d}$, which provides simultaneously the best machine performance and the most satisfying photon beam conditions to the users. $\mathbf{u_d}$ is obtained through an initial (static) orbit correction with corrector magnet settings $\mathbf{\Theta_d}$ following the relation $\mathbf{u_d} = \mathbf{R\Theta_d}$. $\mathbf{R}$ is the response matrix, which is either model-based or derived from corrector-orbit response measurements. It includes the machine optics and establishes the correlation between BPMs and correctors. The "actual orbit" $\mathbf{u_a} = \mathbf{u_d} + \delta\mathbf{u}$ is determined by a set of BPMs, providing M position offsets $\delta\mathbf{u}$. These readings are used to calculate the corresponding correction vector $\delta\mathbf{\Theta}$, consisting of N correction kicks. If more BPMs than corrector magnets or an equal number of both are available for a global position feedback, the correction matrix $\mathbf{R}^{-1}$ can be obtained from the response matrix $\mathbf{R}$ by direct matrix inversion providing a unique solution and the exact reproduction of the "golden orbit". However, ineffective placement of monitors and/or correctors in phase may result in singularities, when inverting the response matrix and thus lead to overly large corrector settings. Likewise, errors of BPM electronics and corrector saturation can lead to ineffective corrections and even to a blow up of the global orbit. Singular value decomposition (SVD) [9] has proven to be a numerically robust method for such cases, which is commonly used in SR facilities as orbit correction algorithms. In case that more correctors than monitors are available, SVD minimizes the rms orbit and rms corrector strengths, in the reverse case it leads to a suppression of BPM errors and a smoothing of the orbit.

Independent from the particular feedback configuration (number of BPMs and correctors) and the applied correction algorithm (matrix inversion, SVD or others), a fast data transfer network has to be established, which allows the collection of the actual position readings in a (central) processing station and the re-distribution of the calculated corrector settings. Modeling of the closed feedback loop performance (see section 3.4) shows, that the processing time and the "dead time" for data transfer should be minimized to obtain high bandwidth with sufficient suppression of orbit fluctuations. Due to the rapid technological progress regarding processing power and fast data transfer links, this seems to be no longer a limiting factor for global feedback systems. Moreover, the decreasing hardware costs allow the inclusion of a higher number of BPMs and correctors in a global scheme. If, at the same time, the reliability and systematic errors of BPM electronics can be improved through features like automated calibration and self tests, exact correction to the desired orbit seems to be the best way for delivering highest machine performance under reproducible conditions. In the following, the performance requirements for feedback key components are summarized and their influence on global position feedback loops is analyzed.

3.2 Beam Position Monitors

Two kinds of beam position monitors are typically utilized in SR facilities: rf and photon BPMs. Rf-BPMs consist of two pairs of button electrodes, which are equally placed on the upper and lower side of a BPM chamber. The capacitive coupling to the electron beam induces a position and intensity dependent rf-signal on each electrode. A dedicated electronics converts these rf-signals to the baseband, limits the bandwidth, normalizes to beam intensity, calculates the actual beam positions and digitizes the results for further data processing. An excellent overview of signal processing systems for beam position monitoring is given in [10]. BPM electronics have either been optimized for high resolution, low current dependency and good linearity or high bandwidth. A BPM system, which is suitable to serve as a position detector in a feedback loop needs to combine all these properties to a certain extent. To prevent the transmission or even amplification of noise from the detector system to the electron beam, it is clearly mandatory that the BPM system's resolution is well below the anticipated level of beam stabilization. If an effective orbit correction to a sub-micron level should be obtained throughout the feedback bandwidth (e.g. up to 100 Hz), the noise contribution of the BPM electronics must not exceed a few hundred nanometers respectively $20\mathrm{nm}/\sqrt{\mathrm{Hz}}$. Likewise, the bandwidth of the data acquisition needs to be high enough to correct beam fluctuations up to frequencies of about 100 Hz. Position sampling rates of a few kHz are required to avoid long latency times through the loop, leading to large phase shifts of correction kicks and thus instable loop performance. In this respect, four channel (parallel) electronics might be favored against multiplexed systems, since kHz multiplexing frequencies may turn longitudinal beam oscillations, which occur at the synchrotron frequency through aliasing into noise in the correction bandwidth. Apart from these high frequency attributes, features like beam current dependency of electronics and mechanical stability of BPM chambers have to reach a sub-micron level as well, if the same BPM system should simultaneously be used for fast and medium term position feedback. Top-up operation of storage rings leads to current stabilization of up to 10^{-4}, relieving requirements for intensity dependency of BPM electronics. However, mechanical movements of BPM chambers still have to be avoided or controlled. Various approaches have been realized, reaching from the use of stiff support materials with low temperature coefficients [11] and mechanical de-coupling of BPM chambers with bellows [12] to monitoring of the mechanical positions of the BPM chambers and consideration of the measured drifts by the determination of the final beam positions [13].

Photon BPMs are located in the beamline front ends. They consist of four electrically isolated blades, which provide - similar to rf-BPMs - position sensitive signals of the photon beam, based on the photoemission effect. P-BPMs usually do not suffer from typical rf-BPM problems like intensity and bunch pattern dependence as well as thermal drifts of monitors. In addition, their high(er) resolution and sufficient bandwidth (up to 2 kHz) makes them extremely attractive for position feedback purposes. However, the contamination from bending magnet radiation and gap dependent undulator mode shapes complicate the correct interpretation of signals in ID straight sections. A number of solutions have been realized to avoid these problems. For VUV and soft X-rays, low-pass and band-pass filtering of photoemission currents as well as precise mapping of undulator modes make p-BPM signals usable [14,15]. In case of hard X-ray machines the introduction of chicanes around ID straights directs unwanted bending magnet radiation away from the monitor blades and improves the signal-to-background ratios to an acceptable level [16].

3.3 Corrector Magnets and Vacuum Chamber

The influence of corrector magnets, their power supplies and vacuum chambers on the efficiency of global position feedbacks is primarily visible at high correction rates (> 10 Hz). Although remagnetisation losses are in most cases negligible, since (fast) feedback correctors are only operated in the small signal domain, eddy current effects in magnet laminations and vacuum chambers lead to noticeable attenuation of feedback gains and introduce phase shifts. Since eddy currents are directly proportional to the thickness and electrical conductivity of materials, only thin laminations (≤ 1 mm thickness) should be used for corrector magnets and low conductive materials are preferred for vacuum chambers. Air core magnets show of course the best high frequency performance. However, they need higher currents than laminated magnets to achieve the same kick strength. If the same magnets should be used for DC and fast orbit corrections, this fact may compensate the high frequency advantage since more noise is introduced in the feedback loop through stronger power requirements. Corrector magnet power supplies have reached short-term noise figures of < 1 ppm, while providing kHz small signal regulation bandwidth at the same time [17]. Thus, eddy currents in vacuum chambers represent above all the major bandwidth limitation for fast position feedback loops. However, their influence on gain and phase delay are still quite moderate and can be treated as a low-pass of first order.

3.4 Feedback Modeling

A global position feedback is a typical example for a multi-input-multi-output (MIMO) loop, which deals with the *rejection of set-point disturbances* rather than with the *tracking of reference changes* as commonly needed in industrial applications. Modeling of the (global) position feedback closed loop behavior can generally be obtained by selecting an appropriate controller function, whose parameters are optimized under consideration of noise sources in SR facilities, user stability requirements and transfer functions of the feedback key components. In case of the classical PID approach [18], the proportional, integral and derivative gains are adjusted for minimal rms orbit fluctuation throughout the anticipated bandwidth range and highest loop stability at the same time. Here, the integral gain coefficient permits effective suppression of low frequency orbit disturbances, while the differential gain provides good step response behavior. Loop stability near the cut-off frequency of the feedback can be obtained with the right choice of the differential gain coefficient. Robustness is in any case an important requirement for a feedback loop, but it is usually achieved at the expense of gain and/or bandwidth. The final loop optimization is an iterative process, which is usually supported by CAD toolboxes. The Bode plot in figure 3 illustrates the behavior of a global position feedback. The closed loop gain and phase are shown for the parameters of the SLS global orbit feedback. The (digital) power supplies provide a small signal bandwidth of up to 2 kHz, while the laminated corrector magnets and the 2 mm thick stainless steel vacuum chamber represent first order low-pass filters with cut-off frequencies of 100 Hz. The position sampling rates of the SLS digital BPM system has been varied between 1 kHz and 4 kHz. All other time consuming operations like calculation of beam positions and corrections, execution of PID control as well as data transfer and corrector (DAC) settings have been assumed to be executed within 250 µs.

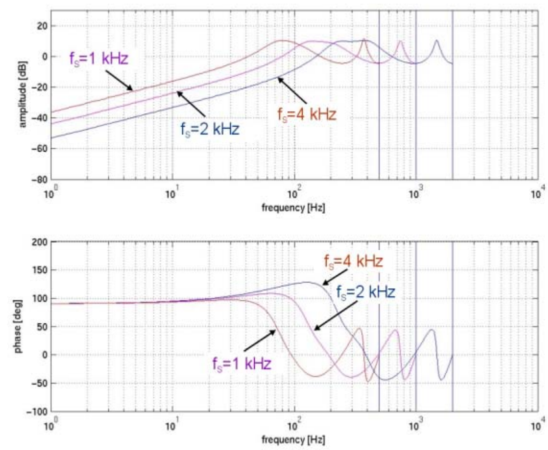

Figure 3: Dependency of closed position feedback loop on the BPM sampling rate f_S = 1 kHz, 2 kHz and 4 kHz.

The simulation shows that the feedback efficiency and its bandwidth scale with the sampling rate of the detector system respectively with the total latency time of the loop. Since resolution and bandwidth of BPM systems are usually strongly correlated, their performance represents a major concern for the efficiency of (global) feedback systems.

4 FEEDBACK IMPLEMENTATIONS

The decision for global and/or local position feedback implementations in SR sources is not only driven by technical considerations. It can also be strongly influenced by economical reasons or by already existing hardware (e.g. BPM system). In this respect, local and global feedback systems as well as combinations of both have been realized in SR sources worldwide. A considerable number of facilities are operating local position feedbacks and feed-forwards for each experiment individually, by introducing closed bumps around ID straight sections. Such solutions are cheaper and easier to implement than global schemes, since requirements for processing power and data transfer rates are more relaxed. However, if ID bumps are not completely closed, coupling of loops may occur, causing global orbit disturbances, which are extremely hard to control. The combination of a fast global and slow local position feedback or vice versa requires careful de-coupling of both loops in frequency domain. This separation leads to dead bands leaving undesirable orbit motions for some of the experiments. Apart from these apparent drawbacks, all of the listed position feedbacks provide the required beam stability, which makes light sources to successful user facilities.

Table 1: Position feedbacks in SR sources worldwide

SR facility	FB type	Monitors	max. BW	Stability
ALS*	G	rf-BPMs	< 100 Hz	< 1 µm
APS	G and L	rf & p-BPMs	< 30 Hz < 50 Hz *	< 2 µm < 1 µm *
NSLS	G	rf-BPMs	< 200 Hz	0.5 µm
SPEAR 3*	G	rf-BPMs	< 200 Hz	< 1 µm
BESSY *	L	rf and p-BPMs	< 100 Hz	< 1 µm
DELTA	G	rf-BPMs	< 1 Hz	< 5 µm
ELETTRA *	L	rf-BPMs	< 20 Hz	< 0.2 µm
ESRF	G	rf-BPMs	100 Hz	0.6 µm
MAX-lab	G	rf-BPMs	1 Hz	< 3 µm
SLS *	G	rf & p-BPMs	100 Hz	< 0.5 µm
SRS	L	p-BPMs	0.03 Hz	1 µm
SUPER-ACO	G	Rf-BPMs	< 150 Hz	< 5 µm
DIAMOND *	G	rf-BPMs	100 Hz	< 1 µm
SOLEIL *	G	rf and p-BPMs	100 Hz	0.2 µm
KEK-PF	G	rf-BPMs	3 Hz	< 5 µm
SPRING-8	G	rf-BPMs	< 0.01 Hz 200 Hz *	< 3 µm < 1 µm *

* feedbacks in commissioning, respectively proposed systems (table comprehends only data, which could be collected until EPAC paper submission deadline and thus might not be complete…)

CONCLUSIONS

Increasing user requirements for beam stability are only achievable with position feedback systems. Global implementations, which cover all frequency ranges with a single system, represent a natural and most effective approach for correcting distributed sources of orbit disturbances as usually found in SR sources. The rapid technological progress provides increasing processing power and data transfer rates at decreasing hardware costs. This should motivate to consider global position feedback systems from the beginning as a vital part of beam diagnostics equipment. If the reliability of beam position measurements can be improved by features like e.g. electronics self tests and data validity checks [19], all BPM stations and corrector magnets of a storage ring could be included in the global position feedback scheme, providing the opportunity of designing and maintaining any desired "golden orbit". Latency times through the feedback loop and BPM resolution represent the key issues (and limitations) for efficient, high bandwidth feedback systems. Although, the performance of rf-BPM systems regarding resolution and bandwidth are already excellent, it might not be sufficient in the future and p-BPMs need to be considered as position monitors in global feedback schemes as well. The storage ring rf-frequency should also be included in a global position feedback, since it represents a unique parameter to correct for ring circumference changes and is thus providing high level beam energy stabilization [19] at the same time.

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