# ORBIT CONTROL AT THE SLS STORAGE RING

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*Abstract*

Precise orbit control is one of the crucial features for stable operation of storage rings. At SLS a digital BPM system measures the orbit with sub-micron resolution at sampling rates of up to 4 kHz at 72 locations in the storage ring. Corrections are made with respect to any desired "Golden Orbit" by applying SVD techniques and a direct response matrix inversion. Presently,a slow global orbit feedback operating at correction rates of up to 1 Hz stabilizes the electron beam to within ~0.5 micrometer RMS horizontally and vertically at the locations of the insertion devices. Energy drifts are automatically corrected using the RF frequency as an additional corrector, thus providing a long term energy stability of dE/E = $2 \cdot 10^{-5}$. Results from user operation are presented along with a report on the upgrade to a fast orbit feedback running at 4 kHz sampling rate.

## 1 INTRODUCTION

The Swiss Light Source is a third generation synchrotron radiation source which is designed to deliver high brightness photon beams to a large number of experimental stations at the same time. One of the most important properties is the stability and reproducibility of the electron orbit at the location of the radiation source points. The photon intensity at the experimental stations and hence the signal-to-noise ratio is strongly depending on the oscillations of the electron beam while the photon energy is directly influenced by the angular stability of the radiation source. It is therefore desirable to suppress the photon beam fluctuations by at least one order of magnitude below the spot size at the location of the experiments. At the SLS this translates into electron beam angular stability along the insertion device straights below 1 $\mu$rad and into beam position stability below 1/10th of the vertical beam size corresponding to $\approx 1$ $\mu$m. As a consequence, a closed orbit feedback has been designed to suppress beam oscillations through ground motions, girder vibrations etc. by at least -20 dB and up to $\approx 100$ Hz. Simulations of feedback loops based on a PID controller model have shown that a sampling frequency up to 4 kHz is required.

## 2 FEEDBACK STRATEGY

The approach of a global orbit feedback has been chosen in case of SLS. The system is based on 72 beam position monitors and 72 corrector magnets in the horizontal and vertical plane distributed around the storage ring. The correlation matrix $\mathbf{A}$ (orbit response matrix) which maps corrector magnet settings on beam position monitor readings is "inverted" using the Singular Value Decomposition technique (SVD) in case of a non quadratic response matrix taking into account all eigenvalues.
For the horizontal orbit correction it is crucial to consider path-length effects by correcting off-energy orbits with the RF frequency. The difference of the original orbit and the SVD fitted off-energy part, where a deviation of dE/E corresponds to a frequency change df, is submitted to the orbit correction.
The realization of the global orbit feedback is carried out in two steps. A Slow Orbit Feedback (SOFB) with much more relaxed requirements ($<$ 3 Hz correction rate) is in operation since August 2001. The experience gained with the various subsystems and the flexibility in the high level software serves as a basis for the final implementation of the Fast Orbit Feedback (FOFB).

## 3 SLOW ORBIT FEEDBACK

Since the beginning of the commissioning, global orbit corrections have been successfully applied manually by the operators with the help of a high level beam dynamics application. Due to the modularity of the beam dynamics software environment [1], thoroughly tested software components could be combined to implement a Slow Orbit

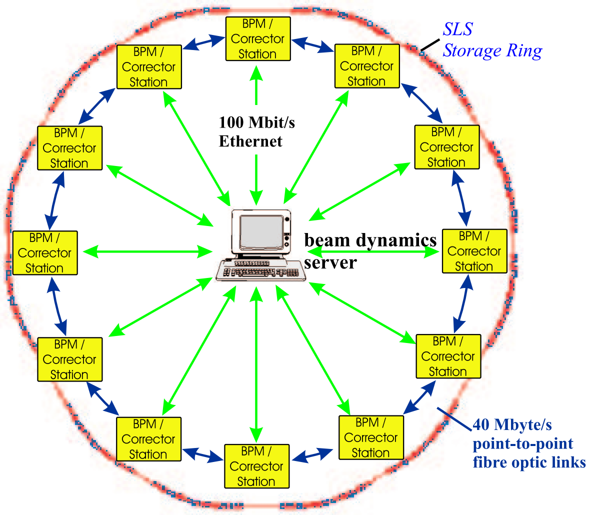


Figure 1: Schematic View of the SOFB/FOFB. SOFB: the "Beam Dynamics Server" retrieves all BPM readings, calculates the corrections and sets the new magnet currents. FOFB: the Beam Dynamics Server calculates only the "inverted" response matrix and distributes the coefficients to the individual BPM stations. The BPM readings are processed and corrections are done decentralized on a DSP based front end. The necessary data exchange between sectors is implemented by means of separate fiber optic links.

Feedback. In this case the operator is "replaced" by a client program, the so-called "Feedback Client", which initiates an orbit correction at a given rate. A central beam dynamics server reads the beam positions at all 72 BPMs, "inverts" the orbit response matrix and calculates the necessary corrector magnet kicks for both planes. The necessary data exchange is carried out over the standard 100 Mbit/s control system Ethernet network. (see Fig. 1). For the SOFB the digital BPM system [2] is operated in an injection triggered batch processing mode with 32 kHz bandwidth. By averaging over 64 orbit samples, corresponding to an interval of 2 ms, it is possible to get "stroboscopic" position readings at a rate of 3 Hz with a resolution $\approx 0.3\ \mu$m. A "BPM Server" monitors, collects and sends the BPM data to the "Feedback Client" with 2 Hz. A low pass filter is applied (sliding average) to several successive BPM data sets. By default the SOFB averages over 3 data sets. The orbit readings are then sent to the "TRACY Server" which predicts a corrector pattern to restore the "Golden Orbit". The "Golden Orbit" is defined by the orbit centered in the quadrupoles which is achieved by means of beam-based alignment techniques. Additionally, local bumps at the location of the insertion devices are taken into account in order to steer the photon beam according to the demands of the experiments. Finally, the proposed correction is applied by toggling between the horizontal and the vertical plane. Thus, a full SOFB cycle takes less than 3 s ($\approx$ 0.4 Hz).

## 4 FAST ORBIT FEEDBACK

Properly placed BPMs around the ring lead to an "inverted" response matrix where only the diagonal and their adjacent coefficients have non zero values. Thus, corrector magnet settings are only determined by position readings from the closest BPMs [3]. This provides the possibility to run the FOFB decentralized, integrated in the twelve BPM stations of the SLS storage ring. Each of the twelve stations handles six BPM inputs and six corrector magnet outputs. The data between adjacent BPM stations are transmitted over dedicated fiber optic point-to-point links (40 MBytes/s) which reflect the localized structure of the "inverted" response matrix. Running the feedback with an update rate of 4 kHz the global data exchange is done within 8 $\mu$s providing enough time for the correction calculations.

An important prerequisite for any feedback which uses as many correctors as BPMs and therefore constrains the orbit to the "Golden Orbit" at each BPM location is the reliability of all position readings. The need of an "intelligent" BPM system which is capable of self diagnosing hardware faults becomes indispensable. At SLS much emphasis has been put on sophisticated low level software in order to detect BPMs with spurious bad readings. Two different strategies are applied. In case of the SOFB, where the positions are calculated based on 64 successive orbit samples, corresponding to 2 ms, the residual orbit fluctuations are typically of the order of 1 $\mu$m. If both RMS values of $x$ and $y$ during this time interval exceed a predefined threshold the DSP software disables the possibly faulty BPM. Since the central orbit feedback monitors the on-line status of all BPMs it automatically recalculates the "inverted" response matrix of the remaining set of BPMs and correctors and continues operation. The approach in case of the FOFB is slightly different. Running an algorithm with 4 kHz sampling rate requires an immediate validation of the data readings. This is achieved with cross checks of the four RF button signals since the sum of the two diagonal BPM buttons have to agree within 20%. After a predefined number of faulty readings the feedback is stopped, the beam dynamics server disables the BPM, recalculates the "inverted" response matrix and distributes the coefficients to the individual BPM stations before the feedback operation is resumed.

## 5 SOFB RESULTS

The results of a typical user run between Aug, 13 - 16 2002 are shown. During this run the storage ring was operated in top-up mode [4] where the electron current was kept constant at 180 mA within a band of 0.5 mA. This top-up mode has the advantage that the storage ring is in thermal equilibrium which results in negligible drifts of vacuum chambers with respect to magnets. Moreover, the BPMs show no beam current dependence and the experiments experience a constant heat load on their beam-line components. The SOFB has stabilized the orbit to RMS values of $\approx 1\ \mu$m with respect to the "Golden Orbit" in both planes (see Fig. 2). The RF frequency is corrected by df when-

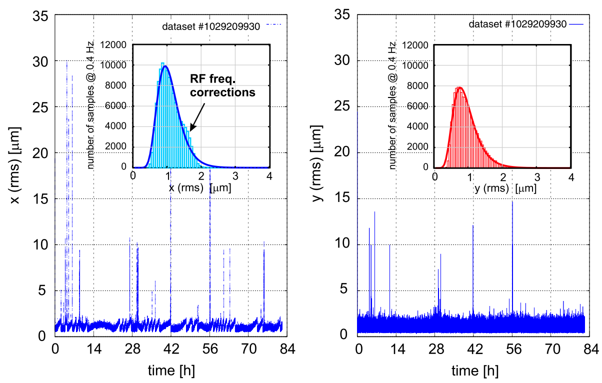


Figure 2: Plot of the RMS values of horizontal and vertical position readings at all 72 BPMs including the histograms of this run.

ever |df| exceeds 5 Hz corresponding to an energy change of dE/E $\approx 2 \cdot 10^{-5}$. In this particular case a frequency correction is performed every $\approx$ 45 min. Consequently the horizontal RMS value increases (see "saw tooth" in Fig. 3) while df is not applied. A frequency change by 5 Hz corresponds to a path length change of 3 $\mu$m for a 288 m circumference of the storage ring and an RF frequency of 500 MHz. Although the tunnel temperature is regulated within $\pm 1^{\circ}$C the daily outside air temperature variations have an influence on the building and hence on the circumference

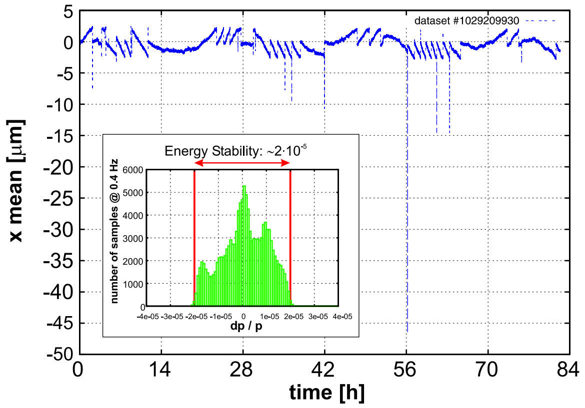


Figure 3: Mean value of the horizontal orbit with respect to the "Golden Orbit" during a 3 days "top-up" run at 180 mA. The proposed frequency correction df is applied whenever a threshold of 5 Hz is passed corresponding to an energy deviation dE/E $\approx 2 \cdot 10^{-5}$.

of the storage ring. This cycle and the corresponding frequency corrections can clearly be observed in Fig. 4.

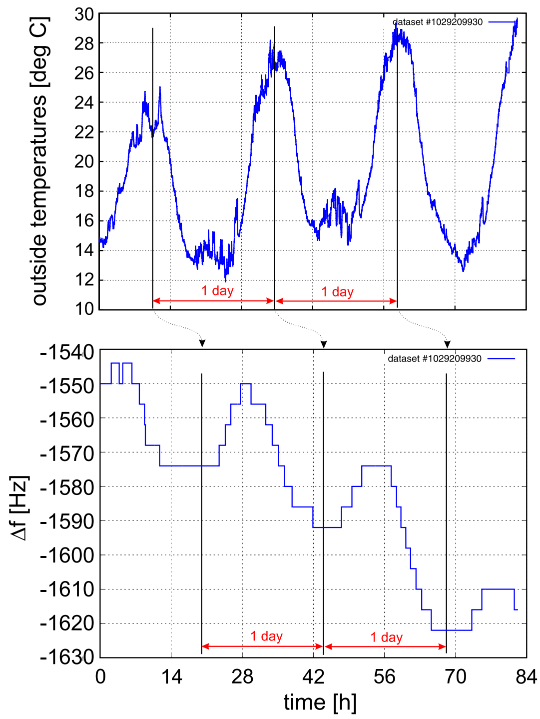


Figure 4: Correlation between the outside air temperature and RF frequency changes during the 3 day user run. With some thermal delay temperature maxima correspond to frequency minima.

The variation of the orbit positions at the adjacent BPMs from ID **U24** over 3 days of top-up operation yields Gaussian distributions with $\sigma_x$ = 1.0 $\mu$m and $\sigma_y$ = 0.7 $\mu$m for both upstream and downstream BPMs. Those fluctuations translate into an angular stability of $\sigma_\Theta$(horizontal) = 0.3 $\mu$rad and $\sigma_\Theta$(vertical) = 0.2 $\mu$rad at the ID.

## 6 X-BPM RESULTS

In the middle of August 2002 the first four blade X-BPM [5] at SLS was commissioned at the protein crystallography beam-line (ID **U24**). A data set taken during a two days run on August, 10-11, shows daily photon beam position drifts of 2.3 $\mu$m and 1.7 $\mu$m horizontally and vertically (Fig. 5). Their source could not yet be identified and thus needs further investigation. However, the residual X-BPM RMS values of $\sigma_x$ = 2.7 $\mu$m and $\sigma_y$ = 1.5 $\mu$m are in good agreement with the estimated position and angle fluctuations at the ID calculated from the up- and downstream RF BPMs when considering the lever arm of ≈9 m from the radiation source point to the X-BPM and the beta functions at the corresponding locations.

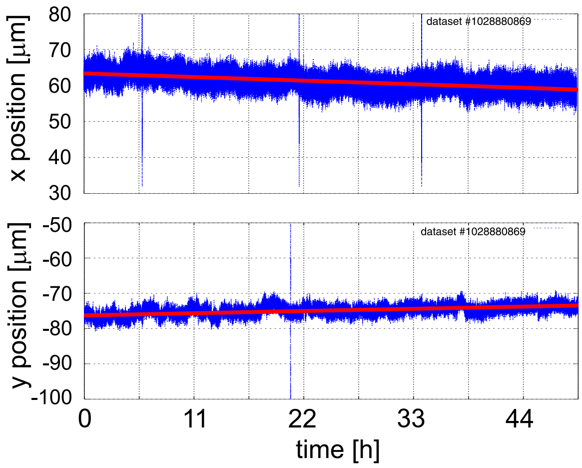


Figure 5: Horizontal and vertical photon beam position at the first X-BPM at the protein crystallography beam-line. The straight lines indicate a daily drift of 2.3 $\mu$m horizontally and 1.7 $\mu$m vertically.

## 7 CONCLUSION

The goal of achieving short and long term orbit stabilities of less than 1 $\mu$m and angular stabilities of below 1 $\mu$rad at the location of ID **U24** has been reached. The energy is kept constant within dE/E $\approx 2 \cdot 10^{-5}$ by the SOFB. It compensates for slow orbit deviations up to frequencies of 0.2 Hz. The operation of the "high level" slow orbit feedback provides valuable information for the implementation of "low level" fast orbit feedback.

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