ORBIT STABILITY AT THE SLS

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The SLS has been designed to allow for excellent orbit stability over a large frequency range covering ten orders of magnitude (10 $^{-8}$–10 ^{2} Hz). This is accomplished by the careful design of all accelerator components including girders, magnets and power supplies, by operating in "top-up" mode, which guarantees a constant thermal load, and by active stabilization by means of a fast orbit feedback. The latter was successfully commissioned at the start of 2003 and has been running routinely during user operation close to design performance since November 2003. The extraordinarily hot summer has been a challenge for the cooling system of the SLS revealing its capacity limitations. In particular, the temporary change of the tunnel temperature had a significant influence on the medium and long term orbit stability.

SLOW AND FAST ORBIT FEEDBACK

It is vital for a successful user operation to reproduce and stabilize a previously established reference orbit within 1/10th of the vertical beam size corresponding to $\approx$ 1 μm at the location of the insertion devices. As a consequence, the digital BPM [1] and corrector hardware [2] have been designed in order to allow for the implementation of a Fast Orbit Feedback (FOFB) that is able to suppress residual orbit oscillations up to $\approx$ 100 Hz [3]. The FOFB imposes tight constraints on the capabilities and reliability of the involved subsystems since the feedback loop runs at a sampling rate of 4 kHz on the DSP level of the BPM hardware. In order to gain experience with the various subsystems, a Slow Orbit Feedback (SOFB) with much relaxed requirements ($<$ 3 Hz correction rate) was implemented in 2001 [5] which communicates with the underlying hardware components through the EPICS based control system [4].

mode	horizontal		vertical	
	x_{rms}	xk_{rms}	y_{rms}	yk_{rms}
SOFB(250)	1.0 μm	410 nrad	750 nm	230 nrad
SOFB(co)	1.0 μm	120 nrad	300 nm	80 nrad
FOFB	**0.7 μm**	**17 nrad**	**60 nm**	**15 nrad**

Tab. 1: Temporal mean of the RMS orbit deviation from the BPM reference settings x_{rms} / y_{rms} and the corresponding RMS corrector strength xk_{rms} / yk_{rms} in 2003 for three different operation modes taken from Fig. 1.

The year 2003 turned out to be the transition period from SOFB to FOFB operation. In July 2003 the "closed orbit" BPM system mode with a bandwidth of 0.2–2 kHz at 0.8 μm resolution (for SOFB averaged over 300 ms) became operational and replaced the 3 Hz triggered "250ms ramped" mode with 16 kHz bandwidth at 3 μm resolution (for SOFB averaged over 6 ms). Fig. 1 depicts the RMS orbit deviation from the BPM reference settings for both modes. It can be seen that the "closed orbit" mode reduced the residual noise y_{rms} within the vertical SOFB feedback loop by more than a factor of two (see also Tab. 1). The FOFB has been in operation since November 2003 [6]. For the frequency range 0–1.5 Hz which covers a significant part of the orbit noise relevant for users a suppression down to y_{rms} = 60 nm RMS was achieved. Furthermore the RMS kick k_{rms} applied was close to the corrector power supply resolution specification of 15 ppm in amplitude corresponding to 13 (11) nrad in the vertical (horizontal)

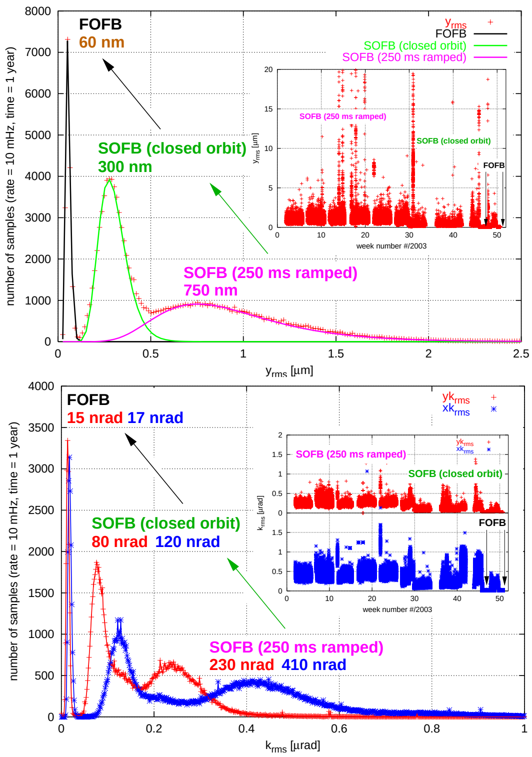

Fig. 1: Histograms of the vertical RMS orbit deviation from the BPM reference settings y_{rms} and the vertical / horizontal RMS corrector strength yk_{rms} / xk_{rms} in 2003. The presented stroboscopic (1 mHz) data are bandwidth limited at 1.5 Hz. In the upper plot the data are fitted by a superposition of three log-normal distributions corresponding to the different operation modes. Gaps in the data mark shutdown periods.

plane [3]. In fact the digital power supply controllers can resolve 1 ppm steps [2]. Infrequent fast orbit transients mainly induced by RF frequency changes and rapid gap changes visible in Fig. 1 are ruled out by the FOFB presently suppressing orbit fluctuations up to $\approx$ 60 Hz. Please refer to [6] for a detailed analysis of orbit noise suppression at higher frequencies.

In the horizontal plane the x_{rms} value is dominated (see Tab. 1) by the contribution of off-energy orbit deviations which are corrected by means of the RF frequency whenever the modulus of the estimated energy deviation dP/P exceeds $\approx 2{\cdot}10^{-5}$ resulting in a maximum $x_{rms} \approx 1.7$ μm. Since the localized FOFB does not presently allow the use of all BPMs for the determination of dP/P on the DSP level at 4 kHz, residual off-energy orbits are picked up by the correctors within the FOFB loop. This in return leads to a gradual build-up of a dispersion related corrector pattern with a nonzero mean xk_{mean}. In order to avoid the build-up, this pattern, which can be characterized by an energy deviation dPk/P, is periodically (every $\approx$ 2 sec) substracted from the actual corrector setting. Fig. 2 depicts the result of this normalization process over 2 weeks of FOFB operation. xk_{mean} is stabilized to 360 nrad RMS corresponding to a dPk/P (dP/P) variation of $4{\cdot}10^{-6}$ ($1.5{\cdot}10^{-5}$) for a dP/P correction threshold of $\approx 2{\cdot}10^{-5}$.

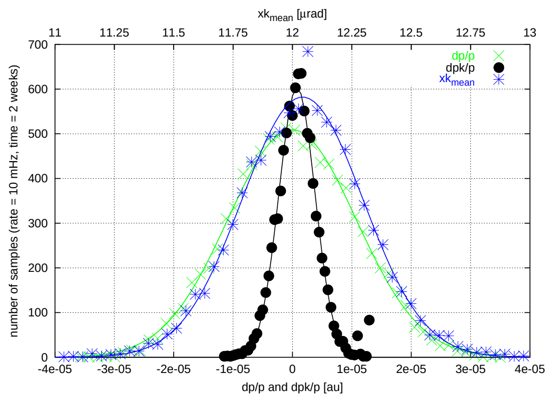

Fig. 2: Stabilization of the mean value of the horizontal corrector pattern xk_{mean} = 12 μrad to 360 nrad RMS corresponding to a dPk/P (dP/P) variation of $4{\cdot}10^{-6}$ ($1.5{\cdot}10^{-5}$) for a dP/P correction threshold of $\approx 2{\cdot}10^{-5}$ over 2 weeks of FOFB operation.

X-BPM FEEDBACK

The presented excellent stability within the FOFB loop confines the closed orbit to the reference positions of the involved BPMs to within less than 1 μm. Unfortunately the reference of these BPMs is not static. Separate BPMs (e.g. "Tune BPM") and X-BPMs are very well suited to independently judge the resulting orbit stability at the photon source points. The analysis of these data revealed a systematic oscillation of the photon beam with slowly changing periodicity ($\approx$ 1 h) [7]. The effect is likely induced by air temperature variations at the location of the four channel digital BPM system electronics in the technical gallery which lead to a change of the FOFB reference and thus the orbit on a sub-micron level. In order to tackle the problem a first slow ($\approx$ 0.5 Hz) feedback loop has been implemented for the single X-BPM of the PX beamline located at a distance of $\approx$ 8.6 m from the in-vacuum undulator **U24**. The feedback, which is only activated for gaps $<$ 8 mm in order to avoid any photon beam profile dependence

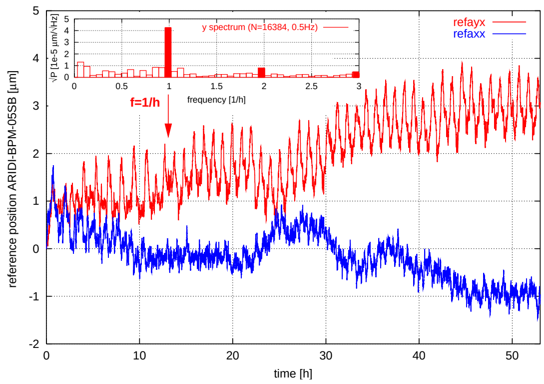

Fig. 3: Variation of the horizontal ("refaxx") and vertical ("refayx") FOFB reference position of the BPM upstream of **U24** over 53 h of FOFB operation. The amplification factors for the corresponding position change at the X-BPM are $a_x \approx 2$ and $a_y \approx 6$. The FFT reveals a vertical oscillation with a fundamental frequency of ≈ 1 h^{-1}.

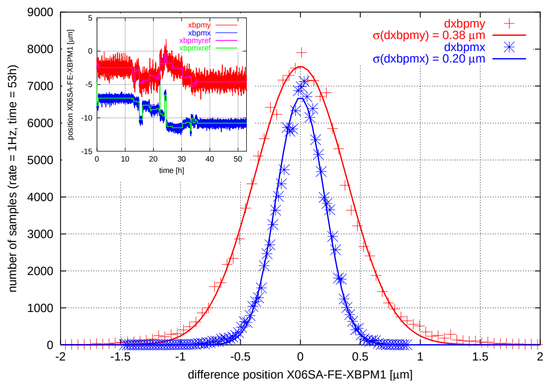

Fig. 4: Horizontal ("dxbpmx") and vertical ("dxbpmy") deviation of the photon beam from the X-BPM reference position with active FOFB and X-BPM feedback. The reference is newly determined whenever the gap of **U24** changes (see inset). The resulting Gaussian distributions exhibit very small 2nd moments of σ_x = 0.2 μm and σ_y = 0.4 μm for frequencies $<$ 0.5 Hz.

of the X-BPM readings, translates the photon beam position change to a pure angle variation of the orbit at the source point and changes the reference of the adjacent BPMs in the FOFB loop accordingly. Fig. 3 shows the variation of the horizontal and vertical reference of the upstream BPM over 53 h of FOFB operation after a beam dump. The FFT reveals a vertical oscillation with a fundamental frequency of ≈ 1 h^{-1} and an amplitude of $\approx$ 0.7 μm which translates to a fluctuation of $\approx$ 4 μm at the X-BPM taking into account the amplification factor $a_y \approx 6$ ($a_x \approx 2$). In the horizontal plane the oscillation ($\approx$ 0.5 μm) is considerably less pronounced ($\approx$ 1.0 μm at the X-BPM). Fig. 4 visualizes the deviation of the photon beam from the X-BPM reference position which is newly determined whenever the gap changes. The resulting Gaussian distributions exhibit very small 2nd moments of σ_x = 0.2 μm and σ_y = 0.4 μm. Thus the photon beam shows sub-micron stability at the X-BPM for frequencies $<$ 0.5 Hz (sampling frequency 1 Hz). First measurements [6] indicate that this also holds for higher frequencies, but at present the synchronous readout of the X-BPM blades is limited to $<$ 10 Hz.

MEDIUM AND LONG TERM STABILITY

The "top-up" operation mode and the temperature regulation especially in the ring tunnel represent key elements to achieve high medium and long term stability at the SLS [8]. The summer 2003 which exhibited temperatures of more then 40 °C challenged the cooling system of the SLS. Starting from the beginning of June (week #22) the tunnel temperature of $\approx$ 24.5 °C could no longer be maintained to within $\pm$0.2 °C (see Fig. 5). At the same time the hall temperature was increased by 1.5 °C in order to reduce the necessary cooling power. In week #32 the tunnel temperature was raised to 27.5 °C which resulted in a circumference increase of the storage ring $>$ 1 mm (see Fig. 6). As a result of these temperature variations the horizontal photon beam position at the X-BPM of the PX beamline changed by $\approx$ 150 μm over a period of 6 weeks. A detailed analysis of the situation following week #36 remains to be carried out. Fig. 6 summarizes the circumference changes over 2 years of SLS operation. In addition to a clear correlation with outside temperature a systematic drift of $\approx$ 1 mm/y can be observed. The box tagged "tunnel" denotes the time period during which the tunnel temperature was increased by 3 °C.

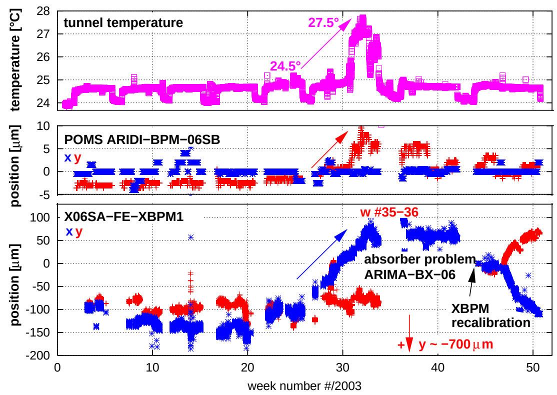

Fig. 5: Storage ring tunnel temperature, X-BPM reading at the PX beamline and POMS [9] reading at the downstream BPM adjacent to the in-vacuum undulator **U24** in 2003. During the summer the horizontal photon beam position at the X-BPM of the PX beamline changed by $\approx$ 150 μm over a period of 6 weeks.

SUMMARY

After 2 years of SOFB operation the FOFB became operational which suppresses orbit fluctuations up to $\approx$ 60 Hz. Slow feedbacks on X-BPM readings can compensate for slow thermal drifts without interfering with the FOFB, by changing the FOFB reference resulting in sub-micron stability at the location of the X-BPM. The hall and tunnel temperature have to be kept within specification, in order to maintain the desired orbit stability.

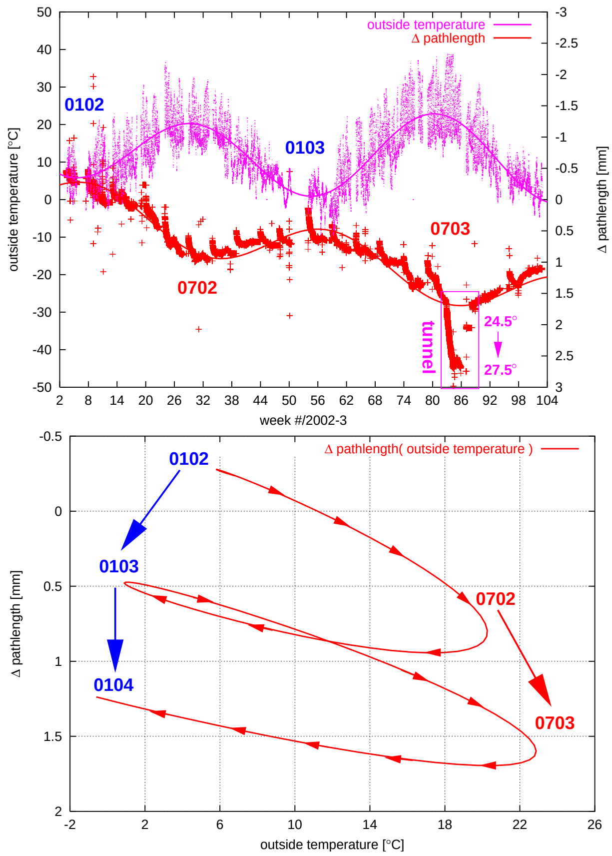

Fig. 6: Summary of circumference changes over 2 years of SLS operation. A systematic drift of $\approx$ 1 mm/y is visible leading to the "spiral" like shape of the lower graph depicting the circumference change vs. outside temperature.

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