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ORBIT FEEDBACK SYSTEM IN SOLARIS SYNCHROTRON FINAL STEP IMPLEMENTATION AND FIRST MEASUREMENTS

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Abstract

SOLARIS, a third-generation synchrotron radiation source in Kraków, Poland, is dedicated to providing high-brilliance X-ray beam for various scientific disciplines. The successful operation of a synchrotron radiation facility heavily relies on precise control of the electron beam orbit within the storage ring. Orbit deviations, even on a small scale, can adversely affect beam quality, leading to decreased performance and efficiency of experimental setups. To mitigate these effects, an Orbit Feedback System is essential, providing correction of orbit deviations. In this study, we introduce an enhanced Orbit Feedback System that integrates both fast and slow orbit correction mechanisms, along with RF drift compensation. The system utilizes advanced feedback algorithms to compute corrective actions for the actuators, which include both fast and slow correction magnets, based on real-time beam position measurements. We also present the initial measurements and tests of the system, demonstrating its effectiveness and capabilities.

HARDWARE

The SOLARIS storage ring consists of 12 double-bend achromat (DBA) cells [1]. The Slow Orbit Feedback (SOFB) system stabilizes the beam using 36 beam position monitors (BPMs) and 72 steering magnets, which operate across both the horizontal and vertical planes. The system features a ±12 A range, enabling significant corrections at a lower frequency of 1 Hz. The arrangement of the particular magnets, namely: dipoles (DIP), combined quadrupoles with sextupole content (SQFI and SQFo), defocusing sextupoles(SDO and SDI), correcting sextupoles with additional coils for slow correctors (SCi and SCo), fast correctors (FOFB), in DBA cell is illustrated in Fig.1.

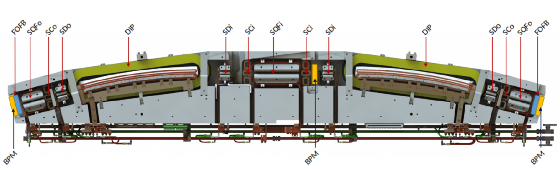

Figure 1: Placement of magnets inside DBA cell.

The newly implemented Fast Orbit Feedback (FOFB) system, which utilizes the same BPMs, employs 24 fast steering dipoles positioned at the beginning and end of each section to apply corrections. This system allows for a significantly faster response to external disturbances, operating at a repetition rate of 10 kHz. A detailed comparison of key parameters for both correction systems is provided in Table 1 below.

Table 1: Comparison of SOFB and FOFB

Correction method	FOFB	SOFB
Speed of correction [Hz]	10 000	1
Max. current on CM [A]	2	12
Number of used CMs	24	36
Number of used BPMs	36	36

FOFB DEPLOYMENT

The critical milestone was the successful launch of the Fast Orbit Feedback (FOFB) system. This deployment was built on the foundation of previously developed software and design principles [2, 3], which provided the framework for controlling the FOFB and included the capability to measure the response matrix. Following the measurement, the matrix required specific modifications to be compatible with the GDX modules in the Liberas, which are responsible for calculating and applying settings to the fast correctors. This process involved bit-cutting and matrix operations. Bit-cutting was particularly crucial, as it allowed the FPGA in the GDX module to achieve the necessary speed for executing the mathematical computations essential to the system's real-time performance.

SOFB Improvement

To ensure seamless cooperation between the SOFB and FOFB systems, the SOFB has been upgraded to respond to events triggered by the Liberas. This upgrade includes the implementation of independent correction for both axes, the integration of RF correction—previously managed by a separate script—into the system, an increase in operating frequency, and real-time updates of the golden orbit for FOFB operation.

FOFB Tuning

The subsequent objective was to fine-tune the FOFB system to ensure optimal performance. Achieving this required careful adjustment of the system's components, particularly the proportional (Kp) and integral (Ki) gains within the feedback loop's integrator. These parameters play a crucial role in dictating the system's responsiveness and stability, directly impacting the precision with which the FOFB can correct orbit deviations.

The tuning process involved systematically introducing controlled disturbances into the system and carefully monitoring its response. By analyzing how the FOFB system

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reacted to these perturbations, adjustments were made to the Kp and Ki values to refine the balance between quick corrective action and overall system stability.

Figures 2 and 3 illustrate the system's response under various tuning conditions, highlighting the impact of different Kp and Ki settings. The goal was to minimize residual oscillations and ensure that the system could swiftly return to the desired orbit with minimal overshoot. This iterative process of disturbance introduction and parameter adjustment was essential in achieving a finely tuned FOFB system, capable of maintaining high beam stability even in the presence of external disturbances.

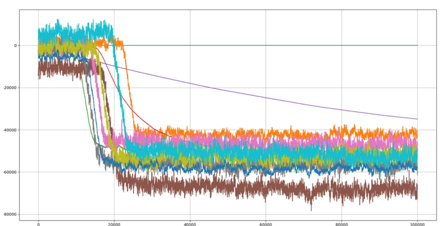

Figure 2: Signal from fast corrector magnet showing FOFB reaction on external disturbance for various Kp.

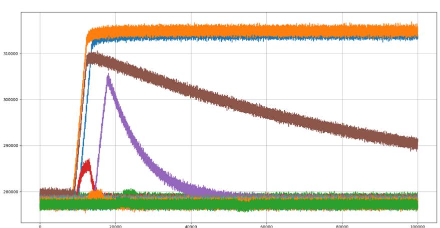

Figure 3: Signal from BPM showing FOFB reaction on external disturbance for various Kp.

When evaluating the response of the correctors, both reaction speed and noise levels were critical factors. The optimal orbit correction was characterized by the system's ability to effectively neutralize disturbances, resulting in minimal to no detectable impact on the beam's stability. This was achieved through the precise compensation provided by the FOFB correction system, which responds within fractions of a millisecond. Notably, the system does not require a derivative term (Kd) typically found in PID controllers. This is due to the natural damping of electron oscillations, which mitigates the need for additional damping through the feedback loop. As illustrated in Fig. 4, the inherent damping characteristics of the system ensure that oscillations induced by the pinger magnet are quickly reduced, allowing the FOFB system to maintain a stable orbit without the complexity of implementing a derivative component. This streamlined approach enhances both the speed and accuracy of the orbit correction process, ensuring consistent beam stability.

Ultimately, we discovered that the integrative Ki factor could be omitted, allowing us to rely solely on the proportional Kp term. This simplification was possible because the SOFB system effectively assumes the role that the Ki factor

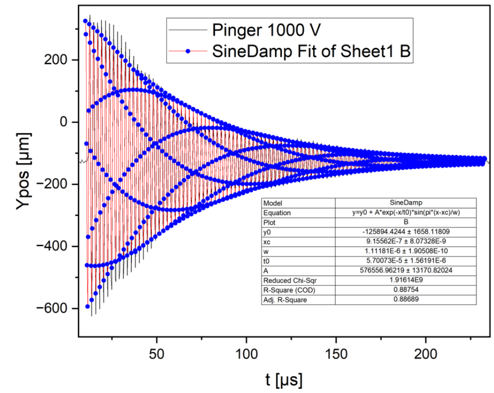

Figure 4: Natural dumping of electrons oscillations.

would typically perform, handling long-term drift correction and ensuring overall system stability.

This careful tuning process not only optimized the FOFB's performance but also enhanced the overall reliability and efficiency of the orbit correction system, ensuring that the storage ring operates at peak precision, delivering consistent and high-quality results for users.

Integrating Slow and Fast Orbit Feedback

During the simultaneous operation of both correction systems, we encountered an issue where the fast correctors gradually approached their maximum values, rather than maintaining values close to zero and only reacting to disturbances. This behavior is a well-documented challenge arising from the interaction between the Slow Orbit Feedback (SOFB) and Fast Orbit Feedback (FOFB) systems [4]. To resolve this issue, an offloading procedure [5] was applied, as described by the following equation:

$$\Delta SCM = R_S^{-1}\Delta BPM + R_S^{-1}R_F\Delta FCM, \qquad (1)$$

where ΔSCM is SOFB correctors change, R_S^{-1} is inverse SOFB response matrix, ΔBPM is difference between measured and golden orbit, R_F is FOFB response matrix and ΔFCM is FOFB correctors change calculated for ΔBPM.

The Slow Orbit Feedback (SOFB) algorithm adjusts the settings for the slow correctors based on the response matrix provided by the Fast Orbit Feedback (FOFB) system. Essentially, SOFB mimics the adjustments that FOFB would make to the fast correctors at any given time step and applies these changes to the slow correctors. This approach effectively slowed the rate at which the fast correctors approached saturation, but it did not completely resolve the issue for the 12-hour continuous operation between the two daily injections.

To address this, we introduced a deadband mechanism. Specifically, if the adjustments to the correctors controlled by SOFB were less than 0.01 A, those changes were disregarded. This modification proved successful, enabling both correction systems to operate continuously throughout the daily cycle.

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FOFB PERFORMANCE

The final assessment of the correction system's effectiveness is conducted by analyzing the orbit's response to changes in the insertion devices (IDs) gap and phase. Figure 5 clearly demonstrates the enhancement in orbit stability achieved with the Fast Orbit Feedback (FOFB) system.

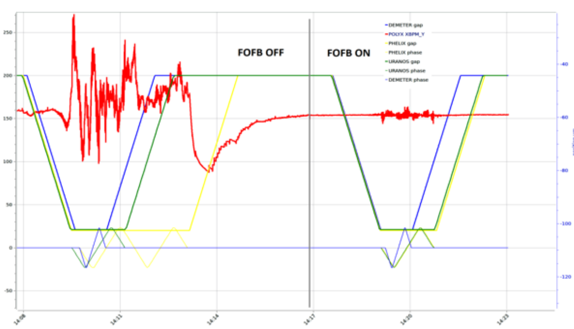

Figure 5: Impact of IDs movement on photon beam.

Without FOFB correction, the photon beam, as measured by the X-ray Beam Position Monitor (XBPM), exhibits oscillations up to 50 microns during ID adjustments. However, with FOFB active, these oscillations are reduced to just a few microns. Additionally, Figure 6 shows a noticeable reduction in the average standard deviation of the beam position across both planes when FOFB is operational. This confirms that FOFB significantly improves the stability of the orbit, ensuring more precise control during dynamic changes.

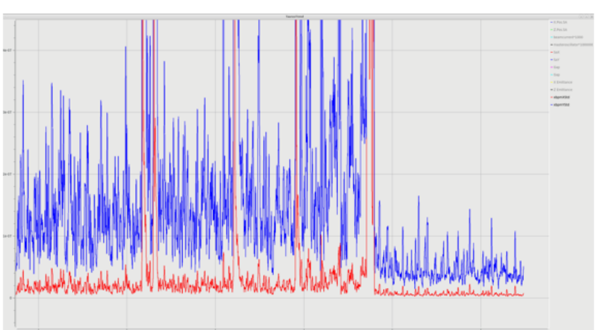

Figure 6: Reduction of horizontal and vertical beam oscillations.

This enhancement allows the insertion devices to operate freely without causing disturbances to the electron beam, which translates into improved measurement capabilities at the end-station beamlines. Subsequent tests demonstrated that the speed of ID gap and phase adjustments could be increased while maintaining a stable orbit. Prior to the implementation of the Fast Orbit Feedback (FOFB) system, feedforward table scans for correctors on the ID jaws were required every few months to minimize beam disturbances. With the new FOFB system, this correction process has become significantly more flexible, reducing the need for such frequent scans and thus conserving valuable machine time.

To further validate the FOFB system's performance, we utilized fast acquisition of signals from Beam Position Monitors (BPMs). By applying Fast Fourier Transform (FFT) analysis, we compared the spectral density and cumulative spectral power with and without FOFB active. The results of these comparisons are illustrated in Figs. 7, 8, 9, and 10.

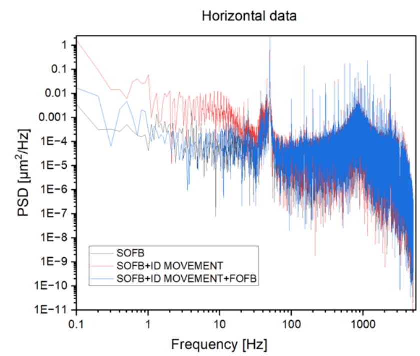

Figure 7: Spectral density from BPM for horizontal plane.

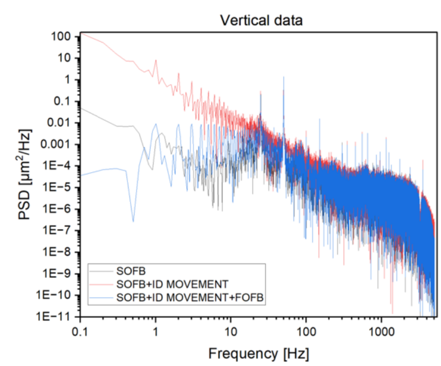

Figure 8: Spectral density from BPM for vertical plane.

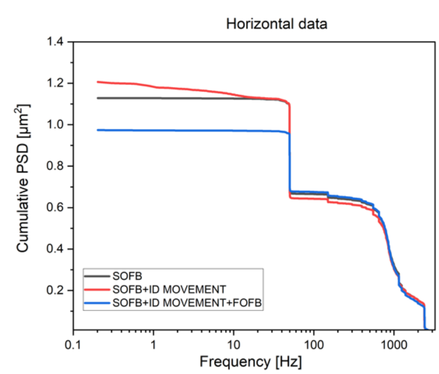

Figure 9: Cumulative power spectral density from BPM obtained horizontal plane.

CONCLUSION

The Fast Orbit Feedback (FOFB) system has been successfully developed and implemented, demonstrating significant advancements in beam stability. The response matrices were

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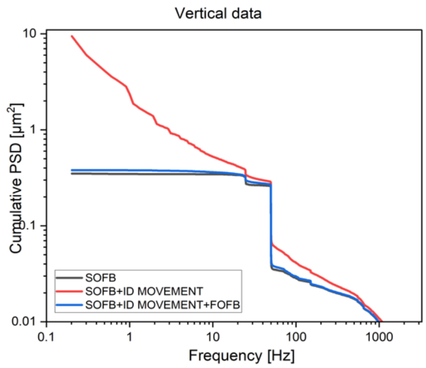

Figure 10: Cumulative power spectral density from BPM obtained vertical plane.

accurately transformed and transmitted to the GDX modules in the Liberas, ensuring precise control over the fast correctors. Through careful tuning of the proportional-integral parameters, the system has achieved remarkable stability improvements, with electron beam positioning now maintained at sub-micron precision.

Furthermore, the Slow Orbit Feedback (SOFB) system underwent a comprehensive redesign, resulting in more than a tenfold increase in its operational speed. A refined offloading procedure was introduced to effectively resolve the previously encountered conflicts between the SOFB and FOFB systems. This optimization has greatly enhanced the overall performance, ensuring minimal impact of insertion device (ID) movements on the electron beam's position.

Overall, the integration of the FOFB and SOFB systems has led to a highly stable electron orbit, significantly reducing disturbances and achieving superior precision in beam stability and control.

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