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IMPLEMENTATION AND INITIAL OPERATION OF THE BUNCH-BY-BUNCH FEEDBACK SYSTEM AT SOLARIS

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Abstract

The SOLARIS synchrotron light source has commissioned a transverse bunch-by-bunch feedback system designed to suppress coupled-bunch instabilities and serve as a diagnostic tool for accelerator studies. The system was successfully installed and integrated with the existing infrastructure, including timing and control systems. After a series of commissioning steps, it was brought into operation and tested under standard user conditions. Although routine instability suppression is not currently needed during regular operation, the system has been effectively used in dedicated machine studies. It enabled detailed observation of transverse bunch motion, instability spectra, and individual bunch tune measurements. The system also played a crucial role in advanced measurements such as LOCO experiments with selectively emptied buckets and tune shift studies under varying machine conditions. The bunch-by-bunch feedback system significantly enhances the diagnostic and research capabilities at SOLARIS and provides a solid foundation for potential future applications in active beam stabilization.

INTRODUCTION

The Solaris synchrotron, located in Kraków, Poland, is a national research facility providing high-quality synchrotron radiation for a wide range of scientific applications [1]. In line with ongoing development, the implementation of a transverse bunch-by-bunch feedback (BBFB) system marks a significant milestone in enhancing beam stability and control. This paper presents the process of system integration, initial operational results, and the impact of the BBFB system on beam dynamics. The results demonstrate its effectiveness in improving machine performance and its potential for supporting future upgrades, including the installation of new insertion devices planned for 2026 and 2027.

FEEDBACK OVERVIEW

The first transverse bunch-by-bunch feedback tests at the Solaris synchrotron were conducted in May 2023, in collaboration with Dimtel Inc. [2]. Following successful trials, the system was installed, commissioned, and integrated into routine user operation in December 2024. The setup includes a dedicated BPM and a stripline kicker, a Dimtel analog front-end, and wideband high-power amplifiers. The commissioning of the bunch-by-bunch feedback system marked a significant milestone, occurring nearly a decade after Solaris began operation and reached its design parameters, including the nominal beam current of 500 mA.

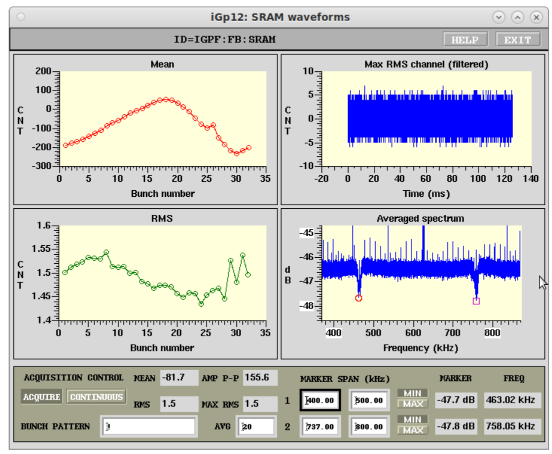

Figure 1: SRAM waveforms recorded during standard operation with closed feedback loop, full filling pattern, and a beam current of 400 mA.

Table 1: The Operating Parameters of the SOLARIS Storage Ring

Parameter	**Value**
Beam energy	1.5 GeV
Filling pattern	29 bunches with 10 ns spacing + 3 empty buckets
Chromaticity	+1 / +1
Nominal beam current	500 mA
Beam current during operation	420 mA decaying to ~220 mA/ 12 h
Average vacuum pressure	$\sim 1 \times 10^{-9}$ mbar

Figure 1 presents SRAM waveforms recorded during standard operation of the Solaris storage ring, with the bunch-by-bunch feedback loop closed, a full filling pattern, and a beam current of 400 mA. The signals confirm stable beam conditions and proper synchronization of the feedback system. These waveforms serve as a reference for evaluating system performance and are routinely used for diagnostic purposes, particularly when tuning feedback parameters or investigating beam instabilities.Beyond its primary role in

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beam stabilization, the system has been adopted as a versatile diagnostic tool. It has proven particularly useful for studies involving non-uniform fill patterns (e.g., LOCO measurements), for observing higher-order mode excitations, and for tune tracking during beam current decay.

Typical operating conditions of the Solaris storage ring [3] are summarized in Table 1.

TUNE MEASUREMENT

One of the most valuable functionalities of the Bunch-by-Bunch Feedback system is its ability to measure the tune using the notch in the bunch spectrum. This technique not only allows for continuous tracking of tune shifts but also enables monitoring of their evolution during the beam energy ramp. In particular, resolving the tune shift during acceleration from 540 MeV to 1.5 GeV has provided new insights into beam dynamics in this regime.

As shown in Fig. 2, the notch marker occasionally "jumps" between the actual betatron tune and the synchro-betatron sidebands. This makes the tune difficult to determine unambiguously, especially at high currents (above 350 mA). To overcome this limitation, a single-bunch measurement method is being progressively implemented. In this scheme, feedback is disabled for a dedicated bunch, which is then excited with a swept sinusoidal signal at low amplitude. The betatron tune can subsequently be measured with high precision from the single-bunch spectrum, as illustrated by the green line in Fig. 2. Because the excitation introduces a slight orbit perturbation, the selected bunch gradually accumulates a higher charge than the rest of the train, leading to a tune different from that of the other bunches. To mitigate this effect, the system is designed to periodically switch the excited bunch, thereby ensuring that the average beam lifetime remains unaffected.

TUNE SHIFT DURING ENERGY RAMPING

The normal operation of the Solaris synchrotron involves ramping the beam energy from 540 MeV at injection to the operational energy of 1.5 GeV. A deeper understanding of the dynamic processes affecting the beam during this phase allows for the implementation of necessary adjustments and improved control over beam parameters. One of the key parameters that can be monitored is the tune shift, including the identification of resonance orders encountered during the ramp and their impact on beam dynamics.

Initially, tune measurements were carried out using beam excitation and the turn-by-turn (TBT) method. After the commissioning of the BBFB system, it became possible to monitor tune evolution during energy ramping with minimal shift gain, which does not influence the tune itself. Figure 3 presents a comparative measurement performed in 2025, showing the results obtained from the BBBF system alongside those from the TBT method. The measurement was conducted using a full filling pattern, at low beam currents of 23 mA for the TBT method and 32 mA for the BBFB system. Chromaticities were set to the measured values of

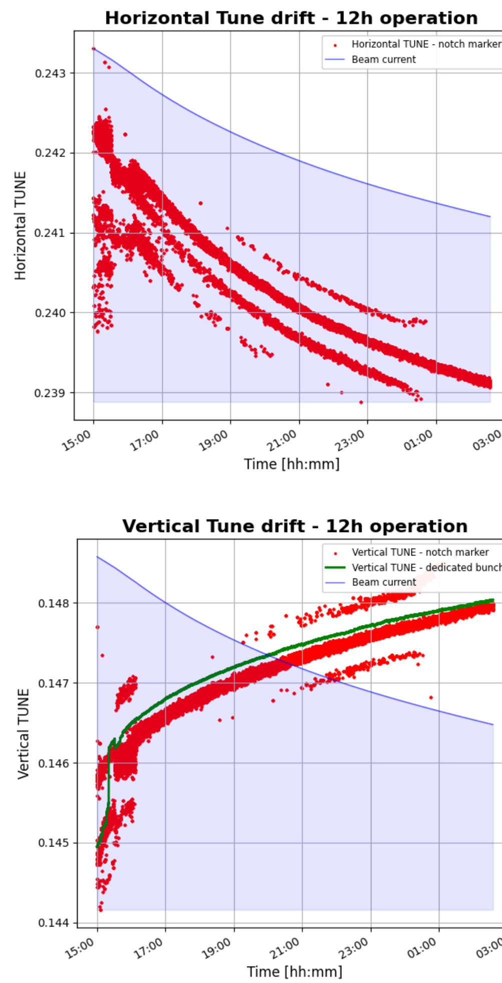

Figure 2: Tune drift observed with the BBFB system. Top canvas: horizontal-plane drift. Bottom canvas: comparison of vertical-plane drift obtained from notch marker tracking and dedicated bunch excitation.

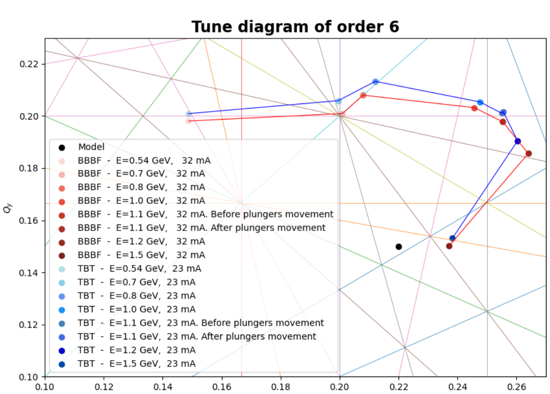

Figure 3: Tune drift comparison during energy ramping, as measured by the BBFB system and the TBT method.

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+1.19 (horizontal) and +1.15 (vertical), and all insertion devices (IDs) were kept open to avoid introducing additional variables. At the minimum energy of 540 MeV, the tune values were Qy/Qx = 0.195/0.15. During the energy ramp, the tune passed through regions associated with fourth- and fifth-order resonances, without any observable impact on beam stability. At the maximum energy of 1.5 GeV, the tune approached the design values of Qy/Qx = 0.15/0.21, reaching measured values of 0.15/0.24.

BUNCH CLEANING

Another valuable functionality of the bunch-by-bunch system is bunch cleaning. It employs a stripline kicker with 150 mm electrodes and two high-power 100 W amplifiers. Initial tests revealed that the kicker power was insufficient to effectively remove bunches from the beam train at an energy of 1.5 GeV. Ultimately, efficient bunch removal was achieved only up to a beam energy of 1 GeV. For tests involving different filling patterns, bunch cleaning was performed at 540 MeV, with no significant differences observed during the energy ramp.

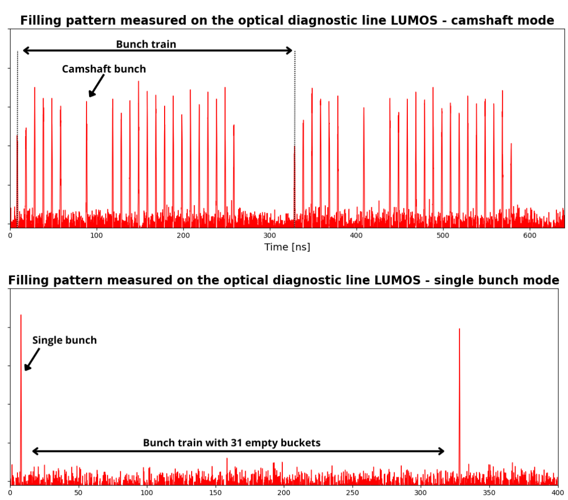

Figure 4: Filling patterns for camshaft and single bunch modes measured using LUMOS diagnostic beamline [4].

Figure 4 illustrates successful operation in both the camshaft mode (a bunch with a two-bucket gap before and after) and the single-bunch mode with a beam current of 16 mA. These two specific modes—camshaft and single-bunch—were successfully utilized for lifetime measurements under various configurations, including single-bunch excitation [5].

VERTICAL EMITTANCE GROWTH EFFECT

An increase in vertical emittance and beam lifetime was observed when the bunch-by-bunch feedback gain was set excessively high. The measurements were performed under standard operating conditions: full filling pattern, beam current of 350 mA, chromaticities of +1.19 (horizontal) and +1.15 (vertical), and with all insertion devices turned off.

As shown in Fig. 5, the beam lifetime nearly doubled—from 700 minutes to over 1300 minutes—at the cost of vertical emittance growth from 9 nm to 12.8 nm. This result enabled the establishment of a compromise between the negative impact of feedback on beam quality, as perceived by the beamlines, and the stabilizing effect provided by the feedback system.

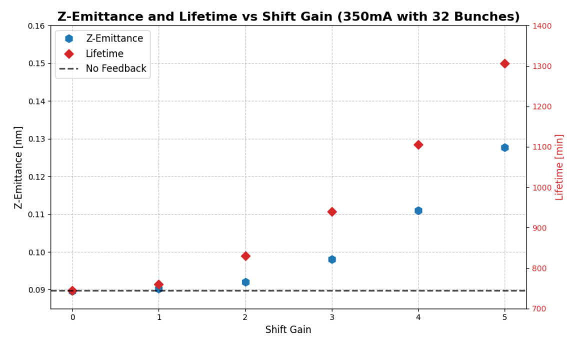

Figure 5: Dependence of vertical emittance growth on BBFB shift gain.

CONCLUSIONS AND FUTURE PLANS

Initial tests and a broad range of measurements have demonstrated the utility of the BBFB system at the Solaris synchrotron. The collected data have not only enabled a more detailed characterization of the machine's performance—particularly during sensitive operational phases such as energy ramping—but have also provided valuable insights for comparative analyses following modifications to the accelerator structure. The planned installation of new insertion devices in 2026 and 2027 will offer a compelling case study of their impact on tune shifts and the generation of higher-order resonances.

The successful and controllable bunch cleaning functionality enables operation in various modes (camshaft and single-bunch), opening new possibilities not only for machine parameter measurements but also for advanced experiments at the beamlines. In the future, further optimization of tune tracking through dedicated bunch excitation is expected to allow more precise determination of tune settings during standard operation.

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