TUNE COMPENSATION FOR INSERTION DEVICES MOTION AT THE SOLARIS STORAGE RING

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Abstract

Precise control of betatron tune is essential for maintaining beam stability in modern synchrotron light sources. At the SOLARIS storage ring, undulator gap and phase changes present a dominant source of tune perturbations. This study presents a method for local tune compensation during the gap and phase motion of APPLE II type undulator, installed upstream of a dedicated beamline.

The approach, seen in other light sources, employs a tune-feedback system based on two local quadrupoles and two global magnet families driven by a feed-forward table generated from a systematic scan of the undulator parameters (gap, phase) and the corresponding tune shifts. Prior to table generation, the magnets' response matrices for both tune planes were independently obtained.

INTRODUCTION

The SOLARIS synchrotron operates at 1.5 GeV and provides light to seven independent beamlines. Three of them are using APPLE II type undulators for producing linear, circular, or elliptical polarization of high-intensity radiation [1]. Such polarization, particularly that generated via phase shift, induces changes in beam properties, which can affect the stability of experimental conditions. Maintaining small tune variations while preserving other beam parameters is contributing for synchrotron operation.

The current approach is using feed-forward table, for one APPLE II type undulator with the strongest influence on tune [2]. The method includes the betatron tune measurements by exciting coherent transverse oscillations with dipole kicker (horizontal) and pinger (vertical) magnets. Tunes are calculated from turn-by-turn BPM signals using the FFT analysis.

Next, response matrices were measured for the selected global magnet families, including two local quadrupole families positioned around the undulator:

- Defocusing Pole-Face Strips (PFS).
- Focusing quadrupoles (SQFO).

The proposed method ensures effective and reproducible mitigation of tune perturbations during undulator motion, enabling stable machine performance and improved beam quality at SOLARIS. The tune shift was then measured across all undulator gap and phase settings. Finally, using the SVD method, a look-up table was constructed, containing undulators settings and corresponding correcting magnets currents.

The table was tested in standard operation conditions with both Fast and Slow Orbit Correction Feedback system active. The results and step-by-step procedure are presented in the following sections. Also, a dedicated software was created to coordinate automated scans, response matrix acquisition, and real-time feed-forward correction.

METHODOLOGY

Response Matrices Creation

The response matrix consists of four columns corresponding to two local and two global quadrupole families, and two rows representing horizontal and vertical tune response.

The measurement was performed with the undulator in the open-gap configuration. Quadrupole currents were varied in steps of 0.05 A for focusing quadrupoles and 0.03 A for defocusing magnets, with ±10 steps around the nominal operational value. For each current setting, three tune measurements were recorded, and the median value was used for analysis. The tune was measured by exciting beam oscillations using kicker magnets with an excitation voltage of 60 V. The measurement results are presented in Fig. 1.

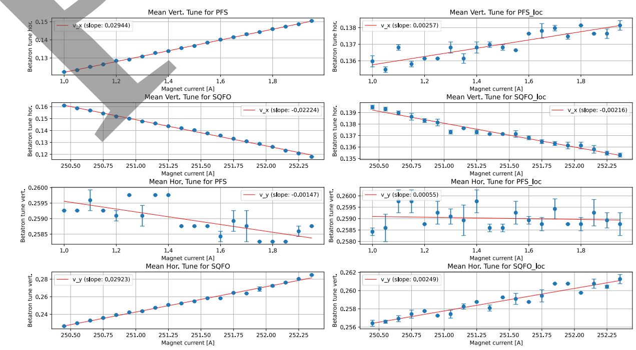

Figure 1: Betatron tune measurements with respect to quadrupole currents. Red line represents the linear fits used to derive response matrix coefficients.

After the measurements, the coefficients a of the linear model was determined from:

$$\nu = a \cdot I + b \,. \tag{1}$$

Where ν denotes fractional tune value and I the quadrupole current. The obtained coefficients are summarized in Table 1. Each measurement was repeated three times per magnet to estimate statistical uncertainty.

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Table 1: Tune Response Matrix with Standard Errors

Magnet type	$\frac{d\nu_y}{dI}$ **±SE [10^{-3} A^{-1}]**	$\frac{d\nu_x}{dI}$ **±SE [10^{-3} A^{-1}]**
PFS loc.	2.60 ± 0.04	0.9 ± 0.4
SQFO loc.	-2.21 ± 0.01	2.50 ± 0.05
PFS	29.3 ± 0.2	-1.5 ± 0.1
SQFO	-22.4 ± 0.1	29.5 ± 0.2

Furthermore, disturbance map of vertical and horizontal tune was measured for selected gap and phase values. The gap was varied from 40 mm to 30 mm in 2 mm steps, and from 30 mm to 20 mm in 1 mm steps. The phase was varied from −0.5° to +0.5°, with 0.025° steps in the central region and 0.0167° steps at the extremes. The selection of operating points was based on observed increasing tune sensitivity below approximately 30 mm gap and ±0.25° phase. At larger gap values and for higher horizontal polarization states, no significant tune variation was observed [2].

Three repeated measurements were performed for each gap–phase combination. The mean value and standard error were calculated, with the relative uncertainty remaining below 0.4%. In Fig. 2, the data points are shown with semi-transparent markers around the mean values, separately for horizontal and vertical tune as a function of gap and phase.

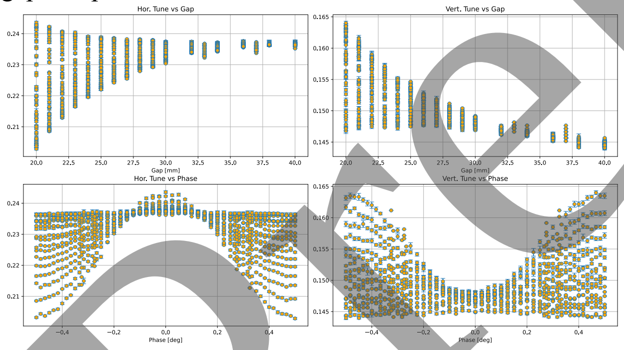

Figure 2: Mean tune response with standard error during undulator gap and phase variation.

Look-up Table Calculations

The tune correction table was calculated using a linear response matrix between tune variations and quadrupole current changes [3]. The correction vector was obtained using a weighted least-squares method based on singular value decomposition (SVD):

$$R = U\Sigma V^T. \qquad (2)$$

Small singular values below a chosen threshold, equal to 10^{-3}, were removed to improve numerical stability and reduce noise amplification. The final correction vector is given by:

$$\Delta I = V\Sigma^{-1}U^T\Delta\nu. \qquad (3)$$

This expression was applied to the response matrix at each undulator gap and phase configuration to generate the correction look-up table.

Operational limits were applied to quadrupole currents to avoid degradation of beam lifetime and to preserve machine performance.

The final correction was therefore obtained using a constrained weighted SVD solution, ensuring stable tune compensation while respecting beam dynamics constraints and hardware limits.

RESULTS

All measurements were performed at an operational beam current of 350–400 mA. The reference tune in the open-gap configuration is $\nu_x = 0.245$ and $\nu_y \approx 0.14$, which was used as the baseline for calculating relative tune variations reported in this study.

The measurement was performed to validate the applied correction and to visualize the results with (Fig. 3) and without (Fig. 4) applied correction. The undulator was moved from open-gap position to minimum gap, and measurements were taken with the correction system disabled and then enabled.

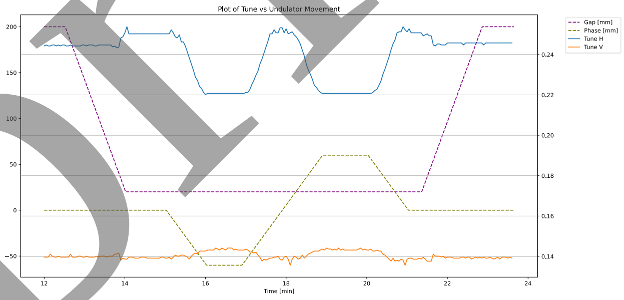

Figure 3: Tune feedback system tests with applied correction.

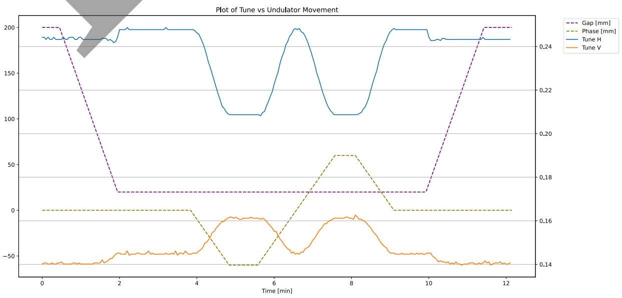

Figure 4: Tune feedback system tests without correction.

The measured tune values correspond to discrete operating points rather than statistical fluctuations; therefore, the analysis is based on mean tune shifts between observed discrete response levels rather than statistical or peak-to-peak measures. For this reason, standard deviation is not used as a stability metric in this analysis.

In the horizontal plane, the mean tune shifts from 0.209 (before correction) to 0.219 (after correction). This corresponds to a reduction of the effective tune shift between operating states by 28%. In the vertical plane, the mean tune shifts from 0.162 to 0.146, corresponding to a 66% reduction of the state-to-state tune shift. The correction could be improved by increasing the limits of magnets currents, but it leads to a significant reduction in beam lifetime, reaching up to approximately 2.3 hours. Solution is a compromise between long-lasting beam and good tune correction. Additionally, orbit stability was monitored during correction. And most important parameters were tracked and compared.

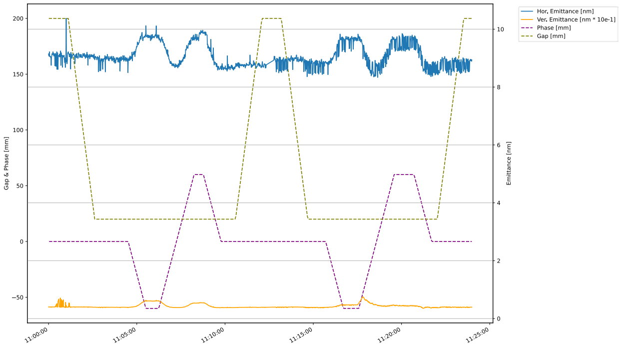

Figure 5: Emittance change with correction on the right and without applied correction on the left.

The decreased horizontal emittance (Fig. 5) up to 23% and 1% for vertical was observed after applied correction. The vertical emittance exhibits higher sensitivity due to the smaller beam size, leading to a more pronounced response to the applied correction. The horizontal plane shows weaker sensitivity to the same perturbations.

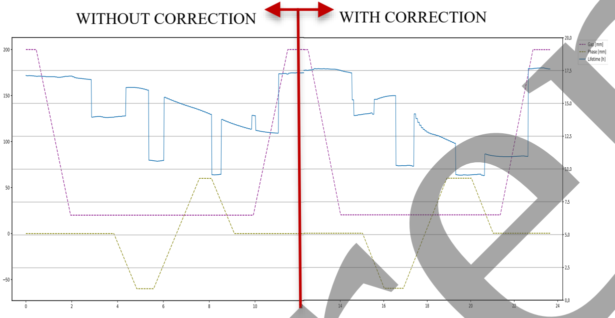

Figure 6: Beam lifetime change with and without applied correction.

Since all BPMs exhibited similar behaviour, only a representative BPM is shown (Fig. 7), serving as a reference for beam position behaviour during the feedback test. The mean BPM position differs negligibly by 0.014 µm, slightly higher before correction, which is within the measurement noise, while beam lifetime degradation remained below 4% (Fig. 6).

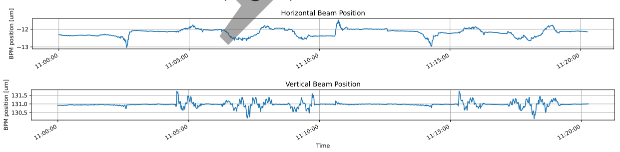

Figure 7: Beam position change with correction on the right and without applied correction on the left.

Linear Optics from Closed Orbits (LOCO) analysis (Fig. 8) was performed [4] for closed gap and lowest phase setting, with and without tune correction. For reference operational open-gap configuration were also included. The RMS beta-beating change between the corrected and uncorrected cases is −0.81% in the horizontal plane and 2.15% in the vertical plane.

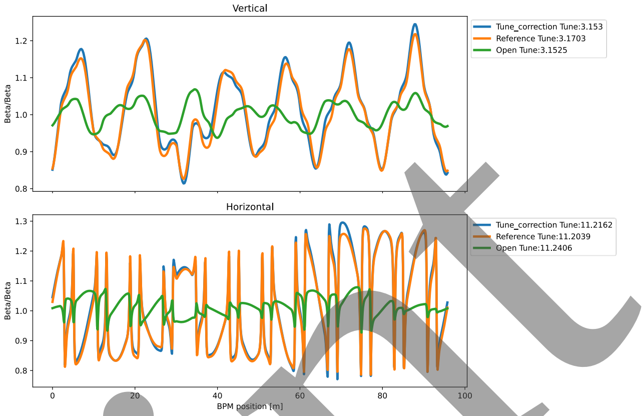

Figure 8: Beta-beating measurement with and without correction.

CONCLUSION

Correction reaching 66% on vertical plane and 28% on horizontal plane for chosen undulator minimum settings was achieved, while maintaining stable and operational parameters like beam position, lifetime and beta beating function.

The presented preliminary solution is promising, and further system improvements are anticipated, including machine learning approaches that could address potential non-linear tune behaviour and account for the influence of additional parameters.

ACKNOWLEDGEMENTS

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