Elliptically Polarized Undulator Coupling Correction at the Taiwan Photon Source

Introduction

Five APPLE-II types of elliptically polarized undulators (EPUs) are installed in the Taiwan Photon Source (TPS) to produce elliptically polarized light, namely, EPU46-45, EPU48A-41, EPU48B-41, EPU168-39, and EPU66-27. An APPLE-II-type EPU comprises four identical quadrants of magnet arrays. By enabling the translation of two diagonal quadrants parallel to the magnetic axis while keeping the other two fixed, adjustments can be made to vary the strength of the horizontal and vertical magnetic field components (B_x and B_y), consequently influencing the ellipticity of the electron beam. Because of manufacturing imperfections in the EPU, it generates a skew quadrupole component that varies at different gaps and phases. The residual skew quadrupole component couple horizontal betatron motion and dispersion to the vertical plane and then results in changes in beam size. When the electron beam encounters the residual skew quadrupole component of the EPU and subsequently traverses a region where vertical acceptance is minimal around the entire ring, there is a risk of beam scraping and loss.

To mitigate the coupling effects from the EPU and to maintain vertical beam size, each EPU is equipped with a pair of skew quadrupole magnets, named upstream skew quadrupole (USQ) and downstream skew quadrupole (DSQ), located at the entrance and exit of the EPU, respectively. This type of coupling correction is similar to the three-magnet bump used for orbit correction.[1] Since the residual skew quadrupole of the EPU varies with gaps and phases, a 2D coupling feed-forward table that accounts for gap and phase for both USQ and DSQ is needed to compensate for the residual skew quadrupole from the EPU and to maintain the beam size. To build such a 2D coupling feed-forward table, an indicator beam loss monitor (BLM) is used to monitor the variations in the beam size. This method is fast and sensitive. If the beam size exceeds the vertical acceptance level, then the beam will be scraped and lost. Conversely, if the beam size remains smaller within the vertical acceptance, then the electron beam will not be scraped.

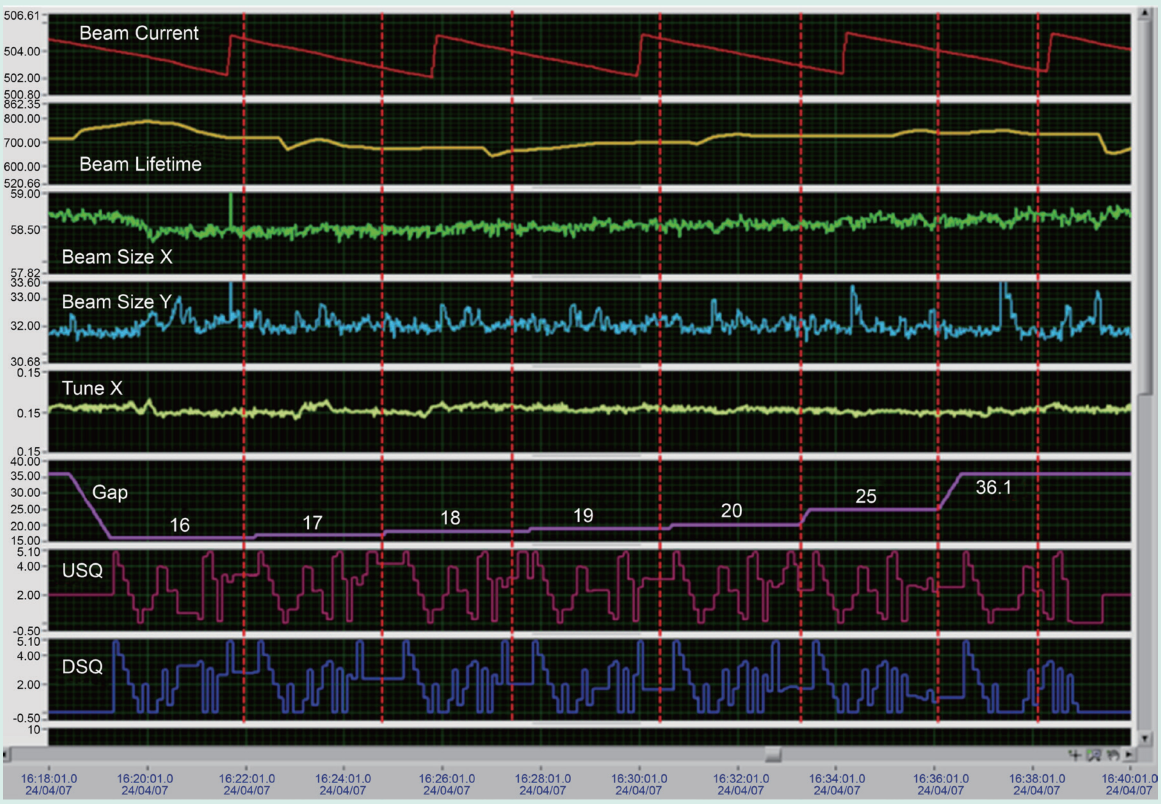

Fig. 1: Optimization process for EPU66-27 coupling feed-forward table by Bayesian optimization.

Coupling Feed-Forward Table

To counteract the undesired coupling effects caused by the residual skew quadrupole component of the EPU, it is essential to construct a 2D coupling feed-forward table based on the gap and phase of the EPU. For this purpose, an automatic measurement program that uses two nested loops to automatically adjust the gap and phase of the EPU has been developed. At each step of the gap and phase, the currents for the USQ and DSQ of the EPU are optimized to minimize the BLM reading using Bayesian optimization. The procedures for building the EPU coupling feed-forward table are outlined as follows:

1. The gaps of all EPUs are ensured to be minimized to their lowest settings to provide appropriate vertical acceptance, while the TPS is operated in top-up injection mode with a beam current of 500 mA.
2. Two nested loops are used to gradually adjust the gap and phase of the EPU to a specific setting and thus modify one gap or phase at a time.
3. For each gap and phase setting, the program automatically adjusts the currents of the USQ and DSQ of the EPU to minimize the BLM reading. The optimization should occur outside of injection periods.
4. Once the minimum BLM reading is achieved, the USQ and DSQ currents corresponding to that gap and phase setting are recorded by the program.
5. This process for each subsequent gap and phase is repeated, with the skew quadrupole currents adjusted and recorded at each step of gap and phase.

This procedure effectively builds the coupling feed-forward table, minimizing the coupling effects across all gap and phase settings of the EPUs. A shell script is then used to convert the 2D feed-forward table into a waveform format to enable the soft IOC to read it and perform interpolation. This allows the soft IOC to adjust the currents of the USQ and DSQ at 200 Hz when the EPU gap or phase varies.

Figure 1 shows the optimization process of the EPU66-27 coupling feed-forward table through Bayesian optimization. The optimization process is described as follows: The program reduces the gap to 16 mm and the phase to 0 mm. In the beginning, 10 sets of initial points are given (the different sets of USQ and DSQ currents and their associated BLM reading). On the basis of these initial measured points, the Bayesian optimization algorithm varies the USQ and DSQ currents to minimize the BLM reading.

Verification of Coupling Correction by Closest-Tune Approach

After the creation of the 2D coupling feed-forward table, it is important to verify the performance of the coupling correction. The closest-tune approach[2] was applied to check whether the minimum gap (tune-split) between the two normal modes was minimized after the correction had been applied. This was achieved by simultaneously scanning the currents of 36 defocusing quadrupoles (referred to as QS1) from -0.49 to -0.88 A relative to their nominal values, with a step size of 0.01 A. These 36 quadrupoles are located on both sides of the 18 short straight sections. At each step, the turn-by-turn data for 7000 turns from 172 beam position monitors were recorded and converted into betatron tunes using fast Fourier transform. A pulsed pinger magnet was used to excite betatron oscillations to ensure that all 172 BPMs were synchronized with the trigger event initiated by the pinger magnet, allowing the TbT signals to be recorded in sync with the revolution period.

The betatron tunes of the two normal modes were plotted against the QS1 currents relative to their nominal values. The normal mode (eigenmode) tunes can be expressed in terms of uncoupled betatron tunes (ν_x, ν_y) and the coupling strength by using the following equation:

$$\nu_{\pm} = \frac{\nu_x + \nu_y - l}{2} \pm \frac{1}{2}\sqrt{\Delta^2 + G^2_{1,-1,l}}$$

, where $\Delta = \nu_x - \nu_y - l$, and $G_{1,-1,l}$ represents the minimum separation between the normal mode tunes. The integer parts of the betatron tunes for the TPS storage ring are 26 and 14 for the horizontal and vertical planes, respectively, resulting in $l = 12$. The minimum gap $G_{1,-1,l}$ between these two normal modes represents the coupling strength.

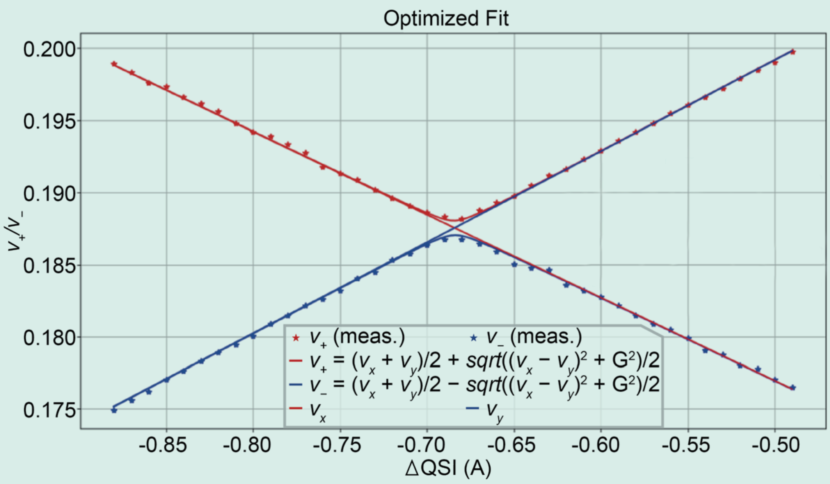

Fig. 2: Measured betatron tunes of two normal modes *versus* the currents of the quadrupole QS1 relative to their nominal values for all EPU ID gaps that are open.

Figure 2 shows the measured betatron tunes of normal modes against the currents of the quadrupole QS1 relative to their nominal values when gaps of all EPU IDs are open. The tune-split $G_{1,-1,l}$ between the two normal modes is 0.001.

Figure 3 shows the measured betatron tunes of normal modes against the currents of the quadrupole QS1 relative to their nominal values when the EPU66-27 gap is closed to 18 mm without coupling correction. The tune-split $G_{1,-1,l}$ between the two normal modes is 0.0046.

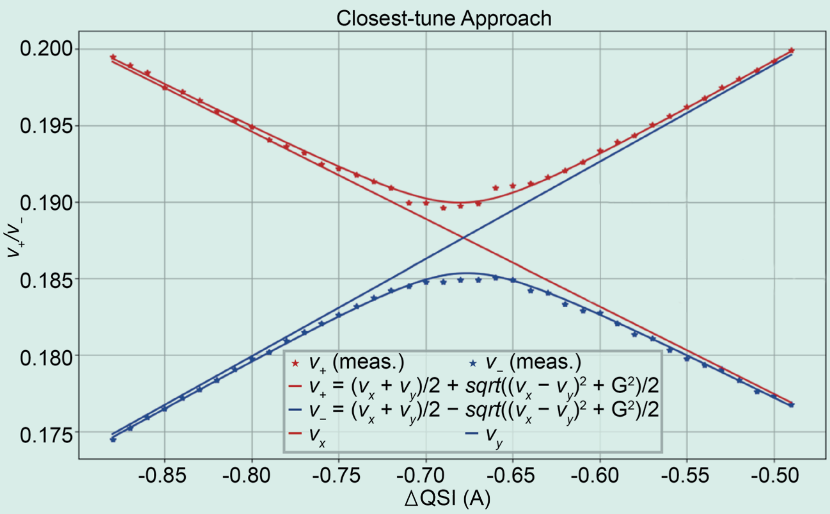

Fig. 3: Measured betatron tunes of two normal modes *versus* the currents of the quadrupole QS1 relative to their nominal values when the EPU66-27 gap is closed to 18 mm.

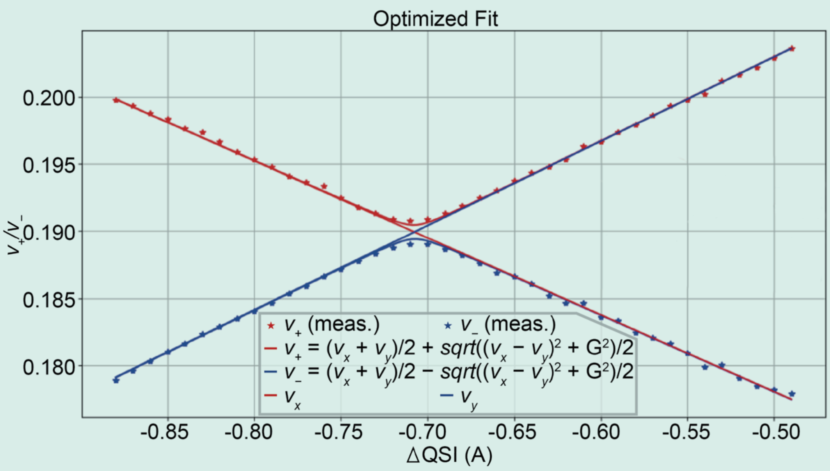

Fig. 4: Measured betatron tunes of two normal modes *versus* the currents of the quadrupole QS1 relative to their nominal values when the EPU66-27 gap is closed to 18 mm after coupling correction by USQ and DSQ.

Figure 4 shows the measured betatron tunes of normal modes against the currents of the quadrupole QS1 relative to their nominal values when the EPU66-27 gap is closed to 18 mm after coupling correction by USQ and DSQ. The tune-split $G_{1,-1,l}$ between the two normal modes is reduced from 0.0046 to 0.001.

Conclusion

Manufacturing imperfections in the EPUs inevitably result in the formation of a residual skew quadrupole component. To mitigate the coupling effects caused by the EPUs and to maintain the vertical beam size, each EPU is equipped with a pair of skew quadrupole magnets. This report demonstrates the feasibility of constructing a 2D coupling feed-forward table based on the gap and phase of EPUs to compensate for the coupling effects using Bayesian optimization. After building this 2D table, the closest-tune approach was employed to verify its performance by checking whether the minimum gap between the two normal modes (tune-split) was minimized after the correction had been applied. (Reported by Mau-Sen Chiu)

References

1. L. Emery, Proc. PAC'**05**, 805 (2005).
2. S. Y. Lee, Accelerator Physics, 4th edition, Singapore: World Scientific (2021).