ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P20

THE ALIGNMENT RESULTS OF THE TANDEM EPU AT TAIWAN PHOTON SOURCE

F. H. Tseng, T. Y. Chung, H.-Y. Huang, C. M. Cheng, C.-Y. Hua, Y. M. Hsiao, Y. C. Liu†
National Synchrotron Radiation Research Center,
Hsinchu Science Park, Hsinchu, Taiwan, R. O. C.

Abstract

Since its inauguration for user applications in 2016, the Taiwan Photon Source (TPS) has facilitated numerous research endeavors. The current investigation focuses on the alignment results of a tandem Elliptically Polarizing Undulator (EPU) situated within an extended double minimum beta y long straight section. The objective is to augment the photon flux of the synchrotron light generated by the tandem EPU via accurate alignment and using a phase shifter to attain temporal coherence. A cross-correlation function is employed to scrutinize the beam parameters associated with the source points to evaluate the temporal coherence of the two light sources emitted from the tandem EPU.

INTRODUCTION

The TPS is a 3 GeV storage ring with a 6-fold symmetry Double Bend Achromat (DBA) lattice structure [1]. Spanning a circumference of 518.4 m, it comprises 24 cells, 18 six-meter-long straights, and six 12-meter-long straights. Tandem undulators are allocated to three 12-meter-long straights, which separate eight cells to maintain the symmetry of optical functions. A quadrupole triplet is positioned in the center of the 12-meter-long straight to minimize the beta y at the core of each undulator [2]. Figure 1 compares optical functions with and without the quadrupole triplet. The tandem undulator beamline was designed to double its flux. However, since TPS began user operation in 2016, only one undulator has been accessible to the three beamlines.

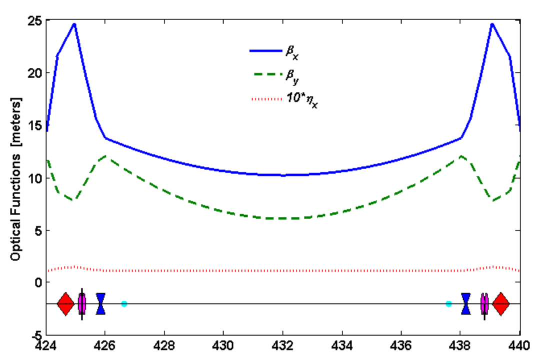

Figure 1a: Optical functions without the quadrupole tripole in the 12-meter-long straight.

† email address yichihl@nsrrc.org.tw

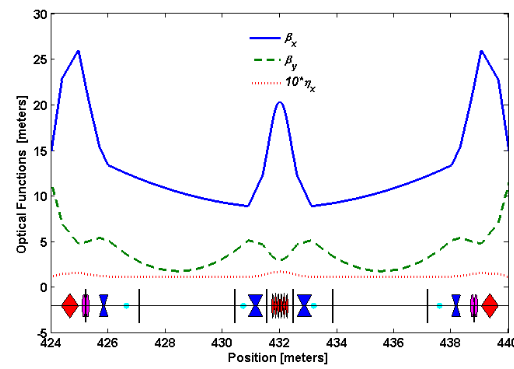

Figure 1b: Optical function with the help of qudrupole triplet to minimize the β_y at the core of each EPU.

Beamline 41A at the TPS consists of two branches [3]: high-resolution resonant inelastic X-ray scattering (RIXS) and coherent soft X-ray scattering. Both branches share the same equipment, such as the monochromator, slits, and front-end focusing optics. The light source comes from two elliptically polarized undulators (EPU) placed one after another in a 12-meter-long straight with a unique design to double the light's brilliance. Each EPU is 3.2 m long with a 48 mm period. Figure 2 presents the tandem EPUs and quadrupole triplet configuration and shows the locations of beam position monitors (BPM) and the pairs of correctors for local orbit feedback.

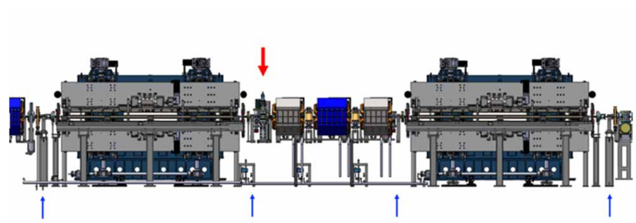

Figure 2: Tandem EPUs and quadrupole triplet configuration, locations of four BPMs (small blue arrow) and the pairs of correctors (black dot) for local orbit feedback, the red arrow indicates the location of the phase shifter.

The EPU tandem is designed to achieve a brilliance greater than 1×10^{20} photons per second per mrad^2 per mm^2 with a 0.1% bandwidth in the energy range from 400 to 1200 eV. In this range, the photon flux in the central cone is over 1×10^{15} photons per second. The calculated beam sizes are roughly 386 um horizontally and 28-35 um vertically at the full width at half-maximum (FWHM). Based on the photon energy range, the beam divergences are 42-61 μrad horizontally and 33-52 μrad vertically at FWHM.

67th ICFA Adv. Beam Dyn. Workshop Future Light Sources FLS2023, Luzern, Switzerland JACoW Publishing
ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P20

We were initially unable to align the synchrotron light emitted from the tandem undulator due to a lack of monitoring equipment. However, after installing screen monitor 2 in the front end, we began the alignment process for the synchrotron light emitted from the tandem undulator to maximize the photon flux for the beamline. Figure 3 depicts the relative positions of screen monitors 1 and 2 and the XBPMs 1 and 2 in the front end. We also implemented a local orbit feedback to ensure consistent alignment performance.

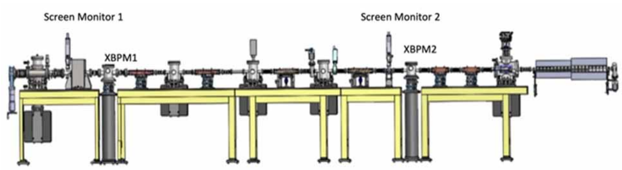

Figure 3: Relative positions of screen monitors 1 and 2 and the XBPMs 1 and 2 in the front end.

ALIGNMENT PROCEDURE

To align the photon trajectory from the upstream EPU, we used the photon trajectory emitted from the accessible downstream EPU projected on the front-end screens 1 and 2 as the target. We determined the appropriate storage beam current to be 30 mA for orbit correction, while we dumped the beam and re-injected it to 0.5 mA to locate the target on front-end screens 1 and 2. This was necessary due to the low signal-to-noise ratio of the electron BPMs at lower beam currents.

In Fig. 4, a comparative analysis of electron beam trajectories at varying beam currents is presented, illustrating discernible deviations which suggest that both the superconducting radiofrequency (SRF) systems and the induced noise have an impact on the beam position monitors (BPMs) located on either side when the beam current is set at 0.4 mA.

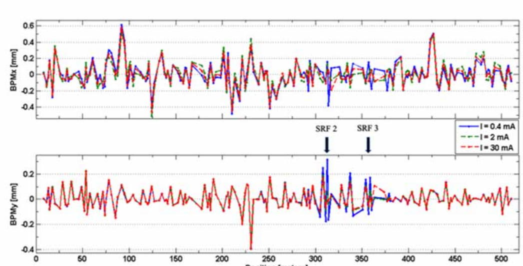

Figure 4: Comparison of the electron beam orbits for different beam currents, with apparent deviations indicating that the superconducting RF system and induced noise affect both-sides BPMs at 0.4 mA beam current.

We designed a local orbit feedback control system based on the original fast orbit feedback (FOFB) constraints [4]. We measured the response matrix of tandem EPU's corrector and both side BPMs when starting the FOFB. Therefore, the response matrix $R_{x_{ij,}} R_{y_{ij,}}$ are a 4 x 4 matrix in the x and y direction, respectively. The inverse response matrix $R^+_{x_{ij},y_{ij}}$ links $\Delta B_{x_{ij},y_{ij}}$ and $\Delta x_{ij}, y_{ij}$:

$$\Delta B_{x_{ij},y_{ij}} = R^+_{ij}\,\Delta x_{ij}, y_{ij} \quad (1)$$

This new system helps maintain the alignment of synchrotron lights emitted from tandem EPUs. When integrating the new feedback system, it is essential to ensure that the original feedback remains continuously active to maintain stability and performance. In Fig. 4, the stability of the local orbital trajectory is demonstrated to effectively preserve the alignment of the two light sources. Measurements were consistently conducted with the implementation of local orbital feedback control mechanisms.

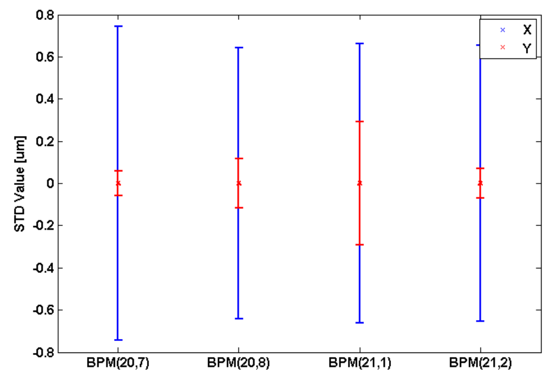

Figure 5: Stability of the local trajectories.

Figure 5 illustrates that the stability of the local trajectories contributes significantly to maintaining the alignment of two distinct light sources. A detailed examination during the gap fully opened and closed reveals that the horizontal peak-to-peak fluctuation, corresponding to the 95% confidence interval, remains confined to a 4 μm range. Similarly, the vertical peak-to-peak fluctuation is observed to be constrained within a 2 μm range, further emphasizing the effectiveness of local trajectory stability in preserving light source alignment.

ALIGNMENT RESULTS

During the alignment experiment, it was observed that the vertical entrance slit experienced an increase in temperature. Upon re-evaluation and recalculation of the beamline optics, it was determined that the primary cause of the heating issue at the vertical entrance slit was the disparate focal points of the emitted photon beam originating from the upstream and downstream EPU. Following the distance from the upstream EPU center and downstream EPU center to the horizontal focusing mirror (VFM), they are 32.555 m and 25.805 m. The emitted photon flux from the tandem is EPU quantified by measuring the current on the sample holder with fully open slits. A detailed schematic of the RIXS branch is illustrated in Fig. 6. This constrain impedes the ability to accurately measure the spatial coherence of the two photon beams.

In the present study, the primary objective is to quantify the temporal coherence of dual photon beams by employing a phase shifter [5] positioned downstream of the upstream EPU, as depicted in Fig. 2. The utilized phase shifter, composed of permanent magnets, incorporates an anti-symmetric magnet end pole configuration to mitigate

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P20

multipole errors and the influence of fringe field effects across a range of gap widths. In its design, the phase shifter exhibits a maximum gap width of 130 mm, at which point the magnetic field effectively approaches zero.

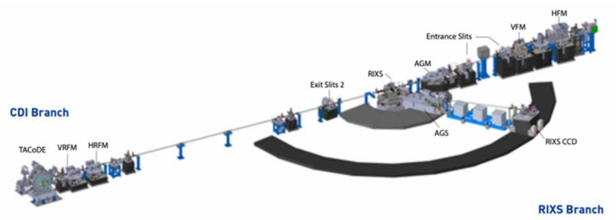

Figure 6: Detailed schematic of the RIXS branch.

The electron beam trajectory varies with the gap of the phase shifter and produces a difference in path length to its maximum gap. The path length difference of e-beam introduces a phase delay to the photon with wavelength λ propagating straight along the phase shifter can be written as:

$$\frac{L-L_0}{\lambda} = \frac{\Delta\phi}{2\pi} \quad (2)$$

We employed a phase shifter to assess the temporal coherence of two monochromatic light sources emitted from the tandem EPU. Figures 7 and 8 present the variations in normalized flux as a function of the phase shifter gap at two distinct photon energies.

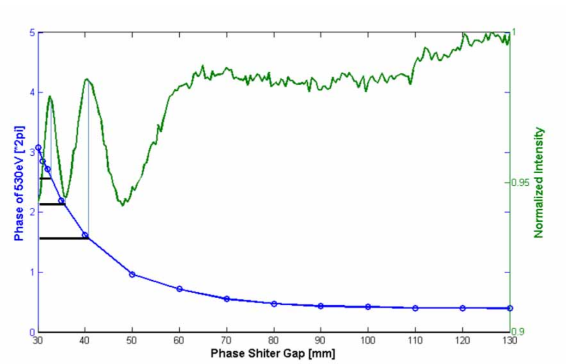

Figure 7: Variations in normalized flux as a function of the phase shifter gap with photon energies at 531.8 eV and a wavelength of 2.33 nm.

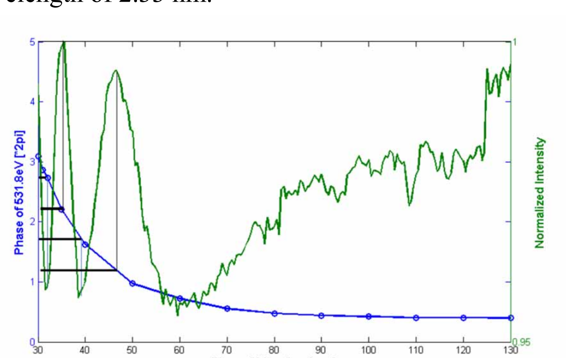

Figure 8: Fluctuations in normalized flux, contingent upon the phase shifter gap, in association with photon energies of 530 eV and a wavelength of 2.34 nm.

Based on the results, we can calculate the cross-correlation function to quantify the degree of temporal coherence of the two monochromatic light sources and determine the visibility [6] V, a measurement of contrast of the interference pattern shown in Figs. 7 and 8, define as:

$$V = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \quad (3)$$

In the observed visibility spectrum, the magnitude lies within 0.016 to 0.022, indicative of weak temporal coherence between the two light sources under investigation. This finding suggests that the emission originating from the EPU constitutes incoherent synchrotron radiation. A graphical representation of the incoherent synchrotron light emissions from an electron bunch is provided in Fig. 9.

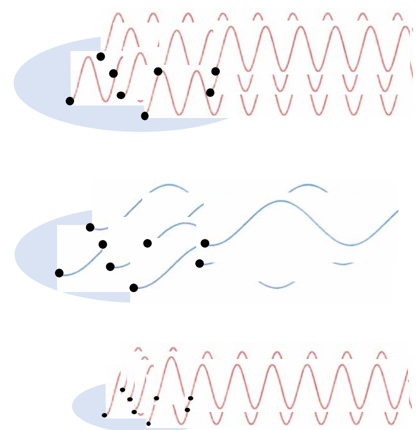
Figure 9: Emission of incoherent synchrotron light from an electron bunch. The top figure displays a highly incoherent synchrotron light, evident when the photon wavelength is significantly shorter than the electron bunch length. Conversely, the middle and bottom figures exhibit a more coherent synchrotron light, which occurs when the photon wavelength is comparable to the electron bunch length.

Constructive interference can be achieved by emitting two monochromatic light sources from the tandem EPU. To accomplish this, the phase delay of the phase shifter and the phase difference ϕ_0 between the centers of the two EPUs must be an integer multiple of 2π. Under these conditions, the normalized intensity (A) can be expressed as follows:

$$A = \frac{1+\nu\cos(\Delta\phi+\phi_0)}{2} \quad (4)$$

For Figs. 7 and 8, the phase difference ϕ_0 is determined to be $0.607 \cdot 2\pi$ and $0.404 \cdot 2\pi$, respectively. Additionally, the experimentally measured phase delay of the phase shifter demonstrates agreement with the anticipated phase delay.

In Figs. 7 and 8, the interference pattern exhibits prominent peaks, the exhibiting positive and negative slope of which is of particular interest in the current investigation. To elucidate the nature of this slope, we introduce R_{56}, R_{56} is a fundamental parameter in accelerator physics to quantify the relationship between changes in longitudinal path length and energy deviations. In the 6-dimensional matrix, the fifth coordinate represents the longitudinal coordinate,

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P20

while the sixth coordinate represents the particle's energy. In case of large momentum deviation (δ), the electron beam's longitudinal slippage (Δz) to its momentum deviation and its square of energy deviation (δ^2) can be written as:

$$\Delta z \approx R_{56}\delta + T_{566}\delta^2 \approx R_{56}\delta - \frac{3}{2}R_{56}\delta^2 \quad (5)$$

T_{566} represents the ratio of the change in longitudinal path length to the square of the energy deviations. Under the 0.1% energy spread, the R_{56} value of the phase shifter spans a range of -12.57 nm to -0.72 nm, corresponding to a gap variation between 30 mm and 70 mm. Compared to the electron bunch length of 5.28 mm observed at a stored beam current of 500 mA, the influence of bunch compression can be considered negligible. The observed phenomena of both position and negative slopes cannot be fully accounted for by equation 5.

The Tandem EPU functions as a type of optical klystron [7, 8], wherein the upstream EPU induces energy modulation, while the phase shifter generates density modulation. Subsequently, the downstream EPU amplifies the harmonic energy of the photons.
In this context, we present the spontaneous emission, denoted as $\frac{d^2I}{d\omega d\Omega}$ representing the energy emitted per electron during each pass through the EPU, per unit solid angle, and per frequency in the forward direction. The expression for spontaneous emission in the case of the tandem EPU can be formulated as follows:

$$\frac{d^2I}{d\omega d\Omega}(the\ tandem\ EPU) = 2\frac{d^2I}{d\omega d\Omega}(1 + cos\alpha) \quad (6)$$

Here, α denotes the cumulative alteration of $t - \frac{\vec{n}\vec{r}}{c}$ in single EPU and throughout the phase shifter. The unit vector $\vec{n}$ corresponds to the direction of $\frac{d^2I}{d\omega d\Omega}$ is computed. The position vector of the electron at a specific time t is denoted by $\vec{r}$. The spontaneous emission spectrum of the tandem EPU exhibits no substantial interference characteristics. The positive and negative slopes of the pronounced peaks in the interference patterns observed in Figs. 7 and 8 currently lack a convincing explanation. Further investigation is required to elucidate the underlying cause.

CONCLUSION

The findings of this investigation underscore a notable deficiency in the temporal coherence of alignment results obtained from the tandem EPU, which is attributable to an erroneous measurement procedure. Specifically, the beamline slits were found to be completely open. Consequently, an excessive overlap of the diffraction patterns was observed, leading to the obliteration of the interference. Nevertheless, the introduction of an innovative local orbit feedback control mechanism has proven to be considered adequate. This research explores the beam properties of the TPS storage ring by examining interference patterns generated by two separate light sources when the electron beam passes through a phase shifter with a variable gap. The experiments substantiate that the antisymmetric permanent-magnet phase shifter meets its design specifications, providing valuable insights for future developments in this field.

REFERENCES

[1] C. C. Kuo *et al.*, "Progress report of TPS lattice design," in *proc. PAC'09*, Vancouver, BC, Canada, 2009.

[2] M. S. Chiu *et al.*, "Double mini-betay lattice of TPS storage ring," in *proc. IPAC'11*, San Sebastián, Spain, 2011

[3] . A. Singh *et al.*, "Development of the soft X-ray AGM-AGS RIXS beamline at the Taiwan Photon Source," *J. Synchrotron Radiat.,* vol. 28, 2021, pp. 977-986. doi:10.1107/S1600577521002897

[4] P. C. Chiu *et al.*, "Beam commissioning of TPS fast orbit feedback system, " *proc. IBIC'16*, Barcelona, Spain, 2016. doi:10.18429/JACoW-IBIC2016-MOPG11

[5] T. Y. Chung, J.-C. Huang, H. Luo, Y. Chu, J. Jan, and C. Hwang, "An antisymmetric design of a permanent-magnet phase shifter for a tandem EPU at TPS," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016. doi:10.1109/TASC.2016.2524525

[6] Emil Wolf, *Introduction to the theory of coherence and polarization of light*, University of Rochester, NY., USA, Cambridge University press, 2007

[7] R. Coisson, "Optical klystrons", *Part. Accel.*, vol. 11, pp. 245-253, 1981. http://cds.cern.ch/record/1107994

[8] P. Elleaume, "Optical klystrons", *Journal de Physique Colloques*, vol. 44, pp. C1333-C1352, Feb. 1983. doi:10.1051/jphyscol:1983127