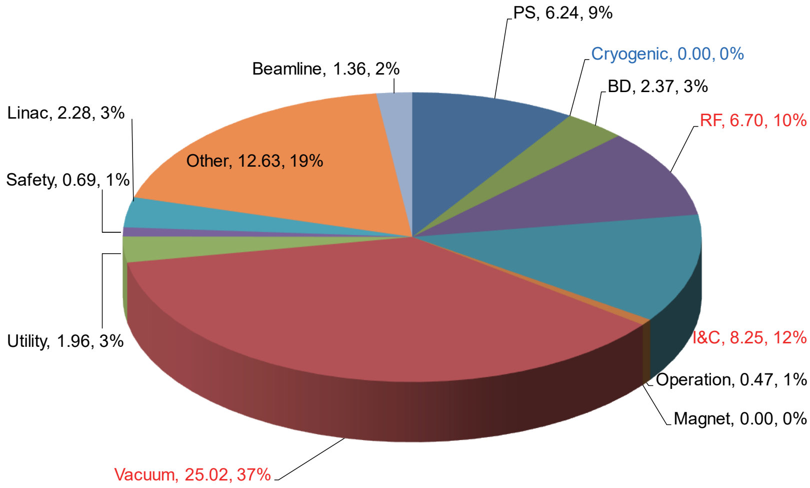

Fig. 7: Downtime distribution of TPS accelerator in 2020. (Downtime 68 hours)

Progress on Elliptically Polarized Undulators at the NSRRC

Introduction

Because demand for circularly polarized radiation is strong, insertion devices (ID) have been used to provide elliptical fields since the late 1980s. The trend is to increase both the degree of circular polarization and the brightness of the radiation. Among many ID designs, an elliptically polarized undulator (EPU) provides the greatest merit flux and has thus become the workhorse in several facilities. NSRRC has also been developing its own EPU since the 1990s. EPU56 (length 3.9 m) with period length 56 mm was the longest EPU in the world at the time, as seen in **Fig. 1(a)**. It was installed at Taiwan Light Source (TLS, 1.5-GeV storage ring) in service to date. At Taiwan Photon Source (TPS, 3-GeV storage ring), the EPU continues to play an important role in fulfil the needs of EUV of the soft X-ray user community. Up to phase II, in total five EPUs have been installed, as seen in **Table 1**. It is worth noting that, for full utilization of the TPS straight section, the EPU installed this year has length 4.36 m; a new device, flat wire, is installed, which is expected to correct the dynamic multipoles induced by the EPU.

Table 1: History of EPU development at NSRRC.

Year	Name	Facility	Contents	Remarks
1999	EPU56	TLS	$\lambda_u{}^a = 56$ mm, $G_{min}{}^b = 20$ mm, $L^c = 3.9$ m	longest EPU in the world, at that time
2015	EPU46	TPS (phase I)	$\lambda_u = 46$ mm, $G_{min} = 14$ mm, $L = 3.8$ m	refurbished by NSRRC
2015	EPU48A		$\lambda_u = 48$ mm, $G_{min} = 13$ mm, $L = 3.4$ m	double EPUs for a long straight section
2015	EPU48B			
2020	EPU66	TPS (phase II)	$\lambda_u = 66$ mm, $G_{min} = 16$ mm, $L = 4.36$ m	flat wire installed within a gap
2020	EPU168		$\lambda_u = 168$ mm, $G_{min} = 27.2$ mm, $L = 4.36$ m	for EUV beamline, flat wire installed

Notes: [a] period length; [b] minimum gap; [c] physical length of EPU.

Description of the Mechanical Structure

The EPU is composed of four Halbach arrays that regulate the amplitude and phase of the vertical and horizontal magnetic fields by the relative motion of the magnet arrays. On driving the diagonal arrays, the EPU can provide various polarizations, such as horizontal linear, circular and vertical linear (VL) polarization. As with general ID operation, the EPU varies the magnetic fields to fulfil the spectral tuning by opening and closing a gap of magnet arrays. In terms of the mechanical structure, the EPU has two driving systems to move magnet arrays: vertical movement to tune photon energy, longitudinal movement to control polarization. The vertical movement is achieved on fixing the magnet arrays on the backing beam, which opens

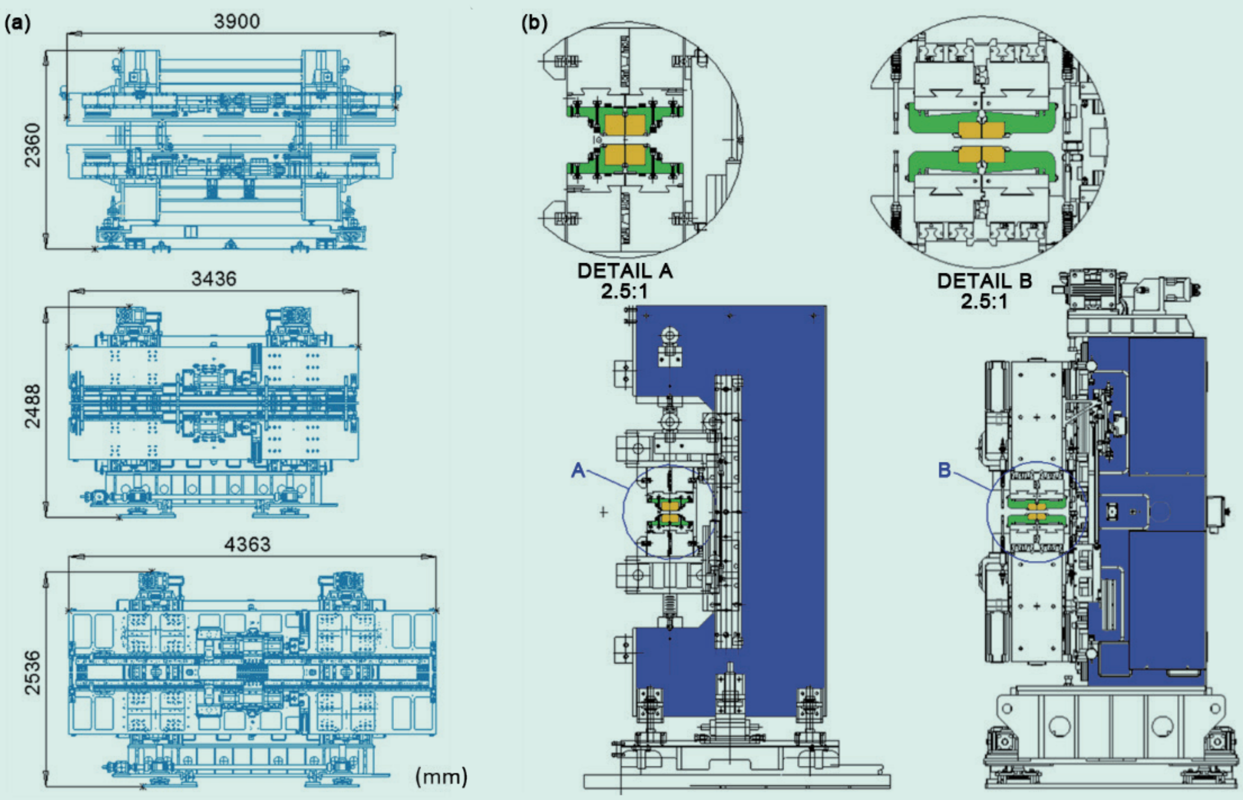

Fig. 1: Mechanical structure of an EPU. Side view (a) on the backing beam side. From top to bottom: EPU56 (TLS), EPU48 (TPS Phase I) and EPU66 (TPS Phase II). (b) In the direction of the electron beam. Left: EPU56 (TLS). Right: EPU66 (TPS Phase II). The magnet block and the fixed structure are enlarged in the figure.

and closes vertically, as seen in **Fig. 1(a)**. In contrast to a general ID, which suffers only a vertical attractive force, the EPU suffers changes in both attractive and repulsive forces and in three directions. A rigid frame and base are hence required to support the backing beams. A cast structure replaces the screwed-in frame to improve the stiffness of the member, as seen in a filled region (blue) in **Fig. 1(b)**. Beginning with the Phase-I EPU, a freely sliding end of a backing beam was designed to diminish the mechanical deformation caused by thermal expansion and contraction of heterogeneous materials due to changes in ambient temperature.

Strategies to Resist Radiation Damage

In addition to a robust mechanical structure, the electronics in a driving system must be stable, even in a radiation environment. Radiation damage to and protection for the EPU becomes a worthy item for discussion to obtain a reliable operation. The experience gained from commissioning and operation of the Phase-I EPUs at the TPS taught us that EPU driving systems can behave erratically following a beam dump or loss. According to the related research, this effect is attributed to the malfunction of memory elements in an optical encoder. Although the damage is "soft" and recovers after a power cycle, the Phase-II EPUs are designed with various strategies to address this issue. Encoders are enclosed in lead material of thickness more than 10 mm, which is a tenth and a half value layer required for gamma rays of energy 412 to 1,332 keV. The distance between the encoder and the nominal electron beam position is increased; the distance with the Phase-II EPUs is more than twice as great as the least distance of an encoder in Phase I. The radiation dose of neutrons is thus supposed to be decreased by 50 to 75%. In addition, we reserve an installation space for a second encoder in the Phase-II EPUs. Apart from the encoders for TR-electronics, Renishaw's encoders will be installed and tested.

Challenges and Methods for Optimization of the Magnetic Field

To achieve the desired properties of radiation and to have no net effect on an electron beam are two main requirements of an EPU. To realize the former objective, the magnetic field is desired to be a purely periodic distribution. Radiation emitted from each pole has a correct correlation, resulting in constructive interference. The phase error describes the deviation of the phase between a real device with field error and an ideal one at each pole. The r.m.s. phase error, which has been shown to be well correlated with the spectral intensity, must thus be minimized. The first and second field integrals represent the exit angle and position of the electron beam, respectively. For the latter objective, these field integrals in transverse directions must be minimized, to effect a negligible multipole error. In contrast to a general ID, an EPU must be operated in several polarization modes, each of which must meet the specified requirements. How to arrange thousands of magnet blocks to fulfil the multiple requirements hence becomes the task of optimization of the magnetic field for an EPU.

The optimization of a magnetic field consists of two parts: the first part is block selection and position determination, called magnet sorting; the second part is adjustment of the local magnetic field, called field shimming. If the magnet sorting has better results, less time is required for field shimming. To develop an effective sorting algorithm in the construction of an EPU is hence important. Before eliminating errors, we must understand their source. Magnetic errors are classified generally into two groups: random and systematic. Random errors result primarily from the variation of the characterizations of individual permanent magnets, such as the magnetic remanence, orientation of the magnetization and magnetic inhomogeneity. Mechanical error, especially the deflection of the backing beam, produces systematic errors. The magnet group has developed an efficient sorting algorithm that measures the strength of the magnetic field of each magnet and the mechanical accuracy of the entire machine. Based on these data, the distribution of magnetic field of the entire machine after installation of magnets can be expected to proceed as follows. The method of simulated annealing is then used to find the best arrangement. This method is similar to a gradual cooling of liquids to form a crystalline state, as opposed to an amorphous state after a sudden cooling. This sorting code is effective. For example, with a phase-II EPU66, the r.m.s. phase error is as large as 30° when the magnets are randomly arranged, and is significantly decreased to 4.1° when the optimal arrangement is determined with the sorting algorithm, as seen in **Fig. 2(a)**. The results of that optimization optimize not only the phase error but also the trajectory of the electron beam, as seen in **Fig. 2(b)**.

Field shimming of the magnetic field is applied in the final stage of tweaking the local magnetic field so as to optimize the performance. Several methods have been developed by the magnet group. The main approach is to perform a mechanical movement of magnets to a sub-millimetre extent. To perform tens of micro-scale adjustments, a movement of magnet blocks using a screw-driven wedge and slide mechanism is convenient, which is called virtual shimming; this method has been implemented for the TPS EPU and is almost a standard. The r.m.s. phase errors eventually decreased to 3.1°, as seen in **Fig. 2(a)**. These results maintain a great spectral intensity, even for a high harmonic energy.

Schemes to Diminish Beam Dynamic Issues

After improvement of the spectral intensity, the next issue is to minimize the net effect on an electron beam. The integral along the actual trajectory of an electron beam must be considered. This integral can be divided into two parts, static and dynamic field integral. The inhomogeneity of the magnet blocks contributes static multipole errors, which become measurable using a stretched wire system. In the case of an EPU, there is a discrepancy of the field integral between separate phase modes, resulting in a phase-dependent multipole error. The magnet group manipulated iron shims with phase-dependent properties to solve this issue. Besides understanding the behaviour of an iron shim on a vertical and horizontal magnetization magnet block, symmetry theory has been used to determine the location of iron shims. After the implementation of iron shims, the vertical and horizontal field integrals of all phase modes were aligned within ± 15 G cm. The residual phase-independent field integral is generally decreased using magnet chips (*i.e.* magic finger), located at both ends of an EPU. The best arrangement of the chips was selected based on simulated annealing. Flattening of the field integral distribution was specifically optimized in the range ± 20 mm. After shimming, the static field integrals are flattened within ± 25 G cm.

As the true trajectory of an electron beam in an ID is wiggling rather than linear, the static field integral can be used only to illustrate the case of an ID with a wide region of

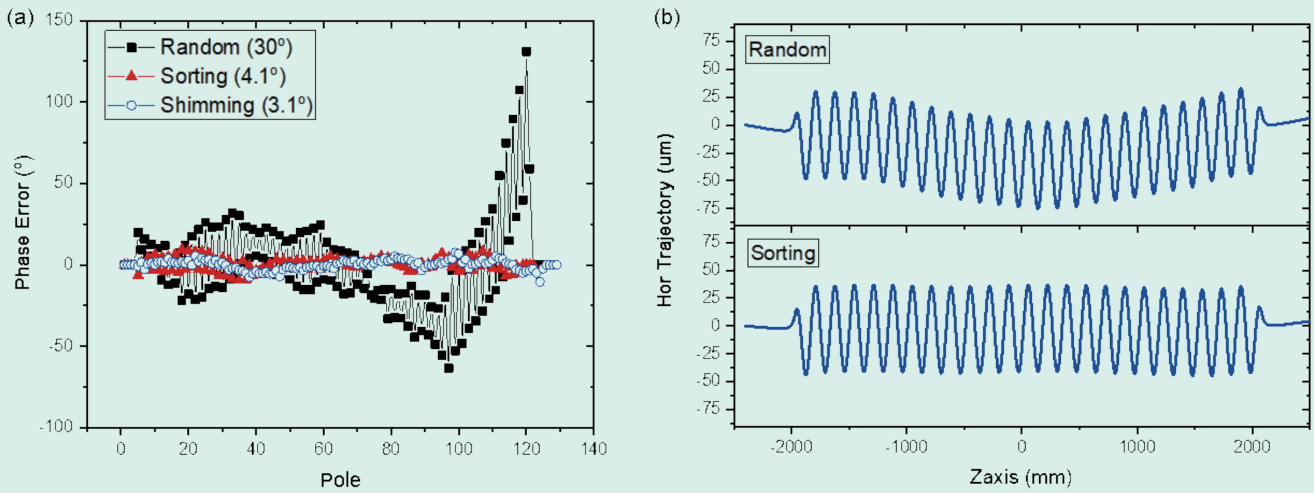

Fig. 2: (a) Distribution of phase error for three cases: random arrangement, the best sorting and shimming result. The number in brackets represents r.m.s. phase error. (b) Trajectory of an electron beam for random and sorting arrangements of magnets.

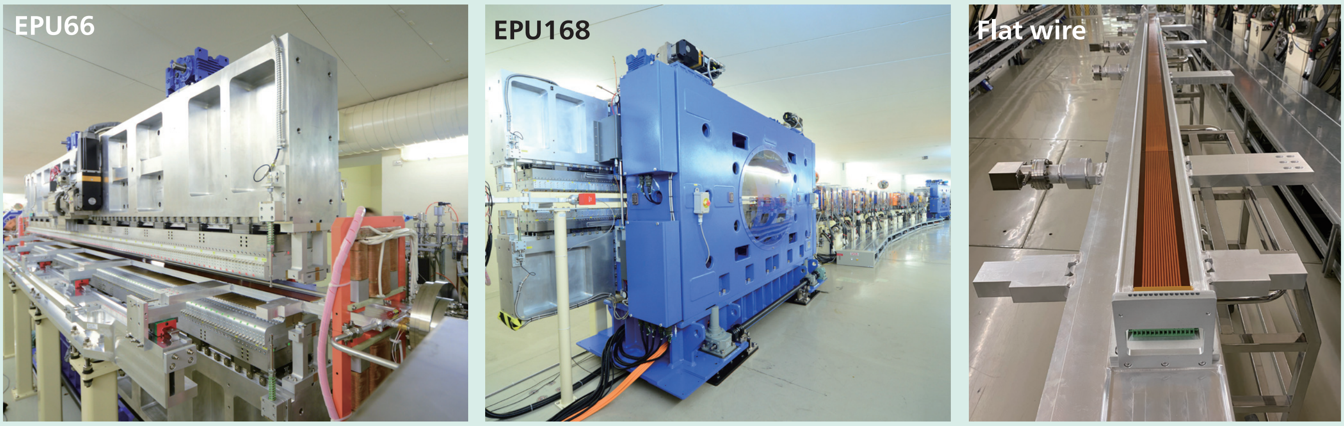

Fig. 3: Photographs of the EPU and flat wire installed in the TPS storage ring this year. From left to right are EPU66, EPU168 and flat wire on EPU chamber.

effective field. The EPU has a narrow horizontal range of uniform field producing strong dynamic multipole errors. In the case of EPU66, the dynamic field integral of the VL mode extends to 210 G cm. To address the inherent problems of the EPU, the magnet group investigated both passive and active approaches. They first experimented with the use of iron shims (L-shim) attached to the corners of the magnets; this approach improved beam dynamics issues. It should be noted that the passive method is convenient but inaccurate for an inclined mode of an EPU and operation of the storage ring at varied energies. To be stable for universal operation, a prototype flat wire was installed on the chamber within the gap of the EPU56 at TLS during the 2017 summer shutdown. The improved ring stability became experimentally evident.

Installation of a Phase-II EPU and Flat Wire

According to the experimental results and experience, both EPU66 and EPU168 of TPS phase II have been completed and installed with flat wire on October 2020, as seen in **Fig. 3**. After that, the EPU will be commissioned according to the construction schedule of the front end and the beam line. (Reported by Ting-Yi Chung)

Global Tune Feedback in TPS

Taiwan Photon Source (TPS) is a 3-GeV dedicated synchrotron light source, consisting of 24 double bend achromat that provide six long straights and 18 short straights to accommodate insertion devices including in-vacuum undulators (IU) and elliptical polarization undulators (EPU). The side effects of the insertion devices on the storage ring are betatron tune shift, lattice function distortion, closed-orbit distortion, variation of emittance and an energy spread. These effects deteriorate the quality of the synchrotron light source. Many actions are taken to cure these undesired effects, among which a global tune feedback system has been implemented to compensate the tune shift caused by the insertion devices.

Introduction

There are two EPU48, one EPU46 and six IU operating in the TPS storage ring. To compensate the tune shift due to the variation of gap and/or phase of these insertion devices, MATLAB was used to develop a global tune feedback system that uses two-family quadrupole magnets (36 defocusing quadrupoles QD1S and 36 focusing quadrupoles QF2S) located besides 18 short straights to maintain the betatron tune at the desired working point.

Algorithm

The correction currents to be applied to the quadrupoles of QD1S and QF2S families are calculated with the model tune response matrix M and the tune difference $\Delta\nu$. The accuracy of the tune response matrix and tune difference determines whether the betatron tunes can be well controlled. The storage ring lattice is well calibrated with Linear Optics from Closed Orbit; the tune response matrix is hence calculated from the model lattice. The tune difference is the difference between the target tune ν_0 and measured tune ν_m from the bunch-by-bunch feedback system (BBF). Before correcting betatron tunes, 2,000 data points of the BBF tunes were collected within about three minutes when all IDs' gaps or phases were at rest; the