Operational Parameters
The main operational parameters of the TPS are shown in Table 2.

Operational Statistics
In 2019, the beam availability was 98.4% with scheduled user time 4635 hours and MTBF 110.4 hours. Figure 2 shows a summary of the beam availability and the MTBF of the TPS user-mode operation. (Reported by Chang-Hor Kuo)

Table 2: Main operational parameters of TPS storage ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>3.0</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>864</td>
</tr>
<tr>
<td>Maximum multi-bunch beam current (mA)</td>
<td>500</td>
</tr>
<tr>
<td>Horizontal beam emittance (nm-rad)</td>
<td>1.6</td>
</tr>
<tr>
<td>Betatron tunes ($\nu_x/\nu_y$)</td>
<td>26.16/14.24</td>
</tr>
<tr>
<td>Lifetime at maximum beam current (hour)</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>RF voltage (MV)</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Operational Statistics
In 2019, the beam availability was 98.4% with scheduled user time 4635 hours and MTBF 110.4 hours. Figure 2 shows a summary of the beam availability and the MTBF of the TPS user-mode operation. (Reported by Chang-Hor Kuo)

Hybrid-Mode Operation of Taiwan Photon Source
The Taiwanese Photon Source (TPS) has started the user-mode operation with a beam current up to 500 mA since March 2016. The circumference of the TPS storage ring (SR) is 518.4 m and the corresponding revolution period is 1.729 μsec, accompanied with the radio frequency (RF) of 500 MHz, totally 864 bunches are available in the storage ring.

For routine operation, the stored beam is injected as a 1.3-μs bunch train with 650 buckets. Another operating mode, called hybrid mode, is considered with an isolated bunch being placed in the middle of two normal bunch trains.

Status of the Hybrid-mode Operation
The test run of hybrid mode with top-up injection has been serving the users in April 2019. This test run is now in operation bi-weekly. Figure 1 demonstrates the beam current monitor of the hybrid-mode operation in the

Fig. 2: Summary of beam availability and MTBF of TPS user-mode operation since 2016.
TPS. The beam current of the hybrid mode was 400 mA with the bunch current of 0.6 mA for each bunch within the multi-bunch train and 2.0 mA for the isolated bunch. The isolated bunch is located at the center of an empty-bucket train, 200 ns away from the upstream and downstream of the multi-bunch train; the signal-to-noise ratio between the solo bunch and the neighboring empty bucket is more than 9999. A higher bunch current for the solo bunch is expected to operate in the hybrid mode at TPS.

To operate efficiently in the hybrid mode, the signal of one electrode button of the beam position monitor (BPM) located at the transfer line between the linear accelerator (Linac) and the booster ring was utilized to investigate the behaviors of injection beam. The 3-GHz bunch distribution was observed through the button’s signal, and helped to control the injection bunch precisely at the optimum RF phase in the TPS booster ring.

Furthermore, the RF sub-harmonic pre-buncher is a cavity of standing-wave type installed in the downstream of the Linac for bunch compression as shown in Fig. 2. Without the pre-buncher modulation, as shown in the blue line in Fig. 3, six bunches with a resonance frequency 3-GHz were observed by the BPM within a RF bucket (1 RF bucket = 2 ns = 499.654 MHz). When the pre-buncher concentrates a few bunches into a single bunch, the amplitude of a single bunch is enhanced substantially, as shown in the orange line in Fig. 3. Making a comparison of beam injection with the pre-buncher in the multi-bunch and single-bunch modes, the injection timings of both cases are mutually consistent, and placed under an optimized phase space, as shown in the yellow and orange lines of Fig. 3 respectively. Figure 4 shows the diagrams of the longitudinal phase space of the TPS booster ring when the beam is injecting. Figure 4(b) indicates that the energy deviation for a stable phase space is within ± 2%. To have an efficient beam capture from the Linac to the booster ring, an energy deviation less than 2% is necessary. The pre-buncher benefits a short (~350 ps) and intense bunch to make the beam injection easily at the optimum RF phase. Figure 4(a) indicates that bunches (yellow solid circle) placed outside the envelope (red), then cause the beam instability and loss in the booster ring. On the contract, bunches were captured stably inside the envelope as shown Fig. 4(b).
An isolated bunch, following a multi-bunch train, is injected with an increased bunch current in the hybrid-mode operation of TPS. The high-current bunch might cause severe interactions with its environment and induce beam instabilities. Operation values of high vertical chromaticity could suppress vertical instabilities and enhance the bunch current in both the TPS booster ring and storage ring, the operational currents of sextupole magnets in the TPS booster ring and storage ring were then adjusted accordingly. Comprehensive improvements of the hybrid-mode operation are summarized in Fig. 5. Figure 5 illustrates the waveform generated with the DC current transformer with ramping cycle 3 Hz in the TPS booster ring; an enhancement 400% of the beam capture was observed after the improvements. The black-dashed line in Fig. 5 represents the timing of the beam extraction from the booster ring to the storage ring in TPS. Figure 6 shows beam current of the single-bunch mode at the beam extraction, in which the bunch current was increased almost 250% in the TPS booster ring.

After optimizing the injection scheme for the high-current single bunch, the operating mode, as shown in Fig. 7, of the TPS storage ring can now be switched smoothly among the single-bunch, multi-bunch and hybrid modes. (Reported by Chia-Hsiang Chen)

Fig. 4: The longitudinal phase space of the TPS booster ring. Bunches place at (a) the unstable and (b) stable phase space.

Fig. 5: Bunch current before and after improvements in the TPS booster ring.

Fig. 6: The extracted beam current of the single-bunch operation mode before and after improvements in the TPS booster ring.

Fig. 7: The schema of current TPS operation modes.
This report features the project done by the Beam Dynamics Group, NSRRC.

References

Technical Challenges of Cryogenic Permanent-Magnet Undulators at Taiwan Photon Source

X-ray beamlines of Phase II are under construction at the Taiwan Photon Source (TPS). As the spectral quality from cryogenic permanent magnet undulators (CPMUs) can be superior to that of in-vacuum undulators (IVUs), a PrFeB-based CPMU with a period length of 15 mm has been constructed to provide highly brilliant X-rays. The magnets of the CPMU must be cooled to 80 K to generate an effective magnetic field of 1.02 T at a gap of 5 mm. Two cryo-coolers, each with cooling capacity 220 W at 80 K, allow for the removal of external heat leaks up to a few hundred watts. An in situ and vacuum compatible field measurement system has been developed to characterize the magnetic field at cryogenic temperatures and to allow correction of gap errors due to temperature variations. The relevant techniques and challenges for the TPS-CPMU are presented here.

Introduction
Brilliant X-rays from undulators are highly desired in third-generation storage rings. The photon flux of coherent synchrotron radiation (SR) can be increased by improving the quality of the electron beam or undulator performance. Many low-emittance storage rings were recently constructed around the world to improve the quality of photon beams, but the construction is costly and a delicate multi-bend-achromat lattice is necessary. An economical option to provide more intense coherent photon flux in the hard X-ray region is hence to use undulators of short period with small phase errors. Among the most important challenges in the development of a short-period undulator is the ability to generate a sufficiently strong magnetic field. A cryogenic permanent magnet undulator can meet such goals and is thus suitable for the development of short-period undulators, which have become a recent focus of interest because most techniques for CPMU have already been developed for in-vacuum undulators.

Ultra-high-vacuum (UHV) compatibility for an undulator is an essential requirement for its installation in a storage ring. One can apply either high-temperature baking of permanent magnets (baking approach) or cool the permanent magnets (PMs) to cryogenic temperature (non-baking approach). A cryogenic permanent-magnet undulator uses the non-baking strategy while operating the undulator at cryogenic temperatures. The rate of outgassing from permanent magnets is very low as the low-temperature magnets and in-vacuum girder act as cryo-pumps.

The development project of TPS-CPMU, CU15, began in 2016 in collaboration with NEOMAX Engineering, Japan. In 2019, the CPMU has been completed and installed in the storage ring of the TPS; the development of related techniques with performance of the CPMU is described below.

Technical Challenges of TPS-CPMU
Several techniques have been developed for the TPS-CPMU, including a new grade PrFeB permanent magnet material with high remnant fields, a mechanical frame with force-compensating spring modules, a temperature-control system on the permanent magnets, a cryo-cooler to compensate for diverse sources of heat loads and compatibility with storage ring ultra-high vacuum standards. When PMs are cooled to 80 K, a CPMU can generate effective magnetic field of 1.02 T at a gap of 5 mm. The target is a minimum magnetic gap of 4 mm with an effective magnetic field of 1.32 T. Table 1 summaries the main parameters of the TPS-CPMU. The expected brilliance energy spectrum is shown in Fig. 1. Compared to a standard undulator (such as an in-vacuum undu-