Experience in the Operation of Taiwan Photon Source

TPS strove toward reliable and high-performance user operation for both experimental use and beamline commissioning on March 24, 2016, just seven months after the installation of two superconducting radio frequency (SRF) cavities and ten insertion devices in seven phase-I beamlines. Four 6-m standard straight sections and three 12-m long straight sections accommodated the ten insertion devices; the six-fold symmetry was replaced with a three-fold symmetrical lattice configuration, the double-minimum β_Y (DMB) lattice. The DMB lattice assured the designed low emittance to provide extremely high brilliance and a high flux for beamline experiments. **Figure 1** shows the optical function of the DMB lattice in 1/3 circumference of the storage ring. The seven in-vacuum undulators (IU) allow a gap of the magnet array down to 7 mm; two elliptical-polarization undulators (EPU) of period length 48 mm and one EPU of period length 46 mm allow a gap of the magnet array down to 13 mm and 14 mm respectively. The optical functions and horizontal emittance of the electron beam at the position of insertion devices determine the photon beam sizes and divergences. A decreased horizontal emittance can provide a photon source with smaller size for nano-focusing applications. **Table 1** presents an overview of β function, electron beam size (rms) and divergence of the electron beam at the centers of ten insertion devices.

Table 1: Overview of β function, electron beam size (rms) and divergence of the electron beam at the center of ten insertion devices of seven phase-I beamlines

Port		β_x/m	β_y/m	σ_x / μm	σ_x' / μrad	σ_y / μm	σ_y' / μrad
05	IU22	5.36	1.75	121.64	17.28	5.28	3.03
09	IU22A	10.47	1.79	164.18	13.75	5.35	2.99
	IU22B	11.01	1.96	167.31	13.75	5.59	2.99
21	IUT22	5.36	1.75	121.64	17.28	5.28	3.03
23	IU22	5.34	1.73	121.02	17.29	5.26	3.04
25	IU22A	10.47	1.79	164.18	13.75	5.35	2.99
	IU22B	11.01	1.96	167.31	13.75	5.59	2.99
41	EPU48A	10.16	1.84	162.67	13.75	5.43	2.99
	EPU48B	10.41	1.79	163.88	13.75	5.35	2.99
45	EPU46	5.36	1.75	121.64	17.28	5.28	3.03

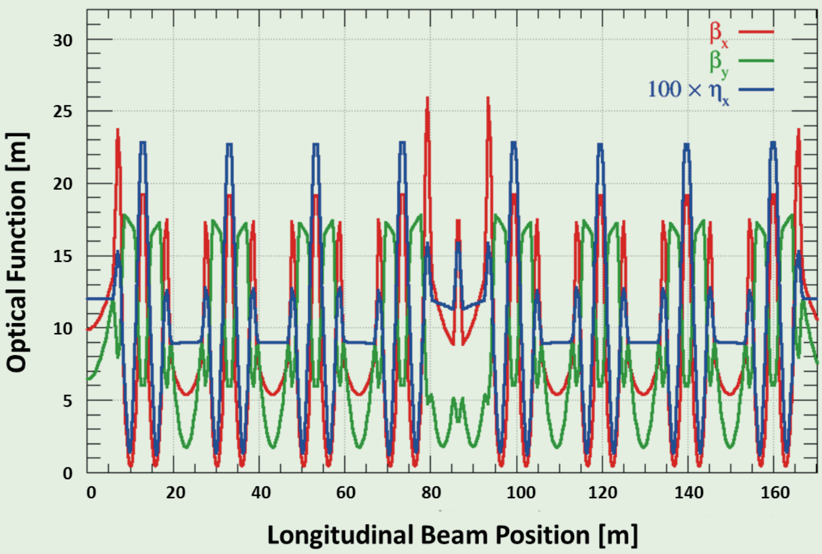

Fig. 1: Optical functions of 1/3 storage ring with distributed dispersion and low emittance.

Operation in top-up mode and hybrid mode

The top-up operation is an essential requirement for facility users in a third-generation light source. The advantages of top-up operation include quasi-constant stored beam current, a large and steady photon flux on average and no interruption for stored-beam reinjection. The steady photon flux contributes a constant heat load to optical components of the beamline and provides a thermal equilibrium environment for accurate measurements.

TPS began top-up operation at 150 mA with 1.3% relative beam-current stability on March

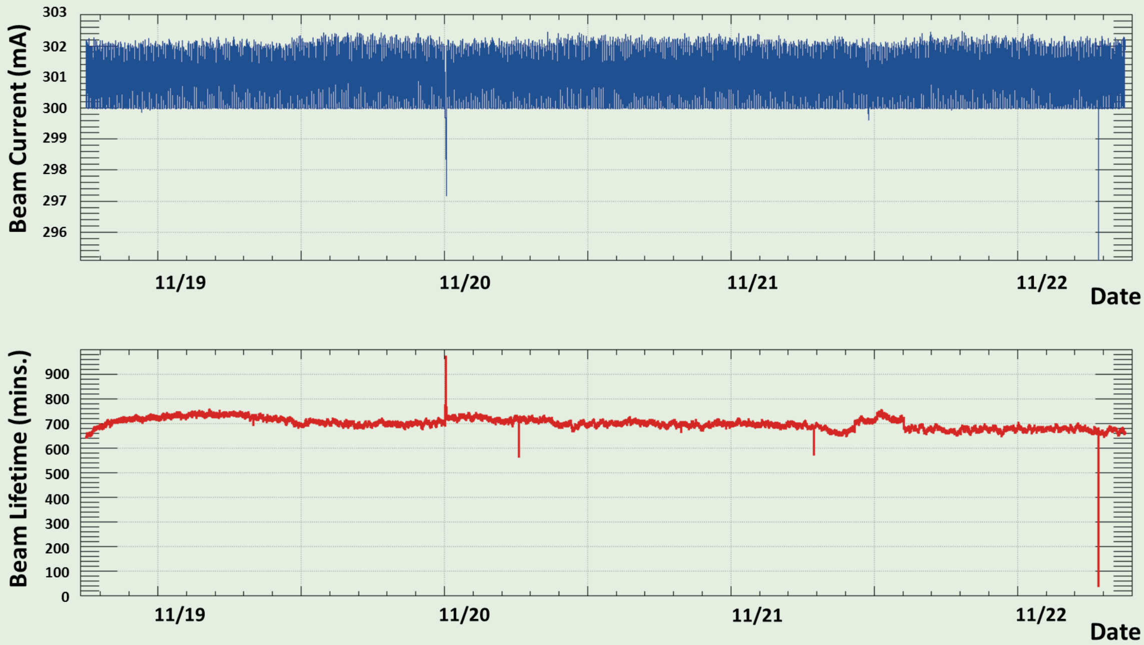

Fig. 2: Beam current stability and beam lifetime of top-up operation at 300 mA. The decreases in the beam current resulted from the trips of the third LINAC modulator.

24; the limitation of the stored beam current resulted from a radiation hot spot in the vicinity of experimental hutch **TPS 09**. After reinforcing the radiation shielding in the beam collimator to fulfil the dose limitation, 2 μSv per 4 h, of the radiation safety requirement for top-up operating mode, the stored beam current gradually increased to 300 mA with 50-mA increments per week from May 12.

TPS initiated top-up operation at 300 mA with 0.66% beam current stability in May; the beam lifetime was about 5 h. A refilling was triggered when the stored beam current was less than 300 mA and was terminated when the stored beam current achieved 302 mA. The stability of the beam current and refilling during the top-up operation at 300 mA are shown in **Fig. 2**.

The beam lifetime, 5 h at 300 mA, was less than the calculated total beam lifetime, 14 h, at 400 mA. Several efforts were implemented to enhance the beam lifetime, including changes of working points and chromaticity, and replacement of the vacuum chamber of the 8-mm full height by one of 20-mm full height with 8-mm tapers at both ends located at Port 41, one of the DMB long straight sections. After that, the beam lifetime could be about 12-16 h at varied gap widths of ten insertion devices. There are two filling modes in top-up operation: 75% filling (650 buckets) and 75% filling with an isolated single bunch of 2 mA at the center of the beam gap (hybrid mode). In the hybrid mode, the bunch current of an isolated single bunch is more than four times that of other bunches. The greater single bunch current was achieved with greater vertical chromaticity.

The injection efficiency is defined as the ratio of charge increase in the storage ring to the delivered charge from the booster. The injection efficiency is improved on matching the optics of the transfer line to the designed value at the entrance of the storage ring, on fine-tuning the launch condition, and with a 45-s dry run of power supplies of extraction pulsed magnets. With these efforts, the injection efficiency varied between 80% and 100% with a strange distribution of bucket addresses.

Because of the regulations regarding radiation safety, the schedule of raising the stored beam current to 500 mA became separated into three stages. The first stage was to obtain an operating license for 300 mA; the beam current then became raised to 400 mA after the approval of an operating license for 400 mA. The final stage would be 500 mA. The top-up operation with 400 mA was implemented in 2016.

Operating procedures

Several procedures are now in use or under test to ensure a reliable performance of the beamlines. A diagnostic beamline consists of a visible synchrotron radiation interferometer and an X-ray pinhole charge-coupled device (CCD) camera used to measure the beam size of X-rays emitted from a bending magnet. The diagnostic beamline can measure the electron-beam emittance from optical functions at

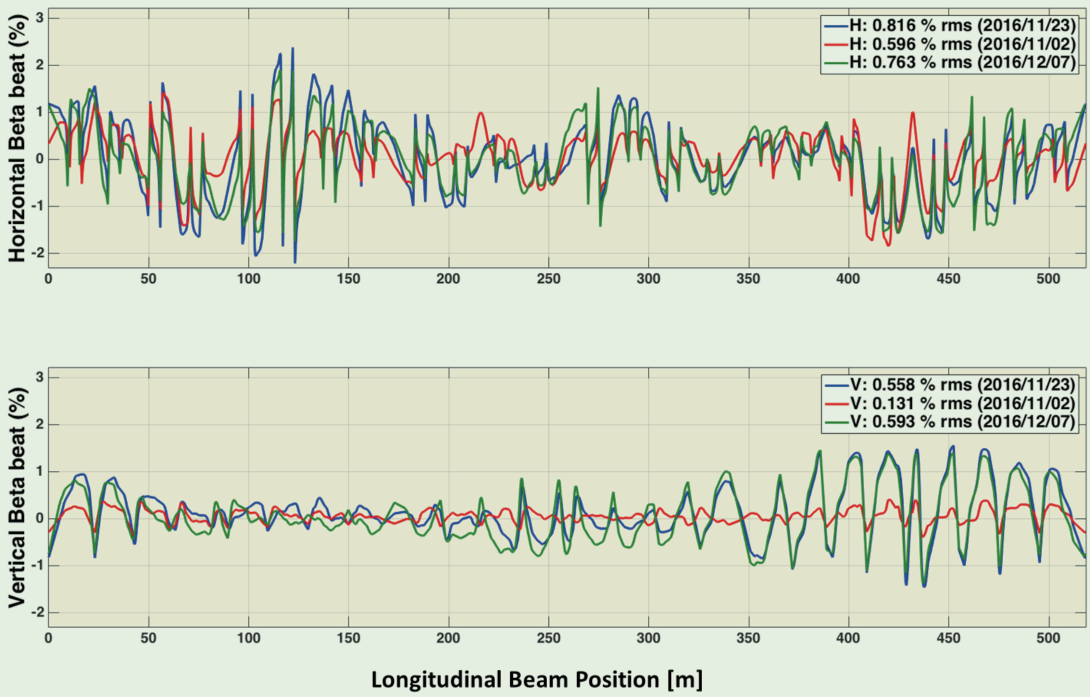

Fig. 3: Three consecutive β beat measurements show that LOCO should be performed every month for daily operation.

the source point and the measured beam size. The measured horizontal emittance and vertical emittance are 1.64 nm rad and 15.7 ± 3 pm rad respectively. The measured emittance-coupling ratio is 0.96%. This result agrees satisfactorily with the natural emittance 1.6 nm rad with coupling ratio 1%. The linear optics of the storage ring are corrected with a widely used algorithm linear optics from closed orbit (LOCO). LOCO is used to calibrate linear optics to maintain the symmetry of the lattice and the working tunes. **Figure 3** shows that the LOCO should be performed every month for daily operation.

Another procedure is a beam-based alignment (BBA), which is used to determine the field center of the quadrupole magnets of the storage ring, then to align the mechanical center of a nearby beam position monitor (BPM) to the field center of the quadrupole magnet. An undulator spectrum optimization is performed to align the trajectory of the electron beam through the center of the magnetic field of an insertion device (ID) to the beamline detector. Re-alignment of the field center of an ID to the field center of both side quadrupole magnets occurs when offsets exist. The undulator spectra after performing the optimization procedure are shown in **Fig. 4**.

The position and angle of a photon source from an ID is determined with BPM located at both ends of an ID. The reference orbit is obtained with a BBA and the results of undulator spectrum optimization. To eliminate the current dependence of the BPM electronics and the possibility of damage from synchrotron radiation to an in-vacuum undulator, stored beam current 30 mA is chosen for beam-based measurements, spectrum optimization and orbit correction. All above operating procedures are in use to achieve reliable performance of the storage ring and a stable photon source from an ID, which results in the reproducibility of the beamline performance.

Beam stability

The criteria of the stability of the photon beam in present use are characterized by the behavior of the electron beam, which include optical

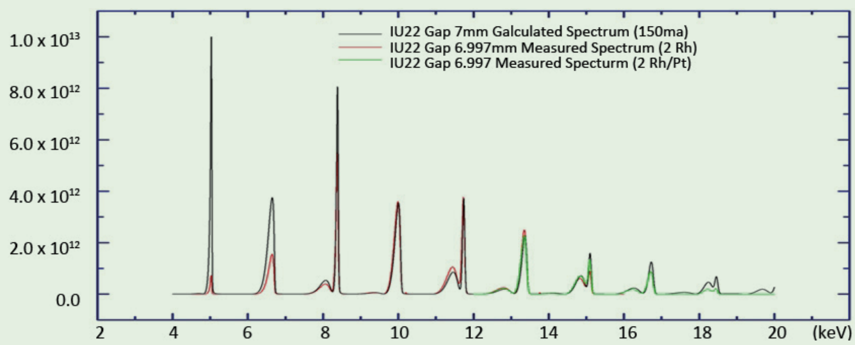

Fig. 4: Measured and theoretical undulator spectra.

functions, horizontal position and angle, vertical position and angle, beam energy, and revolution period. Variation of the electron beam size, a change of the electron orbit or a change of the stored beam current causes instability of the photon beam. The challenge is to stabilize the motion of the electron beam to meet the stability criteria of the photon beam in long-term user operation.

By means of operating procedures, we strive to maintain the reproducibility of lattice functions, electron-beam size, position and angle of the photon source. We exerted efforts also to identify the source of an instability of the electron beam, and then to minimize that instability on decreasing the flow rate of cooling water for the vacuum chamber from 10 L/min to 6 L/min, which decreased the vibration (10-50 Hz) of the vacuum chamber that contributes to the beam fluctuation. A radio frequency (RF) feedback was implemented to compensate the variation of the circumference of the storage ring due to the tide (~12 h) and the diurnal variation of temperature. The feed-forward table for each ID is used to decrease the orbit distortion when the gap width of an ID is altered. The fast-orbit feedback (FOFB) and bunch-by-bunch feedback (BBF) can cure the residual orbit distortion from the movement of an ID, the noise of a power supply and the collective beam instability. **Figure 5** shows the overall performance with feed-forward tables of ID and FOFB.

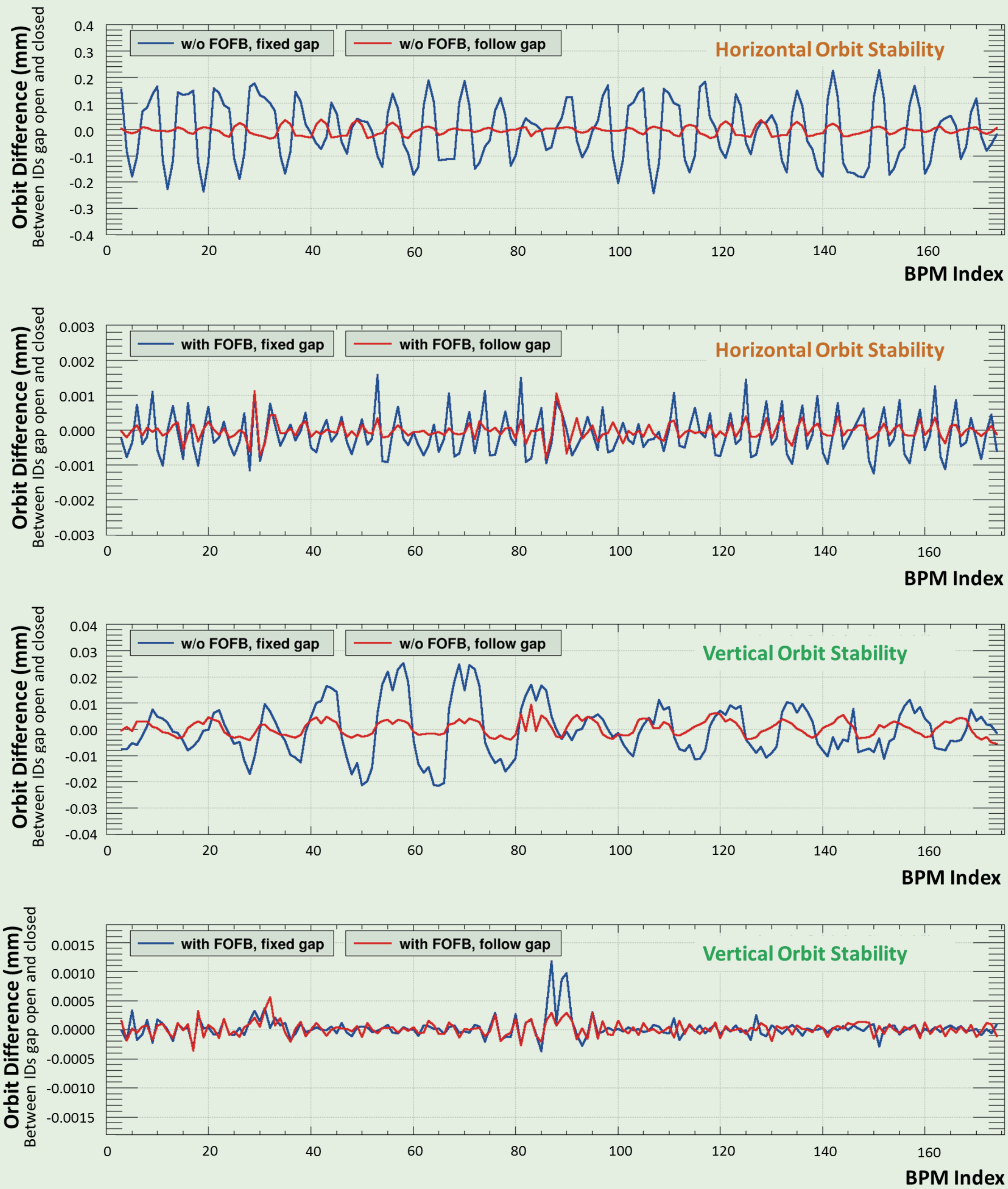

Fig. 5: Overall performance with feed-forward tables of ID and FOFB.

Operational performance

In a third-generation light source, high-power synchrotron radiation causes thermal damage to insertion devices and vacuum chambers. A well protected 3-GeV storage ring delivers synchrotron radiation with a smaller source size to the high-energy X-ray science beamlines and nothing outside it.

The system for machine protection consists of vacuum-system protection, front-end and beamline protection and an active orbit-interlock system. The orbit interlock has been activated several times because of a large horizontal oscillation of the beam from an injection transient, which resulted from a large stray field of a septum or a mismatched injection kicker. Altering the threshold of the horizontal orbit interlock from 1 mm to 3 mm can prevent an activation of this kind. We implemented an appropriate protection of ID with a tight threshold, the vertical orbit interlock of beam position offset 0.2 mm in the BPM on both ends of ID and adjacent upstream dipole magnets. With the above considerations we achieved a reliable performance and machine protection.

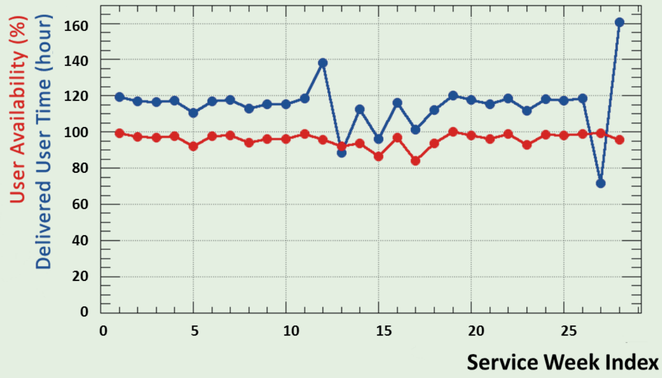

Fig. 6: Statistics of weekly user beam availability.

To understand the performance of an accelerator facility, it is essential to measure the three key parameters of the machine operation – user beam availability, mean time between failures (MTBF) and mean time to recovery (this value is not provided here because of large deviations of the injection time). The scheduled beam time for users of TPS in 2016 was 3351 h; the delivered beam time was 3211.07 h. The beam availability, 95.82%, for the first year of user operation, just met the typical requirement of user beam availability. The MTBF was 52.35 h according to 64 faults in total. The weekly statistics of user operation appear in **Fig. 6.**

The goals of failure analysis are to develop a program for preventive maintenance and to improve the reliability of subsystems. **Table 2** presents the categories of the 64 faults.

Table 2: Failure categories

Machine protection				Pulser	RF	I&C	OP	Other	PS
Magnet	Vacuum	Beamline & FE	Orbit interlock						
5	1	9	5	4	17	6	2	8	7

An error of fast orbit feedback system (FOFB) of any kind has been counted as downtime during the user period from March 24 to June 28. Seventeen faults are attributed to errors from the RF group; four faults were caused by a too small tolerance of the interlock threshold of the low-level radio frequency (LLRF) after parameter adjustment of the machine study in week 16 of **Fig. 6**. The machine protection was triggered 20 times, which implies much scope for improvement. The six trips caused by malfunction of BPM051 electronics are attributed to the I&C group. Seven trips are attributed to other sources, including two earthquakes, two voltage sags, and four unknown trips. We shall focus on these four similar unknown trips to discover the root causes. (Reported by Yi-Chih Liu)