

Fig. 7: Ratios of beam trips for the TPS accelerators in 2025 (21 trip events in total).

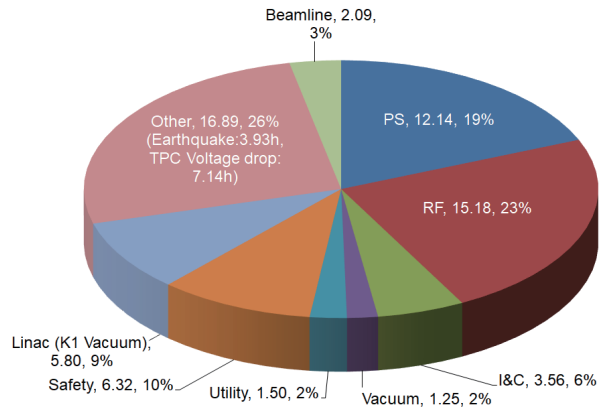


Fig. 8: Proportions of downtime in the TPS accelerators in 2025 (64.73 hours in total). The major downtime contributors are as follows: RF, 15.18 hours; Other, 16.89 hours; PS, 12.14 hours; and Safety, 6.32 hours.

Downtime and Failure Analysis of the TPS

In 2025, there were 21 beam trips and a total of 64.73 hours of downtime. **Figures 7 and 8** illustrate the contributions of each subsystem within the TPS facility to these beam trips and downtime. The PS and SRF subsystems were the most frequently involved in these incidents. The higher failure rate of the SRF system is attributed to sensor aging, solid-state module damage, and cooling system leakage, all resulting from prolonged operation at a high current of 500 mA. Nevertheless, excluding trips caused by earthquakes and unexpected voltage drops by TPC, the overall reliability of these subsystems has significantly improved in recent years, enabling stable operation and extending the MTBF. (Reported by Hung-Jen Tsai)

Feasibility Study for TPS Upgrade: 6BA Solution

The Taiwan Photon Source (TPS) has been in successful user operation since 2016, delivering high-brightness synchrotron radiation source for diverse scientific purposes. Considering that the typical lifecycle of a storage-ring light source is 20–30 years, NSRRC has initiated a feasibility study for upgrading TPS to a next-generation, referred to as TPS-II.

Motivation and Design Concept

TPS is a 3 GeV, 518.4 m storage ring housed in a common shielding tunnel with its booster. It provides synchrotron radiation spanning from soft to hard X-rays, achieving a peak brightness of approximately 10^{21} photons/s-mm²-mrad²-0.1%BW at 10 keV. While the primary objective of the upgrade is to enhance scientific capabilities, energy sustainability is also a key motivation. The new lattice aims to reduce beam emittance by at least tenfold compared to TPS, resulting in an order-of-magnitude increase in its brightness and coherence fraction. This would allow for shorter sampling times, higher data throughput, and more efficient experiments.

The study focuses on an upgrade constrained by the existing tunnel. The tangential angle of all beamlines must remain unchanged to preserve the utility of existing experimental hutches. The straight sections must remain longer than 5 m to accommodate current insertion devices and RF modules. This compact design necessitates combined-function magnets, compact beam position monitors, and Non-Evaporable Getter (NEG)-coated vacuum chambers. Permanent magnets are planned for use in the arcs, which would not only create essential space for vacuum and diagnostic components but also significantly reduce power consumption. To maintain operational flexibility, the quadrupoles adjacent to the straight sections and the multipoles along the ring will remain electromagnets. Additionally, to ensure beamline performance, longitudinal-gradient bends— in which the center field is higher— are incorporated at the specified angle. This study follows the successful third- to fourth-generation upgrades, such as ESRF-EBS,¹ APS-U,² and SLS 2.0,³ which adopted the MBA⁴ or HMBA⁵ concepts.

Toward Ultra-Low Emittance: Strategic Choices and Estimated Performance

To identify the optimal path, the team evaluated various lattice configurations, balancing competing scientific, engineering, and facility constraints. Although minimizing beamline realignment is desirable, maintaining the storage ring circumference is critical to avoid the consequential RF synchronization risks. Additionally, feasible magnet strengths are essential for realistic manufacturing and reliable operation.

Prioritizing long-term competitiveness and machine robustness, the 6BA lattice was selected as the primary candidate. This configuration offers a strategic balance: by releasing the strict constraint on source-point offset, a robust lattice can be achieved while retaining the circumference and using feasible magnet specifications. This approach ensures beam stability and high brightness, in addition to freeing up essential space in the arcs for vacuum and diagnostic systems. **Figure 1** depicts the optical functions of the arc connecting the short and long straight sections. The main parameters of the 6BA candidate are summarized in **Table 1**. The error-free lattice has a dynamic aperture (DA) exceeding 7 mm, which is adequate for off-axis injection. The estimated lifetime reaches 9.6 h when operating at chromaticity (1, 3) and assuming a physical aperture with a radius of ± 8 mm in the error-free model.

As beam emittance approaches the diffraction limit, intrateam scattering (IBS) remains a bottleneck. Analytical estimates indicate that for a 3 GeV beam with 1.036 nC per bunch, IBS increases the emittance and energy spread by a factor of two when the natural emittance is suppressed below 100 pm-rad. To mitigate this, a third-harmonic

cavity and dedicated coupling control are adopted. Upon lengthening the bunch by a factor of three and maintaining a 10 pm-rad vertical emittance, IBS-induced emittance growth can be constrained to 8–25% for natural emittances between 60 and 110 pm-rad.

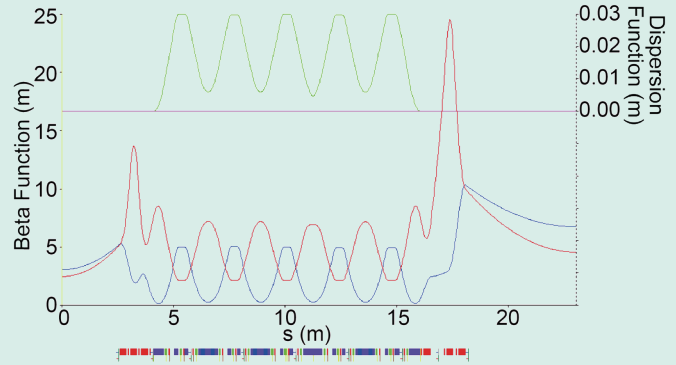


Fig. 1: Optics function of the proposed 6BA lattice. The arrangement of elements is depicted using different colors: blue for dipoles, purple for combined dipoles, red for quadrupoles, and green for sextupoles.

Table 1: Main parameters of TPS and TPS-II.

	TPS	TPS-II 6BA
Emittance (pm-rad)	$\epsilon_0 = 1600$	$\epsilon_0 = 67 \rightarrow \epsilon_x = 83^*$
Energy Spread	8.86×10^{-4}	$8.49 \times 10^{-4} \rightarrow 1.01 \times 10^{-3}^*$
Tune	(26.15, 13.23)	(66.81, 19.74)
Chromaticity	(-75, -29)	(-119, -86)
Momentum compaction Factor	(2.4, 0.21)	(0.61, 2.43)
Damping Time (ms)	(12.2, 6.1, 6.1)	(12.3, 19.6, 14.0)

* with the inclusion of IBS, $\kappa = 12\%$, and a harmonic cavity that stretches the bunch length by a factor of three.

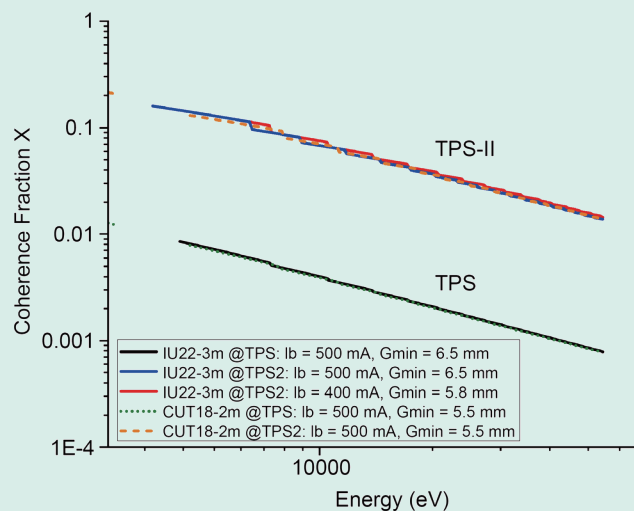
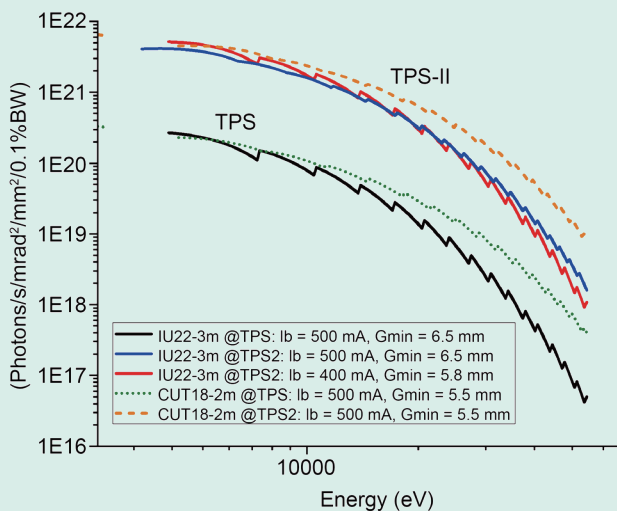


Fig. 2: Estimated performance in brightness and horizontal coherence fraction, assuming a horizontal beam emittance of 94 pm-rad and a coupling coefficient of 10%. [Courtesy of Jui-Che Huang]

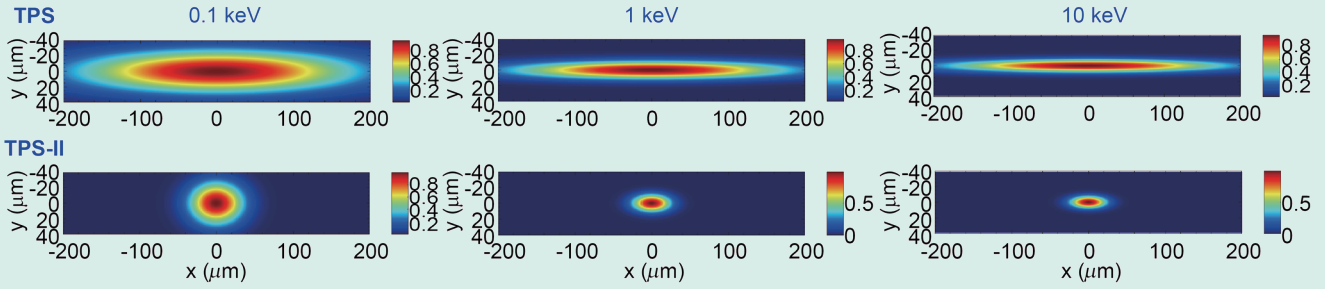


Fig. 3: Photon beam profiles estimated using an undulator at different photon energies for TPS and TPS-II, assuming the same 4 m undulator.

Assuming a horizontal beam emittance of approximately 100 pm-rad, Fig. 2 shows the estimated brightness and coherence fraction in the hard X-ray region. TPS-II brightness is projected to exceed 10^{21} photons/s/mm²/mrad²/0.1%BW, with a corresponding increase in horizontal coherence fraction.

Figure 3 illustrates the estimated photon beam profile from undulator radiation, which evolves from a flat to a nearly round profile, shrinking from approximately 120 to 15 μm (horizontal projection) at 10 keV.

Lattice Optimization and Dynamics

To construct a robust lattice, a new strategy was developed to control amplitude-dependent tune shift while improving dynamic aperture with minimal degradation of momentum acceptance. This was achieved by allocating weak sextupole components within the dipole center.⁶ A unique advantage of this design is the elimination of harmonic multipoles. As a result, the optics near the insertion devices becomes simpler, which allows for independent control of straight sections and improves overall flexibility. Frequency map analysis (FMA) indicated that the dynamic aperture improved significantly from the baseline to the proposed configuration (Fig. 4). The density of the tune footprint increased, and the stable region expanded. The feasibility of incorporating sextupole components within the combined dipole is being evaluated, and further nonlinear optimization with realistic machine errors is ongoing.

Supporting Technologies in Development

Parallel to lattice development, several key technologies are actively being developed. These efforts provide the essential foundation for future TPS upgrades.

- Permanent-magnet technology: facilitates the development of stable, energy-efficient magnet systems.⁷

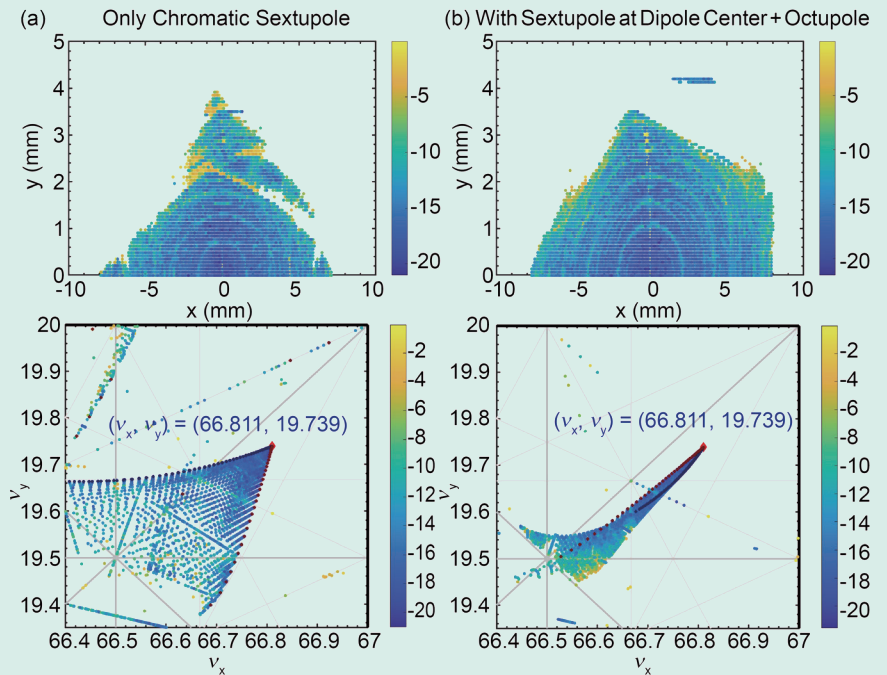


Fig. 4: Tracking the FMA and tune footprint of the 6BA lattice, comparing (a) the baseline configuration and (b) the preliminary proposed configuration.

- Nonlinear injection kicker: allows for off-axis top-up injection with minimal disturbance to the stored beam.⁸
- NEG coating: provides distributed pumping for small-aperture vacuum chambers.⁹
- Passive third-harmonic superconducting cavity: supports bunch lengthening, increased lifetime, reduced heat load, and enhanced beam stability.¹⁰

Outlook and Next Steps

Globally, storage-ring upgrades are trending toward ultra-low emittance and high coherence. As shown in Fig. 5 (see next page), TPS is well positioned to follow this trend. Future efforts will focus on (1) integrated lattice optimization by incorporating realistic magnet and alignment errors; (2) dedicated coupling control and systematic studies of injection schemes; (3) evaluation of low-alpha lattice impacts and the corresponding countermeasures; and (4) most importantly, continuous engagement with beamline scientists and engineers to refine scientific requirements and technical constraints.

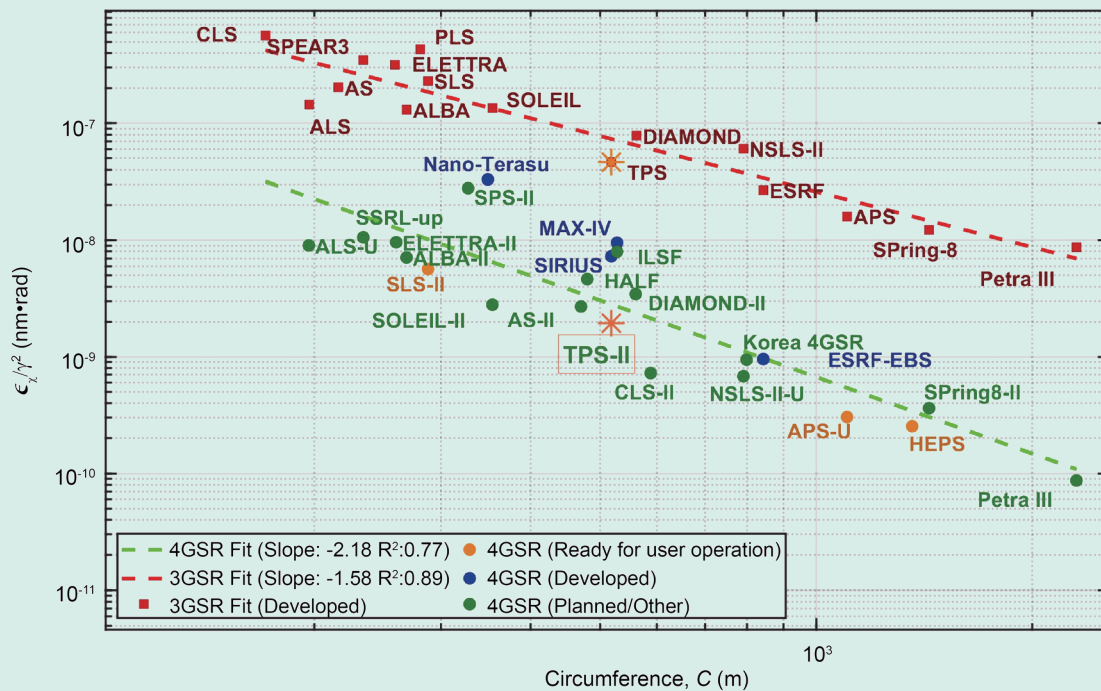


Fig. 5: Statistics of storage rings worldwide showing energy-normalized beam emittance versus circumference. Data compiled from public resources, CDRs, technical reports, and conference proceedings, as of December 2025.

With collaborative efforts throughout the NSRRC, TPS-II can become a next-generation synchrotron source that supports NSRRC's mission to enable cutting-edge research. (Reported by Nuan-Ya Huang)

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