Taiwan Photon Source Delivers its First Synchrotron Light

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Recently the National Synchrotron Radiation Research Center (NSRRC) in Taiwan has successfully constructed a low-emittance 3 GeV synchrotron, the Taiwan Photon Source (TPS). This light source with a circumference of 518 m is a large experimental facility for multidiscipline cutting-edge research in photon science. The initial proposal of the TPS project to the Taiwanese government was first made in 2004. Civil construction of TPS began in February 2010, and was completed in December 2013. Fig. 1 displays an aerial photograph of NSRRC, showing the just- completed TPS and the 21-year-old Taiwan Light Source (TLS). The TPS project came to realization after ten years of efforts.

After resolving the problem of the residual magnetic fields of vacuum chambers in the booster ring, the TPS commissioning proceeded at a speedy pace. In the early afternoon on the last day of 2014, TPS delivered its first synchrotron light at the design energy of 3 GeV shown in Fig. 2. The electron current circulating in the storage ring had surpassed 100 mA as of early February 2015, creating a world record for the fastest commissioning of an advanced accelerator light source. It indicates that the design of the accelerator systems, the quality control for the subsystems, the alignment of all the components, integrated diagnostics and control systems, and the various types of magnets were of the highest standards, as indicated by the speedy commissioning of the synchrotron storage ring.

TPS is designed to emphasize electron beams of low emittance and great brilliance. It aims to be one of the world's brightest synchrotron X-ray sources to explore new scientific opportunities. The completion of TPS

Fig. 1: An aerial photograph of the NSRRC site showing the newly completed TPS (the larger ring) and the existing TLS (the smaller ring).

Fig. 2: The first light from the TPS storage ring with a 3 GeV electron beam delivered on December 31, 2014.

Beamline	Energy	Key features	Typical experiments
Protein micro-crystallography	5.7 – 20 keV	• highly precise and rapid rotation, remote access • micro-diffractometer • on-axis sample video • highly accurate, high-speed, large area detector • real-time computing system • automatic crystal screening and shutterless and shuttered data collection	• microbeam and standard-beam protein crystallography • single-wavelength & multi-wavelength anomalous dispersion phasing • ultrahigh-resolution, ultralow-temperature, and high-throughput, large-unit-cell crystallography
Soft X-ray scattering	0.5 – 1.2 keV	• highly efficient high resolution active gratings • resolving power $E/\Delta E$: ~ 45000 • second branch: coherent soft X-ray scattering	• momentum-resolved RIXS • high-resolution low-energy electronic excitations • coherent soft X-ray scattering • soft X-ray ptychography
Submicron soft X-ray spectroscopy	0.4 – 1.5 keV	• resolving power $E/\Delta E$: ~ 35000 • submicron beam spot size	• high resolution photoemission • polarization-dependent X-ray absorption • emission/resonant inelastic X-ray scattering • X-ray excited optical luminescence
Coherent X-ray scattering	5.5 – 20 keV	• 12 m from sample to detector • large frame rate of a noiseless detector • variable X-ray beam size and coherent flux to minimize radiation damage	• X-ray photon correlation spectra • coherent diffraction imaging • small-angle X-ray scattering • grazing-incidence small-angle X-ray scattering
Submicron X-ray diffraction	7 – 25 keV	• beam spot: < 100 nm • pink or mono- beam mode • vacuum or ambient sample • SEM probe	• differential-aperture X-ray microscope Laue diffraction • scanning transmission X-ray imaging • X-ray excited optical luminescence
X-ray nanoprobe	4 – 15 keV	• Montel nested KB mirrors • horizontal geometry DCM • resolution $\Delta E/E$: ~ 2×10^{-4} • ultimate focal spot of ~ 40 nm • SEM probe and optical microscope	• X-ray fluorescence • X-ray absorption fine structures • X-ray excited optical luminescence • projection X-ray microscope • Bragg ptychography
Temporally coherent XRD	5.6 – 25 keV	• ultra-high-energy resolution $\Delta E/E$: ~ 10^{-8}	• X-ray cavity • two-color pump and probe • magnetic X-ray scattering • thin-film scattering

Table 1: Summary of the TPS phase-I beamlines.

represents Taiwan's capabilities in advanced accelerator technology and photon science, and it is a truly wonderful accomplishment and a source of national pride in Taiwan. TPS will provide X-rays with spectral brilliances of 2–5 orders greater than those of the existing 1.5 GeV Taiwan Light Source. The characteristics of TPS will open up tremendous possibilities for research in physical science and biological science, and further the development of semiconductors, nanotechnology, and pharmaceuticals in Taiwan.

The TPS storage ring is composed of 24 double-bend achromatic (DBA) cells connected by six 12 m straight sections and eighteen 7 m straight sections. The TPS lattice can accommodate 23 insertion devices (IDs) because one straight section is completely used for injection. The natural emittance of TPS is a 1.6 nm rad with a small dispersion in the straight sections. In phase-I operation, TPS will use two sets of KEK-B type superconducting RF cavities to achieve an electron current of 500 mA in a top-up injection mode and to diminish the high-order modes excited by the electron beam.

Seven TPS phase-I beamlines are currently under construction. Taking full advantage of the highly brilliant TPS, these seven beamlines aim for the forefronts of research in physics, chemistry, biology, and material science; they cover the diversity of photon science in an energy range from soft to hard X-rays. These beamlines are optimized for protein micro-crystallography, low-energy excitations of materials with atomic specificity, spectroscopy and diffraction on the submicron or nanometer scale, scattering of coherent X-rays, and scanning nanoprobe studies that will resolve structures with a 40-nm resolution. Table 1 presents a summary of the unique features and typical experiments of each beamline.

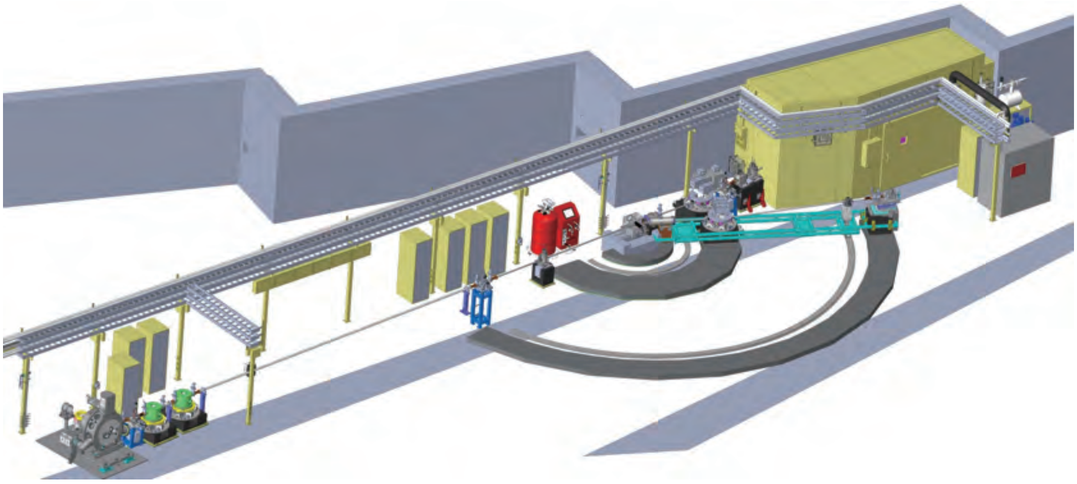

Fig. 3: Design of the AGM-AGS setup with a rotation mechanism of the spectrometer. The AGS grating chamber and the detector are independently positioned on granite slabs situated separately on two sliding platforms made of granite. Both the AGS grating chamber and the detector can be lifted 30 μm through an air-cushion mechanism such that the AGS can swing in the scattering plane about a vertical axis passing through the sample.

Six of the seven phase-I beamlines are scheduled to be completed by the end of 2015 and to be available for users in mid 2016. Once these beamlines and end stations are completed, many researchers will be able to conduct world-class research in many scientific fields with the bright X-rays generated by TPS. For example, the soft X-ray inelastic scattering beamline is an effective tool for fundamental research in condensed matter physics, particularly the electronic and magnetic properties of correlated electron materials. Below we briefly discuss its conceptual design.

Resonant inelastic X-ray scattering (RIXS), one of the most important experimental probes for studying strongly correlated materials, is a second-order photon-in photon-out process. Through measuring the energy changes of the scattered photons compared to the incoming photon, one can use RIXS to unravel material's momentum-dependent two-particle (electron-hole pair) excitations from which both occupied and unoccupied states are elucidated. RIXS gives rise to a measure of the electron or charge transfer dynamics involving multi-particle excitations. Advances in the technology of a synchrotron light source have enabled much improvement in the experimental techniques of RIXS in the soft X-ray regime. The spectral resolution E at the Cu L_3-edge has been improved from 1.6 eV at an early stage to about 0.1 eV. L-edge RIXS has proved effective in detecting charge, orbital and magnetic excitations. For instance, RIXS measurements unraveled the spin–orbital separation in a quasi-one-dimensional Mott insulator. A desirable resolution of RIXS would be about 30 meV, but an experiment to fulfill that resolution requires photon beams of a great brilliance and a highly efficient monochromator or spectrometer. In this beamline design, we exploit a novel design for a RIXS setup comprised of two bendable gratings, termed an active-grating monochromator (AGM) and an active-grating spectrometer (AGS), to enhance the efficiency of measurement of inelastic X-rays through an increased bandwidth of incident photons but without smearing the energy resolution of the scattered photons.

This AGM–AGS design has two prominent features: its scheme ensures that the scattered X-rays of an identical energy loss are dispersed and focused to the same point in the dispersion plane of the spectrometer grating, and a special multipoint bendable grating mechanism produces a unique means to diminish effectively the defocus and coma aberrations, hence improving greatly the spectral resolution. This beamline includes two branches for soft X-ray RIXS and coherent soft X-ray scattering. The arm lengths of the AGM and the AGS are, respectively, 6.5 m and 7.5 m, as illustrated in Fig. 3. The AGS spectrometer also incorporates a multilayer polarization analyzer and a high-resolution CCD detector, aiming to achieve a resolving power greater than 45,000 at 900 eV. The last phase-I beamline, the X-ray nanoprobe (XNP) beamline, will be completed in 2016 to provide nanometer-focused X-ray probes of atomic, chemical, and electronic resolutions to resolve structures with a spatial resolution down to 40 nm in tomographic and nonde-

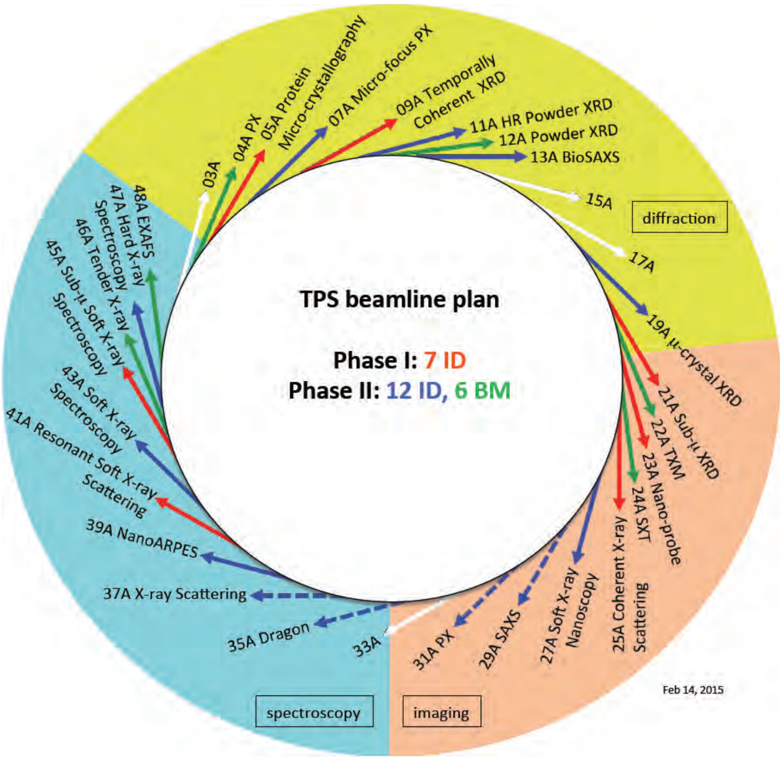

Fig. 4: Layout of the TPS phase-I and phase-II beamlines, grouped according to their major functions of spectroscopy, diffraction, and imaging.

structive manners. The major planned scientific projects of the XNP beamline mostly involve pioneering work closely related to practical semiconductor-based industrial applications. The NSRRC is also planning the phase-II beamlines, consisting of 12 beamlines with photons generated from undulators and 6 bending-magnet beamlines. According to their functions, the TPS beamlines, except for those extracting photons from the IDs at the downstream side of the superconducting RF cavities, are distributed in three sectors. The spectroscopy sector has beamlines that offer the main experimental techniques of X-ray absorption, inelastic X-ray scattering, and photoemission. Beamlines that emphasize scattering and diffraction techniques for determining the structures of materials or biological systems are grouped in the diffraction sector. The third sector is the imaging sector, which includes beamlines with the main techniques of full-field imaging based on absorption or phase contrast, scanning images with focused X-ray beams, or lensless imaging using coherent scattering. Fig. 4 displays the storage ring plan, which includes the seven TPS phase-I beamlines and the eighteen TPS phase-II beamlines scheduled to be completed by 2022. The first five TPS phase II beamlines are scheduled to be completed by 2018. They are: (1) soft X-ray tomography for imaging cellular structures; (2) extended X-ray absorption fine structures; (3) nano-scale angle-resolved photoemission spectroscopy; (4) small angle X-ray scattering for biological systems; and (5) high-resolution X-ray powder diffraction.

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