# STATUS AND FUTURE OF TAIWAN LIGHT SOURCE

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*Abstract*

The Taiwan Light Source of National Synchrotron Radiation Research Center (NSRRC) has reached a very stable operation condition and productive scientific outputs. The copper Doris RF cavities were replaced with a niobium Superconducting (SC) RF cavity in order to eliminate higher-order-modes and deliver higher beam current. Superconducting wigglers were installed to provide higher flux at higher photon energy. The storage ring is now operated at 300 mA top-up mode with better than 97 % of beam availability during users shifts. The original layout of the magnets has been greatly modified to accommodate one SC wavelength shifter at the injection section, one SC wiggler at the RF cavity section, and three SC wigglers in achromatic sections in addition to the original design of one wiggler and three undulators. In view of the future scientific demands, the NSRRC is proposing to construct a new synchrotron storage ring of 3.0~3.3 GeV and ultra low emittance, the Taiwan Photon Source (TPS). The TPS will provide brilliant X-rays at $10^{21}$ photons/s/0.1%BW /mm$^2$/mr$^2$ by SC undulator upon its completion, making it the brightest synchrotron light with the finest performance in the world.

## TOP-UP INJECTION

Several major upgrades are integrated into routine operation in Taiwan Light Source (TLS) in recently years. Top-up injection mode was achieved after series upgraded of injector, transfer line and injection components. The operation current of Top-up injection reached 300 mA during users shift. The commissioning [1] of the first and second Superconducting RF cavities (SRF) was very smooth and exceeded the specification in several measures. The first In-Archromat-Superconducting-Wiggler (IASW) was installed and commissioned successfully. The associated beamlines will be commissioned in the first quarter of 2007.

To reach the ultimate goal of third generation light source, TLS prepared all the necessary steps to provide top-up operation to the users. To improve the thermal relaxing problem of dipole magnets and cure the orbit drift during the energy ramping era at TLS, the injector was upgraded to have the capability of full energy injection to the storage ring. This provided an essential tool to evaluate the feasibility of top-up injection at TLS.

The top-up mode [2, 3, 4, 5] provides the best solution to the thermal variation of beamlines' optical components and locks the launching condition of the synchrotron light to end-stations. This greatly benefits those superconducting wiggler x-ray beamlines which have large thermal load on the optical components and take relatively long time to reach thermal equilibrium. In addition, these beamlines generally have high demands on the photon energy stability after the monochromator, and top-up mode offers the best solution to the short beam lifetime of a storage ring. Top-up injection also opens new opportunities in probing better operation conditions, for example, the lower emittance, the lower gap of insertion device, and the increase of bunch current without the need to worry the impact of beam lifetime.

Figure 1 shows the stored beam current in user's shifts with top-up injection mode. The maximum stored current sets to 302 mA. The zoom-in to one-hour period of stored beam current is shown on top of Fig. 1. The intensity variation of the stored current can be maintained within ±0.25%. During users' shifts, the injection time interval was set to 60 seconds due to low lifetime, around 250 minutes, of stored current.

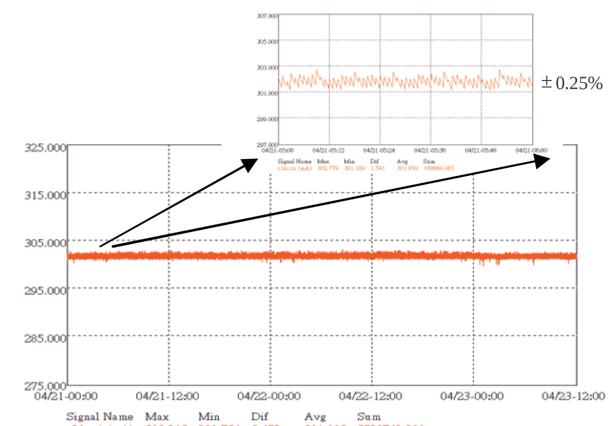


Figure 1: The standard operation of top-up injection and the zoom-in of current variation, ±0.25%.

To increase the transverse acceptance of the ring and have acceptable injection efficiency, the chromaticity is corrected to slight positive. Further help from the digital transverse feedback system, the transverse instability can be suppressed to the most minuscule range without scarifying the transverse acceptance and injection efficiency.

To ensure the radiation safety before switching to top-up operation, a series of radiation safety analyses including calculations and measurements were performed. Additional interlock logic has been integrated into the existing interlock system to prevent dipole failure, injection difficulty as well as excessive radiation exposure.

Six accumulation type dose meters were placed close to the shielding wall at straight sections, which tend to be the hot spots around the ring. The interlock system will be activated when the accumulated dose exceeds the threshold value, 4 μSv within 4 hours. All the surveillance results and the TLD readings of the staff and users in NSRRC demonstrate that the radiation safety measures have been effective and radiological impact to the personnel and environment due to top-up operation is minimum.

## SUPERCONDUCTING RF CAIVTY

A 500 MHz Superconducting RF cavity (SRF) of CESR-III design was installed and successful commissioned at the end of 2004. It started routine operation since February, 2005. The operational performance of the SRF module is impressive. The operating mode of storage ring also was upgraded from decay mode to top-up mode, and the beam current of routine operation was increased from 200 mA to 300 mA at the forth quarter of 2005. The RF system is operated under heavy beam loading with the loading factor of 4.2 at 300 mA. This results in feedback loops of low-level RF system potentially unstable for any change of the machine operational mode. The feedback loops of low-level RF system need to fine-tune to minimize the SRF trip due to potential unstable of feedback loop. The average trip rate, due to RF system fault, is once per week in the user beam shifts during 2005. It is an exceptional good record during the first year of SRF operation in accelerator community. The target of RF system reliability is less than one trip per month in average to fulfill the stringent requirement of TPS project.

The SRF module is powered by an in-house assembled 100kW RF transmitter. A 100 kW klystron, co-developed with manufacturer from standard 60 kW model, was installed into the RF transmitter. Theoretical estimation shows that there is sufficient RF power for storage ring operating at 400 mA of stored beam current. A 400 mA decay and top-up modes were demonstrated without any trips or instability during accelerator development shifts. The integrated RF plant did not experience any difficulty in operation with 400 mA.

The major R&D efforts of RF system are focused on the development of assembly capability of the SRF module, and the conceptual design of 2K cryo-plant for passive Landau cavity. In the meantime, the conceptual design of RF system for the proposing 3 GeV light source, with ultra-low emittance, at NSRRC has been conceived with emphasis on the impact of low momentum compaction factor and heavy beam loading on the performance and reliability of RF plant.

## CRYOGENICS SYSTEM AND SUPERCONDUCTING INSERTION DEVICES

There are three Superconducting Insertion Devices (SCIDs) and one superconducting RF cavity installed in TLS. Additional two SCIDs will be installed in the storage ring. It is crucial to have very stable cryogenic operation parameters for the SRF cavity due to the very high quality factor, Q, of the cavity. Small variation of return pressure of cold He gas or liquid helium level will induce frequency change of SRF cavity in the cryo-module. It is not a desirable solution in sharing the cryogenic system between SRF and SCIDs. The second cryogenic system is installed and dedicates to the SCIDs. Figure 2 indicates the infrastructure of the installed cryogenic system in experimental hall. The first cryogenic plant, MCP1, is dedicated liquid helium plant to the SRF cavity and the second plant, MCP2, provides sufficient cryogenic capacity for the SCIDs. Either MCP1 or MCP2 can provide cooling capacity of 450 W at 4.5 K and serve as the backup system to each other.


Figure 2: The infrastructure of installed cryogenic system in the experimental hall.

The commissioning of the switch valve box and the nitrogen-shielding liquid-helium transfer line completed in February 2005. The shielded transfer line is 100 meters long and situated above the tunnel of storage ring to supply liquid helium to five SCIDs. The second sets of compressor, the oil-removal module, and the frequency driver are installed in a vibration isolated room and sit in remote utility hall to suppress the vibration transmission to the storage ring.

The refrigerator and Dewar are located on a platform at height 2.8 m in the experimental area as shown in Fig. 2. A 2.5-inch discharge pipe and a return suction pipe with diameter of 8-inch, each with length of 160 m, connect the main compressor and the refrigerator. The commission of MCP2 was smooth and reached the specifications in 2006.

User community demands for high flux of hard x-ray source in the field of protein crystallography and advance material research in recent years. A Superconducting (SC) wavelength shifter with 6-Tesla field strength and a 3.2-Tesla SC wiggler were installed at injection section and RF section respectively. The beamlines were fully subscript associated with above SC insertion devices.

A 16-pole, 6.1 cm period IASW with field strength of 3.1 T was constructed in-house and installed between the first and second bending magnets of a Triple-Bends-Archromat (TBA) arc section, , as shown in Fig. 3. The design of the IASW is similar to that of the SW6. The inner horizontal and vertical aperture of the UHV beam duct is 100 x 11 mm to prevent the synchrotron radiation from heating the beam duct. The magnet gap is maintained at 19 mm to accommodate the thickening of UHV beam duct.

A 16-pole magnet was completed and tested in the vertical test dewar. A nominal field strength of 3.1 T was obtained at an excitation current of 264 A. The first and second integral field that is very consistent with the results of the 16-pole magnet measured in the vertical test dewar and the simulated field.

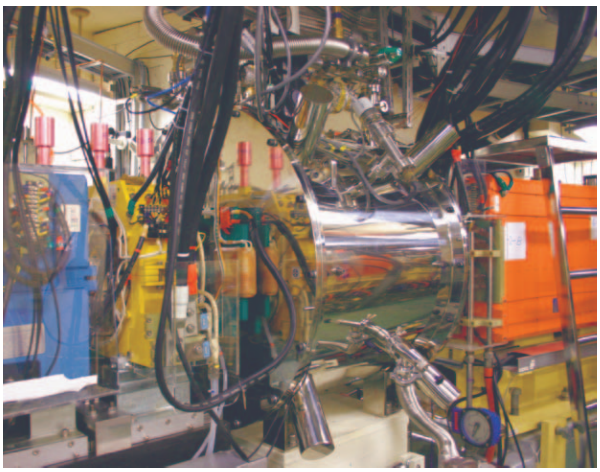

Figure 3: A superconducting wiggler installed between two bending magnets.

The first IASW was commissioned very successfully in March, 2006. The peak field was set to 3.13 Tesla during the measurement. Tune shift as function of excitation strength was measured and compared with theoretical model. Good agreement between measured and predicted values.

The excursion of closed orbit distortion from zero to maximum field (3.13 Tesla) is within acceptable range. There was no beam loss even when the IASW system tripped off. This indicates a very good field quality control during the manufacture process. Working tunes and the closed orbit distortions can be well corrected. The corrected user lattice of storage ring can successfully incorporate with the routine top-up injection mode without disturbing injection efficiency and beam stability. However, the IASW is installed in the dispersive region, which results in an increase of the beam emittance. From the synchrotron light monitor, the beam size information confirmed the prediction of the emittance growth.

## TUNE MEASUREMENT SYSTEM AND FEEDBACK SYSTEM

Online tune measurement using digital Beam Position Monitor (BPM) was implemented. There are three potential application modes for tune measurement system, which include top-up mode, spontaneous excitation without transverse feedback, and continuous excitation. The turn-by-turn information from the digital BPM, after Fourier analysis, gives precise results of the betatron tunes of storage ring. The monitor system will be very helpful to identify occasional beam-loss or beam instability during the users shift.

The closed-orbit of stored beam is perturbed by injection septum and the unbalanced injection kickers in storage ring during injection. The trigger signal of the turn-by-turn BPM synchronizes with the injection signal. Hence, the betatron tunes can be extracted from the turn-by-turn BPM every sixty seconds as top-up mode in operation.

Transverse instability is excited as the stored current exceeds the threshold current, several tens mA in TLS. The turn-by-turn BPM can extract the betatron tunes from the turn-by-turn BPM due to the spontaneous excitation without the transverse feedback system. It is a powerful tool to study the dynamic behaviour of transient perturbation to the accelerator.

The continuous excitation mode, triggered by white noise with narrow bandwidth, provides an effective tool for betatron tunes scanning when the stored beam current lower than the threshold current in the storage ring. Any of measurement modes can provide very accurate tunes measurement and the turn-by-turn information for dynamic analysis in the experiment of accelerator physics.

Multi-bunch instabilities may deteriorate beam quality, increase beam emittance, and even cause beam loss in the synchrotron light source. The feedback system is essential to suppress multi-bunch instabilities caused by the impedances of beam ducts, and trapped ions. A new Field-Programmable Gate Array (FPGA) based transverse and longitudinal bunch-by-bunch feedback system has been commissioned. A single feedback loop is used to suppress the horizontal and vertical multi-bunch instabilities simultaneously. Longitudinal instabilities caused by cavity-like structures are suppressed by the longitudinal feedback loop. The same FPGA processor is employed in the transverse feedback and the longitudinal feedback system respectively. Diagnostic memory is included in the system to capture the bunch oscillation signal, which can be used to support various studies

## RF AND PHOTOCATHODE GUN

Pre-Injectors with high brightness beam, especially RF guns, are critical sub-systems for new generation light sources. The superior performance and elegant configuration of a thermionic RF gun system made it an attractive option as a reliable pre-injector. In cooperate with an alpha-magnet as low energy bunch compressor, ultra-short electron beam pulses can be generated from an RF gun with thermionic-cathode. It can be used to generate intense and coherent short wavelength radiations, for example production of femto-second electron and ultra-fast X-ray pulses with tunable wavelength. Figure 4 shows the 3D assembly of a thermionic RF gun system.

The cathode assembly is installed at the end wall of the half-cell of the gun cavity and this cell is coupled to the full cell through a side-coupled cell. Klystron power will be fed into the cavity at the side wall of the full cell through an iris. When the field amplitude of the full cell approximately equals to two times that of the half cell, the electron beam has a linear energy chirp that is ideal for bunch compression with alpha magnet. Unloaded Q of the $\pi$ /2-mode under such cavity field ratio is about 9000.

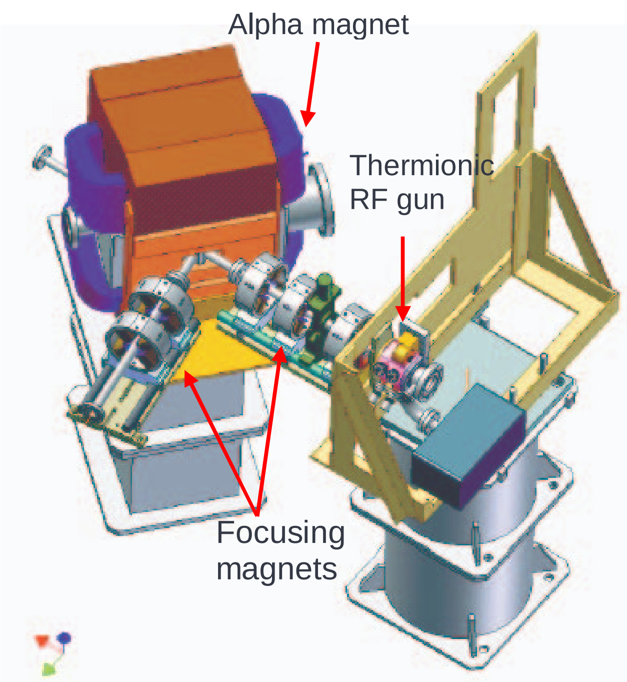


Figure 4: the 3D assembly of a thermionic RF gun system

An alpha magnet has been built and well tested by the magnet construction group. Field gradient at 450 G/cm has been achieved. The gradient of the magnet during normal operation will be at about 400 G/cm. The trimming of field near the beam entrance is in progress. The vacuum chamber of alpha magnet with momentum filter is to be built and put into the alpha. A beam transport system will be needed to guide the beam from RF gun exit to the entrance of alpha magnet, then from the alpha magnet to the S-band linac to reach the desired beam energy. The RF gun project intends to have a high brightness beam injector with future applications on (1) booster synchrotron pre-injector for TPS and (2) advanced accelerator and novel light source research.

## TAIWAN PHOTON SOURCDE

An intermediate energy synchrotron light source has been proposed. The goal is to construct a high performance light source in complementary to the existing 1.5 GeV ring in Taiwan. A 3~3.3 GeV machine with 486 m and 6 super-period DBA/QBA lattice structure is considered and other options are also investigated.

NSRRC Board of Trustee endorsed a new synchrotron light source with energy around 3 GeV to increase the research capacity, especially in the X-ray range. To best use of existing resource, fit into the existing site and to satisfy the user requirements, several configurations of the accelerator systems as well as the size of the storage ring have been discussed. One of the attractive configurations is a 6 super-period's ring with its circumference in 486 m. The site planning of the new ring is shown in Fig. 5 which is coloured in navy-blue.

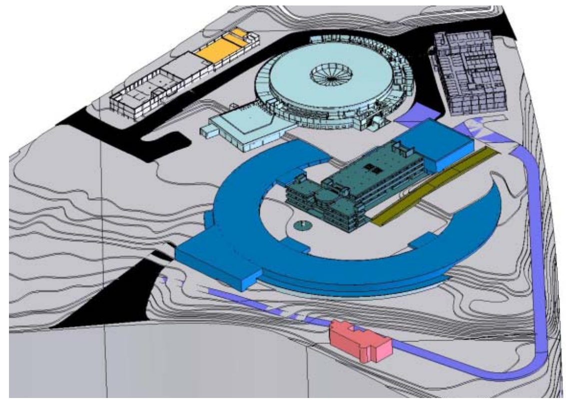

Figure 5: The planned construction site of the new storage ring which co-exists with the TLS.

A 24-cell Double Bend Achromate (DBA) [6] and 12-cell Quadruple Bend hybrid-Achromate (QBA) [7] structure will be the major focus in the coming optimization process. The linear lattice and frequency map analysis of non-linear effect of the DBA structure is shown in Fig. 6. By allowing slight positive dispersion in the long straights, the natural emittance of 1.7 nm-rad can be achieved. With a 6-fold symmetry configuration, the ring provides 6 long straights for injection, long IDs, and SRF modules. With different kind of insertion devices, the calculated brilliance with 1% emittance coupling is plotted in Fig. 7.

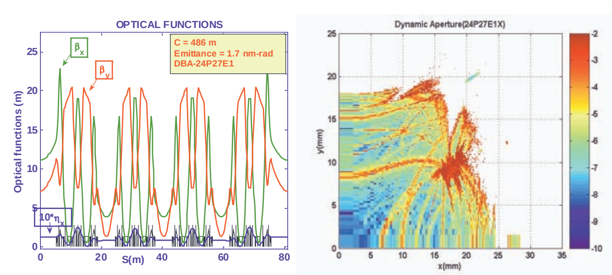


Figure 6: Optic functions of linear lattice and Frequency Map Analysis of a DBA lattice layout with 6-fold symmetry and 24-cells.

To correct chromaticity and to reduce the nonlinear effects we employ a sextuple scheme of 8 families. A sufficient large dynamic aperture, in both on-energy and off-energy particle cases, is obtained to ensure efficient injection and reasonable lifetime.

There will be more than 21 insertion devices in the ring and their effects on the beam dynamics are also investigated. We simulated beam dynamics effects with 21 planned insertion devices in the TPS. The beam dynamics effects such as tune shift, emittance changes, etc. are studied and the tracking results with these IDs show there are significant impacts on the dynamic aperture, but still acceptable.

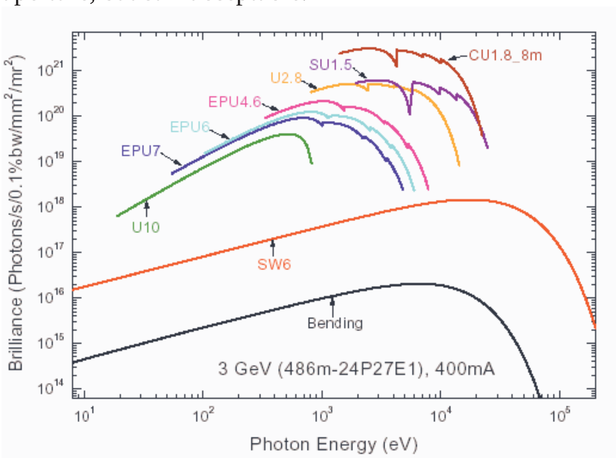


Figure 7: The calculated brilliance with 1% emittance coupling of a DBA lattice with distributed dispersion function.

Vertical beam size in the low emittance and small coupling ring can be less than 10 microns. Stringent request for small vertical beam orbit fluctuation within sub-micron range is necessary to keep the photon flux stable. One of these sources is the ground vibration. The maximum optics response to the plane ground wave in the vertical plane is less than 5 within 10 Hz and around 10 above 10 Hz with the help of girder supports. Careful ground motion control is needed in the facility construction planning. A sophisticated girder design is also necessary.

With the superconducting cavities, no coupled bunch instabilities are anticipated due to higher order modes from cavities. However, the small gap insertion devices can induce transverse instabilities and the impedance budget is also very low to avoid microwave instabilities. Lifetime is estimated to be larger than 10 hours for 5 mm vertical chamber size, 1% coupling, 1 nTorr vacuum, 0.6 mA bunch current and 3.5 MeV RF voltage.

An intensive study of QBA lattice was carried out. The optics function of linear lattice of QBA structure is shown in Figure 8 with the frequency map analysis. The QBA structure is an alternative dispersion and non-dispersion long straights configuration and the lengths of the inner dipoles is 1.5 longer than the outer dipoles such that the emittance can be further minimized. The dipole field strength of the QBA is lower than DBA so that the damping effect with high field IDs is stronger. It also means that the length for IDs of the QBA would be shorter than DBA. The natural emittance of the QBA is higher than DBA distributed-dispersion type but lower than DBA achromate type. With high field IDs, the effective emittance of the QBA in the dispersion-free straights can be smaller.

## SUMMARY

In order to improve the thermal relaxing problem during the energy ramping era at TLS, the injector was upgraded to have the capability to be full energy injection to the storage ring. To reach the ultimate goal of third generation light source, TLS has prepared all the necessary steps to provide top-up operation mode to the users. The TLS operates in top-up mode 100% in users shifts at 302 mA of stored current. The installation of SRF cavity also makes the ring have the capability to provide more photon flux with better beam quality to the users. The installation of SCIDs pushes the delivered photons to hard x-ray range in a 1.5 GeV storage. NSRRC is pursuing a much better synchrotron facility, Taiwan Photon Source.

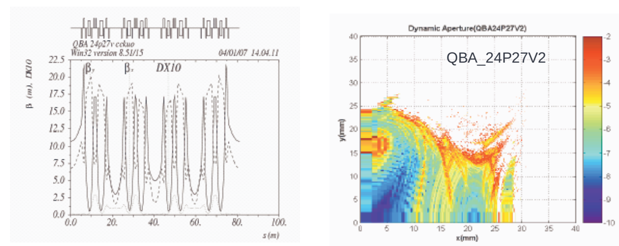


Figure 8: Optic functions of linear lattice and Frequency Map Analysis of a 12-cell QBA lattice layout with 6-fold symmetry.

There are several promising QBA configurations, which has been intensively studied, as alternations to DBA layout. In QBA configuration, the positions of quadrupole and sextupole magnets are almost identical to the DBA structure. Nonlinear optimization shows that the beam dynamic behaviour of the QBA lattices is similar to DBA. Further studies on the nonlinear effects and other beam dynamics issues are in progress.

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