DESIGN FEATURES AND CONSTRUCTION PROGRESS OF 500-MHZ RF SYSTEMS FOR THE TAIWAN PHOTON SOURCE

Ch. Wang*, L.H. Chang, M.C. Lin, M.S. Yeh, T.T. Yang, F.T. Chung, M.H. Tsai, M.H. Chang, Y.H. Lin, C.H. Lo, T.C. Yu, L.J. Chen, M.C. Lee, F.Z. Hsiao, G.H. Luo, C.T. Chen, NSRRC, Taiwan

Abstract

The accelerator complex of the Taiwan Photon Source (TPS) consists of two 500-MHz RF systems: one RF system with KEKB-type single-cell SRF modules is used for the 3-GeV storage ring of circumference 518 m, and the other with five-cell Petra cavities at room temperature is for the concentric full-energy booster synchrotron. This overview of the construction of the 500-MHz RF systems for the TPS is presented with emphasis on our strategy to approach the expectation of highly reliable SRF operation of the TPS. How to complete the construction project on time, on budget and on performance is our unique concern.

BOOSTER RF SYSTEM

The RF parameters for the booster RF system are listed in Table I. Five-cell Petra cavities operated at room temperature were selected for the booster of the TPS. Three (3) sets of Petra cavities including RF windows and plunge tuners, originally manufactured by ACCEL, were obtained (at a substantially decreased cost) from DESY in 2004 via institutional collaboration. The booster low-level RF (LLRF) system is manufactured in house using the most recent RF chips commercially available. The LLRF system has an analogue architecture similar to that used for operation of the 1.5-GeV Taiwan Light Source (TLS). That LLRF system for TLS was originally manufactured by SLAC according to the PEP-I (SLAC) design and upgraded in house several times in recent decades. One of two retired 60-kW crowbar-type RF transmitters originally for TLS to power the DORIS cavities operated at room temperature has been upgraded for 100-kW RF output to power the Petra cavity. The TPS booster RF system and the TLS storage-ring RF system thus use identical 100-kW klystrons each of which is an upgraded version of the CPI standard 70-kW klystron. As expected, the construction of the booster RF system involved minimum manpower and duration of development before successful commissioning in 2009.

STORAGE RING RF SYSTEM

The RF parameters for the storage-ring RF system are listed in Table II. To operate the SRF modules reliably at a huge RF power rating is a major challenge for successful construction and operation of the RF system for TPS. Because the total required beam power for the TPS is about ten times that needed for the TLS, the experience with highly reliable SRF operation at TLS is difficult to

#rfwang@nsrrc.org.tw

Table 1: Operational Parameters of the Booster RF System for the Taiwan Photon Source (TPS)

Parameter	Value		Unit
Machine injection energy	150		MeV
Machine extraction energy	3.0	3.3	GeV
Quantity of five-cell Petra cavity	1	1 or 2	
Coupling coefficient	~1.1	~1.1	
Inject accelerating RF gap voltage	250		kV
Extract accelerating RF gap voltage	900	1300	kV
Forward RF power	30	61	kW
Extract quantum lifetime	>10		Sec
Inject energy acceptance	>2%		p-p

extend for the machine operation at TPS. After consideration of the maximum RF power rating with a reliable operational record and the availability of the external quality factors (Qext) of the SRF module for an optimal operating RF gap voltage for TPS, the KEKB-type single-cell 500-MHz SRF modules were selected for the storage ring of TPS, which have been routinely operated for the high-energy ring of the collider KEKB for more than ten years at a RF power rating up to 350 kW with an excellent record of operational reliability. After the signing of an agreement for technology transfer from KEK to NSRRC at the end of 2009, a commercial contract was awarded to Mitsubishi Heavy Industries Ltd. (MHI) in 2010 June for the mechanical manufacture of three (3) sets of KEKB-type SRF modules. The surface treatments, RF processing and final cryostat assembly including cold helium test will be undertaken at KEK with the joint manpower from NSRRC staff and the assisting manpower from MHI, under supervision of KEK. The SRF cryostats and associated end groups of room-temperature vacuum chambers will be delivered to NSRRC from the beginning of 2012 for each SRF module after every six months. NSRRC is responsible for the final system integration and the high-power horizontal test that should be completed before the end of 2013. Routine operation of two SRF modules for TPS is scheduled after the first quarter of 2014. The production of a 500-MHz single-cell niobium cavity with a resonance frequency suitable for machine operation of TPS is one of the most challenging tasks for MHI. To maintain a qualified clean-room operation to sustain the performance of the SRF module during the system integration is the most critical mission for NSRRC.

The routine operation of SRF modules requires the support of a liquid-helium cryogenic plant and a liquid-helium transfer system. Commissioning of the 700-W (@ 4.5 K) cryogenic plant (from Linde) and the helium transfer system (from A/S) including regulation valve boxes for the SRF modules is scheduled from late 2012 to early 2013. The quantities of cryogenic fluids involved in

Table 2: Operational Parameters of the Storage-ring RF System for the Taiwan Photon Source TPS

Parameter	Value			Unit
RF frequency	499.660			MHz
Machine energy	3.0			GeV
Maximum beam current	300	400	500	mA
Radiation loss from bending magnets	256	341	426	kW
Radiation loss from insertion device	224 (88%)	139 (41%)	54 (13%)	kW
Beam Power	480			kW
Number of KEKB-type SRF modules	2			
Accelerating RF voltage per module	1600			kV
Total accelerating RF voltage	3200 (2800~3400)			kV
External Quality Factor (Qext)	<7E4			
R_s/Q_0 per cell ($R_s = V^2/2P_c$)	46.5			Ω
Cryogenic static loss per module	<35			W at 4.5 K
Cryogenic dynamic loss per module	<35 @ 1.6 MV			W at 4.5 K
Loading factor Y (=Ib*Rs)/(β Vc)	1.22	1.63	2.03	

the SRF operation are regulated by the SRF electronic system via the corresponding SRF valve box. Unlike the Cornell-type SRF module that becomes a turn-key industrial product, the SRF electronics systems of the KEKB-type SRF modules for TPS will be developed in house. Three (3) sets of SRF electronics systems will be available at the end of 2012. A interconnection between the TLS cryogenic plants (2x460W @4.5K) and the TPS cryogenic plan (700W @4.5K) will maintain the SRF modules at cold even during the maintenance of one of the cryogenic plants, that requires extra backup cryogenic transfer lines (~100 m) to be designed in 2011. A careful evaluation of the cryogenic safety relief system for the TPS cryogenic environment will be undertaken from 2011 to 2012.

The RF source provided by a 300-kW klystron (from Thales) powered by a crowbar-less RF transmitter (from Thomson) has been selected to support the SRF operation for operation of the storage ring at TPS. Two (2) sets of RF transmitter and four (4) klystrons (with two as spare) have been accepted by NSRRC before the end of 2010. A few unexpected malfunctions of key components have been fortunately identified during the acceptance tests on site thanks to the performance requirements of long-term reliability, i.e. of faultless operation up to 50 hours continuously. Identified were the mysterious lack of fibreglass layers as high-voltage insulators for the multi-secondary high-voltage transformer (from MF Transformatori) and the falling of many cracked ferrite tiles because of the poorly glued ferrite RF load (from AFT). Thales/Thomson as a trustworthy company accordingly solved these problems together with their subcontractors. The superiority of a PWM-based RF transmitter with great reliability has been demonstrated at various light sources and becomes one of the most popular combinations for modern light sources after its first implementation at SLS. Nevertheless, its unique feature of equalizing the thermal loading by periodically rotating the PWM power modules for highly reliable operation might contaminate the infrared spectra of users of the light source. Decreasing the rotational frequency from the adjustable switching frequency of the individual PWM modules to the top-up injection frequency of the storage ring might provide an easy solution to diminish further its noise level from -60 dBc for its application to a light source. In contrast, similar RF transmitters have been selected for NSLS-II with requirements of a noise level less than -70 dBc, which is now under production. To fulfil this custom expectation, the manufacturer will be forced to improve its performance to a new level.

For the low-level RF (LLRF) system for the storage ring of TPS, analogue technology was selected that is a duplication of the LLRF system for the booster. In our opinion, this analogue solution provides RF performance indistinguishable from that of a digital solution for a continuous-wave RF system. Two (2) sets of analogue LLRF systems, required for the initial operational years of TPS, are now under assembly and will be available in mid 2011. Undoubtedly, FPGA technology, also as a core technology of a digital LLRF system, brings unique features in some other applications of the accelerator. Concerning the competition for resources during the machine construction phase, only minimum manpower is available for development in house of the FPGA technology, which will be refocused after the bottleneck of manpower allocation is overcome. The unstable LLRF system, likely caused by the Robinson instability through RF operation under heavy beam loading, is one of the most critical issues to decrease further the mean time between failures (MTBF) of SRF operation at TLS, which will certainly be a critical issue for the new machine TPS. In particular, cross-talk between or among RF plants via the circulating electron beam is unavoidable for operation of the storage ring of TPS, which will cause deterioration of the stability of LLRF systems. Simulink simulation of the complete feedback loops including the effects of beam loading should be comprehensively undertaken to discover the best combination of feedback bandwidths and gains, which are not yet settled.

The third RF plant will eventually become necessary for the TPS when the radiation loss from insertion devices increases. This condition will occur a few years after the opening of TPS to users of the light source. According to our current understanding, it is quite promising for the KEKB-type SRF module to deliver beam power up to 400 kW each, or even 500 kW, because its high-power input coupler has already demonstrated this capability. The power of the KEKB-type SRF module will be demonstrated soon after the commissioning of the collider SuperKEKB scheduled for 2013, Therefore, combining the RF power from a solid-state RF transmitter with that from the available klystron-based RF transmitter provides an economical solution to meet the next machine requirements of TPS. A small-scale R&D project in house to develop a solid-state RF amplifier module is being undertaken. Generating RF power more than 900 W per circuit board at 500 MHz, CW, has been demonstrated.

FULL-POWER TEST RUN

The duration of commissioning required for RF systems can be significantly decreased on applying a high-power test run before its final installation. Malfunctions or defects of subsystems can be readily identified during the long-term test run. As mentioned previously, oversight of installing fiberglass insulators into the high-voltage transformers and defect of gluing of the RF ferrite loads for the 300-kW RF transmitters were identified during the 50-hour continuous acceptance tests. Similarly, a high-power horizontal test for the SRF modules after their system integration at NSRRC will be undertaken before their installation into the storage ring of TPS. A pair of cryogenic helium transfer lines (length more than 200 m) has been installed in 2008 to deliver the liquid helium from the operating TLS to the cryogenic test area for the horizontal test of SRF modules. A test run of the long-distance liquid-helium transfer was first examined using a 500-L test dewar. A capability to maintain an extra heat loss 150 W @ 4.5K in addition to the transmission loss about 80 W was demonstrated in the beginning of 2010. The practice of clean-room operation using the retired SRF cryostat S0 purchased from Cornell began in 2010 and will be repeated in 2011. Infrastructures for SRF assembly technology such as an ultra-pure water system and a high-pressure rinsing system are currently under test to examine and improve the performance. An exercise of the horizontal test at the cryogenic test area is undertaken currently using the retired SRF cryostat S0. Similar to our action for the cryogenic plant at TLS in 2003, test dewars with built-in heater will be installed as simulator of SRF modules after the SRF valve boxes of TPS for a cryogenic test run of the new cryogenic plant and cryogenic helium-transfer system before its service to the SRF modules. During the commissioning of the storage ring of TPS using Petra cavities (see below), a cryogenic test run for SRF operation will be undertaken on installing the SRF modules inside the tunnel near its final operation location. Figure 1 illustrates the relevant RF activities currently at NSRRC to produce RF systems for the TPS.

MACHINE COMMISSIONING

According to the construction schedule of TPS, a critical path involves alignment of the civil construction, installation and commissioning of both the cryogenic plant and the helium-transfer system, to the commissioning of the SRF modules. Using the SRF modules for machine commissioning will require much more frequent thermal cycling of the SRF modules to diminish the gas loading accumulated on the cold surface of the niobium cavity. Frequent thermal cycling decreases the reliability and lifetime of indium sealing and might result in vacuum leaks. Furthermore, any unexpected vacuum accident of vacuum components of the storage ring during the machine commissioning might damage the surface cleanliness of the SRF module. Using Petra cavities at room temperature in commissioning the storage ring breaks the critical path and allows the machine to become commissioned more aggressively and more effectively. Beam commissioning of the SRF modules for the TPS will therefore be arranged after vacuum cleaning of the storage ring. Two Petra cavities will serve for the initial stage of commissioning the storage ring for a beam current up to 100 mA. Each Petra cavity will consume RF power about 150 kW, much larger than what is required for its operation at the booster. Extra work such as manufacturing a new coupling loop for a larger coupling coefficient up to 2.2, maintaining the cavity vacuum better than 5 nTorr at an RF gap voltage more than 1.4 MV, balancing the field flatness among individual cells of Petra cavity under heavy beam loading via an additional tuner feedback loop is now being elaborated.

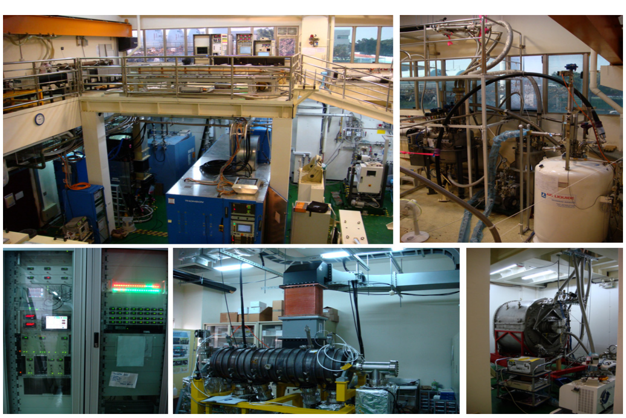

Figure 1: Relevant RF construction activities for the Taiwan Photon Source (TPS).

ACKNOWLEDGMENTS

We are grateful to T. Furuya, S. Kurokawa, and K. Oide (KEK) for their continuous support and encouragement on our construction of KEKB-type SRF modules. The continued technical supports of K. Akai, K. Hosoyama, S. Mitsunobu, Y. Morita, H. Nakai from KEK are especially appreciated. We sincerely thank S. Belomestnykh, M. Ebert, M. de Jong, H. Schwarz, Y. Sun, E. Weihreter, and K. C. Wu for valuable technical consultations. We would like to thank M. Jensen, J. Rose, J.F. Liu, G.W. Wang for sharing SRF operational experience and design considerations.