SYSTEM INTEGRATION AND BEAM COMMISSIONING OF THE 500-MHz RF SYSTEMS FOR TAIWAN PHOTON SOURCE

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Abstract

Operating newly constructed 3-GeV Taiwan Photon Source (TPS) at its maximum designed beam current, 500 mA, was successfully demonstrated just shortly before the end of its scheduled machine commissioning in 2015. Two 500-MHz RF systems have been implemented for the accelerator complex of TPS at National Synchrotron Radiation Research Center (NSRRC). The booster synchrotron adopts one five-cell Petra cavity working at room temperature; the storage-ring RF system is equipped with two KEKB-type single-cell SRF modules operating at cryogenic (liquid-helium) temperature. The construction of RF systems focused on achieving highly reliable and available operation of the storage ring at a large operational beam current, eventually taking the beam current to ampere level. We present an overview of the installation, RF commissioning and initial beam operation of these two 500-MHz RF systems, with emphasis on our proposed solutions to fulfil the strict requirements for RF systems in modern light sources. The difficulties and challenges that we met during the construction and commissioning of the RF systems are also reported.

GENERAL STRATEGY AND PLANNING

The detailed construction strategy, design considerations and nominal operational parameters of the 500-MHz RF systems for Taiwan Photon source (TPS) are reported elsewhere [1]. Before the final installation of the RF systems, comprehensive high-power acceptance tests and long-term reliability tests had been undertaken at the SRF laboratory at NSRRC to minimize unexpected interruptions and surprises experienced during subsequent beam commissioning and routine operation at the maximum designed beam current, 500 mA. Two Petra cavities was installed in the initial phase of machine commissioning for robust machine commissioning and vacuum cleaning with a target maximum beam current 100 mA. Thereafter, the Petra cavities were replaced by SRF modules to service in high-power operation at their maximum designed beam current, 500 mA, which is in the second phase of machine commissioning. RF cavities of both types were over-conditioned considerably beyond their nominal operational requirements, i.e. RF gap voltage 1400 kV instead of 900 kV for each Petra cavity and RF gap voltage to 2400 kV instead of 1400-1600 kV, CW, for the individual SRF modules. It was also planned to modularize the subsystems, which will be suitable for stand-alone transport and re-installation as much as practicable to transplant the fully-tested RF systems from the laboratory to the accelerator tunnel in efficient and convenient manner. These laborious efforts and the conservative strategy considerably speeded the allocated resources and efforts required from the beginning of the final RF installation to the successful commissioning of RF systems with maximum beam current up to 520 mA. The speedy and success commissioning of RF systems with maximum beam current up to 520 mA proved the strategy and enormous efforts. In comparison with the conventional approach, resolving the unexpected problems in situ, the total consumed construction efforts should have no significant difference, but our pace never brought a traceable negative impact on the course of machine commissioning. We will review the relevant tasks that were carried out during the construction in following sections. The challenges, we are facing, and the applied solutions will be addressed accordingly as follows.

PREPARATION AND COMMISSIONING OF PETRA CAVITIES

A booster normally requires a moderate RF accelerating gap voltage for low accelerating beam current. A multi-cells copper cavity is commonly adopted for a booster RF system for a light source facility. Similar requirements are set for the booster of TPS. Nevertheless, not only the booster synchrotron but also the storage ring of TPS relied on multi-cells Petra cavities during its first phase of machine commissioning. The design was to operate the Petra cavity at 900 kV for the booster synchrotron and at 1200 kV for the storage ring during machine commissioning. To have enough operation contingency, every Petra cavity was conditioned to allow reliable operation at 1.4 MV. The three sets of Petra cavities were obtained from DESY, which were originally manufactured tens of years ago (by ACCEL, currently named as Research Instruments). It was identified immediately that available coupling strength was insufficient to support the storage-ring operation with a maximum beam current 100 mA at RF gap voltage 1.2 MV for TPS. A post-modification of the mechanical structure of the coupling loop of the original high-power input coupler was required. Its feasibility and success of our modification have been verified from its low-power cold test and long-term high-power operation.

Several technical solutions were revealed to improve the vacuum pressure of the Petra cavity with the RF power on to achieve cavity vacuum pressure comparable with the vacuum of other parts of the beam line during machine commissioning. The inner surfaces of these Petra cavities had been carefully polished manually to remove the heavily oxidized layers as received. The mechanical

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housing of the tuner plunger was redesigned to allow better ultrasonic water rinsing of the internal structure. Additional cylindrical spacers with water-cooled 100CF vacuum flanges have been implemented for the corresponding vacuum port on the cavity body to prevent over-heating at the interface as the cavity is operated with RF power at a high level. Even after several mechanical modifications and with long-term high-temperature baking out, a cavity vacuum better than 5 nTorr at a RF gap voltage of 1.2 MV was still unreachable. The cavity vacuum pressure was finally resolved by conditioning the cavity continuously with great RF power in a CW mode more than weeks. Identical approaches were applied for Petra cavities in all three sets to reserve the option of random selection during final installation. The cavity vacuum was never a problem during the machine commissioning.

Some unexpected phenomena were nevertheless identified just after attempting to store a higher beam current in the new storage ring. Operating the storage ring at a beam current greater than about 25 mA was possible only on operating two Petra cavities in an unbalanced manner. The bigger the difference of cavities' RF forward power, the higher the stored beam current. When the cavities operated in an unbalanced mode, the equivalent traveling RF power loaded on the RF window of one cavity increased significantly. The maximum stored-beam current was limited to about 70 mA corresponding to the maximum RF gap voltage ever conditioned off site, at RF gap voltage 1400 kV. Here was assumed a ceramic RF window positioned at the location with standing-wave maximum voltage. This problem was finally resolved just before the last week of the first phase of machine commissioning, mainly owing to an improper bandwidth of the amplitude loop of the low-level RF system, not to exclude the synchrotron oscillation frequency.

Overheating the cavity viewports for an arc detector had been detected as the machine was commissioned with higher bunch current in few-bunch mode. The higher-order modes (HOM) of cavity heated the arc view port with increasing single-bunch beam current. This problem could be solved by implementing a RF choke in the front of the view port, as suggested by the staffs from DESY, but which was not recognized during our preparation. It was obviously too late to break the cavity vacuum during the machine commissioning to make a modification, even one that was straightforward. The single-bunch current was therefore limited to lower than 15 mA during the first stage of machine commissioning because of conservative consideration.

PRODUCTION OF SRF MODULES

The storage ring of TPS is powered by SRF modules, similarly to its companion low-energy synchrotron light source, Taiwan Light Source (TLS), at NSRRC. The beam power consumed for the TPS storage ring might exceed 600 kW in its mature operational phase. To operate each SRF modules with extreme high reliability at a loaded beam power up to or eventually more than 300 kW CW, with an optimal total RF gap voltage various from 2.8 MV to 3.2 MV, is obviously a most critical challenge in a successful operation of at TPS. The 500-MHz SRF module of KEKB type was selected for TPS because of its highly reliable operational record with RF power rating up to 350 kW at KEKB. The availability of an extremely small external quality factor (Qext) can be driven down to $7x10^4$, which satisfies the SRF operational requirements at TPS. More details about the production of SRF modules for TPS are available elsewhere [2].

Heavy gas loads on SRF module #2 have been observed during its long-term reliability test, which developed by keeping the cavity at RF gap voltage of 1.6 MV to more than two weeks after its success in a horizontal test. The cavity and coupler vacuum degraded continuously with the elapsed operational duration. This sustained degradation of vacuum pressure was stoppable on switching off the RF power. Gas loads enhanced the multipacting strength on the RF power coupler and resulted in a multipacting-like avalanche at a RF gap voltage about 900 kV and 1100 kV. Gas loads were removed after applying a partial warming, but frequently applying thermal cycling of an operational SRF module is an inconvenient solution for highly available SRF operation. A plan was to install two sets of ion pumps in combination with NEG getters on the second tapers of the operational SRF module, which is expected to provide an extra hydrogen pumping speed up to 2000 L/s in total. A remarkably decreased vacuum pressure of the cold cavity and coupler was identified after connecting the powerful hybrid vacuum pumps to the operational SRF modules. An experience learned here will be reported by other reports.

SRF COMMISSIONING WITH A LARGE BEAM CURRENT

The recipes for successful SRF operation developed at KEK have been applied for the SRF modules at TPS. These include, for example, aging the warm coupler with varied bias voltages before cryogenic cooling and aging a cold coupler (without applying a bias voltage) in a regular base after liquid-helium collection of the SRF module. In addition, we adopted a more aggressive aging strategy. The warm-aging procedure originally developed at KEK was repeatedly applied to the SRF modules in a daily way before their cooling, which takes more than one to two weeks if allowed. It is expected to process the RF power coupler as cleanly as possible but to minimize risk due to over-conditioning of the power coupler. Furthermore, a weekly base of cold coupler aging has been scheduled instead of bi-weekly arranged at KEK. Baking the RF window of the warm SRF module is a routine task for the Cornell-type SRF module operated at TLS. We considered also to apply window baking in situ for the warm KEKB-type SRF module at TPS, which has been successfully applied at IHEP.

Deviations in coupler multipacting behaviour between two operational SRF modules (#2 and #3) installed at TPS were identified in a short run after their operation with a stored beam. Aging the warm coupler of SRF module #2 with bias voltage is much more difficult than what was learned from SRF module #3, but conversely during cold coupler aging. The steady coupler vacuum pressure of SRF module #3 is much more sensitive to the operational RF power level, which reflect that the coupler has a higher operational temperature somewhere. SRF module #3 has a multipacting band corresponding to a RF voltage greater than 2000 kV at a loading angle about +15° (without stored beam), which can be readily processed away during the cold coupler aging. It seems harmless for routine machine operation with an RF gap voltage lower than 1.6 MV even though SRF module #3 has a higher cavity vacuum pressure than that of SRF module #2 as mentioned previously. SRF module #2 exhibits its strong multipacting band corresponding to a RF gap voltage about 900 kV or greater as learned from the long-term reliable test. We identified also an enhanced multipacting strength together with the accumulated beam dose. We observed that the heavy gas loads on the cold coupler surface can be removed more effectively with the stored beam. Manageable beam processing has been applied at TPS, which unloads condensed gases on the cold coupler surface and allows storing a beam current up to 520 mA with two SRF modules alone in a short time without expected difficulty. An experience learned will be published elsewhere. Table 1 outlines the measured quality factors, Q_0, of two operational SRF modules as a function of RF gap voltage at various time points.

Table 1: Measured Quality Factors, Q_0, of Two Operational SRF Modules as a Function of RF Gap Voltages

RF Gap Voltage	1600-kV	1800-kV	2000-kV	2200-kV	2400-kV	
Q0 of #2 SRF Module	2.60E+09	1.53E+09	1.92E+09	1.37E+09	8.70E+08	@TPS, 2016/3/1
	2.19E+09	2.20E+09			5.90E+08	@TPS, 2015/12/23
			1.27E+09	1.00E+09	5.70E+08	@TPS, 2015/12/9
	2.04E+09	2.26E+09	2.01E+09	1.06E+09	6.70E+08	@TPS, 2015/8/3
	1.79E+09		1.49E+09		6.30E+08	@SRF Lab 2nd
	1.77E+09	1.76E+09	1.64E+09	1.35E+09	1.09E+09	@SRF Lab 1st
Q0 of #3 SRF Module	1.83E+09	1.85E+09	1.72E+09	1.89E+09	1.39E+09	@TPS, 2016/3/1
	2.51E+09	1.91E+09	1.77E+09	1.63E+09	1.37E+09	@TPS, 2015/12/9
					1.90E+09	@TPS, 2015/9/9
	2.10E+09	2.72E+09	1.94E+09	1.95E+09	1.70E+09	@TPS, 2015/8/14
	2.00E+09	2.08E+09	2.35E+09	1.95E+09	1.98E+09	@SRF Lab

OTHER PARTS OF RF SYSTEMS

Both 500-MHz RF systems are currently regulated with home-assembled analogue-type low-level RF systems because of constraints of manpower within the scope of the construction time frame, which provides an overall RF noise level better than -60 dB_c mainly from the pick-up of harmonic noises from the interconnection among sub-systems through deviation of the ground potential levels among separate subsystems. Thanks to tight collaboration with BNL, the advanced digital low-level RF systems developed by NSLS-II might be implemented eventually at TPS after success of a lengthy bureaucratic process. Using digital LLRF together with an effort to minimize the pick-up harmonic noises, a further decrease of overall RF noise level better than -70 dB_c is feasible and will benefit the users of the infrared beam lines. The selection of RF sources with high-power klystrons for the 500-MHz RF systems was made unhesitatingly in 2007; in that era high popularity to obtain a RF power via combining inductive output tubes (IOT) was never considered as an option for TPS because of violation of our design strategy. Standard Thomson crowbar-less RF transmitters were selected for the storage ring. The electrical harmonic noise generated by the switching power supply is reducible using its dedicated harmonic suppression module. A retired 60-kW, crowbar-type RF transmitter from TLS was upgraded in house to a 100-kW one for the booster of TPS.

FUTURE CHALLENGES

Beam power more than 600 kW is expected to be required to support the machine operation, following the progression of TPS into mature operation a few years subsequently. The single high-power input coupler for the KEKB-type SRF module demonstrated its capability to operate with RF power more than 500 kW, CW, in the test stand at KEK. It is therefore promising to operate TPS with only two SRF modules, even in its mature operational phase. Combining the available RF power from the existing 300-kW klystron with an additional 180-kW solid-state RF transmitter for each SRF module provides an economical solution for TPS in its mature operational stage. Developing the technology of a solid-state RF transmitter is in progress in house. Alternatively, if the SRF operational reliability at such a high power rating becomes a challenge, the spare SRF module (#1) is ready to install in TPS.

Implementing one or more passive superconducting harmonic cavities becomes, sooner or later, unavoidable for routine operation of TPS at high beam current, which is expected to become an urgent decision issue after successful routine operation of TPS.

REFERENCES

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