PRODUCTION OF 500 MHz SRF MODULES OF KEKB TYPE FOR TAIWAN PHOTON SOURCE

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INTRODUCTION

A new 3-GeV, 500-mA, synchrotron light source named Taiwan Photon Source (TPS) at National Synchrotron Radiation Research Centre (NSRRC) is now entering its final stage of construction with partial occupancy of accelerator components. The commissioning of a new concentric machine is scheduled for 2014 summer. Similarly to its companion low-energy operational synchrotron light source, Taiwan Light Source (TLS), the SRF modules have been selected as accelerating cavities for the storage ring of TPS. The design features of the RF systems for the accelerator complex of TPS are described elsewhere [1].

The beam power consumption for the TPS storage ring will exceed 600 kW at its design beam current 500 mA after the machine is fully occupied with the insertion devices. How to operate the SRF modules highly reliably on consumption of such huge RF power but with an optimal amount of total RF gap voltage from 2.8 MV to 3.5 MV is obviously the most critical challenge in a successful construction and operation of the RF systems for TPS. The 500-MHz SRF module of KEKB type was selected for TPS because of its reliable operational record at a RF power rating up to 350 kW at KEKB [2, 3] and the availability of an external quality factor (Q_{ext}) down to $7*10^4$ satisfying the SRF operation for TPS.

508-MHz SRF modules of KEKB type in eight sets have been operated for the high-energy ring of KEKB since 2000, and are ready in operation for the upgraded collider SuperKEKB. 500-MHz SRF modules of KEKB type in two sets have been in operation for BECP-II at IHEP since 2006 [4]. All those SRF modules of KEKB type were mechanically manufactured by Mitsubishi Electric Corporation (MELCO). Following an agreement of 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 fabrication of 500-MHz SRF modules of KEKB type in three (3) sets for TPS. MHI had delivered SRF modules of several types to KEK but for the first time were manufacturing the 500-MHz SRF modules of KEKB type for routine operation.

The RF processing of high-power input couplers (up to 300 kW, CW) and LBP/SBP HOM dampers (up to 7 kW and 5 kW, CW, respectively) in test stands, the surface treatments, frequency tuning and vertical test of the niobium cavities (up to 3 MV), and liquid-helium test of the MHI-assembled cryo-module were undertaken mainly by the SC group of KEK with joint manpower from MHI and NSRRC. The cryo-modules and associated end groups of room-temperature vacuum beamline components were then delivered to NSRRC for final assembly, system integration with the cryogenic regulation system, SRF electronics and diagnostic system, and RF plant, high-power RF conditioning of the coupler (up to 300 kW, CW), high RF power performance (horizontal) test (up to 2.4 MV or 300 kW, CW), and the long-term reliability test at 1.6 MV. Here we report some results and lessons obtained during the production and tests of these three SRF modules at KEK and NSRRC.

PRODUCTION OF SRF MODULE

The SRF module of KEKB type for TPS has a profile appearance almost identical to that for KEKB fabricated by MELCO but with a unique mechanical design and engineering method developed by MHI following the common conceptual blueprint developed by KEK. The equator width of the niobium cavity was initially extended to 36.5 mm from 13.0 mm of the original design of the niobium cavity for KEKB operated at 508.887 MHz to meet the operational requirements of TPS with nominal RF frequency 499.650 MHz. The total length of the cavity and the position of the high-power input coupler are kept identical on decreasing the length of the niobium large beam pipe (LBP) correspondingly. The expected cavity resonance frequency of the SRF module is 499.500 MHz under a tuner force-free condition. The four individual parts of the niobium cavity, i.e., small beam pipe (SBP), two half-cavity cells, and large beam pipe (LBP), were made of pure niobium with RRR of about 300 from Tokyo Denkai and manufactured by deep drawing, with welding together with an electron beam at MHI.

After receipt of the first niobium cavity from MHI, heavy electropolishing (EP1, 100μm), vacuum annealing (700^{o}C, 1.5 h), frequency tuning and light

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electropolishing (EP2, 20μm) were applied. Following the surface treatment of light electropolishing using a fresh chemical solvent, overflowing with ozonated pure water (3 ppm), and finally ultrasonic rinsing with hot pure water (50^{o}C) were performed to complete the standard procedure for surface treatment developed for the 508-MHz niobium cavity of KEKB type.

Even though without application of high-pressure rinsing to the niobium cavity, the vertical test proceeded smoothly without requirement of an extra pulse or helium processing, but with ramping up the accelerating voltage directly to 3 MV without difficulty. The results of the vertical test of #1 Nb cavity are shown in Fig. 1. The vertically tested resonance frequency of the #1 niobium cavity was, however, too high (499.298 MHz) for machine operation and was corrected with a second frequency tuning. The progress of the following vertical test was still straightforward with an acceptable vertically tested resonance frequency 498.641 MHz but with a degraded RF performance as shown in Fig. 1, likely because of extra contamination during exchange of flanges for the frequency tuning but without further rinsing.

One more millimetre was given for the equator length of the #2 and #3 Nb cavities, to be absorbed by the bellows of the liquid-helium vessel during cryostat assembly. The #2 and #3 Nb cavities gave similar vertical test results as illustrated in Fig. 1, with vertically tested resonance frequencies 498.862 and 498.983 MHz, respectively.

The high-power input couplers were manufactured by MHI with ceramic windows from Toshiba. After receipt of the high-power input coupler, rinsing with ozonated water and baking at 100 ^{o}C for 24 h were applied. CW, RF processing in a test stand has been applied up to 300 kW of equivalent travelling RF power at KEK. Some difficulty was experienced in RF processing of the high-power input coupler of #3 SRF module at a RF power level about 40 kW. Strong multipacting somewhere on the inner surface of the outer conductor of the high-power

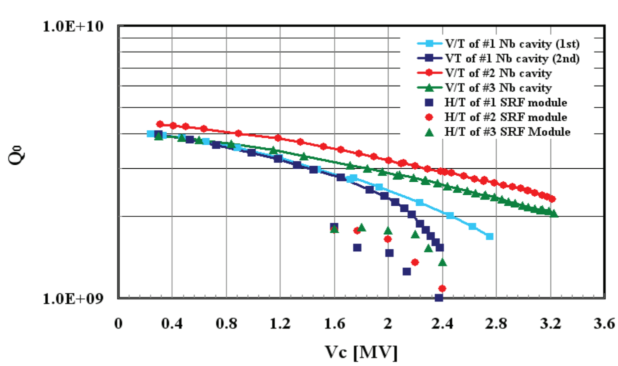

Figure 1: Results of vertical test (V/T) and horizontal test (H/T) of the 500-MHz niobium cavities and SRF modules of KEKB type for TPS. The #1 Nb cavity experienced two vertical tests for extra frequency tuning. The target RF performance is Q_0 of $1*10^9$ and $5*10^8$ at 1.6 MV and 2.4 MV, respectively.

input coupler was suspected. After applying a second spraying with ozonated water to the outer conductor of the high-power input coupler alone and baking, the RF processing of this high-power input coupler became manageable, similar to the others, and attained 300 kW of equivalent travelling RF power. In total, the #1, #2 and #3 high-power input couplers required 10, 6.5 and 12 h to reach the target of RF conditioning, respectively.

After passing the vertical tests, the niobium cavities were attached to the stainless-steel thermal-transition beam pipes in a class-100 clean room to become ready for insertion into the cryostats, without extra light chemical etching before assembly. The high-power input couplers were installed subsequently to complete the cryo-module assembly. Full thermal cycling was then applied to the assembled cryo-modules. After verification of the vacuum tightness through thermal cycling, the high-power input couplers were dismantled for delivery of the cryo-modules to NSRRC.

HORIZONTAL TEST RESULTS

After delivery of the cryo-modules, high-power input couplers and individual vacuum beamline components outside the cryo-modules, the end group of vacuum beamline components was first assembled in a class 10-100 clean room at NSRRC. The end groups were baked to 120 ^{o}C for 36 h before attachment of the HOM dampers. After connecting the HOM dampers to the end groups, the HOM dampers were heated again at 50 ^{o}C for 50 days using hot deionized water circulating in their cooling-water channels. The vacuum pressures attained a few nTorr after removal of the hot-water heating. The final assembly was completed on inserting the high-power input coupler and attaching the end groups to the cryo-module. After the integration of the SRF electronics system developed by NSRRC, the high-power input coupler was first RF-conditioned up to 300 kW without applying a DC bias, then applying a positive bias voltage to 2000 V to clean the inner surface of the outer conductor and a negative bias voltage to -1800 V to clean the outer surface of the inner conductor of the high-power input coupler. Note that the warm niobium cavity is far detuned from the frequency of the RF source. Much adsorbed H_2, H_20, CO and CO_2 were released from the surface during RF processing of the high-power input couplers at room temperature.

Slow cooling was then applied to the assembled SRF modules, with an average rate of cooling less than 2.5 K/h. As the cold niobium cavities are forced-free by the tuners, the (neutral) resonance frequencies of the #1, #2, #3 SRF modules are 499.254, 499.300 and 499.486 MHz, respectively. Note that the ceramic window itself has a design transparent to RF power, but the doorknobs have a narrow bandwidth and some mismatch, resulting in a slightly varied resonance frequency and external quality factor of the SRF module. Consequently, the measured operational external quality factors of the #1, #2, #3 SRF modules are $7.2*10^4$ (with 7 mm gasket), $6.2*10^4$ (with 6 mm gasket) and $6.2*10^4$ (with 5 mm gasket), respectively,

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which were aligned to $7.0*10^4$ without connection of doorknobs.

The high-power tests of three SRF modules up to 2.4 MV were achieved within a few hours with only a few vacuum activities. The results of the horizontal test are shown in Fig. 1 with Q_0 above $1*10^9$ at 2.4 MV for three SRF modules. These results are better than originally expected, $Q_0=5*10^8$ at 2.4 MV.

CHALLENGE OF SRF OPERATION

Hydrogen, water molecule and carbon monoxide are the dominant residual gases in measured cavity vacuum of a fresh SRF module. The water molecules appear to be the most problematic for reliable SRF operation. Because the SRF module adopts indium wires for vacuum seals working at cryogenic temperature and selects the superinsulation layers to minimize the static loss of the cryostat, it is difficult using high-temperature baking of the SRF module to get rid off water molecules after completion of the SRF module assembly. Furthermore, the SRF module of KEKB design utilizes a surface treatment with ozonated water for the high-power input coupler including a ceramic RF window to suppress the multipacting. The scanning acoustic tomography was adopted by using water as a medium to examine the quality of the hot-isostatic-pressed ferrite layer including surface contact between the ferrite layer and the copper cylinder of the HOM dampers during production. Both ceramic and ferrite are porous materials. Complete removing the adsorbed water is unlikely even after baking the RF window at 100 ^{o}C for 24 h and baking the HOM dampers at 150 ^{o}C for seven days before assembly of end group and heating at 50 ^{o}C for 50 days before final assembly.

After operating the SRF module for machine operation, the absorbed water molecules are released from the porous surfaces and bring gas load to the cold surface of the SRF module, eventually resulting in multipacting on the high-power input coupler, extra dynamic cryogenic heat loss and radiation dose, vacuum burst from the niobium cavity, etc. The gas load becomes a critical challenge for the SRF operation with a target to operate with higher RF power, like the SRF modules for TPS. We observed a heavy gas load on the #2 SRF module during long-term reliability testing after its successful horizontal test. Frequently applying full thermal cycling of an operational SRF module provides a solution to get rid of condensed water molecules on the cold surface, but full thermal cycling decreases the available user beam time and must be minimized from an operational point of view of a synchrotron light source. Full thermal cycling might worsen the fatiguing of an indium seal so as to abbreviate its service lifetime.

Some measures will be undertaken during the initial years of SRF operation to minimize the impacts of a heavy gas load on the machine operation. For the gas load originating from the ceramic window of a high-power input coupler, applying a positive bias voltage up to 1500 V to the inner conductor of the high-power input coupler of the SRF module and weekly RF processing with a cavity appropriately detuned will be routinely conducted. The former will destroy the multipacting resonance launching from the cold surface of the outer conductor of the high-power input coupler so as to suppress the prospective multipacting. The latter will force the condensed gas on the cold surface of the outer conductor to redistribute on the cold surface of the cavity. Applying a partial warming of the SRF module will remove the condensed water molecules on the cold surface of the outer conductor but will require one full day.

Regarding the heavy gas load from the ferrite layers of the HOM dampers, we propose to install the SRF modules into the storage ring of TPS after the beam is stored. The 5-cell copper (Petra) cavities will be used for the machine commissioning up to 100 mA of storage-ring current as originally planed for vacuum cleaning, but the HOM dampers of the detuned SRF modules will be beam-processed simultaneously during the machine commissioning of TPS. Because the SRF modules are detuned, the heavy gas load causes no difficulty for machine commissioning. The cold surface of the SRF module effectively adsorbs the released water molecule from the ferrite surface of the HOM dampers during the ramping of the beam current. We expect that our measures will minimize the impacts of heavy gas loads from the RF window and HOM dampers on the reliability and availability of SRF operation.

Following the TPS progressing into mature operation a few years later, beam power more than 250 kW will be delivered to the electron beam from each SRF module. The high-power input coupler for the 508-MHz SRF module of KEKB type had been RF-conditioned up to 500 kW in the test stand at KEK. It is promising for a single SRF module of KEKB type to deliver a beam power up to 400 kW, or even more. Combining the available RF power from the existing 300-kW klystron-based RF transmitter with a 180-kW solid-state RF transmitter for each SRF module provides an economical solution for TPS in its mature operational stage. If the SRF operational reliability becomes an issue at such a high rating of RF power, the #3 SRF module will be installed into the storage-ring complex, which is now a stand-alone spare module.

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