COMMISSIONING EXPERIENCE OF SUPERCONDUCTING RADIO FREQUENCY SYSTEMS FOR THE TAIWAN LIGHT SOURCE

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Abstract

An industrially manufactured SRF module of CESR type has been routinely operated at the Taiwan Light Source (TLS) in the National Synchrotron Radiation Research Centre (NSRRC) since 2005 early March. The original goals of doubling the electron beam current to increase the intensity of synchrotron light and to eliminate the instability caused by the interaction of electron beams with higher-order modes of the cavity have been successfully demonstrated. We report here our operational experience over the past two years of the SRF module at TLS at a large beam current toward a maximum beam current 400 mA (300 mA in routine operation) in top-up mode from originally 200 mA in decay mode. Together with digital feedback systems, fluctuations of the synchrotron light intensity (I_0) are less than 0.1 % for more than 95 % of user beam time on the average. We emphasize the diagnostic analysis of SRF trip events and the continuous improvements of the operational analogue low-level RF system against instability caused by heavy beam loading. The greatest challenge to the operational reliability, which is the brevity of the mean time between failures (MTBF), has been successfully overcome; a mean time between failures of the complete RF system of the TLS storage ring more than 200 hr has been demonstrated.

SRF PROJECT AT NSRRC

Since the successful commissioning of the TLS storage ring in 1993, the electron beam has suffered from strong coupled-bunch instabilities caused mainly by two existing room-temperature RF cavities designed in the 1970s. To improve significantly the electron beam stability, many attempts have been made, including the improvement of the cavity cooling water system, replacement of the cavity's damping antenna with a higher-order mode (HOM) tuner, and the application of an RF modulation technique. Various efforts to increase the photon flux and brightness have also been undertaken, but only a limited improvement was achieved. In 1999, a major accelerator upgrade project [1] was initiated with the objectives to double the TLS photon flux by increasing the electron beam current to 500 mA and to improve substantially the stability of the electron beam by replacing the two existing room-temperature cavities with one SRF module most recently developed of CESR-III design. Figure 1 shows the schematic drawing of the SRF module. The

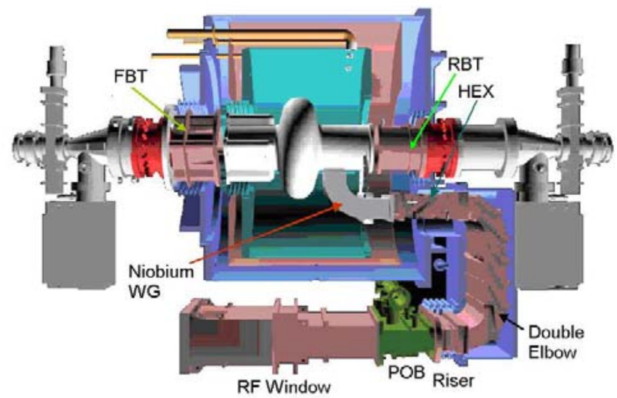

Figure 1: A schematic plot of the SRF module at TLS/NSRRC.

fabrication of the SRF modules was contracted to ACCEL after NSRRC arranged a technical transfer from Cornell University. Various difficulties were encountered during the production. Major faults were the buckling of the niobium waveguide during a warm high-pressure cryogenic safety test and the cracking of the RF ceramic window during high-power RF processing. The delivery of the repaired SRF module (named as S2) was again interrupted by an unexpected quenching at an extremely small field gradient due to indium contamination. An acceptable field gradient was radically achieved after an indium piece was removed from the cavity bottom.

A cryogenic plant has been built and installed by Air Liquide to support the operation of the SRF, according to NSRRC specifications and configurations. The final performance fulfils most design objectives and requirements for SRF operation at synchrotron light sources. These include (a) the capability of long-term continuous operation using a turbine cold box instead of a piston cold box, (b) isolating mechanical vibrations from the helium compressor by locating it remotely from the storage ring, (c) minimizing the two-phase mixture of the liquid helium supply and the diminution of return pressure drop of helium on locating the cold box near the SRF module, (d) convenience of operation on exploiting fully automatic control, (e) a large redundancy of helium cooling capacity by a safety factor 1.5, (f) a large redundancy of inventory of helium gas capable of sustaining once the loss of all helium in the SRF module, (g) capability of rapid cooling with the aid of a 2000-L main dewar, and (h) cryogenic load matching with a frequency driver in various operational modes to save electric power.

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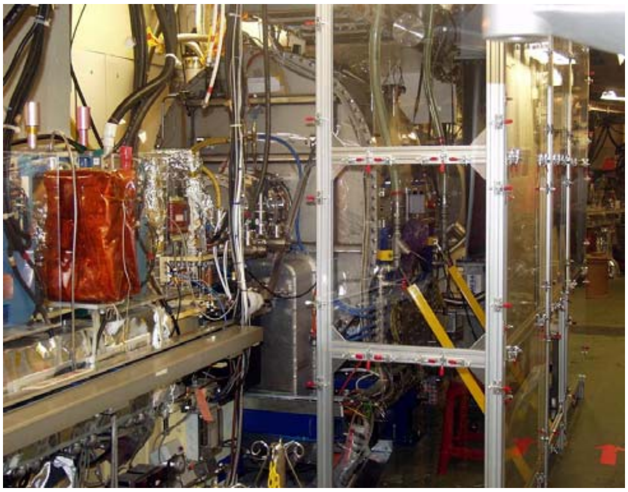

Figure 2: SRF module in routine operation at NSRRC [2].

Additional efforts are required to solve other problems, such as minimizing the large rate of consumption of LN2 through the long transfer line, stabilizing the LN2 supply pressure into the SRF module by installing a phase separator near the SRF module, preventing a surge in helium pressure caused by poor coordination between the main compressor and the helium gas manager during shutdown or failure, and using an effective motor bearing in the main helium compressor that is reliable when the cryogenic plant is operated at full power.

A new RF plant was developed internally and tested thoroughly for SRF operation concurrently with the production of the SRF modules. A new 100-kW RF transmitter of crowbar type was assembled internally, with emphasis on the attenuation of RF noise and operational reliability. Through this independent RF plant, the system integration and the high-power test run of the SRF module were completely independent of routine operation of the synchrotron before decommissioning of the room-temperature cavities. Most individual interface problems were solved during the test run without interrupting the synchrotron operation, significantly decreasing the duration required for commissioning the SRF module during installation in TLS.

Table I: Parameters governing operation of the CESR-III 500-MHz SRF module at TLS [1].

nominal machine energy	1.5 GeV
revolution frequency	2.49827 MHz
maximum beam current	< 500 mA
SR energy loss per turn	<164 keV
RF harmonic number	200
beam power	< 82 kW
RF frequency	499.654 MHz
RF voltage	1.6 MV
number of RF cavities	1
R/Q per cell (V^2/2Pc)	89/2
nominal external Q	250,000
cryogenic static load	< 30 W @ 4.5K

SRF OPERATION

After the SRF module was successfully installed and commissioned in 2004 November-December, NSRRC entered its new era of SRF operation [2]. Figure 2 shows the SRF module (named as S1) in operation at TLS. The parameters that control the operation of the 500-MHz SRF module at TLS appear in Table I. The storage ring was first operated at a maximum beam current 200 mA in decay mode. Doubling the integrated photon flux was first achieved on operating the storage ring in top-up mode at a beam current 300 mA in 2005 November [3]. Protracted (more than 8 h) reliable test runs at a beam current 400 mA in top-up mode were verified in 2006 September, after successfully increasing the available RF power from the RF transmitter. Routine operation at a beam current 360 mA in top-up mode is scheduled for 2007 after solving the problems of thermal loading at some beam lines.

The SRF module features heavily damped higher-order modes. No detectable effect of the coupled-bunch instability, caused by the SRF module, on the photon intensity has been observed. Transverse feedback is, however, absolutely required to stabilize the photon beam that is heavily perturbed by residual instabilities; those were fully suppressed by the coupled-bunch instabilities of the accelerating cavities before the installation of the SRF module. Without competition from the coupled-bunch instabilities driven by higher-order mode impedances of the accelerating cavities, the residual instabilities have become the dominant source of the photon beam turbulence. After those residual instabilities were properly damped, a highly stable photon beam with so-called I_0 fluctuations (dI_0/I_0) better than 0.08% became available for most scheduled user shifts. Further improvement of the I_0 fluctuations, to 0.06 %, has been achieved with the longitudinal digital feedback, as shown in Fig. 3. Few spontaneous spikes or glitches appear in the daily plot of I_0 fluctuations as Figure 3 shows, which is not a direct consequence of frequent injections for operation in top-up mode but somewhat resembling a turbulence of photon flux due to temporal over-excitation of residual instabilities.

Although the use of SRF technology at synchrotron light sources can fundamentally improve both the intensity and the stability of the photon flux, it also challenges the reliability and availability of machine operation, especially at higher operating beam currents. Figure 4 displays the statistics concerning the mean time between failures (MTBF) of the RF plant with SRF module over the past two years, in contrast to those with the room-temperature cavities. A comparable system reliability using an SRF module in comparison with that using a room-temperature cavity is obviously highly promising. A MTBF greater than 200 h is acceptable for the requirement of machine reliability for synchrotron users of TLS that has only one SRF module in operation, but not for the proposed 3-GeV light source, Taiwan

Photon Source (TPS), at NSRRC, which requires four sets of SRF modules for machine operation at its target current 400 mA (and beam power 720 kW). As a trip rate once per week for the completed RF systems is required, the SRF trip rate must be decreased to once per month on average per module.

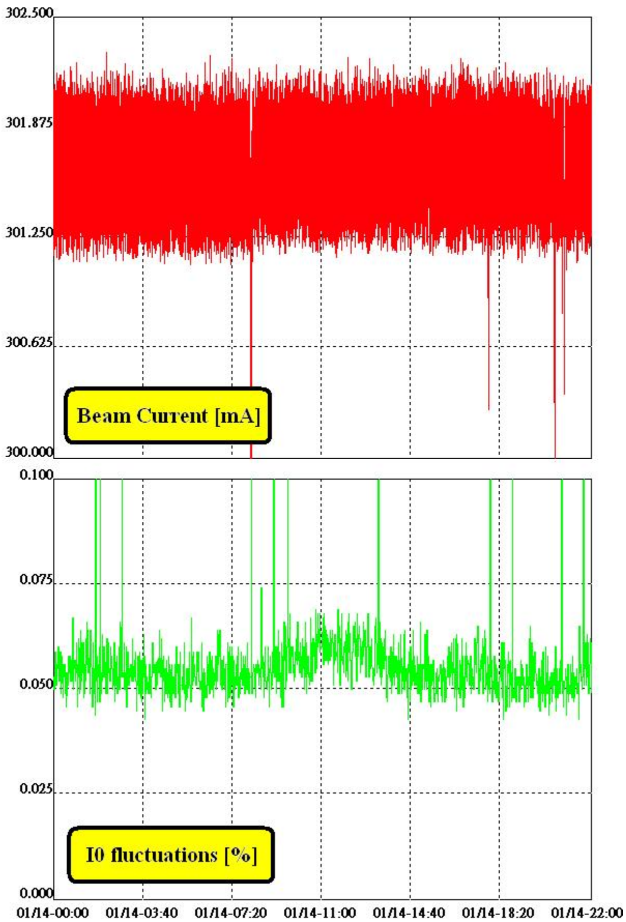

Figure 3: Plot of I_0 fluctuations for the TLS using the SRF module as an accelerating cavity.

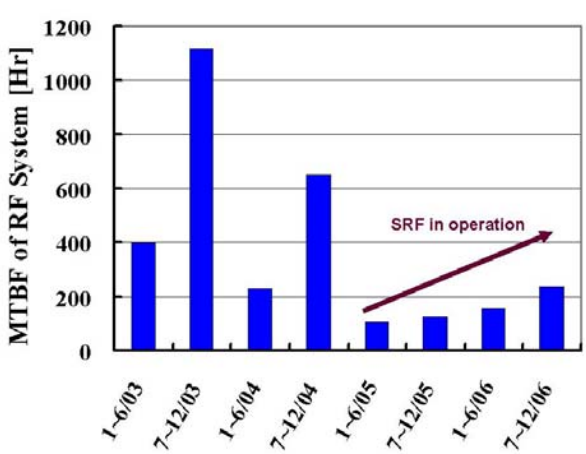

Figure 4: Mean time between failures of the complete RF plant with SRF module as accelerating cavity since 2005.

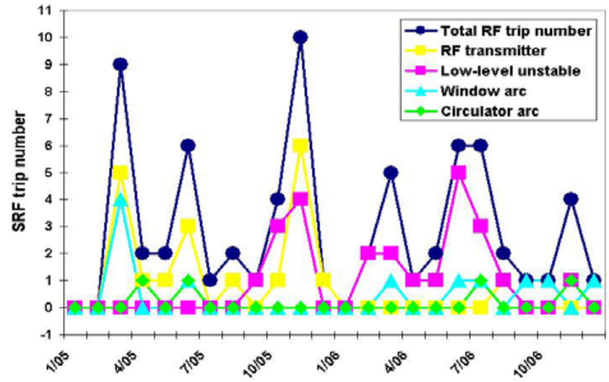

Figure 5: Trip distribution of RF plant with SRF module.

The most challenging trip events of the RF plant with the SRF module at TLS are due mainly to the instability of the feedback loops of the low-level RF system owing to heavy beam loading and false alarm of the window arcing occurring mostly during beam injection into the storage ring, as shown in Fig 5. An instability of the low-level RF feedbacks results in either an activation of the quench detector due to ringing of the RF gap voltage or an overdrive of the RF drive power of the low-level RF system to the klystron for maintenance of the RF gap voltage via an amplitude loop. Even though coherent synchrotron oscillations driven by Robinson instability are not observed at a beam current 360 mA, the insufficient phase margin against the DC Robinson instability occasionally caused ringing of the RF gap voltage that was regulated by the amplitude loop of the low-level RF system. As the ringing was not reproducible at the same beam current but became more frequently (once every few hours) at a higher beam current, it seems to be excited by some external turbulence.

With the increasing operational beam current, the feedback loops were first stabilized on decreasing the loop gains stepwise and then on applying a non-zero loading angle up to -5^{o} to extend the stable margin of Robinson instability. Later, a higher loop gain became available on broadening the bandwidth of the feedback loops. The detailed mechanism of instability of feedback loops of the low-level RF system under a heavy beam loading remains under investigation. Modeling of the feedback loops is in progress. The RF direct feedback has been prepared and will be applied to expand the stable margins of Robinson instability as required.

The tuner loop should ideally behave quietly for the machine operated in top-up mode because the temporal variation of beam current is minor, but the tuner loop is still busy compensating the slow drifts of the cavity resonance frequency in a time interval of about 20-30 min. mainly owing to large fluctuations of the LN2 temperature at the thermal transition flute beam tube (FBT) attached to the niobium cavity. Recent experiments strongly indicate that fluctuations of the LN2 inlet pressure might not be the only source that causes fluctuations of temperature or pressure of LN2 inside the

SRF module. Excellent regulation of LHe pressure with fluctuation less than 3 mbar has been achieved with a low-speed PID loop, but minor effects on the variation of the cavity resonance in a time interval of few seconds are still observable at a low tuner loop gain. Careful functional examination of the helium pressure compensator will be undertaken.

Microphonics might be intensely excited by individual driving pulses of the stepping motor, which was observed when the tuner loop was operated at high gain. A tuner loop with an extremely small gain, however, causes a slow drift of the resonance frequency of the cavity and therefore a temporal variation of the operational loading angle. After applying the micro-stepping controller to decrease the driven torque, the tuner loop is now re-operated at a much high gain without exciting intense microphonics resulting in quenching.

Window arcing is troublesome during operation in the top-up mode. AFT arc detectors are used to drive the interlocks of window arcing. Optical fibers sense the visible arcing and transfer the optical signal to a photo-diode in the circuit of the arc detector. When the photo-induced current increases above a specified threshold, the detector sends a TTL signal as a rapid interlock of SRF protection, regardless of the pulse duration of the photo-induced current. During kicker firing for beam injection, a false alarm of window arcing of the spare SRF module S2 was sometimes observed (the RF of S2 was off), even though the pulse duration of that arcing is of merely a few μs. An interlock mask of window arcing for an ultrabrief pulse of optical signal might be a plausible solution to avoid false alarms of this kind. More evidence for similar events is being collected for a final decision. Implementing dual arcing sensors on the individual view-ports provides a voting mechanism helpful to eliminate false alarms, when the false alarm is a consequence of EMI from high voltage pulse generators of the kickers. Clarification whether the source of false alarm of arcing arises from electronic noise or stray light is under study. The design of SRF modules in the next project will be considered accordingly.

The cavity vacuum is satisfactory: it attains 0.1 nTorr just after thermal cycling and as the vacuum of the cold cavity is isolated from other parts of the beam lines of the storage ring. The cavity vacuum increases to about 0.45 nTorr after opening the vacuum gate valves on both ends of the SRF module but with RF power off. The cavity vacuum is still better than 0.6 nTorr after continuous operation for one year in the top-up mode with a beam current 300 mA. A vacuum burst has been observed at an RF gap voltage 0.9-1.2 MV. Such a vacuum burst appears sometimes during initiation of the RF power to its nominal operational voltage 1.6 MV. We speculate that the vacuum burst is due to the excitation of multipacting near the coupling tongue of the waveguide coupler, but no tangible evidence supports this speculation. The appearance of such a vacuum burst is significantly decreased by rapid ramping of the RF gap voltage across this problematic zone. The condensed residual gases of cavity vacuum are mainly H_2, CO/N_2, and H_2O. The hydrogen has the worst vacuum in a short time interval during warm-up. It was up to 700 nTorr and 400 nTorr during the warm-up after one-year continuous operations in 2005 and 2006, respectively.

A rapid loss of beam current at a large beam current develops an enormous reflection of RF power and causes a great RF loading on the ceramic window of the SRF module. Arcing might be observed. The window vacuum deteriorates and might activate the interlock to close the vacuum gate valves. The RF system is used to terminating the RF after a sudden beam loss to protect the RF window. A super-rapid (TTL) interlock to limit the reverse RF power has been implemented to protect the window. In addition, a fault of the interlock ready chain automatically decreases the RF drive power of the RF transmitter. Abruptly curtailing the RF power on activating slow interlocks will cause a rapid loss of beam current, which is not necessary and can be avoided by a slow termination of RF power. A successful attempt can be made to allow survival of the RF system with warm cavity after a sudden beam loss, but such a design is difficult to implement when operating the SRF module with a quench interlock. A rapid decrease the RF drive power (RF gap voltage) to the RF transmitter corresponding to the increasing amount of reverse RF power is under investigation.

CRYOGENIC PROTECTION

The design philosophy for cryogenic protection of the SRF module operated at TLS is similar to what is used at CESR but with a few modifications. The SRF module is mainly operated as a refrigeration load for the cryogenic plant, with merely about 40 SLPM cold helium gas to cool part of the HEX waveguide section (as shown in Fig 1) to a temperature intermediate between that of LHe and that of LN2.

The cryogenic plant has faults of two types: a fault of the GHe main compressor and a fault of the cold box. A fault of the GHe main compressor automatically terminates the cold box, but the GHe main compressor continues to operate under a fault of the cold box. The fault of the cryo-plant from SRF module's point of view called as *cryo-area trip* is caused by the pressure in the suction line exceeding 4 psig (1.28 bara) for a nominal operational pressure 1.05 bara (15.35 psia) with the GHe main compressor. A cryo-area trip is detected when the GHe main compressor has a fault or is overloaded. A cryo-area trip causes the SRF module (and its cryogenic valve box) to be automatically isolated from other parts of the cryogenic system. Under this condition, the heater of the LHe bath and the RF power are terminated automatically. Meanwhile, the LHe bath pressure increases with time because of evaporation of LHe by the static cryogenic loss about 30 W. Within a few minutes, the LHe bath pressure attains about 22 psia and an extra mechanical thermal-relief valve opens automatically. If the LHe bath pressure increases further, the spring relief valve opens for depressurization. We added a latch function for the opening of the spring relief valve to avoid oscillation of the LHe bath pressure between atmospheric pressure and its threshold pressure 9.0 psig (0.62 barg). Such a design risks contamination from impurity if manual reclosing the spring relief valve cannot be effected before the emptying of the LHe inside the LHe bath of the SRF module. The 1-barg mechanical burst disk is the ultimate safety protection for the SRF module with over-pressure. We twice experienced a broken burst disk before opening the spring relief valve at a pressure below its threshold. The reason is unclear: we speculated that the burst disk might become very fragile after several cycles of purging and pumping even at an extremely small rate, 1000 mbar/50 min. For the operating SRF module (S1), there is notably an additional burst disk at 1.4 bara to protect the cavity buckling when it is warm; this is bypassed when the cavity is cold.

With a fault of the cold box alone, the cold box becomes isolated from its loads, but the interlock of a cryo-area trip cannot be detected. The LHe supply valve becomes closed when the pressure at the cold return valve exceeds 1.4 bara, and the heater of LHe bath is terminated automatically. The cold return valve of the SRF module is expected to become close after fault of cold box but still open to the other cryogenic loads according to the original design to allow depressurization of LHe bath during a real quenching of the superconducting cavity. To solve this conflict, additional protection (without the latch function) was subsequently implemented to close the LHe supply valve and the cold GHe return valve of the SRF module immediately when their pressures at upstream of corresponding cryogenic valves exceed 21 psia and 19 psia, respectively. A cold-to-warm bypass valve on the intermediate switching valve box between the SRF valve box and the main dewar as well as the other cryogenic plant becomes opened automatically when its pressure exceeds about 1.28 bara, depending on the opening of its upstream manual valves.

There is experience with freezing of the readout from the AMI LHe level sensors at some specific levels. This condition causes full opening of the LHe supply valve of the SRF module. The LHe bath of the SRF module consequently becomes over-filled, and the static loss increases significantly. An additional interlock has been implemented to close the ready chain of the interlock of the SRF module when the opening of the LHe supply valve much exceeds its nominal opening (60 % vs. 23 % at 60 W dynamic loss and 30 W static loss of cryostat).

A GHe recovery compressor that has been installed for our cryo-plant becomes automatically actuated when the suction line pressure exceeds 1.2 bara, regardless whether the increase of suction line pressure is due to overloading or a fault of the GHe main compressor. Our SRF module benefits little from the GHe recovery compressor according to the design philosophy of the cryogenic protection. The cryogenic bypass valve from the cold GHe to the warm GHe line is closed as default. Operating the interlock of the cryo-area trip in a non-latched mode allows this bypass valve to open if the suction line pressure becomes small again – after full operation of the recovery compressor. Fully opening the bypass valve according to the current design using an OMEGA PID controller without a function of an upper bound of opening might, however, result in a rapid expansion of cold helium gas, and create a backward pressure to send the warm gas back to accelerate the evaporation of the LHe in the LHe bath. A PLC-based control loop to allow slow opening of the bypass valve with a second unlatched interlock of the cryo-area trip (to allow closing the LHe supply and the GHe cold return valve in a latched mode) will allow the SRF module to benefit the implementation of the recovery compressor.

Taiwan is located on the circum-Pacific seismic belt on which more than 70 % of all global earthquakes occur. Additional mechanical supports have been implemented on both sides of the cryostat of the SRF module. The LHe bath is suspended with four invar wires on the top of the cryostat alone. An earthquake will create rapid fluctuations of LHe pressure on the cavity and consequently rapid variations of the cavity resonance frequency. A similar phenomenon has been observed through a surge of helium pressure caused by malfunction of the cryo-plant. A restriction of the available RF drive power will activate the interlock to terminate the RF power.

CONCLUSION

In 1999, a bold decision was made at NSRRC to adopt SRF technology in a major TLS machine upgrade. The SRF cavity has become the preferred choice in building or planning new synchrotron lamps worldwide. As pioneers in using an SRF module as an accelerating cavity for a third-generation light source, we are pleased to report that our users are satisfied with the SRF performance. Mastering SRF technology internally is vital to the realization of highly reliable and optimal operation of the SRF module in an accelerator. Bridging the SRF technical gap quickly remains a major challenge for our technical staff and requires a continual intensive effort.

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