MATURE OPERATION OF A CESR-TYPE 500-MHz SRF MODULE AT TAIWAN LIGHT SOURCE

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INTRODUCTION

Modern synchrotron light sources pursue low emittance of a storage ring to operate at a great beam current to maximize the photon flux and brightness, but require a high operational reliability, availability and stability. The operation of a SRF module as an accelerating RF cavity intrinsically ensures an operational stability at a large beam current because of its heavy damping of the cavity's modes of higher order, but involves a great risk of compromise with machine reliability and availability because it requires superconductivity and operates at a cryogenic temperature.

Since its opening to the users in 1993, Taiwan Light Source (TLS) suffered greatly from coupled-bunch instabilities through a strong interaction between the circulating beam and the high-order modes of the copper cavities, even at a beam current 200 mA in decay mode. After a long struggle with these instabilities, a risky decision of a major machine upgrade by replacing the copper cavities with superconducting ones was made for TLS in 1999 [1].

A CESR-type SRF module was installed in TLS at the end of year 2004 and began its routine operation from the beginning of 2005 [2]. Within a few months, the beam current for user shifts was increased from 200 mA in decay mode to 360 mA in top-up mode. This large current amplifies the residual beam instabilities that are now fully suppressible with digital transverse and longitudinal feedback.

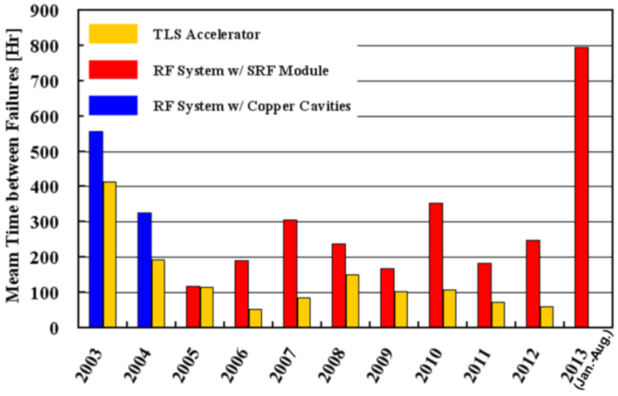

Figure 1: Mean time between failures (MTBF) of the RF system with SRF module in operation in the storage ring of Taiwan Light Source (TLS). The MTBF of the complete accelerator complex of TLS is given for comparison.

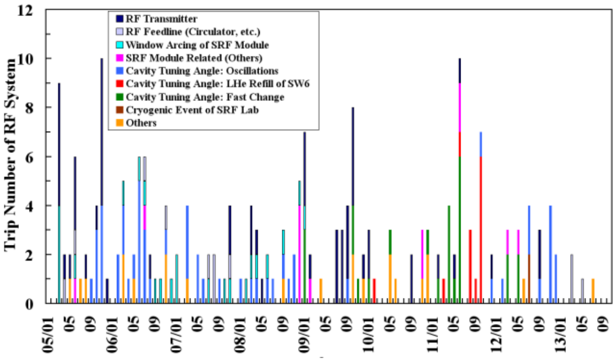

Figure 2: Statistics of classified trip events of the RF system with a SRF module in operation in the storage ring of Taiwan Light Source (TLS).

In selecting a SRF module as accelerating cavity, the reliability of the SRF operation is always a major concern, but it is no longer a critical issue for the machine operation at TLS. Here, we report what we learned from the SRF operation at TLS during the past eight years.

OPERATIONAL STATISTICS AND TRIP ANALYSIS

The mean time between failures (MTBF) of the complete RF system with a SRF module in operation for TLS is now comparable with the best operational record of copper cavities ever achieved in the same machine with a smaller beam current in decay mode, as shown in Fig. 1, after continuous improvement in its operational reliability. The mean time between failures of the complete accelerator complex of TLS is also illustrated in Fig. 1 for comparison, about one-third to one-half of accelerator trip events coming from the RF system. The accumulated downtime caused by trip events of the RF system is however minor relative to the total downtime of TLS.

Regardless whether a trip event of an accelerator complex is due to a fault of a RF system, an automatic termination of a RF system in a short time is absolutely essential to protect the RF window of the SRF module from damage. This unique feature sometimes confuses the clarification and troubleshooting of a machine fault event. It becomes necessary for the RF system, especially with a suspect SRF module, to provide unquestionable evidence of lack of guilt by itself. Under such circumstances, an advanced diagnostic system together with user-friendly event-logging software has been developed at NSRRC and improved continuously during the past eight years to clarify a possible trip sequence and mechanism. Most

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relevant signals providing clues of accelerator trip mechanisms are implemented into the diagnostic system.

The reliability of the machine complex of TLS benefits from our development. For example, separating the trip mechanism from a misfire of any injection kicker during top-up injection from a fault of a RF system becomes straightforward on comparing the variation of the rapid beam-current signal with those RF-related signals such as forward, reverse and transmitted RF power in a time sequence. The analogue signals from photon beam position monitors are extremely helpful to distinguish whether the accelerator trip event is responsible by the rapid orbit feedback system or the RF system. Nevertheless, clarifying whether a beam trip is due to spontaneous excitation of transverse instabilities during top-up injection or to a quench of a superconducting magnet with the fault of a RF system is still ambiguous at TLS. The rapid signal of Betatron tunes might provide a possible clue to clarify the trip mechanism, but it is still missing for TLS.

Several difficulties involved with the SRF operation have been experienced and overcome during the past eight years. Figure 2 illustrates the statistics of classified RF trip events. Our measures against the relevant SRF trip mechanisms are given as follows: The oscillation of a RF gap voltage of a SRF module was one of the most critical operational problems at TLS. Unlike the copper cavity, the operation of a SRF module relies on a quench detector that terminates the SRF operation whenever the RF gap voltage diminishes or oscillates on a time scale of a few microseconds. During the increase of the machine beam current of TLS from 200 mA to 360 mA, oscillation of the RF gap voltage occurred frequently, with a decreasing characteristic (oscillation) frequency accompanied with an increased beam current. Based on experimental observation and intuition, we recognized that a SRF trip event of this kind can be hindered on decreasing the loop gains of a low-level RF system. Operating the SRF module with a sufficiently negative loading angle (~-15^{o}) completely avoided a further SRF trip event of this kind. Note that a direct RF feedback has been prepared but not yet necessary for SRF operation at TLS. Its trip mechanism has been well explained through modelling of the low-level RF system under a heavy beam loading using a Pedersen model, to be reported elsewhere.

The variation of the tuning angle of a SRF module is still a critical issue for stable SRF operation. Several sources create mechanical vibrations of the thin shell structure of the niobium cavity of a SRF module.

For example, the consecutive driven pulses of the stepping motor of the cavity mechanical tuner excite the microphonics and cause the detuning of the cavity resonance frequency whenever the harmonics of pulse-driven vibration are in coincidence with any mechanical resonance modes of the SRF module. This problem was solved on implementing a micro-stepping controller to drive the stepping motor.

A superconducting wiggler with a cold vacuum chamber has been installed downstream of the SRF module. During refilling liquid helium into this superconducting wiggler, which is undertaken twice a day, spontaneous thermal movements of the cold vacuum chamber of the superconducting wiggler (SW6) gives the SRF module a sudden impact that causes the operating SRF module to become heavily detuned to unpredictable degrees within a few ms and sometimes activates the SRF protection. Because of the difficulty in improving the stiffness of the SRF module as it is now in operation, improving the insulation vacuum of the cryogenic transfer line for this superconducting wiggler might be the only feasible approach against a SRF trip mechanism of this kind.

Operating the crossing-neutral position of the frequency tuner creates much backlash that readily causes the cavity to become detuned far from resonance, but it might be not always easy to move the tuner far from its force-free location. Several factors determines the working point of tuner: First, the acceptable range of the operational helium pressure is extremely narrow because of concern about the buckling of the warm cavity structure operated at a higher pressure but not too low to send the cold helium gas back to the cryogenic plant. Second, the annual variation of the circumference of the electron beam orbit in the storage ring because of the seasonal variation of the temperature must be compensated by tuning the RF frequency properly to maintain invariant the position of synchrotron light at the experimental end stations for convenience. A balanced tuner position has fortunately been found.

A few SRF trip events related to cavity detuning, for example, rapid and large change of tuning angle on a time scale of a few tens of ms, remain mysterious. Because the frequency of their occurrence is minute -- only a few times annually in recent years – there is difficulty in clarifying the trip mechanism, but only a negligible impact on the machine operation.

The electric power surges or glitches, even those that occur within less than ten times of frequency cycles of AC line voltage in most cases, might cause shutting down the helium compressor of the cryogenic plant and create a few hours of machine downtime to recover the cold box from cold. A DC bank up to 3 min has finally been implemented (2010) to secure an uninterruptible operation of the cryogenic plant. The turbine-based cryogenic plant has now become really robust for highly reliable operation over a long term.

The EMI causes a false alarm of the interlock for SRF operation. The false alarm of AFT arc detection for the RF window of a SRF module and a circulator of the RF feed-line were tormenting problems that were completely solved on implementing a digital electronic circuit with a two-stage interlock threshold: the amplitude and duration of the electron current converted from the photodiode for arc detection helps in screening a false arc event or improving RF immunity. The readout of various temperature sensors is influenced by the EMI that also triggers a false alarm. Originally, individual analogue comparator circuit boards were implemented to supervise the slowly responding interlock signals of this kind, but were easily trigged by EMI. Implementing distributed small-size PLC with proper programming to screen a false alarm due to EMI is in progress.

The other parts of the RF system such as the RF transmitter and circulator of the RF feed-line becomes the major barriers for extremely highly stable SRF operation at TLS nowadays. Poor regulation of the temperature compensation unit of an AFT circulator recently tripped the SRF operation. Implementing an appropriate PID module to improve its reliability is under investigation.

Vacuum tightness: Since delivery of the operating SRF module to NSRRC in 2004, six courses of full thermal cycle proceeded. A small vacuum leak from the helium vessel to the insulation vacuum of the SRF module was identified just after the last full thermal cycle in 2009 summer, which is still manageable with regular weekly pumping down about a half hour each time, to recover the cryostat insulation vacuum from the range of 10^{-5} Torr to 10^{-6} Torr. The pressure just before weekly pumping down increases slowly, but remains far from the range of 10^{-4} Torr. The increased static heat loss is negligible. Whenever continuous evacuation of the insulation vacuum of SRF module becomes necessary, an external pumping station will be operated steadily. The protection against a pump or power failure has anyhow been implemented to avoid a vacuum accident.

An increased gas load on the cold surfaces of a SRF module might eventually bring extreme difficulty for its reliable operation such as enhancement of multipacting on the cold surface of an input power coupler, increased cryogenic dynamic loss and radiation dose, development of a spontaneous vacuum burst during desorption of condensed residual gas on the cold surface, etc. Nevertheless, the gas load is never a real problem for SRF operation at TLS because its operational maximum forward RF power is less than 100 kW and the average residual (vacuum) pressure of the entire storage ring is maintained in the range of sub-nTorr, thanks to the huge capacity of hydrogen pumping from the distributed NEG pumps around the storage ring. Keeping the SRF module continuously cold for years, the cavity and waveguide coupler vacuum of the operational SRF module remain almost invariant, but weak multipacting resonance owing to a gas load on the input-power waveguide coupler has been observed at a RF gap voltage about 1.1 MV. The multipacting resonance can be processed with a second trial to ramp the RF gap voltage to its routine operational value, i.e., 1.6 MV. The processing memory is impressed. Moreover, no sensible increase of dynamic heat loss has been observed from the real-time Venturi meter since its operation.

FUTURE OPERATIONAL CHALLENGES

The availability of the SRF operation should be the last challenge in selecting a SRF module for a modern synchrotron light source. Unlike the copper cavity that is destined to operate even over a century, the average service time for a SRF module might be less than 10 years. Vacuum leakage due to fatigue of indium seals after unavoidable frequent full thermal cycling is one major reason for the short service lifetime of a SRF module. Eventually, an unexpected, sudden vacuum leak from a helium vessel to the cavity vacuum will be a great catastrophe for any light source operating a SRF module. The spare SRF module passed its horizontal test in 2005 and has maintained an adequate vacuum since then. Concerning the limited service lifetime of a SRF module, we plan to undertake its second high-power test in our SRF test area in coming year.

The cryogenic plant is in general highly reliable for long-term continuous operation following annual regular maintenance work but it is still possible to experience an unexpected malfunction such as damage of a warm or cold turbine, an unacceptable loss of helium pressure inside a heat exchanger(s) of a cold box due to water condensation, a vacuum leak of a cryogenic transfer line, etc. How to avoid full thermal cycling for the SRF module during repair of a cryogenic plant is of great interest to minimize the impact on the availability of SRF operation. The cavity temperature can be maintained below 120 K at least more than two weeks merely by pre-cooling the cryostat using liquid nitrogen during an interruption of supply of liquid helium. That duration is sufficient for maintenance or repair work on a cryogenic plant. For a SRF module with a Q-virus-free niobium cavity, it can be recovered for routine operation within one day after recovery of the supply of liquid helium. Furthermore, an operating mode of such a kind can be applied during annual maintenance of cryogenic plant that typically requires two weeks.

CONCLUSION

In general, the users of Taiwan Light Source are satisfied with the operation of the SRF module and even forget its existence and oddity. We appreciate the intelligent design of the CESR-type 500-MHz SRF module developed by Cornell University and its reliability manufactured by ACCEL (now RI). The CESR-type SRF module fits the operational requirements of Taiwan Light Source extremely well.

REFERENCES

[1] Ch. Wang et al., “Superconducting RF Project at the Synchrotron Radiation Research Centre,” Proceedings of the 10th Workshop on SRF, Tsukuba, Ibaraki, Japan. p. 34 (2001).

[2] Ch. Wang et al., “Operational experience of the superconducting RF module at TLS,” Physica C: Superconductivity, 441(1-2), 2006, p.277-281.