Operating Status of SRF System with Top-up Beam Current at TLS

The Taiwan Light Source (TLS) is the first dedicated synchrotron light source facility that applies a superconducting cavity to upgrade its existing RF system. Since the SRF cavity was successfully integrated with the existing RF subsystem for routine operation, the beam current has increased from 200 mA to 300 mA with top-up mode injection. After a series of improvement in machine operation condition, maximal beam current 400 mA was also successfully demonstrated in 2006 September. The cavity picked-up signal shows that the superconducting cavity module has suppressed the excitation of the cavity high-order modes in routine operation. Together with the digital feedback systems, the fluctuation of the synchrotron light intensity, on average, can be maintain to within 0.1% at the beam current 300 mA for more than 95% of the user beam time. With the dedicated data acquisition systems to find out various machine trip sources, the reliability of the SRF system has been significantly improve; the average mean time between failure has increase from 100 hours to more than 200 hours.

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Since the successful commission of the TLS storage ring in 1993, the beam had suffered from the strong coupled-bunch instability, which was induced by the high order modes of the two traditional copper RF cavities. Various approaches had been applied to suppress the beam instability, including the replacement of the original damping antenna with the plunger tuner, more precise control of the cavity temperature, and the cavity voltage modulation. But only a limited improvement was achieved.

In 1999, an accelerator upgrade project was initiated with the objectives to double the TLS photon flux and to improve the stability of the photon beam. The CESR-III superconducting cavity was then been chosen to replace the existed two traditional cavities for the machine performance upgrade. In addition to the superconducting cavity, the entire SRF system includes one 100 kW, 500 MHz RF transmitter, an analogue low level RF system and one turbine-type cryogenic plant, which has cooling capacity of 460 W, providing the liquid helium for the SRF cavity module and for the superconducting wigglers.

The superconducting cavity module was fabricated by ACCEL, according to our specification and the techniques, transferred from Cornell University. The 100 kW, 500 MHz RF transmitter was developed in-house, based on the existing 60 kW RF transmitter, and assembled with the spare parts of the existing RF transmitter. But to meet the requirement for operating the RF transmitter with more RF output power, we upgraded the klystron and some high voltage components; we also designed new control circuits for the new RF transmitter to enhance its reliability.

The klystron used in the new 100 kW RF transmitter is basically same in the klystron, VKP-7953, which was used in the existed 60 kW transmitter. The new klystron is compatible with the existed 60 kW transmitter. But its cathode voltage insulation and the cooling capacity of the beam collector have been increased to meet the requirement of the higher RF output power for the upgraded beam current.

For fulfilling the operation condition of the new klystron for higher cathode voltage required, we increased the voltage insulation and power rating for the following components in the new 100 kW RF transmitter: the step-up power transformer, the high voltage rectifier and the spark gap that is used in the crowbar protection circuit. Most of the trip events of this 100 kW RF transmitter, shown in Fig. 1, happened before December 2005. The trip events of the RF transmitter became very few after we made improvements on: (1) suppressing the unbalance of three-phase electric power, especially as the klystron beam power is high, (2) depressing the surge in the cathode high voltage by eliminating the cathode's leakage current while transmitter high voltage is turned on, (3) decreasing the klystron beam power automatically as the RF output power is lowering, (4) enhancing the voltage insulation of the filter inductor.

Thanks for this independent 100 kW RF plant, we were able to serve the synchrotron users at TLS continuously, without being interrupted while we were integrating, assembling and commissioning the SRF system. This SRF system is designed to operate with the beam current high up to 500mA. The parameters related to the SRF system operation are listed in Table I. The whole SRF system was successfully integrated and commissioned in December 2004, and started to routine operation in March 2005, with the beam current 200 mA in decay mode. In November 2005, we increased the beam current to 300 mA with top-up mode injection. In September 2006, the SRF system successfully stored the beam current of 400 mA for more than 5 hour, shown in Fig. 2, after we successfully increased the available RF power of the klystron.

The SRF module was designed with ferrite-lined beam tubes on both sides of the cavity for suppressing

Tab. 1: Parameters governing the operation of the SRF system at TLS

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

the cavity high-order modes, which are induced by the beam current. The RF signal, picked up from the cavity, showed that no cavity high-order modes were induced at the beam current of 300 mA. The beam mode spectrum also showed that no obvious coupled-bunch instability is induced by the SRF cavity. But the beam transverse instability obviously became stronger after the SRF cavity replaced the traditional copper cavities. That should be resulted from the weakened competition against the longitudinal coupled-bunch instability. The transverse feedback becomes necessary to stabilize the beam vertical motion while the SRF cavity is in operation. Together with the digital feedback to suppress the residual longitudinal instability, the photon intensity fluctuation, on the average as shown in Fig. 3, can be maintained to within 0.1 % for more than 95 % of the user time at the beam current of 300 mA.

Although the use of SRF module can significantly improve the stability of the photon beam, it also brings the challenge to the machine reliability because it is more sensitive to the variations of the operational condition than the tradition copper cavity. In order to quickly find out the machine failure sources, in addition to the existing archive system which record the data with time resolution of 10 seconds, we have set up several different kinds of data acquisition systems. The oscilloscopes are

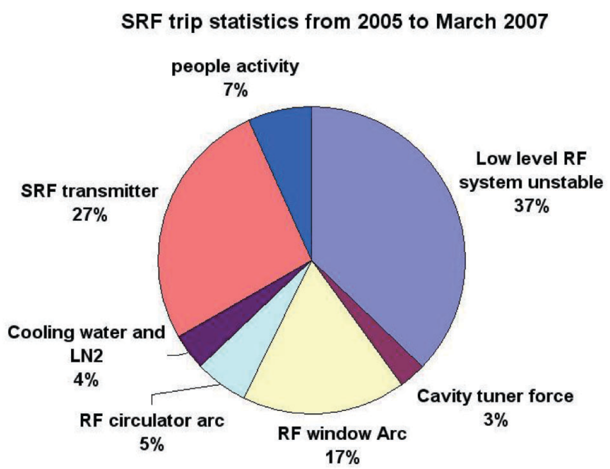

Fig. 1: Statistics for various sources that caused the SRF system failures during user time.

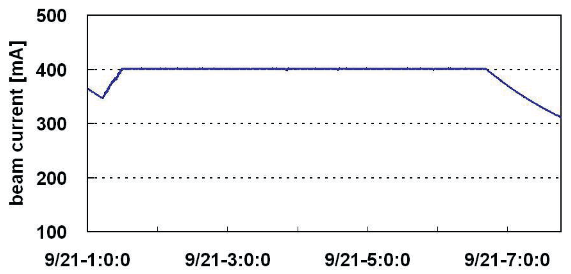

Fig. 2: The maximal beam current, operated with the SRF system.

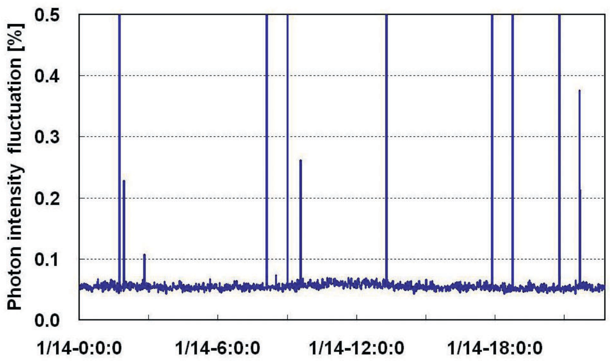

Fig. 3: A daily plot of photon stability at beam current 300 mA, operated with the SRF system in top-up mode

used to record the parameter with the time resolution better than microseconds. As a failure event happened, the oscilloscopes can automatically plot the data and print them to the electric log system. The commercial data acquisition system, LDS Nicolet DAS, is used to record the machine parameter with time resolution better than millisecond. The LDS data acquisition system has 16 channels of data acquisition with the sampling rate of 100 kHz/sec. Besides the above data acquisition systems, two PC-based oscilloscopes are used to display the measured parameters on the PC screens all the time. The data loggers used in the PC-based oscilloscopes are PICO ADC-11/12. Each data logger provides 11 channels of data acquisition; and the sampling rate can be high to 10KS/s. These data acquisition systems describe the behavior of machine parameters with different time resolution and time length, during machine is failed,. They are useful to debug the machine failure.

From the statistics in Fig. 1, we know that the major reason for machine failure is the unstable of the low level RF system. The oscillation of the cavity gap voltage is the first unstable of the low level RF system that we confronted in the SRF system operating with the beam curent. One of the sources to cause the oscillation of the cavity gap voltage is the cavity microphonics. Because the SRF cavity is made from thin-wall cell and its loaded Q is high, about the order of 10^5, all these make the SRF cavity very sensitive to the mechanical vibration, especially while operating with the beam current. We observed that the driven pulse of the cavity's tuner step motor can excite the microphonics as the feedback gain of the tuner loop is set to high. To avoid exciting the microphonics, we reduced the tuner loop gain. But the reduction of the tuner feedback gain also enlarged the variation of the cavity frequency during in operation. In April 2006, we successfully avoided the microphonics by applying the micro-stepping controller to decease the driven torque.

While we were trying to increase the beam current to 300 mA in November 2005, the unstable of the cavity voltage became a problem. Oscillations of the cavity voltage, and of the forward RF power occurred at the beam current higher than 250 mA. It was derived from the insufficient stable phase margin against the Robinson instability. Such oscillation disappeared after we tuned the cavity loading angle to negative side for five degrees and decreased the feedback gain for the cavity voltage.

As the beam current increased to 300 mA in top-up mode operation, we experienced the effect of the heavy beam loading to the SRF cavity. Any abrupt partial loss of the beam current, or suddenly change in the beam orbit may induce the RF mismatch between the cavity and the RF transmission line. The RF mismatch can induce a high reflected RF power from the cavity, and cause cavity voltage dropping. The drop in the cavity voltage can activate the machine protection circuit. The high reflected RF power gives the ceramic RF window a great power loading, which may cause arcing on the ceramic window. The beam partial loss may happen as the injection kickers misfire, machine tunes its operation parameters, or as the superconducting wigglers quench abruptly. Some times, without any beam loss or orbit change being observed by the existing monitor, a sudden RF mismatch can still happen, and causes a machine failure within a few milliseconds after the RF mismatch happens. It is still a puzzle to us.

Another challenge to the system reliability is the arcing in the ceramic RF window and in the RF waveguide circulator. AFT arc detector is used for our system protection, which uses a photo-diode to sense the visible arcing light through an optical fiber. When the photo-induced current increases above a specified threshold, the detector sends an interlock signal to protect the SRF system.

The frequency of arc events increased after we replaced injection kickers and the kicker's modulators to improve the injection efficiency. We speculated that part of the arc events were false alarms, caused by electromagnetic interference (EMI). To verify this, we installed a dummy arc detector near the RF circulator. This dummy detector is the same model as that we are using for the system, but the photon sensor was blinded by aluminum foil. From the arc signal of the dummy detector, we confirmed that EMI can induce the arcing false alarm. To enhance the immunity against the EMI, we surrounded the arc detector module of the waveguide circulator with an additional metal box and covered the module that contains the RF window arc detector with the EMI shielding fabric. The arcing events were significantly reduced to about once a month after we enhanced the noise immunity.

In routine operation, at the gap voltage of 1600 kV for the beam current of 300 mA, the RF power dissipated on the cavity surface, though, is only 30 W, the total RF power, coupled to the cavity, is about 60 kW. As a machine failure happened, the high RF power may destroy the cavity, or other components, if the interlock protection circuit fails to work instantly. In the original design, there is an interlock-chain protection system to shut off the RF power if any interlock signal is activated. This interlock-chain protection is performed through a series of relays, connecting to the interlock signals. To offer the system redundant protections against the events that may damage the system seriously in a short time, for instance the cavity quench, we have designed, and assembled an additional interlock protection system. The protection system is made based on the CPLD (complex programmable logic device). Its response time can be faster than one microsecond. The input and output can be TTL or ECO signals. Under the interlock protection, the SRF system has passed through various kinds of failure events without any damage during in high power operation.

More than two years has passed since the SRF system began routine operation. The goal to double the photon flux has been reached by increasing the beam current from 200 mA to 300 mA in top-up mode. Through SRF module, effective in high order modes damping, and with the digital feedbacks systems, the stability of the photon intensity has been able to maintain to within 0.1 % at 300 mA in top-up mode, which has satisfied most of the synchrotron users at TLS. After our constantly hard works on the improvement in machine reliability, the average machine mean time between failures also increased to the acceptable value, 200 hours, in later half of the year 2006. But we are still not able to prevent the machine from failed by the unstable of the low level RF system, or by arcing interlock in routine operation. How to enhance the machine reliability on high power operation condition is still a challenge facing us, especially if we choose the SRF module for our proposed 3-GeV machine (TPS), there will be four sets of SRF systems, operating with the total beam power of 720 kW; the operating power is twice more for each module than it at TLS now.

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