RF System at TLS and Its Upgrade to Superconducting RF Cavity

The current 500 MHz RF system at SRRC consists of three identical RF plants, two for storage ring operation and the other one for booster operation, as shown in Fig. 1. Each RF plant includes a 70 kW, water-cooled, Varian klystron powered by a 60 kW (RF power) crowbar-type high voltage power supply delivered by Mountain Technology, an EIA 6 1/8" coaxial RF feed-line from Spinner, an AFT circulator, a Byrd RF dummy load, and a Doris cavity cooled by its own secondary water cooling manifold. Each RF plant is regulated by its own low level RF system of SLAC design to facilitate the klystron phase compensation, cavity voltage stabilization, and maintenance of cavity resonance frequency. Table 1 lists the parameters of RF system for routine operation.

The RF system originally was designed for a storage ring operated at 1.3 GeV with synchrotron radiation loss of 72 keV per turn. However, the machine has been routinely operated at 1.5 GeV with various insertion devices and the synchrotron radiation loss is increased to 168 keV per turn.

Table 1: RF parameters in routine operation.

	Doris cavities	SRF module
Nominal machine energy	1.5 GeV	
Revolution frequency	2.49827 MHz	
RF frequency	499.654 MHz	
RF harmonic number	200	
SR energy loss per turn	< 168 keV	> 168 keV
Beam power	< 33 kW	> 82 kW
Maximum beam current	200 mA	500 mA
Number of RF cavities	2	1
Total RF voltage	0.8 MV	1.6 MV
R/Q per cell (V^2/2Pc)	~83	44.5
Ohmic Q	~36000	~1.0E9
Coupling coefficient	~1.3	
External Q (Qe)		2.5E5
Beam loading factor Y	~1.30	~6.95

Only few RF components have malfunctioned during the last decade of continuous operation of the RF system. These include vacuum leak at the bellows of the cavity plunge tuners due to operation at on-resonance with the cavity higher-order modes at a high beam current, burning of the EIA 6 1/8" coaxial bellows causing contamination of the RF ceramic window after operation at a higher beam current up to 300 mA, contamination of the klystron's cathode and recovery by applying pulsed processing with an RF modulator, significant increase of the RF ceramic window's surface temperature owing to improper overnight operation in the high power standing wave mode (30 kW), and degradation of the klystron coupler owing to poor contact with the klystron port. The RF dummy loads were damaged at the very beginning of operation because of the poor conductance of desionized water. Thereafter, regular replacement was still required after a few years of operation due to aging. Periodic cleaning of the circulators has recently become necessary owing to the presence of unknown powders inside which cause frequent arcing after 6 months of

Table 2: Expected cryogenic loads of the SRF module (phase I) and of those with a superconducting harmonic module in the future (phase II).

	Phase I	Phase II
SRF cryostat under normal operation	80 W+0.18g/s	2*(80 W+0.18g/s)
2000 liters liquid He Dewar	30 W (heater)	30 W (heater)
Valve box	10 W	10 W
LHe multi-channel transfer line	5 W	15 W
LHe flexible transfer line	15 W	30 W
Connectors and control valves	20 W	40 W
Subtotal*	160 W+0.18g/s	285W+0.36g/s

*Cryogenic specification is the value multiplied by a safety factor of 1.5

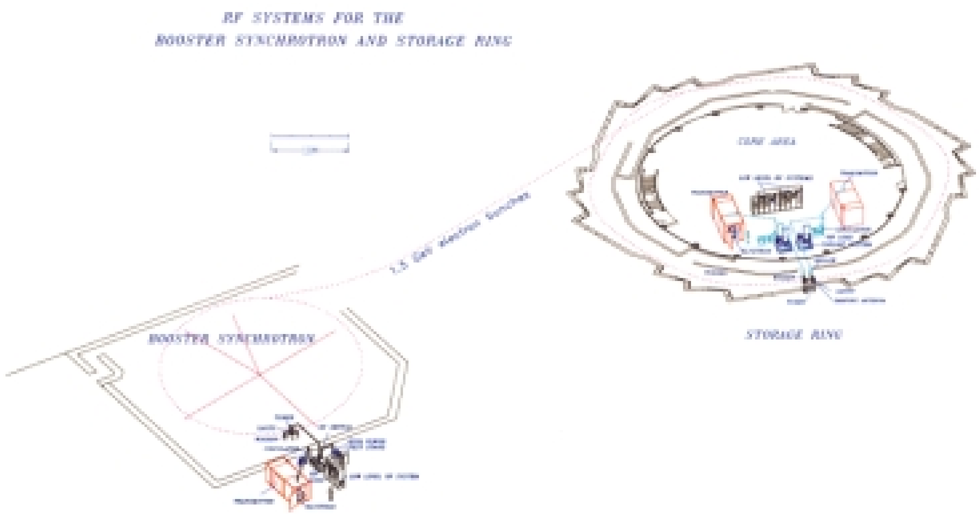

Fig. 1: Schematic layout of the 500 MHz RF system at SRRC.

continuous operation. Most RF components failures only happened once. Careful monitoring of the coaxes' outer surface temperature and use of Teflon as support material of inner coax significantly improved the reliability of the coaxial feed-line. Enhancement of the interlock protection minimizes most of the component damage due to human error, and regular examination of RF leakage reveals component aging before it could cause any machine downtime.

Much attention has been paid to maintaining the RF transmitters. The circuit of the transmitter's high voltage power supply includes 3-phase saturable and AC reactors to regulate the voltage fluctuations of the 3-phase, 380 V power lines and DC high voltage output, the 3-phase HV transformer with a Y-to-2△configuration, 12-pulse HV rectifiers, two-stage HV inductor-capacitor filter, interlock HV circuit board with ignitron and spark gap, and other diagnostic circuits. Contamination of the high voltage circuit board due to cooling with filtered/forced air, and operation of the HV rectifiers in a relatively warm environment are mostly responsible for the rest of the downtime of RF system. Using over-spec rectifiers and enhancing air-cooling capacity extend the lifetime of the HV components. However, regular cleaning of the HV circuit, and HV isolation test of individual components are still required to guarantee reliability, though at the cost of manpower.

The reliability of the RF plants has improved greatly after lessons learned during the very first year of operation. Together with the continuous improvement of maintenance and interlock protection, faults of the RF system have contributed negligibly to the machine downtime, as shown in the downtime statistics of the light source facility since 1997 in Fig. 2.

The HOM characteristics of the accelerating cavity are crucial to the performance of the synchrotron radiation. The observation and cure of saw-tooth instabilities driven by the Doris cavities' higher order modes are discussed as follows. According to the original design, the Doris cavity is equipped with a broadband damping antenna to suppress the coupled-bunch instabilities caused by the cavity's higher-order modes. However, strong saw-tooth instability was observed at higher beam currents, immediately after the storage ring was commissioned, as shown in Fig. 3. The instability

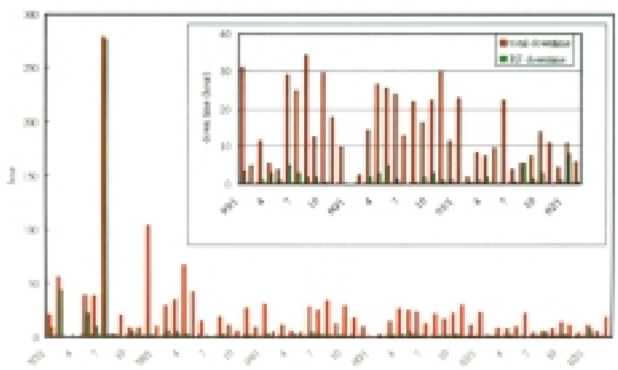

Fig. 2: Statistics concerning system down time, in hours of the light source facility at SRRC since 1997. Faults of the 500 MHz RF system (including secondary cooling water manifolds) contribute only a little.

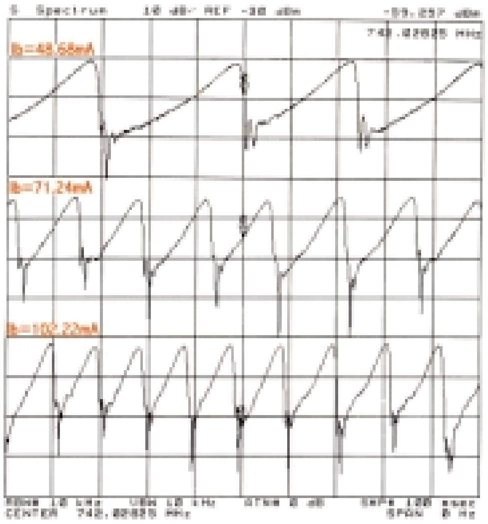

Fig. 3: Saw-tooth instabilities excited by TM011-like mode of the Doris cavity in beam currents of 48.68, 71.24, and 102.22 mA, with the second tuner at its worst position. The repetition rate clearly depends on beam current.

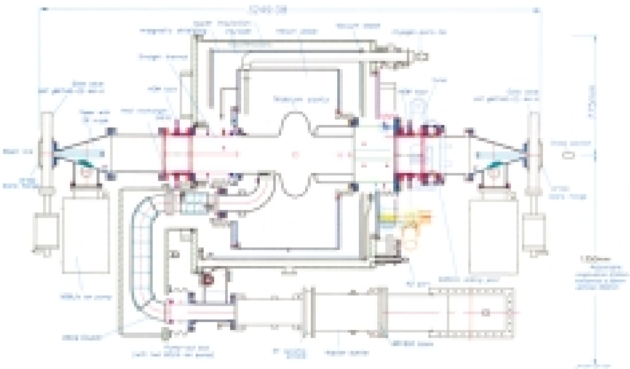

Fig. 4: SRF module to be installed at SRRC.

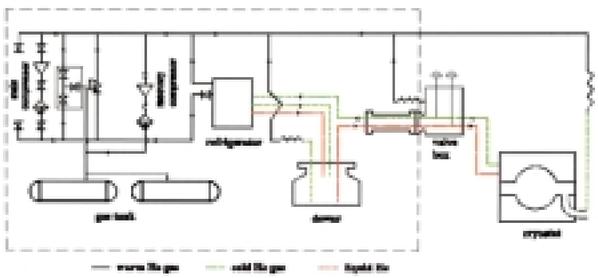

Fig. 5: Cryogenic plant to enable the operation of the SRF module at SRRC.

was primarily excited by the TM011-like mode of the Doris cavity, owing to insufficient damping of this strongest higher order mode. This instability can not easily be prevented by cleverly selecting the temperature of the cavity cooling water because the damped quality factor of TM011-like mode is not sufficiently high for localizing its bandwidth far away from the beam modes which is separated by the revolution frequency of 2.5 MHz. Finally, the damping antenna was replaced by a second tuner to enable the frequency manipulation of cavity's higher order modes. The synchrotron light has since been stabilized by properly selecting the second tuner position and the temperature of the cavity cooling water, and by applying amplitude modulation to RF gap voltage at a frequency close to twice the synchrotron oscillation frequency, at the cost of energy spread dilution which directly affects the undulator performance. This problem ultimately can be resolved by installing a heavily HOM damped accelerating cavity.

Consequently, SRRC has embarked on a major upgrade of machine performance by replacing the Doris cavities designed in 70's with a more recently developed CESR-III HOM heavily damped superconducting RF module, to double the synchrotron light intensity by operating the maximum beam current up to 500 mA, and to eliminate the higher order mode (HOM) effects induced by the accelerating cavity. Commissioning is scheduled for the summer of 2003. Fabrication of the SRF modules, shown in Fig. 4, was contracted out to ACCEL in 2000 after SRRC received a technical transfer from Cornell University. A turbine-based cryogenic plant with a capacity of 460 W will enable the operation of two SRF cavities at 4.5 K. This work was contracted out to AirLiquide in 2001, according to technical specifications developed in-house. Fig. 5 depicts the schematic of the cryogenic plant for SRF operation. Table 2 lists the loading of cryogenic loss. A detailed description of the SRF project can be found elsewhere.

Implementing a new 500 MHz RF plant to operate the SRF module is in the final stage. Only one single SRF module is needed to operate the machine at a beam current of 500 mA or more. A 100 kW transmitter has been assembled with a spare 70 kW Varian klystron and a klystron coupler re-designed in-house. RF output of 85 kW has been demonstrated by increasing the working voltage and cathode current. The delivery of 100 kW RF power is promised by further increasing the cathode current, as shown in Fig. 6. The AFT circulator, MEGA water load, and some WR1800 type waveguide components from DIELECTRIC will be installed to connect the transmitter to the SRF module. Care was taken to minimize the group delay of the RF feed line in order to maximize the open loop gain of the direct feedback. Fig. 7 is a schematic of the RF plant for SRF operation.

The first SRF module of the CESR-III design was installed at CESR in September 1997. Since then, five SRF modules have been fabricated at Cornell and four of them are routinely operated at maximum RF power, each delivering over 200 kW. The operation of SRF modules at CESR offers invaluable lessons in performance and parameter optimization for SRRC. Some operational concerns follow previous experience of operating the SRF modules at CESR. To develop a strategy of highly stable operation at SRRC, we account for the effects of heavy beam loading, multipacting, hydrogen adsorption, and coupled-bunch instabilities as discussed below.

Heavy beam loading: The ratio of the beam-induced voltage at resonance to the cavity voltage, Y, can be considered as a figure of merit that reflects the impact of the Robinson instability on the RF plant due to the effects of heavy beam loading. Operating a machine with a high Y factor reduces the phase margin of the second Robinson instability, as shown in Fig. 8. With an insufficient phase margin, the RF system may become unstable due to RF noise, microphonics driven by mechanical vibrations, coupling between the amplitude loop and the phase loop, among other causes. An unstable RF system either fluctuates spectral intensity of the synchrotron light, trips the RF system through interlock protection, or causes difficulties during beam injection. A phase margin of at least 10 degrees or more is convenient for highly stable operation and can be realized by detuning the cavity resonance frequency and/or by applying direct feedback to reduce the driving impedance of the RF plant. Beam testing of the direct feedback with an open loop gain of over 20 dB has been performed with Doris cavities up to 200 mA, as shown in Fig. 9. Further optimization is in progress.

Multipacting on the in-vacuum waveguide section between the RF window and the RF coupling tongue of the niobium cavity of the SRF module can destroy stable operation. Fortunately, the first hard multipacting barrier observed at CESR was at an RF power of 90 kW that exceeds the required RF power for maximum operating current of 500 mA at SRRC. However, magnetic coils along the in-vacuum waveguide for suppressing multipacting and a 3-stub waveguide transformer for fine-tuning of external Q will be implemented. Because de-tuning the cavity to suppress Robinson instabilities will increase the

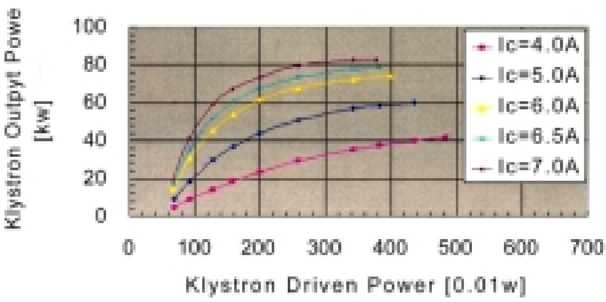

Fig. 6: Performance of the 70 kW klystron operated at an increased cathode voltage and current. Delivery of 100 kW RF power is promised.

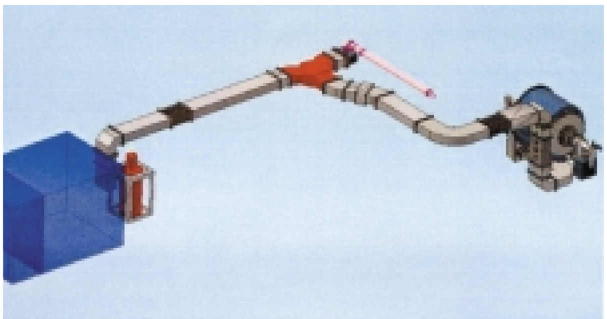

Fig. 7: New RF plant for SRF operation.

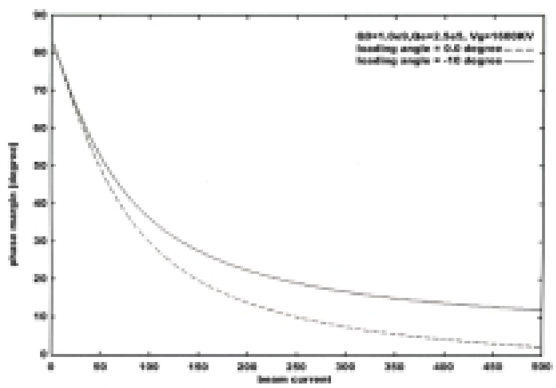

Fig. 8: Dependence of RF phase stability margin of static Robinson instability on the beam current, with CESR-III SRF module at SRRC.

reverse RF power, and may shift the multipacting barrier to an RF power lower than 90 kW.

Hydrogen adsorption of residual gases in the cold vacuum chamber impairs the long-term operation of the SRF module. Periodic warm-up of the SRF module to 60 ~ 70 K may be required. As frequent thermal cycles required for stability affects efficient operation of the light source, much effort on reducing gas load has been made. Baking the RF windows and the other in-vacuum waveguide components (except the niobium cavity) for a long time before assembling the SRF module has been requested. The RF ceramic windows, a major source of gas load, were conditioned off-line at up to 200 kW CW RF power (safety factor of two) in the traveling wave mode, and 50 kW CW RF power in the standing wave mode, with the ceramic window positioned at various phases, over a conditioning time sufficient long (2 hours) to obtain thermal equilibrium. These procedures help to minimize the in-situ RF processing time and to reduce the gas load from ceramic.

Coupled bunch instabilities may still be of concern when the machine is operated at a high beam current. A significant increase of the instability threshold is expected to follow the installation of the SRF module. However, the ultimate suppression of longitudinal coupled bunch instabilities can rely only on broadband

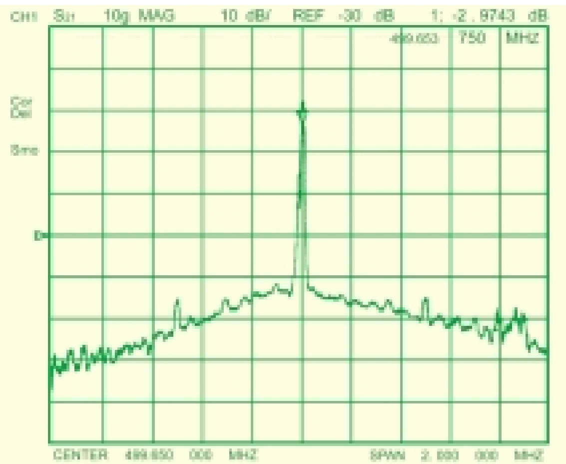

Fig. 9: Closed-loop frequency response of the RF plant with Doris cavities after applying the direct feedback at its maximum allowed open loop gain of 20 dB. The frequency of the central peak corresponds to the RF frequency of the RF plant.

feedback, due to the unavoidable residual impedance of the rest ring components. This phenomenon has been observed in CESR and PF at KEK machines operated at a high beam current with HOM heavily damped accelerating cavities. The digital longitudinal feedback is presently being developed to meet the synchrotron light specifications at high beam current.

Outstanding operational reliability and highly stable performance of the RF plant have been achieved at SRRC using Doris cavities with second tuners. The ultimate upgrade of the beam performance, however, relies on the use of HOM heavily damped cavities and the operation of the machine at a higher beam current. To face these new challenges, intensive SRF training has been organized thanks to the strong technical support from the SRF laboratory at Cornell. The ongoing project of system integration of the SRF module, cryogenic plant, and RF plant since 2000 is on schedule for commissioning of SRF module in the summer of 2003.

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