THE NUMERICAL ANALYSIS OF HIGHER-ORDER MODES FOR SUPERCONDUCTING RF CAVITY AT SRRC

P. J. Chou*, SRRC, Hsinchu, Taiwan

Abstract

The beam current in the storage ring at Taiwan Light Source (TLS) is limited by the longitudinal coupled-bunch instabilities [1] and the available rf power. Two Doris cavities are currently used for particle acceleration in the storage ring at TLS. The higher-order modes (HOMs) from Doris cavities are the major source of longitudinal impedance in the storage ring at TLS. In order to increase the electron beam current in the storage ring, a superconducting (SC) rf cavity developed by Cornell University will be installed to replace those two Doris cavities. The property of HOMs of SC rf cavity is obtained from numerical simulations by using a three-dimensional parallel code GdfidL [2]. The preliminary results show that the storage ring at TLS will not suffer from the longitudinal coupled-bunch instabilities for a beam current not exceeding 450 mA.

INTRODUCTION

The TLS is a third-generation synchrotron radiation facility serving broad scientific community in Taiwan. The storage ring at TLS has encountered longitudinal coupled-bunch instabilities since the commissioning in 1994. The maximum beam current is limited to 200 mA in daily operation. The dominant source of longitudinal coupled-bunch instabilities is contributed by the HOMs of two Doris cavities in the storage ring. At present the technique of rf voltage modulation and detuning of cavity HOMs are applied to stabilize the beam in the storage ring [1]. To raise the flux of photon beams, the maximum beam current has to be increased and HOMs to be damped.

The SC rf cavity developed at Cornell University is chosen for the upgrade of storage ring at TLS [3]. The SC rf cavity of CESR-III type has the same operating frequency as the Doris cavities currently in use at TLS. The fabrication of two SC rf cavities is contracted to ACCEL Instruments GmbH in Germany. The cryogenic system is contracted to Air Liquide in France. The high-power tests of SC rf cavities are conducted at Cornell University. One SC rf cavity will be installed to replace those two Doris cavities in the storage ring at TLS in 2003.

A three-dimensional model of SC rf cavity is built based on the mechanical drawings obtained from Cornell University and modifications required for operating the SC rf module at TLS. The design of taper has been modified to fit into the vacuum chamber of storage ring at TLS. The SC rf cavity will be cooled in a liquid helium bath of 4.5°K. The layout of SC rf module used in the numerical simulations is shown in Fig. 1. The relevant accelerator parameters used in the analysis of longitudinal coupled-bunch instabilities are listed in Table 1. The numerical simulations for SC rf module are performed with a 3D electromagnetic code GdfidL on a Linux PC cluster at TLS.

*pjchou@srrc.gov.tw

Table 1: Accelerator parameters used in the analysis of longitudinal coupled-bunch instabilities for TLS storage ring operating with a SC rf cavity of CESR-III type.

Accelerator Parameters	**CESR-III type SC rf cavity**
beam energy [GeV]	1.5
rf frequency [MHz]	499.666
harmonic number	200
revolution period [ns]	400
rms bunch length [mm]	6.5
momentum compaction factor α_c	0.00678
synchrotron frequency (rf voltage at 1.6 MV) [kHz]	37.8
radiation damping time [ms]	
longitudinal:	5.668
horizontal:	6.959
vertical:	9.372

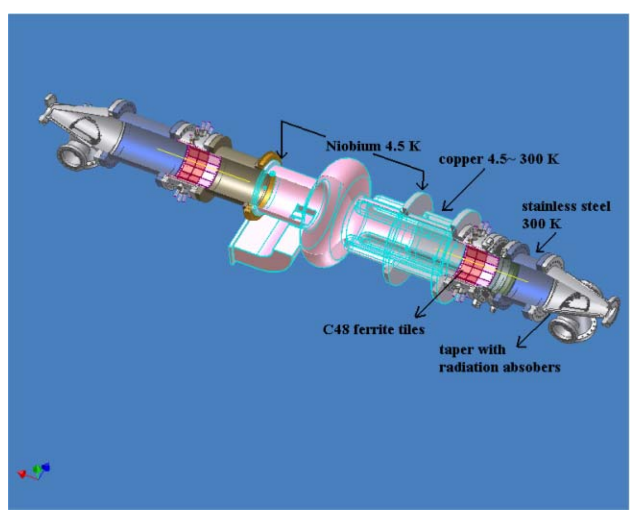

Figure 1: Layout of SC rf module used in the numerical simulations for the HOM studies at TLS. The taper design has been modified in order to fit into the vacuum chamber of storage ring at TLS.

Because the cross section of beam pipe is smaller than the CESR beam pipe, there are still few resonant modes above 4 GHz in the simulated impedance spectrum of SC rf module at TLS. Those resonant modes have a loaded quality factor on the order of a thousand. For the worst estimate, we assume the storage ring to be evenly filled with 200 bunches. The growth time of longitudinal coupled-bunch instabilities will equal to the radiation damping time at a beam current of 450 mA. Since the storage ring is operated with a gap of 40 bunches in routinely operation, the threshold current of longitudinal coupled-bunch instabilities is expected to be higher than 450 mA.

LONGITUDINAL HIGHER-ORDER MODES

The impedance spectrum of SC rf module is obtained from the Fourier transform of wakepotentials computed in time domain. A Gaussian shaped beam is sent through the SC rf module as the source to excite wakefields in the structure. The maximum relevant frequency f_{max} of excited wakefields is [4]

$$f_{\max} = \frac{c}{2\pi\sigma_z} \tag{1}$$

where c is the speed of light in vacuum, and σ_z is the rms bunch length of Gaussian beam. Since the computed wakepotential is excited by the frequency contents of source beam, the impedance spectrum is less reliable above the maximum relevant frequency f_{max}. The lowest cutoff frequency of longitudinal waveguide modes in the beam pipe of TLS storage ring is 4.712 GHz. The rms bunch length used in time-domain simulations should not be larger than 10 mm for TLS SC rf module.

In the case of shorter bunches and longer structures the mesh size of numerical models should satisfy [4]

$$\Delta_z < \sqrt{\frac{\sigma_z^3}{L_z}} \tag{3}$$

where L_z is the structure length. The structure length of SC rf module as shown in Fig. 1 is 3.0165 m. In numerical simulations, straight elliptic beam pipes of 10 cm were attached to both ends of tapers. The actual structure length used in numerical simulations for TLS SC rf module is 3.2165 m. The relation of maximum step size vs. rms bunch length used in simulations for reliable wakepotentials is shown in Table 2.

Table 2: The relation of maximum step size vs. rms bunch length used in simulations for reliable wakepotentials of SC rf module at TLS.

rms bunch length (mm)	maximum step size (mm)
7	0.38
10	0.58

Impedance and Instability Growth Time

The results of simulated wakepotentials depend strongly on the property of C48 ferrite. The C48 ferrite is less lossy at higher frequencies [5]. Therefore, the longitudinal HOMs are less damped by C48 ferrite at higher frequencies. For the worst estimate, the longitudinal wakepotential of SC rf module was calculated with the property of C48 ferrite set at 4750 MHz. The corresponding impedance spectrum is shown in Fig. 2. The simulated impedance spectrum was fit with Lorentzian distributions. The fit results give the HOMs of SC rf module as shown in Table 3. Because of the limitation imposed by available computing resources at TLS, results in Fig. 2 and Table 2 are calculated with a mesh size of 2 mm and rms bunch length of 4 cm respectively.

Table 3: The worst estimate of longitudinal HOMs of SC rf module. The growth time of longitudinal coupled-bunch instability is calculated for a completely filled storage ring at a beam current of 400 mA.

frequency [MHz]	loaded shunt impedance R_s [Ω]	loaded Q-factor Q_L	instability growth time [ms]	instability mode number μ
4127.2	875.9	1267	6.37	52
4209.6	678.5	698	8.20	85
4259.6	738.5	1327	7.46	105
4574.4	481.7	1037	11.36	31

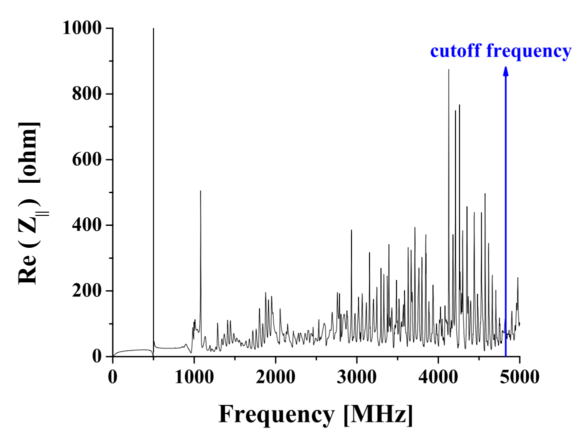

Figure 2: The real part of longitudinal impedance spectrum of SC rf module obtained from numerical simulations for TLS storage ring. The property of C48 ferrite tiles is set at a frequency of 4750 MHz.

Loss Factor and Power Dissipation

The calculated loss factors $K_{||}$ for conducting materials operating at different temperatures are listed in Table 4. The dependence of calculated loss factors on the mesh size of numerical models is shown in Table 5. From those results shown in Table 4, we find that the calculation of loss factors is less sensitive to the operating temperature of conducting materials used in SC rf module. The loss factor is more sensitive to the property of C48 ferrite used to absorb those HOMs in SC rf module.

Table 4: The calculated loss factors of SC rf module with Niobium and Copper operating at different temperatures. The mesh size and rms bunch length used in simulations are 0.5 mm and 10 mm respectively.

Frequency of C48 ferrite [MHz]	$K_{\|\|}$ (V/pC) Nb=293K, Cu=293K	$K_{\|\|}$ (V/pC) Nb=4.5K, Cu=293K	$K_{\|\|}$ (V/pC) Nb=4.5K, Cu=60K
975	0.993	N.A.	N.A.
1950	0.939	0.939	0.939
4750	0.799	0.799	0.799

Table 5: The calculated loss factors of SC rf module with Niobium and Copper operating at 293°K. The rms bunch length used in simulations is 10 mm. The property of C48 ferrite is chosen at 975 MHz.

mesh size (mm)	$K_{\|\|}$ (V/pC)
0.5	0.993
1	1.052

The parasitic energy loss ΔE for a beam bunch passing through the SC rf module is

$$\Delta E = q^2 K_{||} \tag{4}$$

where q is the charge of beam bunch. We calculate the total loss factor of SC rf module by using the property of C48 ferrite at 975 MHz. The total loss factor is 1.854 V/pC for an rms bunch length of 7 mm. Supposed that the storage ring is evenly filled with a beam current of 400 mA for 160 bunches, the energy loss per bunch is 1.854×10^{-6} J. Using a bunching period of 2 ns, we get an estimate for the average power dissipation in the SC rf module as 927 W.

TRANSVERSE HIGHER-ORDER MODES

Preliminary results of vertical impedance obtained from numerical simulations are shown in Fig. 3. The SC rf module does not have reflection symmetry because of the coupling hole for rf input power. The lowest cutoff frequency of vertical waveguide modes for the beam pipe is 2.237 GHz. The vertical wakepotentials are calculated for a beam offset of 15 mm and –15 mm respectively. There is noticeable difference in the vertical impedance spectrum for beam offset of opposite sign. The detailed analysis of vertical HOMs is in progress.

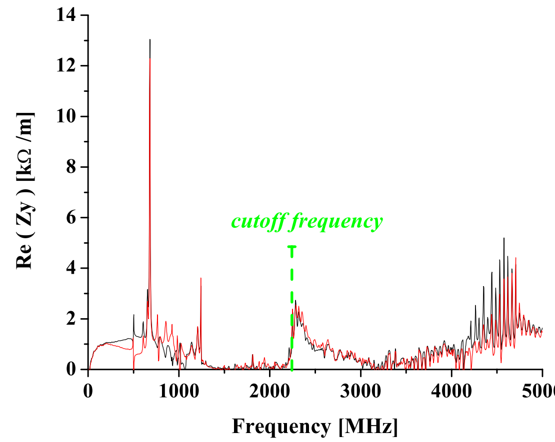

Figure 3: The vertical impedance spectrum calculated with vertical beam offset of 15 mm (black) and –15 mm (red) respectively. The lowest cutoff frequency of the transverse waveguide modes in the vertical direction is 2.237 GHz.

CONCLUSION

The longitudinal HOMs of SC rf module are obtained by fitting the impedance spectrum simulated with GdfidL. From those fit results, we find that the storage ring at TLS will not encounter the longitudinal coupled-bunch instability for a beam current less than 450 mA. If there is other source of resonator impedance not previously known in the storage ring besides the rf cavity, this prediction will need to be modified.

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