COLLECTIVE EFFECTS IN THE STORAGE RING OF TAIWAN PHOTON SOURCE

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Abstract

A new 3- 3.3 GeV synchrotron light source is proposed and named the Taiwan Photon Source (TPS). The TPS design has a natural horizontal emittance less than 2 nm-rad and low emittance coupling, which results in small beam size. The nominal bunch length in TPS storage ring is much shorter compared to the existing Taiwan Light Source (TLS), that makes the issue of parasitic heating more significant. Several small-gap insertion devices are planned to provide extremely bright x-ray photon beam. Those design features have impacts on collective beam instabilities. A preliminary study of collective effects in the TPS storage ring is presented.

INTRODUCTION

The goal of TPS design is to achieve a natural emittance less than 2 nm-rad and low emittance coupling [1]. The nominal operation current is 400 mA. The rms bunch length is short (σ_z= 2.8 mm) due to a small momentum compaction factor (α_1= 2×10^{-4}). The short bunch can pick up impedance at very high frequency (*f*~ 17 GHz), which could lead to a significant heat deposition in vacuum components. Parasitic energy loss due to beam induced wakefields needs to be studied carefully. Since the momentum compaction factor is small, the longitudinal microwave instability is an important issue. It requires serious efforts to minimize the impedance of vacuum components and eliminate structures in the vacuum system where resonant modes can be trapped. The broadband impedance $|Z/n|$ of the storage ring should be reduced to a value less than 0.1 Ω. Based on the successful operation of superconducting (SC) RF cavity at TLS [2], four CESR SC RF cavities are planned in the TPS design. Multibunch instabilities caused by the higher-order modes of SC RF cavities are not expected to be a problem in TPS storage ring. There will be over twenty insertion devices installed in the TPS storage ring. Those insertion devices are the major source of transverse resistive wall impedance. It may not be practical to rely on chromaticity tuning for the suppression of resistive wall instability. A transverse feedback system is required to suppress the resistive wall instability.

LONGITUDINAL COUPLED BUNCH INSTABILITY

The higher-order modes (HOM) of RF cavities are the main source of longitudinal coupled bunch instabilities. Four CESR SC RF cavities are used in the theoretical analysis without the detuning of HOMs. This is the worst-case scenario in terms of instability analysis. A complete SC RF cavity module comprised of a cavity, flute tubes, HOM absorbers, and taper sections is used in the numerical simulation [3]. The impedance spectrum is obtained from the Fourier transform of calculated wakepotential by using the 3-D code GdfidL [4]. The results are shown in Fig. 1. A list of the most significant HOMs is shown in Table 1. Only HOMs below the longitudinal cutoff frequency of standard beam pipe are considered.

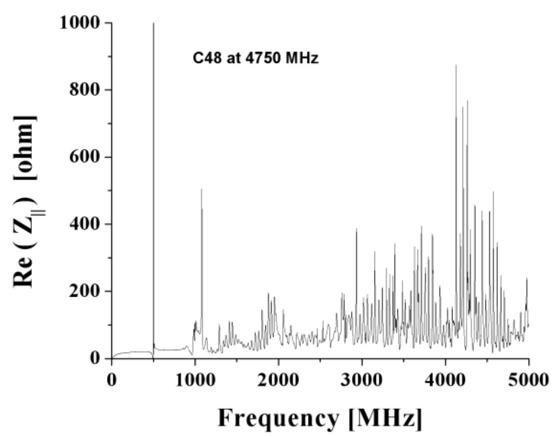

Figure 1: The longitudinal impedance of a CESR SC RF cavity module calculated by the 3-D code GdfidL.

Table 1: The most significant HOMs of one SC RF cavity module calculated by GdfidL

Frequency [MHz]	R/Q [Ω]	Q_{load}
1081.3	2.42	201
2932.3	0.75	471
4127.9	0.69	1267
4210.5	0.97	690
4259.8	0.56	1327
4298.8	0.43	766
4352.3	0.74	587
4574.4	0.46	1037
4617.9	0.31	1019

The growth rate τ^{-1} of longitudinal coupled bunch instability for a Gaussian beam is calculated by the following formula [5]:

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$$1/\tau^{(\ell,\mu)} \approx \frac{i}{2\pi}\frac{\Gamma(\ell+\frac{1}{2})}{2^{\ell}(\ell-1)!}\frac{N_B e^2\eta}{T_0 E\omega_s\sigma_t^3}\frac{\sum_{p=-\infty}^{\infty}\frac{Z_0^{\parallel}(\omega_p)}{\omega_p}h_\ell(\omega_p)}{\sum_{p=-\infty}^{\infty}h_\ell(\omega_p)} \qquad (1)$$

$$= \frac{i}{2\pi^{3/2}}\frac{\Gamma(\ell+\frac{1}{2})}{(\ell-1)!}\frac{I_0 e\eta}{EQ_s\sigma_t^2}\frac{M}{(2\ell-1)!!}\sum_{p=-\infty}^{\infty}\frac{Z_0^{\parallel}(\omega_p)}{\omega_p}h_\ell(\omega_p)$$

where $\omega_p=\omega_0(pM+\mu+\ell Q_s)$, N_B = number of particles per bunch, $h_\ell(\omega)=(\omega\sigma_t)^{2\ell}e^{-\omega^2\sigma_t^2}$, M= number of bunches, μ = multibunch mode index, σ_t = rms bunch length, E= beam energy, T_0 = revolution period, $I_0 = eN_B/T_0$ = average beam current per bunch, Q_s = synchrotron tune, ω_0 = angular revolution frequency, η = phase slip factor, and $Z^{\parallel}_0$ = impedance [Ω].

The calculated growth time for the worst HOM at 4127.9 MHz (ℓ=1 dipole mode, 4 cavities) is 36 ms, which is longer than the radiation damping time 5.25 ms. The HOMs of SC RF cavities should not cause longitudinal coupled bunch instability. Other vacuum components should be carefully designed to avoid cavity-like structures.

TRANSVERSE COUPLED BUNCH INSTABILITY

There are two major sources of transverse impedance that can cause coupled bunch instability: transverse HOMs of RF cavities and resistive wall impedance of beam pipe.

Transverse HOMs of SC RF Cavities

The most significant transverse HOMs of one SC RF cavity module is shown in Table 2 [3]. Only HOMs below the transverse cutoff frequency of standard beam pipe are considered.

Table 2: The most significant transverse HOMs of one SC RF cavity module calculated by GdfidL

Frequency [MHz]	$R_\perp/Q$ [Ω/m]	Q_{load}
679.4	165.2	78
1138.5	38.7	22
1206.8	33.2	46
1240.6	14.4	219

The growth rate τ^{-1} of transverse coupled bunch instability for a Gaussian beam is calculated by the following formula [5]:

$$1/\tau^{(\ell,\mu)} \approx \frac{-i}{4\pi}\frac{\Gamma(\ell+\frac{1}{2})}{2^{\ell}\ell!}\frac{N_B e^2 c}{T_0 E\omega_\beta\sigma_t}\frac{\sum_{p=-\infty}^{\infty}Z_1^{\perp}(\omega_p)h_\ell(\omega_p-\omega_\xi)}{\sum_{p=-\infty}^{\infty}h_\ell(\omega_p-\omega_\xi)} \qquad (2)$$

$$= \frac{-i}{4\pi^{3/2}}\frac{\Gamma(\ell+\frac{1}{2})}{\ell!}\frac{I_0 ec}{EQ_\beta}\frac{M}{(2\ell-1)!!}\sum_{p=-\infty}^{\infty}Z_1^{\perp}(\omega_p)h_\ell(\omega_p-\omega_\xi)$$

where, $\omega_p=\omega_0(pM+\mu+Q_\beta+\ell Q_s)$, $\omega_\xi=\xi\omega_0/\eta$, $\xi=\Delta Q_\beta/(\Delta E/E)$, ω_β= angular betatron frequency, Q_β= betatron tune, $Z_1^{\perp}$ = impedance [Ω/m].

The calculated growth time for the worst HOM at 679.4 MHz (ℓ=0 rigid bunch mode, 4 cavities) is 76 ms, which is much longer than the radiation damping time 10.5 ms. The HOMs of SC RF cavities should not cause transverse coupled bunch instability.

Resistive Wall of Beam Pipe

The transverse cross section of standard beam pipe is an ellipse. The major axis *2a* is 70 mm and the minor axis *2b* is 32 mm. The circumference of TPS storage ring is 518.4 m. The beam pipe will be made of aluminum. The vertical direction is expected to be the worst. The transverse resistive wall impedance $Z^{\perp}$ [Ω/m] of an elliptical beam pipe is given by [6]

$$Z^{\perp}(f)=G_i\frac{Z_0\delta_s[\mathrm{sgn}(f)-i]}{2\pi b^3}L \qquad (3)$$

where Z_0 = 377 Ω, δ_s= skin depth of conductor, *2b*= minor axis of ellipse, f = frequency, L = length of the structure, and G_i = geometry factor. The calculated vertical resistive wall impedance of TPS beam pipe without any insertion device is shown in Fig. 2.

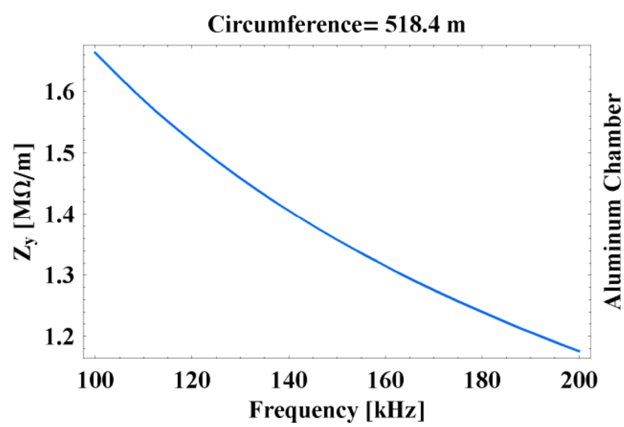

Figure 2: The vertical resistive wall impedance of TPS beam pipe without any insertion device. The frequency of the lowest betatron sideband is around 162 kHz.

The growth time of vertical resistive wall instability is calculated for a beam current 400 mA with uniform fill. The strongest coupled bunch instability occurs at mode 851 (baseband) that has a growth time of 4.7 ms, shorter than the radiation damping time 10.5 ms. One can increase the chromaticity to a large value for the suppression of instability. But this approach will result in a reduction of dynamic aperture.

The dependence of growth time on the vertical chromaticity for mode 851 is shown in Fig. 3. To stabilize the vertical resistive wall instability, the vertical chromaticity has to be larger than four. As insertion devices are installed later on, the resistive wall impedance will increase rapidly for the $Z^{\perp} \propto b^{-3}$ dependence. This will make the chromaticity tuning not practical as a solution of instability suppression. Therefore, a transverse feedback system is required in order to stabilize the transverse coupled bunch instability due to the resistive wall.

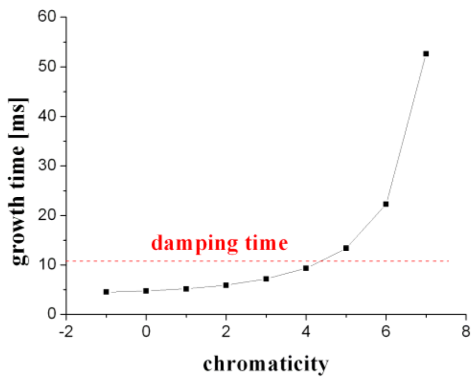

Figure 3: Growth time of resistive wall instability as a function of the vertical chromaticity for coupled bunch mode 851. The radiation damping time is 10.5 ms.

SINGLE BUNCH INSTABILITY

When one increases the chromaticity to stabilize the transverse beam motion (ℓ= 0 rigid bunch mode), one must be careful not to excite the ℓ= 1 head-tail mode. The growth time of vertical ℓ= 1 head-tail mode at chromaticity 4 for different bunch current is shown in Fig. 4. The resistive wall impedance of standard beam pipe is assumed in the analysis.

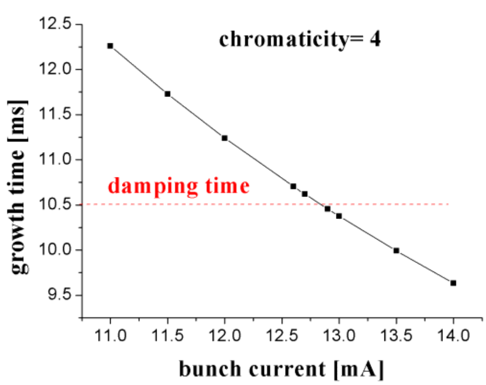

Figure 4: Calculated growth time of ℓ= 1 single bunch head-tail mode. The radiation damping time is 10.5 ms.

The threshold current of longitudinal microwave instability can be estimated by [7]:

$$I_{th} = \frac{\sqrt{2\pi}\alpha_c (E/e)\,\sigma_\ell}{R|Z/n|_{eff}} \left(\frac{\sigma_E}{E}\right)^2 \qquad (4)$$

where R= average storage ring radius, σ_E/E= beam energy spread, σ_ℓ = bunch length, α_c = momentum compaction factor, and $|Z/n|_{eff}$ = effective broadband impedance.

If we assume an effective broadband impedance of 1 Ω and 2.8 mm bunch length, the threshold current calculated with nominal parameters of TPS design is 46 μA. The average bunch current in nominal operation is 0.464 mA for a uniform fill (864 bunches). In user operation a gap in the fill pattern is required to avoid ion trapping. Therefore, the broadband impedance must be reduced to a value less than 0.1 Ω to avoid the onset of microwave instability. Because of the constraints imposed by microwave instability, the fabrication tolerance of vacuum components is quite stringent.

DISCUSSION

The preliminary study of several collective effects in TPS storage ring has been reported. The choice of CESR SC RF cavities will not cause longitudinal and transverse coupled bunch instabilities. The resistive wall impedance is expected to cause transverse beam motion unstable. It will not be sufficient to rely on a large positive chromaticity for the suppression of transverse coupled bunch instability. A transverse feedback system is needed. The broad band impedance must be strictly controlled to a value less than 0.1 Ω. The use of harmonic cavity to lengthen the beam should be considered. The investigation of effects due to trapped ions and small gap insertion devices are under way.

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