BEAM LIFETIME AND COLLECTIVE EFFECTS IN TAIWAN PHOTON SOURCE

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Abstract

The design of Taiwan Photon Source (TPS) has a natural emittance less than 2 nm-rad and low emittance coupling. The nominal rms bunch length is less than 3 mm. Several small-gap undulators are planned to provide x-ray photon beam with extremely high brightness. The vertical gap of these undulators are in the range of 5-7 mm. The TPS ring will be operated at top-up mode with high beam current. Various collective effects due to high beam current are investigated. Impacts of small-gap undulators to the beam lifetime are carefully studied. The results of theoretical analysis are presented. Proposals to overcome deleterious effects due to high beam current and small-gap undulators are also discussed.

INTRODUCTION

The natural emittance of 3 GeV TPS storage ring is 1.6 nm-rad and the circumference is 518.4 m [1]. The total beam current is 400 mA in nominal operation. Collective effects play an important role in the stability of nominal operation. Higher-order modes (HOMs) of rf cavities and resistive wall are typical sources of coupled bunch instabilities. Trapped modes in cavity-like vacuum chambers are also important. We study the effects due to these impedance sources and find that HOM-damped rf cavities will not cause coupled bunch instability. Nevertheless, the transverse coupled bunch instabilities due to resistive wall impedance may arise if proper measures are not taken in advance. If the fill pattern is chosen judiciously, ion trapping can be avoided. The best solution to avoid beam-ion instability is to keep good vacuum condition in the storage ring. One may suppress the transverse coupled bunch instabilities with a positive chromaticity. But a large value of chromaticity will reduce the dynamic aperture needed for good injection efficiency and beam lifetime. Thus, an active feedback system is required to suppress transverse coupled bunch instabilities.

Because the momentum compaction factor is small, the bunch length is less than 3 mm. This makes the concern of microwave instability more pronounced. A careful control of total impedance budget is important. The single bunch head-tail instability is also studied and found not to be a concern in the nominal operation. The effect of coherent synchrotron radiation is examined and no sign of harmful instability is found at the nominal bunch current.

COUPLED BUNCH INSTABILITIES

The accelerator parameters used in our studies of collective effects are given in Table 1.

Table 1: Accelerator Parameters of TPS Storage Ring

RF frequency (MHz)	499.654
RF voltage (MV)	3.5
Momentum compaction ($\times 10^{-4}$)	2.38
Synchrotron tune	0.0061
Betatron tune x /y	26.20/13.25
Coupling (%)	1
Radiation damping time x,y /s (ms)	12.2/ 6.1
RMS energy spread ($\times 10^{-4}$)	8.9
RMS bunch length (mm)	2.86
Harmonic number	64
Dimension of elliptic beam pipe (major axis [mm]/ minor axis [mm])	68 × 30

RF Cavities

We plan to use four Cornell Superconducting (SC) RF cavities for particle acceleration. The HOMs of Cornell SC RF cavities are calculated with the rf code GdfidL [2]. A complete module of SC RF cavity is used in computer simulations including ferrite slabs, tapers, and input waveguide. The instability growth time is calculated by assuming a symmetrically filled bunch train in the storage ring. The longitudinal growth time is given by [3]:

$$\Omega^{(m,\mu)} - m\omega_s \approx \frac{i}{2\pi^{3/2}}\frac{\Gamma(m+\frac{1}{2})}{(m-1)!}\frac{I_0 e\eta}{EQ_s\sigma_t^2}\frac{M}{(2m-1)!!}\sum_{p=-\infty}^{\infty}\frac{Z_0^{\parallel}(\omega_p)}{\omega_p}h_m(\omega_p)$$

The transverse growth time is given by [3]:

$$\Omega^{(m,\mu)} - \omega_\beta - m\omega_s \approx \frac{-i}{4\pi^{3/2}}\frac{\Gamma(m+\frac{1}{2})}{m!}\frac{I_0 ec}{EQ_\beta}\frac{M}{(2m-1)!!}\sum_{p=-\infty}^{\infty}Z_1^{\perp}(\omega_p)h_m(\omega_p-\omega_\xi)$$

$$h_m(\omega) = (\omega\sigma_t)^{2m}e^{-\omega^2\sigma_t^2}$$

where N is the number of particles per bunch, M the number of beam bunches, μ the multibunch mode number, m the azimuthal mode number, σ_t the rms bunch length, E the beam energy, T_0 the revolution period, and I_0 the average beam current per bunch. The instability growth time is calculated for all significant HOMs. We conclude that four Cornell SC RF cavities will not cause coupled bunch instability at 400 mA. The detail of calculated growth time is shown in Table 2 for the longitudinal

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instability and in Table 3 for the transverse instability respectively.

Table 2: Calculated Growth Time of Longitudinal Coupled Bunch Instability (Four SC RF Cavities)

HOM frequency (MHz)	R/Q (Ω)	Q_{load}	Growth time (ms)
1081.3	2.42	201	197.4
4127.9	0.69	1267	32.2
4210.5	0.97	690	36.4
4259.8	0.56	1327	32.4
4352.3	0.74	587	54.3
4574.4	0.46	1037	47.4
4617.9	0.31	1019	71.2

Table 3: Calculated Growth Time of Transverse Coupled Bunch Instability (Four SC RF Cavities)

HOM frequency (MHz)	$R_\perp/Q$ (Ω)	Q_{load}	Growth time (ms)
679.4	165.2	78	81.0
1138.5	38.7	22	1251.6
1206.8	33.2	46	704.2
1240.6	14.4	219	344.8

Cavity-like Vacuum Chambers

Trapped modes may exist in cavity-like vacuum chambers. A flange joint of 80 mm diameter and a gap length of 2 mm without rf shielding is used as a model to assess the possible impact. A trapped cavity mode is found from GdfidL simulations: the resonant frequency is around 3.9 GHz, R/Q= 8.4 Ω, Q_{load}= 265, and the calculated growth time is 6.1 ms at a total beam current of 400 mA. It is important to keep the flange gap below 1 mm and install rf bridges to shield the gap from beam induced wake fields. Bellows and gate valves should also be properly shielded. Otherwise, the longitudinal coupled bunch instability may arise at 400 mA due to cavity-like vacuum chambers.

Resistive Wall Impedance

The resistive wall impedance can drive coupled bunch instabilities at high beam currents. The vacuum chambers will be made of aluminium. At a total beam current of 400 mA, the vertical coupled bunch instability arises with standard beam pipe only. The grow time of the strongest coupled bunch mode n= 850 is 4.4 ms. The grow time of the strongest mode n= 850 vs. vertical chromaticity is shown in Fig. 1. To stabilize the beam requires a positive chromaticity larger than 5. The growth time is calculated by assuming a symmetrically filled bunch train.

To evaluate the effects of insertion devices, we consider four identical insertion devices with a length of 4 m and vertical gap of 10 mm. The impedance is modelled by the summation of impedance from each chamber component as given by [3]

$$Z_\perp(f) = \sum_{n=1}^{M} Z_0 G_n L_n \frac{[sign(f) - i]\delta_{skin}}{2\pi b_n^3}$$

where Z_0 is the impedance of vacuum, G_n the geometric factor, L_n the length of component, δ_{skin} the skin depth, and b_n the radius of chamber component.

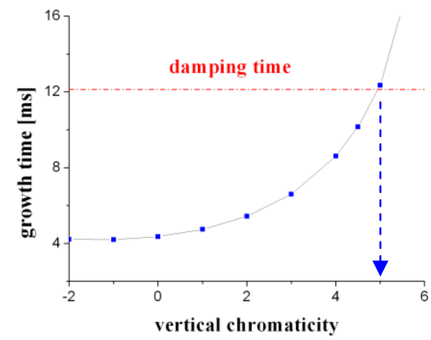

Figure 1: Growth time of vertical coupled bunch instability vs. vertical chromaticity at 400 mA (mode n= 850, no insertion device).

Once those four insertion devices are included, both the horizontal coupled bunch instability and the vertical one arise. Because the resistive wall impedance is proportional to the inverse cubic power of chamber radius, the transverse impedance increases significantly. The growth time of vertical coupled bunch mode n= 850 vs. vertical chromaticity is shown in Fig. 2. To suppress the vertical coupled bunch instability after including four insertion devices, we would need a positive chromaticity larger than 6. Larger values of chromaticity tend to reduce the dynamic aperture, which is important for top-up injection with good capture efficiency. Therefore, an active transverse feedback system is required to suppress transverse coupled bunch instabilities.

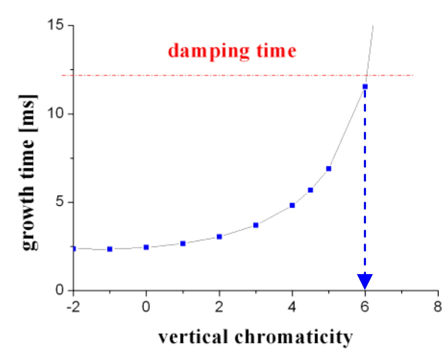

Figure 2: Growth time of vertical coupled bunch instability vs. vertical chromaticity at 400 mA (mode n= 850, 4 insertion devices included).

SINGLE BUNCH INSTABILITIES

If we fill 400 mA of beam current to 600 bunches in the nominal operation, the average bunch current is 0.67 mA. The threshold current of microwave instability can be estimated by the Boussard criterion [3]

$$I_{th} = \frac{\sqrt{2\pi}\,\alpha_c (E/e)\sigma_s}{R\,|Z_{\parallel}/n|_{eff}} \left(\frac{\sigma_E}{E}\right)^2$$

where R is the mean radius of accelerator, $|Z_{\parallel}/n|_{eff}$ the effective broadband impedance, and α_c the momentum compaction factor. According to the preliminary impedance budget [4], the total broadband impedance $|Z_{\parallel}/n|$ is 0.36 Ω. Using the SPEAR scaling law, the effective broadband impedance is

$$\left|\frac{Z_{\parallel}}{n}\right|_{eff} = \left|\frac{Z_{\parallel}}{n}\right|_0 \left(\frac{\sigma_s}{b}\right)^{1.68}$$

Applying the SPEAR scaling law, we obtain a threshold bunch current of 2.2 mA.

The condition that microbunching instability arises due to coherent synchrotron radiation is [5]

$$\frac{\rho}{b} \le \Lambda \text{ and } \sigma_s \ge 0.5\rho\Lambda^{-3/2}$$

$$\Lambda = \frac{N\,r_0\rho}{\sqrt{2\pi}\,\sigma_s\,|\eta|\,\gamma\delta_0^2 R}$$

Considering a bunch current of 1 mA and parameters given in Table 1, we find there will be no coherent synchrotron radiation instability in the nominal operation.

BEAM-ION INSTABILITIES

The composition of residual gas is assumed to be the same as in the existing Taiwan Light Source, namely 85% H_2, 12% CO, and 2% CO_2. The relevant parameters are: σ_x= 128 mm, σ_y= 10 mm, 1% emittance coupling, relative spread of ion frequency= 0.2, total beam current= 400 mA. The ion trapping condition vs. gap in fill pattern is shown in Fig. 3. The growth rate of slow ion instability is given by [3]

$$\tau^{-1} = \frac{\pi^2 f_0}{(\Delta f_i/f_i)_{FWHM}} \frac{r_e \beta_y R \sigma_{ion} 3.3\times10^{22}}{\gamma\sigma_y(\sigma_x+\sigma_y)} P_{gas}[Torr]N$$

where $(\Delta f_i/f_i)_{FWHM}$ is the relative spread of ion frequency, r_e the classical electron radius, N the total number of particles, and σ_{ion} the cross section of residual gas ions. If the gap is not chosen properly, the slow ion instability will occur with a growth time less than 1 ms. A judicious choice of fill pattern can avoid the slow ion instability.

The total beam lifetime of low-emittance light source is mainly limited by the Touschek effect. A preliminary study on the effects of small gap insertion devices is carried out by using the tracking code TRACY [6]. A brief summary of Touschek lifetime vs. different combination of vacuum chambers is given in Table 4.

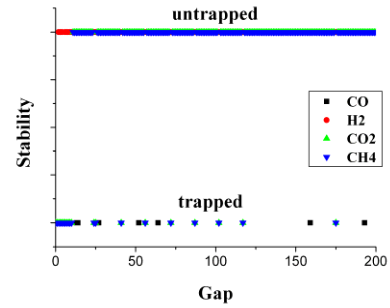

Figure 3: Ion trapping condition vs. gap in bunch train.

BEAM LIFETIME

Table 4: Touschek Lifetime vs. Different Gap Height of Insertion Device

Standard chamber (68 mm × 30 mm)	7.83 hrs.
Std. chamber+ logn ID (±5 mm, 12 m)+ short ID (±5 mm, 5 m)	7.81 hrs.
Std. chamber+ logn ID (±5 mm, 12 m)+ short ID (±2.5 mm, 5 m)	3.65 hrs.
Std. chamber+ logn ID (±5 mm, 12 m)+ short ID (±5 mm, 2 m)	7.75 hrs.

SUMMARY

The SC RF cavities will not cause coupled bunch instability in nominal operation. Resistive wall impedance will cause transverse instabilities at high beam current. The more insertion devices we install, the more detrimental the transverse instabilities are. Small-gap insertion devices not only make the transverse instabilities more severe but also cause noticeable reduction in the beam lifetime. An active transverse feedback is required for stable operation at nominal beam current.

REFERENCES

[1] C.C. Kuo et al., "Design Status of Taiwan Photon Source", EPAC'08, Genoa, June 2008, WEPC004, this proceeding.

[2] GdfidL, Warner Bruns Field Computations, http://www.gdfidl.de.

[3] A.W. Chao & M. Tigner (eds.), Handbook of Accelerator Physics& Engineering, 3rd printing (2006).

[4] A. Rusanov, "Preliminary Impedance Budget for TPS Storage Ring", EPAC'08, Genoa, June 2008, TUPP025, this proceeding.

[5] PRST-AB, vol.5, 054402 (2002), G. Stupakov, and S. Heifets.

[6] TRACY(Soleil version), L. Nadolski (private communication).