COLLECTIVE EFFECTS IN THE PLS STORAGE RING

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Abstract

Stored beam currents of 2.0 GeV at the PLS ring has been limited by coupled-bunch instabilities. It was found that beam currents in 2.0 GeV was mainly limited by 830.45 MHz tranverse mode in RF cavities. Beam instabilities dependences on betatron tune and chromaticity were extensively investigated in the ring. Longitudinal coupled-bunch instabilities due to 758.66 MHz and 1300 MHz modes does not lead to beam loss up to 450 mA. Beam tail distribution and beam lifetime in 2.5 GeV are estimated by a simulation method. The result shows beam lifetime of 27 hours in 170 mA. The estimated lifetime shows a good agreement with that of normal beam operation.

1 INTRODUCTION

The PLS storage ring is a third generation synchrotron radiation source. It consists of a 2 GeV linac and a storage ring which can be accelerated by 2.0 GeV to 2.5 GeV. The storage ring has been operated at 2.0 GeV from 1995 to 1999 and at 2.5 GeV since 2000. The desiged value of the beam current in the PLS storage ring is 400 mA in 2.0 GeV. The parameters of the storage ring are listed in Table 1.

It is a general requirement on the storage ring for a synchrotron radiation source that it provides a stable beam having a small emittance in order to obtain a high brilliance photon beam. It is apparent that the beam quality is strongly determined by beam instabilties in such a machine having a low emittance. Therefore, a study to cure beam instabilities is important to obtain a stable and small beam. PLS storage ring has operated in less beam currents than 190 mA at an energy of 2.0 GeV which has been limited by the coupled-bunch instabilities. The threshold currents due to the transverse and longitudinal coupled-bunch instabilities were extensively investigated. It was found that the transverse 830.45 MHz mode has mainly limited the stored beam current. The transverse beam instabilties could be cured by varying the betatron tune and chromaticity. In this paper, we also present beam tail distribution and beam lifetime by a simulation method. The estimated beam lifetime shows a good agreement with that in normal operation.

2 BEAM INSTABILITIES AT 2.0 GEV

2.1 Transverse coupled-bunch instability

We have observed frequency spectrum of the beam that was analyzed with a spectrum analyzer. The peaks in beam spectrum always appeared when the instability was observed with the beam profile monitor. The frequency spectrum of the beam oscillation has components of

$$f^{\pm}_{\mu,n} = nBf_r \pm (\mu f_r + f_{oscil}) \tag{1}$$

for all integer values of n. Here, B is number of bunches and f_{oscil} is a remainder of the frequency of the oscillation divided by revolution frequency f_r. The integer μ represents the mode number of oscillation. Typically observed frequencies when the beam becomes unstable are 830.45 MHz and 1300 MHz modes (See Fig.1(a)), and 758.66 MHz mode(See Fig.1(b)).

Peak (1) in Fig.1(a) has the relation of $f_{\mu,n}$ = 400f_r − $(377f_r + 200.8kHz)$= 830.45 MHz with $n = 1$, B=400 and μ=377. The relation indicates that the peak (1) is associated with some kind of a coupled bunch oscillation with the frequency f_{oscil} = 200.8 kHz. Since this frequency is close to the remainder of a horizontal betatron oscillation frequency, we have accurately measured the betatron tune. The result was $f_{\beta x}$ = 200.8 kHz, which was in excellent agreement with f_{oscil}. Here, $f_{\beta x}$ is defined by $f_{\beta x}$ =$\delta\nu_x f_r$ with a fractional part $\delta\nu_x$ of the horizonatl tune ν_x. We have also measured the remainder of a vertical betatron oscillation frequency $f_{\beta y}$ and a synchrotron frequency f_s. Measureded values of $f_{\beta y}$=270 kHz and f_s = 11.7 kHz are quite different from f_{oscil}. It is thus concluded that the instability due to the peak (1) in Fig.1(a) is related to the horizontal coupled-bunch oscillation of the mode μ=377.

2.2 Betatron tune effect

We attempted to store the beam current as high as possible at a fixed tune. The horizontal coupled-bunch instability was observed during beam injection and storage. As the stored beam current was increased, beam was blow-up horizontally which was seen on the beam profile monitor. Then, vacuum value inside rf cavities was also increased to above 100 nTorr. At last, the beam was suddenly dropped around 250 mA. In this process the frequency spectrum of the beam was monitored to confirm that the instability was always related with the horizontal coupled-bunch oscillation. It was observed with spectrum analyzer that the resonant frequency was 830.45 MHz. The tune dependence of the instability was studied for a wider range. We could suppress the 830.45 MHz mode by chooing a optimal betatron tune. Then beam blow-up disappeared and beam could be stored up to 450 mA as shown in Fig.3.(b), without showing increased vacuum value inside rf cavities. Then the result is understood in term of the tune dependence of the 830.45 MHz mode. The injection rate was typically 2-3 mA per pulse.

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2.3 Head-Tail Instability

In PLS, the chromaticity was set slightly positive to prevent beam instabilities in normal operation. But transverse instability did not disappear at small positive chromaticity. It was found that the amplitude of the transverse spectrum, which was used to estimate the instability, could be varied by magnitudes of currents in the sextupoles. The horizontal and vertical beam spectra at the multiplier of revolution harmonic of n=297 were investigated. As shown in Figs.2, side-bands near betatron tune were observed. Fig.2(a) shows the side-band near horizontal tune when currents of SD(vertical focusing sextupole) and SF(horizontal focusing sextupole) are 138 A and 90 A, respectively. Fig.2(b) shows the side-band near vertical tune when currents of SD and SF are set to 133 A and 94 A, respectively. To suppress these side-bands, we adjusted the currents of SF and SD. It is shown that the side-bands can be suppressed as shown in Fig.3 when the currents of SF and SD are 138 A and 94 A, respectively. They clearly show that these transverse instabilities are affected by the chromaticity.

2.4 Longitudinal-coupled bunch instability

We have also observed longitudinal coupled-bunch instabilities due to 758.66 MHz and 1300 MHz modes. The instability due to the 1300 MHz mode does not lead to beam loss since the shunt impedance of the mode is small. However, the instability due to the 758.66 MHz mode lead to beam loss in higher beam current than 450 mA. The beam spectrum due to the 758.66 MHz mode in 450 mA is shown in Fig.1(b). The longitudinal beam oscillation enlarges beam size horizontally, and moreover, accompanies with beam size fluctuation and bunch-lengthening. When the fluctuation amplitude due to the 758.66 MHz mode is large, it is observed that the beam lifetime decreases. When we analyze the beam signal of 758.66 MHz with $f^{\pm}_{\mu,n} = nBf_r \pm (\mu f_r + f_s)$, f_s is synchrotron frequency, we get the relation of $f_{\mu,n}$ = 400 $f_r - (310 f_r + 11.7kHz)$= 758.66 MHz with n=1, B=400 and μ=310. The relation indicates that the instability is associated with some kind of a coupled bunch oscillation with the frequency f_s = 11.7 kHz, which is in agreement with synchrotron frequency. Thus we concluded that the instability is associated with the longitudinal coupled-bunch oscillation of the $\mu = 310$.

3 BEAM TAIL DISTRIBUTION AND BEAM LIFETIME AT 2.5 GEV

The beam tail distribution and beam lifetime are obtained by using a simulation method [**?**, **?**].

3.1 Beam-Gas Scattering

The cross section of the elastic scattering with an atom is given by Rutherford scattering formula [**?**].

$$\frac{d\sigma}{d\Omega} = (\frac{2Zr_e}{\gamma})^2 \frac{1}{(\theta^2 + \theta^2_{min})^2}, \quad (2)$$

where Ω is the solid angle, θ the scattering angle, Z the atomic number, r_e the classical electron radius and γ the Lorentz factor. Screening of the atomic electrons is accounted by the angle $\theta_{min} = Z^{1/3}\alpha/\gamma$, where α is the fine-structure constant. Fig.4 shows the vertical distribution produced from the tracking of beam-gas scattering, betatron oscillation, synchrotron oscillation and synchrotron radiation. It is obtained when the vertical aperture of a particle is assumed to be $80\sigma'_y$, where $\sigma'_y = \sigma_y/\beta_y$. The β_y is betatron value at the position where the scattering occur. σ_y is nominal vertical beam size. As a function of vertical aperture, beam lifetime is shown in Table 1.

3.2 Beam-Gas Bremsstrahlung

An electron with energy E_o, which passes a molecule of the residual gas, losses its energy due to the radiation emitted when an electron is deflected. There is a certain probability that a photon with energy u is emitted, producing an electron with energy E', where $E' + u = E_o$. The differential cross section for an energy loss due to bremsstrahlung between E and $E + dE$ is given by [**?**]

$$d\sigma = 4\alpha r_e^2 Z(Z+1)\frac{du}{u}\frac{E'}{E_o}[(\frac{E_o^2 + E'^2}{E_o E'} - \frac{2}{3})log\frac{183}{Z^{1/3}} + \frac{1}{9}], \quad (3)$$

where Z, α and r_e denore the atomic number, the fine structure constant and the classical electron radius, respectively. We assume that CO molecule uniformly exists in the ring. Beam lifetimes verse energy aperture are shown in Table 2.

3.3 Touschek effects

The Touschek lifetime is given by [**?**]

$$\frac{1}{\tau_T} = \frac{\sqrt{\pi} r_e^2 c N_o C(\epsilon)}{\gamma^3 \sigma_{x'} (\Delta E/E_o)^2 V_B}, \quad (4)$$

where $\sigma_{x'}$ is rms horizontal angular speed, $\Delta E/E_o$ is rf acceptance and V_B is bunch volume. $C(\epsilon)$ is Touschek effective function. Figure 5 shows Touschek lifetime at 2.5 GeV as a function of coupling constant for bunch lengths of 7 mm, 8 mm and 9 mm. The number of bunches and beam current are 400 and 170 mA, respectively.

3.4 Lifetime as a Function of Apertures in PLS

Once a particle's amplitude exceeds an aperture, this particle would be lost. The lost particles in our simulation are counted at one position of the ring per turn by comparing the amplitudes of the particle with the apertures. The beam lifetime is defined by $\tau = \frac{N_o}{-(\frac{dN}{dt})}$, where N_o is the initial number of particles in a beam and $-dN/dt$ is the total number of particles that exceed the apertures. In the simulation, we used vacuum value of 0.6 nTorr that is in normal opertion of the ring. When we estimate the lifetime including scattering, bremsstrahlung and Touschek effect, it gives 27 hours in 170 mA of 2.5 GeV for the case of 80 σ^o_y

vertical aperture and 1.5% energy aperture. The estimated lifetime agrees with that of normal operation in 2.5 GeV.

Table 1: Designed parameters in the PLS storage ring

Parameters	**2.0 GeV**	**2.5 GeV**
Lattics type	TBA	TBA
Circumference	280.56 m	280.56 m
Natural emittance	12.1 nm	18.9 nm
Harmonic number	468	468
Energy spread	0.00068	0.00085
Synchrotron frequency	11.7 kHz	10 kHz
RF voltage	1.6 MV	1.6 MV
Damping time(T/L)	16.6/8.3 ms	8.5/4.2 ms
Bunch length	5 mm	8 mm
Energy aperture	1.6%	1.5%

Table 2: Lifetimes due to the scattering

Vertical aperture	**60**σ_y	**70**σ_y	**80**σ_y	**90**σ_y
Lifetime	53 h	75 h	106 h	147 h

Table 3: Lifetimes due to the bremsstrahlung

Energy aperture	**1%**	**1.5%**	**2%**
Lifetime	123 h	139 h	162 h

4 CONCLUSION

Stored beam current of 2.0 GeV in PLS ring has been limited to less than 250 mA. It was found that transverse coupled-bunch instability due to the 830.45 MHz mode has limited maximum stored beam current. The transverse beam instabilities in 2.0 GeV could be cured by optimal choices of betatron tune and chromaticity. Present PLS ring can store up to beam of 450 mA at 2.0 GeV. Longitudinal coupled-bunch instability due to 758.66 MHz mode does not lead to beam loss up to 450 mA at 2.0 GeV. Beam lifetimes due to the scattering, bremsstrahlung and Touschek effect are estimated to 27 hours in 170 mA of 2.5 GeV by a simulation method. The estimated lifetime shows also a good agreement with that of normal operation of 2.5 GeV.

5 REFERENCES

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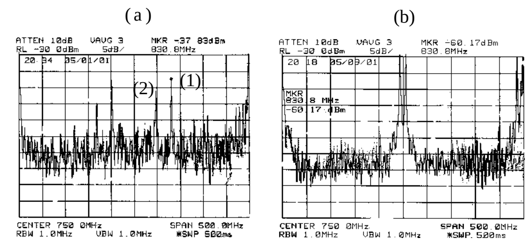

Figure 1: Typical beam spectra that show rf HOM frequencies in 2.0 GeV. They show frequency band betwen 500 MHz and 1 GHz. Peaks denote transverse 830.45 MHz mode ((1) in (a)), longitudinal 1300 MHz mode ((2) in (a)) and longitudinal 758.66 MHz mode (b). Beam currents in (a) and (b) are 273 mA and 450 mA, respectively.

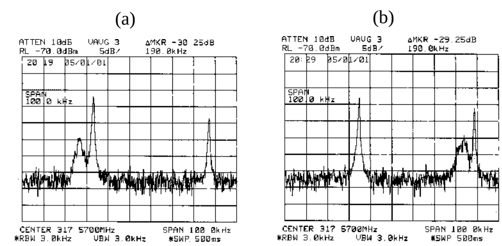

Figure 2: Beam spectra that show batatron tunes and sidebands in 273 mA of 2.0 GeV. (SD,SF)=(138 A,90 A) in (a). (SD,SF)=(133 A,94 A) in (b).

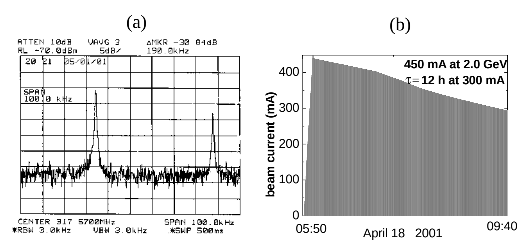

Figure 3: (a) beam spectrum that shows batatron tunes in 2.0 GeV and 273 mA. Side-bands that are shown in Figs.2 disappeared. (SD,SF)=(138 A, 94 A). (b) stored beam current of 450 mA

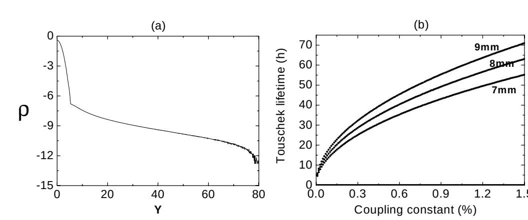

Figure 4: (a) vertical beam distribution in a logarithmic scale obtained from a simulation method. Horizontal axis is the distance normalized by nominal vertical beam size. ν_x=14.19 and ν_y=8.25. (b) calculated Touschek lifetimes for the different bunch lengths (7mm, 8mm and 9mm) as a function of coupling constant in 2.5 GeV. Beam current is 170 mA and number of bunches is 400.