

LONGITUDINAL COUPLED-BUNCH INSTABILITIES IN THE PLS STORAGE RING

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Abstract

Present PLS storage ring has four rf cavity systems and higher beam currents than 200 mA in 2.5 GeV have been limited by total rf power. We have a plan to insert one rf cavity system more in the ring to increase the total rf power and to raise the stored beam current in 2.5 GeV operation. A simulation was performed to investigate longitudinal coupled-bunch instabilities for the five rf cavity systems in 2.5 GeV. The simulation shows results on the bunch-lengthening due to the longitudinal rf-HOMs (higher order modes) that originate from five rf cavities. We also present characteristics and cures of the coupled-bunch instabilities in 2.0 GeV and 2.5 GeV for the present four rf cavities.

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.

It is a general requirement on the storage ring for a synchrotron radiation source that provides a stable beam having a small emittance for a high brilliance photon beam. It is apparent that the beam quality is strongly determined by beam instabilities in such a machine having a low emittance. Therefore, investigation on beam instabilities is important to obtain a stable and small beam.

PLS storage ring has been operated in lower beam currents than 190 mA at an energy of 2.0 GeV which has been limited by the coupled-bunch instabilities. The characteristics on the transverse and longitudinal coupled-bunch instabilities due to four rf cavities in the ring were extensively investigated. It was found that beam currents in 2.0 GeV was mainly limited by 830.45 MHz tranverse mode in rf cavities. The transverse beam instabilities could be cured by surveying the betatron tune and chromaticity. It has been shown that longitudinal coupled-bunch instabilities due to 758.66 MHz and 1300 MHz rf HOMs do not lead to beam loss up to 450 mA in 2.0 GeV [1, 2].

At 2.5 GeV we can store the beam stably up to 200 mA since number of bunches and betatron tune were changed. Higher beam current than 200 mA has been limited by total rf power. We have a plan to insert one rf cavity more in the ring. One purpose of this paper is to investigate the

longitudinal coupled-bunch instabilities for the increased rf HOMs and higher beam currents in the five rf cavities.

2 COUPLED-BUNCH INSTABILITIES IN 2.0 GEV

2.1 Transverse coupled-bunch instabilities

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

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

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 $\mu=377$. 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 horizontal tune ν_x . We have also measured the remainder of a vertical betatron oscillation frequency $f_{\beta y}$ and a synchrotron frequency f_s . Measured 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 $\mu=377$.

We could suppress the 830.45 MHz rf HOM by surveying the betatron tune and chromaticity. Beam could be stored up to 450 mA.

2.2 Longitudinal-coupled bunch instabilities

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.

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However, the instability due to the 758.66 MHz mode may 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 $f_{\mu,n}^{\pm} = nBf_r \pm (\mu f_r + f_s)$, f_s is synchrotron frequency, we get the relation of $f_{\mu,n} = 400 f_r - (310 f_r + 11.7 \text{ kHz}) = 758.66 \text{ MHz}$ with $n=1$, $B=400$ and $\mu=310$. The relation indicates that the instability is associated with some kind of a coupled bunch oscillation with the frequency $f_s = 11.7 \text{ kHz}$, 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 COUPLED-BUNBCH INSTABILITIES IN 2.5 GEV

The storage ring has been operated at 170 mA of 2.5 GeV since January 2000. During the user operation between January 2000 and July 2000, the number of bunches was 468 that was equal to the harmonic number. Operated tune was 14.26 and 8.15 in horizontally and vertically, respectively. We observed resonant frequency of 831.8 MHz in beam spectrum due to higher order mode (HOM) in rf cavities. Figure 2(a) shows the beam oscillation that is observed in streak camera. We see that the beam motions are unstable.

Since September 2000, we have changed the number of bunches and betatron tune for the user operation. The number of bunches is 400 and operating tune is 14.28 and 8.18 in horizontally and vertically, respectively. Figure 2(b) shows the beam oscillation that is observed in streak camera. We see that the beam motions become more stably. We don't observe resonant frequency in beam spectrum due to rf HOMs. Deformed beam shape were not observed in beam profile monitor. At 2.5 GeV we can store the beam stably up to 200 mA. Higher beam current than 200 mA in present operation is limited by total rf power.

4 SIMULATION OF COUPLED-BUNBCH INSTABILITIES FOR FIVE RF CAVITIES IN 2.5 GEV

We have a plan to insert one rf cavity system more in the ring to increase the total rf power. Then we will have five rf cavity systems in the ring and effects of increased rf cavity HOMs and higher beam currents on the beams need to be examined. In this section, we will show the simulation results on the bunch-lengthening due to longitudinal rf HOMs that originate from five rf cavities in 2.5 GeV.

4.1 Macro-particle motion

To describe the electron's motion in the storage ring we use a standard multi-particle tracking method. The initial particle distributions of each bunch in the phase space are given with the Gaussian distributions. Each macro-particle i in each bunch is tracked in phase space of position and energy coordinates (z_i, ϵ_i) with equations of motion which include radiation damping, radiation excitation and wakefield. The wakefield gives the effect on a macro-particle in one bunch from all bunches which precede it.

For tracking we let each beam be represented by N_p macro-particles. The longitudinal motion of the particle i is advanced on each turn according to the equation [3]:

$$\Delta \epsilon_i = -\frac{2T_o}{\tau_d} \epsilon_i + 2\sigma_{\epsilon o} \sqrt{\frac{T_o}{\tau_d}} r_i + V'_{rf} z_i + V_{ind}(z_i) \quad (2)$$

$$\Delta z_i = \frac{\alpha c T_o}{E_o} (\epsilon_i + \Delta \epsilon_i) \quad (3)$$

with T_o the revolution period, τ_d the longitudinal damping time, $\sigma_{\epsilon o}$ the nominal rms energy spread, V'_{rf} the slope of the rf voltage (a negative quantity), α the momentum compaction factor, and E_o the nominal beam energy; r_i is a random number from a normal set with mean 0 and rms 1. The quantity V'_{rf} is given by

$$V'_{rf} = \omega_{rf} V_o \sqrt{1 - (U_o/V_o)^2}, \quad (4)$$

where ω_{rf} is the angular rf frequency, V_o peak energy gain from rf and U_o average synchrotron radiation energy loss per turn. For the simulations we take $T_o=0.93\mu\text{s}$, $E_o=2.5 \text{ GeV}$, rf frequency $\nu_{rf}=500.066 \text{ MHz}$, $\sigma_{\epsilon o}=8.5 \times 10^{-4}$, and $\tau_d=5 \text{ ms}$. We choose $V_o=1.9 \text{ MV}$ and $\sigma_{z o}=6.4 \text{ mm}$. We use $N_p=1000$ for each bunch.

In the simulation, we use longitudinal broad-band impedance model to calculate the beam-induced voltage V_{ind} . We choose 3 main impedances due to rf cavities that are shown in Table-2.

$$Z_{||} = \sum_{i=1}^{i=3} \frac{R_i}{1 + j(\frac{w_{r,i}}{w} - \frac{w}{w_{r,i}})Q}. \quad (5)$$

The wake function due to the broad-band impedance is given by

$$W_o(z) = 2(\alpha R) e^{\alpha z/c} [\cos(\frac{w_a z}{c}) + \frac{\alpha}{w_a} \sin(\frac{w_a z}{c})], \quad (6)$$

where $\alpha = w_r/2Q$, $w_a = \sqrt{w_r^2 - Q^2}$ and $Q = R\sqrt{C/L}$ is the quality factor. w_r is the resonant frequency. R is the shunt impedance [4].

4.2 Results of simulation

For the simulation in the case of five rf cavities, we used one bunch train with 368 bunches among 468 rf buckets. Total beam currents are 234 mA. Figure 3 shows the bunch

length that is normalized by the nominal bunch length for the 6 longitudinal damping times. The dots show the average σ_z/σ_{z0} for 300 bunches in each turn. The simulation results show the bunch-lengthening of about 12% due to the longitudinal rf HOMs.

Table 1: PLS storage ring parameters used in simulation

Parameters	
Beam energy	2.5 GeV
Number of rf cavities	5
Total beam current	234 mA
Momentum compaction factor	0.00181
RF frequency	500.066 MHz
Circumference	280.56 m
Natural emittance	18.9 nm
Harmonic number	468
Number of bunch	368
Energy spread	0.00085
RF voltage	1.9 MV
Synchrotron radiation loss	700 keV /turn
Longitudinal damping time	5 ms
Bunch length	6.4 mm

Table 2: Longitudinal RF HOMs used in simulation

$w_r(MHz)$	$Z(M\Omega)$	Q
500.05	9.86	20000
759.2	2.9	12000
1302.1	1.34	80000

5 CONCLUSION

Stored beam current of 2.0 GeV in PLS ring has been limited by the transverse coupled-bunch instability due to the 830.45 MHz mode. The transverse beam instabilities 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. But, we still observe longitudinal coupled-bunch instabilities around 360 mA due to 758.66 MHz and 1300 MHz modes at 2.0 GeV.

Stored beam current at 2.5 GeV could be increased to 200 mA by optimizing the number of bunches and betatron tune. Higher beam current than 200 mA has been limited by the total rf power. We have a plan to insert one rf cavity more in the ring to increase the total rf power and stored beam current. This may result in increased rf cavities HOMs and can make beam unstable in higher beam currents. We investigated the longitudinal-coupled bunch instabilities that are caused by the five rf cavity HOMs. The simulation results show the about 12 % bunch-lengthening in total beam current of 234 mA. More investigation on the beam instabilities that are caused by the five rf cavities need to be performed.

6 REFERENCES

- [1] Eun-San Kim, Proc. of the 1993 IEEE PAC, TPPH120, Chicago, June 2001.
- [2] Eun-San Kim and et. al., Proc. of the 1993 IEEE PAC, TPPH121, Chicago, June 2001.
- [3] K.Bane and K.Oide, Proc. of the 1993 IEEE PAC, Washington D.C., 1993 p.3339.
- [4] ' Physics of Collective Beam Instability in High Energy Accelerator', by A. Chao, 1993.

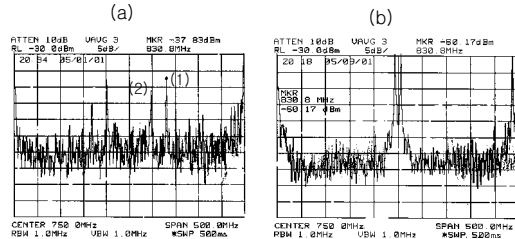


Figure 1: Typical beam spectra that show rf HOM frequencies in 2.0 GeV. They show frequency band between 500 MHz and 1 GHz. Peaks denote transverse 830.45 MHz mode ((1) in (a)), longitudinal 1300 MHz mode ((2) in (a)) and longitudinal 758.66 MHz mode (b). Beam currents in (a) and (b) are 273 mA and 450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



Figure 2: Beam oscillations in 2.5 GeV that are observed in streak camera. (a) the number of bunches are 468, 115 mA, $\nu_x=14.26$ and $\nu_y=8.15$. (b) the number of bunches are 400, 110 mA $\nu_x=14.28$ and $\nu_y=8.18$.

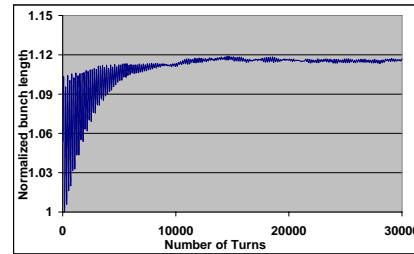


Figure 3: Bunch length that is normalized by nominal bunch length (σ_z/σ_{z0}) for the five rf cavities in 2.5 GeV. The dots show the average σ_z/σ_{z0} for the 300 bunches in each turn. Total beam current and the number of bunches are 234 mA and 300, respectively.