NONLINEAR RF PHASE MODULATION IN PLS STORAGE RING

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Abstract

In the Pohang Light Source (PLS) storage ring, there are various RF noises coming from the RF low level systems. In order to investigate the nonlinear effects of RF noise on the various beam properties such as the bunch length, the beam lifetime, and the longitudinal coupled bunch mode instabilities (CBMI's), we have studied the RF noise driven phase modulation in the PLS storage ring.

1 INTRODUCTION

During the PLS normal operation period, the abnormal large reduction in the beam lifetime, the strong longitudinal stability, and the lowed threshold beam current of the transverse beam instability have been occasionally observed [1]. At other times, we could not supply the uniform intensity beams to users due to the spontaneous bunch length oscillation or beating [1]. Although we did not change any machine parameter and always turned off the active longitudinal feedback system (LFS), these abnormal phenomena had been spontaneously happened during the normal beam service period. By analyzing the LFS and the streak camera data, we have found that the abnormal phenomena are generated by the RF phase modulation due to the RF noise-sidebands in the No. 1 and 3 low level RF systems [1]. In this paper, we have described the nonlinear effects of the RF phase modulation due to the RF noise-sidebands in the PLS storage ring.

2 RF PHASE MODULATION

2.1 Source of RF Phase Modulation

In the PLS storage ring, there are occasionally the RF noise-sidebands around the RF frequency in the No. 3 low level RF system as shown in Fig. 1 whose the third RF noise-sideband is close to the synchrotron frequency of 9.773 kHz at 2.5 GeV [1]. On the contrary, in the No. 1 low level RF system, there is occasionally a similar single RF noise whose the frequency is much lower than the synchrotron frequency of 9.773 kHz, and the amplitude is pseudo-periodically changed [1]. Since these noises are due to the large phase offsets at the front of the phase detectors in the phase loops of the RF stations, they can work as the sources of the natural RF phase modulation in the PLS storage ring [1], [2].

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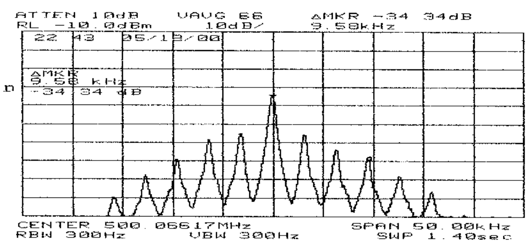

Figure 1: RF noise-sidebands in the No. 3 low level RF system when the abnormal beam lifetime reduction and the longitudinal damping are generated.

2.2 Hamiltonian of RF Phase Modulation

When the modulation frequency f_m of the RF phase modulation is in resonance with an odd multiple of the synchrotron frequency f_s, the oscillating components due to the RF phase modulation are out of phase with the synchrotron oscillations. We call this resonance as the parametric resonance of the RF phase modulation. If the modulation amplitude a_m is small, the dominant contribution of Hamiltonian for the RF phase modulation comes from the dipole mode parametric resonance term [2]. Near the dipole mode parametric resonance condition, $f_m \simeq f_s$, the time averaged Hamiltonian $\langle H \rangle$ in the resonant rotating frame with the modulation frequency is given by

$$\langle H \rangle = (\nu_s - \nu_m)\tilde{J} - \frac{\nu_s}{16}\tilde{J}^2 - \frac{\nu_s a_m \sqrt{2\tilde{J}}}{2}\cos\tilde{\psi}, \quad (1)$$

where $\nu_s = f_s/f_o$ is the synchrotron tune, f_o is the revolution frequency, $\nu_m = f_m/f_o$ is the modulation tune, $\tilde{J}$ and $\tilde{\psi}$ are the action-angle coordinates in the resonant rotating frame [1], [2]. Since the time averaged Hamiltonian $\langle H \rangle$ is time-invariant in the resonant rotating frame $(\tilde{\psi},\, \tilde{J})$, the electron trajectory is a torus which follows a constant Hamiltonian contour. The Hamiltonian equations of Eq. (1) are given by

$$\dot{\tilde{\psi}} = (\nu_s - \nu_m) - \frac{\nu_s}{8}\tilde{J} - \frac{\nu_s a_m}{2\sqrt{2\tilde{J}}}\cos\tilde{\psi}\,, \quad (2)$$

$$\dot{\tilde{J}} = -\frac{1}{2}\nu_s a_m \sqrt{2\tilde{J}}\sin\tilde{\psi}\,. \quad (3)$$

The stable and unstable fixed points of the time averaged Hamiltonian $\langle H \rangle$, which represent the structure of the resonant islands, can be obtained by putting $\dot{\tilde{\psi}} = 0$ and $\dot{\tilde{J}} = 0$ [2]. According to the magnitude of f_m and the bifurcation frequency $f_c = \nu_c f_o \equiv f_s\left(1 - \frac{3}{16}(4a_m)^{2/3}\right)$, the equation for the fixed points has different roots [1], [2].

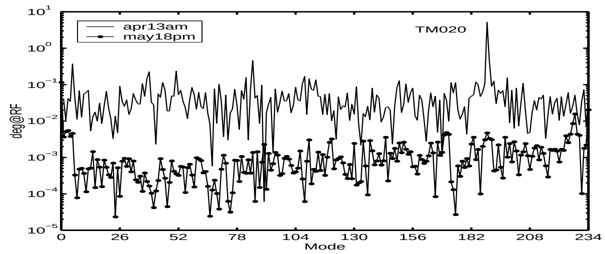

Figure 2: Spectrum levels of the CBMI's obtained by the LFS for two different RF noise-sideband conditions, *apr13am* and *may18pm*.

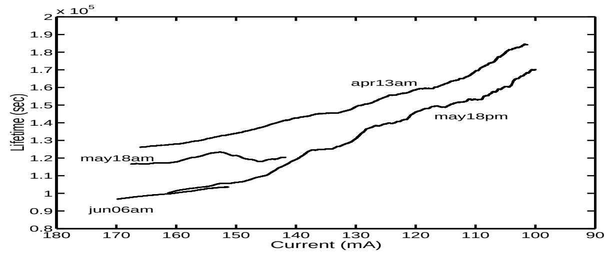

Figure 3: Beam lifetime for the normal operation period, *apr13am* and abnormal beam lifetime reduction due to the various RF noise-sidebands.

3 OBSERVATION AND SIMULATION

3.1 Abnormal Beam Stability and Lifetime

The dipole mode parametric resonance can be generated when one of the RF noise-sidebands with enough amplitude is near the synchrotron frequency [1], [2]. In this case, various beam properties can be changed nonlinearly according to the relation of the RF phase modulation frequency f_m and the bifurcation frequency f_c. Since all bifurcation frequencies of five RF noise-sidebands in Fig. 1 are about 9 kHz for the given modulation amplitude distribution, the modulation frequency f_m means the frequency of an RF noise-sideband close to 9 kHz from now on [1].

Although we have always tuned the RF cavity temperatures to control CBMI during all 468 buckets filled 2.5 GeV operation period, there is still an undamped harmful longitudinal CBMI due to TM_{020} HOM (1301.1 MHz) of the PLS RF cavities as shown in *apr13am* of Fig. 2 [3]. Here, *apr13am* denotes the measured time, that is April 13 AM, 2000, and "deg@RF" means the bunch phase [degree] with respect to a reference oscillator of the PLS LFS [3]. Due to the large momentum spread, the beam lifetime of *apr13am* is larger than 36 hours at 160.00 mA as shown in Fig. 3 [2], [4]. However, the beam lifetime, longitudinal CBMI, and the transverse CBMI of *may18am*, *may18pm*, and *jun06am* are changed according to different modulation frequencies as shown in Figs. 2 and 3 [1]. Related parameters are summarized in Table 1 where LCBMI and TCBMI mean the longitudinal and transverse CBMI, respectively.

To analyze those changes for the *may18am*, *may18pm*,

Table 1: Parameters for various RF noise status.

	apr13am	*may18am*	*may18pm*	*jun06am*
Beam energy, GeV	2.5	2.5	2.5	2.5
Beam current, mA	159.18	159.26	159.13	165.80
f_s, kHz	9.773	9.773	9.773	9.773
f_m, kHz	no noise	8.369	9.662	10.380
a_m, rad	·	0.006	0.003	0.002
f_c, kHz	·	9.615	9.672	9.700
$f_m - f_c$, kHz	·	-1.246	-0.010	+0.680
Peak mode of LCBMI	279	279	241	195
Peak mode of TCBMI	·	·	·	161
LCBMI level, deg@RF	5.500	0.850	0.015	0.003
TCBMI level, deg@RF	·	·	·	0.06
Beam lifetime, hour:min	36h36m	32h57m	27h40m	26h47m

and *jun06am*, we have simulated the dipole mode parametric resonance by solving the time averaged Hamilton equations of motion, Eqs. (2) and (3) [1], [2]. Figure 4 shows the 100000 turn phase space tracking results in the resonant rotating frame for *may18am* with $a_m = 0.006$, *may18am* with $a_m = 0.030$, *may18pm*, and *jun06am*.

As the modulation frequency approaches the bifurcation frequency from below, one stable fixed point A and one unstable fixed point C move in and the other stable fixed point B moves out, and the momentum spread or the bunch length will also be reduced as shown in Fig. 4(a) and (c) [1], [2], [4]. Finally, the stable fixed point B and the unstable fixed point C become one at $f_m = f_c$ [1], [2]. Since two beamlets around two stable fixed points oscillate out of phase in the lab coordinate frame, and enough electrons can be diffused from one beamlet to the other beamlet at f_c, the net dipole mode phase oscillations in the bunches will be disappeared at the dipole mode parametric resonance condition of $f_m = f_c$ [1], [2]. In this case, the driving mechanism of the longitudinal CBMI's will be vanished, and the strong longitudinal stability and the reduction in the momentum spread or the bunch length reduction will be obtained [2], [4]. Therefore, the Touscheck lifetime which is directly proportional to the bunch length will be reduced at the dipole mode parametric resonance [1], [2].

After considering small differences in the modulation frequency and the bifurcation frequency of *may18pm*, we can consider it as near the dipole mode parametric resonance status. Therefore, the strong longitudinal stability, the large reductions in the momentum spread, the bunch length or the beam lifetime can be obtained for *may18pm* as shown in Figs. 2, 3, and 4(c) [2], [4]. This bunch length reduction is also well agreed with the streak camera images as shown in Fig. 5(b).

Since the modulation frequency is well below the bifurcation frequency for *may18am*, the phase space area or the momentum spread is large as shown in Fig. 4(a). And its longitudinal damping and the beam lifetime reduction are small due to the weak resonance strength as shown in Fig. 3 and summarized in Table 1 [1]. In case of *may18am*, beams are reinjected at near 140 mA by the user's request.

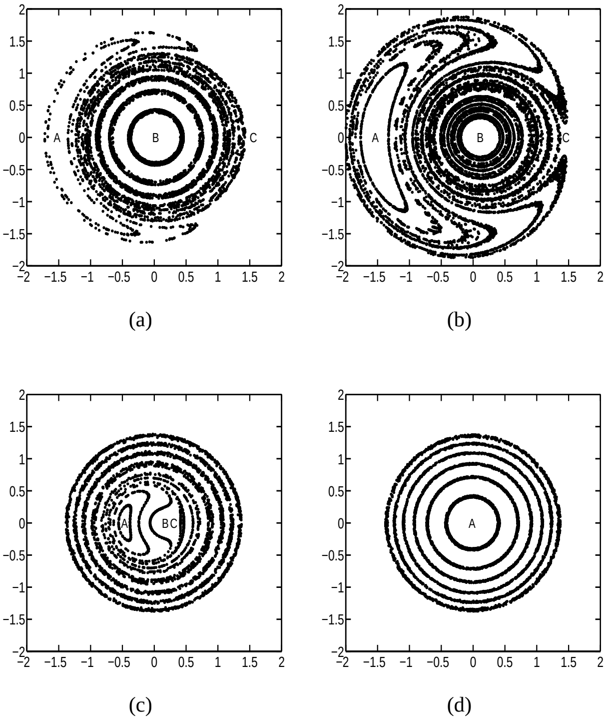

Figure 4: Phase space tracking of the RF phase modulation for (a) *may18am* with $a_m = 0.006$, (b) *may18am* with $a_m = 0.030$, (c) *may18pm*, and (d) *jun06am* conditions. Here, the horizontal and the vertical axes mean $\sqrt{2\tilde{J}}\cos(\tilde{\psi} - \nu_m\theta)$ and $\sqrt{2\tilde{J}}\sin(\tilde{\psi} - \nu_m\theta)$, respectively.

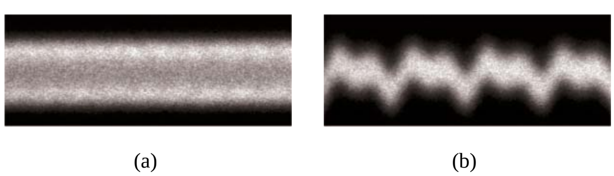

Figure 5: Streak camera images (a) when there is no RF noise-sideband. (b) when 10 hour beam lifetime reduction is generated due to RF noise-sidebands. Maximum horizontal time scale is 1 ms, and vertical time scale which means the bunch length is same for two cases.

Since there is only one stable fixed point at $f_m > f_c$, there is no net dipole mode phase oscillation in the bunches [1], [2]. Therefore, the longitudinal CBMI of *jun06am* is damped to the noise level, 0.003 deg@RF [1]. Since there is little difference in the phase space area between *may18pm* and *jun06am* due to the smaller noise amplitude and $f_m \ll 2f_s$ of *jun06am*, as shown in Fig. 4(c) and (d) its beam lifetime is almost the same as that of *may18pm* as shown in Fig. 3. However, one transverse CBMI with the mode number 161 due to the transverse TM_{110}V HOM (826.4 MHz) of the PLS RF cavities is momentary generated by the strong longitudinally damped beams at much

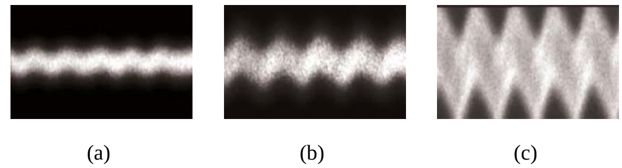

Figure 6: Streak camera images of the beam motion at 140 mA, 2.5 GeV when the bunch length beating is generated due to a single 5.244 kHz RF noise driven phase modulation. The maximum horizontal time scale is 1 ms and the vertical time scale which means the bunch length is same for three cases.

lower beam current than normal, 220 mA [1]. Although the transverse CBMI is generally weak, beams would be occasionally lost due to the instability as shown in *jun06am* of Fig. 3.

3.2 Bunch Length Beating

During the PLS 400 buckets filled operation period, we have occasionally met the bunch length beating due to the a single RF noise whose the noise amplitude is pseudo-periodically changing [1]. Since the modulation frequency of 5.244 kHz is far from the bifurcation frequency, the electrons within a bunch can move between the inner and outer stable fixed points according to the noise amplitude as shown in Fig. 4(a) and (b) [1], [2]. In this case, the bunch length can be also pseudo-periodically changed according to the noise amplitude as shown in Fig. 6. This strong bunch length change or beating is repeated until the amplitude of the RF noise is not severely changed any more.

4 SUMMARY

When one of the RF noise-sidebands with enough amplitude is near the bifurcation frequency, the beam lifetime, the bunch length, and the beam instability can be nonlinearly changed by the RF noise driven dipole mode parametric resonance in the PLS storage ring. After reducing those RF noises by attaching additional mechanical phase shifters in the phase loops of the PLS RF systems in 2000, we cured the abnormal phenomena.

5 REFERENCES

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