SAWTOOTH INSTABILITY AND THE POSSIBILITY OF COHERENT SYNCHROTRON RADIATION IN PLS STORAGE RING

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Abstract

From the recently data analysis of the longitudinal feedback system (LFS) and the streak camera, we have found a special longitudinal sawtooth instability or relaxation oscillation in the Pohang Light Source (PLS) storage ring. The relaxation frequency is always a multiple of 36 Hz and less than 200 Hz. In this case, the charge density modulation or the micro-bunching can be observed due to the strong azimuthal quadrupole mode oscillation. After summarizing our observations of the sawtooth instability, we have checked the possibility of coherent synchrotron radiation (CSR) due to the micro-bunching in the PLS storage ring.

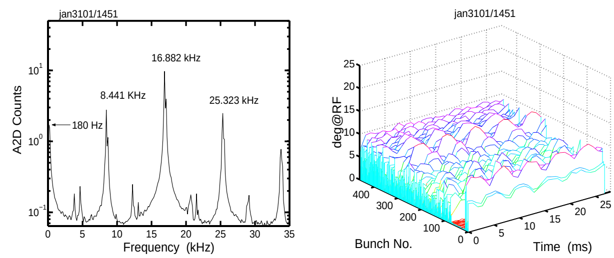
1 INTRODUCTION

Recently, many laboratories have reported the sawtooth instability, the micro-bunching, and their relation to the coherent synchrotron radiation in the electron storage ring or damping ring [1]-[7]. In the PLS storage ring, we have also occasionally observed a special longitudinal relaxation oscillation which generates the sinusoidal modulation in the synchrotron oscillation as well as in the strength of the coupled bunch mode instabilities (CBMI's) [8], [9]. Although our beam bursting behavior is sinusoidal rather than sawtooth, our relaxation oscillation is a kind of the sawtooth instability because the relaxation pattern can be changed to the sawtooth according to the ring impedance or the machine operation parameters [1], [4], [5]. Whenever amplitude of the azimuthal quadrupole mode of the CBMI is higher than that of the dipole mode, the strong relaxation or bursting is always generated, and the charge density modulation or the micro-bunching accompanies [8]. In this paper, we have summarized the observed properties of the sawtooth instability in the PLS storage ring [8] and checked the possibility of the coherent synchrotron radiation due to the charge density modulation or the micro-bunching at the CSR shielded electron ring [4]-[7], [10].

2 SAWTOOTH INSTABILITY IN PLS

2.1 CBMI Modes Vs. Relaxation Amplitude

In the PLS storage ring, when the amplitude of the low frequency relaxation oscillation is high as shown in Fig. 1(a), the synchrotron oscillation amplitude as well as the strength of the longitudinal CBMI's are modulated sinusoidally with its relaxation frequency as shown in Figs. 1(b) and 2 [9]. According to our observations, the amplitude of the beam relaxation oscillation is high whenever the amplitude of the quadrupole mode of the CBMI or the amplitude ratio of the quadrupole mode to the sextupole mode of the CBMI is high enough, and the relaxation can be stopped when the sextupole mode is higher than other modes due to the saturation [1], [8].



(a) (b)

Figure 1: LFS data when the 180 Hz beam relaxation is generated at 125.97 mA, 2.5 GeV: (a) beam signal spectrum whose unit is the analog-to-digital (A2D) count of the LFS, (b) its time domain 400-bunch synchrotron oscillation amplitudes. Since we have turned off one of four RF stations at 2.5 GeV, the synchrotron or the dipole, the quadrupole, and the sextupole mode frequencies are 8.441 kHz, 16.882 kHz, and 25.323 kHz, respectively. Note that the amplitudes of the quadrupole mode and the 180 Hz relaxation are high.

2.2 Strongest CBMI Mode

Normally, the strength of the dipole CBMI is higher than those of other modes. However, in the case of the relaxation oscillation, the strength of the strongest quadrupole CBMI with the mode number of 90 is about two times higher than that of the strongest dipole CBMI with the mode number of 279 as shown in Fig. 2. Here, the CBMI's with the mode numbers of 90 and 279 are generated due to 1596.4 MHz and 1301.1 MHz higher order mode (HOM) of the PLS RF cavities, respectively [9]. Therefore, the beam oscillation is due to mainly the quadrupole mode instead of the dipole mode when the strong relaxation oscillation is generated as shown in Fig. 3(a)-(c). Here, we can clearly see the charge density modulation or the micro-bunching mainly due to the quadrupole mode oscillation though other modes still coexist, and the transverse beam shape is a horizontally oscillating dumbbell-like wide beams due to the dispersion during the relaxation.

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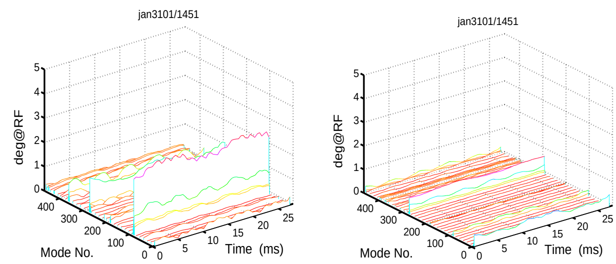
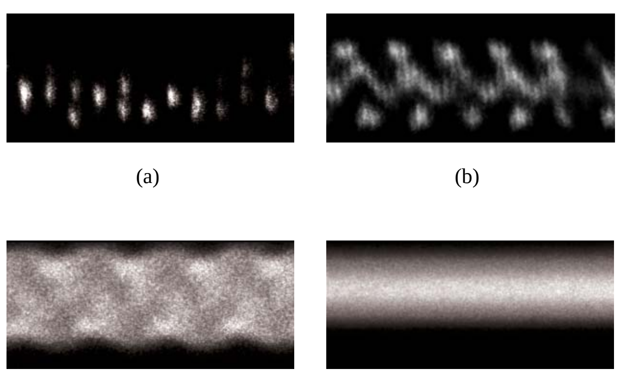


(a) (b)

Figure 2: LFS data when the 180 Hz relaxation oscillation of Fig. 1 is generated: (a) time evolution of the quadrupole CBMI's, (b) time evolution of the dipole CBMI's.



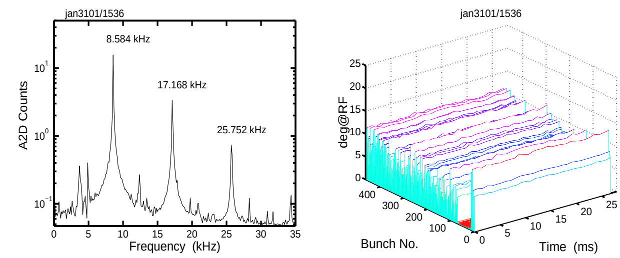
(a) (b)

(c) (d)

Figure 3: Dual scan mode streak camera images of 400-bunch beam motion: (a) when the 36 Hz relaxation is generated at 200 mA, 2.04 GeV, (b) when the 72 Hz relaxation is generated at 220 mA, 2.04 GeV, (c) when the 180 Hz relaxation of Fig. 1 is generated, (d) when the 180 Hz relaxation oscillation of Fig. 1 is stopped by the temperature tuning at 121.39 mA, 2.5 GeV. The maximum time scales of the horizontal axes from (a) to (d) are 100 ns, 500 μs, 500 μs, and 500 μs, respectively, and those of the vertical axes are all 500 ps.

2.3 Cure of Relaxation

Since the HOM frequencies of the RF cavities can be shifted by changing the RF cavity temperatures, it is possible to control the strength of CBMI's by the cavity temperature tuning [2], [9]. In the PLS storage ring, the 180 Hz relaxation oscillation of Fig. 1 can be cured by decreasing the temperature of the fourth RF cavity by 1 °C as shown in Figs. 3(d) and 4 [8], [9]. The amplitude of the 180 Hz relaxation is less than 0.1 A2D count, and the amplitude of the quadrupole mode is downed while that of the dipole mode is increased as shown in Fig. 4(a). All 180 Hz modulations in the synchrotron oscillation and the strength of CBMI's are disappeared as shown in Fig. 4(b) [8]. When the relaxation oscillation is stopped by the temperature tuning,



(a) (b)

Figure 4: LFS data when the 180 Hz beam relaxation oscillation of Fig. 1 is damped by tuning the temperatures of the RF cavities at 121.39 mA, 2.5 GeV: (a) beam signal spectrum, (b) its time domain 400-bunch synchrotron oscillation amplitudes.

the strength of the strongest dipole mode 279 is about four times higher than that of the strongest quadrupole mode 90 [8]. In this case, the beam oscillation is mainly due to the dipole mode, and the bunch length is returned its normal status as shown in Fig. 3(d). The transverse beam shape is returned to the normal shape of the ellipse, and the beam lifetime is also reduced to the normal value.

The beam relaxation frequency in the PLS storage ring is always a multiple of 36 Hz according to the beam instability status. Therefore, we have occasionally observed the low frequency beam relaxations such as 36, 72, 108, 144, and 180 Hz [8]. Note that the 36 Hz relaxation frequency is far from the RF noise frequency or the AC power ripple frequency because the relaxation oscillation can be controlled by the temperature tuning. Further deep investigation will be needed to understand why the relaxation frequency is always a multiple of 36 Hz.

3 POSSIBILITY OF CSR IN PLS

3.1 Coherent Synchrotron Radiation Shielding

When an electron bunch goes through the bending magnet in the storage ring or linac, each electron in the bunch generates the synchrotron radiation. Generally, most CSR may be suppressed when the rms bunch length σ_z is larger than the radiation wavelength λ due to the vacuum chamber shielding effects and the poor coherence [10]. CSR shielding depends on the threshold wavelength $\lambda_{th} \simeq (6h^3/\pi\rho)^{1/2}$ where h is the chamber full height, and ρ is the bending radius [5], [10]. When the rms bunch length is smaller than the threshold wavelength, the shielding effects is weak, and CSR can be observable. For the PLS storage ring, $\lambda_{th} \sim 5.3$ mm or 17.7 ps for the $h = 0.045$ m and $\rho = 6.306$ m. Since the rms single bunch length of the PLS storage ring is larger than 7.0 mm or 21.0 ps at the normal status, it may be difficult to observe strong CSR due to the chamber shielding effects [11].

However, recently, several storage rings have reported strong CSR emission under the relaxation oscillation or the sawtooth instability though there is the chamber shielding effects [4], [5]. They found that during the relaxation, CSR can be generated by the charge density modulation which is a kind of the quadrupole mode, and CSR bursting period is the same as the relaxation oscillation period [4]-[6]. The latter fact means that CSR bursting must be strongly correlated to the relaxation oscillation. If there is the charge density modulation due to the quadrupole or sextupole mode oscillation, the micro-bunches of the bunched beams can be generated at the high beam current as shown in Fig. 3(a) and (b). Since the length of the original bunch is reduced to that of the micro-bunches, the CSR observable condition of $\sigma_z \leq \lambda_{th}$ will be easily satisfied, and strong CSR can be generated [4], [5]. If the charge density modulation or the micro-bunching can be continuously increased due to CSR coming from the smaller micro-bunching, we can observe CSR to shorter wavelength range [7].

Since our relaxation properties are very similar to other laboratory observations, we can expect CSR in the PLS storage ring. When the relaxation is generated in the PLS storage ring, the rms bunch length can be smaller than the threshold wavelength of 5.3 mm due to the charge density modulation or the micro-bunching as shown in Fig. 3. In this case, strong CSR may be observable though we do not confirm its existence experimentally yet. If we can reduce the rms bunch length further by tuning the PLS ring lattice to get the low momentum compaction factor, CSR can be certainly observable at a new undulator with a larger chamber height h and a smaller radius of curvature ρ [12].

3.2 Coherent Synchrotron Radiation Power

When the rms bunch length σ_z is much smaller than the radiation wavelength λ, the synchrotron radiation of each electron generates a strong constructive interference or coherence. In this case, its CSR power is directly proportional to square of the electron number N_e in a single bunch [5]. Since the incoherent synchrotron radiation power is proportional to N_e which is about 10^{11} order for the general storage ring, CSR power is much higher than the incoherent synchrotron radiation power under $\sigma_z \ll \lambda$ condition [4], [5], [10], [12]. By increasing the beam current further, saturated sextupole mode oscillation can be obtained [1], [8]. In this case, there is no relaxation oscillation though there is still the micro-bunching or the charge density modulation due to the sextupole mode oscillation. Therefore, it may be possible to obtain the saturation of CSR without any bursting by operating the sextupole mode oscillation. This fact gives a new possible principle of the high power coherent synchrotron radiation source at the storage ring via the sawtooth instability, which is quite different with the principle of the SASE-FEL [6].

3.3 Mechanism of Micro-Bunching

Although the relaxation and the micro-bunching can be explained by several possible models such as the microwave instability due to shot noises [6], the exponentially decayed CSR under shielding [7], and the narrowband impedance due to the HOM's of RF cavities [3], no model is confirmed experimentally yet. Since the relaxation oscillation can be controlled by the RF cavity temperature tuning though the single bunch beam current is much lower than the threshold of the PLS microwave instability, 2.2 mA, and the charge density modulation is asymmetric as shown in Fig. 3, our observed sawtooth instability is very close to the narrowband impedance model instead of the microwave instability model [2], [3], [8], [9], [11]. According to our streak camera observations, the low frequency relaxation must be generated when the electrons in a bunch perform the continuous bunching and diffusion between two stable fixed points or the micro-bunches [3], [8].

4 SUMMARY

We have observed the low frequency relaxation oscillation or the sawtooth instability and the micro-bunching in the PLS storage ring. Our sawtooth properties are very similar to other laboratory observations though our relaxation frequency is always a multiple of 36 Hz. From our observation of the density modulation or the micro-bunching, we have checked the possibility of CSR in the PLS storage ring though it is not confirmed experimentally yet. Due to the micro-bunching, the LFS may not detect phase errors properly at higher beam current.

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