TRANSVERSE SAWTOOTH INSTABILITY OBSERVED IN PHOTON FACTORY ADVANCED RING

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Abstract

This paper reports a curious instability observed at the Photon Factory Advanced Ring for pulse X-rays (PF-AR). In a low bunch current, the horizontal betatron oscillation induced by an injection error was suppressed well by the beam feedback system. However, when the bunch current was high, the horizontal oscillation grew over several milliseconds and damped again like a sawtooth, after a injection process was finished. To investigate the mechanism of the sawtooth instability, we measured the horizontal beam size turn by turn as well as the dipole oscillation when the parameters (octupole magnets, the beam feedback and RF voltage) were changed. It was found that the transverse feedback for damping the dipole oscillation was suspicious for the instability, when the dipole oscillation and increase of the beam size coexisted.

INTRODUCTION

The PF-AR is an electron storage ring dedicated to pulse X-ray research [1]. The users require a single bunch current as high as possible. The beam injected from the KEK linac at the energy of 2.5 GeV or 3.0 GeV is raised up to the energy of 6.5 GeV for the users by the accelerating cavities. Since a high bunch current of more than 50 mA is expected, we need to take countermeasures against a single bunch instability at the injection energy. Octupole magnets are installed, which makes tune spread depending on the the beam size or the oscillation amplitude and would stabilize the beam. The transverse feedback system is employed to suppress coherent dipole oscillations. Though the bunch current of 47 mA at the energy of 2.5 GeV and of 65 mA at 3.0 GeV was achieved by tuning both the beam feedback and the octupole fields, we observed a curious instability during the injection process. It is important to investigate the cause of the instability from the views of the beam dynamics and the operation.

TRANSVERSE SAWTOOTH INSTABILITY

We observed horizontal bunch oscillations during the injection process. As shown in Fig. 1, a betatron oscillation induced by an injection error damps due to the beam feedback system. The betatron oscillation, however, continues to grow over several milliseconds and damps rapidly, when the bunch current is high enough, greater than about 20 mA. The phenomena appeared repeatedly every injection. We call the phenomena *a transverse sawtooth instability*. At a storage mode with the injection energy, the sawtooth instability was also observed, after an artificial kick was given to a bunch. This result suggests that the sawtooth instability is excited by a stored bunch itself rather than an interaction between an injected beam and a stored bunch. To investigate the cause and the mechanism of the instability, we measured the abnormal growth of the betatron oscillation in details, when the parameters (octupole fields, feedback gain, RF voltage etc.) were changed.

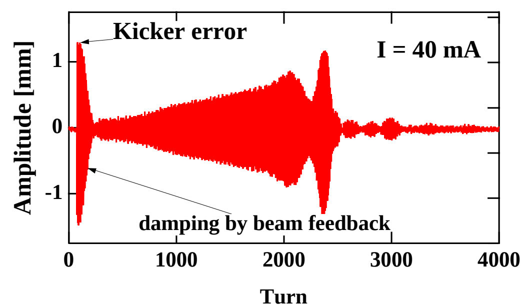

Figure 1: Transverse sawtooth instability. Horizontal betatron oscillations are shown at the injection at the beam energy of 3.0 GeV as a function of turn number. The bunch current is 40 mA. The revolution period is 1.258μs.

MEASUREMENT OF DIPOLE OSCILLATION

Experimental setup

The monitor system measuring the horizontal beam oscillation consists of a stripline, the *Bunch Oscillation Detector* (B.O.D.) [2] and an ADC module. A beam signal was picked up by the stripline horizontally mounted in a vacuum chamber. A picked-up signal was fed into the B.O.D, where the dipole oscillation was detected. The output signal of the B.O.D. was recorded by the ADC module with a memory. The oscillation data were taken turn by turn, after a bunch was horizontally excited by a kicker magnet prepared for the injection.

Influence of RF voltage

We measured a range of the bunch current at which the sawtooth instability appeared, while the voltage of the RF cavity (Vc) changed. The measurement was performed under constant octupole fields and a constant feedback gain. A result is shown in Fig. 2. The maximum amplitude of the oscillation was 1.1 mm and the growth time was about

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3.75 ms at Vc=2.95 MV. The sawtooth instability, however, appeared intermittently when the Vc exceeded 3.0 MV and it did not appear when the voltage was over 4.0 MV. These results suggest that the sawtooth instability is influenced by a longitudinal bunch shape.

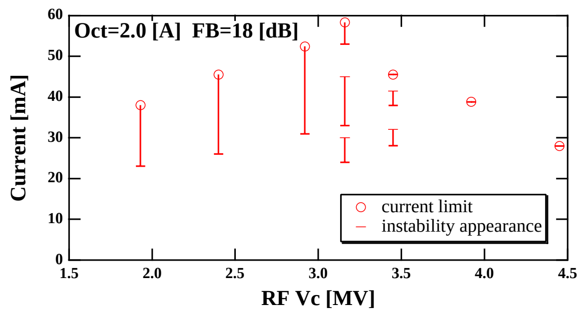

Figure 2: Appearance of the sawtooth instability is shown by bars as a function of the voltage of the RF cavity. A small circle attached with the bars at each voltage shows the maximally stored current. In this experiment, the current of 2 A for the octupole magnets and a relative feedback gain, FB=18 dB are constant.

Influence of octupole fields and beam feedback

An effect of the octupole fields was measured under a constant feedback gain. Figure 3 shows the sawtooth instability for varying the octupole current. The sawtooth instability appears clearly when the octupole current is 1A, however , it eliminates at the current of 3A. This result indicates that octupole magnets contribute to suppress the sawtooth instability. But, there was a trouble in the injection at a low current, when the octupole current was set to be 3 A.

On the other hand, the gain of the beam feedback was changed under a constant octupole current. Figure 4 shows the sawtooth instability for various feedback gains. The appearance time of the instability tends to be shorter and the maximum amplitude of the oscillation is larger as the feedback gain increases. A higher gain of the beam feedback seems to excite the sawtooth instability. The injection was performed with a lower feedback gain, however, we could not store the bunch current of more than 15 mA.

Since some doubts in the feedback system [2] were arisen, the hardware was checked. In this system, a dipole oscillation is picked up by a single stripline and it is fed to deflector electorodes composed of four striplines via power amplifiers. Another method for detecting the bunch oscillation was tried using four button electrodes, where the BOD and a phase shifter were replaced by an amplitude modulation to phase modulation (AM/PM) detector and a 2-tap FIR filter module [3][4]. The sawtooth instability was still observed in the modified system. Moreover, we confirmed that the instability occurred regardless of saturation of the power amplifiers and also regardless of unbalance of deflection. The feedback system itself seems to work well.

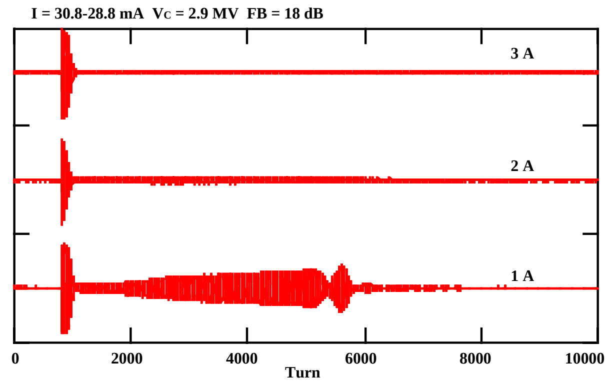

Figure 3: The horizontal oscillations as a function of turn number when the current of the octupole magnets changes. The current of 2 A corresponds to the K_3-value of 90 m^{-3}.

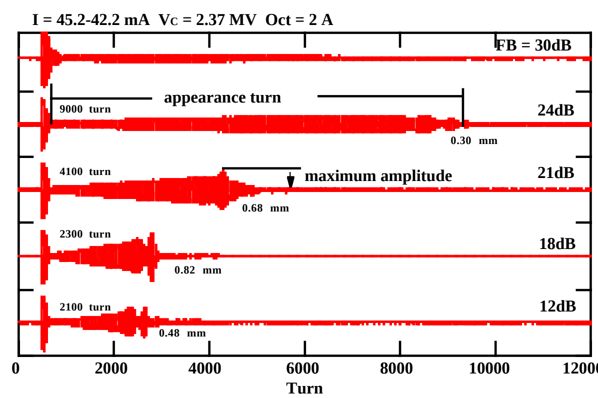

Figure 4: The horizontal oscillations as a function of turn number are shown for various feedback gains. The value of FB shows a value of the attenuators in the feedback loop and the gain of the beam feedback becomes large in inverse proportional to the FB value. The damping rate of the beam feedback is about 0.01 $turn^{-1}$ for FB=18dB.

BEAM SIZE MEASUREMENT

The maximum amplitude of the dipole oscillation is relatively small, about 1 mm and damps quickly, that may not be a serious problem. Other effects should be considered for the instability. Thus, the beam size was measured turn by turn with an electrical method. The beam size can be obtained by measuring the quadrupole moment of the beam [5]. The setup of the beam size monitor is shown in Fig. 5. The signals indicated by A and by B, signals from each button electrode are added horizontally and the vertically, respectively, are expressed as

$$A \propto \frac{I}{\pi R}\left\{1-\frac{2}{R^2}\left[\left(\sigma_x^2-\sigma_y^2\right)+\left(x_0^2-y_0^2\right)\right]\right\}$$
$$B \propto \frac{I}{\pi R}\left\{1+\frac{2}{R^2}\left[\left(\sigma_x^2-\sigma_y^2\right)+\left(x_0^2-y_0^2\right)\right]\right\}, \quad (1)$$

where I is the bunch current, R is the duct radius, σ_x and σ_y are the horizontal and vertical rms sizes of the beam, x_0 and y_0 are the charge center of the bunch and ($\sigma_x, \sigma_y \ll R$). The AM/PM detector compares the signals A and B and the detector outputs a signal proportional to the rms beam size regardless of the bunch current. Assuming the vertical beam size is constant or negligibly small, this signal indicates a change of the horizontal beam size.

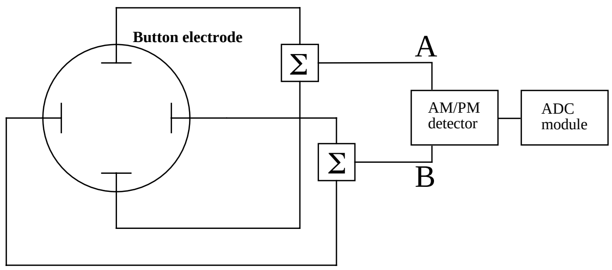

Figure 5: Block diagram of the beam size monitor.

The horizontal dipole oscillation and the beam size were measured at the same time as shown in Fig. 6. While the amplitude of the betatron oscillation grows, the beam size also grows without any oscillations. The time at which the amplitude is maximum corresponds to the maximum of the size. However, the size remains enlarged and shrinks slowly, even after the amplitude of the dipole oscillation fully damps. The size goes back to an initial value with a scale of the radiation damping time.

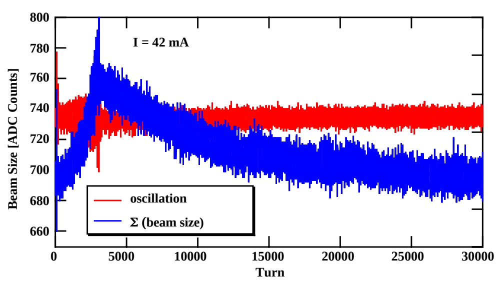

Figure 6: Beam size and the dipole oscillation are shown as a function of turn number. The ADC value in the size corresponds to a change of the rms size, 0.06 mm/count. The radiation damping time is 25 ms.

The beam size was directly measured using a streak camera [6]. Figure 7 shows horizontal beam profiles taken by the streak camera with the bunch oscillations. It is impossible that the beam size data over several ten of thousands of turns are continuously obtained at one time. Thus, sampled data of the beam profile are shown. We confirmed that the horizontal beam size and the oscillation amplitude grow together and the size shrinks slowly after the oscillation fully damps, as measured by the electrical size monitor.

DISCUSSION

From the behavior of the sawtooth instability for the changes of the various parameters, it is found that the beam

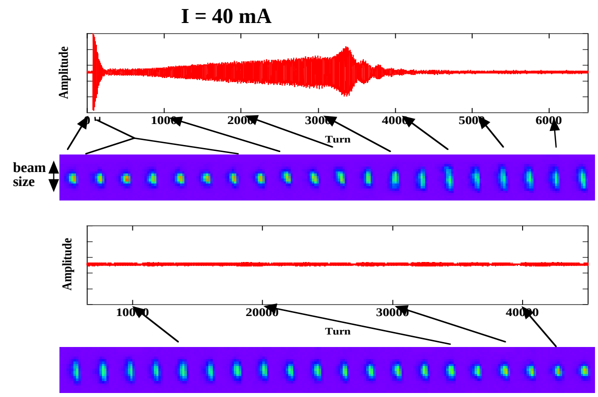

Figure 7: Horizontal beam profiles taken by the streak camera and the horizontal oscillation are shown as a function of turn number. For the beam profiles, the vertical axis indicates a beam size and the bunch goes from left side to right side. The bunch current is 40mA.

feedback is related to the sawtooth instability. Though the feedback system works well, the question remains why the feedback system cannot suppress the slowly growing betatron oscillation with the increase of the beam size. We had similar experiences in the early stage of the PF-AR. A vertical instability was observed [7], where blow-up of the beam size and dipole oscillation appeared at the same time. The beam feedback system for damping the dipole oscillation had no effect on the vertical instability. In the current PF-AR, we observed that the head and the tail of a bunch oscillated individually like a strong head-tail instability using a streak camera at a high bunch current. The different oscillations at the head and the tail of a bunch may influence the detection of the bunch oscillation in the beam feedback. We will clarify a detailed mechanism of the sawtooth instability by a computer simulation including an inside structure of a bunch.

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