DETECTION OF WAKE FIELD USING TEST-BUNCH METHOD AT PHOTON FACTORY ADVANCED RING

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Abstract

Curious phenomena which depend on the beam current have been appeared during injection into PF-AR. In order to get information on the wake field, a test-bunch method has been carried out: a main bunch with a large current and a test bunch with a smaller current are stored and wake field excited by the main bunch is estimated from the motion of the test bunch. Experimental results and an analytical calculation suggest that the wake field excited in rf cavities influence the injection rate. The wake field estimated by the test bunch method is compared with the calculated field and the motions of the stored and injected beam are discussed.

INTRODUCTION

PF-AR (Photon Factory Advanced Ring) is an electron storage ring dedicated to a Pulsed X-ray source. Electrons at the energy of 2.5GeV are injected in a single bunch and are accelerated up to 6.5GeV or 5.0GeV, and synchrotron radiation is delivered to users' stations. Main parameters of PF-AR at the energy of 2.5GeV are shown with symbols used in this paper in Table 1. After the completion of the upgrading project of PF-AR [1], several phenomena are observed during injection. One of them is sudden decrease in an injection rate. Typical change of the beam current and the injection rate are shown in Fig.1. The injection rate of 1mA/sec can be achieved at a low beam current, but the rate decreases suddenly around the beam current of 35mA. After a while, the injection rate recovers a little bit but low injection rate continues up to 40mA that is a usual beam current in users' operation. The other phenomenon is an anomalous oscillation in horizontal plane observed during injection. We call the oscillation as a transverse saw-tooth instability [2]. To ease the effect of instabilities during injection, the injection energy was raised to 3.0GeV from 2.5GeV since Oct. 2002. Although the raise of the injection energy increased the maximum stored current to 65mA, instabilities still have been appeared during injection. These phenomena suggest that the wake field excited in components of the ring affects the motion of the beam. We have tried to detect the wake field using a test-bunch method. In this paper, we report the test-bunch method and preliminary results. We also discuss the motion of the beam stored in the ring and the beam injected into the ring during injection.

Table 1: Main parameters of PF-AR

injection energy	E_0	2.5GeV
circumference	L	377m
acceleration frequency	f_{rf}	508.58MHz
harmonic number	h	640
revolution frequency	f_{rev}	794kHz
betatron tune (H/V)	ν_H/ν_V	10.15/10.21
radiation damping rate (transverse)	α_x	23/sec

THE TEST-BUNCH METHOD

In the test-bunch-method, two bunches called a "main bunch" and a "test bunch" are injected. The bunch current of the test bunch is small enough compared with that of the main bunch. When oscillation of the main bunch is excited artificially, a wake field excited in the ring affects the motion of the test bunch. From the motion of the test bunch, information of the wake field can be obtained. In this method, it is essential that only the main bunch is excited and the test bunch is not affected by the excitation.

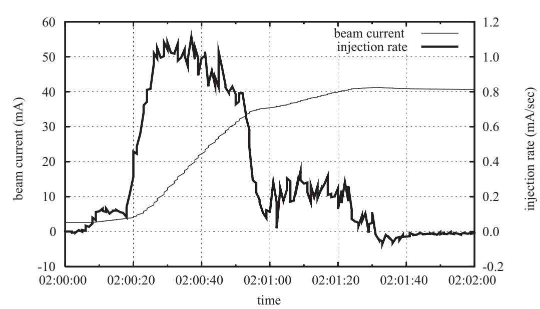

Figure 1: Typical change of beam current and injection rate during injection.

Selective excitation of bunch oscillation

The excitation of the main bunch oscillation without any effect on the test bunch is realized by an excitation signal modulated by a pulse train synchronized to the bunch revolution, however, spectrum lines are scattered in a wide frequency range. In the test-bunch method, we used only three frequency components to excite the main bunch oscillation without any effect on the test bunch as mentioned below.

At first, we define the bucket of the main bunch as the 0-th bucket, and successive buckets as 1st, 2nd and so on.

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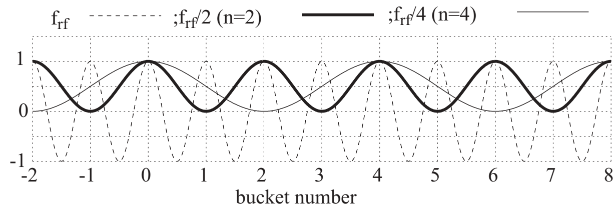

Figure 2: sinusoidal signals with DC offset at the frequency of frf divided by an integer n

Consider a sinusoidal signal at the frequency of f_{rf} divided by an integer n which is a small even factor of the harmonic number. When a DC offset is added to the signal as shown in Fig.2, and fed to the kicker a bunch at the m-th bucket is deflected. The deflection angle is given by

$$\Delta\theta \propto l\left(\frac{nc}{\omega_{rf} l}\sin\frac{\omega_{rf} l}{nc}\cos\frac{2m\pi}{n}+1\right), \qquad (1)$$

where l is a length of the kicker and c is a speed of light. Then the signal is modulated by the betatron frequency. The betatron oscillation of bunches at the (1+2m)-th ((2+4m)-th) bucket are not excited by the signal when n=2 (n=4), i.e., the (n/2+nm)-th bunch are not excited, while the bunch at the 0-th bucket is excited.

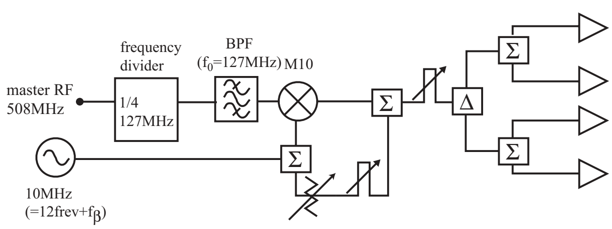

Figure 3: Block diagram of the circuit for main bunch excitation

Fig.3 is a block diagram of the main bunch exciter. The master rf signal is converted to signals with frequencies of f_{rf}/2, f_{rf}/4 or f_{rf}/8 and modulated by the betatron frequency. In order to correct frequency characteristics of transmission line and power amplifier and to cancel out a residual deflection due to a finite length of the kicker, we adjusted the phase and the amplitude of the lowest sideband of the excitation signal observing the betatron sideband. We obtained an isolation, which is defined as the amplitude ratio of test bunch oscillation to main bunch one, of about -40dB.

Detection of test bunch oscillation

We used a strip-line type beam position monitor with a length of 30cm to detect the oscillation of the test bunch. DBMs (Double Balanced Mixer) were used to separate the designated signal from the test bunch in mixture of the signals from the test bunch and the main bunch. The selected signal is filtered by a band-pass filter with the center frequency of 250MHz, and fed to a SA (Spectrum Analyzer). The oscillation amplitude of each bunch was obtained from the bunch spectrum.

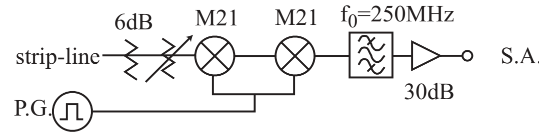

Figure 4: Detection circuit to observe the oscillation of bunches separately

EXPERIMENTAL RESULTS

A feedback damper that suppresses horizontal/vertical instabilities is indispensable for the usual operation. We cannot store the beam current larger than 15mA without the damper. We carried out test-bunch measurement at low beam current with the damper off in order to avoid effects of the damper on the test bunch. The bunch current of the main bunch and the test bunch was 2.0mA and 0.2mA respectively. We adjusted the amplitude of the main bunch oscillation to about 1.0mm adjusting the power of the excitation signal.

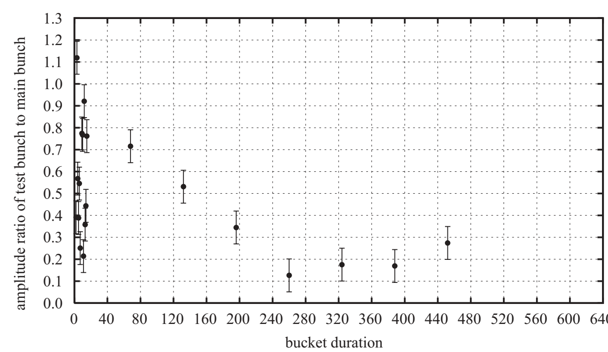

Figure 5: Result of measurement for whole the ring

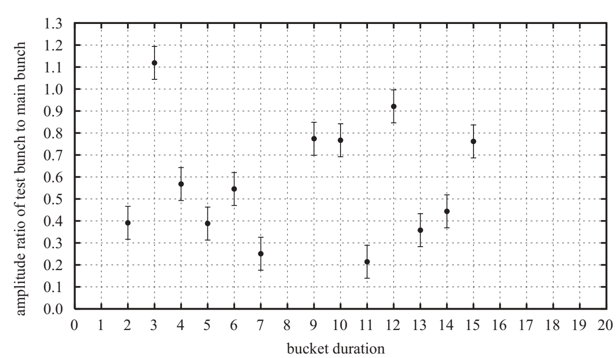

Figure 6: Result of measurement for whole 20 bunches after the main bunch

Results of measurement are shown in Fig.5 and Fig.6. Abscissa and ordinates indicate the bucket number of the test bunch and the amplitude ratio of the test bunch to the main bunch, respectively. The larger value means the stronger wake field at the bucket of the test bunch. In Fig.5, the ratio for whole the ring is shown, and tends to decrease as a whole. In Fig.6, the ratios for 20 buckets after the main bunch are shown. The effect of the wake field is scattered about one order depending on the bucket. But, that is much larger than the measurement error. The frequency component of the wake filed is supposed to be higher than the sampling frequency, which is f_{rf}, therefore no periodicity can be extracted by aliasing.

DISCUSSION

Simple analysis of test-bunch method

In the analysis, the motion of each bunch is described by a damped oscillation with an external force. A bunch feels two kinds of wake fields, one is a short range wake which vanishes in one turn, another is a long range wake which does not decays in one turn. We regarded the long range wake as a decrease in radiation damping rate. Then equations of motion are given by

$$x_m'' + \left(\frac{\nu}{R}\right)^2 x_m + 2\frac{\alpha - g q_m}{c} x_m' = \frac{\theta}{L}\sin\frac{\nu}{R}z + \frac{q_t x_t W_n}{E_0 L} \quad (2)$$

$$x_t'' + \left(\frac{\nu}{R}\right)^2 x_t + 2\frac{\alpha - g q_t}{c} x_t' = \frac{q_m x_m W_n}{E_0 L}, \quad (3)$$

where x, q, g, θ and W_n are the displacement, the bunch charge, the growth rate due to long range wake per coulomb, the deflection angle by the excitation and the wake potential normalized by the beam energy at a distance of n buckets from the main bunch to the test bunch. Subscripts m and t indicate the main bunch and the test bunch, respectively. Motion of bunches, after enough time that is longer than the radiation damping time, is harmonic. From Eqn.2 and Eqn.3, the amplitude ratio is written by

$$\frac{\hat{x}_t}{\hat{x}_m} = \frac{c q_m W_n}{4\pi E_0 \nu(\alpha - g q_t)}. \quad (4)$$

When single bunch of 10mA was stored, self-induced oscillation was observed without the external excitation signal. We get g as 1.98 (1/sec/nC). From g and the test-bunch result, W_n is obtained for each buckets.

We calculated wake potential by an electro-magnetic code MAFIA for the acceleration cavity. In PF-AR, there are 6 cavities called APS (Alternating Periodic Structure), each of which has 11 cells for acceleration and 10 cells for coupling. The calculated wake potential multiplied by 6 is consistent with that obtained from test-bunch measurement and simple analysis in a factor of 2.

Numerical simulation on injection

In order to investigate the motion of the stored beam and the injected beam, we performed a numerical simulation. In this simulation the stored beam is described by one macro-particle with a current of 35mA, and the injected beam is described by 3 macro-particles with a current of 0.08mA. Time separation between the macroparticles is set to be 350ps which is the acceleration period of the injector LINAC. The initial amplitude of the stored beam and the injected beam at the injection point are 4mm and 20mm respectively. The feedback damper is also considered with the damping time of about 0.2ms. We used the wake potential obtained by MAFIA calculation as a short range wake, which vanishes completely after the beam rotates the ring.

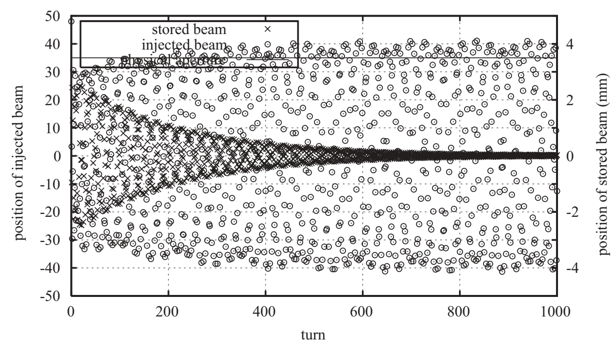

Figure 7: Result of numerical simulation assuming a wake potential

The result of the simulation is shown in Fig.7. In the figure, because the motions of all macro-particles of the injected beam are similar, the macro-particle corresponding to the stored beam and one macro-particle corresponding to the injected beam are shown. The solid line indicates physical aperture by the septum magnet.The injected beam is lost in about 200 turns.

The stored beam oscillates in horizontal plane with betatron frequency and excites wake field. Injected beam which consists of a few bunches from the LINAC with large amplitude of betatron oscillation is kicked by the wake field and lost from the ring aperture. The behavior of the injection beam depends on the initial condition of the stored beam.

SUMMARY

In this paper, we reported the test-bunch method. Devices to excite the main bunch and to observe the test bunch were worked with a good isolation. Wake field detected by the method indicated that about 20 buckets after the main bunch are affected by the wake field. From the numerical simulation, it was found that the injected beam could be lost by the wake field excited by the stored beam.

REFERENCES

[1] K. Ebihara et.al., Present Status of PF-AR, in these proceedings

[2] Y. Minagawa et.al., Transverse Sawtooth instability observed in Photon Factory Advanced Ring, in these proceedings