EXPERIMENTAL STUDY OF HEAD-TAIL DAMPING AND NONLINEAR FILAMENTATION BASED ON PRECISE ANALYSIS OF COHERENT BETATRON OSCILLATIONS IN ELECTRON STORAGE RINGS

N. Akasaka and S. Kamada, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305 Japan

Abstract

Coherent betatron oscillations measured by a single pass position monitor were analysed to give instantaneous tune and amplitude in good accuracy. Based on this precise analysis of coherent oscillations, experimental studies were carried out on head-tail damping and nonlinear filamentation in an electron storage ring of TRISTAN MR.

1 INTRODUCTION

The amplitude dependence of betatron tune is a fundamental index for lattice non-linearity of circular accelerators. In the computer simulation of particle motion, it has clearly indicated the lattice non-linearity and the limit of dynamic-aperture[1,2].

Experimentally, amplitude-dependent tune shift was measured in a hadron machine at first[3]. The transverse emittance of a proton beam was reduced by scraping and the beam was kicked by pulse magnets to oscillate coherently. The position of the kicked beam was measured every turn using a single-passage position monitor and the betatron tune was obtained through Fourier analysis of the turn-by-turn signal. The same way does not work in electron storage rings because the coherent oscillation damps at least in the radiation-damping time and smears out rapidly through the nonlinear filamentation brought by the inherent emittance of beam and the lattice non-linearity. The head-tail effect increases damping rate more according to positive chromaticity, current of beam and imaginary part of transverse impedance of vacuum chambers[4,5]. On the other hand, study of coherent betatron-oscillation may bring about information on the lattice non-linearity and the transverse impedance when damping rate can be measured for each damping process.

In studies on coherent oscillation for this aim, it is essential that tune and amplitude must be determined precisely within a time interval shorter than any damping process in concern, such as radiation damping, head-tail damping and nonlinear filamentation. Otherwise, one should fail to investigate variation of tune and amplitude with time.

We have developed the method to analyse the turn-by-turn signal of beam position. This method gives precise tune and amplitude instantaneously and is presented in section 2. Experimental study was carried out at TRISTAN MR based on this analysing method[6]. Amplitude of coherent oscillation, bunch current, chromaticity and arrangement of sextupole magnets were changed to distinguish each damping process. The experimental conditions and the results are given in section 3. In section 4 discussed are comparisons between experimental results and computational simulations.

2 METHOD

The time variation of the tune and amplitude of the transverse collective oscillation of the bunch is obtained from the sampled signal of a single passage position monitor using Fourier analysis. The instantaneous spectrum is calculated with a series of data which corresponds to N=256 turns. The Hanning window

$$w(n) = 1 - \cos\left(\frac{2\pi n}{N}\right)$$

is adopted as a weight function. In order to find the frequency and amplitude of the peak, parabolic fitting is used, where the true continuous spectrum around the peak is approximated by a parabola fitted to the largest three points. Although this simple peak approximation method has a deviation from the true peak, it is not a serious problem for our purpose. The time variation of the spectrum is obtained by shifting the data for Fourier transformation by 128 turns.

3 RESULTS

The experimental data were collected at TRISTAN MR in single-bunch operation. The coherent oscillation was

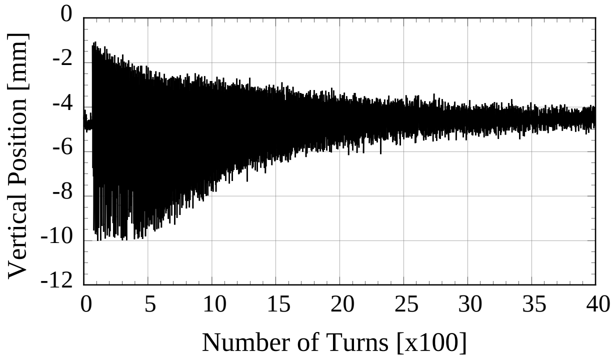

Fig.1 An example of the data taken with the single-passage positon monitor.

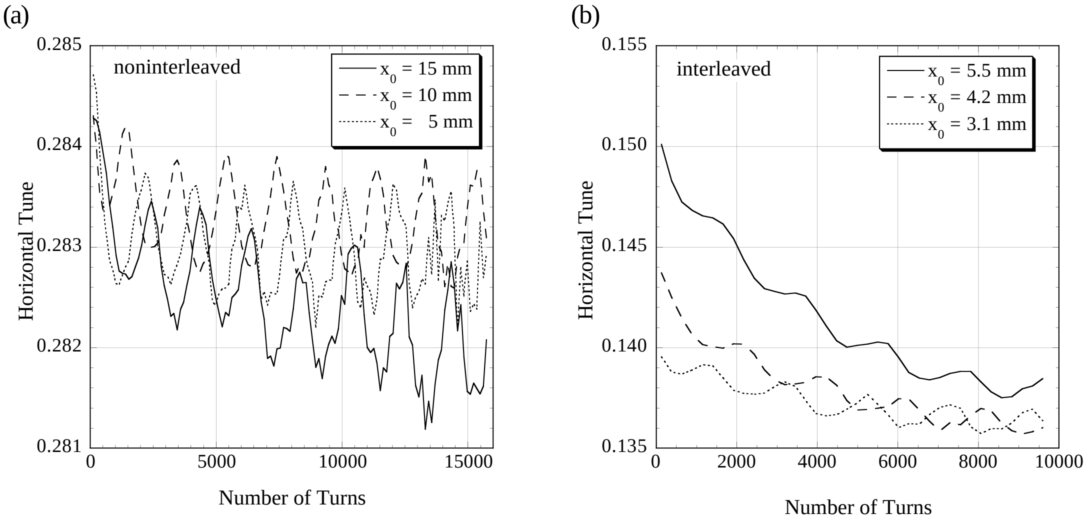

Fig. 2 The shift of the horizontal tune for (a) noninterleaved and (b) interleaved sextupole scheme.

excited by kicking the bunch transversely. The subsequent damping of the oscillation was recorded with a single-passage position monitor[7], which stores the two transverse position data up to 16384 turns from about 70 turns before the kick. With this sensitive position monitor, it was possible to take the data at a current as low as the head-tail damping is suppressed. An example of the data is shown in Fig. 1. When the bunch is kicked horizontally (vertically), the peak near the horizontal (vertical) tune is calculated as described above.

3.1 Amplitude-Dependent Tune Shift

Nonlinearity of the lattice causes the amplitude-dependent tune shift. Figure 2 shows the change of the horizontal tune as the oscillation decays, where (a) noninterleaved sextupole scheme[8] and (b) interleaved sextupole scheme are compared. The current is in the same range, 0.023 mA for (a) and 0.018 mA for (b). The tune modulation with a period of 2000 turns and a peak-to-peak amplitude of about 10^{-4} is 50 Hz ripple. Ignoring the ripple, the amplitude-dependent tune shift in noninterleaved sextupole scheme is smaller than interleaved one by one order of magnitude as expected from the SAD[9] calculation.

3.2 Nonlinear Filamentation

The amplitude-dependent tune shift leads to nonlinear filamentation. An example is shown in Fig. 3, which is observed under noninterleaved sextupole scheme.

Figure 3(a) is the damping of vertical oscillation with different current and fixed initial amplitude of 6 mm. Below 0.036 mA, the oscillation amplitude seems to decay according to $\exp\left(-at^2\right)$ with a being a constant until it reaches the noise level. This time dependence suggests nonlinear filamentation. On the contrary, above 0.088 mA, the oscillation is exponentially damped and its damping rate increases as the current increases by the head-tail damping. Note that the damping rate of nonlinear

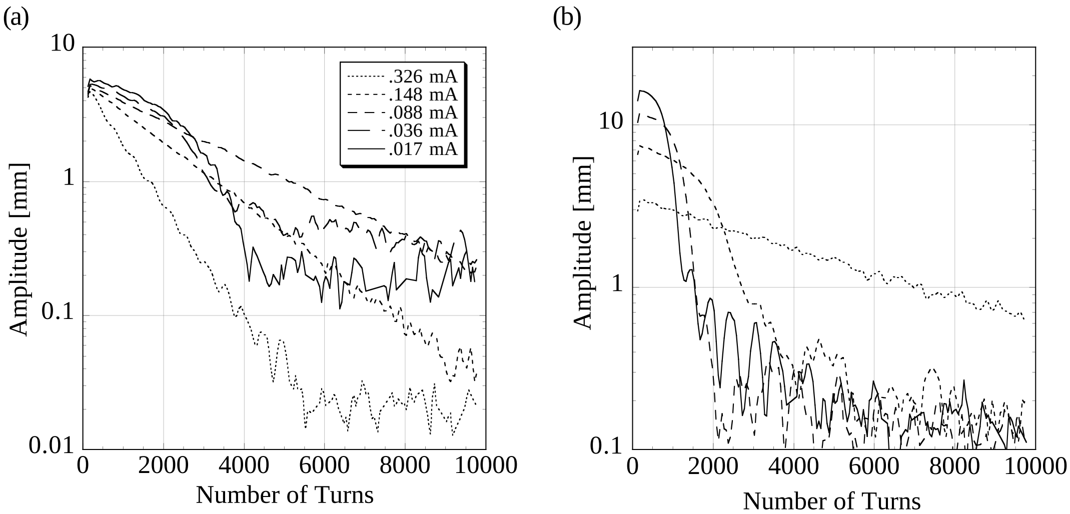

Fig. 3 The vertical oscillation decay. At low current or small initial amplitude, nonlinear filamentation is observed.

Table 1 Head-tail damping rate in the light source operation of TRISTAN MR. The chromaticity was 4.8 for horizontal and 5.9 for vertical.

bunch current	mA	0.46	0.90	1.40
horizontal damping time	ms	8.6	6.6	3.3
vertical damping time	ms	3.80	2.1	1.3

filamentation at 4000 turns is larger than that of the head-tail damping case in Fig. 3(a).

The oscillation decay for different initial oscillation amplitudes and fixedcurrent of 0.03 mA are shown in Figure 3(b). Exponential decay is seen only in the case of the smallest initial amplitude. Nonlinear filamentation appears as the initial amplitude increases. This is because nonlinear effects are stronger at larger transverse offset.

3.3 Head-Tail Damping

When the current is high or the chromaticity is positive and large, the head-tail damping occurs and nonlinear filamentation is suppressed. The damping rate is proportional to the current and chromaticity. In Fig. 4, measured damping rate of the vertical oscillation is plotted as a function of the product of the current and vertical chromaticity under noninterleaved sextupole scheme. The current of the data points ranges from 0.16 mA to 0.6 mA. The bunch length observed with a streak camera was almost the same for all cases, about 13 mm.

Based on this fact, the head-tail damping was intentionally enhanced by making chromaticity high to suppress the coupled bunch instability in the light source operation of TRISTAN MR. The head-tail damping rates measured there are given in Table 1.

4 DISCUSSION

The amplitude-dependent tune shift is one of the outcomes of the lattice nonlinearity. In the case of TRISTAN MR, the main source of the nonlinearity is sextupole magnets. The tune shift was also calculated from the SAD simulation using the same optics as the section 3.1. The tune decay is fitted to

$$\nu(t) = \nu_0 + \Delta\nu \exp(-at)$$

by least square method with ν_0, $\Delta\nu$ and a being fitting parameters. The result is shown in Fig. 5. The tune shift for noninterleaved sextupole scheme was not determined reliably beacause of the 50 Hz modulation and thus not plotted here. The measurement and SAD tracking is in good agreement in the interleaved case.

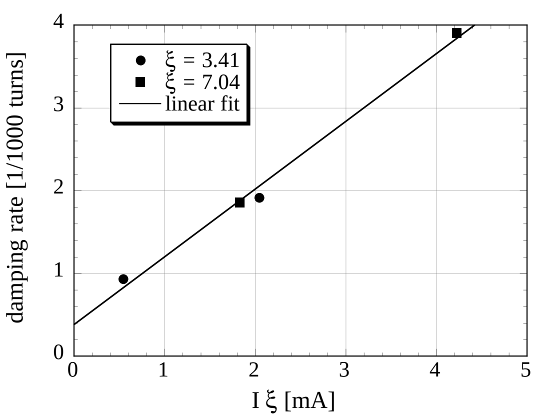

Fig. 4 Damping rate of the vertical oscillation as a function of the product of the current and chromaticity.

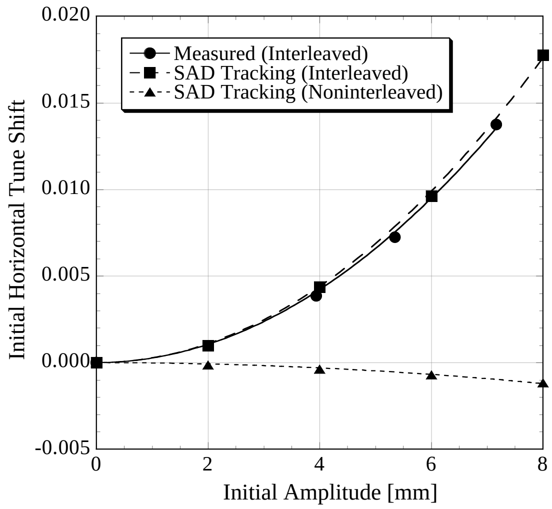

Fig. 5 Measured and numerically simulated tune shift.

In the present analysis, only the oscillation in the same direction as the initial kick was studied. However, as shown in the computer simulations[1,2], the cross term of the amplitude-dependent tune shift is equally important in the nonlinear beam dynamics of circular accelerators. In the further studies, it is planed to measure the tune shift orthogonal to the initial kick.

ACKNOWLEDGEMENT

The authors wish to thank K. Sato, Y. Funakoshi and Y. Kobayashi for helpful discussion and co-operation in the experiment.

REFERENCES

[1] S. Kamada, LEP Note 297 (1981).
[2] J. Lasker, AIP conference proceedings 344 (1995) pp130-159.
[3] J. Gareyte, A. Hilaire, F. Schmidt, IEEE part. Acc. Conf. Chicago (1989) pp1376-1378.
[4] A. W. Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators" (Wiley, New York,1993).
[5] T. Ieiri, K. Nakajima, Y. Yokoya and Y. Mizumachi, Proc. of the 5-th Sympo. on Acc. Sci. and Tech. (1984) pp160-162.
[6] S. Kamada,AIP conference proceedings 344 (1995) pp1-10.
[7] M. Arinaga, K. Mori, H. Ishii, T. Naito and M. Tejima, Proc. of the 9-th Sympo. on Acc. Sci. and Tech. (1993) pp379-381.
[8] K. Oide and H. Koiso, Phys. Rev. E47, 2010 (1993).
[9] http://130.87.74.156/SAD/sad.html