

VERTICAL INSTABILITY WITH TRANSIENT CHARACTERISTICS OBSERVED IN KEK-PF

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Abstract

An optical bunch-by-bunch beam diagnostic system composed of a high-speed light shutter has been developed for the KEK-PF electron storage ring. The system can pick out light emitted by one particular bunch in a bunch train and detect betatron motions of individual bunches independently by detecting spatial oscillation of the picked-out light. Using the system, it is clearly observed that a vertical instability in KEK-PF has a characteristic that betatron tunes and amplitudes of individual bunches depend on their positions in the bunch train.

1 INTRODUCTION

In the KEK-PF electron storage ring, a vertical instability has been observed in a multi-bunch mode. The instability can be suppressed by exciting octupole magnets in routine operation for users, however, the origin of the phenomenon is not perfectly understood yet. A possible cause of the phenomenon seems to be an ion related effect, like the Fast Beam-Ion Instability (FBII)[1]. We have developed a bunch-by-bunch beam diagnostic system which can detect betatron oscillations of individual bunches in a bunch train, and tried to verify the dependence of the frequencies of the betatron oscillations of individual bunches on their positions in the train.

2 BUNCH-BY-BUNCH BEAM DIAGNOSTICS

In order to pick out the synchrotron radiation pulse only from a particular bunch in a bunch train, we have developed a high-speed light shutter that can be opened or closed within 2 ns (corresponding to a bunch spacing in the KEK-PF) [2] [3]. Operation of the shutter is synchronized with a revolution of bunches using an RF signal as a source of a trigger for the shutter. We operate the shutter with a repetition rate of $f_{shutter}=534$ kHz which corresponds to one third of the revolution frequency because of a repetition limit of a high voltage pulser which drives the shutter.

Light through the shutter is focused by a lens to form a image of the beam, and a horizontal edge is set on the focal plane to cut off a half of the image. Intensity of light through the edge is detected by a photomultiplier tube (Hamamatsu Photonics, H6779). Vertical motion of the beam can be detected as amplitude variation of the output signal of the PMT because intensity of the light through the edge varies in response to the movement of the image of the beam on it. The output signal of the PMT is analyzed with a spectrum analyzer (ADVANTEST, R3361D).

Because the light shutter has an extinction ratio of 300 at the most, the contribution of leaked light pulses through the shutter during the close timing is not negligible. Contribution of leaked signal corresponding to all bunches to the spectrum appears on the both sides of harmonics of the revolution frequency. On the other hand, spectral lines corresponding to the selected bunch appear on the both sides of harmonics of the shutter frequency. Therefore we can distinguish the betatron oscillation of the selected bunch from the contribution of the other bunches by detecting the betatron sidebands of a frequency that is non-harmonic of revolution frequency but harmonic of shutter frequency.

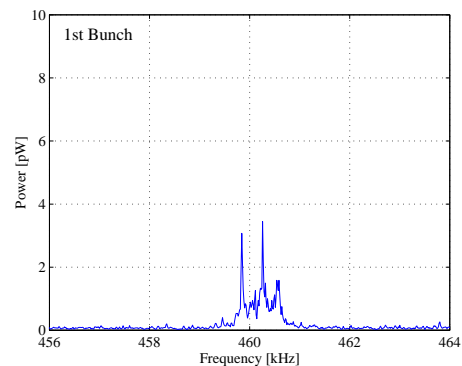


Figure 1: Vertical betatron sideband of the 1st bunch in the bunch train.

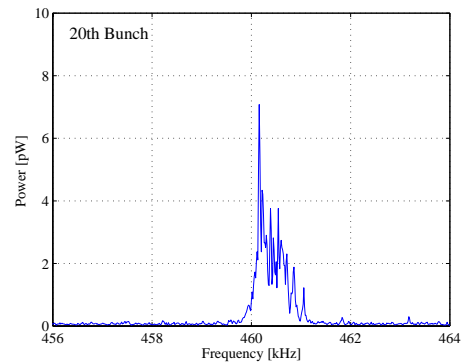


Figure 2: Vertical betatron sideband of the 20th bunch in the bunch train.

3 RESULTS

3.1 Bunch-by-Bunch Detection of Betatron Oscillation

Betatron oscillation of all bunches are detected independently in the multi-bunch mode (successive 278 bunches followed by 34 empty buckets) using the bunch-by-bunch beam diagnostic system. In order to make the observation of the instability clear, we turned off the octupole magnets to avoid the Landau damping effect during the experiment. Figure 1 and 2 show frequency spectra which correspond to the betatron sidebands of the 1st and 20th bunches in the bunch train, respectively. Although the beam currents of these two bunches were much the same, not only these spectral powers but also these frequencies are different as seen in these figures.

Figure 3 shows a vertical betatron tunes of 20 bunches in the head of the train. It is clearly seen that the vertical tune gradually increases along the train.

3.2 Short Bunch Train

The observation of the vertical tunes was performed by changing the length of the bunch train. We formed bunch trains whose total bunch numbers were 50 and 100, but the bunch currents were set to the usual current of 1.6mA. The vertical instability was also observed in those condition. Figure 4 and 5 show the vertical tunes of 20 bunches in the head of the train with 100 bunches and that with 50 bunches, respectively. An increase of the tunes along the train is small compared to the case in 278 bunch train.

We have also tried shorter bunch trains. The instability was not observed if the bunch numbers were smaller than 29 in case that the bunch current of 1.0mA.

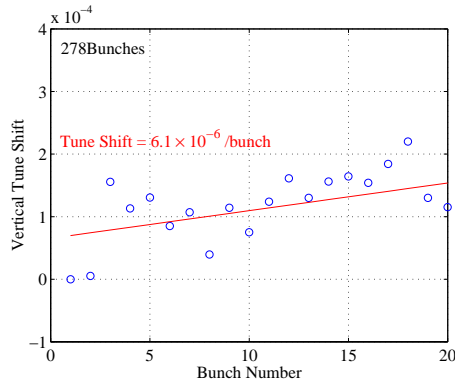


Figure 3: Vertical tunes in the head of 278 bunch train. A line corresponds to the fitting of the experiment.

4 DISCUSSION

4.1 Increase of Tunes

The increase of the tunes seems to be explained by an ion related effect. Because ions at a certain position in the

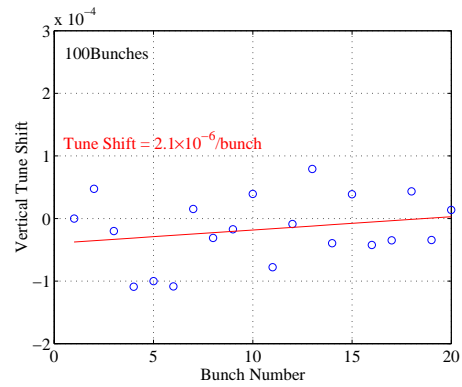


Figure 4: Vertical tunes in the head of 100 bunch train. A line corresponds to the fitting of the experiment.

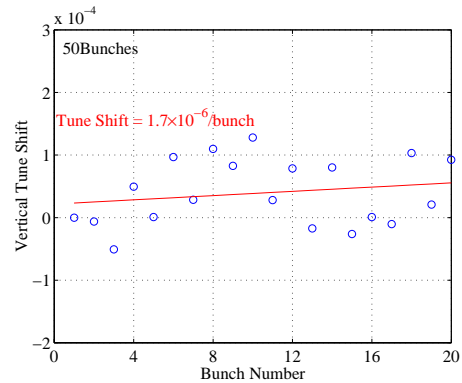


Figure 5: Vertical tunes in the head of 50 bunch train. A line corresponds to the fitting of the experiment.

storage ring are affected by periodic focusing forces corresponding to a configuration of the bunch train, the ion motion can be discussed with a method similar to analysis of the betatron motion in a circular accelerator. Namely, an "ion betatron function β_I " with a period T_{rev} of the revolution time of the beam can be defined as a function of the time lapse τ from passage of the bunch head.

Trapped ions take the "betatron oscillation" around the electron beam with amplitudes proportional to $\sqrt{\beta_I}$. Because β_I is a function of τ , the size of the ion-cloud proportional to $\sqrt{\beta_I}$, or, the density of the ions also change with τ . According to the linear theory[4], the trapped ions can cause tune shifts and the shifts are proportional to the ion density. Therefore, the modulation of the ion density could cause the tune shifts that depends on the position of the train.

The theoretical value of the tune shift along the train $\Delta\nu$ according to the model in which the modulation of the ion density is taking into account is calculated. In the calculation, an ion species is assumed to be CO^+ , and an averaged neutralization factor is assumed to be 3.0×10^{-6} , which is evaluated from another experiment in which an observation of the difference of the tunes in different beam currents was performed. We obtained the $\Delta\nu \approx 6.0 \times 10^{-6}/\text{bunch}$.

That the theoretical value agrees well with the experiment implies that the cause of the instability has some relation to the ion effects.

4.2 FBII in KEK-PF

According to the classical theory for ion-trapping[4], ion like CO^+ cannot be trapped around the beam if the number of bunches in the bunch train is less than 100 in case of the KEK-PF. However, the fast beam ion instability (FBII) can occur even under this condition. Because the tune shift due to the FBII is small in our condition, the fact that increase in the tunes observed in the long bunch train (figure 3) was not observed in the short bunch trains (figure 4 and 5) is explained by the FBII.

According to a theory of the FBII[1], an asymptotic growth rate of the instability is written as follows:

$$\tau^{-1}[\text{1/sec}] \approx 5p[\text{Torr}] \frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2} \omega_\beta}, \quad (1)$$

where p is a residual gas pressure in the ring, N_b the number of the electrons in one bunch, n_b the number of bunches, r_e and r_p the classical radius of the electron and proton, L_{sep} the bunch spacing, γ the Lorentz factor of the beam, σ_x and σ_y horizontal/vertical beam sizes, A the mass number of the trapped ions, and ω_β the betatron wave number ($\approx 1/\beta_y$), respectively. The growth time of the FBII is shown as a function of total bunch numbers in figure 6. In this figure, the gas pressure is assumed to be 60 nPa which is barely equal to the pressure in the KEK-PF, the ion species to be CO^+ , and N_b is settled to the value which corresponds to 1.0mA/bunch. The transverse radiation damping time of the KEK-PF is 7.8ms[5]. If we use (1) as a criterion of growth time although the growth of the FBII is not exponential, the radiation damping time and the growth time balance out each other at the bunch number of ~ 30 . In the experiment the vertical instability was not observed when the bunch train length was less than 29 bunches and the bunch current was 1.0mA. Therefore, the vertical instability observed in the KEK-PF seems to be caused by the FBII.

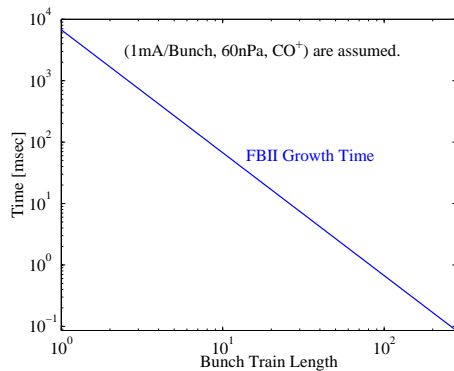


Figure 6: The growth time of the FBII.

5 SUMMARY

In the KEK-PF, a vertical instability has been observed in a multi-bunch mode. A bunch-by-bunch detection system of vertical betatron oscillation has been installed and the dependence of the vertical tunes on the bunch position in the bunch train has been measured. The experiments show that the tunes depend on the position in the bunch train, especially the tunes increase along the head of the train. The phenomenon can be understood as an ion-related effect, in which the ions perform a "betatron oscillation" and the ion density modulates by passing the bunch train.

In case of short bunch trains, variation of the tunes along the train was small. It is supposed that the modulation of the ion density does not occur because almost all of the ions are cleared in the bunch gap (empty buckets).

For shorter bunch train less than 29 bunches, the instability was not observed. The growth time of the FBII is longer than the radiation damping when the number of bunches is less than 30. In this case, the vertical motion is completely suppressed by the radiation damping. A bunch train longer than 30 bunches is excited by the FBII and a longer bunch train with the bunch number more than 100 is affected by the trapped ions whose density varies along the bunch train.

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