Periodic Structure of an Ion-Related Vertical Instability in the KEK Photon Factory Electron Storage Ring

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In the Photon Factory electron storage ring (PF-ring) at the Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), a vertical beam instability has been observed in a multi-bunch condition in which a series of bunches (a bunch train) followed by a series of empty buckets (bunch gaps) are stored in the ring. The instability can be suppressed by exciting octupole magnets in routine operation; however, the origin of the phenomenon has not been perfectly understood yet. The instability depends on the condition of the vacuum in the ring; namely, the instability is enhanced under poor vacuum conditions and becomes weak in good vacuum conditions.

To observe the instability, we have developed an optical bunch-by-bunch beam diagnostic system which is consisted of a high-speed light shutter and an optical betatron oscillation detector[1]. A schematic diagram of the diagnostic system is shown in Fig. 1. A pockels cell (Fastpulse Technology, 1044-FW) is placed between a pair of polarization filters whose polarization angles are perpendicular to each other. The incident light can pass through the shutter while a high voltage pulse is applied to the cell because it rotates the polarization plane. Because the shutter can be opened or closed in a bunch spacing time (2 ns in the PF-ring), it can pick out a light pulse from an individual bunch in a light pulse train. Light through the shutter is focused by a lens system set behind the shutter. Because half of the image is cut off by a horizontal edge, the intensity of the light through the edge varies in response to the vertical motion of the beam. We use a photomultiplier tube (PMT, Hamamatsu Photonics, H2431-50) to measure the intensity. The change in amplitude of the signal selected by the shutter is analyzed with a spectrum analyzer (ADVANTEST, R3361D).

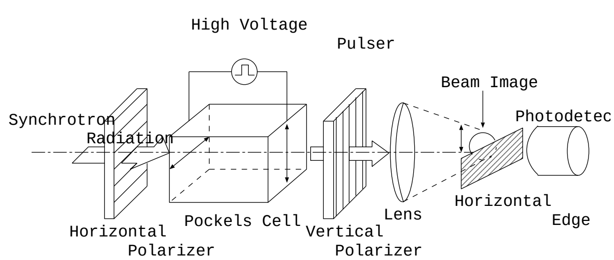

Figure 1: Schematic diagram of the high-speed light shutter and the optical betatron oscillation detector.

With the beam diagnostic system, we have observed betatron oscillations of all bunches due to the instability and analyzed vertical tunes. Figure 2 shows measured tune shifts from the tune of the first bunch as a function of a bunch position in the train. It is clearly seen that the tunes gradually increase along the train in the head and decrease again in the tail as seen in Fig. 2 despite a relatively large error in the tune measurements of around $\pm 0.5 \times 10^{-4}$ which is almost the same as the width of scattering of the tunes in the middle of the train.

In order to explain the phenomenon, we developed a model that shows that density of trapped ions is modulated by passage of the bunch train. Because ions at a certain location in the storage ring are affected by a periodic focusing force with a revolution period t_{rev} of the beam corresponding to a configuration of the bunch train, ion motion can be discussed with a method similar to the theory of the betatron oscillation in circular accelerators. Namely, an "ion betatron function β_i" with the period t_{rev} can be defined as a function of the time lapse τ from passage of the head of the bunch train[2]. Because trapped ions oscillate around the electron beam with amplitudes proportional to $\sqrt{\beta_i}$, the size of an ion-cloud is proportional to $\sqrt{\beta_i}$; and because $\sqrt{\beta_i}$ is a periodic function of τ, density of the ions is a function of τ with a period of t_{rev}. According to the "classical" theory of the ion trapping [3, 4], the trapped ions cause tune shifts proportional to their density. Therefore, the variation of the ion density could cause the tune shifts of bunches that depend on the positions in the train. We calculated the modulation of the ion density along the bunch train and the tune shifts along the train due to the modulation. Figure 2 also shows the theoretical values. In the calculation, the ion species of CO^+, which is a main component of the residual gas ion species in the PF-ring, and a neutralization factor which is consistent with the measured value are assumed. A pattern of the calculated tune shift wiggles in unison with the modulation of the ion density due to the oscillation of the ions, as seen in Fig. 2. The pattern rapidly rise in the head of the train and falls in the tail. This characteristic is also clearly seen in the experimental results, as seen in the figure. To further quantify the phenomenon, we calculated the averaged tune shifts along 20 bunches both in the head and in the tail. Agreement between the experimental values and the theoretical predictions was quite good.

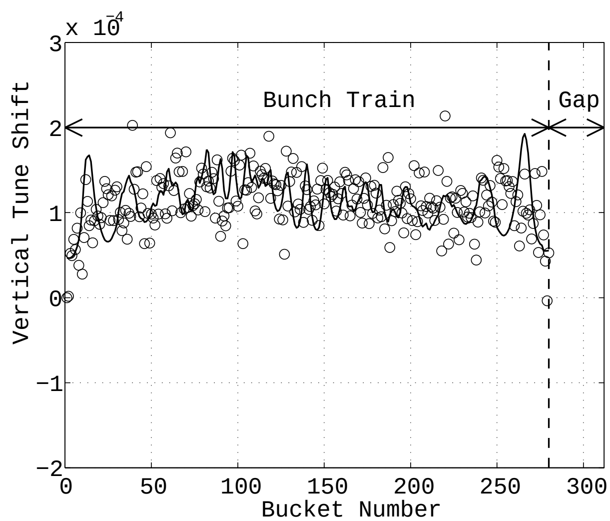

Figure 2: The change of the tunes along the 280 bunch train. Circles and a curve correspond to the experimental results and the theoretical values, respectively.

References

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