The Vertical Instability in a Positron Bunched Beam

M. Izawa, Y. Sato, and T. Toyomasu*

Photon Factory, National Laboratory for High Energy Physics, 1-1 Oho, Tsukuba, Ibaraki 305, Japan

(Received 3 March 1995)

The results of experiments on the vertical instability observed in both positron and electron multibunch accumulations at the Photon Factory storage ring are presented. The betatron sidebands, which indicate a vertical instability, appear at different frequency regions depending on the polarities of the beam. The cause of these instabilities cannot be attributed to the well-known transverse wakefields induced by beam-wall interactions. We propose that these vertical instabilities are induced by electrons in a positron bunched beam, and by trapped ions in an electron bunched beam.

PACS numbers: 29.20.Dh, 29.27.Bd

The Photon Factory storage ring (PF ring) [1] is a 2.5 GeV positron (electron) storage ring dedicated to synchrotron radiation experiments. Operation of this facility started as an electron storage ring in 1982. Since 1988, multibunch positron storage [2] has become the regular operation mode, although the storage of electrons is also available. The machine parameters are listed in Table I.

The vertical instability observed in a positron multibunch beam [3–5] has been among the very important problems, since it increases the vertical beam size and is hard to suppress. The features of the instability are (1) coupled oscillation, (2) a low threshold current ($I_{\rm th}$: 15–20 mA) , (3) broad distribution of the betatron sidebands, and (4) that it is not suppressed by filling positrons partially in rf buckets (referred to as partial filling hereafter).

On the other hand, a vertical instability was observed in an electron multibunch beam, which appears to be a typical coupled-bunch instability. The characteristics of this instability are (1) coupled oscillation, (2) a low threshold current ($I_{\rm th}$: 30–50 mA), (3) narrow distribution of the betatron sidebands, and (4) that it is suppressed by partial filling operation. In addition, the betatron sidebands of these instabilities appear at different frequency regions depending on the two polarities of the beam.

Comparing the result of experiments concerning these vertical instabilities, we show in this paper that the causes of these instabilities cannot be attributed to transverse wakefields induced by beam-wall interactions. Also, we suggest that the probable sources of these instabilities are electrons in the case of a positron beam and trapped ions in the case of an electron beam. Ion trapping [6–8] is a well-known phenomenon in electron storage rings, and is also observed in the PF ring [9–12]. On the other hand, electron trapping [13,14] has been considered to be difficult to take place in a positron bunched beam because of the small electron mass. However, we think that we should investigate the possibility of the interaction between electrons and a positron bunched beam.

These vertical instabilities appear to be very similar to those of the well-known coupled-bunch instability due to transverse wakefields. A phenomenological analysis which very well explains the distribution of observed betatron sideband spectra is also presented.

Figure 1 shows the distribution of betatron sidebands which indicate a vertical instability in electron storage. The measurement was carried out at a stored current of 354 mA with electrons filled in all of the rf buckets (referred to as uniform filling hereafter). In the figure, the amplitude of all betatron sidebands seen in the 0.99 to 1.51 GHz frequency range is plotted. The upper side of the figure shows the distribution of betatron sidebands, expressed as $nf_r - f_\beta$, where f_r is the revolution frequency, $f_\beta = \delta_{\nu_\beta} f_r$ (δ_{ν_β} the fractional part of vertical tune), and $n = 618, 619, \ldots, 942$. The lower side shows the sideband expressed as $nf_r + f_\beta$, where the amplitude is shown with a negative sign in order to see them clearly. As shown in the figure, the main sideband peak appears at $n = 625{,}937$ ($= 2h + 1, 3h + 1$, h the harmonic number) for the upper side group and at $n = 623{,}935$ ($= 2h - 1, 3h - 1$) for the lower side. The spectra seem to show a typical coupled-bunch instability due to a narrow band (high Q) resonator. However, this is not the case. First, under the same magnet and rf operating conditions of the ring, the threshold of this instability (about 50 mA) is comparable to that (40 mA) due to a TM111-like higher order mode (HOM) in a cavity used in the ring [15–17]. The HOM has a Q value of 14 000 and a vertical coupling impedance of 9.5 MΩ/m. There is no cavity working in the ring having such a HOM at the corresponding frequency. Moreover, it seems to be

TABLE I. Basic machine parameters of the PF ring.

E	Beam energy	2.5 GeV
C	Circumference	187 m
ϵ_x	Horizontal emittance	130 nm rad
ν_y	Vertical tune	3.31
σ_t	Bunch length	50 ps
τ_ϵ	Longitudinal damping time	3.9 ms
$f_{\rm rf}$	rf frequency	500.1 MHz
h	Harmonic number	312
$P_{\rm ave}$	Average vacuum pressure at 300 mA	$\sim 3 \times 10^{-10}$ Torr

0031-9007/95/74(25)/5044(4)$06.00

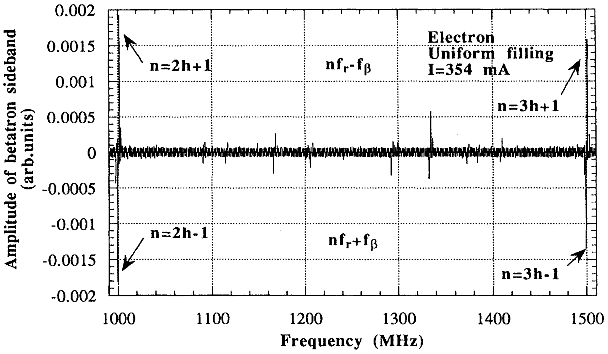

FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

difficult to attribute such a high Q and high impedance to other beam duct components [18,19]. Second, this instability is completely suppressed by a partial filling operation (250 successive buckets followed by 62 vacant buckets) under almost the same condition as that in Fig. 1. This fact shows that the cause of this instability is not a high Q resonator. Third, the spectra shown in Fig. 1 are not observed during positron storage, as shown in Fig. 2.

The partial filling operation is a well-known effective way to suppress the instability due to ion trapping [11,20]. We therefore tried the effect of the clearing electrode by giving an electrostatic potential to 88 position monitors (button type, 29 mm in diameter) attached to the beam duct around the ring [20]. An electrostatic potential was given to these button plates located immediately at the upper and lower sides of the beam. The instability was completely suppressed when the voltage was increased to ±2.5 kV at a low stored current.

From the above-mentioned experimental results, we concluded that the vertical instability in question is due to trapped ions.

As shown in Fig. 2, the distribution of betatron sidebands in positron storage is remarkably different from that in electron storage. The spectra again show a coupled oscillation; however, unlike in an electron beam, the bandwidth of the sideband distribution is very wide. The wide bandwidth of betatron sidebands is seen even at the threshold of the instability. In the following, we show that this instability cannot be attributed to a coupled-bunch instability, due to the transverse wakefield induced by the beam-wall interaction.

We first checked the thresholds of the head-tail instability and the vertical coupled-bunch instability due to a TM111-like HOM in an accelerating cavity under the same magnet and rf operating conditions for both electron and positron storage. The thresholds of the head-tail instability were measured under single-bunch operation at a stored current of 37 mA. By decreasing the vertical chromaticity [21–24], the onset of the head-tail instability was compared. The result was simple. There was no difference in the vertical chromaticity, which introduces the instability for both electron and positron beams. As for the thresholds of the coupled-bunch instability due to a TM111-like HOM, the threshold was 30% higher in electron storage than in positron storage. However, the difference can be well understood by taking into account the tune spread caused by a nonlinear field around trapped ions in an electron beam [3]. Therefore, there is no substantial difference between electron and positron storage as far as the instability induced by the short and long range beam-wall interactions is concerned. Comparing Figs. 1 and 2, and also mentioning the very low threshold, we think that there is no reason to explain that the vertical instability seen in a positron beam does not appear in an electron beam if it is caused by the beam-wall interaction. In other words, it is difficult to determine the transverse impedance which affects only the positron beam.

Second, there is another experimental fact which suggests that the cause is not the well-known transverse impedance. Figure 2 shows a regular and remarkable coupled oscillation. However, the sideband distribution changes drastically, as shown in Fig. 3, where the data were taken several hours after the time when the stored

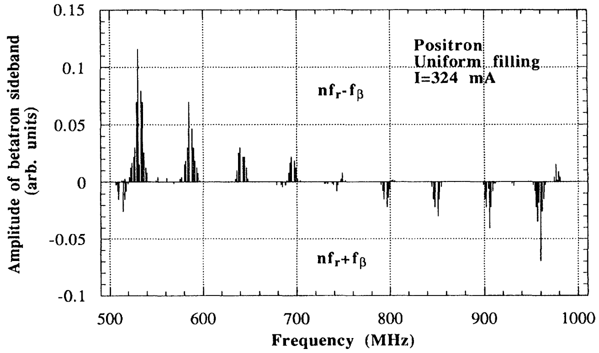

FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

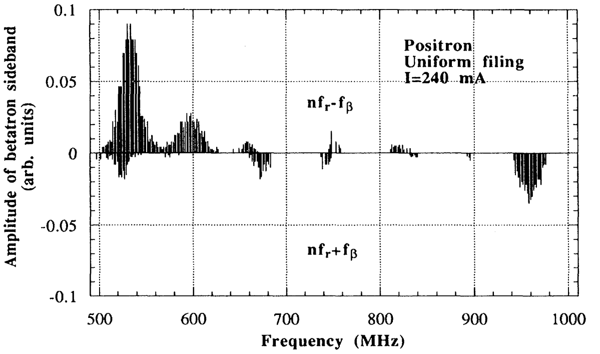

FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

current became 240 mA under the same conditions as in Fig. 2. The change in the sideband distribution is difficult to explain if the instability is caused by the well-known transverse impedance.

Third, as was done for the electron beam, we also tested the clearing electrode effect by supplying an electrostatic potential to the position monitors. The instability was not completely suppressed, unlike the case in electron storage. The vertical beam size, however, was reduced by a factor of about 15%.

The experimental result only gives a suggestion that the cause of the instability would not be the wakefields induced by a beam-wall interaction. However, the positron beam does not strongly interact with ions. This has been shown by the fact that the partial filling operation is not effective for this instability. This instability is also not affected by the operation of distributed ion pumps (DIP) or sputter ion pumps (SIP) working in the ring [25]. Therefore we propose that the cause of the instability is electrons, which represent the only source that has any possibility to interact with the positron beam. In addition, it is well known that a large number of low energy secondary electrons are supplied by a photoemission process.

We present here a phenomenological analysis that explains the remarkable distributions of the betatron sidebands seen in electron and positron accumulations.

Based on the analogy of a coupled-bunch instability, we assume that the equation of motion for M equally spaced, equally populated bunches can be described using a macroparticle model. We can then obtain the complex frequency shift $\Omega^{(\mu)}$ as [26]

$$\Omega^{(\mu)} - \omega_\beta = A \sum_{p=1}^{l} F(-pD) \exp\{i2p\pi(\mu + \nu_\beta)/M\}, \tag{1}$$

where A is a positive constant, F a trial function as an interaction between bunches, which affects only the next l bunches, μ the mode number, ν_β the betatron tune, and D the bunch spacing. In the case of the usual coupled-bunch instability, F is the transverse wake function and A is expressed as $Nr_0c^2/2\gamma C\omega_\beta$, where N is a number of positrons in a bunch, r_0 the classical electron radius, c the speed of light, γ the Lorentz factor, and C the circumference. We assume here that F has a similar character to the usual transverse wake function and is negative while affecting the next bunches. The oscillation is then unstable when $\text{Im}(\Omega)$ is negative. The numerical results of Eq. (1) for $AF = -1$ are presented in Fig. 4, where the unstable (upper side) and damped (lower side) mode numbers are shown for the case of $l = 8$. These results agree qualitatively very well with the experimental results shown in Fig. 2. Figure 5 shows the distribution of the betatron sidebands in the case of an electron beam, where data were taken at a stored current of 354 mA with uniform filling under the same conditions as given in Fig. 1, except that the exciting current of the octupole magnets [27] was lowered, resulting in a lower Landau damping rate due to the tune spread. The figure agrees qualitatively with Fig. 6, where the unstable and damped mode numbers are calculated for the case of $l = 75$. We therefore propose the existence of a semi-long-range force which affects only the next several bunches in a positron beam and the next several tens of bunches in an electron beam.

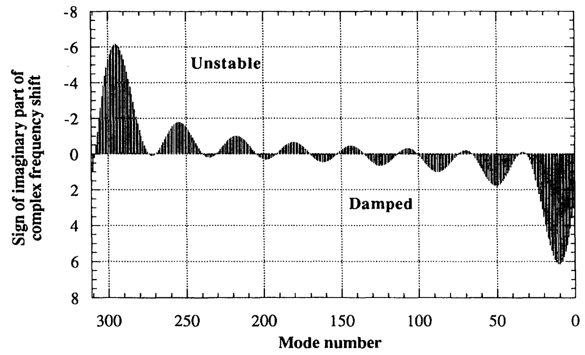

FIG. 4. Numerical results of Eq. (1) for $l = 8$.

According to the coasting beam approximation [9,28,29] for ion trapping, the most dangerous mode number is 4 in the PF ring. The betatron sideband of the vertical instability due to trapped ions appears at a frequency of $(4 - \nu_\beta)f_r$. Therefore the sideband spectra shown in Fig. 1 may be considered to correspond to this frequency. As shown in Fig. 5, however, the unstable mode is not only the above-mentioned mode, but is also distributed over a somewhat wide range. Therefore we suppose that the vertical instability seen in an electron beam (Figs. 1 and 5) is a coupled-bunch instability caused by a low frequency [around $(4 - \nu_\beta)f_r$] impedance (in a wide sense, in the frequency domain) due to trapped ions.

According to ion trapping theory, less than four equally spaced bunches (77 vacant buckets between each bunch)

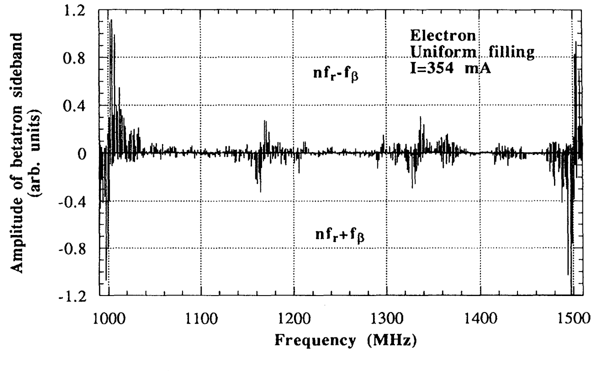

FIG. 5. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling. The exciting current of the octupole magnets is lowered compared to Fig. 1.

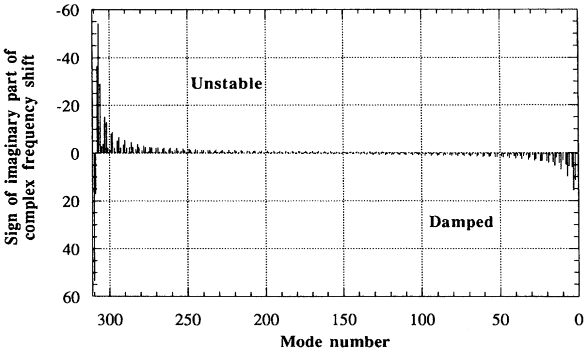

FIG. 6. Numerical results of Eq. (1) for $l = 75$.

cannot capture ions in an electron beam in the case of the PF ring. In the case of a positron beam, it has been experimentally confirmed that 26 equally spaced bunch operation (11 vacant buckets between each bunch) can greatly suppress the vertical instability [4] and that more than 52 equally spaced bunch operation is not effective for suppressing the instability. The range of force that we propose for electron and positron beams seems to be closely related to the number of vacant buckets. We think that the difference in the range of the force is due to the difference in the movability between trapped ions and electrons.

At last, we note here that the vertical instability observed in a positron beam is also observed even in a small bunch train (for example, 37 successive bunches followed by 275 vacant buckets). We point out that the range of force mentioned above does not contradict the experimental results and that the instability must have a very large growth rate.

The authors would like to thank Dr. M. Kato and Dr. Y. Kobayashi for their cooperation in operating the ring. The authors would like to thank Professor Y. Kamiya for considerably helpful discussions and advice. The authors would like to thank A. Higuchi for his operation of the computer-controlled instruments. The authors would like to thank Professor H. Kobayakawa and Professor M. Kihara for their special encouragement. We also thank the staff of the light source for their operation of many instruments and for their helpful discussions.

---

*Accelerator Division.

[1] Photon Factory Activity Reports No. 1–No. 11.
[2] K. Huke, Rev. Sci. Instrum. **60**, 1382 (1989).
[3] Photon Factory Activity Report No. 7, 1989, p. R-8.
[4] Photon Factory Activity Report No. 8, 1990, p. R-5.
[5] H. Kobayakawa, Rev. Sci. Instrum. **63**, 509 (1992).
[6] Y. Baconnier and G. Brianti CERN Report No. CERN/SPS/80-2 (DI), 1980.
[7] M.E. Biagini, S. Guiducci, M. Preger, M. Serio, and S. Tazzari, in *Proceedings of the 11th International Conference on High Energy Accelerators* (CERN, Geneva, Switzerland, 1980), p. 687.
[8] G. Brianti, CERN Report No. CERN 84-15, 1984, p. 369.
[9] Y. Kamiya, M. Izawa, T. Katsura, M. Kihara, H. Kobayakawa, and S. Shibata, in *Proceedings of the 5th Symposium on Accelerator Science and Technology, Tuskuba, 1984* (KEK, 1984), p. 292.
[10] H. Kobayakawa, K. Fuke, M. Izawa, Y. Kamiya, M. Kihara, M. Kobayashi, and S. Sakanaka, Nucl. Instrum. Methods Phys. Res., Sect. A **248**, 565 (1986).
[11] S. Sakanaka, M. Izawa, H. Kobayakawa, and K. Kobayashi, Nucl. Instrum. Methods Phys. Res., Sect. A **256**, 184 (1987).
[12] S. Sakanaka, M. Izawa, H. Kobayakawa, and M. Kobayashi, Jpn. J. Appl. Phys. **27**, 1031 (1988).
[13] W. Schnell, IEEE Trans. Nucl. Sci. **22**, 1358 (1975).
[14] O. Grobner, in *Proceedings of the International Conference on High Energy Accelerators, Protvino, 1977*, Vol. 2, p. 277.
[15] Y. Yamazaki, K. Takata, and S. Tokumoto, KEK Report No. KEK 80-8, 1980.
[16] H. Kobayakawa, Y. Yamazaki, Y. Kamiya, and M. Kihara, Jpn. J. Appl. Phys. **25**, 864 (1986).
[17] M. Izawa, H. Kobayakawa, S. Sakanaka, and S. Tokumoto KEK Report No. KEK Internal 88-7, 1988.
[18] M. Izawa, T. Kiuchi, S. Tokumoto, Y. Hori, S. Sakanaka, M. Kobayashi, and H. Kobayakawa, Rev. Sci. Instrum. **63**, 363 (1992).
[19] T. Kiuchi, M. Izawa, S. Tokumoto, Y. Hori, S. Sakanaka, M. Kobayashi, and H. Kobayakawa, KEK Report No. KEK Report 92-4, 1992.
[20] Photon Factory Activity Report No. 1983/84, 1984, p. IV-3.
[21] Y. Kamiya, M. Katoh, and I. Honjo, in *Proceedings of the 1987 IEEE Particle Accelerator Conference* (IEEE, New York, 1987), p. 1310.
[22] Y. Kobayashi and Y. Kamiya, Rev. Sci. Instrum. **63**, 1726 (1991).
[23] Photon Factory Activity Report No. 9, 1991, p. R-13.
[24] Photon Factory Activity Report No. 10, 1992, p. R-9.
[25] M.G. Billing, M. Giannella, R.M. Littauer, and G.R. Rouse, in *Proceedings of the 1989 IEEE Particle Accelerator Conference* (IEEE, New York, 1989) Vol. 2, p. 1163.
[26] A.W. Chao, in *Physics of Collective Beam Instabilities in High Energy Accelerators*, Wiley Series in Beam Physics and Accelerator Technology, edited by M. Month (John Wiley & Sons, New York, 1993), p. 208.
[27] Photon Factory Activity Report No. 7, 1989, p. R-10.
[28] E. Keil and B. Zotter, CERN Report No. CERN-ISR-TH/71-58, 1971.
[29] Y. Baconnier, CERN Report NO. CERN 85-19, 1985, p. 267.