ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK050

THE REPORT OF MACHINE STUDIES RELATED TO THE VERTICAL BEAM SIZE BLOW-UP IN SuperKEKB LER*

S. Terui†, T. Ishibashi, K. Ohmi, Y. Funakoshi, H. Fukuma, R. Ueki, Y. Ohnishi, M. Tobiyama
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
T. Nakamura, High Energy Accelerator Research Organization (KEK) J-PARC Center, Tokai, Japan

Abstract

In the Low Energy Ring (LER) for positrons in the SuperKEKB, a vertical beam size blow-up was observed when the bunch current was approximately 1 mA. If a beam size blow-up occurs, the design luminosity cannot be achieved. Therefore, beam size blow-ups must be prevented. According to calculations, the bunch current threshold of the Transverse Mode Coupling instability (TMCI) is 2 mA or more, and the observed value is 50% or smaller. Ordinary TMCI cannot explain this vertical beam size blow-up. This paper shows that the cause of the vertical beam size blow-up can be determined by analyzing factors such as beam oscillation. The study results showed that the vertical beam size blow-up in the LER was caused by a -1 mode instability.

INTRODUCTION

SuperKEKB is a high-luminosity electron-positron collider with asymmetric energies of 7 GeV (electron, High Energy Ring: HER) and 4 GeV (positron, Low Energy Ring: LER) [1]. SuperKEKB adopts a nanobeam scheme in which the vertical beta function ($\beta_y{}^*$) at the collision point is squeezed to the limit. The design value of $\beta_y{}^*$ in the LER is 0.27 mm [2]. The minimum value of $\beta_y{}^*$= 0.8 mm was achieved in 2022. In the 2020c run (October 19, 2020–December 18, 2020), a vertical beam size blow-up was observed when the bunch current was increased. The vertical beam size blow-up subsided when the vertical collimator gap was widened, even under the same bunch current conditions [3]. This observation established that the instability causing the vertical beam size blow-up is related to the wake generated by the vertical collimator. The impedance of the collimator was calculated using GdfidL [4], assuming a bunch length of 6 mm. The following measurements were performed at $\beta_y{}^*$=1 mm in both the LER and HER, under the condition that the sum of the vertical beta function at the collimator location multiplied by the kick factor of the vertical collimator in the LER is approximately 31 × 10^{35} V/C, with fewer bunches (30 - 393) than the number of bunches under normal physics experiments (about 1600) to reduce the effect of multi-bunch instability and the synchrotron tune (ν_s) in the LER is 0.0227.

VERTICAL BEAM SIZE BLOW-UP IN THE LER DURING SINGLE-BEAM CONDITION

The beam sizes were measured using an X-ray beam size monitor [5]. Figure 1 shows the bunch current on the horizontal axis and vertical emittance on the vertical axis. The orange plots were measured with nominal settings of the Bunch-by-Bunch Feedback system (BBF) [6], which are set the same way as in normal physics experiments. The setting of the BBF for vertical oscillation during normal physics experiments is intended to dump the frequency of the 0 mode (vertical betatron tune: ν_y). The points circled by the black dashed line in Fig. 1 indicate that the vertical beam size blow-up occurs when the bunch current is about 0.9 mA or higher. The BBF and vertical beam size blow-up relationship will be explained later.

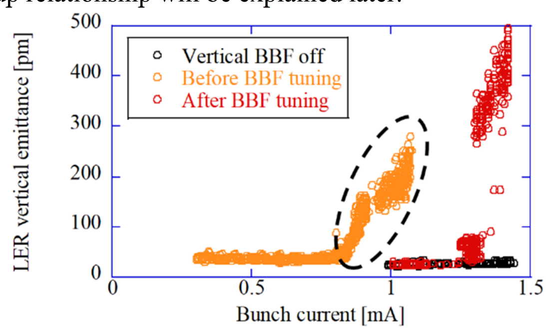

Figure 1: The LER vertical emittance before and after BBF tuning and BBF off versus bunch current.

To measure the tune, a pilot bunch is excited at varying frequencies near the betatron tune.The tune shift was calculated using PyHEADTAIL [7] and the Fast Fourier Transform (FFT) analysis of the vertical motion in the LER was conducted using the Bunch Oscillation Recorder (BOR) [8], as shown in Fig. 2. The orange and light blue dashed lines in Fig. 2 show the frequencies of the 0 mode and -1 mode ($\nu_y - \nu_s$), respectively, with the bunch current on the horizontal axis. ν_y at a bunch current of 0 mA is denoted as ν_{y0}. ν_{y0} is 0.5977 during the measurement in Fig. 2.

The measurement results showed different spectra in the oscillation of the pilot bunch and the non-pilot bunches. The FFT analysis of the pilot bunch revealed two high peaks. These two peaks, corresponding to the 0 mode in red and the -1 mode in blue, are plotted in Fig. 2. The tune shift of the measured value (red line) differs from the calculated value (orange dashed line) by approximately 20% in the slope. This difference may be due to an impedance source not yet included in the calculations.

The results of the FFT analysis for the non-pilot bunches showed no peaks at a low bunch current and only one high peak at a high bunch current. The frequency of the single peak point at the high bunch current for the non-pilot bunches is plotted in black in Fig. 2. This peak was found to have nearly the same frequency as that of the -1 mode for the pilot bunch. At low bunch currents, the peak of the

† sterui@mail.kek.jp

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK050

-1 mode for the pilot bunch cannot be measured. Therefore, in the region of low bunch currents, the regression curves of measured values (blue line) do not match simulation results (light blue dashed line).

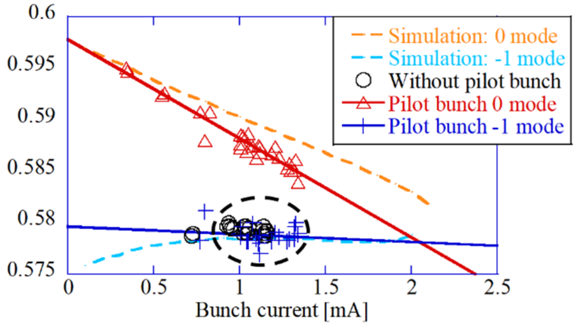

Figure 2: FFT peaks of the LER vertical oscillation versus the bunch current.

The measurements circled by the black dashed lines in Figs. 1 and 2 were taken simultaneously. A single peak for the non-pilot bunches in Fig. 2 was observed around the time when the vertical beam size blow-up started. Interestingly, Fig. 2 shows that Transverse Mode Coupling Instability (TMCI) theory [9] predicts that the vertical beam size blow-up would occur at a bunch current of over 2 mA (the point where the blue and red lines cross), but our experiment showed that it occurred at a bunch current of approximately 0.9 mA.

On reading reference [10], we thought if there was a relationship between the vertical beam size blow-up and BBF. The BBF parameters (number of taps and phases) were changed during our study, and measurements were per-formed.

Figure 1 also plots the beam size when the BBF is tuned to not enhance the oscillation of the -1 mode as much as possible (hereafter referred to as "BBF tuning") and when the BBF is turned off (BBF off). The bunch current threshold of the vertical beam size blow-up was found to be higher with BBF off (black) or after BBF tuning (red) than before BBF tuning (orange). By the way, the number of bunches cannot be increased due to multi-bunch instability with BBF off.

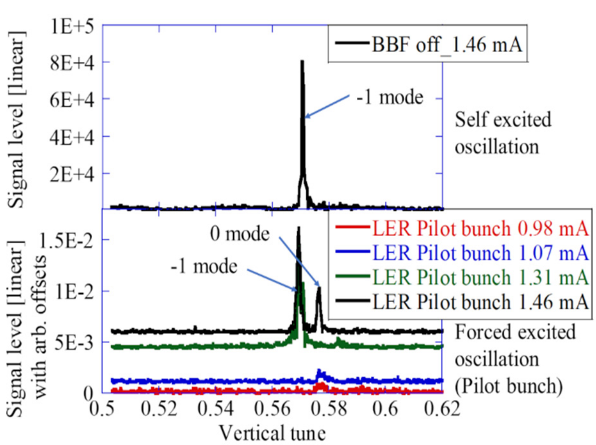

Figure 3: Results of the FFT analysis of the vertical motion in the LER.

Next, the growth rate of the dipole oscillation was measured with the BBF off. Figure 3 shows the results of the FFT analysis of the vertical motion in the LER for the pilot bunch (lower plot of Fig. 3) and the non-pilot bunches (upper plot of Fig. 3) when the growth rate was measured. We found that even with the BBF off, there was a high peak corresponding to the -1 mode. ν_{y0} is 0.5900 during the measurements in Fig. 3.

Figure 4 shows three bunches each with time on the horizontal axis and vertical amplitudes on the vertical axis. There are bunches with small and large amplitudes. The independent oscillation of other bunches indicates that it is a single-bunch instability. It can also be seen that some bunches grow and then dampen after the oscillations have grown.

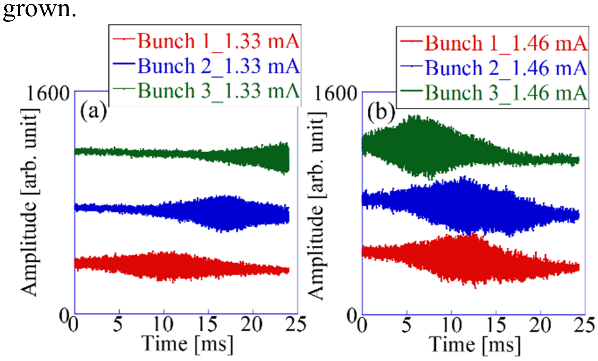

Figure 4: Vertical oscillations in the LER at a bunch current of (a) 1.33 mA and (b) 1.46 mA during growth rate measurement.

During normal physics experiments in the SuperKEKB LER, the accelerator is operated at a chromaticity of about 1.5 units in both planes. Figure 5 shows the growth rate of head-tail instability by chromaticity as a dashed orange line. The growth rate is obtained by calculating the eigenvalues and eigenmodes of a single-bunch oscillation [11]. The black circles in Fig. 5 represent the measurement points. Figure 5 shows that the measured and simulated results exhibit similar trends.

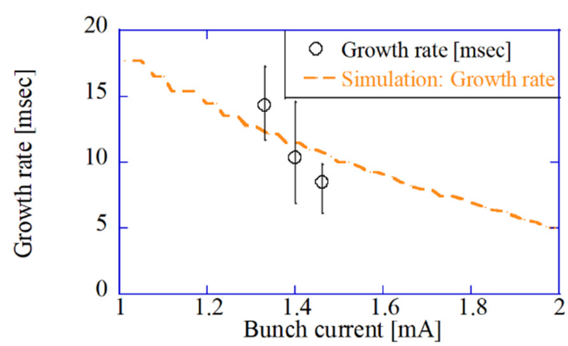

Figure 5: Measured and simulated results of growth rate.

VERTICAL BEAM SIZE BLOW-UP IN THE LER DURING COLLISION CONDITION

We wondered whether the beam-beam effect might mitigate the vertical oscillation in the LER during the collision condition. The following measurements were performed after the BBF tuning.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK050

The lower plots of Figs. 6(a) and (b) show the results of the FFT analysis of the vertical motion in the LER for the non-pilot bunches during the collision and single-beam conditions. The maximum bunch current is 1.43 mA in the LER and 0.97 mA in the HER for this study. The results of the FFT analysis of the vertical motion in the HER are also plotted in the upper plot of Fig. 6(a) under the collision condition. The HER data are included in Fig. 6(a) because the vertical tune in the HER (dashed black line) affects the results of the FFT analysis of the vertical motion in the LER in the collision condition (the lower plot of Fig. 6(a)).

In the upper plot of Fig. 6(b), the results of the FFT analysis of the vertical motion for the pilot bunch in the LER are plotted together for the 0 and -1 modes oscillations and can be distinguished. The frequency of the -1 mode for the non-pilot bunches are the same as the frequency of the -1 mode for the pilot bunches. Comparing the blue circles in the lower plots of Fig. 6(a) and (b), the signal peaks for the single-beam condition are higher than any other peak in the collision condition. The blue circle is the point where the tune shifted due to high bunch current (about 1.4 mA). From these measurements, it can be inferred that the beam-beam effect mitigates the oscillation in the vertical motion in the LER. ν_{y0} is 0.5890 during the measurement in Fig 6.

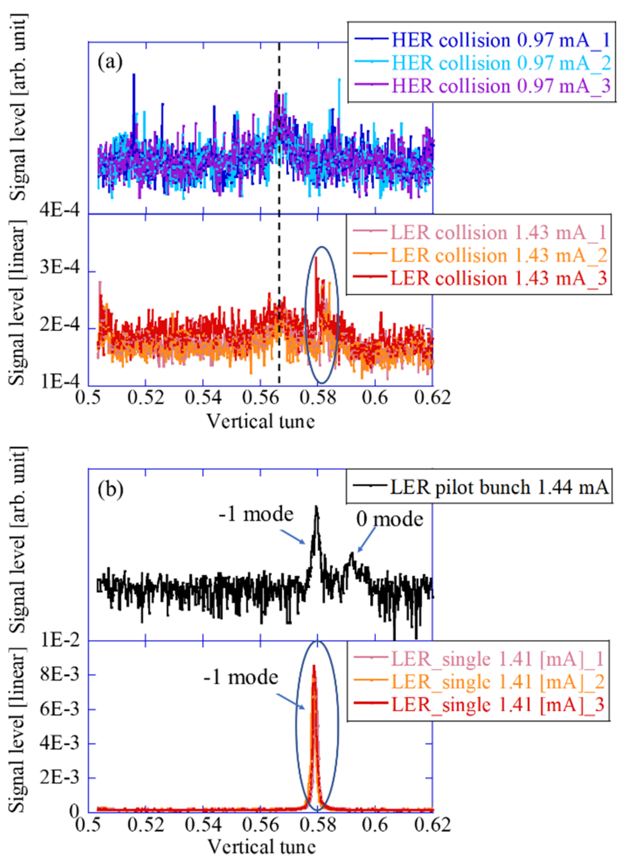

Figure 6: Results of the FFT analysis of the vertical motion during (a) the collision and (b) the single-beam conditions.

Figure 7 shows (a) the specific luminosity and (b) the vertical emittance during the high bunch current collision. Figure 7(b) shows that after BBF tuning, vertical emittance blow-up in the LER is less likely to occur even under high bunch current conditions. For this reason, after BBF tuning, it was possible to perform the collision study at a higher bunch current, which was not possible before BBF tuning, as shown in Fig. 7(a).

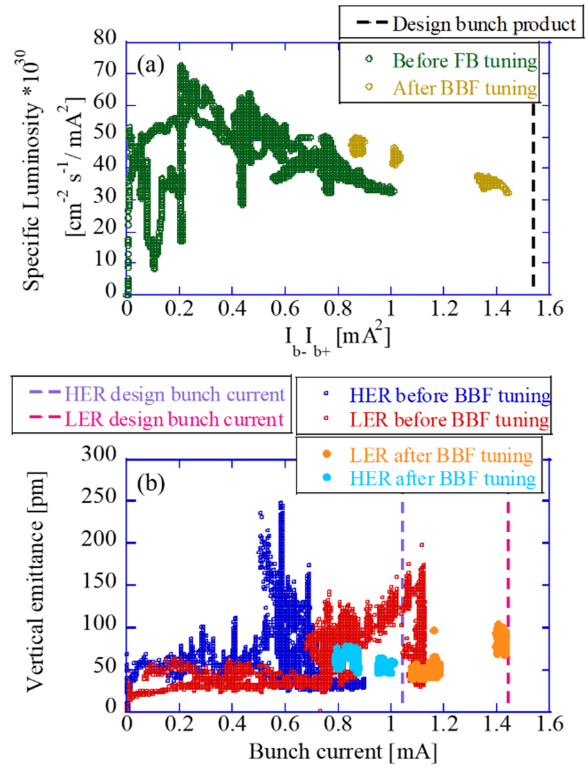

Figure 7: (a) Specific luminosity (b) vertical emittance before and after BBF tuning during high bunch current collision study.

CONCLUSION AND FUTURE WORK

The conclusions of the main measurements are as follows:

- The vertical beam size blow-up in the LER during the single-beam condition occurred when the bunch current was higher than approximately 0.9 mA and was attributed to oscillations caused by the -1 mode.
- It was found that the threshold of the beam size blow-up could be increased by BBF tuning such that the oscillation of the -1 mode is not enhanced, as much as possible. After BBF tuning, the collision could be performed at the designed bunch current for the first time.
- From the collision and single-beam condition measurements, it could be inferred that the beam-beam effect mitigates the vertical oscillation in the LER caused by the -1 mode.

Future studies will determine why the oscillation caused by the -1 mode is larger than that caused by the 0 mode when the bunch current increases.

REFERENCES

[1] Y. Ohnishi *et al.*, "Accelerator design at SuperKEK," *Progress of Theoretical and Experimental Physics*, vol. 2013, no. 3, p. 03A011, 2013. doi:10.1093/ptep/pts083

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK050

[2] Y. Ohnishi *et al.*, "SuperKEKB operation using crab waist collision scheme," *Eur. Phys. J. Plus*, vol. 136: p. 1023, 2021. doi:10.1140/epjp/s13360-021-01979-8

[3] S. Terui *et al.*, "Development of Low-Z Collimator for SuperKEKB," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3537-3540. doi:10.18429/JACoW-IPAC2021-WEPAB358

[4] The GDFIDL Electromagnetic Field Simulator, http://www.gdfidl.de

[5] M. Tobiyama, "Beam instrumentation and bunch feedback systems," *the 21th KEKB Accelerator Review Committee (2016)*, June 13-15, 2016. https://www-kekb.kek.jp/MAC/2016/Report/Tobiyama.pdf

[6] PyHEADTAIL code repository, https://github.com/PyCOMPLETE/

[7] M. Tobiyama and J. W. Flanagan, "Development of Bunch Current and Oscillation Recorder for SuperKEKB Accelerator," in *Proc. IBIC'12*, Tsukuba, Japan, Oct. 2012, paper MOPA36, pp. 138-142.

[8] A. Chao, "Transverse mode coupling instability (TMCI)", *Handbook of Accelerator Physics and Engineering*, 3rd Printing (2009).

[9] M. Tobiyama and K. Ohmi, "Study of Beam Size Blowup due to Transverse Bunch Feed-back Noise on e^+e^- Collider," in *Proc. DIPAC'11*, Hamburg, Germany, May 2011, paper MOPD73, pp. 212-214.

[10] J. W. Flanagan *et al.*, "X-ray Monitor Based on Coded-aperture Imaging for KEKB Upgrade and ILC Damping Ring", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper TUOCM02, pp. 1029-1031.

[11] N. Kuroo, K. Ohmi, K. Oide, D. Zhou, and F. Zimmermann, "Cross-wake force and correlated head-tail instability in beam-beam collisions with a large crossing angle", March 2018, *Physical Review Accelerators and Beams,* vol. 21. doi:10.1103/PhysRevAccelBeams.21.031002