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# BENCHMARKING OF SIMULATIONS OF COHERENT BEAM-BEAM INSTABILITY WITH SUPERKEKB MEASUREMENT

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*Abstract*

Coherent beam-beam instability in head-tail mode has been predicted in collision with a large crossing angle. The instability is serious for design of future $e^+e^-$ colliders based on the large crossing angle collision. It is possible to observe the instability in SuperKEKB commissioning. Horizontal beam size blow-up of both beams has been seen depending on the tune operating point. We report the measurement results of the instability in SuperKEKB phase II commissioning.

## INTRODUCTION

Coherent beam-beam instability in head-tail mode has been studied for Phase II commissioning of SuperKEKB. $\beta_x^*$ is squeezed to $\sim 3$ cm in the SuperKEKB design. The instability was seen in $\beta_x^* \sim 24$ cm (8× of the design) but not in 12 cm (4×) at the design bunch population $N_\pm$ [1] in strong-strong beam-beam simulation. The instability is serious for large $\beta_x^*$, because two beams correlate proportional to $\beta_x^*$.

$\beta_x^*/\beta_y^*$ were squeezed step-by-step in Phase II commissioning. During the squeezing $\beta^*$, we had the chance to measure the instability. Table 1 shows the parameters of SuperKEKB. Beam-beam collision was established with the expected $\beta^*$ in Phase II. The bunch population was 50-60% of the design, and the beam-beam parameter is limited for electron beam $\xi_y = 0.02$ [2]: that is, positron beam enlarges in vertical, increasing the bunch currents. Tune operating point is $(\nu_x, \nu_y) = (44.569, 46.609)$ and (45.541, 43.608) for LER and HER, respectively. Any instability signal has not been seen in this operating point, but by changing the horizontal tune of one beam, the horizontal beam sizes of the both beams increase simultaneously. We present the experimental results and the beam-beam simulations in this paper.

Table 1: Parameters for SuperKEKB

| parameter | design | | Phase-II | |
|---|---|---|---|---|
| | LER | HER | LER | HER |
| $N_\pm(10^{10})$ | 9 | 6.5 | 4.8 | 4.0 |
| $\varepsilon_{x/y}$ (nm/pm) | 3.2/8.64 | 4.6/13 | 2.1/21 | 4.6/30 |
| $\beta^*_{x/y}$ (mm) | 32/0.27 | 25/0.3 | 200/3 | 100/3 |
| $\nu_z$ | 0.0247 | 0.028 | 0.022 | 0.026 |
| $\xi_x$ | 0.0028 | 0.0012 | 0.0073 | 0.0025 |
| $\sigma_z\theta_c/\sigma_x$ | 24.7 | 19.4 | 10 | 10 |

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## STUDY USING STRONG-STRONG BEAM-BEAM SIMULATION

Figure 1 shows the instability simulation for SuperKEKB commissioning before starting Phase II. Two cases of $\beta^*_{x,y}$ with (8×, 8×) and (4×, 8×) of the design were examined. The instability was seen in (8×, 8×), but not in (4×, 8×). Horizontal and synchrotron tunes are $\nu_x = 0.53$ and $\nu_z = 0.025$ for both rings.

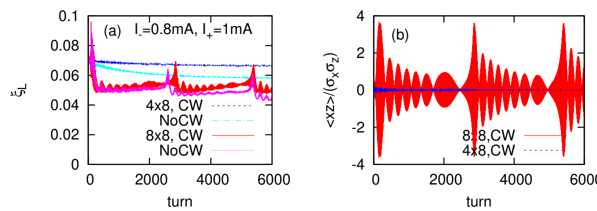


Figure 1: Strong-strong simulation results for SuperKEKB [1]. (a) and (b) show the beam-beam parameter and head-tail motion $\langle xz \rangle$, respectively, at the commissioning stage with IP beta, (8×, 8×), and (4×, 8×).

In reality, synchrotron tunes of two beams are different, $\nu_z^{(+)} = 0.0247$ and $\nu_z^{(-)} = 0.028$ for LER and HER respectively. Complex head-tail mode coupling between two beams can occur with combination of head-tail modes of two beams [3]. Figure 2 presents variation of tune and growth rate of beam-beam head-tail mode, where the horizontal tune is $\nu_x^{(\pm)} = 0.53$ for both beams. The threshold of the instability is very low (0.05× of the design bunch population). Mode coupling between $\nu_x^{(+)} + \nu_z^{(+)}$ and $\nu_x^{(-)} - 3\nu_z^{(-)}$ is seen in the right plot of Fig. 2.

Strong-strong simulations using the code (BBSS) have been performed for collision with different synchrotron tunes. Figure 3 presents the evolution of luminosity, dipole moment $\langle x \rangle$, beam size $\sigma_x$ and correlation of $\langle xz \rangle$, where the horizontal tune is 0.53 for both beams. The horizontal beta function of IP is 4 times of the design, $\beta_x^* = 128/100$ mm. Instability was not seen for equal synchrotron tune ($\nu_z = 0.025$) as shown in Fig. 1. Oscillation in $\langle xz \rangle$ was seen in 1000 turns, but disappeared after that. Horizontal beam size of two beams increased about two times. Small coherent motion in $\langle x \rangle$ remained after 10,000 turns.

Table 2 summarizes simulation results for several horizontal tunes. The horizontal beam size is normalized by the design value. The width (range) of the luminosity and beam size represents lower and upper value; namely presence of a coherent oscillation. Even without coherent oscillation, the

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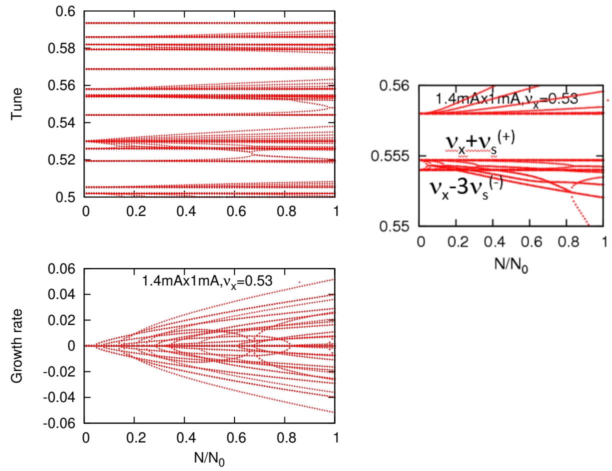


Figure 2: Variation of tune (top left) and growth rate (bottom left) of beam-beam head-tail mode as function of bunch population normalized by the design value. Right plot shows detailed tune behavior near $\nu = 0.55 - 0.56$.

beam size may become large. Stable condition is realized only for $\nu_x = 0.535$ and $\beta^* = (4\times, 8\times)$.

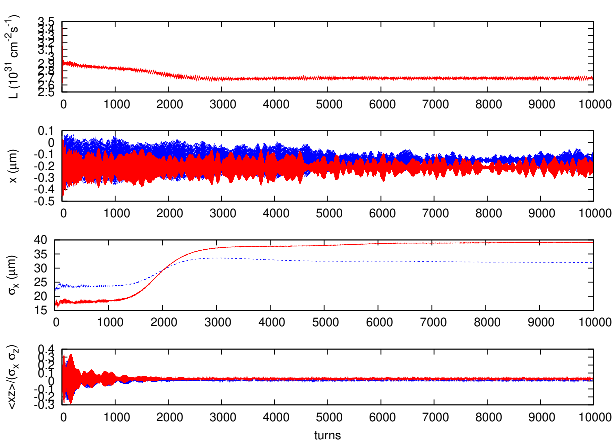


Figure 3: Evolution of luminosity, dipole moment $\langle x\rangle$, beam size $\sigma_x$ and correlation of $\langle xz\rangle$ given by the strong-strong simulation. Those of positron and electron beams are plotted with red and blue lines, respectively. Tune is $\nu_x^{(\pm)} = 0.53$, $\nu_z^{(+)} = 0.0247$ and $\nu_z^{(-)} = 0.028$.

## INSTABILITY MEASUREMENT IN PHASE-II COMMISSIONING

Machine experiments were held to study the beam-beam instability two times, July 7 and 13, 2018. Tune scan was performed to find instability condition in 7 July. Beam current was $(I_{+,tot}, I_{-,tot})$ = (270, 225), (220, 180) and (200, 160) mA. Bunches of 395 were stored with 25 ns spacing. Horizontal tune of LER and HER was scanned near the usual operating point $(\nu_x^{(+)}, \nu_x^{(-)})$=(0.567, 0.542), where the integer part is removed. Figure 4 presents log data

Table 2: Summary of the strong-strong simulation

| $\nu_x$ | $8\times 8\times$ | | | |
|---|---|---|---|---|
| | $L/L_0$ | $\sigma_x$ (L) | $\sigma_x$ (H) | osc. |
| 0.53 | 0.58-0.66 | 6.5 | 4.5 | Y |
| 0.535 | 0.70-0.95 | 2.5-6.2 | 1.4-4.0 | Y |
| 0.54 | 0.75-0.95 | 2.5-6.0 | 1.4-4.0 | Y |
| 0.545 | 0.83 | 7.2 | 1.2 | N |
| | $4\times 8\times$ | | | |
| 0.53 | 0.75-1.0 | 3.0-7.5 | 2.2-6.2 | Y |
| 0.535 | 1.04 | 1.2 | 1.0 | N |
| 0.54 | 1.05 | 2.1 | 1.1 | N |
| 0.545 | 0.94 | 5.2 | 1.7 | N |
| 0.55 | 0.75-0.77 | 8.6 | 3.5 | N |

of beam current, luminosity, beam sizes and tunes during the measurement. Horizontal beam size increase of both beams is seen for decreasing horizontal tune of $e^+$ beam to 0.551. The size was recovered when $\nu_x$ of e$^-$ beam increased $\nu_x^{(-)} = 0.54 \to 0.546$ with keeping $n_x(e^-) = 0.553$. Further decreasing. $\nu_x^{(+)} = 0.553 \to 0.543$, beam size increased at $\nu_x^{(-)} = 0.546$. Then increasing $\nu_x^{(+)} = 0.543 \to 0.553$ and decreasing $\nu_x^{(-)} = 0.548 \to 0.542$, the horizontal beam size blow-up was seen. The beam size enlargement appeared at condition $\nu_x^{(+)} + \nu_x^{(-)}$ =constant. The beam size increase was not observed in single beam for scanning the horizontal tune. The beam size increase was not seen at (170, 142) mA.

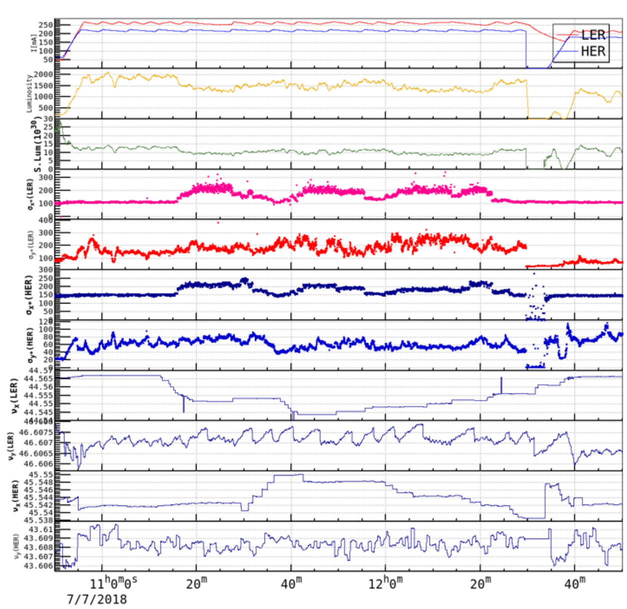


Figure 4: Log of operating condition during the measurement.

Figure 5 shows horizontal beam size as function of $\nu_x(e^\pm)$ at (270,225) mA.

Figures 6 and 7 present horizontal beam size as function of $\nu_x(e^\pm)$ at (220,180) and (200,160) mA, respectively.

Another machine experiment was held to observe beam oscillation in the horizontal blow-up on 13 July. Figure 8

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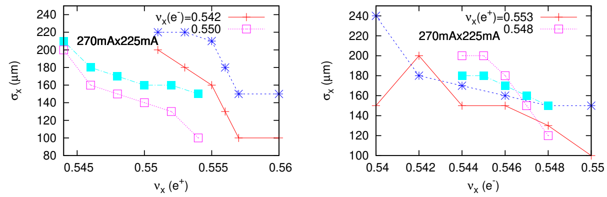


Figure 5: Horizontal beam size of two beams as function of $\nu_x(e^{\pm})$ at (270, 225) mA.

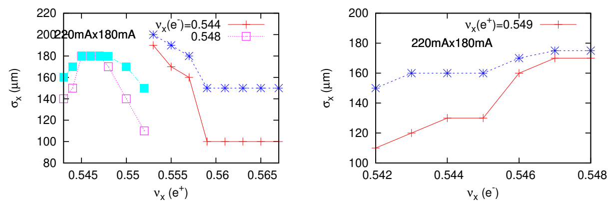


Figure 6: Horizontal beam size of two beams as function of $\nu_x(e^{\pm})$ at (220, 180) mA..

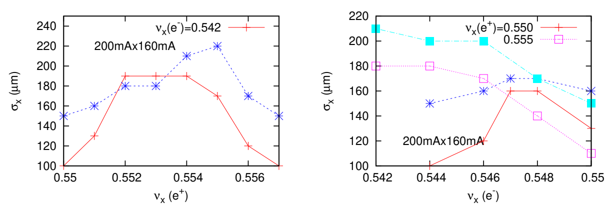


Figure 7: Horizontal beam size of two beams as function of $\nu_x(e^{\pm})$ at (200, 160) mA.

shows beam size variation during the measurement. Horizontal tune of e$^+$ beam was scanned from 0.565 $\rightarrow\sim$ 0.55. e$^-$ beam is aborted at 17:24 due to background increase induced by the instability. Beam current is increased to (300, 250) mA. for the measurement. Bunch oscillation and snap shot using streak camera were taken at 0.552, 0.5435, when a strong beam size blowup was seen.

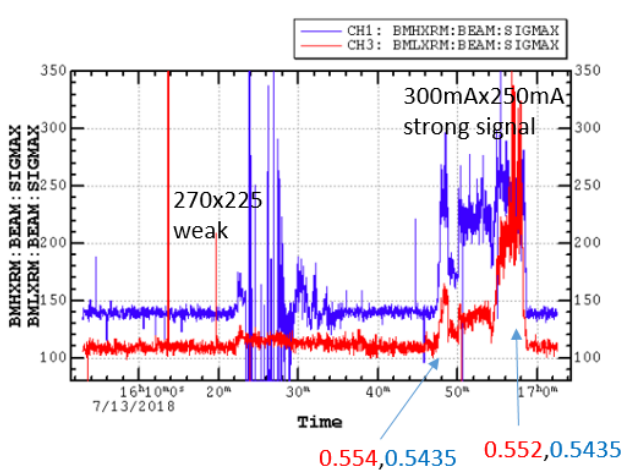


Figure 8: Log of beam size at an machine experiment held on 13 July.

Figure 9 presents FFT amplitude of Bunch Oscillation Recorder for LER. Clear signals at $\nu = 0.564$ and its sideband 0.585 were seen. Since noise level of HER data was high, clear oscillation was not seen.

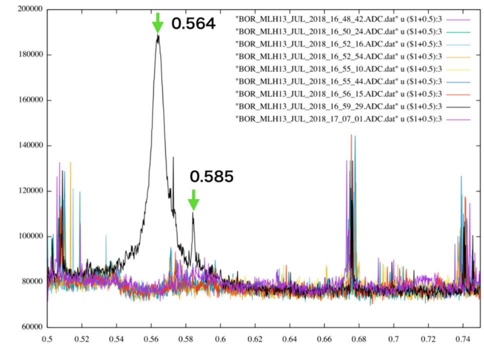


Figure 9: FFT amplitude of Bunch Oscillation Recorder for LER, when a strong beam size blowup was seen.

Figure 10 presents results for streak camera measurement. Shot-by-shot (left) and average (right) of the horizontal beam size were plotted. No clear signal was seen. Probably, the resolution is not sufficient.

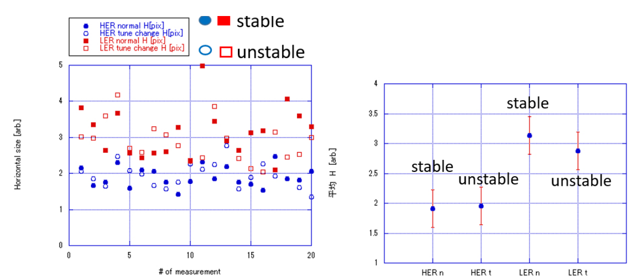


Figure 10: Beam size measured by streak camera. Left is shot-by-shot and right is averaged.

## SUMMARY

Coherent beam-beam instability due to head-tail mode coupling of two beams has been predicted in collision with a large crossing angle. Experiments to verify the instability were held in SuperKEKB commissioning. Horizontal beam size of both beams increased when horizontal tune of e$^-$ beam was scanned. This observation can be evidence of the beam-beam instability.

## REFERENCES

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