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STUDY FOR -1 MODE INSTABILITY IN SuperKEKB LOW ENERGY RING

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Abstract

A beam size blow-up has been observed in increasing beam current in superKEKB Low Energy Ring (LER). The blow-up is a single bunch effect, which appears at high bunch current $I_b \approx 1$ mA. -1 mode ($\nu_y - \nu_s$) signal was detected in a beam position monitor at the appearance of the blow-up. The blow up is suppressed at vertical tune $\nu_y > 0.59$, while the beam injection is hard at the tune. The blow-up disappeared at turning off a bunch-by-bunch feedback. The luminosity performance of SuperKEKB is limited by the blowup, because it depends on the feedback tuning, operating point and collimator conditions Measurements and simulations for the blow-up are presented to explain the phenomenon.

INTRODUCTION

SuperKEKB consists of Low Energy Ring (LER) and High Energy Ring (HER), which store 4 GeV positron beam and 7 GeV electron beam, respectively. In physics operation, lower vertical tune in LER has tended to have lower luminosity and beam instability. We began to measure LER beam size without collision to make clear the reason. A beam size blow-up has been observed increasing beam current ∼ 1 A in LER since 2021 spring.

Several times of measurements have been performed since 2021. The blow-up has been seen in single beam operation of LER. The blow-up was independent of the number of bunch stored: i.e. it was seen at I = 90 mA in 99 bunches storage, while at around 1 A in 1000-1500 bunches storage in physics run. The beam size depended only on the bunch current. Therefore this phenomenon was concluded as single beam and single bunch effect.

The blow-up also depended on the collimator aperture. In LER, a few number of collimators contributes dominantly as impedance sources. Narrower aperture of the collimators resulted in larger beam size blow-up. The phenomenon was concluded as an impedance related effect. - 1 mode ($\nu_y - \nu_s$) signal was detected in a beam position monitor at the appearance of the blow-up. The separation of ν_y and $\nu_y - \nu_s$ signals was sufficient to exclude the possibility of TMCI.

The blow-up depends on bunch-by-bunch feedback system. The bunch-by-bunch feedback is essential for multi-bunch and high-current operation. The feedback could be turned off in accelerator experiments with a very small number of bunches (∼ 30) and beam current I=30mA. The blow-up disappeared when turn off the feedback.

We call this beam-size blow-up -1 mode instability. This paper shows the experimental results and discussions for mechanism of the beam-size blow up or -1 mode instability.

MEASUREMENTS OF LER

The beam size blow-up is related to the vertical impedance. Amplitude of the vertical impedance is evaluated by measurement of current dependent tune shift, which is expressed by the well known formula,

$$\Delta\nu_y = \frac{Ne^2}{4\pi E}\sum_i \beta_{y,i}k_{y,i} \quad (1)$$

$$= 2\times 10^{-19}\sum_i \beta_{y,i}k_{y,i}[V/C]I[mA]. \quad (2)$$

where LER parameters are substituted into Eq. (1) on Eq.(2). The vertical kick factor (k_y) is express by the vertical wake field and/or impedance

$$k_y = \iint_{-\infty}^{\infty} W_y(z-z')\rho(z)\rho(z')dzdz' \quad (3)$$

$$= -\frac{i}{2\pi}\int_{-\infty}^{\infty} d\omega Z_y(\omega)e^{-\omega^2\sigma_z^2/c^2} \quad (4)$$

where Gaussian density distribution $\rho(z) = e^{-z^2/(2\sigma_z^2)}/(\sqrt{2\pi}\sigma_z)$ is assumed in Eq. (4).

Four vertical collimators D2V1,V2 (s =1800 m), D3V1 (s =2714 m) and D6V1 (s =1800 m) are installed to protect the physics detector Bell-II from beam background, where s is position from the Interaction Point. The collimators, especially D2V1 and D6V1, are dominant source of the vertical impedance.

Electro-magnetic filed simulations using GdFidl citeGDFDL and ECHO3D [2] gave $\sum\beta_y k_y = 3.3\times10^{16}$ V/C for collimators and 1.8×10^{16} V/C for the beam chamber in Interaction Region and others: i.e., 5.1×10^{16} V/C in total [3]. The impedance corresponds to a collimator aperture setting used in the measurements presented in this paper. The collimators are slightly opened in physics run: i.e., the collimator impedance is 2.9×10^{16} V/C.

The current dependent tune shift was measured in a single bunch operation. Figure 1 shows vertical tune shifts for $\nu_{y,0}$ =0.614 and 0.592 as functions of bunch current. Tune shift is linear for the bunch current. The linear coefficients are fitted as seen in the figure. The tune shift was determined as $\Delta\nu_y/I = 1.1$ mA^{-1}. Corresponding impedance/ kick factor is $\sum\beta_y k_y = 5.5\times10^{16}$ V/C. The difference between the measurement and simulations is within 10%.

Vertical beam size has been measured by Xray monitor using coded aperture mask [5] in SuperKEKB. Figure 2 shows the beam size as a function of the bunch current. Beam sizes for the two collimator apertures of D6V1 are plotted by blue and orange points. Corresponding collimator

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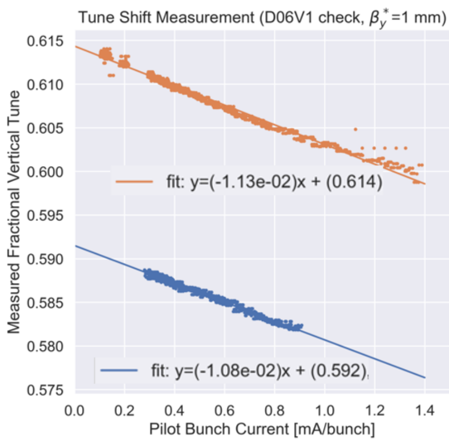

Figure 1: Vertical tune as functions of bunch current for $\nu_{y,0}$ =0.614 and 0.592.

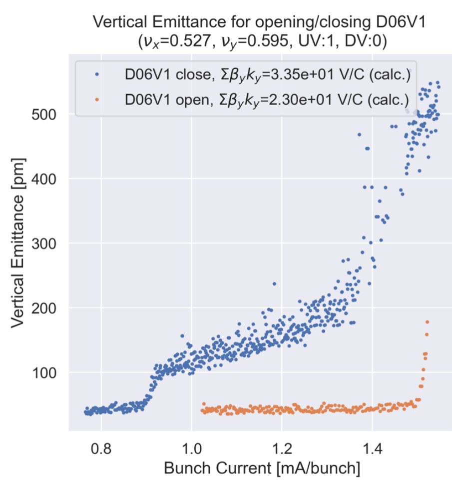

Figure 2: Beam size as function of bunch current. Blue and orange points are given for the total (collimator) impedance $\sum \beta_y k_y = 5.2(3.35)$ and $4.1(2.30)\times10^{16}$ V/C, respectively.

impedance is $\sum \beta_y k_y = 3.35$ and 2.30×10^{16} V/C. The total impedance is 5.2 and 4.1×10^{16} V/C for blue and orange. The impedance ratio is 1.27. The products of the impedance times bunch current at $\varepsilon_y = 200$ pm are nearly equal, $1.3 \times 5.2 \approx 1.55 \times 4.1$. Scaling for the product is not perfect as shown in the figure: i.e., the lines are not coincide for scaling in the horizontal axis..

Beam size was measured for varying the vertical tune. The beam size blow-up caused by the synchro-beta resonances $\nu_x - \nu_y + n_z\nu_s$ =integer for n_z =1 and 2 has been observed at a low bunch current in KEKB and SuperKEKB [4]. In the early stage of the measurements, the beam size increased at lower tune $\nu_y < 0.6$ at high bunch current $I_b \geq 0.9$ mA. Thus we speculated that the synchro beta resonance had some effects on this beam size blow up. A machine experiment was performed to understand whether the phenomenon was related to x-y coupling. Vertical beam size was measured with scanning the vertical tune at two different horizontal tune $\nu_x = 0.5310$ (left) and 0.5935 (right) as shown in the top two plots in Fig. 3. The bottom two plots show the vertical

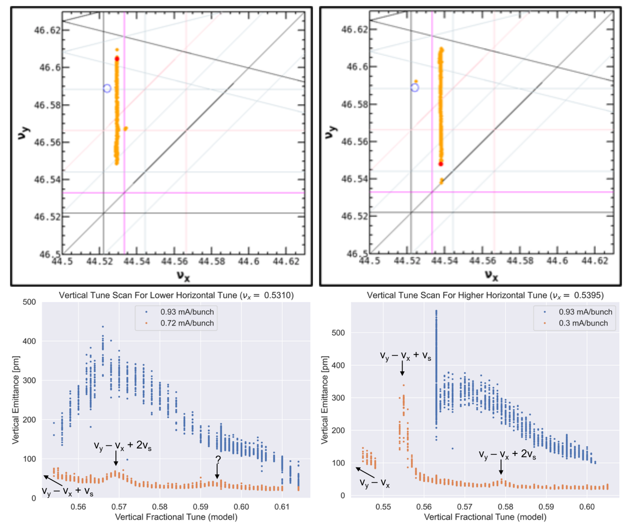

Figure 3: Beam size scanning along the vertical tune. Top plots show the history of the tune scan, and bottom left and right plots are given for $\nu_x = 0.5310$ and 0.5395 corresponding to top plots, respectively.

beam size at the corresponding horizontal tunes. Orange and blue points depicts the vertical emittance at below (0.3-0.7 mA) and above (0.9 mA) the threshold of the beam size blowup. First ($n_z = 1$) and second ($n_z = 2$) synchro-beta side bands were seen below the threshold current. On the other hand a broad peak was seen at $\nu_y < 0.61$ above the threshold current. Beam size as a function of the vertical tune is independent of ν_x at high bunch current. We concluded that the beam size blow up was irrelevant to x-y coupling.

A beam position monitor, which is used for bunch-by-bunch feedback, can record positions of all bunches in every turns (typically 2048 or 4096 turns). The device is called Bunch Oscillation Recorder. An unstable oscillation mode as single bunch instability is detected by taking Fourier analysis of the BOR data. Figure 4 shows the Fourier spectra for varying the beam current, where the number of bunches are 99. This signal means occurrence of self-excited oscillation. 5 plots (top and bottom left/center) shows Fourier amplitude of the bunch current 0.3, 0.5, 0.7, 0.9 and 1.1 mA. The last plot placed at right bottom shows amplitude at 1.1 mA after increasing feedback gain. The vertical emittance is kept to be 30 pm at I_b ≤0.7 mA. Increasing the bunch current, the vertical emittance increases. The sharp peak was seen around $\nu_y - \nu_s$ in the Fourier amplitude when vertical emittance begin to increase. Increasing the feedback gain, both the beam size and Fourier amplitude of -1 mode are reduced.

Stable and unstable oscillation modes are also measured by detecting a response for forced oscillation scanning the frequency. Left picture of Fig. 5 shows the frequency response in horizontal and vertical positions of the pilot bunch at $I = 1.5$ mA. Betatron and its synchrotron sideband are seen. The fact, in which betatron and its sideband are seen, means that it is below the TMCI threshold. The peak posi-

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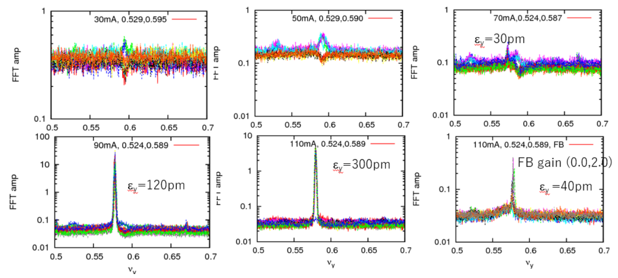

Figure 4: Fourier amplitude of the bunch oscillation recorder. Top three and bottom left and center are given for the bunch current 0.3, 0.5, 0.7, 0.9 and 1.1 mA. Bottom right plot is given for increasing feedback gain.

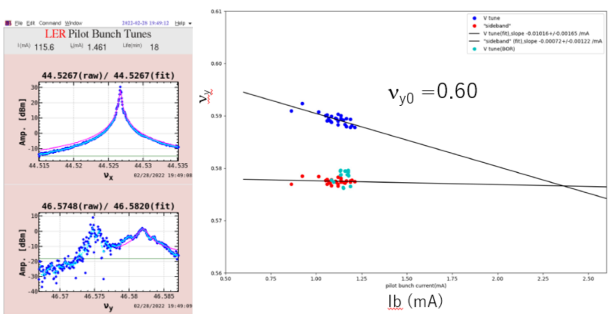

Figure 5: Left: Mode tune seen in response for frequency scanning forced oscillation. Right: Tune peak positions detected in self excitation (Fig. 4, cyan) and forced oscillation (blue and red).

tions of the self-excited signal and the response signal are plotted in Fig. 5 right. The self excited signal was coincide with the synchro-beta sideband. Changing the vertical betatron tune, the two peaks shifted simultaneously: i.e., it is clear that the lower peak is synchro-beta sideband. The beam size blowup was concluded to be caused by excitation of $\nu_y - \nu_s$ mode, and was called the -1 mode instability.

Bunch-by-bunch feedback system is necessary to suppress coupled bunch instability at total current $I > 50$ mA typically. Reducing the number of bunches to 30 bunch and total current 30mA, the beam size measurement becomes possible without the bunch-by-bunch feedback. Figure 6 shows the beam size as function of bunch current for feedback ON/OFF. Orange and blue points are vertical emittance in the first trial of the feedback ON/OFF. The emittance increase disappeared completely by turning off the bunch-by-bunch feedback. Green points are that after feedback tuning as is discussed in next section.

BUNCH-BY-BUNCH FEEDBACK

In the end of previous section, we show that the bunch-by-bunch feedback system has an important role in the vertical emittance growth as shown in Fig. 6.

Feedback system equips two independent feedback loops. Each set consists of transverse strip line kicker and beam position monitor. Table 1 shows the betatron function and

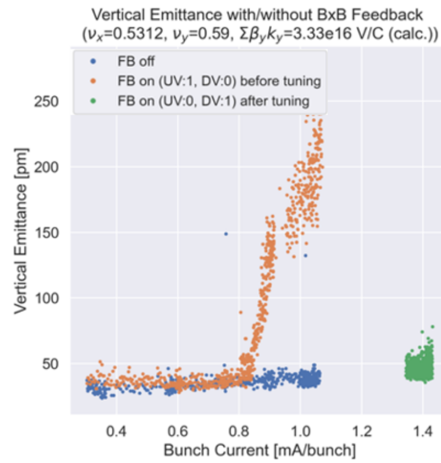

Figure 6: Beam size as functions of bunch current for feedback ON/OFF.

phase at feedback kickers, monitors and major impedance source D6V1. Another major collimator D2V1 is located at a position with an integer betatron phase difference from D6V1.

Figure 7 shows schematic view of the feedback system configuration. Beam is kicked by the kickers 1 and 2 based on the beam positions measured by the monitors 1 and 2 in previous turns.

Kicker strength is determined by the measured beam positions using Finite Impulse Response filter as follows,

$$\Delta P_K(n) = \sum_{k=1}^{N_{tap}} c(k) X(n-k) \tag{5}$$

where $X(n)$ is vertical position measured by the monitor at n-th turn, and $\Delta P_K(n)$ is momentum kick applied at kicker. X and P are normalized as $X(n) = y(n)/\sqrt{\beta_y}$ and $P(n) = \sqrt{\beta_y} p_y(n) + \alpha_y y(n)/\sqrt{\beta_y}$ for measured $y(n)$ and $p_y(n)$, respectively. N_{tap} is called the tap number. Position data

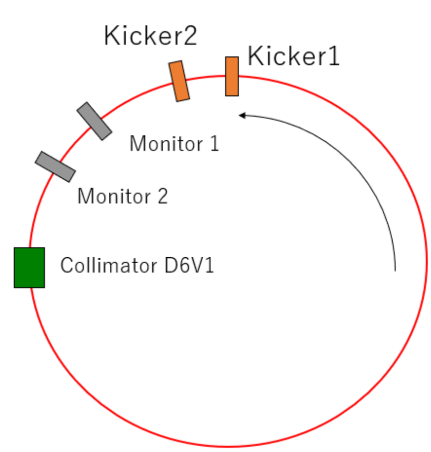

Figure 7: Schematic view of the feedback system configuration.

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Table 1: Position, beta function, and phase at the feedback kickers, monitors and the collimator D6V1.

Element	α_x	β_x	$\phi_x/2\pi$	s(m)	α_x	β_x	$\phi_y/2\pi$
Kicker 1	.68	19.6	21.9781	1489.30	-1.14	6.3	22.7721
Kicker 2	.56	17.6	21.9913	1490.84	-1.70	10.7	22.8020
Mon. 1	.50	23.9	22.0432	1499.91	.85	19.4	22.9117
Mon. 2	-.50	23.9	22.1906	1519.07	-.85	19.4	23.1355
D6V1	1.71	14.6	27.4756	1870.27	-10.1	67.3	28.8574
IP	0.00	.080	44.5250	3016.30	0.00	.001	46.5870

up to N_{tap} turns before are used for the feedback. Beam positions at the monitor are transferred to those at the kicker,

$$X(n) = X_K(n)\cos(k\mu + \Delta\phi) - P_K(n)\sin(k\mu + \Delta\phi), \quad (6)$$

where $\Delta\phi = \phi_K - \phi_M$ is vertical betatron phase difference from the monitor to kicker. $\Delta\phi/2\pi = -0.1396$ and -0.3335 for the first and second feedback loops as shown in Table 1. $\mu = 2\pi\nu_y$ is (angular) tune of an oscillation mode. Tune is changed in arc section outside of Kicker-Monitor system.

Resistive and reactive components of the feedback are expressed by

$$\Delta P_K(n) = -2d_P P_K(n) - 2d_X X_K(n). \quad (7)$$

The components are given by

$$d_P = \frac{1}{2}\sum_{k=1}^{N_{tap}} c(k)\sin(k\mu + \Delta\phi) \quad (8)$$

$$d_X = -\frac{1}{2}\sum_{k=1}^{N_{tap}} c(k)\cos(k\mu + \Delta\phi). \quad (9)$$

The coefficients are used before March 11, 2022 as

$$c_1 = \{21623, -5530, -11430, 25925, -32767, 31362, -20832, 5288, 12317, -25956\};$$
$$c_2 = \{26781, -26182, 7149, 2479, -22777, 25564, -32767, 19752\}; \quad (10)$$

N_{tap} are 10 and 8 for the 1-st and 2-nd feedback loops.

They are changed at March 12 as

$$c_1 = \{29144, -32767, -16328, 19950\}; \quad (11)$$
$$c_2 = \{10883, -32767, 28452, -20750, -7342, 21524\};$$

N_{tap}'s are reduced to be 4 and 6.

Using Eqs. (8) and (9), resistive and reactive components as a function of mode tune are evaluated. Figure 8 shows resistive and reactive components of the filter coefficients of Eq. (10). Blue and orange points are given for 1-st and 2-nd feedback loops. The feedback gain is maximum at around $\nu_y = 0.58$. While the gain is poor for synchro-beta side band ($\nu < 0.54$) at $\nu_y \approx 0.56$. The reactive component change the sign at the peak of resistive component.

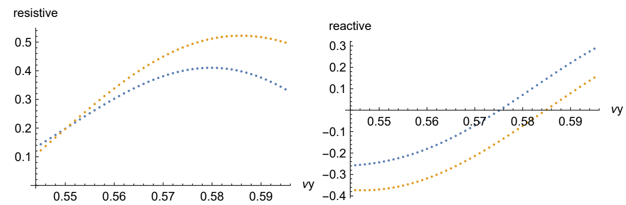

Figure 8: Resistive and reactive components for the FIR filter in Eq. (10) (before Mar. 11).

Figure 9 shows resistive and reactive components of the filter coefficients of Eq. (11). The resistive component is kept a sufficient level at low frequency.

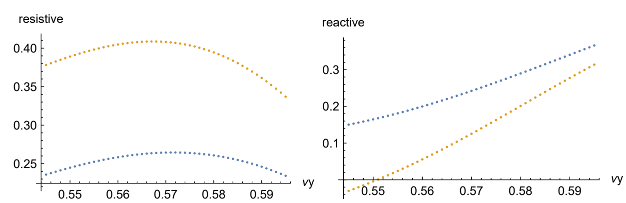

Figure 9: Resistive and reactive components for the FIR filter in Eq. (11) (Mar. 12).

SIMULATION OF HEAD-TAIL INSTABILITY CONSIDERING THE BUNCH-BY-BUNCH FEEDBACK

Multi-particle tracking simulation is performed with considering the wake field and the bunch-by-bunch feedback system. The total wake field of every accelerator component evaluated by ECHO3D [2] (collimators), GDFidl [1] (cavities and other vacuum components) and analytic formula(resistivity) is shown in Fig. 10. $W(z)$ is calculated by using a virtual short bunch with the length of 0.5 mm. Red and magenta lines are dipole field induced by dipole moment and quadrupole field induced by monopole (density) component. The kick factor k_y is given by -4.7×10^{16} and -1.0×10^{16} V/C. Corresponding vertical tune shift is 0.011 mA^{-1}. Quadrupole and dipole kick are almost cancelled in horizontal. The vertical quadrupole component is similar and opposite sign with the horizontal quadrupole component. These are characteristics of vertical collimator, which has translational symmetry in horizontal.

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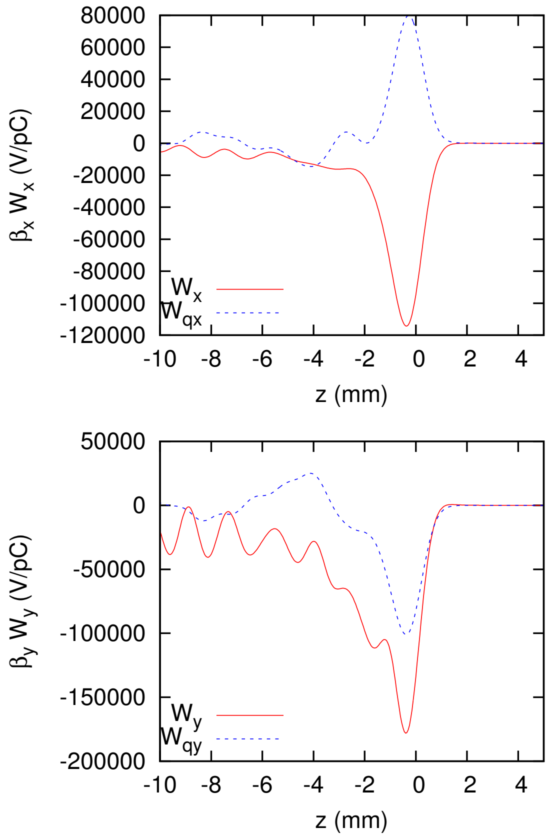

Figure 10: Transverse wake field. Red and blue lines are dipole field induced by dipole moment and quadrupole field induced by monopole component, respectively.

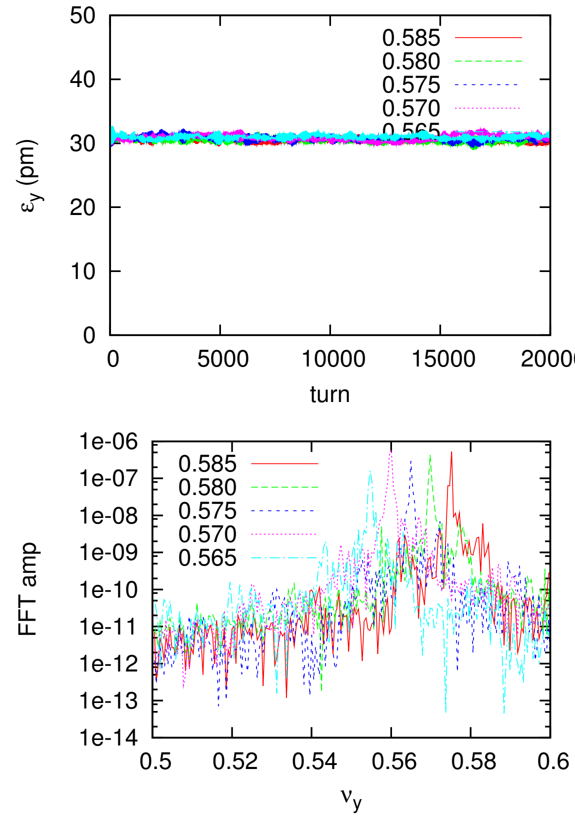

Figure 11: Evolution of vertical emittance and Fourier coefficients for the dipole motion, where thefeedback was turning off.

The particle tracking simulation was performed by momentum kick given by convolution of the dipole-quadrupole wake fields and dipole-monopole moments.

$$\Delta p_y = -\frac{Ne^2}{E}\int_{-\infty}^{\infty}[W_y(z-z')\rho_y(z')+W_{Q,y}(z-z')\rho(z')]dz', \quad (12)$$

where $\rho(z)$ is the bunch density (monopole moment) and $\rho_y(z) = \rho(z)\langle y(z)\rangle$ is dipole moment as a function of z. Macro-particles of 100,000 are used in the simulation. Bunch current is set to be 1 mA, $N = 6.25 \times 10^{10}$.

Figure 11 shows vertical emittance and Fourier spectra for the vertical dipole motion $\langle y\rangle = \int \rho_y(z)dz$, where the feedback was turning off. The vertical tune was scanned between 0.565-0.585 in steps of 0.005. There was no emittance growth in every tune. Betatron tune is seen in the peak of Fourier coefficient. Tune shift around 0.01 is seen.

Figure 12 shows vertical emittance and Fourier coefficient for the vertical dipole motion using bunch-by-bunch feedback system. where FIR filter of Eq. (10) with the damping rate 0.1 is used. Strong emittance growth is seen in lower betatron tune $\nu_y = 0.570, 0.565$. In Fourier spectrum, -1 mode signal is seen around $\nu_y - \nu_s$ in every tune, while the betatron signal is suppressed. These behaviors are consistent with the experimental results seen in Figs. 3-6.

Figure 13 shows the results at the bunch current of 0.5 mA. Other conditions are the same as in Fig. 12. There was no emittance growth in every tune. -1 mode is seen in the peak of Fourier spectra.

Simulations for a weak feedback strength with the damping rates of 0.04, 0.06 and 0.08 were performed. Emittance growth was seen at 0.08. The feedback damping time is estimated around 0.01-0.02 in the measurement for damping of injected beam. The blow-up was also not seen in a simple single tap feedback with only resistive component with the damping rate of 0.1.

SUMMARY

We have studied a beam size blow-up observed in superKEKB Low Energy Ring (LER). The experimental results are summarized as follows:

- The blowup is single bunch effect.
- It is irrelevant to x-y coupling.
- It is impedance phenomenon. As far as the tune shift was concerned, the threshold is about half that of TMCI.
- -1 mode signal ($\nu_y - \nu_s$) is seen with the appearance of the blow-up.
- Turning off the bunch-by-bunch feedback results in disappearance of the blow up.

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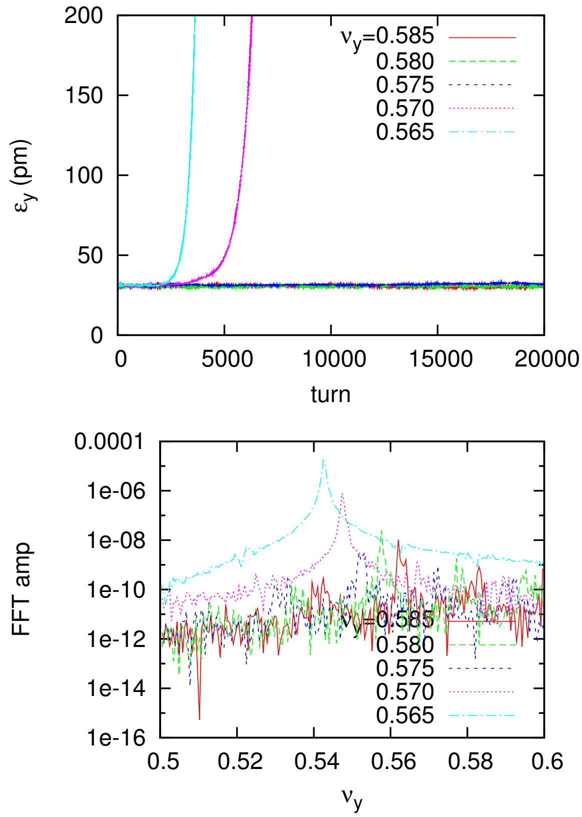

Figure 12: Evolution of vertical emittance and Fourier coefficients for the dipole motion at the bunch current 1 mA, where the feedback is turned on with FIR filter of Eq. (10) and the damping rate of 0.1.

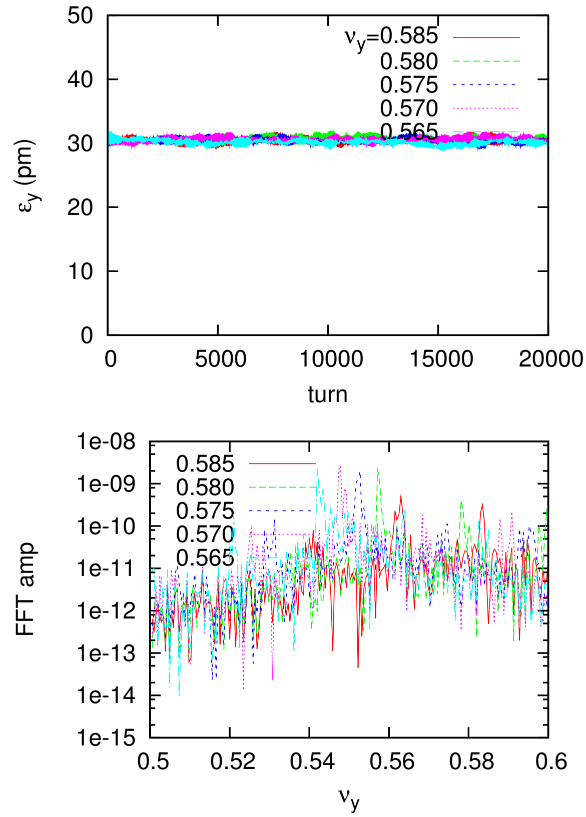

Figure 13: Evolution of vertical emittance and Fourier coefficients for the dipole motion at the bunch current 0.5 mA, where the feedback is turned on with FIR filter of Eq. (10) and the damping rate of 0.1.

The bunch-by-bunch feedback system in SuperKEKB adopted multitap scheme with a digital FIR filter. Resistive and reactive component of the feedback depends on the filter parameters and the frequency of unstable mode. Multi-particle tracking simulation has been done considering the impedance and feedback. Using the filter parameters and high damping rate 0.1, -1 mode instability was reproduced in the simulation. Emittance growth appeared at low vertical tune $\nu_y \leq 0.57$. There was no instability in lower bunch current, lower impedance, simple single tap feedback nor filter parameter change as was done in the experiment.

The assumed feedback gain 0.1 in the simulation is higher than the actual setting, 0.01-0.02. It seems that we have not yet reached perfect understanding of the -1 mode instability. Digital noise/step of the monitor and kicker is studied in the future.

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