ION INSTABILITY IN SuperKEKB PHASE I COMMISSIONING

K. Ohmi*, H. Fukuma, Y. Suetsugu, M. Tobiyama, KEK, Tsukuba, Japan

Abstract

Ion instability has been observed in SuperKEKB phase I commissioning. Unstable modes, their growth rates, tune shift were measured. Frequencies of the unstable modes is lower than theoretical prediction and the growth rate is also smaller. We discuss a possible model to explain the measurements.

INTRODUCTION

Commissioning of SuperKEKB had been performed from February to June 2016 to test performance as low emittance storage rings. Study of ion effects in the high energy electron ring (HER) was an important subject in the commissioning.

Ion instability is caused by ion oscillation trapped in an electron bunch train [1]. The frequency of ion is expressed by

$$\omega_{i,x}^2 = \frac{2\lambda_e r_A c^2}{A_i \Sigma_x(\Sigma_x + \Sigma_y)} \qquad \omega_{i,y}^2 = \frac{2\lambda_e r_A c^2}{A_i \Sigma_y(\Sigma_x + \Sigma_y)}, \quad (1)$$

where $\Sigma_{x(y)} = \sqrt{\sigma_{e,x(y)}^2 + \sigma_{i,x(y)}^2}$ is convoluted beam sizes of beam and ion, and $\lambda_e = N_e/L_{sp}$ is the line density of electron beam. When $\omega_i L_{sp}/c > 1$, ions are not trapped along the bunch train.

Ion production rate $n_i(\mathrm{m}^{-1})$ created by a bunch with population N_e is expressed by

$$n_i = d_m \sigma_m N_e \quad (2)$$

where d_m is the molecular density, which is given by partial pressure of the molecule

$$d_m(\mathrm{m}^{-3}) = 2.42 \times 10^{20} P_m(\mathrm{Pa}). \quad (3)$$

σ_m is ionization cross-section,

$$\sigma_{CO} = 190 \times 10^{-24}\mathrm{m}^2 \qquad \sigma_{H_2} = 32 \times 10^{-24}\mathrm{m}^2 \quad (4)$$

Table 1 shows parameters of HER. Vacuum pressure is 100 nPa for both of CO and H_2 molecules. We focus CO with larger cross-section. The ion production rate is $n_i = 144$ and 283 m^{-1} for phase I and the design, respectively.

COUPLED BUNCH INSTABILITY IN HER

Coupled bunch instability has been observed since the early stage of Phase I commissioning. Beam current is gradually increased with taking care of vacuum pressure. We observe a coupled bunch instability with modes slightly lower than RF harmonic. Since unstable mode changes day-by-day, it is considered that the instability is caused by ion. Figure 1 shows horizontal and vertical strongest unstable mode and its growth rate. The legends of points are date (Mon/Day), in which the beam current and the number of bunches are written at the side of the figure.

Table 1: Parameter List of SuperKEKB-HER

	Phase I	design
Energy, E (GeV)	7	7
current, I (A)	0.8	2.6
# bunches	1576	2500
bunch population, N_e (10^{10})	3.2	6.3
bunch spacing, L_{sp} (m)	1.8	1.2
emittance, $\varepsilon_{x/y}$ (nm)	4.5/0.045	4.5/0.011
averaged β_{xy} (m)	12	12

The unstable mode is related to the ion frequency as follows,

$$\mathrm{Mode} = 5120 - \frac{\omega_i}{\omega_0}. \quad (5)$$

where 5120 is the harmonic number of SuperKEKB and ω_0 is the revolution angular frequency. Figure 2 shows unstable mode as function of the beam current given by Eq.(1).

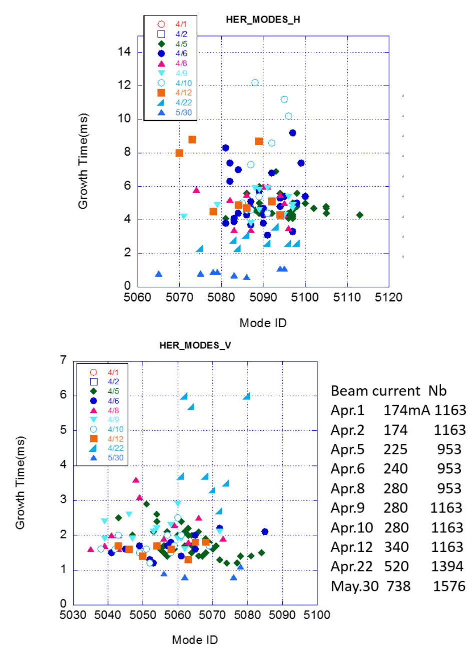

Figure 1: Unstable mode and growth rate of a coupled bunch instability in HER.

TUNE SHIFT ALONG BUNCH TRAIN

Bunch-by-bunch tune is measured along the bunch train. Bunches are filled every 3 bucket, exactly speaking 16 bunches are filled in 49 bucket (3.06 spacing) due to the timing between Linac and SuperKEKB ring. A pilot bunch

* ohmi@post.kek.jp

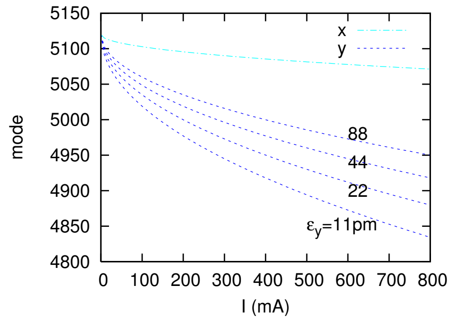

Figure 2: Predicted unstable mode as function of the beam current.

is injected with separation of 23 buckets at the end of bunch train.

Figure 3 shows the horizontal (top) and vertical (bottom) tune shift along the bunch train at the beam current I = 500 mA. The tune shift is $\Delta\nu_x = 0.0014$ and $\Delta\nu_y = 0.00075$. We have to note that the horizontal tune shift is larger than vertical one. The tune shift of the pilot bunch decreases. This is due to that ions are cleared at the empty bucket of 23.

The bunch population is $N_e = 2 \times 10^{10}$. Ion production rate is $n_i = 90$ m^{-1} per bunch, and the total is $N_i = n_i \times 1576 = 1.4 \times 10^5$ m^{-1} for CO, 100nPa at the end of the train. Tune shift caused by ion cloud is given by

$$\Delta\nu_x + \Delta\nu_y = \frac{\rho_i r_e \beta_{xy}}{\gamma} C, \tag{6}$$

where ρ_i is the volume density of ions. The tune shift ratio $\Delta\nu_x/\Delta\nu_y$ equals to the aspect ratio of the ion cloud size, $\sigma_{i,y}/\sigma_{i,x}$. The beam size is $\sigma_{e,x}$ = 0.35 mm and $\sigma_{e,y}$ = 0.025 mm. If ions are trapped, ions are located at the beam size area $2\pi\sigma_{e,x}\sigma_{e,y}$. The tune shift should be $\Delta\nu_x = 0.0017$ and $\nu_y = 0.017$.

On the other hand, if we start discussion from the measured tune shift, the ion density is $\rho_i = 2.8 \times 10^{11}$ m^{-3}. Number of ions near the beam area is $2\pi\sigma_{e,x}\sigma_{e,y}\rho_i = 1.6 \times 10^4$ m^{-1}, that is one order lower than the prediction $N_i = 1.4 \times 10^5$ m^{-1}. The aspect ratio of ion cloud size is $\sigma_{i,x}/\sigma_{i,y} = 0.54$. We should believe the total ion production $N_i = 1.4 \times 10^5$ m^{-1}. The size is $\sigma_{i,x} = 0.28$ mm and $\sigma_{i,y} = 0.53$ mm at the end of the train. Using these ion sizes and Eq.(1), the mode numbers are 64 and 61 for the horizontal and vertical, repectively. These numbers are closed to the experimental results in Fig.1.

SIMULATION OF ION INSTABILITY

Simulation of ion instability is done using interaction of rigid Gaussian bunches and ion cloud [2]. This simulation method is valid as far as transverse beam size is kept at the design value determined by $\sigma_{e,x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y} + \eta_{x,y}^2\sigma_\delta^2}$. The simulation calculates position of every bunches interacting with ion cloud turn-by-turn. Ions are tracked with

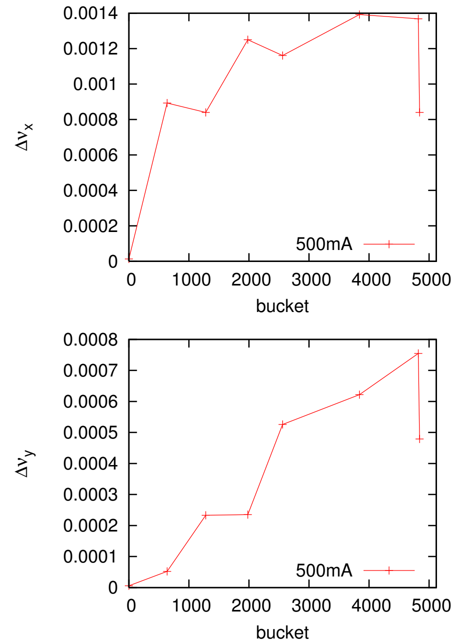

Figure 3: Horizontal (top) and vertical (bottom) tune shift along the bunch train.

interaction with the bunch train. Ions are not cleared artificially at the end of the bunch train. Ions drift between the bunch and train interactions.

Simulation for the Design

Simulation of ion instability had been performed at the design stage of SuperKEKB. We use bunch-by-bunch feedback to suppress coupled bunch instabilities. The feedback gain is $G = 0.02$, corresponding to the damping time 0.5ms (50 turns). Figure 4 presents ion instability for the design parameter of HER. Top plot shows evolution of maximum dipole amplitude of the bunch train with length of 2,500 bunches. Several lines are given for feedback gain $G = 0.02 - 0.05$ (0.5-0.2ms). The amplitude is saturated at a certain value depending on the feedback gain. Bottom plot shows the saturated amplitude as function of feedback gain. Three lines corresponding to vacuum pressure 40, 20 and 10 nPa. Several 10% of betatron oscillation for the beam size remains. The betatron oscillation may affect the beam-beam performance, or may be damped by strong beam-beam tune spread.

The saturated amplitude does not depend on the length of bunch train and clearing gap. The behavior is completely different from analytic theory [1]. Ions are diffused by small betatron motion at downstream of the bunch train, and saturation of instability growth arises. The ion diffusion is seen later.

Simulation for the Experimental Condition

The simulation was performed for a train with 1576 bunches and 3 bucket spacing, and with the beam current, I=500mA. Figure 5 presents the ion instability in the experi-

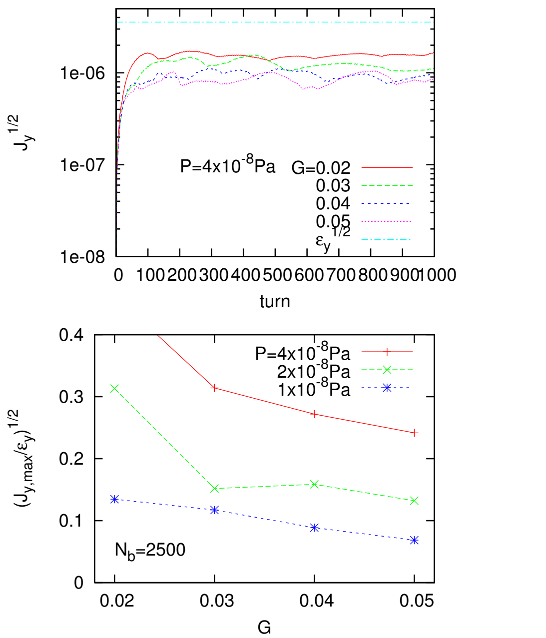

Figure 4: Ion instability for the design parameter of SuperKEKB HER.

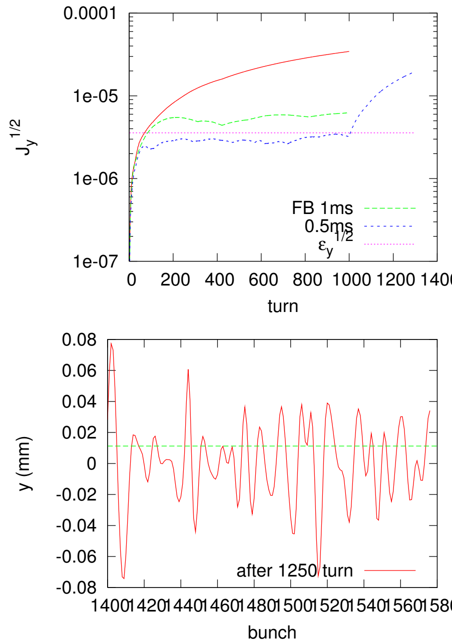

Figure 5: Ion instability in the experimental condition, N_b = 1576, 3 bucket spacing, I = 500 mA, 100 nPa.

mental condition, where the vacuum pressure is 100 nPa. To measure the unstable mode, the bunch-by-bunch feedback is turned off at a timing. Top plot shows evolution of maximum betatron amplitude of bunches. No feedback (red), feedback with $G = 0.01$ (1ms, green) and $G = 0.02$ (0.5ms, blue) are plotted. The feedback with the gain $G = 0.02$ (0.5 ms) is turned off at 1000-th turn (blue). The bunch oscillation is plotted in the bottom plot. The frequency of the collective bunch motion seen in the plot is consistent with the formula, Eq. (1) for $\sigma_{i,x,y} \approx \sigma_{e,x,y}$. The mode frequency is not low with contrast as seen in experiments (Fig.1).

Figure 6 presents ion distribution interacting with bunch train. Top, middle and bottom show ion distribution at times interacting with 78-th, 780-th and 1576-th bunches. Ion size increases, but is insufficient to explain the experimental tune shift.

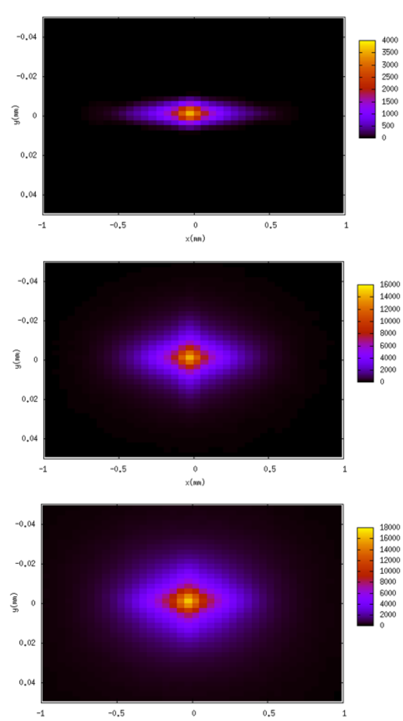

Figure 6: Ion distribution interacting with bunch train.

CONCLUSION

Ion instability has been observed at SuperKEKB Phase I commissioning. Unstable mode frequency of the coupled bunch instability is lower than the prediction. Growth mode and its rate changes day-by-day. Tune shift due to ions was measured. Ion size evaluated by the tune shift is much larger than the beam size and evaluated ion vertical size is larger than horizontal. When we use ion sizes obtained by tune shift measurement, the unstable mode numbers are closed to the measured ones. Simulations explains the ion effects partially, but still unsolved phenomena remains.

ACKNOWLEDGEMENT

The authors thank SuperKEKB team for the commissioning, operation and cooperation of machine experiments.

REFERENCES

[1] T.O. Raubenheimer, F. Zimmermann, Phys. Rev. E52, 5487 (1995).

[2] K. Ohmi, Phys. Rev. E55, 7550 (1997).