ELECTRON CLOUD AND ION EFFECTS AND THEIR MITIGATION IN FCC-ee

K. Ohmi, M. Tobiyama, H. Fukuma
KEK, 1-1 Oho, Tsukuba, 305-0801, Japan

Abstract

High current and high repetition beam causes electron cloud and ion build-up, which result in two stream type of instability. We discuss build-up of electron cloud and ion, and related instabilities in FCC-ee. Latest result of ion instability in SuperKEKB is reported.

INTRODUCTION

Electron cloud and ion effects in FCC-ee is preseneted in this paper. These effect is serious for storage rings operated with high current and high repetition beam. FCC-ee is designed so that total synchrotron radiation loss is 50 MW. The effects in FCC-ee Z is most serious, because bunches are stored every 2.5 or 7.5 ns with total current of 1.45 A. In high energy FCC-ee; H and t options, the number of bunch is limited by handreds due to the total radiation loss. These instability is less serious in W, H and t options.

Ion effects in SuperKEKB is discussed, while electron cloud effects in SuperKEKB is discussed in Ref. [1].

ELECTRON CLOUD EFFECTS

We first evaluate threshold of fast head-tail instability caused by electron cloud, and then how the electron cloud build-up compare with the threshold value.

Threshold of Electron Density for Fast Head-Tail Instability

The fast head-tail instability is caused by the electron cloud moving in a positron bunch with a frequency

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}, \tag{1}$$

where λ_p is a positron line density in a bunch, namely $\lambda_p = N_p/(\sqrt{2\pi}\sigma_z)$. Beam, which is modulated by the electron oscillation, experiences the fast head-tail instability above a threshold density of the electrons. The threshould density of electron cloud is expressed by [2]

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\langle\beta_y\rangle L}, \tag{2}$$

where $K = \omega_e\sigma_z/c$ and $Q = min(\omega_e\sigma_z/c, 7)$. Table 1 shows beam parameters, the fequency in Eq.(1) and the threshold density in Eq.(2) for FCC-ee.

Coherent Head-Tail Instability in the Simulation

The fast head-tail instability caused by the electron cloud is simulated by a code "PEHTS" [3]. Electrons with a density distribution are placed in a beam line, and interaction with beam is calculated in every passage of a bunch. The bunch is transffered by a revolution matrix for the next interaction. Figure 1 shows evolution of the vertical beam size and the beam-electron centroid along a bunch after 500 turns at the electron density $\rho_e = 1.0 \times 10^{10}$ m^{-3}. The threshold density in the simulation, $\rho_{e,th,sim} = 0.8 \times 10^{10}$ m^{-3}, agrees with that in Table 1.

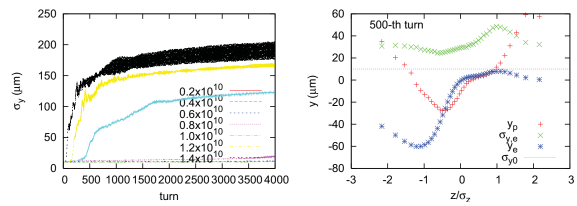

Figure 1: Evolution of the vertical beam size (left) and beam-electron centroid along a bunch after 500 turn (right).

Electron Cloud Build-up

We next discuss how high density of the electron cloud is built-up. The electron cloud is formed by photo-electrons and their secondary electrons. Photon production rate per revolution per positron is given by

$$n_\gamma = \frac{5}{2\sqrt{3}}\frac{\alpha\gamma}{\rho_{bend}}, \tag{3}$$

where $\alpha = 1/137$ is the fine structure constant. The critical energy is

$$u_c = \frac{3\hbar c}{2}\frac{\gamma^3}{\rho_{bend}}. \tag{4}$$

Electrons are created by photons hitting a chamber wall with a quantum efficiency around $Y_1 \approx 0.1$. Electron production by a bunch per meter passage is given by

$$n_{e,1} = n_\gamma Y_1 N_p \tag{5}$$

For FCC-ee-Z, $\rho_{Bend} = 11.3$ km and $N_+ = 3.3 \times 10^{10}$, the eletrcon production is $n_{e,1} = 1.8 \times 10^8$ m^{-1}. Assuming the chamber cross section of 0.005 m^2, increment of the electron density by a bunch passage is $\Delta\rho_e = 3.5 \times 10^{10}$ m^{-3}. This density after a passage of a bunch is already 4.4 times higher than the threshold $\rho_{e,th} = 0.8 \times 10^{10}$ m^{-3} in Table. 1. An ante-chamber protect the density increment, because most of electrons are produced at the chamber slot. The effective increment of the density near the beam is order of 1% of the above value. Secondary emission amplifies the electrons even the number of initial electrons are small. To evaluate the electron density more precisely, a simulation in which

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Table 1: Parameters for Electron cloud instability.

Parameter		CEPC	FCC-ee-Z	FCC-ee-W	FCC-ee-H	FCC-ee-t
Energy	E (GeV)	120	45.5	80	120	175
Bunch population	$N_{\pm}(10^{10})$	37.1	3.3	6	8	17
Number of bunch	N_b	50	90300	5162	770	78
Beam size	σ_x/σ_y (μm)	583/32	95/10	164/10	247/11	360/16
Bunch length	σ_z (mm)	2.6	5	3	2.4	2.5
Averaged vert. beta	β_y (m)	50	100	100	100	100
Synchrotron tune	ν_z	0.216	0.015	0.037	0.056	0.075
Electron frequency	$\omega_e/2\pi$ (GHz)	137	127	171	174	171
Electron osc. period	$\omega_e\sigma_z/c$	7.5	13	11	8.7	9.0
Threshold density	$\rho_{e,th}$ (10^{10} m^{-3})	104	0.8	3.4	7.7	15

electron motion is simulated with considering beam force and magnetic field, is used.

Electron cloud build-up is simulated using a code "PEI" [4] for FCC-ee. Maximum secondary emission yield is assumed $Y_{2,max} = 1.8$ at $E_e = 300$ eV. This number is somewhat pesimistic. The best number is around $Y_{2,max} \sim 1$. Figure 2 shows the electron line density in every passages of bunches. For uniform distribution, the electron density is given by dividing the chamber cross section. Actually the electron density near the beam is several or 10 times higher than the averaged density. The central density m^{-3} is estimated to be 10^3 times larger than the line density m^{-1}. Top left plot in Fig.2 depicts the electron density for FCC-ee-Z. The density is several times 10^{13} m^{-3}. Even if the density is reduced by 1% using the antechamber, it is difficult to achieve the threshold density 0.8×10^{10} m^{-3}.Very careful cure is necessary, for exmple, using weak magnets, grove, coating and so on. Top right plot depicts the electron density for W. The density is 10 times higher than the threshold. 1/10 reduction of electron cloud is not difficult. In FCC-ee-W the electron cloud effects are critical, but are managiable. In H and t, the density is lower than the threshold; they are safe for the instability.

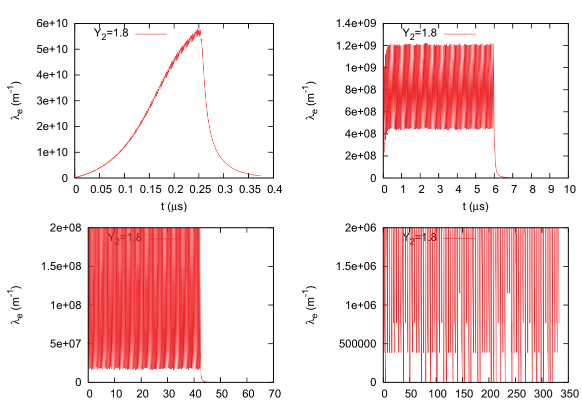

Figure 2: Electron cloud build-up in FCC-ee. Top left, right, bottom left and right are given for Z, W, H and t, respectively.

CEPC is designed as a single ring collider. To get gain in a Z factory, a partial double ring is proposed. Bunches are injected in a train with the length of 3,000 m. Bunch spacing is much narrower than that with uniform filling in the initial design. In Higgs operation, a bunch train contains 50 bunches with 50 m spacing. Figure 3 shows electron cloud build-up for $Y_{2,max} = 1.8$ and 2.2. The density is $\rho_e \sim 1 \times 10^{12}$ and 4×10^{13} for $Y_{2,max} = 1.8$ and 2.2, respectively, where $\rho_{e,th} = 1 \times 10^{12}$ m^{-3}. The electron cloud instability may be critical, but not very serious for H.

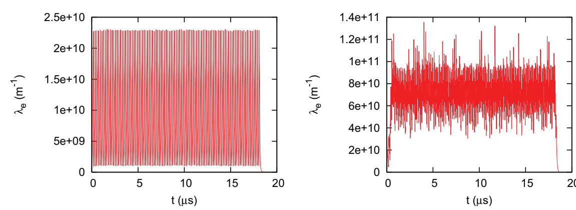

Figure 3: Electron cloud build-up in CEPC. A bunch train contains 50 bunches with 50 m spacing.

ION INSTABILITY

Ion instability can be serious in high current and high repetition electron storage rings [5]. Ions, which are trapped in a electron bunch train, oscillate with a frequency

$$\omega_{i,x/y} = \sqrt{\frac{\lambda_e r_i c^2}{\sigma_{x/y}(\sigma_x + \sigma_y)}}, \quad (6)$$

where the ion freqency is far slower than that of electrons, because $r_i = e^2/(4\pi\epsilon_0 M_i c^2)$ is smaller than r_e due to the mass ratio m_e/M_i. The oscillation is not inside a bunch, but is along a bunch train. The electron line density is now that of the bunch train, $\lambda_e = N_e/L_{sp}$.

There is no stabilization due to the synchrotron oscillation. The bunch train is basically unstable for ion instability; no threshold exists. The threshold is determined by other damping mechanisms like head-tail damping, feedback damping time, and so on.

A simulation code based on a rigid bunch model has been used for studying the ion instability in both of trapping and fast instability [7].

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Ion Instability in FCC-ee-Z

We focus on the Z factory. FCC-ee uses 400MHz cavities, thus bunch spacing is 2.5 ns. Using parameters in Table 1, the ion frequency is given by $\omega_i = 2\pi \times 87$ MHz and $\omega_i L_{sp}/c = 1.4$, where $\beta_{xy} = 50$ m. The horizontal beam size is assumed to be $\sigma_x = \sqrt{2\varepsilon_x\beta_x}$ by taking into account of dispersion. The number $\omega_i L_{sp}/c = 1.4$ is critical to judge whether ions are trapped or not in the bunch train. A simulation based on a ridig bunch model [7] is performed. The simulation calculates betatron amplitude of every bunches interacting with an ion cloud in turn-by-turn. The betaron amplitude grows when the ion instability arises, while the bunch-by bunch feedback, which is implimented in the simulation, suppress the betatron oscillation. Figure 4 shows the growth of the vertical betatron amplitude due to the ion instability. 100, 200, 400 and 800-th bunch. Ions are kept and drift after interaction with the end of bunch train. Top left depcis growth of the ion instability. Thr growth time is around 20 turns. Top right and bottom plots shows the growth with the bunch-by-bunch feedback with the damping time 10 and 50 turns, respectively. The betatron motion is suppressed by the feedback with 10 turns of damping time, but not suppressed by that with 50 turn.

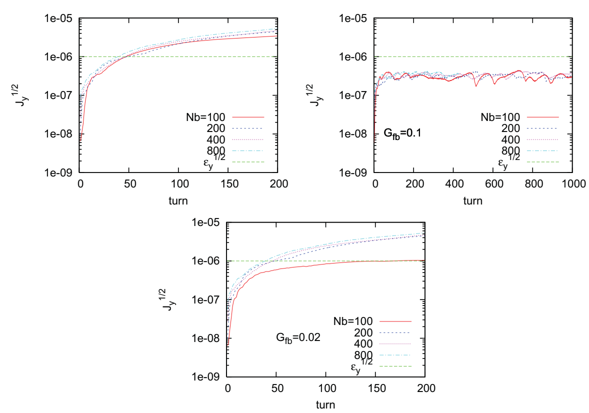

Figure 4: Evolution of the vertical betatron amplitude of 100,200,400 and 800-th bunch. Top left, top right and bottom plots depict the growth without feeback, with feedback damping time 10 and 50 turns, respectively.

Ion Instability in SuperKEKB

An instability, which seems to be caused by ions, has been observed in SuperKEKB. Figure 5 shows growth time for horizontal and vertical unstable mode. The instability is suppressed by the bunch-by-bunch feedback system normally. The measurement was done by recording motion of every bunches after switch off of the feedback. The beam condition, which is date, current and the number of bunches, is written in the right part of the plots.

The mode number is defined by

$$\text{Mode} = 5120 - \frac{\omega_i}{\omega_0}, \tag{7}$$

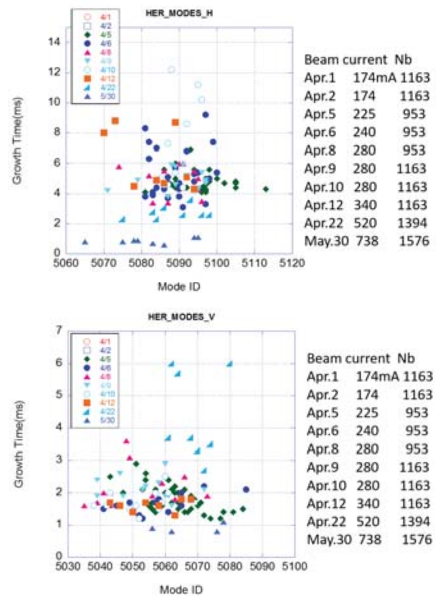

Figure 5: Unstable mode and their growth time in HER. Top and bottom plot are horizontaland vertical mode, respectively.

where ω_i is given by Eq.(6) as in the usual theory. The measurement gave $\omega_{i,x} = 2\pi \times 3$ MHz and $\omega_{i,y} = 2\pi \times 6$ MHz. Figure 6 shows the vertical mode number as a function of the beam current, Carbon monooxiside (CO) is dominant in SuperKEKB [6]. The horizontal mode which is drawn by the cyan lines is consistent with the measurement. Vertical mode is drawn by blue lines for various vertical emittance. The design emittance is $\varepsilon_y = 11$ pm.

The frequency ratio of vertical/horizontal in Fig.5 is 60/30=2. This means emittance coupling is 25%, if beam size ratio equal to ion size ratio in a naive theory. If ion size is large, beam size ratio is not necessary so large as shown later.

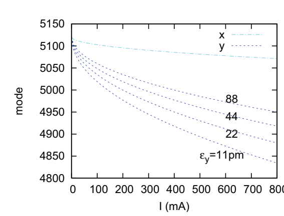

Figure 6: Mode number as function of beam current estimated by Eq.(6) for various vertical emittance.

Ion density can be estimated by measuring the tune shift. To measure the bunch-by-bunch tune, ion induced coherent motion is suppressed by the bunch-by-bunch feedback system. The tune of each bunch is measured by frequency response in the gated excitation of the bunch. Figure 7 shows the tune shift along a bunch train. The tune shift increases along the train. The last point of the tune shift is given for the pilot bunch separated 23 buckets (46ns) from the train end. We note the horizontal tune shift is roughly twice larger than

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the vertical one. Tune shift due to the ion cloud is expressed by

$$\Delta\nu_x + \Delta\nu_y = \frac{\rho_i r_e \beta_{x,y}}{\gamma} L. \quad (8)$$

The tune shift sum is 0.0022 as shown in Fig.7. The ratio of the vertical/horizontal tune shifts is equal to the aspect ration of the ion size, $\Delta\nu_x/\Delta\nu_y = \sigma_{i,y}/\sigma_{i,x}$=2. For $\beta_{x,y}$ = 12 m, ion density is obtained as $\rho_i = 2.8 \times 10^{11}$ m^{-3}.

Vacuum presure in SuperKEKB is about 10^{-7} Pa for CO [6]. The number of created ions is 90 m^{-1} for the bunch population $N_e = 2 \times 10^{10}$. The line density of ion at the last bunch passage is $\lambda_i = 90 \times 1576 = 1.4 \times 10^5$ m^{-1}. Since ions are trapped by the bunch train, ions are expected to be located at the beam position. The density should be $\rho_i = \lambda_i/(2\pi\sigma_{e,x}\sigma_{e,y}) = 7.4 \times 10^{12}$ m^{-3}, therefore the tune shift sum should be $\Delta\nu_x + \Delta\nu_y = 0.057$, where the beam size is $\sigma_{e,x} = 0.25$ mm and $\sigma_{e,y} = 0.012$ mm.

Considering the tune shift ratio and density reduction, ion cloud size is estimeted as $\sigma_{i,x} = 0.28$ mm and $\sigma_{i,y} = 0.56$ mm. This ion size can not be explained by a simple theory.

We attempt to reproduce the measurement of mode spectra mentioned above using a simulation, where I=600 mA, 1576 bunches by 3 buckets. Figure 8 shows growth of betatron amplitude with the feedback. Green and blue lines of the left plot correspond to for the feedback damping time, 1ms and 0.5ms, respectively. Ion instability is suppressed by the feedback with 0.5ms damping time. The feedback is cut off after 1,000 turn (0.5ms damping). Right plot depicts unstable bunch oscillation in vertical after the feedback OFF, at 1250-th turn. The frequency is around f_{sim} = 13 MHz, that is slower than $\omega_i/2\pi$ = 25 MHz in Eq.(6) but is faster than that in mode spectra ($f_{mes.} \sim 6$ MHz).

Figure 9 shows ion distribution along the bunch train, where bunch motion is suppressed by the feedback but remains ~ 10% as shown in Fig.8. The ion cloud is enlarged due to interaction with the beam. The vertical size seems to be still smaller than horizontal one. In a bending magnet, since only vertical ion size increase, better agreement with the eperimentmay be expected.

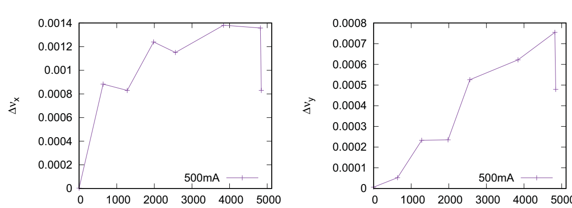

Figure 7: Horizontal and vertical tune shift along a bunch train. The last bunch is separated from train end by 23 buckets.

SUMMARY

Electron cloud build-up and the threshold of the electron density were evaluated for FCC-ee. The electron density

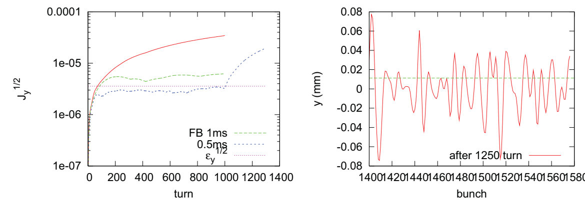

Figure 8: Left plot depicts evolution of vertical amplitude for No feedback (red), feedback with 1ms and feedback with 0.5ms. Feed back is OFF at 1000-th turn (blue line). Right plot depicts bunch oscillation pattern after OFF (1250-th turn).

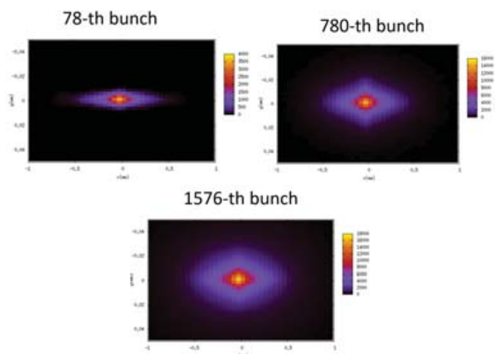

Figure 9: Ion distribution along the bunch train. Top left, right and bottom are ion distributions when 78, 780 and 1576-th bunches pass, respectively.

produced by a bunch is $\rho_e = 3.5 \times 10^{10}$ m^{-3} per bunch passage, while the threshold is $\rho_{e,th} = 0.8 \times 10^{10}$ m^{-3} for FCC-ee Z. In SuperKEKB, $\rho_e = 1.5 \times 10^{11}$ m^{-3} per bunch passage and $\rho_{e,th} = 1 \times 10^{11}$ m^{-3}. FCC-ee Z is harder than SuperKEKB to suppress the instability. Antechamber suppresses the primary photo-electrons to 1%. Ante-chamber is indispensable to suppress the electron cloud. Further cures, such as weak magnets, groove, coating etc., are necessary. Comparison of the measurement with simulation/theory is being performed in SuperKEKB.

Ion instability should be serious in FCC-ee Z. In simulation, vacuum pressure 10^{-8} Pa and the bunch-by-bunch feedback with 10 turns damping time are reqired. Ion instability has been observed in SuperKEKB. There are several unintelligible facts:

- Unstable mode (frequency) is slower than the prediction in Eq.(6).
- Tune shift is far smaller than a prediction from ion production rate.
- Horizontal tune shift is larger than vertical one.

They can be solved partially in simulation. Anyway the ion density is far smaller than the prediction, therefore ion instability may not be serious in high intensity electron storage rings.

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