ELECTRON CLOUD EFFECTS IN POSITRON STORAGE RINGS

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Abstract

This is a review of electron cloud effects/instabilities observed in positron storage rings. Coupled bunch and fast head-tail instabilities caused by an electron cloud have been studied for a long time, and the agreement of experiments and simulations/theory is almost perfect in positron storage rings. Mitigation of the instabilities based on the experiments and simulations have improved the accelerator performance drastically. It is essential to mitigate the instabilities in the present and future positron and proton rings.

INTRODUCTION

Electron cloud effects have been observed clearly in positron storage ring. The primary electron source is identified without ambiguity as photo-emission. Synchrotron radiation is completely understood, and the electron production rate of the photoemission is very high: that is, the quantum efficiency is ≈ 0.1. For the secondary emission, many measurements have been performed using samples in beam lines of synchrotron radiation sources. Electron density in accelerator chambers has been evaluated by computer simulation using the primary and secondary rates. The electron density also has been measured in the accelerator operation. The agreement of the density is reasonable.

The electron cloud causes fast coupled bunch instability [1] and fast head-tail instability [2]. These instabilities have been a serious problem for the last 30 years, and mitigation of them have improved accelerator performance, especially in e^+e^- colliders. A strong coupled bunch instability had been observed in positron beam operation of KEK photon factory since 1990 [3]. Computer simulations and theory based on a photoemission model are in a good agreement with the growth rate and unstable mode of the coupled bunch instability. The instability have been observed also in e^+e^- collider, KEK B factory and PEP-II. A beam size blow-up has limited the luminosity performance in KEKB. It had been identified as fast a head-tail instability caused by electron cloud. Suppression of the electron cloud contributes drastically to the luminosity increase. This effort has been continued in SuperKEKB, which is an upgrade of KEKB. In this paper, we summarize the history of the electron cloud instabilities in positron storage rings.

COUPLED BUNCH INSTABILITY OBSERVED IN KEK-PHOTON FACTORY

KEK-PF is 2nd generation light source with the energy of 2.5 GeV and the circumference of 186 m. KEK-PF had been operated with positron storage to avoid ion instability since 1989. A coupled bunch instability was observed at a very low threshold current of 10-20 mA under multi-bunch operation with 200-300 bunches [3], where the harmonic number was $h = 312$. This instability was not observed in electron storage in the same ring, KEK-PF.

Figure 1 presents an example of unstable mode spectrum published in the paper [3]. The unstable modes are distributed broadly and relatively low frequency betatron side band, $nf_0 - f_\beta$ ($n = 20 \sim 30$), where f_0 and f_β are revolution and betatron frequency, respectively. These unstable modes are explained by a short range wake up to 10 ns induced by electron cloud.

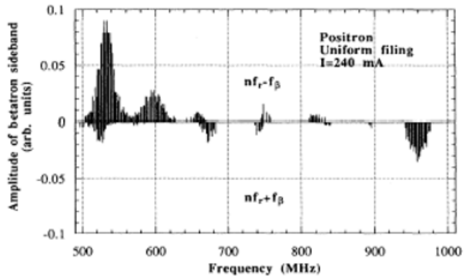

Figure 1: Unstable mode of a coupled bunch instability observed in positron beam operation in KEK-PF [3].

To understand this instability, photo-electron cloud model was proposed [1]. The scenario is summarized as follows,

1. Positron beam emits photons due to synchrotron radiation.
2. Electrons are produced at the beam pipe wall due to photo-emission, where electron production efficiency is $\sim 0.1e^-/\gamma$.
3. Electrons are attracted by positron beam and they interact with each other. Electrons travel in the beam pipe for 20-50 ns and then it is absorbed into the wall. Secondary electrons are produced from the electron absorption.
4. In multibunch operation ($\leq$ 10 ns spacing), electrons are introduced continuously, leading to the formation of the electron cloud.
5. The electron cloud induces bunch-by-bunch correlation and results in an coupled bunch instability.

Figure 2 presents a simulation model and electron cloud distribution given by the model based on this scenario [1]. Top picture sketches electron production in a beam chamber cross-section. The electron density in the chamber is shown in the bottom picture. The typical electron density in KEK-PF was $\rho_e = 10^{12}$ m$^-$3.

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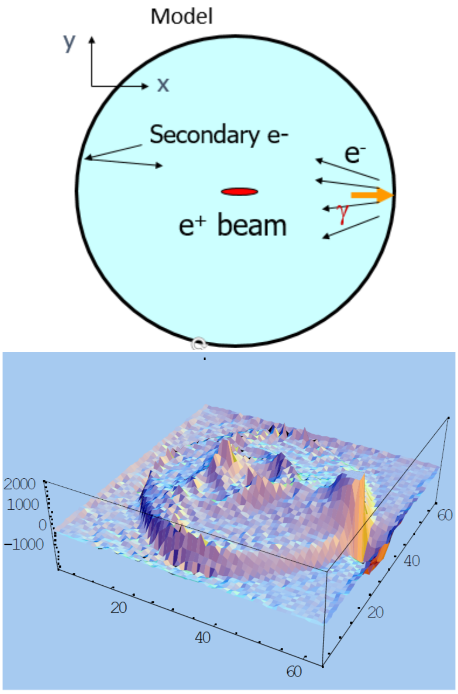

Figure 2: Simulation model of electron cloud build-up (top) and an example of electron cloud density in a beam chamber (bottom) [1].

B factories, KEKB and PEP-II planned to start the operation in 1998-1999. People were afraid of the significant impact of electron cloud instability effects on the performance of the B factories. Electron cloud study for feasibility of B factories had been performed in BEPC under a collaboration of IHEP and KEK. Similar coupled bunch instability had been observed in BEPC (Beijing electron positron collider) [4].

ELECTRON CLOUD INSTABILITIES IN KEKB

KEKB, which is asymmetric electron-positron collider, had started operation in 1999. The energy was 3.5 and 8 GeV for positron and electron beams, respectively. 1585 bunches with the population of $6.3 \times 10^{10}(e^+)$ and $4.4 \times 10^{10}(e^-)$ were stored in the rings with the circumference 3016 m. KEKB achieved the luminosity of 2.2×10^{34} cm^{-2}s^{-1} in 2009. Electron cloud phenomena had been observed since the start of the operation.

Coupled bunch instability

A coupled bunch instability, which was similar to the one observed at KEK-PF and BEPC, had been observed in KEKB. Though the instability had been basically suppressed by bunch-by-bunch feedback, it was an observed phenomenon, in which stored beam was sometimes dumped suddenly due to the instability. The coupled bunch instability was studied by ON-OFF of the bunch-by-bunch feedback system. Every bunch position was recorded several thousand turns after feed back OFF.

The coupled bunch instability was analyzed theoretically by evaluating the wake force of the electron cloud [1] and by simulating bunch motion under the interaction with electron cloud. The interaction between positron bunches and electron cloud is expressed by

$$\frac{d^2\boldsymbol{x}_p}{ds^2} + K(s)\boldsymbol{x}_p = \frac{r_e}{\gamma}\sum_{e=1}^{N_e}\boldsymbol{F}(\boldsymbol{x}_p - \boldsymbol{x}_e)\delta_P(s - s_e) \quad (1)$$

$$\frac{d^2\boldsymbol{x}_e}{dt^2} = 2r_e c^2 \sum_{p=1}^{N_b}\boldsymbol{F}(\boldsymbol{x}_e - \boldsymbol{x}_p)\delta_P(t - t_p(s_e)) + \frac{e}{m_e}\frac{d\boldsymbol{x}_e}{dt}\times\boldsymbol{B} - \frac{e}{m_e}\frac{\partial\phi}{\partial\boldsymbol{x}}, \quad (2)$$

where indices p and e of $\boldsymbol{x}$ denote the positron and electron, r_e the classical electron radius, m_e the electron mass, c the speed of light, e the electron charge, σ the transverse beam size, ϕ the normalized photoelectron potential, δ_P, the periodic delta function for the circumference, and F the Coulomb force in two-dimensional space expressed by the Bassetti-Erskine formula. The schematic view of the simulation is shown in Figure 3.

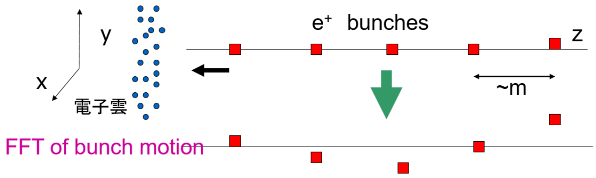

Figure 3: Simulation model of the coupled bunch instability. A bunch train interacts with electron cloud represented by macro-particles. Successive interaction induces a coupled bunch instability with certain unstable modes.

Figure 4 presents unstable modes of the coupled bunch instability given by bunch-by-bunch position measurement and the simulation. In KEKB, weak solenoid magnets are installed to suppress the electron cloud as shown later in detail. Top and bottom raws show unstable modes without and with solenoid magnets, respectively. Left and right columns present the results of the measurement and the simulation, respectively. The unstable modes of the coupled bunch instability depend on collective electron motion in the electron cloud. Electrons in the solenoid magnet slowly move along chamber surface with a frequency $\omega = \lambda_p r_e c^2/r^2\omega_c$, where λ_p the average line density of positron beam, r the radius of electron motion (smaller than chamber radius), $\omega_c = eB/m_e c$ the cyclotron frequency. Figure 5 shows the electron distribution in the drift space (top) and solenoid magnets (bottom). The radius of electron motion is around $r = 4.5$ cm, while the chamber radius is 5 cm. White dot is position of the bunch passing through. The dot oscillates each bunch passage with the mode frequency. The electron distribution also changes its shape in each bunch passage.

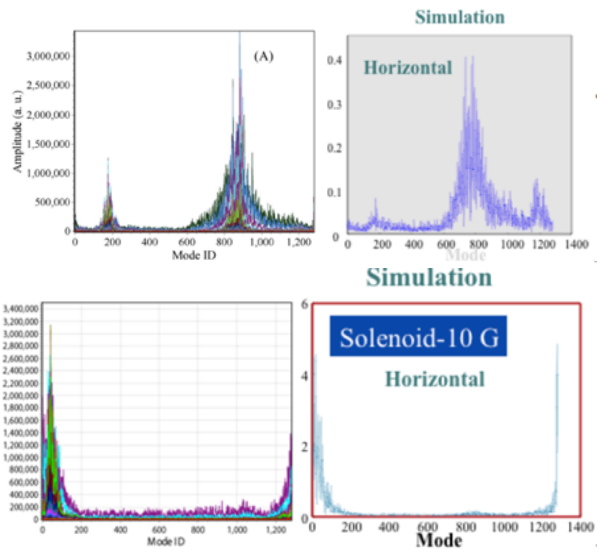

Figure 4: Unstable modes of the coupled bunch instability caused by electron cloud in KEKB positron ring. Top and bottom plots show unstable modes without and with solenoid magnets, respectively. Left and right are given by the measurement and the simulation.

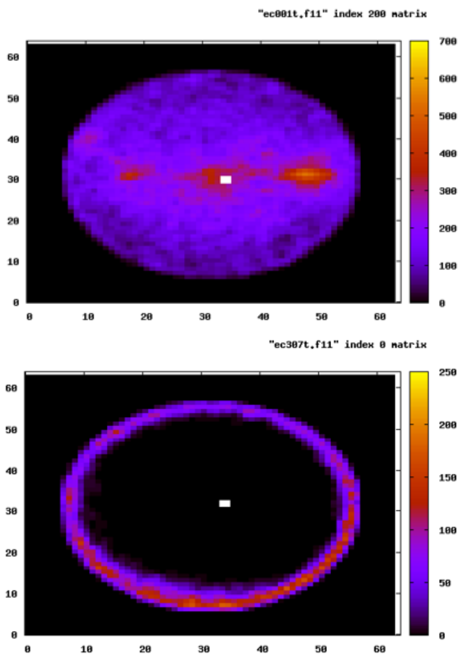

Figure 5: Simulated electron distribution in the beam chamber cross-section. White dot is bunch position passing through.

Another typical coupled bunch instability had been observed in DAFNE. Electrons in the bending magnets are dominant in DAFNE. Simulations show vertical stripe of electron density is formed in the bending magnet. Corrective motion between positron beam and the stripe induces very slow unstable mode of coupled bunch instability. Figure 6 presents simulation of beam motion, unstable modes and electron distribution interacting with the beam. Horizontal instability dominate the vertical as shown in top plot. A mode with the slowest frequency is induced as shown in the mid plot. The vertical stripe from the bottom picture of Fig.6 oscillates slowly coherently and correctively. Its collective motion is correlated with the bunch motion.

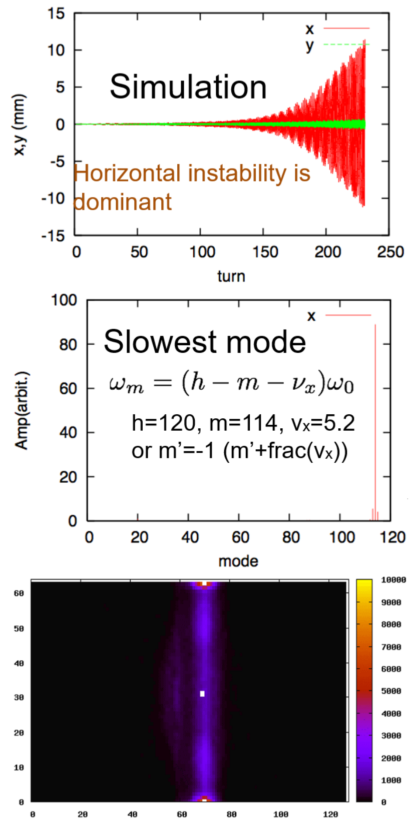

Figure 6: Simulation of a coupled bunch instability observed in DAFNE. Top and middle plots show simulated bunch motion and unstable modes. Bottom shows electron distribution interacting with bunch train (white dot).

Beam size blow-up and its cure

In KEKB, a blow-up of vertical size of the positron beam had been observed above a threshold current in multibunch operation. The blow-up limited luminosity performance. Figure 7 presents the beam size blow-up. The beam size blowup started at 400 mA (green dots) for filling by 4 bucket (8ns) spacing. The beam size increased more than 5 times at 600 mA.

To cure the beam size blow-up, solenoid field is applied on the beam chamber of entire positron ring. First, permanent magnets were attached on the chamber surface. The effect was not clear because the area length attached was not sufficient (~800m) and response for magnets ON/OFF was not observable. A strong and strange beam loss caused by coupled bunch instability was observed after attachment. The growth seemed somewhat stronger than before. The permanent magnets were replaced by solenoid coil in the

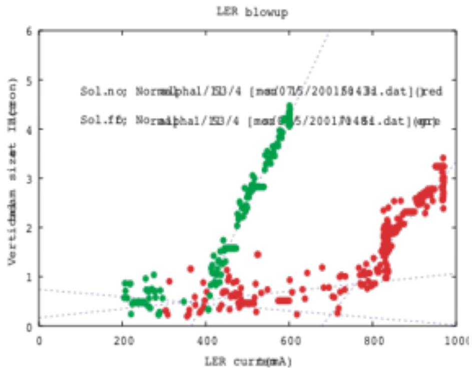

Figure 7: Beam size blow-up as function of positron beam current. Green and red dots are given for without/with solenoid magnets.

summer of 2000. Figure 8 presents pictures of the solenoid magnets wound in the ring.

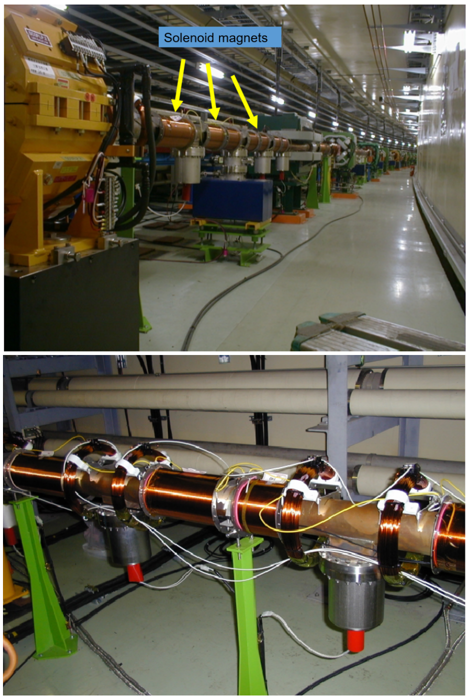

Figure 8: Weak solenoid magnets wound in the whole of KEKB-LER positron ring.

The solenoid magnets were added year-by-year. The winding history is summarized as

1. A lot of permanent magnets were put along the arc section in the ring ~800m.
2. These magnets (800m) were replaced by solenoid magnets (Summer 2000).
3. Additionally 500m magnets are wounded (Jan. 2001).
4. Magnets were added in the straight section (Apr. 2001).
5. Add solenoids even in a short free space (Summer 2001).
6. Solenoid magnets cover 95 % of the free space (~2005).
7. Inside of ¼ of Quadrupoles (2005)

The beam size blow-up was remarkably suppressed by the solenoid magnets as shown by the red dots of Figure 7.

The effect of the solenoid magnets became significant when additional winding (800+500=1300m) has been done in 2001. Luminosity performance was compared for solenoids ON/OFF. Figure 9 presents the luminosity performance for filling by 4 buckets. Top plot shows the specific luminosity for solenoids ON/OFF. The improvement of luminosity performance was more than twice in those days. Furthermore higher current operation made possible with help of the solenoid magnets. Bottom plot shows comparison of the luminosity for solenoid winding of 800 and 1300 m. The luminosity was saturated at 500 mA at 800 m winding, while the luminosity increased linearly by 750 mA at 1300m winding. Winding more solenoids, saturation of beam current and luminosity increased further. The design luminosity 1×10^{34} cm^{-2}s^{-1} was achieved in 2003.

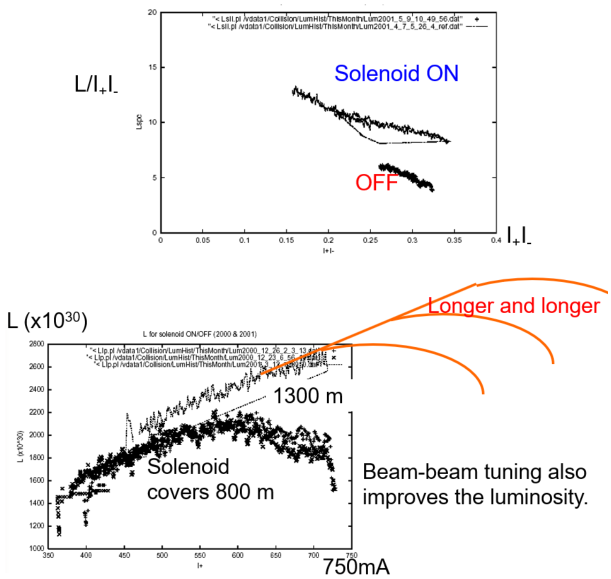

Figure 9: Luminosity performance with/without the weak solenoid magnets. Top plot shows the specific luminosity for solenoid ON/OFF. Bottom plot shows comparison of the luminosity for solenoid winding of 800 and 1300 m.

Figure 10 presents luminosity history of KEKB. We can observe luminosity increase for the solenoid winding. Finally maximum luminosity 2.2×10^{34} cm^{-2}s^{-1} was achived in 2009.

Interpretation of Fast head-tail instability

Studies why the beam size blowup occur had continued in parallel with the solenoid winding. The blow-up was observed at multi-bunch operation with narrow bunch spacing ($\leq$ 16 ns). There were no correlation in motion between bunches. It seemed that the blow-up was due to a single

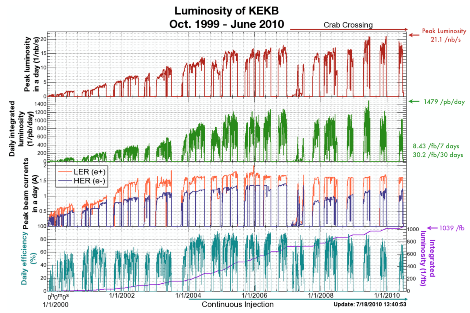

Figure 10: History of luminosity in KEKB.

bunch effect, though instability sources are accumulated in multi-bunch operation.

A synchrotron sideband correlating with the beam size blow-up had been measured in experiments [5]. Figure 11 shows the sideband along the bunch train. The sideband appears $\approx \nu_y + 1.5\nu_s$. Betatron and sideband shift is increasing along the bunch train. This tendency is explained by increasing electron cloud density along the bunch train.

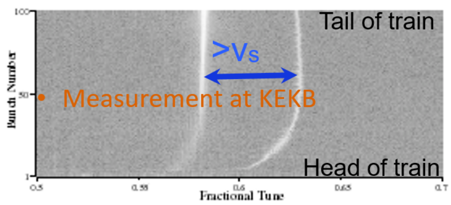

Figure 11: Measurement of synchro-betatron sideband correlated to the beam size blow-up [5].

The beam size blow-up was finally explained by fast head-tail instability caused by electron cloud. The instability was analyzed by a short range wake force induced by an electron cloud [2,6] and a simulation of bunch-electron cloud interaction. Figure 12 presents simulation results given by similar approach as the strong-strong beam-beam simulation [7]. A bunch represented by macro-particles interacts with macro electrons refreshed collision-by-collision. Top and bottom plots show variation of the vertical beam size and Fourier amplitude of vertical motion, respectively. Top plot shows the threshold of electron cloud density is $\rho_e = 0.8 \times 10^{12}$ m^{-3}. Synchro-betatron sideband appeared above the threshold in the Fourier analysis. Fourier amplitude for various feed back gain was given by the simulation. The betatron peak around 0.59 is suppressed by the feedback, while the sideband is not suppressed. The sideband appears somewhat higher than $\nu_y + \nu_s$. The sideband tune agrees with the measurement in Fig.11.

ELECTRON CLOUD INSTABILITIES IN SUPERKEKB

SuperKEKB, which was an upgrade of KEKB, was designed to realize collision with a large crossing (Piwinski) angle. Piwinski angle is designed to have a very large value, $\sigma_z\theta_c/\sigma_x \approx 20-25$. Beam commissioning of Phase-I was

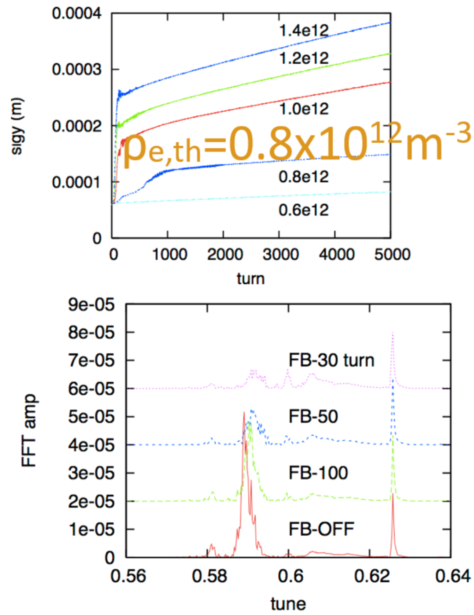

Figure 12: Simulation of bunch electron cloud interaction. Top plot depicts variation of beam size for evolution of turns, and bottom plot depicts Fourier spectrum of the vertical dipole amplitude of the bunch.

performed in 2016 from February to June without interaction region and Phase-II commissioning was performed from March to July 2018 after installation of IR magnets and the BELLE-II detector. Vertical beam size blow-up due to the electron cloud has been observed in the positron ring (LER) in the early stage of Phase-I commissioning. Occurrence of electron multi-pacting was suspected at area near bellows in the early stage of commissioning, since this area, which occupies about 5% of whole ring, was not coated by TiN. The emittance growth was suppressed by weak permanent magnets, which cover the bellow drift space. This means the electron cloud in the bellow area dominates the instability. It was good opportunity to bench mark the threshold of electron density, knowing electron density at the uncoated bellow area. Electron cloud has been monitored at an Aluminum test chamber w and w/o TiN coating.

The vertical beam size was measured for bunch train with various filling in the early stage of the commissioning as shown in Figure 13. The measurements were performed for several bunch filling, 2, 3, 4, 6 bucket spacing, where the total number of bunches is 600. Threshold current of the beam size blow-up for each bunch spacing were obtained from the figure. They are 160, 200, 260 and 500 mA for 2, 3, 4 and 6 bucket spacing, respectively. Corresponding bunch populations are 1.6, 2.0, 2.7 and 5.2×10^{10}, respectively.

Simulations using the beam parameters were executed to evaluate the threshold of electron density. Figure 14 presents simulation results for $N_p = 1.6, 2.0, 2.7$ and 5.2×10^{10}. The threshold density is weakly dependent on the bunch population, $\rho_{e,th} = 3 \sim 4 \times 10^{11}$ m^{-3}.

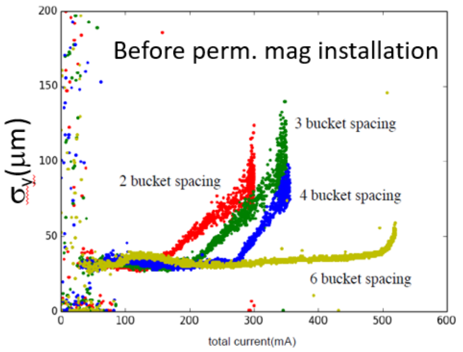

Figure 13: Beam size as a function of beam current in the early stage of SuperKEKB commissioning (June, 2018).

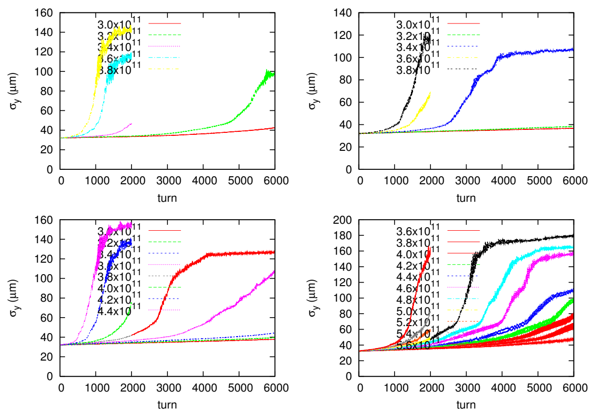

Figure 14: Vertical emittance growth in simulation PEHTS. Top left, top right, bottom left and bottom right are evolution of the vertical beam size for N_p = 1.6, 2.0, 2.7 and $5.2{\times}10^{10}$, respectively.

Figure 15 shows measured electron density in the uncoated test chamber as a function of the beam current for the various filling. The threshold given by the blow-up measurement and simulation is plotted by circles and stars, respectively. Note that the density is the value in the uncoated chamber which occupies 5% of the ring, thus the simulated density is multiplied by 20. The brown line is given by a simple formula based on a coasting beam model [6, 8],

$$\rho_{th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta_y L} \tag{3}$$

The electron oscillation frequency inner bunch is $\omega_e\sigma_z/c \approx 17$, where $\omega_e^2 = .2\lambda_b r_e c^2/(\sigma_y\sigma_x)$. The quality factor of electron cloud induced by the wake force is less than 10 [6]. Assuming electron accumulation factor near the beam $K = \omega_e\sigma_z/c$ and $Q = 7$, the threshold density is constant as shown in Figure 15. $Q = 7$ due to beam-electron interaction works as the quality factor in the instability, because electron oscillation frequency $\omega_e\sigma_z/c \approx 17$ is sufficiently larger than Q. In this condition, the threshold is independent of the bunch intensity. For short bunch, Q is truncated by $\omega_e\sigma_z/c$, thus the threshold density decreases for increasing beam current. Measurement and simulation show the threshold increases for the beam current. K may be somewhat smaller than $\omega_e\sigma_z/c$, or electrons other than the bellow section may contribute the instability. Nevertheless, we observe agreement between measurement and simulations of a factor of 2.

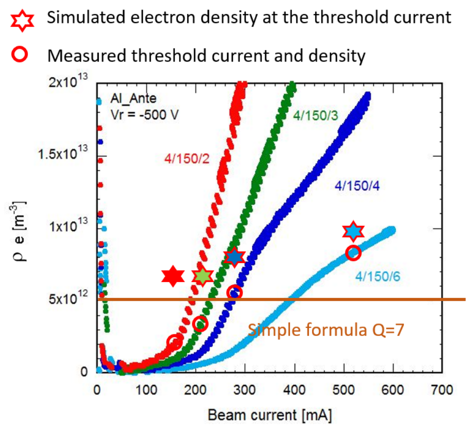

Figure 15: Measured electron density as function of the beam current for the various filling at the uncoated test chamber. The measured blow-up threshold current is plotted circle, and the simulated threshold density at the beam condition was plotted by star.

Tune shift and electron cloud density

Electron cloud causes a positive tune shift due to the attractive force between beam and electron cloud. The tune shift depends on the electron density and distribution. For flat distribution along x, only vertcal tune shift appears as

$$\Delta\nu_y = \frac{\rho_e r_e \langle\beta_{x,y}\rangle}{\gamma} C. \tag{4}$$

Transverse tune was measured along the bunch train for 3 bucket spacing filling. Figure 16 shows horizontal (top) and vertical (bottom) tune of bunches at 0, 150,300 and 450-th bucket.

The horizontal tune shift depends on the beam current (I): i.e., $\nu_x = 0.003$ for $I = 450$ mA and $\nu_x = 0.001$ for $I = 300$ and 400 mA. The vertical tune shift is $\nu_y = 0.005$, while the horizontal tune shift seems to be ambiguous. The averaged electron density is estimated to be $\rho_e = 4 \times 10^{11}$, that is, the local density is to be $\rho_e = 8 \times 10^{12}$ m^{-3} at the bellow area, if only the vertical tune shift is considered. Considering horizontal tune shift, the density is somewhat larger. The estimated density is in a good agreement with the one directly measured in the test chamber without TiN coating.

The coupled bunch instability caused by electron cloud has also been observed in SuperKEKB. Appearance of unstable mode was similar to that of KEKB. Attaching more solenoid magnets, unstable mode change from the drift type (top of Fig. 4) to the solenoid type (bottom of Fig. 4). Further addition of solenoid magnets suppressed the coupled bunch instability.

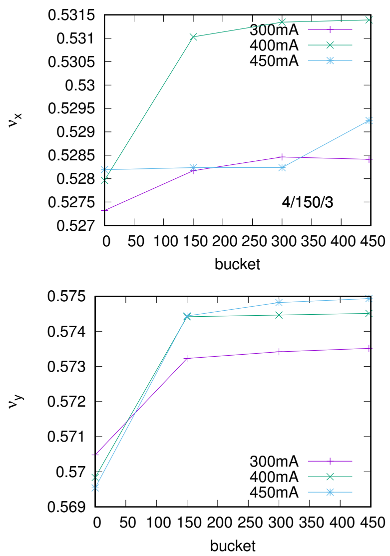

Figure 16: Tune shift along bunch train for 3 spacing filling.

SUMMARY

Electron cloud effects have been observed at positron storage rings. Electron cloud effects presented a significant challenge to the accelerator operation for the first time in KEKB/PEP-II. The history of mitigation of the electron cloud effects can be tracked by observing the success of KEKB

Luckily, electron cloud effects have been observed at KEK-PF before KEKB started operation. Electron cloud effects have been observed since the start of KEKB operation in 1999. Vertical beam size blow-up was one of the most serious issue for the achievement of the target luminosity $L = 10^{34}$ cm^{-2}s^{-1} in KEKB. Many collaborations have been done with SLAC, IHEP, CERN, INFN, BINP. Peak luminosity $L = 2.17 \times 10^{34}$ cm^{-2}s^{-1} and integrated luminosity 1 ab^{-1} was achieved in KEKB.

SuperKEKB was designed so as to mitigate the electron cloud effects. Beam size blow-up had been seen in the early stage of the commissioning. The electron source, which was uncoated bellow area, was cured by solenoid magnets. In 2020, the beam size blow up and coupled bunch instability have not been observed below the beam current of 1 A. The design beam current is 3.6 A. Further studies and cures may be necessary in the future.

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