ELECTRON CLOUD AT SuperKEKB

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Abstract

Several measures such as TiN coated aluminum ante-chambers, clearing electrodes and grooved structure have been taken to mitigate the electron cloud effects in the SuperKEKB positron ring. During phase 1 operation of SuperKEKB, where solenoid windings were not applied as a measure against the electron cloud, the electron cloud effects such as the beam size blowup, the nonlinear pressure rise, the betatron tune shift along a bunch train and the transverse coupled bunch instability were observed. Permanent magnets attached at aluminum-bellows-chambers that generate longitudinal magnetic field in the chambers were effective to reduce the electron cloud. In case of no solenoid windings, the threshold linear current density of the blowup was increased from 0.04mA/RF bucket in KEKB to 0.17mA/RF bucket in SuperKEKB owing to the measures mentioned above. This paper covers following subjects about the electron cloud at SuperKEKB, 1) mitigation methods against the electron cloud, 2) observation of the electron cloud effects in phase 1 operation and 3) measures against the EC toward phase 2 operation which will start in the late FY2017.

MEASURES AGAINST THE ELECTRON CLOUD IN SUPERKEKB

SuperKEKB is the upgraded electron-positron collider of the KEKB B-factory [1]. The design luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ will be achieved by so called nano-beam scheme. Machine upgrades include the replacement of round copper chambers in LER to aluminum TiN coated ante-chambers so as to withstand large beam currents and mitigate the electron cloud effects.

A threshold electron density of the strong head-tail instability caused by the electron cloud (EC) in SuperKEKB Low Energy Ring (LER) is estimated to be 2.7×10^{11} m^{-3} by an analytic estimate [2]. A threshold electron density of 2.2×10^{11} m^{-3} calculated by a simulation [3] is consistent with the analytic estimate. Growth time of the coupled bunch instability (CBI) due to the EC is estimated to be 50 turns at the threshold electron density of the single bunch instability [3], which is larger than an expected damping time of the transverse bunch by bunch feedback system. Thus the target electron density near the beam against the EC instabilities was taken to be less than 1×10^{11} m^{-3}.

The electron density near the beam in SuperKEKB was estimated to be 5×10^{12} m^{-3} based on results from measurements at KEKB assuming a round copper chamber with a diameter of 94 mm, no solenoid field, 4 ns bunch spacing and the bunch current of 1 mA [4]. Main contribution comes from the drift space. Based on studies at KEK following measures were considered at the SuperKEKB LER [4], TiN coated aluminum ante-chambers and solenoid windings in the drift space in arc sections, TiN coated aluminum ante-chambers with grooved surface in dipole chambers and copper ante-chambers with clearing electrodes in wiggler chambers. Taking these measures, the electron density near the beam is expected to be less than 1.0×10^{11} m^{-3}[4].

OBSERVATION OF THE ELECTRON CLOUD EFFECTS IN PHASE 1

Phase 1 operation of SuperKEKB was carried out from February 2016 to June 2016 without final focus quads and the Bell-II detector. The main purposes of the phase 1 were vacuum scrubbing, optics tuning to achieve small emittance beams and a background study with Beast detectors. Measures against the EC taken until the start of phase 1 operation were TiN coated aluminum ante-chambers, grooved surface in dipole chambers and clearing electrodes in wiggler sections. Solenoid windings which were assumed at the initial design were not applied in this stage of the commissioning.

EC Related Events

The vertical beam size blowup was observed at LER by an x-ray beam size monitor. At the same time, pressures at whole LER ring showed a nonlinear behavior against the beam current above ~500 mA [5]. The fill pattern was one long train of 1576 bunches with average bunch separation of 3.06 RF buckets. A separation of adjacent

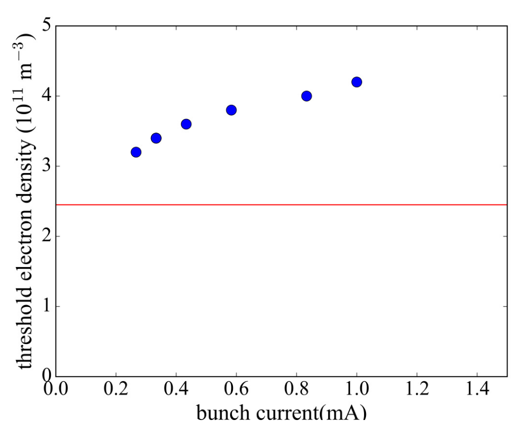

Figure 1: Simulated threshold electron density of the strong head-tail instability caused by the electron cloud as a function of the bunch current. A red line shows an analytic estimate.

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two RF buckets is 2 ns. The behavior was quite similar to that of electron current measured at an aluminum chamber without TiN coating. Aluminum bellows-chambers without TiN coating were suspected to be a source of the nonlinear pressure rise which would be caused by the electron stimulated desorption in the aluminum bellows-chambers by the EC. The bellows-chamber has a length of 0.2 m and located every 3 m on average. They cover ~5 % of the ring in length.

An axial magnetic field was applied by solenoids or permanent magnets at nine aluminum bellows-chambers in a section of ~30 m long. The field strength is 40 ~ 100 G near the inner wall at the center of bellows. The rate of the pressure rise at this section was relaxed after the application of the magnetic field. The solenoids and the permanent magnets had nearly same effect on the pressure. Then permanent magnets of ~800 sets were installed at most aluminum-alloy bellows-chambers. The rate of pressure rise was relaxed in whole ring and threshold current of the beam size blowup was increased. However the nonlinear pressure rise and the beam size blowup are still remain at high beam current.

Measurement of the Threshold of Beam Size Blowup

A vertical beam size was measured by an x-ray monitor [6] as a function of the beam current in various fill patterns. Threshold points of the blowup coincided if the beam size was plotted as a function of linear current density which is defined as the bunch current divided by the bunch separation in RF bucket. This scaling behavior was observed in KEKB [7].

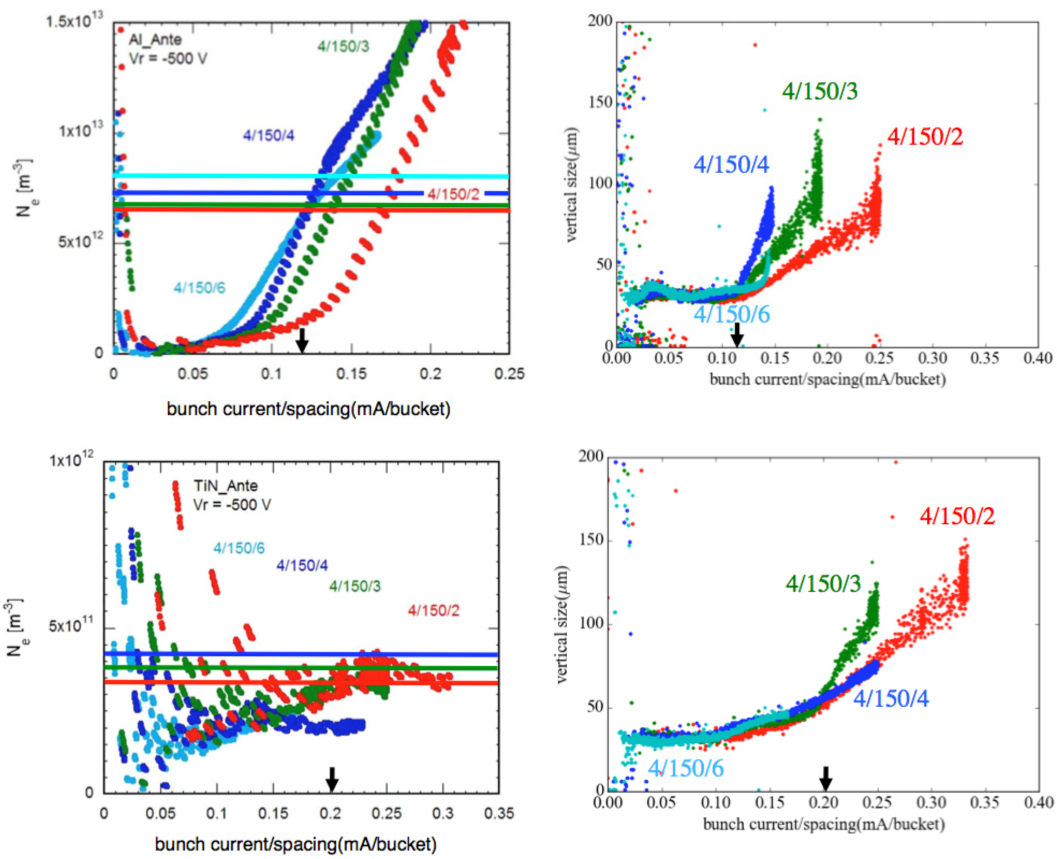

Figure 2: Electron density (left column) and vertical beam size (right column) as a function of the linear current density before (1st raw) and after (2nd raw) the installation of the permanent magnets. The upper-left figure shows the electron density measured at a bare aluminum ante-chamber, while the lower-left figure shows that measured at a TiN coated aluminum ante-chamber. Black arrows show the threshold of the blowup. Colored solid lines are the threshold electron density of the blowup obtained by the simulation. Since the total length of the bellows-chambers is about 5% of the circumference, the electron density that is 20 times as large as the simulated threshold electron density is plotted as the colored line in the upper-left figure. XXX/YYY/ZZZ represents a fill pattern, i.e. the number of trains/the number of bunches per train/bunch separation or spacing in RF bucket.

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Threshold increased by 1.7 after installation of the permanent magnets as shown in Fig 2. The blowup was not seen up to 1A in one long train of 4 RF buckets separation. Beam size seems slowly increase with the beam current.

Measurement of Electron Density

The electron density was measured by retarding field analyzers (RFA) [8]. One RFA was installed at a bare aluminum chamber, while another RFA at a TiN coated chamber. Electron density on the bare aluminum chamber was 50 times larger than that on the TiN coated aluminum chamber in 3 RF bucket separation at 350mA.

Figure 1 shows the threshold electron density as a function of the bunch current simulated by PEHTS [9]. The solid line is an analytic estimate of the threshold [3] which is constant if $\omega_e\sigma_z/c>Q$ in which Q=6, while it increases with increasing bunch current in the simulation, where ω_e, σ_z and c are the angular oscillation frequency of electrons, the bunch length and the speed of light respectively. Q characterizes damping of electron coherent motion due to the nonlinear interaction with the beam.

Figure 2 shows the measured electron density and the beam size as a function of the linear current density before and after installation of permanent magnets. Before the installation of the permanent magnets the electron density at the blowup threshold is consistent with the simulation in 3, 4 and 6 RF bucket separation. For 6 RF bucket separation the threshold linear current density is higher than that of other bucket separations, which is probably due to higher bunch current as suggested by the simulation. After the installation of the permanent magnets the electron density at the blowup threshold is consistent with the simulation in 2 and 4 RF bucket separation. No blowup was observed up to 1A in a long train with 1200 bunches and 4 RF bucket separation, which is consistent with the simulation.

Laboratory measurements of the maximum secondary emission yield (SEY) δ_{max} of TiN coated surface is 0.9 to 1.2 at the estimated electron dose (5×10^{-4} C mm^{-2}) in phase 1. On the other hand an EC buildup simulation by CLOUDLAND suggests δ_{max} of 1.4. The reason of difference between the laboratory measurements and the simulation is not clarified yet. Possible reasons would be high maximum SEY in the actual machine, insufficiently conditioned sections such as far downstream of bends or inside bends, high SEY at non-coated parts and better conditions of materials at the laboratory such as the good pressure and baking of sample. Further investigation is required in phase 2 operation.

Tune Shift Along a Bunch Train

Tune shift along a bunch train was measured after the installation of the permanent magnets with an iGp12 digital filter by kicking a specific bunch by a strip-line kicker of the bunch by bunch feedback system [10]. The fill pattern was 4 trains, 150 bunches in a train and bunch separation of 3 RF buckets. Figure 3 shows a measured

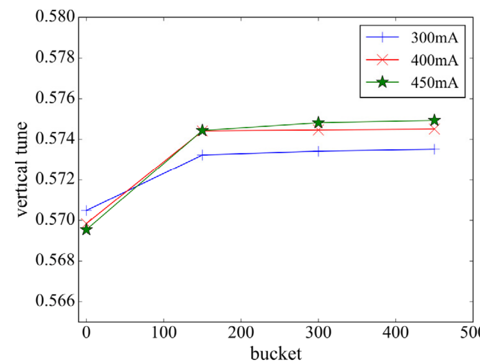

Figure 3: Vertical tune shift along a bunch train.

vertical tune shift along the train. The tune shift saturates at about 0.005. A simple analytic formula gives the tune shift caused by the EC [11] as

$$\Delta\nu_y = \frac{\rho_e r_e \beta_y}{k\gamma} C,$$

where ρ_e is the electron density, r_e the classical electron radius, β_y the vertical beta function, C the ring circumference and k is 1 or 2 for flat or round EC distribution respectively. The estimated tune shift is 8×10^{11} m^{-3} or 4×10^{11} m^{-3} if the EC distribution is round or flat respectively. The measured electron density at the tune shift measurement was 3.5×10^{11} m^{-3}. The tune shift is consistent with the measurement of the electron density if the EC is flat.

Coupled Bunch Instability

Bunches can oscillate by coupled bunch motion mediated by the EC. A sideband spectrum of bunch oscillation reflects the motion of the EC [12]. Electrons in drift space cause a short range wake whose range is ~10ns. Electrons in a solenoid slowly rotate around a chamber surface (magnetron motion). Measurements in KEKB showed totally different sideband spectra, i.e. drift mode and solenoid mode with and without the solenoid field respectively [13]. In phase 1 operation the sideband spectrum was measured by the bunch by bunch feedback system. Figure 4 shows the measured vertical sideband spectrum before and after the installation of the permanent magnets. It clearly shows the drift and solenoid mode before and after the installation of the permanent magnets respectively. Growth time was measured in the fill pattern of 4 trains, 150 bunches in a train and bunch separation of 2, 3 and 4 RF buckets. Growth time was larger than 0.8ms after the installation of the permanent magnets.

Remaining Electron Cloud

The blowup and the nonlinear pressure rise are still observed in a fill pattern in the vacuum scrubbing (one train, 1576 bunches in a train, average bunch separation of 3.06 RF buckets) after the installation of the permanent magnets. The drift mode in a sideband spectrum still

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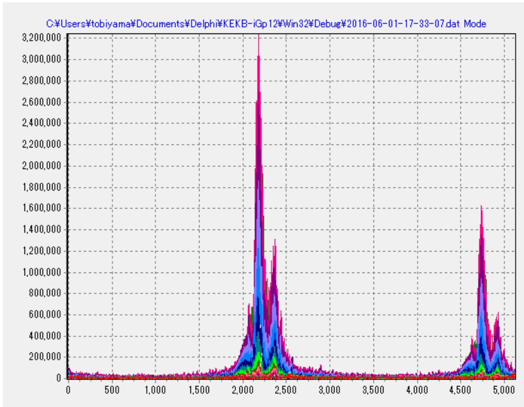

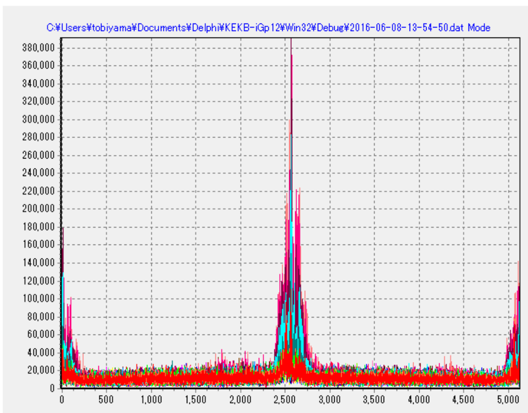

Figure 4: Vertical sideband spectrum before (top) and after (bottom) the installation of the permanent magnets. Bunch separation is two RF buckets. The number of trains is four. The number of bunches in a train is 150. Beam current is 300mA.

appeared at high current after the installation of the permanent magnets in 2 RF bucket separation where electron density is larger than that in other fill patterns. A test installation of the permanent magnets in a long straight section improved pressure in that region. These facts suggest the EC still remains in drift regions.

EC AT HIGH BETA SECTIONS

The EC in high beta function regions might give strong impact on the blowup because of a large kick to the beam by the EC. To investigate this effect, cloud densities were estimated in two cases, 1) high density in high beta section and 2) low density in high beta section and then the threshold electron density was compared by a simulation. It shows the threshold electron density in the case 1 is lowered by ~70% compared with the case 2 [14].

It was pointed out that if photon scattering on a chamber wall is considered, the number of synchrotron light photons incident on a chamber of a final focus quadrupole QC1RP is 30 times larger compared with the case without photon scattering [15]. Since the vertical beta function is very large (~3000m), the EC in the quad could be a source of the blowup.

PLAN TOWARD PHASE 2

Tentative parameters in phase 2 operation of SuperKEKB [16] with final focus quads and the Belle II detector being installed are,

Target luminosity : 1×10^{34} cm^{-2} s^{-1} ,
Target values of IP beta functions :
βx^*: 4 times the design, βy^*: 8 times the design,
Beam current : 1 / 0.8 A (LER/HER).

At the end of phase 1, the blowup started at the linear current density of ~0.2mA/RF bucket. This means total current at the threshold will be hxI_b/s_b=1024mA, where h is the harmonic number, i.e. 5120, I_b the bunch current and s_b the bunch separation in RF bucket. The threshold is marginal in the phase 2 operation.

The maximum growth rate of the CBI due to the EC is proportional to the bunch current if the wake affects only next bunch [12]. Fill pattern of 4 RF buckets separation fits this condition since range of the wake is ~10ns. Growth time of the CBI at phase 1 was 0.8ms to 1ms at the bunch current of 1mA in the fill pattern of 4 trains, 150 bunches in a train and bunch separation of 4 RF buckets. The damping time of bunch by bunch feedback system was about 0.5 ms near 1A [10]. If the bunch separation is 4 RF buckets, the present feedback system would suppress the CBI at phase 2 where the maximum bunch current will be around 1mA.

Budget has been requested to install permanent magnets in most drift sections (mainly arc sections) until phase 2 to keep an enough margin for the blowup.

SUMMARY

In order to reduce the EC, many measures such as the TiN coated aluminum ante-chamber, the grooved surface and the clearing electrode have been applied in SuperKEKB. Measurements in phase 1 operation without solenoid winding show the evidence of the EC effects such as nonlinear pressure rise, the beam size blowup, the sideband spectrum of the coupled bunch instability and the tune shift along a bunch train. The permanent magnets at the bellows-chambers were very effective in reducing the EC. In case of no solenoid windings, the threshold linear current density of the blowup was increased from 0.04mA/RF bucket in KEKB [7], where round copper chambers were equipped, to 0.17mA/RF bucket in SuperKEKB owing to the measures mentioned above.

At the end of the phase 1 no blowup is observed up to 1A in 4 RF bucket separation without solenoid windings. However, measurements of the electron density and the CBI sideband spectrum suggest the EC still remains in drift regions if the current increases further. Installation of the permanent magnets in drift regions before phase 2 is proposed.

The EC effects in high beta sections will be studied in phase 2.

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