ELECTRON CLOUD EFFECTS AT KEKB

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Abstract

This paper describes a review of an experimental study of electron cloud effects at the KEKB LER.

1 INTRODUCTION

Vertical beam blow-up has been observed in the KEKB low energy positron ring (LER) since early operation period [1]. The beam size as a function of beam current started to increase at a threshold beam current and was almost doubled at 300 mA under typical operating conditions. Thus the blow-up was one of the most serious problems limiting the luminosity of KEKB.

The main characteristics of the blow-up observed in early operation period are summarized as: 1) the blow-up was a single beam and a multi-bunch effect; 2) the blow-up has a threshold intensity which was determined roughly by (bunch current)/(bunch spacing); 3) no dipole oscillation has been observed when the vertical chromaticity is enough high; 4) the blow-up was almost independent of betatron tunes; 5) the blow-up did not depend on the positions of the vertical masks, which are among the main impedance sources; 6) the blow-up did not depend on the vacuum pressure, especially for hydrogen, in the arc; and 7) no blow-up was observed in the horizontal plane.

A model to explain the blow-up was proposed by F. Zimmermann and K. Ohmi [2]. In their model the blow-up is explained as a single-bunch instability of a positron bunch due to a large number of electrons, i.e. "electron cloud", generated by photoemission or secondary emission. The instability will occur only in multi-bunch operation since the electron cloud is built up by the successive passage of the bunches. The coherent dipole oscillation of positrons along the bunch caused by the “wake” force due to the electron cloud appears as either regular or strong head-tail instability. A beam size blow-up will be observed as a result of the head-tail oscillation of the instability.

Many small permanent magnets, called “C-yokes”, were attached to vacuum ducts to sweep out the electrons from November 1999 to July 2000. The C-yokes were replaced to solenoid magnets in September 2000 because a simulation showed that the solenoid magnets were more effective than C-yokes to suppress the buildup of the electron cloud [6]. The effect of the solenoids on the blow-up was confirmed by the measurements of the vertical beam size by an interferometer and a gated camera and by the measurement of the luminosity. Then more solenoids were installed in the ring. The number of the solenoids installed so far amount to about 8600. As the result the measurement by the interferometer in February 2002 showed no beam size blow-up up to 1300mA in regular operation condition for the physics experiment.

Table 1 : Main parameters of the KEKB LER

Beam energy (GeV)	3.5
Circumference (m)	3016
rf bucket spacing (ns)	2
Bunch length (mm)	4
Bunch spacing (ns)	8
Number of bunch	1200
Beam current (mA)	1400
Particles / bunch (10^{10})	7
Emittance $\varepsilon_x / \varepsilon_y (10^{-8}$m)	1.8 / 0.036
Average beta function (m)	15
Critical energy (keV)	5.8
Vacuum chamber	copper (round)
Chamber radius (mm)	47

The electron cloud can cause not only the beam blow-up but also a tune shift along the train and a coupled bunch instability, which are both observed in the KEKB LER.

This paper describes an experimental study of the electron cloud effects at the KEKB LER[3,4]. As a reference main parameters of the KEKB LER in present operation condition are listed in Table 1.

2 CLOUD BUILDUP

2.1 Electron measurement

An electron yield was measured by retarded field analysers (RFA's) [5] which are located at 1.2m and 8.0m downstream from a bend. Figure 1 shows the electron current measured by the RFA's. A simulation by K. Ohmi gives an electron current of 10μA and 1μA at the upstream- and downstream-RFA respectively. Thus the measurement is roughly consistent with the simulation.

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Energy distribution of the electrons was also measured by the RFA. Measured energy distribution (Fig. 2 (a)) is well reproduced by a simulation [6] (Fig. 2 (b)).

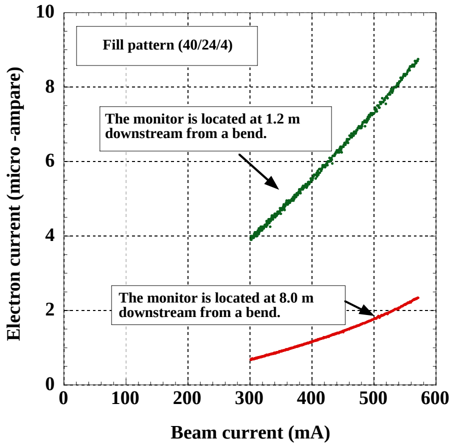

Figure 1 : Electron current measured by the retarded field analysers.

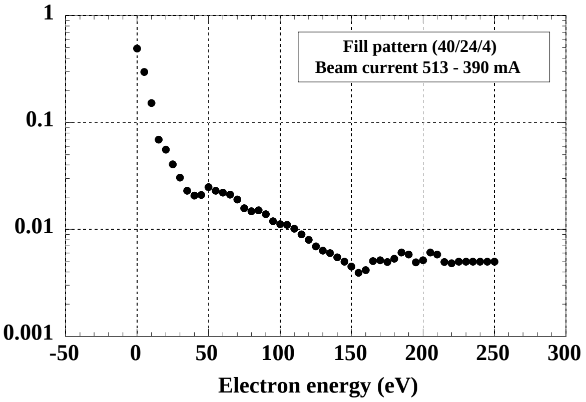

Figure 2 (a) : Energy distribution of the electrons measured by the retarded field analyser.

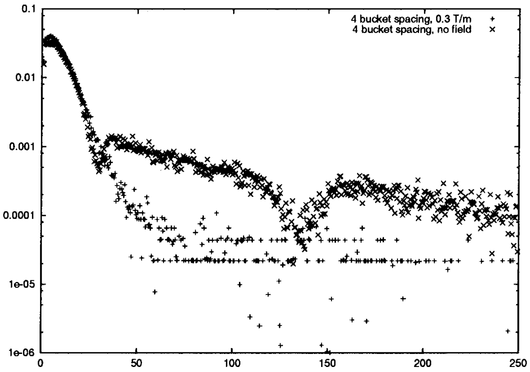

Figure 2 (b) : Energy distribution of the electrons by the simulation [6].

2.2 Tune shift and build-up time

Fig. 3 (a) shows a tune shift along the bunch train normalised by the charge density of the beam. The tune shift was measured by a gated tune meter [7]. As shown by K. Ohmi et al. the tune shift is a good measure of the density of the electron cloud [8]. The saturated tune shift is consistent with the result of the simulation which is indicated by a dotted line [9]. Build-up time of the tune shift, as seen in Fig. 3 (a), is about 20 bunches which is also consistent with the build-up time of the electron cloud density obtained by the simulation [9] ; see Fig. 3 (b).

2.3 Decay time

To measure the decay time of the electron cloud a test bunch was injected at the end of a train with variable distance between the last bunch of the train and the test bunch, then the tune shift and the vertical beam size was measured. Fig. 4 (a) and (b) show the tune shift [7] and the vertical beam size respectively. The decay time was 28ns

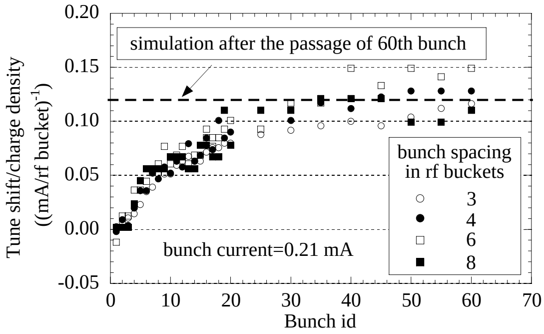

Figure 3 (a) : Vertical betatron tune shift along the train for four different bunch spacing, 3, 4, 6 and 8 rf buckets. The tune shift is normalised by the charge density of the beam (i.e. bunch current/bunch spacing in the unit of rf bucket) [3].

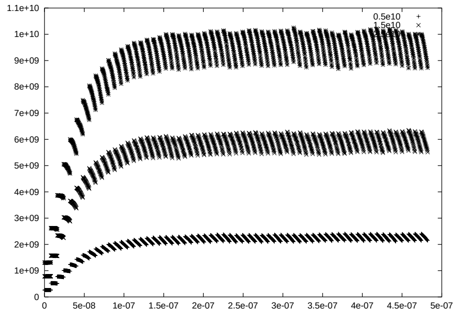

Figure 3 (b) : Simulation result of the cloud build-up [9]. The horizontal axis is the time in ns and the vertical axis is the number of the electrons / meter in m^{-1}.

from the data of the tune shift. For the vertical beam size the blow-up was disappeared when the test bunch was injected 24ns after from the end of the train. Two measurements are roughly consistent with each other.

Fig. 5 (a) shows the result of an another experiment which also indicates the decay time of the electron cloud [3]. Two trains which were separated by 64ns were injected in the ring, then the vertical beam size of each bunch was measured by the gated camera [10]. While the blow-up started at about 7th bunch in the first train, second bunch already blew-up in the second train. The result is supported by a simulation [6] as shown in Fig. 5 (b).

While the data in Fig. 4 suggest the decay time of about 30ns, the data in Fig. 5 (a) suggest the decay time longer than 64ns. It seems that there are two components which govern the decay time [11].

2.4 Change of vertical tune shift

Fig. 6 compares the tune shift in July 2000 and April 2001. The data in July 2000 was taken after removing all C-yokes and before the installation of the solenoids. The data in July 2001 was taken when all solenoids were turned off. The build-up time in April 2001 is larger than that in July 2000. The result may suggest conditioning effects which cause the decrease of the cloud density.

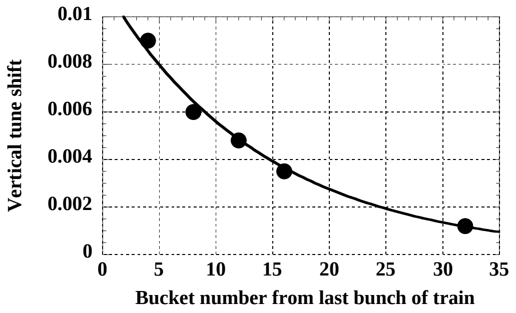

Figure 4 (a) : Vertical tune shift of the test bunch as a function of the distance between the last bunch of the train and the test bunch. The train consisted of 32 bunches. Bunch spacing was 4 rf buckets. Bunch current was 0.8mA.

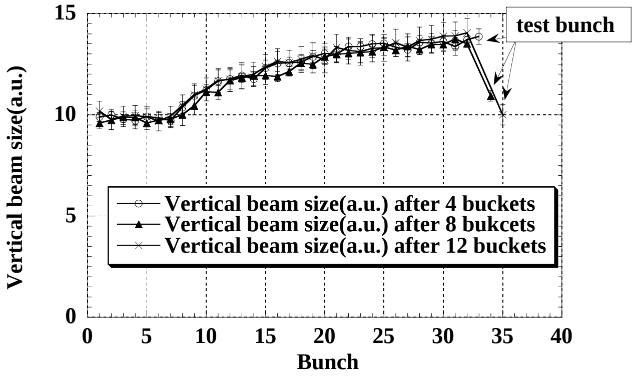

Figure 4 (b) : Vertical beam size of the test bunch as a function of the distance between the last bunch of the train and the test bunch. The train consisted of 32 bunches. Bunch spacing was 4 rf buckets.

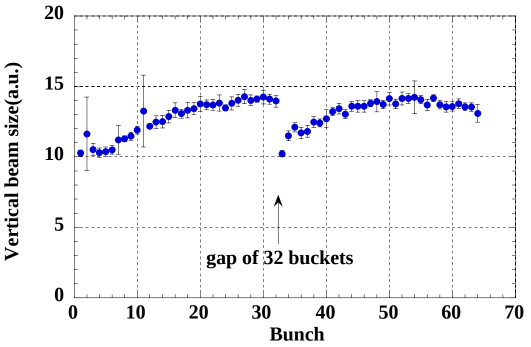

Figure 5 (a) : Beam sizes over two trains measured by the fast gated camera. Train-to-train gap which is not shown in the Figure, is 32 rf buckets [3].

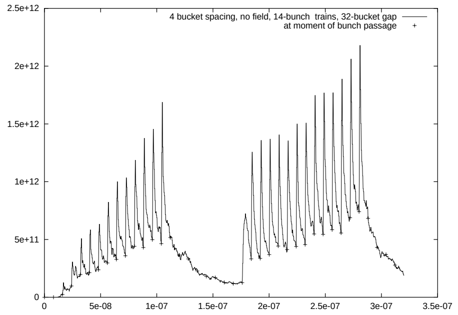

Figure 5 (b) : Simulated electron density near the beam per cubic meters as a function of time in sec in a field free region [6].

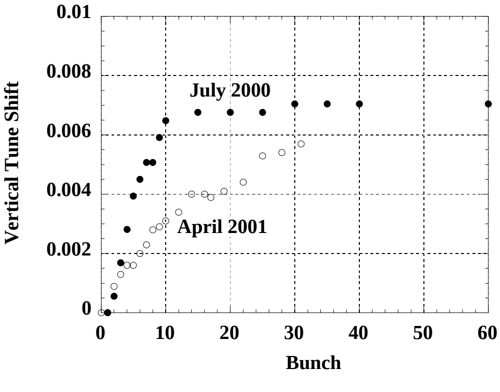

Figure 6 : Vertical tune shift along the train in July 2000 and April 2001.

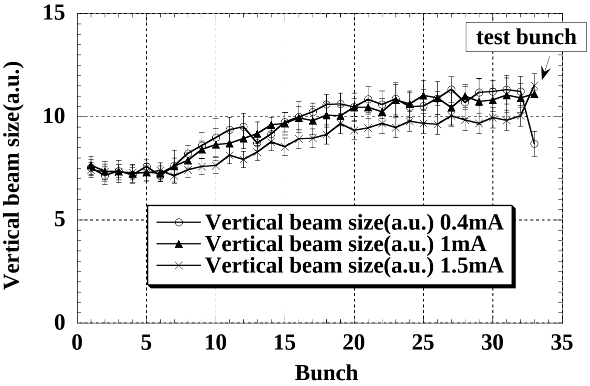

Figure 7 : Vertical beam size of the test bunch as a function of the bunch current. The test bunch was injected after the train apart from 4 rf buckets. Bunch spacing of the train was 4 rf buckets.

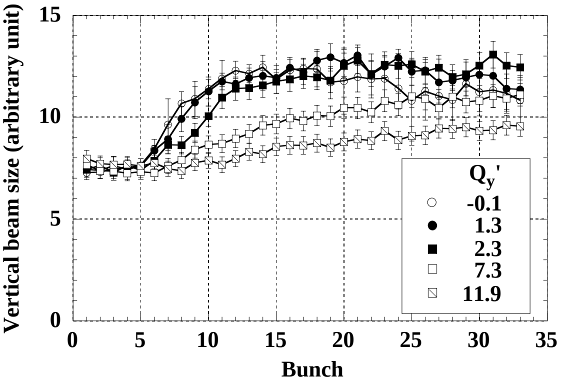

Figure 8 : Beam size along the train observed by the fast gated camera in various chromaticities. Diffraction effect is not corrected [3].

3 BEAM BLOW-UP

3.1 Single bunch characteristics

A test bunch was injected immediately behind a train to prove the single bunch nature of the blow-up. The beam size of the test bunch was measured at several bunch currents of the test bunch. Fig. 7 shows the result in which the beam size of the test bunch increased when its bunch current increased. The measurement demonstrates that the blow-up is a single bunch effect.

3.2 Effect of chromaticity

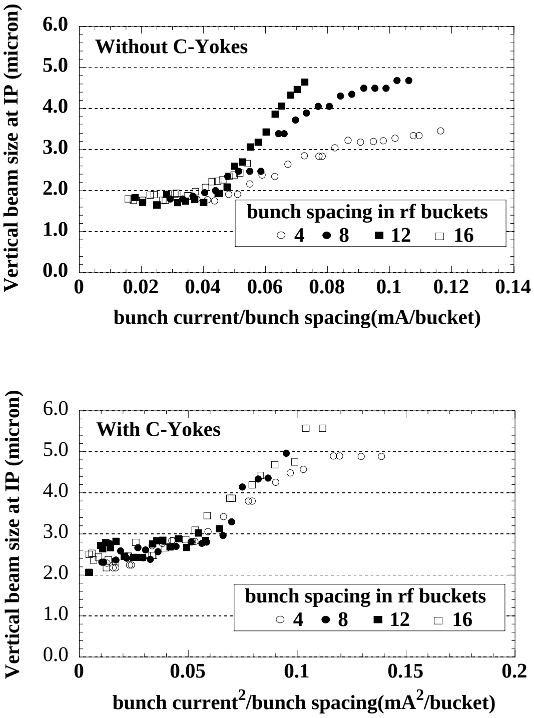

Figure 9 : Blow-up of the beam size in various bunch spacing without and with C-Yokes [3].

The effect of the vertical chromaticity on the blow-up was measured by the fast gated camera. If the blow-up is caused by the head-tail instability it should be sensitive to the chromaticity. Fig. 8 shows that the blow-up along the train became weaker when the chromaticity was increased [3]. According to a calculation based on the transverse mode coupling instability (TMCI) theory, the dependence of the threshold cloud density on the vertical chromaticity is rather weak, i.e. it increases 17 % if the chromaticity increases by 10 [13]. It is not clear that the observation is consistent with the result of the TMCI theory.

3.3 Threshold intensity of blow-up

The average beam size at various bunch spacing was measured by the interferometer [12] as a function of the beam current [3]. As shown in Fig. 9, without C-yokes the threshold intensity $I_{b,th}$ was proportional to the bunch spacing s_b while with C-yokes $I_{b,th}$ was proportional to square root of s_b. According to a model of the single bunch instability caused by the electron cloud $I_{b,th}$ is proportional to s_b for the head-tail instability and the TMCI and is proportional to the square root of s_b for the beam break-up instability [14]. After these experiments the blow-up at bunch spacing of 3 and 4 rf buckets was measured in July 2001 when the solenoids were turned on. The results showed the scaling of $I_{b,th} \propto s_b$. The reason why the scaling changed after the installation of C-Yokes is not understood yet.

3.4 Bunch by bunch luminosity

A bunch by bunch luminosity was measured by the "zero-degree luminosity monitor" [15]. In a beam-fill the luminosity of first several bunches was higher than that of remaining bunches, while in other beam-fill it showed almost flat behaviour. It may be difficult to separate the single beam blow-up from the beam-beam blow-up because during collision the beam size is intentionally controlled by automatic programs and/or operators to obtain the high luminosity.

4 COUPLED BUNCH INSTABILITY

The coupled bunch instability is observed in LER [16]. As shown in Fig. 10, totally different mode spectra were observed with and without solenoid field, which strongly suggests that the instability is caused by the electron cloud as usual wake fields are not affected by weak solenoid field. In Fig. 10 peaks of the mode spectra in horizontal and vertical planes appeared at almost same position when the solenoids were turned off. A simulation shows that the observed mode spectra, especially position of the peaks, are well reproduced if the electrons are produced uniformly on the chamber wall [17]. Almost equal horizontal and vertical tune shift along the train, shown in Fig. 19, also suggests the transverse distribution of the electron cloud is round [18]. Growth rates of the instability shown in Fig. 11 are roughly consistent with the simulation [17].

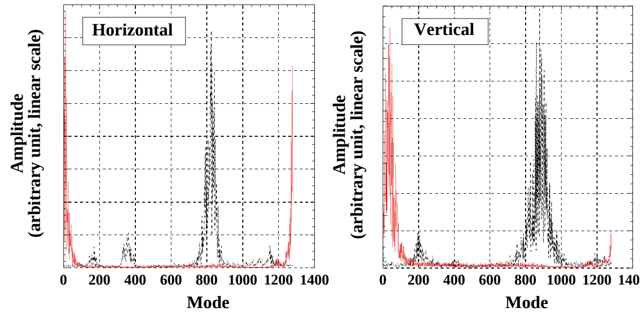

Figure 10 : Observed mode spectrum of the coupled bunch instability with and without solenoids at 600mA. Red-solid (black-broken) lines are the data taken when the solenoids were turned on (off).

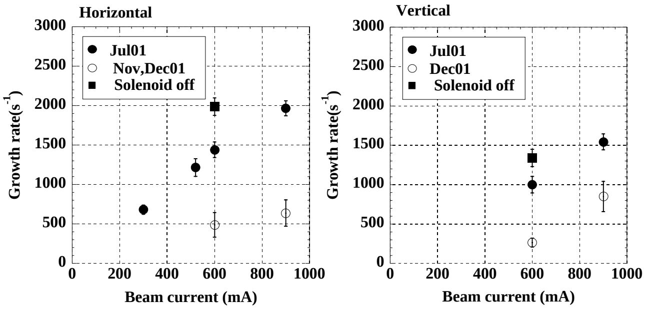

Figure 11 : Measured growth rates of the coupled bunch instability. Closed and open circles indicate the data were taken with the solenoids being turned on. The data shown by closed squares were taken in July 2001.

5 EFFECT OF SOLENOID

5.1 Solenoid system

Since September 2000 the solenoids to sweep out the electrons have been installed in LER [4]. Parameters of solenoid system are shown in Tables 2 and 3. There are two kind of solenoids, one is a bobbin-type solenoid and the other a bobbinless-type solenoid. The length of the bobbin-type solenoid is from 150 to 650 mm depending on the length of available free space for winding. The bobbinless-

Table 2 : Parameters of solenoids.

Type	Length (mm)	Diameter (mm)	Turns	Bz (center) @ 5A (Gauss)
Bobbin	150 - 650	148	250(typ.)	45
Bobbinless	40	220	190, 200	48
Bobbinless	40	250	200	43
Bobbinless	40	300	200	37

Table 3 : Parameters of power supply for the solenoids.

	KEKB corrector P.S.	TRISTAN corrector P.S.
Current(A)	5	3
Units	616	40

Table 4 : Installation history of the solenoids. Second and third columns show the number of the installed solenoids.

Date	Bobbinless	Bobbin	Location
2000. 9.	0	2783	Arc section straight section (Cu chamber)
2001. 1.	1950	0	Arc section (Bellows+NEG)
2001. 4.	254	10	Straight section of Fuji andTsukuba (Bellows, Cu chamber)
2001. 9.	3411	43	Straight section (Bellows, Cu chamber) Arc section (NEG,IP, Bellows+NEG)
2002. 1.	119	0	Arc section (Between Quad and Sext)
Total	5734	2836	

type solenoid has a length of 40mm and mainly located on bellows and both sides of NEG pumps and ion pumps to cover regions in which the bobbin-type solenoids can not be wound. The magnetic field along the beam line at the centre of a solenoid is about 45 Gauss. Pictures of the solenoids are shown in Fig. 12. The power supplies for the correctors of the KEKB rings are partly diverted to those for the solenoids. And several power supplies for the correctors of the TRISTAN collider are also used.

The solenoids were installed in LER five times as shown in Table 4. First (in 2000.9), 2nd (in 2001.1) and 4th (in

Figure 12 : Solenoids in a NEG pump and bellows section (upper) and in a NEG section (lower). Long solenoids are the bobbin-type solenoids and short solenoids the bobbinless-type solenoids.

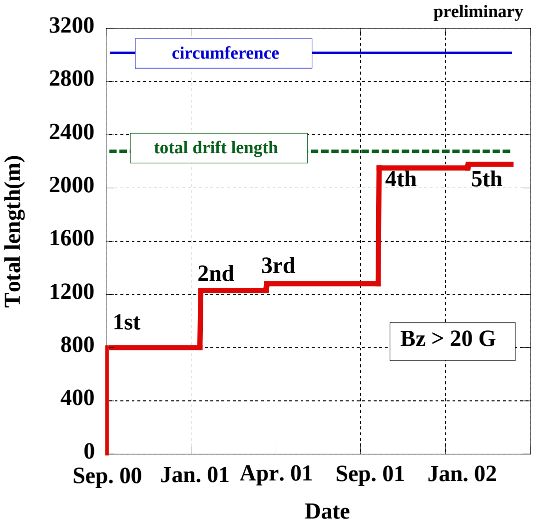

Figure 13 : Length of the regions covered by the solenoids. "1st" to "5th" mean the installation stages of the solenoids.

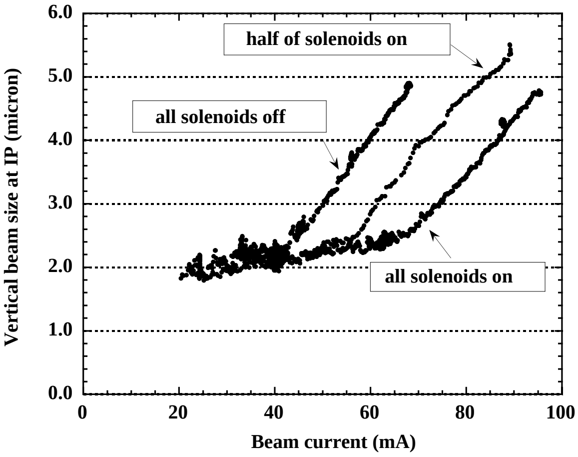

Figure 14 : Vertical beam size as a function of the beam current measured by the interferometer. In the measurement two trains were injected on opposite sides in the ring. Each train contained 60 bunches. Bunch spacing was 4 rf buckets. [4].

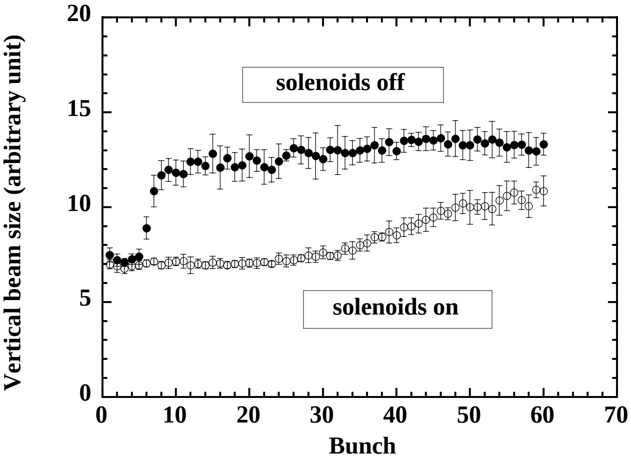

Figure 15 : Vertical beam size along the train taken by the gated camera with and without the solenoids. The train consisted of 60 bunches. Bunch spacing was 4 rf buckets. Bunch current was 0.67 mA [4].

2001.9) installations are major installations. Fig. 13 shows a very rough estimation of the length covered by the solenoid field larger than 20 Gauss. Now about 75% of the circumference are covered by the solenoids.

5.2 Beam blow-up

The effect of the solenoids on the beam blow-up was confirmed by the measurement of the vertical beam size of a single beam. Fig. 14 shows the beam size as a function of beam current in a short train after 1st installation of the solenoids [4]. Turning on the solenoids, the threshold current increased from 40 mA to 70 mA. Fig. 15 shows the beam size along the train measured by the gated camera after 1st installation of the solenoids [4]. The blow-up started at 7th bunch when the solenoids were turned off while it started at 30th bunch when the solenoids were turned on.

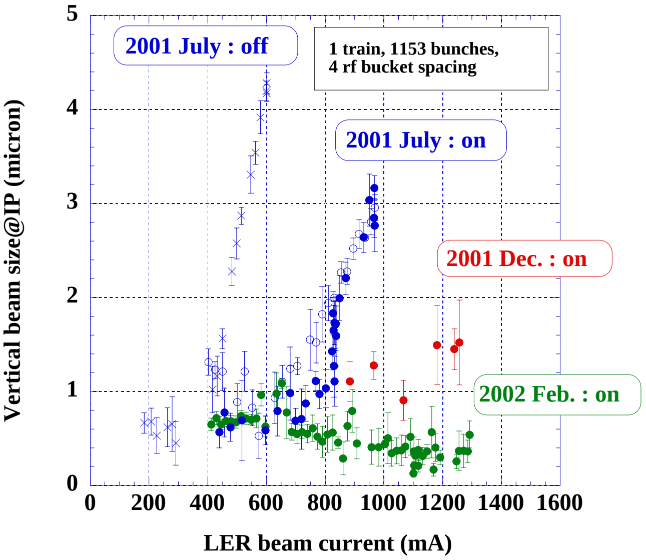

Figure 16 : Effect of solenoids on the vertical beam size for a long train measured by the interferometer. "On/off" means the solenoids were turned on/off.

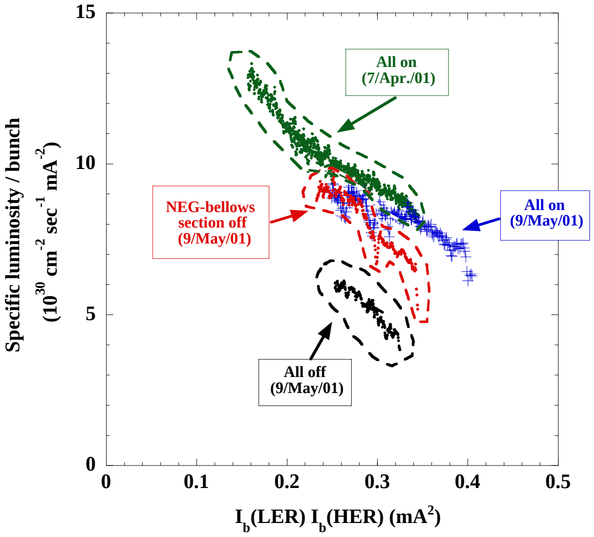

Figure 17 : Effect of solenoids on the luminosity after 3rd installation of the solenoids.

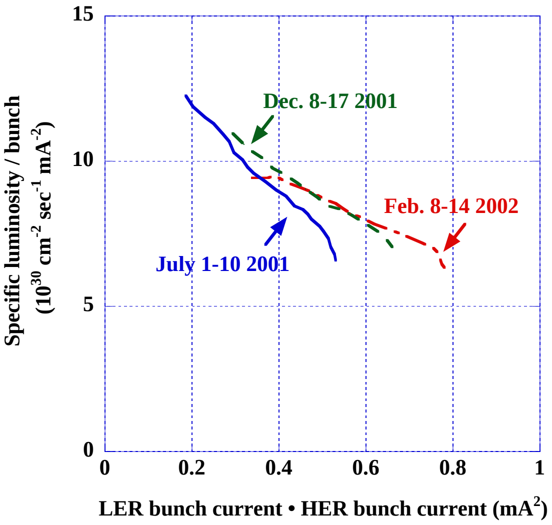

Figure 18 : Effect of solenoids on the luminosity after 3rd, 4th and 5th installations of the solenoids.

Fig. 16 shows the beam size in a long train for the physics experiment after several installation stages of the solenoids. For every additional installations of the solenoids the threshold current of the blow-up increased and finally the blow-up disappeared in the measurement in February 2002.

5.3 Luminosity

The effect of the solenoids was also confirmed by the luminosity measurement. Fig. 17 shows the specific luminosity as a function of the bunch current product of HER and LER after 3rd installation of the solenoids. When all solenoids were turned off the specific luminosity decreased by 40%. Fig. 18 shows the specific luminosity after 3rd, 4th and 5th installations of the solenoids. In Fig. 18 an envelope curve of the specific luminosity taken for a week is plotted for each data set because the specific luminosity is affected by the beam tuning. As seen in Fig. 18 the specific luminosity was improved after 4th installation of the solenoids. It seems that the specific luminosity was slightly improved above 0.6mA^2 after 5th installation of the solenoids though the luminosity drop above 0.6mA^2 in Dec. 2001 might be caused by the beam tuning.

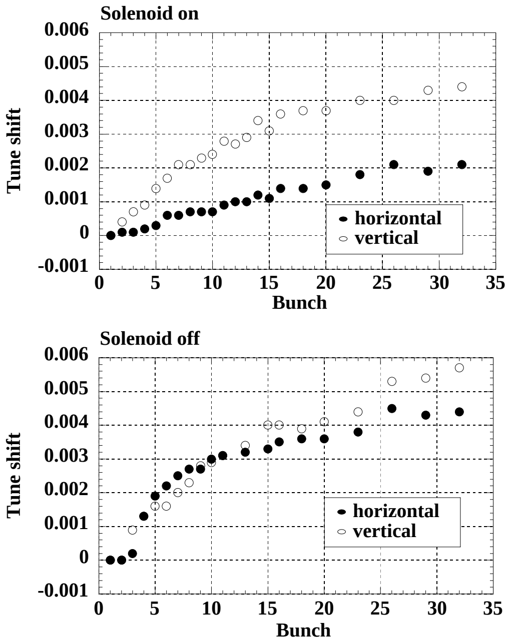

Figure 19 : The effect of the solenoids on the horizontal and vertical tune shift along the train. Bunch current was 0.31 mA [18].

5.4 Tune shift and coupled bunch luminosity

The tune shift along the train decreased when the solenoids were turned on. Fig. 19 compares the tune shift with and without solenoid field [18].

The mode spectrum of the coupled bunch instability was changed with and without solenoid field as described in section 4. The effect of the solenoids on the growth rate of the coupled bunch instability was also observed as shown in Fig. 11. The mode spectrum and the growth rate when the solenoids are turned on are studied by a simulation. The mode spectrum can be explained by the simulation assuming the effective solenoid field of 5 to 20 Gauss [17]. The growth rate obtained by the simulation is roughly consistent with the measurement [17].

6 OPEN QUESTIONS

Several open questions remain about the electron cloud effects at KEKB.

1) Beam blow-up has been observed in the vertical plane and not observed in the horizontal plane. A calculation based on the TMCI theory gives almost same horizontal and vertical threshold cloud density of the TMCI, i.e. 2.0 x $10^{-12}m^{-3}$ horizontally and 2.3 x $10^{-12}m^{-3}$ vertically [13]. The threshold cloud density in the vertical plane may be reduced by the focusing of the electron cloud during the bunch passage as pointed out in [13].

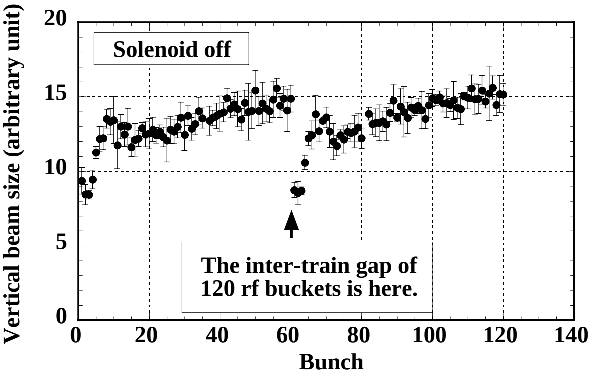

Figure 20 : Beam sizes over two trains measured by the fast gated camera. Train-to-train gap which is not shown in the Figure, is 120 rf buckets.

2) The decay time of the cloud density seems very long. Fig. 20 shows the vertical beam size of two trains injected 240ns apart from each other. The 4th bunch of the second train already blew-up while that of the 1st train did not, which indicates very long decay time of the cloud density. The electron cloud may be trapped in quadrupole and sextupole field as L. Wang et al. recently pointed out [19]. But no experimental evidence of such trapping is observed yet. A large puzzle is that the experiments described in subsection 2.3 imply a short decay time of the cloud density.

3) Very slow blow-up along the train was observed after 1st installation of the solenoids. This slow blow-up is not explained by simulations yet.

4) Conditioning effect for the cloud density is not clear. Change of the build-up time of the tune shift and the fact that the luminosity did not immediately improve after the installation of the solenoids but after several weeks of beam operation may suggest the decrease of the cloud density due to the conditioning by the beam. But the conditioning effect is not confirmed by a measurement of the electron yield yet.

5) Transverse distribution of the electron cloud may not concentrate near an illumination point by the direct synchrotron radiation but be round when the solenoids are turned off. Mode spectrum of the coupled bunch instability and almost equal horizontal and vertical tune shifts support this hypothesis. A measurement of the cloud distribution around the chamber wall will be welcome.

7 SUMMARY

Cloud build-up studied by the measurements of the electron yield, the energy distribution, the tune shift along the train, the build-up time of the tune shift and the beam blow-up along the train is well explained by the simulations.

Observations such as single bunch characteristics of the blow-up and the scaling of the threshold beam current of the blow-up on the bunch spacing are consistent with the single bunch head-tail instability model. It is unclear whether the chromaticity dependence of the beam blow-up and no horizontal blow-up are well explained by the TMCI theory or not.

Mode spectrum of the coupled bunch instability can be explained by the simulation assuming a uniform production of the electrons on the chamber wall. Growth rate is roughly consistent with the simulation.

Effect of the weak solenoid field on the electron cloud effects was confirmed by the measurements of the beam blow-up, the luminosity, the tune shift and the coupled bunch instability.

Several questions about the absence of a horizontal blow-up, the decay time of the cloud, very slow blow-up along the train, the conditioning effect and the transverse distribution of the electron cloud still remain to be studied.

8 ACKNOWREDGEMENTS

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