COUPLED-BUNCH INSTABILITIES AND RELATED EFFECTS DUE TO ELECTRON CLOUD IN SuperKEKB LER

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Abstract

Coupled-bunch instabilities due to electron cloud effect have been observed in KEKB LER. The effect was clearly explained by the electron cloud effect (ECE) in the drift space by the numerical simulations. For SuperKEKB collider which is the upgrade of the KEKB collider, several methods to mitigate the ECE have been applied. The effectiveness of those methods has been evaluated using the beam in Phase 1 and Phase 2 operation of SuperKEKB. Preliminary experimental results will be shown.

INTRODUCTION

The KEKB collider has been upgraded to the SuperKEKB collider with a final target of 40 times higher luminosity than that of KEKB. It consists of a 7 GeV high energy ring (HER, electrons) and a 4 GeV low energy ring (LER, positrons). About 2500 bunches per ring will be stored at total beam currents of 2.6 A (HER) and 3.6 A (LER) in the final design goal. After the first stage of commissioning (Phase 1) without the Belle-II detector, which started in Feb. 2016 and continued until the end of June [1, 2], we have installed the superconducting final quadrupoles (QCS) and the Belle-II detector, without innermost detectors vertex detectors such as Pixel detectors nor Silicon Vertex Detectors (VXD) [3,4].

In KEKB LER, we have observed unexpected strong transverse coupled-bunch instabilities (CBI) and an increase of the vertical beam size with beam current. Both the unstable modes and the growth time had strong dependence of the bunch filling patterns. Though the CBI had been suppressed by the transverse bunch-by-bunch feedback systems, the increase of the vertical beam size still remained which strongly reduced the luminosity.

To suppress the beam blow-up and the coupled-bunch instabilities, we wound solenoid magnets in almost all the straight sections (>95%) with magnetic field of 4.5 mT.

The solenoid had worked well to suppress the increase of the vertical beam size and to achieve high luminosity, though the growth rate of the unstable modes had not changed too much. The result of the transient-domain analysis of the CBI with the several conditions of the solenoid magnets such as turning-on, turning-off, partly activated, agreed with the numerical simulations very well.

For SuperKEKB, we had employed several mitigation methods to suppress the electron cloud effects [5]. The bunch feedback systems have also improved with improved digital signal processing technique to have faster feedback damping with less noise effect in the systems. The effectiveness of the methods has been evaluated with the beam during the Phase 1 operation and the Phase 2 operation of the SuperKEKB LER where Phase 2 operation have been performed from March 2018 to middle of June 2018. In this paper we describe the results of the electron cloud effect in LER in the view point of the coupled bunch instabilities. The main parameters of the SuperKEKB rings in the Phase 2 operation are shown in Table 1.

Table 1: Main Parameters of SuperKEKB HER/LER/DR in Phase 2 Operation

	HER	LER	DR
Energy (GeV)	7	4	1.1
Circumference(m)	3016		135
Max. current (mA)	800	860	12
Bunch length (mm)	5	6	6.6
RF frequency (MHz)	508.887		
Harmonic number (h)	5120		230
Betatron tune(H/V)	44.54/ 46.56	45.54/ 43.56	8.24/ 7.17
Synchrotron tune	0.02	0.018	0.025
T. rad. damp time (ms)	58	43	12
x-y coupling (%)	0.27	0.28	10
Emittance (nm)	3.2	4.6	29
Peak luminosity	$5.5\text{x}10^{33}/\text{cm}^2/\text{s}$		
Beam position monitor	486	444	83
Turn by turn monitor	69	70	83
Trans. FB system	2	2	1
Visible SR monitor	1	1	1
X-ray size monitor	1	1	0
Beta. tune monitor	1	1	1
DCCT	1	1	1
Bunch current mon.	1	1	1
Beam loss monitor	105(IC)/101(PIN)		34

TRANSVERSE BUNCH-BY-BUNCH FEEDBACK SYSTEMS

Figure 1 shows the block diagram of the bunch-by-bunch feedback systems installed in SuperKEKB rings [6]. The system consists of position detection systems, high-speed digital signal processing systems with a base clock of 509

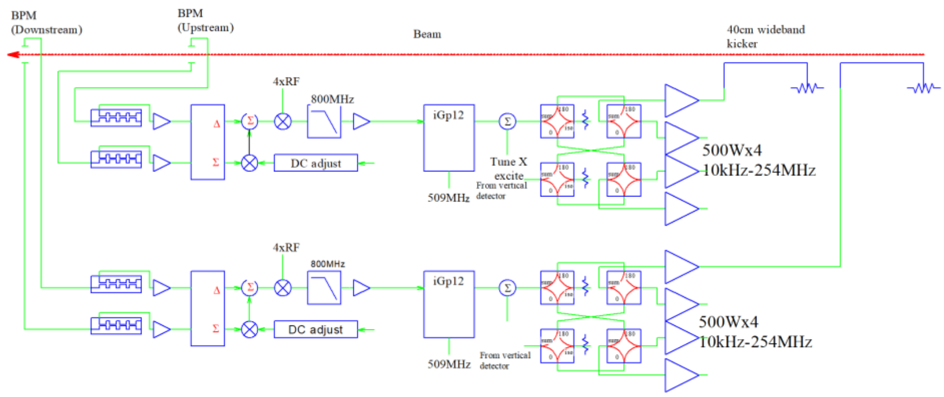

Figure 1. Block diagram of the transverse bunch feedback systems.

MHz (iGp12 [7]), and wide-band kickers fed by wide-band, high-power amplifiers.

For SuperKEKB rings, we have changed the button electrodes with better time response using feedthroughs with glass-type sealing, developed bunch position detection circuits with better bunch separation and lower electrical noise, employed iGp12 feedback signal processors with larger FPGA, exchanged the wideband high-power amplifiers with higher maximum power and with much better time-domain response than before. Finally, we have doubled the transverse feedback loop to cope with the lower fractional betatron tune around 0.52.

In the early stage of the commissioning of both rings we encountered very strong transverse coupled-bunch instabilities which limited the maximum beam currents. After the tuning of the timing and phase of the transverse feedback systems, we successfully suppressed the coupled-bunch instabilities up to the maximum beam current of around 1000 mA with the minimum bunch separation of 4 ns.

The transient behaviour of the beam just after closing or opening of the feedback loop reveals many important characteristics of the coupled-bunch motions as well as the performance of the feedback systems [8,9]. The iGp12 has intrinsic functions to initiate and record the grow-damp measurement. Since we are using two iGp12s on one transverse plane, we triggered both iGp12s with a hardware line simultaneously.

In the transient-domain analysis, we at first open the transverse (horizontal or vertical) feedback loop, which means to change the feedback gain to be zero, and start recording each bunch position observed in the iGp12 feedback processors. As the maximum recording length without down-sampling in the iGp12 processor is around 23 ms, we have set the nominal growth time of iGp12s, which is the "Feedback OFF period", to be around 4 ms to 10 ms depending on the growth rate. After the growth time, we close the feedback loop again before losing beam.

In the analysis, we at first make FFT of base 5 for the oscillation data of 256 turns (5120 bunches × 256 data points) to obtain the whole spectrum. Then extract amplitude of the spectrum that corresponds to the betatron frequencies ($f_b+m \times f_{rev}$), where f_b, m and f_{rev} represent the betatron frequency, mode of the oscillation and revolution frequency, respectively, and align the amplitude by increasing order of the mode IDs. By repeating the above procedure while advancing the starting point of the data by 128 turn, we obtain the growth or damp of the instabilities in the view of unstable modes. Figure 2 shows an example of the grow-damp experiment on SuperKEKB HER of by 3 filling patterns with the beam current of around 730 mA. The unstable modes are concentrated around the lower (negative) modes and the amplitudes of the growing unstable modes are out of the exponential growth with the progress of the unstable modes. In this case the growth rate was around 1/0.9 ms^{-1} while the feedback damping rate without the correction of grow rate was faster than 1/0.5 ms^{-1}.

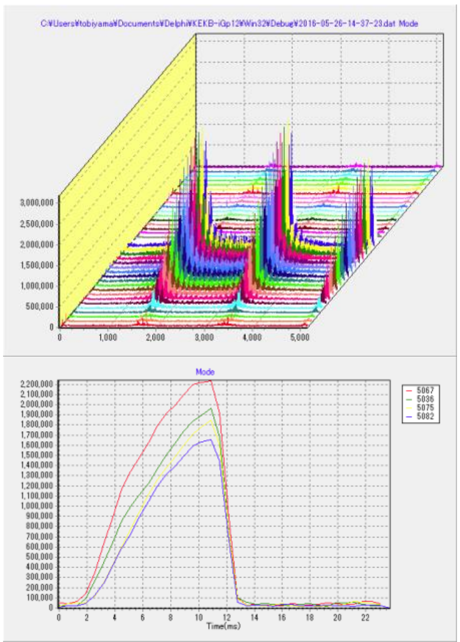

Figure 2. An example of transient-domain analysis at SuperKEKB HER (electron ring) at by 3 filling patterns with the beam current of around 730 mA. (Upper): Change of unstable modes (horizontal, from 0 to 5119) with time (depth, from 0 to 24 ms). (Lower): Growth and damp of some unstable modes. The growth time was around 0.9 ms.

ELECTRON CLOUD EFFECT AND ITS MITIGATION

KEKB LER

In KEKB LER, we have performed many experiments to measure the electron cloud effect with changing the filling patterns and strength of the solenoid magnets including the excitation pattern of magnets, which have been installed mainly at the drift space. The results have shown good agreements with the numerical simulation with the assumption of the electron cloud at the drift space mainly contributing the ECE [10]. In this case, coupled-bunch instabilities due to ECE behaves as follows:

- Rather broad unstable modes appear which reflect the cloud distributions. Modes around higher part come from the natural electron clouds in the drift space region. The modes around lower part come from the electron clouds near the chamber surface due to the higher solenoidal field (>few mT).
- The growth rate of the unstable modes has relation to the strength of the applied solenoid magnetic fields. Intermediate field levels actually enhance the growth rate, which result in a more severe situation for the bunch feedback systems. On the contrary, no solenoid field and enough solenoid field case show similar growth rate of the instabilities. Therefore, adding external solenoid field might suppress the vertical beam size blow-up but does not suppress the coupled-bunch instabilities.

Figures 3 and 4 show examples of measured unstable modes without a solenoid field and with full field at KEKB LER with by 4 patterns [9]. The unstable modes have changed drastically from the higher modes (without solenoid field) to the lower modes (with fully applied solenoid field).

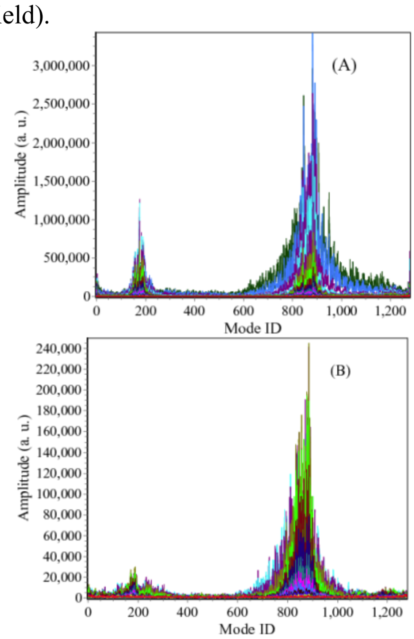

Figure 3. Unstable modes without a solenoid field for the horizontal plane (A) and vertical plane (B) with by 4 filling patterns.

In Fig. 5, the measured growth rates of the instabilities with various solenoid field are shown. As seen in the figure, a large enhancement of the growth rate for both the horizontal and vertical planes has been seen at lower (insufficient) solenoid fields. It was concluded that insufficient solenoid field made the coupled-bunch situation much worse than no-solenoid case.

Mitigation for SuperKEKB

The main bending magnets of LER have been replaced with much longer ones with lower magnetic field. To fit the modified lattice and to mitigate the ECE for SuperKEKB, most of the vacuum chambers of LER have been replaced with the antechamber made of aluminium alloy with TiN coating with a thickness of around 200 nm. In addition, vacuum chambers for bending magnets have been processed with a grooved surface around the top and bottom of the chamber. In the wiggler straight section to increase synchrotron radiation loss, we have prepared vacuum chambers made of copper alloy with clearing electrodes which are capable to sustain external DC electrical field up to 1 kV with maximum current of 100 mA. The detailed discussion of the mitigation of ECE and the experimental results on the Phase 1 and Phase 2 operation are shown in another the document of theses proceedings [5].

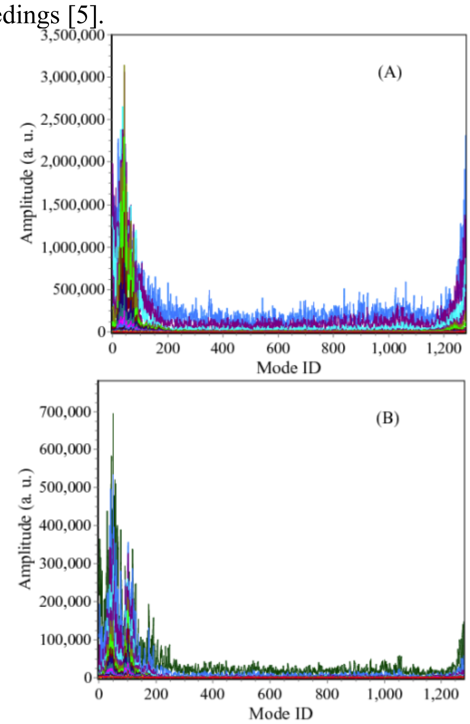

Figure 4. Unstable modes with a full (~4.5 mT) solenoid field for the horizontal plane (A) and the vertical plane (B).

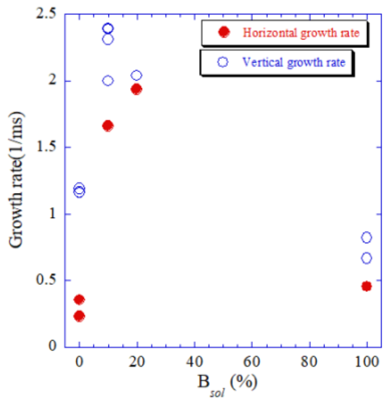

Figure 5. Measured growth rates against the magnetic field strength of the solenoid magnets where total number of bunches was 1154 (600 mA) with by 4 (=8 ns) spacing.

MEASUREMENTS OF ELECTRON CLOUD EFFECT

Phase 1 operation

During the Phase 1 operation of SuperKEKB, we have found the vertical beam size blow-up starting at 0.6 A with the filling pattern of 3.06, which means the repeating by 3 filling of 15 buckets and 4 RF bucket spacing. Figure 6 shows the measured vertical beam size increase with the beam current.

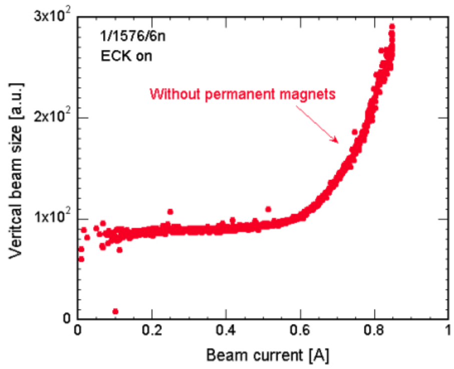

Figure 6. Vertical beam size blow-up with beam current at Phase 1 operation of SuperKEKB LER.

The measurements have been examined with by 2, by 3, by 4 and by 6 RF bucket patterns with 150 bunches per bunch train, 4 or 8 bunch trains, up to 600 mA. The grow-damp measurements have been also performed with several beam currents. Note for some filling patterns with much faster growth rate, the re-capture of the oscillation was not easy, which meant the growth of the coupled-bunch oscillation had caused the beam loss, especially for the vertical plane. Figure 7 and 8 show examples of grow-damp experiment with by 2 filling patterns (300 mA).

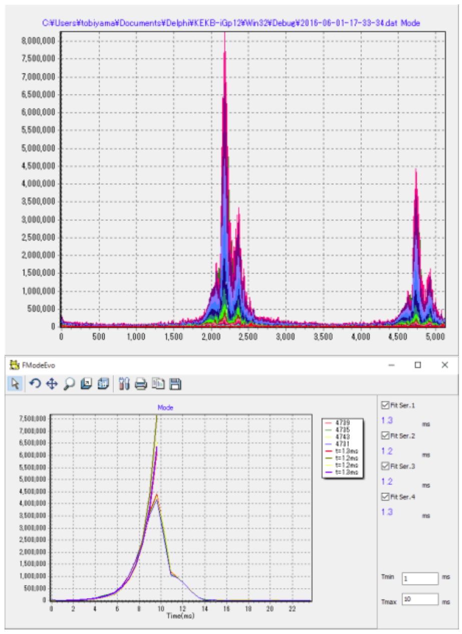

Figure 7. Unstable modes and growth behaviours of major modes on vertical plane with total number of bunches of 600 (300 mA) with by 2 (=4 ns) filling parttren.

The growth time of the unstable modes are around 0.6 ms and 1.2 ms for horizontal and vertical plane, respectively. The feedback damping time for both planes were less than 0.5 ms in this case. Figure 9 shows the summary of the unstable modes.

The main unstable modes are concentrated around mode numbers 400 and 500 modes far from zero mode for horizontal and vertical planes, respectively. Those higher modes strongly support the coupled-bunch instabilities has been caused by the electron clouds around the drift space of the ring.

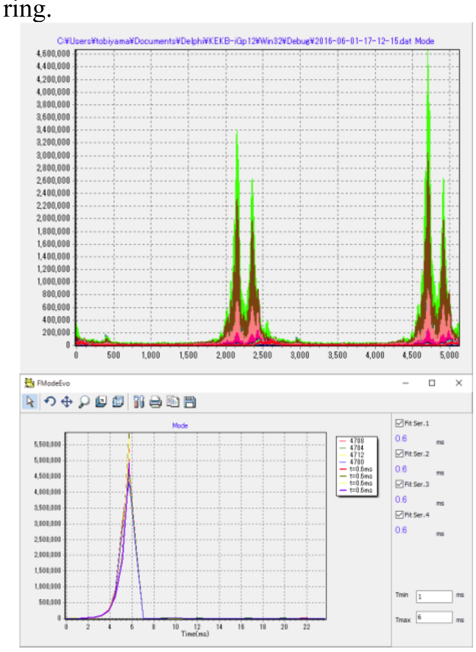

Figure 8. Unstable modes and growth behaviours of major modes on horizontal plane.

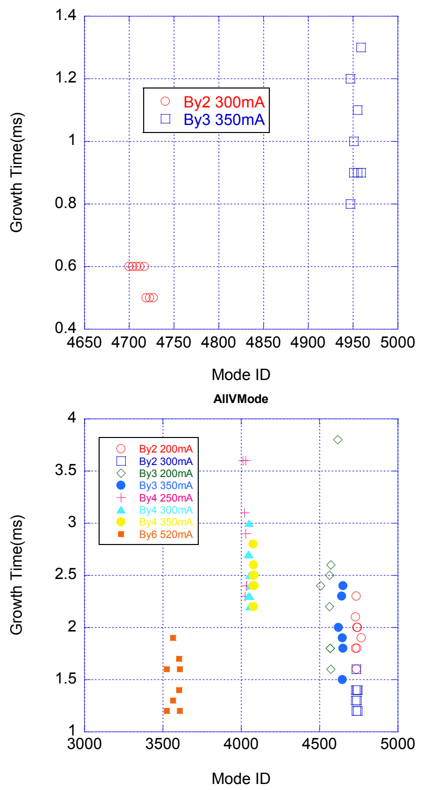

Figure 9. Summary of unstable modes for horizontal (upper) and vertical (lower) plane with various filling patterns.

At the same time, a non-linear pressure rise against the beam current around the bellows made of aluminium alloy without TiN coating was found. As a test, we applied solenoid magnetic field with 40 to 100 G near the inner wall at the center of bellows. As a result, the rate of pressure rise at the section was relaxed which confirmed the pressure rise was caused by the electron cloud effect.

After installing solenoidal-field made of permanent magnets and return yokes all the bellows section, we have made the measurements of the vertical beam size with grow-damp measurements. As seen in Fig. 10, typical unstable modes caused by the electrons in solenoid field (lower modes) on both horizontal and vertical planes have appeared at the lower to middle beam current. Also the growth rate of the horizontal plane has been reduced around 4 times, though in the vertical plane the rate was not too much affected. Nevertheless, at higher beam current unstable modes of higher mode region appeared again. According to the numerical simulation, magnetic field at the bellows section should be enough to suppress the cloud effect. Therefore the higher-unstable modes with high beam current were suspected to be caused by the electron clouds at normal drift spaces with antechamber structure and with TiN coating.

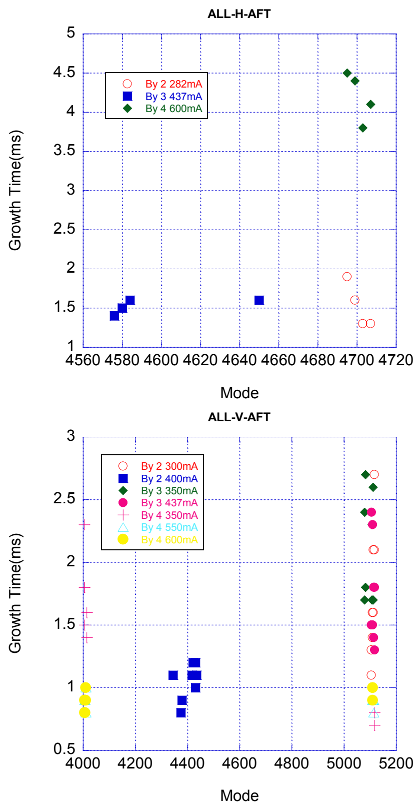

Figure 10. Summary of unstable modes for horizontal (upper) and vertical (lower) plane with various filling patterns after installing the solenoid magnets around bellows.

In measurements of vertical beam size, a beam size blow-up as a function of beam current was observed for several filling patterns, though the threshold line density of a bunch train of blow-up has increased up to 1.5 times higher than before installing the solenoid magnets.

As a countermeasure against the ECE difficulties, 'quasi-solenoid' magnets consist of permanent magnets and iron yokes have been attached to most of the drift space of the ring. For drift space near to existing electro-magnets the units without iron yokes have been installed.

Phase 2 operation

In the Phase 2 operation, we have measured the vertical beam size and the grow-damp behaviours of the coupled-bunch instabilities with similar conditions as Phase 1 experiments. Up to the maximum beam current, no vertical beam size blow-up has been observed. Figure 11 shows the summary of vertical unstable modes. Note for horizontal plane, the typical growth rates were much slower than that of Phase 1 cases and was not easy to analyse with enough accuracy. The growth rates of the vertical unstable modes have further reduced around the factor of two or three. As seen in Fig 12, the distribution of unstable modes has also changed to be narrower than that of Phase 1, which suggest the contribution of electron cloud effects to the unstable mode might not be so large now. Further study including numerical simulations to investigate the cause will be needed.

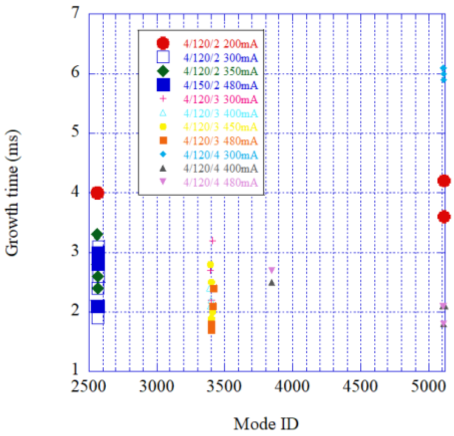

Figure 11. Summary of unstable modes for vertical plane with various filling patterns and beam currents on the Phase 2 operation of SuperKEKB LER.

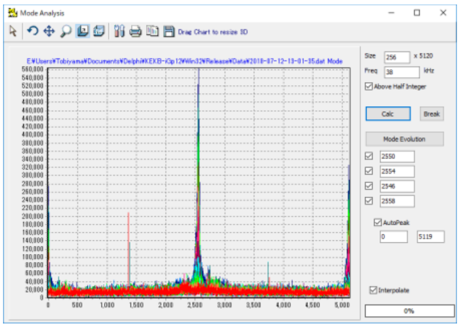

Figure 12. Vertical unstable modes of by 2 filling pattern at Phase 2 operation. The mode distribution is narrower than that of phase 1.

SUMMARY

Coupled-bunch instabilities caused by electron cloud effect have been observed in SuperKEKB Phase 1 operation, which were mainly caused by the vacuum bellows made of aluminium alloy without TiN coating. Mode analysis of trasient-domain measurements show the typical behavior of electron cloud effect coming from the drift electrons. By adding weak solenoid field at bellows section, the increase of vacuum pressure and the vertical beam size blow-ups have been sucessfully suppressed. The unstable modes have changed to those from solenoid field electrons. For higher beam current, drift electron pattern appeared again which suggest mitigation at normal drift space might be needed. After adding solenoid magnet around most of the drift space for the Phase 2 operation of SuperKEKB LER, no vertical blow-up has been observed up to the maximum beam current. On the transient-domain analysis, the unstable modes pattern has changed and much slower growth rates have been observed. The mitigations applied during Phase 1 to Phase 2 have been confirmed to work well up to now.

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