# COUPLED BUNCH INSTABILITY CAUSED BY ELECTRON CLOUD

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## *Abstract*

Coupled bunch instability caused by electron cloud has been observed in the KEKB-LER. Time evolution of the instabilities just after the turning-off the transverse bunch feedback have been recorded with several solenoid-field conditions to suppress the blowup due to electron cloud. The mode spectra of the coupled-bunch instabilities have been compaired with the simulations of electrons moving in drift space, weak solenoid field and strong bending field.

## INTRODUCTION

In a multi-bunch positron storage ring with a narrow bunch spacing, electrons created by the synchrotron radiation and the secondary emission due to the absorption of primary electrons at the vacuum chamber surface build up in the vacuum chamber by successive production. An electron cloud with a certain density is formed in the chamber and interacts with the beam passes though it. The motions of the bunches will be correlated with each other if the information of the previous bunch is retained in the cloud. A small betatron oscillation of a bunch will be transmitted, amplified to other bunches via the electron cloud, with the result that a coupled-bunch instability is caused.

Transverse coupled-bunch instabilities caused by electron clouds have been observed in many positron storage rings[1, 2]. In the KEKB-LER, we also have observed strong transverse coupled-bunch instabilities and increase of the vertical beam size, both of them are believed to be caused by the electron cloud effect[3]. To suppress the beam-blowup and the coupled-bunch instability, we have wound weak solenoid magnets in almost all the straight sections of the LER ring with the typical magnetic field of $4.5 \times 10^{-3}$ T. Now the solenoids cover more than 95% of the drift space of the KEKB-LER. The bunch-by-bunch feedback systems also have been used to suppress the coupled-bunch instabilities. Both systems have been showing excellent performance to suppress electron-cloud effect, resulting to achieve very high luminosity of larger than $1.5 \times 10^{34}\mathrm{cm}^2/\mathrm{s}$.

The bunch-by-bunch feedback systems of KEKB has the function of recording the individual bunch motion in 4096 turns (BOR: Bunch Oscillation Recorder) with synchronizing the feedback event, such as opening or closing the feedback loop[4]. By analyzing the BOR's data obtained just after opening the transverse feedback loop, we can know the clear mode spectrum of the coupled-bunch instabilities which can be compared with the model of the instabilities. Early experiment performed at the KEKB-LER showed that the existence of the solenoid field strongly affects the mode of the coupled-bunch instability[3].

In order to study the effect of solenoid field further, we have measured the evolution of coupled-bunch instabilities in KEKB-LER with changing the magnetic-field of the solenoid magnets, or the length of the drift space covered with the solenoid field. The results have been compared with the numerical simulation with electrons moving in drift space, weak solenoid field and strong bending field dominating drift space. The basic parameters of the KEKB-LER are shown in Table 1.

Table 1: Basic parameters of the KEKB-LER.

| Parameter | Symbol | |
|---|---|---|
| Energy | $E$ | 3.5 GeV |
| Circumference | $L$ | 3016.26 m |
| Bunch current | $I_b$ | 1.3 mA |
| Bunch spacing | $t_{sp}$ | 2∼8 ns |
| Harmonic number | $h$ | 5120 |
| rms beam sizes | $\sigma_x$ | 0.42 mm |
| | $\sigma_y$ | 0.06 mm |
| | $\sigma_z$ | 7 mm |
| Betatron tune | $\nu_x/\nu_y$ | 45.51/43.57 |
| RF voltage | $V_{RF}$ | 8.0 MV |
| Synchrotron tune | $\nu_s$ | 0.024 |
| Damping time | $\tau_x, \tau_y$ | 40 ms |

## EXPERIMENTAL CONDITIONS

The bunch-filling pattern used in the experiment was 4 buckets (8 ns)-equally-spaced pattern with total number of stored bunch of 1154 bunches, with about 1 $\mu$s of empty buckets for beam abort system. We have stored 600 mA (0.5 mA / bunch) only in the LER and opened the transverse (either horizontal or vertical) feedback loop, recorded the evolution of the instability during 4096 turns (41 ms) using the BOR, then closed the loop again to avoid beam loss. As the growth times of the instability in many cases were much shorter than the feedback-off period, typically around 2 ms, re-capturing the beam were very difficult.

The conditions of the weak solenoid field in the drift space of the ring of the experiments are shown in Table 2, where $B_{sol}$ means the ratio of the field strength and $L_{sol}$ means the ratio of the length covered by solenoid field relative to normal operating conditions.

As we found that the growth rate of the instability strongly depends on the experimental conditions above, we have tried to moderate the growth rate by increasing the linear chromaticity because it is fairly difficult to analyze the

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Table 2: Experimental conditions of solenoid field.

| Experiments | $B_{sol}$ | $L_{sol}$ |
|---|---|---|
| Reference | 100% | 100% |
| No solenoid | 0% | 0% |
| Effect of $B_{sol}$ | 10%,20% | 100% |
| Effect of $L_{sol}$ | 100% | 50% |

mode of the instability with data of very short time interval. The effect of the chromaticity was roughly corrected with the data of same solenoid-field but different chromaticity.

## MODE OF THE COUPLED-BUNCH INSTABILITY

We have recorded 4096 turns of bunch positions for all 5120 buckets. The unstable modes of the instability have been calculated by the following method:

- Make FFT of base 5 for the oscillation data of 256 turns(= 5120 bunches × 256 data points) to get the whole spectrum.
- Extract amplitude of the spectrum which corresponds to the betatron frequencies ($f_\beta + m \times f_{rev}$), where $m$ represents the mode of the oscillation. By aligning the amplitude by increasing order of the mode-id, we obtain the mode spectrum of the instability.
- Repeat above procedure with advancing the starting-point of the data by 256 turns. The time-evolution of the unstable mode is clearly shown.

Figures 1 and 2 show the unstable modes with full solenoid field and without solenoid filed, respectively. The mode spectra at intervals of 256 turns are overlapped. Clearly, the unstable modes have been affected by the existence of the weak solenoid field both for horizontal and vertical planes. The result is completely consistent with the previous experiments; with the solenoid field, the mode of the instability is governed by the circular motion of the electrons in the solenoid magnets.

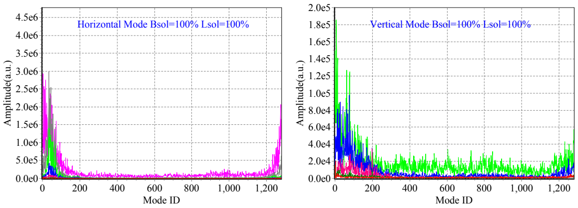

Figure 1: Unstable modes for full solenoid field for horizontal plane (left) and vertical plane (right).

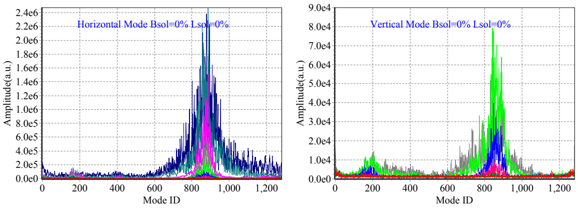

Figure 2: Unstable modes without solenoid field for horizontal plane (left) and vertical plane( right).

### *Effect of the strength of solenoid*

We have changed the magnetic field of the solenoid from 100% to 20%, 10% and 0% of the maximum field and measured the unstable modes. Figures 3 and 4 show the obtained unstable modes. Even with very weak solenoid field, the unstable modes show that the motion of electron clouds has been governed by the solenoid field, though the peak of the unstable modes are slightly moving to higher mode.

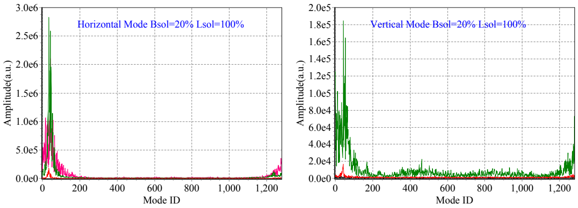

Figure 3: Unstable modes with 20% of solenoid field for horizontal plane (left) and vertical plane (right).

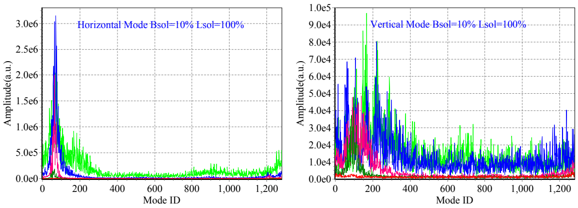

Figure 4: Unstable modes with 10% of solenoid field for horizontal plane (left) and vertical plane( right).

The growth rate of the instability is shown in Fig. 5. Note that we have roughly corrected the change of the growth rate due to the change of the linear chromaticity. Unexpectedly large enhancement of the growth rate both for horizontal and vertical planes are seen on lower solenoid field.

### *Effect of length of the solenoid*

Next, we have turned-off the half of the solenoid magnets in the ring, that was east half of the ring, with restoring the field-strength of the rest of the magnets to nominal ones. Under this condition, we had expected two unstable modes, i.e. lower modes from the clouds in the solenoid field and higher modes from the cloud in field free regions. Figure 6 shows the unstable modes with $L_{sol} = 50\%$. Only a group of the modes that might be coming from solenoid is shown for horizontal plane. On the other hand, two groups of the modes for the vertical

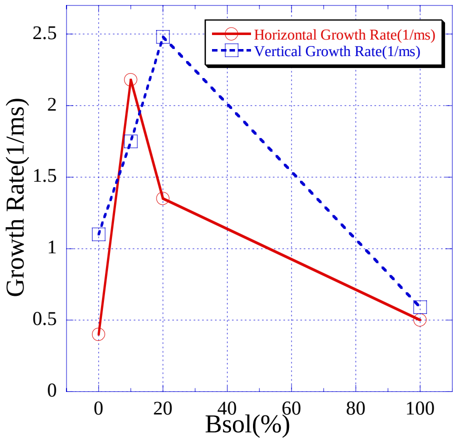

Figure 5: Horizontal (solid) and vertical (dashed) growth rate of the instability with different $B_{sol}$ settings.

plane appear. Though the higher modes are consistent with the modes without solenoids, the lower modes are higher than those with solenoid field of 100%.

The growth rate of the instability with $L_{sol} = 50\%$ was similar to or slightly slower than that with $L_{sol} = 100\%$.

## COMPARISON WITH THE SIMULATION STUDY

Numerical study of coupled-bunch instability caused by electron cloud has been made for the similar bunch-filling pattern for KEKB-LER[5]. The instabilities caused by the electron cloud in the simple drift-space without magnetic field, drift-space with solenoid field (1∼3 mT), and strong dipole magnetic field of bending magnets have been simulated and spectrum of unstable modes have been shown in Table 3.

Figure 7 shows the summary of unstable modes obtained by the simulation for the different solenoid field.

Experiment without solenoid field supports the simulation where the electrons are almost uniformly emitted form the chamber wall and secondary emission rate is small both for horizontal and vetical case.

The behavior of unstable modes when we have changed the solenoid field have been showing good agreements with the simulations. The tendency where the mode number increases with lowering the magnetic field also agreed between the experiment and the simulation.

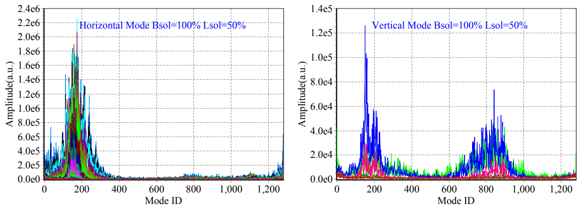

Figure 6: Unstable modes with half of solenoid magnets had turned off for horizontal plane (left) and vertical plane (right).

Table 3: Simulated unstable modes, where $\delta_2$ means secondary emission rate.

| Cases | Horizontal | Vertical |
|---|---|---|
| Drift space w/o solenoid | | |
| e$^-$ from hit point by SR | 180 | 840 |
| uniform emission | 840 | 840 |
| larger $\delta_2$ | 1100 | 1100 |
| Weak solenoid field | | |
| 1 mT | 20 | 10 |
| 2 mT & 3 mT | $\sim 0$ | $\sim 0$ |
| Bending magnet | 1230 | 160 & 840 |

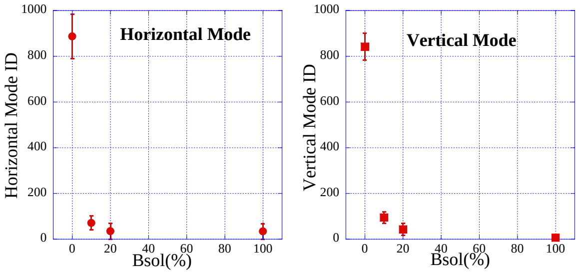

Figure 7: Unstable modes (horizontal : left, vertical : right) with the solenoid field.

## SUMMARY

We have measured the unstable modes of the coupled-bunch instability caused by electron clouds. Both in horizontal and vertical planes, experimental result support the simulation where the instability is dominated by the electron clouds in the drift space with lower secondary emission rate. Further study is needed for the unexpected behavior of the enhancement of growth rate of the instability with lower solenoid field.

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