BEAM-PHOTOELECTRON INSTABILITY AT KEKB: APPLYING A MAGNETIC FIELD

K. Ohmi and S. Matsumoto, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

The beam-photoelectron instability at KEKB is considered to be very serious. To recover the instability, we are considering to apply a magnetic field which traps photoelectrons near to the boundary of the beam chamber. We discuss the motion of photoelectrons in a magnetic field and the effects on the beam.

1 INTRODUCTION

An instability which seems to be due to a photoelectron cloud[1] was observed during the operation of positron storage at the KEK Photon Factory (PF)[2]. The instability is considered to be very serious for KEKB, because many more positrons must be stored in the low-energy ring (LER) than that in the PF. The instability at KEKB has been studied, and its growth rate has been estimated to be $0.05 \sim 0.1 (0.2 \sim 0.1 ms)$ in one revolution[3]. It was too high to be recovered by our feedback system[4], which had a damping rate of $0.01 (1 ms)$. Applying a magnetic field to the beam chamber of the arc section is proposed to reduce the growth rate[5]. We discuss the effects of the magnetic field on the beam-photoelectron instability. The parameters of KEKB-LER and PF are given in Tab.1.

Table 1: *Parameters of KEKB-LER.*

	KEKB-LER
Energy (GeV)	3.5
Current (A)	2.6
Circumference (m)	3016
Number of e^+ in a bunch	3.3×10^{10}
Emittances ($\varepsilon_x / \varepsilon_y$)	$1.8 \times 10^{-8} / 3.6 \times 10^{-10}$
Bunch spacing (ns)	2

Photoelectrons are produced at the surface of the chamber wall, and propagate to beam position because of an attraction due to the positron beam potential. A beam chamber with a radius of 5cm is used at KEKB-LER. The number of photoelectrons produced by a positron in one revolution is expressed as

$$N_{e_\gamma} = \frac{5\pi}{\sqrt{3}} \alpha\gamma \times (Y_{local} + Y_{unif}), \qquad (1)$$

where Y_{local} and Y_{unif} are the photoelectron conversion rates. Since synchrotron photons produced at a bending section illuminate a side of the chamber wall, a considerable number of photoelectrons, which were characterized by Y_{local}, are produced there. On the other hand,

Y_{unif} characterize the number of photon produced uniformly. This production is due to reflected photons etc. We call these localized and uniform production, respectively. The initial energy of the photoelectrons is considered to distributed at around $5 \pm 10 eV$.

Electrons in the magnetic field move along a circular orbit (cyclotron motion). The frequency and radius of the cyclotron motion are expressed as

$$\omega_c = \frac{eB}{m}, \qquad \rho_c = \frac{mv}{eB}. \qquad (2)$$

Typically, in a magnetic field of $B = 10G$, an electron with an energy of $E = 10eV$ has $\omega_c = 2\pi \times 29MHz$ and $\rho_c = 1cm$. Since photoelectrons have initial energies of $\sim 10eV$, they are expected to be trapped near to the chamber surface by applying a magnetic field of $\sim 10G$.

A vertical bending field works to protect photoelectrons only from the horizontal direction, but not from other directions. A horizontal field guides photoelectrons from side to the beam position, and plays a role in enhancing the instability. A solenoid field seems to be suitable for our purpose. We investigated the motion of photoelectrons in a solenoid magnetic field, and evaluated the growth rate of a multi-bunch instability due to photoelectrons.

2 MOTION OF PHOTOELECTRONS

We use a rigid Gaussian bunch model: each bunch is assumed to be a rigid Gaussian distribution in the transverse plane, and the longitudinal distribution is neglected. Bunches pass through the beam chamber at a transverse position of $\bar{x}_{+,a}$. The equations of motion for photoelectrons ($x_{e,j}$) are expressed by

$$
\begin{aligned}
\frac{d^2 x_{e,j}}{dt^2} &= 2N_e r_e c^2 \sum_a F_G(x_{e,j} - \bar{x}_{+,a}) \\
&+ \frac{e}{m_e} \left(\frac{dx_{e,j}}{dt} \times B - \frac{\partial\phi}{\partial x_{e,j}} \right), \qquad (3)
\end{aligned}
$$

where $+$ and e denote the positron bunches and photoelectrons, respectively; ϕ is the electric potential due to the photoelectron distribution. F_G is approximated by Bassetti-Erskine formula, since $\bar{x}_{+,a} \sim 0$. The mirror force of the beam is included by $\propto 1/r$, where r is a distance between the mirror beam and the photoelectron. To simplify the model, all of the photoelectrons are located at the same longitudinal position ($s_e(t) = const$). The bunches and photoelectrons interact with each other when $s_e(t) = s_+(t)$. The coulomb potential (ϕ) due to the photoelectrons is calculated using the PIC method and spline fitting.

We first calculate the equilibrium density. Macro-photoelectrons are produced on the surface of the beam chamber, and move while obeying Eq.(3). All of the bunches pass through the center of the beam chamber, $\bar{x}_{+,a} = 0$. Most of the computer resources are spent for calculations of F_G and the cyclotron motion of electrons. We obtain an equilibrium distribution of photoelectrons by supplying new photoelectrons in every bunch passage. Fig.1 shows the equilibrium distributions of photoelectrons for $B_z = 10, 20, 30, 40 Gauss$. Photoelectrons are assumed to be produced at a local position illuminated by photons ($Y_{local} = 0.1$). The distributions are obtained after the passage of 100 bunches. We must note that all photoelectrons are not absorbed within one cyclotron period. This characteristic is due to the fact that the beam-photoelectron force is time-dependent. An example of a complex trajectory is shown in Fig.2. The electron moves along a corrected cyclotron trajectory due to the magnetic field and beam force. The time-dependent characteristic is found to be a variation of the maximum amplitude in one cyclotron period.

Figure 2: Example of a complex trajectory in a magnetic field ($B_z = 10G$)

photoelectron cloud. We calculate the wake force by summing the beam-photoelectron force (first term of RHS of Eq.(3)).

We first consider the case that the localized production is dominant: $Y_{local} = 0.1$ and $Y_{inif} = 0$. Fig.3 shows the wake force for $B_z = 10, 20, 30, 40G$.

Figure 3: Wake force for $B_z = 10, 20, 30, 40 Gauss$. A bunch with a vertical displacement of 1mm passes through the equilibrium distribution.

We found long-range wake forces for $B_z = 10G$ and $20G$. The frequency of the wake is the same as the cyclotron frequency in the beam chamber. This feature seems to be due to trapped electrons whose trajectories are as in Fig.2. For $B_z \geq 30G$, the wake force was short range, and was weaker than that for $B_z \leq 20G$.

We now assume that the wake force depends linearly on the displacement, and satisfies a superposition for the displacement of bunches. The growth rate is expressed as

$$\Omega_m - \omega_\beta = \frac{1}{4\pi\gamma\nu_y} \frac{N_{e_\gamma}}{N_b} \sum_{n=1}^{n_0} \frac{d\bar{v}_y}{dy} \left(-\frac{ncT_{rev}}{h} \right) e^{2\pi in(m+\nu_y)/h},$$
(4)

where $d\bar{v}_y/dy$ is an averaged kick which photoelectrons feel due to bunches, which corresponds to the wake force.

The growth rates were calculated for the wake forces given in Fig.3. The rates for each multi-bunch mode are shown in Fig.4. The growth rate for $B_z = 30G$ was
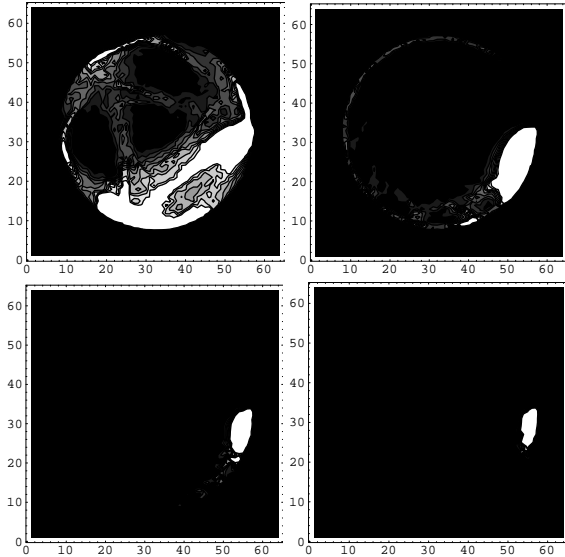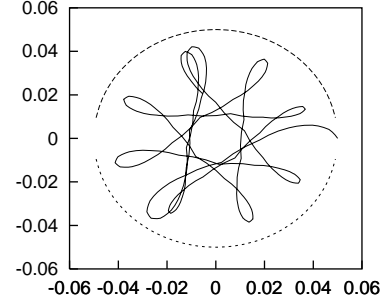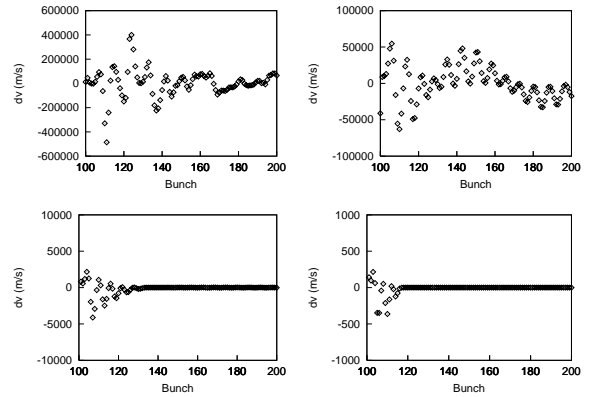

Figure 1: Equilibrium distribution of a photoelectron cloud for $B_z = 10, 20, 30, 40 Gauss$. The beam center is (32,32) and the unit of both axes is 2mm.

The same calculations were performed for uniform production. The equilibrium distribution was like a doughnut, and its thickness was the same as that of local production.

3 WAKE FORCE AND GROWTH RATE OF AN INSTABILITY

The effect on the beam of the photoelectron cloud is estimated by calculating the wake force, which is performed as follows. A bunch with a slight transverse displacement passes through the photoelectron cloud, with the result that the bunch disturbs the cloud. The following bunches without any displacement feel a wake force due to a disturbed

0.002 per revolution (5ms). This rate comes true when we cover the entire ring with a magnetic field. The feedback system[4] has a damping rate of $0.01\,(1ms)$. We must cover more than 90% to reduce the growth rate to $0.01\,(1ms)$. It will be difficult to actually do this.
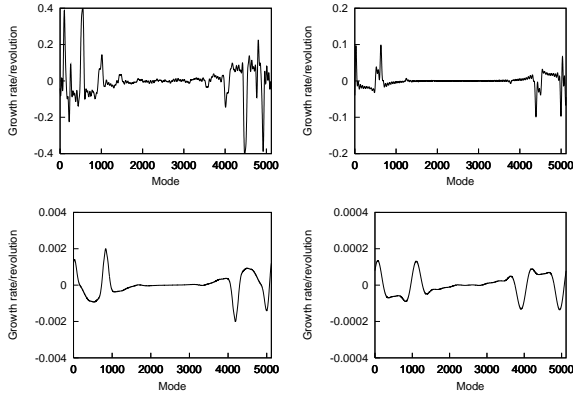

Figure 4: Growth rate of various multi-bunch modes.

We next consider the case that uniform production is dominant. We assumed that a solenoid magnetic field of $30G$ was applied and that the production efficiency (Y_{unif}) was 0.1. The wake force and growth rate were obtained, as shown in Fig.5. A strong medium(long)-range wake can be seen in the Figure. Comparing the wake forces for different bunch displacements showed that the wake did not have linearity for the bunch amplitude. The growth rate using Eq.(4) was 0.18 per revolution, and a band of the growth mode was narrow. We checked the high growth rate according to the rigid-bunch tracking method[6], in which the linearity and superposition of the wake force were not assumed. Fig.6 shows the bunch correlation pattern and growth of the amplitudes due to the instability. A bunch train including 200 bunches with $2ns$ spacing was tracked. Photoelectrons were created by each bunch, and were cleared at the end of the train. Though the beam amplitude did not increase exponentially, we found a very rapid growth in the small amplitude. The growth mode obtained by the wake force (Fig.4) was consistent with the tracking result.

The wake effect is due to trapped photoelectrons in the beam chamber, as shown in Fig.2. The maximum amplitude of electrons for the cyclotron motion is close to the radius of the beam chamber. It is sensitive to the initial and boundary conditions of electrons whether they are trapped or not. In the previous case, that localized production is dominant, the trapping phenomena is suppressed by the space-charge force due to the localized distribution. The space-charge force is not dominant in the uniform production case. Though it may be a delicate problem that such a wake force actually causes an instability, we must take account of this possibility.
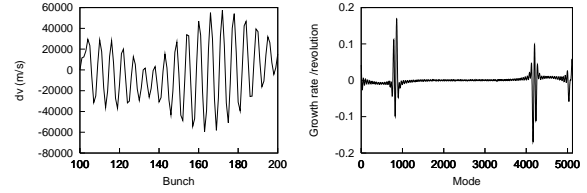

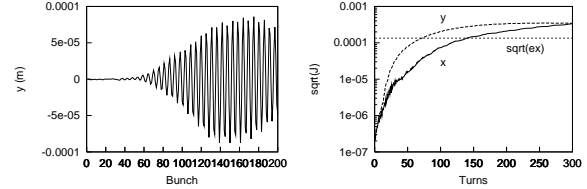Figure 5: Wake force and growth rate for uniform photo-electron production.

Figure 6: Bunch correlation pattern and growth of the amplitude due to an instability.

4 SUMMARY

We discussed the effects of a magnetic field on the beam-photoelectron instability. Two types of initial conditions, uniform and local production, were taken into account. If local production is dominant, growth rate reduced to be 0.002 by applying a solenoid magnetic field of $30G$. The space-charge force of the localized distribution contributes to suppress the instability. If the uniform production is dominant, the space-charge force has little effect. Photoelectrons are trapped in the beam chamber, with the result that the beam grows rapidly. Though the trapping process is delicate for the initial and boundary conditions, we can not deny that the rapid growth actually occurs.

We comment on the secondary emission of electrons. Since primary photoelectrons do not approach the beam, they are not accelerated very strongly in a solenoid magnetic field of $30G$. Most of the energy of the absorbed photoelectron was less than 50eV. We thus did not take into account the secondary electrons.

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