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Build up of Electron Cloud with Different Bunch Pattern in the Presence of Solenoid Field*

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Abstract

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INTRODUCTION

It is well established by many experimental evidences [1, 2] at KEKB and PEP-II that the instabilities caused by electron impose a severe limitation upon the luminosity in e^+e^- storage rings. Based on the experiments [1] at KEKB, there exists a current threshold beyond which the vertical beam size at the interaction point starts to grow like $\sigma_y^* \propto N_p^2/S_b$, where N_p is the bunch population and S_b is the spacing between two sequential bunches. Since N_p is normally set at the limit allowed by the beam-beam interaction, this observation implies that S_b cannot be too small otherwise the vertical blow-up degrades the luminosity. As a result, both B-factories are currently operated $S_b \approx 2$m, which is larger than its design value.

Experimentally, the solenoid field raises the threshold of the blow-up and therefore allows the increase of luminosity. On the other hand, we know from the simulation performed by Zimmermann [3] that longitudinal solenoid field B_s confines the electrons near the wall of the vacuum chamber and therefore reduces the cloud density near the positron beam. All this indicates that both S_b and B_s play vital roles in the physics of electron cloud instability. In this paper, we will study the dynamics between the positron beam and electron cloud with different S_b and B_s to reveal the physics indicated from the simulations and experiments.

ELECTRON MOTION

Our work starts with implementing longitudinal solenoid field in the code POSINST [4]. For simplicity, we assume that $\vec{B}$ is a constant and ignore any end effects of the solenoid. For a relativistic electron, the equation of motion can be written

$$\dot{\vec{v}} = -\vec{v} \times \frac{e\vec{B}}{\gamma mc} = \vec{\omega} \times \vec{v}, \qquad (1)$$

where $\vec{\omega} = e\vec{B}/\gamma mc$ is the cyclotron frequency of the electron. The solution of Eq. (1) is a helical orbit with the axis of the helix parallel to the magnetic field and the Larmor radius $r = v_\perp/\omega$. Along the field, electron moves in a constant speed $v_\parallel$. This solution is programmed in the code to compute the motion of the electrons where the solenoid field is at presence.

Parameter	Description	Value
E(Gev)	beam energy	3.1
C(m)	circumference	2200
N_p	bunch population	1.0×10^{11}
$\bar{\beta}$(m)	average beta function	17.0
$\epsilon_{x,y}$(nm-rad)	emittance x,y	24.0, 3.0
σ_z(cm)	bunch length	1.3
S_{RF}(m)	RF bucket spacing	0.63
δ_{max}	max secondary yield	2.0
E_{max}(eV)	energy at yield max	300
$\delta(0)$	yield low energy el.	0.5
r_b(cm)	beam pipe radius	4.5

Table 1: Simulation parameters for the LER at PEP-II

The parameters used in the simulation is tabulated in Table 1. S_b has to be a multiple of the RF spacing S_{RF}. N_p corresponds to the value at the peak of a typical fill in the recent operation. The values of δ_{max}, E_{max}, and δ_0 are chosen for the beam pipe of stainless steel in the straight sections where we have seen most electrons in the ring.

BUNCH TRAIN

Our simulation focuses on the electrons accumulated through the secondary emission from the beam pipe in the straight sections where not many primary electrons should be generated because of lack of synchrotron radiation. In the simulation, we generate a large number of electrons only at the first bunch passage and let electron cloud develops by the secondary emission process until a saturation density is reached.

The bunch pattern used in the simulation consists of a short train, long abort gap, and a long train. The density of electron cloud is clearly building up along the long train after the gap as shown in Fig. 1. Without solenoid field,

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the average density grows extremely fast along the train but saturates quickly near twice the neutralization density $\rho_e = N_p/\pi r_b^2 S_b$ due to the balance between the space charge and secondary yield. As the solenoid field increases, both the growth rate and the saturation level decrease. At $B_s = 15$G, we see a very gradual growth of the density along the train of 600 bunches. Assuming that the cloud density is proportional to the vertical beam blow-up, this simulation may be used to explain the observation of the very slow blow-up along the train after the initial installation of the solenoids at KEKB [1]. As B_s reaches 25G, the average electron density does not grow and is kept below 5% of ρ_e. That is near the density at which the head-tail instability occurs in the LER [5]. Fortunately, the density near the beam drops even more since the solenoid field restraints the electrons near the wall.

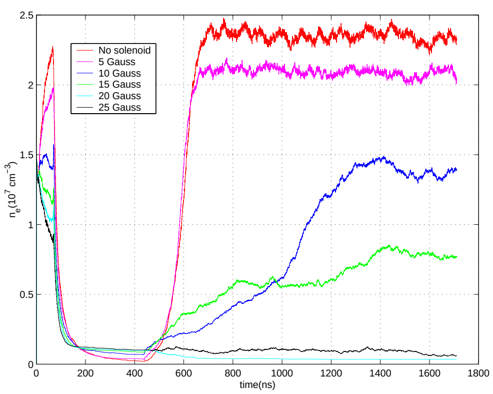

Figure 1: Density of electron cloud as a function of time when a bunch train passes through a stainless-steel beam pipe and longitudinal solenoid at different settings. The bunch spacing $S_b = 2S_{RF}$.

CYCLOTRON RESONANCE

As B_s increases further, we find at 40G that the saturation density along the bunch train actually become larger than the density without solenoid as shown in Fig. 2. However, with a close inspection of the distribution, we observed that nearly all electrons are confined in the vicinity of the wall. It is clearly seen from the figure that this phenomenon appears as a resonance.

Indeed, the result can be explained by a resonance associated with the cyclotron frequency ω and the bunch spacing S_b. Given the low-energy nature of the secondary electrons (100 eV), the radius of cyclotron motions is much smaller than the radius of beam pipe. The time for an electron coming out of the wall and then bending back by the magnetic filed and finally hitting the wall is nearly half of the cyclotron period $T_c = 2\pi/\omega$. The resonance occurs when this time coincides with the time interval between two consecutive bunches, namely

$$T_c/2 = S_b/c. \quad (2)$$

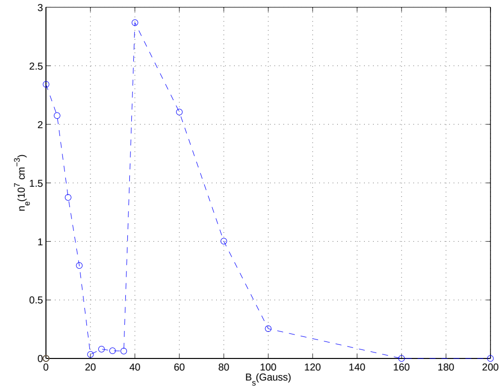

Figure 2: Saturation density along the bunch train as a function of solenoid field. The bunch spacing $S_b = 2S_{RF}$.

Since $\gamma \approx 1$ for typical secondary electrons, this resonance is almost independent of the velocities of electron and therefore much stronger than the resonance occurred in drift space. The condition of cyclotron resonance is given by

$$B_s^c = \frac{\pi mc^2}{eS_b}. \quad (3)$$

Given $S_b = 1.26$m, we have $B_s^c = 40$G. That agrees with the simulation. In addition, we can see from Fig. 2 that minimum density occurs at $B_s = B_s^c/2$. If the bunch spacing is increased to $S_b = 3S_{RF}, 4S_{RF}$, B_s^c is reduced to 30G, 20G according to Eq. (3). Indeed, that is well confirmed by the simulation. Moreover, we find that the characters of dynamics are essentially the same if we keep the product of S_b and B_s as a constant.

THRESHOLD OF MULTIPACTING

A threshold of multipacting was observed[2] between 700mA to 900mA with 692 bunches spaced 4-RF buckets at PEP-II. The measurement was carried out without or with the solenoid field of 30G. To understand the threshold mechanism, we run simulations with the similar parameters as in the experiments.

The results of the simulation are shown in Fig 3. It is clearly seen from the figure that there exists a threshold beyond which the density of the electron cloud grows until it reaches the saturation. The threshold is independent of the bunch spacing S_b if one retains $S_b B_s$ as a constant. Above threshold, the saturated density is proportional to the line density of the beam N_p/S_b indicating it is limited by the space charge. Since the peak beam current at PEP-II is already operated well above the threshold, the simulation predicts that a two-fold increase of the electrons when the bunch spacing is shorten from $4S_{FR}$ to $2S_{RF}$ even if the solenoid field is doubled.

The threshold in the simulation is about 6.5×10^{10} compared with $(4.6 - 6.0) \times 10^{10}$ in the observation. Without solenoid, however, the simulation disagrees with the observation because the absence of the nearby threshold in the

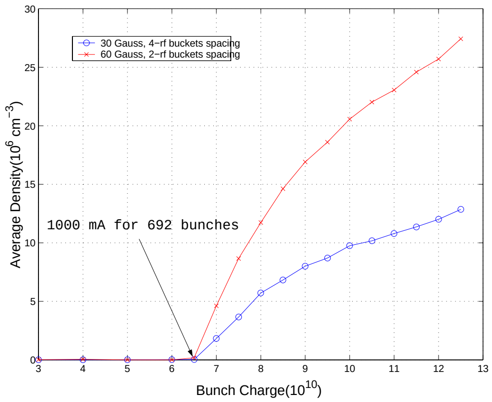

Figure 3: Saturated density as a function of the bunch population. The circles represent the case of 4-RF spacing and 30G solenoid field. The crosses represent 2-RF spacing and 60G field.

simulation.

For an electron near the wall, the momentum kick due to a bunch is given by [4]

$$\Delta p \simeq -\frac{e^2 N_p}{c} \frac{2}{r_b} \tag{4}$$

and thus the energy received from the bunch is

$$\Delta E \simeq \frac{2mc^2 N_p^2 r_e^2}{r_b^2}, \tag{5}$$

where r_e is the classic radius of electron. If the electron reaches the wall before the next bunch arrives ($B_s > B_s^c$), multipacting of electrons occurs if

$$\Delta E \geq E_{\delta=1}, \tag{6}$$

where $E_{\delta=1}$ (typically 20-100eV) is the energy above which the secondary yield δ larger than one. This yields the threshold of bunch population

$$N_p^{th} \simeq \frac{r_b}{r_e} \sqrt{\frac{E_{\delta=1}}{2E_0}}, \tag{7}$$

where $E_0 = mc^2$. In this simulation, we have $E_{\delta=1} \simeq 30$ eV. Using Eq. (7), we obtain $N_p^{th} \simeq 8.8 \times 10^{10}$ compared with 6.5×10^{10} found in the simulation. Besides reducing the secondary yield, enlarging the radius of beam pipe may be more effective way to increase the threshold as indicated in Eq. (7).

MULTI-BUNCH INSTABILITY

As the solenoid field increases, the electrons are gradually confined within the vicinity of the wall. However, under the condition of cyclotron resonance, there exist even more electrons than without solenoid. It was not clear if these electrons could cause any instability since they are so far away from the beam.

To answer this question, we compute the long-range wake as a function of the solenoid field and estimate the growth rate $1/\tau$. The wakes are shown in Fig 4. In this simulation, we have used a bunch spacing $S_b = 3S_{RF}$. Clearly from the figure, the peak values of wake are comparable at $B_s = 0$ and $B_s = 30$G (at the resonance). The growth time $\tau = 31, 9870, 145\mu s$ at $B_s = 0, 20, 30$G respectively.

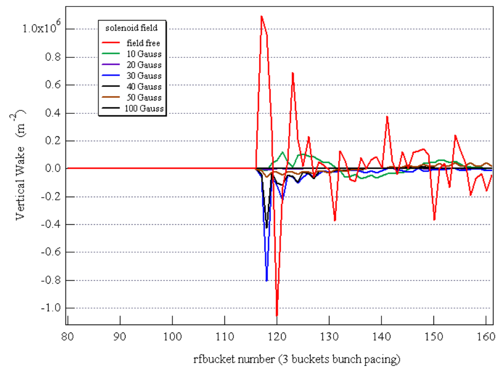

Figure 4: Long-range wake function due to electron cloud for bunch spacing $S_b = 3S_{RF}$.

DISCUSSION

Based on the simulation, we find that the cyclotron motion of electrons plays important role in generating and accumulating secondary electrons. When the resonance condition is satisfied, we see huge amount electrons near the wall. Although they are far away from the positron beam, they still create the long-range wake strong enough to cause multi-bunch instability.

In addition, if the solenoid field is strong enough $B_s > B_s^c$, we find that there exists a threshold for multipacting under which there is no accumulated electrons. This discovery may provide us a method to completely eliminate the electron cloud with larger enough beam pipe and lower enough secondary yield.

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