WEAK-STRONG SIMULATION OF BEAM-PHOTOELECTRON INSTABILITY IN A POSITRON STORAGE RING

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Abstract

Growth of the photoelectron instability has been discussed by using a wake force occurred by electron cloud. Concept of the conventional wake force is available for the force which satisfies linearity and superposition for the coherent amplitude of bunches. Weak-strong simulation method for beam-photoelectron interactions is proposed to study the nonlinear wake effect. In the method, photoelectrons are expressed by macro-particles and the beam by a series of rigid Gaussian bunch. We can investigate by the method not only nonlinear wake effect but also instability for a bunch train and an arbitrary bunch filling.

1 INTRODUCTION

In positron storage rings, a huge number of photoelectrons are produced by the synchrotron radiation of the positron beam at the surface of the vacuum chamber. Positron bunches filled with a narrow spacing create photoelectrons successively, and attract them by coulomb force. Consequently the photoelectrons distributes near to the positron beam. It is presented that a coupled bunch instability may be caused by the interactions between the positron beam and the photoelectrons[1, 2]. In electron storage rings, ions are trapped by the attractive force due to the electron beam, and oscillate in the beam potential with a frequency. The oscillation induces the two beam instability. In the case of positron storage rings, the photoelectrons are not trapped and not oscillate a definite frequency in the beam potential. However in a sense that bunches leave an electric 'wake' field after their passage, both phenomena is the same, thus we can say that the photoelectron instability is a kind of two beam instability.

In the photoelectron issue, we used the idea of the wake force which was conventional in impedance issue. We assumed that the linearity and superposition rule of the wake force were satisfied in beam-photoelectron interactions. However the linearity and superposition may not be always guarantied. We now propose a simulation method which is based on the weak strong model. This method was available for studying the two beam instability due to the ion-beam interactions[3]. This method, which does not require linearity of the wake, can be solved nonlinear wake effects. In this method, a weak beam, which is photoelectrons here, is expressed by macro-particles, and the barycenter motion of a strong beam is taken into consideration.

In considering the simulation, the beam-photoelectron and beam-ion interactions are very similar. The differences between them only mass and initial condition of the mediated particle, i.e., photoelectrons or ions. Photoelectrons are produced at the surface of the beam chamber, though ions are at near to the beam. Production rates are extremely different, that is, those of photoelectrons and ions are $0.16m^{-1}$ and $3\times10^{-9}m^{-1}$ by a beam particle par meter in the case of KEK-PF, respectively. The difference is revealed in the neutralization factor $\eta = n_{e(i)}/n_{beam}$, where n_e, n_i and n_{beam} are number of photoelectrons, ions and beam particles in a unit length, respectively. η of photoelectrons will be about 1, but that of ions will be is much less than 1, maybe about a few $\%$ in trapped case, or 10^{-5} or less in bunch train case. It means that a space-charge force between the photoelectrons is important than that of ions. The distribution of them in the chamber will contrast with each other. The photoelectrons distribute in whole of the chamber, while ions are localized near to the beam. The distributions affect the characteristics of the interactions of the beam-photoelectron and the beam-ion. Beam-photoelectron force is nearly linear for the oscillation amplitude. Growth of the photoelectron instability is not saturated till the size of beam chamber. While beam-ion force is strongly nonlinear. Growth of the ion instability is reduced when the amplitude exceed the beam size. Landau damping for the beam oscillation due to the nonlinearity is strong.

From a view point of simulation technique, macro-photoelectrons are required more and more than macro-ion to avoid a statistical noise of mean amplitude of photoelectrons. Since Landau damping is expected to be small, weak-strong approximation is more reliable than ion case.

2 EQUATION OF MOTION

We now discuss equation of motion of positrons and photoelectrons. We consider only the transverse motion. The photoelectron distribution is assumed to be uniform in longitudinal direction. The equations of motion are expressed as

$$\frac{d^2\boldsymbol{x}_{p,a}}{ds^2} + K(s)\boldsymbol{x}_{p,a} = \frac{2r_e}{\gamma}\sum_{j=1}^{N_e}\boldsymbol{F}(\boldsymbol{x}_{p,a}-\boldsymbol{x}_{e,j}), \qquad (1)$$

$$\begin{aligned}\frac{d^2\boldsymbol{x}_{e,j}}{dt^2} &= 2r_ec^2\left[\sum_{a=1}^{N_p}\boldsymbol{F}(\boldsymbol{x}_{e,j}-\boldsymbol{x}_{p,a})\right.\\ &\quad\left.+\sum_{i\neq j}^{N_e}\boldsymbol{F}(\boldsymbol{x}_{e,j}-\boldsymbol{x}_{e,i})\right], \qquad (2)\end{aligned}$$

where suffices p and e denote the positron and photoelectron, respectively. N_p and N_e are the number of each and

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Table 1: Parameters of KEK Photon Factory

Energy (GeV)	2.5
Circumference (m)	187
Stored current (mA)	300
Number of bunch (=h)	312
Beam size (mm)	1.14/0.114

γ is the Lorenz factor of the beam. $\boldsymbol{F}(\boldsymbol{x})$ is the Coulomb force in two dimensional space. We should take into account the boundary condition to obtain $\boldsymbol{F}(\boldsymbol{x})$, since photoelectrons are not localized near to the center of the chamber. These consist of differential $N_e + N_i$ equations, where that of each positron couples to the motion of all photoelectrons, and that of each photoelectron couples to the motion of all positrons and other photoelectrons.

We now focus the dipole coupled bunch instability due to photoelectrons. Dipole moment of bunches $\bar{\boldsymbol{x}}_p$ is taken into considered in Eq.(1). By assuming Gaussian transverse distribution for positrons in a bunch, Eqs.(1) are reduced to one equation, and an averaged force $\boldsymbol{F}_G(\bar{\boldsymbol{x}}_p - \boldsymbol{x}_{e,j}; \boldsymbol{\sigma}(s)))$ is introduced, where $\boldsymbol{\sigma}$ is beam size. $\boldsymbol{F}_G$ is expressed by Bassetti-Erskine formula[4], if the vacuum chamber is cylindrical and the beam passes through the center of the chamber.

To simplify the second term of right hand side of Eq.(2), a mean field $\phi(\boldsymbol{x}_e)$ of photoelectrons are introduced. $\phi(\boldsymbol{x}_e)$ is obtained by solving the Poisson equation

$$\triangle\phi(\boldsymbol{x}) = \frac{e}{\epsilon_0}\sum_{i}^{N_e}\delta(\boldsymbol{x}-\boldsymbol{x}_i). \qquad (3)$$

The equations of motion for a positron bunch and photoelectrons are expressed as

$$\frac{d^2\bar{\boldsymbol{x}}_p}{ds^2} + K(s)\bar{\boldsymbol{x}}_p = \frac{2r_e}{\gamma}\sum_{j=1}^{N_e}\boldsymbol{F}_G(\bar{\boldsymbol{x}}_p - \boldsymbol{x}_{e,j}; \boldsymbol{\sigma}(s)), \qquad (4)$$

$$\frac{d^2\boldsymbol{x}_{e,j}}{dt^2} = 2N_p r_e c^2 \boldsymbol{F}_G(\boldsymbol{x}_{e,j} - \bar{\boldsymbol{x}}_p; \boldsymbol{\sigma}(s)) - \frac{e}{m_e}\frac{\partial\phi(\boldsymbol{x}_{e,j})}{\partial\boldsymbol{x}_{e,j}}. \qquad (5)$$

We solve these equations by using macro-particles.

3 SIMULATION AND RESULTS

We show simulation results with an example of KEK-Photon Factory. Parameters of Photon Factory is shown in Table 1.

We consider cylindrical vacuum chamber with a radius of 5cm. Electric potential is easily obtained by Green function and mirror charge,

$$\boldsymbol{G}(\boldsymbol{x}) = -\frac{\boldsymbol{x}}{|\boldsymbol{x}|^2}\delta(s). \qquad (6)$$

We used a mesh with $2mm$ spacing to obtain the electric potential. The size is insufficient for using dynamically because we consider beam motion with an amplitude less than it. To avoid the noise comes from the potential calculation, we assumed the electric potential was static. Since the photoelectron distribution become stationary after passage of several dozen bunches, this assumption will be reasonable. We neglected the potential disturbance due to beam motion.

Fig.1 shows the electric potential by the photoelectron distribution. The initial condition of photoelectrons is the same as that in Ref.[2], that is, we consider that the direct (primary) photoelectron production due to photon is dominant and magnetic field is negligible. 50,000 macro photoelectrons were produced for every bunch passage in the potential calculation. We assumed an actual photoelectron density is $6 \times 10^8 m^{-1}$ for one bunch passing. The density means that photoelectrons are produced in whole ring uniformly with the photon-photoelectron conversion efficiency of 0.1. The figure is the electric potential after passage of 100 bunches. In stationary distribution, there were 590,000 macro photoelectrons in the chamber. The neutralization factor was 1.1.

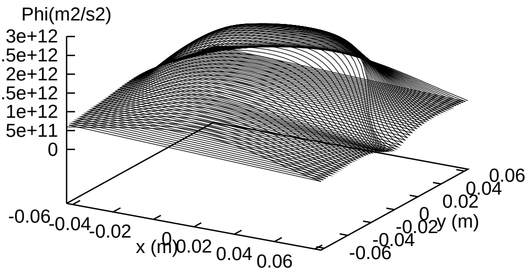

Figure 1: Electric potential created by photoelectron distribution.

In the weak-strong simulation, the electric potential, which is calculated with the high statistics (50,000), is treated as external field in the photoelectron motion. We solve Eqs.(4) and (5) by tracking the motion of macro-photoelctrons which feel the external field and beam force. Now 1000 macro-photoelectrons are produced in every bunch passage in the tracking. Fig.2 shows the growth of the maximum amplitude of all bunches. Growth of vertical oscillation dominate in this model. Growth time is estimated to be 700 turns from the figure. The growth was well fitted to exponential curve. Fig.3 shows transverse positions of all bunches after 3000 turns. It shows that a coupled bunch instability occurs. Since the bunch pattern had about 9 nodes, mode number ~ 300 was dominant. These results were consistent with results obtained by wake method.

We now consider another model to study interactions in bending magnets. It is guessed that photon density is very

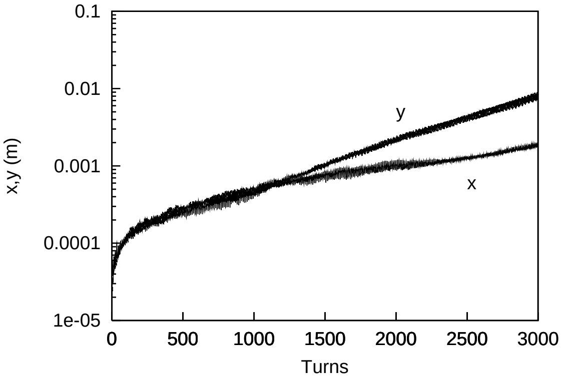

Figure 2: Growth of bunch amplitude. Primary photoelectrons which move in a region of no magnetic field are considered.

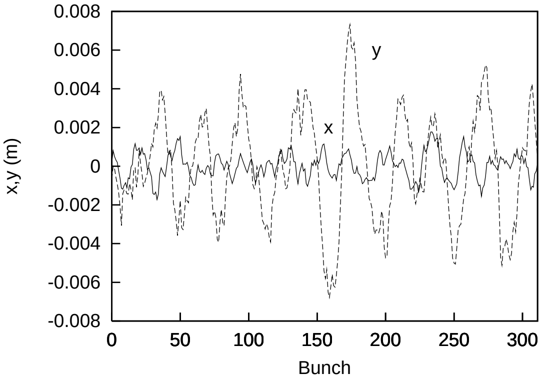

Figure 3: Transverse positions of all bunches after 3000 turns.

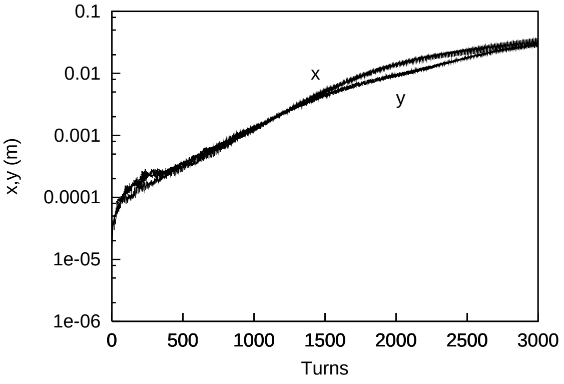

Figure 4: Growth of bunch amplitude. in bending magnet section. Photoelectrons move in a region of strong bending field.

high there. Reflected photon and secondary photoelectron production may be important. In strong vertical magnetic field $\sim T$, motion of photoelectrons is restricted along vertical direction. In the second model, photoelectrons are assumed to be created uniformly on the surface of the vacuum chamber. The photoelectron production rate is the same as the first model. In this production rate, since photoelectrons are accumulated till space charge limit, the detail of the production will not be important. Fig.4 shows a preliminary results for this model. Both of horizontal and vertical growth are seen. This figure is obtained for the case that whole ring is in bending magnet. Actual growth will be obtained by an adequate combination of these two model.

4 CONCLUSIONS

The weak strong based simulation is available for the beam-photoelectron instability. The simulation showed that coupled bunch instability was caused by photoelectron cloud.

These works are still in progress. Further study will be done.

5 REFERENCES

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