SIMULATION STUDY OF THE BEAM-PHOTOELECTRON INSTABILITY IN BEPC

Z. Y. Guo[1], K. Ohmi and H. Fukuma
KEK High Energy Accelerator Research Organization, Tsukuba, Japan

Abstract

The beam-photoelectron instability (PEI) is a transverse coupled-bunch instability in positron beam caused by photoelectrons which are produced by synchrotron radiation. To investigate the PEI, an experimental study was carried out in Beijing Electron Positron Collider (BEPC) with collaboration between IHEP, China and KEK, Japan. The behavior of the PEI has been analyzed and simulated. The results of simulation comparing with the observation are summarized in this paper.

1 INTRODUCTION

A vertical instability was observed years ago in the PF at KEK when the machine was operated with a positron beam[1]. The photoelectrons start at the surface of the beam tube by synchrotron radiation, and propagate while receiving an electric force from the positron bunches. The coupled-bunch instability can be caused by a photoelectron cloud as a wake force. It was explained as the PEI[2]. As the PEI may influence the performance of B factory and Tau charm factory significantly, a series of experiment has been carried out in BEPC since 1996[3]. The RF frequency of BEPC is 199.526 MHz and the harmonic number is 160. It is possible to provide a variety of the bunch patterns on the beam level of the PEI at the beam energies from 1.3 GeV to 2.2 GeV.

In the experiment, similar instability to KEK PF was observed. It is a coupled-bunch oscillation which can be detected with a spectrum analyzer and the bunch by bunch BPM system. The beam spectrum has a broad distribution of the vertical betatron sideband. This instability does not occur in an electron beam under the same conditions. The HOM at the corresponding frequency in RF cavities could not be found in the spectrum. The dependence of the threshold current and strength of the instability on a large number of variable parameters was measured.

To examine whether the observed instability can be explained by the model of the beam photoelectron instability, we are doing extensive simulation study. The results so far obtained are presented in this paper.

2 OBSERVATION

The coupled-bunch instability was observed in the positron beam at the beam current of about 9.4 mA at 1.3 GeV and with 160 bunches filled uniformly (0.06 mA per bunch)[4]. The vertical betatron sidebands, $nf_0 \pm f_y$, by each revolution frequency were observed on the spectrum analyzer, where f_y is the vertical betatron frequency and f_0 the revolutionary frequency.

The instability is very sensitive to vertical chromaticity at the beam current near by the threshold. It is in fact influenced by the sextupole configuration. The instability is getting stronger when the strength of the sextupoles is getting weaker.

We scanned the beam energy from 1.3 GeV to 2.2 GeV at a beam current about 15 mA to survey the dependence of the instability on the beam energy. The amplitude of the vertical sidebands slightly decreased as the energy is increased.

The observed amplitude of the sidebands was weaker at a RF frequency change of -20 KHz than that of +20 KHz which is corresponding to a horizontal orbit change of +4 mm and -4 mm on average respectively, and corresponding to a beam emittance change +79.0% and -36.4% respectively. It was also observed the instability is weaker when the beam emittance is larger.

The instability strongly depends on the bunch spacing. The threshold current of the instability was higher than 40 mA when the positrons were injected into every other two buckets, i.e. 80 bunches filled uniformly in the ring. This shows that the wake field of the photoelectrons decreases quickly along the bunches.

The observation shows that the transverse and longitudinal tunes do not influence the instability, while the tunes are changed in a stable region.

Many observations were carried out above the threshold current of the instability with electron beam under the same conditions as the positron beam. The phenomena are totally different comparing to the positron beam. Vertical sidebands were observed at only $2f_{rf}$ and $3f_{rf}$, but none were observed at other revolution harmonics.

3 MODEL OF SIMULATION

In a computer code which was developed to simulate this instability[2], we assume that a large number of photoelectron are produced by the photons from synchrotron radiation of the positron beam. The photo-electrons receive an attractive force from position beam, some of them being lost on the wall of the vacuum chamber, but new one propagating continually; then, the photoelectrons

[1] On leave of absence from IHEP, Beijing, China

accumulate to the equilibrium distribution. The number of photoelectrons is determined by the beam energy and the photoelectron conversion rate. We neglect the generation of the secondary electrons when the photoelectrons hit the wall of the beam tube. The conver-sion rate of 0.1 on average is assumed in the simulation. We do not involve any damping mechanism in the simulation.

When a bunch passes through the stationary photo-electron distribution with a transverse displacement from the beam axis, the photoelectron distribution is disturbed and affects the following bunches. The coherent interac-tion between bunches can be developed by the electron cloud, and it can be estimated by means of a wake force.

The growth rate can then be calculated by the disper-sion relation, assuming a linear wake force, as[5]:

$$\Omega_m - \omega_\beta = \frac{-N_e c T_0}{4\pi\gamma\upsilon_y h N_b}\sum_{k=1}^{k_0} k \frac{d\overline{V_y}}{dy} e^{2\pi k i(m+\upsilon_y)/h}, \qquad (1)$$

where N_e is the number of photoelectron produced by a bunch throughout the ring circumference, N_b the posi-trons in a bunch, γ the Lorentz factor of the beam, h the harmonic number, T_0 the revolution period, υ_y the verti-cal betatron tune, $d\overline{V_y}$ the average velocity change of the photoelectron, and k a bunch which is k-th ahead of the 0-th bunch and the wake is summed to the bunch k_0. The growth rate of the instability is calculated in this way as a function of the mode number m, plotted in Figure 1.

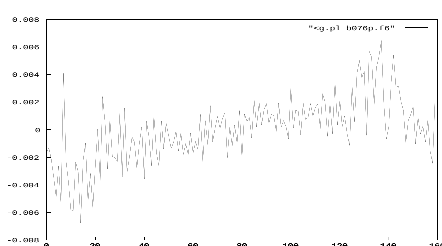

Figure 1: Growth rate of the instability

The rigid bunch simulation method for the beam pho-toelectron interaction is used to track the coherent oscilla-tion of the bunches[6]. The nonlinear wake force, which is not took into account in the wake method, is involved in the tracking, and it can survey a bunch train with any bunch spacing. In this method, the photo-electrons are described by micro-particles, and the posi-trons described by a series of rigid Gaussian bunches. The photoelectron distribution is assumed to be uniform in the longitudinal direction. The equations of the transverse motion are ex-pressed as follows:

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

$$\frac{d^2 x_{e,j}}{dt^2} = 2N_p r_e c^2 F(x_{e,j}-\bar{x}_p;\sigma(s)) - \frac{e}{m_e}\frac{\partial\phi(x_{e,j})}{\partial x_{e,j}}, \qquad (3)$$

where p and e denote the positron and photoelectron, σ the transverse beam size, ϕ the photoelectron potential and F the Coulomb force in two-dimensional space ex-pressed by the Bassetti-Erskine formula[7].

4 RESULTS

The tracking results show that the coherent coupled-bunch oscillation appears along the bunches. The growth behavior of the coupled-bunch oscillation is shown in Figure 2. The growth time can be obtained by fitting the amplitude of the oscillation; the same result, about 3 ms, was obtained by the wake method at experiment condi-tions. This indicates the nonlinear effect in the beam-photoelectron interaction is not strong. The reason is that the photoelectrons are distributed in whole of the beam chamber. The beam-photoelectron force is quite linear for the oscillation amplitude in the beam chamber.

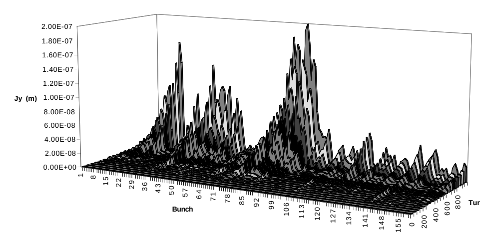

Figure 2: Growth behavior of coupled-bunch oscillation

The coupled-bunch oscillation obtained by tracking is transferred to the spectrum with FFT. The simulated spec-trum at the different beam current of 15, 20 and 25 times threshold of the instability are shown in Figure 3. The lower and upper side in the figure show the betatron side-bands as $nf_0 \pm f_y$ respectively.

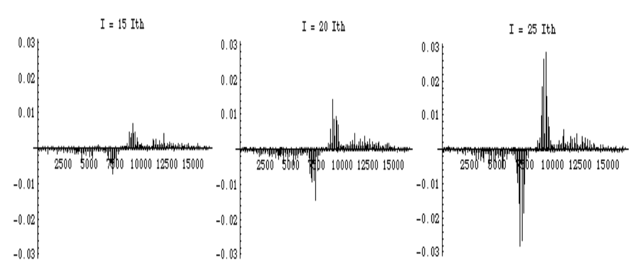

Figure 3: Current dependence of the instability

Since the growth rate of the instability is proportional to the bunch current from the simulation results in the range where the nonlinear effect can be neglected, the pic-ture of the bunch oscillation is much clearer at a stronger bunch current and we can save the computer time. Thus, we take the bunch current to be about 20 times stronger than the threshold current of the observation as shown in the following figures.

Figure 4 shows the oscillation of bunches and "center" of the photoelectrons in the vertical direction which are represented by solid and dot curves respectively. It shows that the coupled-bunch oscillation occurs simultaneously with the photoelectron oscillation.

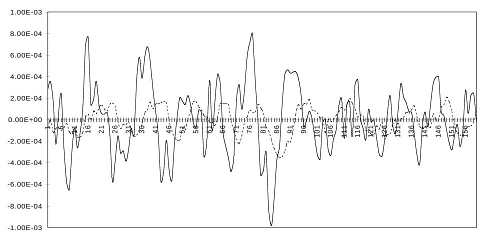

Figure 4 : Oscillation of bunches and photoelectrons

The simulated spectrum of the coupled-bunch oscillation at different beam energies of 1.3 GeV, 1.55 GeV and 2.1 GeV are shown in Figure 5. It can be seen that the amplitude of the sidebands decreases with energy. It indicates the strength of the instability is weakened when the beam energy is increased.

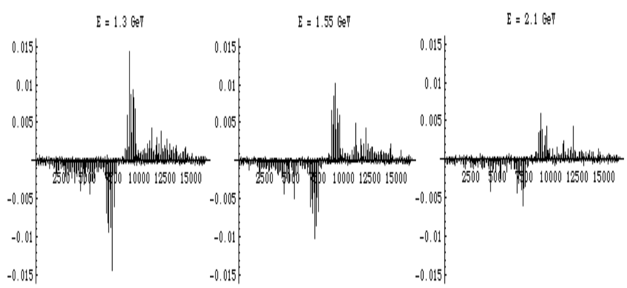

Figure 5: Energy dependence of the instability

The simulated spectrum at different beam emittance of 1.0, 1.5 and 2.0 times normal emittance are shown in Figure 6. The normal emittance which was used in the experiment is 0.134 mmmrad. It indicates the strength of the instability is weaker as the beam emittance is larger.

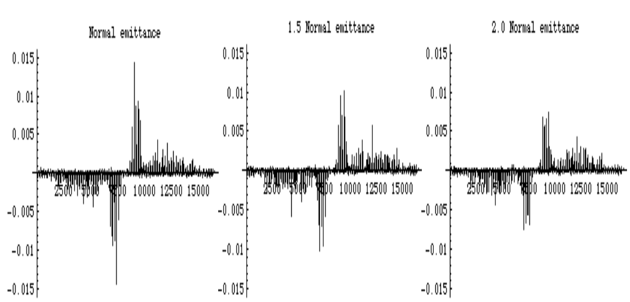

Figure 6 : Emittance dependence of the instability

The simulation show that the bunch spacing has very strong effect to the instability. At the bunch spacing of 10 ns, the amplitude of the spectrum is two order lower than the case of 5 ns.

To estimate the growth time of the instability, we compared three potential damping mechanisms as a Landau damping due to the nonlinearity of the lattice, as a coherent effect of the head-tail damping of single bunch, and as a coherent effect of multibunch head-tail phase effect. The conclusion of calculation is that the nonlinear effect of the sextupoles is the dominant factor[8]. The calculated Landau damping time has the same order as that of the calculated growth time of the instability, about 3 ms under the experiment conditions. The mechanism of chromaticity influence can be understood as the Landau damping.

5 DISCUSSION

The photoelectron instability has been studied in detail at BEPC under the conditions of the different related parameters. The experiment shows that the instability is a unique phenomenon to the positron storage rings. The simulation based on the conventional instability theory reproduce some characteristics of the observation. The instability is weakened at higher beam energy and at lower beam current. The threshold of the instability is much higher when the bunch spacing is increased. The simulation results are comparable with the observation.

The status of the simulation of the photoelectron instability is still not satisfied. The reason is that this effect is subtle and the simulation contain assumptions. A small change of some details, such as, the conversion rate of the photoelectron, the second emission, the photo spectrum and some others, can significantly affect the final answer[9]. Even so, the results shown in this paper are inspired and can help to understand the mechanism of this instability. Both experiment and simulation results are meaningful for the modern electron positron colliders like B factories and Tau-charm factories.

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