# STUDY OF THE BEAM-PHOTOELECTRON INSTABILITY IN BEPC


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*Abstract*

An experimental study of the beam-photoelectron instability (PEI) was carried out in the Beijing Electron Positron Collider (BEPC) with collaboration between IHEP, China and KEK, Japan. The PEI is a transverse coupled-bunch instability in the positron beam. In the experiment, betatron sidebands were surveyed as a function of various beam parameters. The observed phenomena were analyzed and simulated with a computer code. The results of the experiment and the analysis 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]. Similar phenomena have recently been studied in BEPC. This instability is a coupled-bunch oscillation with a low threshold current of about a few 10 mA in both machines. The broad distribution of the betatron side-bands were raised when the instability occurred. The HOM at the corresponding frequency in the RF cavities could not be found from the spectrum. It is hard to be suppres-sed by partially filling positrons in RF buckets. This instability does not occur in an electron beam under the same conditions. It has been explained as being the PEI.

Since B factories and Tau-charm factories will be built, and these colliders will be operated at high current with multibunch electrons and positrons, a series of machine studies on the PEI in BEPC have been proposed and carried out under cooperation between IHEP and KEK[2].

BEPC can be operated as a collider and as a synchrotron radiation source with beam energies from 1.3 GeV to 2.2 GeV. The RF frequency is 199.526 MHz and the har-monic number is 160. It is possible to provide a variety of the bunch patterns on the beam level of the PEI.

Four periods of PEI experiment have been executed at BEPC since June, 1996. The instruments used to observe the PEI were prepared by both IHEP and KEK. A spec-trum analyzer (HP8568B) with a 1.5 GHz bandwidth has been used for beam-spectrum observations. The investiga-ted effects on the PEI include the chromaticity, bunch space, emittance, beam energy, RF frequency, distributed ion bumps, betatron tunes, magnetic field, RF voltage and some other parameters.

A computer code has been developed to simulate this instability[3]. The photoelectrons start at the surface of the beam tube by synchrotron radiation, and propagate while receiving an electric force from the positron bun-ches. The coupled-bunch instability can be caused by a photoelectron cloud as a wake force. We can analyze the characteristics of the instability by conventional instabi-lity theory.

## 2 OBSERVATION

The observed coupled-bunch instability in the positron beam has a low threshold current of about 9.4 mA at 1.3 GeV and full filling with 160 bunches uniformly (0.06 mA/bunch)[4]. The vertical betatron sidebands, $nf_0 \pm f_y$, by each revolution frequency were observed on a spectrum analyzer, where $f_y$ is the vertical betatron frequency and $f_0$ the revolutionary frequency. The vertical oscillation could also be observed on a synchrotron light monitor.

The instability is quite sensitive to vertical chroma-ticity around the threshold current. The vertical sidebands disappeared when the vertical chromaticity increased by 1 or 2 from the normal value of 4 at a beam current slightly above the threshold of the instability. On the contrary, sidebands appeared when the chromaticity decreased by 1 or 2 in the observation.

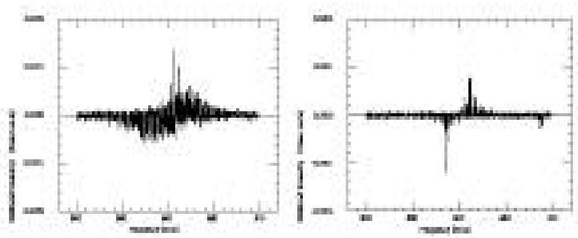

Figure 1: The observed sideband distributions

We have scanned the beam energy from 1.3 GeV to 2.2 GeV at a beam current about 15 mA to survey the depen-dence of the instability on the beam energy. The ampli-tude of the vertical sidebands slightly decreased at 2.0 GeV and the vertical sidebands disappeared at 2.2 GeV. The sideband distributions observed at 1.55 GeV and at 2.1 GeV are

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shown in Figure 1. We also scanned the energy from 1.55 GeV to 2.1 GeV at a beam current of about 10.3 mA, which is near to the threshold. It can be found the energy dependence on the instability is not very strong from control of the instability by the chromaticity.

If the distance between the center of the positron beam and the wall of the beam tube is changed, the distribution of the photoelectrons is modified. We changed the RF frequency at a beam current near to the threshold by +/- 20 KHz, respectively, which corresponded to a horizontal orbit change of -/+ 4 mm on the average. The amplitude of the sideband was slightly weaker at a RF frequency change of -20 KHz than that of +20 KHz.

Most observations in our experiment were under the condition of full filling with 160 bunches uniformly. To investigate the bunch spacing effect, we injected a beam into every other two buckets, i.e. 80 bunches uniformly in the ring. The threshold current of the instability was above 40 mA. This shows that the instability strongly depends on the bunch spacing, that is, the wake field of the photoelectrons decreases quickly along bunch space.

The distribution of the vertical sidebands was compared for the case of distributed ion pumps (DIP) being turned on and off, however, the instability phenomena did not change any more. This is different than in the case of CESR, because the calculated leakage electrostatic field of the DIP in BEPC is about 50-times weaker[5].

When the instability was observed near to the threshold by adjusting the chromaticity, there was no response on the HOM signal to be probed from cavities through loop pickups. This indicates the instability is not related to the HOM of the BEPC cavities.

The observation shows that the transverse and longitudinal tunes do not affect the distribution of the vertical sidebands of the instability, while the tunes are changed in a stable region. The horizontal magnetic field effect on the instability was also surveyed by increasing the field of all vertical correctors to 10, 20 and 40 Gauss; no different phenomena were observed.

Comparing the electron beam, many observations were carried out above the beam level of the instability threshold current with electron beams under the same conditions as the positron beam. Vertical sidebands were observed at $2f_{rf}$ and $3f_{rf}$ only, but none were observed at other revolution harmonics.

## 3 SIMULATION

The physics model in the simulation is that a large number of photoelectron are created by the synchrotron radiation of the positron beam at the inner wall of the vacuum chamber; the photoelectrons receive an attractive force from the following bunches to the beam position, some of them being lost, but new one propagating conti-nually; then, the photoelectrons accumulate to the equilib-rium distribution. The number of photoelectrons is deter-mined by the beam energy and the photoelectron conver-sion rate. In the BEPC case, the conversion rate is 0.1, assumed in the simulation.

When a bunch passes through the stationary photoelectron 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 estimated by means of a wake force, as in conventional beam instability theory. The growth rate can be estimated from the dispersion rela-tion, assuming a linear wake force, as[6]:

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

where $N_e$ is the number of photoelectron produced by a bunch throughout the ring circumference, $N_b$ the posi-trons in a bunch, $\gamma$ the Lorentz factor of the beam, $h$ the harmonic number, $T_0$ the revolution period, $\upsilon_y$ the ver-tical 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 summered to the bunch $k_0$. The growth rate of the instability was estimated in this way as a function of the mode number m, and growth rate is plotted in Figure 2.

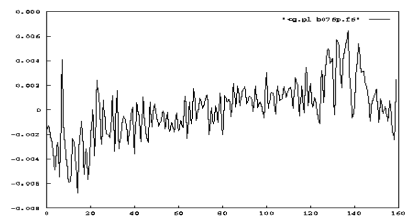

Figure 2: The growth rate of the instability

The weak-strong interaction for tracking the coherent oscillation of the bunches is used in the simulation code[7]. In this method, the photoelectrons are described by micro-particles and the beam by a series of rigid Gaussian bunches. The nonlinear wake force could be involved, and the tracking can survey for a bunch train with any spacing. The equations of the transverse motion are expressed as follows:

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

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

where $p$ and $e$ denote the positron and photoelectrons, $\sigma$ the transverse beam size, $\varphi$ the photoelectron potential and $F$ the Coulomb force in two-dimensional space expressed by the Bassetti-Erskine formula[8].

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, and the picture of the bunch oscillation is much clearer at a stronger bunch current, we take the bunch current to be a few times stronger than the threshold current of the obser-vation, as shown in the following figures.

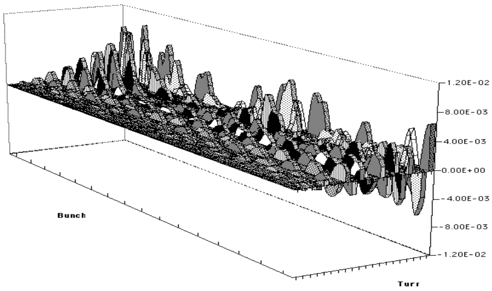


Figure 3: The behavior of the coupled-bunch oscillation

The coherent coupled-bunch oscillation and its growth behavior in the vertical direction are shown in Figure 3. A coherent coupled-bunch oscillation appeared along the bunches. The growth time could be fitted from the amplitude of the oscillation; the same result, about 2.5 ms, was obtained by the wake method at experiment conditions.

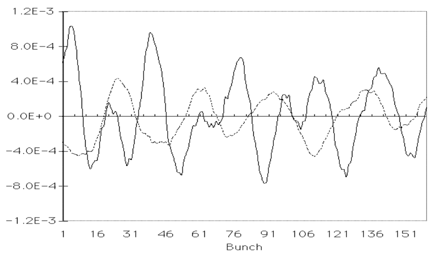


Figure 4: The Oscillation of bunches and photoelectrons

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

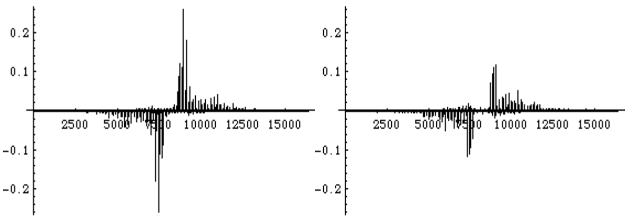


Figure 5: The simulated sideband distributions

The simulated spectrum of the coupled-bunch oscillation at different beam energies of 1.55 GeV and 2.0 GeV are shown in the left and right part of Figure 5 respec-tively. It can be seen that the amplitude of the sidebands decreases with energy. This indicates the strength of the instability is weakened when the beam energy is increased.

To estimate the damping effect, we compared three potential damping mechanisms as a single particle effect of Landau damping due to the nonlinearity of the lattice, a coherent effect of the head-tail damping of a single bunch and a multibunch head-tail phase effect. The conclusion is that the nonlinear effect of the lattice by sextupoles is the dominate factor[9]. The calculated Landau damping time has the same order as that of the calculated growth time of the instability, about 2.5 ms of the magnitude under the experiment conditions. The mechanism of chromaticity influence can be understood as Landau damping.

## 4 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 in positron storage rings. This is very meaningful for the modern electron positron colliders like B factories and Tau-charm factories.

The simulation by an analysis of the conventional instability theory expresses the same characteristics comparing with the observation. The instability can be sensitively influenced by the chromaticity due to the Landau damping effect of the lattice nonlinearity. The instability is weakened at a higher beam energy. The threshold of the instability is much higher when the bunch space is increased. This instability is being further studied both experimentally and theoretically with the cooperation of IHEP and KEK. A detailed comparison of the observation and simulation is on the way.

The next PEI experiment will soon be executed at BEPC. The items for further studies include a bunch oscil-lation observation using a single pass BPM system, an exact damping time measurement, the threshold current dependence on the octupoles and a more detailed study of the emittance dependence under the conditions of the dif-ferent sextupole corrections.

## 5 ACKNOWLEDGMENTS

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