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Transverse Blowup along Bunch Train Caused by Electron Cloud in BEPC*

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Abstract Electron cloud instability (ECI) may take place in a storage ring when the machine is operated with a multi-bunch positively charged beam. Transverse blowup due to electron cloud has been observed in some machines and is considered to be a major limit factor in the development of high current and high luminosity electron positron colliders. With a streak camera, the transverse blowup along the bunch train was first observed in an experiment at the Beijing Electron-Positron Collider (BEPC) and the simulation results were used to compare with the observation.

Key words electron cloud, streak camera, single bunch instability, head-tail model

1 Introduction

It is clear that the electron cloud instability (ECI), identified by Izawa[1] at the KEK Photon Factory, can be seriously detrimental to the positively charged, high current and multi-bunch beams. The electron cloud (EC) in positively charged beam storage rings can cause not only the multi-bunch dipole mode instabilities but also the single bunch instability, which are represented by the transverse bunch blowup. The blowup of the bunch size caused by EC restricts the luminosity of collider seriously in KEKB and PEP-Ⅱ[2].

The Beijing Electron-Position Collider (BEPC) can be operated as a collider, and also as a synchrotron light source when it is operated in single electron beam. It can be injected with positron beam bunch by bunch, so the ECI can be studied experimentally. The coupled bunch instability caused by EC has been observed in earlier experiments and explained as a wake field produced by the disturbed EC[3]. In this paper the experimental results and the simulation focus on the single bunch instability that is the bunch size blowup along the bunch train. One proposed mechanism for the beam blowup due to the presence of EC is the head-tail instability caused by wake fields created by the passage of the bunch particles through the electron cloud. Based on the head-tail model[4], a code was developed to simulate the beam size blowup[5]. The experiment and simulation about the beam size blowup along the bunch train are introduced and discussed in this paper.

2 Experiments

The main parameters of the BEPC under the experimental studies are: beam energy of 1.3GeV, betatron tune 5.82 and 6.74 in horizontal and vertical direction respectively, natural beam emittance as 134mm·mrad, RF frequency as 200MHz with a harmonic number of 160, minimum bunch spacing of 5ns and all the experiment parameters are listed in Table 1.

We use a Hamamatsu C5680-11 streak camera to measure the bunch vertical size and its length, associated with a set of optical lenses put on a platform

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Table 1. Parameters of the BEPC.

beam energy E/GeV	1.3
bunch current $I_{\rm b}$/mA	2.5
bunch spacing $L_{\rm sep}$/ns	5.0
bunch number n	22
average bunch sizes $\sigma_{x,y}$/mm	1.15,0.52
chamber half dimensions R/mm	60
tune $Q_{x,y}$	5.82,6.74
circumference C/m	240.4
average beta function $\langle\beta\rangle$/m	10

at the end of the synchrotron light extraction line. Reflected by the optical lenses, the synchrotron light pulse enters the streak camera directly. A Macintosh 8100 computer is used to control the streak camera and the light image can be shown on the screen. Fig. 1(a) is the bunch train light image taken by the streak camera. A software U5565 is applied for manipulating the streak camera with friendly graphical interfaces. The software also can do some preliminary data analyses, such as obtaining the light brightness of every bunch. Fig. 1(b) is the light flux of every bunch.

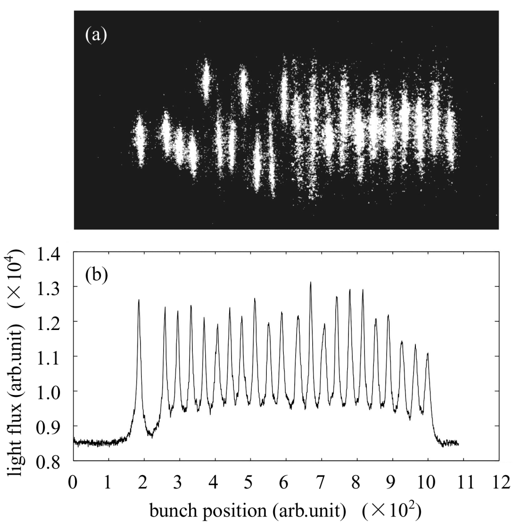

Fig. 1. Bunch image taken by the streak camera.

The vertical bunch size, corresponding to the RMS value in the fitting result, can be obtained by fitting the data with a Gaussian distribution. In different chromaticities, every bunch's vertical size was obtained, shown in Fig. 2. In fact, in the observation with larger chromaticities, the images taken by the streak camera become blurry because of the nonlinear motion. But it can be seen clearly that the bunch vertical size blowup along the bunch train was observed and after a few bunches (about 15 bunches) the blowup was saturated. One possible interpretation to this phenomenon is that under multibunch operation with uniformly filled bunches, a constant number of electrons is launched into the chamber during every passage of the bunch and in the same time the electrons may hit the wall and be absorbed. Thus, after the passage of a few bunches, the electron supply is cancelled by the absorption and electron cloud density is stationary. In the next turn, the same progress repeats again. So before the saturation of the electron cloud, the different bunches will get different interactions from the electron cloud and the bunch size blowup will be different. Until the electron cloud density saturates, the bunch blowup will not get saturation.

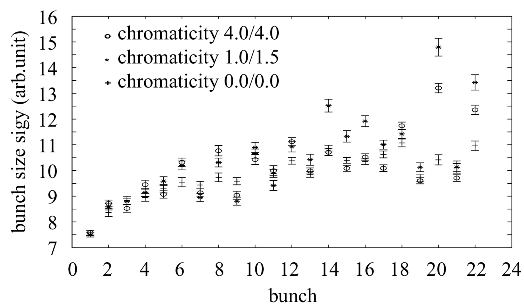

Fig. 2. Bunch vertical size blowup along the train.

3 Simulations

A code, developed for the BEPC, can be used to simulate the electron cloud density[6]. In the physical model, there are two main sources of electrons: photoelectrons generated from the synchrotron radiation and secondary electrons from the multipacting on the wall of vacuum chamber. Without TiN coating in the BEPC vacuum chamber, the secondary electron yield (SEY) is assumed to be 1.8 in the simulation. Fig. 3 shows the buildup of an electron cloud along the bunch train and saturation after the passing of about 15 bunches. According to the simulation results, the electron density is linearly proportional to the bunch current. If the bunch current is 2.5mA, the same as the bunch current in experiments, the saturated electron density is about $1.4\times10^{13}/\mathrm{m}^3$.

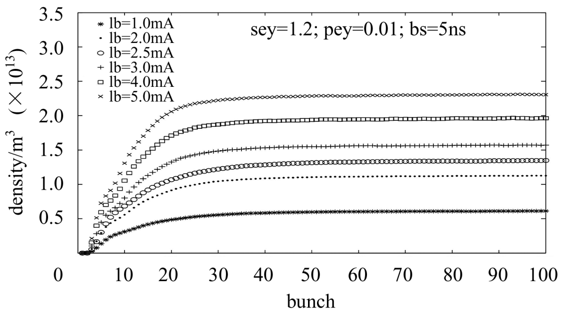

Fig. 3. Simulated electron cloud density in BEPC.

The electron cloud interacts with the particles of bunch and drives single bunch instability. Based on the head-tail model, a code was developed to simulate the bunch size blowup. In the model, the electron cloud and the bunch are represented by N_e and N_p macro-particles with transverse uniform and Gaussian distributions, respectively, and the electron cloud is concentrated on a location s of the ring longitudinally. Including the synchrotron oscillation of a particle, the motion of bunch macro-particles is described by a 3-D vector, $\left(x_p, x'_p, y_p, y'_p, z, \dfrac{\Delta P}{P}\right)$. The bunch is divided into N_s slices, which interact with the electron cloud one by one and cause the distortion of the electron cloud distribution. The macro-particles in different slices can change their positions as the synchrotron oscillation occurs. Using $X_{p,i}$ to present the vertical or horizontal positions of the macro-particles, $X_{p,i}=y_{p,i}$ or $x_{p,i}$, the equations of the motion of electrons and bunch particles can be expressed as

$$\frac{\mathrm{d}^2\boldsymbol{X}_{p,i}}{\mathrm{d}s^2}+K(s)\boldsymbol{X}_{p,i}=\left(\frac{2r_e}{\gamma}\right)\cdot\sum_{j=1}^{n_e}\boldsymbol{F}(\boldsymbol{X}_{p,i}-\boldsymbol{X}_{e,j}), \quad (1)$$

$$\frac{\mathrm{d}^2X_{e,j}}{\mathrm{d}s^2}=-2r_e\cdot\sum_{i=1}^{n_b}\boldsymbol{F}(\boldsymbol{X}_{p,i}-\boldsymbol{X}_{e,j}), \quad (2)$$

$$\boldsymbol{F}=-\frac{\boldsymbol{X}}{|\boldsymbol{X}|^2}\delta(s), \quad (3)$$

$$M(s)=\begin{pmatrix}\cos(2\pi\nu_{x,y}) & \bar{\beta}\sin(2\pi\nu_{x,y})\\ -\dfrac{\sin(2\pi\nu_{x,y})}{\bar{\beta}} & \cos(2\pi\nu_{x,y})\end{pmatrix}, \quad (4)$$

$\boldsymbol{F}(\boldsymbol{X}_{p,i}-\boldsymbol{X}_{e,j})$ is the force between the bunch particles and the electrons and the Particle in Cell (PIC) method was used to calculate the potential of bunch and electron cloud in the program. r_e is the classical radius of electron, $\nu_{x,y}$ the betatron tune in x or y direction, $\bar{\beta}$ the average beta function, $K(s)$ the focusing functions in y or x direction, i.e., $K(s)=k_y(s)$ or $k_x(s)$ the focus factor, and $M(s)$ the transfer matrix of the ring. In Eq. (3), $\delta(s)$ is the Delta function, which means that the interaction between the bunch and the electron cloud occurs only when the bunch passes through the position where the electrons are concentrated. Including the quantum exaction and radiation damping, the transportation of the ring is

$$\begin{pmatrix}X_{p,i}\\ X'_{p,i}\end{pmatrix}\rightarrow\lambda M(s)\begin{pmatrix}X_{p,i}\\ X'_{p,i}\end{pmatrix}+\sqrt{\varepsilon_{x,y}(1-\lambda^2)}\begin{pmatrix}\hat{r}_1\\ \hat{r}_2\end{pmatrix}. \quad (5)$$

Here $\hat{r}_{1,2}$ are independent Gaussian random variables with unit variance, $\lambda=\mathrm{e}^{-1/T_{x,y}}$ with $T_{x,y}$ the damping time in unit of the number of turns and $\varepsilon_{x,y}$ is transverse emittance.

According to the simulation of the electron cloud buildup, it is clear that after the passage of a few bunches (about 20 bunches), the electron cloud density is stationary. Before the saturation of the electron cloud, the interaction between the bunch and the electron cloud will be different, so the bunch size blowup will be unequal. The simulated result for the bunch vertical size blowup along the bunch train is shown in Fig. 4. Compared with the experimental result, the simulated bunch blowup, about 25%, is a little smaller than the measurement results, 31%. In different chromaticities, the simulation gives almost the same results which are different from the experimental observation. The difference can be explained as that higher chromaticity may lead to nonlinear motion, which could be shown as the oscillation of the bunch blowup in the experimental observation.

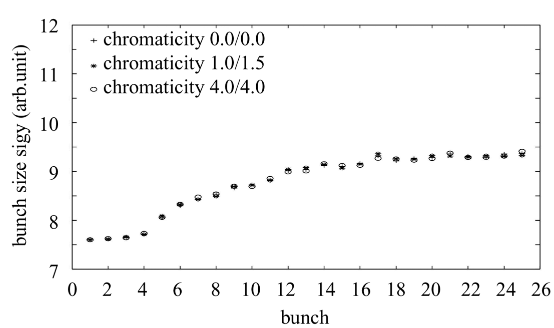

Fig. 4. Simulated vertical bunch size blowup along the train.

4 Conclusions

In the BEPC, the vertical bunch size blowup along the train has been observed with a streak camera, and a code was used to simulate the progress of the bunch blowup. By comparing the observation and simulation results, it is verified that the electron cloud, accumulated around the bunch train, can lead the particle motion in a bunch which is similar to the head-tail instability caused by the wake field. So the electron cloud can be considered as a medium to couple the motion of the head and tail particles in bunch. The most effective way to restrain the bunch size blowup is to reduce the electron cloud density. Another experimental result is the oscillation of the bunch size in higher chromaticity and further study will be focused in the next experiments.

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BEPC 中电子云导致的束团横向尺寸增长研究*

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摘要　多束团正电子储存环中可能发生电子云不稳定性. 由于电子云导致的束团横向尺寸增长已经成为提高对撞机对撞亮度的主要限制因素之一. 介绍了在BEPC储存环中, 利用条纹相机直接测量由于电子云导致的束团横向尺寸增长结果, 并与模拟计算进行了比较.

关键词　电子云　条纹相机　单束团不稳定性　头尾模型

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