第28卷 第11期 高 能 物 理 与 核 物 理 Vol.28, No.11
2004年11月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Nov., 2004

Electron Cloud Instability Simulation Studies for BEPCⅡ *

LIU Yu-Dong[1)] GUO Zhi-Yuan QIN Qing WANG Jiu-Qing
(Institute of High Energy Physics, CAS, Beijing 100049, China)

Abstract Electron cloud instability (ECI) may take place in a storage ring when the machine is operated with multi-bunch positively charged beam. According to the actual shape of vacuum chamber in BEPCⅡ, a computer simulation program has been developed. With the code, the electron density in the chamber with the different widths of antechamber and the different secondary electron yields, respectively, can be obtained. The possibility to put clearing electrodes in the normal chamber or ante-chamber to reduce the electron density in the central region of the chamber is also investigated. In the simulation, the coherent oscillation of bunches and the formation of electron cloud (EC) are tracked simultaneously. The sideband distribution and growth rate can be obtained through tracking and dealing the bunch oscillation amplitude with FFT. Based on the head-tail model, the single bunch instability induced by EC is also studied. By the simulation, for BEPCⅡ the threshold density for the single bunch instability is estimated to be ~ $10^{12}m^{-3}$ and the restraining measures that might be adopted in BEPCⅡ can control the EC density under the threshold. According to the simulation results, a relatively big positive chromaticity should be used to suppress the bunch blow up.

Key words electron cloud, coupled bunch instability, single bunch instability, chromaticity

1 Introduction

It is clear that the ECI, identified by Izawa et al. at Photo Factory[1], can be seriously detrimental to the positively charged, high current, multi-bunch beams. In recent years, the observation on beam size blow up showed that the electron cloud also causes the single bunch instability[2,3]. The instability can be suppressed by reducing the electron density around the beam. Many restraining methods for suppressing the EC density, such as antechamber, TiN coating in the vacuum pipe, photon absorber, clearing electrodes, etc. have been suggested. The Beijing Electron Positron Collider (BEPC) will be upgraded to a double-ring machine (BEPCⅡ) and the luminosity will be enhanced to two orders higher, say $10^{33}cm^{-2}\cdot s^{-1}$. The ECI is suspected to occur in the positron ring and influence the luminosity performance of BEPCⅡ. A code has been developed, based on the physical model proposed by Ohmi and Furman[4,5], to simulate the EC density under different restraining conditions and to track the oscillation of bunches[6]. The tracking method is based on a

Table 1. Parameters of the BEPCⅡ.

parameters	value
beam energy E/GeV	1.89
bunch population $N_b(10^{10})$	4.84
bunch spacing L_{sep}/m	2.4
bunch number n	93
average bunch length σ_z/m	0.015
average bunch sizes $\sigma_{x,y}$/mm	1.18, 0.15
chamber half dimensions $h_{x,y}$/mm	60, 27
slippage factor $\eta(10^{-3})$	23.5
synchrotron tune Q_s	0.033
tune $Q_{x,y}$	6.53, 7.58
circumference C/km	0.237
average beta function $\langle\beta\rangle$/m	10

Received 26 April 2004
* Supported by the Chinese National Foundation of Natural Sciences (10275079, 10375076)
1) E-mail: liuyd@mail.ihep.ac.cn

simple model in which the bunch represented by a macro-particle with rigid transverse Gaussian distribution, and the EC is represented by many macro-particles. Based on the head-tail model, we have developed another code to study the possibility of beam blow up in BEPCⅡ. The main parameters of BEPCⅡ are listed in Table 1.

2 Coupled bunch instability

In the computer code, which was developed to simulate the electron density, we assume that a large number of photo-electrons are produced by the photons from synchrotron radiation of the positron beam. The photoelectrons accelerated by the beam field strike the chamber surface and yield the secondary electrons. All the electrons will get a kick imposed by the bunch. In the simulation, a bunch is expressed as a macro-particle and the EC can be represented by macro-particles. The force between the bunch and electron is represented by the Bassetti-Erskine formula[7] and the solver of Poisson-Superfish in the central region of $(10\sigma_x, 10\sigma_y)$ and out of the region, respectively. By tracking the motion of the bunch and the formation of the EC at the same time, the oscillation amplitudes of 93 bunches and the EC density are recorded. The growth time can be obtained by fitting the amplitude of the oscillation. From the previous results[6], without any restraining methods the EC density is $1.03\times10^{13}\mathrm{m}^{-3}$, but when using the antechamber, photon absorber and TiN coating, the density will be decreasd to $1.35\times10^{11}\mathrm{m}^{-3}$. In these two conditions we track the coupled bunches' oscillation in vertical direction, obtaining the growth time $\tau_{1y}\approx0.08$ms and $\tau_{2y}\approx4.3$ms. The growth behavior of the coupled bunch oscillation and the sideband spectra are shown in Fig. 1.

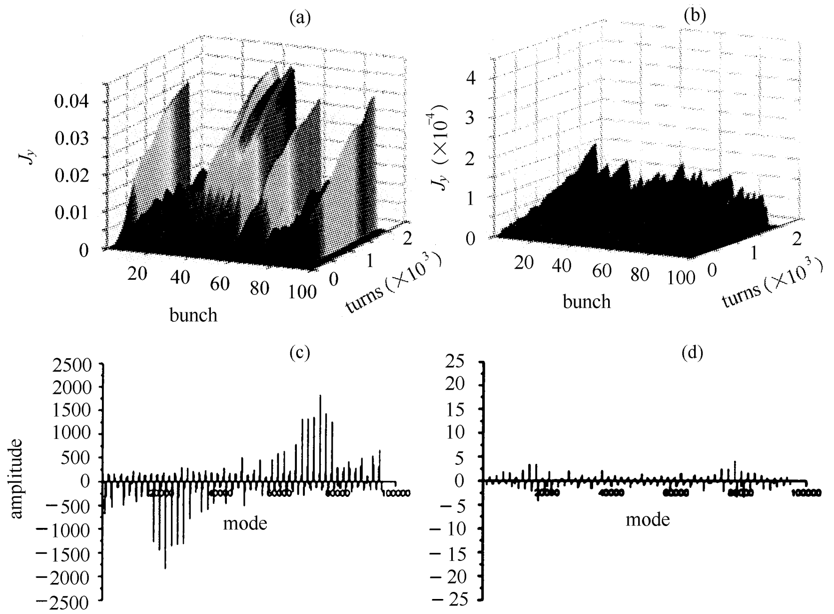

Fig. 1. Growth behavior of coupled-bunch oscillation. (Tracking result: a and b; sideband spectra: c and d)
(a, c: EC density $1.03\times10^{13}\mathrm{m}^{-3}$; b, d: EC density $1.35\times10^{11}\mathrm{m}^{-3}$)

3 Single bunch instability

The EC can act as a short range wake field, and drive single bunch instability. Based on the head-tail model[8], a code was developed to simulate the beam size blow up. In the model, concentrating electron cloud at one location s of the ring, the EC and the bunch are represented by N_e and N_p macroparticles with transverse uniform and Gaussian distributions, respectively, as shown in Fig. 2. We use vectors (x_e, x'_e) and (y_e, y'_e) to describe the transverse motion of electron respectively, without considering the longitudinal force imposed by the EC. With the particle's synchrotron oscillation in a bunch included, the motion of bunch macro-particles are described by the 3D vector, $\left(x_p, x'_p, y_p, y'_p, z, \frac{\Delta P}{P}\right)$. The bunch is dividedinto N_s slices, which interact with the EC one another and cause the distortion of the EC 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 $x_{p,i}$, we can express the motion equations of electrons and bunch particles as

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

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

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

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

where $\boldsymbol{F}(\boldsymbol{X}_{p,i}-\boldsymbol{X}_{e,j})$ is the force between the bunch particles and the electrons, r_e the classical radius of electron, $v_{x,y}$ the tune in x or y, $\bar{\beta}$ the average beta function, $K(s)$ the focusing functions in y or x direction, i.e., $K(s)=k_y(s)$ or $k_x(s)$, $M(s)$ 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 EC occurs only when the bunch passes through the position where the electrons are concentrated.

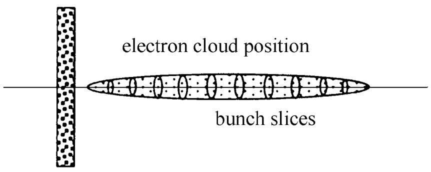

Fig. 2. Schematic plot of the simulation recipe

We have simulated the wake field caused by the displacement of the head particle in different EC density. First, by giving the head particle a displacement, we have calculated the force between the following particles and the EC. Simulation results show that the wake increases with the EC density, as shown in Fig. 3.

Based on the strong head-tail instability theory[8], we may use the following equation to estimate the threshold theoretically,

$$\Gamma=\frac{N_b r_e\,|W_y(0)|\,\bar{\beta}_y}{16\gamma v_s}\leqslant 1, \quad (5)$$

where N_b is the bunch population, r_e the classical radius of electron, v_s the synchrotron tune, $\bar{\beta}$ the average beta

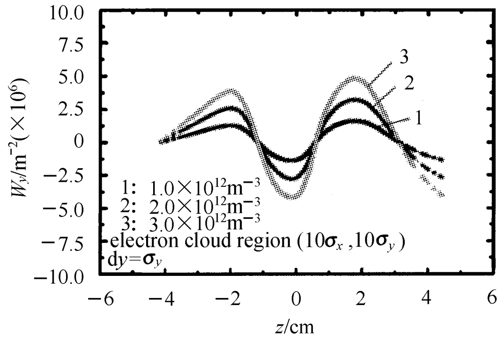

Fig.3. EC short wake

function, $W_y(0)$ the wake field in the position of $z=0$. With Eq. (5), the wake field threshold is estimated as $1.47\times10^6 m^{-2}$, corresponding to the EC density about $9.2\times10^{11} m^{-3}$.

The simulation results for BEPCⅡ are obtained under the following conditions. 10000 macro-particles for the EC are used, and electrons in the cloud are initialized as a uniform distribution in transverse planes with a size of $10\sigma_x\times10\sigma_y$, where the electrons are concentrated, at the beginning of an interaction with beam. The bunch, which is sliced into 10 pieces, is represented by 10000 macro-particles whose distribution is a Gaussian type in

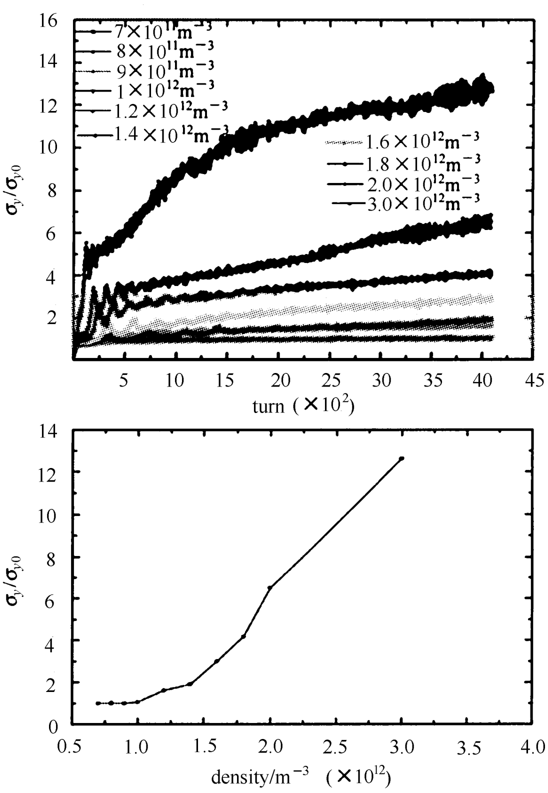

Fig.4. Beam vertical size in different EC densities

x_p, x_p', y_p, y_p', z, $\frac{\Delta P}{P}$. After tracking the motions of bunch macro-particles for 4096 turns in different EC densities, we find that the threshold by simulation is comparable to the analysis result. The tracking results are shown in Figs.4 and 5.

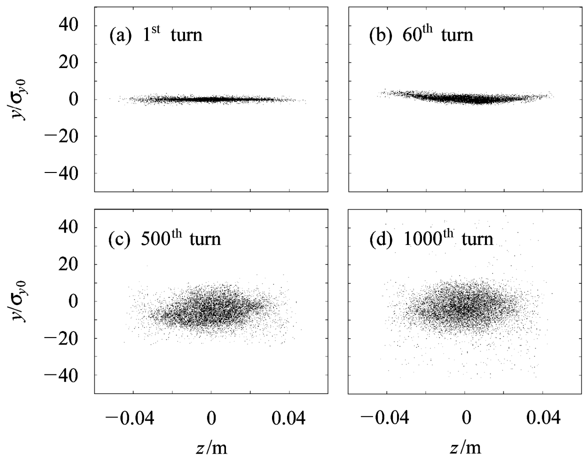

Fig.5. Bunch shape (EC density: $3.0\times10^{12}\ m^{-3}$)

Then the chromaticity dependence of the instability has been also studied, as shown in Fig. 6. The different particles in a bunch have different tunes as the energy deviation exists. The betatron and synchrotron motions are coupled by chromaticity, which can be a damping mechanism to restrain the beam blow up. We have simulated the beam size blow up in different chromaticities (from −10 to 10) under the EC density of $1.0\times10^{12}m^{-3}$, which is above the threshold. The tunes and phases of the particles are described as[8],

$$v_{x,y} = v_{0x,0y} + \xi_{x,y}\left(\frac{\Delta P}{P}\right)_{x,y}, \qquad (6)$$

$$\varphi_{x,y} = \varphi_{0x,0y} + \frac{\omega_0 \xi_{x,y}}{c}\int_C \left(\frac{\Delta P}{P}\right)_{x,y} \mathrm{d}s, \qquad (7)$$

where $\frac{\Delta P}{P}$ is the momentum deviation, ω_0 the angular frequency of particle, $\xi_{x,y}$ the chromaticity in horizontal or vertical direction, $v_{x,y}$ and $\varphi_{x,y}$ the tunes and phases in x or y, respectively.

The results in Fig.6 can be understood as the head-tail model[8]. According to this theory, the positive chromaticity can offer a damping effect to the beam instability.

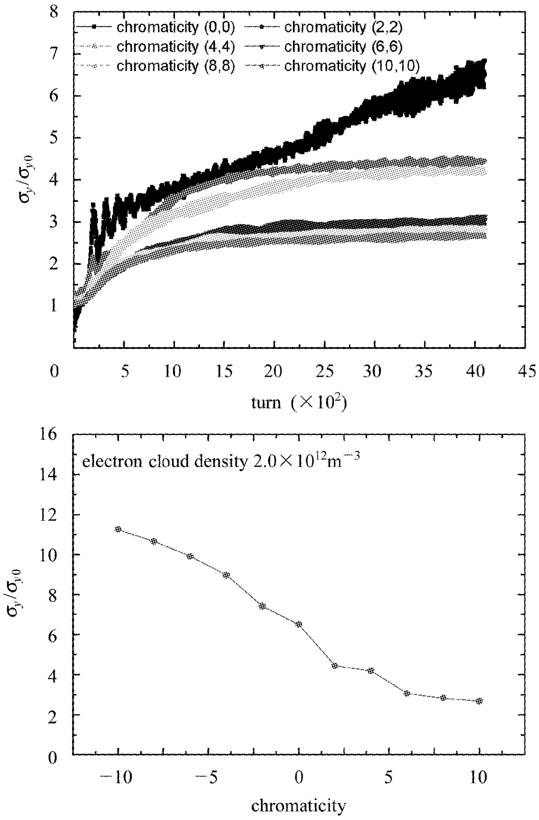

Fig.6. Beam vertical size in different chromaticities

4 Conclusion

The electron cloud instability, including the EC density, coupled bunch instability and single bunch instability, has been studied in detail in BEPCⅡ under the conditions of the different restraining methods. The methods, such as antechamber, TiN coating and photon absorber, may be used in BEPCⅡ. Then the central EC density will be reduced from $1.03\times10^{13}\ m^{-3}$ to $1.35\times10^{11}\ m^{-3}$, and the coupled bunch instability can be suppressed by transverse feedback system. As these restraining methods are adopted, the central EC density, in the BEPCⅡ operation condition, will be below the threshold of the single bunch instability, say $1.0\times10^{12}m^{-3}$. In the design, we also should try to increase the chromaticity to suppress the beam size blow up. These simulation results are meaningful for the BEPCⅡ project.

References

1 Izawa M et al. Phys. Rev. Lett., 1995, **74**, 5044
2 Fukuma H et al. EPAC2000, 2000, Vienna
3 Guo Z Y et al. APAC2004, 2004, Gyeongju
4 Ohmi K. Phys. Rev. Lett. 1995, **75**:1526
5 Furman M A et al. 1997, LBNL-41123
6 LIU Y D et al. HEP & NP, 2004, **28**(3): 222(in Chinese)
(刘瑜冬等.高能物理与核物理,2004,**28**(3):222)
7 Bassetti M, Erskine. Report No CERN ISR Th/80-06, 1980
8 Chao A. Physics of Collective Instability in High Energy Accelerators. New York: J. Wiley, 1993

BEPCⅡ中电子云不稳定性模拟研究*

刘瑜冬[1)] 国智元 秦 庆 王九庆

(中国科学院高能物理研究所 北京 100049)

摘要 正电子储存环在多束团运行时有可能发生电子云不稳定性(ECI).本文针对北京正负电子对撞机二期工程(BEPCⅡ)的具体条件,编写发展了模拟计算程序,以不同电子云密度抑制措施下的计算结果为基础,研究了耦合束团不稳定性和单束团不稳定性,给出了电子云不稳定性增长率和阈值密度以及色品对束团尺寸增长的抑制作用,为储存环中电子云不稳定性的前沿科学研究和BEPCⅡ工程设计提供了有意义的结果.

关键词 电子云 耦合束团不稳定性 单束团不稳定性 色品

2004-04-26 收稿

*国家自然科学基金(10275079,10375076)资助

1)E-mail:liuyd@mail.ihep.ac.cn