SIMULATION STUDY ON BUNCH LENGTHENING

Y. P. Sun#, Key Laboratory of Heavy Ion Physics, Peking University& IHEP, Beijing
J. Gao, IHEP, Beijing; Z. Y. Guo, Key Laboratory of Heavy Ion Physics, Peking University, Beijing

Abstract

The bunch lengthening phenomenon is resulted from one of the most severe single bunch instabilities in electron storage rings. As for BEPCII, controlling the bunch length is the most critical task to fulfil the designed luminosity goal. A new code is developed to calculate the single bunch length and energy spread in storage rings using FORTRAN. In this code, the wake field is calculated using an analytical formula. The bunch length and energy spread under different bunch current are calculated for BEPCII. The tracking results clearly show that the microwave instability threshold is around 65 mA for BEPCII storage ring. The tracking results of this code are in good accordance with those from other codes.

INTRODUCTION

The bunch lengthening phenomenon is resulted from one of the most severe single bunch instabilities in electron storage rings. It is well known that in an electron storage ring an electron will lose energy due to synchrotron radiations. Since this radiation is compensated by the RF cavities in the ring there exists a damping effect on the synchrotron oscillation with the corresponding damping time. The synchrotron radiation energy loss is in the form of randomly emitted photons, and this random quantum excitations together with the previously mentioned synchrotron radiation damping effects result in the single particle equilibrium energy spread and bunch length. The distribution in the normalized time displacement is as a Gaussian with a standard deviation that is equal to the standard deviation of the energy oscillations [1]. It follows that the fluctuating energy oscillations are accompanied by associated fluctuations in the time displacement. And the standard deviation of these fluctuations can be deducted to be (zero current case):

$$\sigma_{l0} = \frac{\alpha_P \bar{R} \sigma_{\varepsilon 0}}{v_s} \tag{1}$$

where σ_{l0} is the natural bunch length, α_P is the momentum compaction factor, $\sigma_{\varepsilon 0}$ is the natural energy spread and v_s is the synchrotron tune.

The bunch length is equal to its natural values when the bunch current is low. However, when the bunch current is higher, the bunch length and energy spread increase due to collective effects.

Numerically there are normally three kind of approach to calculate the longitudinal stability of the beam: solving of linearized Vlasov integral equation in frequency domain which has a lot of neutrally stable spurious modes [2]; solving full Vlasov-Fokker-Planck equation in time domain which is slow but accurate [3]; particle tracking with wake fields which is fast but may be noisy [4]. For the macro-particle tracking approach with wake fields, longitudinal single bunch effect is simulated in electron storage rings to study the single bunch lengthening and energy spread. The turn by turn energy and phase deviations of N macro-particles are tracked. The input parameters consist of the usual RF and lattice associated parameters as well as the wake potential. Most of the other codes use the wake potential from the measured or calculated impedance values, but in this code an analytical wake potential is used.

ypsun@ihep.ac.cn

STRUCTURE OF THE CODE

The phase space distribution of the bunch is represented by M randomly chosen test particles which are in Gaussian distribution in both longitudinal position and energy deviation. The turn by turn energy and phase deviations of M macro-particles are tracked as follows: [3]

$$t_m(n) = t_m(n-1) + \frac{\alpha_P T_0}{E_0} \varepsilon_m(n) \tag{2}$$

$$\begin{aligned} \varepsilon_m(n) &= \varepsilon_m(n-1) - \frac{2T_0}{\tau_\varepsilon}\varepsilon_m(n-1) \\ &- U_0\left(1-\cos\left(\omega_{rf}t_m(n-1)\right)\right) - \hat{U}\sin\left(\omega_{rf}t_m(n-1)\right)\sin\phi_s \\ &+ 2\sigma_{\varepsilon 0}\sqrt{\frac{T_0}{\tau_\varepsilon}}R_m(n) + eV_m(n) \end{aligned} \tag{3}$$

where m represents the mth test particle, n is the number of the turn, t and ε are the phase and energy deviations, T_0 is the revolutionary time, E_0 is the beam energy, τ_ε is the radiation damping time for energy oscillations, U_0 is the average synchrotron radiation energy loss per turn, $\hat{U}$ is the peak energy gain from RF cavity, ω_{rf} is the angular frequency of the RF cavity, Φ_S is the zero current synchronous phase angle, R_m is a Gaussian distributed random number with mean value equal to 0 and RMS value equal to 1, $\sigma_{\varepsilon 0}$ is the natural energy spread, and V_m is the wake field. In the above equations collective effects are contained in the term of wake field and the wake field gives the effect on particle m from all the particles which precede it in the bunch. Usually the bunch is separated into several bins every sigma. The spectrum of the bunch is gotten by Fourier transformation. Then the wake field is the reverse Fourier transformation of the product of impedance and the bunch spectrum.

The new contribution in this work is the treatment of the wake potential. An analytical expression that describes the wake potential of a storage ring is found to be effective on several storage rings in Ref. [5]. For the convenience of the theoretical treatment in Ref. [5], three parameters, i.e., bunch length σ_z, total loss factor $k(\sigma_z)$, and the total inductance $L(\sigma_z)$ are used to describe the total wake potential of the machine.

SIMULATION RESULT ON BEPCII

BEPCII, the upgrading project of the Beijing Electron-Positron Collider (BEPC), has been designed with a luminosity of 10^{33} $cm^{-2}s^{-1}$ at the τ-charm energy region. To reach such a high luminosity, well controlling the bunch length is one of the most critical tasks.

In Figure 1 the dark line shows the longitudinal wake potential of BEPCII storage ring with σ_{z0}=0.0134 m, L=28.89 nH, and $k(\sigma_{z0})$=2.017 V/pC [5,6]; and the light line is the numerical result of MAFIA, where the wake potential of a short Gaussian bunch with 2 mm bunch length as the wake function of the storage ring is calculated (in time domain) [6,7]. The main parameters of the BEPCII storage ring used in this code are from the BEPCII design report [6].

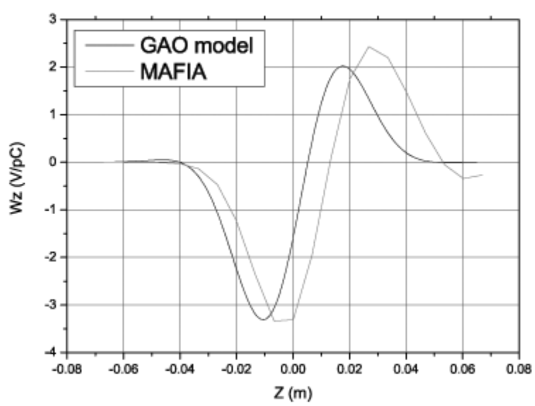

Figure 1: Wake potential for BEPCII storage ring.

First, we should check the convergence of the code without wake field. That means when we do the tracking, we shall take different macro-particle numbers to see if we can get the same result. The initial distribution of the particles is Gaussian in both the energy and time plane. After tracking for 5 longitudinal damping times, and calculating the bunch length and energy spread in each damping time, we can see that without wake field the bunch length and energy spread tend to be around 1.35 cm and 5.19×10^4, which are almost the natural bunch length and natural energy spread. This shows that the tracking result of this code is not depending on the number of the macro-particles and this code has a good convergence.

Fifty thousand macro-particles are randomly selected to represent the real electron bunch. The initial distributions in both time and energy are Gaussian with the RMS value equal to the natural bunch length and natural energy spread. When there is no wake field in the tracking process, the tracking results show the natural bunch length and natural energy spread just as predicted by the theory of longitudinal motion, and the electron bunch distribution in both time and energy domain will be kept the same as the initial Gaussian distribution. However, after the wake field is added in, the total longitudinal voltage which is experienced by each electron is distorted, and the distribution of the electron bunch will be influenced. The bunch length will be lengthened accompanied with the bunch current increasing, and at the same time the energy spread will not vary. After the bunch current exceeds a threshold which is called the microwave instability threshold, both the bunch length and the energy spread will be increased significantly and the instability will emerge. The phenomenon is explained by several theories, and confirmed by many experimental and numerical results. The tracking results of this code on BEPCII should confirm this point.

As the microwave instability threshold predicted by the Boussard criteria is 36 mA [6] for BEPCII and at the same time the tracking results of Oide's code show that the threshold is 70 mA for BEPCII, we set the single bunch current from 5 mA to 100 mA in our tracking process.

Tracking these fifty thousand macro-particles for 5 longitudinal damping time, and calculate the bunch length and energy spread in each turn to get the new wake potential for the next turn. The result of single bunch lengthening and energy spread versus single bunch current is shown in Figure 2, where black line and red line are the bunch lengthening and energy spread results of this code; green dots and blue dots are the tracking results of Oide's code [6]. It should be pointed out here that in this code the analytical wake potential is used which is denoted by the dark line in Figure. 1, and in the tracking code of Oide's the MAFIA calculated wake potential is used which is denoted by the light line in Figure. 1.

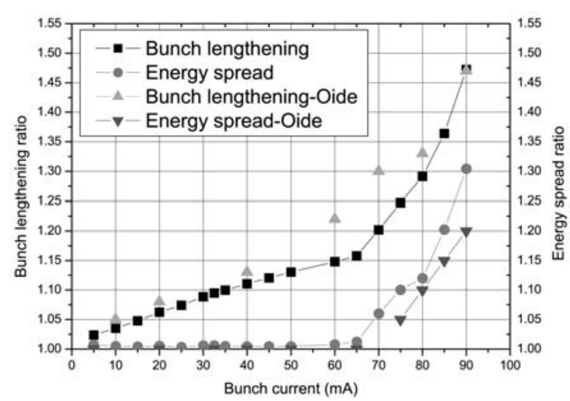

Figure 2: Bunch lengthening and energy spread versus single bunch current.

From Figure 2 we can see that the tracking results of Oide's code show that the microwave instability threshold is 70 mA for BEPCII and the tracking results of this code show that the microwave instability threshold is 65 mA for BEPCII. The little difference of the results is from the difference in wake potential that they used and the computer noise.

The initial and end distribution of the macro-particles at different bunch current are shown in Figure 3, which clearly shows the effect of potential well distortion. The bunch shape is Gaussian at low beam intensities, and it distorts as the beam intensity is increased [8]. One feature of Figure 3 is that the distribution leans forward as the beam intensity increases. This effect comes from the parasitic loss of the beam bunch, and is a consequence of the real (resistive) part of the impedance. As most of the electron storage rings are operated above the transition, the bunch moves forward so that the parasitic energy loss can be compensated by the RF voltage, as shown by the curve of stable phase visa beam current in Figure 4. Another feature of Figure 3 is that the bunch length increases as the beam intensity increases. That is because the bunch shape distortion comes mainly from the imaginary part of the impedance. And the bunch lengthens in Figure 3 is a consequences of the fact that the imaginary part of the impedance seen by the beam is mostly inductive.

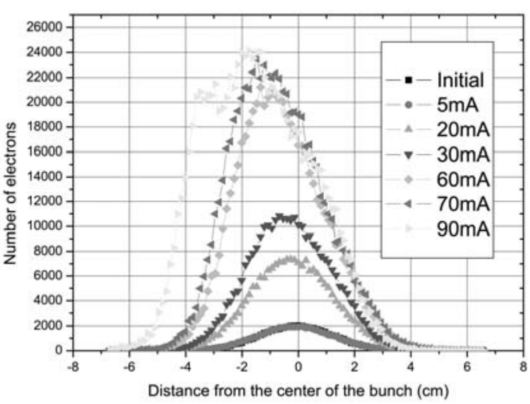

Figure 3: Initial and end distribution of the macro-particles at different bunch current.

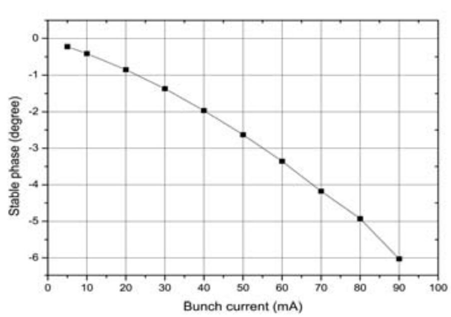

Figure 4: Stable RF phase versus bunch current.

A random electron's phase space is plot for five damping times, which is 80000 turns (For two current case: 5 and 90 mA). The result is shown in Figure 5. From the phase space plot we can see that when the bunch current is higher, the motion of the electrons in the bunch is much more chaotic.

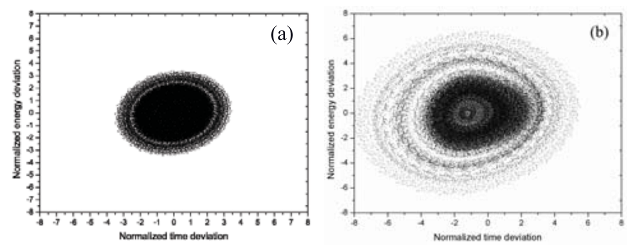

Figure 5: One electron's phase space plot (a): 5 mA case; (b): 90 mA case.

CONCLUSIONS

A new code is developed to simulate the particles' longitudinal phase space motion. First the convergence of this code is checked. The checking result shows that the tracking result of this code is independent on the number of macro-particles. In this code a new expression of the wake potential is used in contrast with the former simulation codes. And simulation results on BEPCII can clearly show the microwave instability threshold and the effect of the potential well distortion, which are in accordance with the other codes' results. Next step we will set up proper longitudinal broadband impedance model for BEPCII and use it in this code to get the new wake potential. The new result will be compared with the result in this paper. And the physical mechanism of the microwave instability and intra-beam scattering should be studied in detail.

REFERENCES

[1] M. Sands, SLAC-121 (1970)

[2] K. Oide and K. Yokoya, KEK-Preprint 10 (1990)

[3] R. Warnock, M. Venturini, and J. Ellison, in Proceedings of EPAC 2002 p. 1589 (2002)

[4] A. Renieri, LNF-76/11(R) Frascati (1976) [5] J. Gao, Nucl. Instrum. Methods, A 491 1-8 (2002)

[6] Institute of High Energy Physics, Design Report of BEPCII (2003)

[7] J. Q. Wang, Private communication (2006)

[8] A. W. Chao, Physics of collective beam instabilities in high energy accelerators (John Willy) (1993)