CEPC BUNCH LENGTHENING AND CAVITY HOM ANALYSIS

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Abstract

In this paper we will show the higher order mode (HOM) analysis of the cavity for the Circular Electron-Positron Collider (CEPC) partial double ring (PDR) scheme. In order to study the single bunch longitudinal instability in CEPC, bunch lengthening and energy spread are estimated based on Gao's theory. Different models are used to study the bunch lengthening and energy spread of the ring.

INTRODUCTION

With the discovery of the Higgs boson at the LHC in 2012, the world's high energy physics (HEP) community is interested in future large circular colliders to study the Higgs boson. Because the Higgs mass is low (126 GeV), a circular *e+e-* collider can serve as a Higgs factory. The Institute of High Energy Physics (IHEP) in Beijing, in collaboration with a number of other institutes, has launched a study of a 50-100 km ring collider [1]. It will serve as an *e+e-* collider for a Higgs factory with the name of Circular Electron-Positron Collider (CEPC). A Preliminary Conceptual Design Report (Pre-CDR) was published in March, 2015 [2]. The synchrotron radiation power of CEPC is 50 MW and its goal is to deliver a luminosity greater than 1×10^{34} cm^{-2}s^{-1} per IP[3]. The *e+e-* beams are in the same beam pipe with a pretzel orbit, which is not suitable for a high luminosity Z factory. To solve the problem, a partial double ring scheme was raised[3, 4].

The bunch lengthening phenomenon in an electron storage ring was first observed in ACO[5] at Orsay and later in other machines, where accompanying bunch lengthening, one finds an increase in the single bunch energy spread with a more or less appreciable threshold current. In this paper, we try to analyse the single bunch longitudinal collective instability of CEPC by Gao's theory[6, 7]. We use different methods to give a prediction for the bunch lengthening and energy spread of CEPC.

Main HOM related issues are the beam instabilities and the HOM induced power especially from TM monopoles. The analysis for the beam induced HOM voltage and power are also given in this paper based on the partial double ring scheme.

MAIN PARAMETERS OF CEPC

The analysis results of this paper are based on the main parameters of the CEPC PDR scheme shown in Table 1[8].

Table 1: Machine Parameters of CEPC PDR Scheme

parameter	**Symbol**	**H-High lumi.**	**H-Low power**
Energy (GeV)	E	120	120
Circumference (km)	C	54	54
Beam current (mA)	I_b	16.9	10.5
Bunch length (mm)	σ_z	4.1	4.0
Bunch number	n_b	67	44
Bunch population (10^{11})	N_b	2.85	2.67
Momentum compaction (10^{-4})	α_p	0.25	0.22
SR loss/turn (GeV)	U_0	2.96	2.96
SR power/beam (MW)	P_0	50	31.2
Harmonic number (10^5)	h	1.174	1.174
RF frequency (MHz)	f_{fr}	650	650
Synchrotron tune	υ_s	0.08	0.08
RF voltage (GV)	V_{rf}	3.62	3.53
Luminosity (10^{34}cm^{-2}s^{-1})	L_0	2.96	2.01

BUNCH LENGTHENING ANALYSIS

According to ref. [6], with the wake potential and its Taylor expansion, the bunch lengthening, energy spread and the threshold of particle population inside the bunch are expressed as follows:

$$R_z^2 = 1 + \frac{eBk(\sigma_{z0})J_\varepsilon I_b R}{m_0 c^3 \alpha C_q \gamma^3 (R_z)^\zeta} + \frac{\ell(R_{av} RBk(\sigma_{z0}) I_b)^2}{\gamma^7 (R_z)^{2\zeta}} \quad (1)$$

$$R_\varepsilon^2 = 1 + \frac{\ell(R_{av} RBk(\sigma_{z0}) I_b)^2}{\gamma^7 (R_z)^{2\zeta}} \quad (2)$$

$$C_q = \frac{55\hbar}{32\sqrt{3} m_0 c} \quad (3)$$

$$J_\varepsilon = 1 + \frac{\alpha R_{av}}{R} \quad (4)$$

$$N_{e,th} = \sqrt{\frac{2}{3}} \frac{\sigma_{z0} V \cos(\phi_{s0})}{eCk(\sigma_{z0}) T_0 f_{s0} \lambda_{rf}} \quad (5)$$

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$$B = \frac{0.289 a Z_i (1 + 0.637 \operatorname{atan}(\operatorname{atan}(Z_i / 2Z_r)))^2}{Z_r \sqrt{1 + (Z_i / 2Z_r)^2}} \qquad (6)$$

where T_0 is the revolution period, fs_0 is the synchrotron oscillation frequency, λ_{rf} is the wave length of rf field, φ_{s0} is the synchrotron phase and V is the peak rf field. $N_{e,th}$ is the so called phase instability threshold above which the particles will execute stochastic motions.

H-high Lumi. Scheme

1. Only cavities and resistive wall

With total bunch length 4.1 mm, the longitudinal loss factor for one cavity is 0.8008 V/pC from ABCI[9].

The cavity number is 384, the total loss factor of superconducting cavities and resistive wall is $k(\sigma_z)$= 454.3 V/pC, the total inductance is 22 nH[10].

With bunch current of 0.25 mA and 384 cavities, the bunch lengthening is R_z=1.019 and energy spread is R_ε= 1.001.

2. KEKB parameters scaled to CEPC

According to ref.[11], the circumference of KEKB is 3016.26 m, total inductance of LER is 24 nH, total loss factor is 32.1 V/pC, and bunch length is 4 mm. The loss factor of superconducting cavities and resistive wall in KEKB LER is 21.8 V/pC, which is 67.9% of total loss factor. If we calculate the total loss factor in CEPC according to the superconducting cavities and resistive wall proportion in KEKB, the total loss factors in CEPC is 669.072 V/pC. The inductance of resistive wall in KEKB LER is 8.327 nH, which is 34.7% of total inductance. If we calculate the total inductance in CEPC according to the resistive wall proportion in KEKB, the total inductance in CEPC is 63.401 nH. SPEAR scaling law shows $k{\sim}\sigma^{-1.21}$[12]. So, when σ_z =4.1 mm, the total loss factor of CEPC is 649.377 V/ pC.

With bunch current of 0.25 mA and 384 cavities, the bunch lengthening is R_z=1.06 and energy spread is R_ε= 1.01.

H-low Power Scheme

1. Only cavities and resistive wall

With total bunch length 4.1 mm, the longitudinal loss factor for one cavity is 0.8111 V/pC from ABCI[9].

The cavity number is 384, the total loss factor of superconducting cavities and resistive wall is $k(\sigma_z)$= 462.8 V/pC, the total inductance is 27 nH[10].

With bunch current of 0.24 mA and 384 cavities, the bunch lengthening is R_z=1.027 and energy spread is R_ε= 1.002.

2. KEKB parameters scaled to CEPC

The scaled loss factor in CEPC is 681.591 V/pC and the scaled inductance in CEPC is 77.81 nH.

With bunch current of 0.24 mA and 384 cavities, the bunch lengthening is R_z=1.082 and energy spread is R_ε= 1.015.

HOMS POWER ANALYSIS

The cavities in different sites see different time structures of the beam because of the bunch train scheme. The time-averaged HOM power spectrums are different for different cavities. Taking the low power scheme for example, we analyze the HOM power spectrums in IP1 & IP3 and IP2 & IP4[9, 13].

HOM Power Spectrum in IP1 & IP3

The time structure seen by the cavities in IP1 & IP3 is shown in Figure 1.

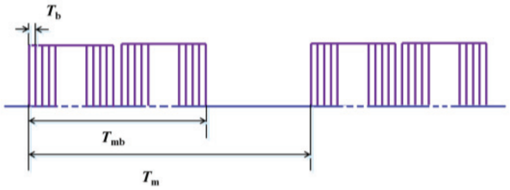

Figure 1: Time structure in IP1 & IP3.

T_m is the macro pulse period and its value is 180 μs. T_{mb} is the macro pulse length and its value is 21.4 μs. T_G is the macro pulse gap period and its value is 158.6 μs. T_b is the bunch spacing and its value is 243.1 ns.

Figure 2 is the normalized HOM power at f=1.164 GHz (which is the 283 harmonic of the bunch spacing frequency and near the TM011 mode) between the macro pulses in steady state at different Q_e. Figure 3 is the time averaged HOM spectrum at different Q_e. If $Q_e > 10^5$, the macro pulse without gap anti-resonance appears. If $Q_e > 10^6$, 5.55 kHz resonance appears since the damping during the macro pulse is not enough. That means the damping time constant T_d is longer than the macro pulse gap. In order to avoid the higher order mode resonance in operation, the Q_e should be lower than 10^5.

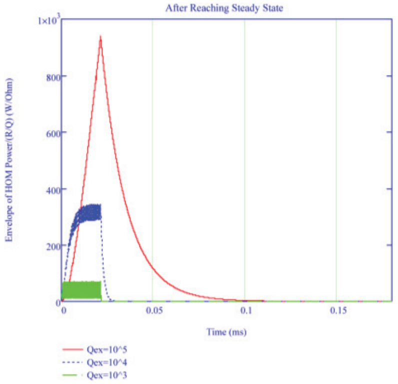

Figure 2: Normalized HOM power at f=1.164 GHz between the macro pulses in steady state at different Q_e.

HOM Power Spectrum in IP2 & IP4

The time structure seen by the cavities in IP2 & IP4 is shown in Figure 4.

T_m is the macro pulse period and its value is 90.06 μs. T_{mb} is the macro pulse length and its value is 10.7 μs. T_G is the macro pulse gap period and its value is 79.37 μs. T_b is the bunch spacing and its value is 243.1 ns.

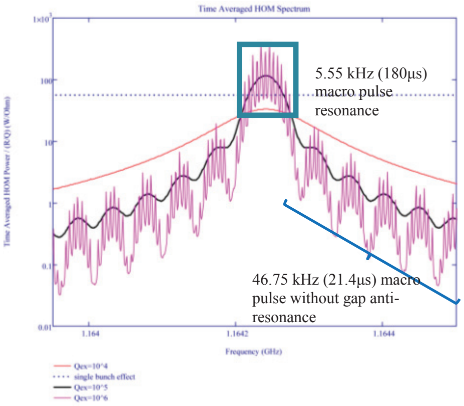

Figure 3: The normalized HOM power at different Q_e.

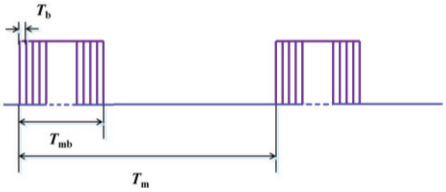

Figure 4: Time structure in IP2 & IP4.

Figure 5 is the normalized HOM power at f=1.164 GHz (which is the 283 harmonic of the bunch spacing frequency and near the TM011 mode) between the macro pulses in steady state at different Q_e. Figure 6 is the time averaged HOM spectrum at different Q_e. If $Q_e > 10^5$, the macro pulse without gap anti-resonance appears. If $Q_e > 10^6$, 11.1 kHz resonance appears since the damping during the macro-pulse is not enough. That means the damping time constant T_d is longer than the macro pulse gap. In order to avoid the higher order mode resonance in operation, the Q_e should be lower than 10^5.

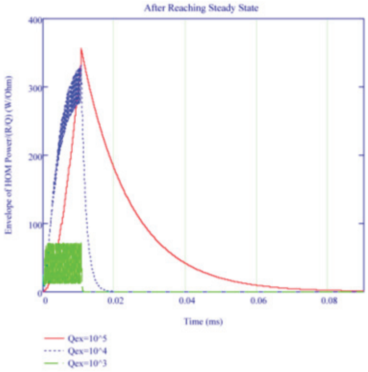

Figure 5: Normalized HOM power at f=1.164 GHz between the macro pulses in steady state at different Q_e.

CONCLUSIONS

This paper is mainly focus on the bunch lengthening and HOM analysis based on the PDR scheme. If only consider the cavities and resistive wall, the bunch lengthening is 1.9% for H-lumi. scheme and 2.7% for low power scheme. If we use the KEKB LER model, the bunch lengthening is 6% for H-lumi. scheme and 8.2% for low power scheme. The HOM analysis results show that in order to avoid the higher order mode resonance during the macro-pulse, the Q_e should be lower than 10^5.

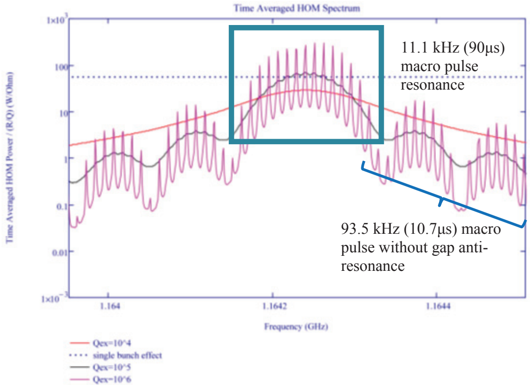

Figure 6: The normalized HOM power at different Q_e.

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