INSTABILITY ISSUES IN CEPC*

N. Wang†, D.J. Gong, H. J. Zheng, Y. Zhang, Y.S. Sun, G. Xu, Y.W. Wang, D. Wang, Q. Qin, J. Gao, W. Chou, J. He, Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Beijing 100049, China
D. Zhou, K. Ohmi, KEK, Ibaraki, Japan

Abstract

The CEPC is a high-energy circular electron-positron collider under design. Large bunch population is required to achieve the design luminosity. Instabilities driven by the coupling impedance are possible limitations for reaching high machine performance. An updated impedance model, including the resistive wall and the main vacuum components, has been obtained for the main ring. Based on the impedance model, the collective instability issues of the beam with the partial-double ring design are discussed.

INTRODUCTION

In high-energy circular e+e- colliders, large efforts have been made to increase the bunch intensity in order to reach high luminosity. Meanwhile, large circumferences are often chosen due to restricted synchrotron radiation power, which means a further enhancement of the machine impedance. The interaction of the beam with the impedances may lead to collective instabilities, which can induce beam quality degradation or beam losses. Moreover, the large bending radius and small horizontal dispersion in dipoles will generate small momentum compaction factor, which can make the beam more sensitive to the collective instabilities. Therefore, collective instability becomes a potential restriction for the machine performance. In this paper, the instability issues for the partial double ring design of CEPC are studied. The impedance budget for the CEPC main ring is first given. Based on the impedance studies, the single bunch and coupled bunch instabilities are investigated. The main parameters used in the calculation are listed in Table. 1.

Table 1: Main Parameters

Parameter	Symbol, unit	Value
Beam energy	E, GeV	120
Circumference	C, km	54
Beam current	I_0, mA	16.9
Bunch number	n_b	50
Bunch length	σ_z, mm	4.1
RF frequency	f_{RF}, GHz	0.65
Energy spread	σ_e	1.3E-3
Slipping factor	α_p	2.5E-5
Betatron tune	ν_x/ν_y	319.21/318.42
Synchrotron tune	ν_s	0.08
Damping time	$\tau_x/\tau_y/\tau_z$, ms	14/14/7

* Work supported by NSFC (11205171), NKPSTRD (2016YFA0400400)
† wangn@ihep.ac.cn

IMPEDANCE BUDGET

The impedance and wake are calculated with both analytical formula and numerical simulations. The vacuum components considered in the calculation include resistive wall, RF cavities, flanges, shielded bellows, BPMs and pumping ports. The short range wake at nominal bunch length is shown in Fig. 1. The impedance budget of the objects considered is listed in Table 2, where $Z_{||}/n$ is the longitudinal effective impedance, k_l is the loss factor, R and L are effective resistance and inductance of the components obtained by fitting the wake potential with the analytical formula [1]

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s). \quad (1)$$

Here, c is the speed of light, and $\lambda(s)$ is the bunch line density.

Table 2: Summary of Impedance Budget

Objects	R, kΩ	L, nH	$Z_{\|\|}/n$, mΩ	k_l, V/pC
Resistive wall	6.7	487.7	17.0	138.4
RF cavity	14.9	-132.7	-	307.5
Flange	0.7	165.5	5.8	15.1
Bellows	5.9	331.5	11.6	122.3
BPM	0.6	21.4	0.7	11.6
Pumping port	0.007	3.1	0.1	0.1
Total	28.8	876.5	35.2	595.0

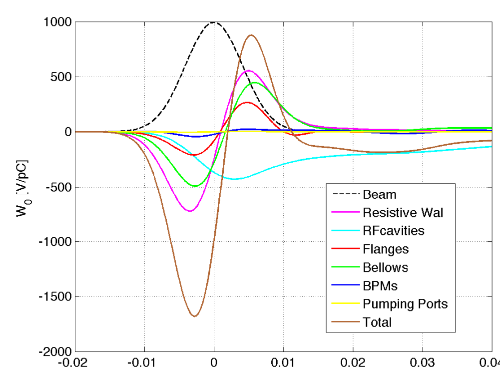

Figure 1: Longitudinal wake potential at nominal bunch length of 4.1 mm.

From the impedance budget we can conclude that the longitudinal impedance is dominated by the resistive wall and the vacuum components with large quantity, such as flanges and bellows. A more complete impedance budget

ISBN 978-3-95450-187-8

will be obtained as more vacuum components are designed.

SINGLE BUNCH EFFECTS

Broadband impedance can induce single bunch instabilities, which will result in emittance blow-up, bunch lengthening or beam losses. Since the bunch intensity is quite high in CEPC, the single bunch instability is more critical compare to the coupled bunch instability. The instabilities are evaluated base on the beam parameters listed in Table1.

Microwave Instability

The longitudinal microwave instability is estimated accoring to the Boussard or Keil-Schnell criterion [2, 3]. With a longitudinal impedance of $|Z_{\|}/n|$=35 mΩ, the threshold bunch current is around 0.17 mA, which is lower than the design current of 0.25mA. This instability will rarely induce beam losses, but may reduce the luminosity due to the deformed beam distribution and increase of the energy spread. For short bunches, the impedance seen by the beam is dominated by the high frequency resonances, therefore the analytical criteria is often believed to be too passive. However, the high frequency part of the impedance may lead to turbulent distributions in the longitudinal phase space. More detailed simulation studies are required.

CSR

The coherent synchrotron radiation (CSR) is generated when beam pass through the bending magnets. It can induce microwave instability with high bunch intensity. With the linear theory, the shielding parameter is [4]

$$\chi = \sigma_z \rho^{1/2} / h^{3/2}. \tag{2}$$

where σ_z is the rms bunch length, ρ the bending radius, and h the distance between the parallel plates. For the case of CEPC, the shielding parameter is much higher than 2. According to the studies in Ref. [4], the coasting beam theory with the shielding impedance should be used for estimating the threshold. The beam becomes unstable when [4]

$$I_b > \frac{3\sqrt{2}\alpha_p \gamma \sigma_e^2 I_A \sigma_z}{\pi^{3/2} h}. \tag{3}$$

where α_p is the momentum compaction, γ the relativistic energy, σ_e the relative energy spread, and I_A=17045 A.

The instability threshold given by Eq. (3) is about 30 times higher than the design bunch population. Therefore, CSR is not a concern in the present design.

Transverse Beam Tilt

In the transverse plane, when a beam passes through an impedance with a transverse offset, the tail particles will receive transverse kicks, which can lead to a transverse displacement of the bunch tail at the interaction point and increase the beam emittance. With the parameters of CEPC, the kick angle along the bunch due to a single RF cavity is shown in Fig. 2. The maximum kick angle at the bunch tail is 1.2 nrad. As there are 384 cavities located in 8 places in the ring, the displacement at IP is around 23 nm, which is about one fifth of the beam size at the IP.

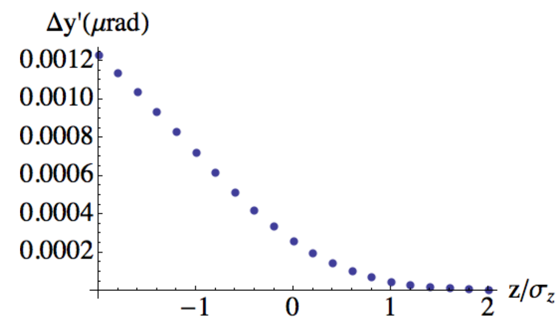

Figure 2: Transverse kick angle along the bunch due to single RF cavity in CEPC ring.

Transverse Mode Coupling Instability

The threshold of the transvers mode coupling instability is estimated with both analytical formula and Eigen mode analysis. For a Gaussian bunch, the threshold intensity can be expressed with the transverse kick factor [5, 6]

$$I_0^{th} = \frac{2\nu_s \omega_0 E / e}{\sum_j \beta_{y,j} \kappa_{y,j}} \Theta. \tag{4}$$

where ν_s the longitudinal tune, ω_0 the angular revolution frequency, E the beam energy, $\beta_{y,j}$ the betatron function at the jth impedance element, $\kappa_{y,j}$ the transverse kick factor, and Θ≈0.7. With the impedance model considered, the total kick factor is 18.9 kV/pC/m. The analytical criterion gives threshold bunch current of 0.9mA.

The Eigen mode analysis gives the dependences of the head-tail mode frequencies on the bunch current as shown in Fig. 3. The Eigen mode analysis shows the threshold bunch current is around 1.9 mA, which is about two times higher than the analytical formula. Both analyses leave us with an enough safety margin to avoid transverse mode coupling instability.

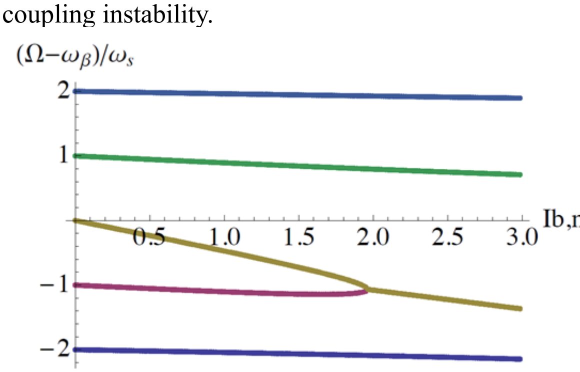

Figure 3: Dependences of the head-tail mode frequencies on the bunch current.

ISBN 978-3-95450-187-8

MULTI-BUNCH EFFECTS

In large-scale circular colliders, the revolution frequency is considerably low, which will generate dense beam spectra and is more easily to be coupled with the narrowband impedances. The interaction of the beam with the narrowband impedances may induce coupled bunch instabilities.

In the present design of CEPC, a partial double ring design is proposed. The electron and positron beam will share the beam pipe except in the collision region. Each beam has a long bunch train of 67 bunches, which will be filled in about 3.2 km in the ring circumference. So that there is a long gap of around 50 km. Therefore, the multi-bunch effects with uneven fills are investigated.

Coupled Bunch Instabilities with Uneven Fills

Coupled bunch instabilities are commonly studied with equal bunch spacing [7]. In the general frame of uneven filled ring, there are two effects due to the uneven fill: damping from the additional tune spread and modulation coupling of the strong even-fill eigenmodes. Here, only the second effect is investigated.

Consider a long bunch train of M identical bunches with bunch spacing of T_b, the longitudinal and transverse beam oscillation with rigid bunch model can be described as

$$\ddot{z}_n(t)+\omega_s^2 z_n(t)=-\frac{Nr_0\alpha_p c}{\gamma T_0}\sum_{m=0}^{M-1}\sum_{k=0}^{\infty} W_0'(-kC-(m-n)T_b c+z_n(t)-z_m(t-kT_0-(m-n)T_b)) \quad (5)$$

and

$$\ddot{y}_n(t)+\omega_\beta^2 y_n(t)=-\frac{Nr_0 c}{\gamma\beta T_0}\sum_{m=0}^{M-1}\sum_{k=0}^{\infty} y_m(t-(kT_0+(m-n)T_b))W_1(-(kT_0+(m-n)T_b)) \quad (6)$$

respectively, where N is the bunch intensity, r_0 the critical radius of the electron, T_0 the revolution time, β the relativistic velocity, and C the circumference.

By solving the equation above, the tune shift can be expressed in form of impedances as

$$\Delta\Omega=\Omega-\omega_s=\frac{iNMr_0\alpha_p}{2\gamma T_0^2\omega_s}\sum_{p=-\infty}^{\infty}(\omega_0(p+\frac{\mu}{M})M'+\omega_s)Z_0(\omega_0(p+\frac{\mu}{M})M'+\omega_s), \quad (7)$$

$$\Delta\Omega=\Omega-\omega_\beta=-\frac{iNMr_0 c}{2\gamma\beta T_0^2\omega_\beta}\sum_{p=-\infty}^{\infty}Z_1(\omega_0(p+\frac{\mu}{M})M'+\omega_\beta), \quad (8)$$

where $M'=T_0/T_b$.

Transverse Resistive Wall Instability

One dominant contribution to the coupled bunch instability is the resonance at zero frequency of the transverse resistive wall impedance. Figure 4 shows the growth rate of the transverse resistive wall instability with different mode numbers. The growth rate for the most dangerous instability mode is 3.1 Hz, which is much lower than the transverse radiation damping. So the beam should be safe from the resistive wall coupled bunch instability.

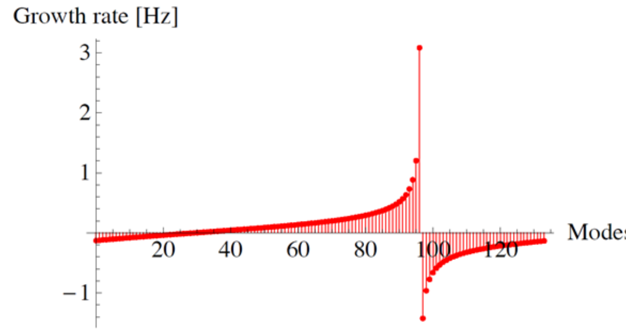

Figure 4: Growth rate of the transverse resistive wall instability with mode numbers.

RF HOMs

Another important contribution to the coupled bunch instability is the HOMs of the accelerating cavities. To keep the beam stable, the rise time of any oscillation mode should be larger than the radiation damping time. In resonant condition, the threshold for the shunt impedances of any HOMs are given by

$$\frac{R_L^{thresh}}{\mathrm{M\Omega}}\frac{f_L}{\mathrm{GHz}}<\frac{2(E/e)\nu_s}{N_c I_0\alpha_p\tau_z}=16.9. \quad (9)$$

and

$$\frac{R_T^{thresh}}{\mathrm{M\Omega/m}}<\frac{2(E/e)}{N_c f_{rev} I_0\beta_{x,y}\tau_{x,y}}=17.6. \quad (10)$$

where N_c is the cavity number along the ring, f_L the frequencies of the HOMs, f_{rev} the revolution frequency of the ring, I_0 the beam current, $\tau_{x,y,z}$ the damping time in transverse and longitudinal directions, and $\beta_{x,y}$ the transverse beta functions. With two counter-rotating beam sharing the RF cavities, the threshold impedance could be further reduced by a factor of two.

However, considering the whole RF system, the threshold value greatly depends on the actual tolerance of the cavity construction. Assuming the resonant frequencies of the RF cavities have a Gaussian distribution with rms frequency spread of 0.5MHz, the threshold shunt impedance considering the whole RF system can be increased by a factor of 50.

ISBN 978-3-95450-187-8

CONCLUSION

An updated impedance model is derived for the CEPC main ring. Based on the impedance model, the potential instability issues with the partial double ring design are investigated. The impedance budget shows a total longitudinal effective impedance of 35.2 mΩ, and a total transverse kick factor of 18.9 kV/pC/m. Single bunch instability is more critical compare to coupled bunch instability, especially the microwave instability. Bunch lengthening is expected to happen. Bunch shape distortion due to the transverse wake is another potential restriction to the high luminosity.

REFERENCES

[1] K. Bane *et al.*, "PEP-X impedance and instability calculations", SLAC-PUB-14151, 2010.

[2] D. Boussard, "Observation of microwave longitudinal instabilities in the CPS", CERN LabII/RF/Int. 75-2, 1975.

[3] E. Keil and W. Schnell, "Concerning longitudinal stability in the ISR", CERN ISR-TH-RF 69/48, 1969.

[4] Y. Cai, "Theory of microwave instability and coherent synchrotron radiation in electron storage rings", in *Proc. IPAC'11*, San Sebastián, Spain, September 2011, paper FRXAA01, pp. 3774-3778.

[5] S. Krinsky *et al.*, "Collective effects in the NSLS-II storage ring", in *Proc. PAC'07*, Albuquerque, NM, USA, June 2007, paper TUPMS074, pp1344-1346.

[6] L. Wang and G. Stupakov, "Transverse single bunch instability in PEP-X", SLAC-PUB-13658, 2009.

[7] A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, Wiley-Interscience Publication, John Wiley & Sons, Inc., 1992.

ISBN 978-3-95450-187-8