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SOME ISSUES ON BEAM-BEAM INTERACTION AT CEPC*

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Abstract

In this paper, the beam-beam study in CEPC CDR is briefly introduced. Some issues related with beam-beam interaction will be emphasized. The bunch lengthening caused by impedance and beamstrahlung is simulated in a more self-consistent method. The initial result shows that the stable collision bunch current is lower considering the longitudinal wake field. During the coures of dynamic aperture optimization, it is found that there exist some disagreement between dynamic aperture and beam lifetime. We try to define the so-called diffusion map analysis to explain the difference between different lattices. Some initial result for different lattice solution is shown.

INTRODUCTION

The circular Electron Positron Collider(CEPC) is a large international scientific project initiated and housed by China. It was presented for the first time to the international community at the ICFA Workshop "Accelerators for a Higgs Factory: Linear vs. Circular"(HF2012) in November 2012 at Fermilab. The Conceptual Design Report (CDR, the Blue Report) was published in September 2018 [1]. The CEPC is a circular e+e- collider located in a 100-km circumference underground tunnel. The CEPC center-of-mass energy is 240 GeV, and at that collision energy will server as a Higgs factory, generating more than one million Higgs particles. The design also allows operation at 91 GeV for a Z factory and at 160 GeV for a W factory. The number of Z particles will be close to one trillion, and W^+W^- pairs about 15 million. Theses unprecedented large number of particles make the CEPC a powerful instrument not only for precision measurments on these important particles, but also in the search for new physics.

Beam-beam interactions are one of the most important limitation to luminosity. Beamstrahlung is synchrotron radiation excited by the beam-beam force, which is a new phenomenon in such high energy storage ring based e+e- collider. It will increase the energy spread, lengthen the bunch and may reduce the beam lifetime due to the long tail of photon spectrum [2, 3]. In this paper, we'll first briefly show some simulation result in CEPC CDR. And then some initial result with self-consistent longitudinal wake field and beam-beam interaction is shown. In the end, we'll discuss some disagreement between dynamic aperture and beam lifetime. We also did some attempt to define the so-called diffusion map analysis to explain the cause of more halo particles in some lattice.

BEAM-BEAM STATUS IN CDR

The main parameters of CEPC CDR is shown in Table 1. There are two options for Z, where the detector solenoid strength is 3T or 2T. The 3T options is ignored in Table 1.

Table 1: Main Parameters (CDR)

	Higgs	**W**	**Z(2T)**
C_0 (km)		100	
IP		2	
E (GeV)	120	80	45.5
U0/turn (GeV)	1.73	0.34	0.036
θ (mrad)		16.5×2	
Piwinski Angle	3.48	7.0	23.8
N_p (10^{10})	15	12	8
Bunch Number	242	1524	12000
SR Power (MW)	30	30	16.5
β_x^*/β_y^* (m/mm)	0.36/1.5	0.36/1.5	0.2/1.0
ϵ_x/ϵ_y (nm/pm)	1.21/2.4	0.54/1.6	0.18/1.6
ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.079
RF Voltage (GV)	2.17	0.47	0.1
f_{RF} (MHz)		650	
σ_{z0} (mm)	2.72	2.98	2.42
σ_z (mm)	4.4	5.9	8.5
ν_s	0.065	0.04	0.028
σ_p (10^{-4})	13.4	9.8	8
L (10^{34}cm^{-2}s^{-1})	3	10	32

According to the LEP2 experience, the achieved maximum beam-beam parameter strongly depdens on the SR damping decrement. Figure. 1 shows the beam-beam performance of CEPC and LEP2. The design beam-beam parameter is nearly 2-3 times higher that of LEP2 experience, which is the contribution of crab-wasit scheme [4]. The crab-waist scheme helps to suppress the nonlinear betatron resonance with large Piwinski angle collision and crab-waist transformation. It has been tested in DAΦNE with new detector SIDDHARTA, where the peak luminosity increases with a factor of about 3. In a more complicated physics running with detector KLOE2, the peak luminosity increase about 50% [5].

Higgs

Figure. 2 shows the luminosity versus horizontal tune. There exist strong instability near the resonance $\nu_x - m\nu_s = n/2$, where the new found coherent X-Z instability causes xz moment oscillation and horizontal beam size blow up [6].

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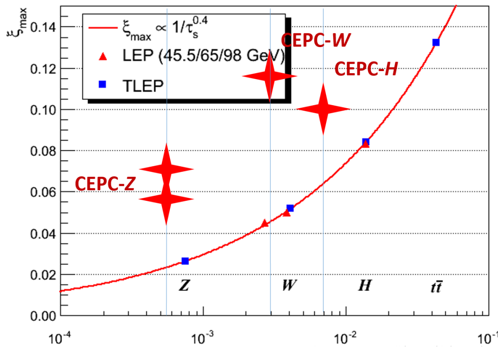

Figure 1: Comparison of beam-beam parameter between CEPC and LEP2. The horizontal axis is the damping decrement between IP.

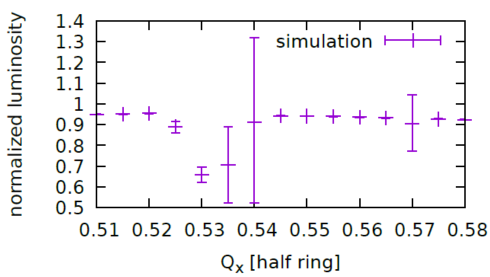

Figure 2: The normalized luminosity versus horizontal tune(half ring) at Higgs. The error bar shows the turn-by-turn luminosity distortion.

We define the achienved beam-beam parameter with luminsotiy to evalute the performance and check the margin between design and maximum values,

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0} \tag{1}$$

where N the bunch population, f_0 the revolution frequency, r_e electron classical radius, β_y^0 the vertical β function, and L the bunch luminosity. Figure. 3 shows the beam-beam parameter versus bunch population. It seems we have enough maring to ensure the reliabitly.

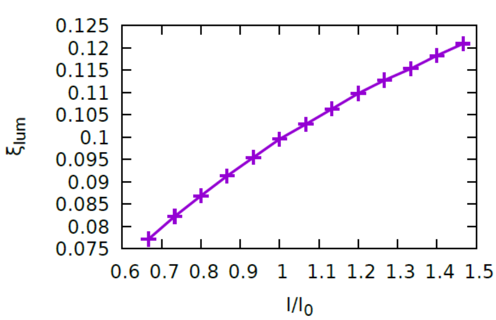

Figure 3: Beam-beam performance versus bunch population at Higgs.

The beamstrahlung lifetime is a serious issue in a higgs factory. The lifetime is evalutated as [3]

$$\tau_{bs} = \frac{\tau_z}{2Af(A)} \tag{2}$$

where A is the boundary of momentum acceptance in action, $f(J)$ is the distribution of action with beam-beam $\int_0^\infty f(J)dJ = 1$, and τ_z is the longitudinal damping time. Figure. 4 shows the beamstrahlung lifetime versus the bunch population. To ensure 100 minutes lifetime limited by momentum acceptance, it require about 1.3% with design bunch current, while nearly 1.6% with bunch popuatlion 22×10^{10}. Considering the present dyanmic aperture optimization result and possible machine error tolerance, it is reasonable to choose the design value. In one words, the bunch population is maily limited by beamstrahlung lifetime at Higgs mode of CEPC.

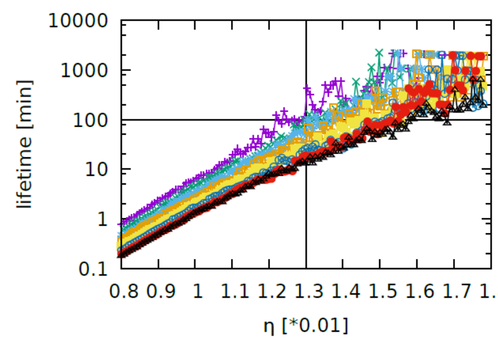

Figure 4: Beamstrahlung lifetime eastimated with strong-strong beam-beam interaction at Higgs. Different line represent different bunch population from 15×10^{10} to 22×10^{10}.

W

Since the horizontal beam size blow up is the most prominent phenomenon caused by the x-z coherent instability, the 2D tunes scan result in Fig. 5. Figure. 6 shows the turn-by-turn evolution of σ_x. The simulation shows that there exist very narrow stable workding point space($\nu_x = 0.552{-}0.555$) with CDR parameters at W. The parameters is to be optimized further, such as squeezing β_x^* or increasing RF voltage [7], to suppress the instablity.

Z

The luminostiy performance at Z is limited by HOM of RF cavity and electrong cloud instability instead of beam-beam interaction. However we still simulate the beam-beam interaction at different bunch intensity, shown in Fig. 7. With same beam current, comparing to 3T detector solenoid, weaker solenoid (2T) reduces the verticla emittance and allow squeze β_y^*, luminsoty increase by a factor of 2. If we increase the bunch population from 8×10^{10} to 12×10^{10} and keep the beam current constant, the luminosity will increase 20%.

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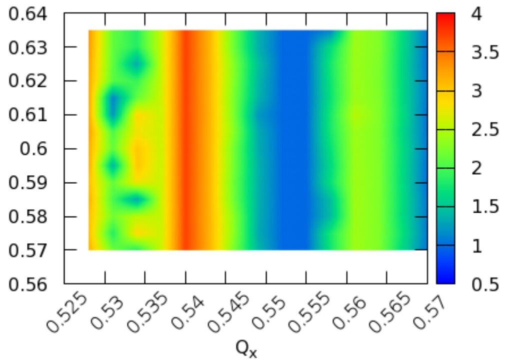

Figure 5: Normalized horizontal beam size versus the tune(half ring) at W.

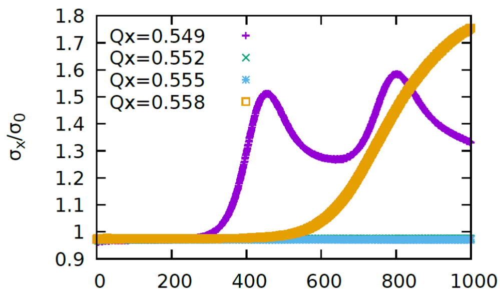

Figure 6: Horizontal bunch size evolution at different tune($\nu_y = 0.59$)(half ring) at W.

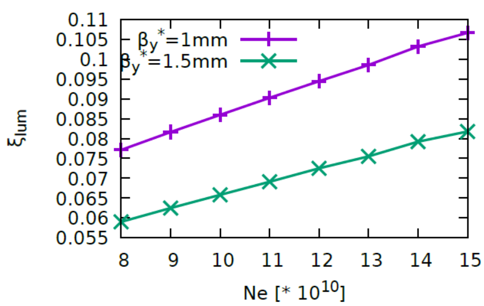

Figure 7: Beam-beam performance at Z ($\beta_y^* = 1.5$mm for 3T and 1mm for 2T).

LONGITUDINAL IMPEDANCE

In conventional e+e- storage ring colliders, we only use lengthend bunch length in beam-beam simulation instead fo considering impedance directly. It is no problem since the longitudianl dynamics is not sensitive to beam-beam interaction. But it is different since the bunch will also be lengthend during beam-beam interaction by beamstrahlung effect. It is very natural and more self-consistent to include the longitudinal impedance in the beam-beam simulation. The longitudinal kick along the bunch $V(t)$ is calculated each turn [8],

$$I(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \tilde{I}_{||}(\omega), \quad \tilde{V}(\omega) = -\tilde{I}(\omega)\tilde{Z}_{||}(\omega) \quad (3)$$

where $I(t)$ is the bunch distribution. Here we only consider the Higgs mode.

Figure. 8 shows the rms bunch length without/with beam-beam interaction. The bunch length obatined with IBB [9] is shorter than that of ELEGANT [10] with beam-beam off. Smooth approximation is adotped in our code, while there is local RF cavity in ELEGANT. With beam-beam, we simulate 3 cases:

- the conventional method, initialize the bunch using the length calculated by ELEGANT
- the conventional method , initialize the bunch using the length calculated by IBB
- self-consistent method, initialize the bunch using the zero-current natural bunch length, considering the longitudianl impedance

It is found that the bunch length saturate near bunch population 19×10^{10}. We alos check the transverse dimension, shown in Figure. 9. It is found that there exist transverse blowup. We do not find any dipole or coherent x-z instablity so far. The beam-beam parameter saturate near 19×10^{10}, as shown in Fig. 10, when we consider the longitudinal kick from impedance.

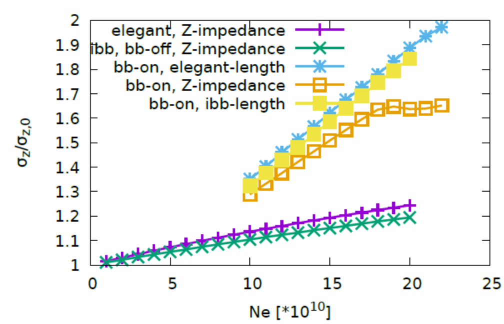

Figure 8: Bunch length with and without longitudinal impedance.

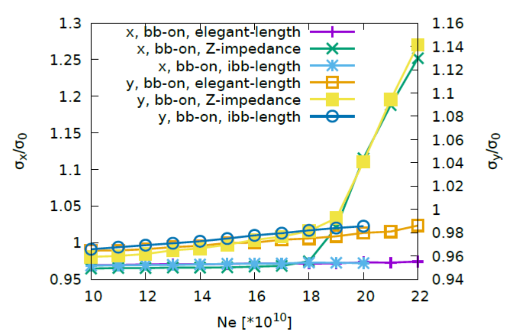

Figure 9: Transverse beam size with and without longitudinal impedance.

DYNAMIC APERTURE & LIFETIME

After dynamic aperture optimization, we usually do the many particle(1000) and long turns(10^5) tracking with the

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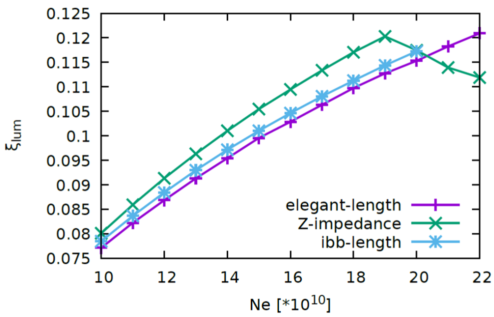

Figure 10: Beam-beam parameter with and without longitudinal impedance.

lattice and beam-beam interaction to check if the beam lifetime is long enough. It is found that larger dynamic aperture does not ensure longer lifetime, as shown in Fig. 11. It should be mentioned that the beam-beam interaction is on during the tracking of dynamic aperture and lifetime.

There exist strong nonlinearity, strong synchrotron radiation(even depedent on amplitude), strong beam-beam interaction and beamstrahlung effect in CEPC. The popular frequency map analysis [11] method does not work now. Following some work [12–15], we attempt to define the figure of merit of diffusion as

$$D \equiv \log_{10}\left(\sum_{turn} \sigma_a^2\right) \tag{4}$$

where $\sigma_a^2 = \sigma_{ax}^2 + \sigma_{ay}^2 + \sigma_{az}^2$, with A_i the normalized amplitude,

$$A_i = \sqrt{2J_i/\epsilon_i}, \quad i = x, y, z \tag{5}$$

We track 200 particles,25 turns with same initial transverse amplitude, and scan the transverse amplitude space to calculate the diffusion. The diffusion map analysis for 4 different lattices is shown in Fig. 12. It seems the result concides well with the lifetime tracking result.

SUMMARY

We briefly present the beam-beam simulation result for CEPC CDR. The beam-beam performance is limited by beamstrahlung effect at Higgs. It nearly reaches the beam-beam limit at W. The limition of luminosity performance at H is not limited at Z.

The very initial simulation shows that the beam-beam performance is reduced when considering the longitudinal impedance. We attempt to use the diffusion map alanysis method to explain the lifetime difference of different sextupole configurations. The initial result shows googd agreement. It is expected that we could add some constraint during dynamic aperture optimization to ensure long lifetime.

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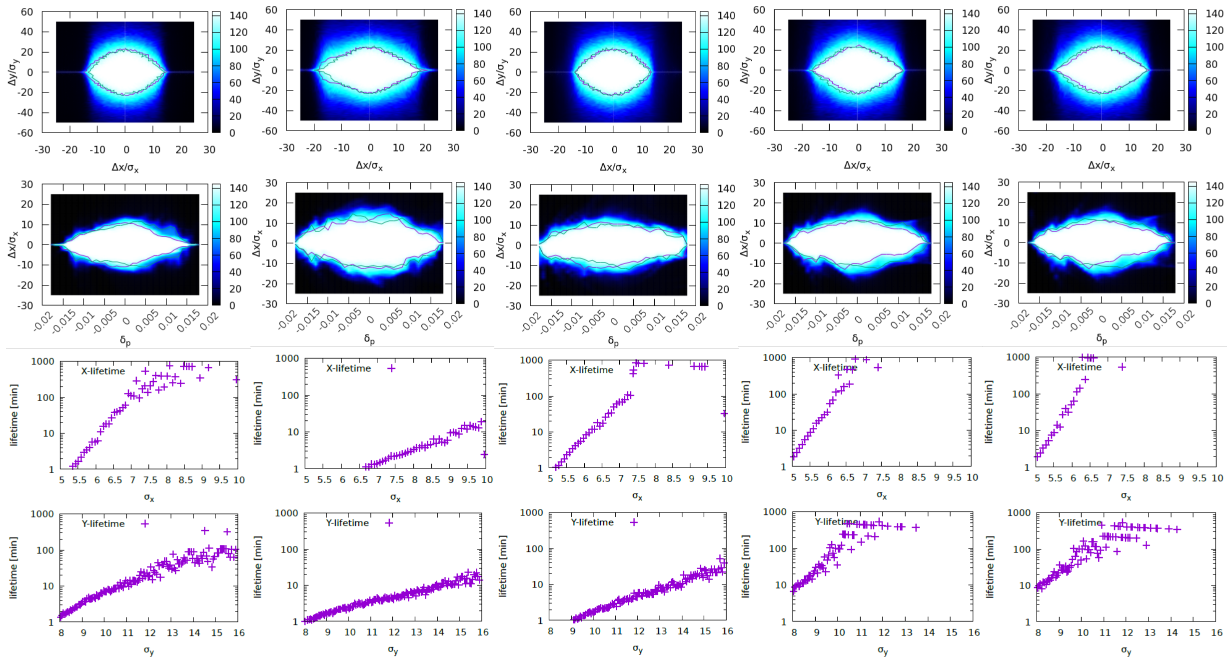

(a) case 0 (b) case 1 (c) case 2 (d) case 3 (e) case 4

Figure 11: Dynamic aperture and lifetime of 5 different sextupole configurations.

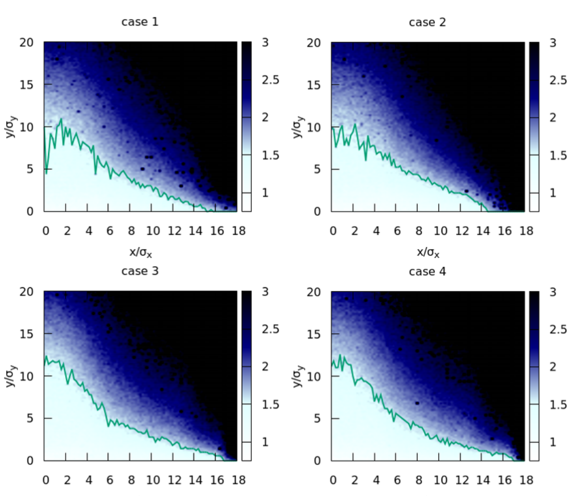

Figure 12: Diffusion map analysis of 4 different sextupole configurations.