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BEAM-BEAM SIMULATION STUDY FOR CEPC*

K. Ohmi, D. Zhou, KEK, Ibaraki, Japan
D. Shatilov, BINP, Novosibirsk, Russia
Y. Zhang†, IHEP, Beijing, China

Abstract

CEPC is a Circular Electron Positron Collider proposed to carry out high precision study on Higgs bosons. The luminosity and beam lifetime may be determined by the beamstrahlung effect. We try to check the resonability of the machine parameters with weak-strong and strong-strong simulation. At the same time we also do some cross-check between different codes. We wish the work could help determine the beam parameters which could achieve design luminosity.

INTRODUCTION

The idea of a circular e+e- collider (CEPC) as a Higgs Factory had been proposed in China at several “Accelerator Based HEP Program Workshops” during 2011-2012. In September, 2012, an idea to upgrade CEPC to a 50-70 TeV pp collider adds life and physics potentials to the project.

A circular Higgs factory fits our strategic needs in terms of: science (great & definite physics), timing (after BEPCII), technological feasibility (experience at BEPC/BEPCII and other machines in the world), manpower reality (our hands are free after 2020), economical scale (although slightly too high). And the risk of no-new-physics is complement by a pp collider in the same tunnel. The main consideration will be the Project cost. The total budget is preliminarily capped at 20B CNY($3.3B). The main parameters are listed in Table. 1.

Table 1: Design Parameters of CEPC

Beam Energy	120 GeV
Circumference	53.6 km
Luminosity	1.8e34 cm^{-2}s^{-1}
SR power/beam	50 MW
Number of IP	2
Number of Bunch	50
Momentum compaction factor	4.15e-5
Energy acceptance	0.02
Bunch population	3.71e11
horizontal emittance	6.79e-9 mrad
emittance coupling	0.003
Bunch length(SR)	2.26mm
Beam-beam parameter (x/y)	0.104/0.074

BEAMSTRAHLUNG EFFECT

The so-called beamstrahlung effect in high energy storage ring was first named in [1]. It describes the synchrotron radiation of the particle when it transverse the colliding bunch and bend by the bunch. Oide has noted that beamstrahlung effect may be a very key problem when comparing rings and linear colliders in very high energy machine. [2]. Telnov worked on this issue and find that beamstrahlung is very important [3]. Electron will be lost after emission of beamstrahlung photon with energy greater than the energy acceptance . Beamstrahlung will be very important to the beam lifetime if machine paramers are not designed reasonably. Telnov gives an analytic lifetime estatimation formula [4],

$$\tau_{bs} = \frac{10}{f_0}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\eta}{\alpha r_e}}\times \exp\left(\frac{2}{3}\frac{\eta\alpha}{r_e\gamma^2}\times\frac{\gamma\sigma_x\sigma_s}{2r_eN_p}\right)\frac{2}{\sigma_s\gamma^2}\left(\frac{\gamma\sigma_x\sigma_s}{2r_eN_p}\right)^{3/2} \tag{1}$$

Bogomyagkov also presents theoretical calculatios of beamstrahlung [5],

$$\tau_{bs} = \frac{1}{f_0}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\eta}{\alpha r_e}}\times \exp\left(\frac{2}{3}\frac{\eta\alpha}{r_e\gamma^2}\times\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_eN_p}\right)\frac{\sqrt{2}}{\sqrt{\pi}\sigma_z\gamma^2}\left(\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_eN_p}\right)^{3/2} \tag{2}$$

Here α is the fine structure constant, r_e classical electron radius, η energy acceptance, γ Lorentz factor, N_p bunch popluation, $\sigma_{x,z}$ horizontal and longitudinal beam size, f_0 revolution frequency. We will not focus on the difference between the two equations, but focus on the similarity. The lifetime contributed by the beamstrahlung can be expressed by a function $\tau(\eta, \sigma_z, \frac{\sigma_x\sigma_z}{N_p})$. That is to say,

- larger momentum acceptance η is preferred for lifetime, but the optimization of dynamic aperture is a hard work
- longer bunch length σ_z is preferred for lifetime, but the conventional hourglass effect in beam-beam interaction is a problem
- larger $\frac{\sigma_x\sigma_s}{N_p} \propto \frac{\sqrt{\beta_x}\sigma_s}{\sqrt{\epsilon_x}}$ is preferred for lifetime, which means large β_x and small ϵ_x is preferred

Beamstrahlung effect will also increase the beam energy spread, which means the colliding bunch will be lengthendedd, enhance the hourglass effect and reduce the luminosity.

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† zhangy@ihep.ac.cn

SIMULATION TOOLS

The machine parameters of storage ring colliders must be checked by simulation and proved the feasibility. In the preliminary beam-beam simulation study, we use Shatilov's lifetrack [6] , which is weak-strong code and the beamstrahlung effect is considered. The model used in the beam-beam simulations is introduced in [5]. Ohmi's BBWS code also consider the beamstrahlung effect, first with a gaussian fluctuation of ordinary synchrotron radiation excitation, then with a real spectrum distribution. The only difference is the tail distribution, which would affect the lifetime estimation. The breamstrahlung spectrum result of BBWS has been checked with CAIN and GuineaPig.

Shatilov's LIFETRAC use a similar method developed by J. Irwin [7] to track the beam tails and estimate the lifetime. Here we mainly introduce the method used in BBWS to calculate lifetime. For a gaussian distribution in phase space, the distribution of action J is

$$f(J_i) = \frac{1}{\epsilon_i}\exp(-J_i/\epsilon_i), \text{ with } \int_0^\infty dJ_i f(J_i) = 1 \quad (3)$$

With synchrotron radiation damping time τ_i, the damping rate of the action is

$$\frac{dJ_i}{dt} = -\frac{2J}{\tau_i} \quad (4)$$

So in time dt, near a boundary A, the change of the action by the damping is

$$dJ = -\frac{2A}{\tau_i}dt \quad (5)$$

That is to say in time dt, the partcile number dN that cross the boundary is

$$dN = \frac{2A}{\tau_i}dtf(A)N_0 \quad (6)$$

For equilibrim distribution, the partciles cross the boundary from outside to inside is equal to that crosss the boundary in reverse direction. The loss rate of the particles cross the boundary A is assumed as,

$$\frac{dN}{dt} = \frac{2A}{\tau_i}f(A)N_0 \quad (7)$$

And the lifetime τ is defined as

$$\frac{dN}{dt} \equiv \frac{N_0}{\tau} \quad (8)$$

It could be concluded that the lifetime is

$$\tau = \frac{\tau_i}{2Af(A)} = \frac{\tau_i}{2}\frac{\epsilon_i}{A}\exp\frac{A}{\epsilon_i} \quad (9)$$

The current version of LIFETRAC is a pure weak-strong code. The real collision is a strong-strong model. Since beamstrahlung effect makes the bunch longer, and also depends on the bunch length. Therefore a quasi-strong-strong method, where in the several repeated iterations the weak and strong bunches exchanged their roles and the length of the strong bunch was assigned geometric mean of strong and weak bunches; thus the equilibrium of the bunch length was found.

In the code BBWS, only the bunch length of strong beam was changed during collision. The strong-strong code BBSS developed by Ohmi is also used in the simulations.

SIMULATION RESULTS

The tune scan result with beamstrahlung is shown in Fig. 1. The maximum luminosity is about 1.6e34 $cm^{-2}s^{-1}$. Since there are 2 IPs in the ring, the horizontal tune of the whole ring is near integer. According to the experience of the real machines, it seems the fractional part of horizontal tune should be greater than 0.08. Since the lattice design of the machine just begin, we still not consider the posibblity with the tune advance of half ring above integer.

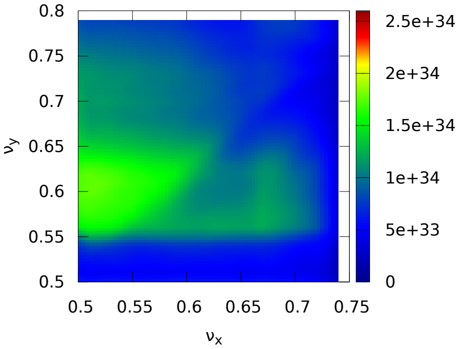

Figure 1: Tune scan of luminosity with beamstrahlung. The tune is half of the ring.

Beam lifetime is very critical for the feasiblity of the collider. Figure 2 shows the lifetime versus energy acceptance. It should be mentioned that the aperture check is before collision in the case. The lifetime will decrese about a factor of 3 if the aperture check is put after collision, which was found by Shatilov. In other words the lifetime estimation is very roughly in the simplied model (linear arc plus collision at IP). Ohmi's BBWS shows the lifetime maybe about 300min with transverse aperture $20\sigma_x \times 40\sigma_y$ and momentum acceptance 0.02, and Lifetrac's estimation is about 200min.

The bunch length is lengthened from 2.3mm to about 2.7mm according to the simulation. Figure 3 shows the effective beam-beam parameter for the particle with an longitudinal offset. In the conventional definition of beam-beam parameter, the bunch length is not considered. The so-called effective beam-beam parameter integrate the beam-beam force along the longitudinal direction when the particle transverse the collidng bunch, and the hourglass effect is also included. The figure could explain why we are not free to squeeze β_y^* even without considering the dynamic aperture problem.

Figure 4 shows the luminosity simulated by strong-strong simulation. It seems β_y^*=2mm is better, even though the effect ξ_y per IP increases from 0.108 to 0.113. The lifetime

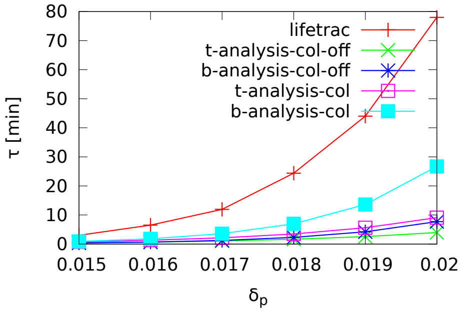

Figure 2: Lifetime estimation with different methods. The horizontal axis is the energy acceptance. 't' represents Telnov's formula, and 'b' represents Bogomyagkov's formula. 'col' means use the equilibrium beam parameters to calculate, and 'col-off' means use the nominal beam parameters to calculate. The parameters used here is not same as that in Table.1.

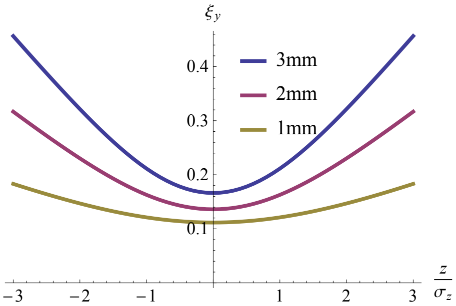

Figure 3: The effective beam-beam parameter versus the particle's longitudinal offset for different bunch length. The nominal ξ_y is 0.1 and $\beta_y^* = 1mm$ assumed.

is nearly same, but it seems the vertical dynamic aperture requirement is more relaxed according to the beam tail distribution. That is to say, we'll not lose luminosity with larger β_y^* and it is more easy for the lattice people to optimize the dynamic aperture.

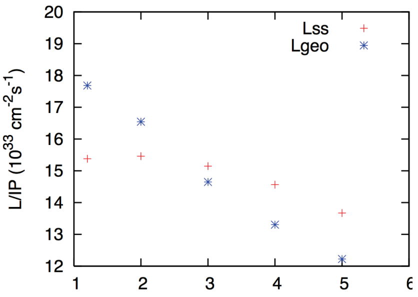

Figure 4: Bunch luminosity versus β_y^* simulated by BBSS. Lss means simulation result, and Lgeo means geometric luminosity.

In the trial of several working point with strong-strong simulation, it shows more complicated pheonomenon than the weak-strong result. Fig. 5 shows the luminosity behavior at different working point. The beam-beam interaction has shown complicated phenomenon. In the determination of working point, we'll still have to consider the dynamic aperture problem. Maybe at some high luminosity area it is very hard to achived large dynamic aperture.

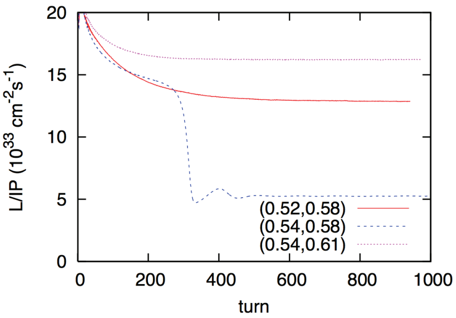

Figure 5: Luminosity behavior at different working point with strong-strong simulation.

CONCLUSION

The project of CEPC was first proposed in 2012. Since the end of 2013, we began to review the machine parameters from the point view of beam-beam simultions. We've done some work and make the machine parmaeters more reasonable. It will be a complicated problem when we study the crosstalk between beam-beam and real lattice according to the experience of SuperKEKB.

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