PRELIMINARY ACCELERATOR DESIGN OF A CIRCULAR HIGGS FACTORY IN CHINA

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Abstract

Since the Higgs boson was announced to find at LHC in CERN last July, many labs around the world have showed their interests on building electron positron colliders as Higgs factories to investigate the features of the Higgs boson. IHEP also proposed a circular Higgs factory last Sept. with a circumference of 50 – 70 km, and can be converted to a super proton-proton collider, which can be a discovery machine for new particles and physics. A preliminary design of circular electron positron collider as a Higgs factory is given here.

INTRODUCTION

On July 4, 2012, CERN announced that the Higgs boson was found at the Atlas and CMS experiments of LHC. The mass of the Higgs boson is about 125 GeV, which is only 20 GeV higher than the maximum beam energy LEP reached. After that moment, concept of Higgs factory were proposed, including circular e^+-e^- collider, linear collider, muon collider and γ-γ collider. Among these machines, the international linear collider has been studied by global efforts for more than 10 years, with the TDR [1] just released, but the accelerator technologies of circular machine seem more mature after being developed during the past decades. Muon and γ-γ colliders are also considered as the candidates of Higgs factory, but some of their technologies are still under development. Reviews of these machines can be found in [2].

As the development of future high energy accelerator , a circular e^+-e^- collider (CEPC) as the Higgs factory was proposed in IHEP, China, last Sept. with a circumference of 50–70 km. It can also be converted to a super p-p collider (SppC), with the beam energy of 50 TeV or more, as a discovery machine in the far future. Figure 1 shows a schematic graph of the whole machine (CEPC+SppC).

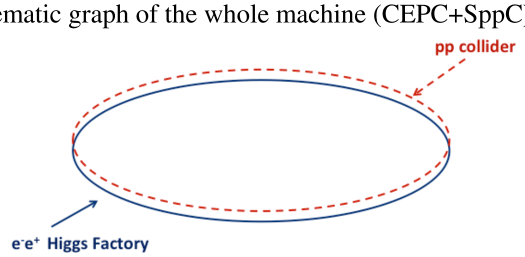

Figure 1: Schematic graph of the CEPC+SppC.

In this paper, we will first describe the determination of beam and machine parameters of the CEPC. Then, the linear lattice of the main ring will be given. The preliminary linear lattice design of the possible SppC converted from the CEPC by using the same tunnel is also presented. Some problems, covering both accelerator physics and technologies, are discussed at last.

PARAMETER DETERMINATION

In this section, main parameters for such a high energy collider will be given, after considering some important effects of beamstrahlung and the limit of synchrotron radiation power.

Beam Energy, Circumference, and Luminosity

As to a collider, beam energy and peak luminosity are the most important parameters.

Since the mass of Higgs particle is 125 GeV, the beam energy of CEPC can be set in the range of 120 – 125 GeV. In such a high energy region, beamstrahlung due to very strong synchrotron radiation (SR) when the two beams interact at IP, will be the main reason of the beam energy spread increase and thus the luminosity reduction. Under this concerning, we choose the lower limit of the Higgs particle, say 120 GeV, as the design energy of the storage ring of CEPC. Figure 2 shows the crossing-section of the Higgs at this energy region [3], from which we can see that though the lower beam energy was taken, the cross-section doesn't decrease too much.

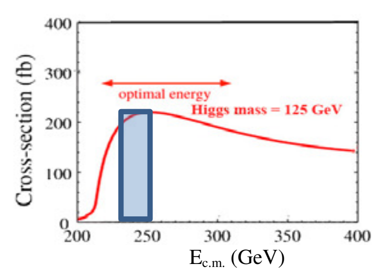

Figure 2: Cross-section at the Higgs energy region.

If we take cross-section of 200 fb and we need 20000 Higgs events per IP every year, we can easily get that the average luminosity will be $1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$, which is then the design value for the CEPC.

The circumference of the CEPC storage ring can be determined by the future super p-p collider, converted from the CEPC. So the maximum proton beam energy, for example, E_{cm}=50–90 TeV, will be the energy of SppC, and thus we take 50–70 km as the circumference of the CEPC. Here we first use 50 km as the input parameter.

Considering the operation experience of LEP, we take the design value of vertical beam-beam parameter ξ_y as large as 0.1 for the CEPC, and 0.004 for the SppC. Besides these restrictions, another limit comes from the synchrotron radiation power of beam, which is taken as large as 50 MW. As to the 50 km circumference ring, if

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we take the filling factor of bending magnets around the ring as 0.78, we can get the bending radius of dipoles as ρ = 6.2 km. With these parameters, we can get the beam current from the following equation

$$P[kW] = 88.5\frac{E^4[GeV]}{\rho[m]}I[mA]\ , \quad (1)$$

as $I = k_b I_b$ = 16.9mA. If we don't consider the hour glass effect, or beamstrahlung, the luminosity is expressed as

$$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = 2.17\times 10^{34}(1+r)\xi_y\frac{E[\mathrm{GeV}]I[\mathrm{A}]}{\beta_y^*[\mathrm{cm}]}\ , \quad (2)$$

where r is the aspect factor, β_y^* the vertical beta function at IP, and I the beam current. With Eq. (2), we can get the luminosity can reach $4.42\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$if we take β_y^*=1mm.

Energy Spread, Emittance and Aspect Factor

Beamstrahlung plays an important role in such a high energy e^+-e^- collider when two beams interact at the IP. Theories on how beamstrahlung affects beam parameters and the corresponding formulae can be found in [4]. Beam energy spread and lifetime are seriously influenced with the following equations

$$\delta_{BS} = \frac{2r_e^3 N_e^2\gamma F}{3\sigma_x\sigma_y\sigma_z}\ ,\quad R = \frac{\sigma_x}{\sigma_y}, F(R=1) = 0.325, F(R>>1)\approx\frac{1.3}{R}\ , \quad (3)$$

and

$$\tau = \frac{20C\sqrt{6\pi}r_e\gamma}{\alpha^2\eta c\sigma_z}u^{3/2}e^u,\ u = \frac{\alpha\eta\sigma_x\sigma_z}{3r_e^2\gamma N_e}\ , \quad (4)$$

where C is the circumference, r_e the classical electron radius, N_e the number of particles per bunch, γ the relativistic energy factor, η the energy acceptance, and σ_x, σ_y and σ_z the 3-D bunch sizes. With some typical beam parameters, we can get the beam lifetime is about 10–20 min, which is much shorter than the existing or previous colliders. So the top-off injection should be adopted in the future CEPC.

Combining beam-beam parameter ξ_y with Eqs. (3) and (4), we can have the beam energy spread due to beamstrahlung as

$$\delta_{\mathrm{BS}} \equiv \frac{\langle\Delta E_{\mathrm{BS}}\rangle}{E\sigma r} = 0.864 r_e^3\gamma\left(\frac{N_e}{\sigma_z(\sigma_x+\ _y)}\right)^2\beta_y \quad 0.864 r_e^3\gamma\frac{r}{\sigma_z^2}\frac{2\pi\gamma}{_e}\xi_y N_e\ . \quad (5)$$

If we take ξ_y = 0.1, we will have $N_e = 5.26\times10^{19}\varepsilon_x$. From the above equations, one can find that small N_e can reduce the beam energy spread δ_{BS}, but one has to increase bunch number and decrease the horizontal emittance to keep the luminosity as high as possible. So, 50 bunches per beam can be adopted with the particle number of 3.52×10^{11} per bunch and the horizontal emittance of 6.69 nm.rad. Eq. (6) shows the luminosity concerning the beamstrahlung effect and limit of synchrotron radiation power.

$$L_{\mathrm{limit}} = 0.4565\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}\frac{\rho(\mathrm{km})P_{\mathrm{SR}}(100\mathrm{MW})\sqrt{\delta_{\mathrm{BS}}(0.1\%)}}{(E/100\mathrm{GeV})^{4.5}\sqrt{\varepsilon_y(\mathrm{nm})}}$$

$$= 0.4565\quad 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}\frac{\rho(\mathrm{km})P_{\mathrm{SR}}(100\mathrm{MW})}{(E/100\mathrm{GeV})^{4.5}}\times\frac{\sqrt{\delta_{\mathrm{BS}}(0.1\%)}}{\sqrt{r\varepsilon_x(\mathrm{nm})}}\ . \quad (6)$$

Here, we can take the aspect factor, r, as small as 0.005, which was already realized in the existing particle factories, like KEKB, DAFNE and BEPCII.

Longitudinal and RF Parameters

Energy spread and acceptance due to synchrotron radiation are main parameters in longitudinal, together with bunch length and momentum compaction. Beam lifetime due to beamstrahlung as a function of V_{rf} at different RF frequency can be got and shown as Fig. 3.

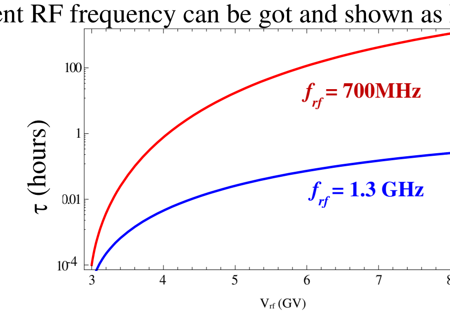

Figure 3: Beam lifetime as a function of RF voltage at different RF frequency.

If we take some typical values of σ_z<3mm, ν_s<0.3, δ_{BS} <σ_e/3, η<0.05 and τ>10 min, the correlation between α_p and V_{rf} can be got and shown as Fig. 4.

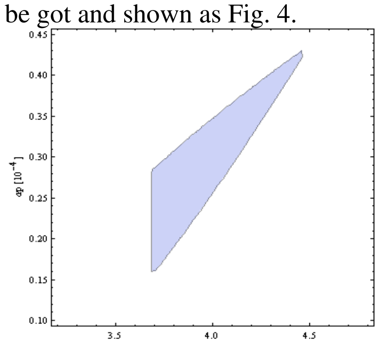

Figure 4: Momentum compaction vs. RF voltage (Grey: stable area).

If we choose the simplest FODO cell, as the basic unit of the arc, the momentum compaction can be got from

$$\alpha_p = \frac{\varphi^2}{4}\left(\frac{1}{\sin^2\frac{\mu}{2}} - \frac{1}{12}\right), \quad (7)$$

and

$$\varepsilon_x = \frac{1-\frac{3}{4}\sin^2\frac{\mu}{2}}{\sin^3\frac{\mu}{2}\cos\frac{\mu}{2}}C_q\gamma^2\frac{\varphi^2}{4}\ . \quad (8)$$

With ε_x = 6.69 nm.rad, we can choose $\alpha_p = 0.4\times10^{-4}$. Then from Fig. 4, we can get the total RF voltage V_{rf}= 4.2GV. The 5-cell RF cavity can be the candidate of the RF system, so we can take the acceleration field E_{acc}=10 MV/m with V_c=2 MV for each cavity. The total number of RF cavity will be 420.

Table 1 lists all the main parameters of the CEPC. The L_{limit} means the luminosity with the beamstrahlung effect. The luminosity with the beamstrahlung effect will be about half of the calculated luminosity. Here we take the hourglass coefficient as 0.6.

LINEAR LATTICE DESING OF CEPC

As we mentioned in previous section, the FODO cell is chosen as the basic unit of arcs. The phase advance of each cell is 60 degree for both horizontal and vertical planes. 16-folder symmetry is used for the whole ring and RF sections are distributed in each folder. A booster is assumed to be in the same tunnel as the main ring, with the energy range from 6 – 120 GeV. A 6-GeV linac is hoped to be the injector of the booster. For more IPs around the ring, pretzel scheme can be adopted. Figure 5 shows the Twiss functions for the standard cell in arcs.

Table 1: Main Parameters of the CEPS Storage Ring

Para.	Unit	Value	Para.	Unit	Value
Energy	GeV	120	Circum.	km	50
N_e	1E11	3.52	N_b/beam		50
Beam current	mA	16.9	SR power /beam	MW	50
Dipole field	T	0.065	Bending radius	km	6.2
$\varepsilon_{x,y}$	nm	6.69, 0.033	σ_x/σ_y	μm	36.6/0.2
β_{IP} (x/y)	mm	200/1	SR loss	GeV/ turn	2.96
$\xi_{x,y}$		0.1, 0.1	σ_z	mm	3
α_p	1E-4	0.4	IP No.		1
V_{rf}	GV	4.2	f_{rf}	GHz	0.7
ν_s		0.13	Harmonic		116747
δ_{SR}		0.0013	δ_{BS}		0.00014
η	%	2.7	τ_{BS}	hr	1.6
L_0/IP (10^{34})	/cm^2/s	2.65	$L_{\rm limit}$/IP (10^{34})	/cm^2/s	1.26

To promote the luminosity at the same SR power, one has to increase the circumference of the ring. Another scheme with the circumference of 70 km is under design. Option for pretzel scheme is kept for more IPs, which can also have the luminosity enhanced, but not linearly with the number of IP. The final focusing system in the interaction region (IR) is still in its design, which will be one of the most difficult and critical parts of the machine.

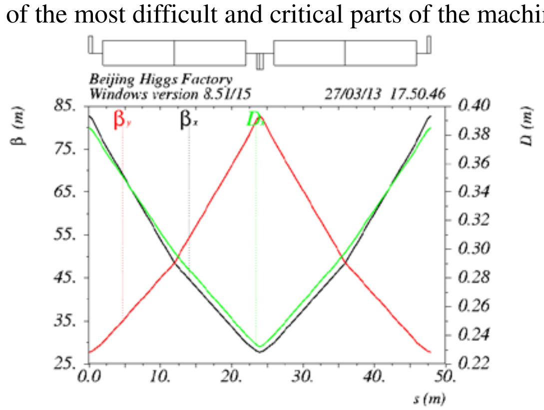

Figure 5: Twiss functions of a 60 degree cell.

The SppC, which will be constructed as a discovery machine using the tunnel of CEPC, can also have two scenarios with different circumferences, 50 km or 70 km. The maximum proton beam energy could reach 45 TeV, if the dipole field is about 20 Tesla using superconducting magnets. The energy limit mainly comes from the dipole field. The arc can also apply the standard cell with a phase advance of 60 or 90 degree.

With the empirical value of beam-beam parameter, say $\xi_y = 0.004$, beam current = 0.5mA, vertical beta function at the IP = 0.1m, we can get the luminosity of the SppC can be 2-3×10^{35}cm^{-2}s^{-1}. Table 2 gives the main parameters of SppC for 2 scenarios of 50 and 70 km circumference.

Table 2: Main Parameters of SppC for Two Schemes

Para.	SppC-1	SppC-2
Beam Energy (TeV)	20	45
Circumference (km)	50	70
No. of IPs	2	2
SR loss/turn (keV)	440	4090
N_p/bunch (10^{11})	1.3	0.98
Bunch No.	3000	6000
Beam current (mA)	0.5	0.405
SR power/ring(MW)	0.22	1.66
Dipole field (T)	12	19.24
Bending radius (km)	6.9	7.8
Momentum compaction (10^{-4})	3.5	2.5
$\beta_{\rm IP}$ x/y (m)	0.1/0.1	0.1/0.1
Norm. Trans. emit, x/y (μm.rad)	4	3
Geo. Lumi. reduction factor	0.8	0.9
L_0/IP (10^{35} cm^{-2}s^{-1})	2.15	2.85

DISCUSSION AND CONCLUSION

Although we have the preliminary design of the storage ring, but still a lot of problems remain. The accelerator physics related topics, such as dynamic aperture, low emittance ring design with pretzel orbits, beamstrahlung effect, design of the interaction ragion, beam background, beam polarization, collective effect and heat loading due to SR power, machine and detector interface (MDI), etc., are all very important to the machine design, and can influence the hardware system of the whole machine. Meanwhile, accelerator technology towards such a future machine needs to be developed too. The technique of very low field dipole and very high gradient quadrupole will be critical. Ultra-high field dipoles, such as 20 T, will be difficult for both superconducting and cryogenics system. How to realize the beam polarization at such a high beam energy, will be a challenge to both accelerator physics and technology.

In a word, the CEPC is very promising in physics, with some mature technologies. It could be converted to a p-p collider as a discovery machine. Some technologies need R&D, and accelerator physics studies need more efforts.

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