CEPC cost model study and circumference optimization

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ABSTRACT: The CEPC is a proposed high luminosity Higgs/Z factory, with the potential to be upgraded to top factory at center-of-mass energy of 360 GeV. We perform an optimization study on the circumference of CEPC. We calculate the instant luminosity, the construction and operation cost for different circumferences. With respect to the total cost and average cost per particle, we conclude that the optimal circumference for the CEPC Higgs operation is 80 km. Taking into account of the Z pole operation, the potential high-energy upgrade of CEPC (top factory), the optimal circumference increased to 100 km. The long future proton-proton upgrade of CEPC (SPPC) also favors a larger circumference, and we conclude that 100 km is the global optimized circumference for this facility.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Beam dynamics; Beam Optics

ArXiv ePrint: 2206.09531

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1 Introduction

After the discovery of the Higgs boson [1, 2], precision measurement of the Higgs boson properties became a new, and extremely sensitive probe to the new Physics Principles underneath the Standard Model. The Higgs factories based on electron-positron colliders provide crucial information on top of the intensive Higgs program at the Large Hadron Collider (LHC) [3] and its high luminosity upgrade [4–6]. They could significantly boost the precisions of the Higgs property measurements and are regarded as the highest priority for future collider facilities. Multiple electron-positron Higgs factories are proposed, including both linear colliders (International Linear Collider (ILC) [7] and Compact Linear Collider (CLIC) [8]) and circular colliders (Circular Electron Positron Collider (CEPC) [9] and Future Circular Collider (FCC) [10, 11]). Accordingly, intensive physics studies and critical R&D are underway.

The modest Higgs mass of \(125 \text{ GeV}\) enables a circular electron-positron collider as a Higgs factory, which has the advantage of a higher luminosity-to-cost ratio compared to the linear collider and the potential to be upgraded to a proton-proton collider to achieve unprecedented high energy (\(\sim 100 \text{ TeV}\)) and discover new physics beyond standard model. Both FCC-ee and CEPC which has a similar scope is a good candidate for the future Higgs factory based on a circular electron-positron collider. The CEPC will operate in three different modes: \(H (e^+e^-\rightarrow ZH)\), \(Z (e^+e^-\rightarrow Z)\) and \(W (e^+e^-\rightarrow W^+W^-)\). The center-of-mass energies are 240 GeV, 91 GeV and 160 GeV, and the luminosities are expected to be \(5.0 \times 10^{34}\), \(1.0 \times 10^{36}\) and \(1.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\), respectively [9].

A tentative “7-2-1” operation plan is to run CEPC first as a Higgs factory for 7 years and create two million Higgs particles or more, followed by 2 years of operation as a Super Z factory to create one trillion Z bosons and then 1 year as a W factory to create about 100 million W bosons. After that, the energy of CEPC will be increased to 360 GeV with an upgrade, in order to improve the width measurement accuracy of Higgs and increase the accuracy of top mass measurement.

In September 2012, Chinese scientists proposed a 240 GeV Circular Electron Positron Collider (CEPC) with a circumference of 50 km to house two large detectors for Higgs studies. The tunnel for such a machine could also house a Super Proton Proton Collider (SPPC) to reach energies beyond the LHC. It was first presented to the International Committee for Future Accelerators (ICFA) at the Workshop “Accelerators for a Higgs factory: Linear vs. Circular” (HF2012) in November 2012 at Fermilab [12]. A Preliminary Conceptual Design Report (Pre-CDR, the White Report) for a 54 km circular collider was published in March 2015 [13], followed by a Progress Report (the Yellow Report) for the 61 km and 100 km design in April 2017 [14]. The Conceptual Design Report (CDR, the Blue Report) published in August 2018 [15] is a summary of the work done by hundreds of scientists and engineers over the past five years. At that time, we chose 100 km to increase the luminosity of CEPC and push the energy potential of SPPC as much as possible. The luminosity of CEPC is the main reason for choosing 100 km scope with a certain criterion for total power consumption. 30 MW synchrotron radiation power per beam is an assumption for CEPC with consideration of the grid distribution status, the electricity capability in China and also the operation cost due to power consumption, while this limitation can be increased to 50 MW with upgrade. For CEPC, we are still not quite clear now whether 100 km is the optimum. It is time to look at the circumference of CEPC quantitatively and understand the machine with proper rationale. Therefore, this study develops a cost model to evaluate the cost performance of CEPC. The experiences of existing projects [16–19] are kept in mind and are helpful to CEPC cost study.
2 CEPC cost model introduction

The total Higgs number can be expressed as:

\[ N_{\text{Higgs}} = N_{\text{IP}} \cdot L_{\text{design}} \times 0.8 \times \sigma \times T_{\text{physics}} \]  \hspace{1cm} (2.1)

where \( T_{\text{physics}} \) is the expected total detector operation time with data taking in the unit of second which is expressed as:

\[ T_{\text{physics}} = N_{\text{year}} \times \text{month}_{\text{physics}} \times 30(\text{days/month}) \times 24(\text{hours/day}) \times 3600(\text{seconds/hour}) \]  \hspace{1cm} (2.2)

where \( N_{\text{year}} \) is the required years of operation for certain high energy physics and \( \text{month}_{\text{physics}} \) is the detector operating months of data taking for each year, which is assumed to be 5 for CEPC. The average physics efficiency of CEPC is expected to be around 60%, which is comparable with LEP/LEP2 (50%), KEKB (70%), PEPII (60%) and BEPCII (70%) [20].

In eq. (2.1), \( N_{\text{IP}} \) is the number of interaction points, \( L_{\text{design}} \) is the design luminosity per IP, \( \sigma \) is the cross section of certain physics. Here, we introduced a luminosity reduction factor of 0.8 to approximate the real luminosity considering the possible accelerator commissioning status.

The total cost of the Higgs factory is composed of five parts which is expressed as follows:

\[ \text{Cost}_{\text{total}} = \text{Cost}_{\text{machine}} + \text{Cost}_{\text{detector}} + \text{Cost}_{\text{elect}} + \text{Cost}_{\text{maintain}} + \text{Cost}_{\text{staff}} \]  \hspace{1cm} (2.3)

The first part \( \text{Cost}_{\text{machine}} \) is the construction costs for the accelerator which is modeled by:

\[ \text{Cost}_{\text{machine}} = \frac{C}{100} \cdot 24 \text{ (billion)} + 6 \text{ (billion)} \]  \hspace{1cm} (2.4)

where \( C \) is the circumference of CEPC. The construction costs of accelerator \( \text{Cost}_{\text{machine}} \) is broken down into a fixed part (6 billion CNY) and a variable part which is linear as the circumference. When the circumference is 100 km, the construction costs of accelerator will be 30 billion CNY which is same as the cost estimate in CDR [15]. The construction cost of the CEPC in CDR is estimated using two different methods to be around 30 billion CNY. In the first method, the total cost is calculated by adding the expenses for each subsystems according to the CDR design. The second method is extrapolating roughly from the LEP spending while accounting for size differences, country differences, technology advancements, and historical inflation rates. Cost projections from the two systems agree within 10%. For the Pre-CDR design with 54 km circumference, the cost of CEPC has been estimated roughly based on the similar methods as CDR and the construction costs for the accelerator was around 18 billion CNY [13]. So the fixed part in eq. (2.4) is assumed to be 6 billion CNY and we regard eq. (2.4) valid for a circumference range of 30–200 km.

The second part \( \text{Cost}_{\text{detector}} \) in eq. (2.3) is the construction costs for the detectors, modeled as:

\[ \text{Cost}_{\text{detector}} = 2 \text{ (billion)} \times N_{\text{IP}} \]  \hspace{1cm} (2.5)

The construction cost of detector is also estimated in CDR stage [15] which is about 2 billion for each, and hence the total cost for the detectors is the product of single detector cost and the number of interaction point (\( N_{\text{IP}} \)).
The last three parts of eq. (2.3) are modeled by eq. (2.6) to eq. (2.8), which are related to the operating time of the machine, and the total operating year \(N_{\text{year}}\) is given by eq. (2.1).

\[
\text{Cost}_{\text{elect}} = P_{\text{SR}} \times F_{\text{AC}} \times (N_{\text{year}} \times \text{month}_{\text{operation}} \times 30 \text{ (days/month)} \times 24 \text{ (hours/day)}) \times C_{\text{power}} \\
\text{(2.6)}
\]

\[
\text{Cost}_{\text{maintain}} = \text{Cost}_{\text{machine}} \times 3\% \times N_{\text{year}} \quad \text{(2.7)}
\]

\[
\text{Cost}_{\text{staff}} = (\text{Cost}_{\text{machine}} \times 1\% + 0.1 \text{ (billion)}) \times N_{\text{year}} \quad \text{(2.8)}
\]

Here, \(\text{Cost}_{\text{elect}}\) is the cost of electricity where \(P_{\text{SR}}\) is the SR power per beam and the factor \(F_{\text{AC}}\) is the magnification coefficient for the total power consumption which is dominated by the operation energy. This magnification factor \(F_{\text{AC}}\) is assumed to be 10 for CEPC at 120 GeV. We gave this factor an approximate value to make a simplified model based on the power consumption estimation in Pre-CDR [13] and CDR [15] including different circumference and different SR power. We found that the total power consumption of CEPC is also related to the SR power and the local average temperature besides the beam energy. As a reference, the value of this power magnification factor assumed for CEPC at 120 GeV agrees with LEP2 at 104 GeV [21]. The factor \(C_{\text{power}}\) in eq. (2.6) is the electricity cost per kWh which is 0.5 CNY/kWh in China and \(\text{month}_{\text{operation}}\) is the machine operation months per year which is assumed to be 9 for CEPC. As stated in eq. (2.6), the CEPC is planned to operate 6500 hours each year. For 100 km CEPC, the electricity usage will be \(1.95 \times 10^9\) kWh a year, resulting in an electricity bill of one billion CNY at Higgs energy.

\(\text{Cost}_{\text{maintain}}\) is the cost of daily repair and maintenance of the accelerator where the factor of 3\% is from the experience of Beijing Electron Positron Collider (BEPC). This factor for LHC is also at the same level [22].

\(\text{Cost}_{\text{staff}}\) is the personnel cost where only the people work on the accelerator and administration is considered while the physicists are not included. When the circumference is 100 km, the personnel cost per year is 0.4 billion CNY which correspond to one thousand persons involved and 400 thousand CNY for each person. As a reference for the manpower requirement, CERN has about 2500 staff members [23] and the number related to LHC operation and exploitation may reach the level of thousand.

3 CEPC cost for the Higgs factory configuration

3.1 Higgs luminosity scan with different circumference

3.1.1 Scaling law for beam-beam parameter limit and luminosity

In \(e^+e^-\) storage ring colliders, particles are confined in a bunch due to strong quantum excitation and synchrotron damping effects. The position of each particle is random and the state of the particles can be considered as a gas in which the positions of the particles follow statistical laws. Apparently, synchrotron radiation is the main source of heating. Besides, when two bunches undergo collision at an interaction point (IP), every particle in each bunch will feel the deflected electromagnetic field of the opposite bunch and the particles will suffer from additional heating. The larger the particle population \(N_e\) is, the stronger this type of heating becomes and the greater the beam emittance becomes. There is a limiting condition beyond which the beam emittance will blow up [24, 25].
Beam-beam studies shown that crab waist scheme can substantially boost the luminosity of existing and future electron-positron colliders [26, 27], so we proposed this concept in CEPC since 2015 [28].

The beam-beam tune shift is introduced to define the frequency change of the betatron oscillation due to collision. Besides the emittance blow-up mechanism for the maximum value of beam-beam tune shift, a crab waist enhancement factor is introduced to estimate the potential of the beam-beam tune shift. The maximum beam-beam tune shift is also called as beam-beam limit and can be expressed by [25]:

$$\xi_{y,\text{max}} = \frac{2845}{2\pi} \sqrt{\frac{U_0}{2yE_0N_{\text{IP}}}} \times F_l$$

(3.1)

where $N_{\text{IP}}$ is the number of interaction points (If there are $N_{\text{IP}}$ interaction points, the independent heating effects must be added in a statistical manner), $U_0$ is the synchrotron radiation loss per turn and $E_0$ is the beam energy. The crab waist enhancement factor $F_l$ is related to the Pinwinski angle $\Phi$ and the vertical beta function at IP, which can be expressed approximately by:

$$F_l = \begin{cases} \frac{1}{\sqrt{\Phi \beta_y^2}} & (\Phi \gg 1) \\ \frac{1}{\sqrt{\beta_y}} & (\Phi \leq 1) \end{cases}$$

(3.2)

and the Pinwinski angle $\Phi$ is defined as:

$$\Phi = \frac{\sigma_z}{\sigma_x} \tan \theta_h$$

(3.3)

where $\sigma_x$ and $\sigma_z$ are the horizontal beam size and bunch length at IP and $\theta_h$ is the half crossing angle.

The luminosity of a circular collider is expressed by:

$$L \left[ \text{cm}^{-2} \text{s}^{-1} \right] = 2.17 \times 10^{34} (1 + r) \xi_y \frac{eE_0 (\text{GeV}) N_b N_e}{T_0 (\text{s}) \beta_y (\text{cm})} F_h$$

(3.4)

where $r = \sigma_y/\sigma_x$ is the aspect ratio of the bunch at IP, $T_0$ is the revolution period, $\beta_y^*$ is the value of the vertical beta function at the interaction point, $\xi_y$ is the vertical beam-beam tune shift, and $F_h$ is the luminosity reduction factor due to hour glass effect, expressed as follows [29]:

$$F_h = \frac{\beta_y^*}{\sqrt{\pi \sigma_z}} \exp \left( \frac{\beta_y^* \gamma^2}{2 \sigma_z^2} \right) K_0 \left( \frac{\beta_y^* \gamma^2}{2 \sigma_z^2} \right)$$

(3.5)

where $K_0$ is the zero order modified Bessel function of the second kind.

Combining eq. (3.1) and eq. (3.4), one finds that:

$$L \propto \xi_{y,\text{max}} I_b \propto \frac{\xi_{y,\text{max}}}{U_0} \propto \frac{1}{\sqrt{U_0}} \propto \sqrt{C}$$

(3.6)

In deriving eq. (3.6), it is assumed that the radiation power for each beam is fixed ($P_{\text{SR}} = U_0 \times I_b = \text{const}$). Thus, the luminosity is approximately proportional to the square root of the size of the circular collider when the beam-beam tune shift reaches its limit.
3.1.2 CEPC parameters choice with different circumference at Higgs energy

A general method has been developed to optimize the parameters of a circular $e^+e^-$ Higgs factory by using analytical expressions for the maximum beam-beam parameter and the beamstrahlung beam lifetime, starting from a given design goal and technical constraints \[28, 30, 31\]. A parameter space has been explored. Based on the scan of beam parameters and RF parameters, a set of optimized parameter designs for CEPC with different circumference was proposed. The luminosity for the Higgs energy as a function of the size of the circular collider is shown in figure 1. To maximize the luminosity for each circumference, the IP beam parameters and the lattice structure were carefully optimized. For example, the FODO length is 55m for 100 km circumference, while it is 80m for 200 km circumference. Also, we chose different $\beta^*$ for different circumferences to achieve the maximum beam-beam tune shift, and meanwhile to keep the beam lifetime (dominated by the beamstrahlung lifetime and barbar lifetime) at the same level for different machine sizes. The requirement for the dynamic aperture energy acceptance of larger ring is smaller than the smaller ring according to the beamstahlung lifetime estimation \[32, 33\], so a slightly smaller $\beta_{y^*}$ can be used for a larger ring. Additionally, the RF voltage is lower for a larger ring than for a smaller ring due to the lower momentum compaction factor of the lattice.

![Luminosity vs. Circumference](image)

**Figure 1.** Results of the luminosity optimization studies for the CEPC collider at the beam energy of 120 GeV (Higgs factory configuration) vs. machine circumference ($P_{SR}$=30 MW).

3.2 CEPC 4 IP scheme

CEPC schematic design with four IPs is also studied without detail optics design. For CEPC, we keep focus on 2 IP scheme during TDR period \[9\], while FCC-ee has moved on to 4 IP scheme after its CDR publication \[34–36\]. The layout of CEPC four IP scheme is shown in figure 2. We assume equal space between four IPs and shared RF systems are used. The RF stations are located in the middle of two adjacent IPs to ensure that the same beam energy arrives at each detector. Therefore, there are a total of four RF sections in the colliding rings. In the 4 IP scheme, there are two bunch trains per beam and therefore it is a two-by-two collision, which is different from the 2 IP scheme.
From eq. (3.1), the maximum beam-beam tune shift is inversely proportional to the square root of the IP number, and from eq. (3.6), the luminosity per IP is also inversely proportional to the square root of the SR loss $U_0$. Meanwhile considering the total length reduction of arc section due to more insertion space for detectors and beam focusing, $U_0$ will increase slightly and hence the single IP luminosity for different IP number can be scaled by the luminosity of the 2 IP case by:

$$L(N_{IP}) = L(2_{IP}) \frac{\sqrt{\frac{2}{N_{IP}}}}{\sqrt{1 + \frac{4(N_{IP}-2)}{C}}}$$ \hspace{1cm} (3.7)

### 3.3 Cost of Higgs factory

#### 3.3.1 Required years of operation

Number of years of required operation can be calculated according to eq. (2.1) and the luminosity value in figure 1, where the cross section at 240 GeV is assumed to be 200fb. Figure 3 shows the operating years for a Higgs factory with different operating conditions and different physics goals. For the operating conditions with 50 MW SR beam power, the luminosity per IP can be scaled from 30 MW case linearly with the beam power. And the single IP luminosity for the 4 IP scheme can be scaled from the 2 IP case by eq. (3.7). From figure 3, we know that about 1.5 million Higgs particles can be achieved with 7 years’ planning running time if we choose a circumference of 100 km and 30 MW operating conditions.

#### 3.3.2 Total cost for Higgs factory

Figure 4 shows the CEPC total costs only for a Higgs factory with different operating conditions. The lower three lines are the costs for the 1 million Higgs goal and the upper three lines are the costs for 2 million Higgs goal. The minimum cost for a Higgs factory is CNY 40 billion and the optimum circumference is 80 km. If the requirement of total Higgs bosons reach 2 million, the total cost is almost the same for 80 km and 100 km option.
Figure 3. Required years of operation for the CEPC collider at the beam energy of 120 GeV (Higgs factory configuration) with different operation conditions and different physics goal.

Figure 4. The total cost for the CEPC collider at the beam energy of 120 GeV (Higgs factory configuration) vs. machine circumference.

3.3.3 Cost per Higgs particle

Figure 5 shows the cost per Higgs particle produced under different operation conditions. We can see that all lines are distributed in three series, which is related to the physical requirements. The upper three lines are the single Higgs cost for the 1 million Higgs goal, which is roughly 45 thousand CNY at 100 km circumference; the middle three lines are the single Higgs cost for the 2 million Higgs goal which is roughly 28 thousand CNY at 100 km circumference, and the lowest two dashed lines are the single Higgs cost even for the 10 million Higgs goal with much lower Higgs cost which are shown here just as a reference. We know that the single Higgs cost is dominated by the physical requirements rather than the detail operation condition.
Figure 5. The cost per Higgs particle for the CEPC collider at the beam energy of 120 GeV (Higgs factory configuration) with different operation conditions and different physics goal.

3.3.4 Comparison between 2 IP and 4 IP

Figure 6 shows the total cost comparison of a Higgs factory for the 2 IP and 4 IP schemes with different SR power. For 30 MW beam power, the crossing point of 2 IP and 4 IP scheme refer to 1.5 million Higgs which coincides with the real achievement for 7 years of Higgs operation. Thus, the 4 IP scheme is more economical when the requirement for Higgs particles is more than 1.5 million. In the 50 MW case, the crossing point of 2 IP and 4 IP scheme refer to 1.9 million Higgs which is also close to the real achievement with 7 years of Higgs operation. Overall speaking, the total cost of the Higgs factory is almost same for the 2 IP scheme and the 4 IP scheme, regardless of how much beam power we use when the requirement for Higgs particles is between 1.5 million and 1.9 million.

Figure 6. The total cost comparison of a Higgs factory between 2 IP and 4 IP scheme with different SR power (left: 30 MW SR power per beam, right: 50 MW SR power per beam).
4 CEPC cost combining Z factory

4.1 Z luminosity scan with different circumference

Just as with the Higgs energy, we have optimized the beam parameters and the phase advance of FODO cell while the lattice structure is kept same as the lattice of the Higgs factory configuration. CEPC’s parameters and lattice design is optimized at Higgs energy (120 GeV), so only figure 1 at Higgs energy is consistent with eq. (3.6) and the operation at Z pole (45.5 GeV) is in a compatible way. The phase advance of FODO cell for Z operation is 60 degree while the circumference is smaller than 120 km, and the FODO phase advance is reduced to 45 degrees when the circumference is larger than 120 km to achieve the highest luminosity. We have found that larger rings require much more bunches than smaller rings because of the lower beam-beam limit and lower bunch charge. While the bunch number at Z pole is limited by the electron cloud instability and the maximum bunch number for a 200 km long ring is assumed to be 35000 by a rough analytical estimate. The optimized luminosity at the Z pole with different circumferences is shown in figure 7 and the corresponding SR power for each beam is shown in figure 8. From figure 8 we see that the beam power cannot reach the full design value (30 MW) because of the electron cloud instability, so that the luminosity in figure 7 starts to decrease after 120 km.

![Figure 7. Results of the luminosity optimization studies for the CEPC collider at the beam energy of 45.4 GeV (Z factory configuration) vs. machine circumference.](image)

4.2 CEPC cost considering compatibility with Z factory

4.2.1 Required years of operation for Z factory

The total operating year of the CEPC as a Z-factory can be calculated according to eq. (2.1) and the luminosity value in figure 7 where the cross section at 91 GeV is assumed to be 30 nb. Figure 9 shows the operation years for a Z-factory with different physics goals. From figure 9, we know that about 1.3 tera of Z bosons can be achieved with 2 years’ planning running time if we choose a circumference of 100 km.
Figure 8. SR power per beam for the CEPC collider at the beam energy of 45.4 GeV (Z factory configuration) vs. machine circumference.

Figure 9. Required years of operation for the CEPC collider at the beam energy of 45.4 GeV (Z factory configuration) vs. machine circumference.

4.2.2 Cost per Z particle

At the Z pole, the cost of electricity in eq. (2.6) should be changed to eq. (4.1) due to lower energy running.

\[
\text{Cost}_{\text{elect}} = P_{\text{SR}} \times 6 \times (N_{\text{year}} \times \text{month}_{\text{operation}} \times 30 \times \text{days/month}) \times 24 \times \text{hours/day}) \times C_{\text{power}} \quad (4.1)
\]

Figure 10 shows the cost per Z boson with different physics goal. We can see that Z boson becomes cheaper if we require more Z bosons and the cost of single Z boson with the goal of 1 tera Z is roughly 0.035 CNY at 100 km circumference. We also know that the Z-factory prefers the smaller ring if we only consider Z physics without Higgs.

4.2.3 Cost per Higgs particle combining Higgs and Z

The cost of each Higgs boson can be reduced if we combine Higgs physics and Z physics. The cost per Higgs can be revised considering the construction cost allocation between the Higgs factory
and the Z factory according to their operation year, which is given by eq. (4.2) eq. (4.3). As an example, figure 11 shows the cost per Higgs particle for a given operating condition with different Z bosons goal. We can see that the single Higgs cost for the case with 1 million Higgs requirement and 30 MW SR power can be reduced from 45 thousand CNY to 36 thousand CNY while including 1 tera of Z bosons with 100 km circumference.

\[ F_{\text{Higgs}} = \frac{\text{Year}_{\text{Higgs}}}{\text{Year}_{\text{Higgs}} + \text{Year}_{Z}} \] (4.2)

\[ \text{Cost}_{\text{machine @ Higgs}} + \text{Cost}_{\text{detector @ Higgs}} = (\text{Cost}_{\text{machine}} + \text{Cost}_{\text{detector}}) \times F_{\text{Higgs}} \] (4.3)

Figure 10. The cost per Z boson for the CEPC collider at the beam energy of 45.5 GeV (Z factory configuration) with different physics goal.

Figure 11. The cost per Higgs boson for the CEPC collider combining Higgs physics and Z physics vs. machine circumference.

4.2.4 CEPC total cost combining Higgs and Z

Figure 12 shows the CEPC total cost combining Higgs physics and Z physics with different operation conditions. The lower two lines are the costs for 1 million Higgs goal with 1 tera Z bosons and the
upper two lines are the costs for 2 million Higgs goal with 1 tera Z bosons. The minimum cost for a CEPC is CNY 42 billion and the optimum circumference is 80 km for the case of 1 million Higgs. Again, if the total demand for Higgs bosons is more than 2 million, the cost of 100 km circumference would be almost same as that of 80 km.

Figure 12. CEPC total cost combining Higgs physics and Z physics with different operation conditions and different physics goal.

5 CEPC cost combining tt physics

5.1 tt luminosity scan with different circumference

Just as with the Higgs energy, the beam parameters at 180 GeV are optimized at each circumference to achieve higher luminosity as much as possible, while the lattice structure is kept same as the lattice of Higgs factory configuration. So far, the CEPC parameters and the lattice design have been optimized at the Higgs energy. For higher energy of tt, if we still use the same lattice as Higgs, the strength of the FD SC quadrupoles will exceed the maximum capability of the technology. Moreover, the beam stay clear region will be larger than the beam pipe designed for Higgs energy because the emittance of tbar becomes larger than that of Higgs. So for tt mode, we need to redesign the IR lattice and relax the $\beta_x^*/\beta_y^*$ which can fulfill the constraint for the FD quadrupole strength and beam stay clear region. A larger horizontal $\beta_x^*$ ($\sim 1$ m for 100 km) is chosen to ensure that the new beam stay clear region would not be larger than that of Higgs at IR SC quadrupole region, and a larger vertical $\beta_y^*$ ($\sim 2.7$ mm for 100 km) is chosen to get larger DA energy acceptance according to stronger beamstrahlung effect with higher energy. Overall speaking, with larger ring, the IP vertical $\beta_y^*$ can be slightly lower than smaller ring due to smaller requirement of DA energy acceptance and lower beam-beam limit. In addition, the RF voltage of smaller ring is higher than larger ring due to larger momentum compaction factor, and hence the smaller collider under 50 km cannot work at tt energy because the space ratio kept for RF systems would be too high compared with the total circumference. The optimized luminosity at tt energy with different circumferences is shown in figure 13 with 30 MW SR power for each beam.
Figure 13. Results of the luminosity optimization studies for the CEPC collider at the beam energy of 180 GeV vs. machine circumference ($P_{SR} = 30$ MW).

5.2 CEPC cost considering compatibility with top factory

5.2.1 Required years of operation for top factory

The total operation year of CEPC at tt energy can be calculated according to eq. (2.1) and the luminosity value in figure 13 where the cross section at 360 GeV is assumed to be 500 fb. Also considering two top quarks will be produced by one reaction, figure 14 shows the operation years for the tt study with different physics goals. From figure 14, we know that the minimum operation year for 1 million top quarks is about 6 years if we choose 100 km circumference and 50 MW running condition.

Figure 14. Required years of operation for the CEPC collider at the beam energy of 180 GeV vs. machine circumference.

5.2.2 Cost per top quark

For the tt physics study, the construction cost for the accelerator in eq. (2.4) should be modified to eq. (5.1) taking into account the upgrade cost for the additional RF systems at tt energy. The machine cost will increase due to the upgrade of RF system because tt operation needs much more RF cavities. In eq. (5.1), the factor $k$ is related to the detail RF voltage and its value is 1 when the circumference is 100 km. The cost of electricity in eq. (2.6) should be modified to eq. (5.2) due to
the higher beam energy. Figure 15 shows the cost per top quark with different physics goal. We can see that each top quark becomes cheaper if more top quarks are expected. Also the highest cost of each top quark for 1 million total top quarks and 30 MW SR power is roughly 68 thousand CNY at 100 km circumference. Furthermore, we can see that the tt physics favors the larger ring if we only consider the tt physics compared to the Higgs energy.

\[
\text{Cost (machine)} = \frac{C}{100} \cdot 24 \text{ (billion)} + 6 \text{ (billion)} + k \times 6 \text{ (billion)}
\]

\[
\text{Cost (elect)} = P_{SR} \times 13 \times (N_{\text{year}} \times month_{\text{operation}} \times 30 \text{ (days/month)} \times 24 \text{ (hours/day)}) \times C_{\text{power}}
\]

**Figure 15.** The cost per top quark for the CEPC collider at the beam energy of 180 GeV with different physics goal vs. machine circumference.

### 5.2.3 CEPC total cost combining Higgs, Z and tt operation

Figure 16 shows the total costs of the CEPC for the combination of Higgs physics, Z physics and top quark under different operating conditions. The lower four lines are the costs without top quark study and the upper four lines are the costs with 1 million top quarks. The minimum CEPC cost is about CNY 73 billion if we consider Higgs, Z and top quark physics together and the optimal circumference changes to 100 km.

### 6 The potential of SPPC on energy frontier

The CEPC has the potential to be upgraded to a proton-proton collider to achieve unprecedented high energy and discover New Physics. It is planned to build a super proton-proton collider (SPPC) in the same tunnel of the CEPC after 10 years of operation. The construction of CEPC and SPPC in a common accelerator complex also provides a great opportunity to realize collisions of ultra-high energy protons or ions with very high energy electrons or positrons (e-p or e-A). Figure 17 shows the dipole strength of SPPC related with the different circumference and figure 18 shows the center-of-mass energy of SPPC related with the different circumference. The energy potential of SPPC is strongly depends on the size of the collider and the technology of the superconducting dipole magnets. From figure 18, it can be seen that a larger ring can achieve a higher energy with a certain technology level and that a larger circumference is helpful to push the energy frontier.
Figure 16. CEPC total cost combining Higgs physics, Z physics and top quark with different operation conditions and different physics goal vs. machine circumference.

Figure 17. The dipole strength of SPPC corresponding to the different C. M. energy vs. machine circumference.

Figure 18. The C. M. energy of SPPC corresponding to the different dipole strength vs. machine circumference.
7 Summary

We have performed simplistic cost optimization studies for CEPC (Circular Electron Positron Collider) based on a rough cost model and the circumference choice of CEPC is reconsidered in a quantitative way. Higgs physics is the first goal of CEPC and hence the machine design is optimized for Higgs energy. If the total Higgs boson demand is about 1 million, a circumference of 80 km is a good choice, while 80 km and 100 km are almost the same if the total Higgs boson demand is more than 2 million. Combining the physics of Higgs and top quarks, 100 km is the best choice. Overall, 100 km circumference is a good choice for the CEPC, considering the compatibility of the machine and the future potential of t#bar{b}, Z and SPPC.

Acknowledgments

This work is supported by the Key Research Program of Frontier Sciences, CAS (Grant No. QYZDJ-SSW-SLH004) and the National Foundation of Natural Sciences (Grant No. 12175249).

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