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CEPC 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 360GeV. 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.

INTRODUCTION

The modest Higgs mass of ~125 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 (~100 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- →ZH), Z (e+e- →Z) and W (e+e- →W+W-). The center-of-mass energies are 240 GeV, 91 GeV and 160 GeV, and the luminosities are expected to be 5.0×10^{34}, 1.0×10^{36} and 1.6×10^{35} $cm^{-2}s^{-1}$, respectively [1]. 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 360GeV 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. A Preliminary Conceptual Design Report (Pre-CDR, the White Report) for a 54 km circular collider was published in March 2015, followed by a Progress Report (the Yellow Report) for the 61 km and 100 km design in April 2017. The Conceptual Design Report (CDR, the Blue Report) published in August 2018 [2] 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. 30MW 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 50MW 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, a cost model is developed to evaluate the cost performance of CEPC [3].

CEPC COST MODEL INTRODUCTION

The total Higgs number can be expressed as:

$$N(higgs) = N_{IP} \cdot L_{design} \times 0.8 \times \sigma\left(year \times month_{physics} \times 30 \times 24 \times 60 \times 60\right) \quad (1)$$

where N_{IP} is the number of interaction points, L_{design} is the design luminosity per IP, *year* is the required years of operation for the Higgs physics, and $month_{physics}$ is the detector operating months of data taking for each year, which is assumed to be 5 for CEPC. In eq. (1), 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:

$$\mathrm{Cost}_{total} = \mathrm{Cost}(machine) + \mathrm{Cost}(detector) + \mathrm{Cost}(elect) + \mathrm{Cost}(repair) + \mathrm{Cost}(staff) \quad (2)$$

where the first two parts *cost*(*machine)* and *cost*(*detector*) are the construction costs for the accelerator and detectors, modeled as follows:

$$\mathrm{Cost}(machine) = \frac{C}{100} 24(billion) + 6(billion) \quad (3)$$

$$\mathrm{Cost}(detector) = 2(billion) \times N_{IP} \quad (4)$$

The last three parts are modeled by eq. (5) to eq. (7), which are related to the operating time of the machine, and the total operating year is given by eq. (1).

$$\mathrm{Cost}(elect) = P_{SR} \times 10 \times year \times month_{operation} \times 30 \times 24 \times 0.5 \quad (5)$$

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$$\mathrm{Cost}(repair) = \mathrm{Cost}(machine) \times 3\% \times year \quad (6)$$

$$\mathrm{Cost}(staff) = (\mathrm{Cost}(machine) \times 1\% + 0.1(billion)) \times year \quad (7)$$

Here, *cost*(*elect*) is the cost of electricity, *cost*(*repair*) is the cost of daily care and maintenance of the accelerator, *cost*(*staff*) is the personnel cost, *year* is the total operation year for certain high energy physics, and $month_{operation}$ is the machine operation months per year which is assumed to be 9 for CEPC.

CEPC COST BASED ON A HIGGS FACTORY

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 [4, 5]. 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 Fig. 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 100km circumference, while it is 80m for 200km circumference. Also, we chose different β* 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, so a slightly smaller β_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.

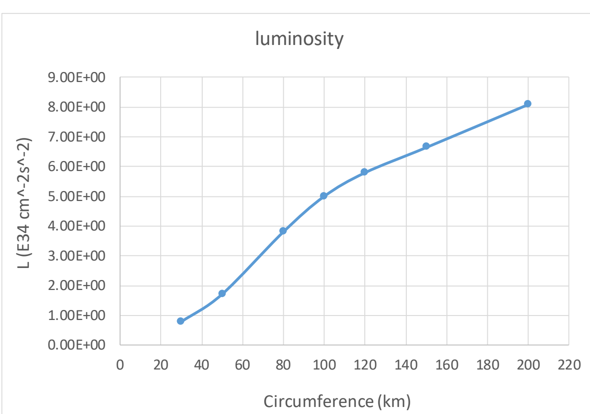

Figure 1: Higgs luminosity scan with different circumference (PSR=30MW).

Figure 2 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 RMB 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.

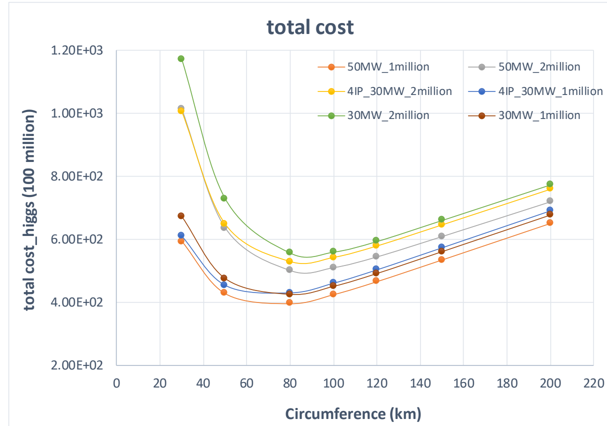

Figure 2: CEPC total cost only for a Higgs factory.

CEPC COST COMBING Z FACTORY

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 Higgs's lattice. The advance of FODO cell is 60 degree while the circumference is smaller than 120km, and the FODO 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 Fig. 3. The beam power cannot reach the full design value (30 MW) because of the electron cloud instability, so that the luminosity in Fig. 3 starts to decrease after 120 km.

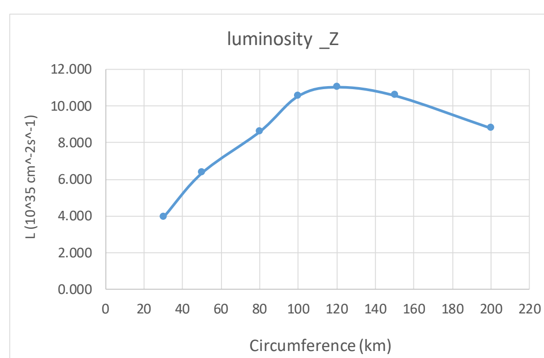

Figure 3: luminosity scan at Z pole with different circumference.

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.

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Figure 4 shows the CEPC total cost combing Higgs physics and Z physics with different operation conditions. The lower two lines are the costs for 1 million Higgs goal with 1 teta Z bosons and the upper two lines are the costs for 2 million Higgs goal with 1 teta Z bosons. The minimum cost for a Higgs factory is RMB 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 circumference of 100 km would be almost the same as that of 80 km.

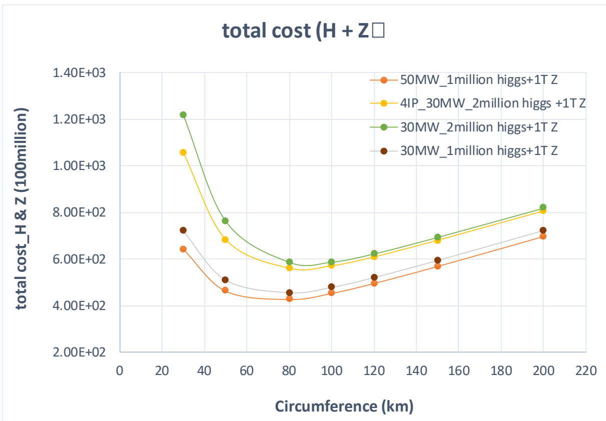

Figure 4: CEPC total cost combing Higgs physics and Z physics with different operation conditions.

CEPC COST COMBING TT PHYSICS

Just as with the Higgs energy, the beam parameters are optimized at each circumference to achieve the maximum luminosity, while the lattice structure is kept same as higgs's lattice. 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 because the emittance of ttbar 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 fulfil the constraint for the FD quadrupole strength and beam stay clear region. A larger horizontal βx^* (~1 m for 100km) 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 βy^* (~2.7 mm for 100km) is chosen to get larger DA energy acceptance according to stronger beamtrahlung effect with higher energy. Overall speaking, with larger ring, the IP vertical βy^* 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 long compared with the total circumference. The optimized luminosity at tt energy with different circumferences is shown in Fig. 5 with 30MW SR power for each beam.

Figure 6 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 100km.

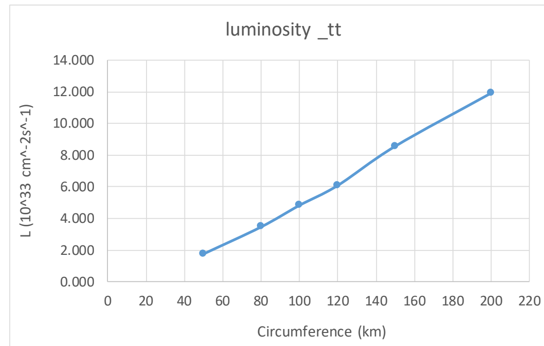

Figure 5: luminosity scan at tt for different circumference with 30MW SR power.

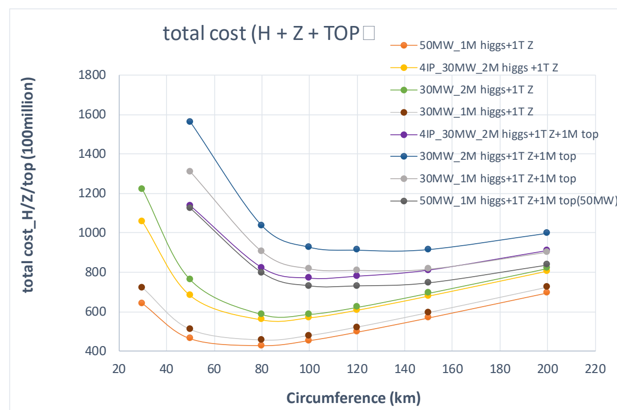

Figure 6. CEPC total cost combining Higgs physics, Z physics and top quark with different operation conditions and different physics goal vs machine circumference.

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 ttbar, Z and SPPC.

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