CEPC cost model study and circumference optimization

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Outline

- CEPC cost model introduction
- CEPC cost based on a Higgs factory (240GeV)
- CEPC cost combing Z factory (91GeV)
- CEPC cost combing tt physics (360GeV)
- Energy potential of SPPC
- Summary

Introduction

- We perform an optimization study on the circumference of CEPC.
- We calculate the instant luminosity, the construction and operation cost for different circumferences.
- CEPC cost performance is studied with the calculation of the total cost and the average cost per particle.

CEPC Cost model

$$N(higgs) = N_{IP} \cdot L_{design} \times 0.8 \times \sigma \left(year \times month_{physics} \times 30 \times 24 \times 60 \times 60 \right) \qquad (month_{physics} = 5)$$

- N_{IP} : the number of interaction points,
- L_{design} : the design luminosity per IP,
- σ : cross section of certain physics,
- *year* : the required years of operation for certain high energy physics,
- $month_{physics}$: the detector operating months of data taking for each year,
- Luminosity reduction factor (0.8): approximate the real luminosity considering the possible accelerator commissioning status.

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

- *cost*(*machine*)/*cost*(*detector*) : the construction costs for the accelerator and detectors,
- *cost*(*elect*) : the cost of electricity,
- *cost*(*repair*) : the cost of daily care and maintenance of the accelerator,
- *cost*(*staff*) : the personnel cost,

CEPC Cost model

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

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

$$\mathrm{Cost}(elect) = P_{SR} \times 10 \times year \times month_{operation} \times 30 \times 24 \times 0.5 \quad (month_{operation} = 9)$$

- P_{SR} : SR power per beam,
- $month_{operation}$: the machine operating months per year,
- Electricity cost/kwh: 0.5 RMB.

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

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

Scaling law for beam-beam parameter limit and luminosity

- Beam-beam limit: $$\xi_{y,\max} = \frac{2845}{2\pi}\sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}} \times F_l$$ (Gao theory)

enhancement factor by crab waist:

$$F_l = \begin{cases} \frac{1}{28}\sqrt{\frac{\Phi}{\beta_y^*}} & (\Phi >> 1) \\ \frac{1}{28}\frac{\sqrt{\Phi}}{\left(\beta_y^*\right)^{0.6}} & (\Phi \le 1) \end{cases}$$

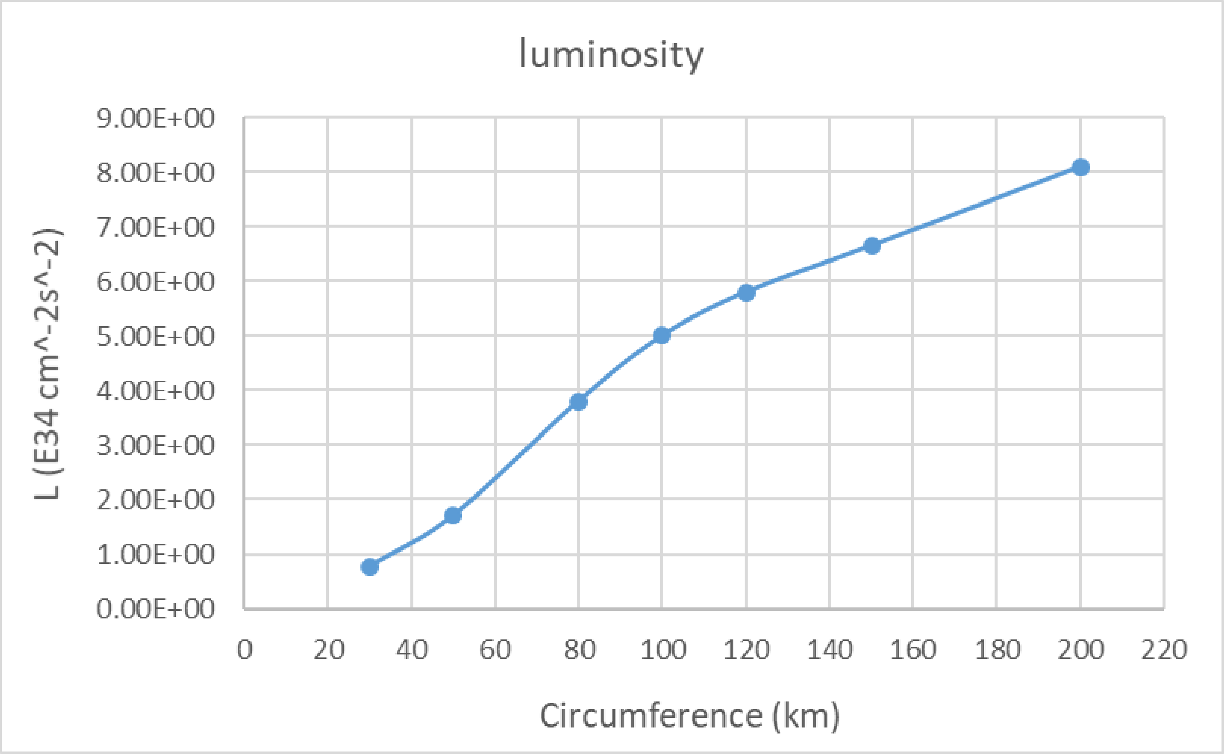
$$\Phi = \frac{\sigma_z}{\sigma_x} tg\theta_h$$ (Pinwinski angle)

- Luminosity: $$L[cm^{-2}s^{-1}] = 2.17\times10^{34}\left(1+r\right)\xi_y \frac{eE_0(GeV)N_b N_e}{T_0(s)\beta_y^*(cm)} F_h$$

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

CEPC parameters choice with different circumference @Higgs

- Make accelerator design for different machine size (30km~200km)
- P_{SR}=30MW, 2 IP scheme

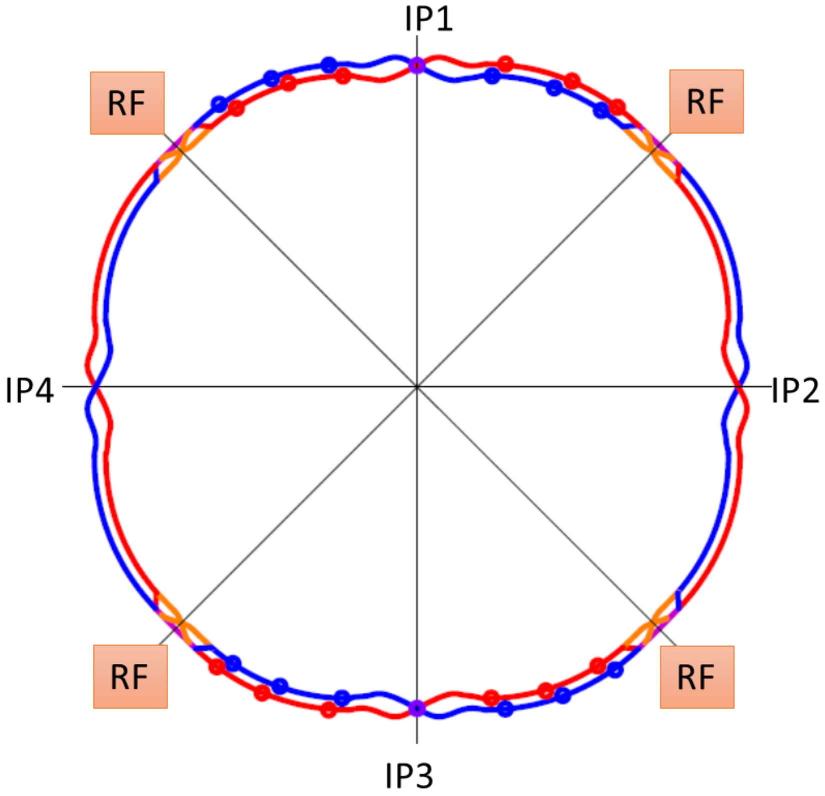


- Optimize IP parameters
- Optimize lattice structure
- Maximize luminosity for each circumference

CEPC 4IP scheme

- Luminosity for 4 IP can be scaled from 2 IP case

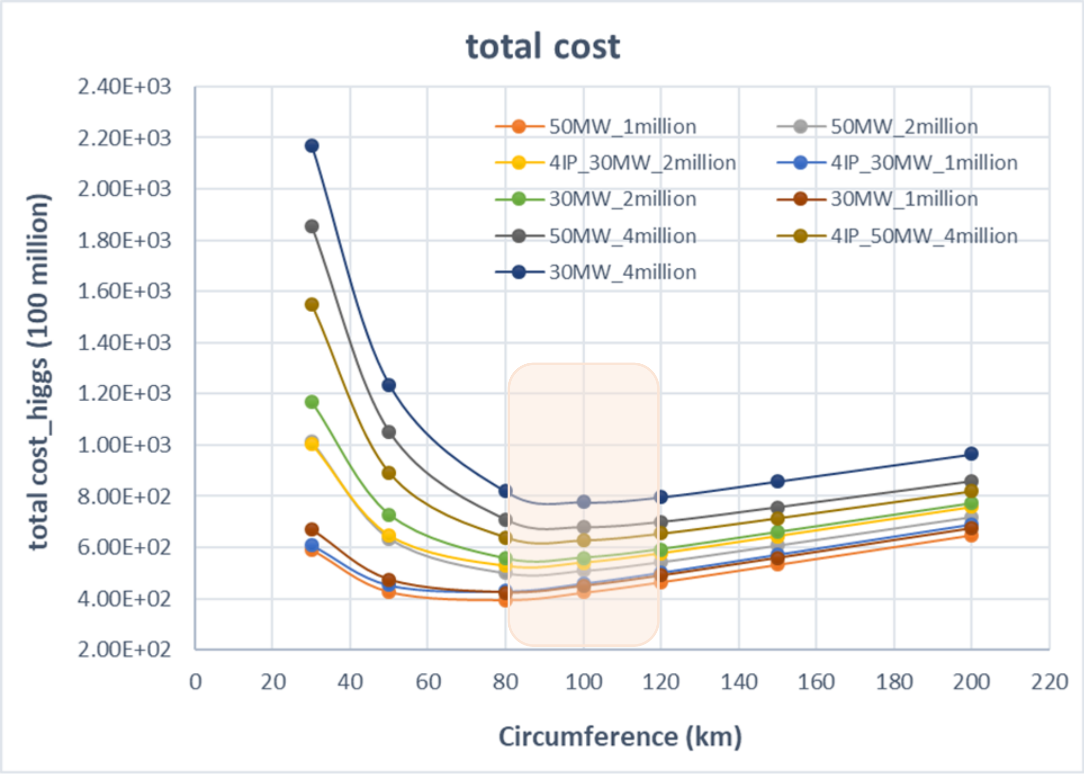
$$L(N_{IP}) = L(2IP)\frac{\sqrt{\frac{2}{N_{IP}}}}{\sqrt{1+\frac{4*(N_{IP}-2)}{C}}}$$



- 4 IPs
  - Equal spacing between IPs
- 4 RFs
  - RF at the midpoint of 2 IPs
  - shared RFs
- 2×2 collision
  - 2 trains/beam
- Compatibility with SPPC
  - 2 CEPC detectors (IP2, IP4) removed when SPPC is constructed.

Total cost for Higgs factory --Higgs only

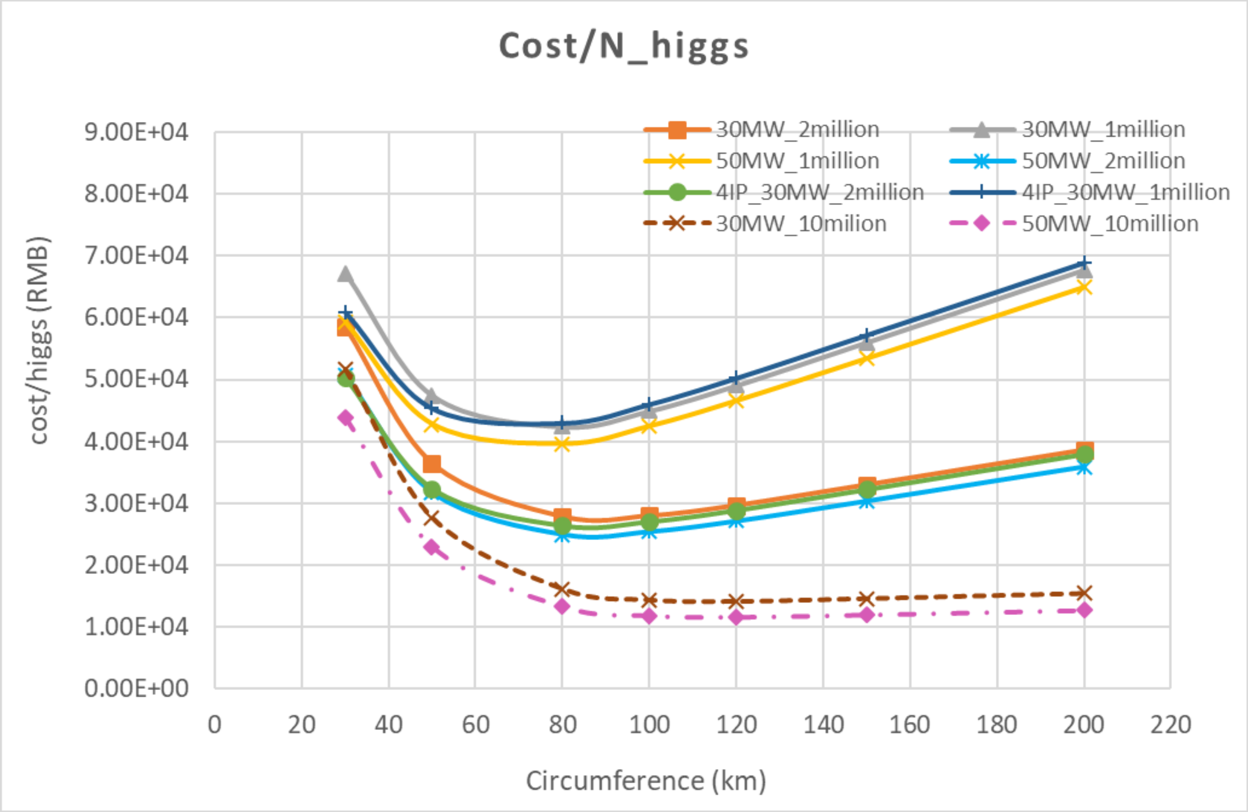
- Cross section @240GeV=200fb



- The minimum cost is RMB 40 billion and the optimum circumference is 80 km (for 1M Higgs).
- If the Higgs requirement = 2M, the total cost is almost the same for 80 km and 100 km.

Cost per Higgs particle

- Single Higgs cost is dominated by the physical requirements rather than the detail operation condition.



➢ 2M Higgs:

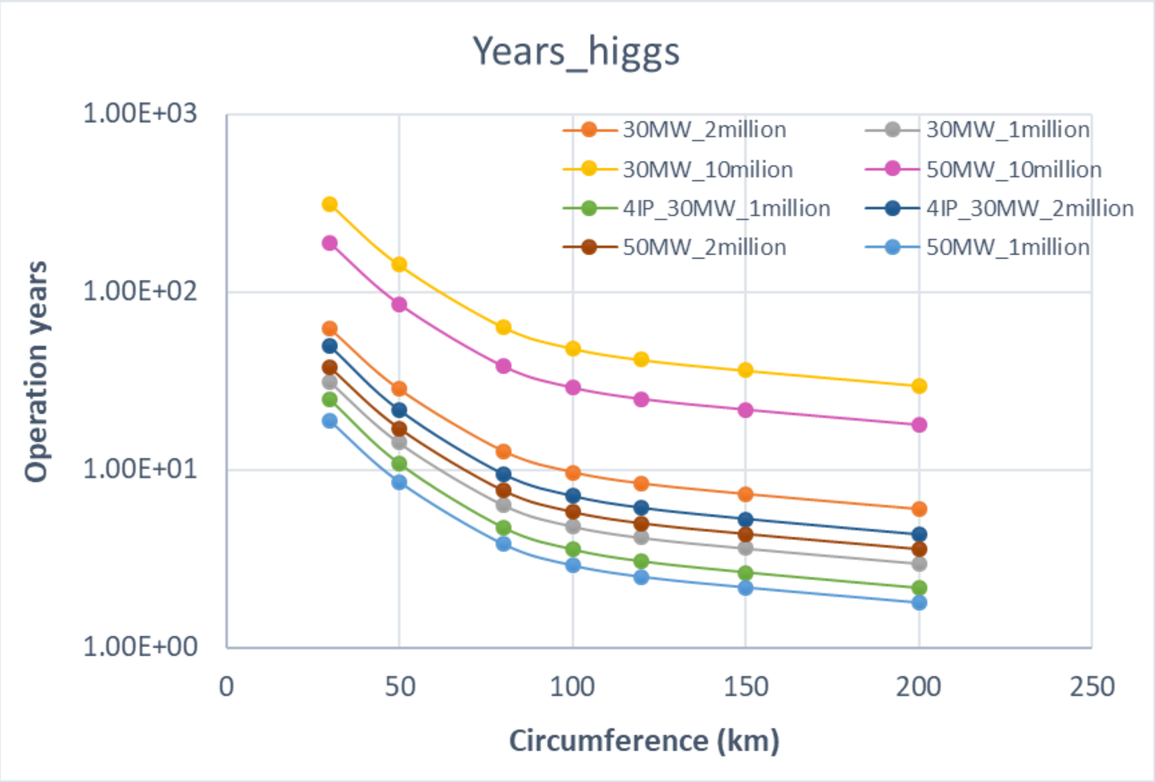
- 30MW(2IP): 28.0 thousand
- 30MW(4IP): 27.1 thousand
- 50MW(2IP): 25.4 thousand

➢ 4M Higgs:

- 30MW(2IP): 19.5 thousand
- 50MW(2IP): 16.9 thousand
- 50MW(4IP): 15.7 thousand

Operation year for Higgs physics

- Required operation years is calculated with different operating conditions and different physics goals
- Cross section @240GeV=200fb



➢ 2M Higgs:

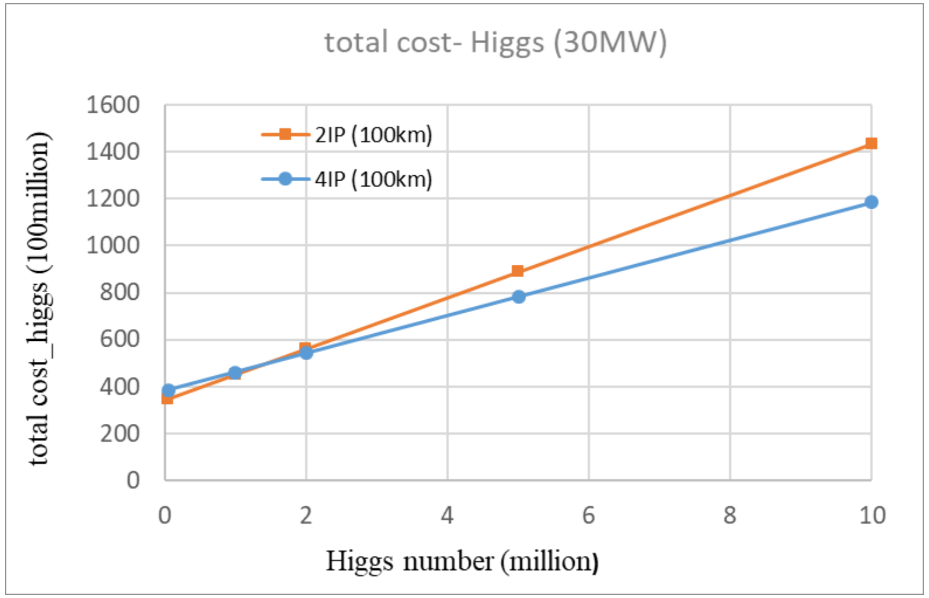
- 30MW(2IP): 9.7 years
- 30MW(4IP): 7.1 years
- 50MW(2IP): 5.8 years

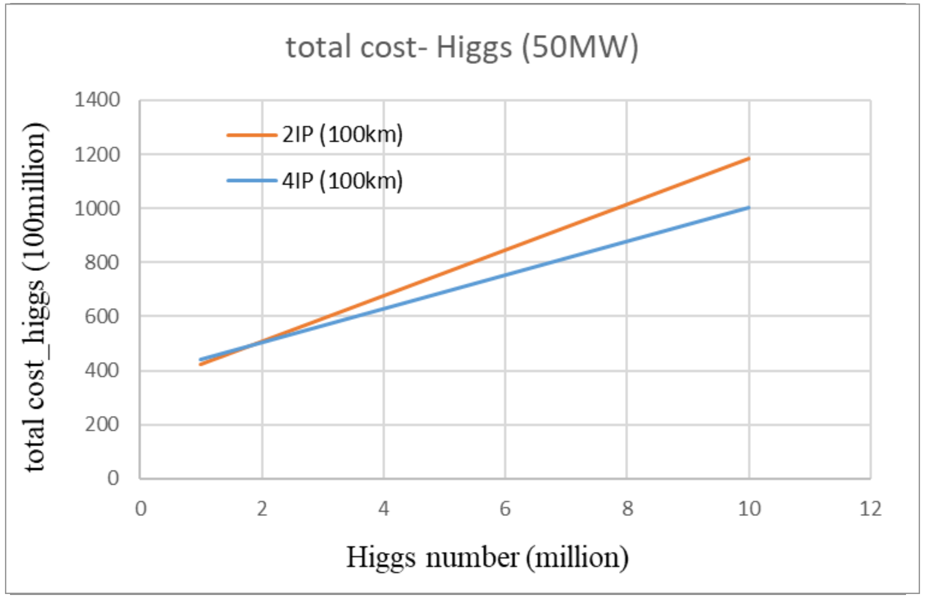
➢ 4M Higgs:

- 30MW(2IP): 19 years
- 50MW(2IP): 12 years
- 50MW(4IP): 8.5 years

Comparison between 2 IP and 4 IP- Higgs only

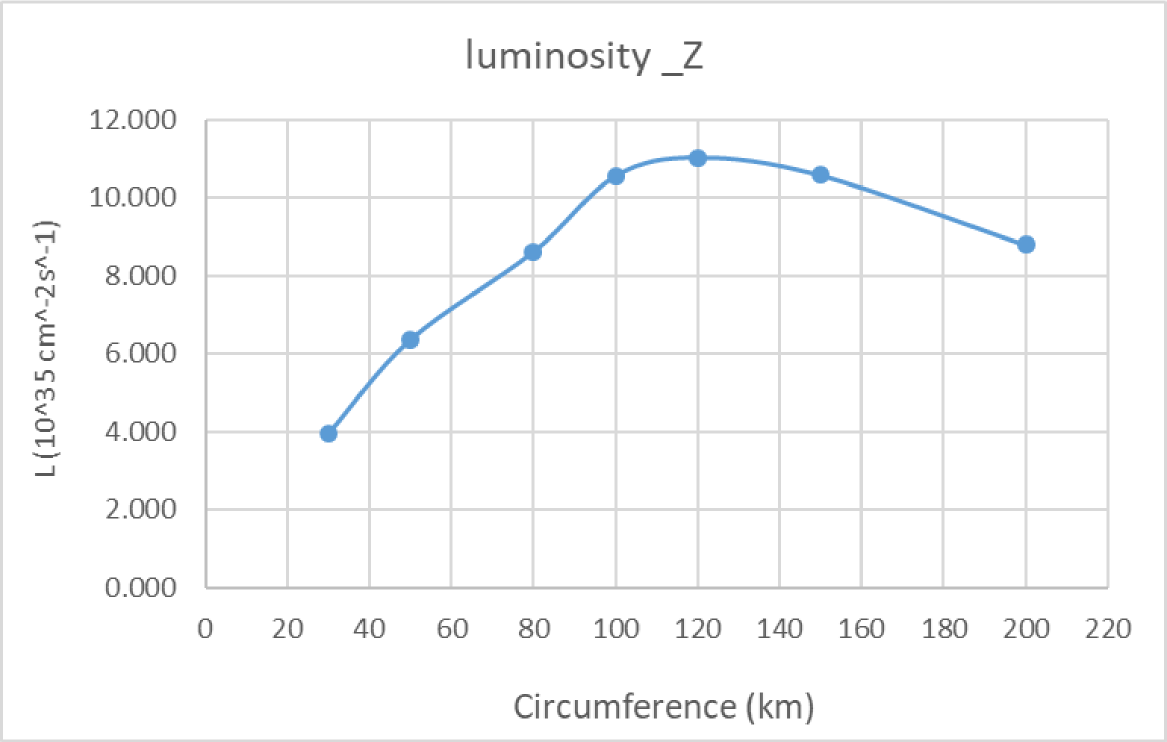
- 4 IP more efficient/economical when the requirement for Higgs particle >2 million.

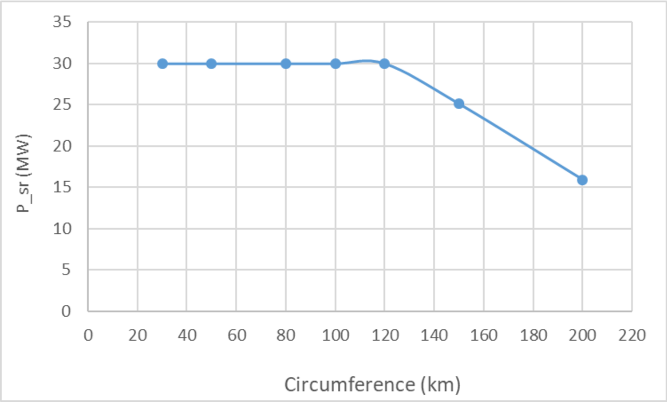




Z luminosity scan with different circumference

- 60° FODO cell while C ≤ 120km, 45° FODO cell while C >120km



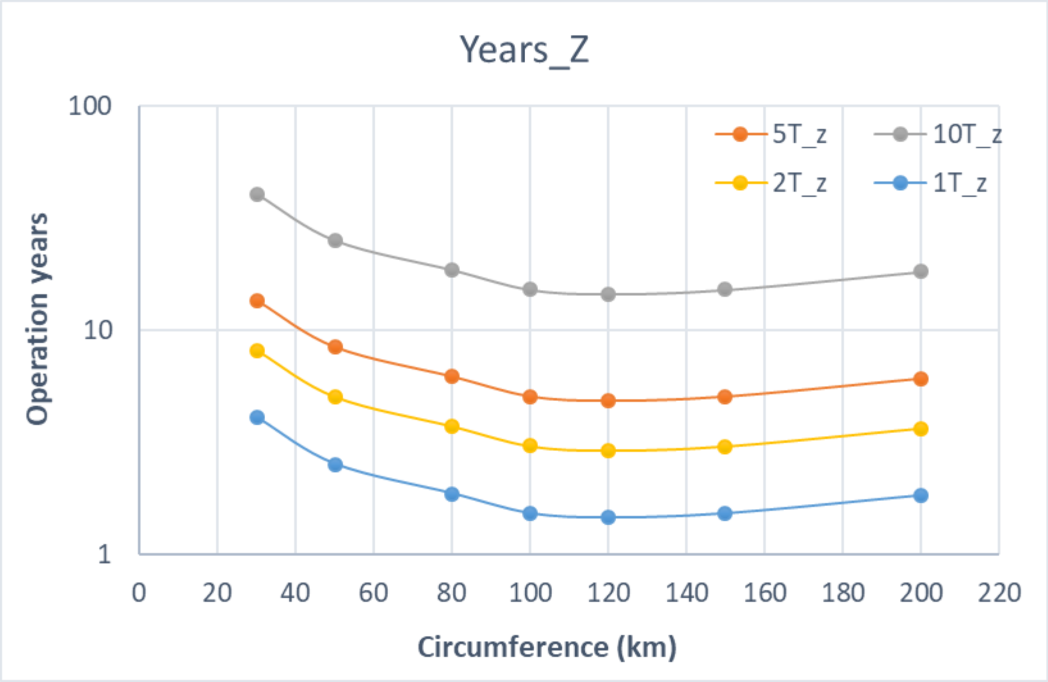


- Same lattice structure as Higgs
- Larger ring require much more bunches than smaller ring.
- Bunch number is limited by EC instability.
- Max N_b is 35000 for 200km ring (Y. D. Liu).

Operation year for Z factory

- Cross section @91GeV=30nb

- ~ 1.3 tera of Z bosons can be achieved with 2 years' planning running time.



Cost per Z particle – Z factory only

- Cross section @91GeV=30nb

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

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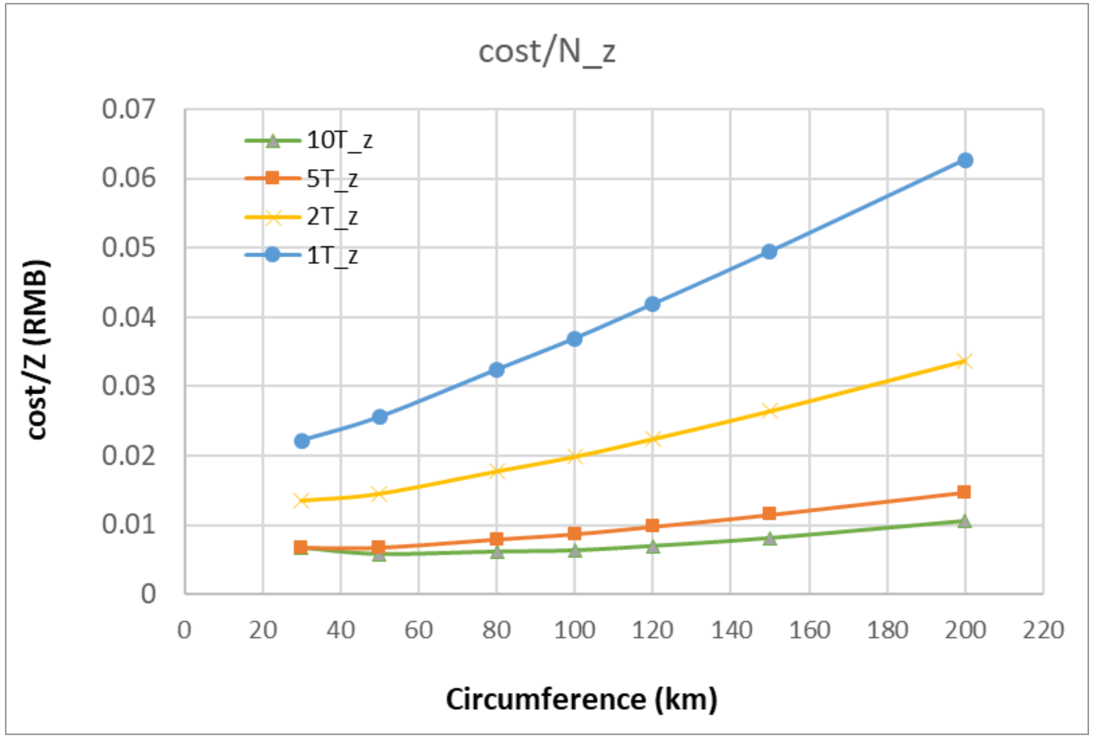
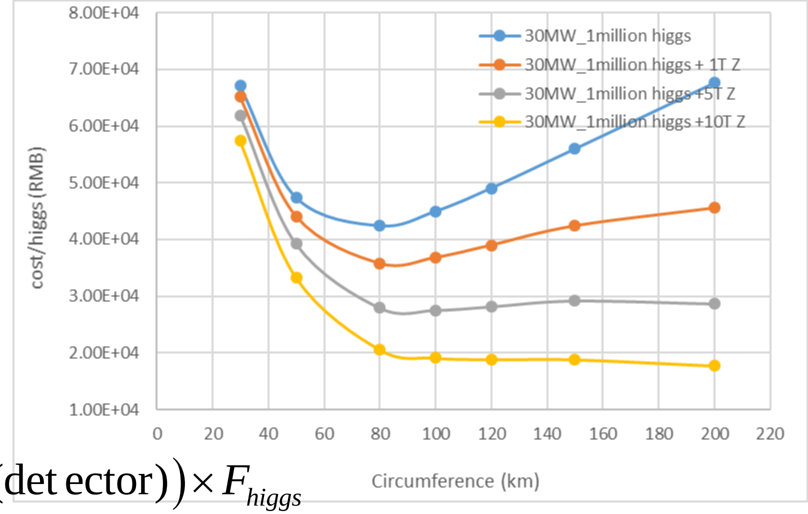


- Z-factory prefers the smaller ring if we only consider Z physics without Higgs.

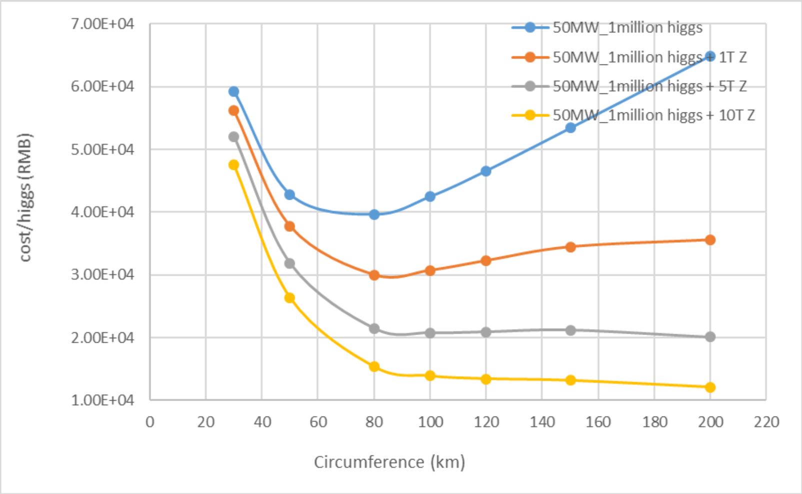
Cost per higgs vs. circumference (combining Higgs & Z)

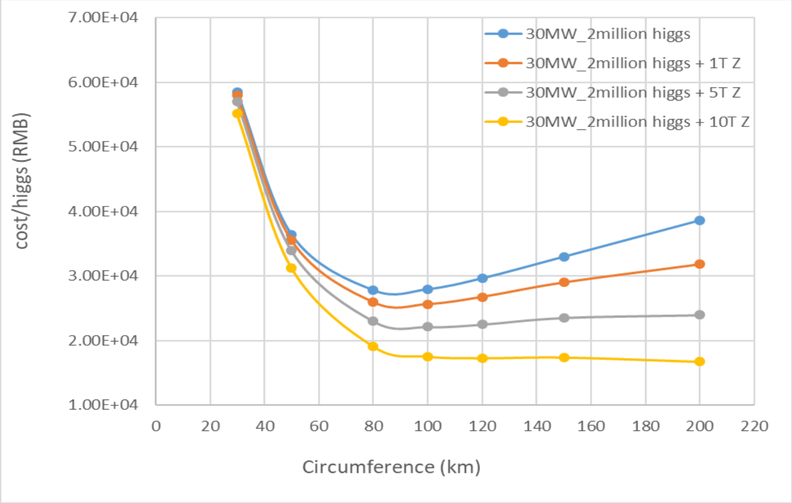
- The cost per Higgs is reduced considering the construction cost allocation between the Higgs factory and the Z factory.

$$F_{higgs} = \frac{Year_{higgs}}{Year_{higgs} + Year_Z}$$



$$Cost_{higgs}(machine) + Cost_{higgs}(detector) = \left(Cost(machine) + Cost(detector)\right) \times F_{higgs}$$



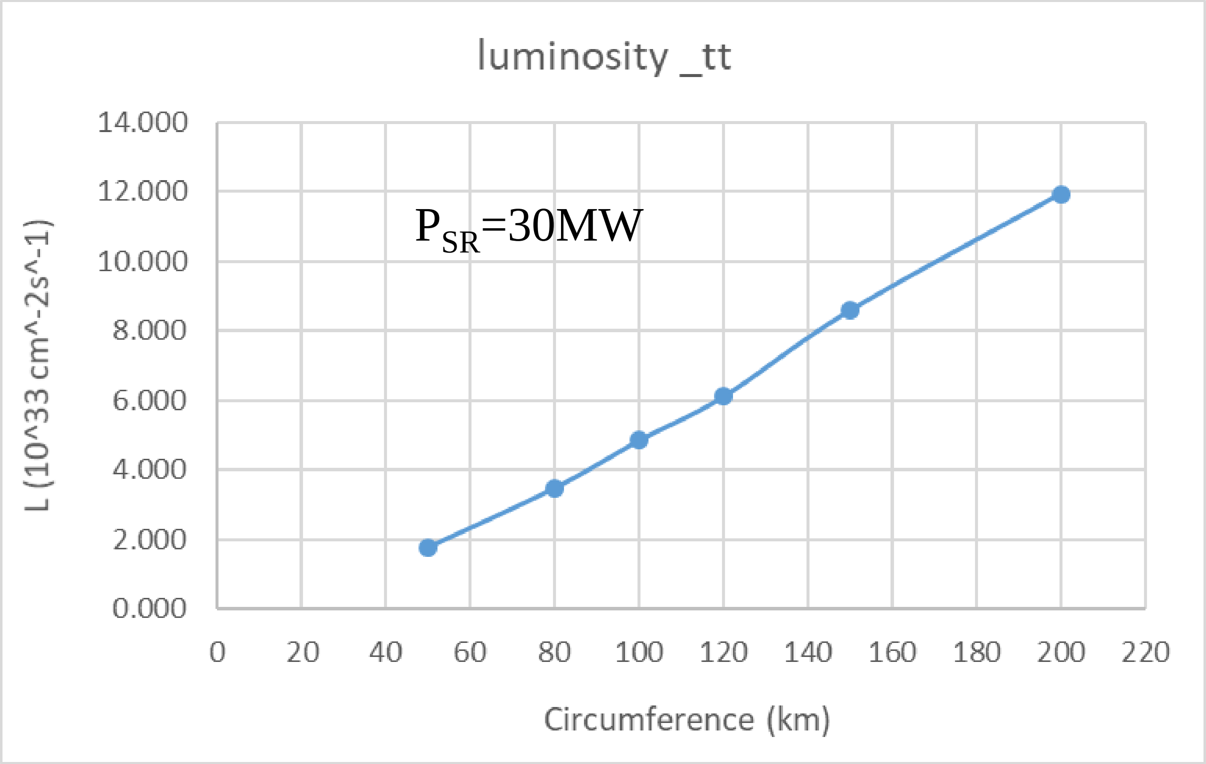


CEPC total cost combining Higgs and Z

- For 1M Higgs, 80km is the optimal circumference.
- Optimal circumference move to larger size if the Higgs requirement more than 2M.

tt luminosity scan with different circumference

- tt energy mode needs much more RF cavities.
- Collider smaller than 50 km cannot work at tt energy.



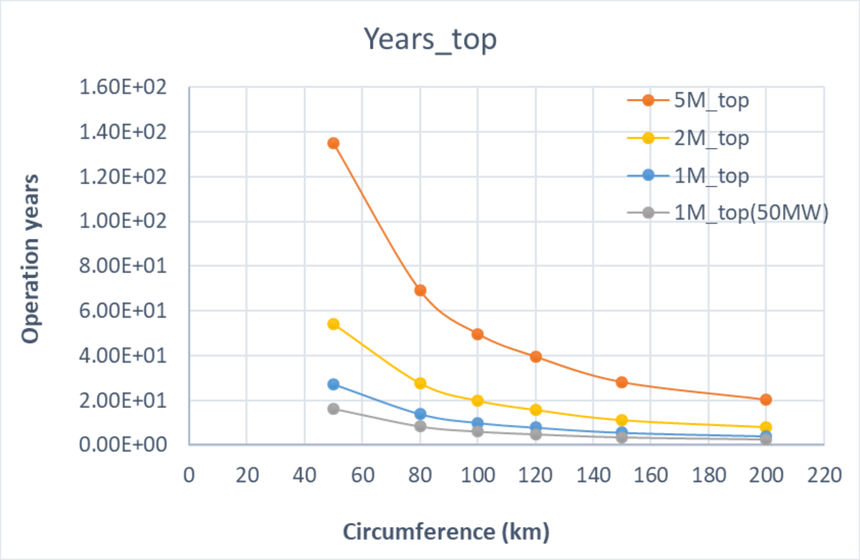
- Optimize IP parameters
- Same lattice as Higgs
- Maximize luminosity for each circumference

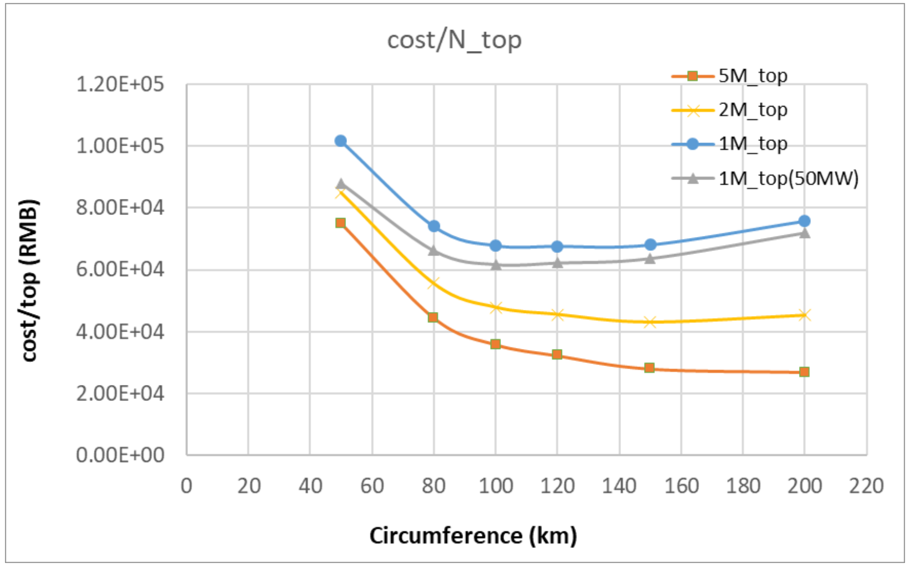
Cost per top quark vs. circumference

- Cross section @360GeV=500fb

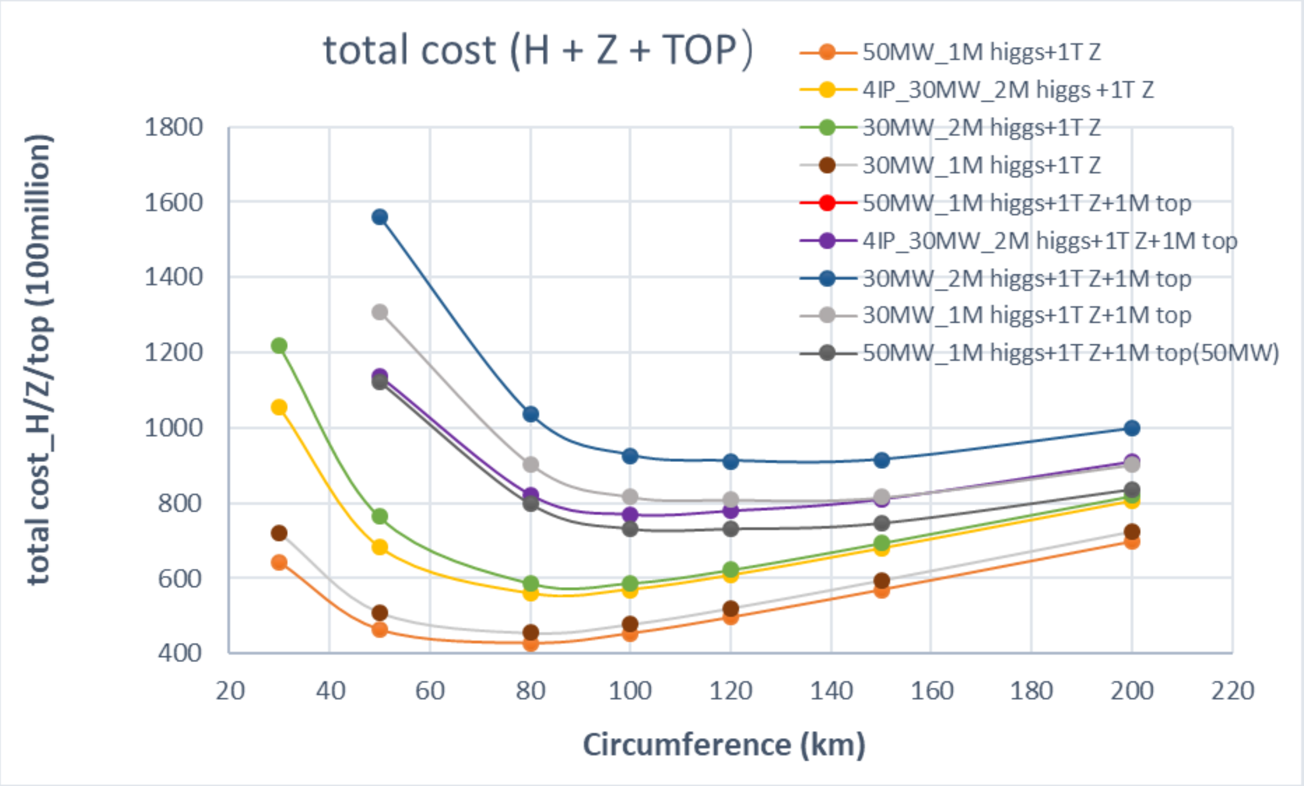
$$Cost(machine) = \frac{C}{100} \cdot 240(亿) + 60(亿) + k \times 60（亿）$$ (k related to Vrf)

$$Cost(elect) = P_{SR} \times 10 \times year \times month_{operation} \times 30 \times 24 \times 0.5$$ → 13



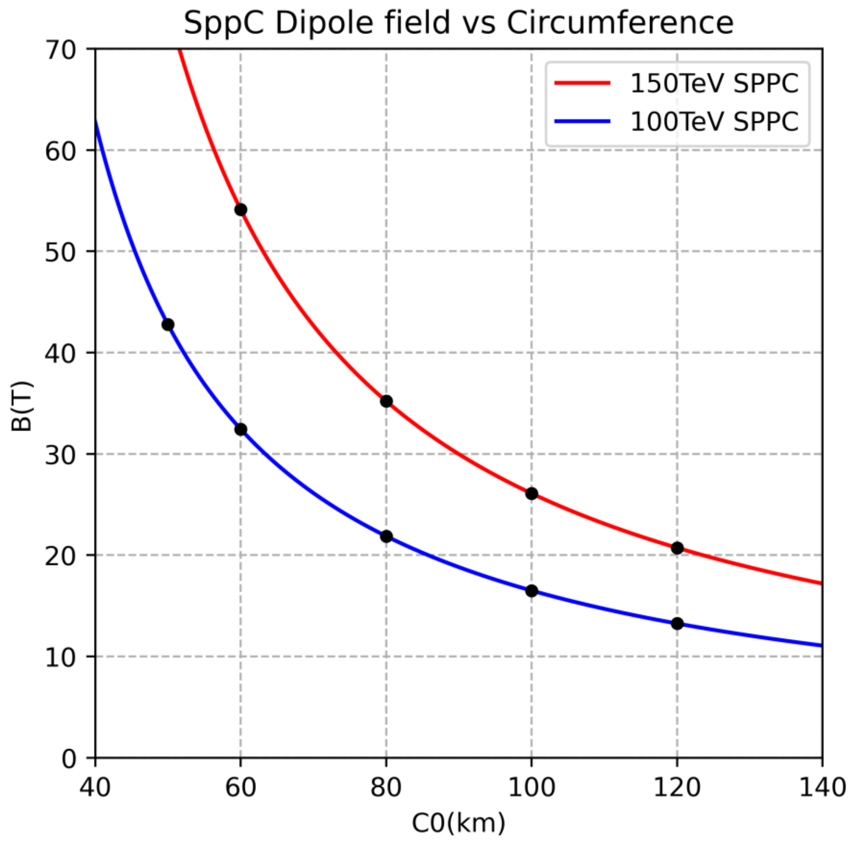


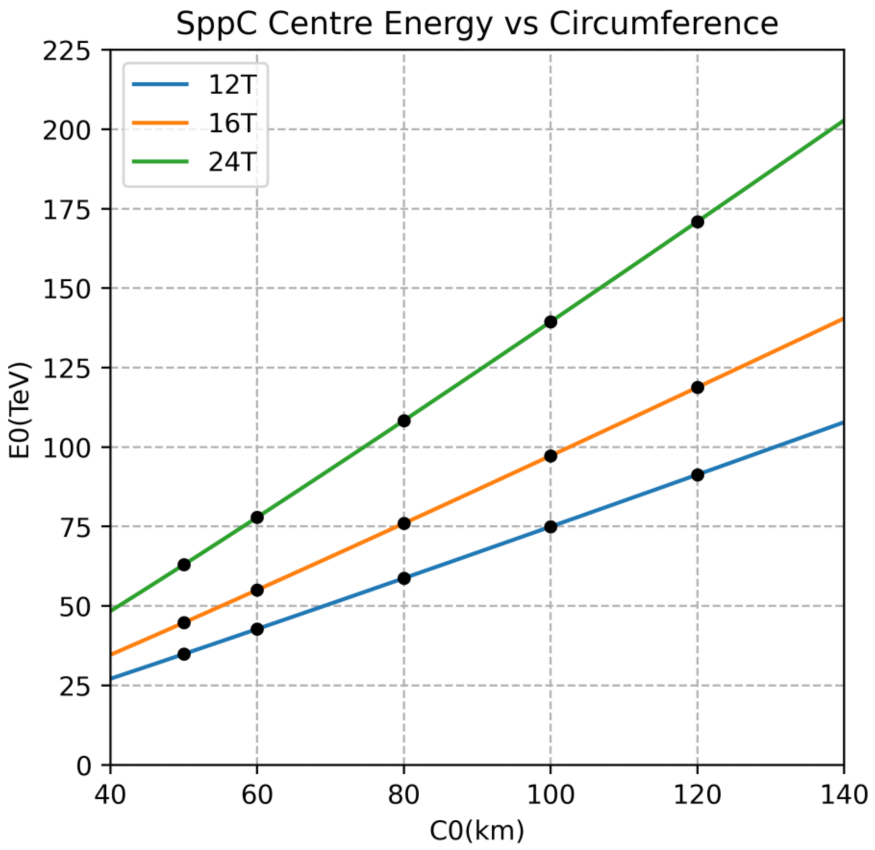
CEPC total cost combining Higgs, Z and tt operation



- The optimal circumference changes to 100km if we consider Higgs, Z and top quark physics together.

Dipole strength & energy potential of SPPC





Summary

- CEPC cost performance is studied based on a rough cost model.
  - the instant luminosity, construction and operation cost for different size is calculated.
- Higgs physics is the first goal of CEPC
  - Requirement of total higgs: 1million $\rightarrow$ 80km is a good choice
  - Requirement of total higgs: ≥2million $\rightarrow$ 80km and 100km almost same
  - Combining higgs and ttbar: $\rightarrow$ 100km is the best choice
  - The long future proton-proton upgrade of CEPC (SPPC) also favors a larger circumference.
- 100 km is a global optimized circumference for CEPC with consideration of the potential at ttbar, Z and SPPC.