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Study of CEPC performance with different collision energies and geometric layouts *

Ming Xiao(肖铭)1) Jie Gao(高杰)2) Dou Wang(王逗)
Feng Su(苏峰) Yi-Wei Wang(王毅伟) Sha Bai(白莎) Tian-Jian Bian(边天剑)
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: The Circular Electron-Positron Collider (CEPC) is one of the largest projects planned for high energy physics in China. It would serve first as a Higgs factory and then upgrade to a hadron collider. In this paper we give the 50 km and 100 km design for both single ring and double ring schemes, including Z boson, W boson and Higgs boson, by using an optimized method. Also, we give the potential of CEPC running at the Z and W poles. We analyse the relationship of luminosity with circumference and filling factor, which gives a way to evaluate the choice of geometry, and compare the nominal performances of CEPC-SPPC, LHC and FCC.

Keywords: Circular Electron Positron Collider (CEPC), parameter design, geometric layouts

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1 Introduction

After the discovery of the Higgs boson at the LHC in 2012, it is natural to measure its properties, including mass, spin, CP nature and couplings, as precisely as possible. Compared with the International Linear Collider (ILC) working at 250 GeV, a circular e^+e^- collider serving as a Higgs factory seems possible due to the low mass of the Higgs. A circular scheme also has the potential to upgrade to a hadron collider for high energy frontier studies. There are two ambitious international plans for such a collider. One is TLEP (later renamed FCC-ee) at CERN, aiming to construct a 100 km circular Higgs factory; the other is the Circular Electron-Positron Collider (CEPC), a 50 km scheme initiated by IHEP in Beijing.

CEPC is one of the largest projects planned in high energy physics research in China. It would first serve as a Higgs factory and then upgrade to a 70–100 TeV Super Proton-Proton Collider (SPPC) in the same tunnel. The goal of the CEPC is to provide e^+e^- collisions at the center-of-mass energy of 240 GeV, where the Higgs events are produced primarily through the interaction $e^+e^- \rightarrow ZH$, and to deliver a peak luminosity greater than 1×10^{34} $cm^{-2}\cdot s^{-1}$ per interaction point (IP) [1].

The Z boson and W boson were discovered at LEP, which made a great contribution to particle physics. As an e^+e^- collider, CEPC working as a Z or W factory would be another interesting story. We use an optimized method [2] for parameter choice and compare the results of the 50 km and 100 km schemes for both single ring and double ring designs, covering the energy region from the Z-pole to the t-pole. We analyse the relationship of luminosity with circumference and filling factor to evaluate the geometry choice. A comparison of nominal performance of CEPC-SPPC with that of LHC and FCC is also shown.

2 Optimized method of parameter choice

The performance of a circular e^+e^- collider is connected to its luminosity, which can be expressed as

$$L[\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}]=2.17\times10^{34}(1+r)\xi_y\frac{eE_0[\mathrm{GeV}]N_\mathrm{b}N_\mathrm{e}}{T_0[\mathrm{s}]\beta_y^*[\mathrm{cm}]}F_\mathrm{h}, \quad (1)$$

where $r=\dfrac{\sigma_y}{\sigma_x}$ is the aspect ratio of the beam at the IP, T_0 is the revolution period, β_y^* is the beta function at the IP, ξ_y is the vertical beam-beam tune shift, N_b is the number of bunches and N_e is the number of particles in one bunch. F_h is the hour glass effect, expressed as

$$F_\mathrm{h}=\frac{\beta_y^*}{\sqrt{\pi}\sigma_z}\exp\left(\frac{\beta_y^{*2}}{2{\sigma_z}^2}\right)K_0\left(\frac{\beta_y^{*2}}{2{\sigma_z}^2}\right), \quad (2)$$

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1) E-mail: xiaoming@ihep.ac.cn
2) E-mail: gaoj@ihep.ac.cn

where K_0 is the zero order modified Bessel function of the second kind. From Eq. (1), it is the beam-beam tune shift that has a significant influence on the luminosity of a collider directly.

An optimized method has been well studied in Ref. [2], which has taken several important effects into consideration, such as the beam-beam limit from beam emittance blow-up, beam lifetime and energy spread limit constrained by beamstrahlung, and so on. Each particle in a beam will feel a strong nonlinear force when the beam encounters the counter rotating beam. This has deleterious effects on the dynamic behavior of the particle. Within this interaction, the particles will suffer from additional heating, which would cause beam emittance blow-up. This emittance blow-up mechanism has been studied in Refs. [3, 4]; the beam-beam limit can be expressed as:

$$\xi_y \leqslant \frac{2845}{2\pi}\sqrt{\frac{T_0}{\tau_y \gamma N_{\mathrm{IP}}}}, \tag{3}$$

where $\mathrm{N_{IP}}$ is the number of interaction points, τ_y is the transverse damping time and T_0 is the revolution time.

Beam lifetime is determined by beamstrahlung in a high energy storage ring collider [5]. In order to achieve a beam lifetime as long as 30 minutes, the relationship between the bunch population and beam size must satisfy

$$\frac{N_{\mathrm{e}}}{\sigma_x \sigma_z} \leqslant 0.1\eta \frac{\alpha}{3\gamma r_{\mathrm{e}}{}^2}, \tag{4}$$

where N_{e} is the bunch population, σ_x and σ_z are the horizontal and longitudinal beam size at the IP, α is the fine structure constant, r_e is the classical electron radius and η is the energy acceptance of the ring.

Substituting Eq. (3) into Eq. (1), one acquires a relationship between luminosity and several key parameters of a collider:

$$L_0[\mathrm{cm^{-2}\cdot s^{-1}}] = 0.7\times 10^{34}\frac{1+r}{\beta_y^*[\mathrm{cm}]}\sqrt{\frac{E_0[\mathrm{GeV}]I_{\mathrm{b}}[\mathrm{mA}]P_0[\mathrm{MW}]}{\gamma N_{\mathrm{IP}}}}, \tag{5}$$

$$L[\mathrm{cm^{-2}\cdot s^{-1}}] = L_0 F_{\mathrm{h}}, \tag{6}$$

where E_0 is the beam energy, I_{b} is the average beam current, P_0 is the synchrotron radiation, N_{IP} is the number of interaction points and L_0 is the peak luminosity. Equation (5) tells us that the synchrotron radiation power is one of the most important parameters for the luminosity of a circular $\mathrm{e^+e^-}$ collider. Obviously, when one tries to reduce the synchrotron radiation power, it might have deleterious effects on the luminosity.

According to the expression $U_0 = 88.5\times 10^3 \frac{E_0^4[\mathrm{GeV}]}{\rho[\mathrm{m}]}$, there are two ordinary ways to reduce synchrotron radiation. One is to make the machine work at lower energy, and the other is to enlarge the bending radius. The former way leads to the plan of making CEPC serve as a Z or W factory, while the latter leads to the question whether a 100 km scheme(like FCC-ee) is better or not. Next, we will show the results by using the optimized method.

3 Study of CEPC at different collision energies and geometries

Restricting the synchrotron radiation power to no more than 50 MW, we give the parameter choices for CEPC in both 50 km and 100 km schemes, and compare the performance of the double ring and single ring design. The potential of CEPC serving as a Z and W factory is included. The higher energy run at $\mathrm{t\bar{t}}$ of the 100 km design is also taken into consideration. All the results are listed in Table 1. At this stage, we only consider that all the bunches are equally spaced around the ring and the collider is in head-on collision mode.

4 Discussion

There are many interesting topics in circular collider ring design. We will discuss three aspects of the CEPC design.

4.1 Single ring vs. two rings in CEPC baseline design

Two beam pipes are used by many $\mathrm{e^+e^-}$ machines, such as BEPC-II, PEP-II, KEKB and DAΦNE, because high luminosity can be achieved with a large number of bunches. However, when constraining the synchrotron radiation power to no more than 50 MW, the average beam current is restricted at the same time because the energy loss from synchrotron radiation is the same within a certain geometry. When choosing the number of bunches N_{b} and particle population N_{e} with a reasonable value, the luminosity of CEPC running as a Higgs factory is the same whether one beam pipe is used or two. This is because from Eq. (5), the luminosity is proportional to $\sqrt{P_0}$ when other parameters are fixed. It is therefore an economical choice to take the one ring scheme for a Higgs factory.

4.2 Potential of CEPC running at Z or W poles

There is active interest in a high-luminosity run of CEPC at the Z and W poles. Due to the lower energy of Z and W, the synchrotron radiation at the Z and W poles is much lower than a Higgs factory. We give the results of the parameters directly in Table 2. More than 220 bunches are needed at the Z pole to achieve luminosity as high as $1\times 10^{34}\ \mathrm{cm^{-2}\cdot s^{-1}}$, while 60 bunches are enough to reach the same luminosity at the W pole.

Though the synchrotron radiation power at the Z pole is far away from 50 MW, it unimaginable to arrange 220 equal bunches around the ring within a pretzel orbit. It is even more impossible to achieve a high luminosity of 1×10^{35} cm$^{-2}\cdot$s^{-1} at the Z-pole with a 50 km single ring design of CEPC with equal bunches and head-on collision, because the ring would have to be full of electrostatic separators to separate about 2200 bunches, and the pretzel orbit would be too complicated. A bunch train scheme [6] offers some hope of avoiding this problem. However, this would make the length of the interaction regions longer and the machine-detector interface (MDI) design more complicated. So under these considerations, two beam pipes seems better.

Table 1. Comparing 50 km and 100 km CEPC design with single ring and double ring schemes.

parameters	50 km CEPC design						100 km CEPC design							
	single ring scheme			double ring scheme			single ring scheme				double ring scheme			
	Z	W	H	Z	W	H	Z	W	H	$t\bar{t}$	Z	W	H	$t\bar{t}$
beam energy E/GeV	45.5	80	120	45.5	80	120	45.5	80	120	175	45.5	80	120	175
circumference C/km	50	50	50	50	50	50	100	100	100	100	100	100	100	100
number of IP N_{IP}	2	2	2	2	2	2	2	2	2	2	2	2	2	2
bending radius ρ/km	6.094	6.094	6.094	6.094	6.094	6.094	10	10	10	10	10	10	10	10
sR power/beam P/MW	0.89	10.32	50	50	50	50	0.615	8.35	50	50	50	50	50	50
sR loss/turn U_0/GeV	0.062	0.6	3.01	0.062	0.6	3.01	0.038	0.36	1.84	8.3	0.038	0.36	1.84	8.3
ring energy acceptance η	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
magnetic rigidity $B\rho$/(T$\cdot$m)	151.8	266.9	400.4	151.8	266.9	400.4	151.8	266.9	400.4	584	151.8	266.9	400.4	584
momentum compaction factor $\alpha_{\mathrm{p}}[10^{-5}]$	0.364	1.527	0.729	0.364	1.527	0.729	0.453	0.371	0.196	0.117	0.453	0.371	0.196	0.117
lifetime due to radiative Bhabha scattering τ_{L}/hour	8.26	2.67	1.19	8.26	2.67	1.19	17.6	5.7	2.55	1.19	17.6	5.7	2.55	1.19
beam current I/mA	14.23	16.8	16.6	796.81	84.04	16.62	16.21	23.02	27.63	5.96	1317	138.1	27.63	5.96
bunch number N_{b}	48	48	48	2688	240	48	192	192	192	48	15600	1152	192	48
bunch population $N_{\mathrm{e}}[10^{11}]$	3.09	3.65	3.61	3.09	3.65	3.61	1.76	2.5	3.0	2.59	1.76	2.5	3.0	2.59
emittance at IP-horizontal ϵ_x/(nm$\cdot$rad)	48	18.68	6.12	48	20	6.9	32	18	6.8	2.2	32	18	6.8	2.2
emittance at IP-vertical ϵ_y/(pm$\cdot$rad)	96	36	21.2	96	36	21.2	64	24	18.2	9.2	64	24	18.2	9.2
betatron function at IP-horizontal β_x/m	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
betatron function at IP-vertical β_y/mm	1.2	1.2	1.2	1.2	1.2	1.2	1	1	1	1	1	1	1	1
transverse beam size at IP-horizontal σ_x/μm	196	122.2	70	196	122.2	70	160	120	73.8	41.95	160	120	73.8	41.95
transverse beam size at IP-vertical σ_y/μm	0.339	0.208	0.159	0.339	0.208	0.159	0.253	0.155	0.135	0.096	0.253	0.155	0.135	0.096
bunch length σ_{s}/mm	2.65	2.65	2.65	2.65	2.65	2.65	2.44	2	2	1.8	2.44	2	2	1.8
beam-beam parameter ξ_x	0.032	0.056	0.112	0.032	0.056	0.112	0.028	0.04	0.084	0.154	0.028	0.04	0.084	0.154
beam-beam parameter ξ_y	0.028	0.049	0.074	0.028	0.049	0.074	0.022	0.038	0.057	0.084	0.022	0.038	0.057	0.084
hourglass factor F_{h}	0.68	0.68	0.68	0.68	0.68	0.68	0.654	0.706	0.706	0.732	0.654	0.706	0.706	0.732
luminosity per IP $L/(10^{34}$ cm$^{-2}\cdot$s$^{-1})$	0.22	0.82	1.82	12.5	4.08	1.82	0.23	1.09	2.93	1.4	18.6	6.52	2.93	1.4
RF voltage V_{rf}/GV	0.21	2.53	4.98	0.21	2.53	4.98	0.36	1.33	2.93	9.8	0.36	1.33	2.93	9.8
RF frequency f_{rf}/GHz	0.7	1.3	1.3	0.7	1.3	1.3	0.7	1.3	1.3	1.3	0.7	1.3	1.3	1.3
synchrotron tune Q_s	0.017	0.127	0.091	0.017	0.127	0.09	0.036	0.064	0.051	0.049	0.036	0.064	0.051	0.049
energy spread $\sigma_{\delta.\mathrm{SR}}$[%]	0.05	0.09	0.13	0.05	0.09	0.13	0.04	0.07	0.10	0.15	0.04	0.07	0.10	0.15
average number of photons emitted per electron during the collision n_γ	0.065	0.122	0.209	0.065	0.122	0.209	0.045	0.086	0.167	0.253	0.045	0.086	0.167	0.253

Table 2. Parameter study for Z and W-poles under baseline design of CEPC.

parameters	Z-pole			W-pole			
E/GeV	45.5			80			
C/km	50						
N_{IP}	2						
P/MW	0.89	1.85	4.06	10.0	12.5	20.8	45.8
U_0/GeV	0.62			0.59			
I/mA	14.22	29.6	74.1	16.8	21.0	35.0	77.0
N_{b}	48	100	220	48	60	100	220
$N_{\mathrm{e}}[10^{11}]$	3.09			3.65			
$\epsilon_x/(\mathrm{nm\cdot rad})$	48			18.68			
$\epsilon_y/(\mathrm{pm\cdot rad})$	96			36			
β_x/mm	0.8			0.8			
β_y/mm	1.2			1.2			
σ_x/m	196			122.25			
σ_y/m	0.34			0.208			
ξ_x	0.032			0.056			
ξ_y	0.028			0.049			
σ_{s}/mm	2.65			2.65			
hourglass factor	0.68			0.68			
$L/(10^{34}\ \mathrm{cm^{-2}\cdot s^{-1}})$	0.22	0.466	1.02	0.82	1.02	1.70	3.74

4.3 Choice of geometry

At the moment, different geometric designs of the future circular collider are under discussion. There are two attractive plans, CEPC with the 50 km preliminary design and FCC-ee at 100 km. From Table 1, the luminosity per IP in the 100 km design is only 1.6 times that of the 50 km scheme. It is not economical to spend double the money to gain about 60% luminosity. However, the 100 km scheme could cover the energy range of 175 GeV, which allows $\mathrm{t\bar{t}}$ experiments and makes it possible to upgrade to a 100 Tev proton-proton collider. The advantage of a larger geometry is the possibility of higher energy frontier but not luminosity gain. So, the question arises of what size is a better choice for a Higgs factory right now.

No matter whether 50 km or 100 km, these are general designs for the future circular collider. It is the circumference and filling factor that affect the synchrotron radiation.

We compare the parameters for 50 km, 70 km and 100 km rings. The results are shown in Table 3.

Using the data in Table 3, we give the relationship between the luminosity and circumference, which obeys a power law:

$$L[\mathrm{cm^{-2}\ s^{-1}}] \sim 0.11833 \times C[\mathrm{km}]^{0.69612}. \tag{7}$$

This is shown more clearly in Fig. 1.

The synchrotron radiation is directly related to the bending radius when the beam energy is set. The filling factor, which is defined as the length of dipoles in a ring over the circumference of the whole ring, will influence the luminosity under a certain circumference. Choosing 50 km as an example, the relationship between luminosity and filling factor is listed in Table 4. The fitting result is in Eq. (8).

Table 3. Higgs Factory with different circumferences.

parameters	value		
beam energy E/GeV		120	
circumference C/km	50	70	100
number of IP N_{IP}		2	
bending radius ρ/km	6.094	8.60	10.0
SR power/beam P/MW		50	
SR loss/turn U_0/GeV	3.01	2.13	1.84
beam current I/mA	16.6	23.4	27.6
bunch number N_b	48	114	192
bunch population $N_e[10^{11}]$	3.61	3.0	3.0
horizontal emittance $\epsilon_x/(\mathrm{nm\cdot rad})$	6.12	6.36	6.8
vertical emittance $\epsilon_y/(\mathrm{pm\cdot rad})$	21.2	20.0	18.2
betatron function at IP-vertical β_y/mm	1.2	1.2	1.0
betatron function at IP-horizontal β_x/mm	0.8	0.8	0.8
transverse beam size σ_x/m	70.0	71.3	73.8
transverse beam size σ_y/m	0.160	0.155	0.135
beam-beam parameter ξ_x	0.112	0.090	0.084
beam-beam parameter ξ_y	0.074	0.062	0.057
bunch length σ_{s}/mm	2.65	2.35	2.00
hourglass factor	0.68	0.71	0.71
luminosity $L/(10^{34}\ \mathrm{cm^{-2}\cdot s^{-1}})$	1.82	2.25	2.93

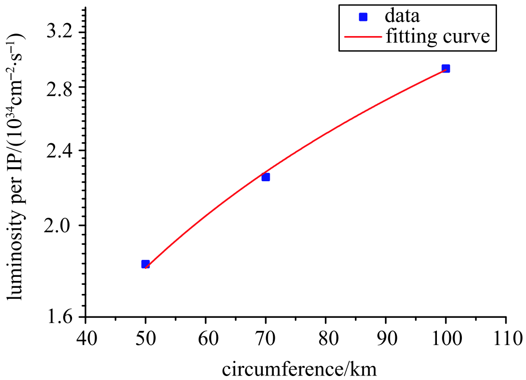

Fig. 1. Power law of luminosity vs. circumference.

$$L[\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}]\sim 0.18097\times\zeta[\%]^{0.53155} \tag{8}$$

This is shown more clearly in Fig. 2.

Table 4. Filling factor.

parameters							
filling factor $\zeta/\%$	70	74	77	78	80	90	100
luminosity $L/(10^{34}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1})$	1.73	1.78	1.82	1.83	1.85	2.02	2.07

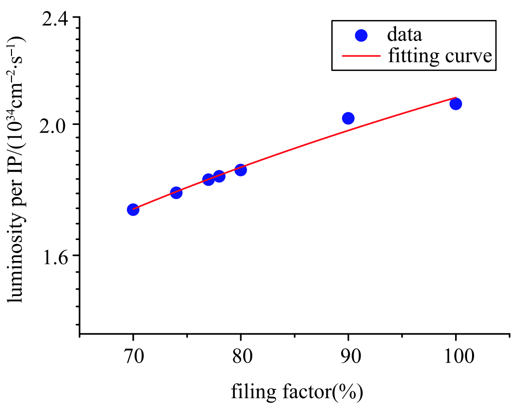

Fig. 2. Power law of luminosity vs. filling factor. The data points are from the 50 km design.

The circumference and filling factor affect the synchrotron radiation. We compare the parameters in the 50 km, 70 km and 100 km rings, and the results are shown in Table 3.

To evaluate the geometry choice, we combine Eq. (7) and Eq. (8) and give the result in Fig. 3. According to Fig. 3, the longer the circumference and the higher the filling factor, the higher the luminosity. However, doubling the circumference does not give double the gain in luminosity, from Eq. (7), and a suitable filling factor should be taken into consideration because one should make room for other insertions around the ring. For a 50 km design of circular electron positron collider, a filling factor from 60% to 80% is reasonable due to the design of other function insertions. Our choice is marked with a diamond in Fig. 3.

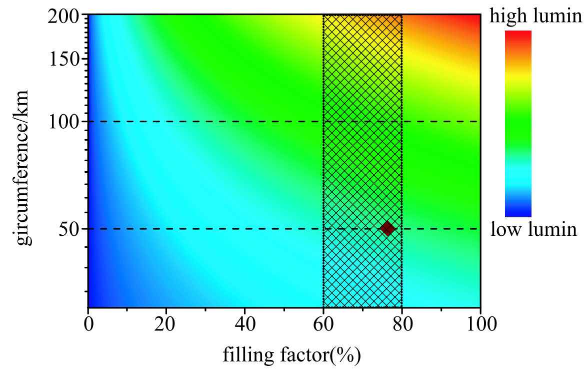

Fig. 3. The relationship of luminosity with circumference and filling factor. The shaded area shows the reasonable choice range from experience. The diamond represents the choice of 50 km CEPC design.

Here we compare the nominal performance of CEPC-SPPC with LHC and FCC [7, 8], and show the luminosity vs. energy in Fig. 4. For CEPC and FCC-ee, the synchrotron radiation power limits the luminosity. The expected luminosity in FCC-ee might be too high because the beam-beam parameter in Ref. [7] exceeds the theoretical beam-beam limit in Ref. [3]. The comparison results are shown in Table 5.

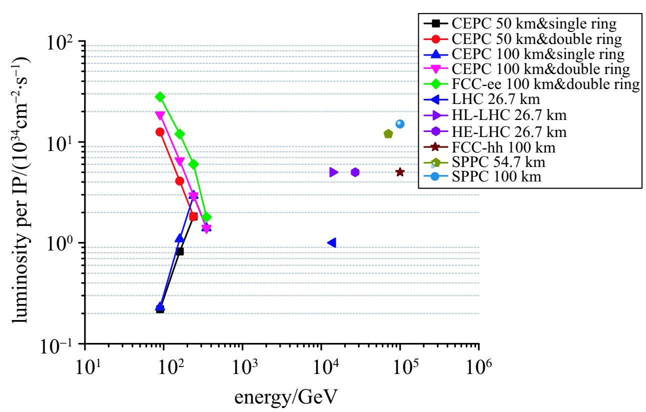

Fig. 4. Comparison of the luminosity potential of CEPC-SPPC with LHC and FCC. The results are measured by the luminosity per IP vs. energy.

5 Summary

In this paper, we give the results of CEPC performance with different collision energies and geometric layouts, including Z, W and Higgs energy runs for 50 km and 100 km (covering $t\bar{t}$) circumference, in both single ring and double ring schemes. When limiting the synchrotron radiation power to 50 MW and adopting a pretzel orbit, it is more economical to construct a 50 km circular electron positron collider than a 100 km one, and one beam pipe for CEPC serving as a Higgs factory could achieve the same luminosity as a double ring scheme. However, these conditions are not so good for working at the Z or W poles with high luminosity. Furthermore, we studied the relationship of luminosity with circumference and filling factor, which could evaluate the geometry choice. A large size of circular collider ring would be more attractive for its ability to upgrade to a higher energy proton-proton collider. We compared the nominal performance of the CEPC-SPPC with LHC and FCC, showing the future landscape of the high luminosity and high energy frontiers.

Table 5. Comparison of CEPC with FCC-ee and LEP2.

parameters	LEP2	FCC-ee				CEPC
circumference/km	26.7	100				50
bending radius/km	3.1	11				6.094
momentum acceptance	0.01	0.02				0.02
beam energy/GeV	104	45.5	80	120	175	120
IP number N_{IP}			4			2
beam current/mA	3.04	1450	152	30	6.6	17.45
bunches per beam	4	16700	4490	1360	98	48
bunch population/10^{11}	4.2	1.8	0.7	0.46	1.4	3.79
transverse emittance ϵ						
-horizontal/nm	22	29.2	3.3	0.94	2	6.9
-vertical/pm	250	60	7	1.9	2	21.2
momentum comp./10^{-5}	14	18	2	0.5	0.5	0.729
betatron function at IP β						
-horizontal/m	1.2	0.5	0.5	0.5	1	0.8
-vertical/mm	50	1	1	1	1	1.2
beam size at IP σ/μm						
-horizontal	182	121	26	22	45	74.3
-vertical	3.2	0.25	0.13	0.044	0.045	0.16
energy loss/turn/GeV	3.34	0.03	0.33	1.67	7.55	3.01
SR power/beam/MW	11	50				50
total RF voltage/GV	3.5	2.5	4	5.5	11	4.98
RF frequency/MHz	352	800				700
synchrotron tune Q_{s}	0.083	0.65	0.21	0.096	0.1	0.09
hourglass factor	1	0.64	0.77	0.83	0.78	0.68
luminosity/IP/(10^{34} cm$^{-2}\cdot$s^{-1})	0.012	28	12	6	1.8	1.89
beam-beam parameter						
-horizontal	0.04	0.031	0.06	0.093	0.092	0.105
-vertical	0.06	0.03	0.059	0.093	0.092	0.073
beam-beam limit(vertical)/IP	0.064	0.015	0.026	0.038	0.057	0.073

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