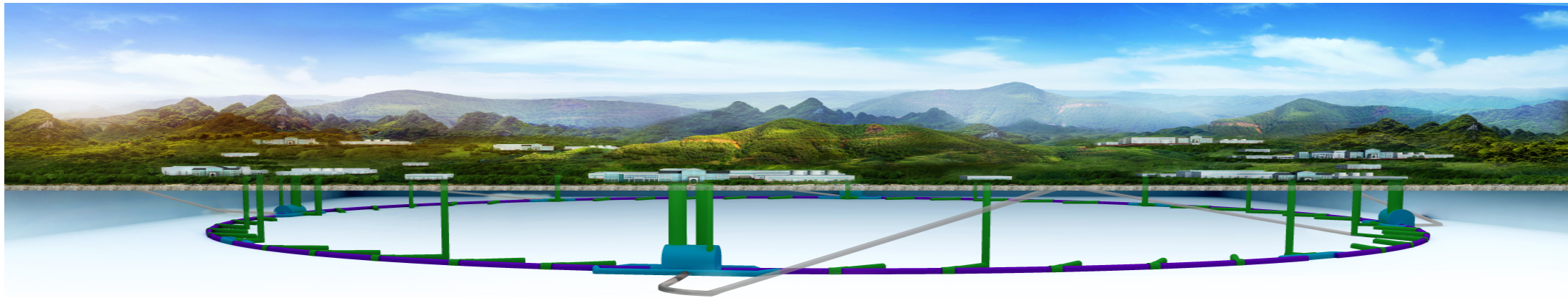


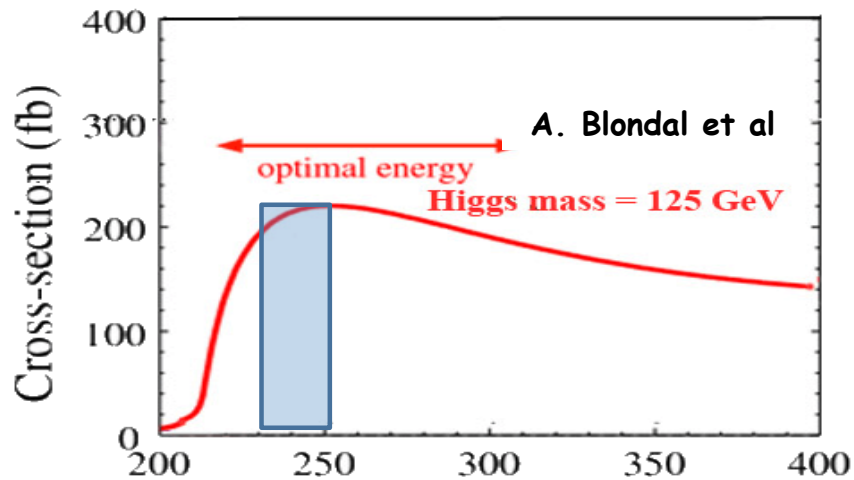
Accelerator physics challenges for high-luminosity frontier at CEPC

Chenghui Yu
for the CEPC accelerator team
Sep. 26, 2019

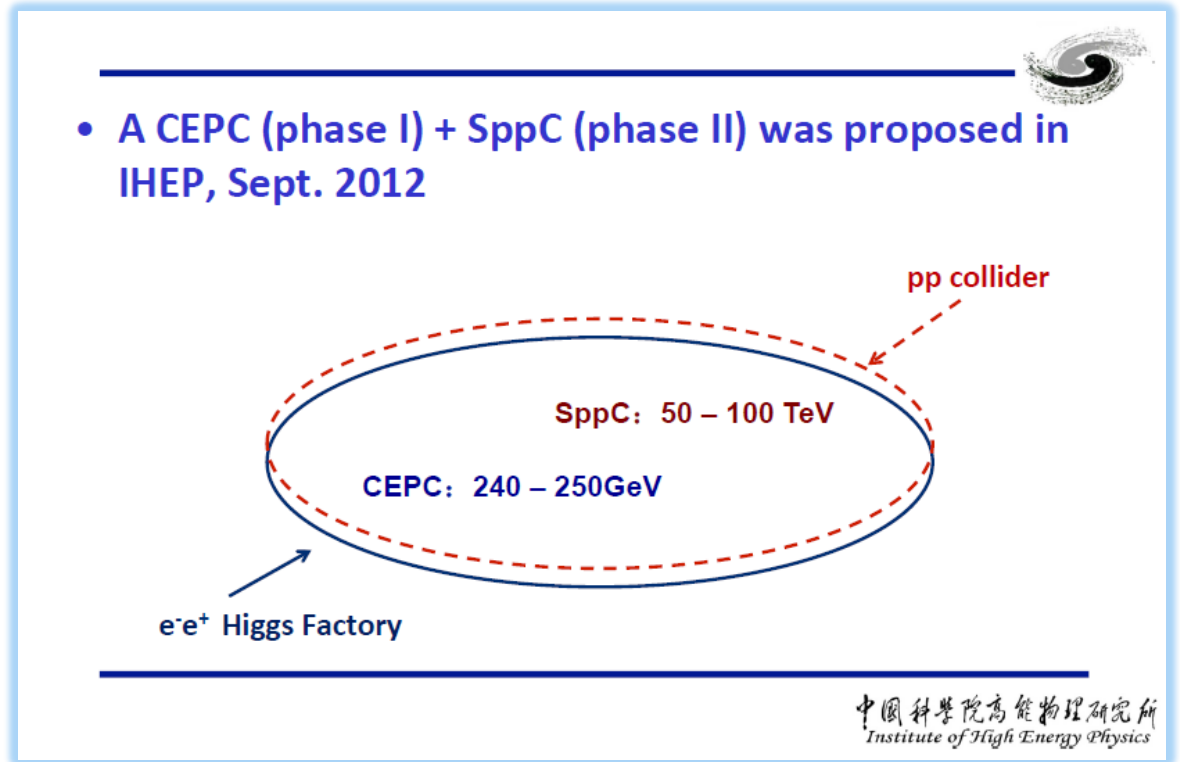


CEPC-SppC outline

- $E_b=120\text{GeV}$ for CEPC



- $E_{b,\text{max}}=50\text{TeV}$ for SppC



Physics goals of CEPC-SppC

e^+e^- Higgs & Z factory

$E_{\text{cm}} \approx 240\text{GeV}$, luminosity/IP $\approx 3 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, 2 IPs, $>1\text{M}$ Higgs in 10 years

$E_{\text{cm}} \approx 91\text{GeV}$, luminosity/IP $> 1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, 2 IPs, 10^{10} Z /year

Precision measurement of the Higgs boson and the Z boson

Higgs precision 1% or better

p-p collider

Upgradable to pp collision with $E_{\text{cm}} \approx 50\text{-}100\text{ TeV}$ (with ep, HI options) in the tunnel of CEPC

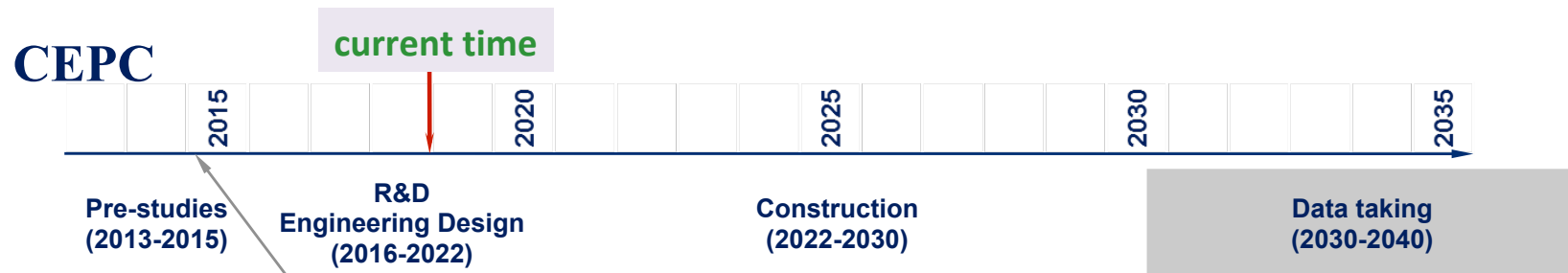
A discovery machine for BSM new physics

BEPCII has already operated for 11 years

CEPC – possible accelerator based particle physics program in China after BEPCII

Precision measurement + Discovery
Complementary with each other

CEPC-SPPC Timeline (preliminary and ideal)



- 1st Milestone:** Pre-CDR (by the end of 2014) ;
- 2nd Milestone:** R&D funding from MOST (in Mid 2016);
- 3rd Milestone:** CEPC CDR progress Report (by the end of 2016);
- 4th Milestone:** CEPC CDR Report (by the end of Aug 2018);
- 5th Milestone:** CEPC TDR Report and Proto R&D (by the end of 2022);
- 6th Milestone:** CEPC construction start (2022);

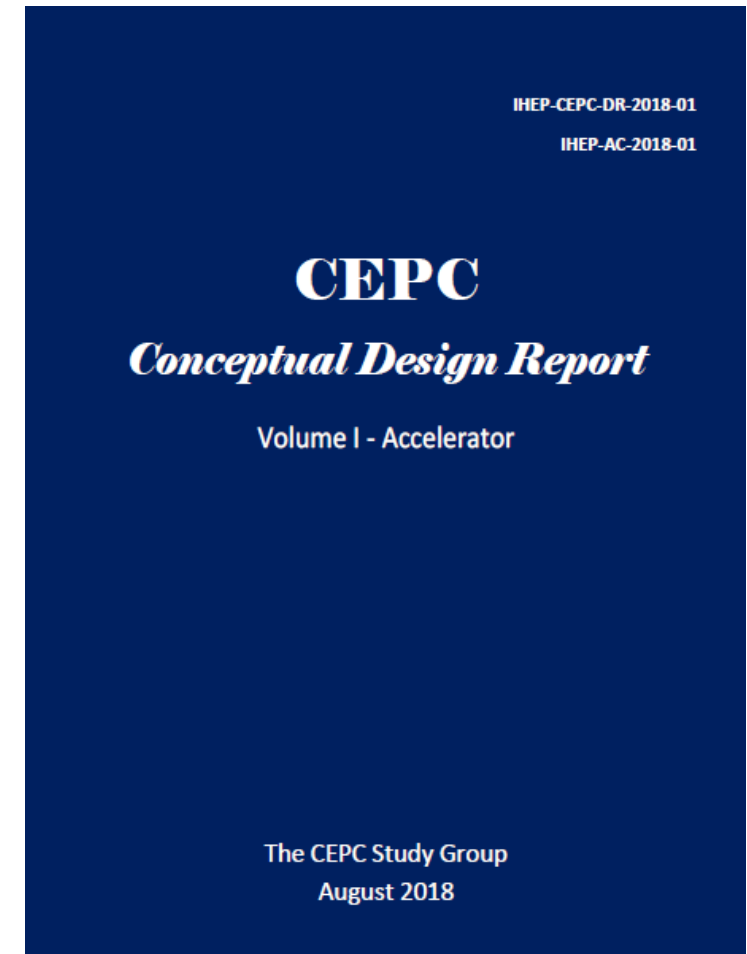
SPPC



arXiv:1809.00285

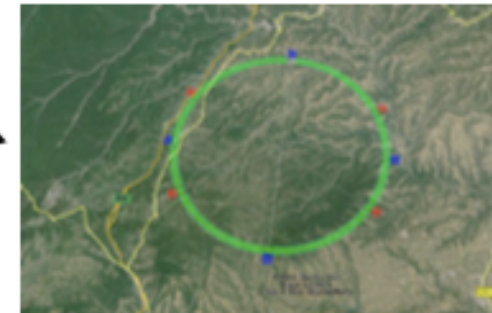
CEPC accelerator CDR completed in June 2018

1. Introduction
2. Machine Layout and Performance
3. Operation Scenarios
4. CEPC Collider
5. CEPC Booster
6. CEPC Linac
7. Systems Common to the CEPC Linac, Booster and Collider
8. Super Proton Proton Collider
9. Conventional Facilities
10. Environment, Health and Safety
11. R&D Program
12. Project Plan, Cost and Schedule

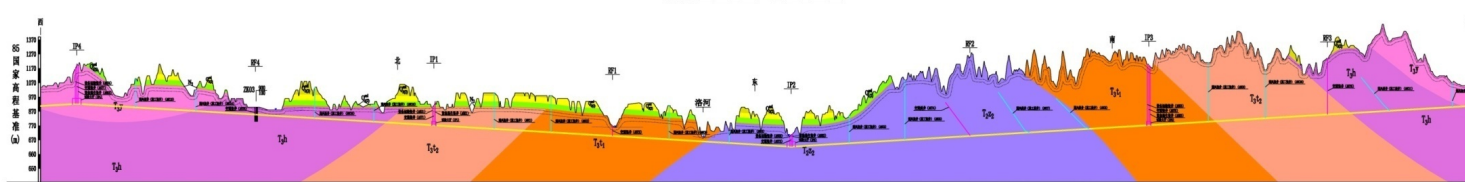
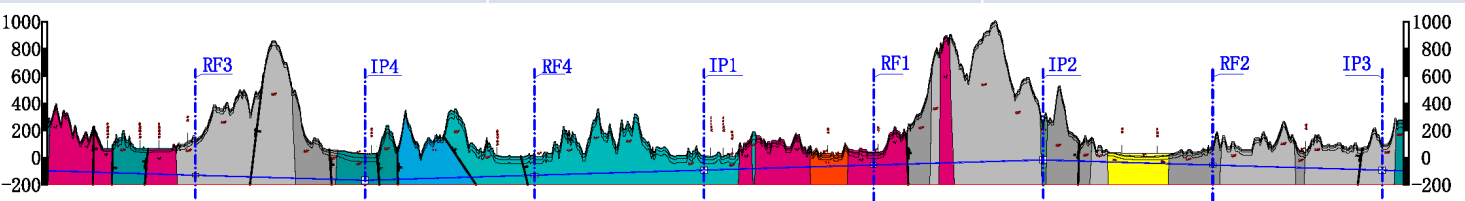
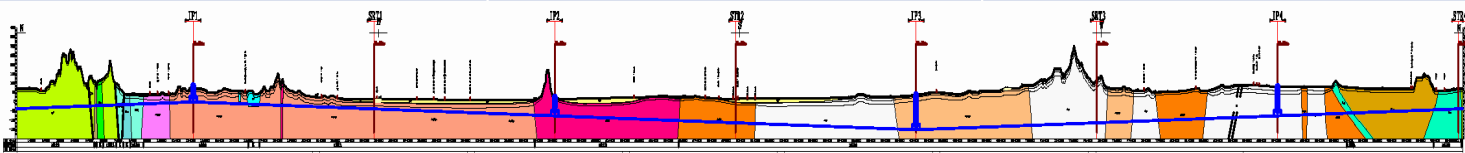


CDR International Review June 28-30, 2018. Final CDR (accelerator) released on Sept. 2, 2018

Candidate sites of CEPC-SppC



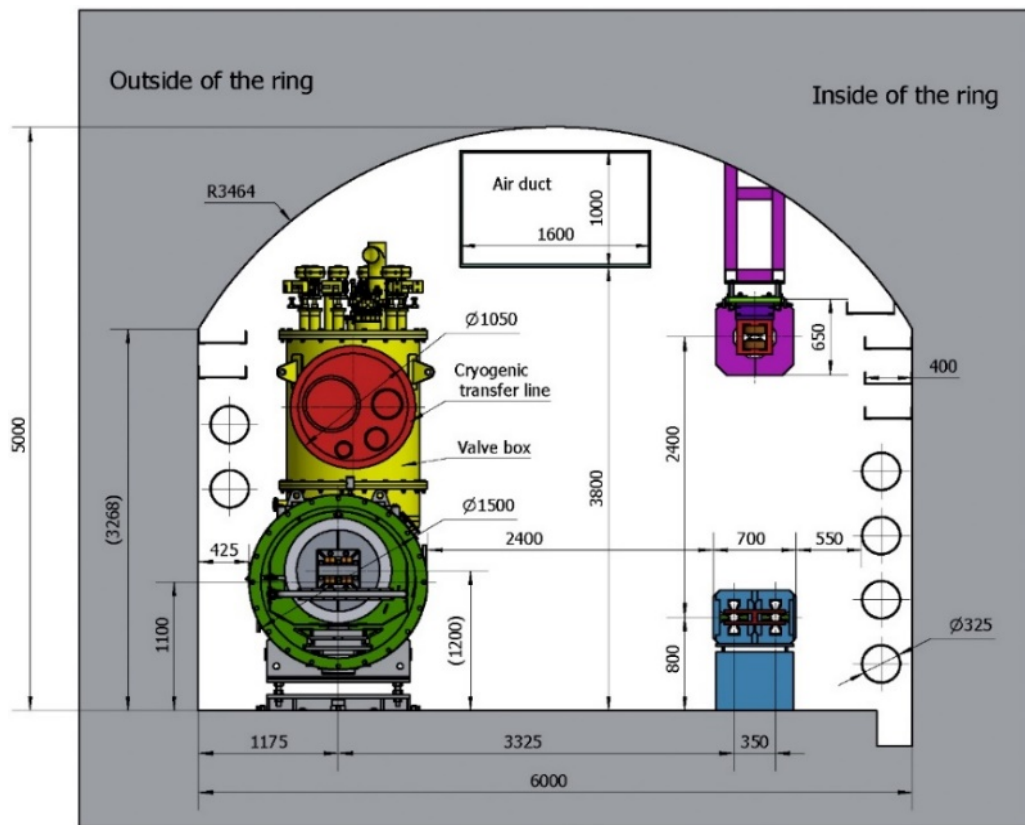
1. QingHuangDao, Hebei (completed preCDR)
2. Huangling, Shaanxi (2017.1 signed contract to exp.)
3. ShenShan, Guangdong, (completed in August, 2016)
4. ...

	Huangling	Shen-Shan	Funing
Construction difficulty	Moderate	Relatively difficult	Relatively easy
Project layout	Huangling (100km)		
			
	Shen-Shan (100km)		
			
	Funing (100km)		
			

Outline

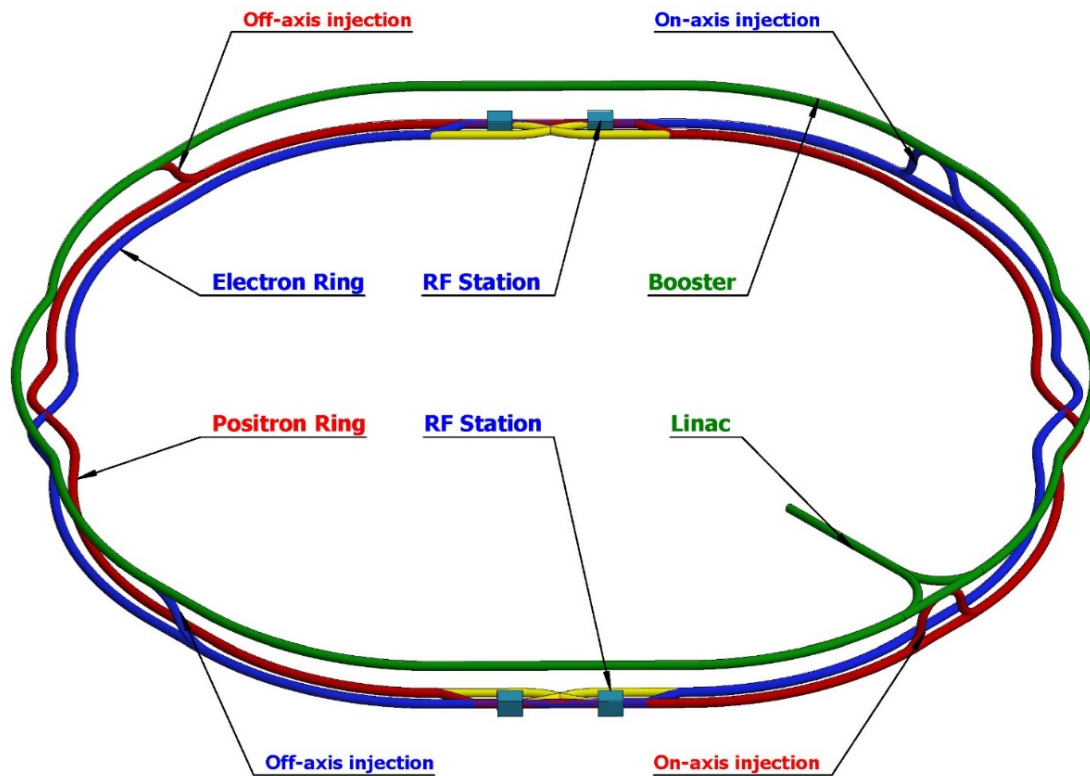
- **Geometry design**
- **Beam performance of CEPC collider ring**
- **Injection chain Collider ring \leftarrow Booster \leftarrow Linac**
- **Some engineering progresses**
- **Summary**

Geometry design

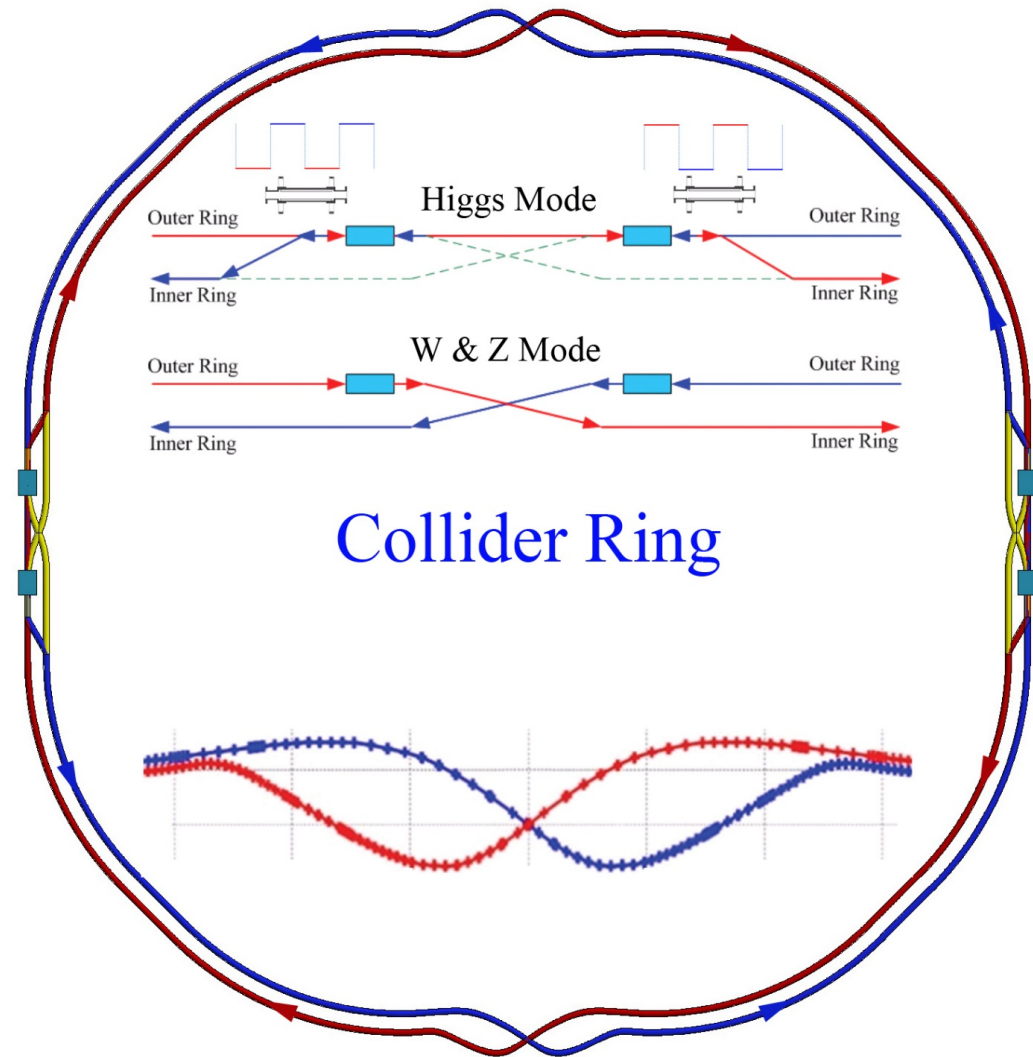


- CEPC which aims at researching Higgs boson is a double ring scheme optimized at the beam energy of 120GeV.
- Super proton-proton collider (SPPC) will be the next project after the operation of CEPC in the future.
- The circumference of CEPC is 100km which is determined by the requirements of SPPC.
- The arc regions of the SPPC collider ring, the CEPC collider ring and the CEPC booster ring are in the same tunnel.
- The booster ring of CEPC is located above collider ring with the distance of 2.4m.

Geometry design



- Double ring collider with 2 IPs
- Compatible with the geometry of SPPC



Beam performance of CEPC collider ring

	<i>Higgs</i>	<i>W</i>	<i>Z</i>
Number of IPs	2		
Beam energy (GeV)	120	80 100	45.5
Circumference (km)			
Synchrotron radiation loss/turn (GeV)	1.73	0.34 16.5×2	0.036
Crossing angle at IP (mrad)			
Piwinski angle	3.48	7.0	23.8
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)
Beam current (mA)	17.4	87.9	461.0
Synchrotron radiation power /beam (MW)	30	30	16.5
Bending radius (km)	10.7		
Momentum compact (10^{-5})	1.11		
β function at IP β_x^*/β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0024	0.54/0.0016	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47 650 (216816)	0.10
RF frequency f_{RF} (MHz) (harmonic)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42
Bunch length σ_z (mm)	4.4	5.9	8.5
HOM power/cavity (2 cell) (kw)	0.46	0.75	1.94
Energy spread (%)	0.134	0.098	0.080
Energy acceptance requirement (%)	1.35	0.90	0.49
Energy acceptance by RF (%)	2.06	1.47	1.7
Photon number due to beamstrahlung	0.082	0.050	0.023
Beamstrahlung lifetime /quantum lifetime* (min)	80/80	>400	
Lifetime (hour)	0.43	1.4	2.5
F (hour glass)	0.89	0.94	0.99
Luminosity/IP L ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	3	10	32

- Physics goals
- Performance
- Construction cost
- Operation cost

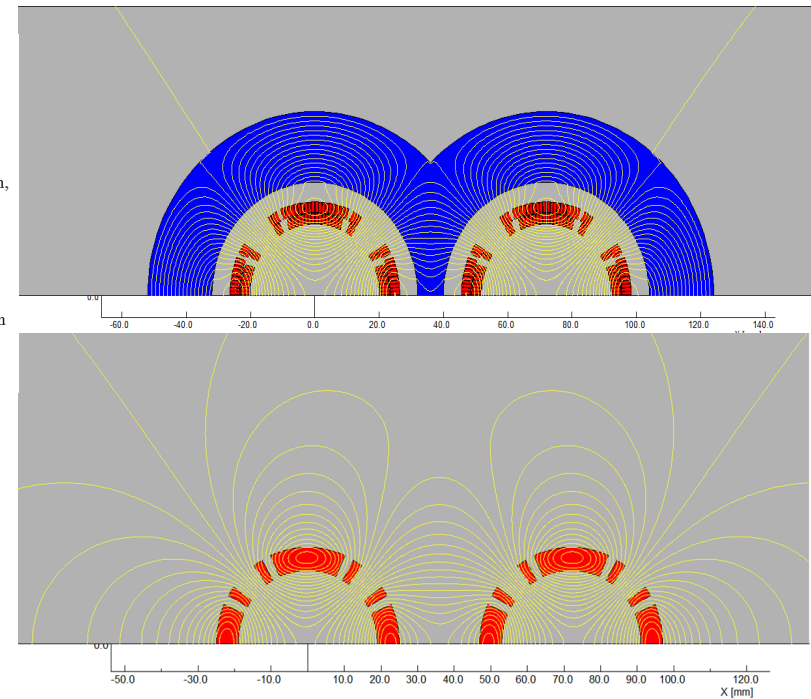
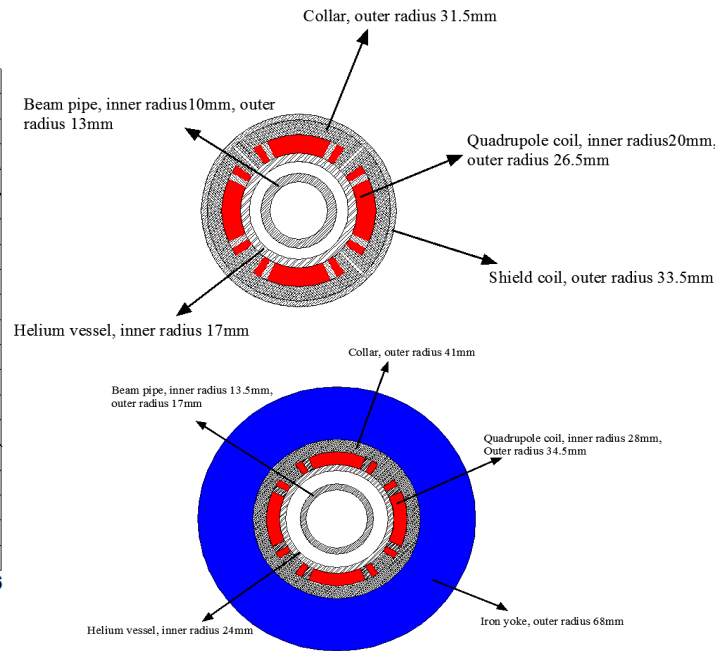
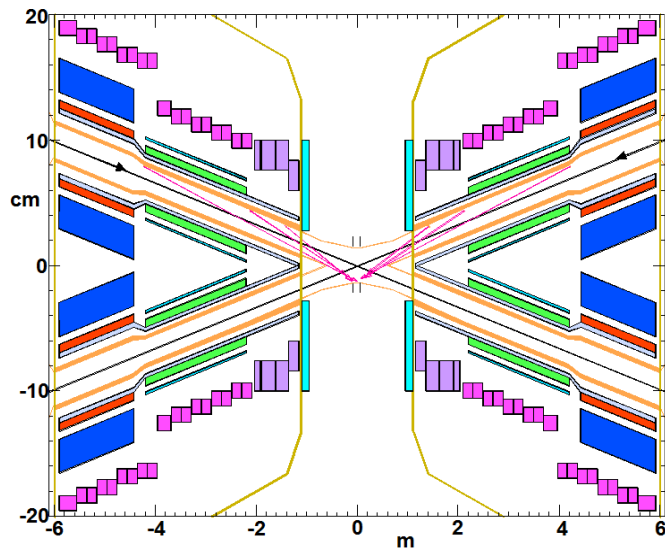


- Fluctuation
- Beamstrahlung
- Flexibility
- Robust
-

Beam performance of CEPC collider ring

Interaction region

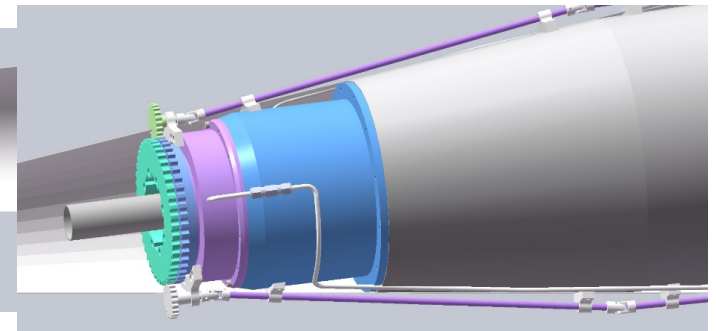
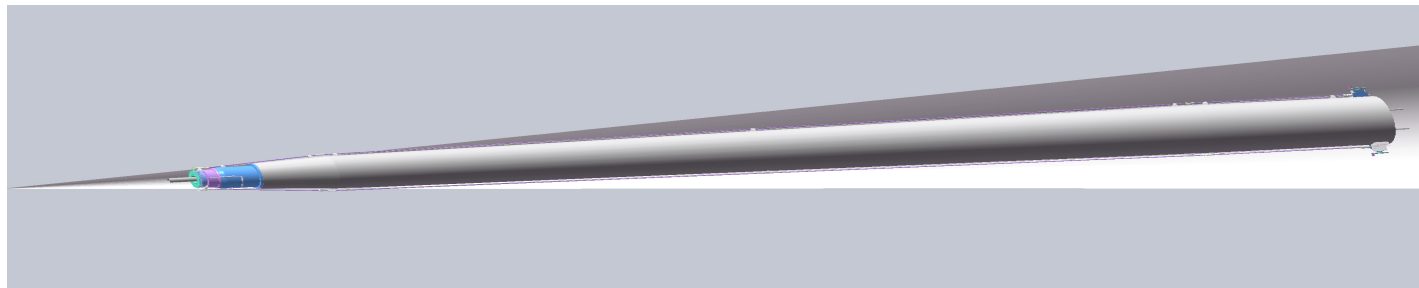
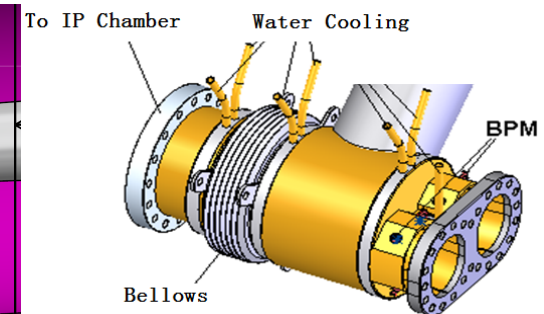
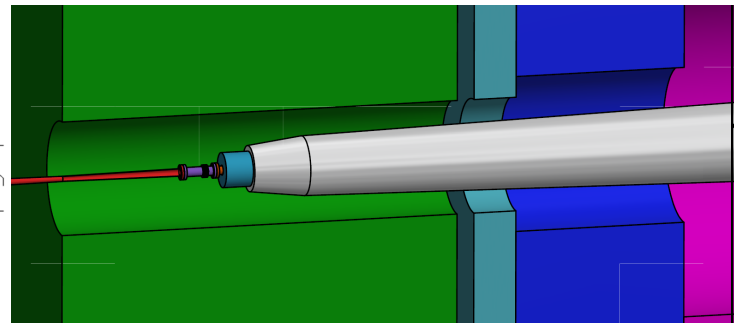
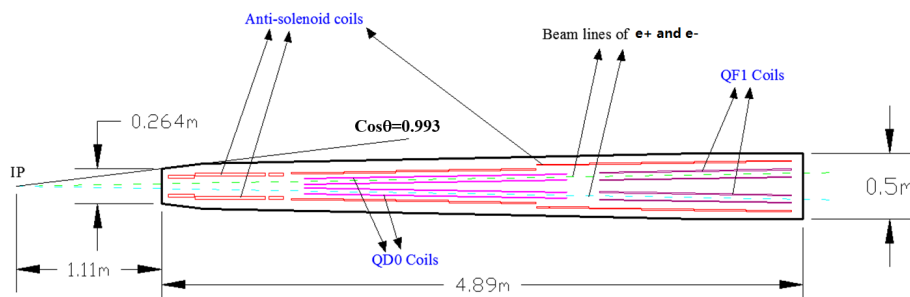
- ✓ $L^*=2.2\text{m}$, $\theta_c=33\text{mrad}$, $\beta_x^*=0.36\text{m}$, $\beta_y^*=1.5\text{mm}$, Detector solenoid=3.0T
- Lower strength requirements of anti-solenoids ($B_z \sim 7.2\text{T}$)
- Enough space for the SC quadrupole coils in two-in-one type (Peak field 3.8T & 136T/m) with room temperature vacuum chamber.



Beam performance of CEPC collider ring

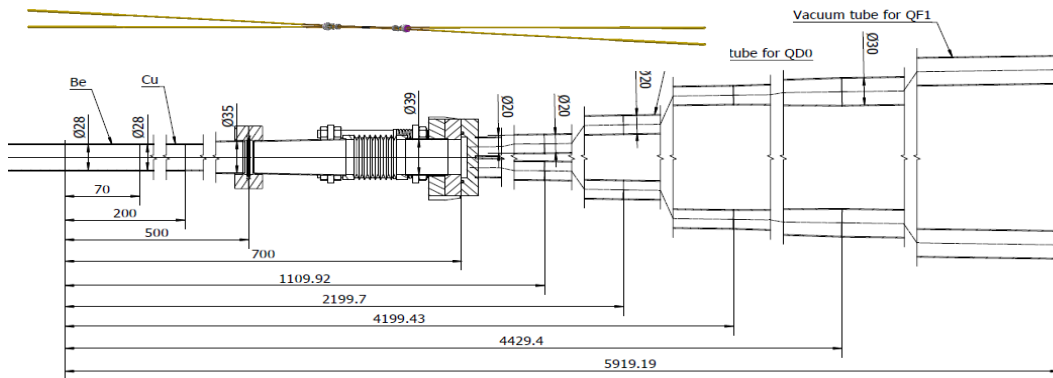
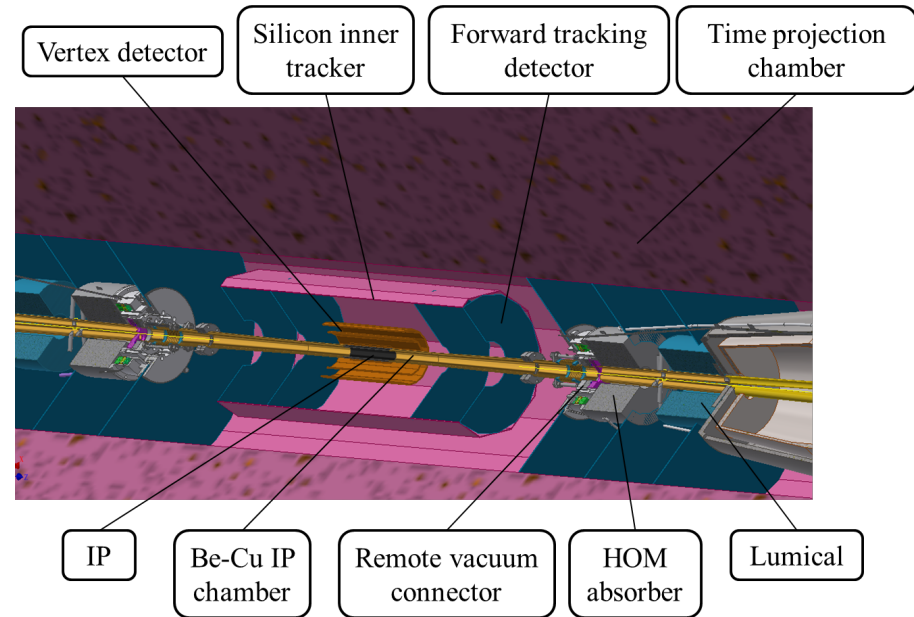
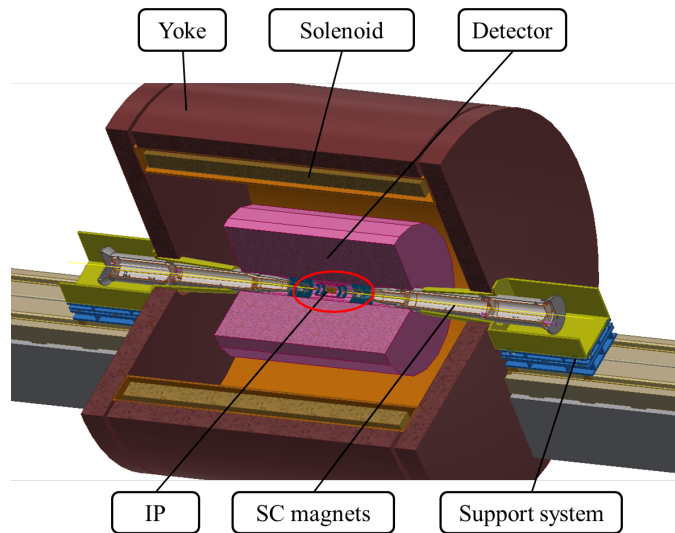
Interaction region

- The most complicated part. Realizability must be considered carefully.



Beam performance of CEPC collider ring

Interaction region

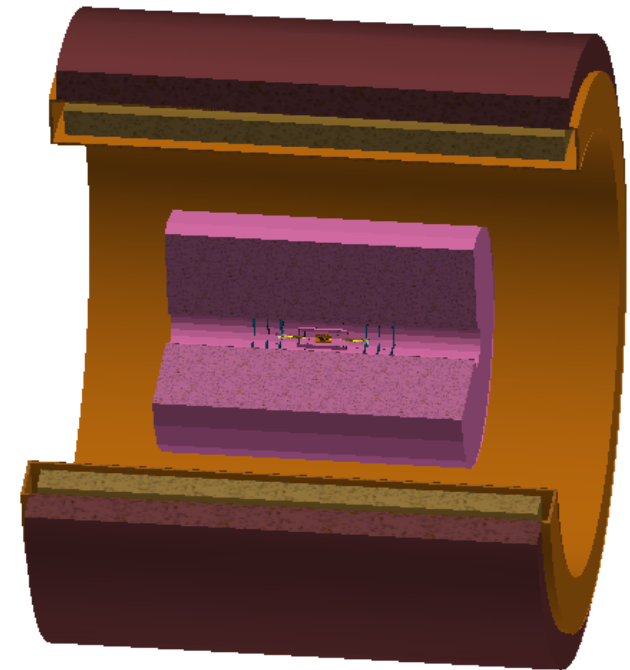
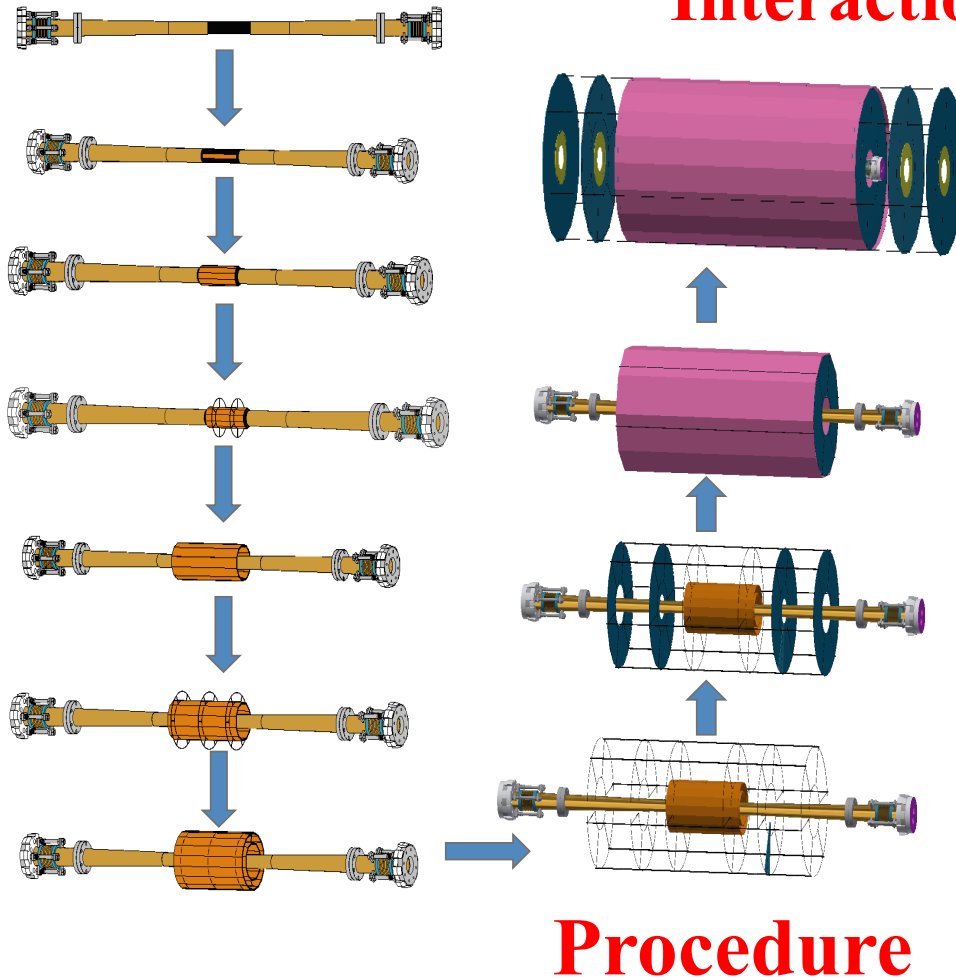


The installation design nearby the IP

Beam performance of CEPC collider ring

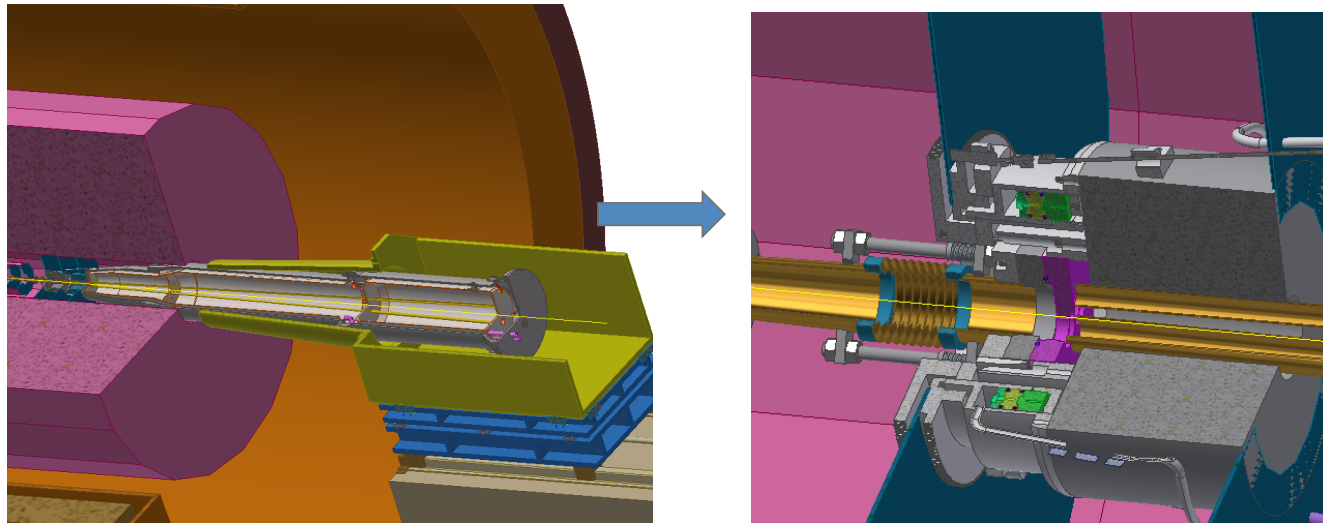
Interaction region

- Support and fixing.
- Alignment.
- The detailed design is ongoing.



Beam performance of CEPC collider ring

Interaction region

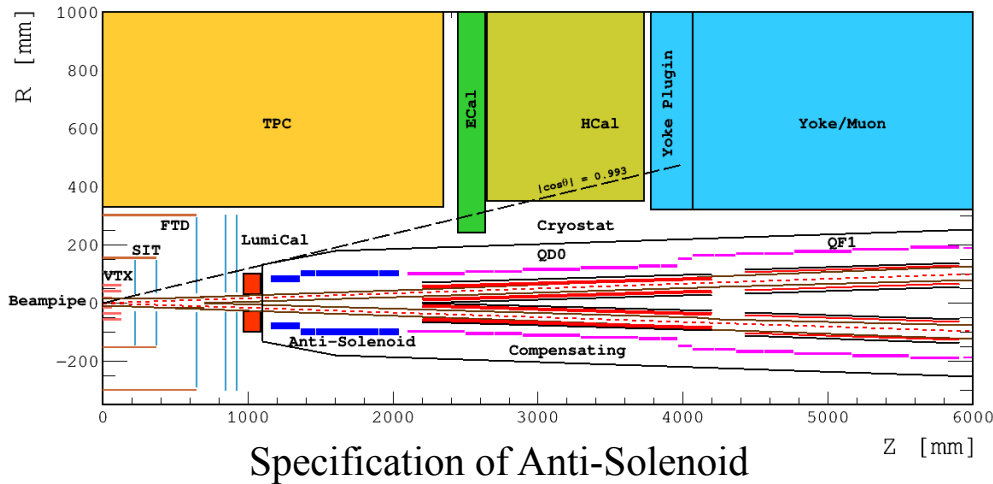


- Move the SC magnet to working location. Connect the flanges using RVC. Alignment.
- Requirements: **accuracy: $\leq (30 \mu\text{m})$, leak rate $\leq 2\text{e-}10 \text{ Torr.L/s}$**
- Alternative design for remote vacuum connection is also under consideration.

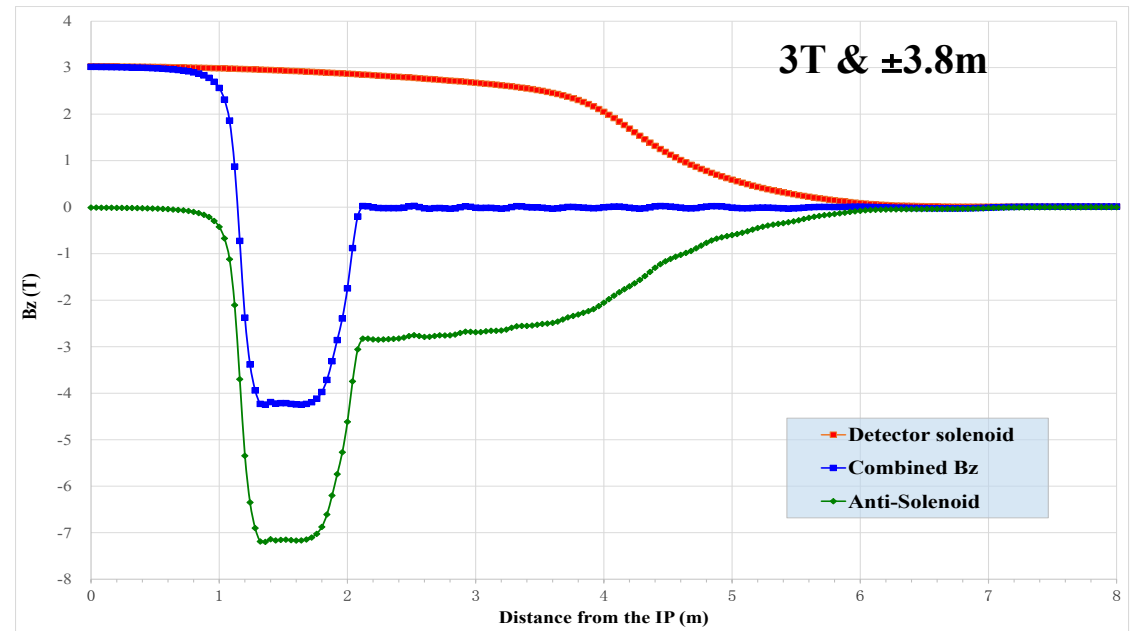
Supporting system nearby the IP

Beam performance of CEPC collider ring

Interaction region



Anti-solenoid	Before QD0	Within QD0	After QD0
Central field (T)	7.2	2.8	1.8
Magnetic length (m)	1.1	2.0	1.98
Conductor (NbTi-Cu, mm)	2.5×1.5		
Coil layers	16	8	4/2
Excitation current (kA)	1.0		
Inductance (H)	1.2		
Peak field in coil (T)	7.7	3.0	1.9
Number of sections	4	11	7
Solenoid coil inner diameter (mm)	120		
Solenoid coil outer diameter (mm)	390		
Total Lorentz force F_z (kN)	-75	-13	88
Cryostat diameter (mm)	500		



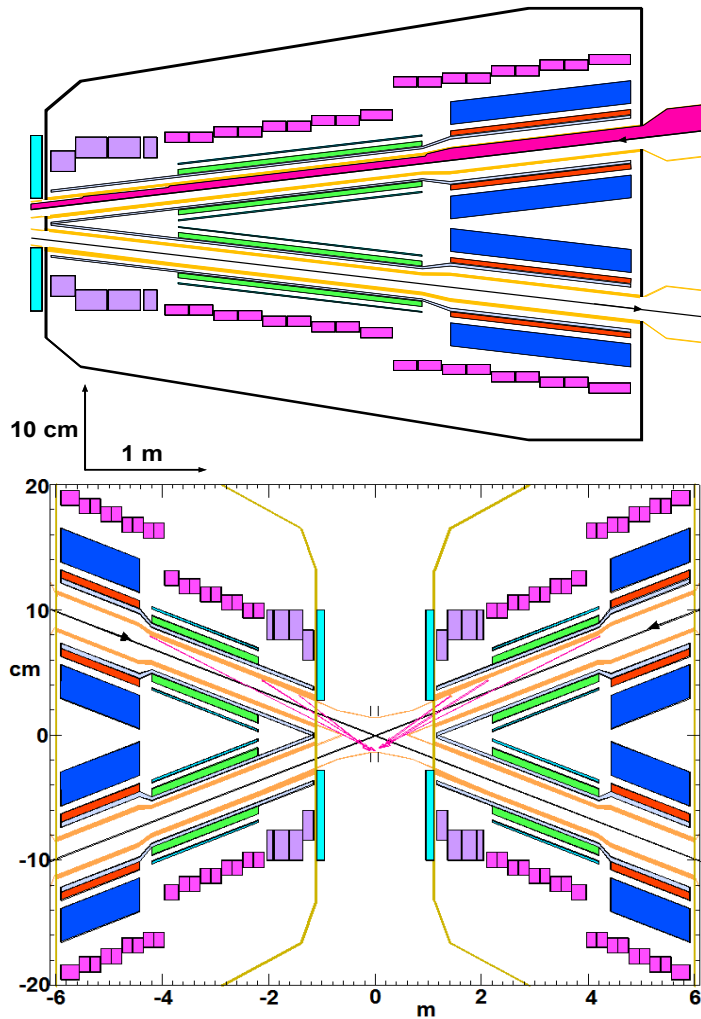
22 anti-Solenoid sections with different inner coil diameters

**$\int B_z ds$ within 0~2.12m. $B_z < 300\text{Gauss}$ away from 2.12m
with local cancellation structure**

The skew quadrupole coils are designed to make fine tuning of B_z over the QF&QD region instead of the mechanical rotation.

Beam performance of CEPC collider ring

Interaction region



Element	SR in horizontal	SR in vertical
Last Dipole	$E_c=45\text{keV}$	
QD0	639W, 1.3MeV	165W, 397keV
QF1	1567W, 1.6MeV	42W, 225keV

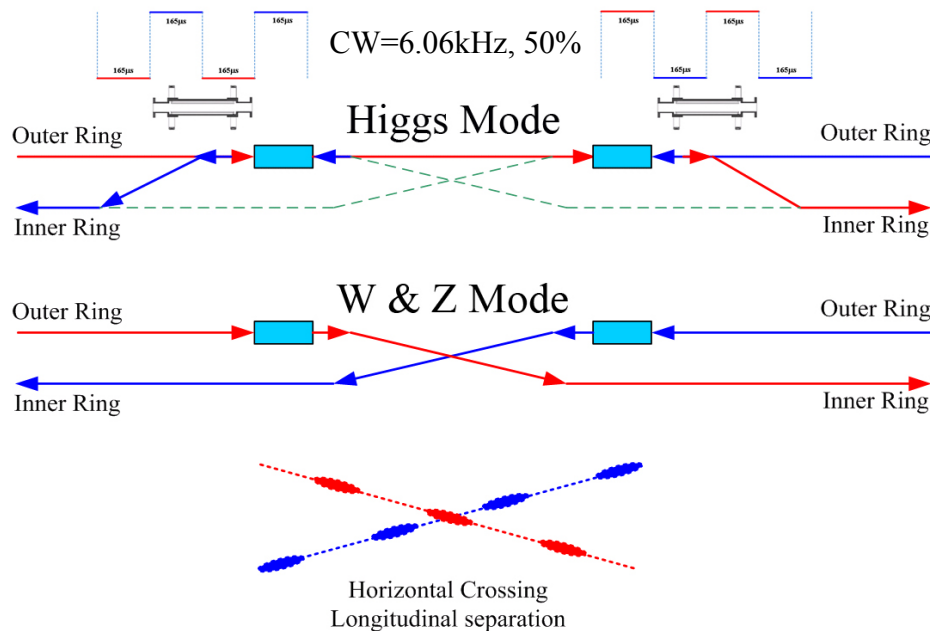
No SR hits directly on the beryllium pipe. SR power contributed within $\pm 10\sigma_x$ will go through the IP.

3 mask tips are added to shadow the beam pipe wall from 0.7 m to 3.93 m reduces the number of photons that hit the Be pipe from 2×10^4 to about 200 (100 times lower).

Beam performance of CEPC collider ring

RF region

- **Common cavities** for Higgs mode, bunches filled in half ring for e^+ and e^- .
- **Independent cavities** for W & Z mode, bunches filled in full ring.
- **Two cell & 650MHz** RF cavity.



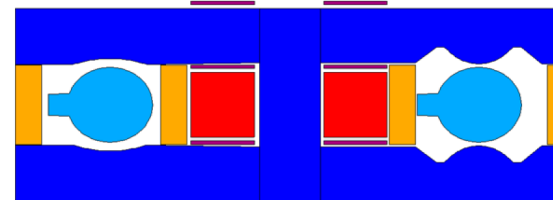
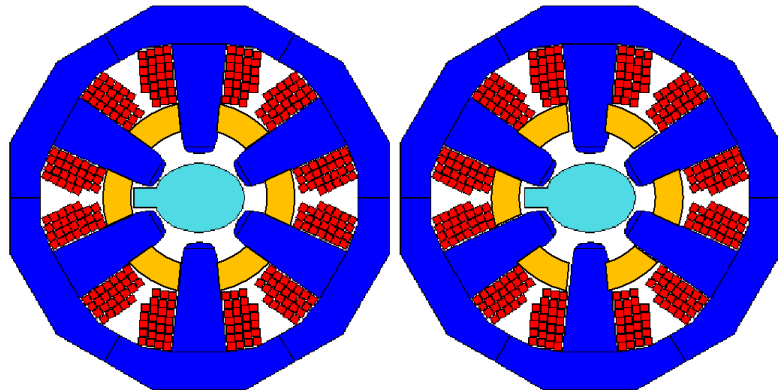
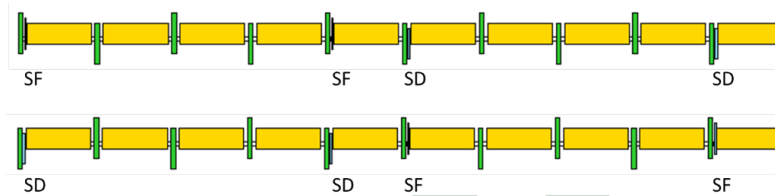
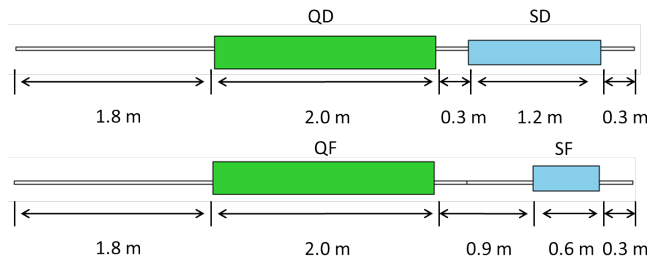
- During the operation of Higgs mode all the RF cavities are shared by both e^+ and e^- beams with the application of the kickers and pulser power supply nearby the RF cavities.
- For the W and Z modes the surveys of e^+ and e^- rings in the RF region are designed independently by turning off the kickers so that all bunches can be filled along the whole rings.

Beam performance of CEPC collider ring

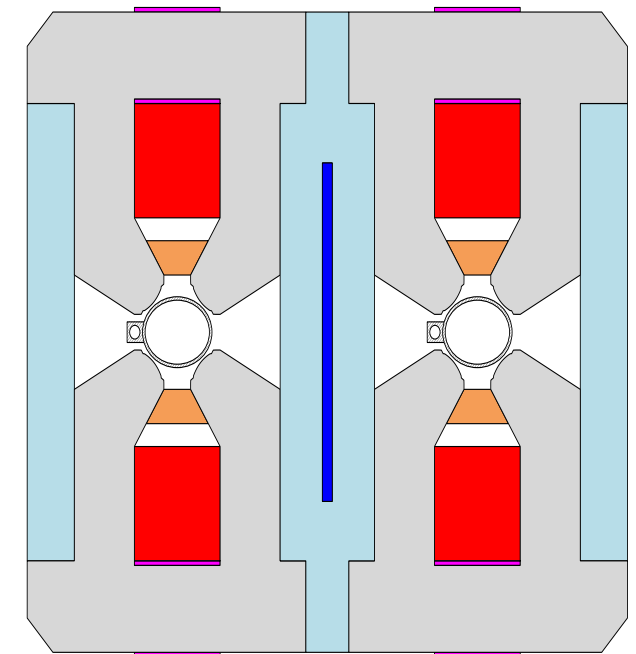
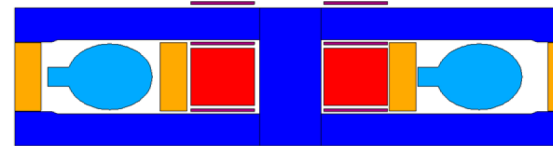
ARC region

- Distance of two ring is 0.35m to adopt twin-aperture Q & B magnets.
- FODO cell, $90^\circ/90^\circ$, non-interleaved sextupole scheme.
- Sextupoles are independent type for the flexibility of optics.

A. Milanese



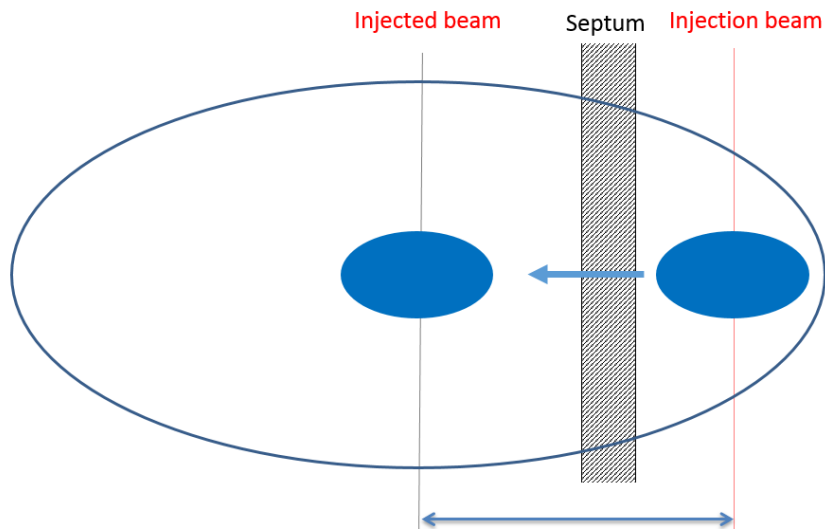
The three middle segments - dipole only.



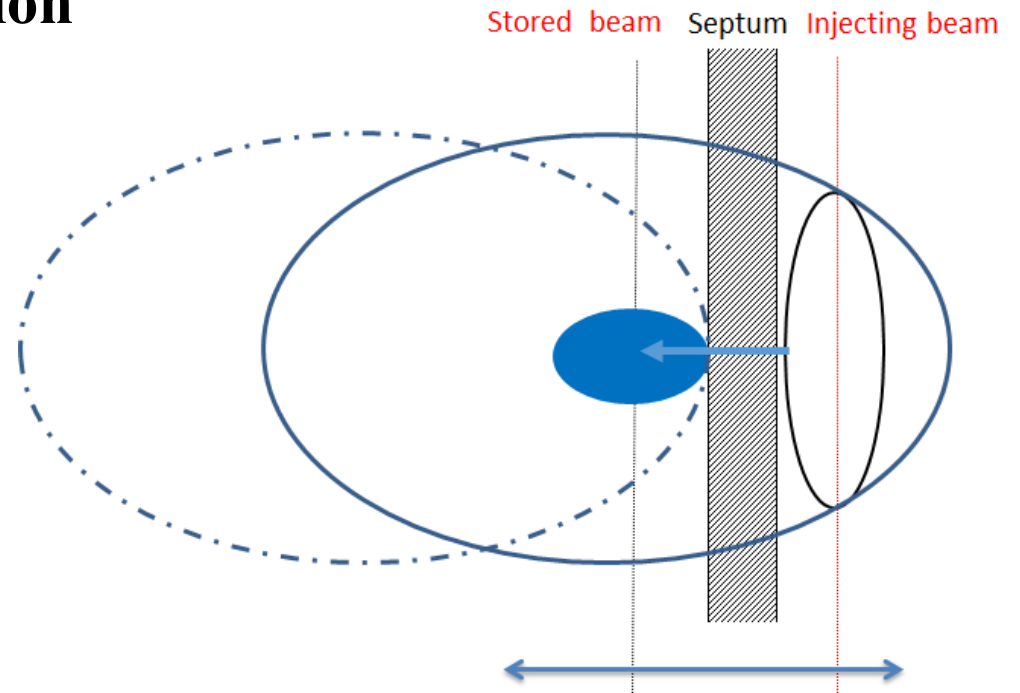
Beam performance of CEPC collider ring

Injection region

On-axis and Off-axis injection



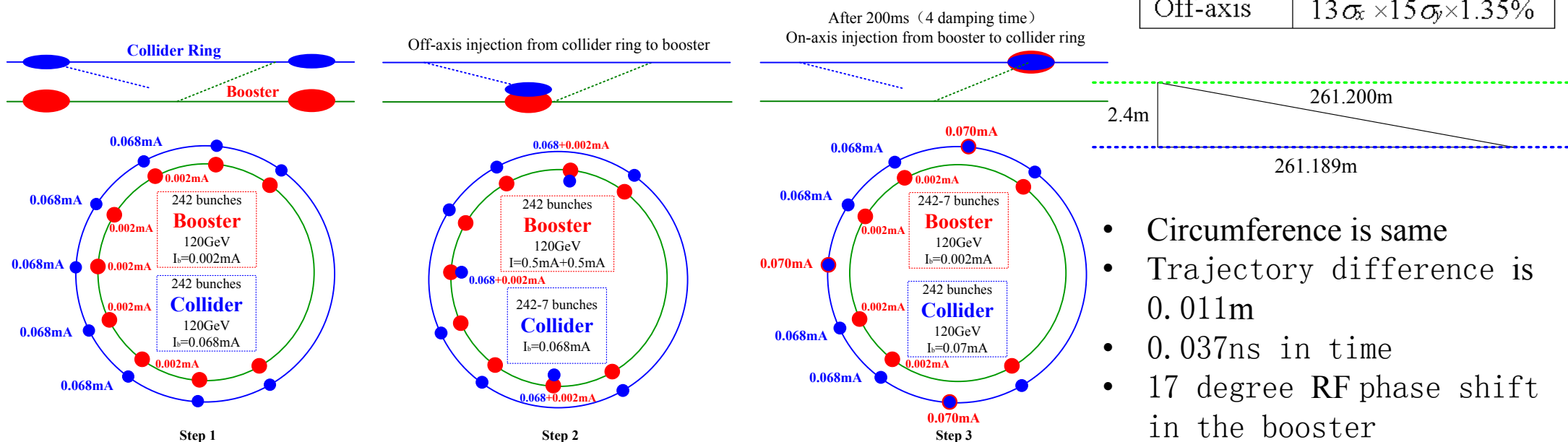
Only for Higgs mode
On-axis injection



For Higgs, W and Z modes
Off-axis injection

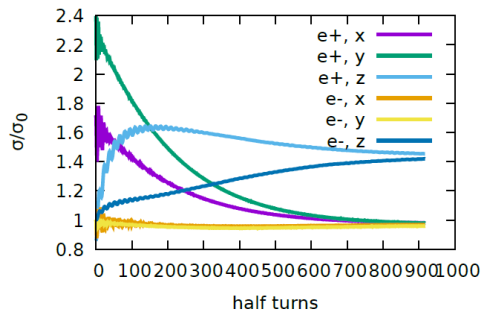
The on-axis injection

Higgs	DA requirements
On-axis	$8\sigma_x \times 15\sigma_y \times 1.35\%$
Off-axis	$13\sigma_x \times 15\sigma_y \times 1.35\%$

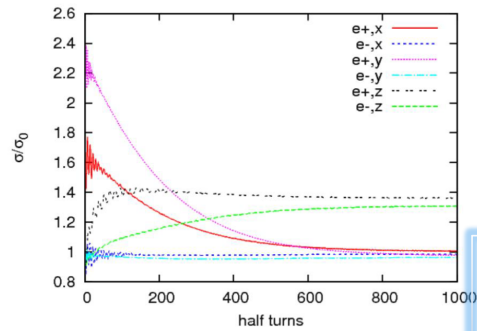


Several circulating bunches from Collider are extracted to the Booster. The Booster circulating bunches are then merged with the injected bunches from Collider. Then, the merged bunches in the Booster are injected back into collider ring by **vertical on-axis injection**. The procedure will be repeated several times so that all the circulating bunches in the Booster can be accumulated into the Collider. The **beamloading effect** in the Booster RF system is weak. The maximum cavity voltage drop is 0.48% and the maximum phase shift is 0.63 degree. The **peak HOM power** per RF cavity is 62W.

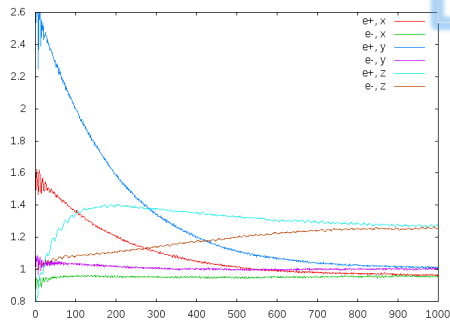
The on-axis injection



Y. Zhang



K. Ohmi

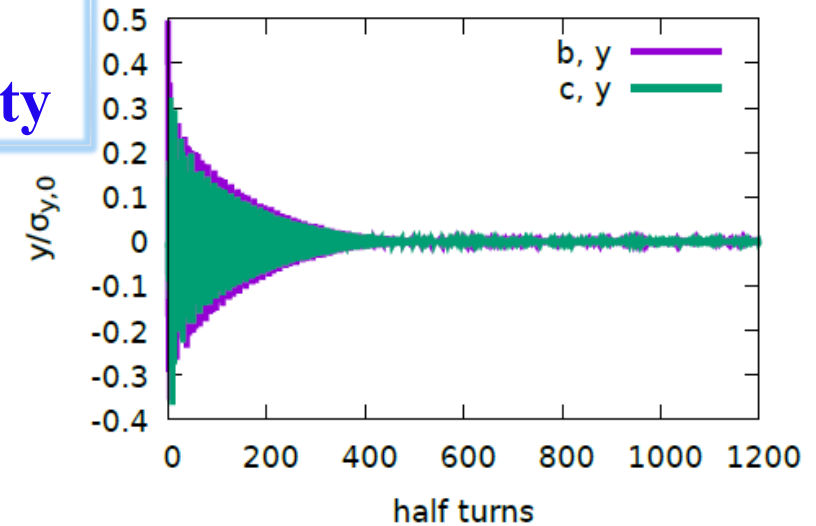
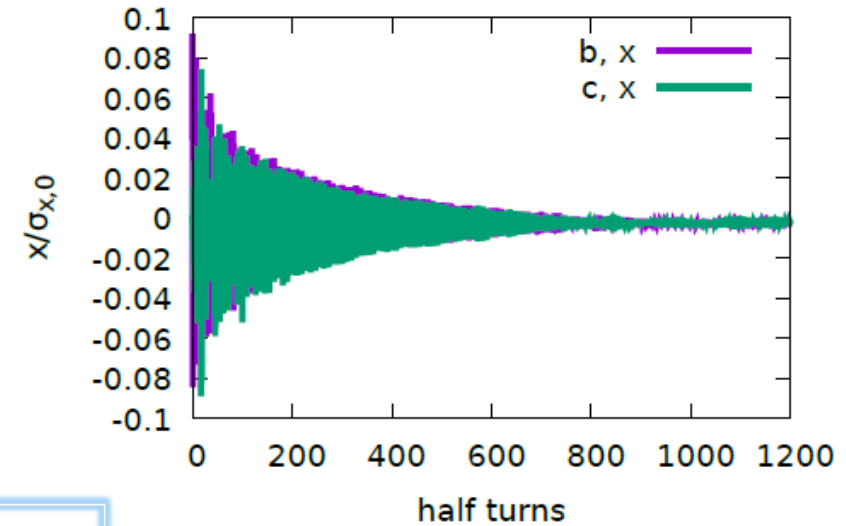


D. Shatilov

Even with the conditions:
Horizontal offset 9% σ_X
Vertical offset 50 % σ_Y
Intensity difference 3%

- Different codes agree well
- There is no flip-flop instability

Collision is stable

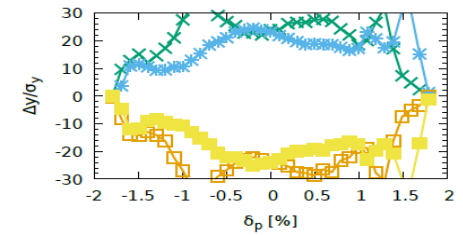
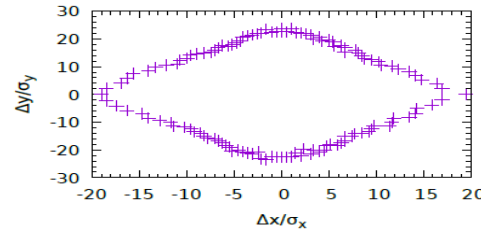
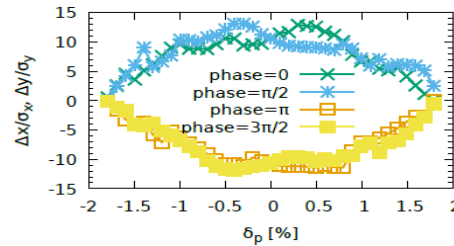


Beam performance of CEPC collider ring

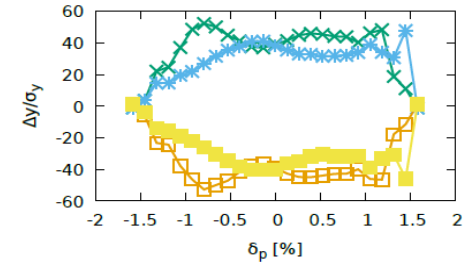
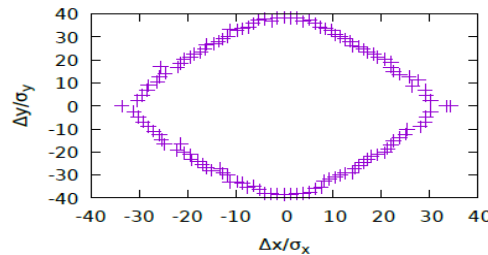
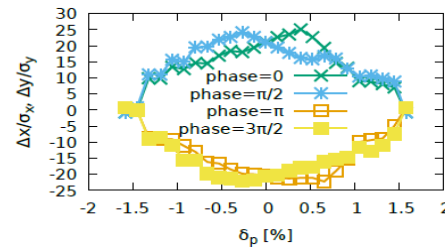
Dynamic aperture optimization

Higgs mode

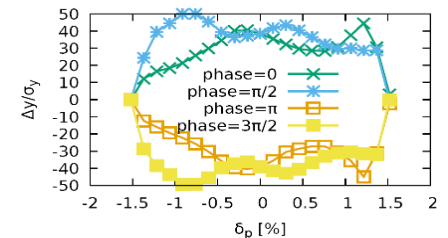
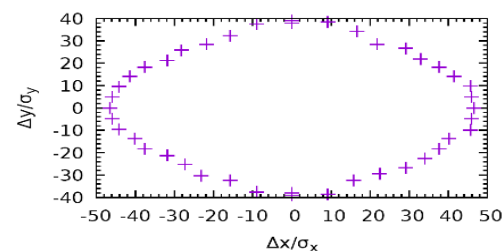
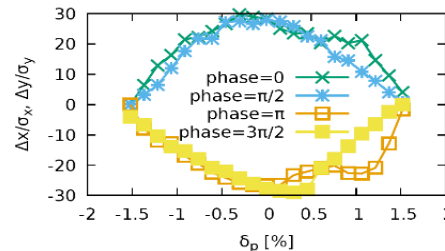
$8\sigma_x \times 15\sigma_y$ & 0.0135



$20\sigma_x \times 23\sigma_y$ & 0.018 without errors



$32\sigma_x \times 40\sigma_y$ & 0.015 without errors



$46\sigma_x \times 40\sigma_y$ & 0.015 without errors

Z mode

$17\sigma_x \times 9\sigma_y$ & 0.0049

Beam performance of CEPC collider ring

Dynamic aperture optimization with errors @ Higgs

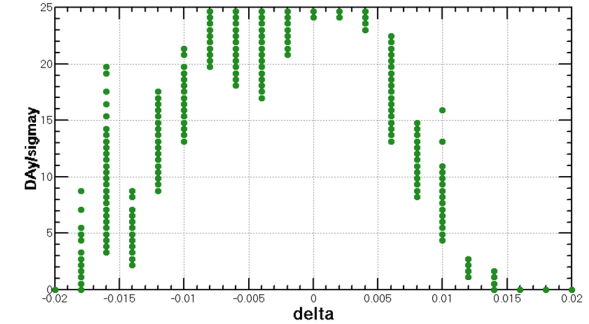
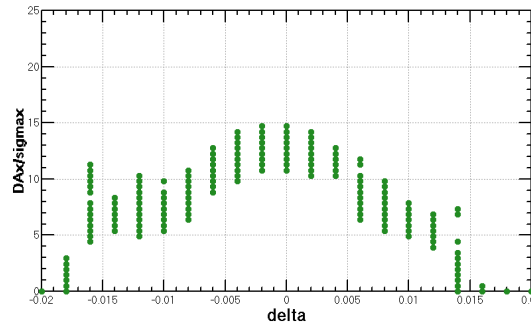
Crab waist=100%

- SAD is used
- 145 turns tracked
- 100 samples
- IR sextupoles + 32 arc sextupoles

KEK

(Max. free various=254)

- Damping at each element
- RF ON
- Radiation fluctuation ON
- Sawtooth on with tapering



$10\sigma_x \times 17\sigma_y$ & 0.014

Component	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.1	0.1	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.1	0.1	0.1	0.02%
FF Quadrupole	0.03	0.03	0.03	0.03	0.03	0.03	
Sextupole	0.10	0.10	0.10	0.1	0.1	0.1	

Higgs	DA requirements
On-axis	$8\sigma_x \times 15\sigma_y \times 1.35\%$
Off-axis	$13\sigma_x \times 15\sigma_y \times 1.35\%$

Dipole	Quadrupole(Without FF)	Sextupole
$B_2/B_0 \leq 4 \times 10^{-4}$	$B_2/B_1 \leq 4 \times 10^{-4}$	$B_3/B_2 \leq 20 \times 10^{-4}$
$B_3/B_0 \leq 0.8 \times 10^{-4}$	$B_3/B_1 \leq 4 \times 10^{-4}$	$B_4/B_2 \leq 3 \times 10^{-4}$
$B_4/B_0 \leq 0.2 \times 10^{-4}$	$B_4/B_1 \leq 2 \times 10^{-4}$	$B_5/B_2 \leq 20 \times 10^{-4}$
$B_n(n>4)/B_0 \leq 0.8 \times 10^{-4}$	$B_n(n>4)/B_1 \leq 1 \times 10^{-4}$	$B_n(n>5)/B_2 \leq 10 \times 10^{-4}$

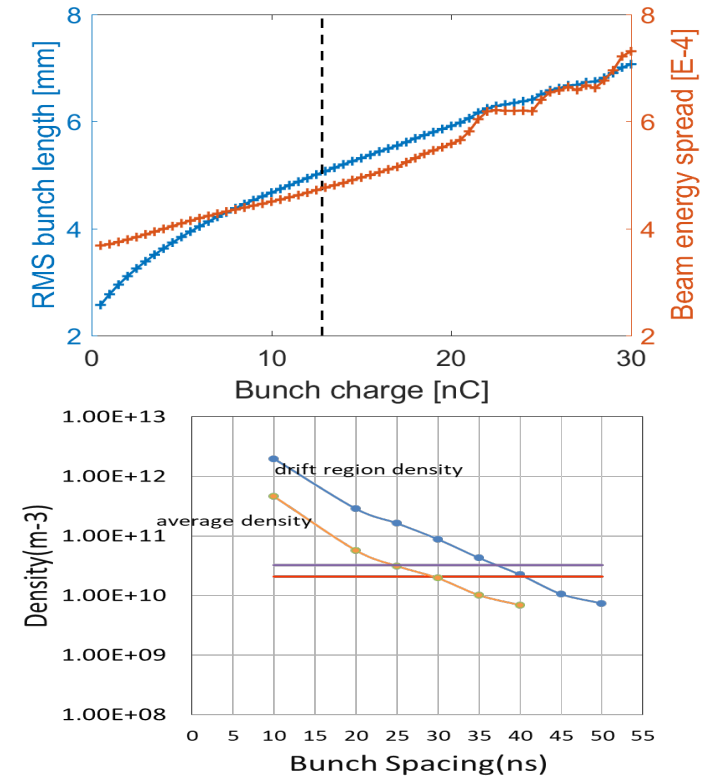
RMS
R=12mm

RMS close orbit distortions are smaller than 30 μm and 50 μm in horizontal and vertical plane. Beta beatings < 1% , Coupling < 0.2%

Beam performance of CEPC collider ring

The impedance and instabilities

Components	Number	$Z_{ }/n$, m Ω	k_{loss} , V/pC	k_y , kV/pC/m
Resistive wall	-	6.2	363.7	11.3
RF cavities	240	-1.0	225.2	0.3
Flanges	20000	2.8	19.8	2.8
BPMs	1450	0.12	13.1	0.3
Bellows	12000	2.2	65.8	2.9
Pumping ports	5000	0.02	0.4	0.6
IP chambers	2	0.02	6.7	1.3
Electro-separators	22	0.2	41.2	0.2
Taper transitions	164	0.8	50.9	0.5
Total		11.4	786.8	20.2

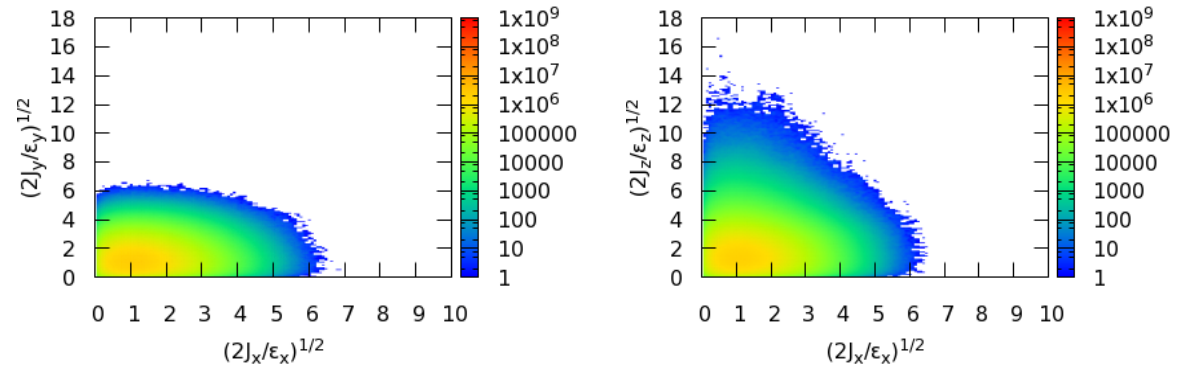


At the design bunch intensity, the bunch length will increase 22% and 113% for H and Z respectively. Bunch spacing >25ns will be needed to eliminate the electron cloud instability.

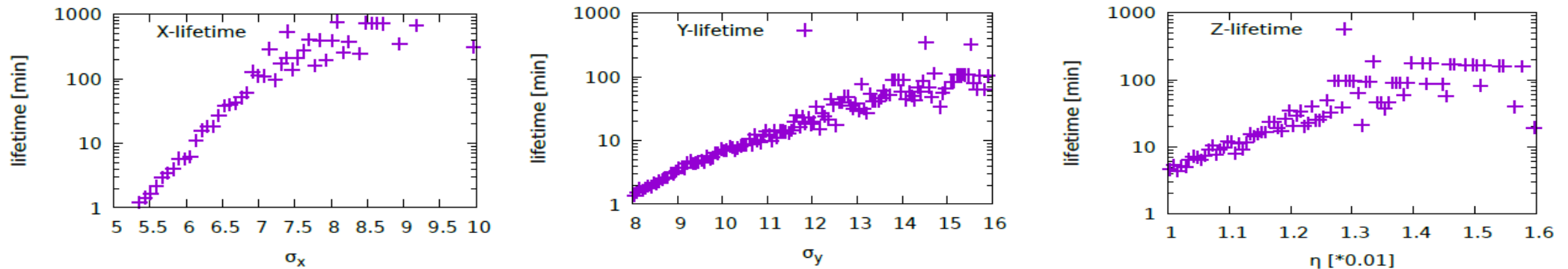
Beam performance of CEPC collider ring

Beambeam effect

- Dynamic aperture requirements
- Beam lifetime
- Optimized parameters for luminosity



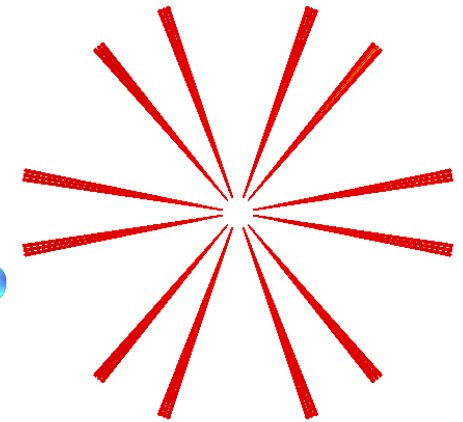
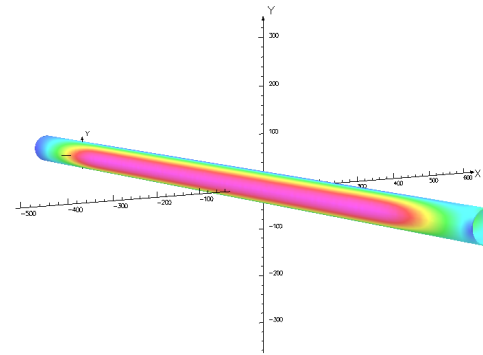
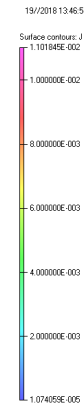
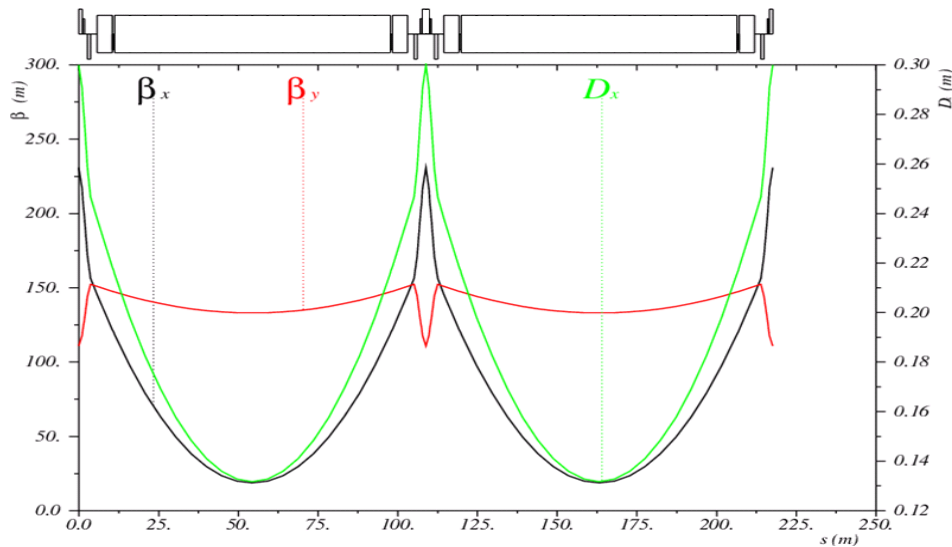
Beam tail distribution with crab-waist collision.



Lifetime with real lattice and beam-beam interaction at Higgs

CEPC injection chain

Booster ring



- The diameter of the inner aperture of the vacuum chamber is chosen to be 44 mm from consideration of impedance to improve the threshold of bunch current.
- Standard TME cells are chosen for the booster to control the emittance.
- Sextupole coils are considered on the outside of vacuum chamber to compensate the effect of eddy current during energy ramping.

CEPC injection chain

Booster ring

Main parameters of CEPC booster at injection energy

		<i>H</i>	<i>W</i>	<i>Z</i>
Beam energy	GeV	10		
Bunch number		242	1524	6000
Threshold of single bunch current	μA	25.7		
Threshold of beam current (limited by coupled bunch instability)	mA	100		
Bunch charge	nC	0.78	0.63	0.45
Single bunch current	μA	2.3	1.8	1.3
Beam current	mA	0.57	2.86	7.51
Energy spread	%	0.0078		
Synchrotron radiation loss/turn	keV	73.5		
Momentum compaction factor	10^{-5}	2.44		
Emittance	nm	0.025		
Natural chromaticity	H/V	-336/-333		
RF voltage	MV	62.7		
Betatron tune $\nu_x/\nu_y/\nu_z$		263.2/261.2/0.1		
RF energy acceptance	%	1.9		
Damping time	s	90.7		
Bunch length of linac beam	mm	1.0		
Energy spread of linac beam	%	0.16		
Emittance of linac beam	nm	40~120		

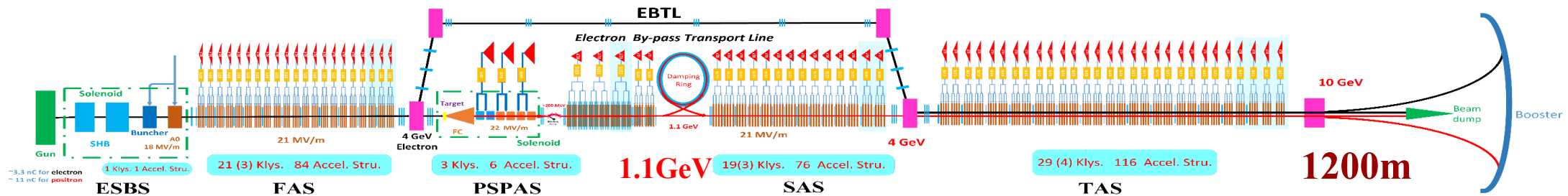
9 cell & 1.3GHz RF cavity

Main parameters of CEPC booster at extraction energy

		<i>H</i>		<i>W</i>	<i>Z</i>
		Off axis injection	On axis injection	Off axis injection	Off axis injection
Beam energy	GeV	120		80	45.5
Bunch number		242	235+7	1524	6000
Maximum bunch charge	nC	0.72	24.0	0.58	0.41
Maximum single bunch current	μA	2.1	70	1.7	1.2
Threshold of single bunch current	μA	300			
Threshold of beam current (limited by RF power)	mA	1.0		4.0	10.0
Beam current	mA	0.52	1.0	2.63	6.91
Injection duration for top-up (Both beams)	s	25.8	35.4	45.8	275.2
Injection interval for top-up	s	47.0		153.0	504.0
Current decay during injection interval		3%			
Energy spread	%	0.094		0.062	0.036
Synchrotron radiation loss/turn	GeV	1.52		0.3	0.032
Momentum compaction factor	10^{-5}	2.44			
Emittance	nm	3.57		1.59	0.51
Natural chromaticity	H/V	-336/-333			
Betatron tune ν_x/ν_y		263.2/261.2			
RF voltage	GV	1.97		0.585	0.287
Longitudinal tune		0.13		0.10	0.10
RF energy acceptance	%	1.0		1.2	1.8
Damping time	ms	52		177	963
Natural bunch length	mm	2.8		2.4	1.3
Injection duration from empty ring	h	0.17		0.25	2.2

CEPC injection chain

Linac



- The total beam transfer efficiency from transfer line to the injection point of collider ring is greater than 90%.
- The transfer efficiency can be made much higher with a damping ring of energy 1.1GeV while the beam emittance of Linac can be controlled below 40 nm.

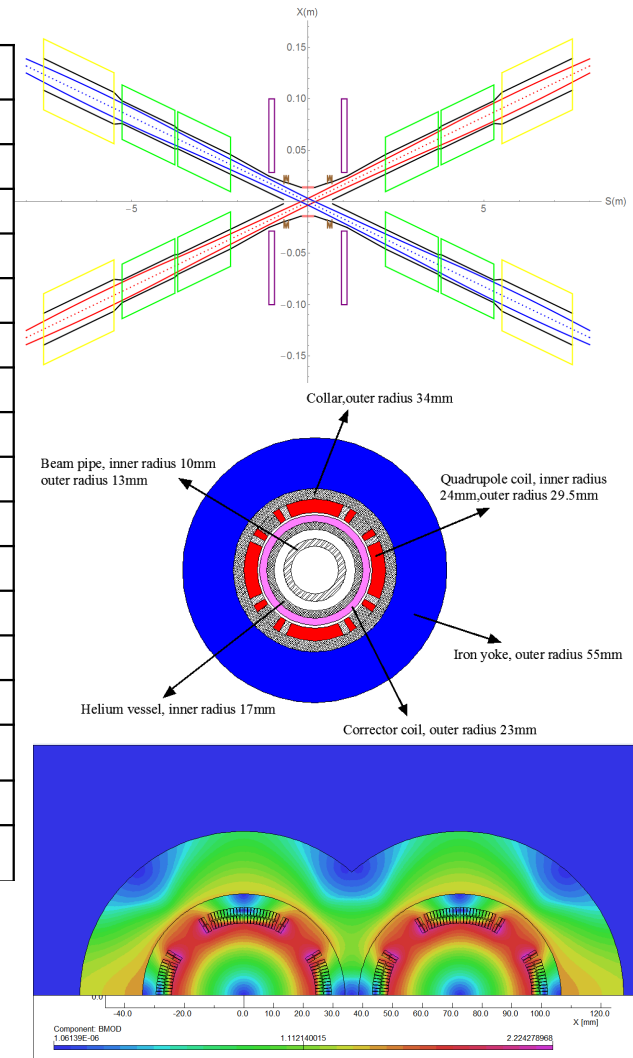
Parameter	Symbol	Unit	Designed
e^-/e^+ beam energy	E_{e^-}/E_{e^+}	GeV	10
Repetition rate	f_{rep}	Hz	100
e^-/e^+ bunch population	N_{e^-}/N_{e^+}		$> 9.4 \times 10^9$ / $> 9.4 \times 10^9$
		nC	> 1.5
Energy spread (e^-/e^+)	σ_e		$< 2 \times 10^{-3}$ / $< 2 \times 10^{-3}$
Emittance (e^-/e^+)	ε_r	nm·rad	40
Bunch length (e^-/e^+)	σ_l	mm	1 / 1
e^- beam energy on Target		GeV	4
e^- bunch charge on Target		nC	10

Some engineering progresses

New parameters of CEPC collider ring

	<i>Higgs</i>	<i>W</i>	<i>Z (2T)</i>
Beam energy (GeV)	120	80	45.5
Circumference (km)	100		
Synchrotron radiation loss/turn (GeV)	1.68	0.33	0.035
Crossing angle at IP (mrad)	16.5×2		
Bunch number (bunch spacing)	218 (0.76μs)	1568 (0.20μs)	12000 (25ns+10%gap)
Beam current (mA)	17.8	90.4	461.0
Synchrotron radiation power/beam (MW)	30	30	16.5
β function at IP β_x^*/β_y^* (m)	0.33/0.001	0.33/0.001	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	0.89/0.0018	0.395/0.0012	0.13/0.00115
Beam size at IP σ_x/σ_y (μm)	17.1/0.042	11.4/0.035	5.1/0.034
RF voltage V_{RF} (GV)	2.4	0.43	0.082
RF frequency f_{RF} (MHz) / harmonics	650 / 216816		
Natural bunch length σ_z (mm)	2.2	2.98	2.42
Bunch length σ_z (mm)	3.93	5.9	8.5
Beamstrahlung lifetime/quantum lifetime (min)	30/50	>400	
Lifetime (hour)	0.22	1.2	2.0
Luminosity/IP L ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	5.2	14.5	37.7

- ✓ Smaller emittance and β_y^*
- ✓ Reduction of quadrupoles radiation: longer QD0, QF1 and ARC quadrupoles
- ✓ Reduction of DA requirement: larger β_x at injection point.
- ✓ Maximization of bending filling factor to reduce SR loss.



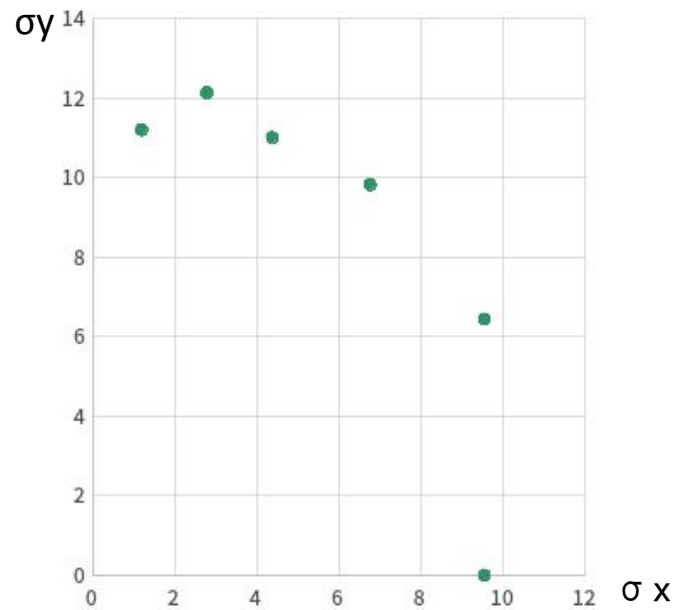
Some engineering progresses

SPPC main parameters

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	cm ⁻² s ⁻¹	1.2e35	1.0e35	-
Beta function at collision	m	0.75	0.75	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		2.0e11	1.5e11	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

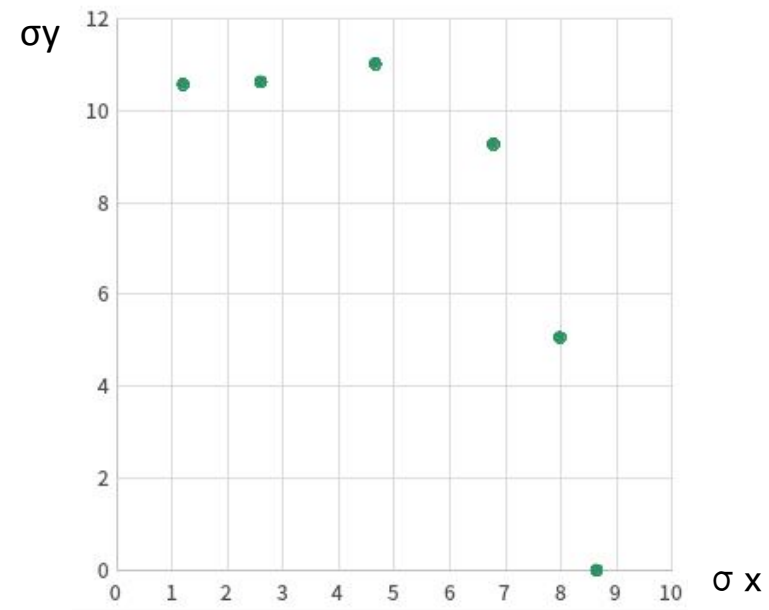
Some engineering progresses

Estimation of SPPC Dynamics Aperture



DA result at **injection energy**
considering sextupole and dipole error

$Q_x = 119.28$, $Q_y = 118.31$
Normalized rms transverse emittance: $2.4 \mu\text{m}$
Proton energy: 2.1 TeV
Track 1000 turns



DA result at **collision energy**
considering sextupole and dipole error

$Q_x = 121.28$, $Q_y = 118.31$
Normalized rms transverse emittance: $2.4 \mu\text{m}$
Proton energy: 37.5 TeV
Track 1000 turns

Summary

- CEPC Accelerator CDR has been completed (formally released on Sept 2, 2018) with all systems reaching the design goals.
- The work on CEPC TDR is now in progress at IHEP.
- AP & technology challenges, are the main contents of CEPC TDR.
- Technological systems, both of CEPC and mainly HTS magnet of SppC, are gradually developed, with the support from industry in China.
- A lot of work ahead, for both CEPC & SppC, and more budget and collaborations on R&D are expected.