Status of CEPC

Chenghui Yu

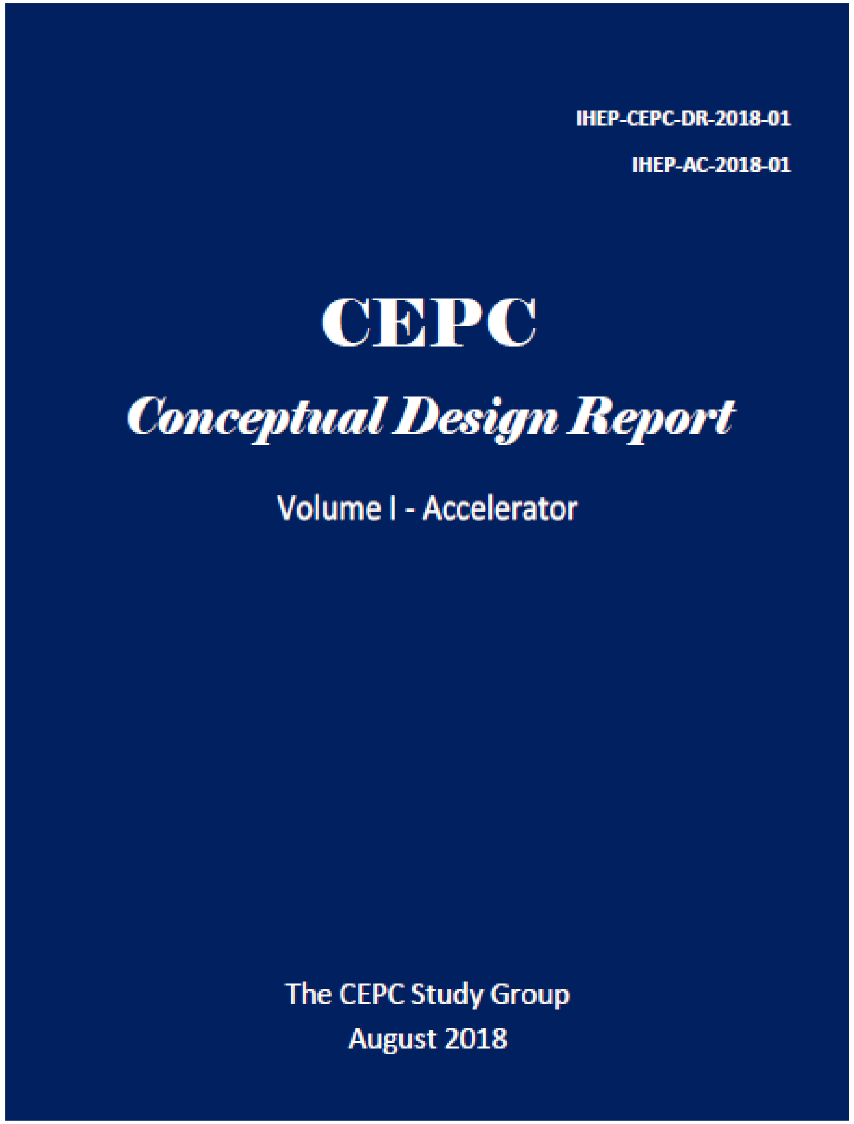
for CEPC team

Sep. 24, 2018

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



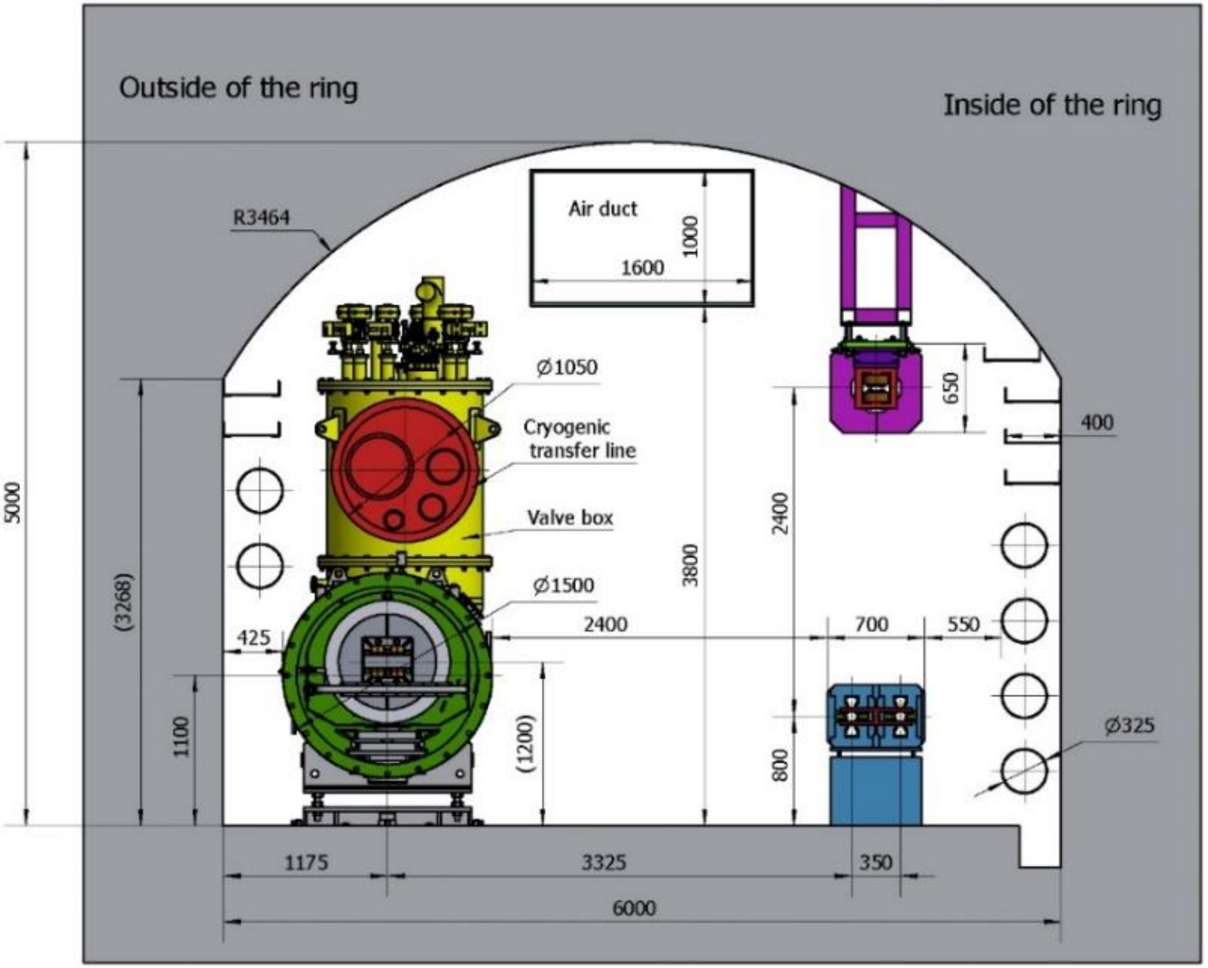
CDR International Review June 28-30, 2018. Final CDR (accelerator) released on Sept. 2, 2018

Outline

- Geometry design
- Beam performance of collider ring
- Injection chain

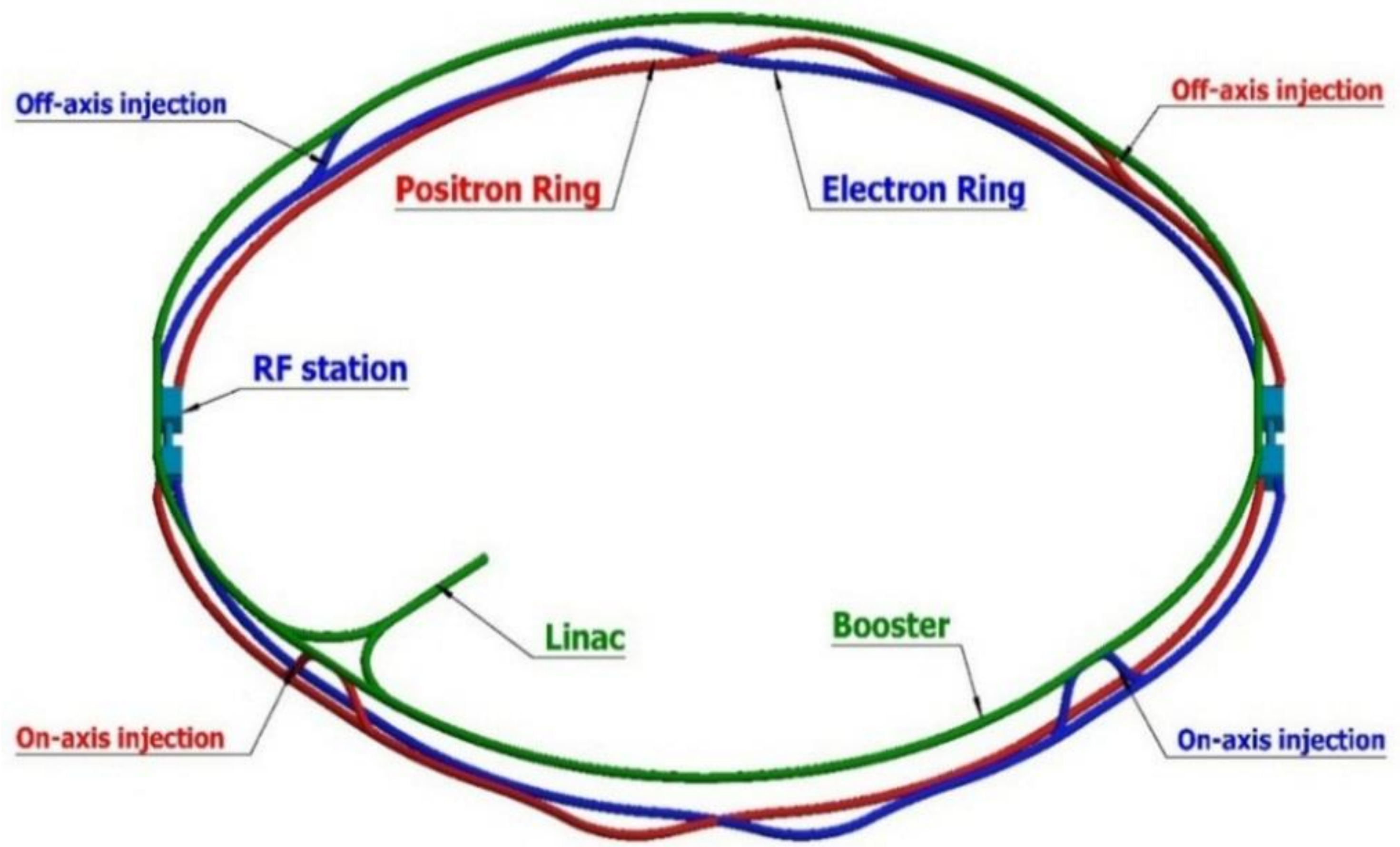
  Collider ring ← Booster ← Linac
- Engineering progress
- Summary

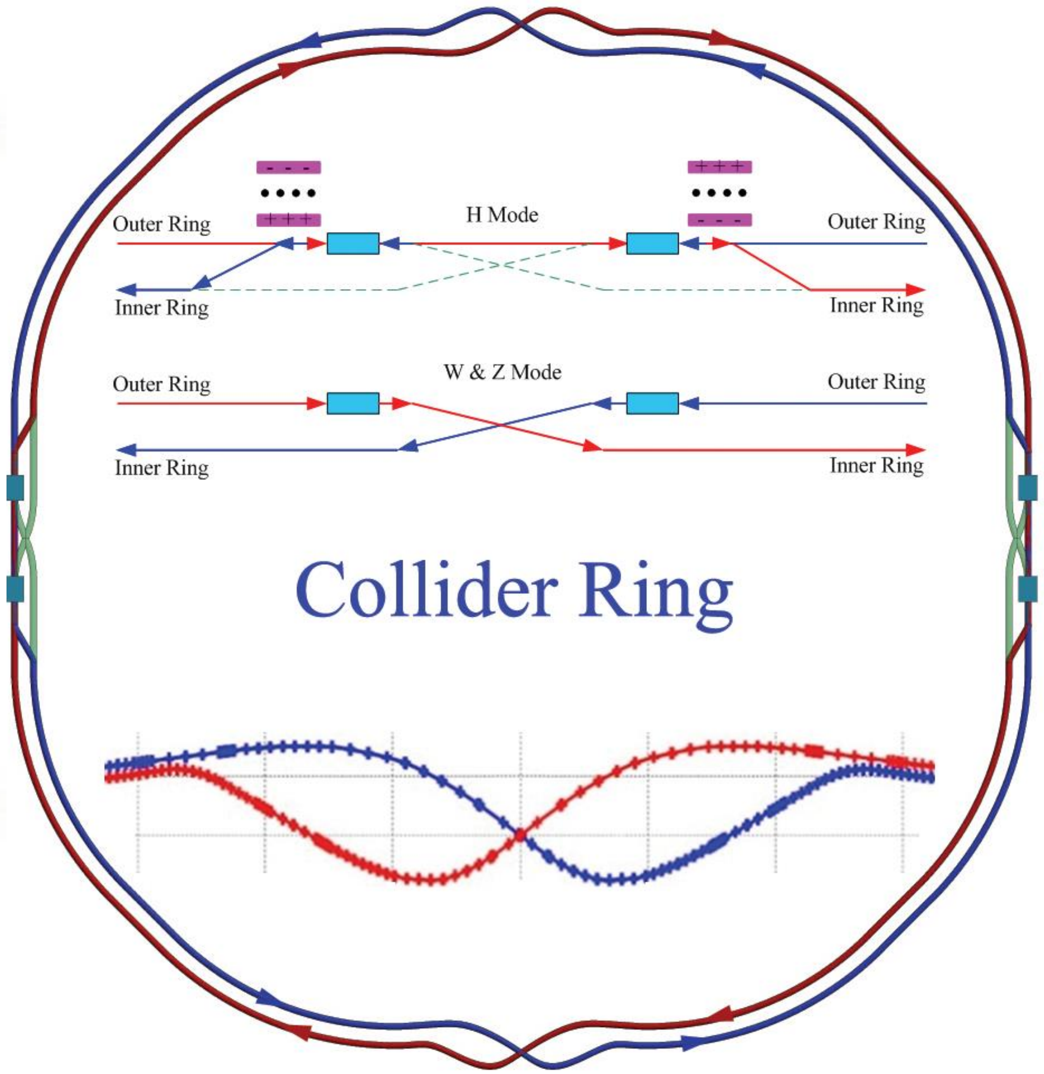
Geometry design



- 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

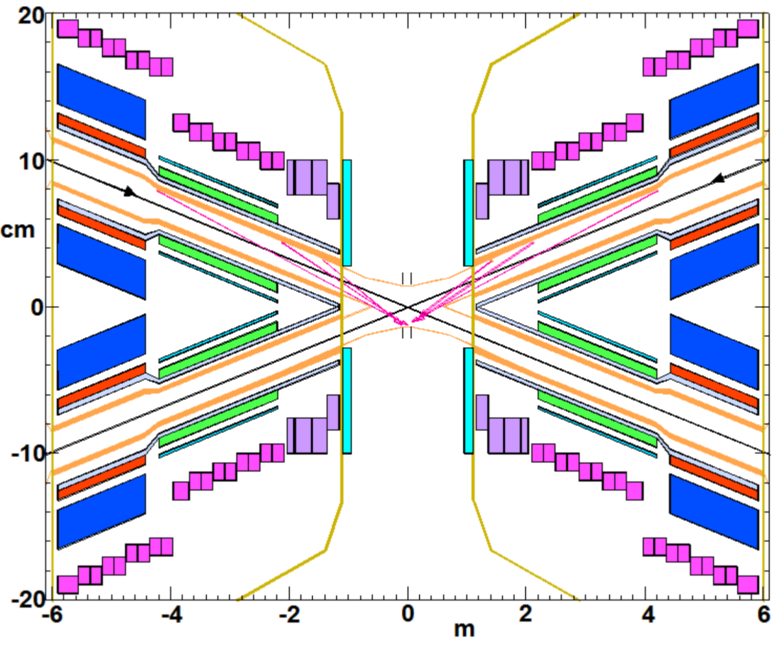
Beam performance of collider ring

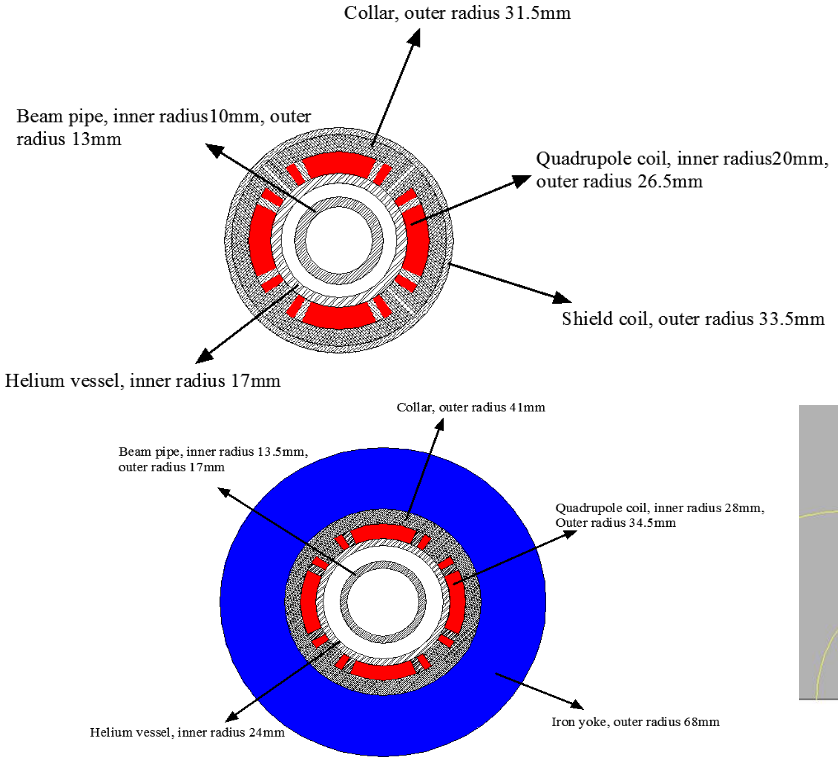
	Higgs	*W*	*Z*（*3T*）	*Z*（*2T*）
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	**100**			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	**16.5×2**			
Piwinski angle	**3.48**	**7.0**	**23.8**	
Number of particles/bunch N_e (10^{10})	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**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	**0.018/0.109**	**0.013/0.123**	**0.004/0.06**	**0.004/0.079**
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
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	
Beamstruhlung lifetime /quantum lifetime* (min)	80/80	>400		
Lifetime (hour)	**0.43**	**1.4**	**4.6**	**2.5**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	**2.93**	**10.1**	**16.6**	**32.1**

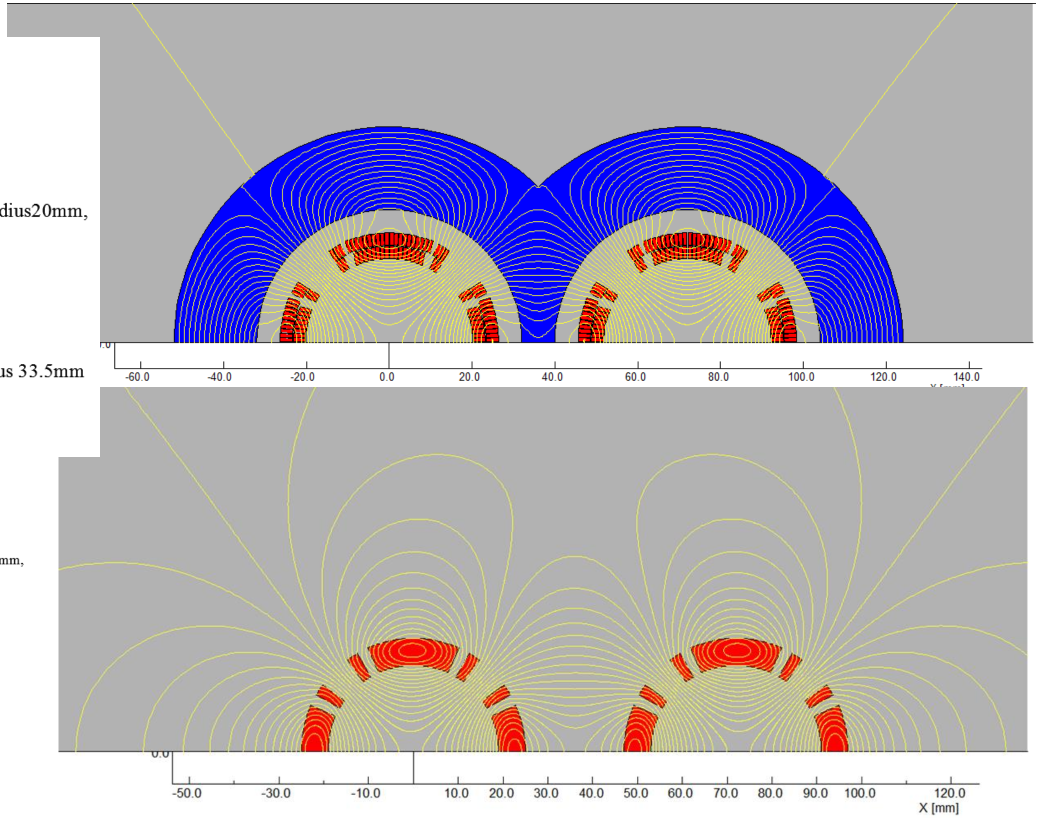
Beam performance of collider ring

Interaction region

- ✓ **L*=2.2m, θc=33mrad, βx*=0.36m, βy*=1.5mm, Detector solenoid=3.0T**
  - Lower strength requirements of anti-solenoids **(B_z~7.2T)**
  - Enough space for the SC quadrupole coils in two-in-one type (Peak field 3.8T & 136T/m) with room temperature vacuum chamber.



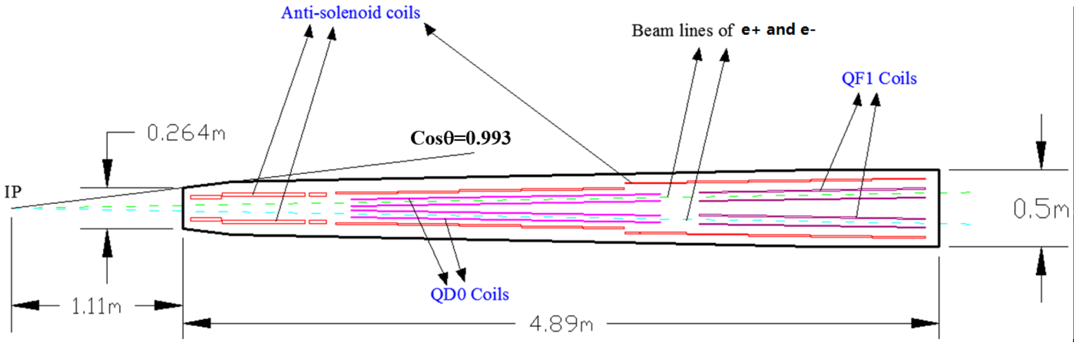


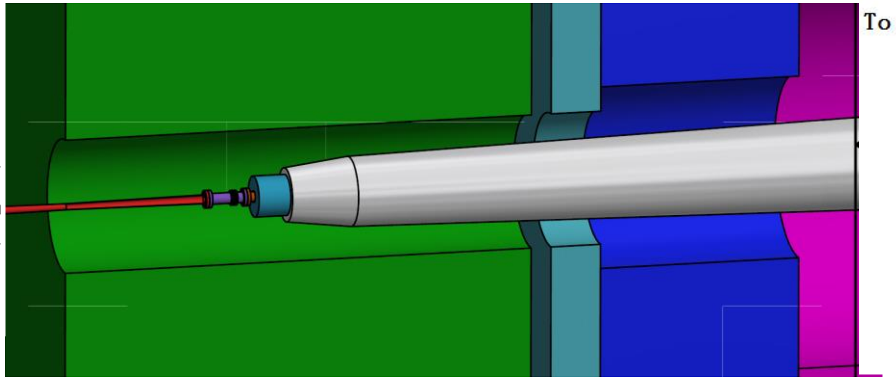


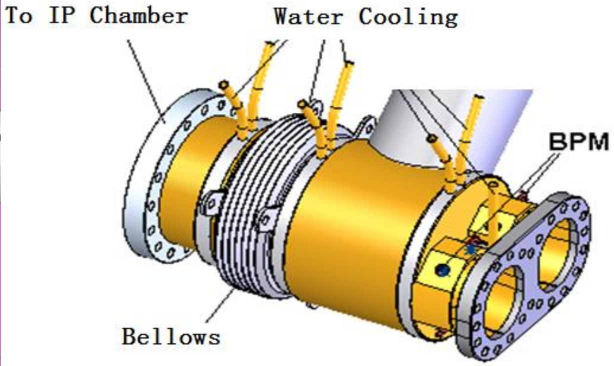
Beam performance of collider ring

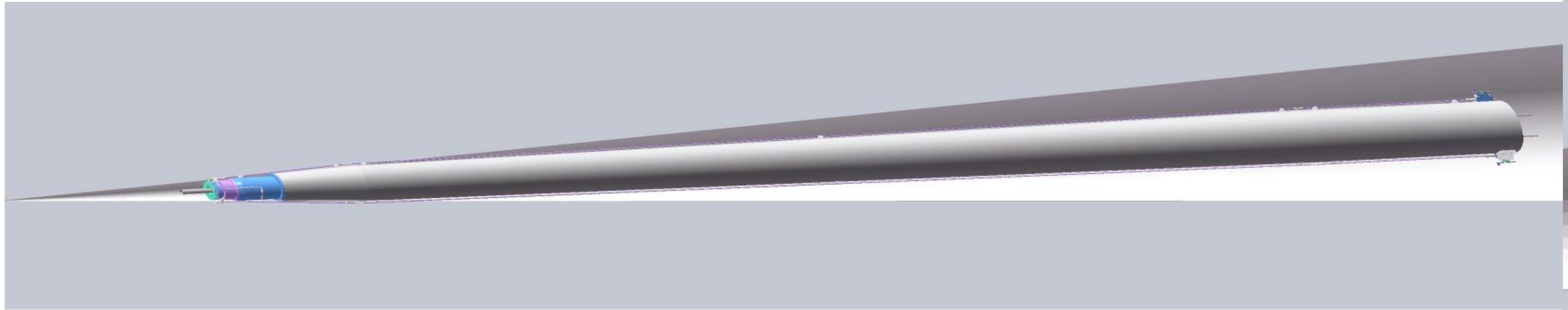
Interaction region

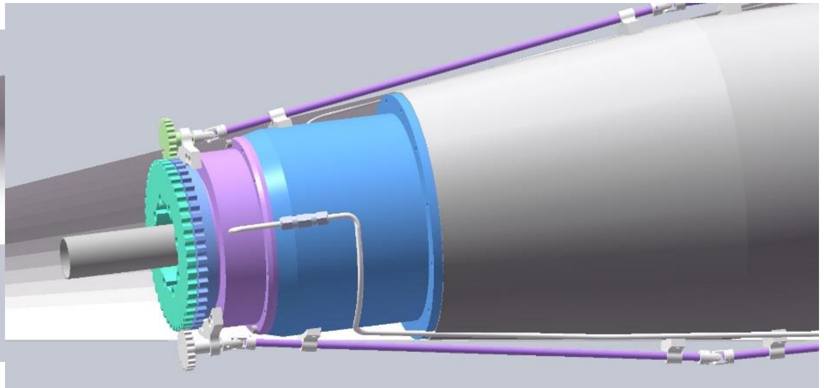
- The supporting system nearby IP is under design.
- We are studying the installation procedure for the remote connection of bellows.





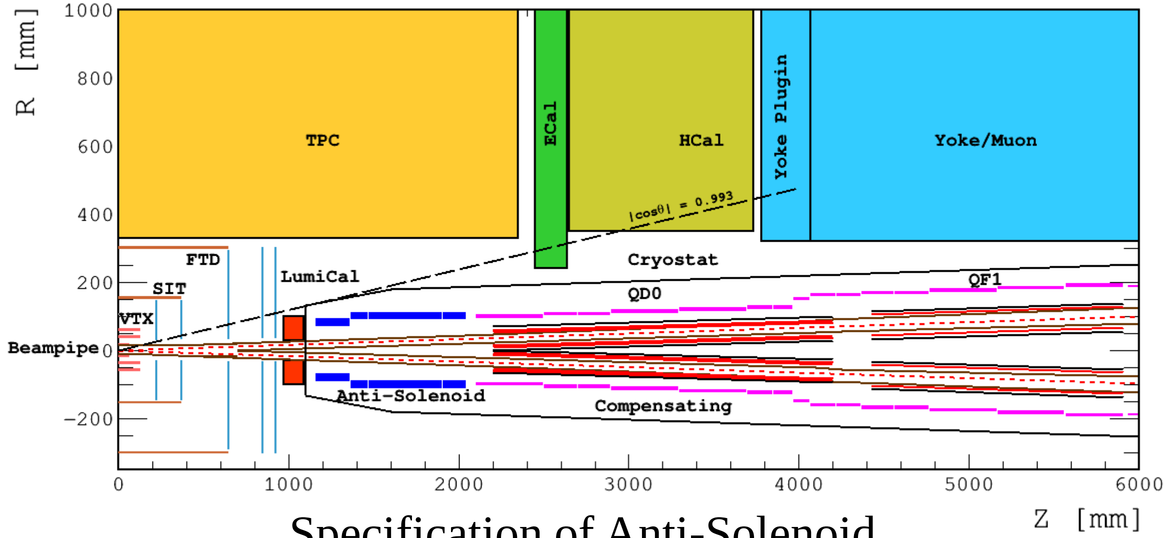






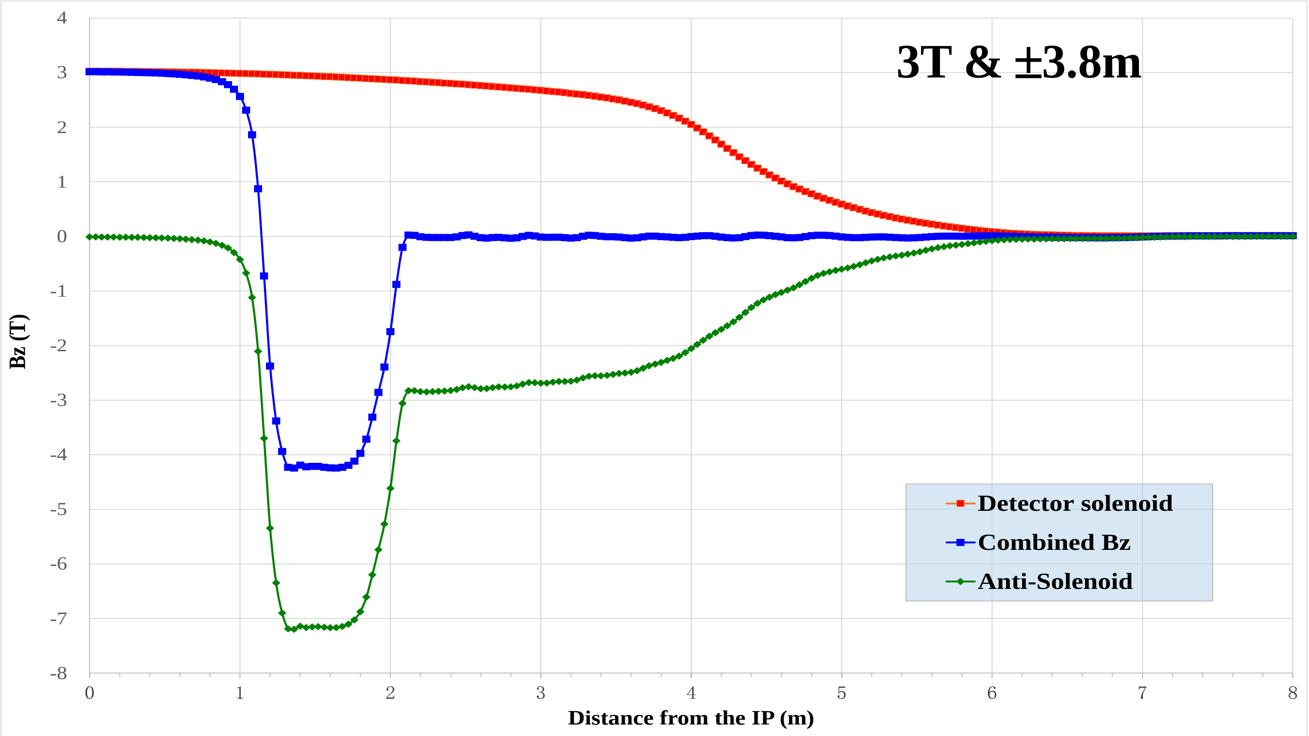
Beam performance of collider ring

Interaction region



Specification of Anti-Solenoid

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		



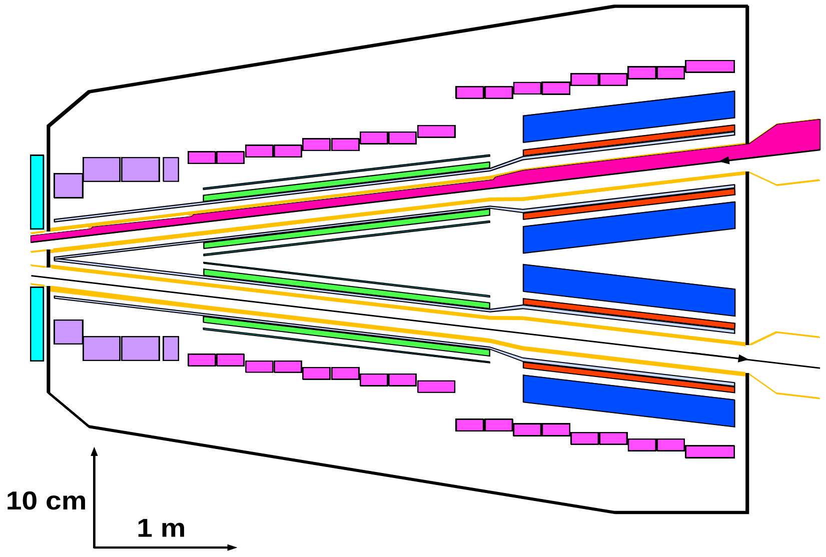
22 anti-Solenoid **sections with different inner coil diameters**

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

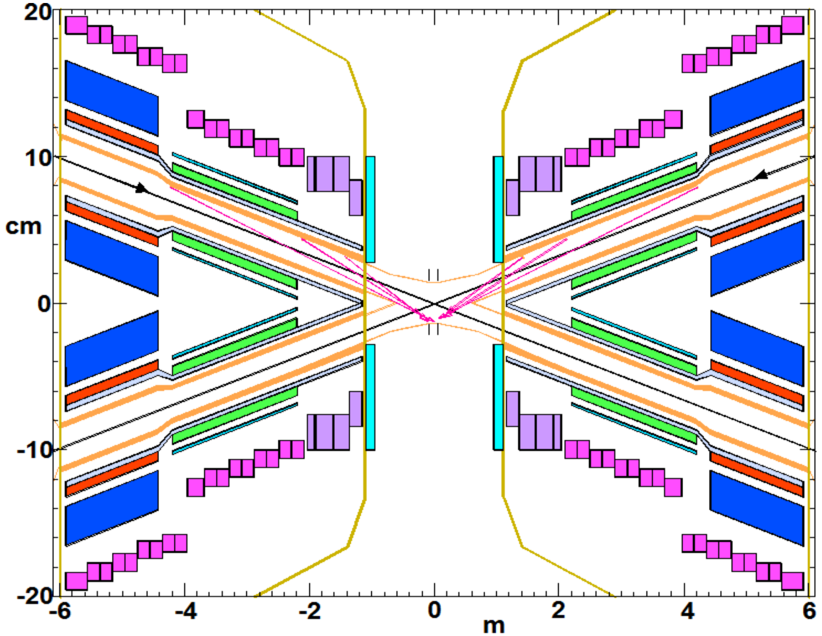
The skew quadrupole coils are designed to make fine tuning of Bz over the QF&QD region instead of the mechanical rotation.

Beam performance of collider ring

Interaction region



Element	SR in horizontal	SR in vertical
Last Dipole	Ec=45keV	
QD0	639W, 1.3MeV	165W, 397keV
QF1	1567W, 1.6MeV	42W, 225keV



No SR hits directly on the beryllium pipe. SR power contributed within ±10σ_x will go through the IP.

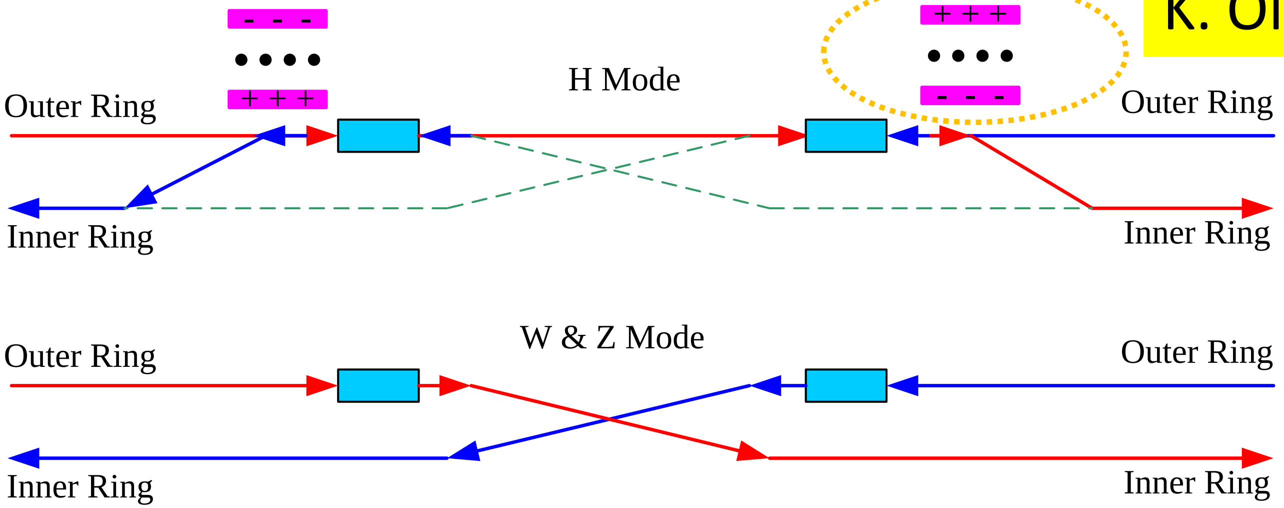
3 mask tips are added to shadow the beam pipe wall from 0.7 m to 3.93 m reduces the number of photons that hit the Be pipe from 2×10^4 to about 200 (100 times lower).

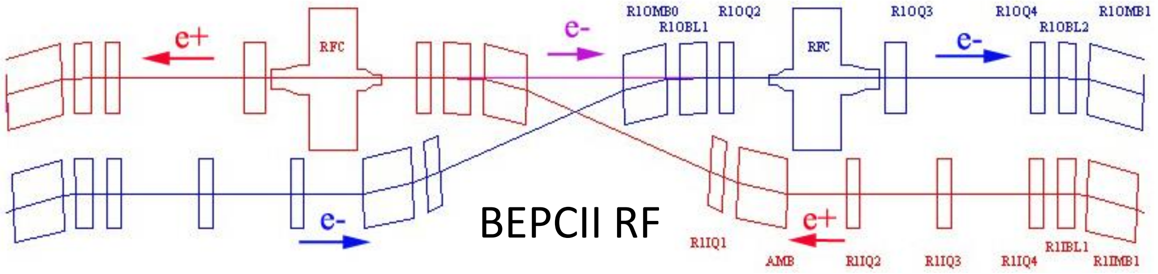
Beam performance of collider ring

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. The outer diameter is 1.5m. **Distance of two ring is 1.0m**.

K. Oide





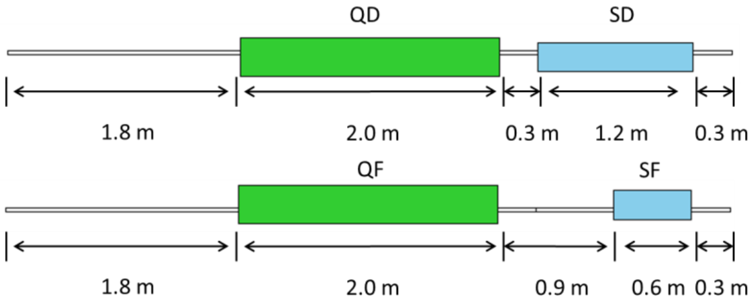
- During the operation of Higgs mode all the RF cavities are shared by both e+ and e- beams with the application of the combining magnets nearby the RF cavities.
- For the W and Z modes the surveys of e+ and e- rings in the RF region are designed independently by turning off the combining magnets so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

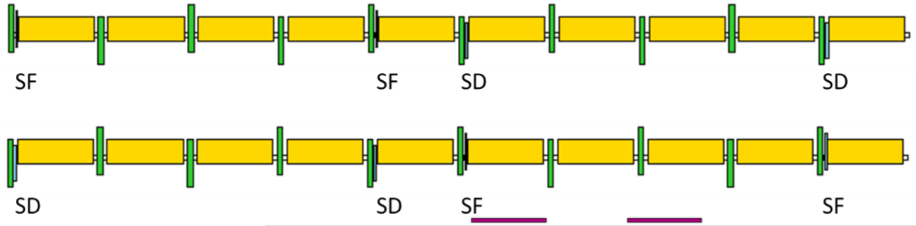
Beam performance of collider ring

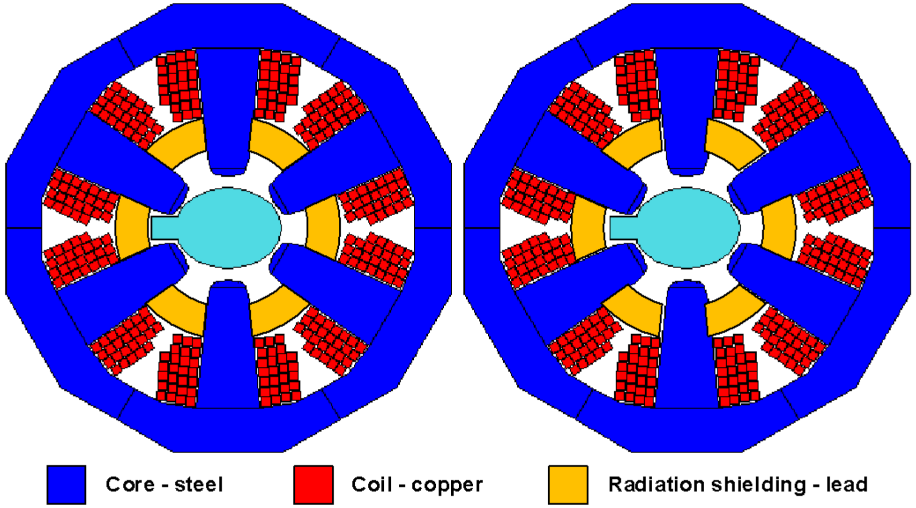
ARC region

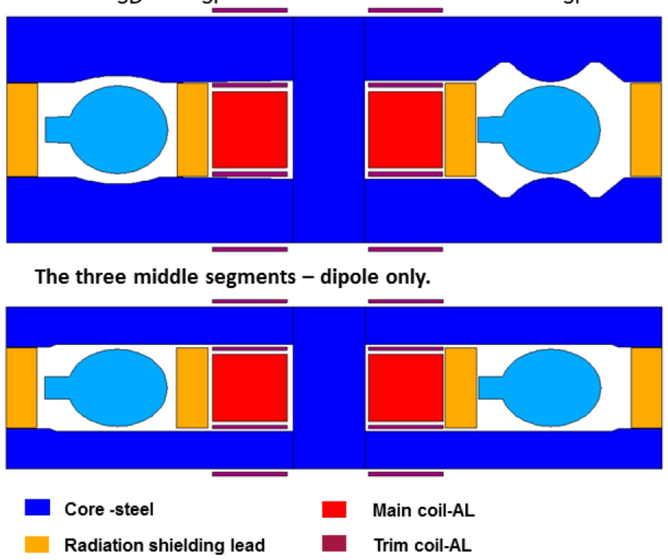
A. Milanese

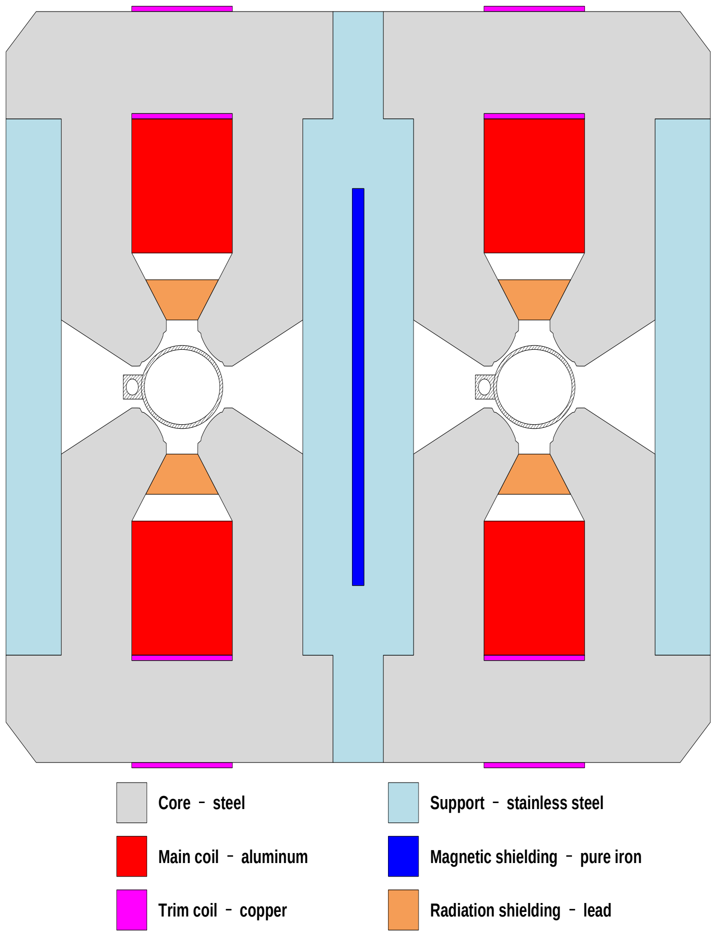
- **Distance of two ring is 0.35m** to adopt **twin-aperture** Q & B magnets.
- FODO cell, 90°/90°, non-interleaved sextupole scheme.
- Sextupoles are independent type for the flexibility of optics.







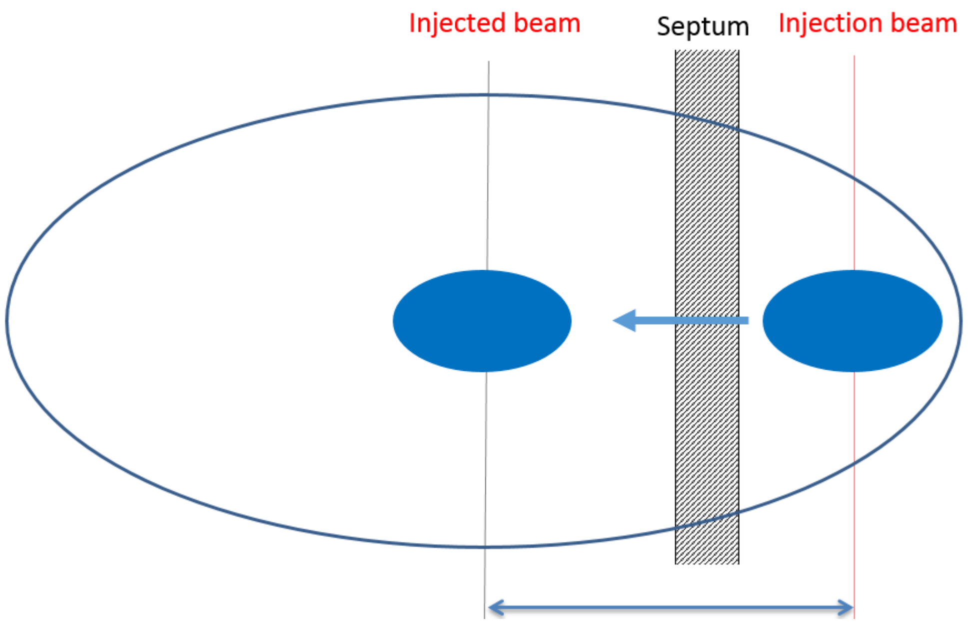




Beam performance of collider ring

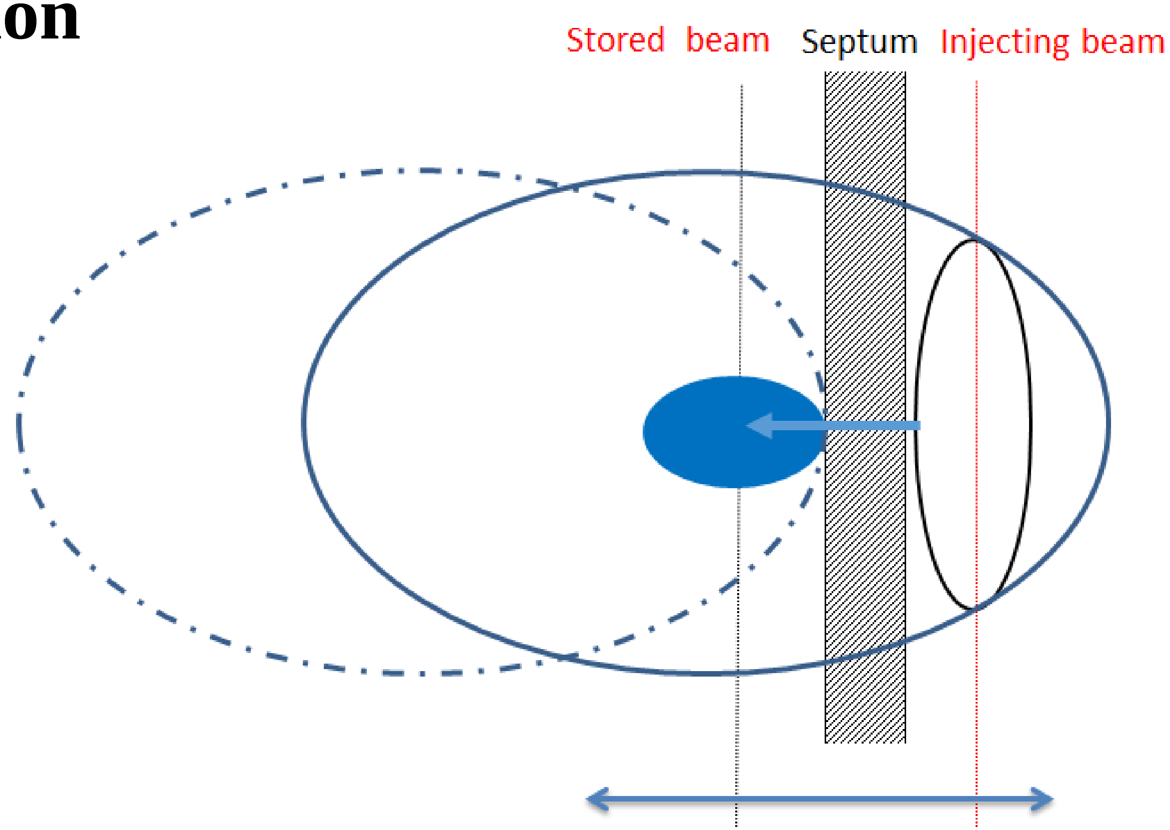
Injection region

On-axis and Off-axis injection



Only for Higgs mode

On-axis injection

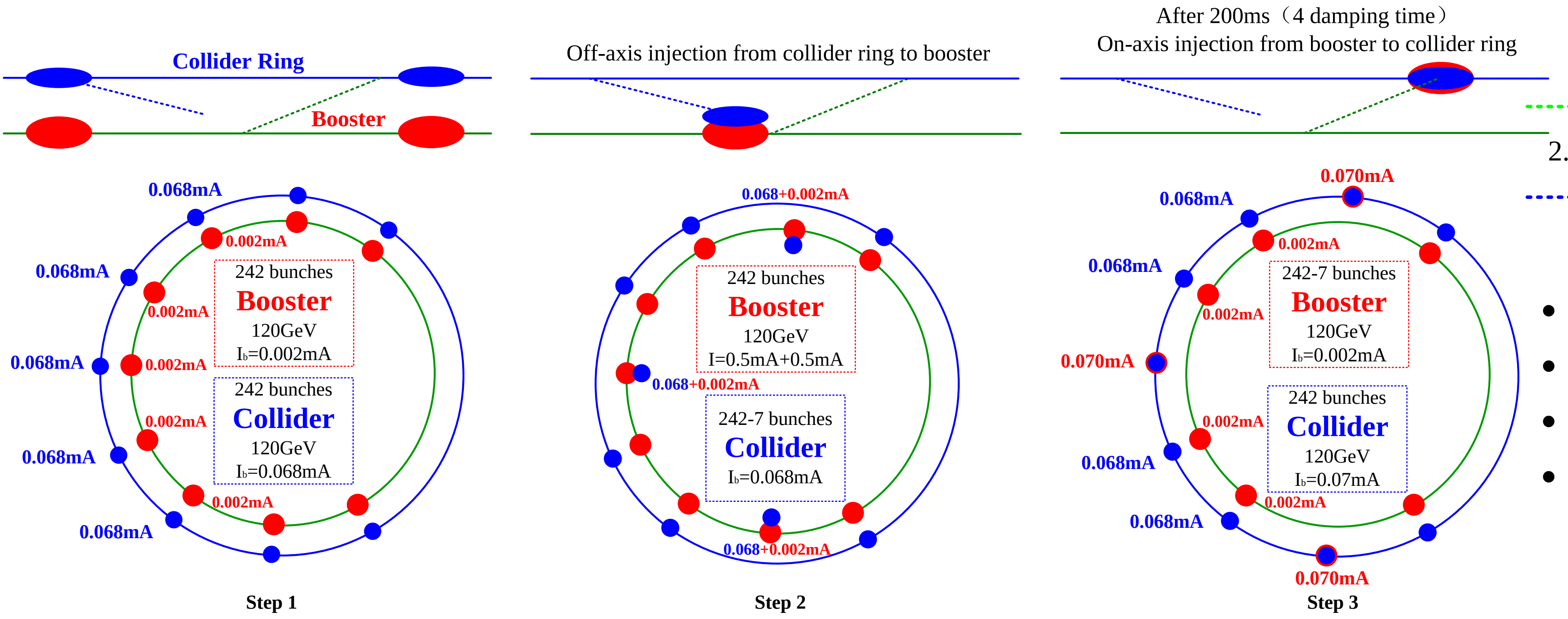


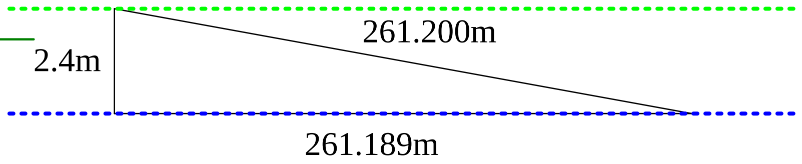
For Higgs, W and Z modes

Off-axis injection

The on-axis injection

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

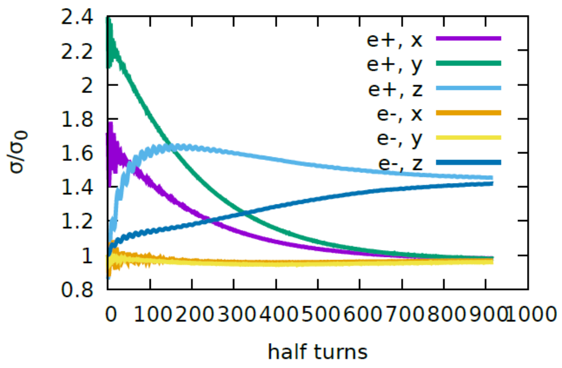




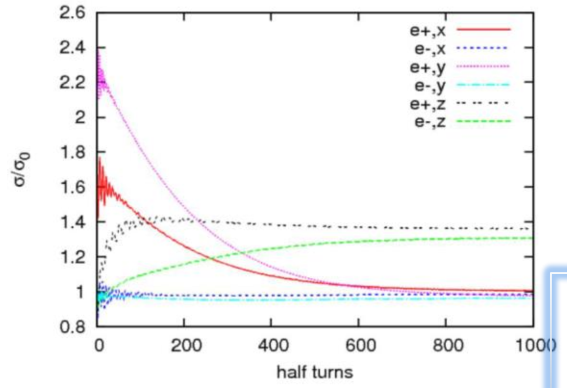
- Circumference is same
- Trajectory difference is 0.011m
- 0.037ns in time
- 17 degree RF phase shift in the booster

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.

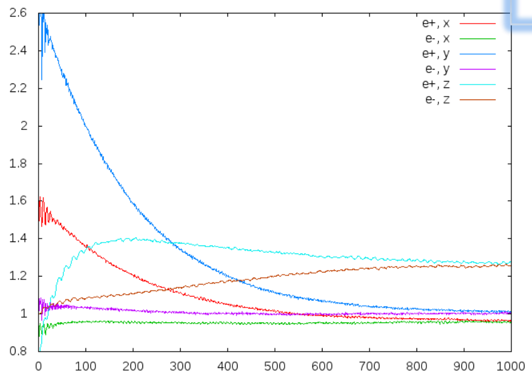
The on-axis injection



Y. Zhang



K. Ohmi



D. Shatilov

Even with the conditions:

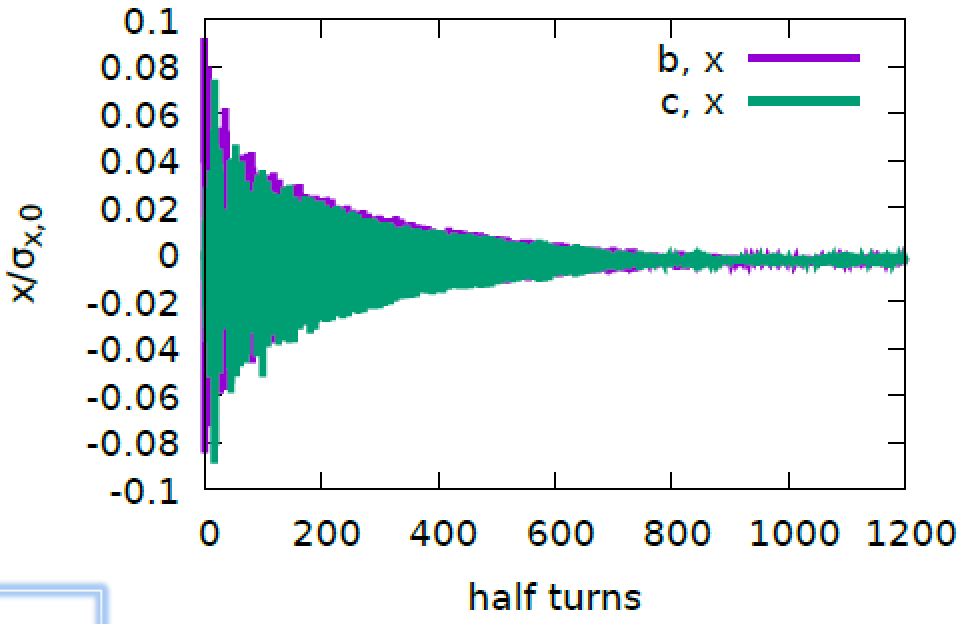
Horizontal offset 9% sigma_X

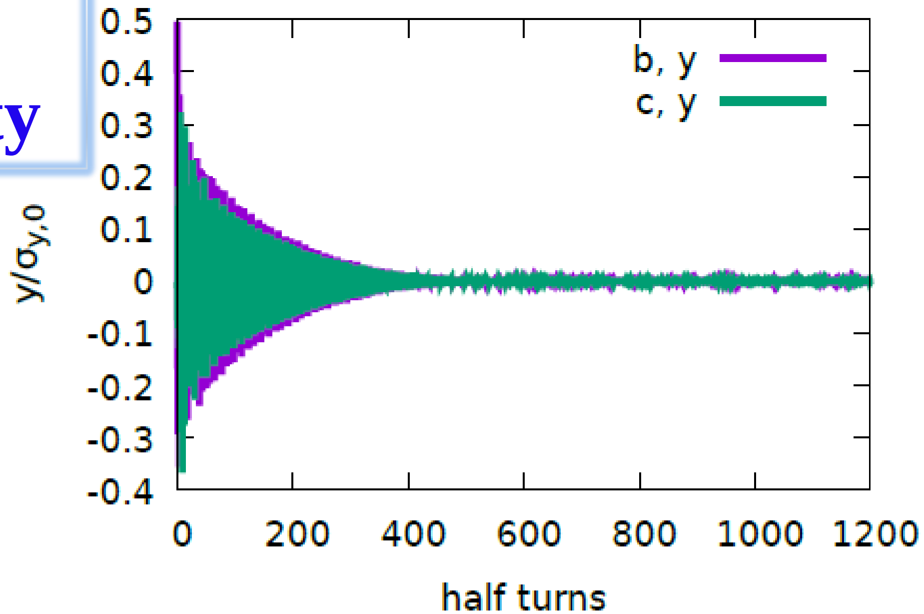
Vertical offset 50 % sigma_Y

Intensity difference 3%

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

Collision is stable



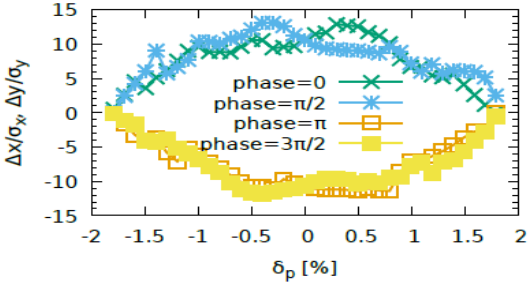


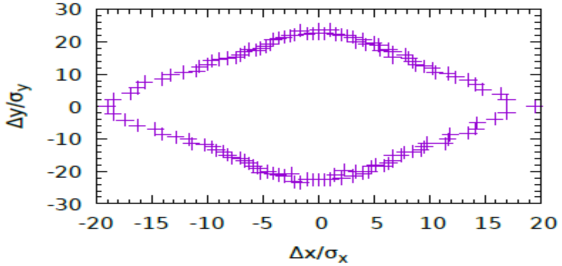
Beam performance of collider ring

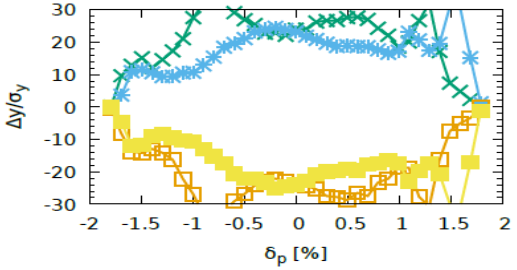
Dynamic aperture optimization

Higgs mode

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



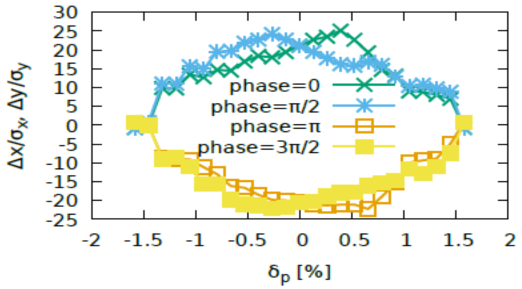


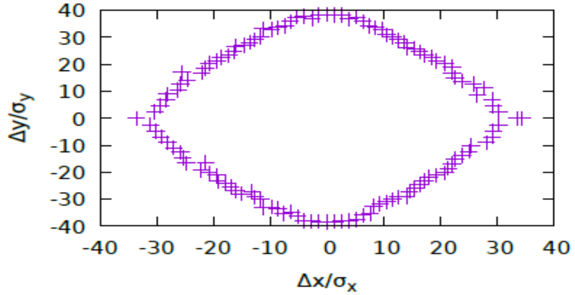


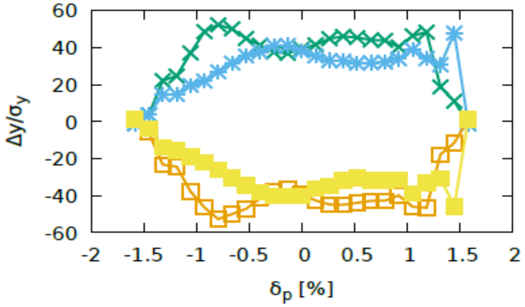
$20\sigma_x \times 23\sigma_y$ & 0.018 without errors

W mode

$15\,\sigma_x \times 9\sigma_y$ & 0.009



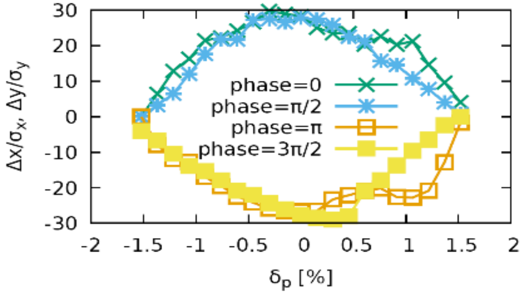


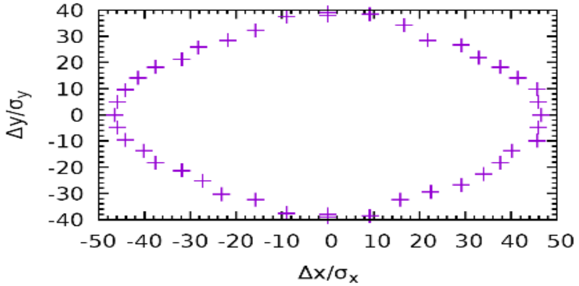


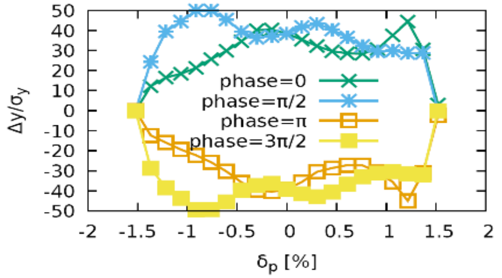
$32\sigma_x \times 40\sigma_y$ & 0.015 without errors

Z mode

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







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

Beam performance of collider ring

Dynamic aperture optimization

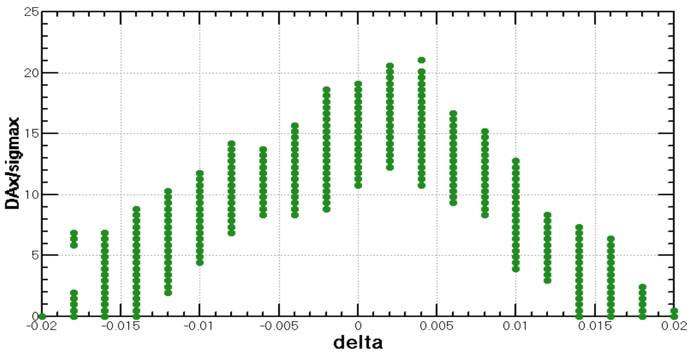
Crab waist=100%

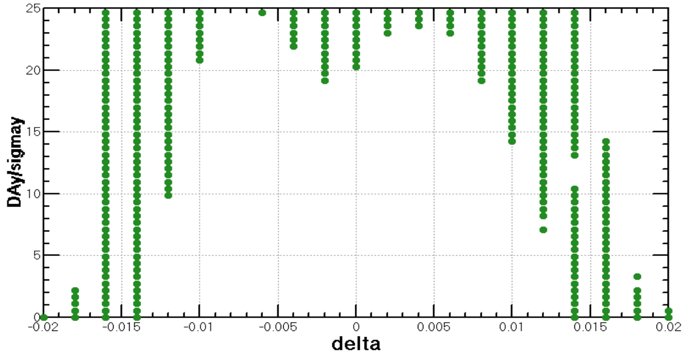
- SAD is used KEK
- 145 turns tracked
- 100 samples
- **IR sextupoles + 32 arc sextupoles**

  (Max. free various=254)
- Damping at each element
- RF ON
- Radiation fluctuation ON
- Sawtooth on with tapering
- **The requirements**

  $\mathbf{8\,\sigma_x \times 15\sigma_y\,\&\,0.0135}$

Higgs mode with errors





$\mathbf{11\sigma_x \times 19\sigma_y\,\&\,0.014}$

Component	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.05	0.05	0.15	0.2	0.2	0.1	0.01%
Quadrupole	0.03	0.03	0.15	0.2	0.2	0.1	0.02%

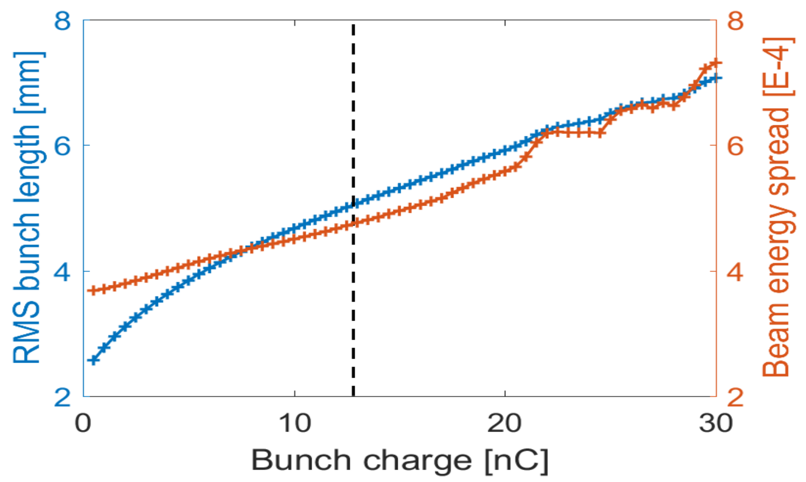
Errors setting of misalignment and field for the collider ring.

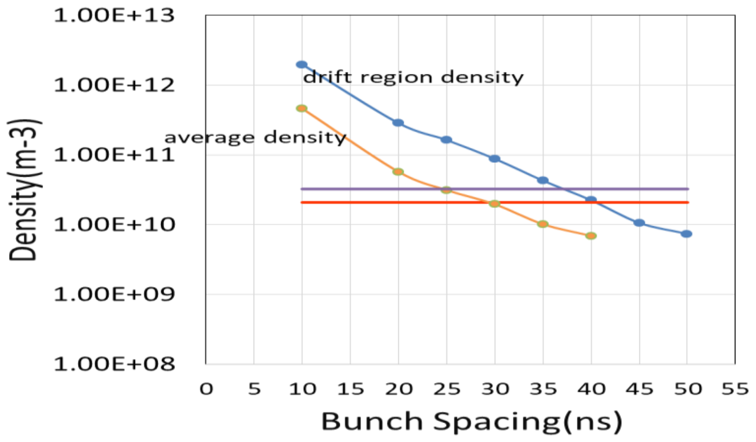
After close orbit and optics correction, the RMS close orbits in the arcs are smaller than 30 μm horizontally and 50 um vertically. The beta beatings are less than 1% and the coupling can be controlled under 0.26%.

Beam performance of collider ring

The impedance and instabilities

Components	Number	$Z_{\|}/n$, mΩ	k_{loss}, V/pC	ky, 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**



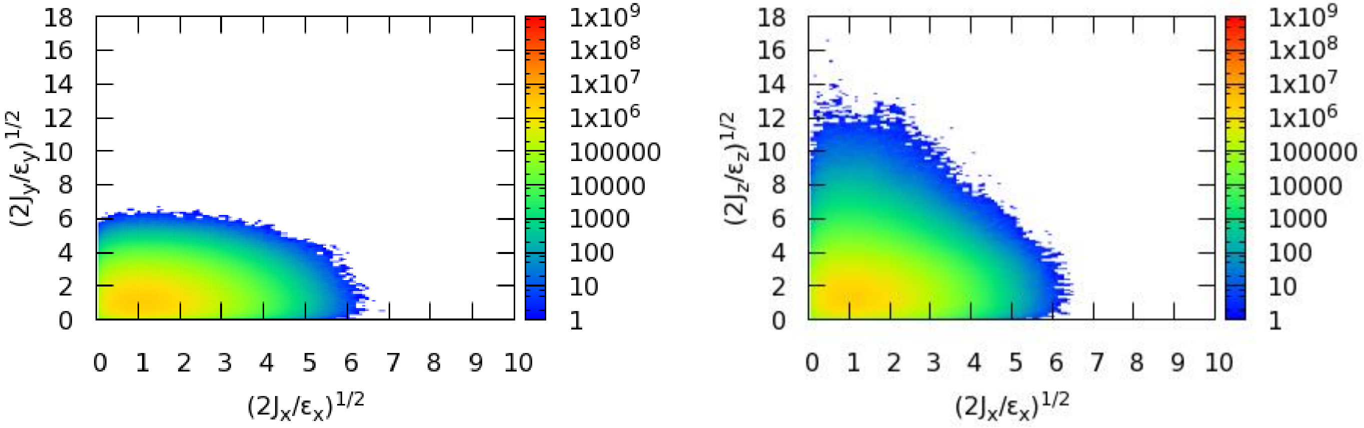


At the design bunch intensity, the bunch length will increase 22% and 113% for H and Z respectively. Bunch spacing >25ns will be needed to eliminate the electron cloud instability.

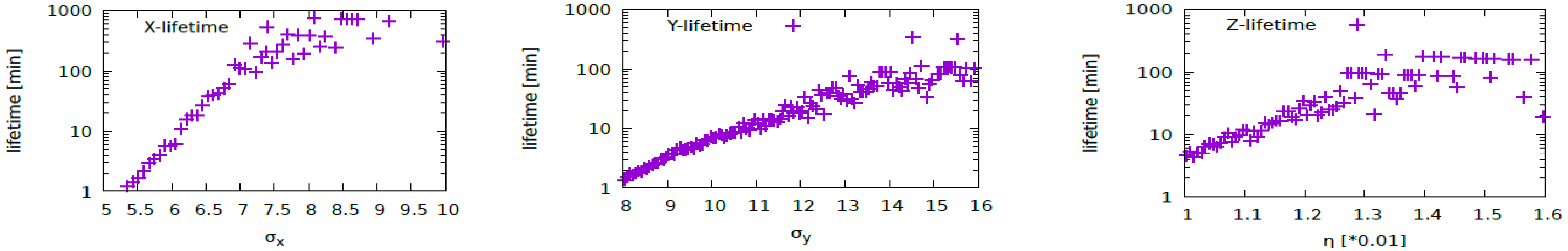
Beam performance of collider ring

Beambeam effect

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



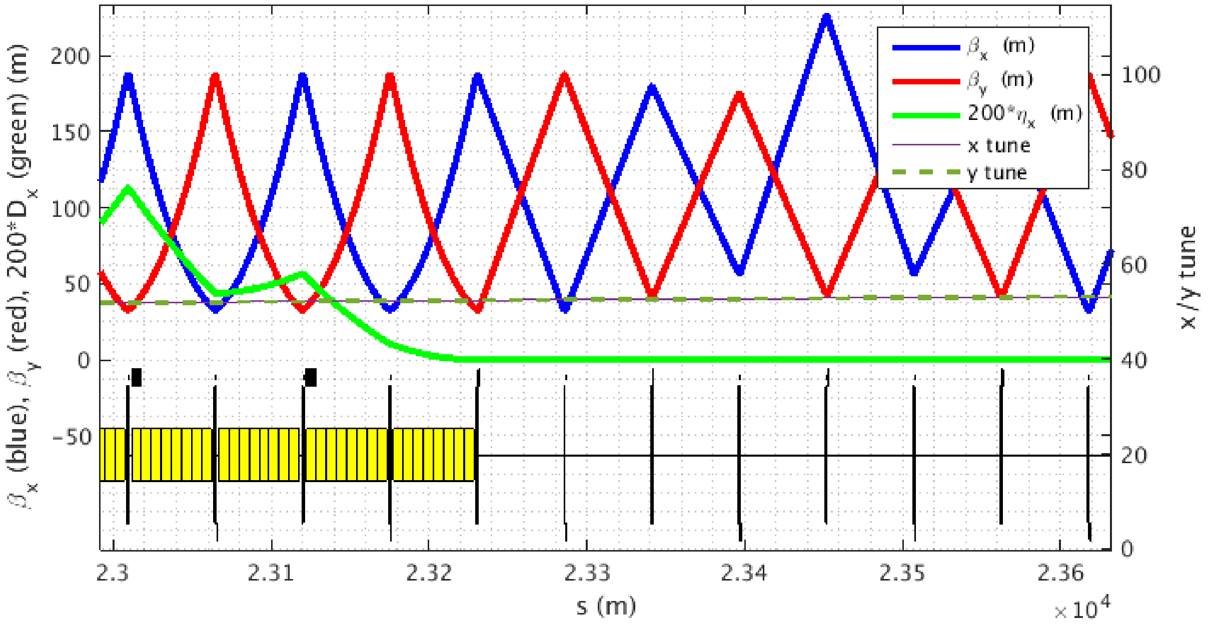
Beam tail distribution with crab-waist collision.

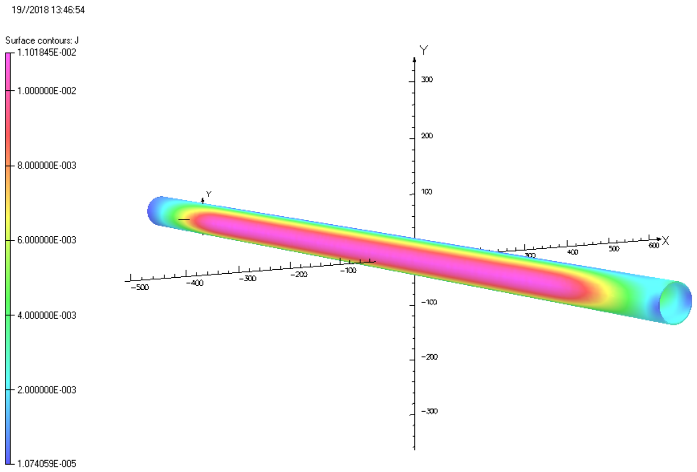


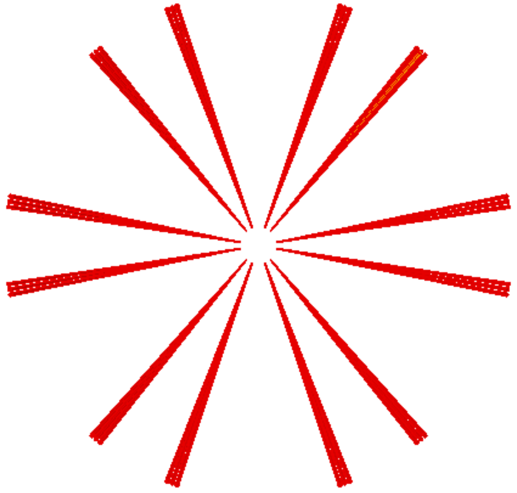
Lifetime with real lattice and beam-beam interaction at Higgs

Injection chain

Booster ring







- The diameter of the inner aperture of the vacuum chamber is chosen to be 55 mm from considerations of impedance to improve the threshold of bunch current.
- Standard FODO cells are chosen for the booster lattice with 90 degrees phase advance of each cell in the horizontal and vertical planes.
- Sextupole coils are considered on the outside of vacuum chamber to compensate the effect of eddy current.

Injection chain

Booster ring

Main parameters of CEPC booster at injection energy

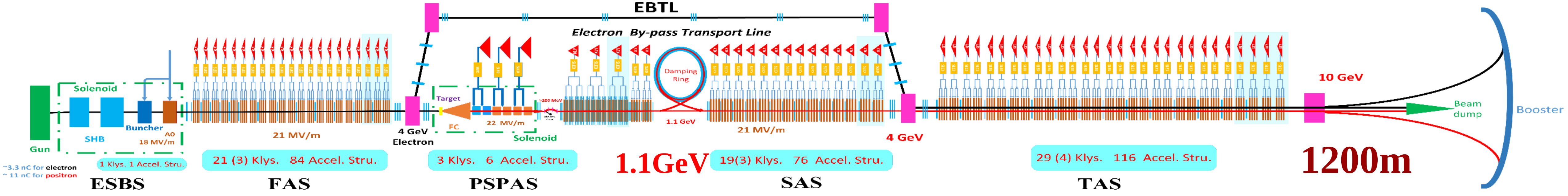
		H	*W*	*Z*
Beam energy	GeV	10		
Bunch number		242	1524	6000
Threshold of single bunch current	μA	25.7		
Threshold of beam current (limited by coupled bunch instability)	mA	100		
Bunch charge	nC	0.78	0.63	0.45
Single bunch current	μA	2.3	1.8	1.3
Beam current	mA	0.57	2.86	7.51
Energy spread	%	0.0078		
Synchrotron 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 $\nu_x/\nu_y/\nu_s$		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		

Main parameters of CEPC booster at extraction energy

		H		*W*	*Z*
		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

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 reduced to 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+}		> 9.4×10^9 / >9.4×10^9
		nC	> 1.5
Energy spread (e^- /e^+)	σ_e		< 2×10^{-3} / < 2×10^{-3}
Emittance (e^- /e^+)	ε_r	nm· rad	< 120
Bunch length (e^- /e^+)	σ_l	mm	1 / 1
e^- beam energy on Target		GeV	4
e^- bunch charge on Target		nC	10

The engineering progress

SRF Challenges

	H	W	Z
Collider Ring	**650 MHz 2-cell cavity**		
Lumi. / IP (10^{34} $cm^{-2}s^{-1}$)	2.93	10.1	16.6 / 32.1
RF voltage (GV)	2.17	0.47	0.1
Beam current (mA)	17.4 x 2	87.7	460
Cavity number	240	108 x 2	60 x 2
SR power (MW)	30	30	16.5
2 K cavity wall loss (kW)	6.1	1.3	0.1
Booster Ring (extraction)	**1.3 GHz 9-cell cavity**		
RF voltage (GV)	1.97	0.585	0.287
Beam current (mA)	0.52	2.63	6.91
Cavity number	96	64	32
RF input power (MW) avg.	0.07	0.02	0.02
2 K wall loss (kW) avg.	0.17	0.01	0.02

- High energy, low current: high gradient, high Q, more cells, narrow bandwidth
- Low energy, high current: HOM power (less cells), parasitic loss, HOM CBI, FM CBI (low voltage, large detuning)
- Large ring: gap transient, dense beam spectrum
- Special issues with CEPC: parking cavities for W and Z, gap transient for Higgs half-fill, transient beam loading of bunch swapping for on-axis injection
- Booster cavity voltage ramp: narrow bandwidth

The engineering progress

SRF Status

- CEPC CDR SRF parameters and layout have been established in view of high Higgs priority
- Beam cavity interaction issues (FM and HOM CBI, parking cavities, RF transients of bunch gap and swapping, HOM power) are challenging but manageable, especially for Z-pole.
- SRF key components design and R&D launched, with support of PAPS SRF facility. SRF industrialization will be synergy with SHINE and ADANES etc. in China (~ 1000 cavities in next five years).

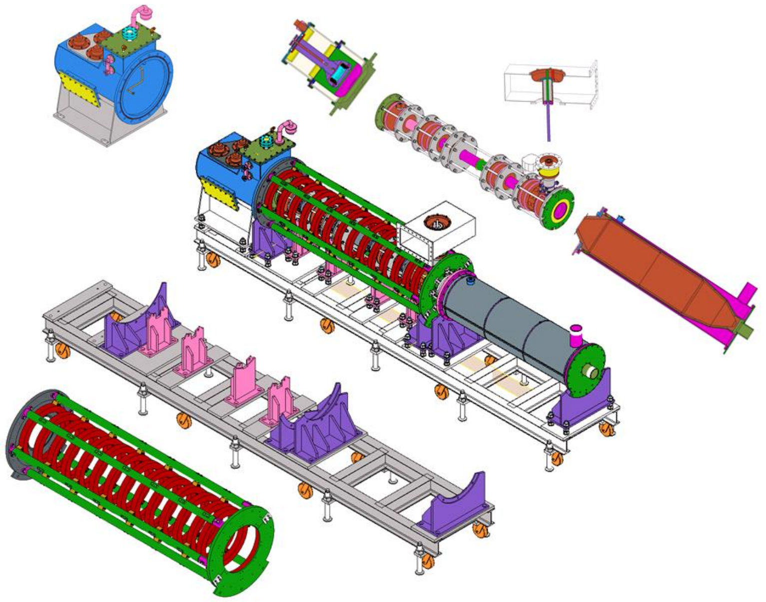
CEPC 650 MHz 2-cell cavity

The engineering progress

High efficiency klystron

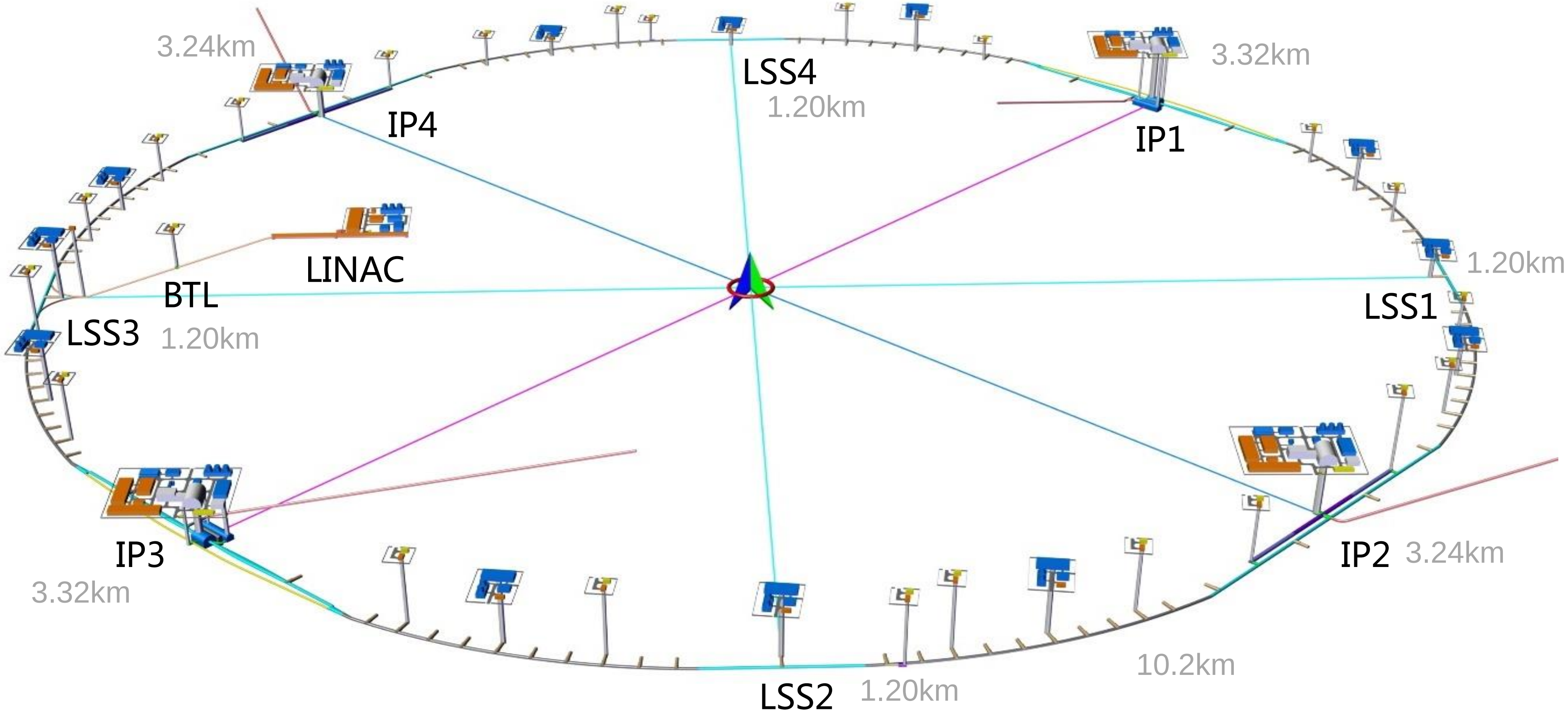
Wall to PSM power supply/modulator	95%
Modulator to klystron	96%
Klystron to waveguide	70%
Waveguide to coupler	95%
Coupler to cavity	~100%
Cavity to beam	~100%
Overall efficiency	~60.6%

- High efficiency of RF power sources is considered as a high priority issue.
- The manufacture of the first tube will be completed this year in China and 3 schemes for the high efficiency design are on going.



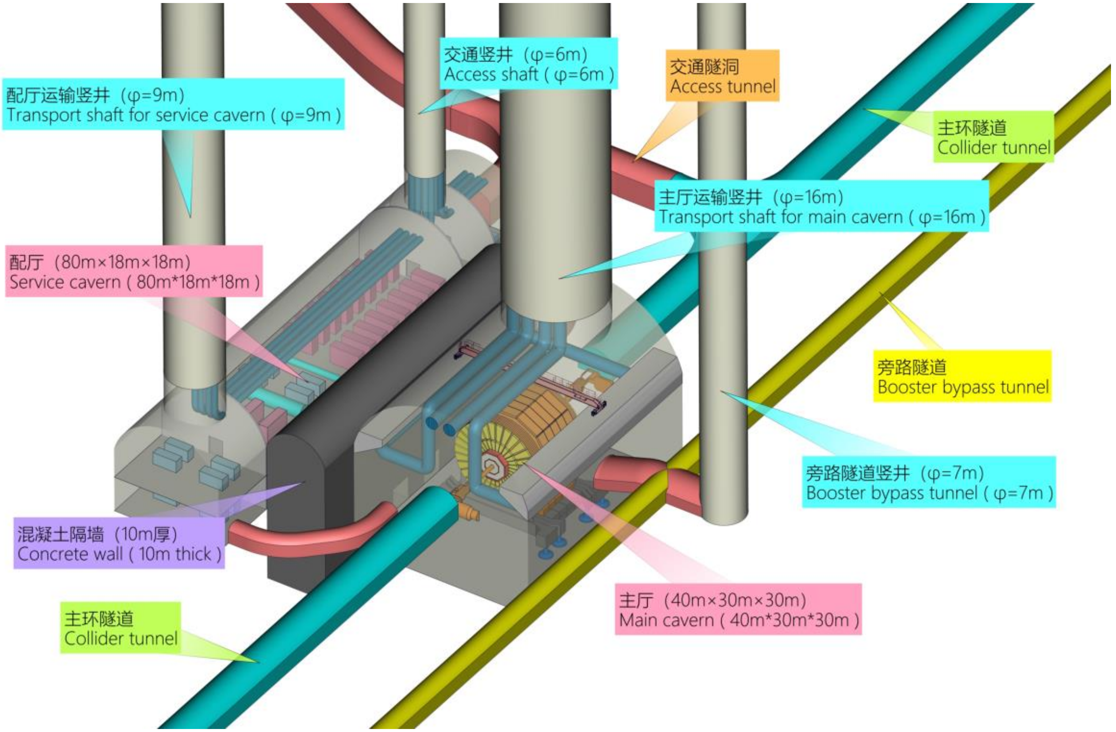
The engineering progress

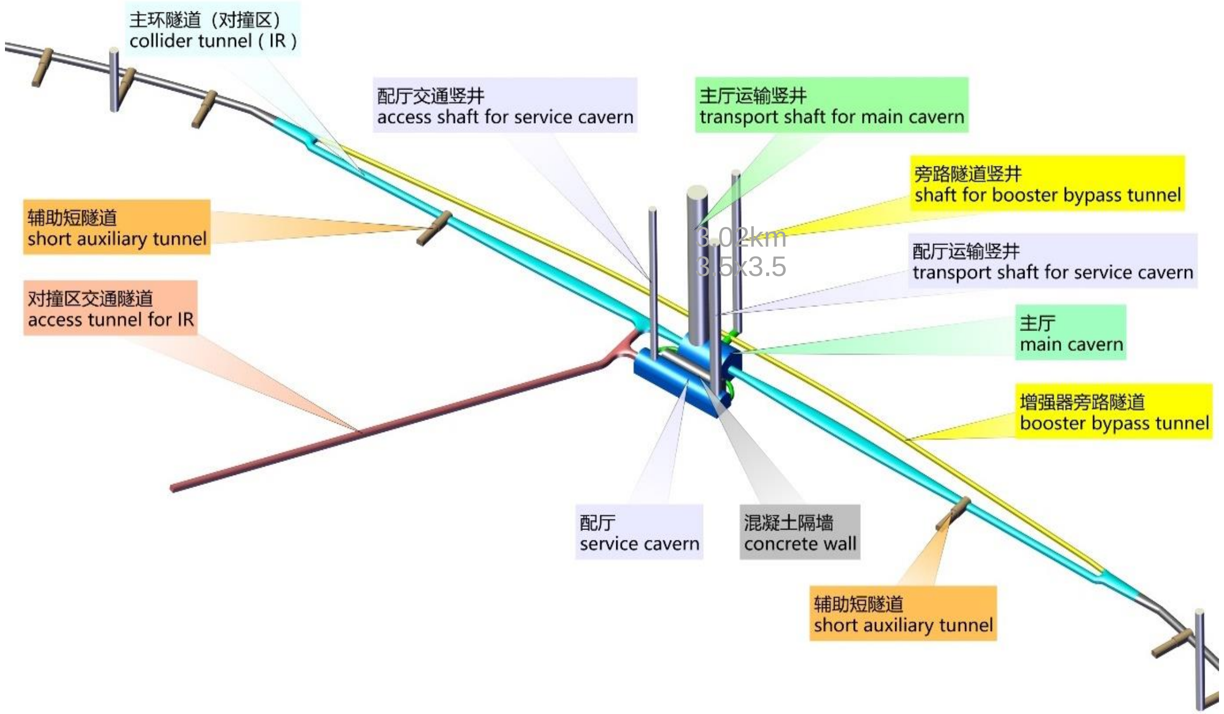
General Civil Layout



The engineering progress

CEPC Tunnel





Summary

- CEPC Accelerator CDR has been completed (formally released on Sept 2, 2018) with all systems reaching the design goals.
- A preliminary procedure for the IP elements assembly has been studied.
- Low magnetic field problem, eddy current effect, simulation with errors , mechanical optimization of IR, etc. are still under studying.
- We are on the road to TDR.