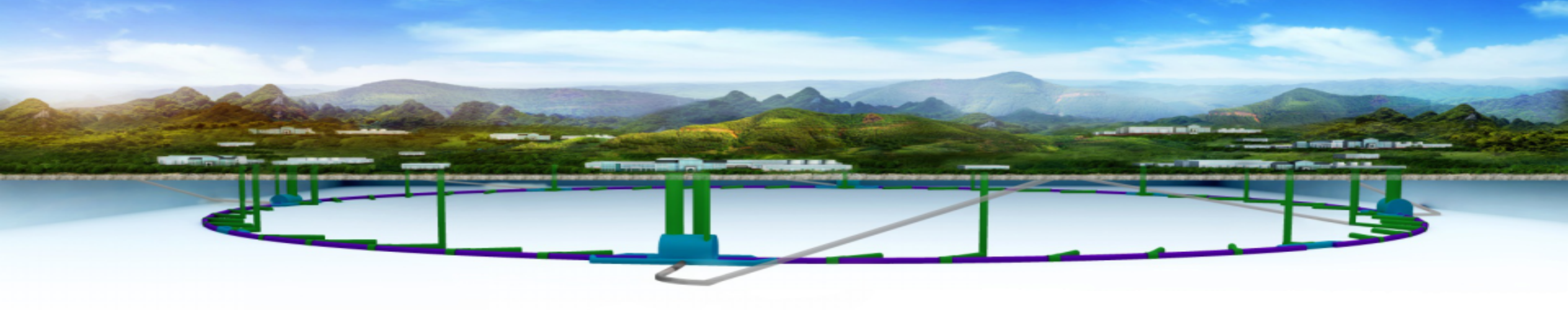


R&D status of CEPC Accelerator

Yunlong Chi

On behalf of CEPC Accelerator Team

Institute of High Energy Physics

10TH INTERNATIONAL PARTICLE ACCELERATOR CONFERENCE

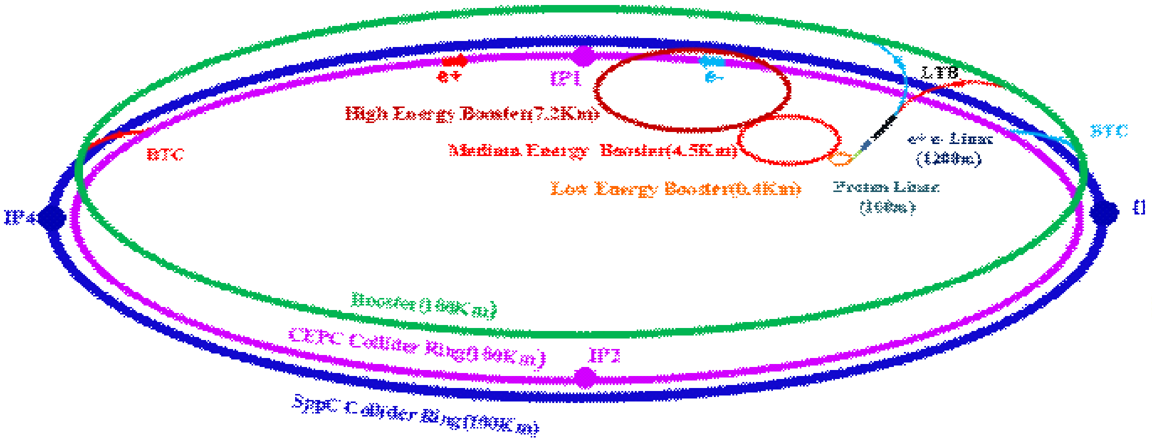
19 – 24 MAY 2019

Hosted by ANSTO's Australian Synchrotron at the Melbourne Convention & Exhibition Centre

IPAC19

Contents

CEPC as a Higgs Factory
(Z,W and followed by SppC)

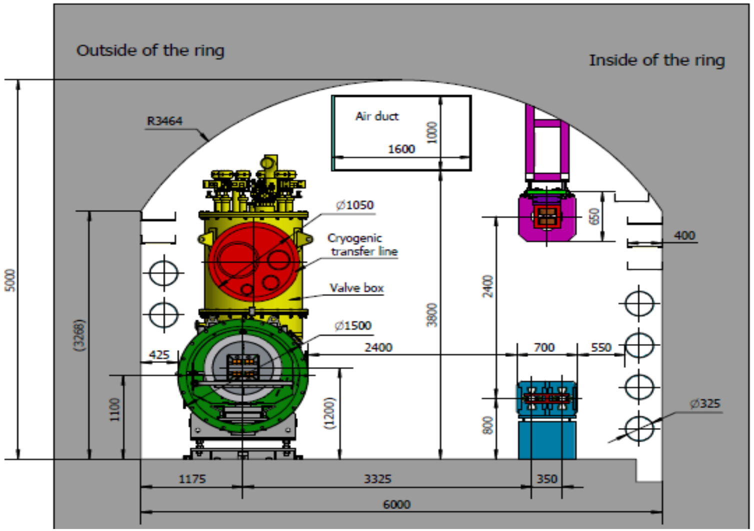


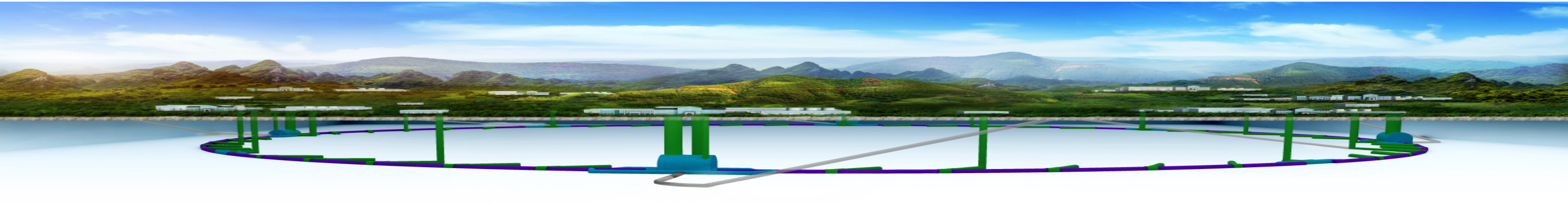
LTB : Linac to Booster

BTC : Booster to Collider Ring

CEPC Linac injector , 1.2km , 10GeV
CEPC booster ring , 100km , 10 -> 45/120GeV
CEPC collider ring , 100km , 45/120GeV

TUNNEL CROSS SECTION OF THE ARC AREA





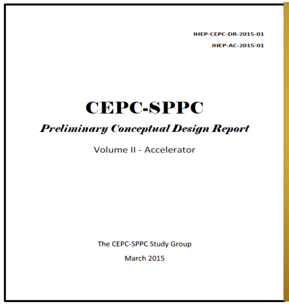
Physics Goals of CEPC-SppC

- Circular Electron-Positron Collider (91, 160，240 GeV)
  - Higgs Factory（10^6 Higgs）:
    - Precision study of Higgs (m_H, J^{PC}, couplings)，Similar & complementary to ILC
    - Looking for hints of new physics
  - Z & W factory（10^{10} Z^0）:
    - precision test of SM
    - Rare decays ?
  - Flavor factory: b, c, t and QCD studies
- Super proton-proton Collider(~100 TeV)
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Precision measurement + searches: Complementary with each other !

CEPC accelerator CDR completed and released on Sept. 2, 2018

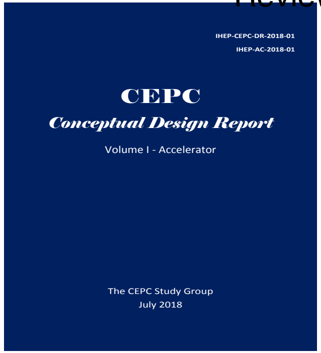
- Executive Summary
1. Introduction
2. Machine Layout and Performance
3. Operation Scenarios
4. CEPC Collider
5. CEPC Booster
6. CEPC Linac
7. Systems Common to the CEPC Linac, Booster and Collider
8. Super Proton Proton Collider
9. Conventional Facilities
10. Environment, Health and Safety
11. R&D Program
12. Project Plan, Cost and Schedule
- Appendix 1: CEPC Parameter List
- Appendix 2: CEPC Technical Component List
- Appendix 3: CEPC Electric Power Requirement
- Appendix 4: Advanced Partial Double Ring
- Appendix 5: CEPC Injector Based on Plasma Wakefield Accelerator
- Appendix 6: Operation as a High Intensity γ-ray Source
- Appendix 7: Operation for e-p, e-A and Heavy Ion Collision
- Appendix 8: Opportunities for Polarization in the CEPC
- Appendix 9: International Review Report



March 2015

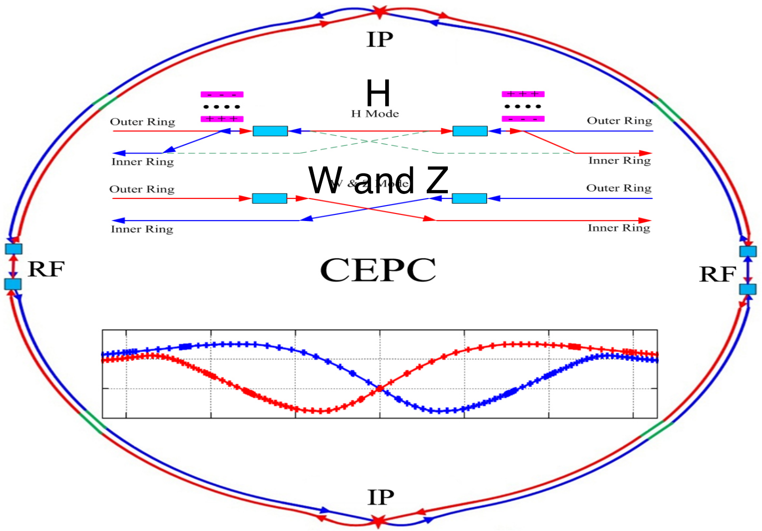
April 2017

Draft CDR for Mini International Review in Nov. 2017

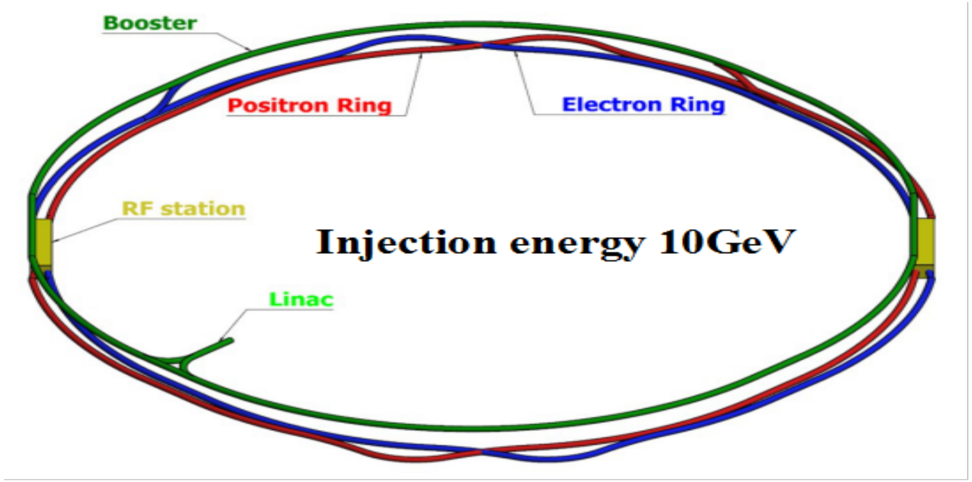


CDR Version for International Review June 2018, and formally relased on Sept. 2, 2018:arXiv：1809.00285, http://cepc.ihep.ac.cn/CDR_v6_201808.pdf

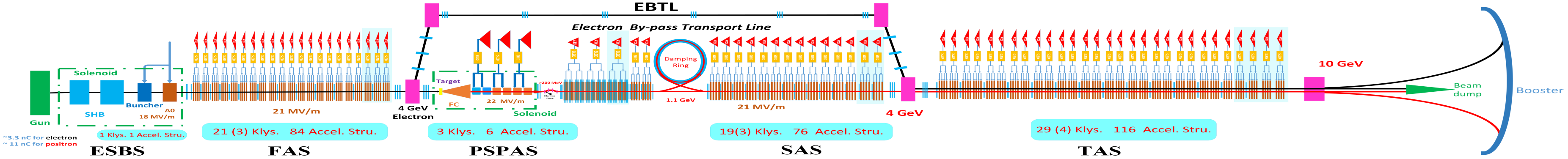
CEPC CDR Baseline Layout



CEPC collider ring (100km)



CEPC booster ring (100km)



CEPC Linac injector (1.2km, 10GeV)

CEPC CDR Parameters

	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	2.58	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)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
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)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	**1.94**	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	**1.35**	**0.4**	**0.23**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	**0.67**	**1.4**	**4.0**	**2.1**
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**

CEPC Accelerator Key technology R&D

- Polarized electron gun
  - Super-lattice GaAs photocathode DC-Gun
- High current positron source
  - bunch charge of ~3nC,
  - 6Tesla Flux Concentrator peak magnetic field
- High gradient accelerating tube
  - 30Mev/m for S-band structure
  - 50Mev/m for C-band structure（option）
- High Q SC Cavity and High power coupler
  - Max operation Q0 = 2E10 @ 2 K
  - High power coupler: 300kW/ 650MHz
- High efficiency Klystron
  - ~ 80% goal for 650MHz/ 800kW klystron
- Large Scale Cryogenics
  - 12 kW @4.5K refrigerator, Oversized,
  - Custom-made, Site integration
- Low field dipole magnet for booster
  - Lmag=4m, Bmin=31Gs, Errors <5E-4
- IR region QD0
  - Field gradient 200T/m， magnetic length 1.46m
  - Central field 13T
- Electro-static separator for deflect the e+ and e- bunches
  - Maximum operating field strength: 2MV/m
  - Maximum deflection: 145 urad
- Vacuum system
  - Dipole copper chamber
  - RF shielding bellows
  - NEG coating
- HTS magnet
  - Advanced HTS Cable R&D: > 10kA
  - Advanced High Field HTS Magnet R&D: main field 12~12T

CEPC Accelerator R&D Funding (~ 318 M CNY)

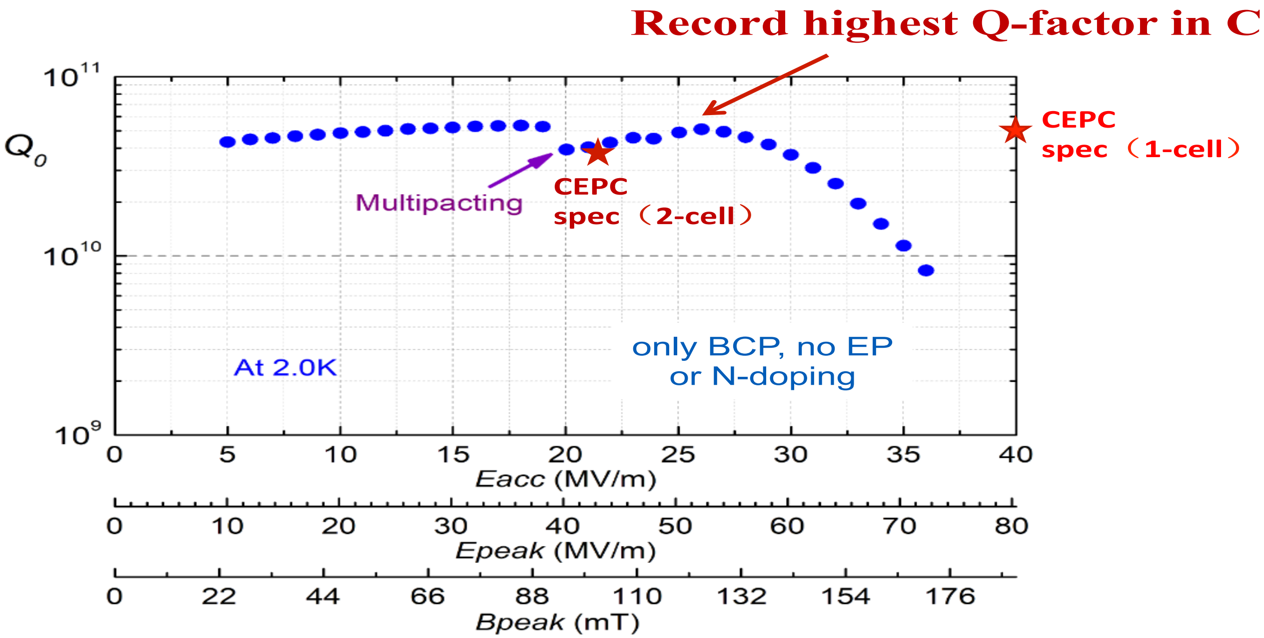
- IHEP Innovation fund: ~ 6.5 M CNY
  - High Q cavity R&D
  - Digital BPM R&D
- MOST Key R&D fund (2016~2021): ~ 11.5 M CNY
  - SRF Technology R&D
  - Injector key technology R&D
- MOST Key R&D fund (2018~2023): ~ 30 M CNY
  - Booster low field magnet
  - Vacuum pipe
  - Electro static separator
  - Polarization
- PAPS (Platform of Advanced Photon Source Technology R&D): ~ 210 M CNY
  - SRF infrastructure construction
  - SRF Technology R&D
  - High power test (SRF Cavity and High efficiency klystron)
- Scientist studio & Outstanding center: ~ 60 M CNY
  - 650MH/ 800kW/80% klystron development
  - PWFA R&D
  - etc.

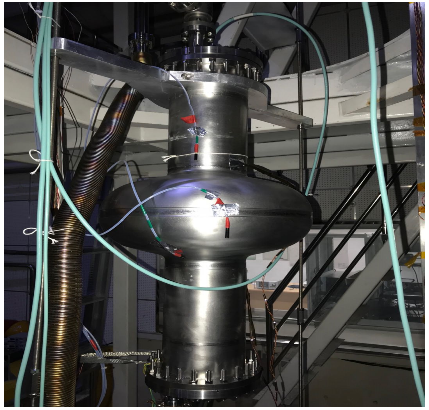
CEPC SRF R&D Plan (2017-2022)

- **Two small Test Cryomodules** (650 MHz 2 x 2-cell, 1.3 GHz 2 x 9-cell)
- **Two full scale Prototype Cryomodules** (650 MHz 6 x 2-cell, 1.3 GHz 8 x 9-cell)
- **Schedule:**
  - 2017-2018 (key components, IHEP Campus)
    - high Q 650 MHz and 1.3 GHz cavities, N-doping + EP
    - 650 MHz variable couplers (300 kW) , 1.3 GHz variable couplers (10 kW)
    - high power HOM coupler and damper, fast-cool-down and low magnetic module, reliable tuner
  - 2019-2020 (test modules integration, Huairou PAPS)
    - Horizontal test 16 MV/m, $Q_0 > 2E10$
    - beam test 1~10 mA
  - 2021-2022 (prototype modules assembly and test, Huairou PAPS)

650MHz 1-cell cavity R&D

- Accelerating gradient (Eacc) reach 36.0 MV/m， Q = 5.1E10 @ Eacc = 26 MV/m。
- Next, increase the Q and Eacc through N-doping, EP, etc. Target: 5E10@42MV/m for vertical test.

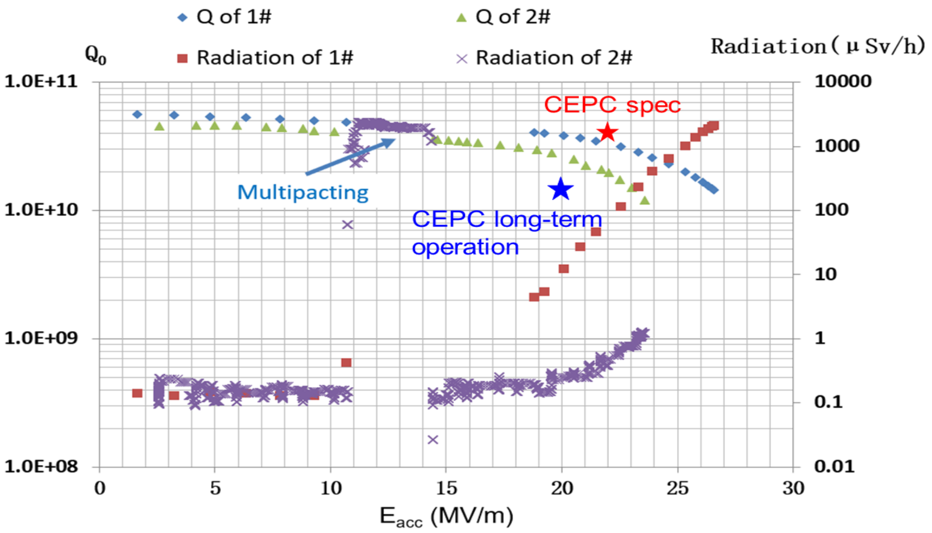




650 MHz 1-cell cavity

650MHz 2-cell cavity R&D

- 650 MHz 2-cell cavity (BCP without Nitrogen-doping) reached 3.2E10 @ 22 MV/m (Nearly reached CEPC collider cavity vertical test spec 4E10 @ 22 MV/m)
- Nitrogen-doping and EP on 650 MHz cavity under investigation.

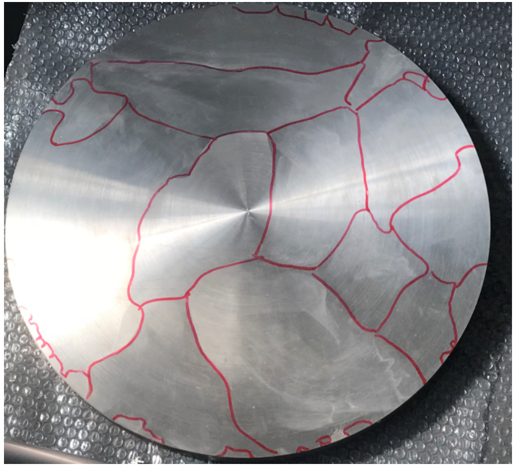


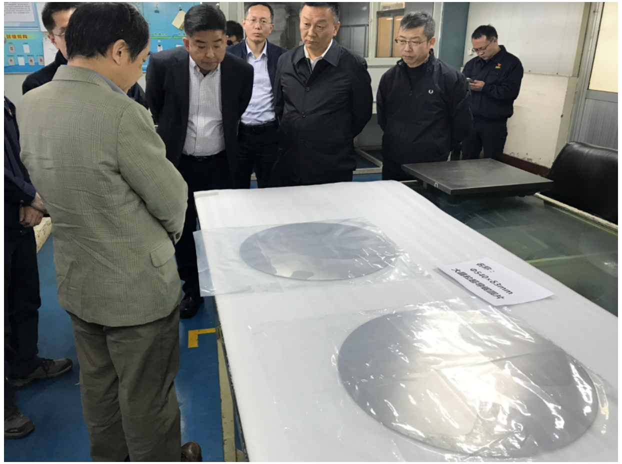
CEPC 650 MHz 2-cell cavity by HERT

CEPC 650 MHz 2-cell cavity by OTIC

650MHz Large grain cavity R&D

- 650 MHz 1-cell cavity (large grain) is favorable for HL-Z, which have higher Q and gradient than fine grain.
- Target of Vertical test: 5E10 @ 42MV/m at 2.0 K.
- Four cavities are under fabrication now, which will be tested in the middle 2019.

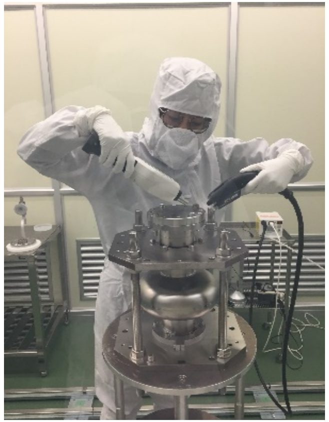


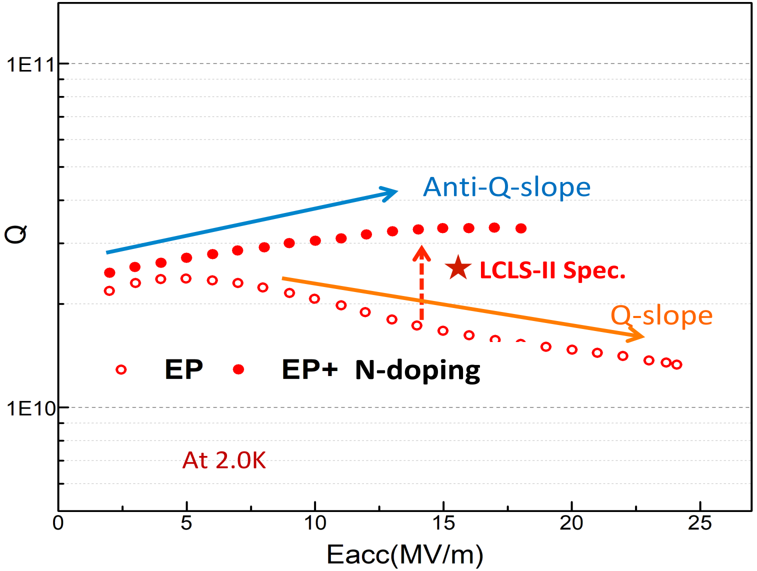


Large grain Nb sheets made by OTIC

N-doping of 1.3GHz cavity

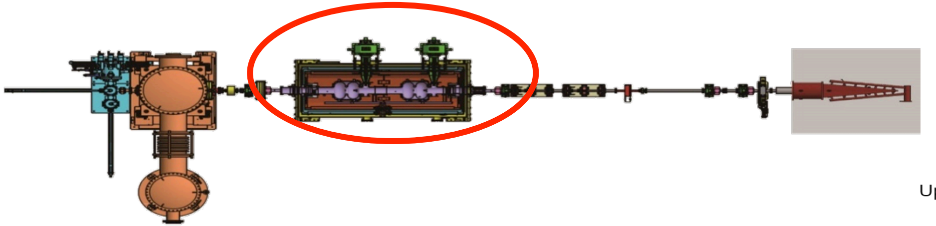
- After N-doping, 1.3 GHz 1-cell cavity reached 3.3E10 @ 18MV/m, twice of baseline Q, which exceeded LCLS-II Spec (2.7E10 @ 16MV/m) domestically for the first time. This result is also very exciting for Shanghai hard X-FEL (SHINE), which have a 8-GeV SRF LINAC and adopted N-doping as baseline.
- This work is collaborated with KEK colleagues.

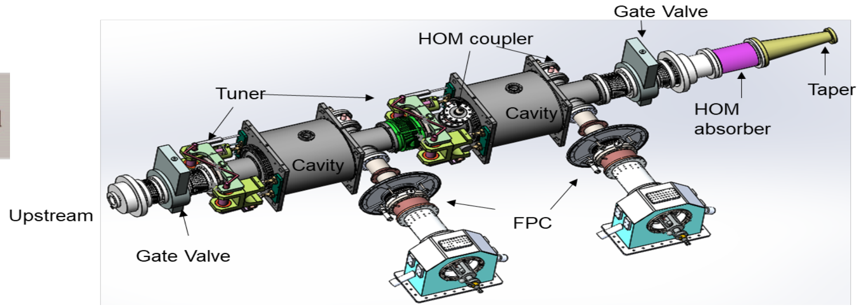


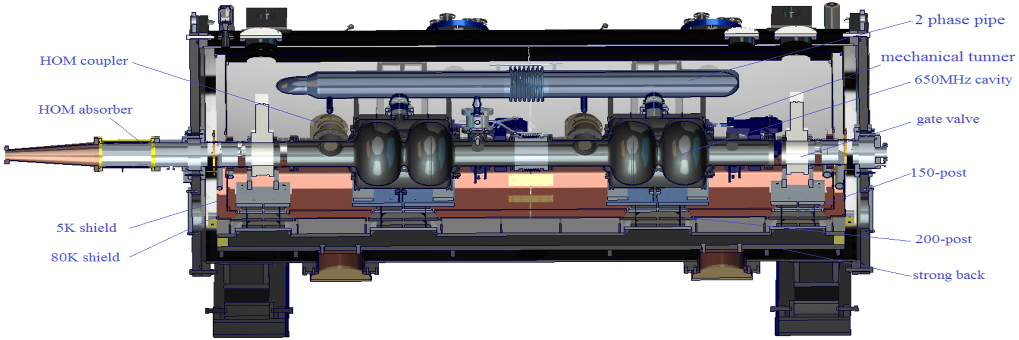


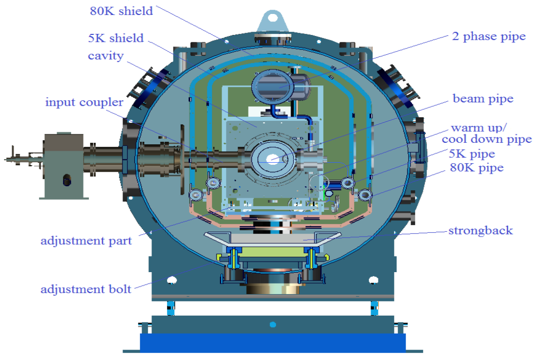
CEPC Collider Test Cryomodule

- Cryomodule with two 650 MHz 2-cell cavities: in fabrication, assemble in 2019
- Beam test with DC photo cathode gun (CW 10 mA) in 2020 at new PAPS SRF lab



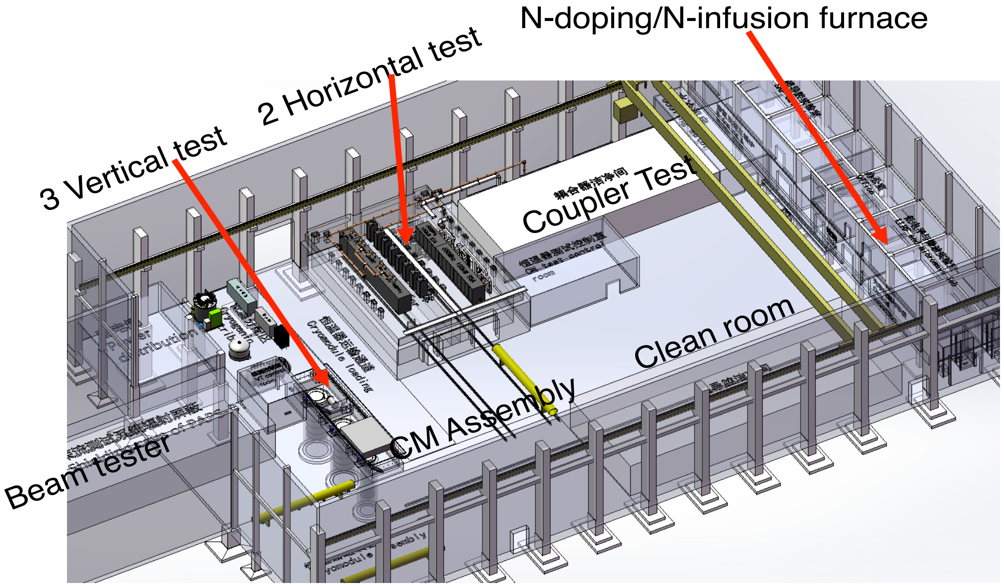






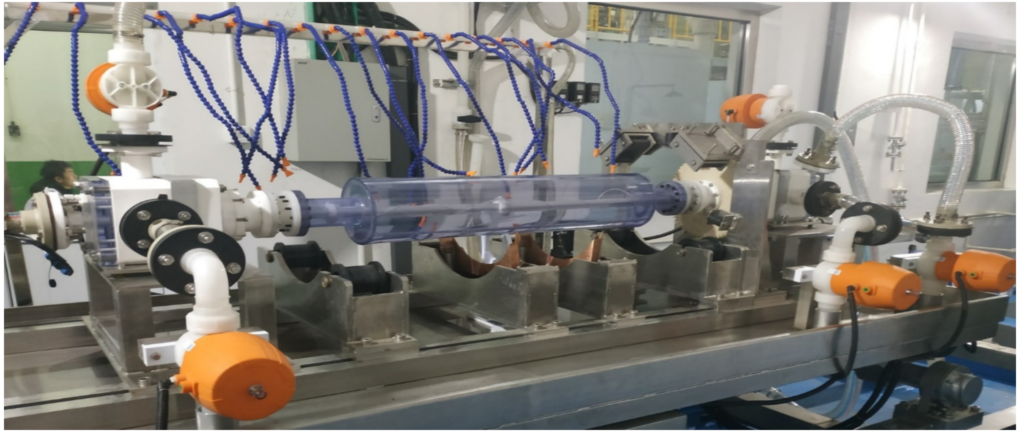
IHEP New SRF Infrastructure

- **4500 m^2 SRF lab** in the **PAPS** (Platform of Advanced Photon Source Technology R&D), Huairou Science Park, Beijing.
- **Mission** to be World-leading SRF Lab for Superconducting Accelerator Projects and SRF Frontier R&D.
- **Mass Production**:
  - 200 ~ 400 cavities & couplers test per year
  - 20 cryomodules assembly and horizontal test per year
- **Construction : 2017 - 2020**



EP system construction

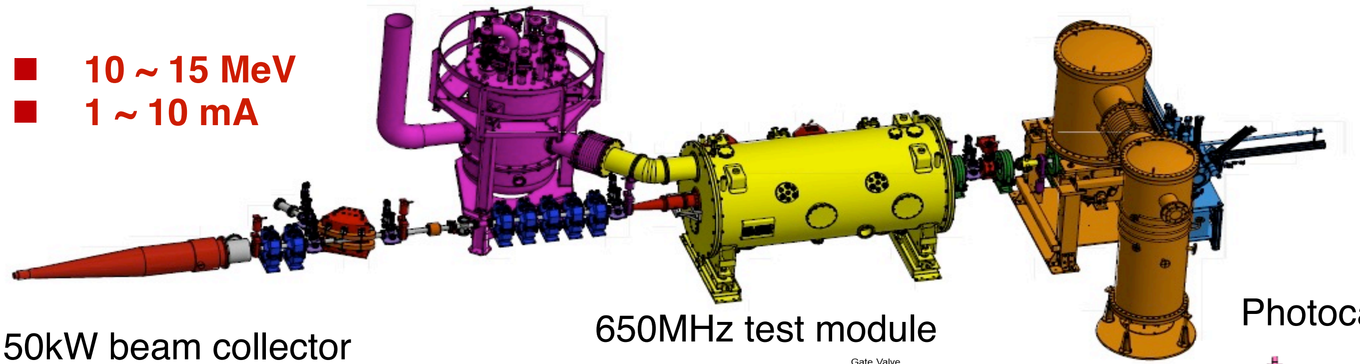
- Horizontal
- Compatible: 500MHz single cell, 1.3GHz up to 9 cell , 650MHz up to 5 cell



PAPS Beam Tester

- Beam test system is based on **a photocathode DC-Gun** and **a 650MHz test module** powered by a high efficiency klystron
- Research and development of key equipment for advanced accelerator technology and beam experiment
- Technical verification for a 650MHz small test module
- Building a high power testing platform for high efficiency klystron

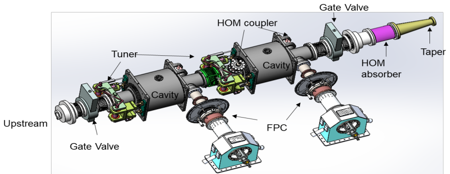
- **10 ~ 15 MeV**
- **1 ~ 10 mA**

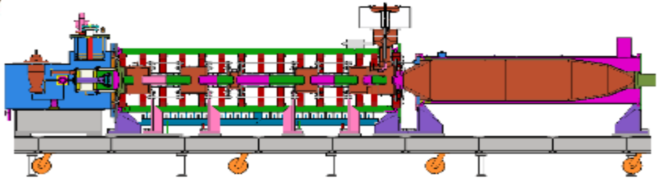


150kW beam collector

650MHz test module

Photocathode DC-Gun



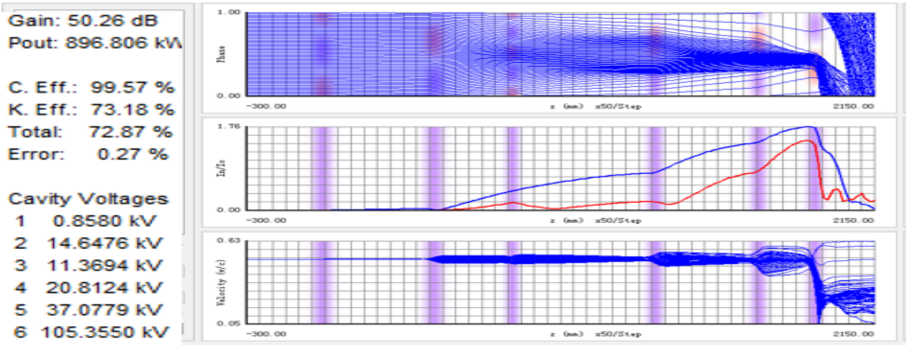


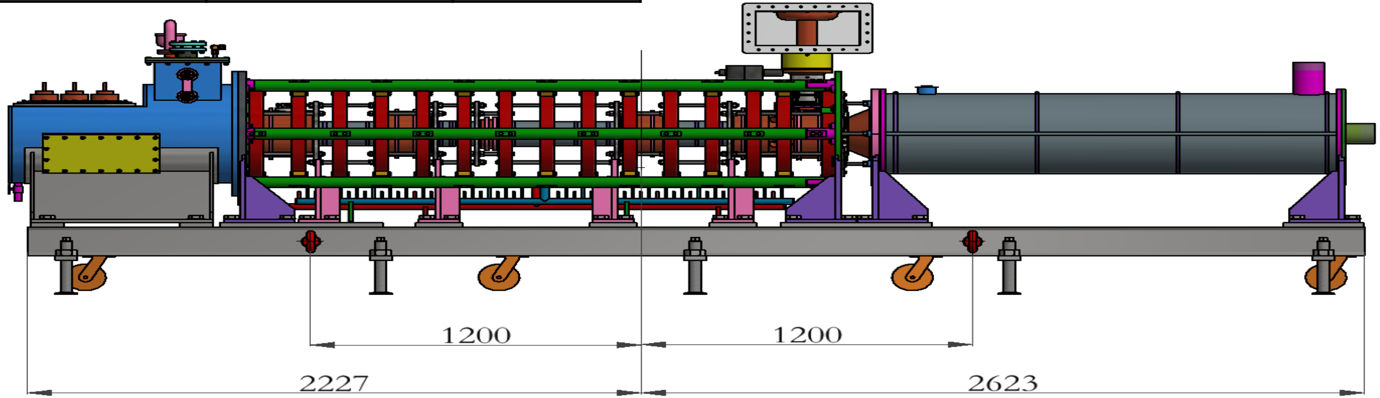
High Efficiency Klystron Development

- Jun. 2019 : 1st prototype - conventional type
- Aug. 2019 : Start Test

⇨ 73%/68%/65% efficiencies for 1D/2D/3D

Parameters	Conventional efficiency	High efficiency
Centre frequency (MHz)	650+/-0.5	650+/-0.5
Output power (kW)	800	800
Beam voltage (kV)	80	-
Beam current (A)	16	-
Efficiency (%)	~ 65	> 80

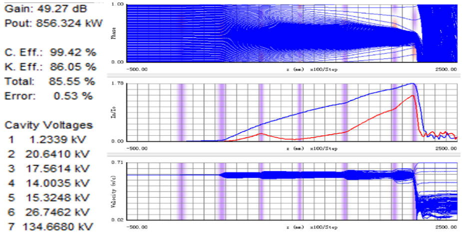




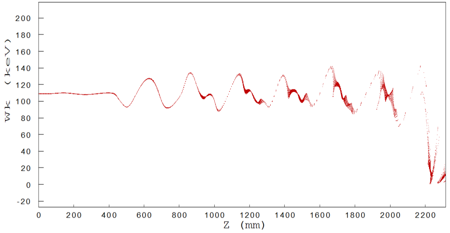
High Efficiency Klystron Development

- Jun. 2020: 2nd prototype - High efficiency
  - Single beam high voltage, 110kV/9.1A
- Multi-beam klystron consideration

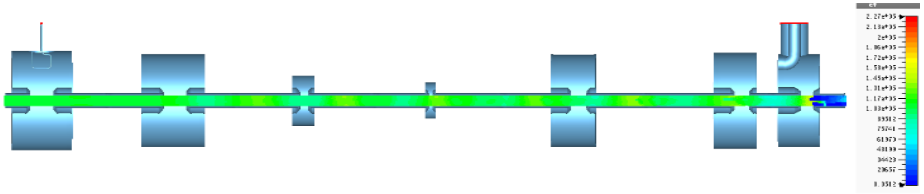
Single beam klystron@110kV/9.1A



AJDISK code/Efficiency 85.6%

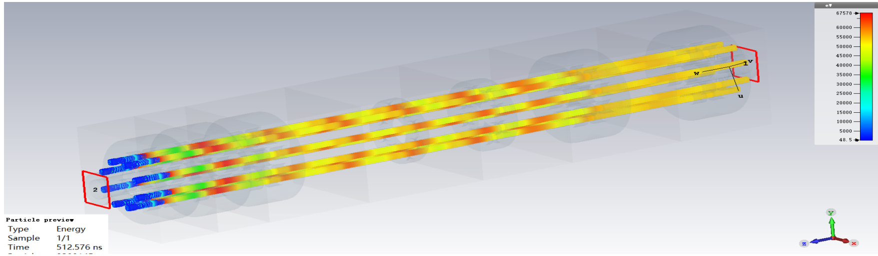


EMSYS-2.5D/Efficiency 81.4%

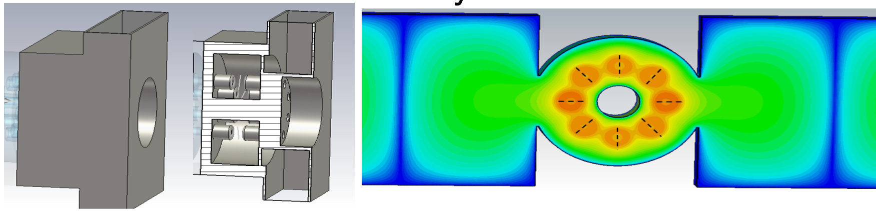


CST-3D/Efficiency>78%

Multi-beam klystron@8 beams



CST-3D/Efficiency ~80%



Cavity detailed design

High Efficiency Klystron Development

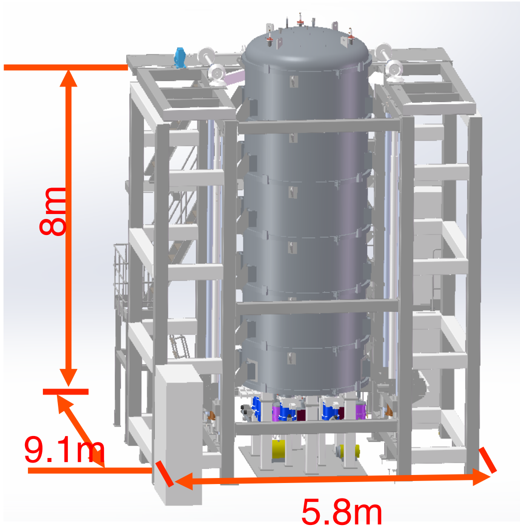
1st 650MHz Klystron Manufacturer

Modulator anode components

Cavities components

Klystron output window

Infrastructure Preparation



Furnace cover and body

Factory testing

CEPC Collider and Booster Ring Magnets

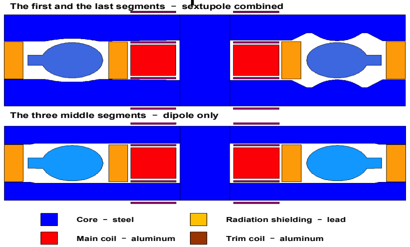
Collider ring magnets

	Dipole	Quad.	Sext.	Corrector	Total
Dual aperture	2384	2392	-	-	13742
Single aperture	80*2+2	480*2+172	932*2	2904*2	
Total length [km]	71.5	5.9	1.0	2.5	80.8
Power [MW]	7.0	20.2	4.6	2.2	34

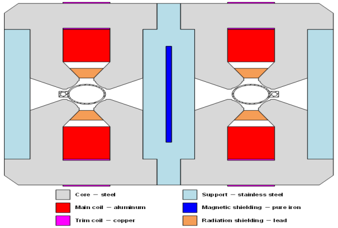
Booster ring low field magnets

Quantity	16320
Magnetic length(m)	4.711
Max. strength(Gs)	338
Min. strength(Gs)	28
Gap height(mm)	63
GFR(mm)	55
Field uniformity	5E-4

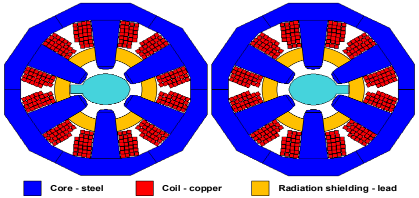
Dipole

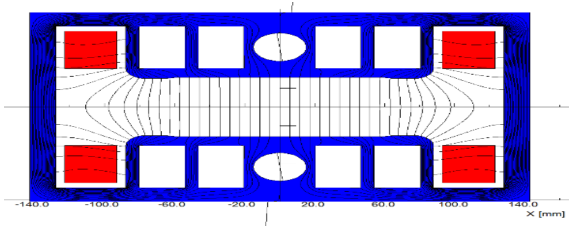


Quadruple



Sextuple

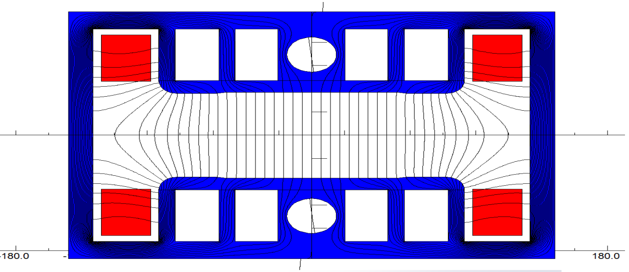


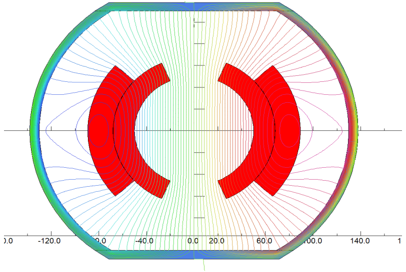


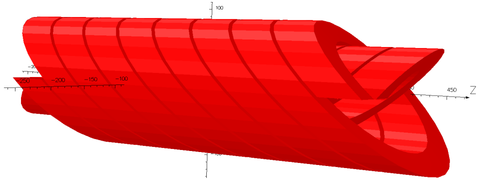
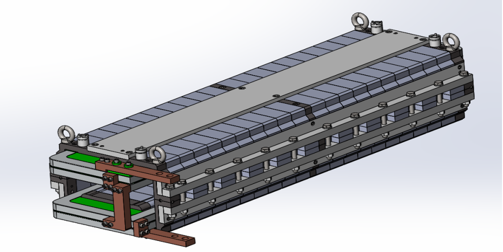
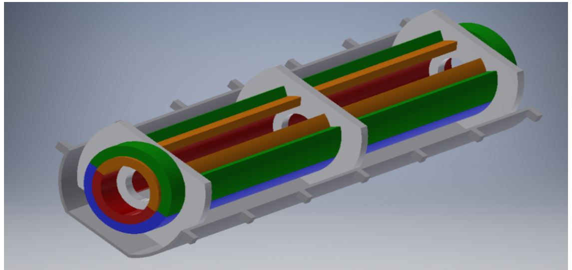
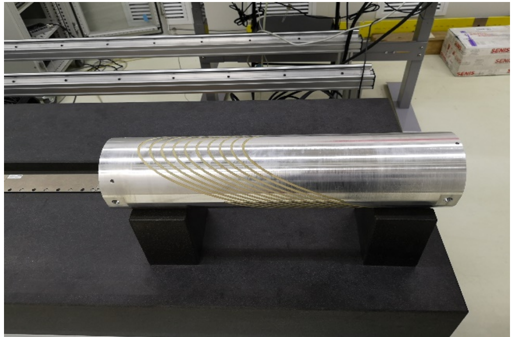
- Over 80% of collider ring is covered by conventional magnets.
- The most important issues are Cost & Power Consumption.
  - Make the magnets compact and simple.
  - Use aluminum for the coils.
  - Dual aperture magnets save nearly 50% power.
  - Consider the combined function magnets.
  - Increase the coil cross section and decrease the operating current.

Booster Low Field Dipole Magnet R&D

- From the view of the excitation efficiency at high field level, the design of the dipole magnet with iron cores is the best. To reduce the influence of the remnant field on the field quality at low field level, grain oriented silicon steel laminations will be used to stack the cores.
- The two designs (CT and CCT) of the dipole magnets without iron cores can meet the requirement of the field uniformity at low field level, they will consume more electricity power due to lower excitation efficiency at high field level .
- The dipole magnet with iron cores is easier to be produced than the dipole magnets without iron cores, so the former is cheaper to be produced than the latter ones.





Booster Low Field Dipole Magnet design parameters

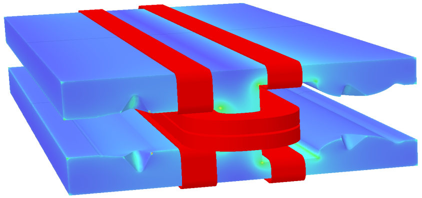
(Iron Yoke, CT, CCT)

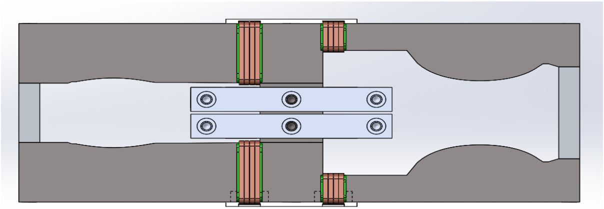
	Iron Yoke	CT	CCT
Max. field [Gs]	338	338	338
Min. field [Gs]	29	29	29
Good field region (mm)	55	55	55
Field uniformity	0.1%	0.1%	0.1%
Turns per magnet	2	4	234
Max. current (A)	856	1275	481
Min. current (A)	73	109	41
Conductor area (mm^2)	1200	1945	900
Max. current density(A/mm^2)	0.71	0.66	0.53
Max. power loss (W)	425	1320	1665
Avg. power loss (W)	170	528	666
Inductance (mH)	0.08	0.36	1.5
Magnet size（mm）	330	300	360
Magnet length (mm)	4650	4632	4865
Magnet weight (ton)	1.4	0.6	0.65

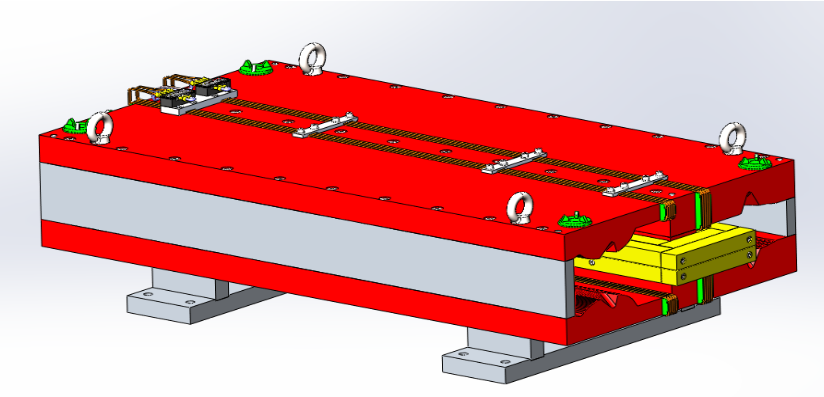
Dual aperture Dipole magnet R&D

- Requirements of the 1m prototype
  - Center field B1：141Gs @45GeV to 373Gs @120GeV
  - Difference of B_{cen} in the two apertures < 0.5%
  - Harmonics $<5\times10^{-4}$ @R=13.5mm(except the sextuple component b3)
  - Correct coil: ±1.5% adjust capability

Magnetic strength [T]		0.037
Aperture [mm]		70
Main coil	Turns	4
	Material	Aluminum
	Current [A]	563
	Current density [A/mm²]	0.7
	Power consumption [kW]	0.12
Trim coil	Turns	1×4
	Material	Copper
	Current [A]	16.7
	Current density [A/mm²]	0.093
	Power consumption [kW]	0.0005

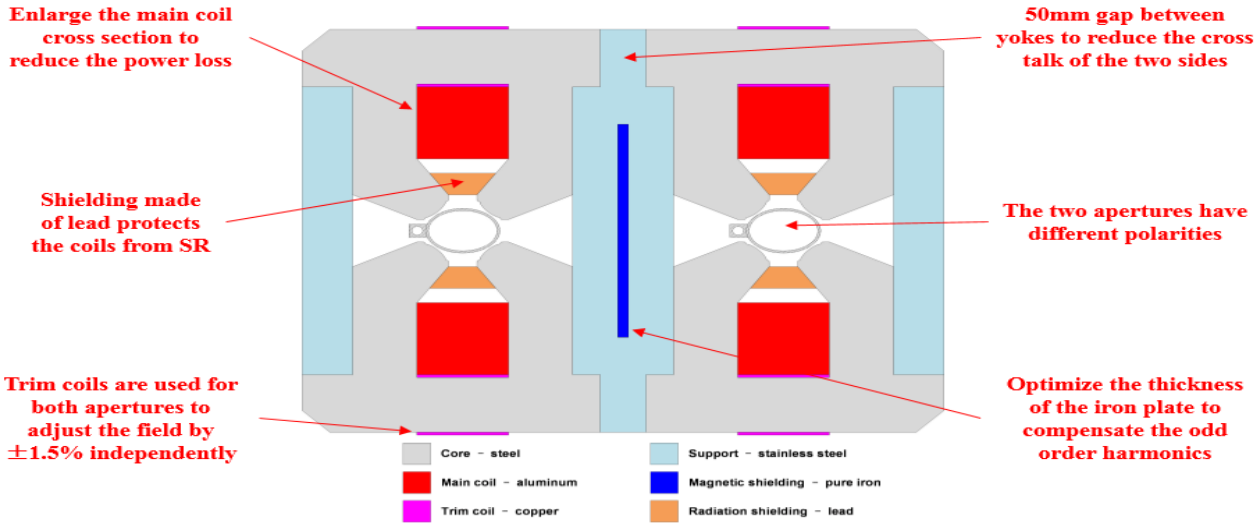






Dual aperture Quadruple magnet R&D

- Basic parameters of DAQ
  - Apertures: 76mm
  - Effective length: 1m or 2m
  - Gradient：3.2T/m@45GeV to 8.42T/m @120GeV
  - Good field region: 5×10^{-4}@Rref=12.2mm

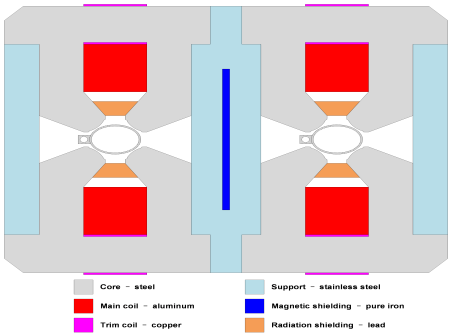


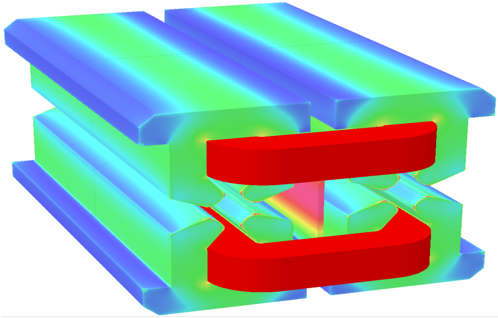
Dual aperture Quadruple magnet R&D

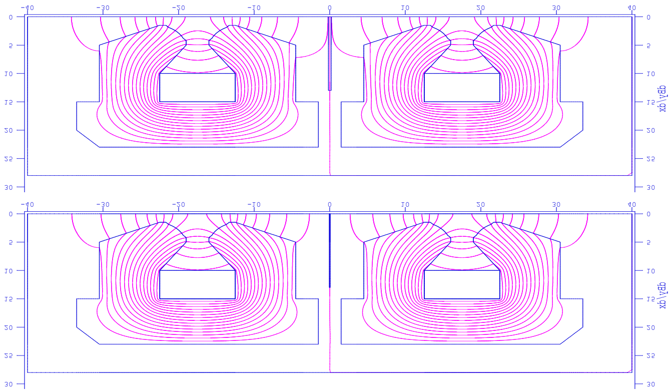
1m long pre-prototype

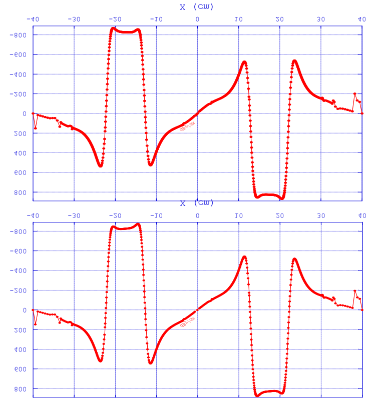
Aperture [mm]		76
Mail Coil	Number	2
	Shape	Racetrack
	Material	Aluminum
	Turns	64
	Conductor specs. [mm]	11×11, φ7, R1
Current [A]		154
Current density [A/mm²]		1.89
Resistance [mΩ]		221.2
Voltage [V]		34.1
Power consumption [kW]		5.3
Cooling water	Loop number	4
	Pressure drop [kg/cm²]	6
	Velocity [m/s]	1.3
	Flux [l/s]	0.201
	Temperature rise [°C]	6.3

Magnetic shielding (30mm gap between core)



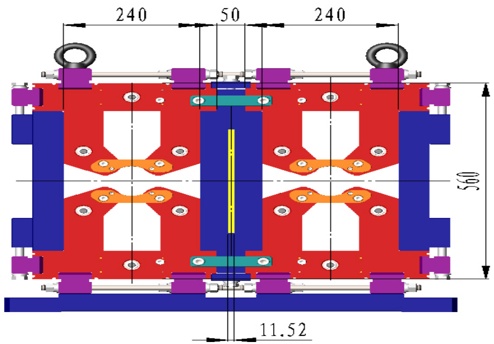


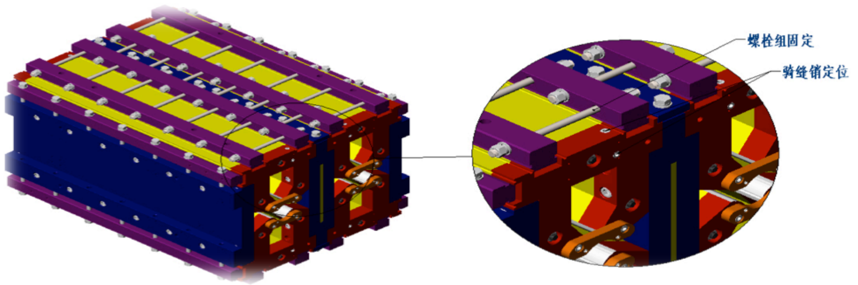


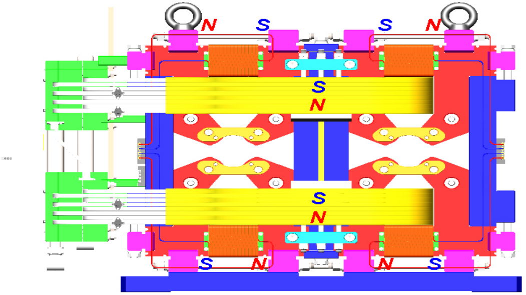


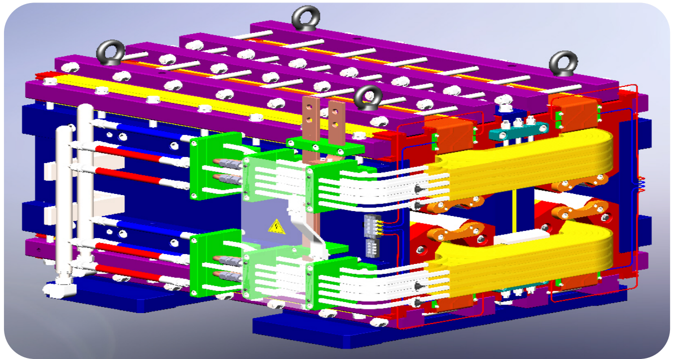
Dual aperture Quadruple magnet R&D

- 1m long DAQ prototype
  - The iron is a laminated one. In order to assemble the coil, the core is divided into 10 parts and has two kinds of punching sheet.
  - Field cross talk between two apertures while changing trim current.
  - Compensation effect of the middle iron plate with different shape.

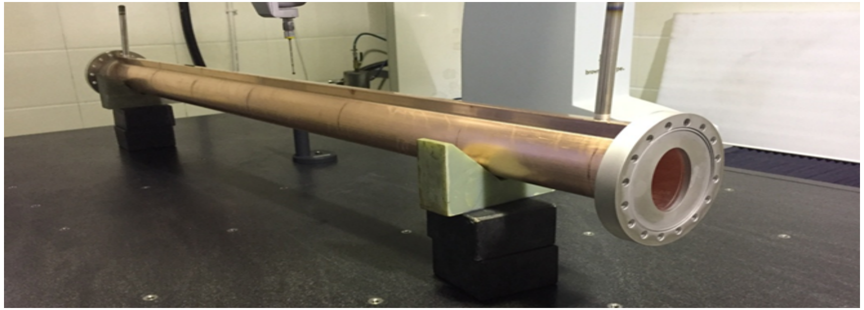




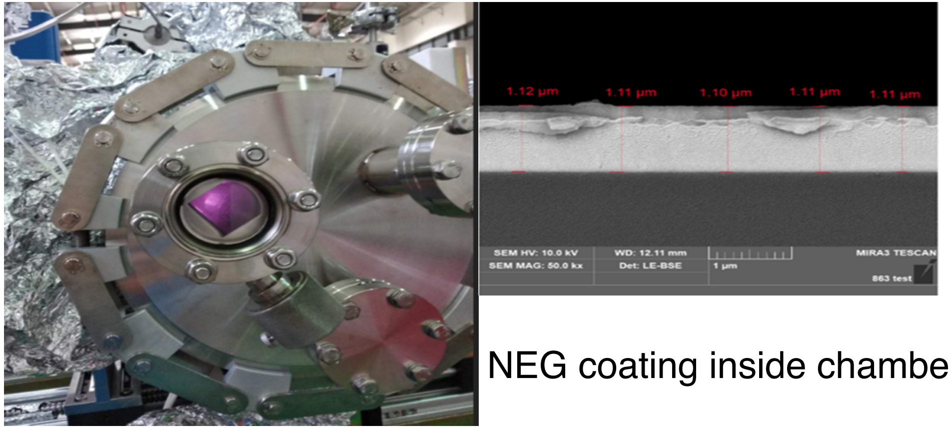




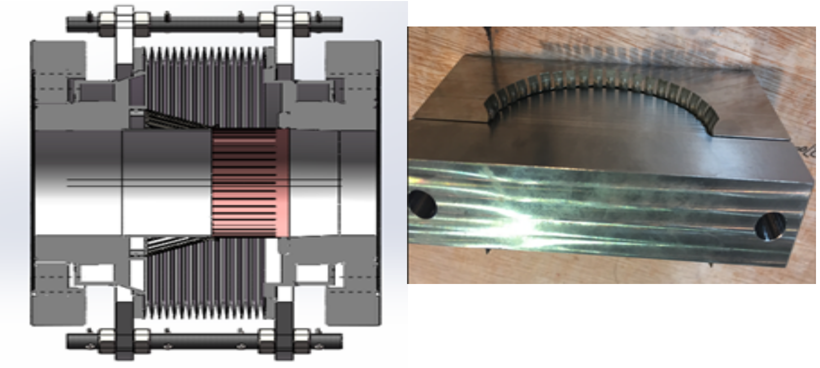
CEPC Vacuum system R&D



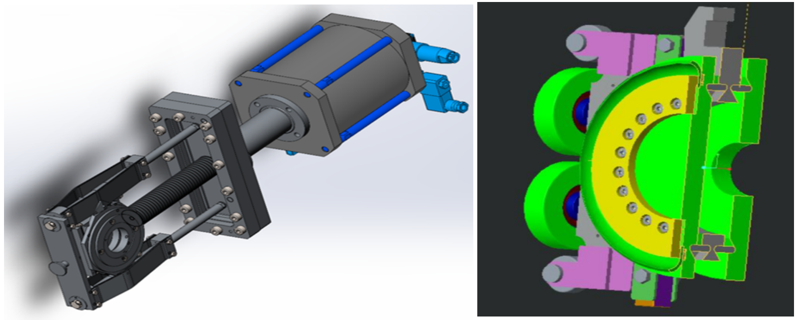
1.5m long copper vacuum chamber prototype



NEG coating inside chamber



Model and tool of RF shielding bellows

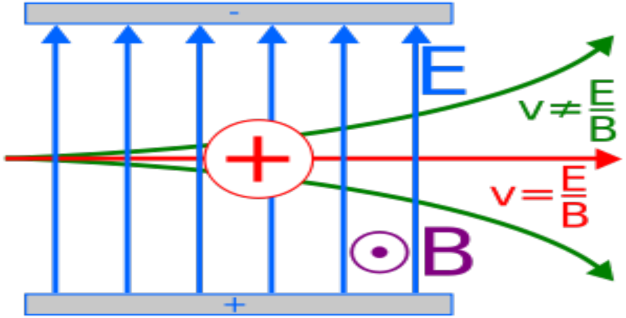


3-D drawings of all metal gate valve

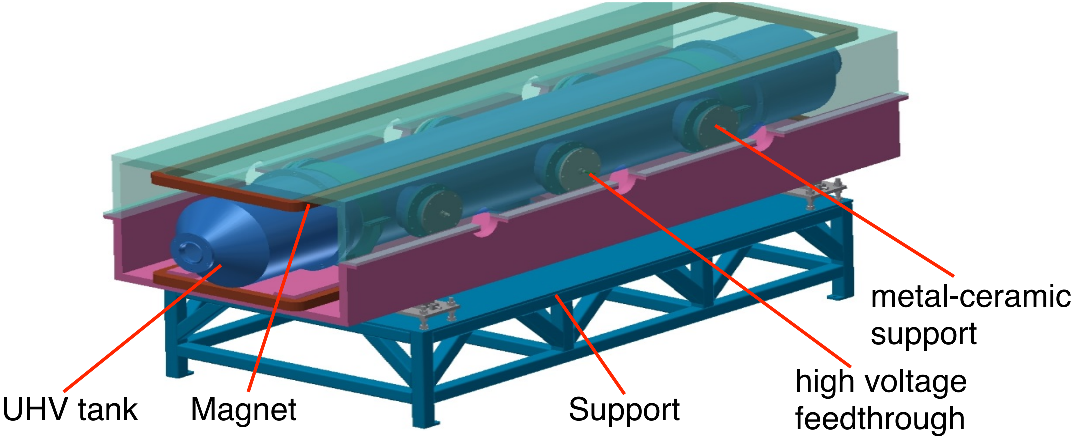
CEPC Collider Ring Electro-Magnet Separator

- The **Electrostatic-Magnetic Deflector** is a device consisting of perpendicular **electric** and **magnetic** fields, just like **Wien filter**.
- **Challenges:** To maintain E/B ration in fringe field region

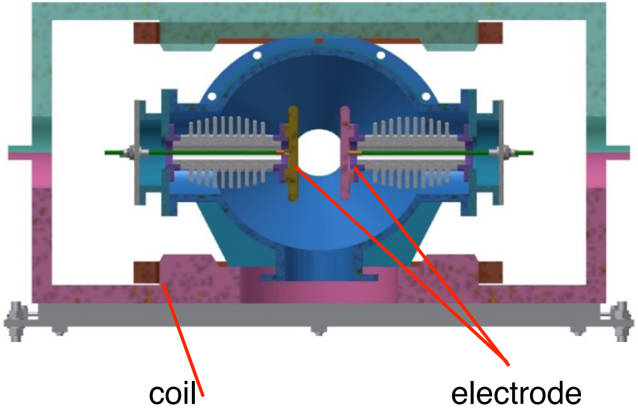
  Reduce the impedance and loss factor of the separator



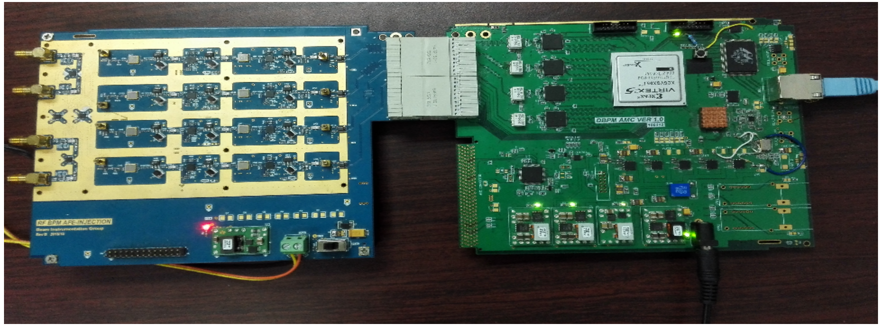
	Filed	Effective Length	Gap	Good field region	Stability
Electrostatic separator	2.0MV/m	4m	110mm	70mm x30mm	5×10^{-4}
Dipole	66.7Gauss	4m	600mm	70mm x30mm	5×10^{-4}



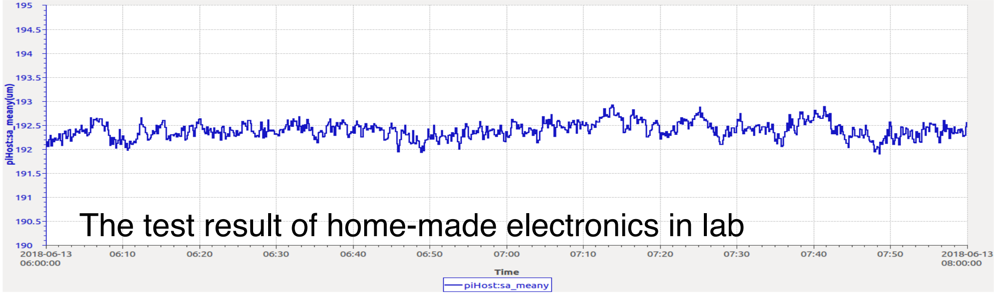
structure drawing of Electrostatic-Magnetic Deflector



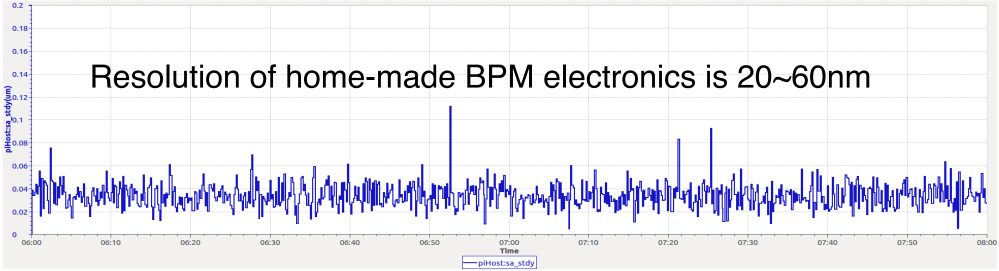
CEPC Beam Position Monitor R&D



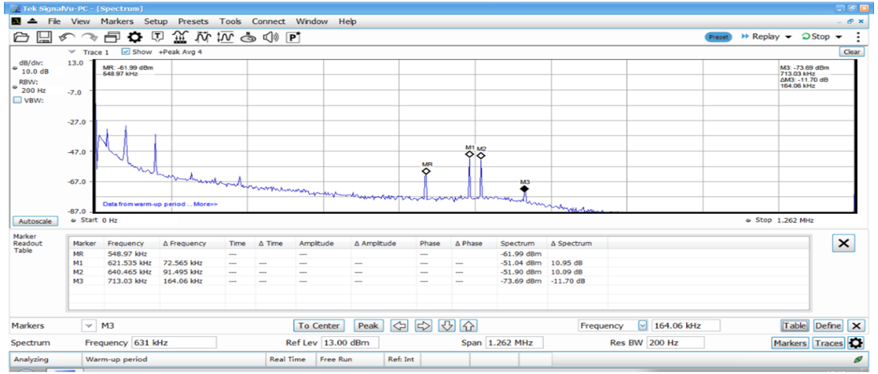
BPM electronics



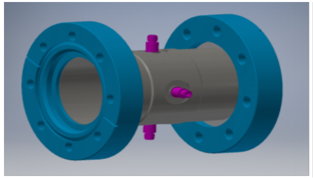
The test result of home-made electronics in lab



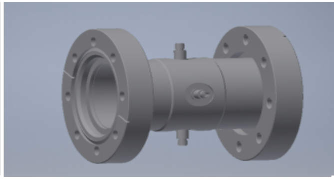
Resolution of home-made BPM electronics is 20~60nm



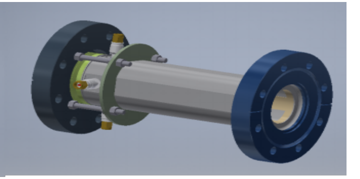
The result of DDD tune system



The BPM of storage ring



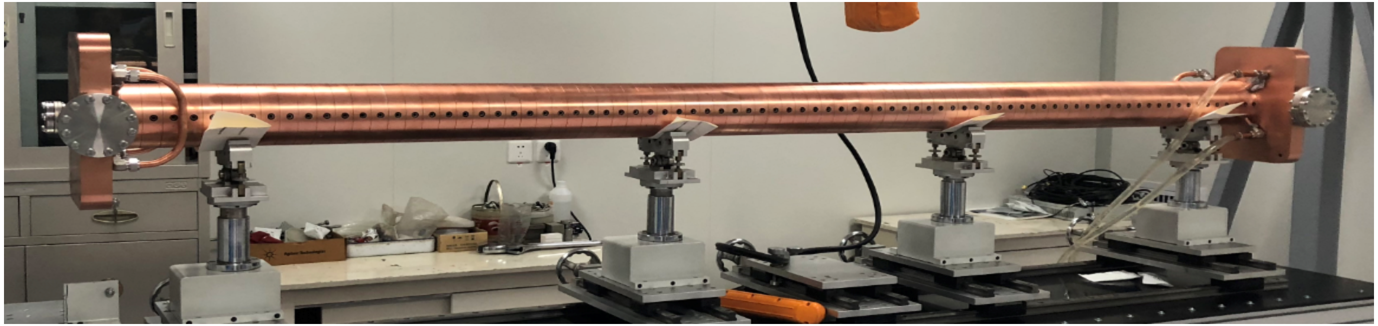
The BPM of Booster



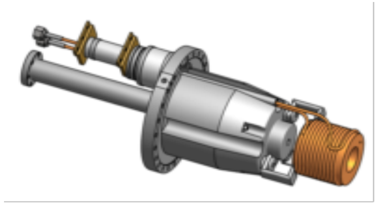
The BPM of Linac and BT

CEPC Linac Injector R&D

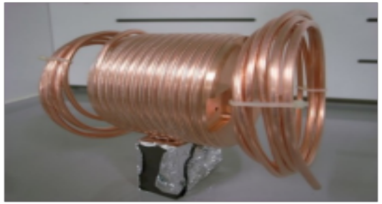
- High gradient S-band accelerating under cold test



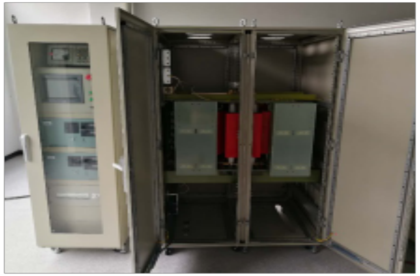
- Positron flux concentrator design



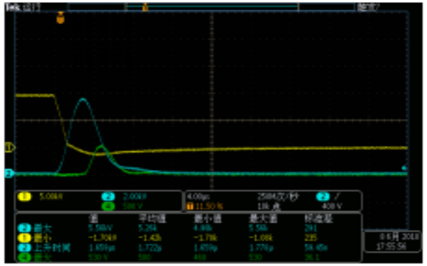
The mechanical design of FLUX concentrator



The finished FLUX concentrator



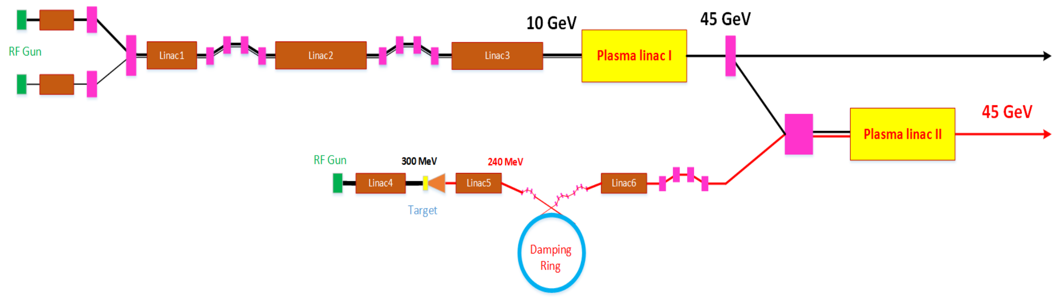
solid-state pulsed power generator

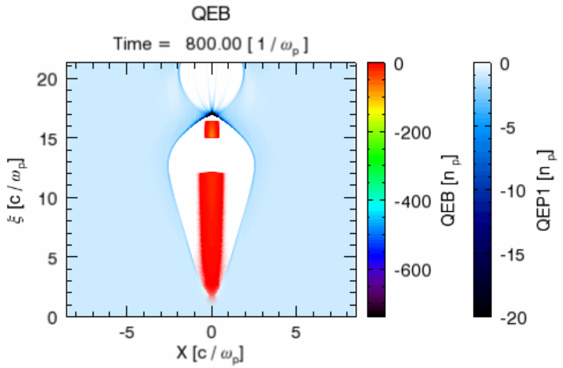


The output of 10kA measurement

PWFA：CEPC Linac Injector Alternative

Plasma Accelerator Scheme up to 45GeV (single stage)~120GeV (cascade)



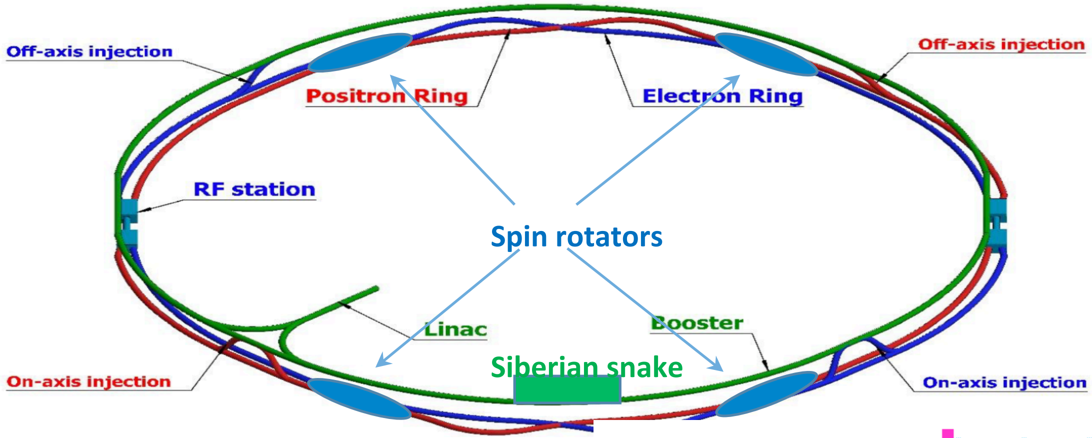


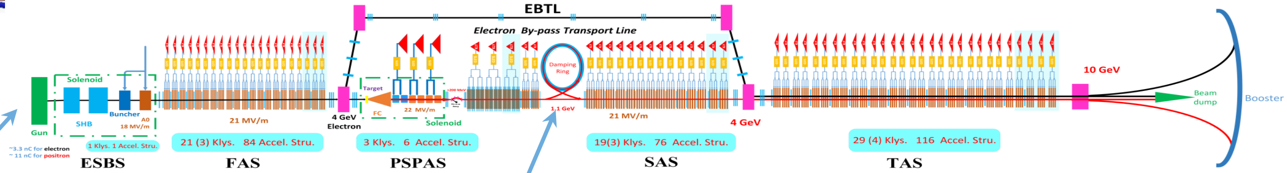
Plasma density $n_0(cm^{-3})$	5.15×10^{16}
Driver charge $Q_d(nC)$	6.47
Driver energy $E_d(GeV)$	10
Driver length $L_d(\mu m)$	285
Driver RMS size $\sigma_d(\mu m)$	10
Driver normalized emittance $\epsilon_{nd}(mm\ mrad)$	10
Trailor charge $Q_t(nC)$	1.25
Trailor energy $E_t(GeV)$	10
Trailor length $L_t(\mu m)$	35
Trailor RMS size $\sigma_t(\mu m)$	5
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	100

or energy $E_t(GeV)$	45.5
r normalized emittance *rad*)	98.9
	3.55
y spread $\delta_E(\%)$	0.7
ency (driver -> trailor)	68.6%

The simulations show that plasma scheme satisfies the CEPC booster requirement

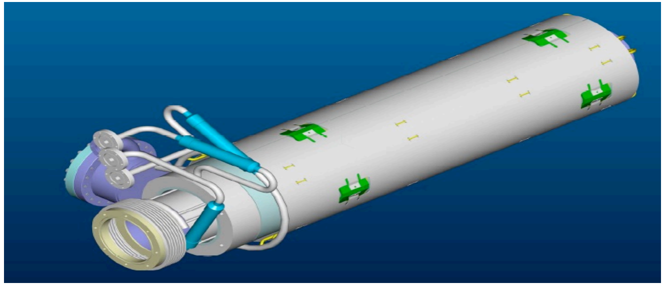
Beam Polarization Considerations at CEPC-Z

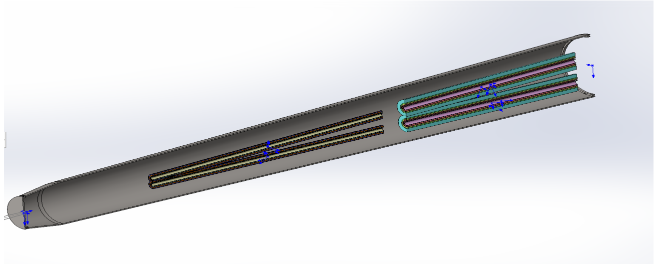


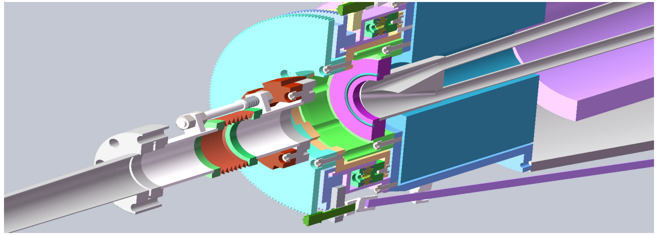


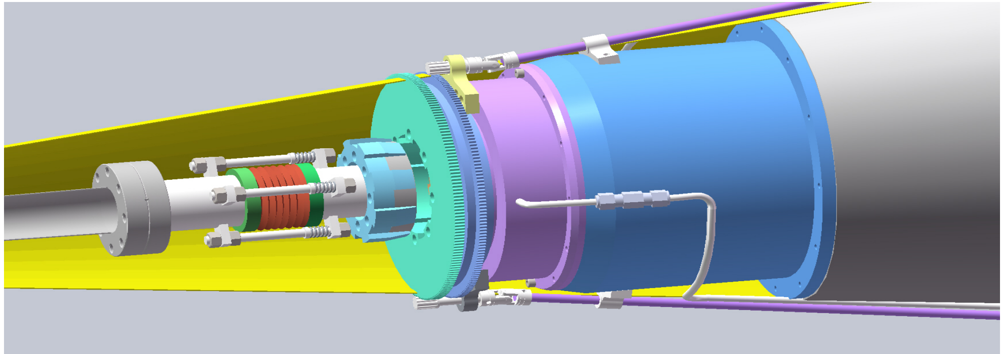
- **Minimal** inclusion of beam polarization @ Z-pole
  - Resonant Depolarization for energy calibration only
  - Dedicated polarization wigglers, rf depolarizer, polarimeter in the storage ring
- **Comprehensive** inclusion of beam polarization @ Z-pole
  - Resonant Depolarization for energy calibration + **polarized e+e- colliding beams**
  - Dedicated polarization wigglers (not necessary), rf depolarizer, polarimeter in the storage ring
  - Polarized e- gun, low energy e+ damping/polarizing ring (optional)
  - Siberian snake in the booster
  - Spin rotators in the storage ring and the injector chain

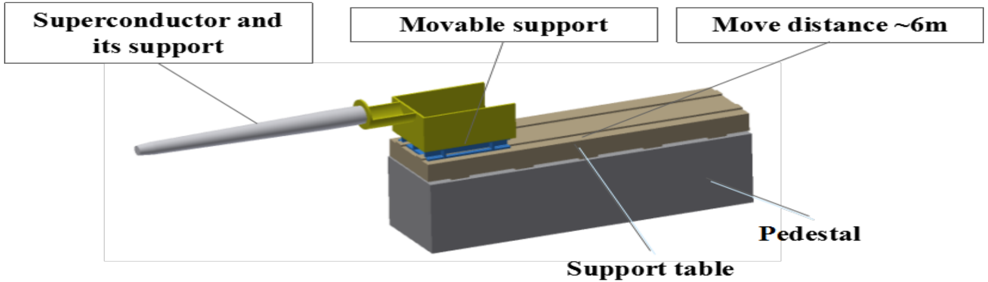
CEPC MDI SC Magnets and Mechanical Study







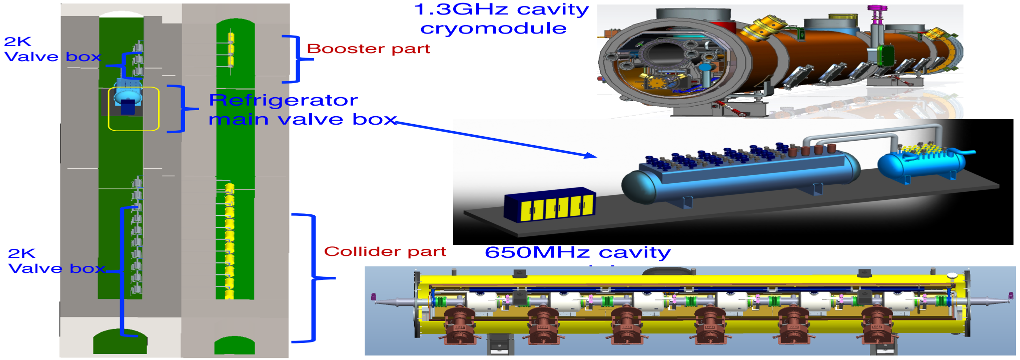


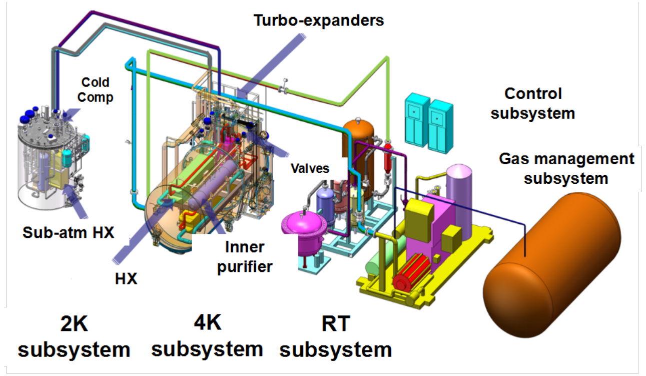


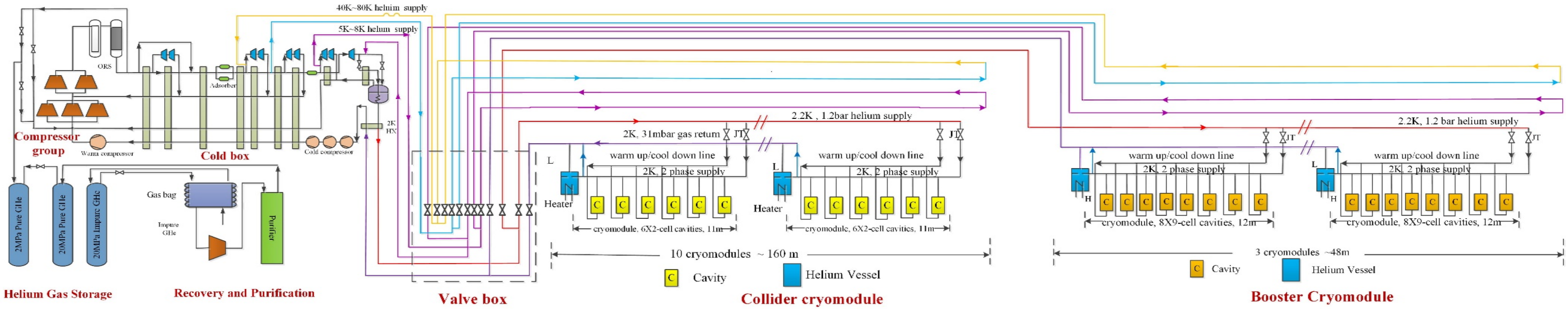
Schematic of support system of superconducting magnets

Layout of CEPC cryogenic system

- CEPC superconducting cavity cryogenic system is four18KW@4.5K
- CEPC superconducting magnet cryogenic system is 6KW@4.5K

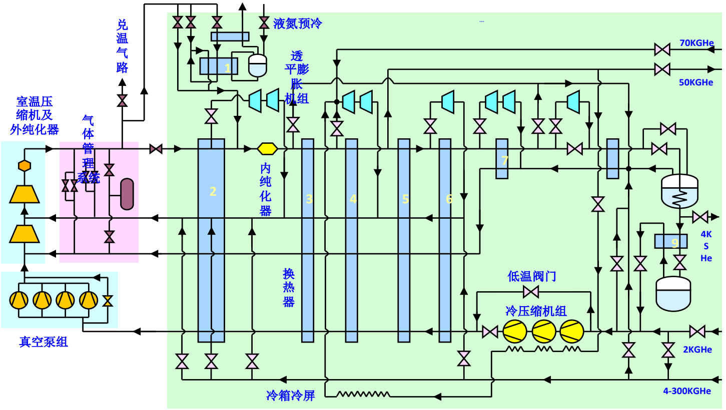






Flowchart of One Cryo-station

Future Work towards 18kW@4.5K Cryoplant



- IPC Proposed scheme for 10-12kW@4.5K Cryo-plants for CEPC, ADS, HIAF, etc.

CEPC Industrial Promotion Consortium (CIPC)

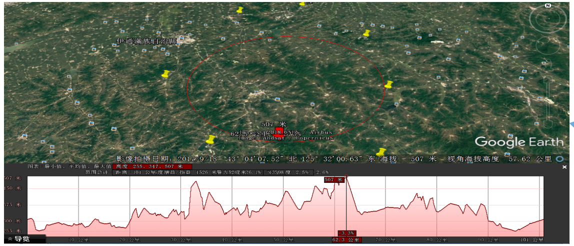
Established in Nov. 7 , 2017

1) Superconducting materials (for cavity and for magnets)
2) Superconducting cavities
3) Cryomodules
4) Cryogenics
5) Klystrons
6) Vacuum technologies
7) Electronics
8) SRF
9) Power sources
10) Civil engineering
11) Precise machinery.....

More than 60 companies joined CIPC during last two years.

CEPC Site Selections

6



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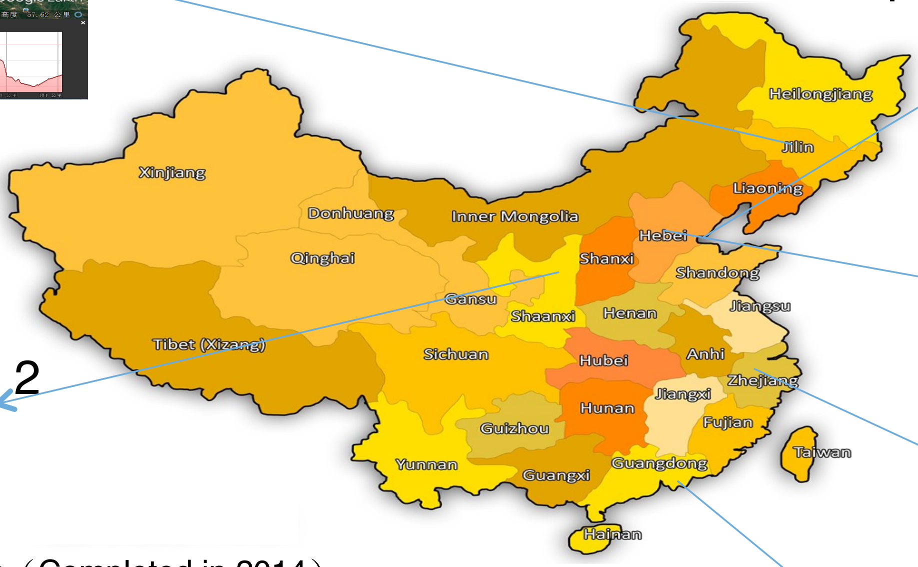

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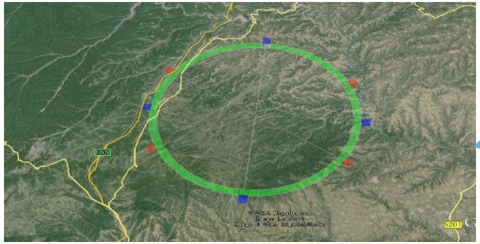

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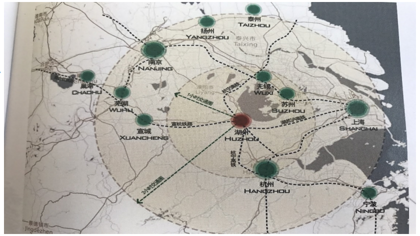


3

1) Qinhuangdao, Hebei Province（Completed in 2014）

2) Huangling, Shanxi Province（Completed in 2017)

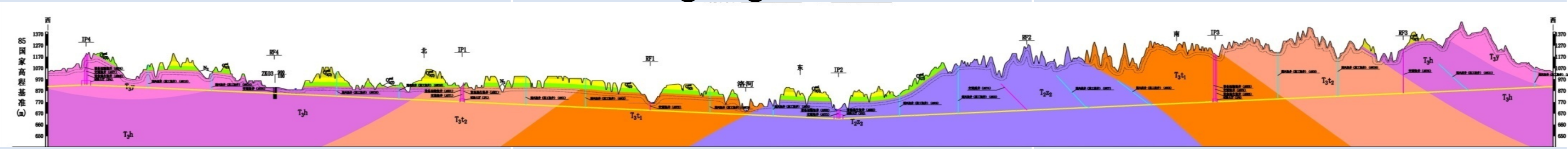
3) Shenshan, Guangdong Province(Completed in 2016)

4) Baoding (Xiong an), Hebei Province (Started in August 2017)

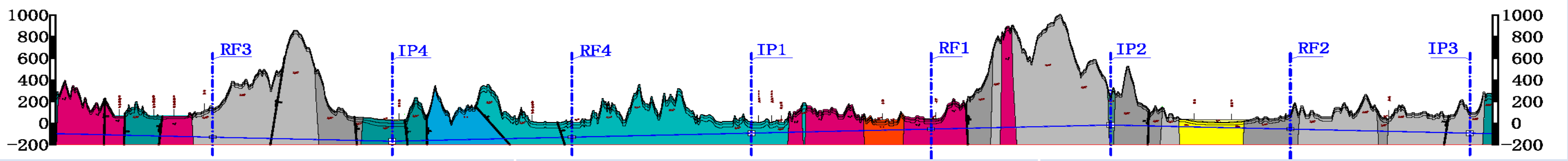
5) Huzhou, Zhejiang Province (Started in March 2018)

6) Changchun, Jilin Province (Started in May 2018)

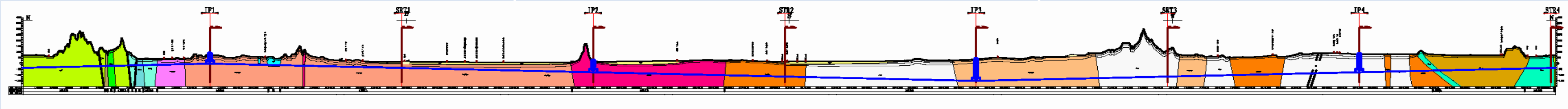
<table>
<tr><th>Item</th><th>Huangling</th><th>Shen-Shan</th><th>Funing</th></tr>
<tr><td>Project layout</td><td colspan="3">
Huangling（100km）



Shen-Shan（100km）



Funing（100km）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<tr><td>Construction difficulty</td><td>Moderate</td><td>Relatively difficult</td><td>Relatively easy</td></tr>
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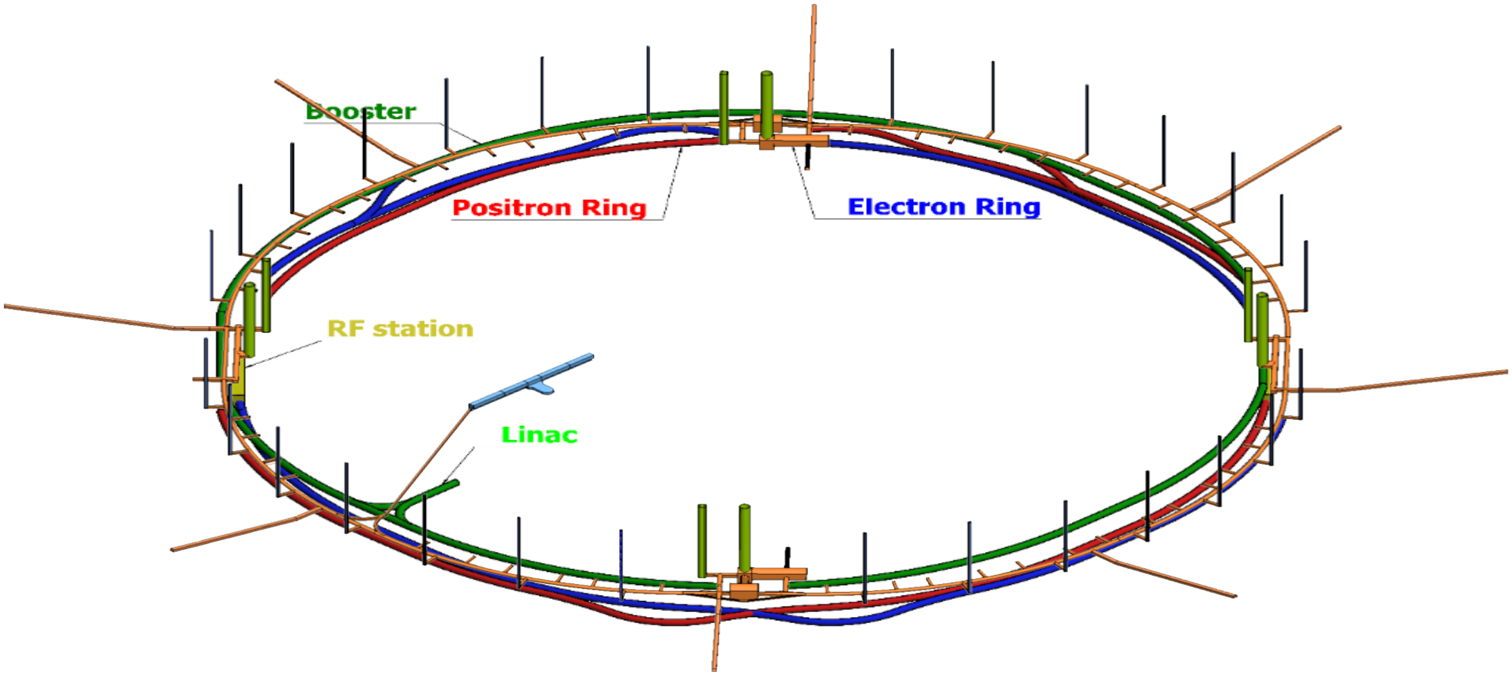
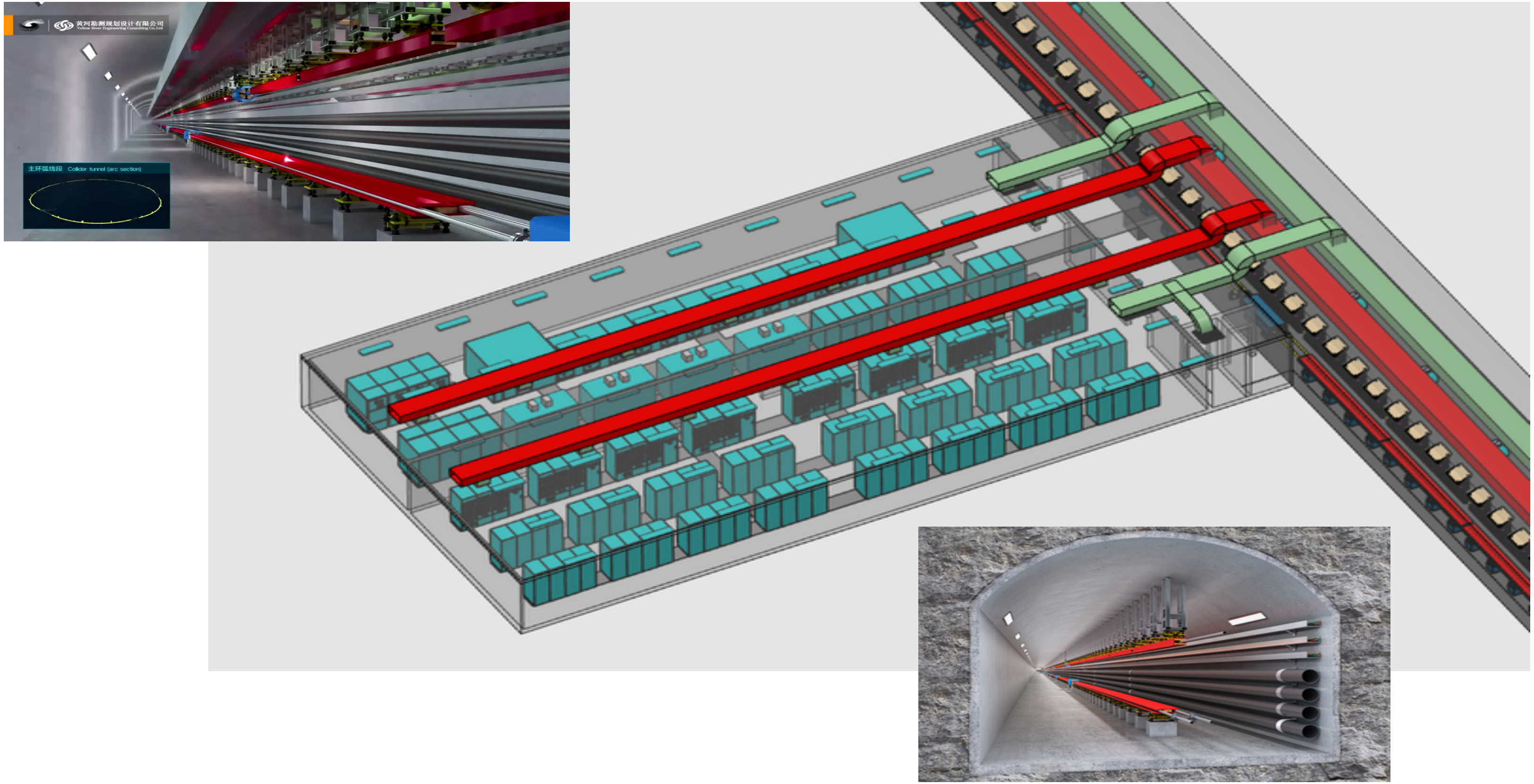
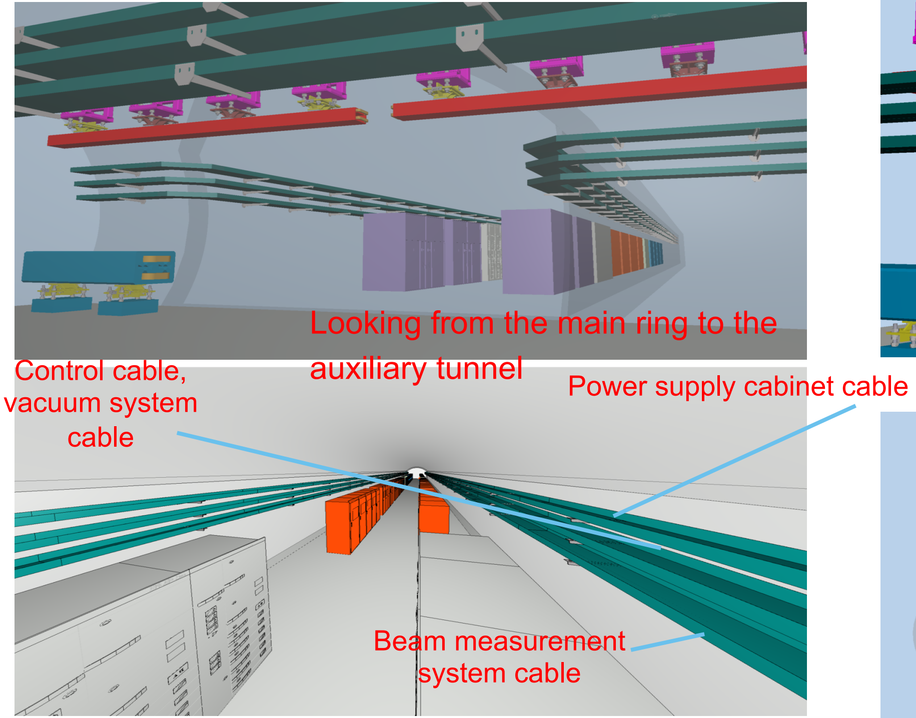
CEPC Civil Engineering Design

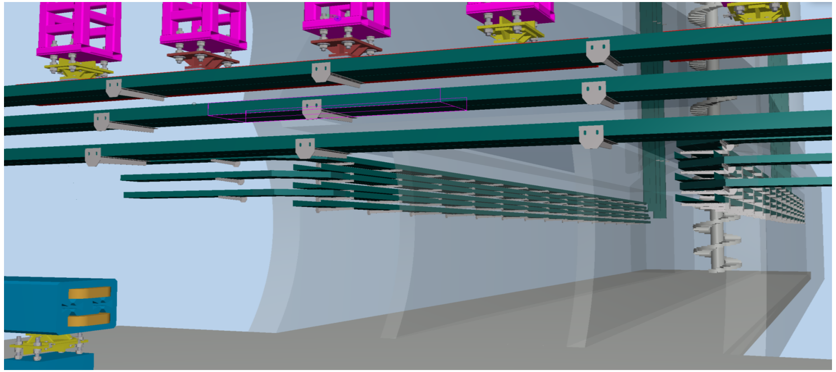


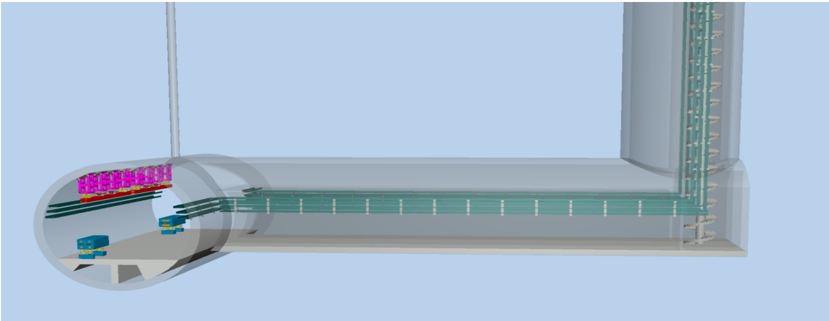
CEPC Main and Auxiliary Tunnel Design



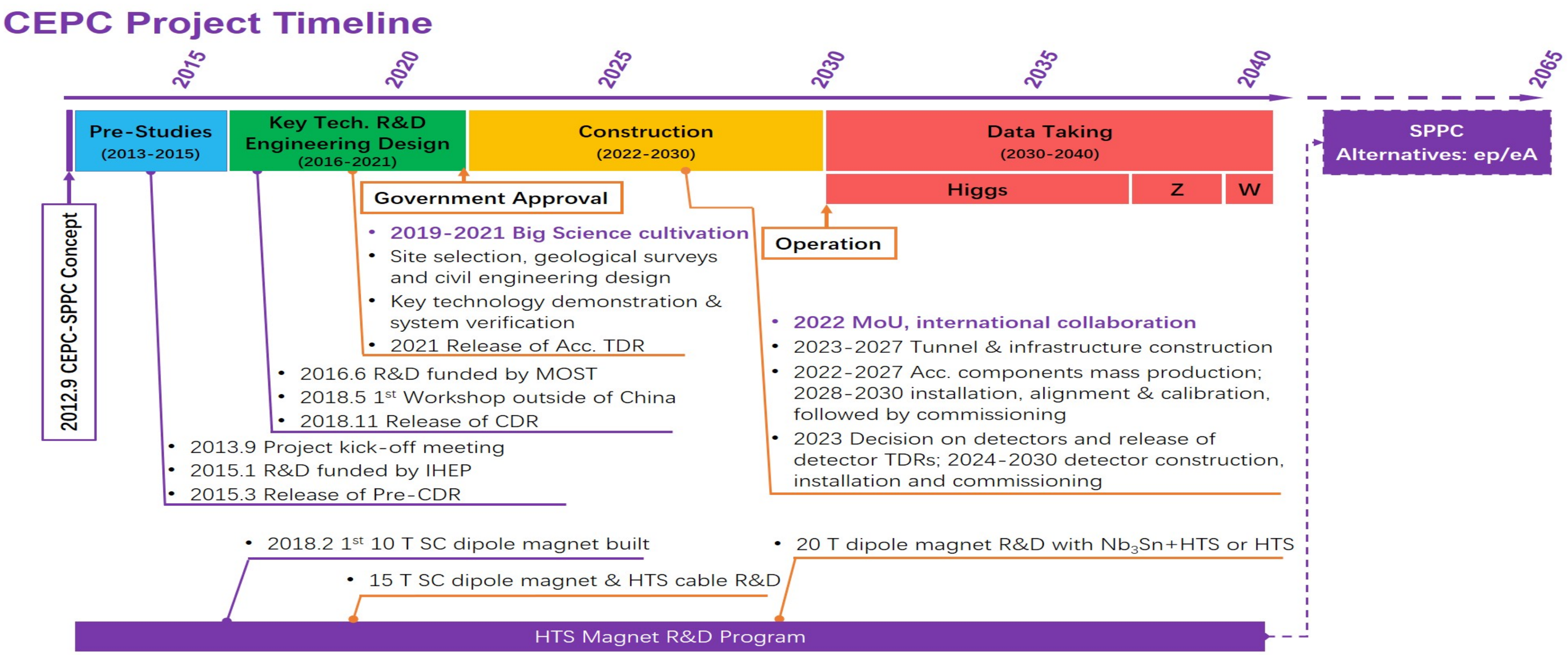
CEPC Auxiliary Tunnel and Shaft







CEPC Project Timeline



Summary

- CEPC Accelerator CDR has been completed and released with all systems reaching the CDR design goals with new ideas beyond CDR.
- CEPC hardware design and key technologies' R&D progress well with financial funds towards TDR to be completed in 2022.
- CEPC siting and engineering implementation progress well.