



中国科学院高能物理研究所  
*Institute of High Energy Physics*  
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# CEPC SRF Progress

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On behalf of CEPC SRF Team

IAS Program on Fundamental Physics (FP 2026)  
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# Content

1. CEPC SRF EDR Design
2. CEPC SRF R&D Progress
3. Summary

# CEPC and FCC-ee RF System Design Evolution

Evolution of CEPC collider 650 MHz RF system layout

Operating point	Z	W	H	ttbar
Preliminary conceptual design report (Pre-CDR, 2015)				
Common RF system for two beams			Pretzel	
Number of cavities (54 km, 6.87 GV)			384	
Number of cells per cavity			5	
RF power per cavity [kW] (52 MW/beam)			280	
Conceptual design report (CDR, 2018)				
Common RF system for two beams	no		yes	
Number of cavities (100 km, 2.17 GV)	120	216	240	
Number of cells per cavity	2			
RF power per cavity [kW] (H/W 30 MW per beam, Z 16.5 MW/beam)	275	278	250	
Technical design report (TDR, 2023)				
Common RF system for two beams	no		yes	
Number of cavities	100	336	336/192	
Number of cells per cavity (Z 50/10 MW/beam)	1/2	2	2/5	
RF power per cavity [kW] (H/W 50 MW per beam, Z 50/10 MW/beam)	1000 /200	298	118/315	

Evolution of FCC-ee collider RF system layout.

Operating point	Z	WW	ZH	t $\bar{t}$
Conceptual design report (2019)				
RF frequency [MHz]	400			400/800
Common RF system for two beams	no			yes
Number of cavities	104		272	272/372
Number of cells per cavity	1		4	4/5
RF power per cavity [kW]	962		368	149/155
Feasibility study mid-term report (2024)				
RF frequency [MHz]	400			400/800
Common RF system for two beams	no			yes
Number of cavities	112	264	264	264/488
Number of cells per cavity	1		2	2/5
RF power per cavity [kW]	901	378	382	78/163
Feasibility study final report (2025)				
RF frequency [MHz]	400			400/800
Common RF system for two beams	no			yes
Number of cavities	264			264/408
Number of cells per cavity	2			2/6
RF power per cavity [kW]	380			78/195

# Collider RF Parameters of CEPC TDR and FCC-ee FSR

Main RF parameters of the CEPC collider

Parameters (50 MW/beam)	Z (50/10 MW)		W	H		ttbar
Common RF system for two beams	no		no	yes		yes
RPO	no		no	no		no
Total RF voltage [MV]	0.12		0.7	2.2	6.1	3.9
Beam current [mA]	1345	267	140	2×27.8		2×5.6
RF frequency [MHz]			650			
Operating temperature [K]			2			
Number of cells per cavity	1	2	2	2	2	5
Quality factor $Q_0$	2E10		3E10			
Cavity voltage [MV]	2	2.5	4.2	6.6	11.6	31.8
Accelerating gradient $E_{acc}$ [MV/m]	8.7	5.4	9.1	14.2	25.2	27.6
RF power per cavity [kW]	1000	206	298		118	315
Coupling factor $Q_L$	3.8E4	1.4E5	2.7E5	6.8E5	5.4E6	6E6
Number of cryomodules	100	16	56		48	
Number of cavities	2×50	2×48	336		192	
Optimal detuning [kHz]	21.7	7	2	0.2	0.03	0.02
HOM power per cavity [kW]	6.2	1.9	1.54	0.67	0.26	0.66

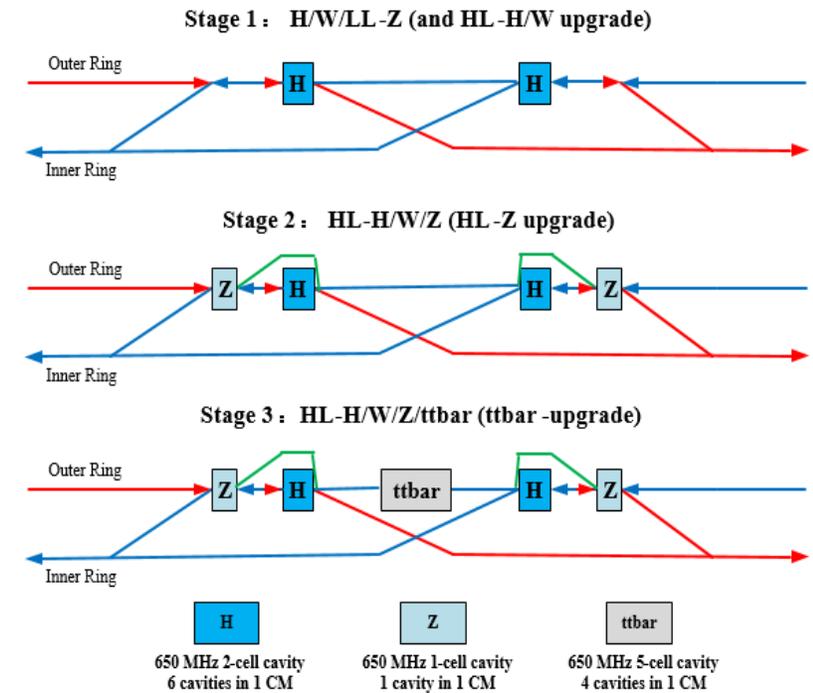
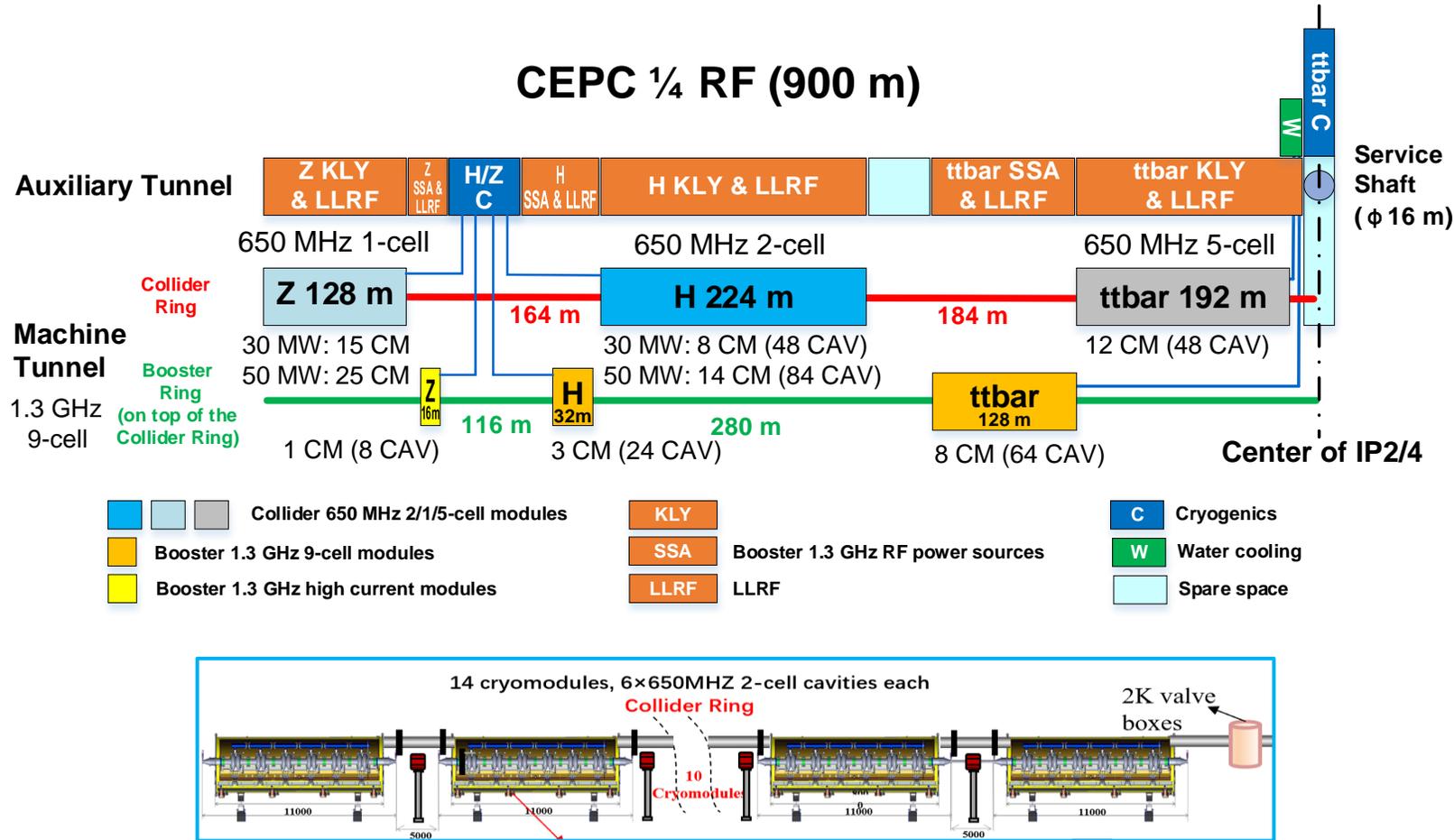
- Coupler inner conductor moving to change  $Q_L$

Main RF parameters of the FCC collider.

Parameters	Z	W	ZH	tt̄	
Common RF system for two beams	no	no	yes	yes	
RPO	yes	no	no	no	
Total RF voltage [MV]	89	1049	2098	2098	9202
Beam current [mA]	1283	135	53.6	10	
RF frequency [MHz]	400.79		400.79	801.58	
Operating temperature [K]	4.5		4.5	2	
Number of cells per cavity	2		2	6	
Quality factor $Q_0$	$2.7 \times 10^9$		$2.7 \times 10^9$	$3 \times 10^{10}$	
Cavity voltage [MV]	7.95		7.95	22.5	
Accelerating gradient $E_{acc}$ [MV/m]	10.6		10.6	20.1	
RF power per cavity [kW]	380		78	195	
Coupling factor $Q_L$	$9.2 \times 10^5$		$4.5 \times 10^6$	$4.1 \times 10^6$	
Number of cryomodules	66		66	102	
Number of cavities	264		264	408	

- Same cavity voltage and  $Q_L$  for Z/W/H, RPO for Z operation
- Reactive waveguide tuning to change  $Q_L$  for ttbar operation

# RF Configuration: H-W-LLZ ↔ HLZ ↔ ttbar (CEPC EDR)



**Collider RF Staging and Bypass Scheme**

- 2x1.8 km RF section, 3 km RF module footprint, 2 km RF module length
- **628 650 MHz cavities, 384 1.3 GHz cavities, total 1012 cavities, 5188 cells**
- Collider and booster RF bypass for mode switch.

# Integrate High Luminosity Z to Higgs Cavities

## **FCC-ee FSR: universal 2-cell cavity for H, W, Z (HL)**

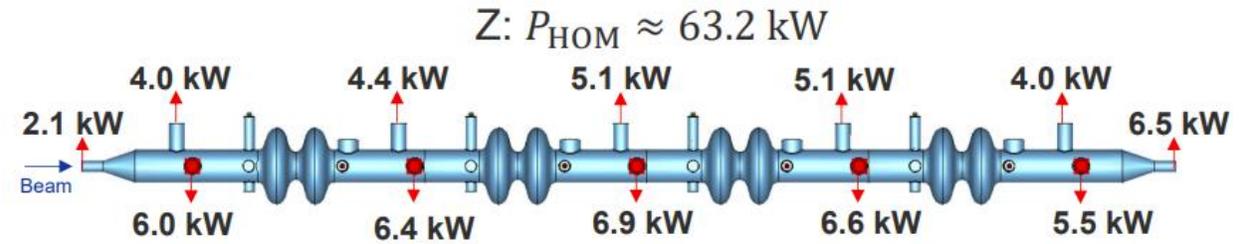
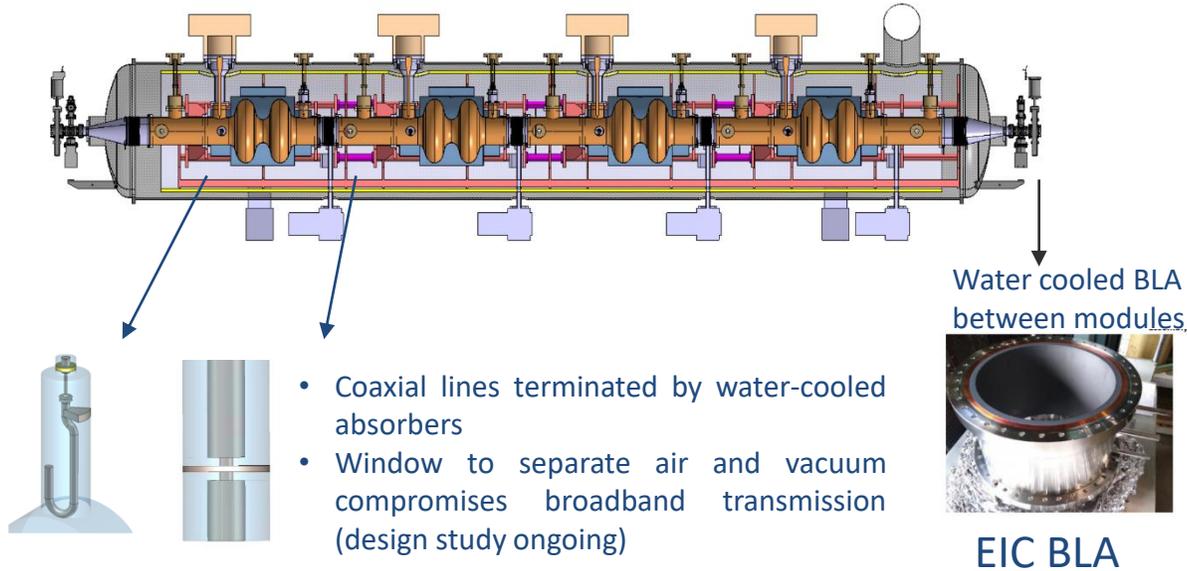
- More than 100 x  $Q_e$  tuning (reverse phase operation, RPO)
- Transient beam loading and FM instability: twice R/Q, lower stored energy, RPO will help?
- Higher HOM power in multi-cavity cryomodule for Z-pole
- 4 x impedance for Z-pole HOM damping

## **CEPC TDR alternative: universal 1-cell cavity for H, W, Z (HL)**

- 2 x 168 1-cell cavities for Z. More cavities than the optimized 2 x 50 1-cell cavities.
- Partly solve the HOM issue of Z-pole 2-cell (still huge HOM in multi-cavity CM), but worse for FM than baseline. Detune some cavities? Increase input power for the operating cavities.
- $Q_e$  tuning range
- Cavity gradient increase: FCC-ee 10  $\rightarrow$  20 MV/m (Nb/Cu  $\rightarrow$  Nb?), CEPC (50 MW) 15  $\rightarrow$  30 MV/m (because of higher freq. and RF voltage than FCC-ee).
- Need to double  $Q_0$  at twice the gradient to have same Higgs cavity wall loss heat load.
- Combine high Q, high gradient, high current and high power in one cavity. Risk.

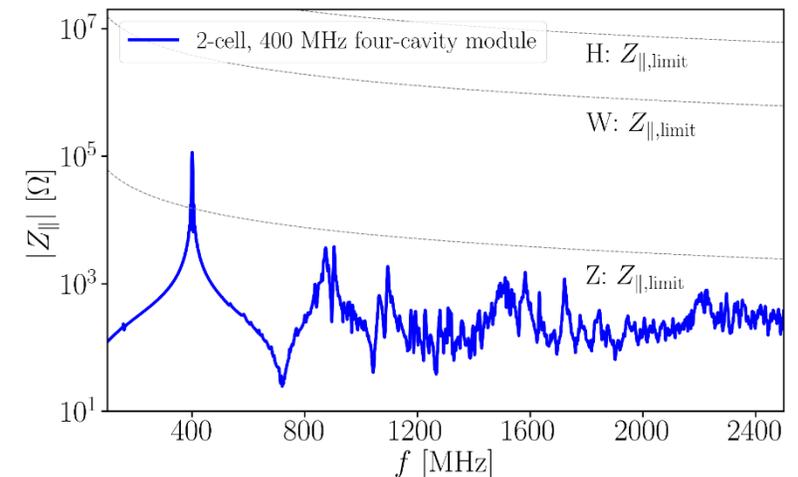
# HOM Damping of FCC-ee 400 MHz Cavities

- Two hook-type coaxial couplers per cavity used for trapped dipole mode damping. **Total numbers:  $8 \times 66 = 528$**
- Two coaxial lines between cavities for high-power HOM extraction. **Total numbers:  $10 \times 66 = 660$**   
(possibility of reducing this number should be checked)
- BLA between modules to absorb power propagating from modules out. **Total numbers =  $66 + 1 = 67$**



HOM power of all 8 hook-type HOM couplers combined is around 0.7 kW (not shown in the figure above)

CEPC has higher HOM power due to smaller cavity. BS bunch length control critical to limit HOM power.



# Z 2-cell vs 1-cell (FCC-ee)

Scenario	56 1-cell cav.	56 2-cell cav.	132 2-cell cav.
QL range	Fixed FPC coupling with moderate $Q_L$	Wide-range of FPC coupling	Wide-range of FPC coupling + extremely low $Q_L$
CBI due to fundamental mode	Strong RF feedback	Strong RF feedback	Strong RF feedback Small margin (factor of 4)
Longitudinal HOM CBI	No trapped HOMs	0-mode strong damping and/or longitudinal feedback	0-mode strong damping and/or longitudinal feedback
Transverse HOM CBI	Weak TFB system is useful	TFB system with 100-turn damping time	TFB system with 50-turn damping time
Higher-order-mode power	"2-coax concept" needs demonstration	"2-coax concept" needs demonstration + 40% HOM power increase	"2-coax concept" needs demonstration + 40% HOM power increase
Availability challenges	Longitudinal feedback system (main RF system as kicker) + ~10% RF power margin		

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# EDR Plan of CEPC SRF System

EDR major goal is to prepare for the **first stage** construction of the CEPC SRF system (30 MW H/W & low-lumi Z):

- Complete **engineering design** of the Collider 650 MHz and Booster 1.3 GHz cryomodule for Higgs 30/50 MW & Z 10 MW ( $3.8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ ).
- Complete Higgs **650 MHz full-scale cryomodule prototyping** to achieve TDR specification.
- High Q high gradient cavity and high power RF components R&D.

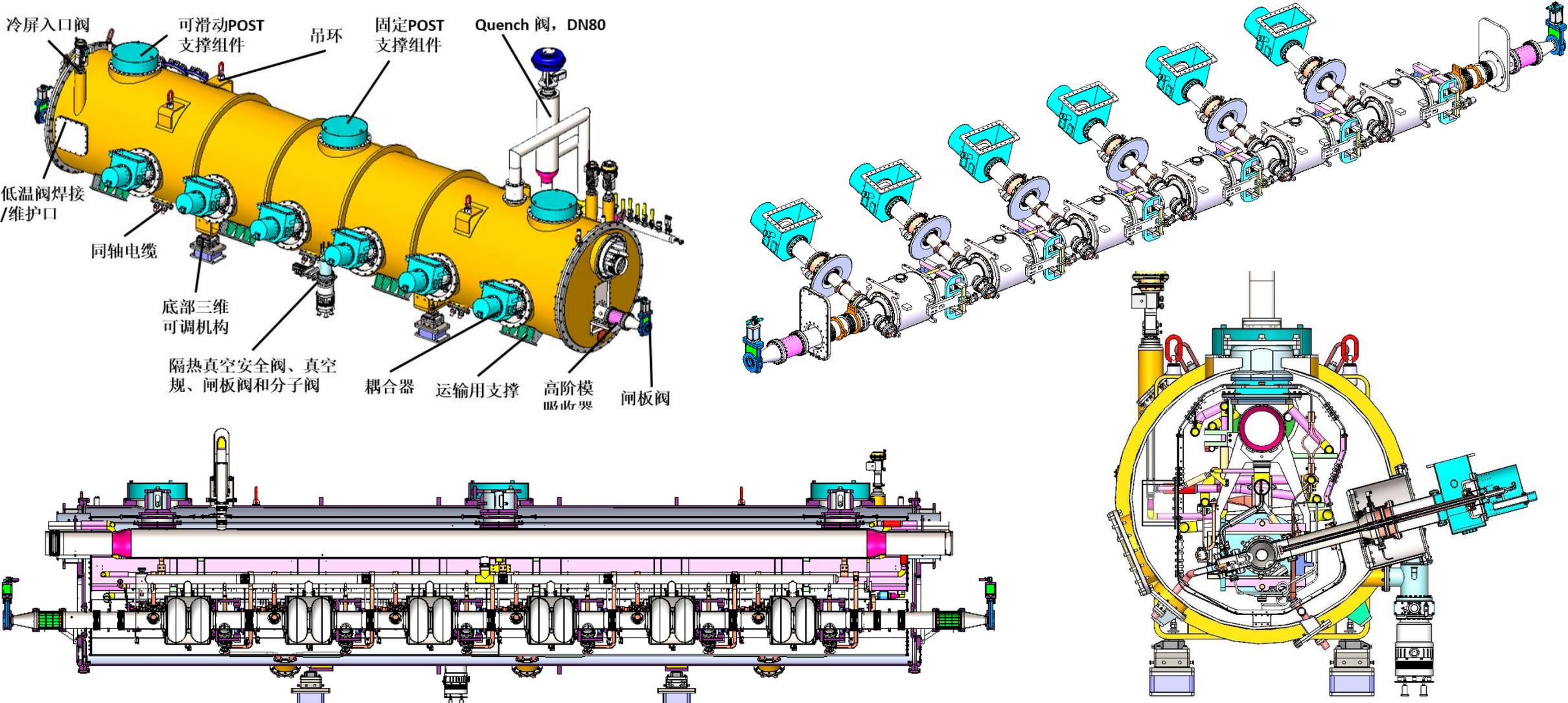
CEPC SRF EDR	Preliminary Design	Engineering Design	Full-scale Prototyping	Industrial Preparation
<b>Collider H/W/LL-Z</b> (high Q / G 650 M)		✓	✓	✓
<b>Collider HL-Z</b> (high current 650 M)	✓			
<b>Collider ttbar</b> (high G / Q 650 M)	✓			
<b>Booster H/W/ttbar</b> (high Q / G 1.3 G)		✓	CW/pulse FEL	CW FEL
<b>Booster Z</b> (high current 1.3 G)	✓	ERL	ERL	

## Collider Higgs 650 MHz Cryomodule Parameters

Spec.

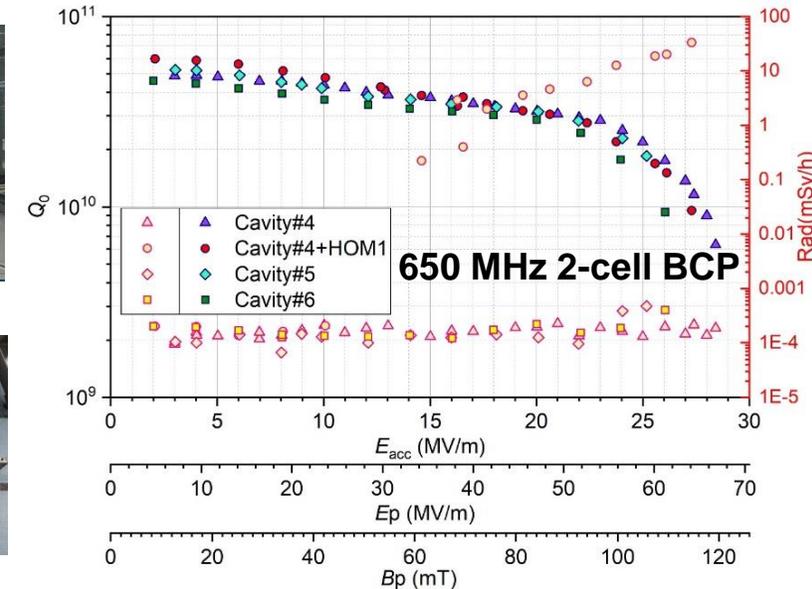
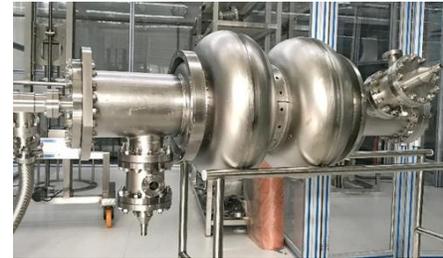
Module operating temperature	2 K
Cavity vertical test gradient	28 MV/m
Cavity vertical test $Q_0$ at 25 MV/m	3.3E10
Module RF voltage (six 2-cell cavities)	70 MV
Module average cavity gradient	<b>25 MV/m</b>
Module average cavity $Q_0$ at 25 MV/m	<b>3.0E10</b>
Module total 2 K heat load at 70 MV	160 W
Input coupler conditioning power	<b>300 kW</b>
Input coupler $Q_e$ adjusting range	<b>1E5 ~ 1E7</b>
HOM coupler power (cryogenic test)	<b>1 kW</b>
HOM absorber power (test stand)	5 kW

# CEPC 650 MHz Full-Scale Prototype Cryomodule



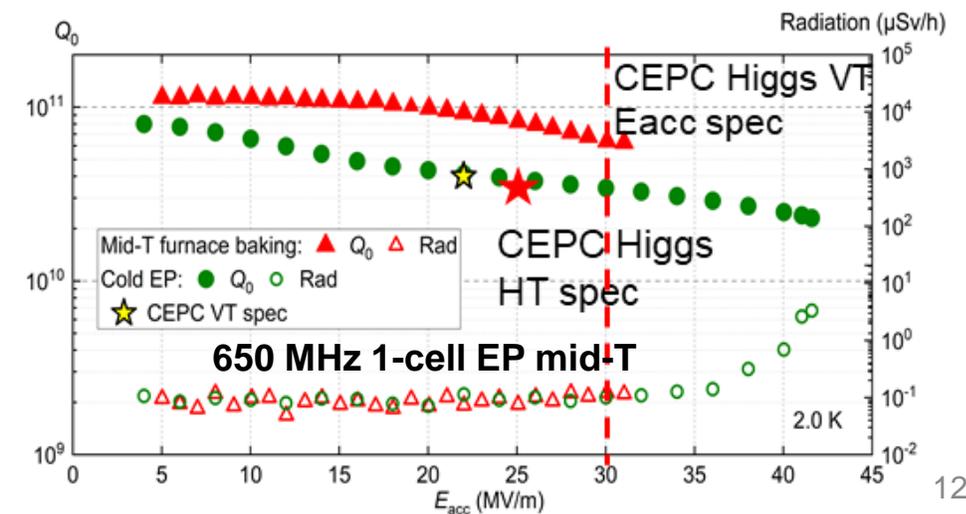
# High Gradient and High Q 650 MHz Cavity

CEPC 650 MHz CM		EDR Specification
650 MHz 2-cell cavity vertical test	$E_{acc.max}$	30 MV/m
	$Q_0$	3.6E10 @ 25 MV/m
Module horizontal test acceptance	$E_{acc.max}$	28 MV/m
	$Q_0$	3.3E10 @ 25 MV/m
Module long term operation	$E_{acc.max}$	28 MV/m
	$Q_0$	3.0E10 @ 25 MV/m



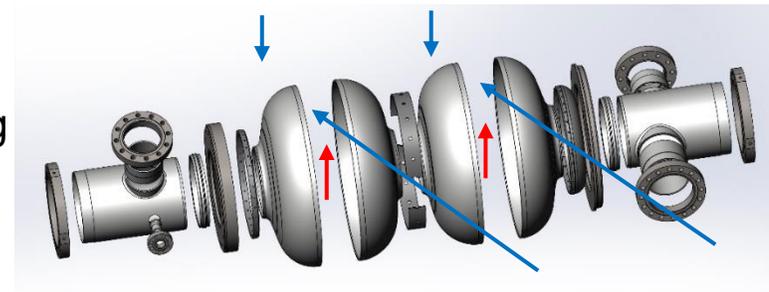
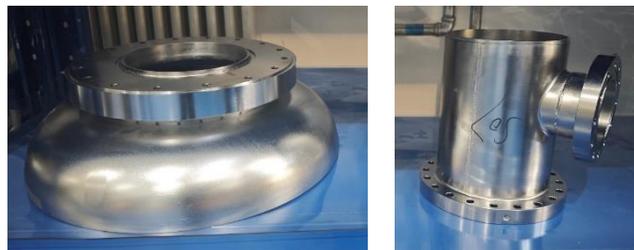
20 % margin from vertical test to operation spec.

- **BCP dressed 2-cell VT:** 2E10 @ 25 MV/m, max ~ 26.5 MV/m
- **BCP 2-cell module test:** 2E10 @ 8 MV/m (coupler cooling limited?)
- **EP + mid-T 1-cell VT:** 8E10 @ 25 MV/m, max 31.5 MV/m
- **Apply 1-cell recipe to 2-cell**



# 650 MHz 2-cell Cavity Fabrication

- Will complete EBW of **two 2-cell cavities in January** and other six cavities later.
- Processing (EP + improved mid-T) and vertical test to start soon.



## Equator welding:

- outside back-forming
- **two-side** (now)
- **inside** (next step)

**Inside EBW system** installed and in commissioning

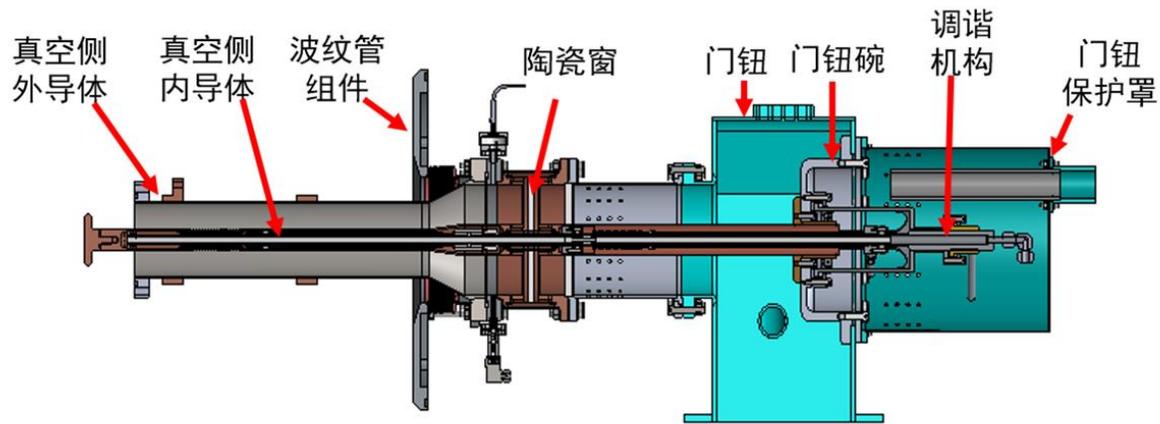
## Advantages:

- still cylindrical and homogeneous beam after bending
- extremely smooth weld seam for high performance cavity
- welding of unreachable seam for design flexibility

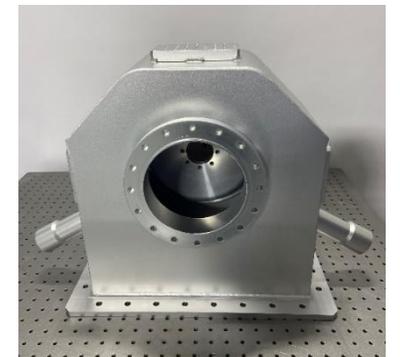


# 650 MHz Variable High Power Input Coupler

- **Six variable 300 kW CW 650 MHz input couplers for the full-size module.** In TDR phase, both fixed and variable couplers are tested to CW TW 150 kW (SSA power limit), SW 100 kW. Two fixed couplers in test cryomodule.
- **Two variable couplers will be delivered in January** (now outer conductor copper plating and ceramic TiN coating)
- High power tested (> 300 kW) with 800 kW CW klystron
- The other four variable couplers in fabrication

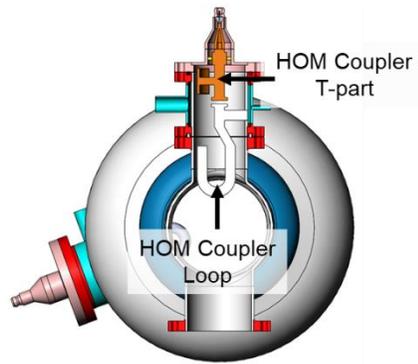


- |                           |               |
|---------------------------|---------------|
| ① 陶瓷窗: 芬兰无氧铜+德国摩根陶瓷+304   | ⑤ 门钮碗: 6061   |
| ② 真空侧内导体: 芬兰无氧铜+316L      | ⑥ 门钮保护罩: 6061 |
| ③ 真空侧外导体: 316L/304 (刀口法兰) | ⑦ 调谐机构: 304   |
| ④ 门钮: 6061                | ⑧ 波纹管组件: 316L |



# 650 MHz HOM Coupler and Absorber

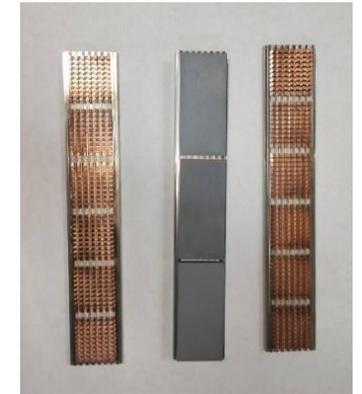
12 HOM couplers and two HOM absorbers fabrication completed. Processing and testing soon.



1 kW HOM coupler  
Free of notch-tuning



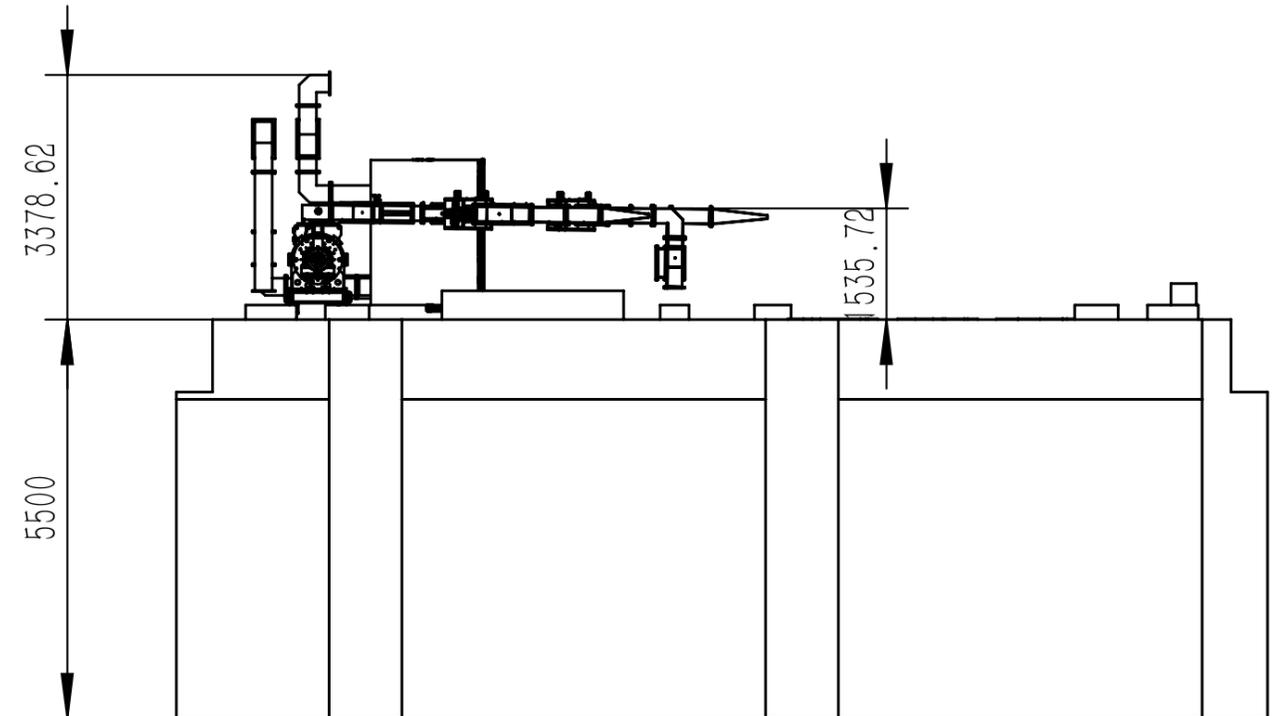
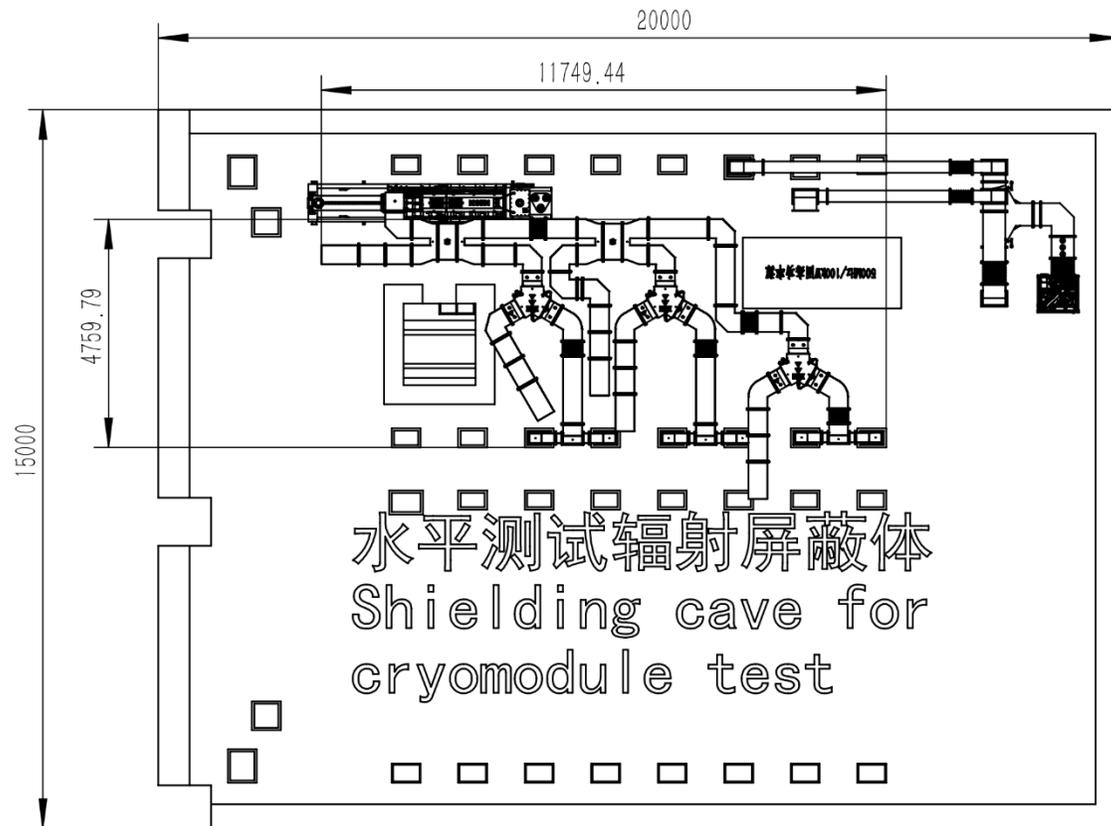
HOM absorber with  
SiC + AlN material



# HLRF System for 650 MHz Module Test

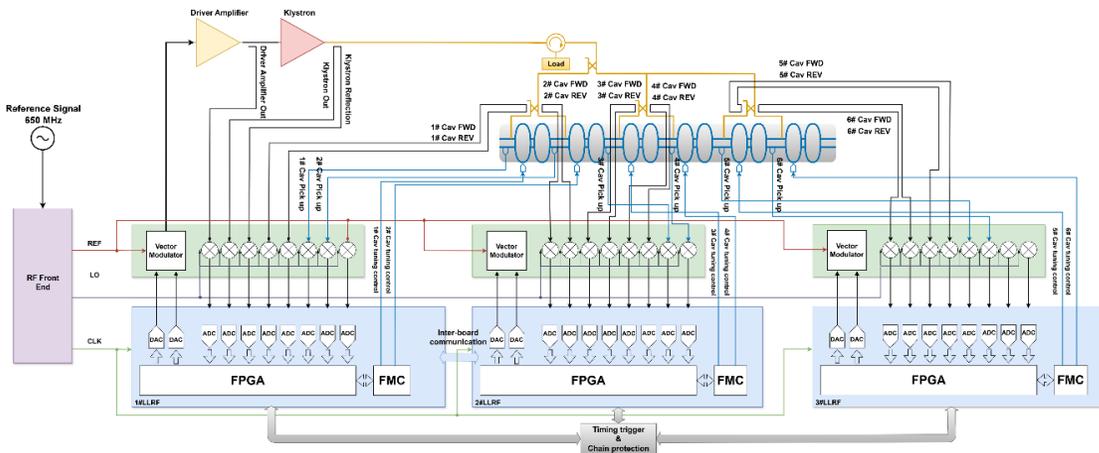
Zusheng Zhou

- CEPC 800 kW high efficiency 650 MHz klystron to feed six 2-cell cavities (150 kW SSA as backup).
- RF distribution under design for the six 2-cell cavities.



# LLRF System for 650 MHz Module Test

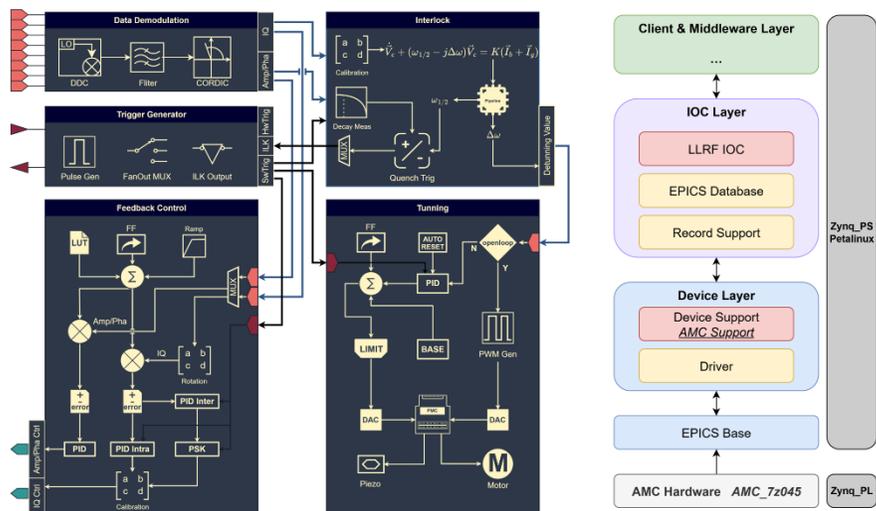
Wenbin Gao  
Nan Gan  
Zusheng Zhou



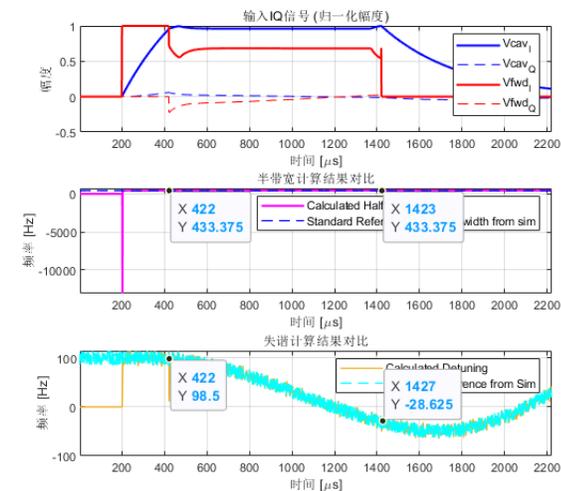
LLRF system design scheme



Control boards and other hardware (domestic MicroTCA platform)



FPGA firmware and EPICS software architecture



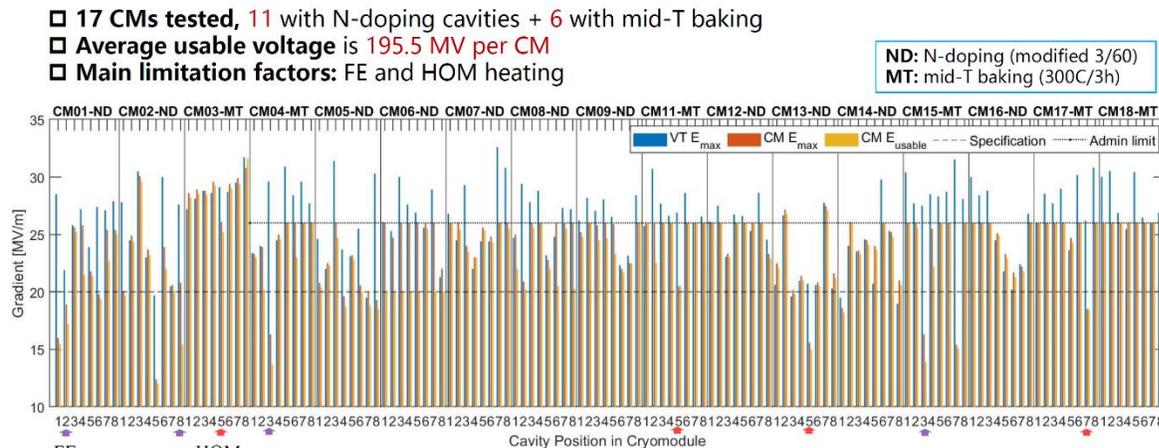
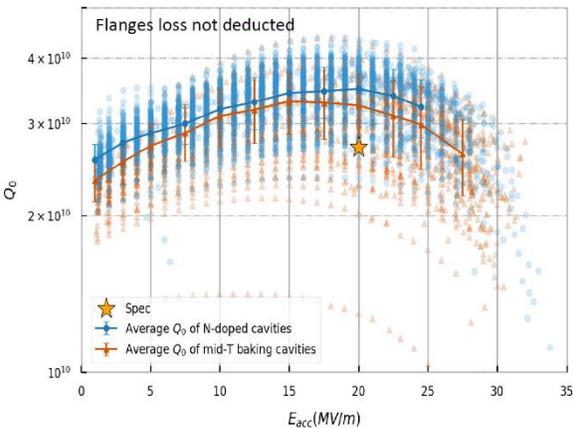
Integration and testing

# 1.3 GHz High Q Cavity and Module

- IHEP and SARI significantly advanced high Q mid-T bake application [PRAB 27, 092003 (2024) & NST 36,25 (2025)]
- SHINE mass production of high Q cavity / module (as of Sept. 2025) : **126 mid-T cavities and 6 mid-T modules tested**



	Domestic			International	
Nb materials	TD/NX	NX/TD	NX	NX	NX
1.3GHz cavity manufacturing	HERT (8+72+64)	OSTEC (8+40+40)	Shanghai Electric (2+64)	RI (8+60)	ZANON (8+60)
High-Q recipes	Mid-T baking (300°C/3h)			N-doping (modified 3/60)	
Surface treatment	SHINE facilities at Wuxi Creative			RI	ZANON
VT	SHINE				



Recipes	Ave. max Eacc (MV/m)	Ave. $Q_0$
Mid-T	27.5	3.2E+10
N-doping	24.5	3.5E+10

<Eusable> = 23.5 MV/m  
<Q0> = 3.4 E+10 @ 20 MV/m

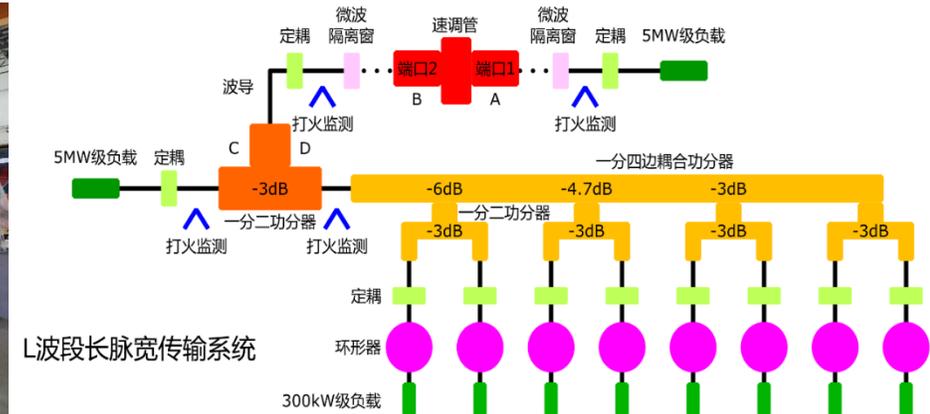
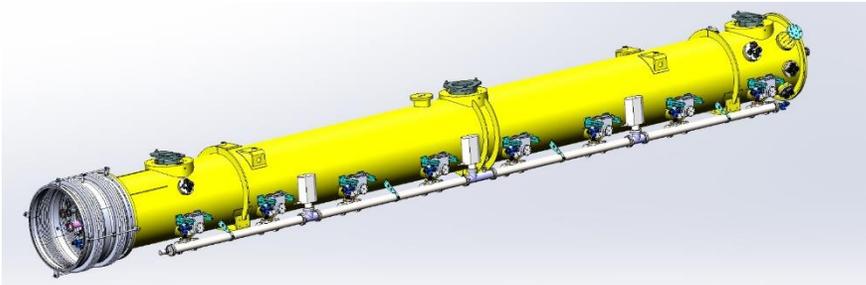
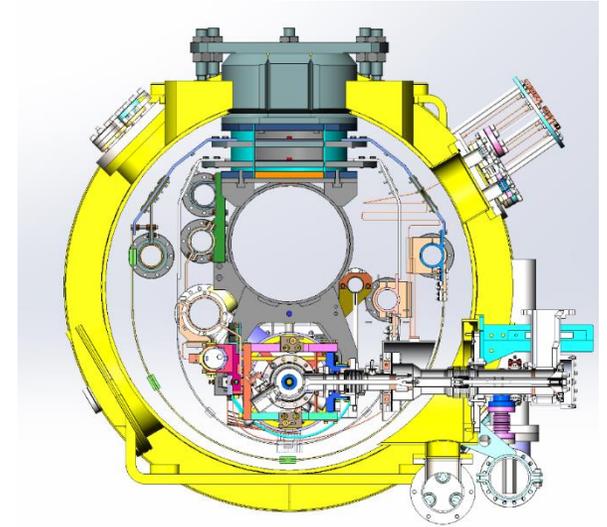
- CM06/08, the  $E_{usable}$  at ~20 MV/m (significantly lower than max Eacc) are due to MP, not enough time processing
- CM10 not in statistics: abnormally low Eacc, under investigation, individual case



Jinfang Chen, Hongtao Hou, SRF2025

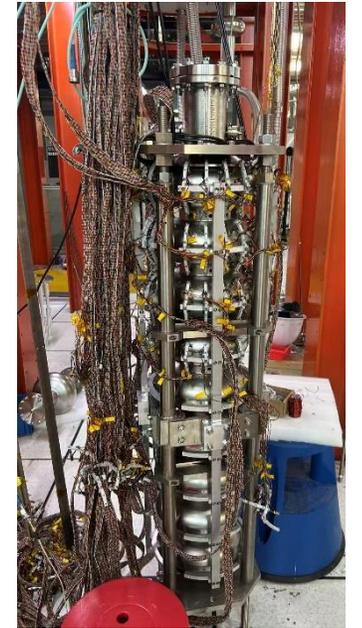
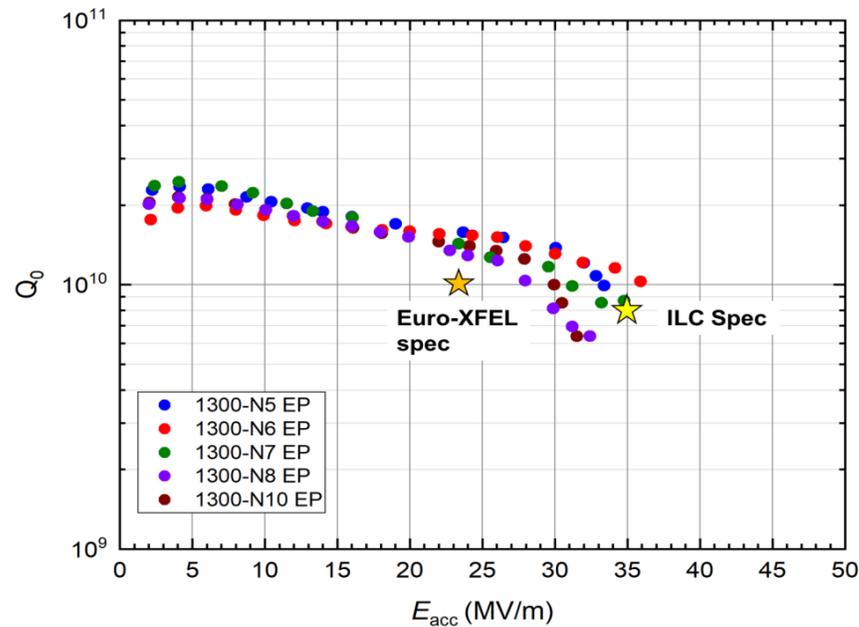
# 1.3 GHz High Gradient Module

- 1.3 GHz high gradient cavity and cryomodule R&D, aiming for 40 MV/m operation (pulsed). Module to be assembled and tested in 2026.
- Module structure similar to TESLA/XFEL/ILC:
  - Two layers of thermal shields (add 5 K shield).
  - No JT and CD valves on the module, one helium vessel pre-cooling inlet (no fast cool down requirement)
- 1.3 GHz 5 MW klystron and power distribution system to feed 8 cavities
- Lorentz force detuning compensation for eight cavities operation



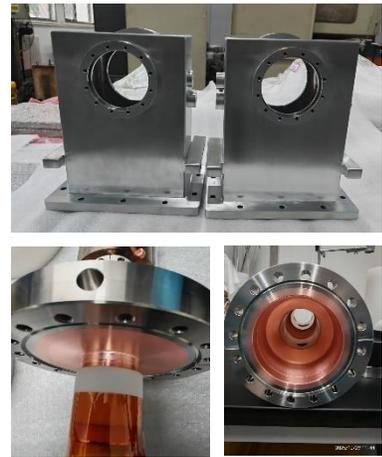
# 1.3 GHz High Gradient Cavity

- Established China's first EP system and demonstrated high gradient 1-cell and 9-cell results in 2019-2020
- Troubleshooting with field emission to recover and improve performance (1-cell OK, now 9-cell)
- Developing T-mapping and second sound system for defect diagnostics



1.3 GHz 9-cell (2020)

# 1.3 GHz High Gradient Module Components



# Summary and Outlook

- CEPC SRF EDR R&D is focused on a full-size **Higgs 650 MHz cryomodule**, targeting high Q, high gradient, and high-power handling. This prototype can also be used for future advanced test facilities.
- CEPC 1.3 GHz R&D to leverage synergies: **ttbar booster 1.3 GHz high-gradient module** aligns with national pulsed XFEL R&D, **Z booster 1.3 GHz high-current module** is with the planned ERL facility.
- Optimize CEPC RF configuration to a more compact and efficient system — **integrate high-luminosity Z operation into Higgs** by using **uniform 2-cell or 1-cell** cavities (RPO, large HOM power extraction, high gradient high Q cavity...)