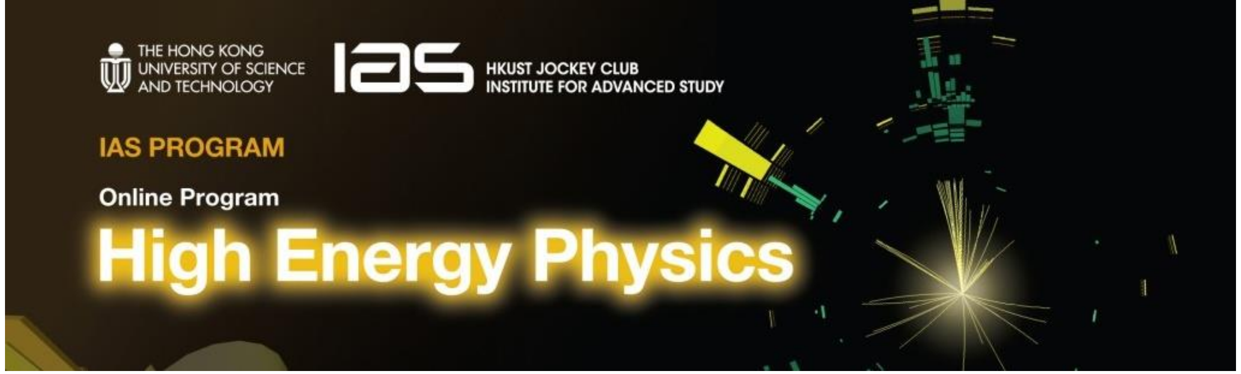

CEPC RF System and R&D

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Mini-workshop - Key Beam Physics and Technologies Issues for Colliders
January 13, 2022

Outline

1. CEPC SRF system design
2. CEPC SRF technology R&D
    - 650 MHz SRF for CEPC Collider
    - 1.3 GHz SRF for CEPC Booster
    - SRF infrastructure

Dou Wang (IHEP)

CEPC Collider TDR Parameters

	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	**180**	**120**	**80**	**45.5**
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	**35**	**249**	**1297**	**11951**
Bunch spacing [ns]	4524	636	257	23 (10% gap)
Bunch population [10^{10}]	20	14	13.5	14
Beam current [mA]	**3.3**	**16.7**	**84.1**	**803.5**
Momentum compaction [10^{-5}]	0.71	0.71	1.43	1.43
Beta functions at IP ($\beta x/\beta y$) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance ($\varepsilon x/\varepsilon y$) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP ($\sigma x/\sigma y$) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	**2.2/2.9**	**2.3/3.9**	**2.5/4.9**	**2.5/8.7**
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters ($\xi x/\xi y$)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	**10**	**2.2**	**0.7**	**0.12**
RF frequency [MHz]	650	650	650	650
Longitudinal tune νs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[10^{34}/cm^2/s]	**0.5**	**5.0**	**16**	**115**

Dou Wang (IHEP)

CEPC Booster TDR Parameters

- Injection energy: 10 GeV → 20 GeV
- Max energy: 120 GeV → 180 GeV
- Lower emittance – new lattice (TME)

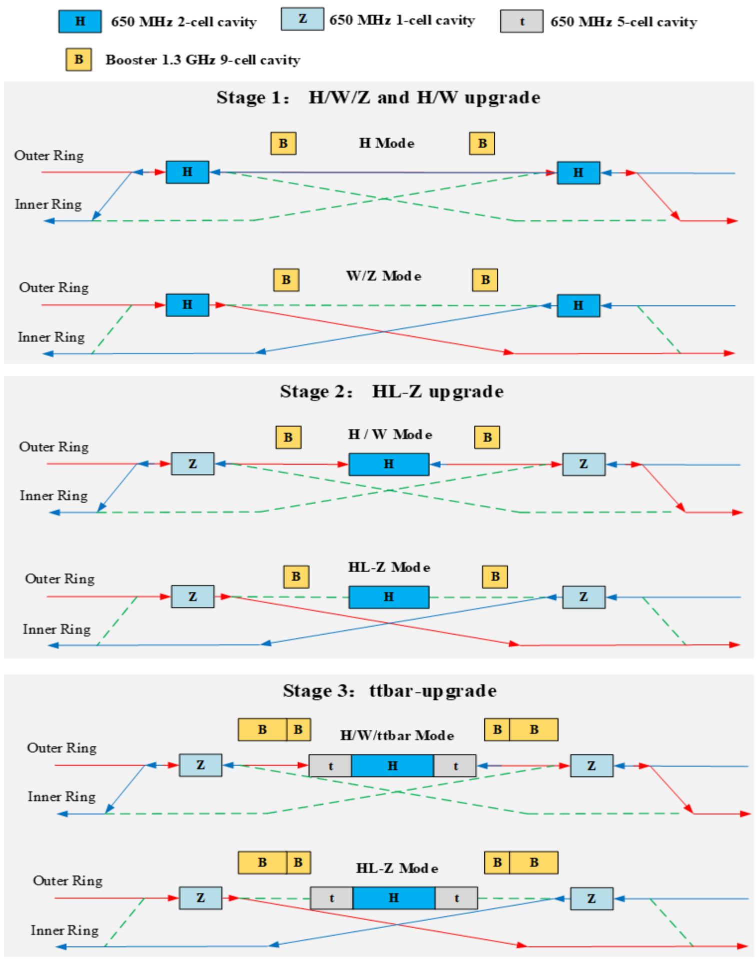
Injection		*tt*	*H*	*W*	*Z*	
Beam energy	GeV	20				
Bunch number		37	240	1230	3840	5760
Threshold of single bunch current	μA	7.18	4.58	3.8		
Threshold of beam current (limited by coupled bunch instability)	mA	27				
Bunch charge	nC	1.07	0.78	0.81	0.89	0.92
Single bunch current	μA	3.2	2.3	2.4	2.7	2.78
Beam current	mA	0.12	0.56	2.99	10.3	16.0
Energy spread	%	0.016				
Synchrotron radiation loss/turn	MeV	1.3				
Momentum compaction factor	10^{-5}	1.12				
Emittance	nm	0.035				
Natural chromaticity	H/V	-372/-269				
RF voltage	MV	438.0	197.1	122.4		
Betatron tune ν_x/ν_y		321.23/117.18				
Longitudinal tune		0.13	0.087	0.069		
RF energy acceptance	%	5.4	3.6	2.8		
Damping time	s	10.4				
Bunch length of linac beam	mm	0.5				
Energy spread of linac beam	%	0.16				
Emittance of linac beam	nm	10				

Extraction		*tt*	*H*		*W*	*Z*	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
Beam energy	GeV	180	120		80	45.5	
Bunch number		37	240	233+7	1230	3840	5760
Maximum bunch charge	nC	0.96	0.7	23.2	0.73	0.8	0.83
Maximum single bunch current	μA	2.9	2.1	69.7	2.2	2.4	2.5
Threshold of single bunch current	μA	95	79				
Threshold of beam current (limited by RF system)	mA	0.3	1		4	10	16
Beam current	mA	0.11	0.51	0.99	2.69	9.2	14.4
Bunches per pulse of Linac		1	1		1	2	
Time for ramping up	s	7.3	4.5		2.7	1.6	
Injection duration for top-up (Both beams)	s	30.0	23.3	32.8	39.3	134.7	128.2
Injection interval for top-up	s	65	38		155	153.5	
Current decay during injection interval		3%					
Energy spread	%	0.15	0.099		0.066	0.037	
Synchrotron radiation loss/turn	GeV	8.45	1.69		0.33	0.034	
Momentum compaction factor	10^{-5}	1.12					
Emittance	nm	2.83	1.26		0.56	0.19	
Natural chromaticity	H/V	-372/-269					
Betatron tune ν_x/ν_y		321.27/117.19					
RF voltage	GV	9.3	2.05		0.59	0.284	
Longitudinal tune		0.13	0.087		0.069	0.069	
RF energy acceptance	%	1.34	1.31		1.6	2.6	
Damping time	ms	14.2	47.6		160.8	879	
Natural bunch length	mm	2.0	2.0		1.7	0.96	
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

*Diameter of beam pipe is 55mm for re-injection with high single bunch current @120GeV.

CEPC TDR RF Parameters (Collider Ring)

Version. 2022.01.12. Machine parameters: 2021.11 30 MW SR power per beam for each mode. ttbar and Higgs half fill with common cavities for two rings, W and Z with separate cavities for two rings, Z use high current 1-cell cavity with RF bypass	ttbar		Higgs	W	Z
	Additional 5-cell cavities	Existing 2-cell cavities			
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	0.5		5	16	115
RF voltage [GV]	10 (7.8 + 2.2)		2.2	0.7	0.12
Beam current / beam [mA]	3.4		16.4	84	803
Bunch charge [nC]	32		22	21.6	22.4
Bunch length [mm]	2.9		3.9	4.9	8.7
650 MHz cavity number	**240**	**240**	**240**	**120/ring**	**30/ring**
Cell number / cavity	**5**	**2**	**2**	**2**	**1**
Gradient [MV/m]	**28.5**	20	20	12.7	8.7
Q_0 @ 2 K at operating gradient (long term)	**5E10**	2E10			
HOM power / cavity [kW]	0.4	0.16	0.45	0.93	**2.9**
Input power / cavity [kW]	194	56	250	250	**1000**
Optimal Q_L	1E7	7E6	1.6E6	6.4E5	7.5E4
Optimal detuning [kHz]	0.01	0.02	0.1	0.9	**13.3**
Cavity number / klystron	**4**	**12**	**2**	**2**	**1**
Klystron power [kW]	**1400**	**1400**	**800**	**800**	**1400**
Klystron number	60	20	120	60	60
Cavity number / cryomodule	4	6			1
Cryomodule number	60	40			30
Total cavity wall loss @ 2 K [kW]	9.5	4.7		1.9	0.45



- RF staging and bypass. Seamless mode switching.
- Z lower lumi in Stage 1.
- If start from Stage 2: W~1/2 Lumi, Z~1/10 Lumi.
- Transfer Higgs/ttbar RF power to high lumi Z.
- Klystron power and HOM handling capacity allow for 50 MW upgrade of ttbar, H, W. Add 30 cavities for Z 50 MW upgrade.

CEPC TDR RF Parameters (Booster Ring)

Version. 2022.01.12. Machine parameters: 2021.11 30 MW Collider SR power per beam for each mode. 20 GeV injection.	**ttbar**	**Higgs** off/on-axis	**W**	**Z** high current
Extraction beam energy [GeV]	180	120	80	45.5
Extraction average SR power [MW]	0.087	0.09	0.01	0.004
Bunch charge [nC]	0.96	0.7	0.73	0.83
Beam current [mA]	0.11	0.5/1	2.7	14.3
Injection RF voltage [GV]	0.438	0.197	0.122	0.122
Extraction RF voltage [GV]	9.3	2.05	0.59	0.28
Extraction bunch length [mm]	1.9	1.9	1.6	0.9
Cavity number (1.3 GHz 9-cell)	**336**	**96**	**64**	**16**
Extraction gradient [MV/m]	**26.7**	20.6	8.9	17.1
Q_0 @ 2 K at operating gradient (long term)	1E10			
Q_L	4E7	1E7		
Cavity bandwidth [Hz]	**33**	130		
Peak HOM power per cavity [W]	0.4	1.2/2.3	7.8	105
Input peak power per cavity [kW]	7.5	16/21.4	15	31
SSA peak power [kW] (one cavity per SSA)	**10**	**25**	**25**	**40**
Cryomodule number (8 cavities per module)	42	12	8	2

- Higgs and ttbar half fill for injection timing with Collider ring. Transient beam loading tolerable.
- Transient beam loading of the booster for Higgs on-axis injection tolerable.
- Standard quasi-CW TESLA cryomodules for Higgs, W and ttbar.
- Two high current 8x9-cell cryomodules for Z with RF bypass, as well as more SSAs (or RF power transfer and combine from Higgs SSAs?) even for 50 MW upgrade. Not the limit for booster Z beam current ramp up.
- High gradient high Q 9-cell cavities for ttbar. Narrow bandwidth high gradient cavity voltage ramping through the multipacting region to be studied.
- SR, RF power, HOM power, cryogenic duty factors to be calculated with the real time structures.

CEPC SRF Hardware Specifications

Suitable for 30/50 MW SR per beam	**H, W, Z** high gradient & high Q	**HL-Z** high current & power	**ttbar** very high gradient & high Q
Collider 650 MHz Cavity at 2 K	**2-cell** VT 4E10 @ 22 MV/m HT 2E10 @ 20 MV/m OP 1.5E10 @ 20 MV/m	**1-cell** 1E10 @ 8.7 MV/m	**5-cell** VT 6E10 @ 32 MV/m HT 5E10 @ 32 MV/m OP 5E10 @ 28.3 MV/m
Booster 1.3 GHz 9-cell Cavity at 2 K	VT 3E10 @ 24 MV/m HT 3E10 @ 22 MV/m OP 1E10 @ 20 MV/m	1E10@17 MV/m	VT 3E10 @ 32 MV/m HT 2E10 @ 32 MV/m OP 1E10 @ 26.7 MV/m
650 MHz Input Coupler variable	300/500 kW variable	1000 kW	300 kW variable
650 MHz HOM Coupler	1 kW	\	1 kW
650 MHz HOM Absorber	5 kW	10 kW	\

Outline

1. CEPC SRF system design
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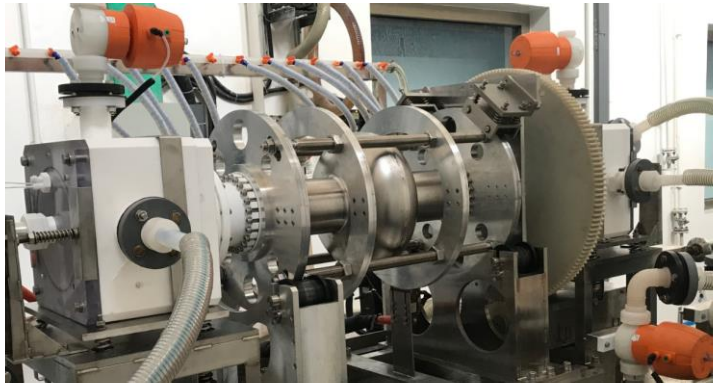
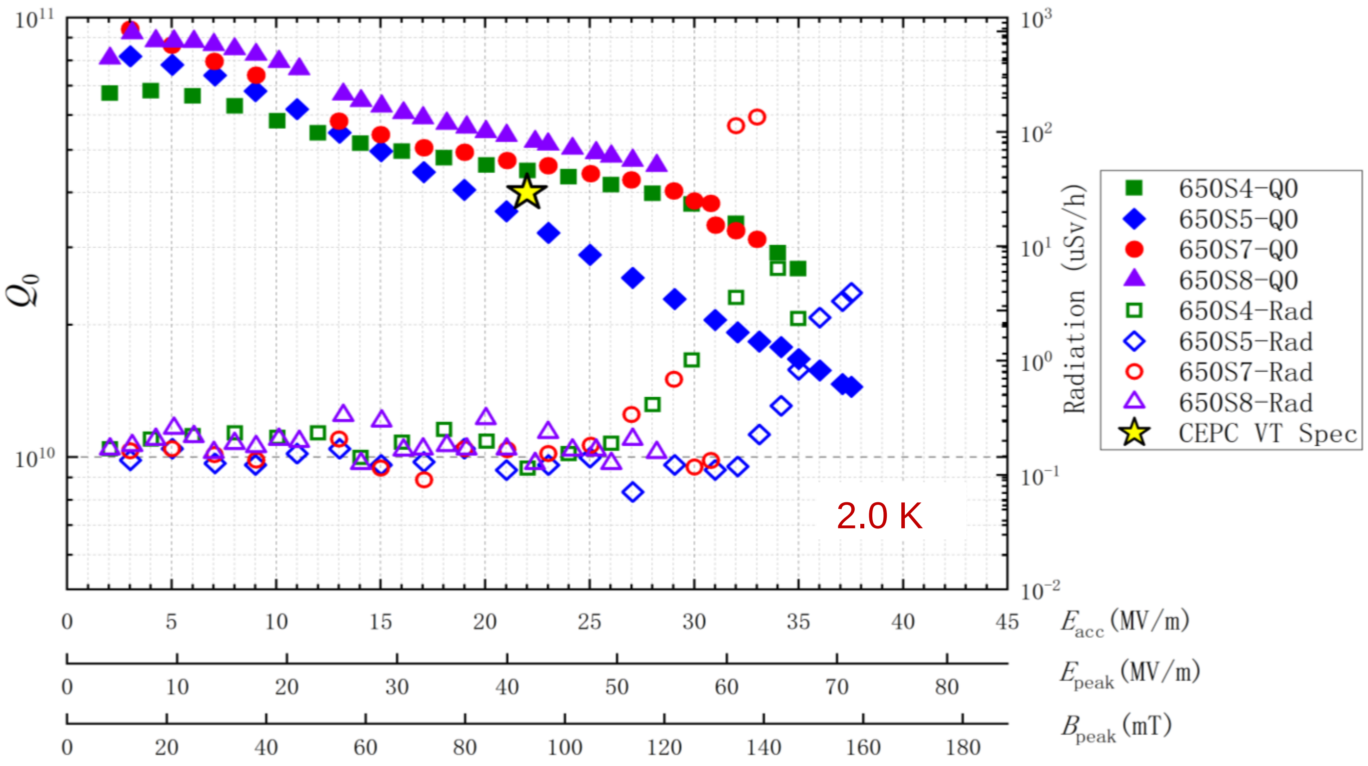
High Gradient 650 MHz Cavity

- EP fine grain 1-cell: 3.9E10@30MV/m,1.5E10@37.5MV/m.
- State-of-the-art high gradient 650 MHz cavity.



EP of 650 MHz single-cell cavity

S. Jin et al., *Materials,* 2021, 14(24), 7654

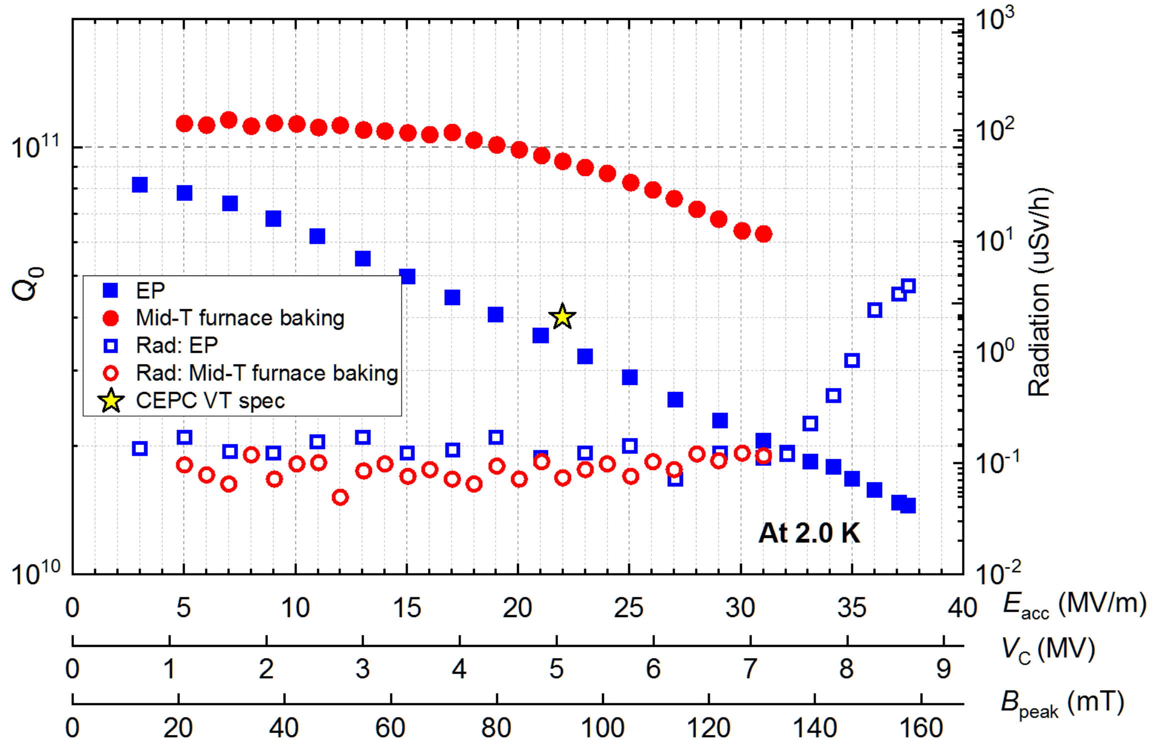


Vertical test results of 650 MHz single-cell cavities

High Q 650 MHz Cavity

- After medium-temperature (mid-T) furnace baking, Q reached 6.4E10 at 30 MV/m.
- World record high Q at high gradient for 650 MHz cavity.

Mid-T furnace baking of 650 MHz single-cell cavity



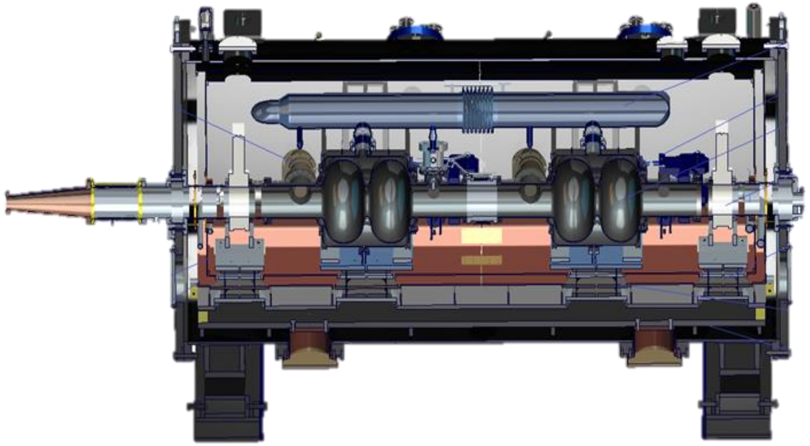
P. Sha et al., *Applied Sciences*. 2022; 12(2):546.

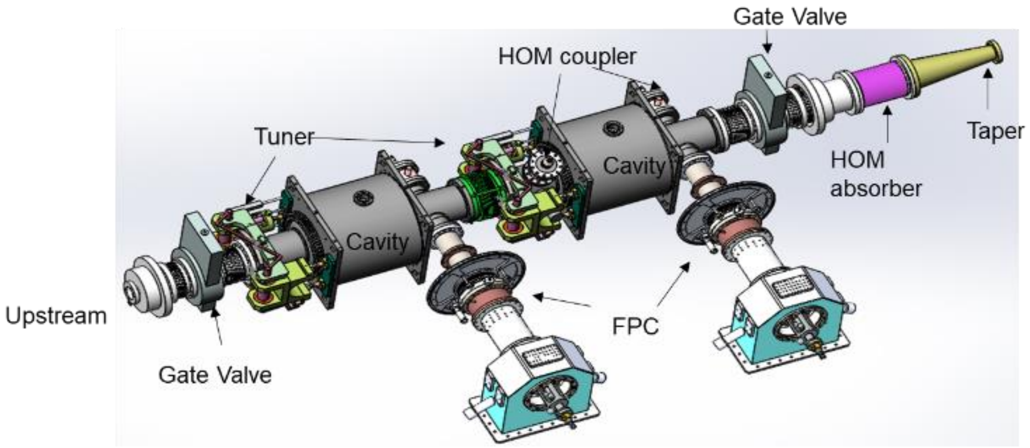
Vertical test results of 650 MHz single-cell cavity

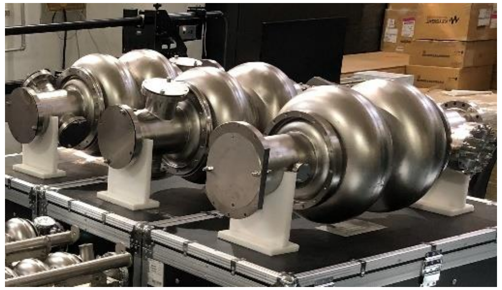
CEPC 650 MHz Test Cryomodule

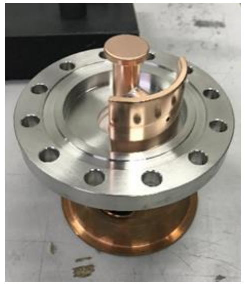
- Cavity string and module assembly. Modul installation in beamline, 2 K cool down test and RT coupler conditioning. Horizontal and beam test soon.
- IR laser output to 116 W. Photo-cathode QE to 5 %. DC gun vacuum to 1.5E-10 Pa, voltage to 350 kV. Buncher cavity high power tested.

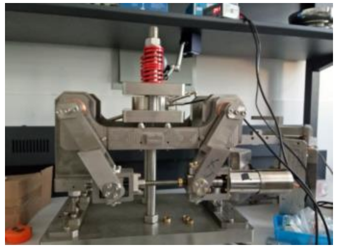
CEPC 650 MHz Test Cryomodule

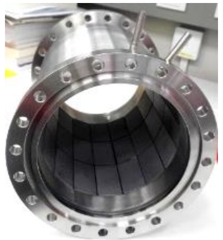




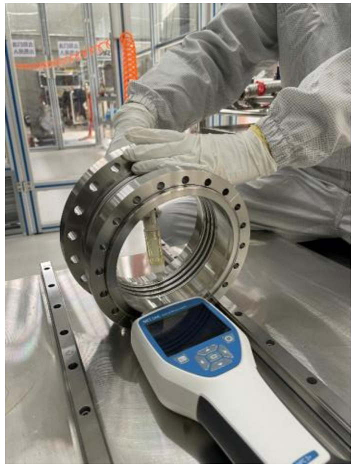
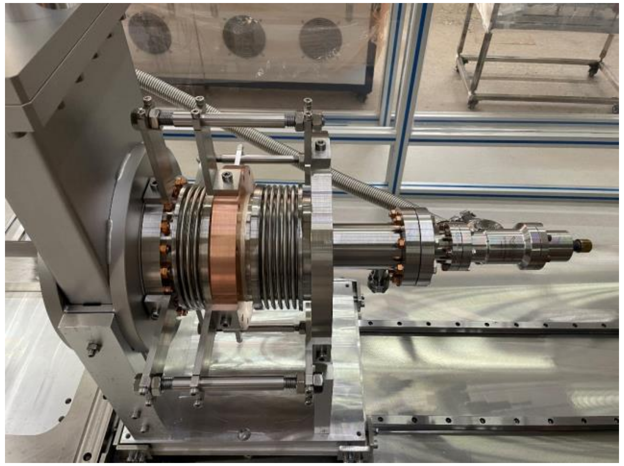


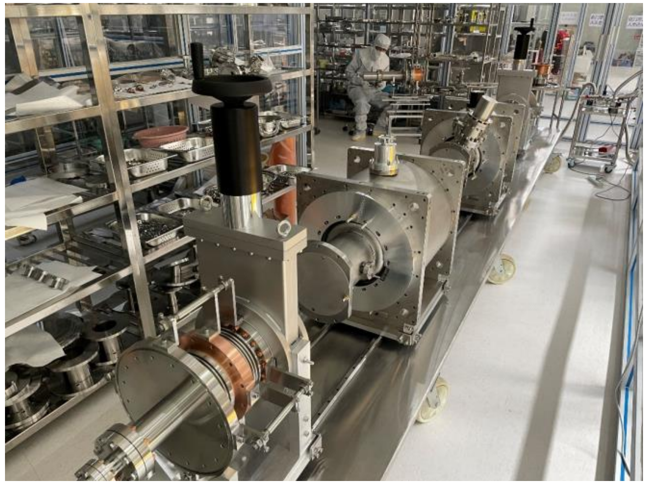


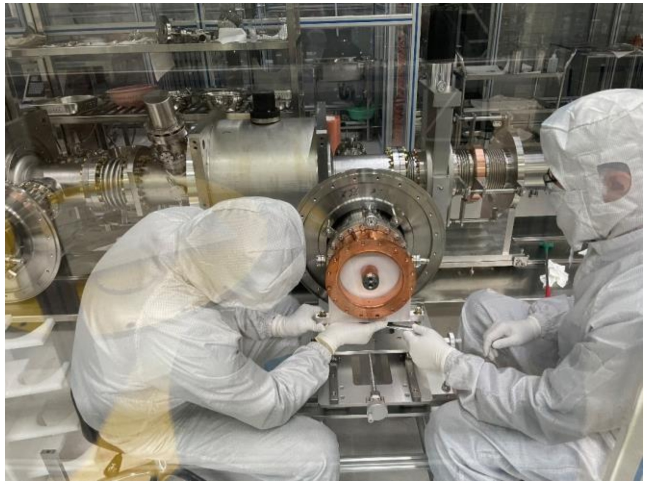




650 MHz 2 x 2-cell Cavity String Assembly

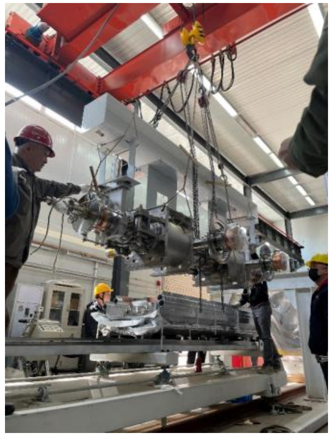




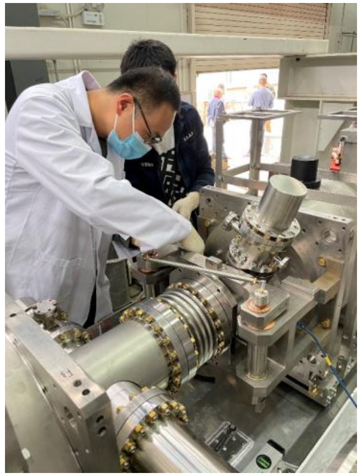



650 MHz Test Cryomodule Assembly

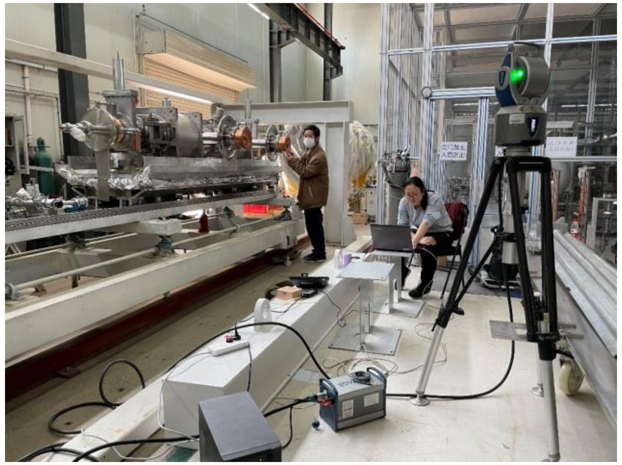
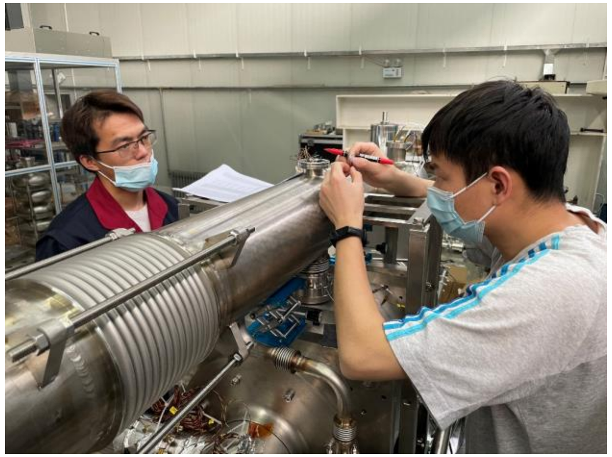
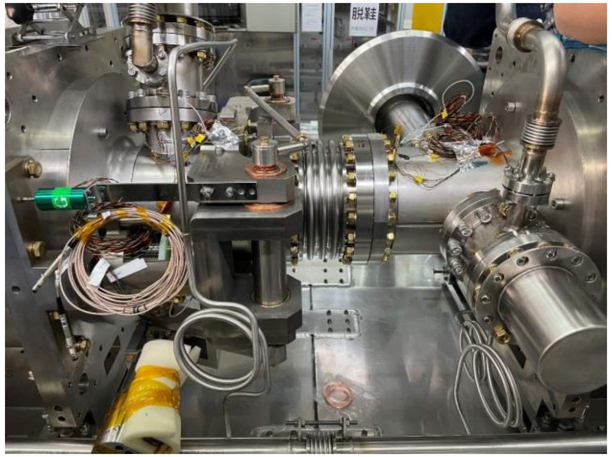
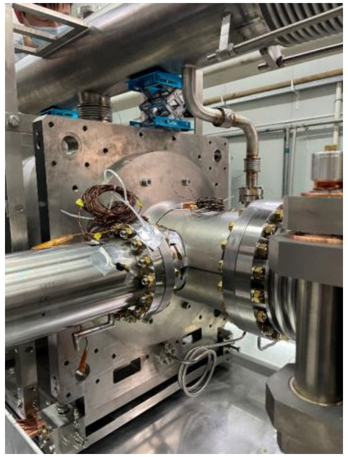


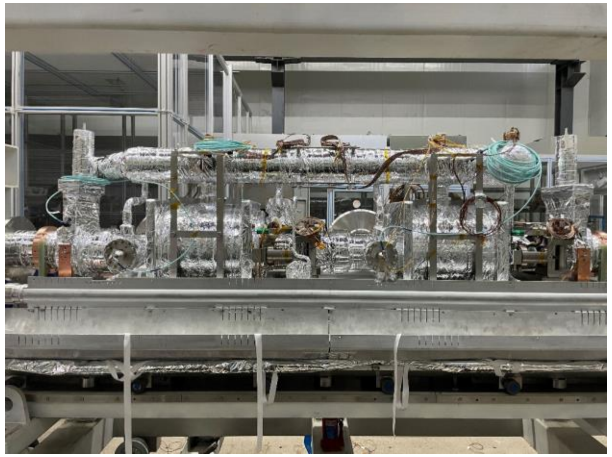
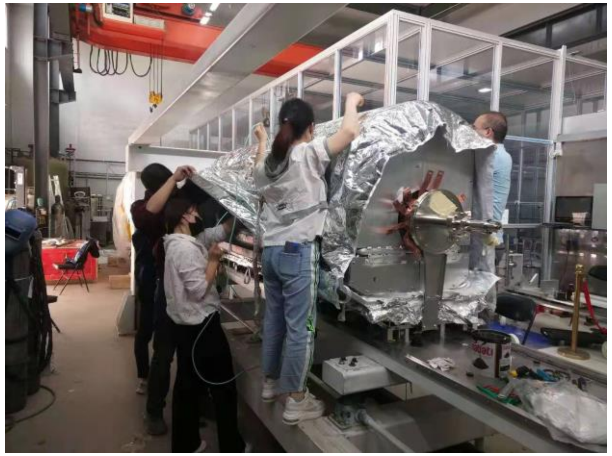





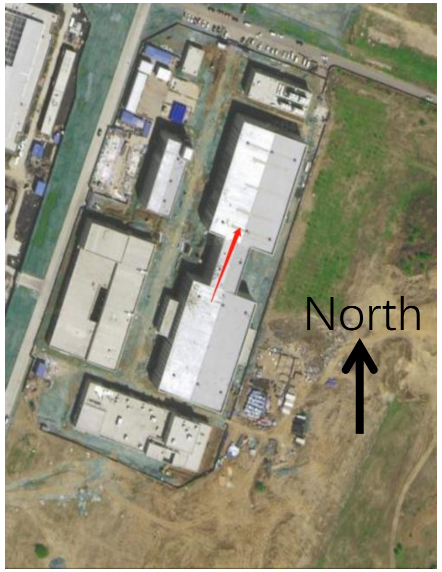


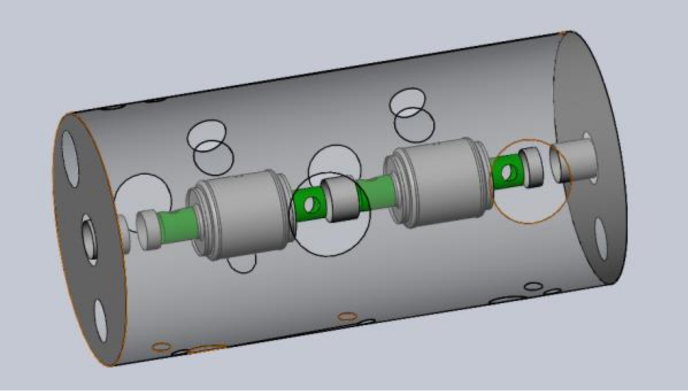
650 MHz Test Cryomodule Assembly

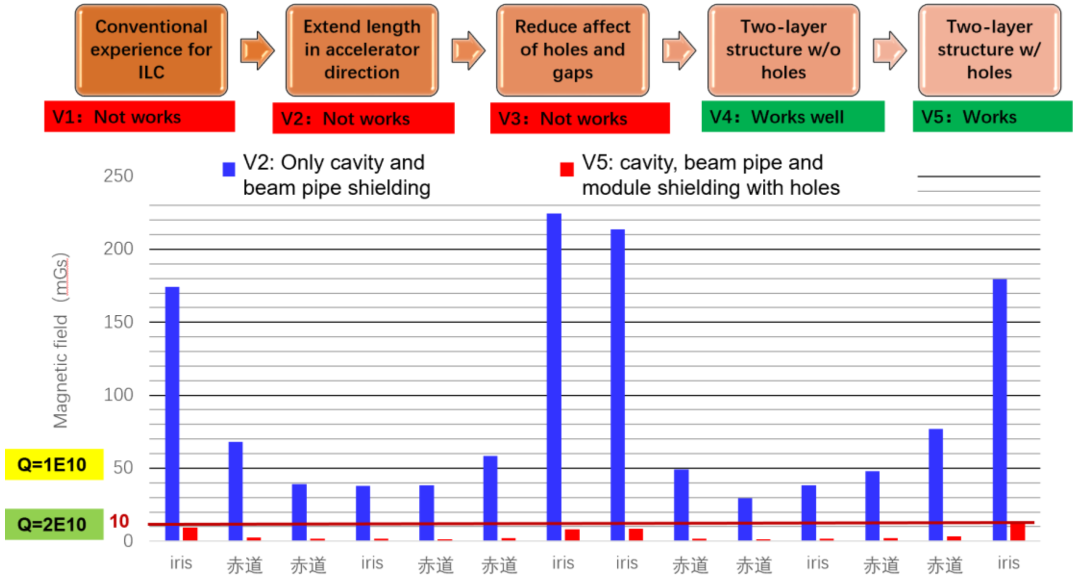




Magnetic Shielding and Compensating



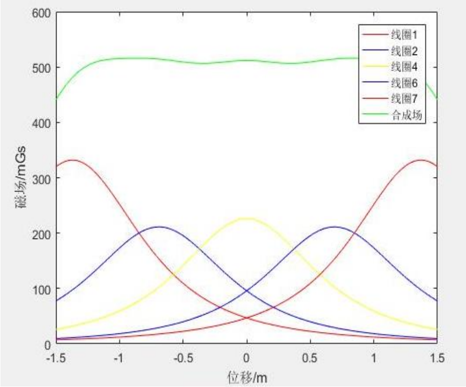


Because of beam direction and larger beam pipe than 1.3 GHz, **only two shieldings** can reach the magnetic field requirement of high Q 650 MHz cavity: **cavity (2 K local) shield and module (RT global) shield**.



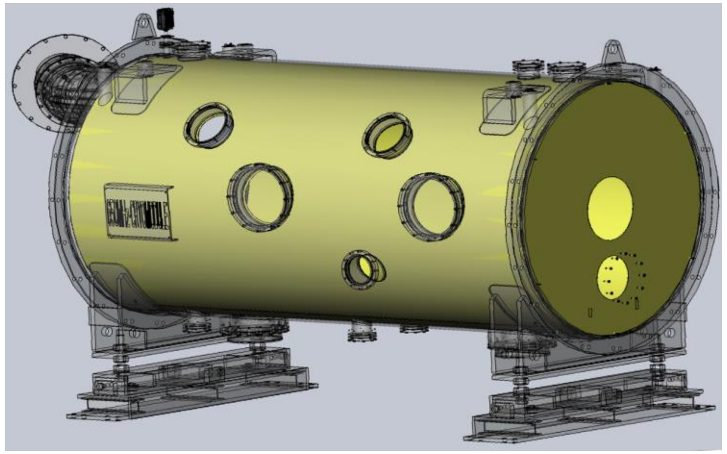
$$R_{mag} = \eta \cdot S(l) \cdot (B_{ext}+B_{tc})\sqrt{f}$$

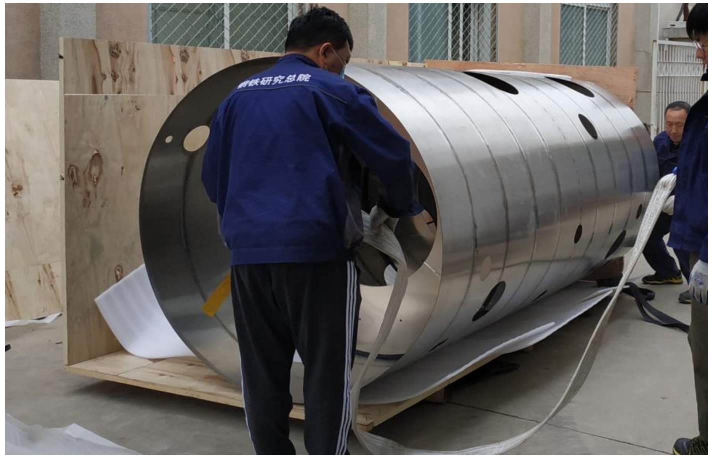
1. Flux trapping ratio: grain size, high-T annealing, fast cold down
2. Magnetic sensitivity: mean free path and other
3. Remnant magnetic field: demagnetization, magnetic shield, magnetic compensation
4. Thermocurrent induced magnetic field



Magnetic compensation with coils

Global Magnetic Shield of the 650 MHz CM



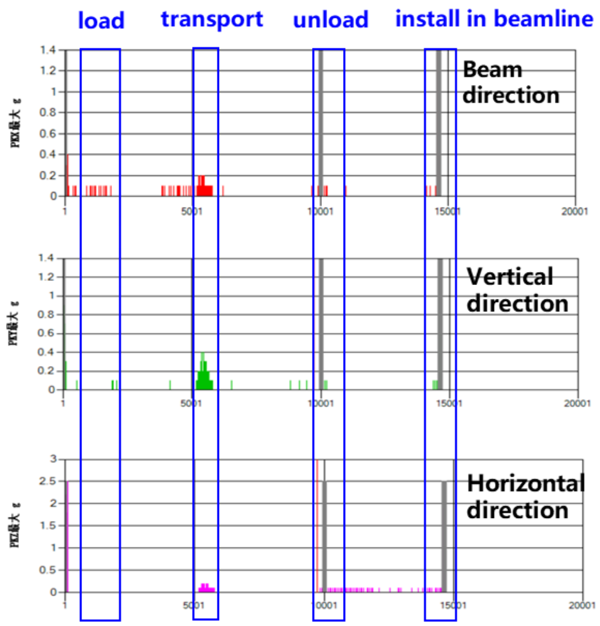


650 MHz Test Cryomodule Assembly



650 MHz Module Transport (IHEP to PAPS 80 km)

- Module transport on a frame with isolator springs. Three accelerometers attached.
- Max acceleration 0.4 g (average 0.1 g) in the whole process (< 1.5 g spec)
- Cavity string vacuum monitored with cold gauge (powered by UPS). No leak.

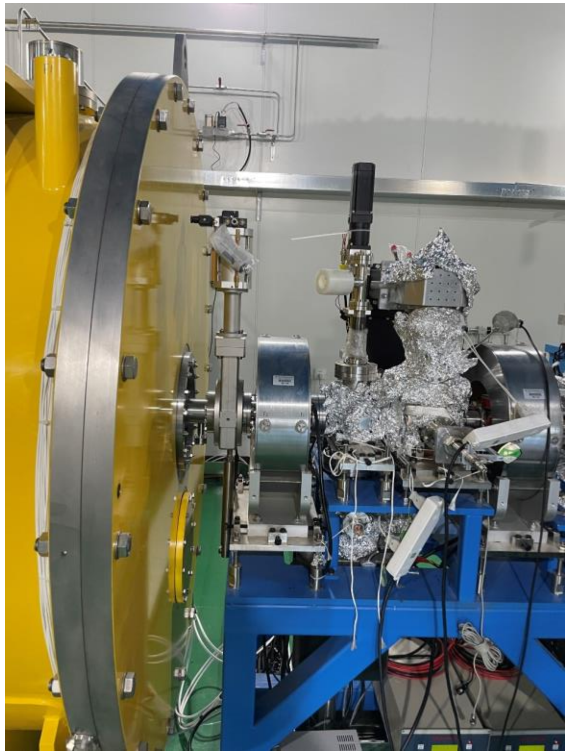


Shocklog 298-17069 coupler position
(every slot 10 s)

650 MHz Module Beamline Installation

Upstream gate valve installation

Downstream HOM absorber, taper, ion pump, gate valve



Upstream beamline connection

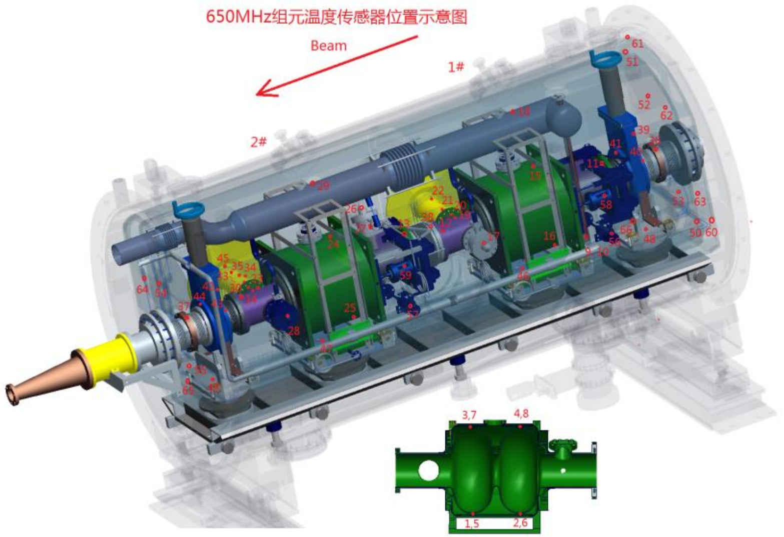
Downstream beamline and valve box connection

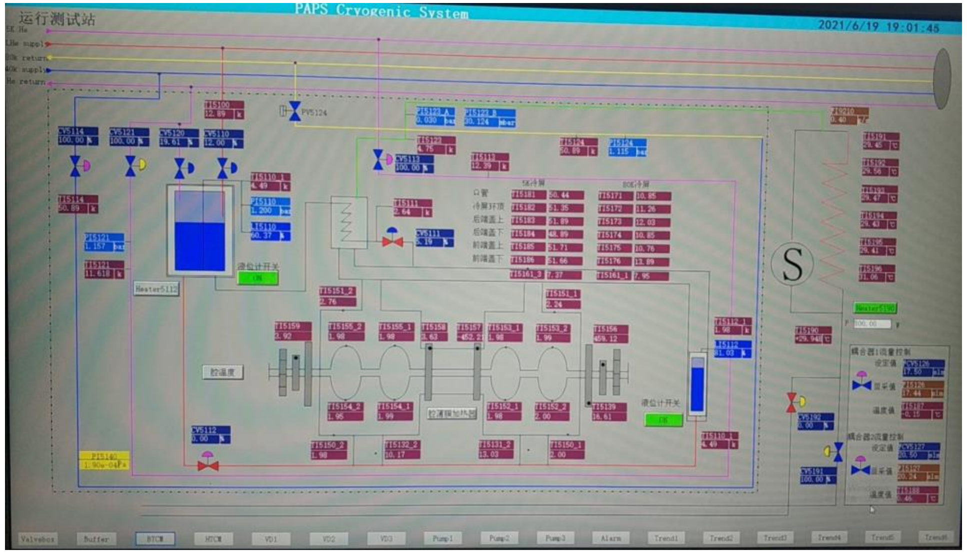
650 MHz Module Beamline Installation

Input coupler warm part, doorknob, waveguide

Module in the beamline

650 MHz Module 2 K Cool Down Test

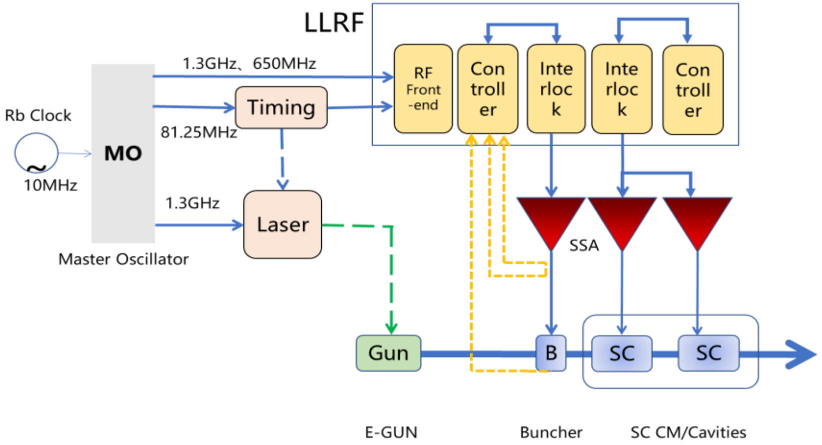




- Cavity vacuum @ 2 K: 6E-7 Pa
- Cryogenics lines no leak. Most temperatures OK. Input coupler helium gas cooling test (need further optimize).
- Frequency: CAV#1 649.856 MHz, CAV#2 649.816 MHz. Tuners stretch the cavities ~150 kHz to 650 MHz.
- Input coupler Qin:
  - CAV#1: 1.2E6 (HT 35 kW@13 MV/m, Beam Test 49 kW@9.7 MV/m, 10 mA)
  - CAV#2: 1.8E6 (HT 35 kW@16 MV/m, Beam Test 76 kW@15 MV/m, 10 mA)
- HOM couplers fundamental mode Qe (double notch, tuning not needed): #1 6.8E13, #2 1.9E13. #3 2.1E12.
- Flux gates on cavity wall in the helium vessel: < 3 mG (with cavity local and vacuum vessel global shields)
- Warm up for couplers RT conditioning (up to 35 kW full reflection limited by the SSA).

650 MHz HLRF and LLRF

- 150 kW (total) solid state amplifier
- LLRF and timing system for 650 MHz module, laser, DC-Gun and buncher.



LLRF Rack

Power Meter

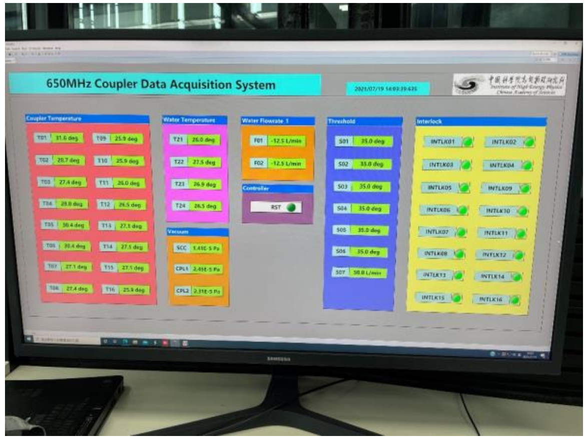
Timing Module

Master Oscillator

LLRF Front-end

LLRF Controller (MicroTCA.4 Crate)

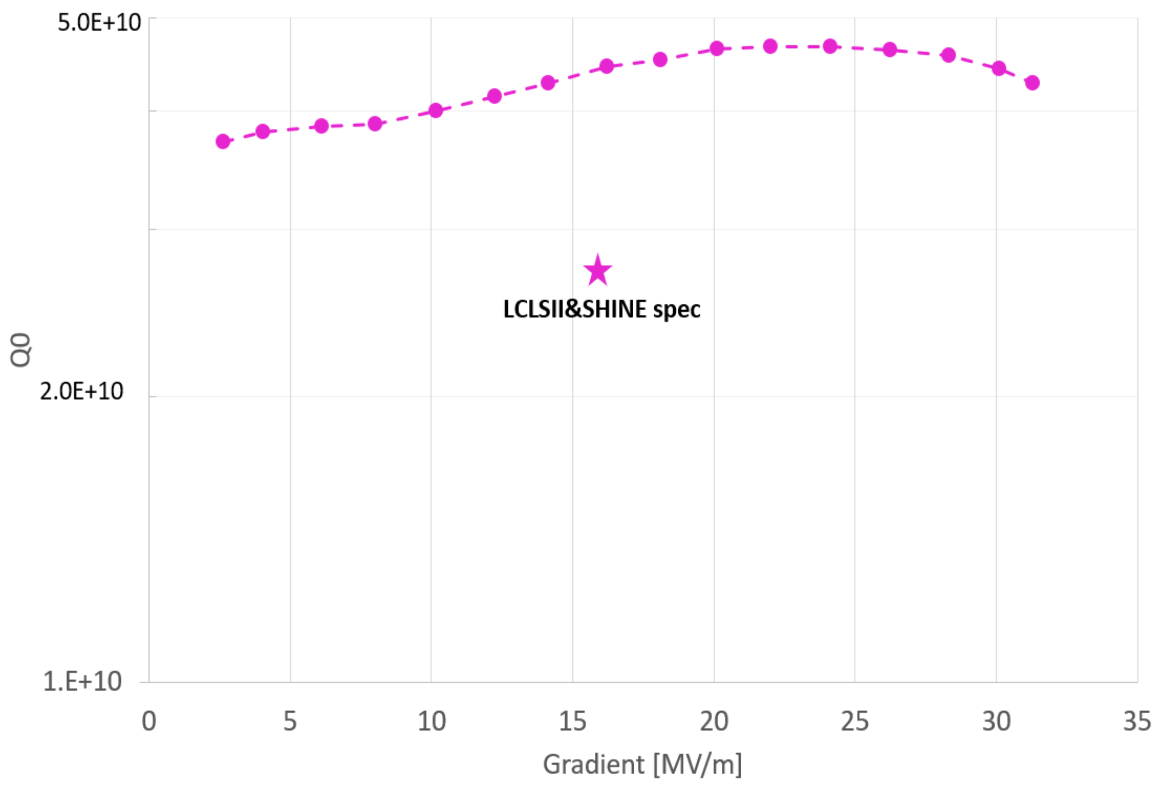
10MHz Rb Clock



Outline

1. CEPC SRF system design
2. CEPC SRF technology R&D
   - 650 MHz SRF for CEPC Collider
   - 1.3 GHz SRF for CEPC Booster
   - SRF infrastructure

Word Record high Q 9-cell cavity at high gradient



1300-N11

Mid-T furnace baked

Bulk EP+900C+oxidation in air +300C+HPR

Vertical Test on Dec 31, 2021 at PAPS VTS

4.5E+10 @ 16 MV/m

4.3E+10 @ 31.3 MV/m

1.3 GHz High Q Mid-T Cavity Horizontal Test

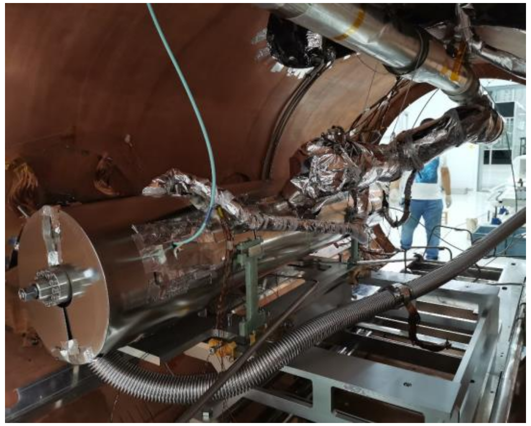
- Step 1a: Horizontal test with vertical test antenna (self excitation mode) at IHEP campus
  - Low Q0 (unknow heat load?) , abnormal HOM notch change (HOM can thermal anchor?)
  - Flux gates and thermal sensors on cavity outside wall in helium vessel, double-layer magnetic shield and foils, thermal straps (HOM coupler, beam pipe), fast cool down and flux expulsion

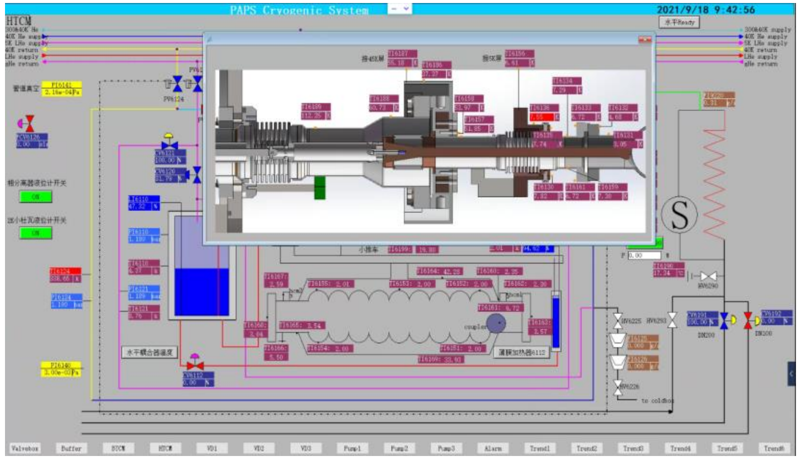
- Step 1b: Horizontal test with vertical test antenna (self excitation mode) at PAPS
  - Successful, similar Q0 as vertical test, abnormal frequency and field flatness change (bellow support, overpressure)
  - Add thermal intercepts for cables, Q0 measurement comparison (mass-flow vs RF), input coupler flange heating

- Step 2: Horizontal test with input coupler (self excitation mode) at PAPS
  - Ongoing, got high Q0 for four 9-cell cavities but unstable for long time at high gradient (sporadic quench), need long-time conditioning, similar to LCLS-II and LCLS-II-HE cavities.
  - Input coupler thermal sensors, interlocks, thermal straps, RT online conditioning, cavity active pumping

- Step 3: Horizontal test with input coupler and tuner (GDR mode) at PAPS
  - Tuner, LLRF, microphonics …

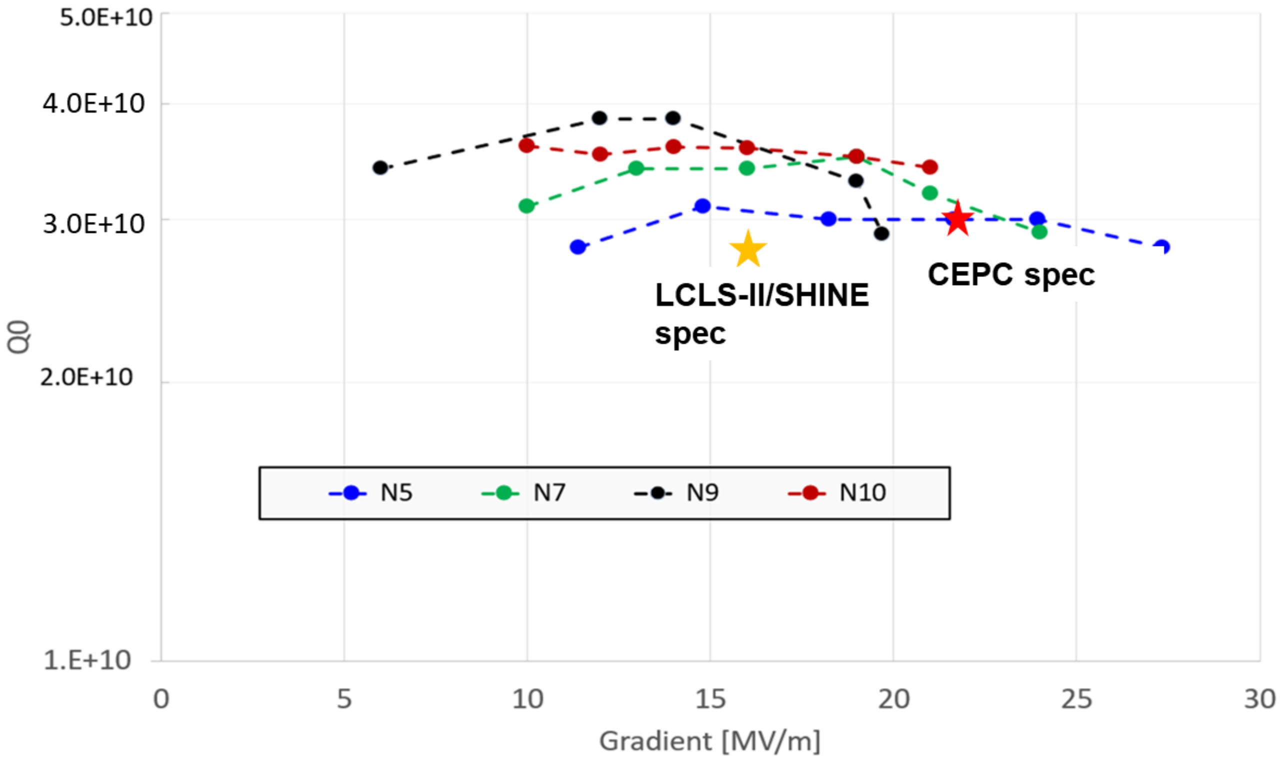
1.3 GHz High Q Mid-T Cavity Horizontal Test



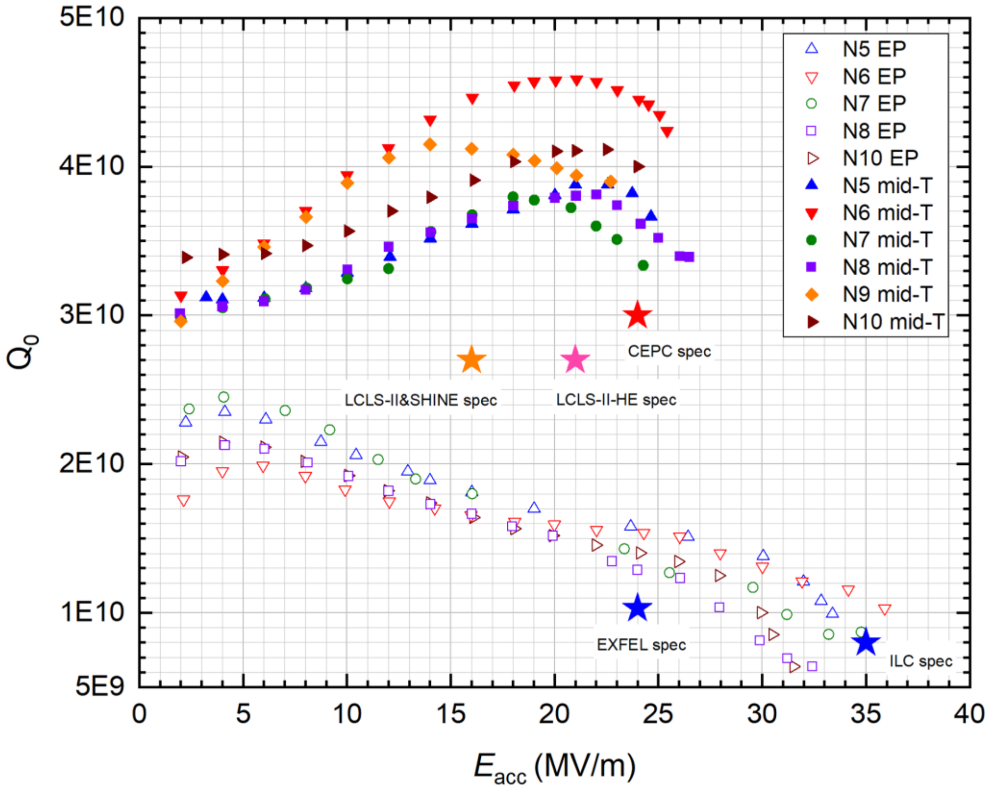


1.3 GHz High Q Mid-T Cavity Horizontal Test

Horizontal test with high power input coupler (self excitation mode)

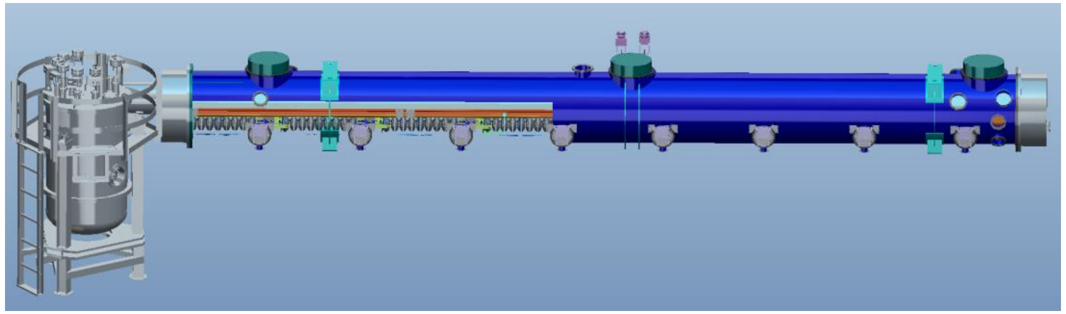


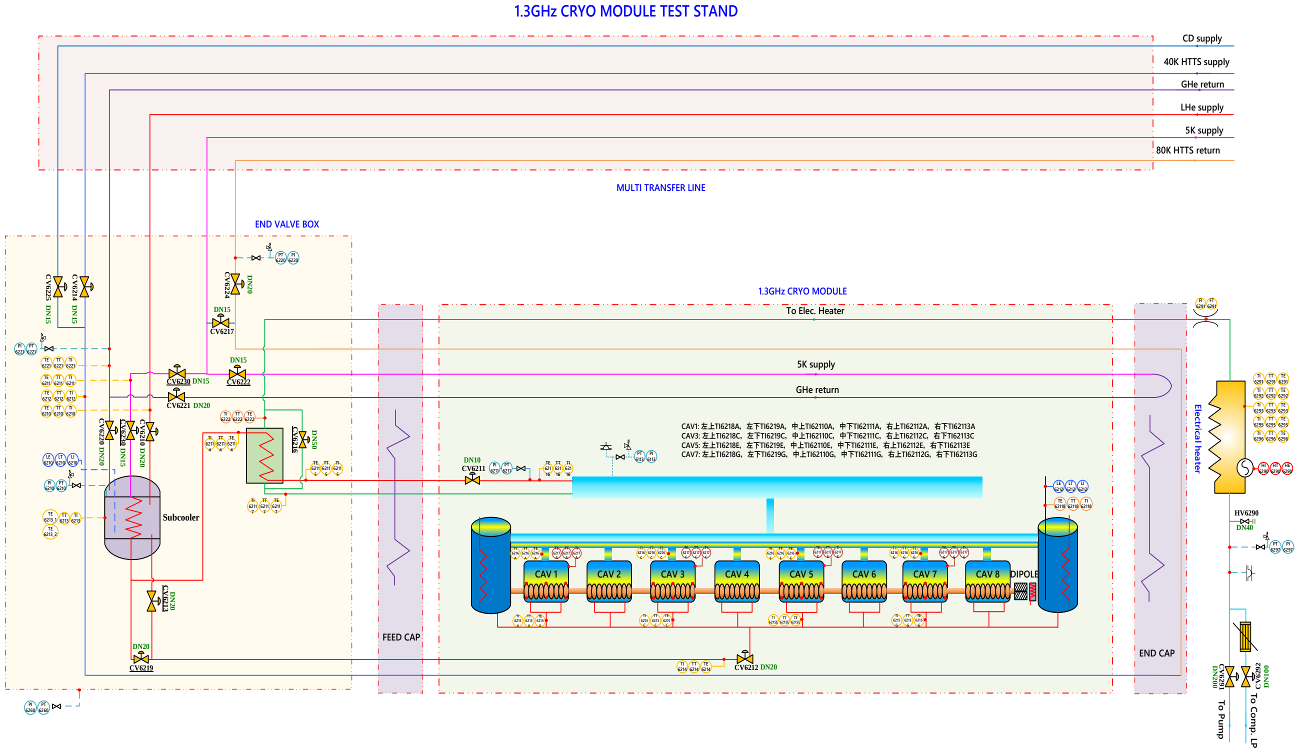
IHEP 1.3 GHz 9-cell Cavity Vertical Test



1.3 GHz High Q Cryomodule (8x9-cell)

CEPC booster 1.3 GHz SRF technology R&D and industrialization in synergy with domestic CW FEL projects.





- 1.3 GHz 8x9-cell high Q cryomodule prototype
- Component fabrication in 2021 to mid 2022
- Assemble and horizontal test in 2022
- Ship to Dalian in 2023

Outline

1. CEPC SRF system design
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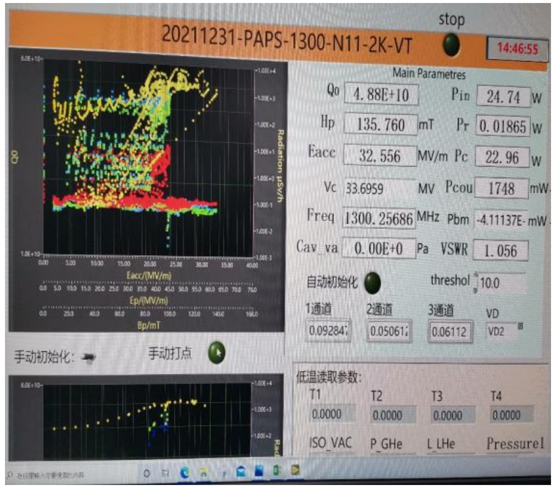
New SRF Facility in Full Operation

New SRF Facility in Full Operation





Summary

- CEPC RF system design and parameters are converging towards TDR. Many challenges in system design and technical R&D.
- Achieved high Q and high gradient cavity with mid-T baking.
- 650 MHz and 1.3 GHz module prototyping in progress.
- New SRF facility PAPS at IHEP Huairou Campus is supporting these R&D as well as the near term cryomodule mass production practice for the domestic projects.

Thank you