中国科学院高能物理研究所
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Cavity and Cryomodules Developments for CEPC

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Outline

1. CEPC RF parameters and new layout
2. RF feedback for FM CBI
3. Collider 650 MHz cavity and cryomodule
4. Booster 1.3 GHz cavity and cryomodule
5. Summary

CEPC Collider TDR Parameters

2 June 2022	Higgs	Z	W	ttbar
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			
RF frequency [MHz]	650			
Energy [GeV]	120	45.5	80	180
Energy loss per turn [GeV]	1.8	0.037	0.357	9.1
Piwinski angle	5.94	24.68	6.08	1.21
Bunch number	**268**	**11934**	**1297**	**35**
Bunch spacing [ns]	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population [10^10]	13	14	13.5	20
Beam current [mA]	**16.7**	**803.5**	**84.1**	**3.3**
Momentum compaction [10^-5]	0.71	1.43	1.43	0.71
Beta functions at IP (bx/by) [m/mm]	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP (sigx/sigy) [um/nm]	14/36	6/35	13/42	39/113
Bunch length (natural/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) [%]	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) [%]	1.6/2.2	1.3/1.7	1.2/2.5	2.3/2.6
Beam-beam parameters (ksix/ksiy)	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage [GV]	**2.2**	**0.12**	**0.7**	**10**
Longitudinal tune Qs	0.049	0.035	0.062	0.078
Beam lifetime (bhabha/beamstrahlung)[min]	39/40	80/18000	60/700	81/23
Beam lifetime [min]	20	80	55	18
Hour glass Factor	0.9	0.97	0.9	0.89
Luminosity per IP[1e34/cm^2/s]	5.0	115	16	0.5

CEPC TDR RF Parameters (Collider Ring)

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 upgrade 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]	3.3		16.7	84.1	803.5
Bunch charge [nC]	32		20.8	21.6	22.4
Bunch length [mm]	2.9		4.1	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

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		35	249	1297	3978	5967
Threshold of single bunch current	μA	5.79	4.20	3.92		
Threshold of beam current (limited by coupled bunch instability)	mA	27				
Bunch charge	nC	1.1	0.78	0.81	0.87	0.9
Single bunch current	μA	3.4	2.3	2.4	2.65	2.69
Beam current	mA	0.12	0.57	3.1	10.5	16.0
Growth time (coupled bunch instability)	ms	1690	358	67	19.4	12.5
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	531.0	230.2	200.0		
Betatron tune ν_x/ν_y		321.23/117.18				
Longitudinal tune		0.14	0.0943	0.0879		
RF energy acceptance	%	5.9	3.7	3.6		
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		35	249	242+7	1297	3978	5967
Maximum bunch charge	nC	0.99	0.7	23.2	0.73	0.8	0.81
Maximum single bunch current	μA	3.0	2.1	69.7	2.2	2.4	2.42
Threshold of single bunch current	μA	91.5	70		22.16	9.57	
Threshold of beam current (limited by RF system)	mA	0.3	1		4	16	
Beam current	mA	0.11	0.52	0.99	2.85	9.5	14.4
Growth time (coupled bunch instability)	ms	16611	2359	1215	297.8	49.5	31.6
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	9.7	2.17		0.87	0.46	
Longitudinal tune		0.14	0.0943		0.0879	0.0879	
RF energy acceptance	%	1.78	1.59		2.6	3.4	
Damping time	ms	14.2	47.6		160.8	879	
Natural bunch length	mm	1.8	1.85		1.3	0.75	
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

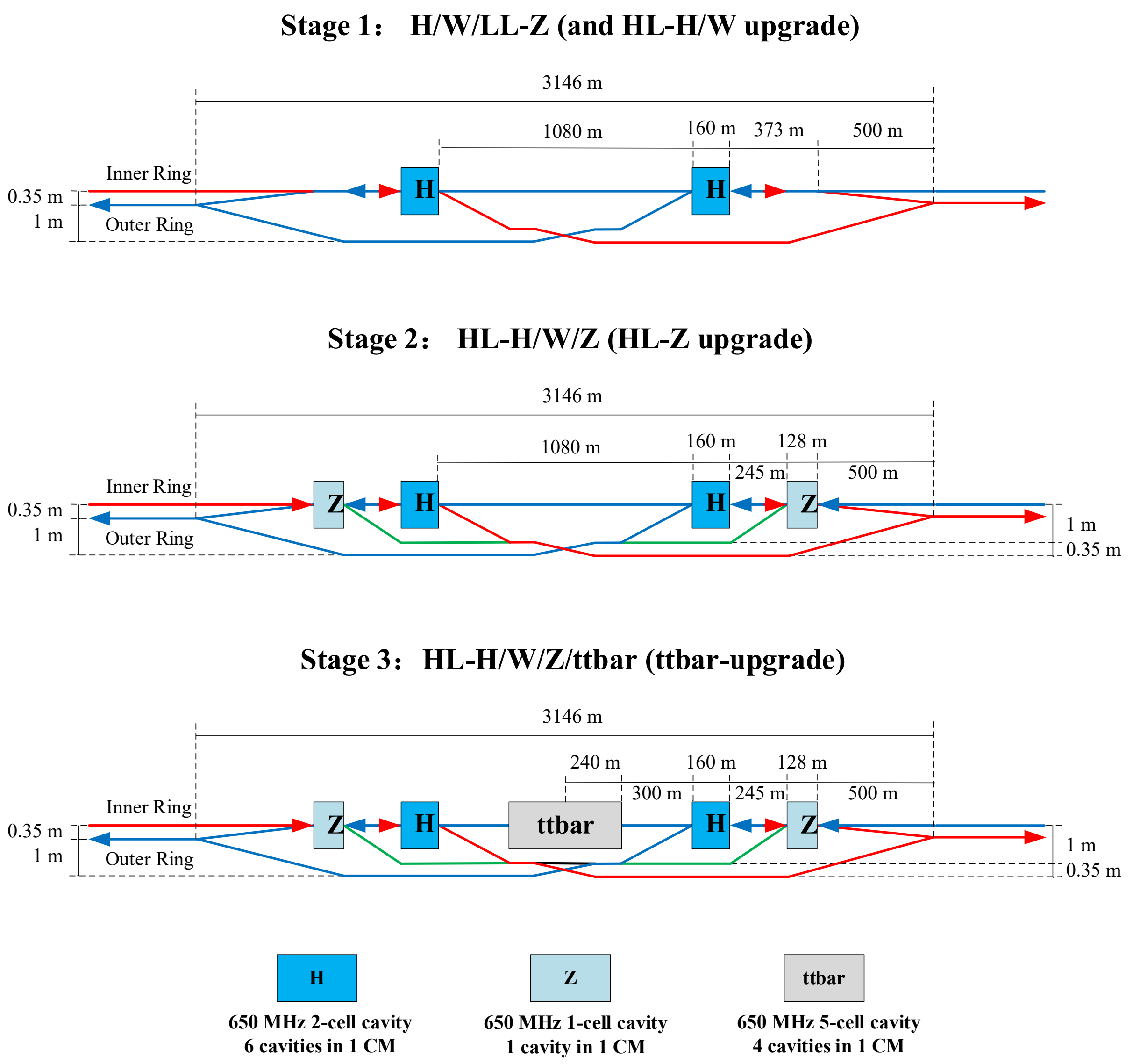
*Diameter of beam pipe is 55mm for re-injection with high single bunch current @120GeV.

CEPC TDR RF Parameters (Booster Ring)

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	**0.7/23.2**	0.73	0.83
Beam current [mA]	0.11	**0.56/0.98**	2.85	14.4
Injection RF voltage [GV]	0.438	0.197	0.122	0.122
Extraction RF voltage [GV]	9.7	2.17	0.87	0.46
Extraction bunch length [mm]	1.8	1.85	1.3	0.75
Cavity number (1.3 GHz 9-cell)	**336**	**96**	**64**	**32**
Extraction gradient [MV/m]	**27.8**	21.8	13.1	13.8
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	1.4/2.7	9.8	108.5
Input peak power per cavity [kW]	7.9	15.3/21.3	15	33
SSA peak power [kW] (one cavity per SSA)	**10**	**25**	**25**	**40**
Cryomodule number (8 cavities per module)	42	12	8	4

- 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 (swap-out) injection tolerable.
- Standard quasi-CW TESLA cryomodules for Higgs, W and ttbar. HOM power of Higgs on-axis injection?
- Two high current 8x9-cell cryomodules for Z in each ring with RF bypass. 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.

CEPC TDR New RF Layout



- Higgs first priority. And aiming for all-mode seamless switching in whole project lifecycle without hardware movement
- Maximize performance and flexibility for future circular electron positron collider
- Add center connection line (short black line) for Higgs operation after ttbar upgrade. Need to check if the dipole SR light will hit the cavity after effective shielding.

CEPC SRF TDR and Upgrade 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	**HL-Z 1-cell** 1E10 @ 8.7 MV/m **Optional 1-cell for H&Z** VT 4E10 @ 45 MV/m HT 4E10 @ 40MV/m OP 3E10 @ 40 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	1 MW	300 kW variable
650 MHz HOM Coupler	1 kW	\	1 kW
650 MHz HOM Absorber	5 kW	10 kW	\

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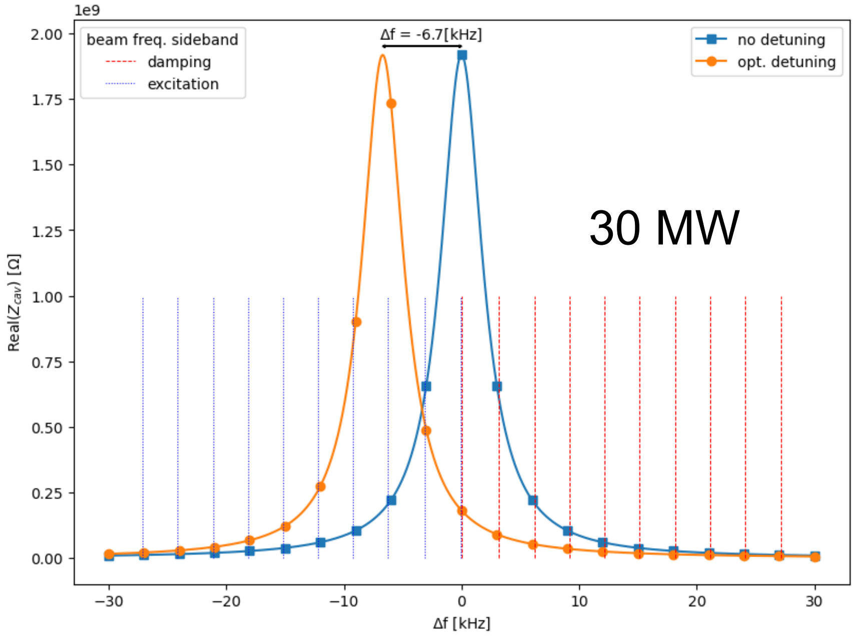
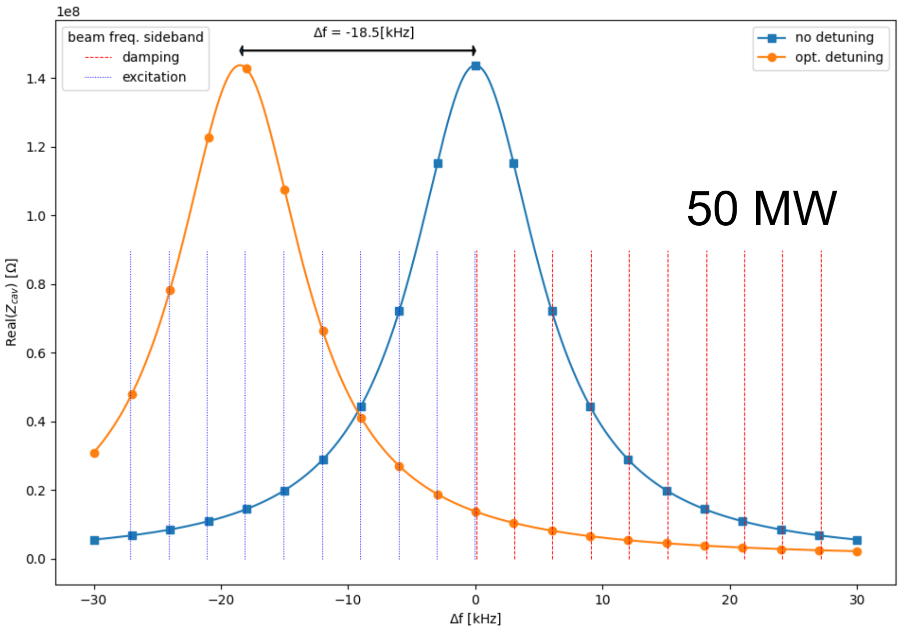
FM Coupled Bunch Instability in Z mode

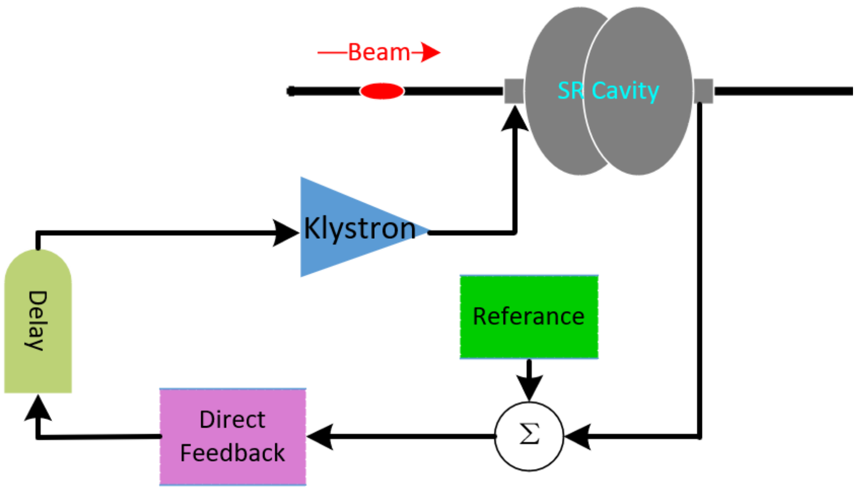


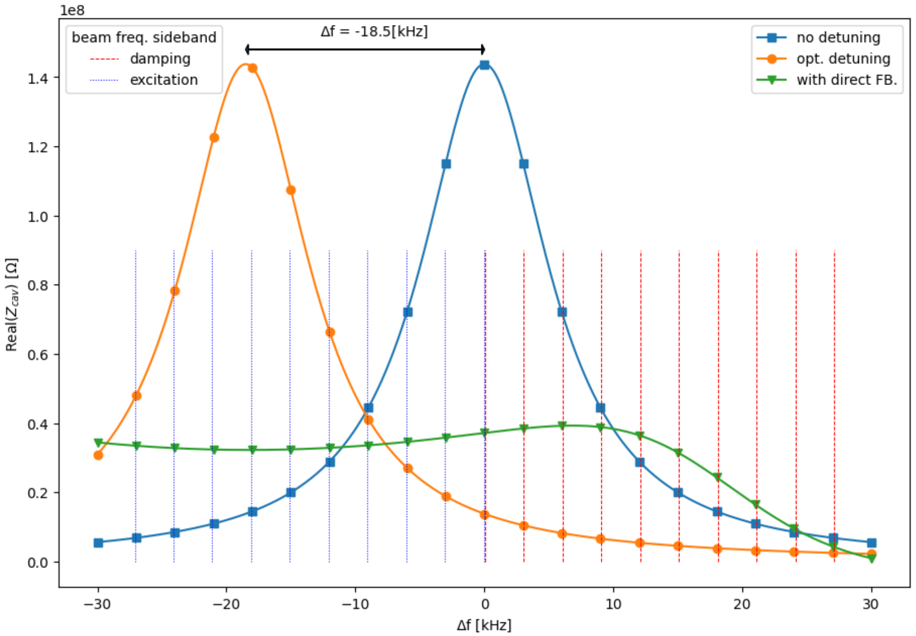


- High beam current: 800 mA @ 30 MW, 1338 mA @ 50 MW per beam.
- Relatively low cavity voltage: 0.12 GV
- Weak radiation damping: damping time ~ 410 ms
- More than 10 modes that are anti-damped.
- Has to rely on feedback system.

FM Coupled Bunch Instability in 50 MW Z Mode

RF feedback loops to suppress the strong growing modes. (Goal: growth rate < 50 s^{-1})





Couple Bunch Mode Number	Growth rate [s^{-1}]
-1	-8.4
-2	17.2
-3	41.4
-4	62.3
-5	77.4
-6	**84.8**
-7	84.2
-8	77.3
-9	67.2

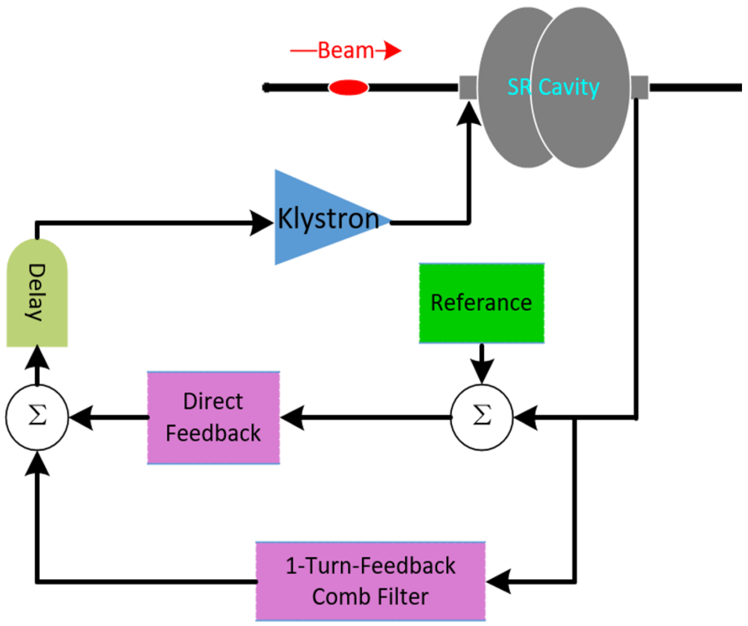
$G = 3.5$

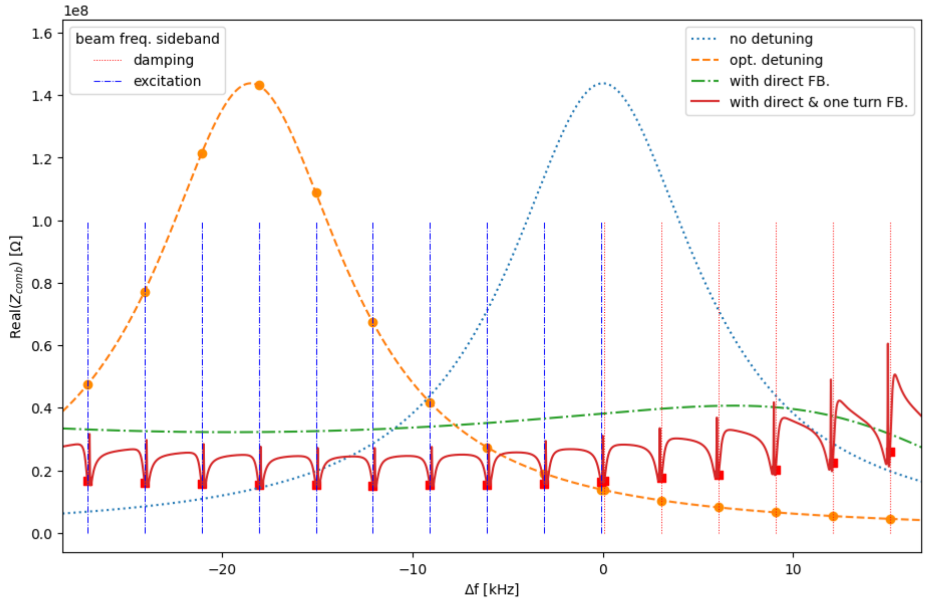
Direct feedback loop will reduce the apparent impedance of the main cavities, but the calculation of growth rate shows that the direct feedback alone is insufficient.

$$Z_{\mathrm{cl}}(\omega) = \frac{V_c(\omega)}{I_b(\omega)} = \frac{Z(\omega)}{1 + e^{-i\tau\omega} G Z(\omega) e^{i\phi}}$$

FM Coupled Bunch Instability in 50 MW Z Mode

Add double comb filter to suppress the dangerous modes.





Couple Bunch Mode Number	Growth rate [s^{-1}]
-1	-7.3
-2	5.0
-3	16.6
-4	26.9
-5	35.3
-6	41.6
-7	**45.5**
-8	47.0
-9	46.4

In order to bring the growth rate below the half of the synchrotron oscillation frequency (< 50 Hz). We had to add a comb filter alongside the direct feedback loop.

$$H_{\text{dual - comb}}(\omega) = \frac{G\left(1 - e^{-i\omega T_{\text{rev}}}\right) e^{-i\omega(T_{\text{rev}} - T_G)}}{\left[1 - Ke^{-i(\omega T_{\text{rev}} - v_s)}\right]\left[1 - Ke^{-i(\omega T_{\text{rev}} + v_s)}\right]}$$

$$Z_{\text{cl}}(\omega) = \frac{Z(\omega)}{1 + e^{-i\tau\omega} G e^{i\phi} Z(\omega)\left[1 + H_{\text{comb}}(\omega)\right]}$$

$K = 0.5,\ G = 3.5$

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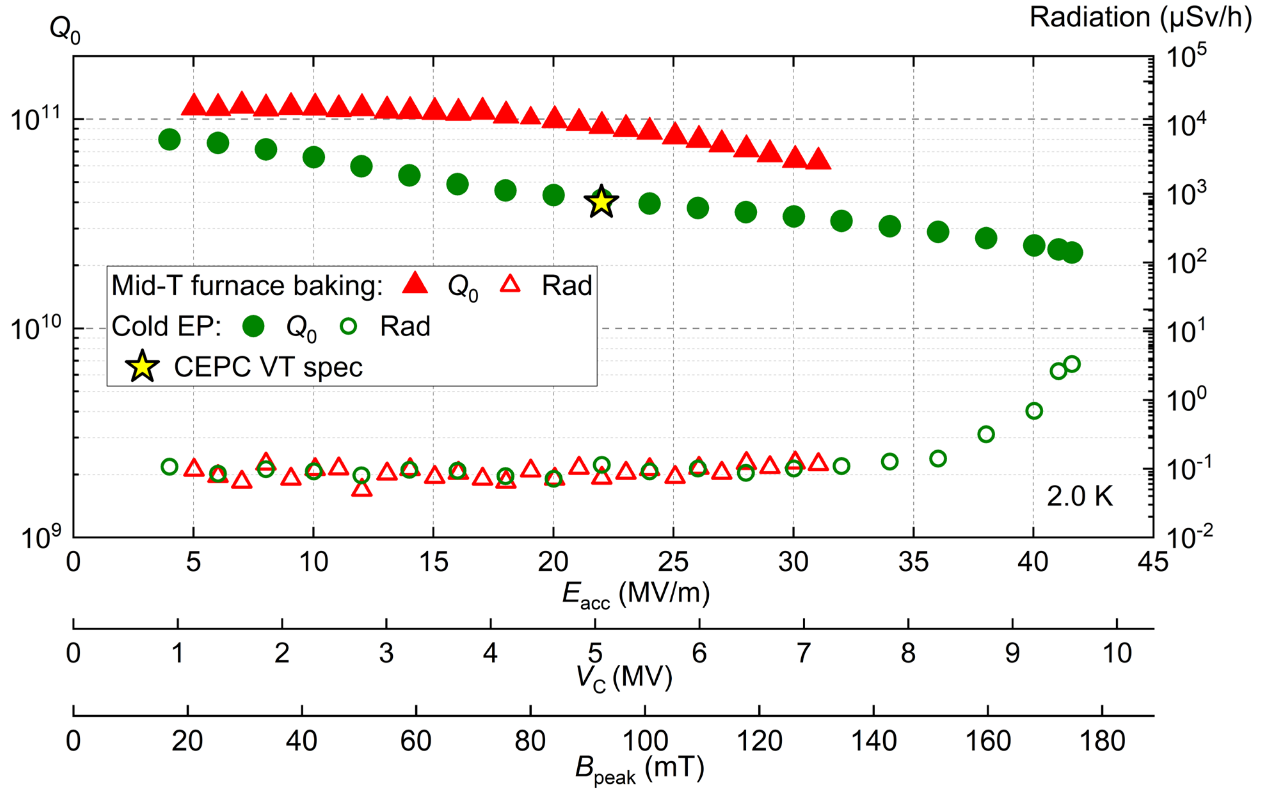
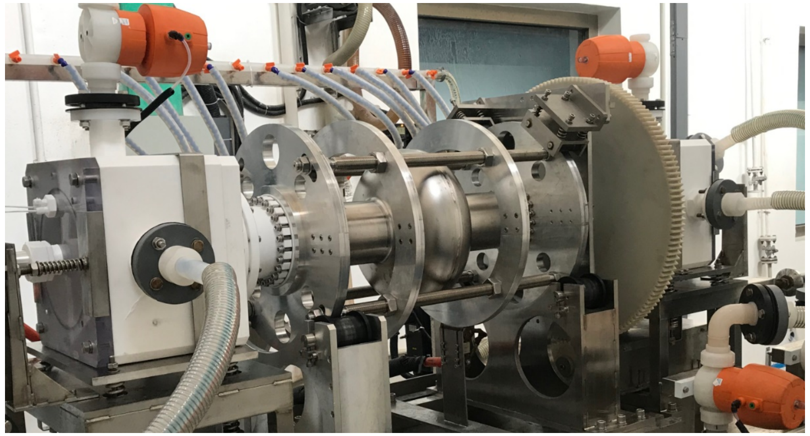
High G High Q 650 MHz 1-cell Cavity



650 MHz 1-cell cavity vertical test

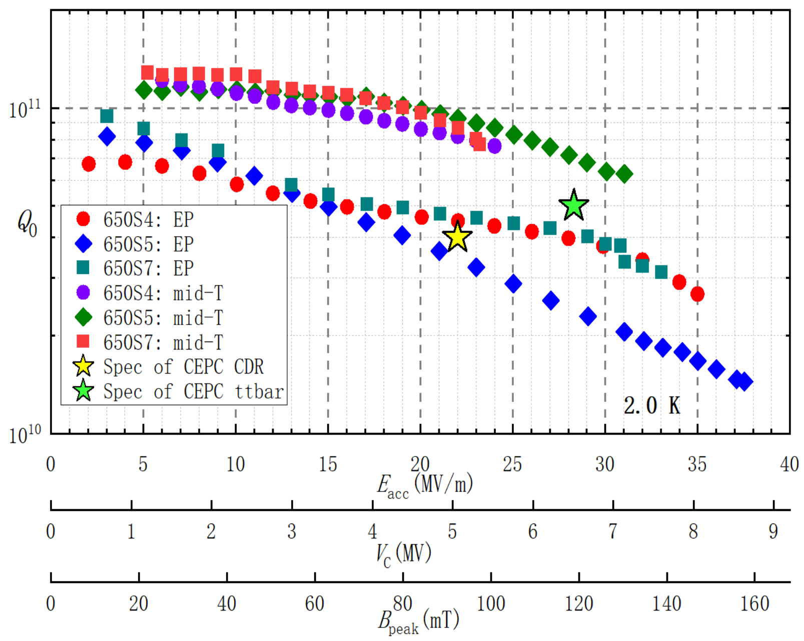
EP treated: 2.3E10@41.6 MV/m@2 K

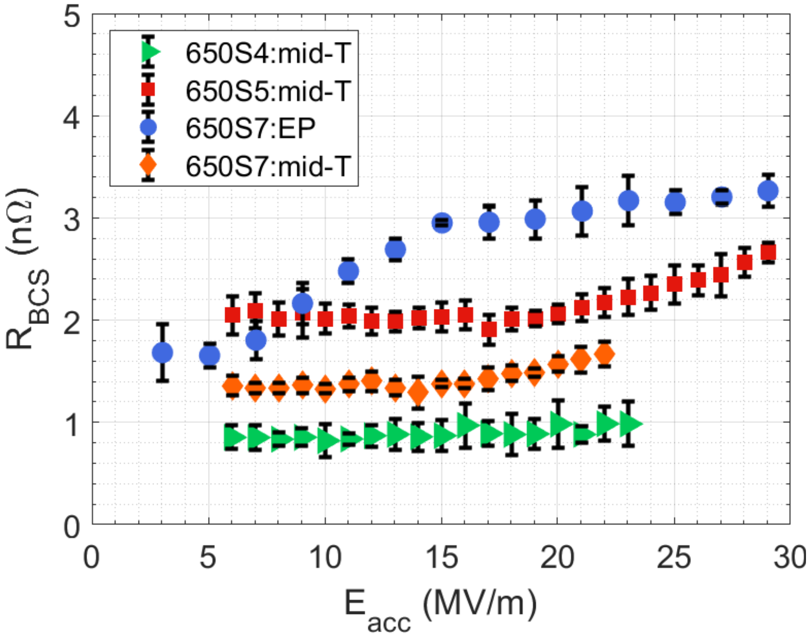
Mid-T treated: 6.3E10@31 MV/m@2 K

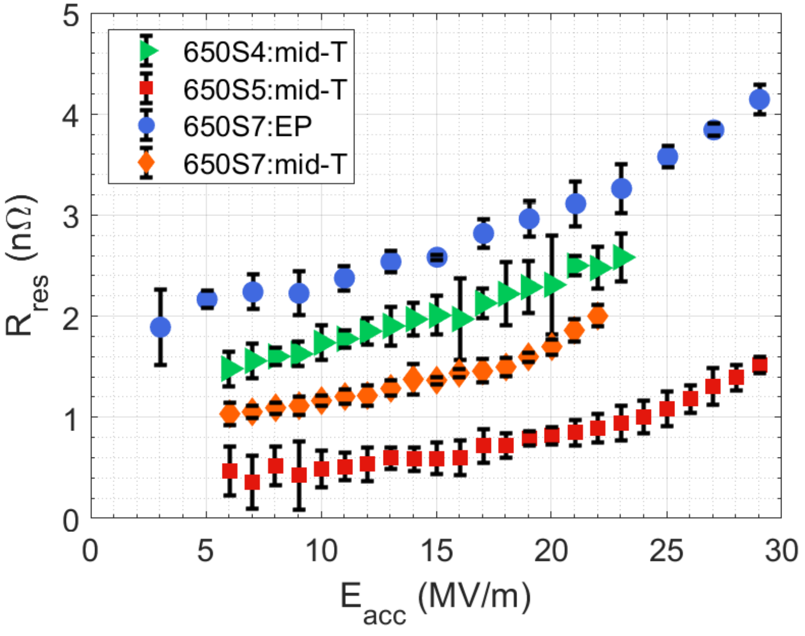


Breakthrough in High Q 650 MHz Cavity

- Extremely high Q (> 1E11 up to 20 MV/m at 2 K) of several mid-T treated (900 C 3h + exposure to air + 300 C 3h + HPR) 650 MHz single cell cavities.
- Best cavity reaches the world record of 6.4E10 at 31 MV/m at 2 K.
- The lowest BCS resistance and residual resistance is only 1 nΩ or even less, significantly decreased relative to EP cavities. Similar ultra low resistance in FNAL's mid-T baked (after HPR) 1.3 GHz cavities.

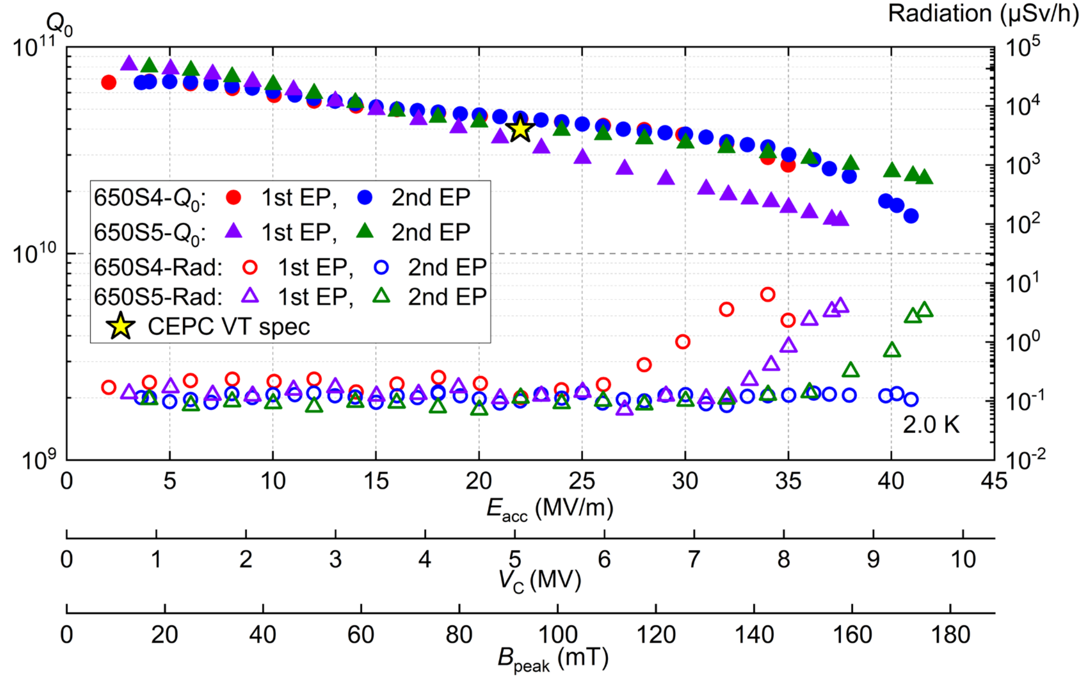


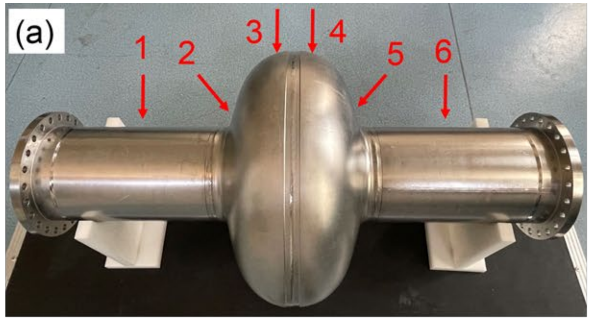


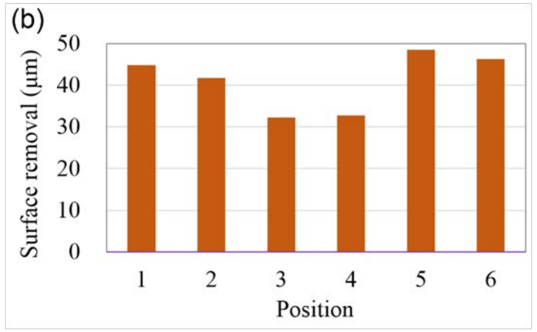


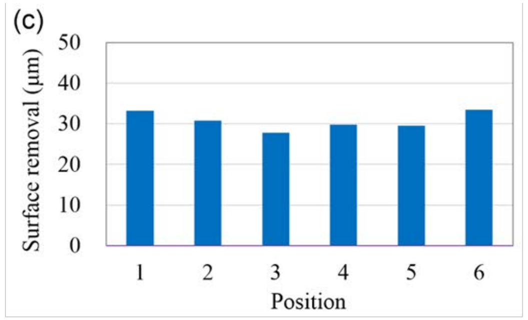
High Gradient 650 MHz 1-cell Cavity

- 2nd EP in June (cold EP, 30 um, 12 C for more uniform removal) + HPR + baking at 120 C 48 h.
- 650S4 quenched at 1.5E10@41MV/m, 650S5 quenched at 2.3E10@41.6MV/m. Cold EP increased quench field.
- One of the highest gradient low frequency elliptical cavities in the world.







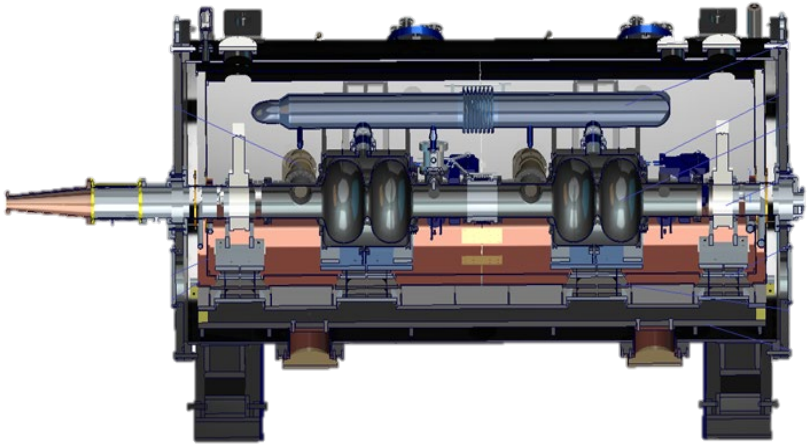


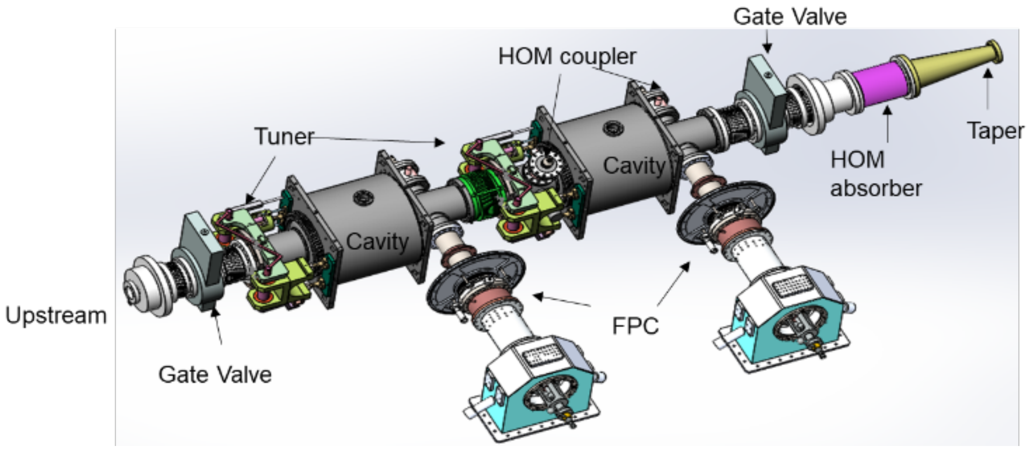
Locations for thickness measurement

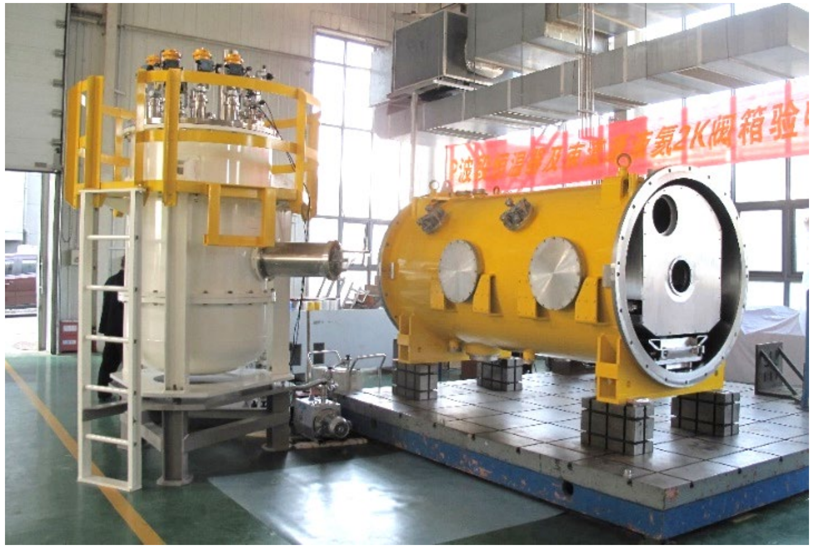
Surface removal of the 1st EP (~ 17.5 °C)

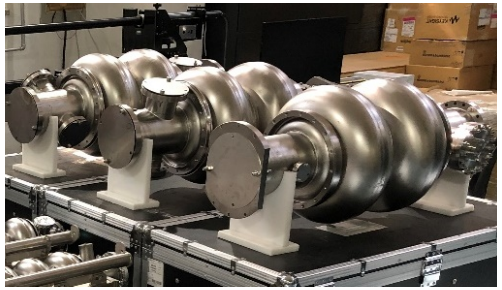
Surface removal of 2nd EP (~ 12 °C)

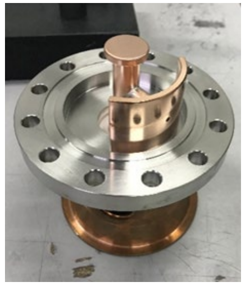
CEPC 650 MHz Test Cryomodule

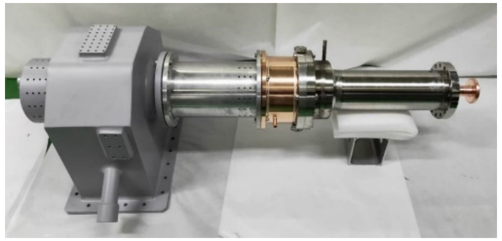


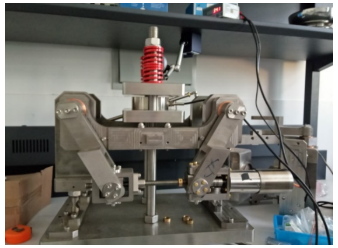


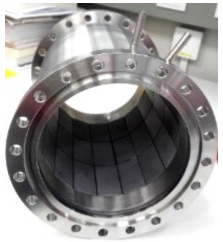




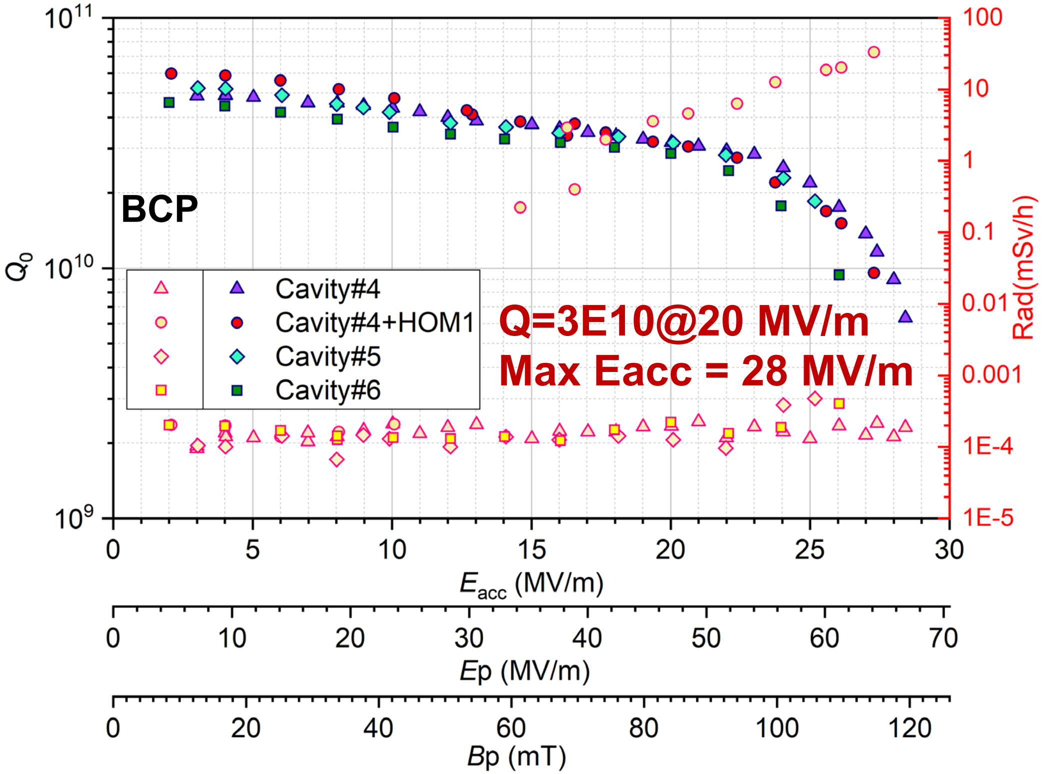






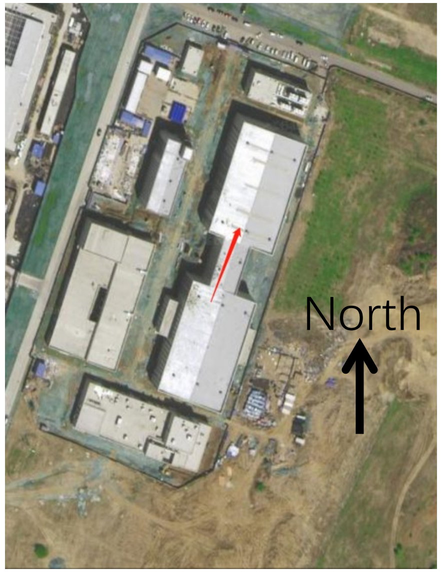


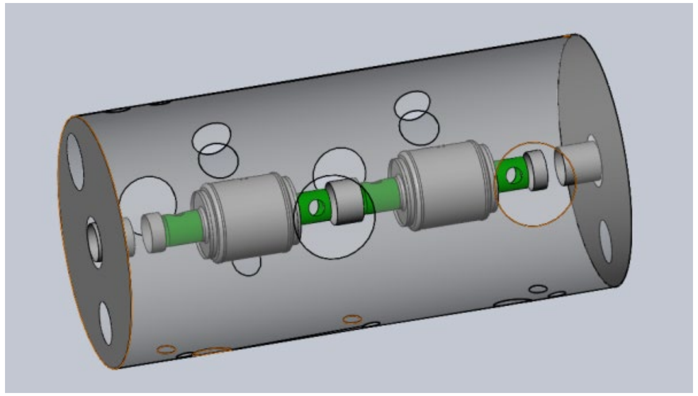
650 MHz 2-cell Cavity Vertical Test with HOM Couplers



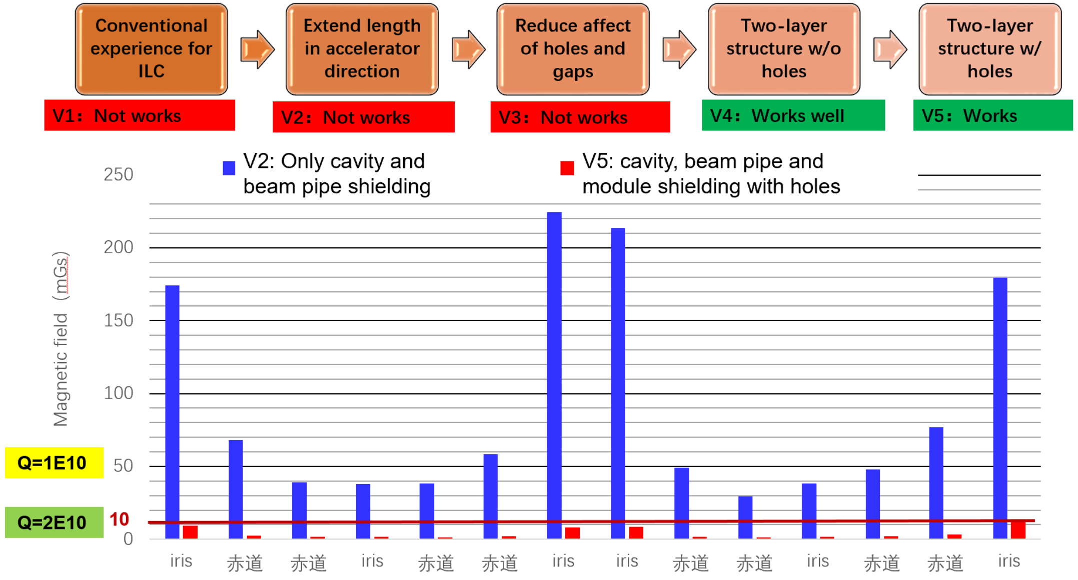
- BCP 650 MHz 2-cell cavities: 2.8E10@22 MV/m (CEPC VT spec: 4E10@22 MV/m)
- Performance no change after install HOM coupler
- EP/heat treatment to further improve gradient and Q

Preserve Q_0 in Module: Magnetic Shielding and Compensating



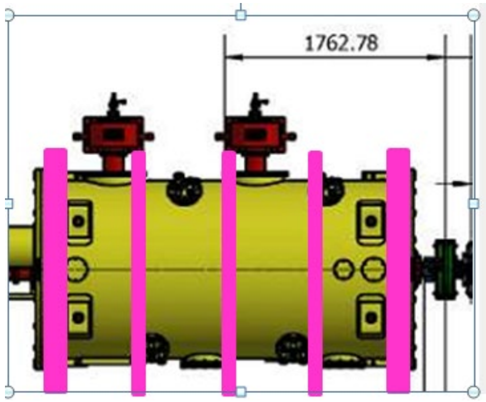


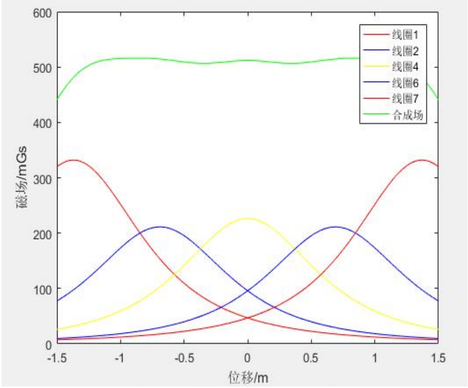
Because of beam direction and larger beam pipe than 1.3 GHz, **only two shieldings** can reach the magnetic field requirement of high Q 650 MHz cavity: **cavity (2 K local) shield and module (RT global) shield**.



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

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

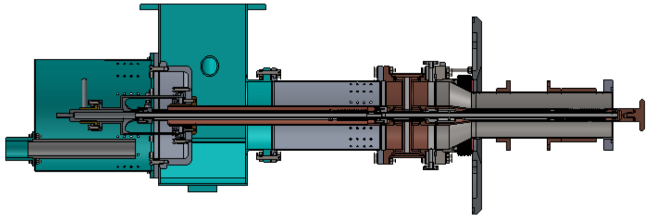




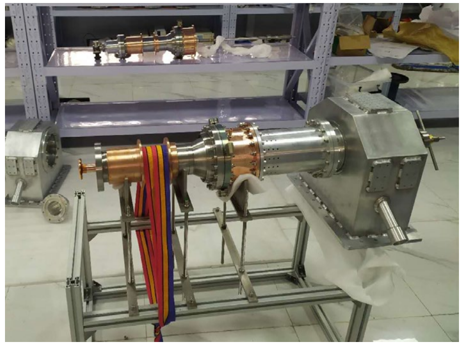
Magnetic compensation with coils

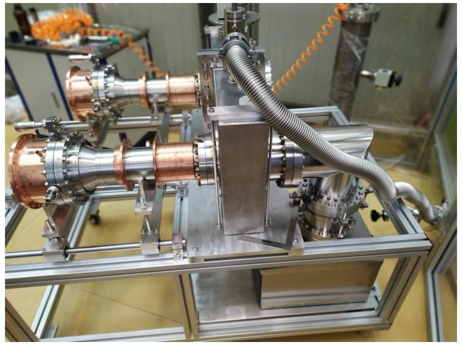
650 MHz High Power Variable Coupler

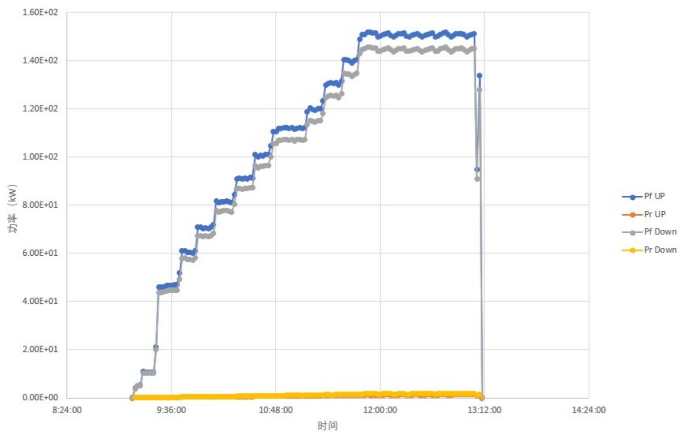
- 650 MHz **variable couplers** tested to CW TW 150 kW (SSA power limit), SW 100 kW (corresponding to 400 kW TW power at the window, exceeds CEPC spec 300 kW). One of the world highest variable couplers.



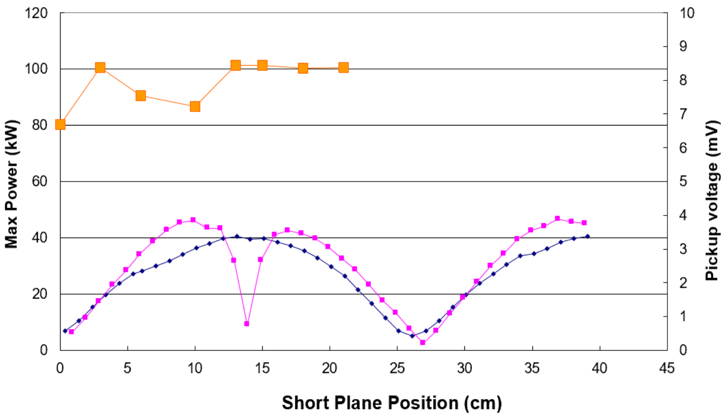
Bellow on inner conductor. Inner conductor water cooling. Outer conductor He gas cooling.



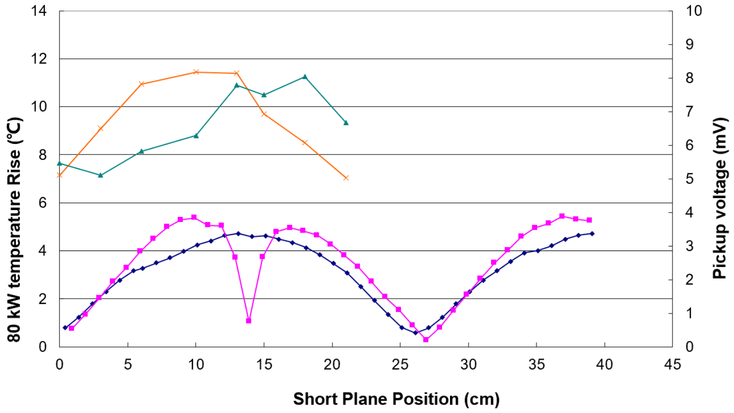




TW high power test to 150 kW

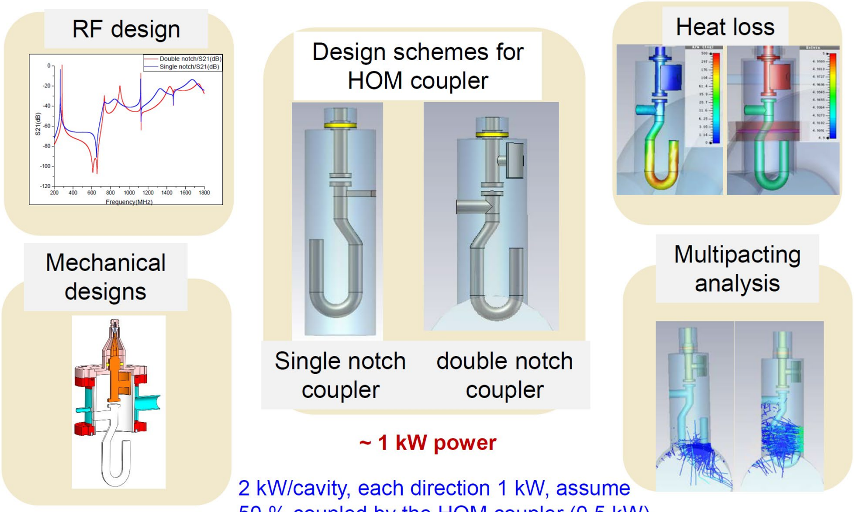


Window SW field and power



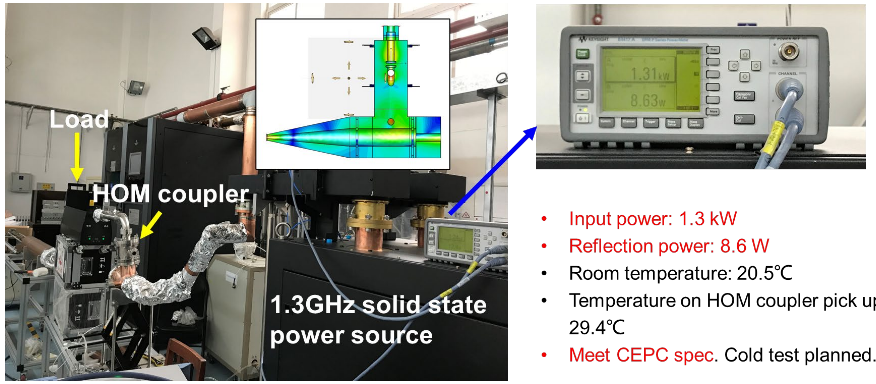
Window SW field and temperature rise

Double Notch HOM Coupler



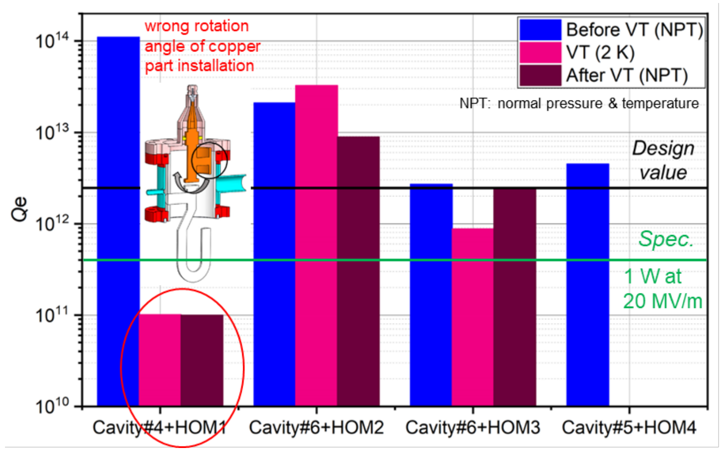
~ 1 kW power

2 kW/cavity, each direction 1 kW, assume 50 % coupled by the HOM coupler (0.5 kW).



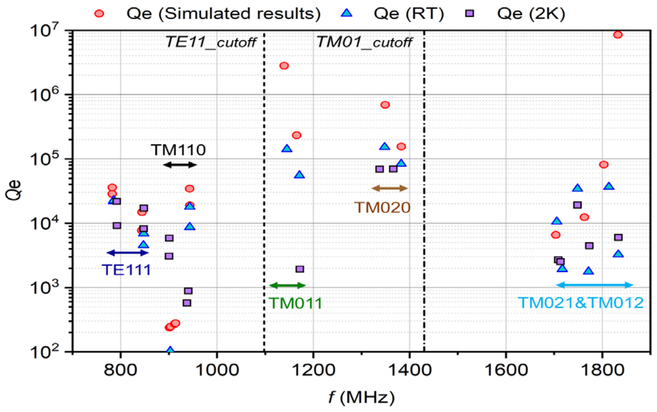
- Input power: 1.3 kW
- Reflection power: 8.6 W
- Room temperature: 20.5℃
- Temperature on HOM coupler pick up: 29.4℃
- Meet CEPC spec. Cold test planned.

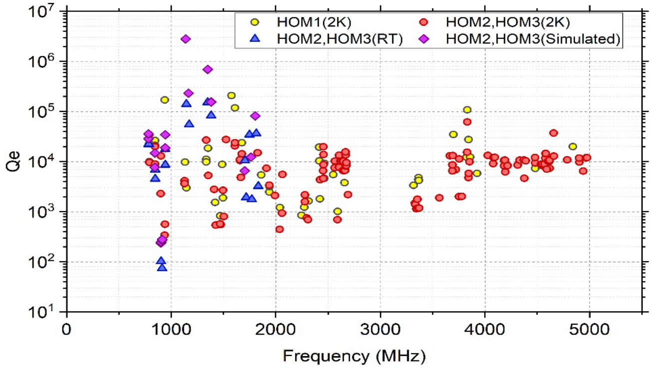
https://doi.org/10.1016/j.nima.2019.163094
https://doi.org/10.1007/s41605-019-0143-x



Fundamental mode rejecting Q_e

Test results before and after VT are repeatable if installed correctly. In the module: HOM1 6.8E13, HOM2 1.9E13. HOM3 2.1E12. **No tuning needed.**



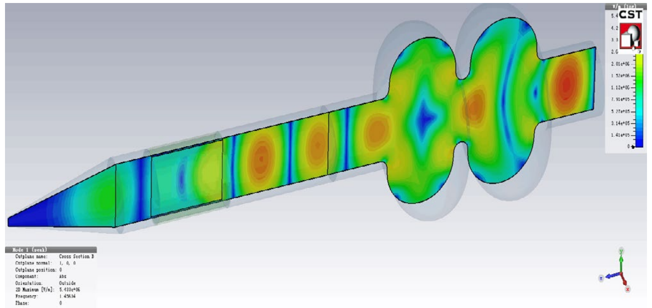


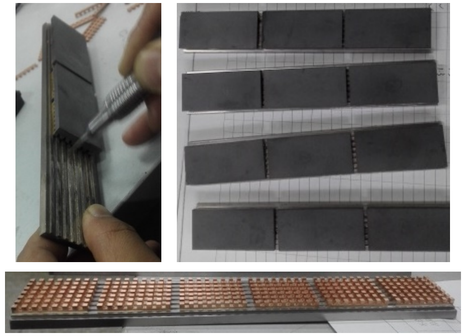
HOM damping Q_e

Fulfill Higgs CBI requirement. Need beam feedback for Z. Further damping optimization is under way.

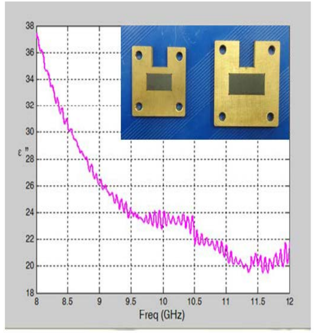
Broadband High Power HOM Absorber

Due to short bunch length thus wide HOM frequency range, **SiC+AIN** composite is chosen for cavity HOM absorbing material. 5 kW high power test show high absorbing efficiency, meet CEPC spec.

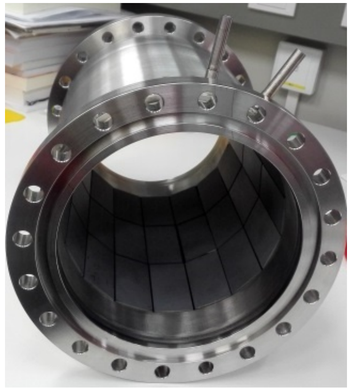


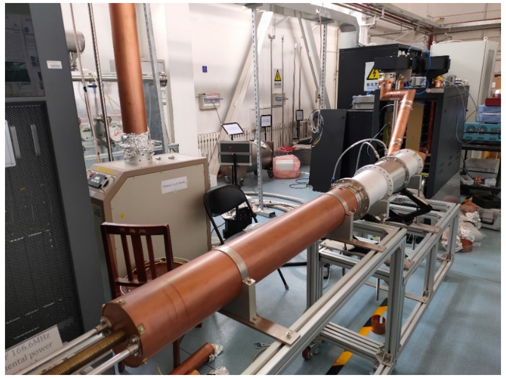


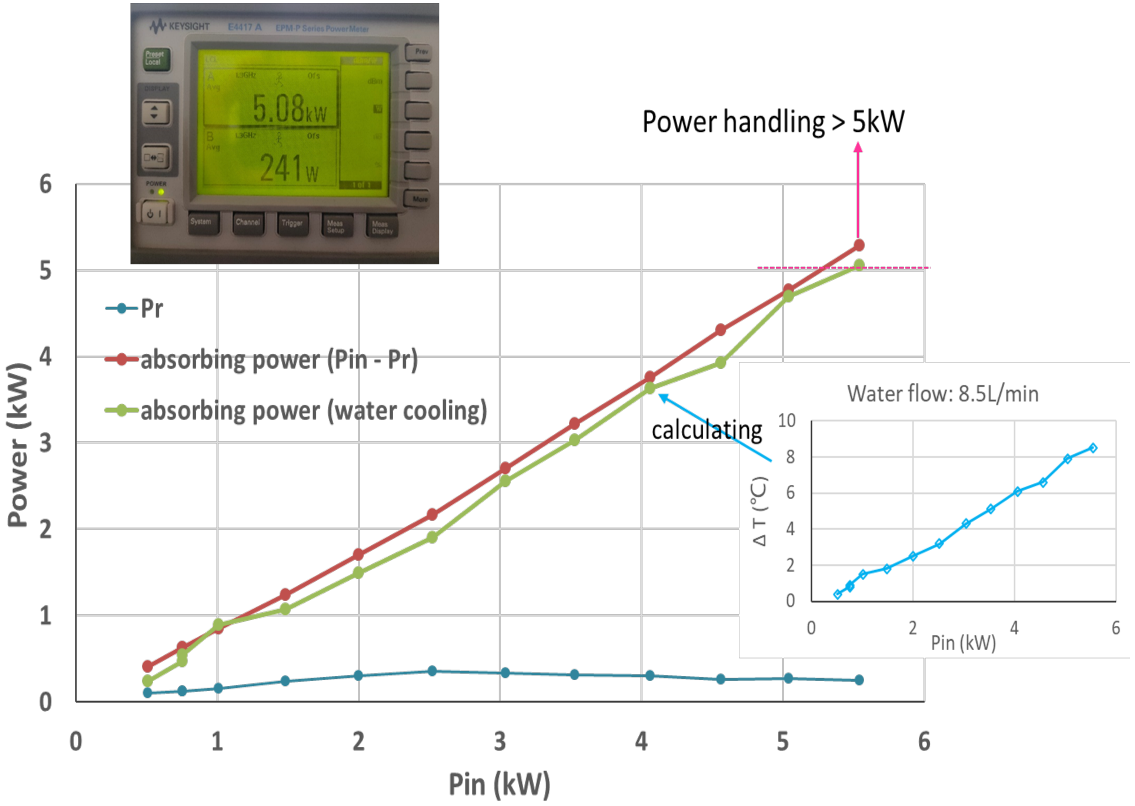
SiC+AIN composite bricks brazed on copper and then on kovar plate



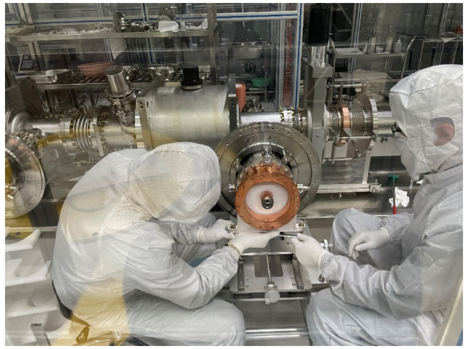
Measured permittivity of SiC+AIN composite (for broadband microwave absorbing)

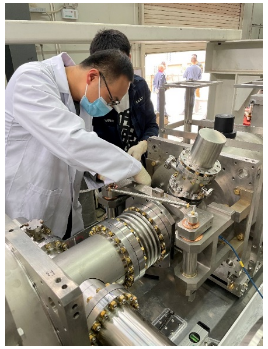


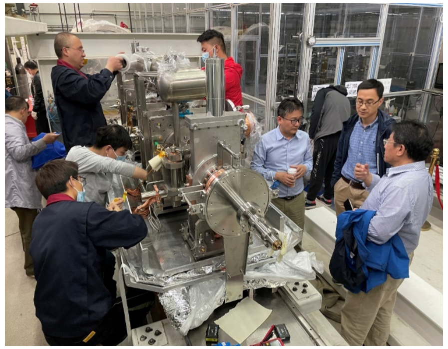
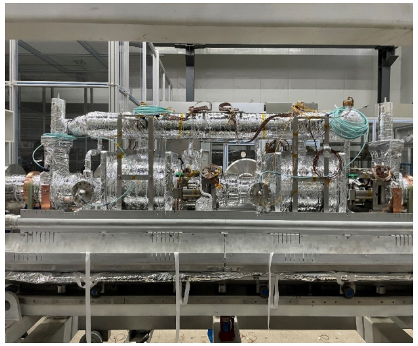




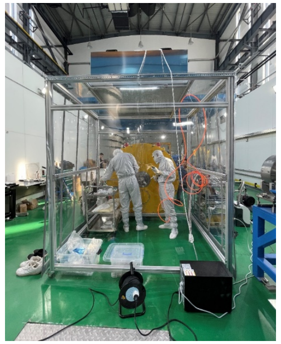
650 MHz Cryomodule Assembly

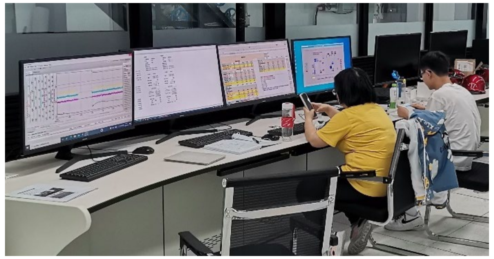


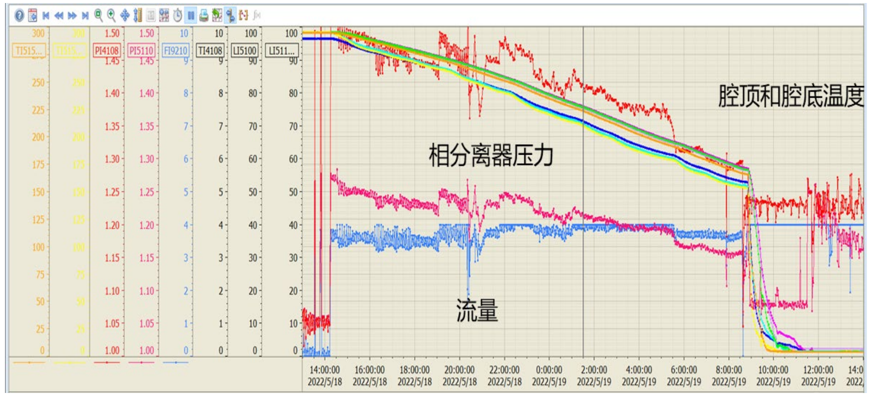

650 MHz Cryomodule Cool Down and Testing







- DC photo-cathode gun voltage conditioned up to 400 kV
- Cavity frequency, HOM coupler double notch filter, tuner, vacuum, cryogenics perform well
- Cavity magnetic field at 2 K < 2 mG (large beam pipe North to South)
- LLRF system commissioning and high power test ongoing
    - Optimizing the outer conductor helium gas cooling of the input coupler. Cavity early quench if with poor coupler cooling.



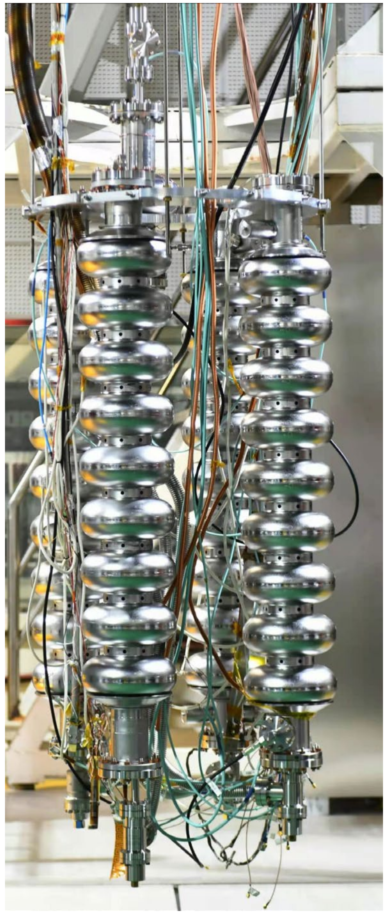
Module automatic cool-down experiment

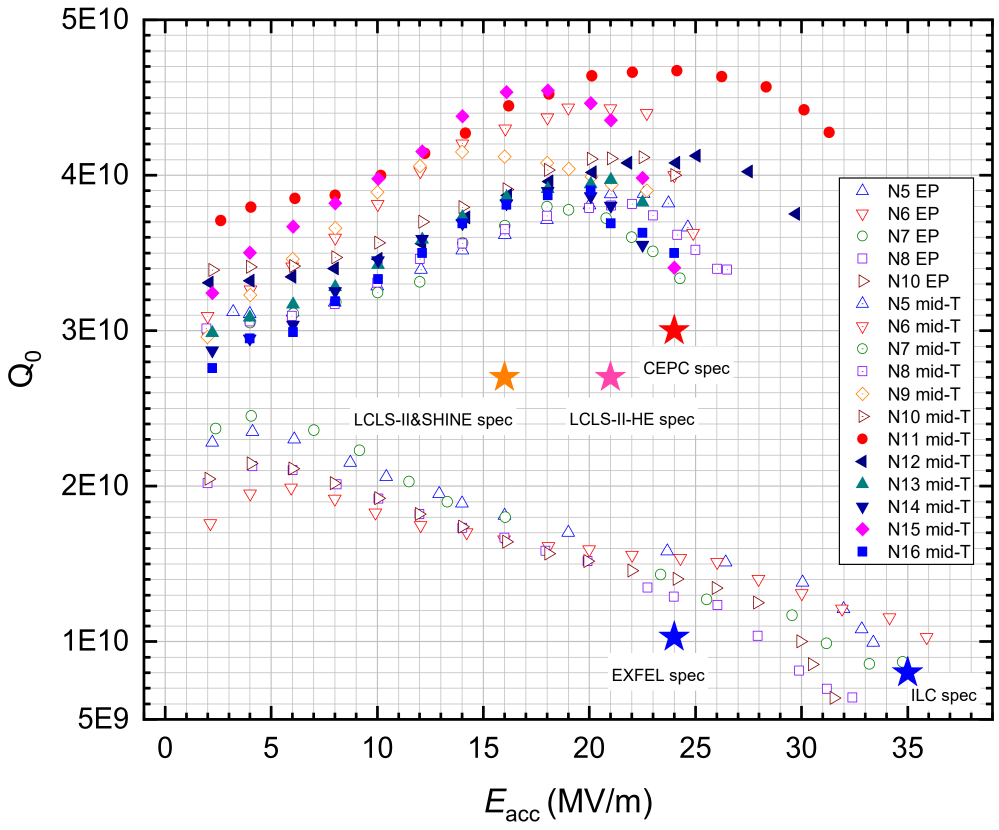
1. 300 to 150 K: < 10 K/hr. Cavity top and bottom $\Delta T < 20$ K
2. 150 to 4.5 K: Cavity surface > 1 K/min
3. 4.5 to 2 K

Outline

1. CEPC RF parameters and new layout
2. RF feedback for FM CBI
3. Collider 650 MHz cavity and cryomodule
4. Booster 1.3 GHz cavity and cryomodule
5. Summary

World Leading Mid-T High Q 1.3 GHz 9-cell Cavity





2 K VT	1st batch average	2nd batch average
E_{acc} (MV/m)	24	27.7
Q_0@16 MV/m	3.8E10	4.1E10
Q_0@21 MV/m	3.8E10	4.1E10

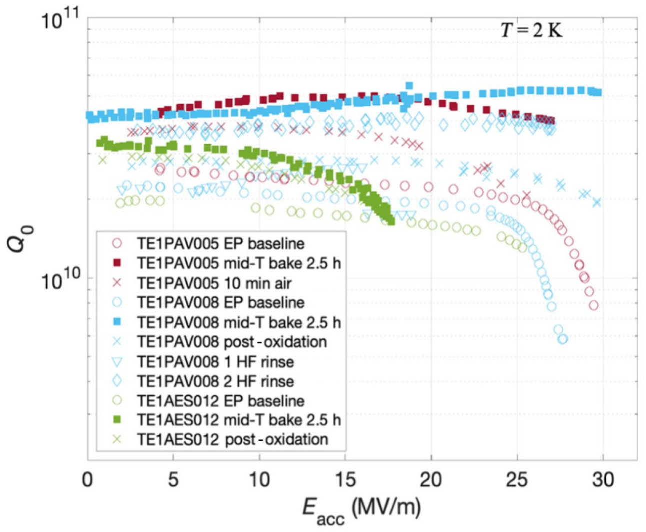
First batch (6 cavities): N5-N10

Second batch (8 cavities): N11-N18 (N11-16 tested)

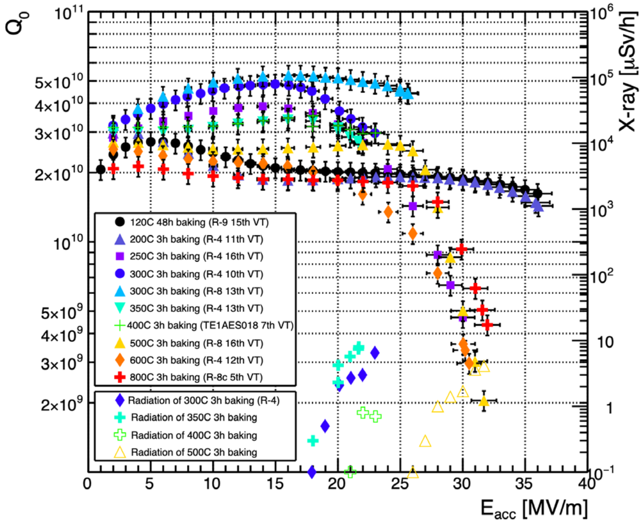
- Best Cavity (N11): 4.6E10@21 MV/m, 4.3E10@31MV/m
- Q spread due to cool down difference?
- One of the best high Q 1.3 GHz 9-cell cavities and cavity batches in the world.
- Will install to high Q module at IHEP PAPS

Mid-T Potential and Advantage

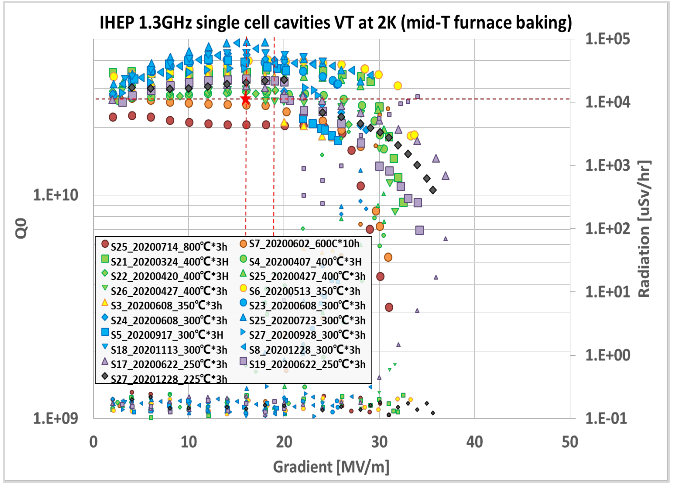
- **High G&Q potential**: We now have 4.3E10@31MV/m of one 9-cell cavity, better than most mid-T 1-cell cavities. Need 1-cell data to go > 35 MV/m with high Q.



Fermilab 1-cell



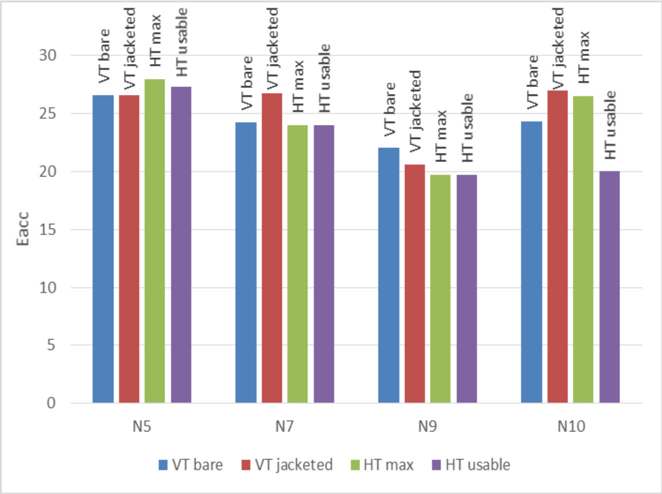
KEK 1-cell

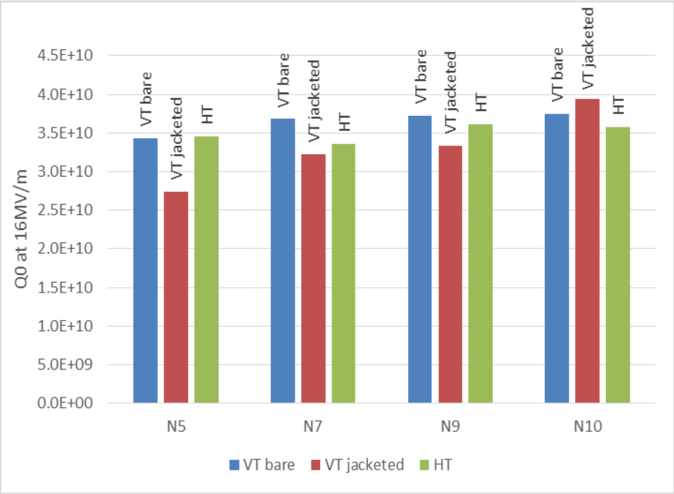


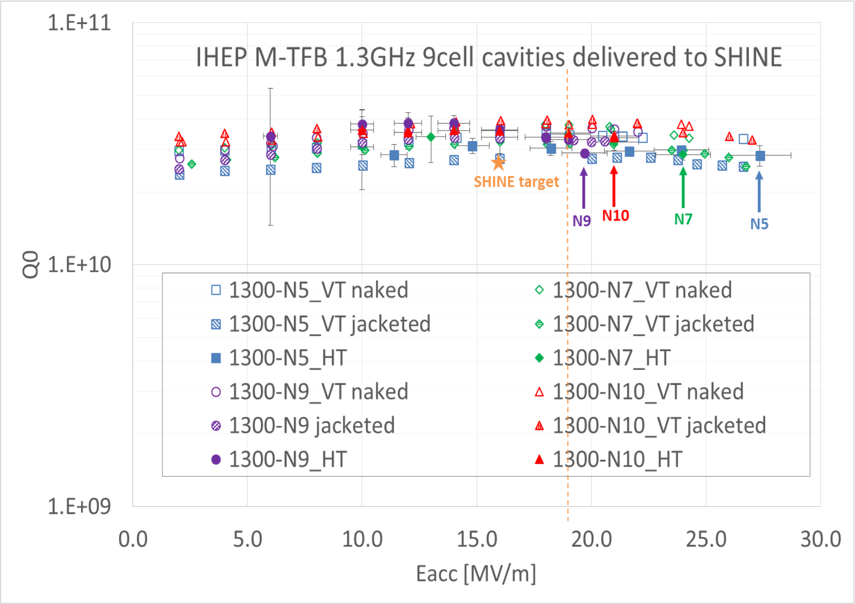
IHEP 1-cell

- **Advantage**: Mid-T cavities have comparable or even higher gradient and Q than Nitrogen doped cavities with less EP process: 1 EP vs 3 EPs, only bulk EP, no EP after high temperature baking, no EP after medium temperature baking. However, only cryomodule horizontal test or even beam test and long-time operation test can finally verify the mid-T feasibility.

Horizontal Test of Mid-T 9-cell Cavities



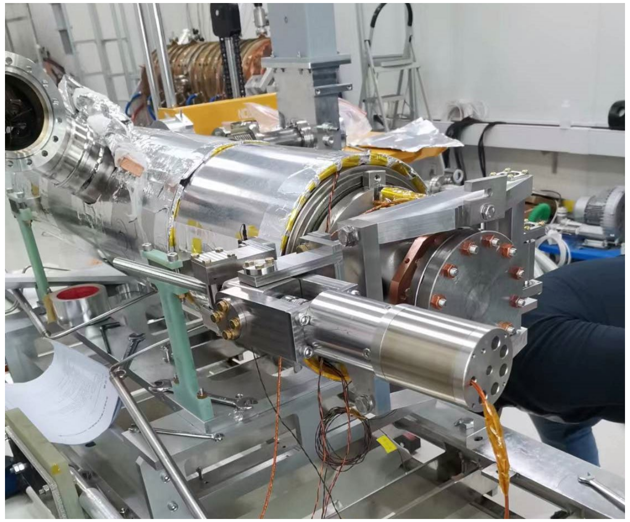


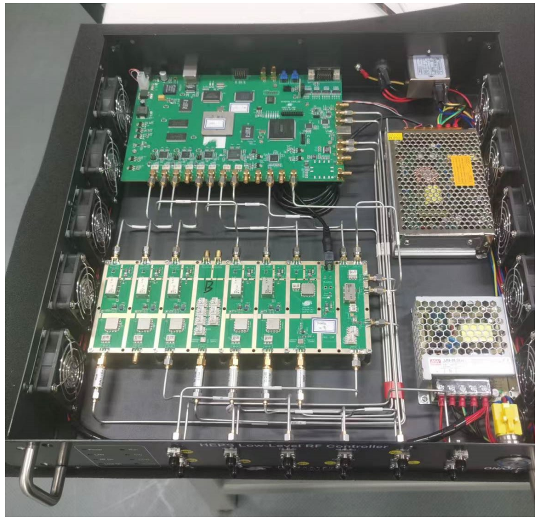


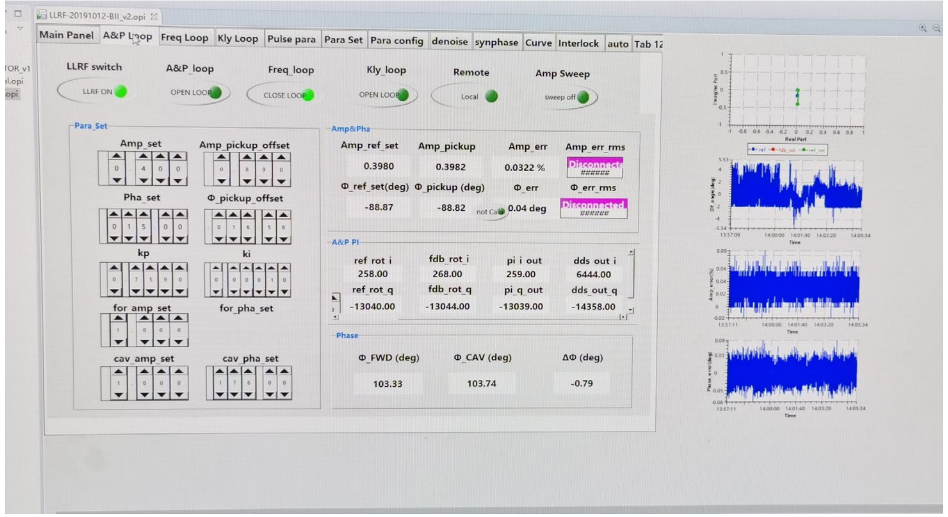
CAV#	Cavity VT with helium vessel			Cavity horizontal test				
	$E_{acc.max}$ (MV/m)	$Q_0/10^{10}$ @ 16 MV/m	$Q_0/10^{10}$ @ 21 MV/m or $E_{acc.max}$	$E_{acc.max}$ (MV/m)	$E_{acc.use}$ (MV/m)	FE onset (MV/m)	$Q_0/10^{10}$ @ 16 MV/m	$Q_0/10^{10}$ @ 21 MV/m or $E_{acc.max}$
N5	26.6	2.7	2.8	28	27.3	none	3.5	3.3
N7	26.7	3.2	3.1	24	24	none	3.4	3.2
N9	20.6	3.3	3.2	19.7	19	none	3.6	2.9
N10	27	3.9	3.9	26.5	20	none	3.6	3.1
Average	**25.2**	**3.3**	**3.3**	**24.6**	**22.6**	/	**3.5**	**3.1**

9-cell cavity with power coupler, self-excited horizontal test (not GDR mode, w/ tuner)
Usable gradient: radiation < 0.5 mSv/h, 0.5 MV/m below Eacc.max, one hour stable operation

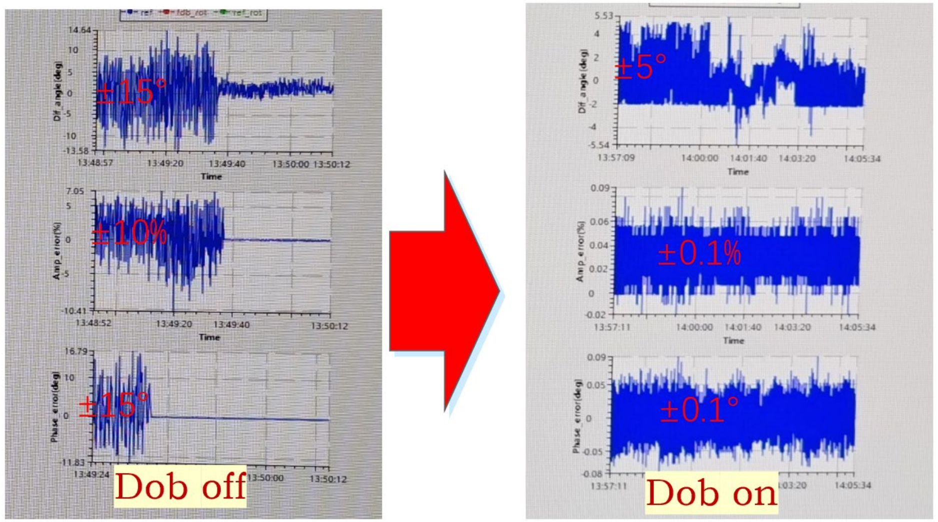
Horizontal Test of Mid-T 9-cell Cavities



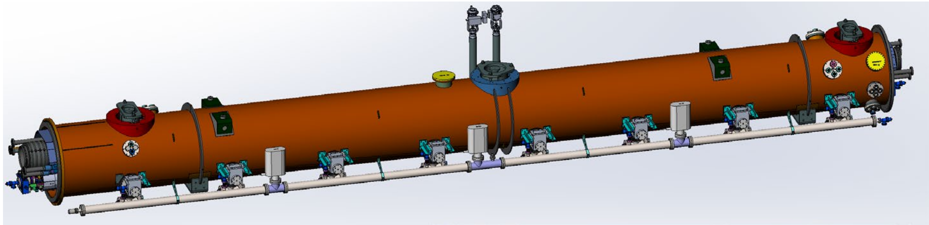




- **Tuner test at 2 K**
  - motor tuning range: 420 kHz (design 400 kHz)
  - piezo tuning range: 3 kHz (design 1 kHz)
  - tuning resolution: < 1 Hz
- **LLRF commissioning**
  - SEL & GDR mode
  - DOB (disturbance observer based) better than PI controller
  - optimizing loop parameters to improve field stability

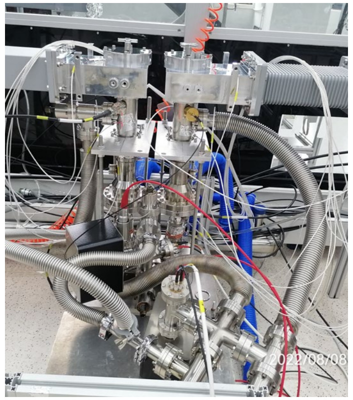
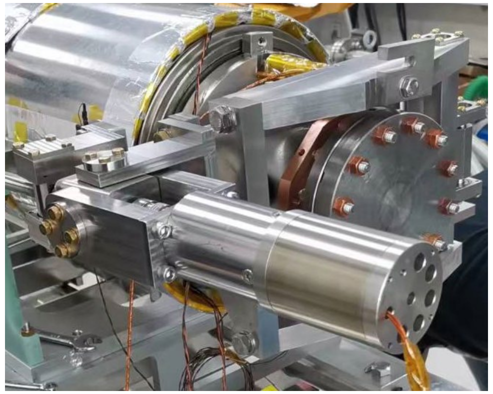


1.3 GHz High Q Cryomodule



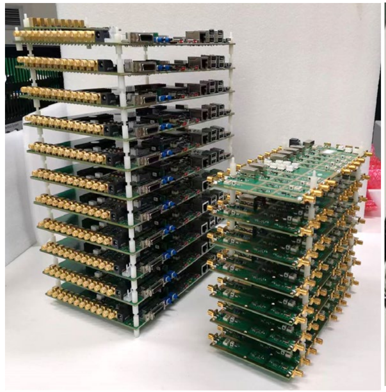
- 8 cavities, input couplers, tuners, SC magnet, BPM, cryostat, other components and tooling are near ready for module assembly
- Module cart, feed/end-cap, volve-box, SSAs, LLRF etc. will be ready soon for horizontal test in early 2023



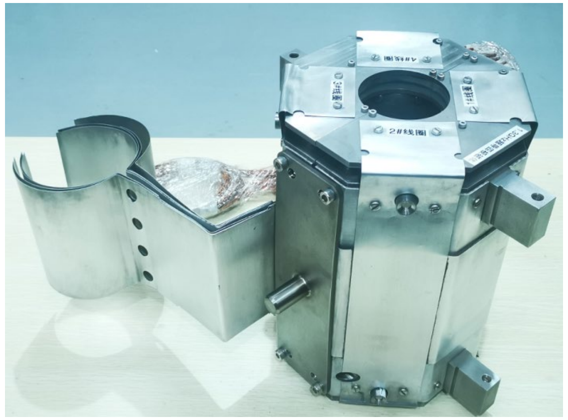








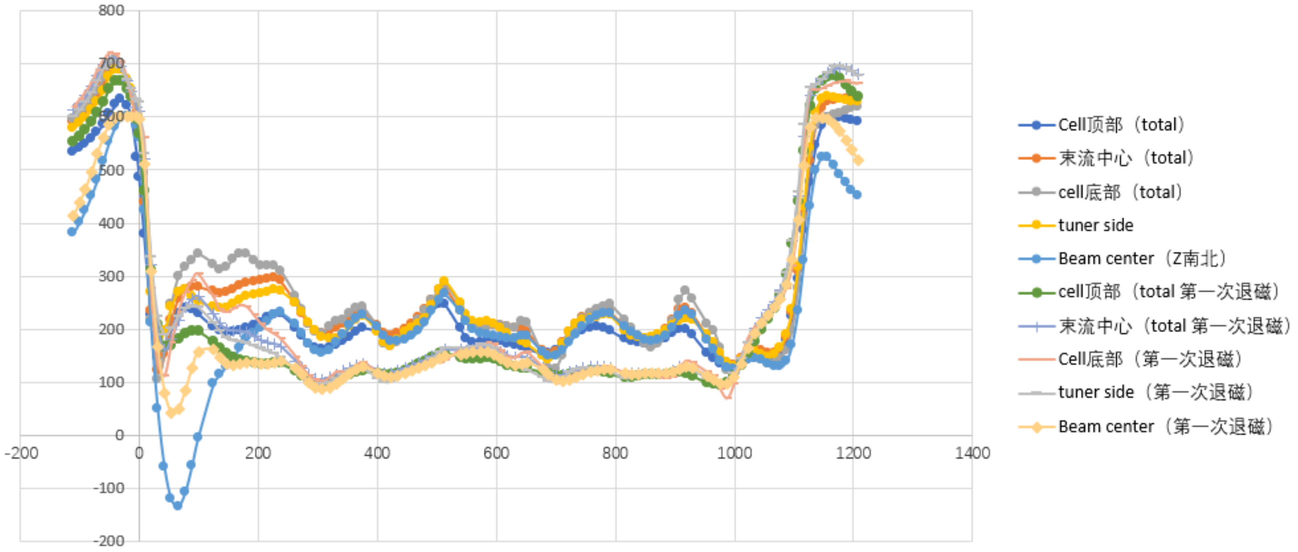

Superconducting Magnet and Degaussing

- The magnet includes one set of quadrupole coils, two sets of correction coils and one set of heating coils with power source and quench protection system.
- Conducting cooling excitation and magnetic field test in liquid helium was done. All coils can run stably at 35 A. The magnetic field results meet the design values.
- Remnant field at 0 A is over 20 Gs at a distance of 400 mm from the end of the magnet (cavity position). After a dedicated degaussing cycle, the remnant field is less than 50 mGs. Need to degauss before each warm up of the module.

	Parameter	Unit	Design value	Measured value@20A
Quadrupole coil@5mm	Peak integral field gradient	T	2.0	2.6381
	Peak field gradient	T/m	8.67	11.6090
	Higher-order field components		0.3%	<0.1%
	Gradient stability (r=5mm)		0.5%	<0.1%
Correction Coil	The integration of the bipolar field	Tm	0.005	HC：0.018 VC：0.017
	Effective length	mm	230	HC：238 VC：234

Cryomodule Vacuum Vessel Degaussing



- Module north to south
- Before degaussing ~ 200 mG
- Degaussing on going

Summary

- CEPC SRF layout and parameters are converging to final TDR design. Consistent with CEPC physics run requirement (Higgs First, All-Mode-Switching), different from FCC-ee.
- Both 650 MHz and 1.3 GHz Mid-T high Q cavities already achieved world leading performance. High performance demonstration of the prototype cryomodule is the next major goal.
- Focus on optimization of the Higgs cavity and cryomodule design. Develop high current HL-Z cavity /module and high gradient high Q ttbar cavity/module concept for the future upgrade.