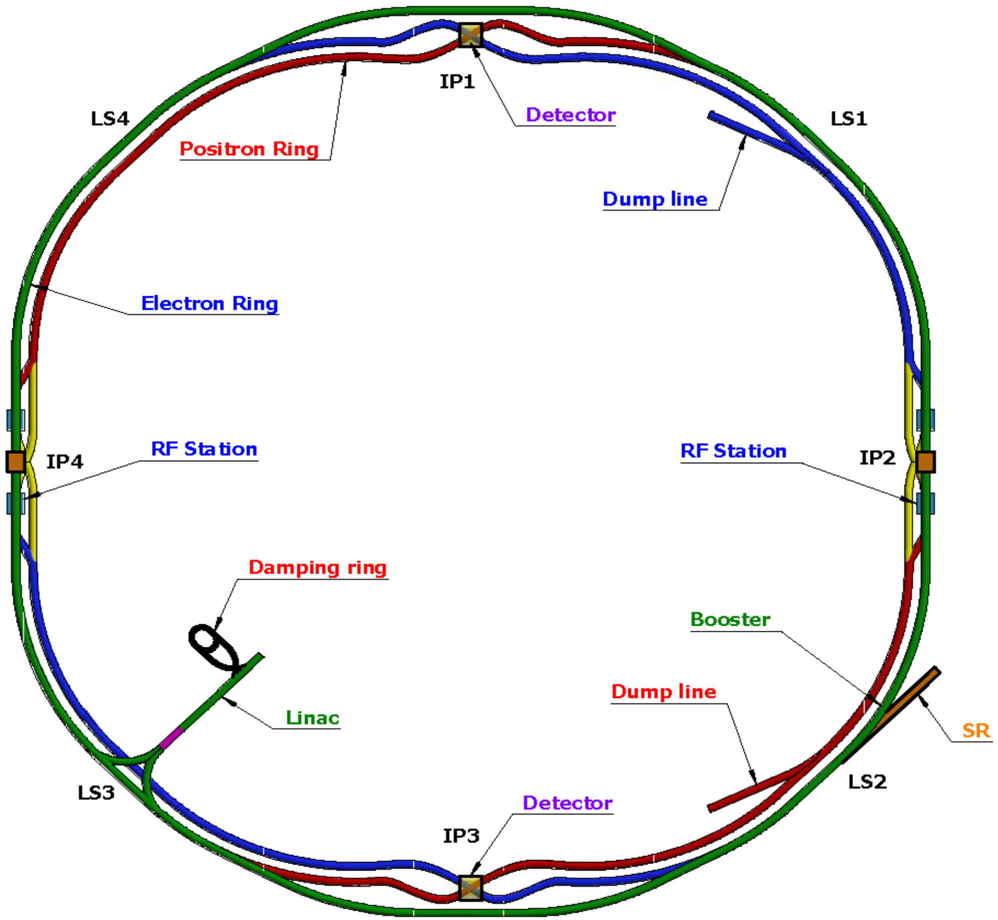
CEPC SRF System Design and R&D Progress

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Jiyuan Zhai (IHEP)

Content

1. TDR design of CEPC SRF system
2. SRF technology R&D and EDR plan
3. Summary



Design Requirement and Challenges of SRF System

Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	8.3	2.2	10	21.6	4.3×10^6
Z	91	192*	50	2	100	4.1×10^{12}
W	160	26.7	6.9	1	6.9	2.1×10^8
$t\bar{t}$**	360	0.8	0.2	5	1.0	0.6×10^6

CEPC collider 50 MW	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.5	1345	0.1
W	80	140	0.7
H	120	27.8	2.2
ttbar	180	5.6	10

1. **Higgs priority**
   - timeline and performance priority
2. **Upgradable**
   - power (luminosity) and energy upgrade
3. **Low cost** (especially first stage)
   - staged cost and in-kind contribution
4. **Max luminosity for each mode**
   - up to 50 MW SR power per beam
5. **Seamless mode switch**
   - switch among H/W/Z/(ttbar)

- <u>45.5-180 GeV</u> double-ring collider with a full energy booster, RF system cost and reliability
- <u>6.6/30 GV</u> total RF voltage, cavity G & Q, heat load
- <u>1.3 A</u> beam current, 100 km large ring, low cavity RF voltage, beam-cavity interaction
- <u>60/100 MW</u> SR power, coupler capacity and match
- <u>6 kW</u> HOM power / cell, HOM damper, #CAV in CM

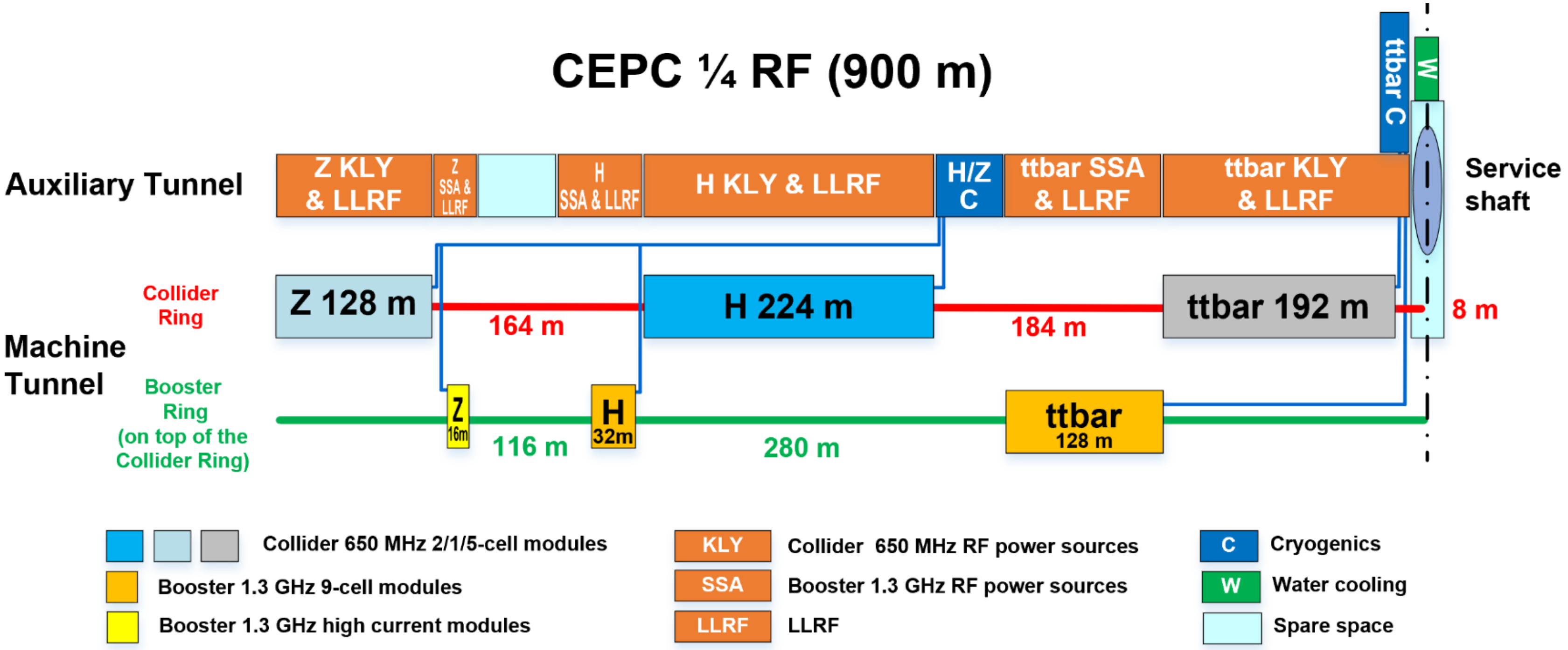
Design Features of SRF System

- **Share cavities for the two rings for H and ttbar (low cost)**
  - Shared cavities for H/ttbar, separate cavities for W/Z
  - Save 2.2/10 GV, reduce by half cavities, klystrons, cryogenics construction and operation cost
  - Cons: double coupler power, half filling of both collider and booster

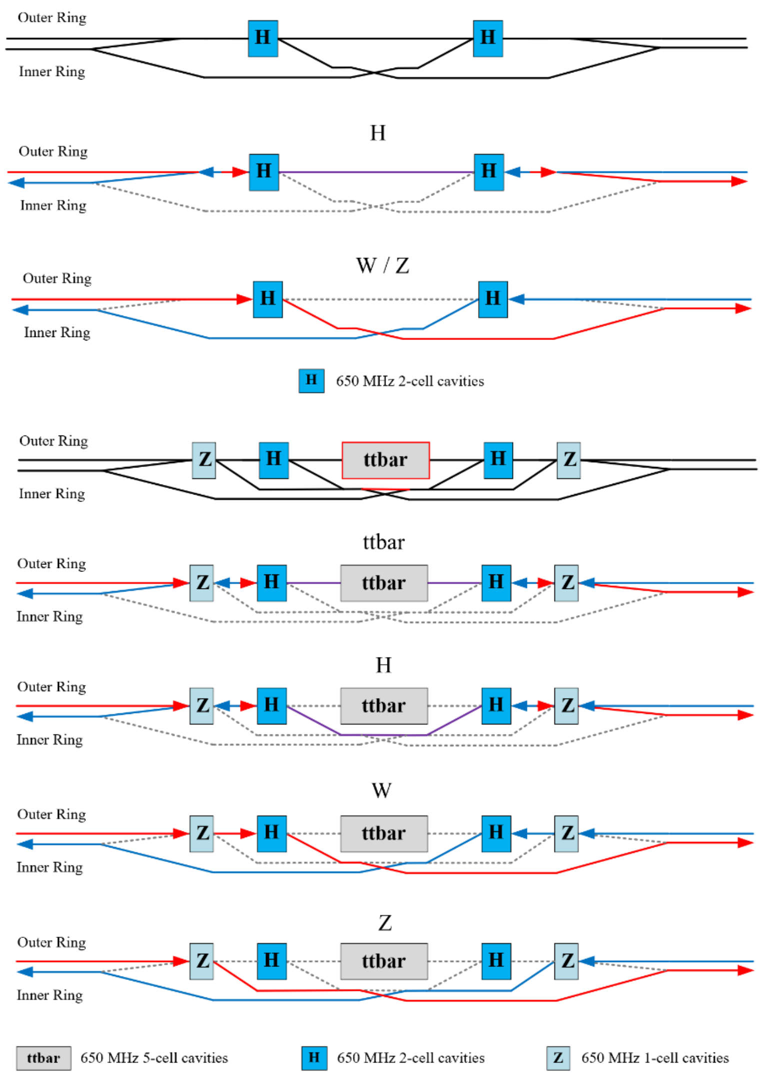
- **RF system optimized for Higgs (Higgs priority)**
  - Coupler power, cavity and cell number, cavity gradient, HOM power, Qin match, beam-cavity interactions (FM/HOM CBI, RF transient), cavity material, operating temperature, Q_0, number of cavities in a module, module heat load, HOM damper, cavities per klystron, power overhead for LLRF... Balance all the parameters with technology maturity, reliability, performance degradation, operational margins, cost, risk and maintenance.

- **RF system for W, Z and ttbar (mode switch and max luminosity)**
  - Due to the wide range of machine parameters, it is impossible to have a single common SRF system for the highest possible luminosity in each mode. A staged SRF complex with bypass lines for both collider and booster is inevitable.
  - W: fully share and use half of the Higgs cavities per ring due to similar beam parameters
  - Z: only low power Z can use Higgs cavities (half parking cavities). 1-cell cavity for > 10 MW to 30 / 50 MW.
  - ttbar: reuse Higgs (& Z) cavities, add new 5-cell cavities. Add more 9-cell cavities for the booster.
  - Add new RF power sources for Z and ttbar
  - Bypass the low current cavities for both collider and booster

CEPC RF Layout

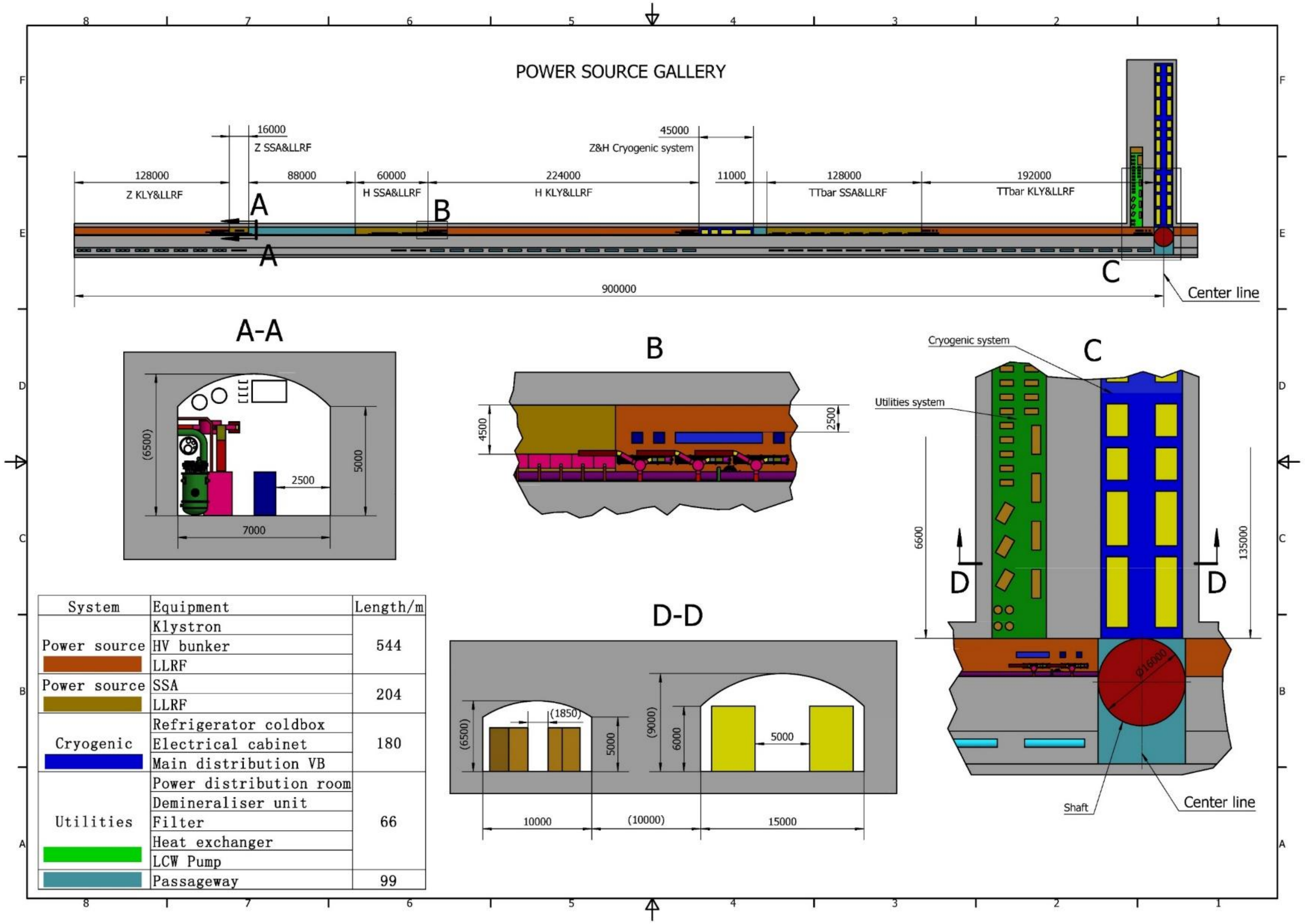


Collider RF Staging and Bypass Scheme

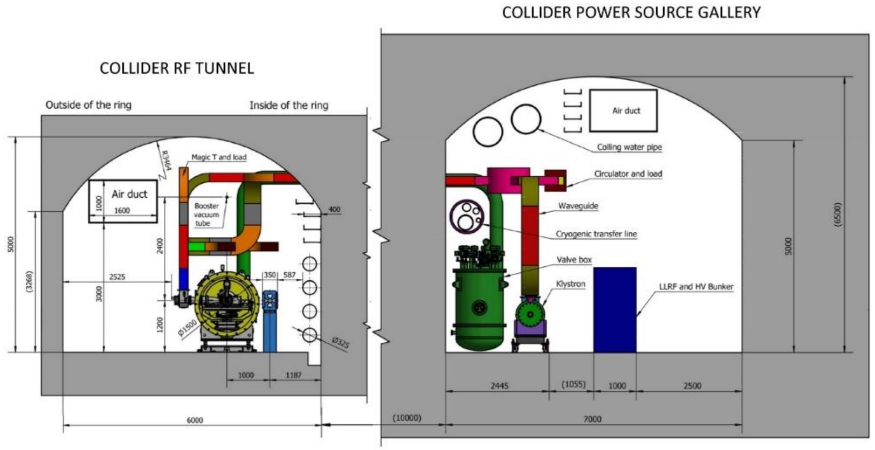


- Bypass booster H cavities for low luminosity Z (< 10 MW) operation.
- 2x3.7 km long straight section, 2x1.8 km RF section
- 3 km RF module footprint, 2 km RF module
- 628 650 MHz cavities, 352 1.3 GHz cav, total 980 cav, 4900 cells

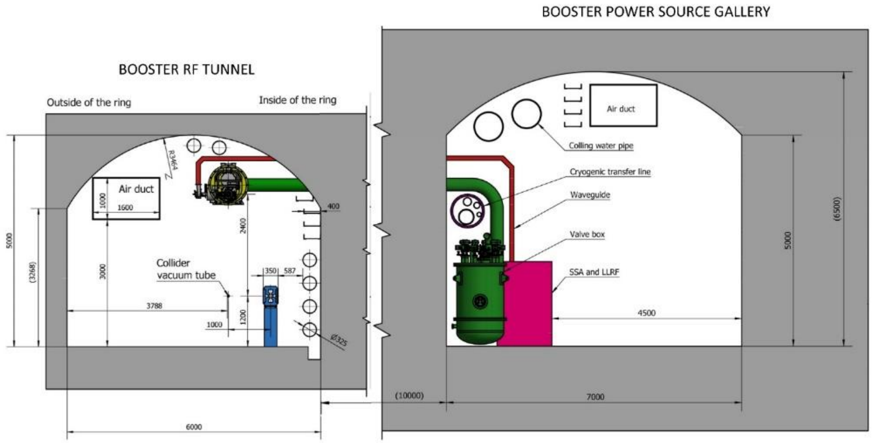
CEPC RF Tunnel



System	Equipment	Length/m
Power source	Klystron HV bunker LLRF	544
Power source	SSA LLRF	204
Cryogenic	Refrigerator coldbox Electrical cabinet Main distribution VB	180
Utilities	Power distribution room Demineraliser unit Filter Heat exchanger LCW Pump	66
	Passageway	99



650 MHz cryomodules mounted on tunnel floor. Cavities operate in CW mode.



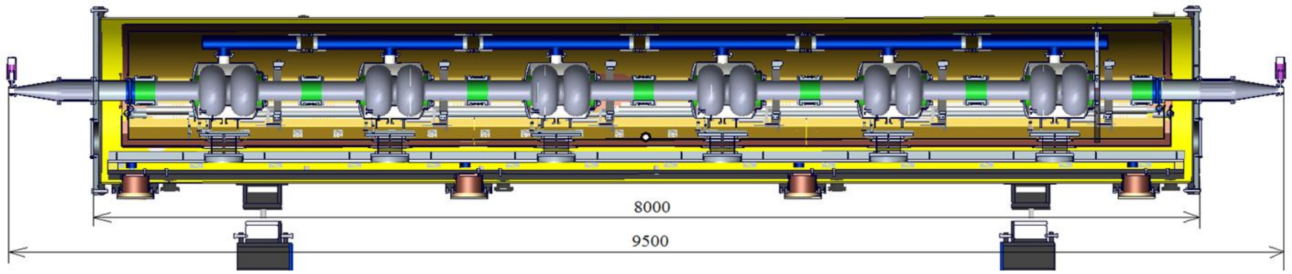
1.3 GHz cryomodules hung from ceiling at a different beamline height and in between collider cryomodule sections. Cavities operate in fast voltage ramp mode.

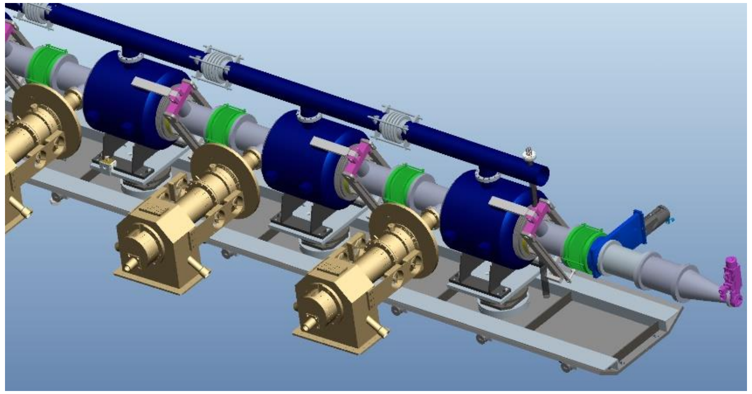
CEPC Collider Ring 650 MHz RF Parameters

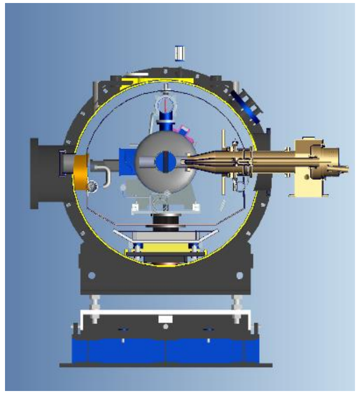
30/50 MW SR power per beam for each mode. Higgs/ttbar shared cavities for the two rings. W/Z separate cavities. HL-Z cavities bypass.	**ttbar 30/50 MW**		**Higgs 30/50 MW**	**W 30/50 MW**	**Z 10 MW**	**Z 30/50 MW**
	New cavities	**Higgs cavities**				
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	0.5 / 0.8		5 / 8.3	16 / 26.7	38	115 / 192
RF voltage [GV]	10 (6.1 + 3.9)		2.2	0.7	0.12	0.12 / 0.1
Beam current / beam [mA]	3.4 / 5.6		16.7 / 27.8	84 / 140	267	801 / 1345
Bunch charge [nC]	32		21	21.6	22.4	22.4 / 34.2
Bunch length [mm]	2.9		4.1	4.9	8.7	8.7 / 10.6
650 MHz cavity number	192	336	192/336	96 / 168 / ring	48 / ring	30 / 50 / ring
Cell number / cavity	5	2	2	2	2	1
Gradient [MV/m]	27.6	25.2	24.9 / 14.2	15.9 / 9.1	5.4	17.4 / 8.7
Q_0 @ 2 K at operating gradient	3E10	3E10	3E10	3E10	3E10	2E10
HOM power / cavity [kW]	0.4 / 0.66	0.16 / 0.26	0.4 / 0.67	0.93 / 1.54	1.9	2.9 / 6.2
Input power / cavity [kW]	188 / 315	71 / 118	313 / 298	313 / 298	206	1000
Optimal Q_L	1E7 / 6E6	9E6 / 5.4E6	1.6E6 / 9.5E5	8E5 / 2.7E5	1.4E5	1.5E5 / 3.8E4
Optimal detuning [kHz]	0.01 / 0.02	0.02 / 0.03	0.1 / 0.2	0.7 / 2	7	6.7 / 21.7
Cavity number / klystron	4 / 2	2	2	2	2	1
Klystron power [kW]	800	800	800	800	800	1200
Klystron number	48 / 96	168	96 / 168	96 / 168	48	60 / 100
Cavity number / cryomodule	4	6	6	6	6	1
Cryomodule number	48	56	32 / 56	32 / 56	16	60 / 100
Total cavity wall loss @ 2 K [kW]	12.1	7.1	3.9 / 2.3	1.6 / 0.9	0.1	0.45 / 0.2

- ttbar and Higgs half filled with common cavities for two rings, W and Z with separate cavities for two rings.
- High luminosity Z upgrade use high current 1-cell cavity with RF bypass.
- Add more 2-cell cavities for Higgs 50 MW upgrade.
- Add 5-cell cavities for ttbar while using the original 2-cell Higgs cavities.
- Fundamental mode instability of Z-mode due to large detuning will be suppressed by RF & beam feedback.
- No beam feedback needed for HL-Z because of deep damping 1-cell cavities.

Collider 650 MHz Cryomodule







- The collider Higgs mode will require 30 MW SR power per beam and will use a 650 MHz RF system with 192 2-cell cavities.
- Each of the 11 m-long collider cryomodules will contain six 650 MHz 2-cell cavities.
- Each cavity will have two detachable coaxial HOM couplers mounted on the cavity beam pipe with a HOM power handling capacity of 1 kW. Additionally, each cryomodule will have two beamline HOM absorbers at room temperature outside the vacuum vessel with a HOM power handling capacity of 5 kW each.

Beam Cavity Interaction

- CEPC large ring features:
  - Large circumference and small revolution frequency (3 kHz, dense beam spectrum)
  - W and Z low energy and small radiation damping
  - Low injection energy of Booster
- Beam cavity interaction issues:
  - Transient beam loading of beam gaps for beam abort, ion-clearing or in bunch trains
  - Fundamental mode (FM) induced coupled bunch instabilities (CBI), due to large cavity detuning (low RF voltage and high current) and the parked cavities
  - Higher-order-modes (HOM) induced coupled bunch instabilities
- Less cavities and cells are preferred to have high stored energy and low impedance.

Details in CEPC TDR

CEPC Booster Ring 1.3 GHz RF Parameters

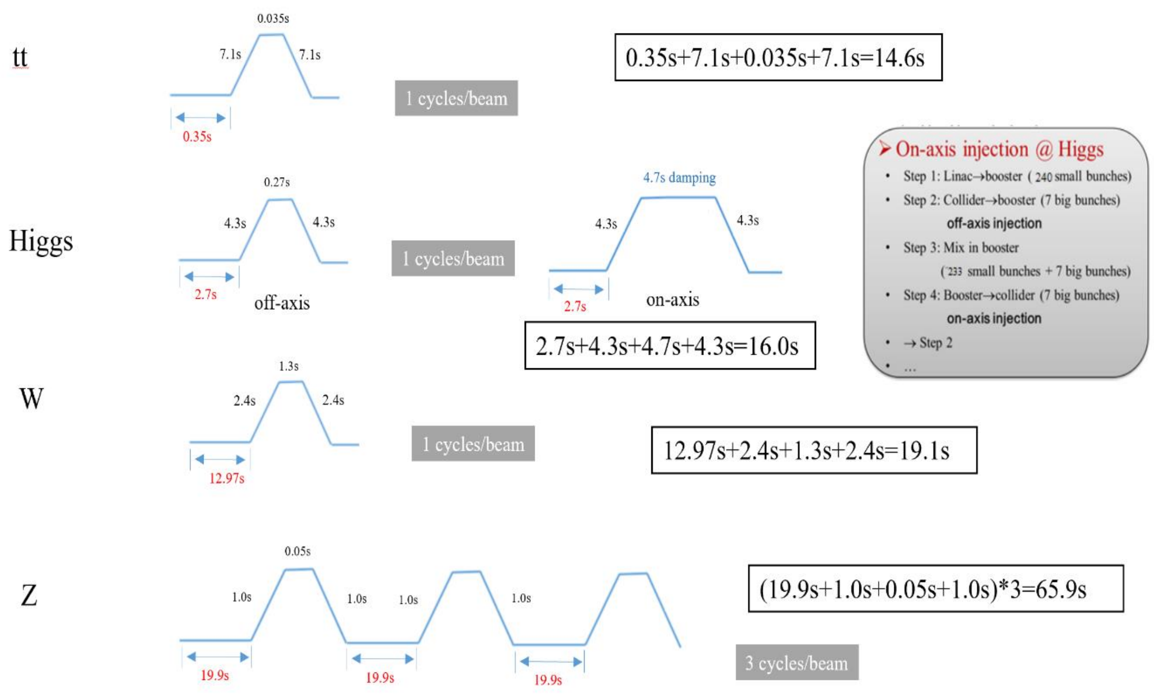
30/50 MW Collider SR power per beam. 30 GeV injection. Higgs & ttbar half filled. Higgs on-axis injection with bunch swapping. Z injection from empty ring.	**ttbar 30/50 MW**		**Higgs 30/50 MW on-axis**	**W 30/50 MW**	**Z 30/50 MW**
	New cavities	**Higgs cavities**			
Extraction beam energy [GeV]	180		120	80	45.5
Extraction average SR power [MW]	0.05		0.5 / 0.67	0.02 / 0.04	0.05 / 0.1
Bunch charge [nC]	1.1		0.78 (20.3)*	0.73	0.81
Beam current [mA]	0.12 / 0.19		1 / 1.4	3.1 / 5.3	16 / 30
Injection RF voltage [GV]	0.761		0.346	0.3	0.3
Extraction RF voltage [GV]	9.7 (7.53 + 2.17)		2.17	0.87	0.46
Extraction bunch length [mm]	1.8		1.86	1.3	0.75
Cavity number (1.3 GHz 9-cell)	256	96	96	96	32
Module number (8 cavities / module)	32	12	12	12	4
Extraction gradient [MV/m]	28.3	21.8	21.8	8.7	13.8
Q_0 @ 2 K at operating gradient	2E10	3E10	3E10	3E10	3E10
Q_L	4E7	4E7	1.2E7	7.3E6 / 4.4E6	1.2E7 / 6.3E6
Cavity bandwidth [Hz]	33	33	110	178 / 296	111 / 208
Peak HOM power per cavity [W]	0.5 / 0.8		~ 75 / ~ 100	11.8 / 19.6	146 / 272
Average HOM power per cavity [W]	0.2 / 0.32		~ 10 / ~ 15	3.8 / 6.3	80 / 150
Input peak power per cavity [kW]	8.3 / 9.2	5.1 / 5.9	22 / 32	10.9 / 18.1	17 / 32
Input average power per cavity [kW]	0.3	0.2	6.5 / 9.2	0.3 / 0.5	2.5 / 4.5
SSA power [kW] (1 cavity / SSA)	10	10	25 / 30	25 / 30	25 / 40
Total cavity wall loss @ 2 K [kW]	0.36	0.05	0.5	0.02	0.08

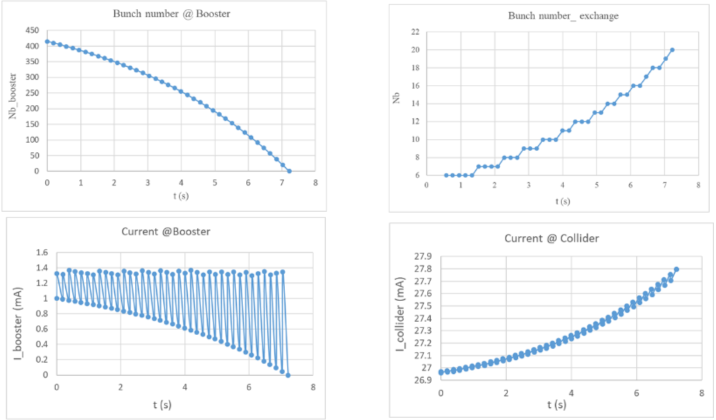
- 1.3 GHz 9-cell cavities
- Higgs and ttbar booster are half filled for the injection timing with Collider ring.
- Transient beam loading for Higgs on-axis injection tolerable (both at injection and extraction).
- Increased average HOM power of HL-Z requires ERL-type 1.3 GHz cryomodule (HOM absorber at low temperature between cavities). Four cryomodules for Z with RF bypass, also to reduce impedance and increase current limit.
- High gradient high Q 9-cell cavities for ttbar.
- Narrow bandwidth high gradient cavity voltage ramping through the multipacting region to be studied. Counter-phasing ramp.

* The small bunch charge number before the parenthesis is for the bunches injected from the linac. The large bunch charge number in the parenthesis is for the bunches injected back from the Collider ring during the swap-out injection at Higgs energy.

Booster Ramp and Duty Factors

- Booster cavities operate in fast ramp mode, and the beam energy increases almost linearly with time. The total RF voltage must be increased during the energy ramp to keep the synchrotron tune constant.
- Cryogenic, RF power and HOM power duty factor change with the cavity voltage, Q0, ramp time, circulating and swapping bunch charge, bunch length, beam current, etc. Big impact on Higgs on-axis injection.

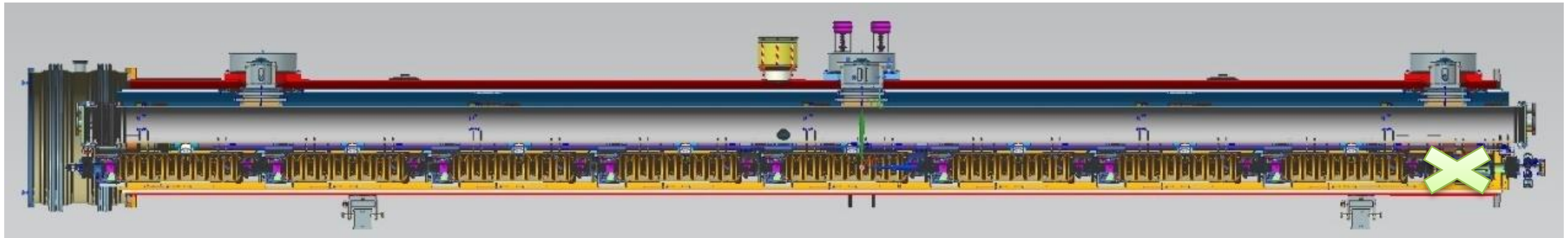




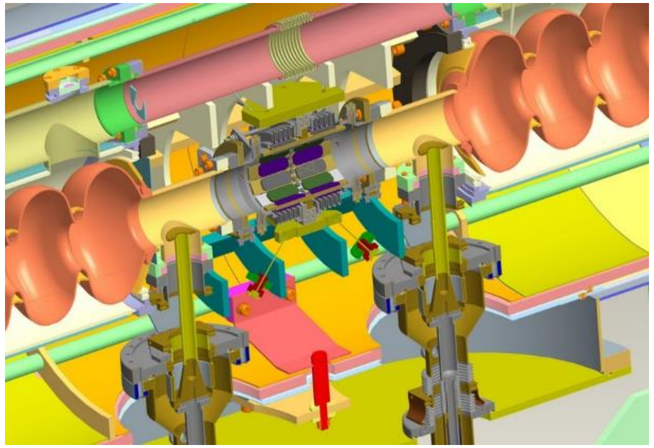
	$t\bar{t}$ 30/50 MW		Higgs 30/50 MW	W 30/50 MW	Z 30/50 MW
	New cavities	Higgs cavities			
Cryogenic dynamic heat load duty factor	3.4 %	3.4 %	31 %	6.5 %	36.6 %
RF power duty factor	3.9 %	3.9 %	30 %	3 %	14.6 %
HOM power duty factor	42 %	42 %	42 % / 49 %	32 %	55 %

Booster 1.3 GHz Cryomodule

- TESLA/TTF/Euro-XFEL/ILC/LCLS-II/SHINE type 1.3 GHz cryomodule will be used for the Booster. Each of the 12-meter-long cryomodules contains eight 1.3 GHz 9-cell cavities, with each cavity having two welded HOM couplers on the cavity beam pipe. **No superconducting magnet and cold BPM in the module.**



- Due to the high beam current and high HOM power per cavity in the high luminosity Z mode (up to 30 mA for injection into the empty Collider ring), an ERL-type 1.3 GHz cryomodule with a HOM absorber at 100 K between cavities will be used instead of the low current TESLA cavities for Higgs, W and $t\bar{t}$ mode. To reduce the impedance, the Z-mode beams will only go through Z-cavities and bypass the Higgs and $t\bar{t}$ cavities.



CEPC Power and Energy Upgrade Plan

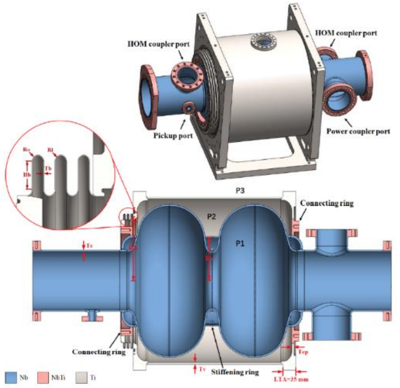
	Baseline			Power Upgrade			Energy Upgrade			
	Higgs	**W**	**Z**	**Higgs**	**W**	**Z**	$t\bar{t}$			
Collider SR power / beam [MW]	**30**			**50**			**30**		**50**	
Beam energy [GeV]	**120**	**80**	**45.5**	**120**	**80**	**45.5**	**180**			
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	**5**	**16**	**115**	**8.3**	**26.7**	**192**	**0.5**		**0.8**	
Collider 650 MHz cavities	**2-cell**		**1-cell**	**2-cell**		**1-cell**	**Add 5-cell**	**Existing 2-cell**	**Add 5-cell**	**Existing 2-cell**
RF voltage [GV]	2.2	0.7	0.12	2.2	0.7	0.1	10 (6.1 + 3.9)		10 (6.1 + 3.9)	
Beam current / ring [mA]	16.7	84	801	27.8	140	1345	3.4		5.6	
Cavity number	192	96×2	30×2	336	168×2	50×2	192	336	192	336
Cryomodule number	32	32	60	56	56	100	48	56	48	56
Klystron number	96	96	60	168	168	100	48	168	96	168
Klystron power [kW]	800	800	1200	800	800	1200	800	800	800	800
Collider 4.5 K equiv. heat load [kW]	44.4	28.1	15.2	41.9	20	20.1	128.3		128.3	
Booster 1.3 GHz cavities	**9-cell**			**9-cell**			**Add 9-cell**	**Existing 9-cell**	**Add 9-cell**	**Existing 9-cell**
Extraction RF voltage [GV]	2.17	0.87	0.46	2.17	0.87	0.46	9.7 (7.53 + 2.17)		9.7 (7.53 + 2.17)	
Beam current [mA]	1	3.1	16	1.4	5.3	30	0.12		0.19	
Cavity number	96	96	32	96	96	32	256	96	256	96
Cryomodule number	12	12	4	12	12	4	32	12	32	12
SSA number	96	96	32	96	96	32	256	96	256	96
SSA power [kW]	25	25	25	30	30	40	10	10	10	10
Booster 4.5 K equiv. heat load [kW]	7.8	3.1	3.5	8.1	3.2	3.7	11.4		11.4	
Total RF length [m]	**704**	**704**	**384**	**1088**	**1088**	**608**	**2368**		**2368**	
Total 4.5 K equiv. heat load [kW]	**52.2**	**31.2**	**18.7**	**50.0**	**23.2**	**23.8**	**139.7**		**139.7**	

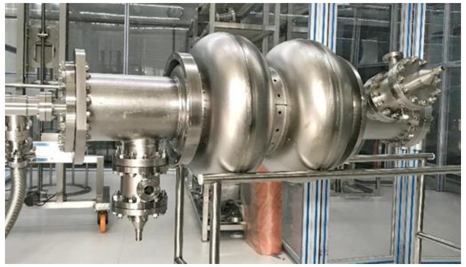
Content

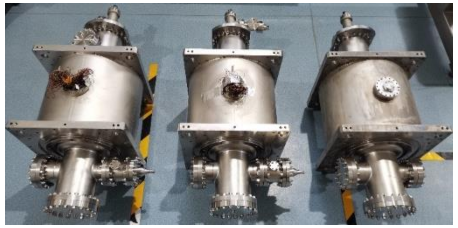
1. TDR design of CEPC SRF system
2. CEPC SRF technology R&D and EDR plan
3. Summary

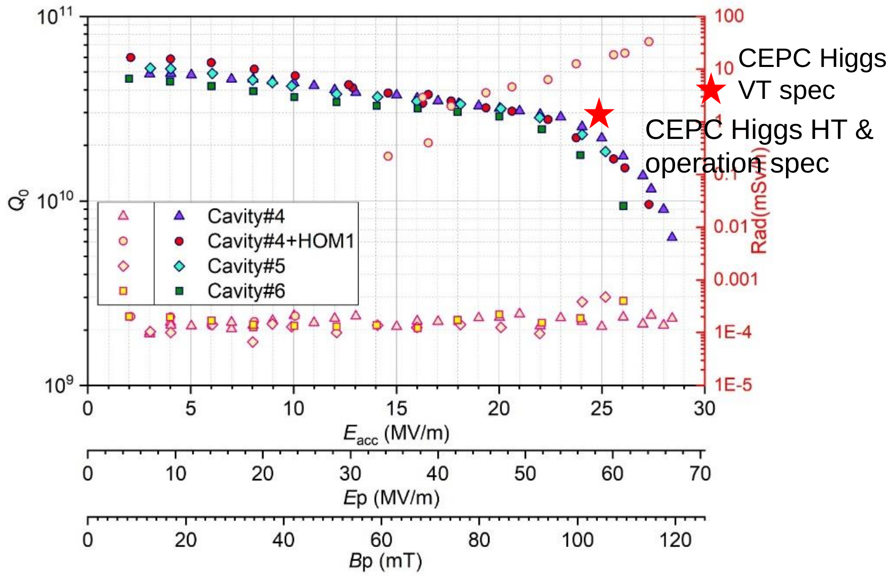
650 MHz and 1.3 GHz Cavity

650 MHz 2-cell BCP

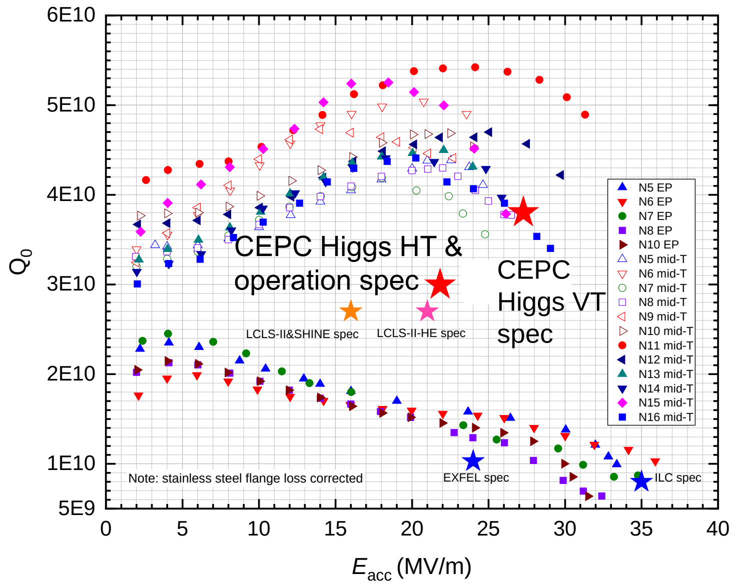




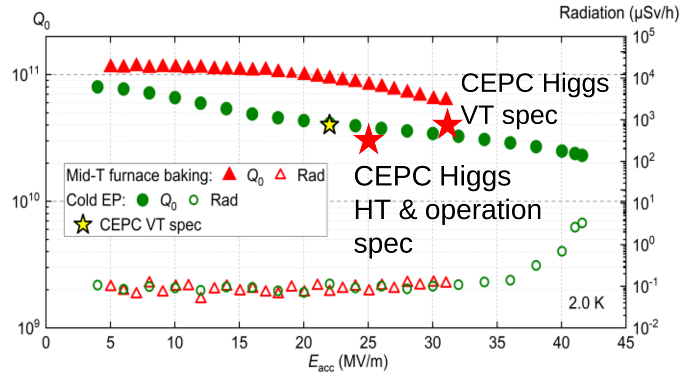




1.3 GHz 9-cell EP / mid-T



650 MHz 1-cell EP / mid-T



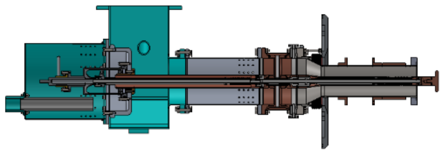
EDR cavity R&D (about 20 % margin from vertical test to operation spec) **:**

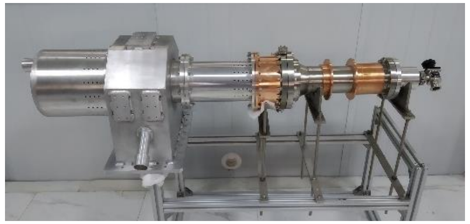
- 650 MHz 2-cell cavity: 3.8E10 @ 25 MV/m, > 31 MV/m (achieved in 1-cell) . Six cavities in the module.
- 1.3 GHz 9-cell cavity: 3.6E10 @ 21.8 MV/m, > 27 MV/m (increase gradient). 16 cavities in two modules.

Other Key SRF Components

650 MHz input coupler

Variable, one-window, 300 kW CW





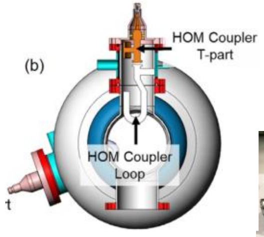
Tested to CW TW 150 kW (SSA power limit), SW 100 kW (corresponding to 400 kW TW power at the window)

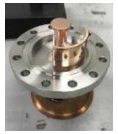
1.3 GHz input coupler

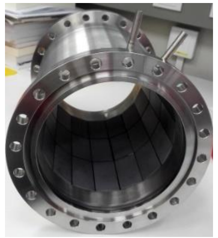
Variable, 2-window, 7 kW CW

Tested to CW SW 7 kW

650 MHz HOM coupler & HOM absorber



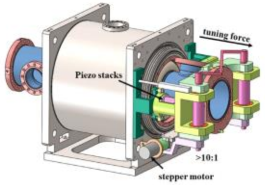


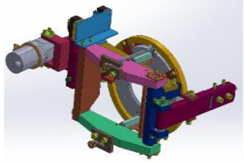


Double-notch wide-band 1 kW HOM coupler without FM tuning.

Broad band 5 kW absorber with SiC+AlN composite

650 MHz and 1.3 GHz tuner

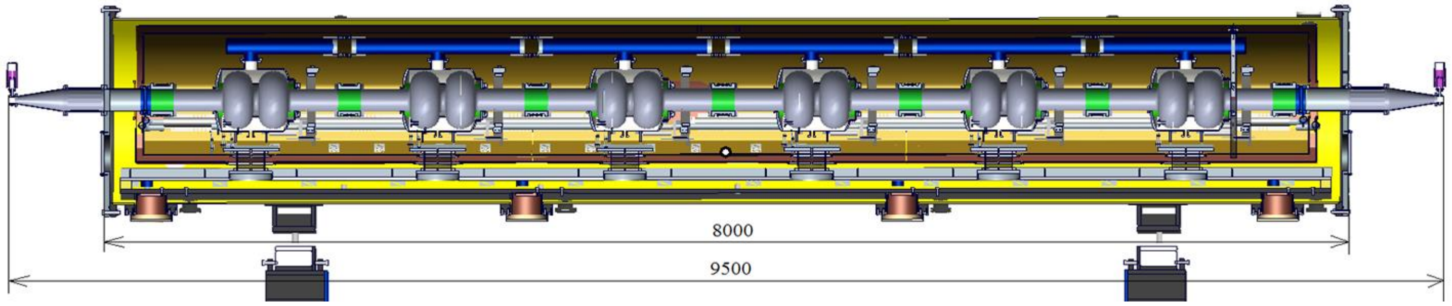


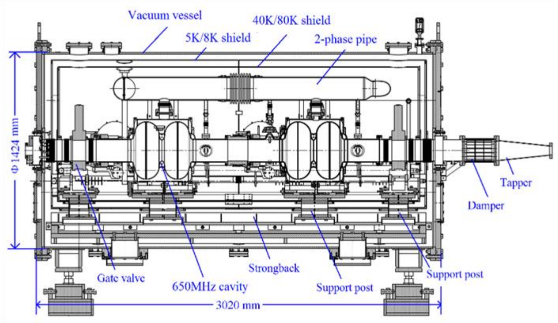


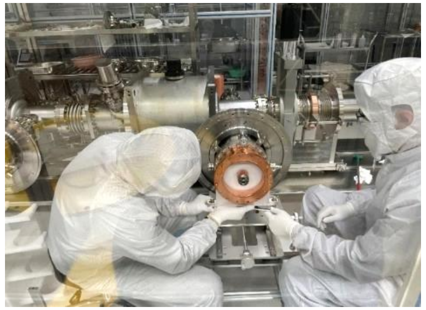
EDR R&D plan (hope to collaborate with CERN FCC-ee)**:**

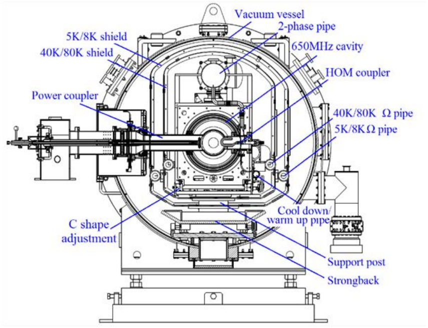
- High power variable couplers. Cooling and heat load design optimization. Conditioning with 650 MHz klystron 600 kW TW, 300 kW SW. Six couplers in the pCM operation. Design and develop 1 MW variable input coupler for Z-pole.
- HOM couplers. HOM power coaxial line design. 1 kW high power test at 2 K in the horizontal test stand (in vacuum, heating measurement).

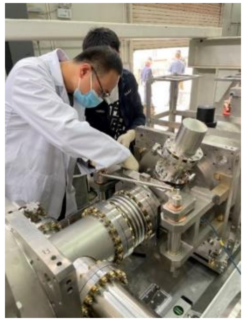
650 MHz Cryomodule











EDR R&D plan:

1. Solve coupler GHe cooling issue of the test cryomodule. Achieve 2E10@15 MV/m operation with beam.
2. Replace with high Q cavity and variable coupler. Demonstrate 3E10@25 MV/m in the test module.
3. Design, build and test a CEPC 650 MHz 6x2-cell cryomodule prototype and meet CEPC spec.

1.3 GHz Cryomodule

- World's first 1.3 GHz cryomodule with 8 mid-T (medium-temperature furnace bake) 9-cell cavities.
- Mid-T bake has distinct advantages over N-doping. Will be used in CEPC and other SRF projects.

Parameters	IHEP Mid-T CM Horizontal Test	LCLS-II & HE Spec	CEPC Booster Higgs mode Spec
Avg. usable CW E_{acc}	> 23 MV/m	2.7×10^{10} @ 16 & 20.8 MV/m	3.0×10^{10} @ 21.8 MV/m
Avg. Q_0 @ 21 MV/m	3.6×10^{10}		

130 MV operation: radiation < 0.08 mSv/h (spec 0.5 mSv/h), dark current < 1 nA

EDR R&D plan:

- Build two more high Q 1.3 GHz modules to meet CEPC Higgs spec by supporting domestic FEL projects. Minimum statistics of mid-T module.
- Design high current high Q ERL-type 1.3 GHz module for Z-pole. In synergy with ERL-FEL EUV project. (hope to collaborate with KEK)

EDR Phase and Future Plan for CEPC SRF System

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034-2035	2036-2045	2046-2047	2048	2049-2053
EDR																
Civil construction																
Acc. construction & installation																
Commission & operation													H	Z	W	ttbar
SRF system engineering design	Layout, cost, module, beam-cavity, LLRF, interfaces …															
650 MHz test module (2x2-cell)	Beam operation, replace with high Q cav & variable coupler															
650 MHz H module (6x2-cell)	Design	pCM fabrication		pCM test	Prepare	Production of 32 CM / 192 2-cell CAV for 30 MW H				Installation, Commissioning			Op & +24 CM	Operation		
1.3 GHz H module	High Q module	Mass production of modules with SCM and BPM			pCM fab	pCM test	Production of 12 CM / 96 9-cell CAV			Installation, Commissioning			Operation			
1.3 GHz Z module (high current)		Design and R&D			pCM fabrication		pCM test		Production of 4 CM / 32 9-cell CAV		Installation, Commissioning		Operation			
650 MHz HL-Z module	Conceptual design. 500 MHz high current module production.				Design and R&D							Produce and Install 60+40 1-cell CM		Op		
ttbar cavity and module	Design and R&D of high gradient high Q and new material (Nb3Sn etc.) 650 MHz and 1.3 GHz cavities and module for ttbar								pCM fabrication and test				Production and Installation of 48 CM / 192 650 MHz 5-cell CAV 32 CM / 256 1.3 GHz 9-cell CAV			Op

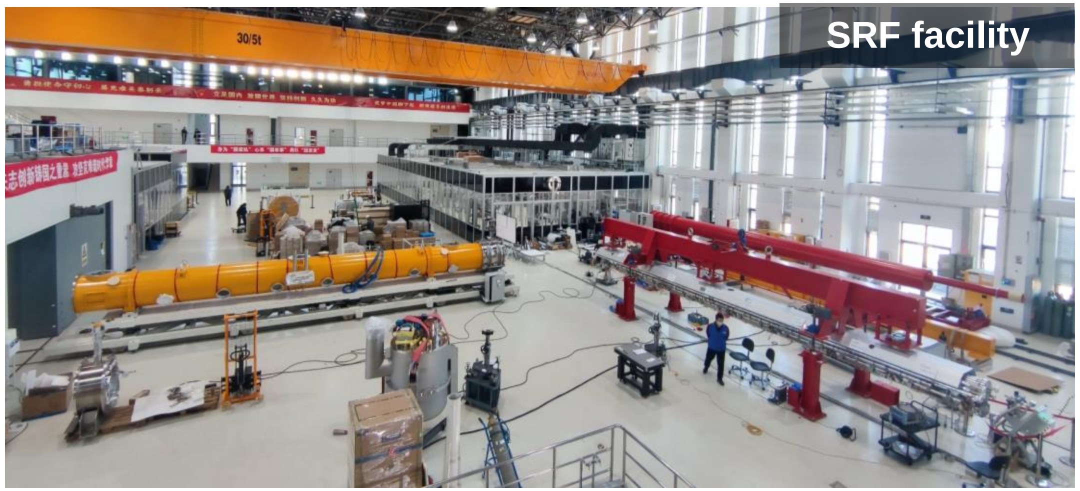
30-year plan. CEPC EDR, construction, installation, commission, operation and upgrade. Push SRF technology frontiers in high gradient, high Q, high current, high power and new material in synergy with storage ring light sources, FELs and other SRF projects in China and the world.

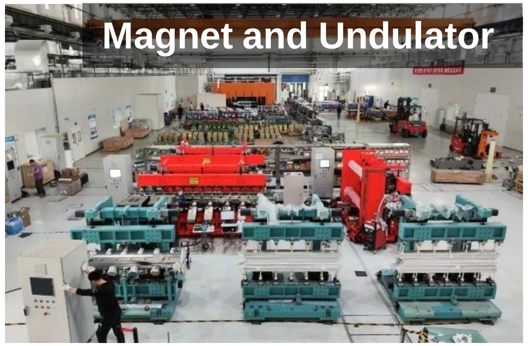
SRF System Risks and New Ideas

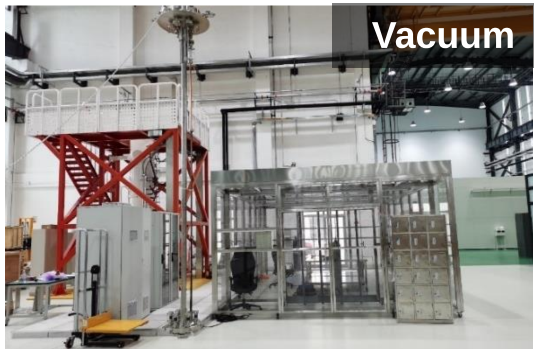
- **Input coupler**: Matching and coupling adjusting range: key issue of a green accelerator, same as klystron efficiency. Most critical RF part: high power, low heat load, high reliability, long lifetime. If fails, input power reduction, cavity number and cost increases, extra RF power, cavity contamination, RF trips...
- **RF voltage** operation margin, standby cavities and power sources
- Preventing and mitigating cavity Q_0 degradation, as well as enough margin of cryogenics capacity
- Power overhead for Z-pole mode LLRF control
- LLRF control of multi-cavity fed by one klystron

- New material (thin film e.g. Nb3Sn) (collaborate with PKU, IMP, KEK and other labs)
- Multi-cavity high current cryomodule (collaborate with CERN), HOM coupler and mode propagation
- RF power transfer from H to Z to have less klystrons? Waveguide loss, group delay.
- Add 1.3 GHz 9-cell cavities instead of 650 MHz 5-cell cavities for ttbar collider ring?

PAPS



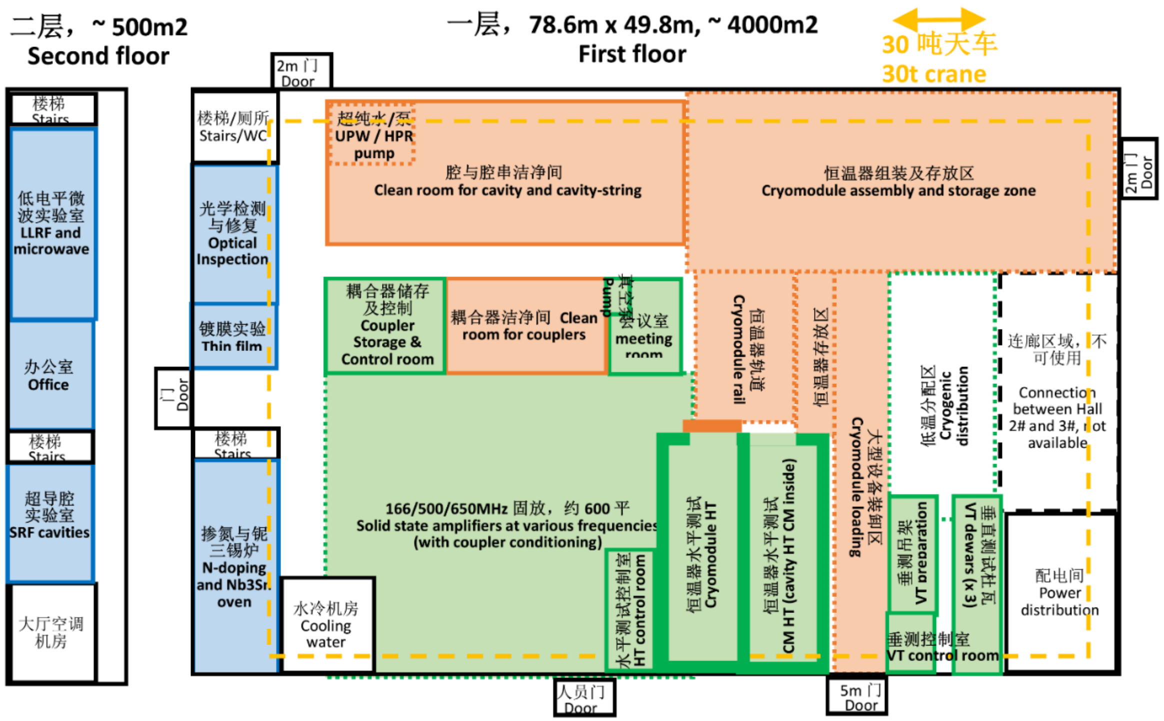


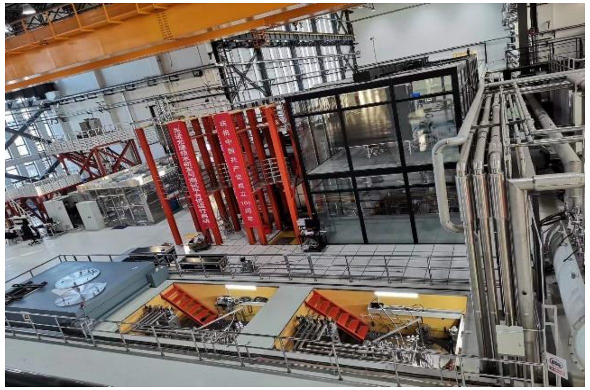


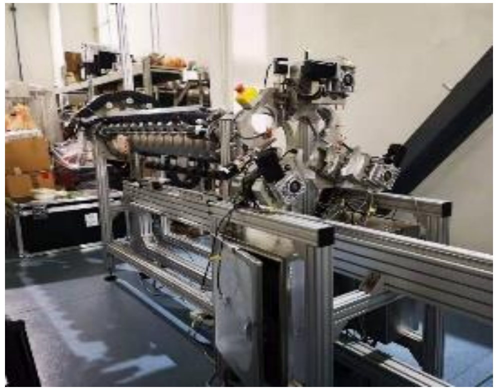
Accelerator key technology R&D and Testing platform:

- ➢ SRF cavity and module
- ➢ High precision magnet
- ➢ Vacuum assembly & coating
- ➢ High efficiency Klystron
- ➢ Mechanics and alignment
- ➢ Beam test facility

PAPS SRF Infrastructure Fully Operational







IHEP EP system in Ningxia

PAPS SRF Infrastructure Operation Status

Facilities (capability per year)	Devices	Tests since 2021	Related Projects
VT stand (400 cavities)	166 MHz / 325 MHz / 500 MHz / 650 MHz / 1.3 GHz CAV	~ 160	HEPS/BEPCII-U/CEPC/CSNS-II/SHINE/DALS/HALF/(CiADS)
HT stand (20 modules, including assembly)	1.3 GHz CAV	~ 20	CEPC/SHINE/DALS/HEPS/(BEPCII-U/CSNS-II)
High power test stand (200 couplers)	Coupler / Circulator / RF load / Copper cavity	~ 20	HEPS/SHINE/DALS/CSNS-II/(HALF)
Clean assembly and HPR	166MHz / 325MHz / 500MHz / 650MHz / 1.3 GHz CAV	~ 160	HEPS/CEPC/CSNS-II/SHINE/DALS/BEPCII-U/(HALF)
Vacuum furnace	650 MHz / 1.3 GHz CAV	~ 50	CEPC/CSNS-II/SHINE/DALS

IHEP (Beijing) SRF Team Experience

- IHEP SRF and cryogenics team (19 RF experts, 16 cryogenics experts, 14 graduate students, 5 workshop engineers, 15 technicians) has experience in SRF technology, system and infrastructure design / construction / operation for various accelerators:
  - **High Energy Collider**: BEPC-II&U 500 MHz, CEPC 650 MHz and 1.3 GHz R&D
  - **Light Source**: HEPS 166 MHz and 500 MHz; **FEL**: 1.3 GHz for SHINE, DALS and S3FEL
  - **High Intensity Proton Linac**: ADS injector 325 MHz spoke, CSNS-II 324 MHz double-spoke
  - **SRF infrastructure**: PAPS 4500 m^2 SRF lab, 400 cavities testing, 20 cryomodule assembly/testing per year

166 MHz

World's first very low freq β=1 QWR module

325 MHz

CW 10 mA proton beam of world's first spoke module

500 MHz

CW 900 mA e+/e- beam operation for 6 years

650 MHz

World's first 650 MHz cryomodule

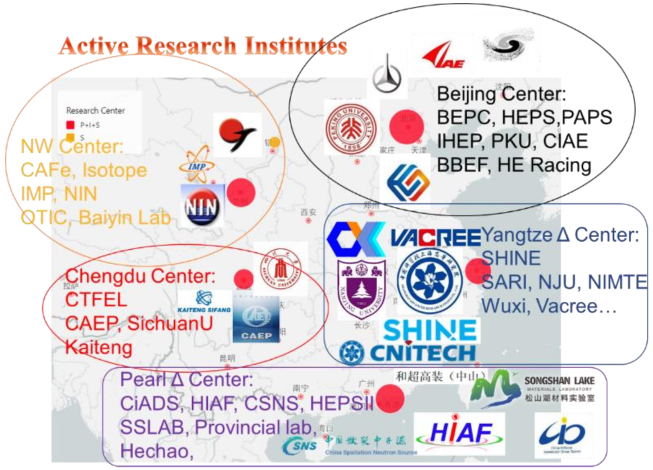
1.3 GHz

World's first mid-T cryomodule with record high Q at 21 MV/m

SRF Accelerator Projects in China

	Operation	Construction	Design & R&D	Sum
Collider	**BEPCII** (1.89 GeV, 2 CAV, since 2006)	**BEPCII upgrade** (2.35 GeV, 4 CAV, complete in 2024)	**CEPC** (45.5-180 GeV, 288 ~ 980 CAV)	**2 circular colliders** tau-charm, Z, W, Higgs, ttbar
Synchrotron Light Source	**BSRF** (2.5 GeV, 2 CAV, since 2006) **SSRF** (3.5 GeV, 3 CAV, since 2009)	**HEPS** (6 GeV, 10 CAV, complete in 2025) **HALF** (2.2 GeV, 1 CAV, complete in 2028)	**SAPS** (3.5 GeV, 4 CAV) And more…	**5++ light sources** 3rd & 4th generations 2.2 ~ 6 GeV
FEL	**PKU FEL & DC-SRF Gun** (30 MeV, 3 CAV) **CTFEL** (10 MeV, 2 CAV, since 2017)	**SHINE** (8 GeV, 616 CAV, complete in 2027) **S3FEL** (2.5 GeV, 224 CAV, complete in 2031) **ZJLAB EUV-FEL** **CTFEL upgrade** (50 MeV)	**DALS** (1 GeV, 96 CAV) **CAEP XFEL** (pulsed hard X-ray, 16 GeV) And more…	**8+ FELs** 2 hard X-ray 1 soft X-ray 2 EUV, 1 IR, 2 THz
Proton & Heavy Ion	**ADS injector I** (10 MeV, 14 CAV, since 2016) **CAFe** (25 MeV, 23 CAV, since 2017)	**CiADS** (0.5 GeV, 151 CAV, complete in 2025) **HIAF** (4.25 GeV/u, 96 CAV) **CSNS-II** (300 MeV, 54 CAV, complete in 2028)	**CSNS-III** (1 GeV) **ADS** (1 GeV) **CIAE proton linac** (1 GeV) And more…	**6+ proton & heavy ion SRF accelerators**
Sum	**Operating 6 facilities** **~ 50 cavities**	**Constructing 9 projects** **~ 1200 cavities by 2028** **~ 40 billion CNY**	**Proposing 7+ projects** **2000+ cavities**	**CEPC SRF design, cost estimate, industrialization and construction will benefit a lot from all of these projects**

SRF Accelerator Research Institutes, Infrastructures, Projects and Industry in China



Part of CIPC members'

IHEP is and will be supporting other SRF projects in China: CSNS-II, SAPS, SHINE, DALS, S3FEL, HALF, other FELs…

Summary

- CEPC TDR SRF system layout and parameters are designed to meet physics run requirement (Higgs first, upgradable, low cost for first-stage, mode-switching) by RF staging and bypass with different SRF systems and by exploiting the most advanced technology.

- During the five-year TDR phase, major SRF components and cryomodules developed with domestic industries reached good performances, but not all ready for construction.

- EDR phase work planned for SRF system design optimization, components R&D and yield study, full-scale module prototyping and mass production preparation toward the construction stage.

- We will continue to gain SRF experience by supporting other SRF projects in China.

- We hope to collaborate with PKU, CERN (FCC-ee), KEK, INFN, DESY, JLAB and other labs in the SRF system design and technology development for the next high-energy lepton collider to be realized soon.

Z-pole Operation with Higgs 2-cell Cavities

- The HOM power limit per cavity and the fast-growing coupled-bunch instabilities (CBI) driven by both fundamental modes (FM) and higher-order modes (HOM) impedance of the RF cavities will determine to a large extent the highest beam current and luminosity obtainable in the Z mode.

- Using Higgs 2-cell cavities, Z mode can only operate at low luminosity and low power (up to about 10 MW SR power per beam).

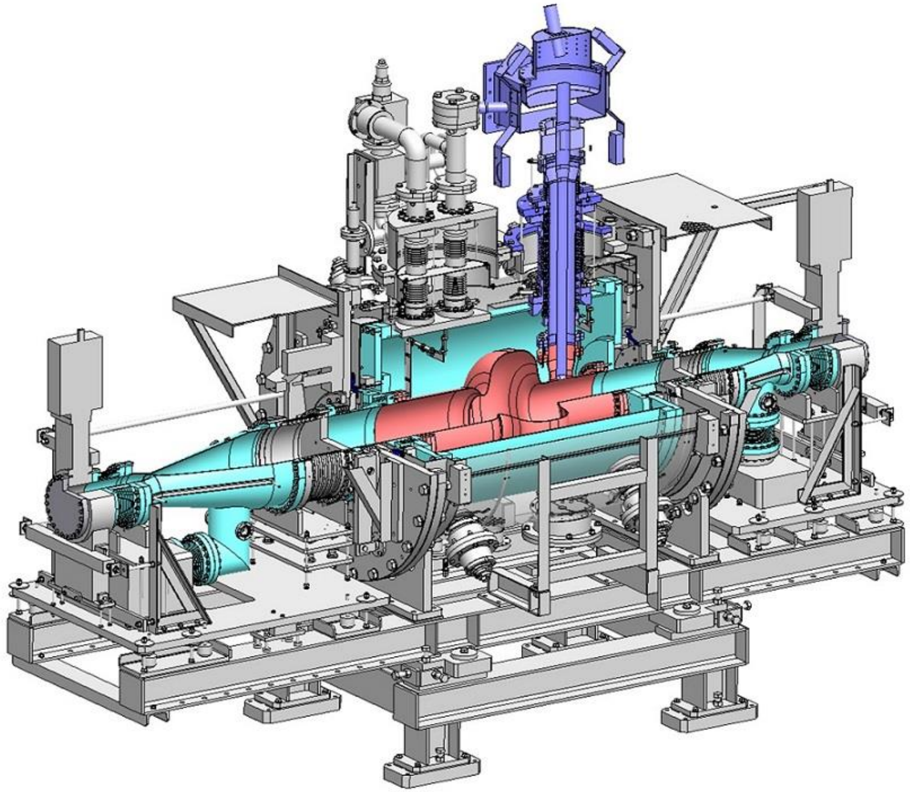
- The low luminosity Z mode will use 48 cavities per ring and park the other 48 cavities in the ring.

- However, the beam will go through all the 96 cavities and interact with the cavity impedance. Therefore, the parking cavities will be kept at 2 K to extract the HOM power.

- They will be symmetrically detuned to cancel FM impedance and adjust the variable input coupler to high loaded Q with a narrow bandwidth to avoid FM CBI.

High Current 650 MHz Cavity for HL-Z mode

- For high luminosity Z, i.e., 30 and 50 MW SR per beam, 30 and 50 KEKB / BEPCII type high current SRF-cavity cryomodules for each ring will be chosen as the baseline due to their excellent HOM damping.
- The high current beam will bypass the Higgs / $t\bar{t}$ cavities. The cryomodule will have only one 1-cell cavity inside with HOM absorbers at room temperature.
- The cavity number is a balance between the input power and the stored energy per cavity for the sake of FM CBI and transient beam loading. Fewer cavities and cell numbers are preferred to have high stored energy and low impedance. The counter-phasing operation method (originated at KEKB) could be used to further increase the cavity stored energy.
- A multi-1-cell-cavity cryomodule with deep HOM damping (CERN LHC type) will be developed as an alternative.



High Current 650 MHz Cavity for HL-Z mode

- Based on the successful construction and stable operation of BEPCII 500 MHz cavity system. Small batch production for HEPS, BEPCII-U and HALF (~ 4).
- Higher gradient (x3, 18 MV/m) and Q (x20, 2E10), 2 K operation
- Higher input power (x10, 1 MW per cavity, two couplers and two 600 kW klystrons as alternative).
- Deep HOM damping.