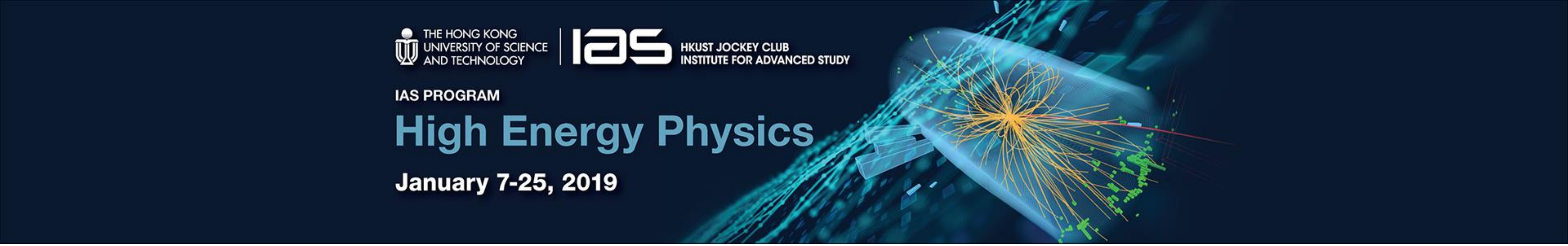


CEPC SCRF R&D Towards TDR

Jiyuan Zhai

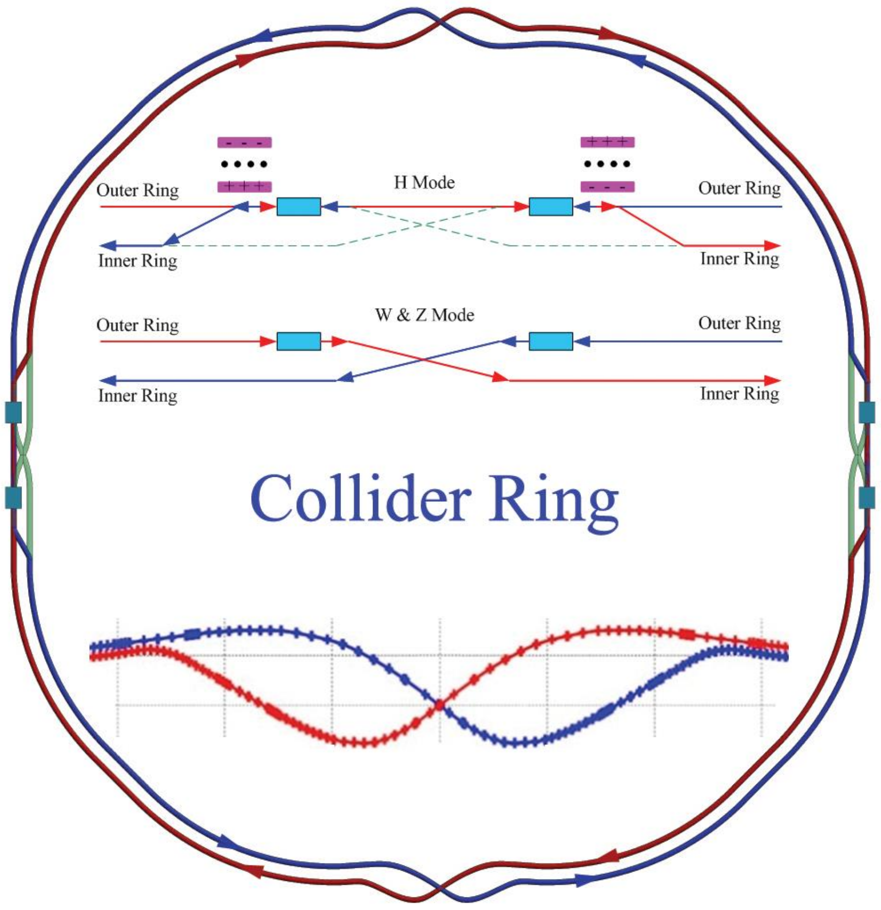
for the CEPC SRF Study Team

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

Outline

- CDR design of CEPC SRF system
- SCRF TDR plan and R&D status
- Summary

CEPC SRF Design Requirements

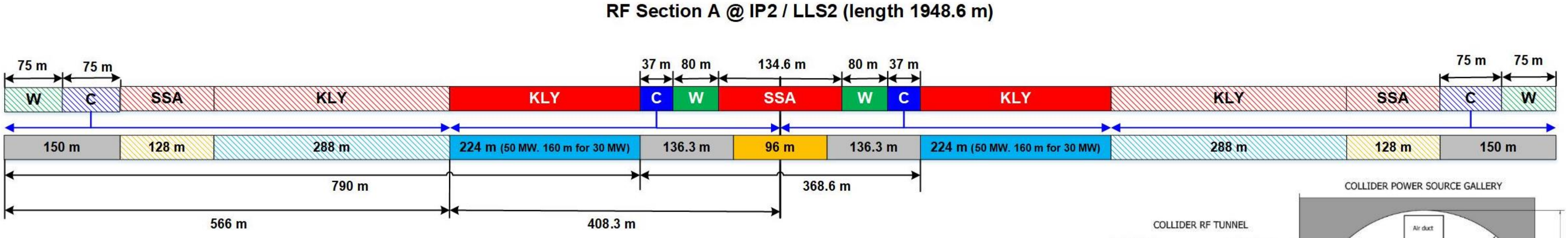


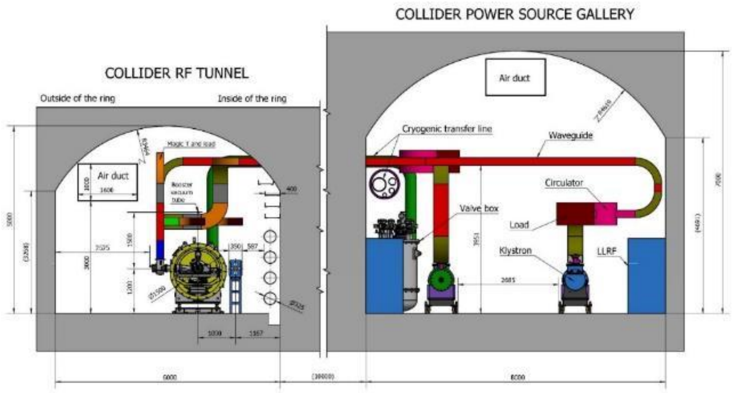
CEPC Operation Plan

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 particles
H	240	3	0.8	7	5.6	1×10^6
Z	91	32 (*)	8	2	16	7×10^{11}
W^+W^-	160	10	2.6	1	2.6	2×10^7

- Higgs long run first:
  one-time full installation of cavities. Part of the Higgs cavities for W and Z.
- Cost reduction:
  common H cavities, separate W/Z cavities.
- Upgradable:
  reserved RF tunnel, variable coupler.

CEPC SRF Layout



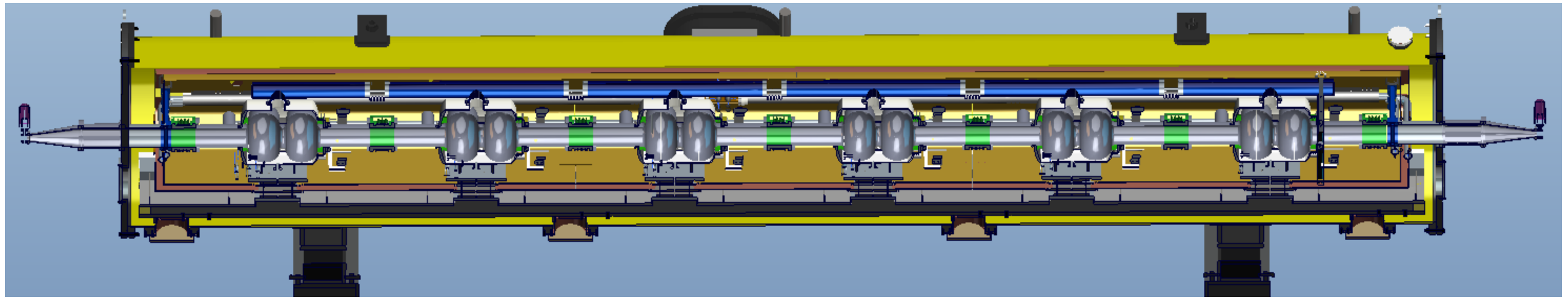


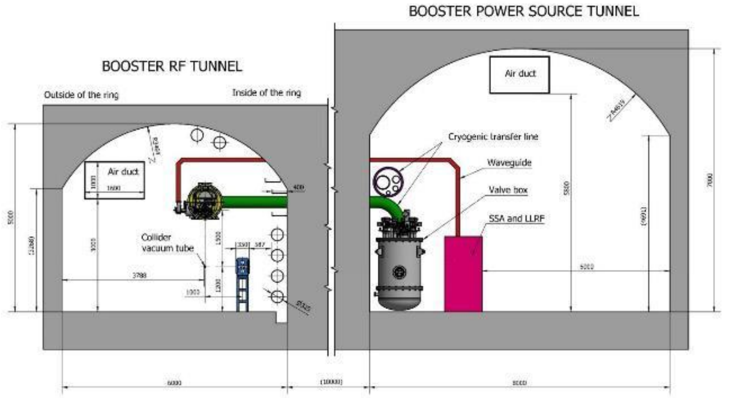
30 MW Higgs:

Collider: 240 650 MHz 2-cell cavities in 40 cryomodules (6 cav./ module).

Booster: 96 1.3 GHz 9-cell cavities in 12 cryomodules (8 cav. / module).

50 MW Higgs upgrade: add 16 Collider modules.





CEPC Collider Ring SRF Parameters

Collider parameters: 20180330	H	W	Z
SR power / beam [MW]	30	30	16.5
RF voltage [GV]	2.17	0.47	0.1
Beam current / beam [mA]	17.4	87.7	460
Bunch charge [nC]	24	19.2	12.8
Bunch number / beam	242	1524	12000
Bunch length [mm]	3.26	5.9	8.5
Cavity number (650 MHz 2-cell)	**240**	2 x 108	2 x 60
Idle cavities on line / ring	0	12	60
Cavity gradient [MV/m]	**19.7**	9.5	3.6
Q_0 for long term operation	**1.5E10**	1.5E10	1.5E10
Input power / cavity [kW]	250	278	275
Klystron power [kW] (2 cavities / klystron)	800	800	800
HOM power / cavity [kW]	0.57	0.75	1.94
Optimal Q_L	1.5E6	3.2E5	4.7E4
Optimal detuning [kHz]	0.2	1.0	17.8

Optimized for the Higgs mode of 30 MW SR power per beam. Will add stand-by cavities (power source) for operating margin.

Cavity number determined by coupler power capacity, less is better for W and Z to reduce the detuning. 2-cell is a balance of gradient, beam loading and HOM power and damping.

Input coupler power limit: 300 kW

HOM power per cavity limit: 2 kW

Input coupler variable

CEPC Booster SRF Parameters

10 GeV injection	H	H (HC)	W	Z	Z (HC)
Extraction beam energy [GeV]	120		80	45.5	
Bunch number	242		1524	6000	
Bunch charge [nC]	0.72		0.576	0.384	
Beam current [mA]	**0.52**	**1**	2.63	**6.91**	**20**
Extraction RF voltage [GV]	1.97		0.585	0.287	
Extraction bunch length [mm]	2.7		2.4	1.3	
Cavity number in use (1.3 GHz TESLA 9-cell)	96	96	64	32	32
Gradient [MV/m]	19.8	19.8	8.8	8.6	8.6
Q_L (4E6-2E7)	1E7		6.5E6	**1E7**	**4E6**
Cavity bandwidth [Hz]	130		200	130	
Beam peak power / cavity [kW]	8.3	16	12.3	6.9	20
Input peak power / cavity [kW] (w/ detuning)	**15**	**22**	12.4	**7.1**	**20.1**
Input average power per cavity [kW] (w/ detuning)	0.7		0.3	0.5	
SSA peak power [kW] (one cavity per SSA)	25	25	25	25	25
HOM average power / cavity [W]	0.2	0.2	0.7	**4.1**	**12**
Q_0 @ 2 K at operating gradient (long term)	1E10		1E10	1E10	
Total average cavity wall loss @ 2 K eq. [kW]	0.2		0.01	0.02	

H (HC, high current) for on-axis injection.
Z (HC) for higher injection rate.

For HC Z, optimal detuning near or larger than revolution frequency, FM CBI

Variable range limit

Assume 15 Hz microphonics and remained Lorentz detuning

Z HOM DF: 34%
HOM coupler capacity ~ 20 W

CEPC Collider RF Challenges for Z

Challenging RF hardware and beam operation, but feasible [1-3]:

- HOM power up to 1 kW per coupler with safe fill patterns, within the technology reach [4-6].
- HOM CBI is OK with deeper TM011 mode damping (and large cavity frequency spread and fast bunch-by-bunch feedback), but critical. Better to have idle cavities off-line.
- FM CBI manageable by RF feedback [7]. Parking cavities FM CBI mitigate by symmetry detuning.
- Phase shift is moderate for small gaps [7].
- Multi-cavity HOM power propagation and CBI under investigation.

[1] J. Zhai. Workshop on the Circular Electron Positron Collider, Rome, May 25, 2018
[2] J. Zhai. eeFACT2018, Hongkong, Sept 26, 2018
[3] J. Zhai, et al. International Journal of Modern Physics A: to be published.
[4] H. Zheng, et al. CEPC HOM coupler R&D. CEPC workshop, November 2018.
[5] D. Gong, et al. International Journal of Modern Physics A: to be published.
[6] D. Gong, et al. HOM power loss in CEPC Collider ring cavity. CEPC workshop, November 2018.
[7] D. Gong, et al. Radiation Detection Technology and Methods (2018) 2:17

Outline

- CDR design of CEPC SCRF system
- SCRF TDR plan and R&D status
- Summary

TDR Plan of CEPC SRF System

Time	TDR R&D Plan	Resources (in CNY)
2018-2020	• System Design and Optimization • Key Technology R&D • 650 MHz Test Cryomodule • High Q, high gradient, new material	• MOST CEPC 7 M (650 MHz, IHEP & PKU) • PAPS 15 M (650 MHz & 1.3 GHz) • SHINE R&D 13 M (1.3 GHz cavity and coupler) • New material research fund 12 M (2018-2022) • 4 FTEs now, 2 more FTEs needed
2020-2022	• Engineering Design • Full Cryomodule Prototyping • High Q, high gradient, new material	• 80 M (one 650 MHz & one 1.3 GHz module with power sources) • SHINE pre- and mass production ? M (1.3 GHz) • New material research fund 12 M (2018-2022) • 12 FTEs
2022-2023	• Industrialization and Pre-production • Cryomodule Beam Test	• 90 M (three 650 MHz modules + two 1.3 GHz modules) • SHINE mass production ? M (1.3 GHz) • 18 FTEs

CEPC SRF Technological Uncertainties

Uncertainty	Impact	Mitigation Method
High Q operation (long term)	Cryogenic capacity, Field emission	Practical Q target, Moderate gradient, Clean (tunnel) assembly
Power coupler (variable)	Window event or failure, RF trip	Limit coupler power, Stand-by cavities, Fast closing valves between modules
HOM coupler and bellow	RF heating, cable heating, bellow heating	High power test at 2 K Special designed rigid coaxial line Class 10, RF shielded bellow at 2 K
LLRF (hardware in RF power source system)	FM CBI, Parking cavities for W & Z, Booster RF ramp	Direct RF feedback, symmetry detuning, Booster cavity para-phase ramp

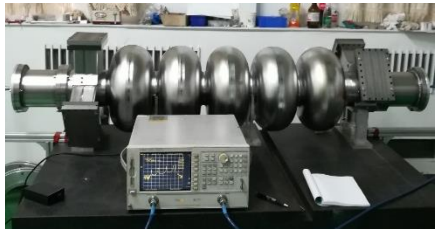
CEPC SRF Hardware Specifications

Hardware	Qualification	Normal Operation	Max. Operation
650 MHz 2-cell Cavity	VT 4E10 @ 22 MV/m HT 2E10 @ 20 MV/m	1.5E10 @ 20 MV/m	2E10 @ 20 MV/m
1.3 GHz 9-cell Cavity	VT 3E10 @ 24 MV/m	1E10 @ 20 MV/m	2E10 @ 23 MV/m
650 MHz Input Coupler (variable)	HPT 300 kW sw	< 280 kW	300 kW
1.3 GHz Input Coupler (variable)	HPT 20 kW peak, 4 kW avr.	< 20 kW peak	20 kW peak
650 MHz HOM Coupler	High power test at RT and 2 K: 1 kW	< 1 kW	1 kW
650 MHz HOM Absorber	High power test at RT: 5 kW	< 5 kW	5 kW
650 MHz Cryomodule (six 2-cell cavities)	static loss 5 W @ 2 K	static loss 8 W @ 2 K	static loss 10 W @ 2 K
Tuner (Collider & Booster)	tuning range and resolution 400 kHz / 1 Hz	300 kHz / 1 Hz	400 kHz / 1 Hz

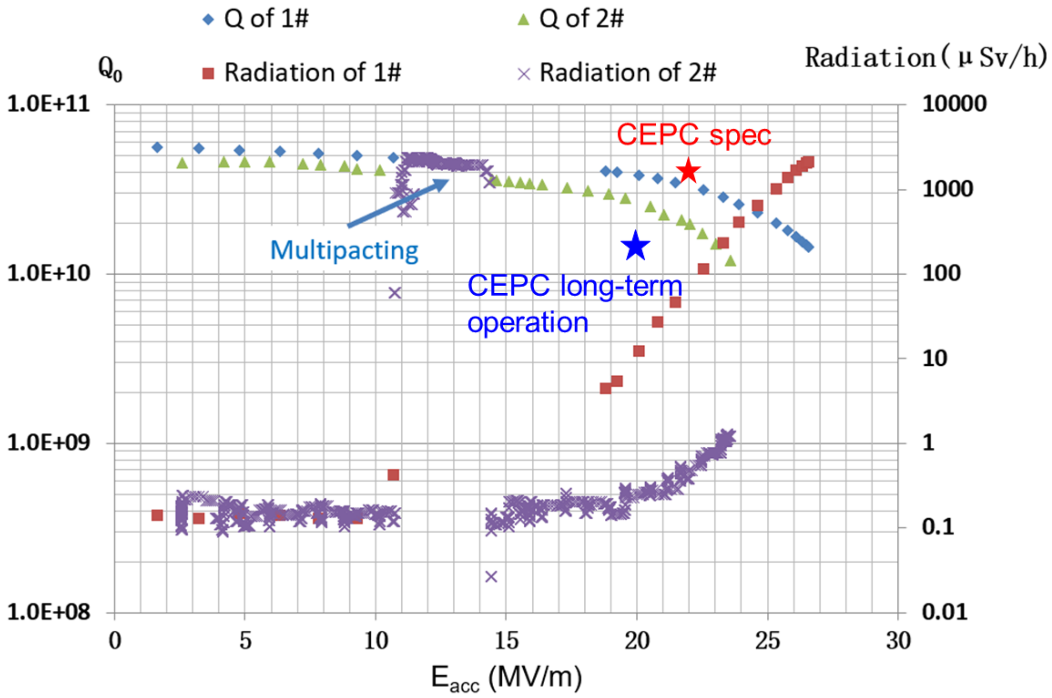
CEPC SRF Technology R&D Status

CEPC 650 MHz **2-cell cavity** by OTIC

CEPC 650 MHz **2-cell cavity** by HERT



CEPC 650 MHz **5-cell cavity** with waveguide HOM coupler by HERT

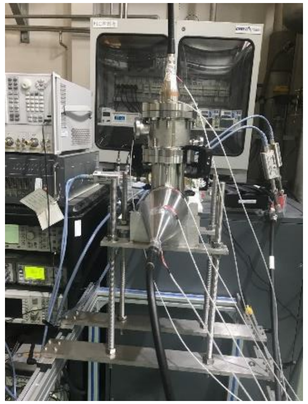


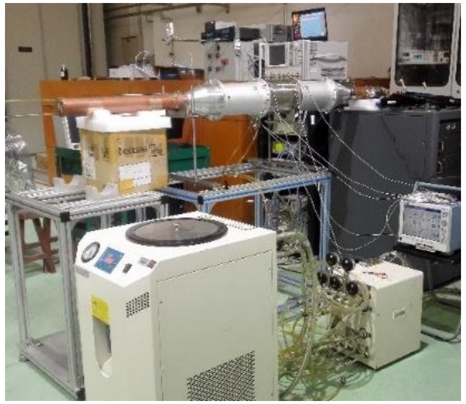
- 650 MHz 2-cell cavity (BCP without Nitrogen-doping) reached 3.2E10 @ 22 MV/m (**nearly reached CEPC collider cavity vertical test spec 4E10 @ 22 MV/m**)
- Nitrogen-doping and EP on 650 MHz cavity under investigation.
- EP facility under commissioning.

CEPC SRF Technology R&D Status

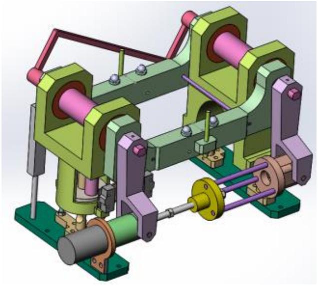
CEPC Collider HOM coupler (1 kW CW) by OTIC and HD

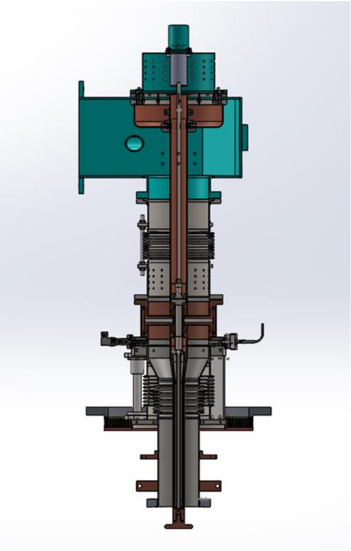
CEPC HOM absorber of SiC & AlN (5 kW CW)



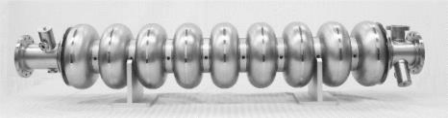


High power test of HOM coupler (left) and absorber (right) at room temperature. Up to 100 W transmitted power through the HOM coupler and 1 kW RF power absorbed by the HOM absorber.

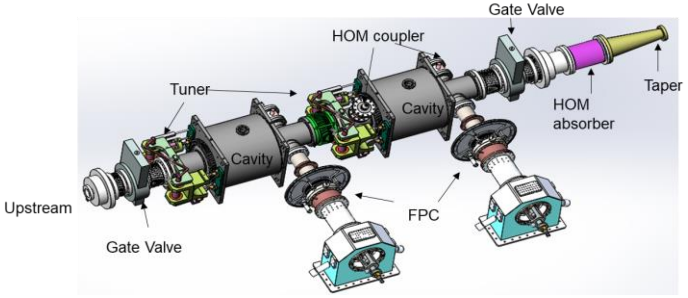


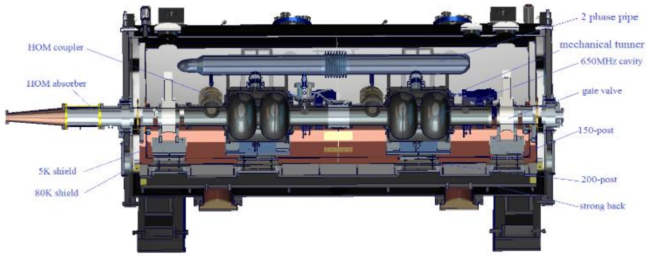


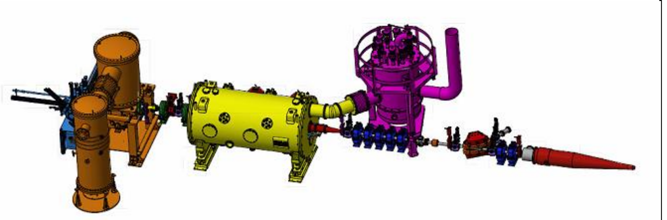
Tuner and input coupler (variable 300 kW CW) for CEPC 650 MHz cavity in fabrication



CEPC Booster 1.3 GHz TESLA 9-cell cavity mass production and variable double window coupler by HERT

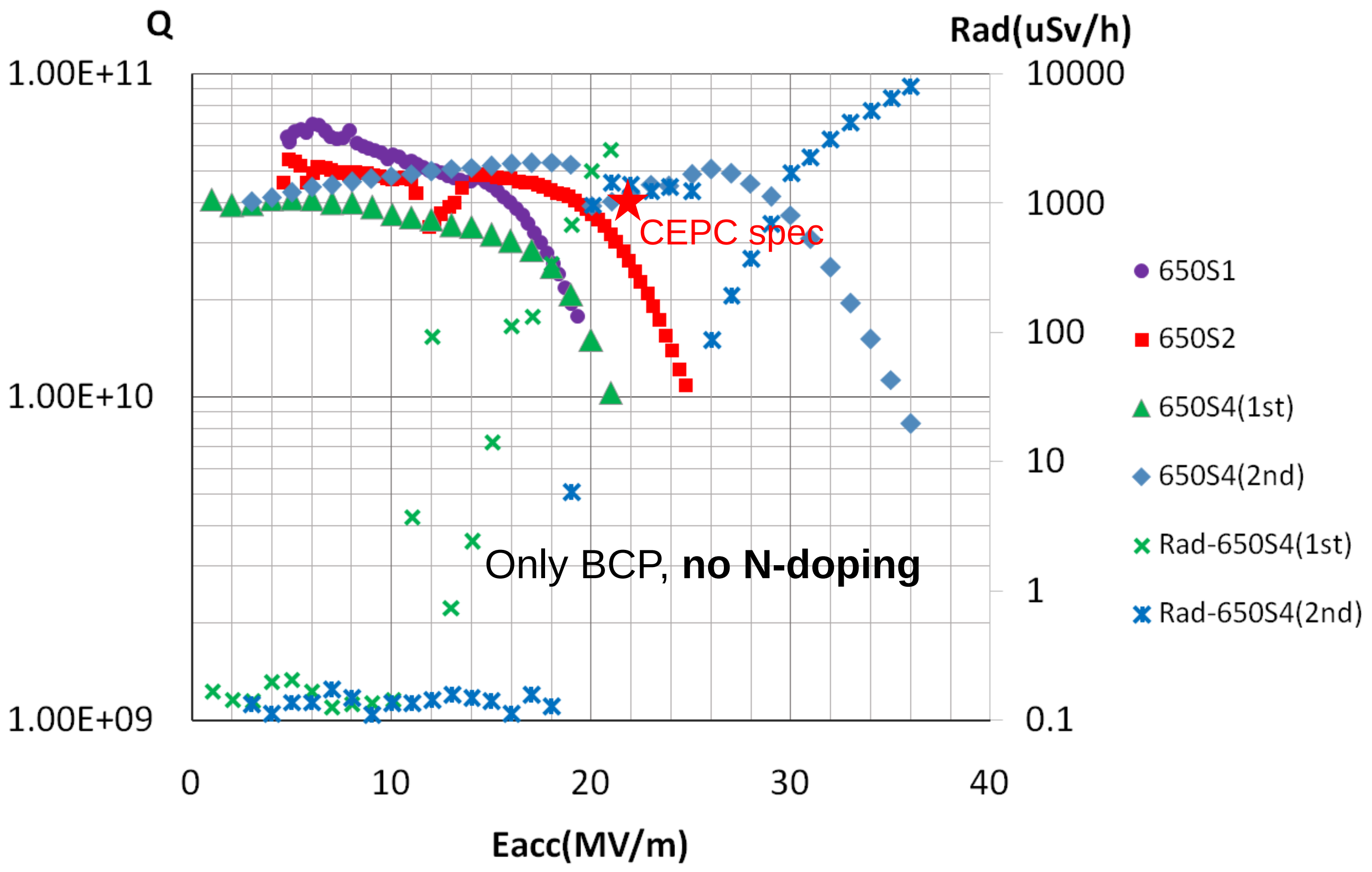






CEPC Collider Test Cryomodule with two 650 MHz 2-cell cavities and 10 mA CW beam.

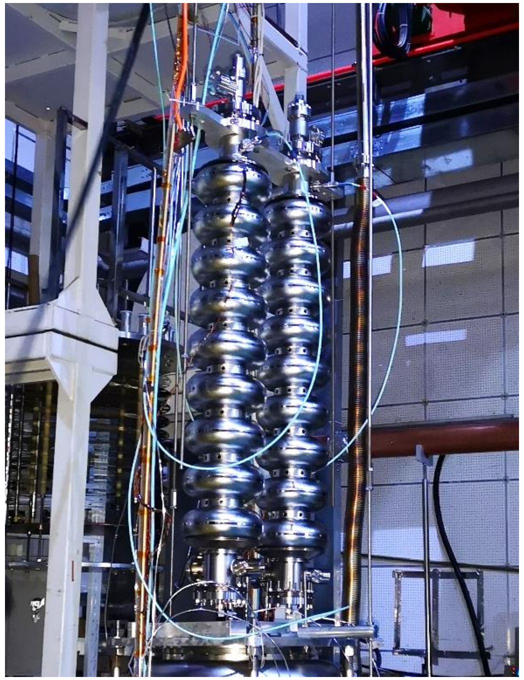
Vertical test of CEPC 650 MHz 1-cell Cavity

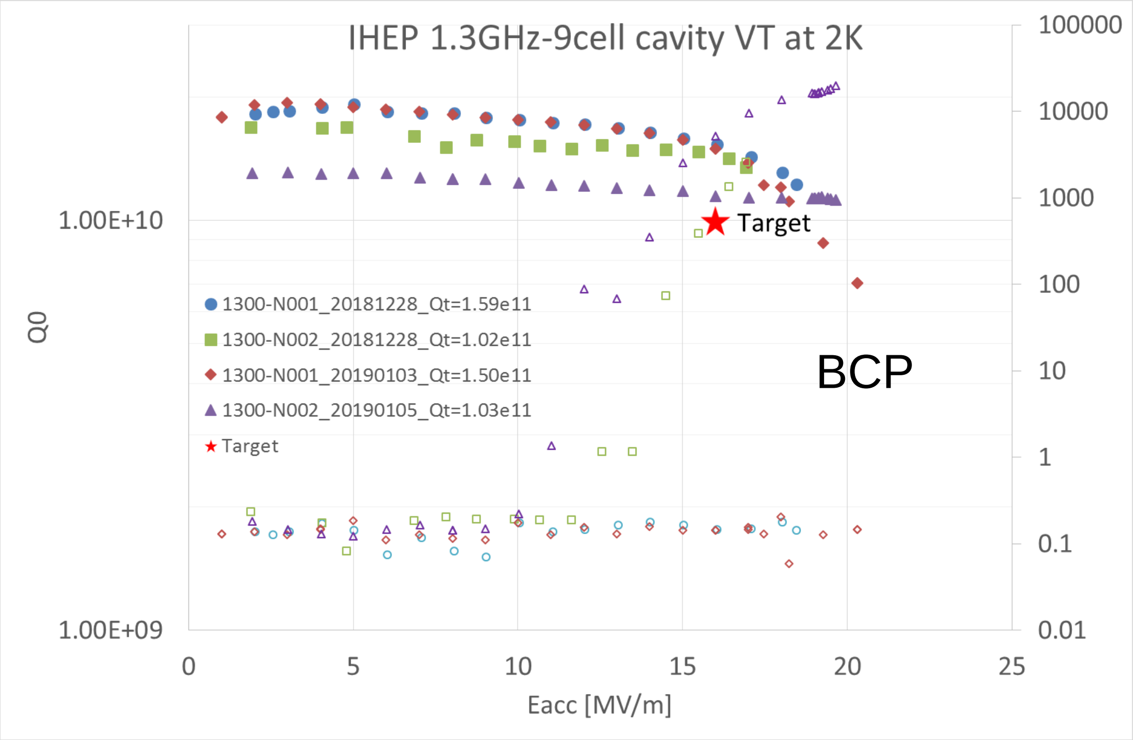


Vertical test result: Q_0 = 5.1E10 @ 26.0 MV/m (max 36 MV/m, field emission and RF power limited), exceed the CEPC VT spec (Q_0 = 4.0E10 @ 22.0 MV/m).

1.3 GHz TESLA 9-cell Cavities

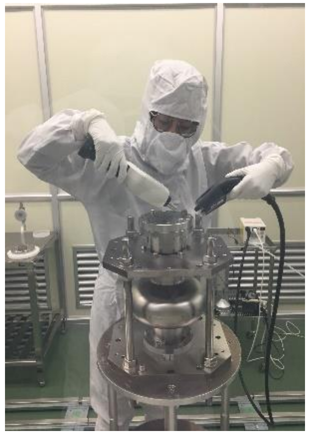
- Prepare for mass production (SHINE project ~ 600 cavities)
- 10 (2+8) prototype cavities in fabrication at IHEP (BCP → EP → N-dope)
- 8 cavities dressing this year and install to cryomodule next year

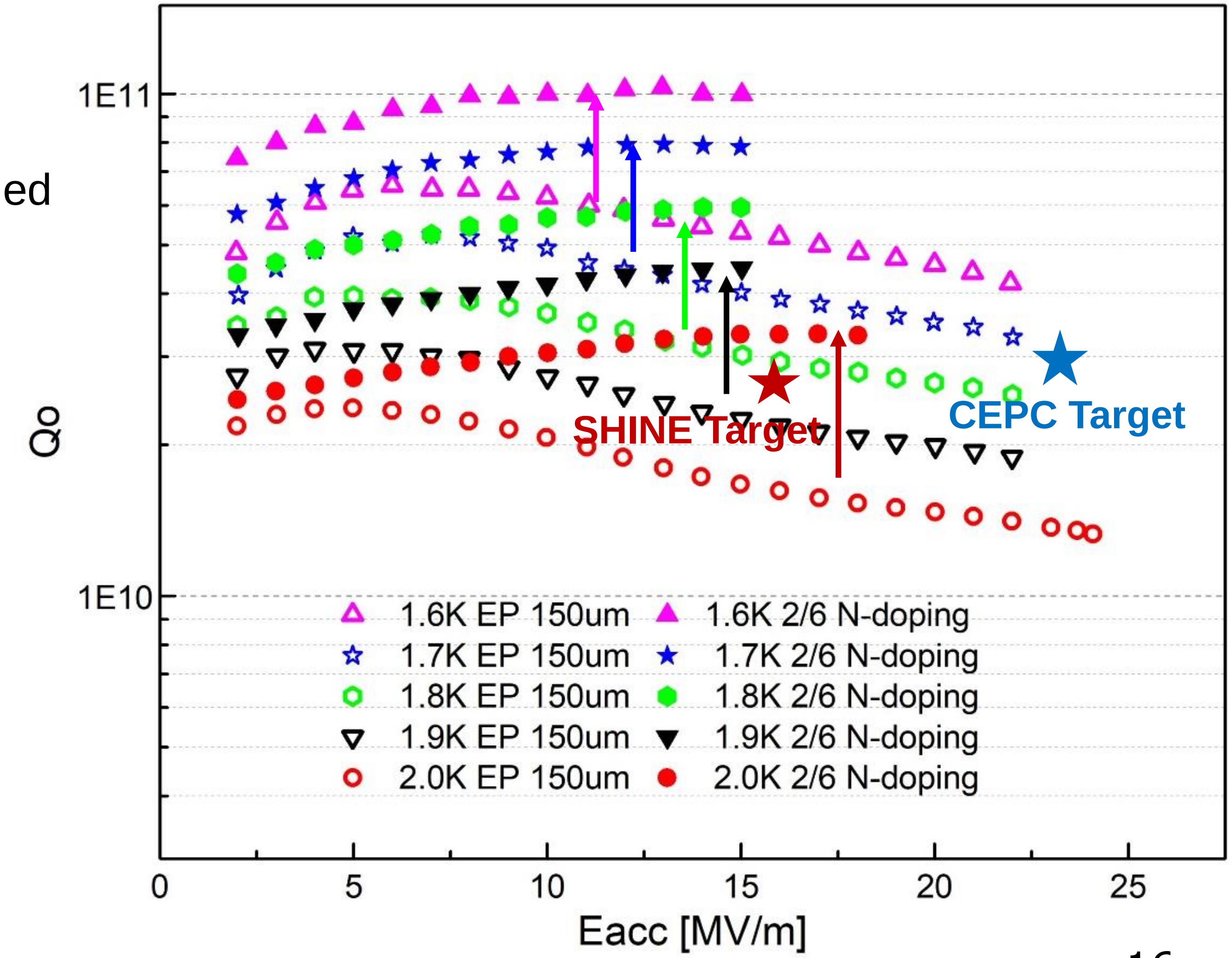




N-doping of 1.3 GHz 1-cell Cavity

- After N-doping, a 1.3 GHz 1-cell cavity reached 3.3E10 @ 18 MV/m, twice of baseline Q_0.
- Processing and vertical test at KEK.



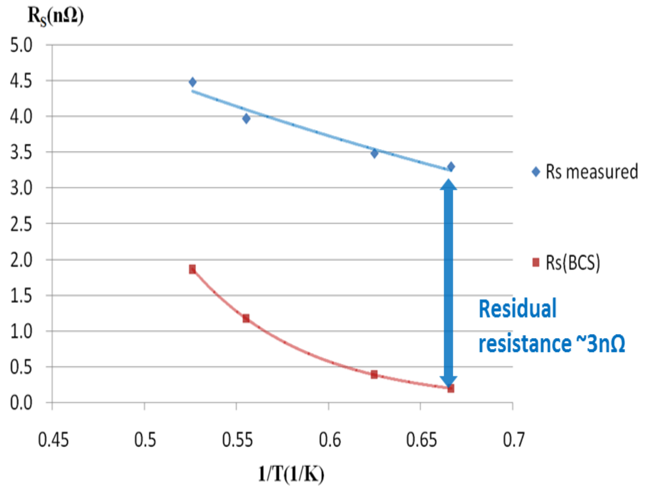


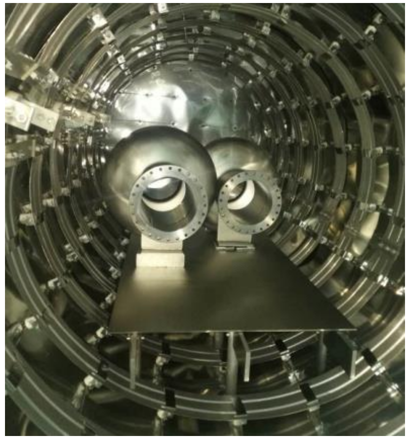
N-doping of 650 MHz 1-cell Cavity

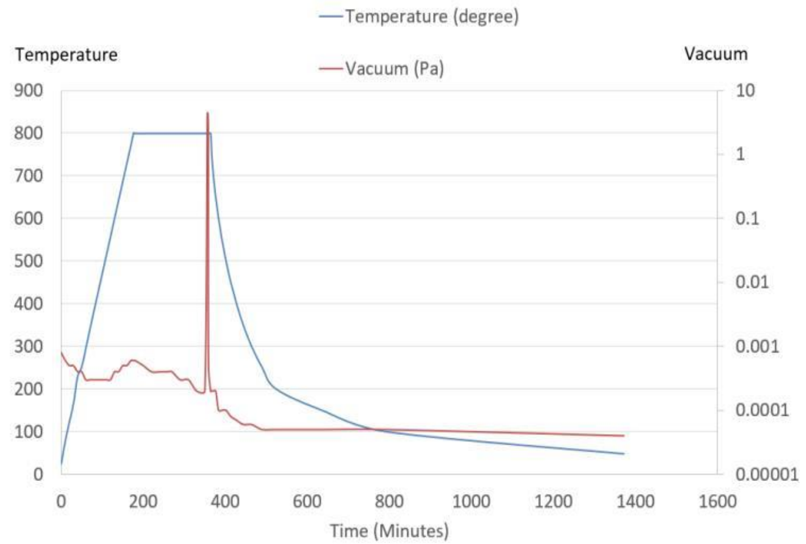
After N-doping of two 650 MHz single cell cavities, Q_0 increased obviously at low field for both cavities.

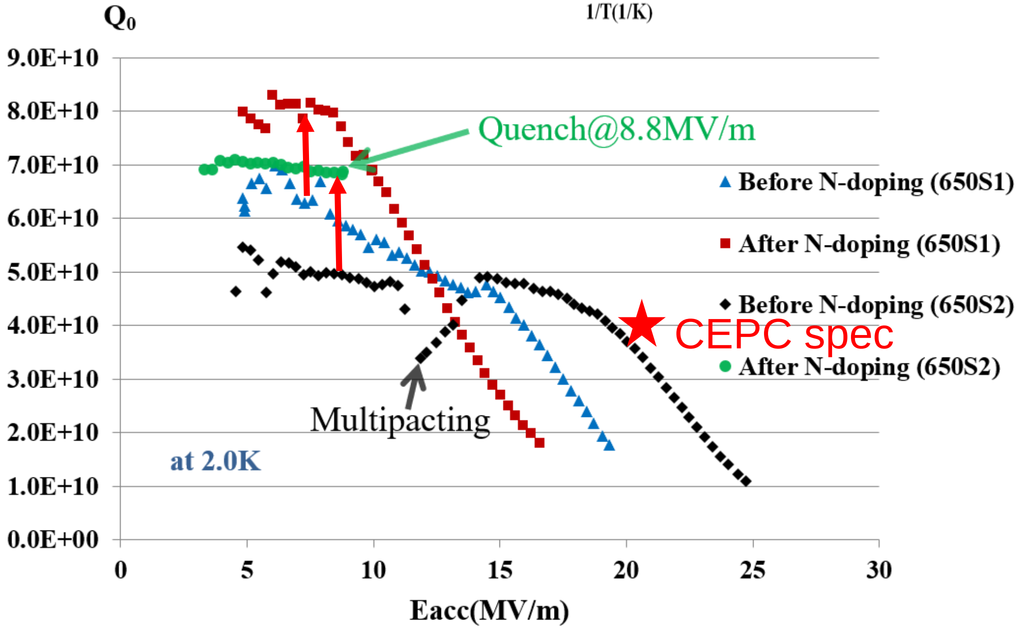
- 650S1: Q_0=7e10 @ Eacc=10 MV/m. But Q_0 decreased quickly at high field (>10 MV/m).
- 650S2: Quench at Q_0=6.9e10 @ Eacc=8.8 MV/m.

Flux gate and Helmholtz coil for demagnetization. EP facility necessary for the treatment.







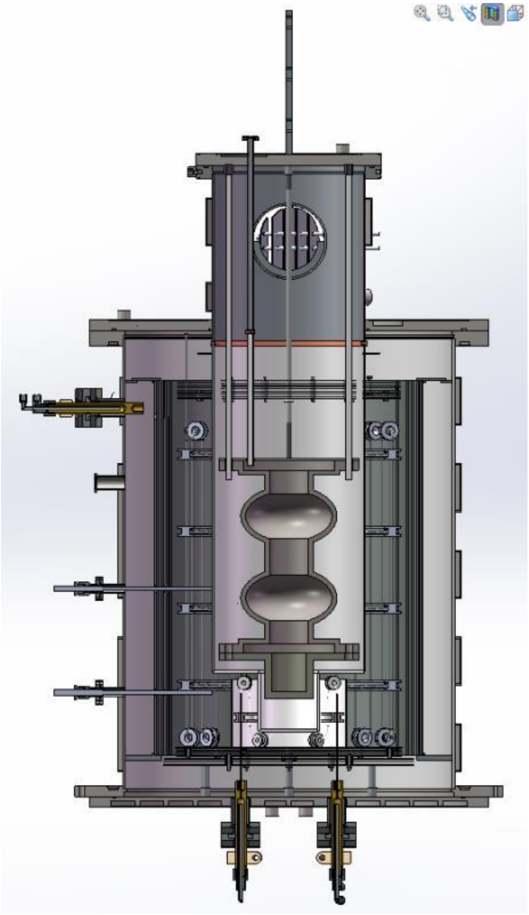


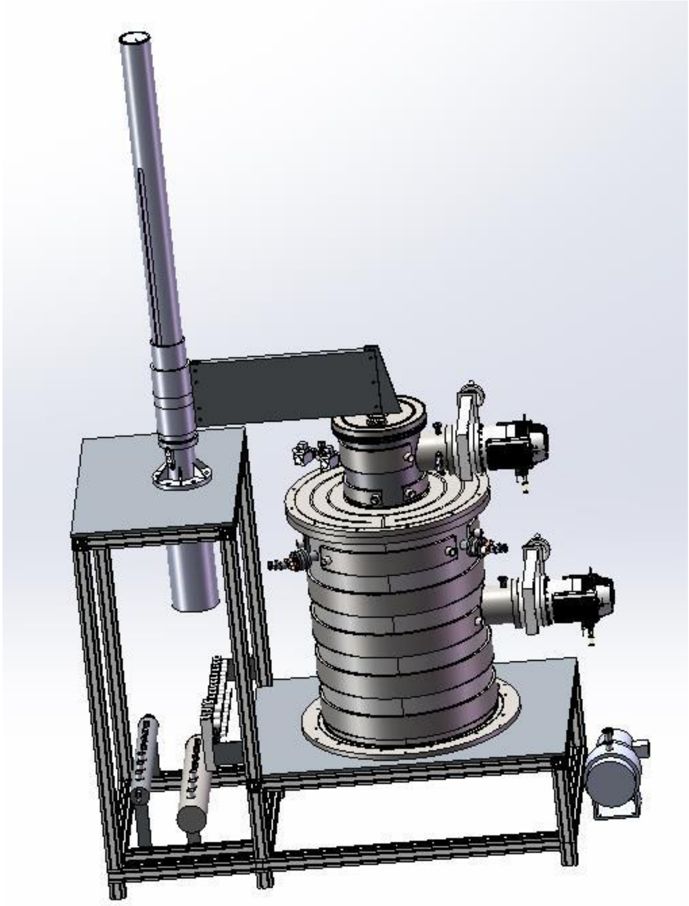
New N-doping Furnaces

Big furnace under commissioning

Small furnace for N-doping / N-infusion of 1.3 GHz 1-cavity

New Nb_3Sn Furnace



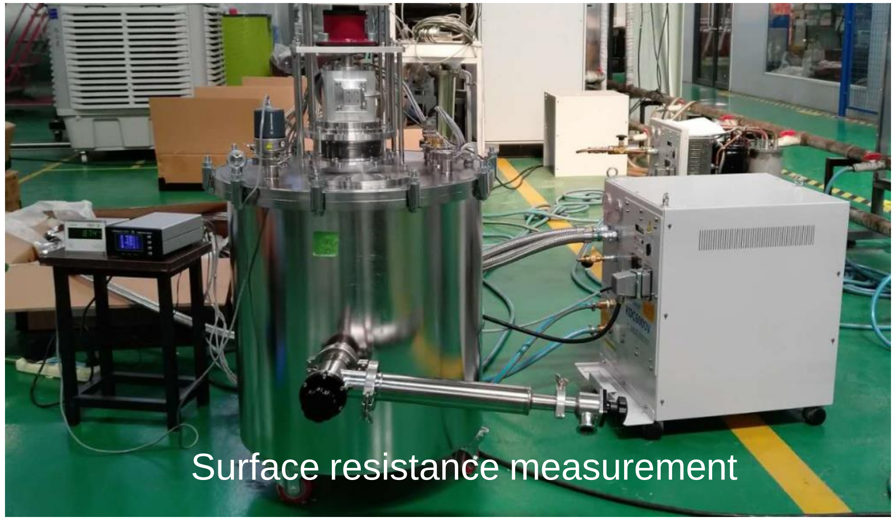


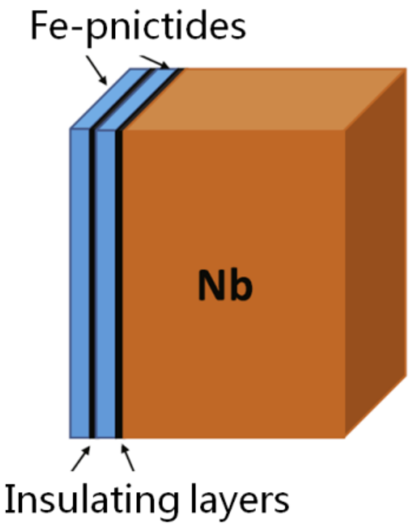
Nb_3Sn furnace under fabrication

Iron-based Superconductor

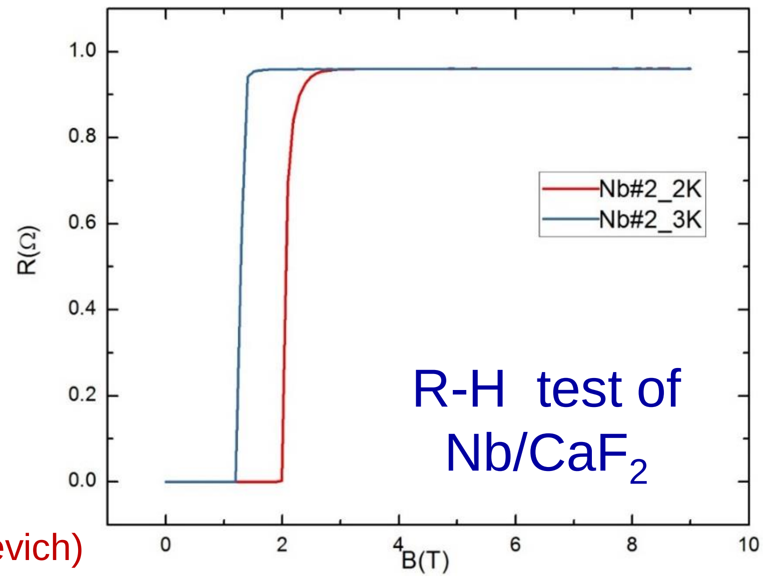
Iron-based Superconductor

- high Tc
- much higher gradient (200 MV/m in theory) than Nb (50 MV/m)

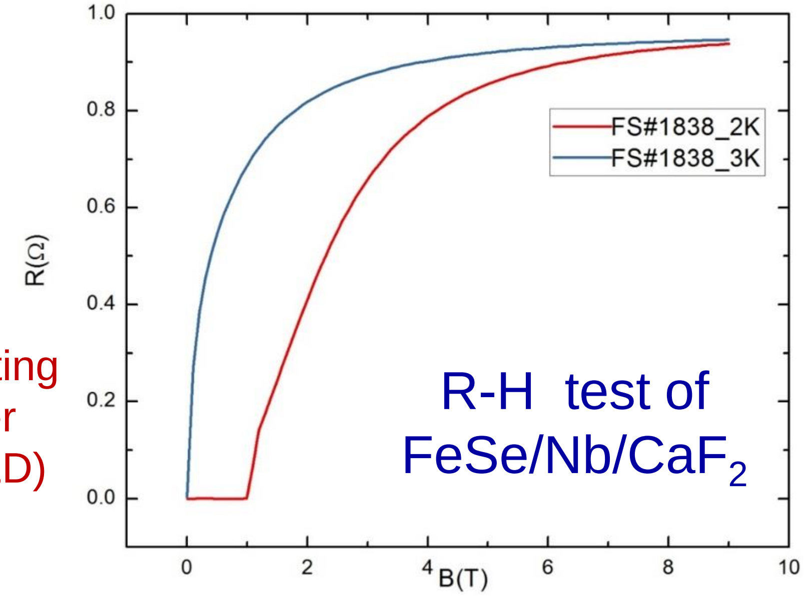




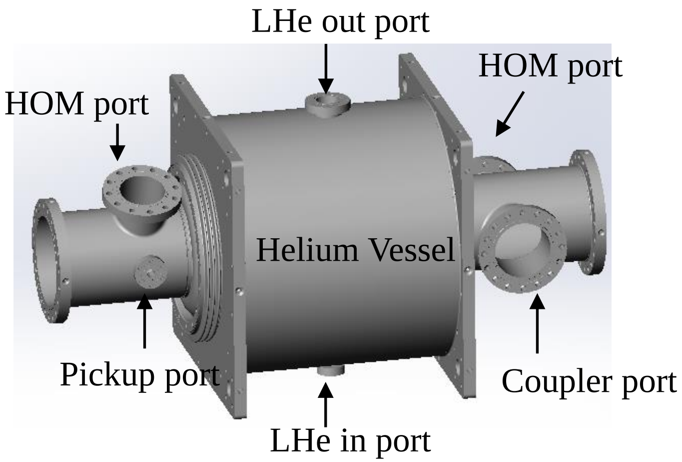
Theoretical Model (by Alex Gurevich)



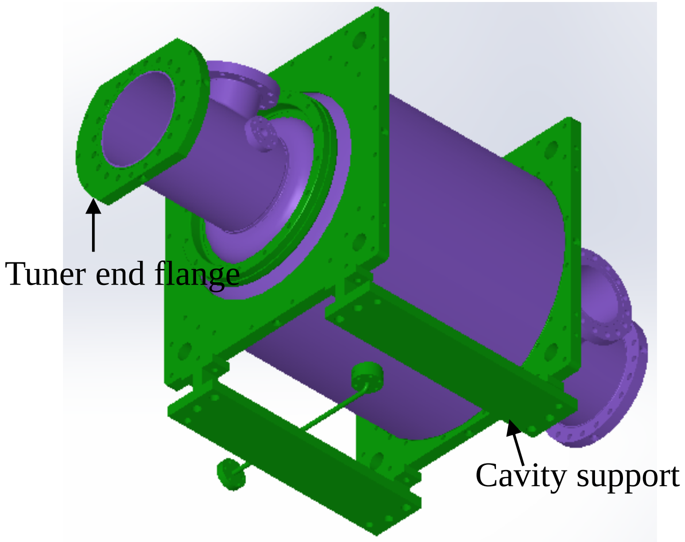
FeSe film coating by pulsed laser deposition (PLD)

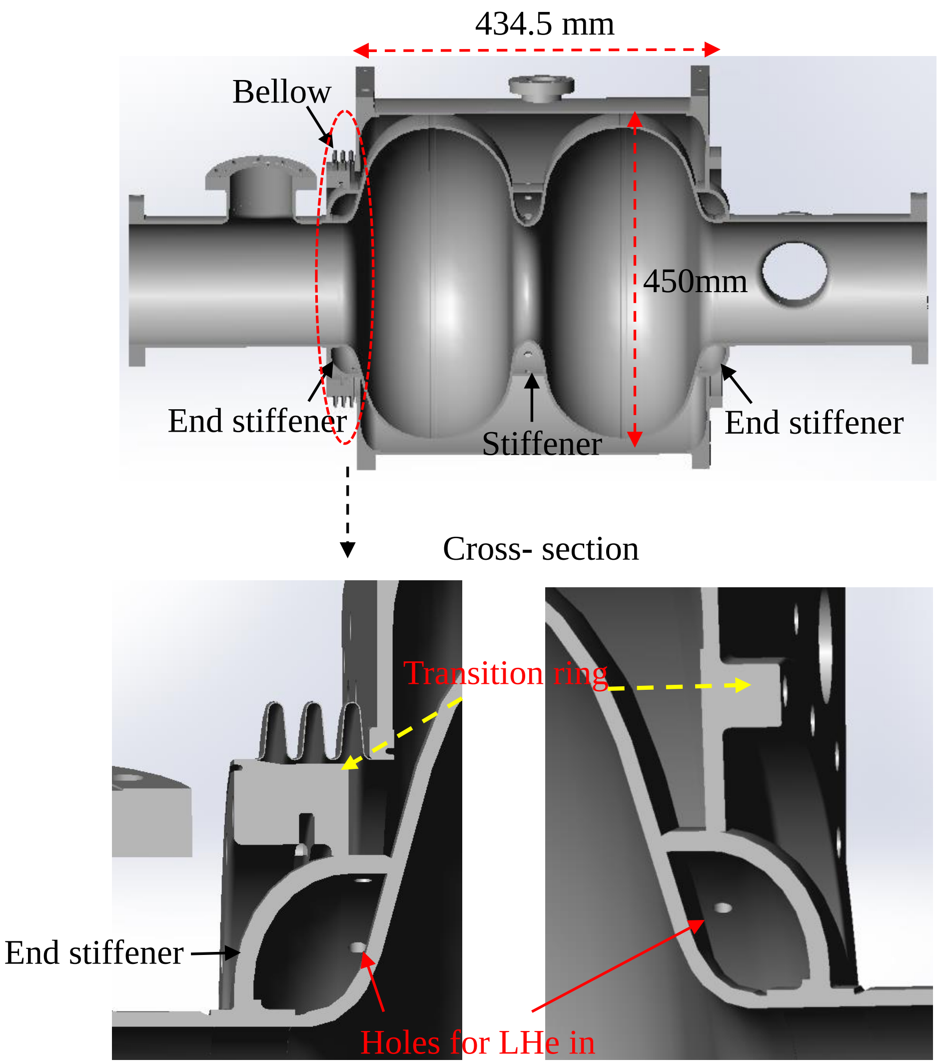


Helium Vessel

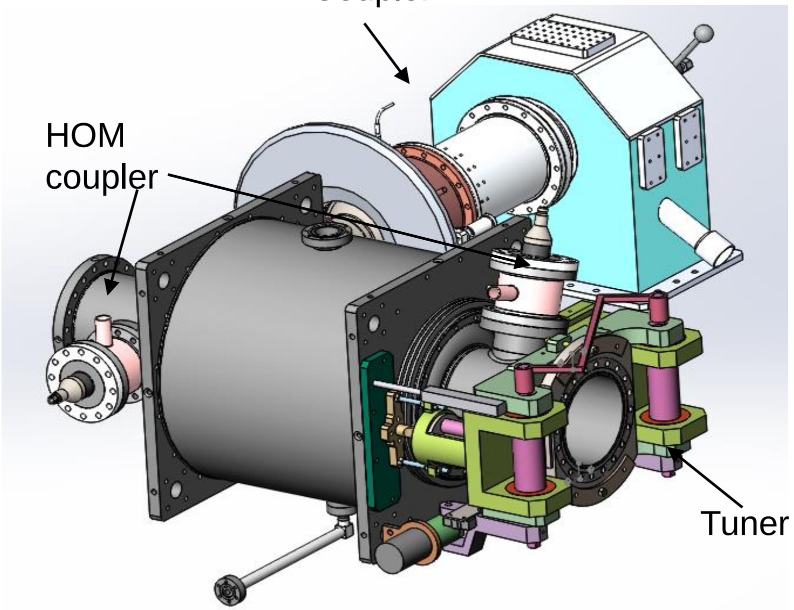


650 MHz 2-cell cavity + Helium Vessel 3D module





Tuners for 650 MHz Cavity

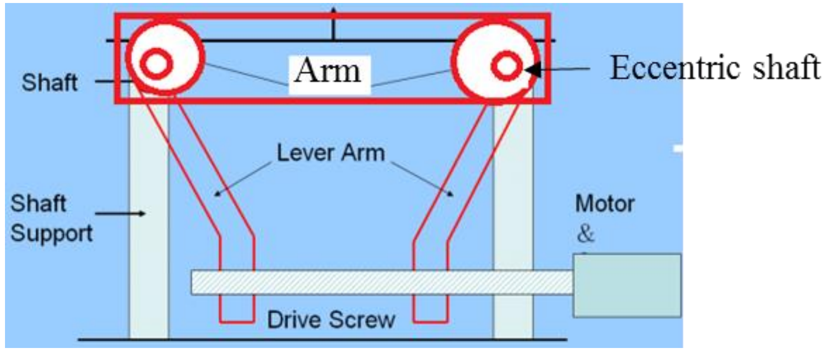


Cavity + Coupler + HOM Coupler + Tuner

- Space tight due to the HOM coupler
- Improved from Saclay type tuner
- Cavity will be stretched

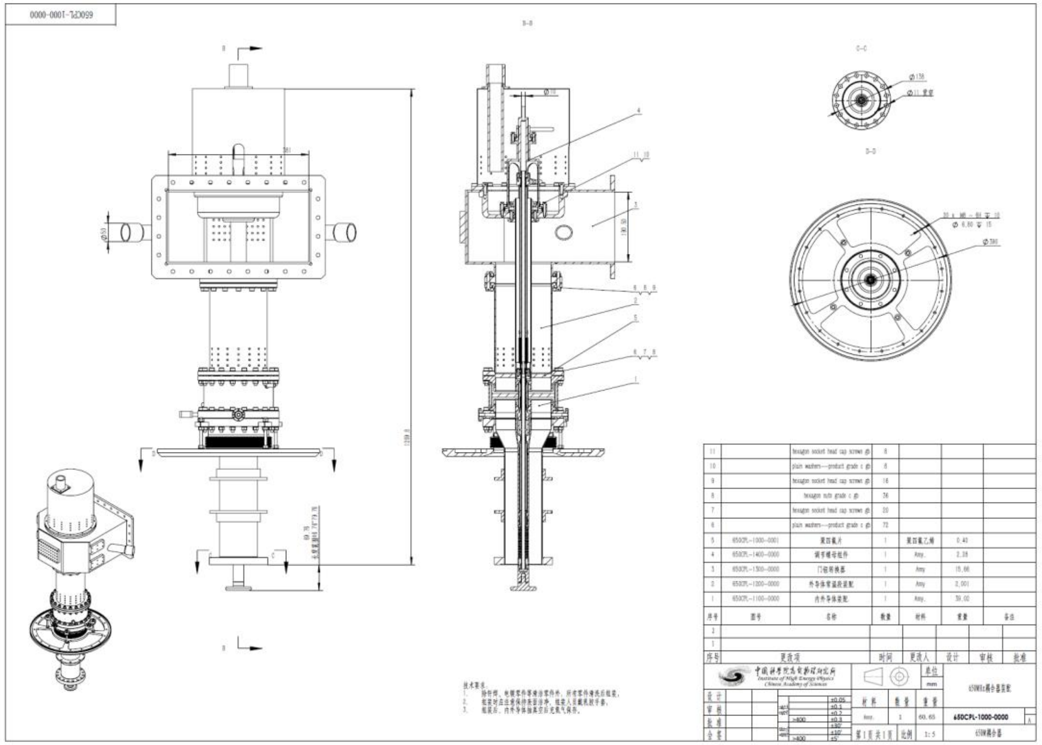
Main parameters of tuner

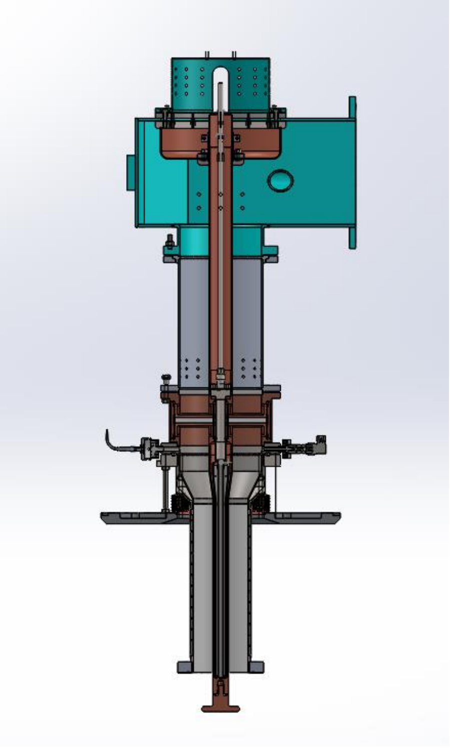
Parameters	Unit	Collider tuners
Tuning sensitivity	kHz / mm	310
Spring Constant	kN / mm	16
Operating Pressure	Torr	＜5E-5
Operating lifetime	Year	20
Coarse (slow) tuner frequency range	kHz	340
Coarse tuner frequency resolution	Hz	＜ 20
Fine (fast) tuner frequency range	kHz	＞ 1.5
Fine tuner frequency resolution	Hz	3
Motor and Piezo temperature	K	5~10
Motor number		1
Piezo number		2

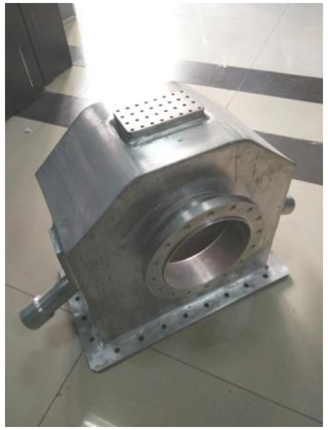


650 MHz Input Coupler (fixed and variable)

- Prototype of the fixed coupler in fabrication.
- Engineering design of the variable coupler (two bellows on inner conductor) completed.

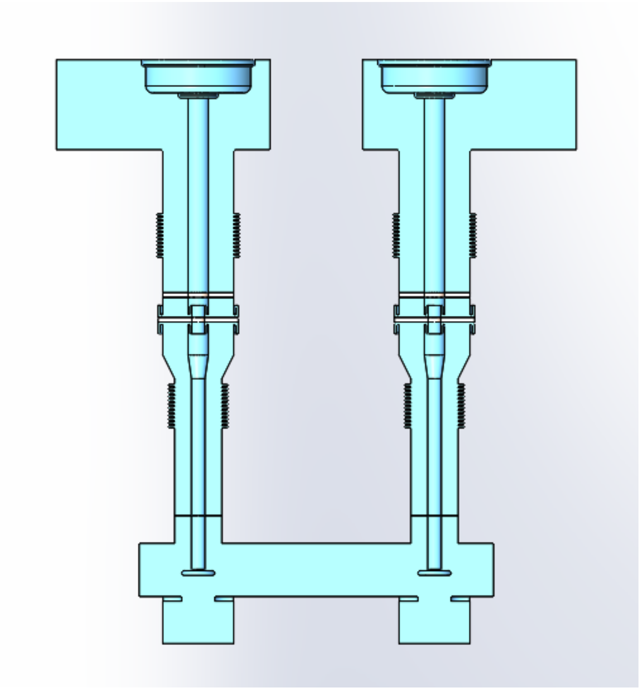


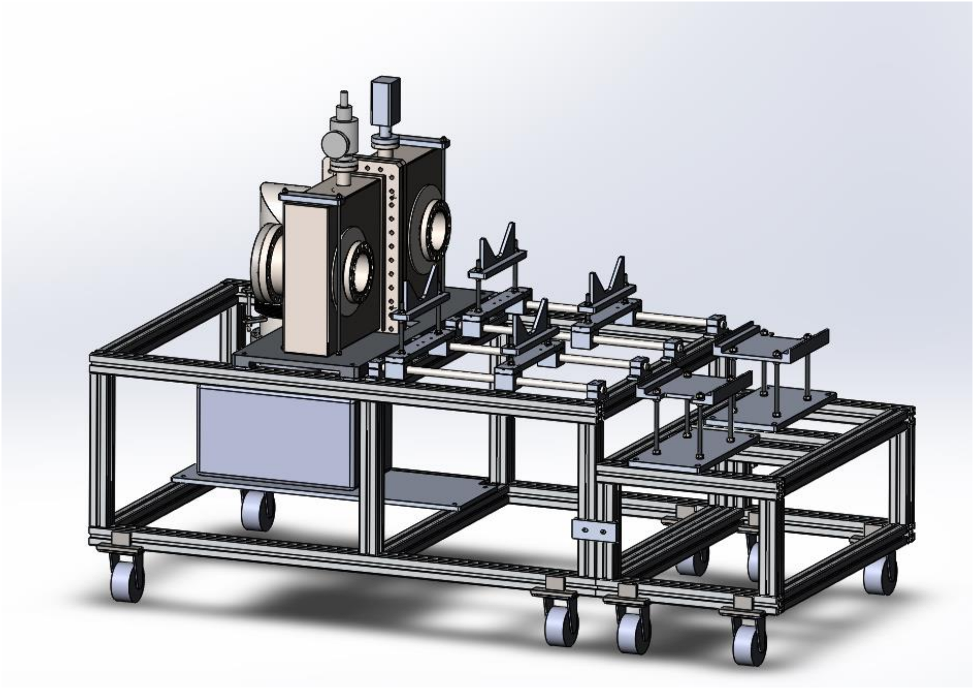


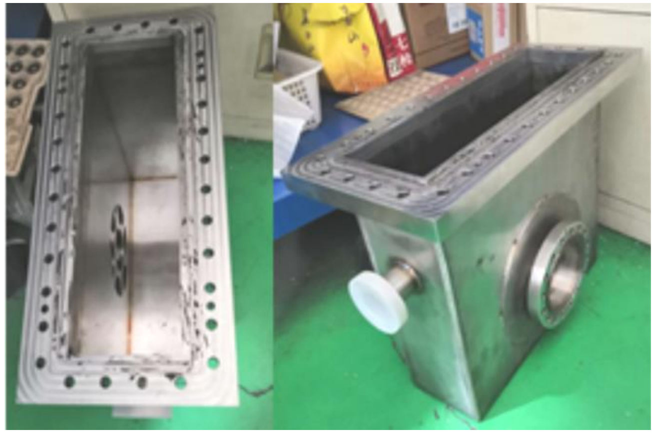


650 MHz Coupler Test Stand

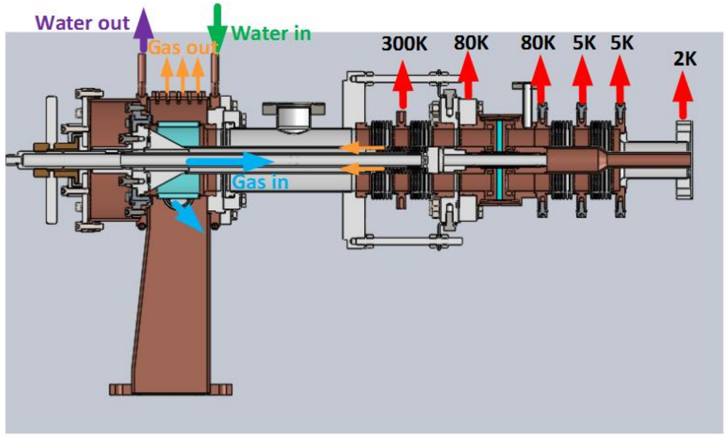
650 MHz coupler test stand in fabrication



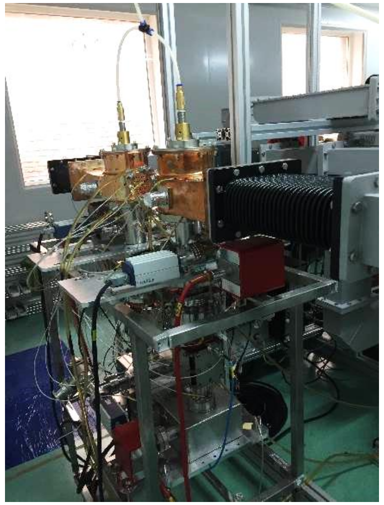




1.3 GHz Variable Coupler with Double Window

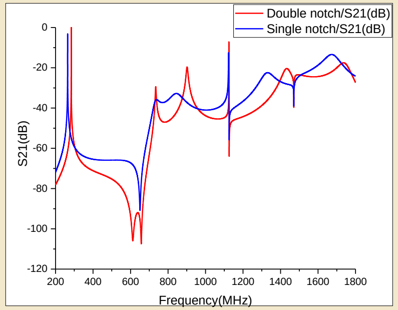


- Design for 70 kW CW power. Can be used for CEPC booster cavity (< 20 kW peak).
- High power conditioning in a resonance ring (up to 10 times of the 8 kW SSA power). Forward CW power 30 kW for 1 hour. Max power above 50 kW.

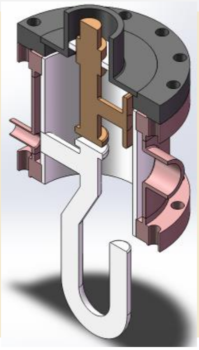


HOM Coupler for 650 MHz Cavity

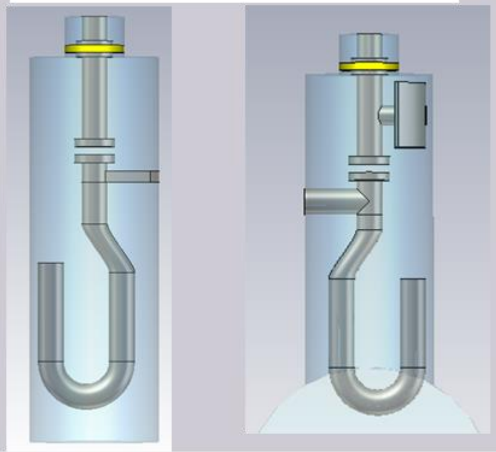
RF design



Mechanical designs



Design approach for HOM coupler



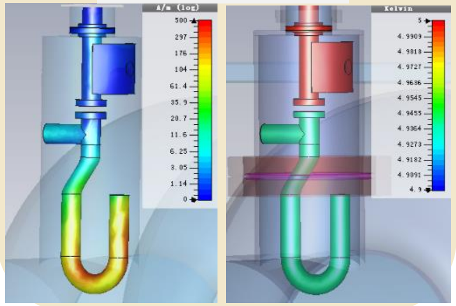
Single notch coupler

double notch coupler

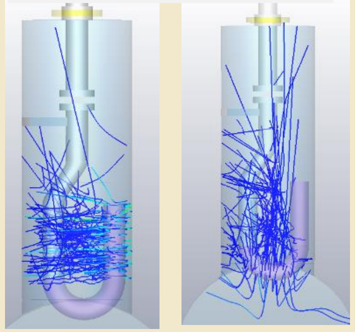
> 1 kW power

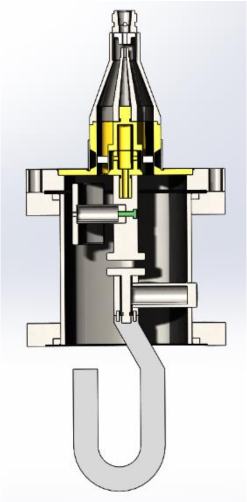
2 kW power per cavity, each direction 1 kW, assume 50 % coupled by the HOM coupler (0.5 kW). 1 kW power capacity will have enough margin.

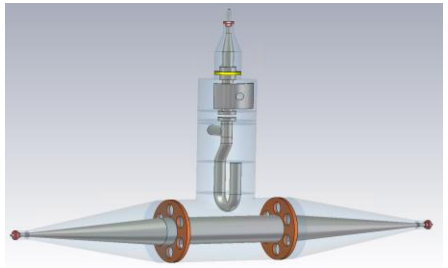
Thermal Design

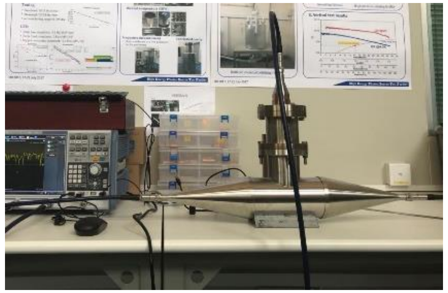


Multipacting analysis

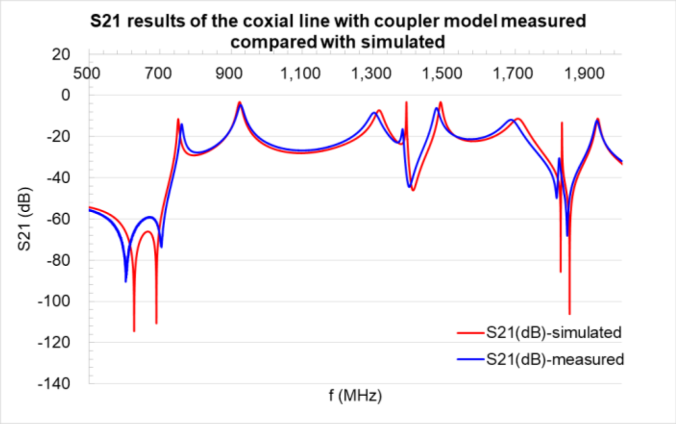








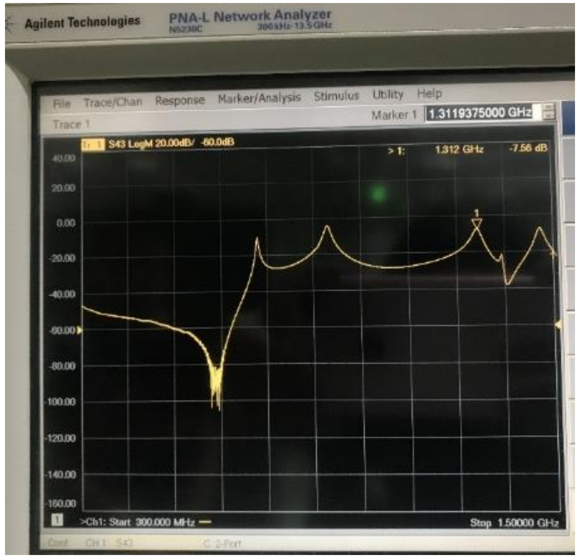
SS model

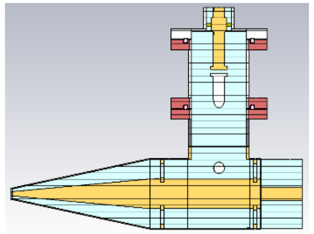


HOM Coupler High Power Test

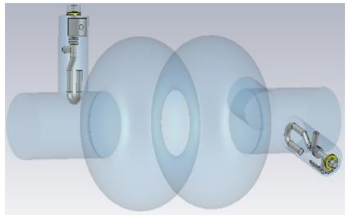
- Condition: room temperature
- Power source: 1.3 GHz 3 kW
- Test results: input power 639 W, pick up power from HOM coupler port 104 W, temperature near pick up port 34.3°C.
- 1 kW room temperature and 2 K test (VT with cavity and in horizontal test stand) planned.

Nb prototype



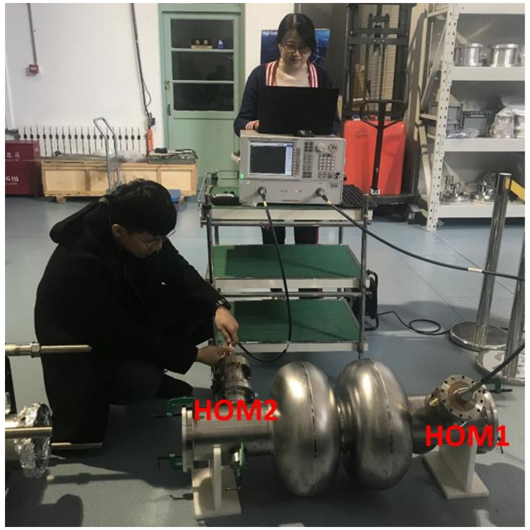


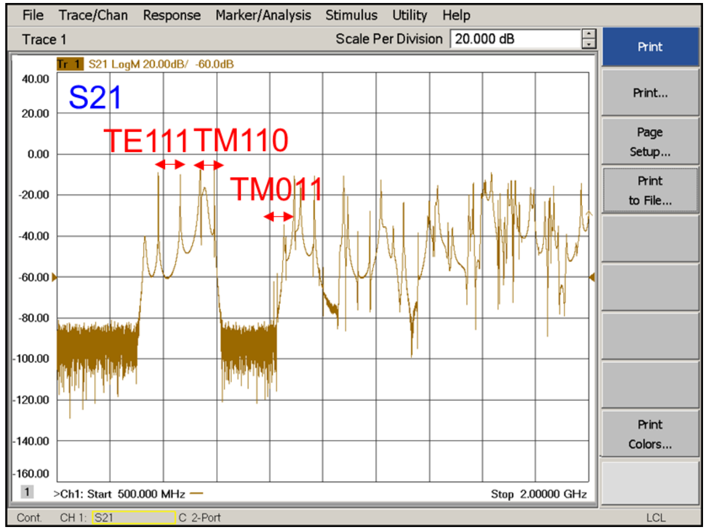
End plate match at RT

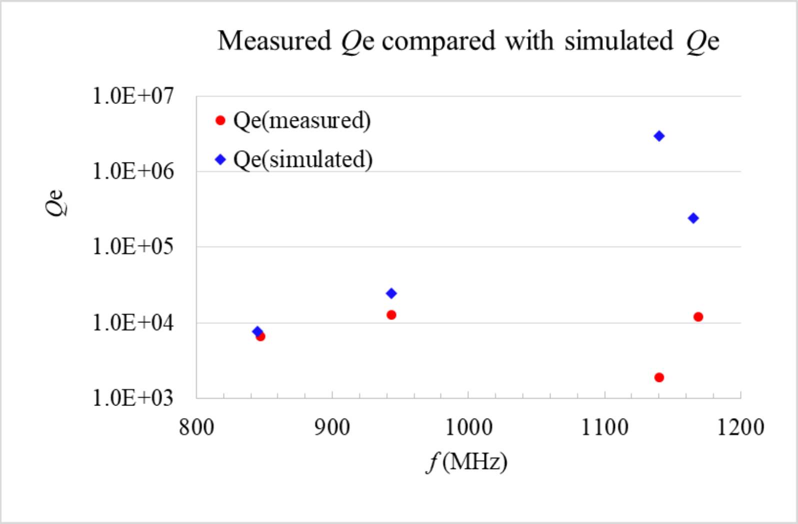


On and off-resonance excitation at 2 K

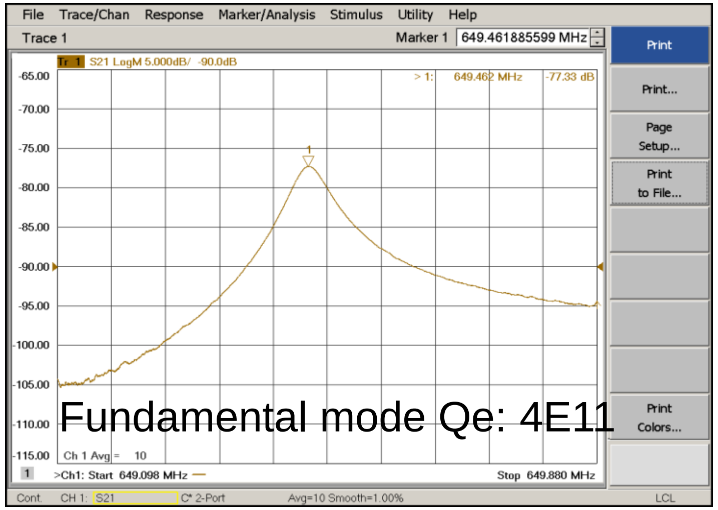
Qe Measurement on Cavity



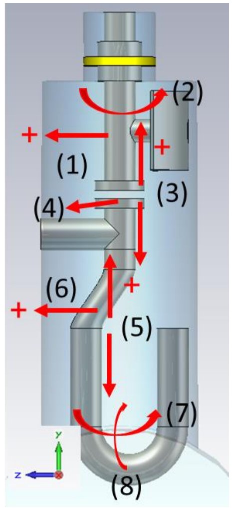


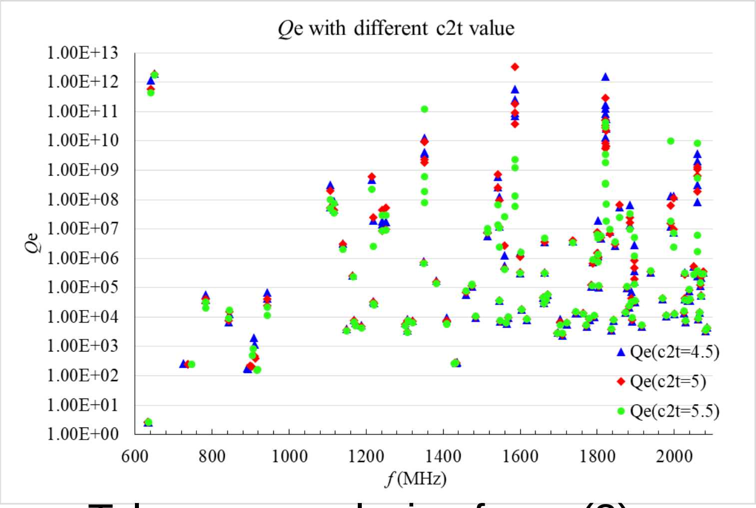


HOM couplers are used for HOM power input and output.



Fundamental mode Qe: 4E11

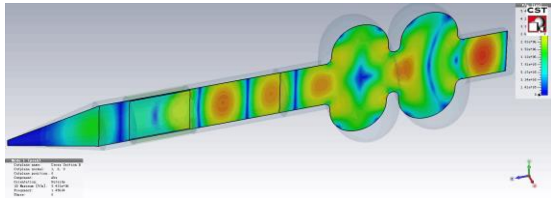




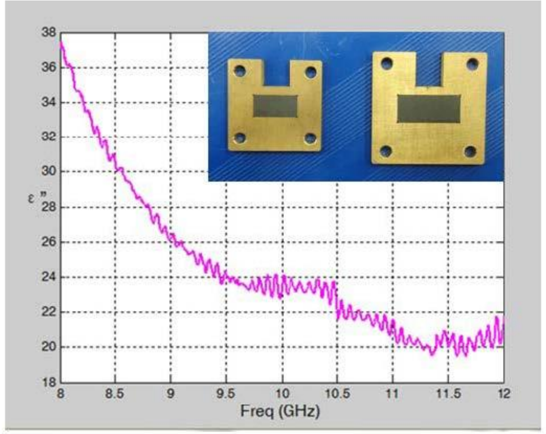
Tolerance analysis of gap (3)

HOM Absorber for 650 MHz Cavity

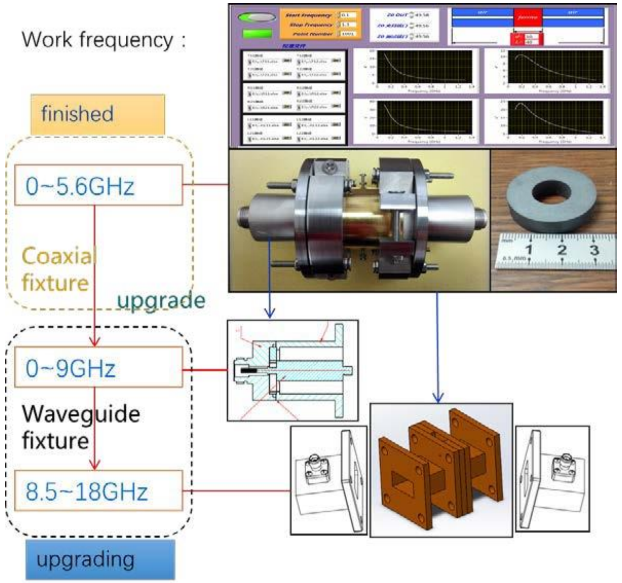
Due to short bunch length thus wide HOM frequency range, **SiC+AlN** composite is chosen for cavity HOM absorbing material.



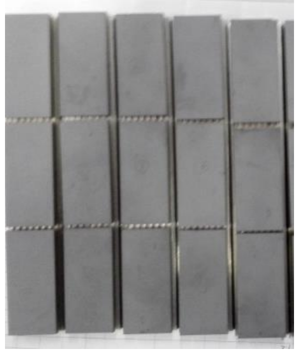
Beam-pipe HOM absorber at room temperature outside the cryomodule

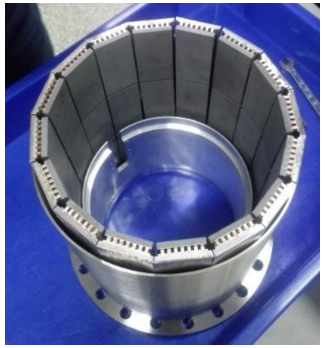


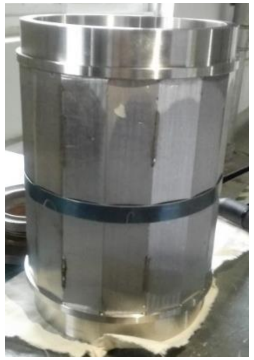
Measured permittivity of SiC+AlN composite (for broadband microwave absorbing)

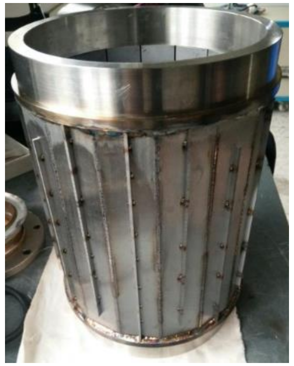


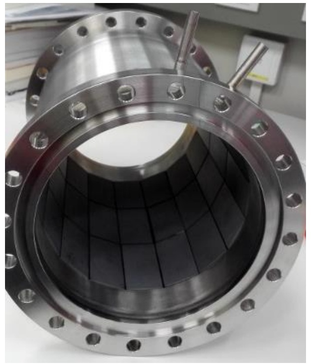
Microwave absorbing material test system



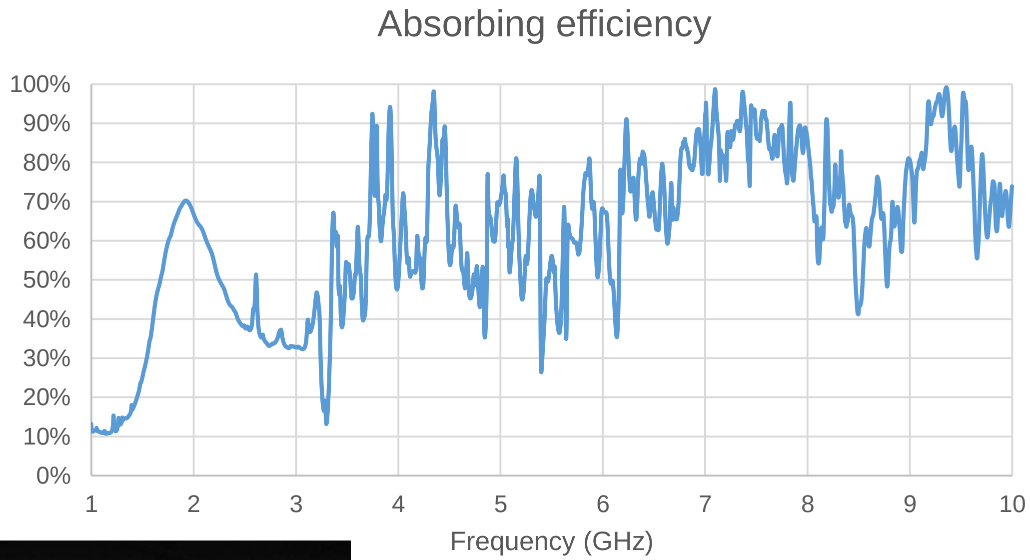


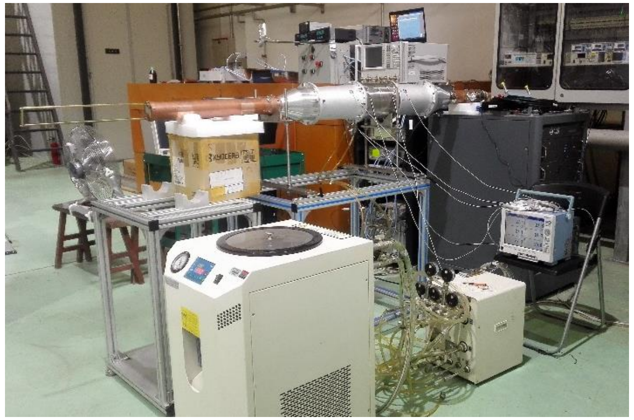






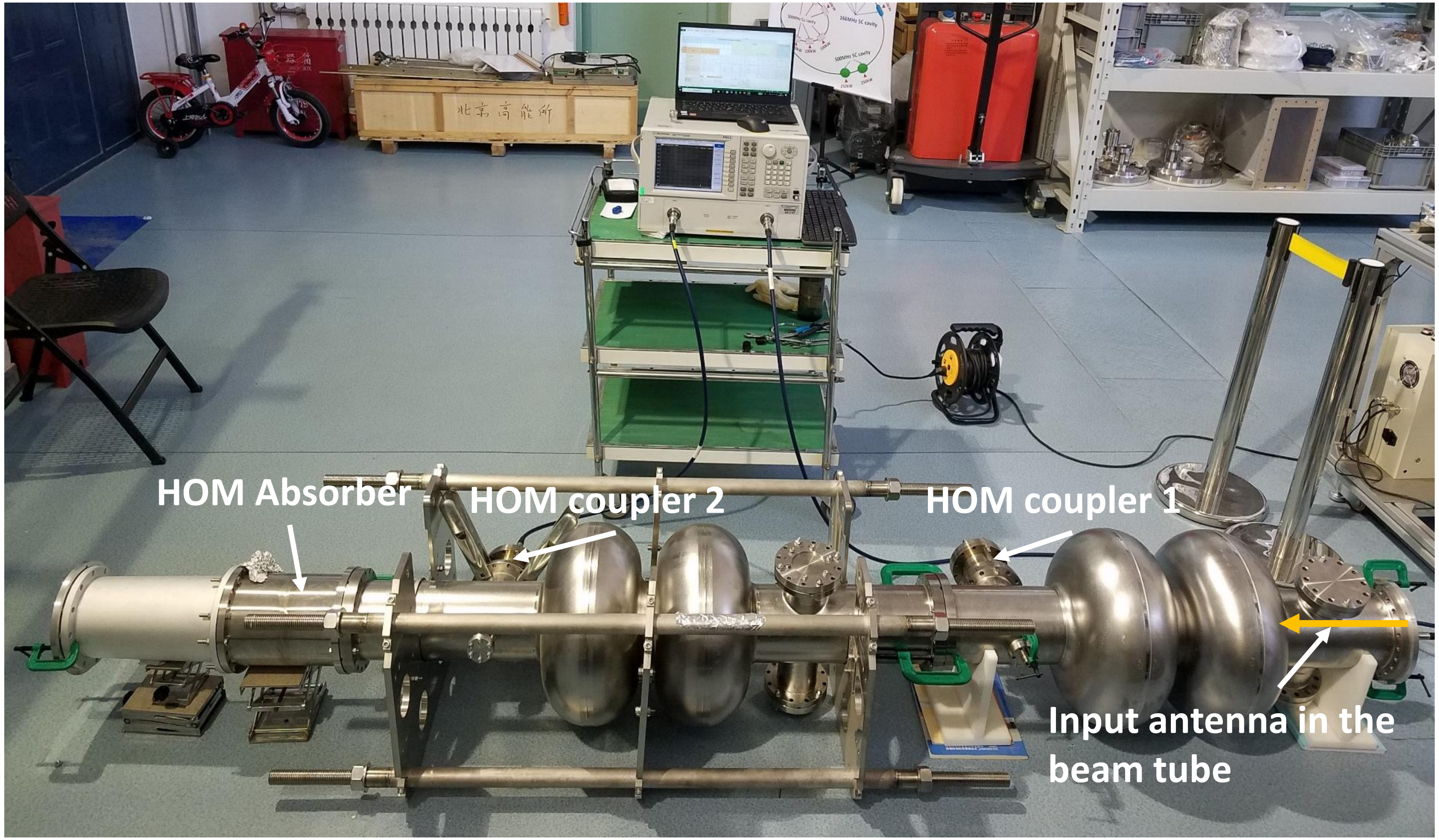
HOM Absorber High Power Test





1.3 GHz input power is 2 kW, the reflect power is 0.94 kW, and the absorber absorbing power is 1 kW.

HOM Propagation through Two 2-cell Cavities

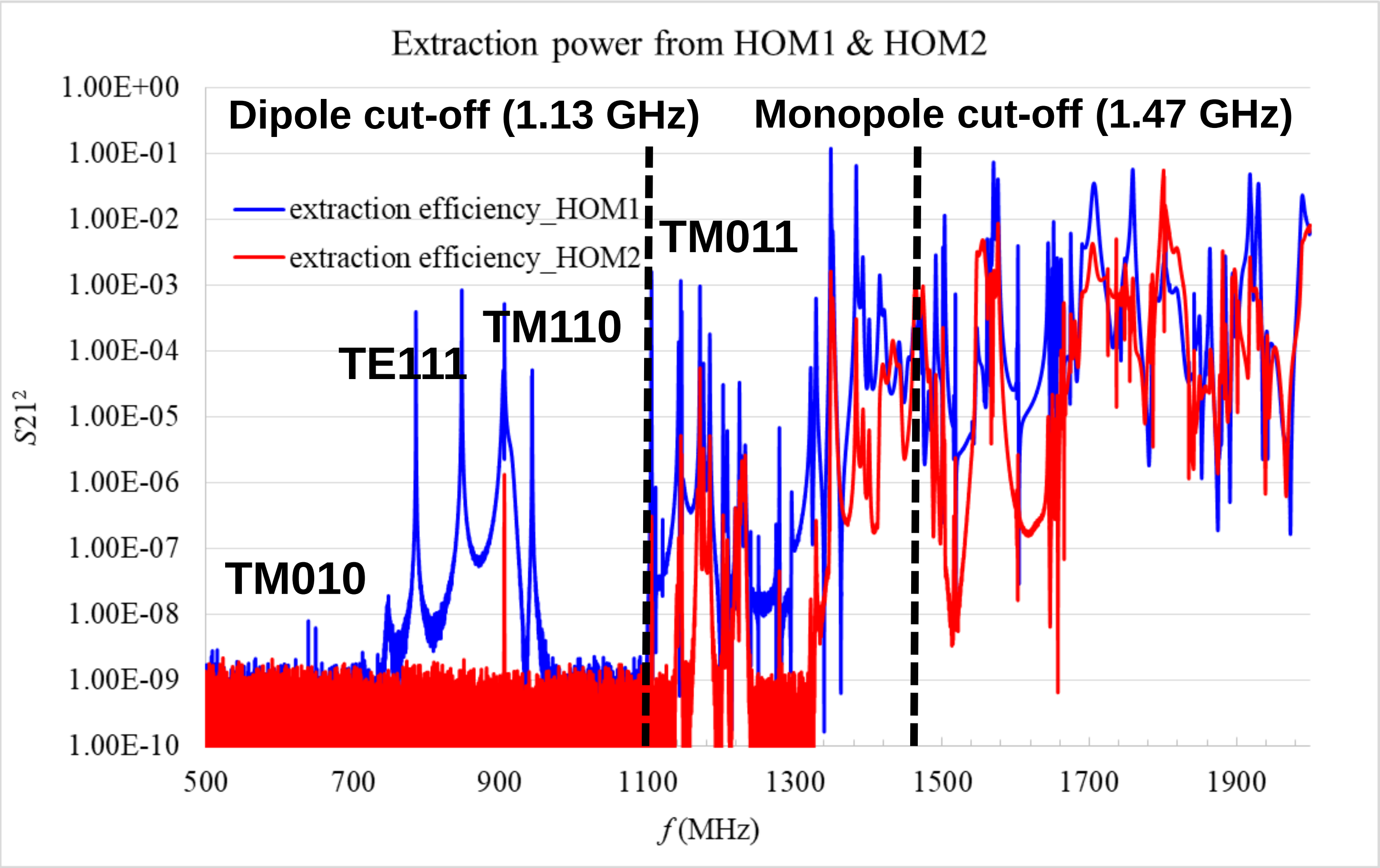


Transmission properties from input port to HOM1 port, HOM2 with matched load.

Transmission properties from input port to HOM2 port, HOM1 with matched load.

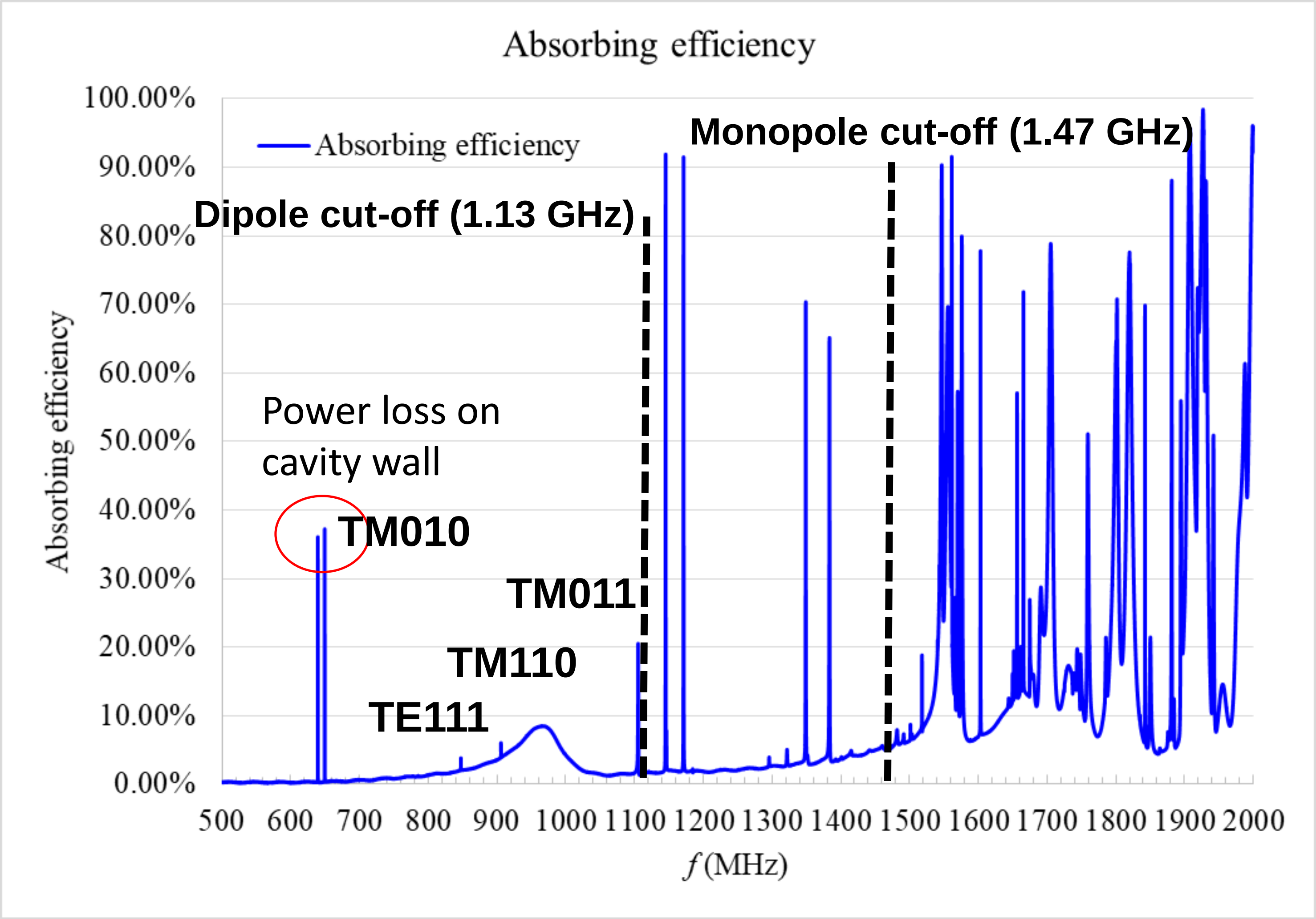
Plan to collaborate with Rostock University on the simulation technique.

Extraction Power from HOM1 & HOM2



- HOM1 is the same with the actual design.
- HOM2's loop antenna penetration depth into the beam tube is 10 mm shorter than the design.

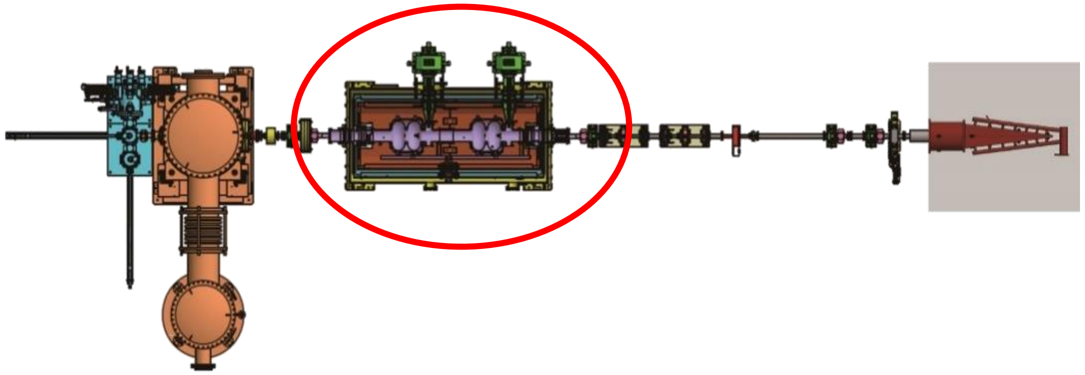
HOM Absorber Absorbing Efficiency

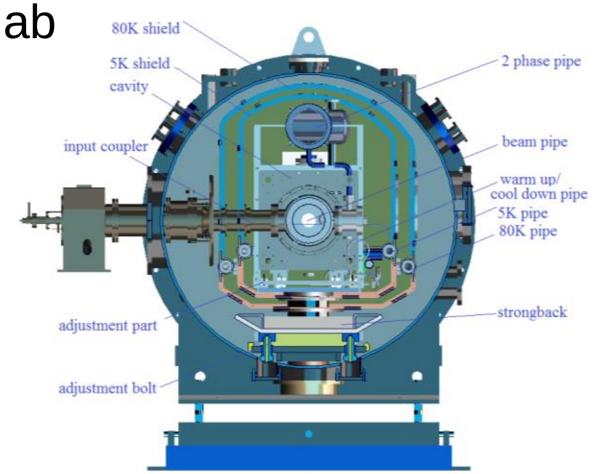


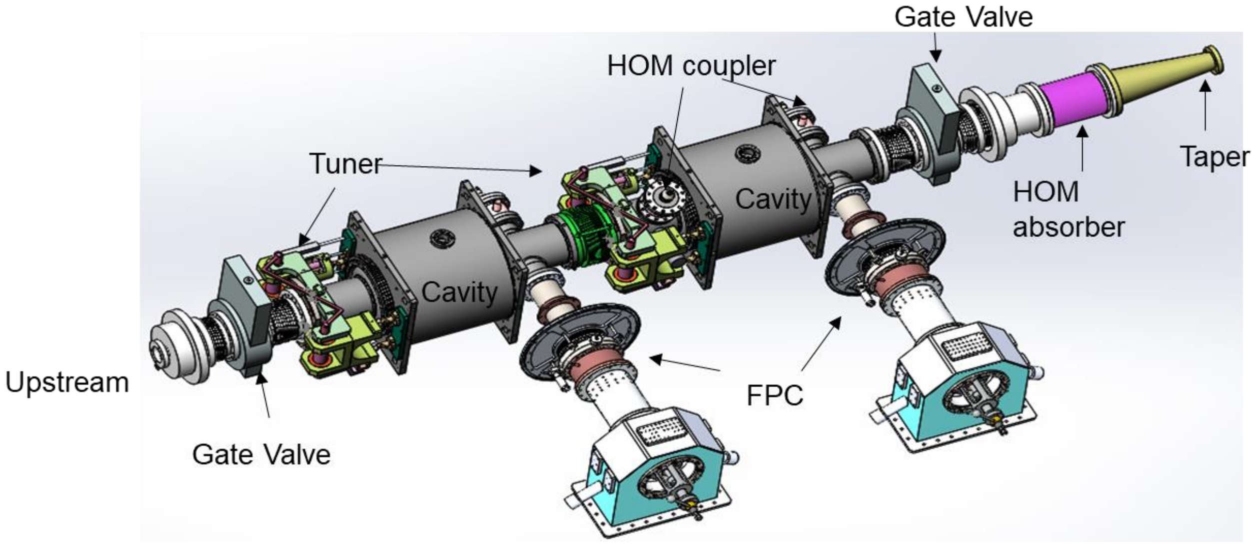
- The absorbing efficiency includes the power loss on cavity wall. The cavity wall loss can be subtracted by replacing the absorber with a blank flange.
- Q_L change due to the absorber will be measured.

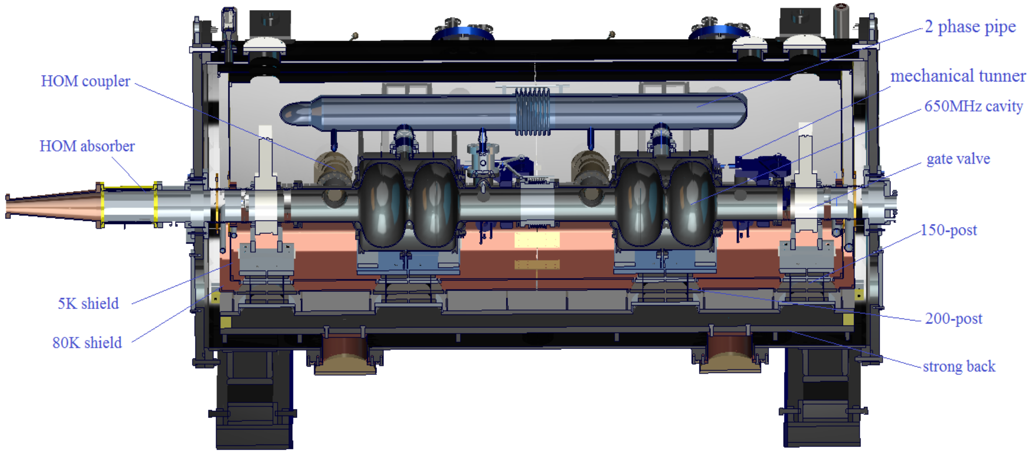
CEPC Collider SRF Test Cryomodule

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









Summary

- CDR design of CEPC SRF system completed with considerations on various operational requirements & scenarios and particular beam-cavity interactions and technical issues.
- SRF key components and test cryomodule design and R&D progress well, especially the world leading storage ring high Q cavity and high power SRF components.
- More resources needed to complete TDR R&D in 2019-2023.