The Fundamental Power Coupler for CEPC Booster Cavity

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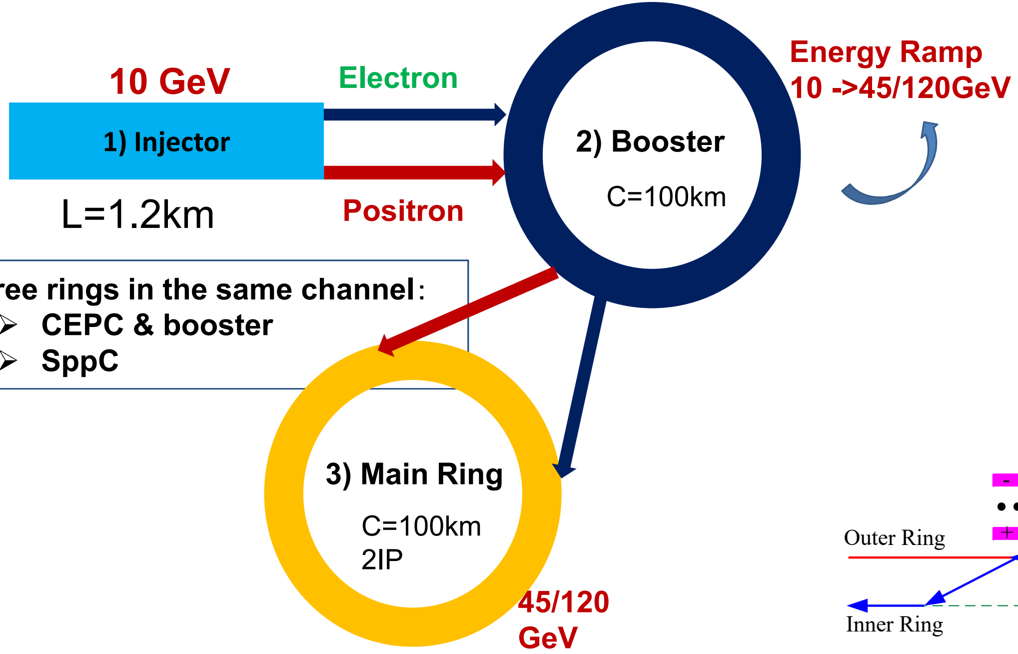
Outline

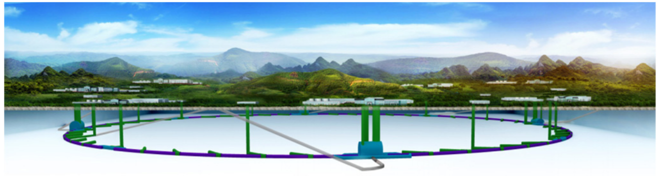
1	Introduction to CEPC SRF system
2	Design issues of the FPC
3	Fabrication of the FPC
4	High power test of the FPC
5	Summary

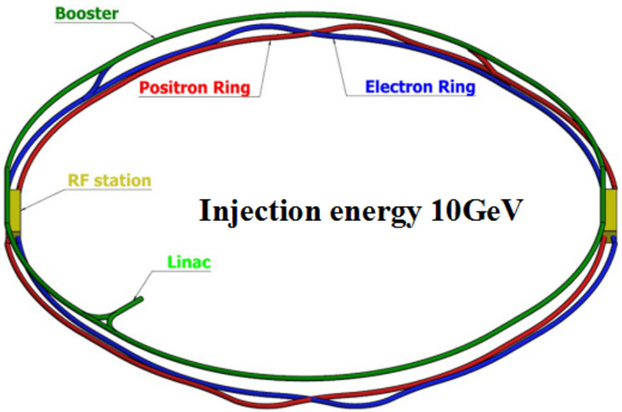
Introduction to CEPC SRF system

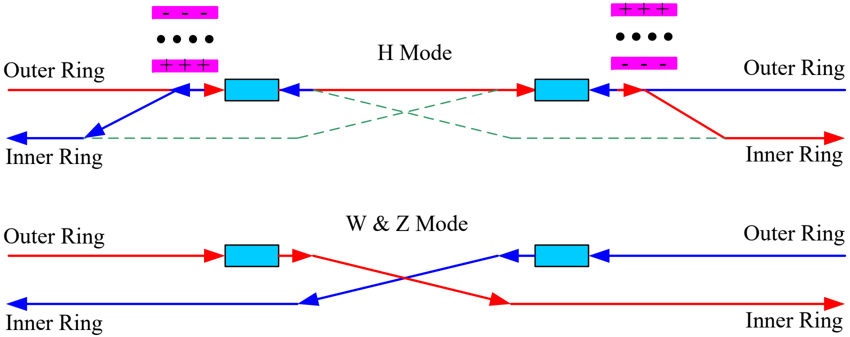
General



Three rings in the same channel:
- CEPC & booster
- SppC







Time schedule of CEPC

CEPC

2015 | 2020 | 2025 | 2030 | 2035

Pre-studies (2013-2015)

R&D Engineering Design (2016-2022)

Construction (2024-2030)

Data taking (2030-2040)

1st Milestone: Pre-CDR (March 2015) ;
2nd Milestone: R&D funding from MOST (Mid 2016);
3rd Milestone: CEPC CDR Progress Report (April 2017);
4th Milestone: CEPC CDR Report (publsih in July, 2018);
5th Milestone: CEPC TDR Report and Prototype R&D (by the end of 2022);
6th Milestone: CEPC construction start (2024);

SPPC

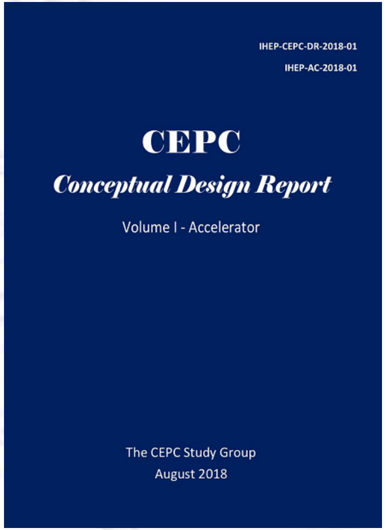
2020 | 2030 | 2040

CDR and R&D (2014-2035)

Engineering Design (2035-2040)

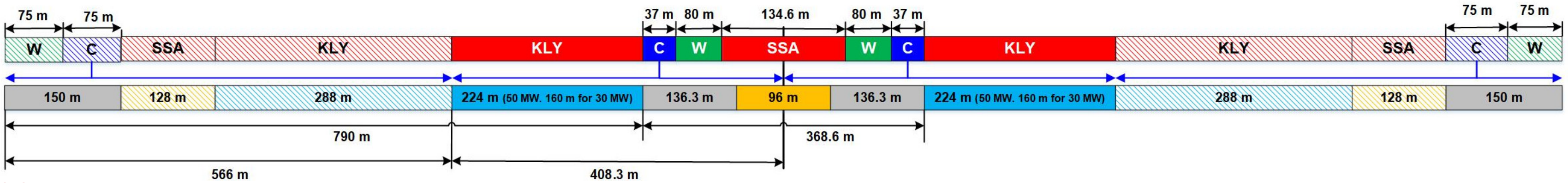
Construction (2040-2045)

Data taking (2045-2060)



CEPC SRF Layout

RF Section A @ IP2 / LLS2 (length 1948.6 m)

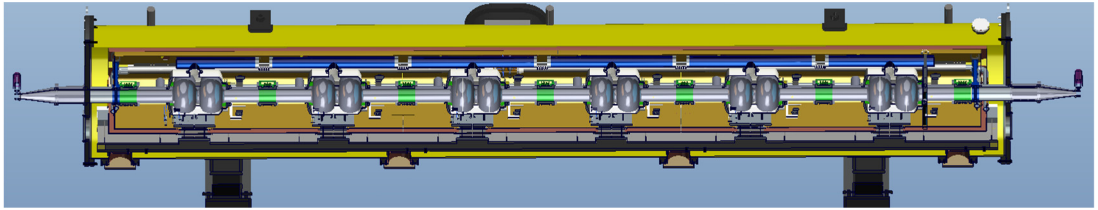


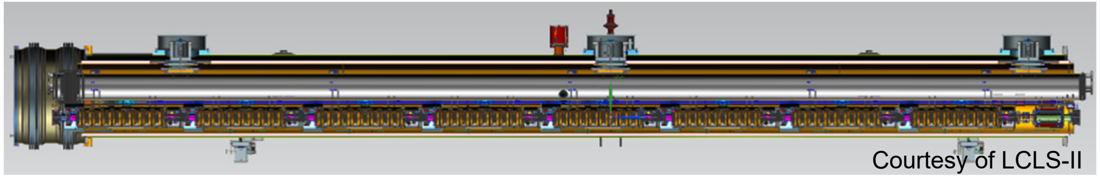
30 MW Higgs:

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

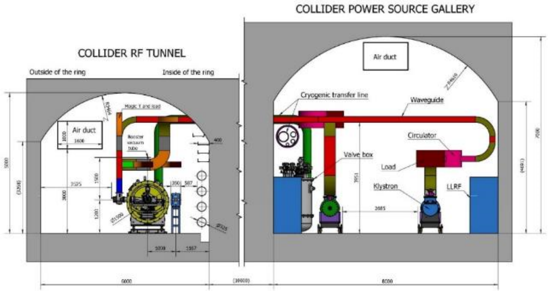
Booster: 96 1.3 GHz 9-cell cavities in 12 cryomodules (8 cav. / module).

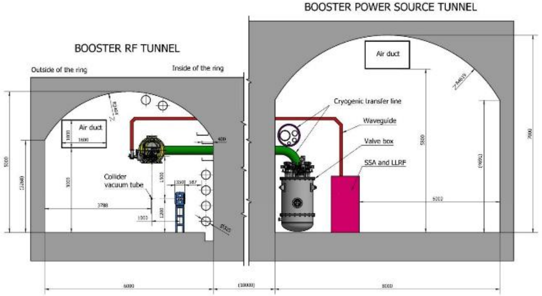
50 MW Higgs upgrade: add 16 Collider modules.





Courtesy of LCLS-II





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	

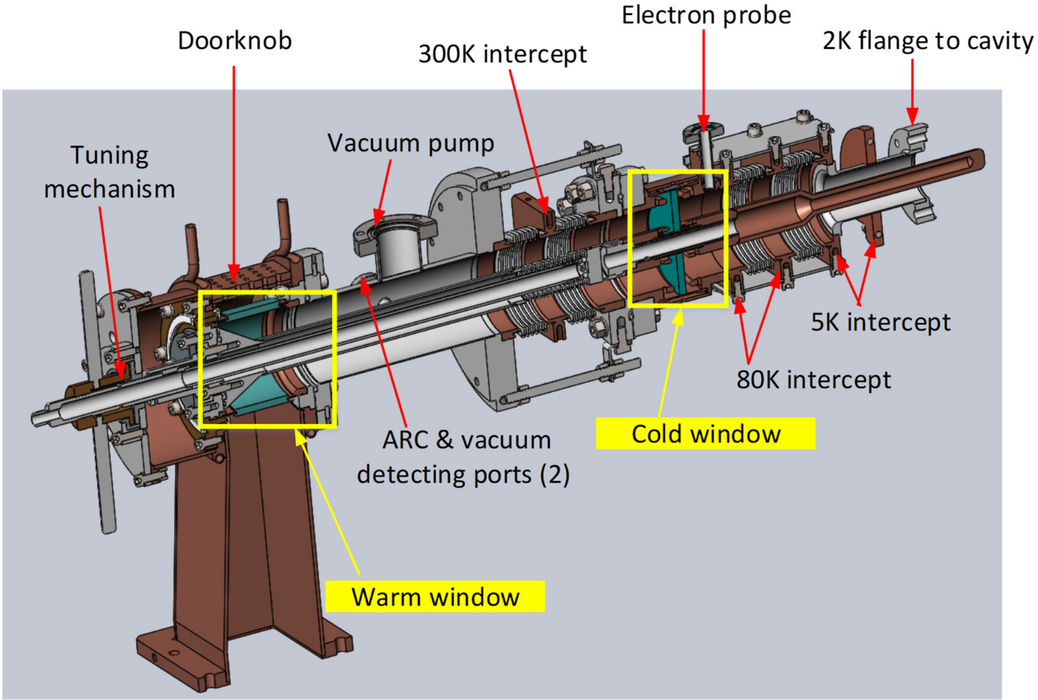
Design issues of the FPC

Requirements and design criteria

- **Not only for CEPC, but also a pure R&D project aiming for CW, variable and clean assembly.**

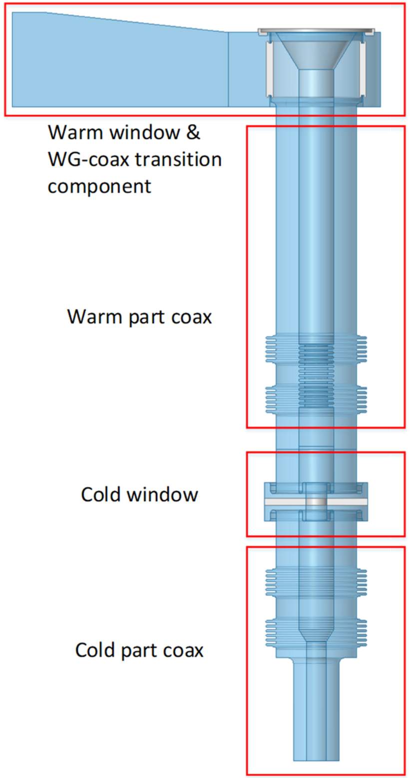
Requirements	Design criteria
Frequency: 1.3 GHz	• Satisfy the interfaces: --Power source side: WR650 waveguide --Cavity side: 1.3GHz 9-cell cavity and cryo-module
Power: • **R &D: CW 75kW** • **CEPC Booster: Peak, 20 kW; Average, 4 kW**	• Sufficient cooling to remove the high RF power dissipation
Variable Qext: 4E6~1E7	• Coaxial type is determined for easy coupling adjusting; • With bellows and tuning mechanism.
Dynamic 2K heat load: • **R &D: 0.5W (TW,CW,75kW)** • **CEPC Booster: 0.06W (TW,CW,4kW)**	• Optimized thermal intercepts design
Clean assembly	• Two windows: --Cold window assembly to the cavity in class 10 clean room --Warm window double the vacuum safe
Multipacting free	• RF structure optimization to avoid MP at nominal power; • TiN coating of ceramic • A DC bias voltage is adopted to suppress MP.
Safe operation	• With sufficient diagnostic monitors.

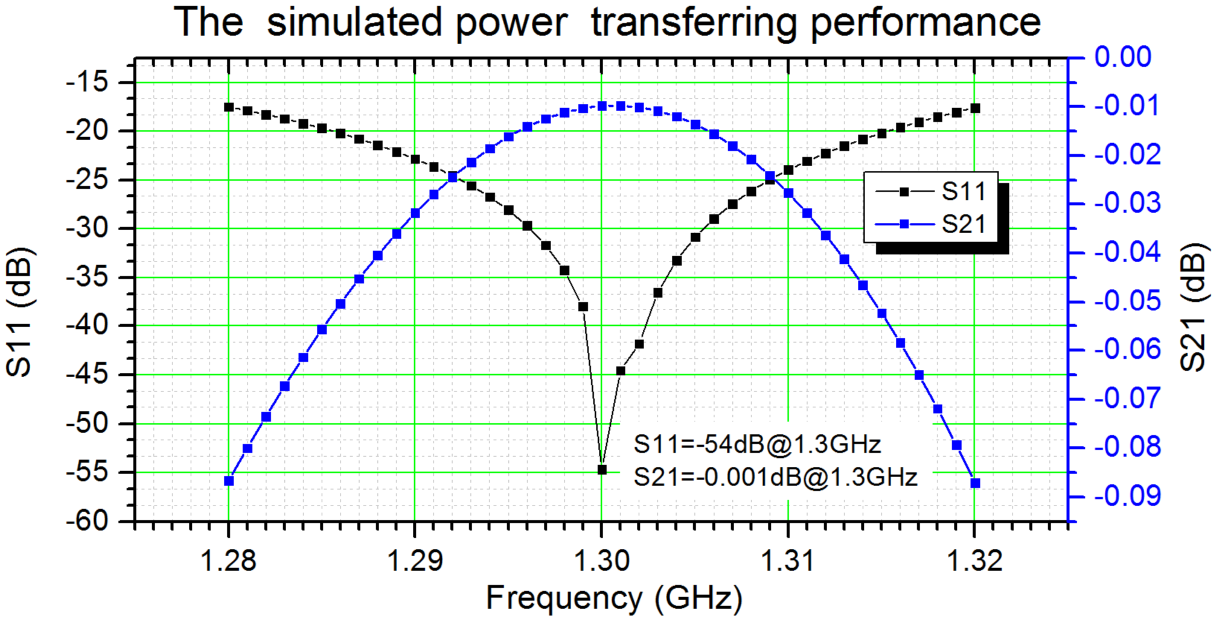
Design features



- The warm window is derived from TTF-III coupler and the cold window is belong to the Tristan-type family;
- In order to handle a higher average power, a series of modifications are made:
  - ✓ The warm window size is enlarged (OD=87mm);
  - ✓ Air cooling is added to the IC of the warm coax;
  - ✓ Both air and water cooling are applied to the warm window;
  - ✓ Larger coaxial size for a larger cold window(OD=90mm);
- A DC bias voltage mechanism is arranged to suppress Multipacting;
- The travel range of the antenna is designed to be 20mm to meet the coupling adjusting requirement.

Power transferring optimization

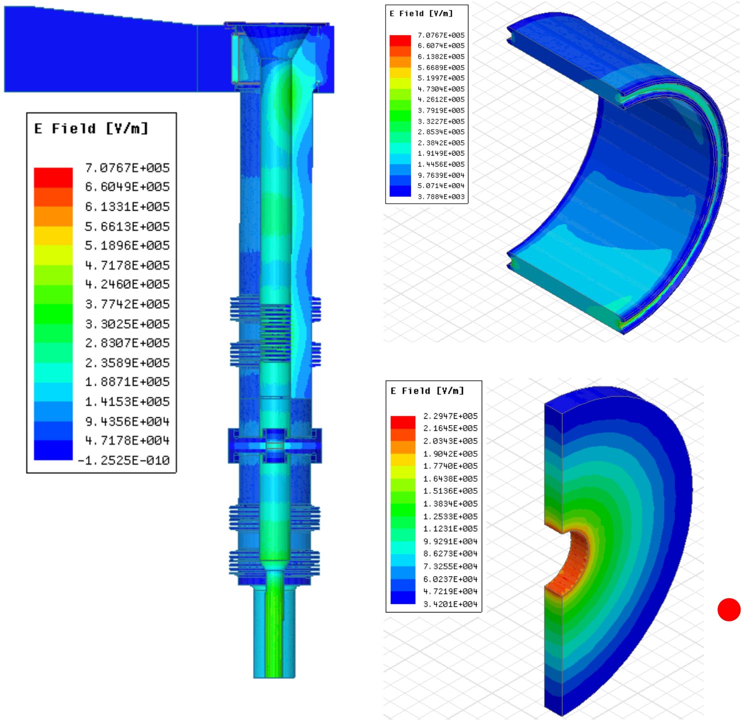




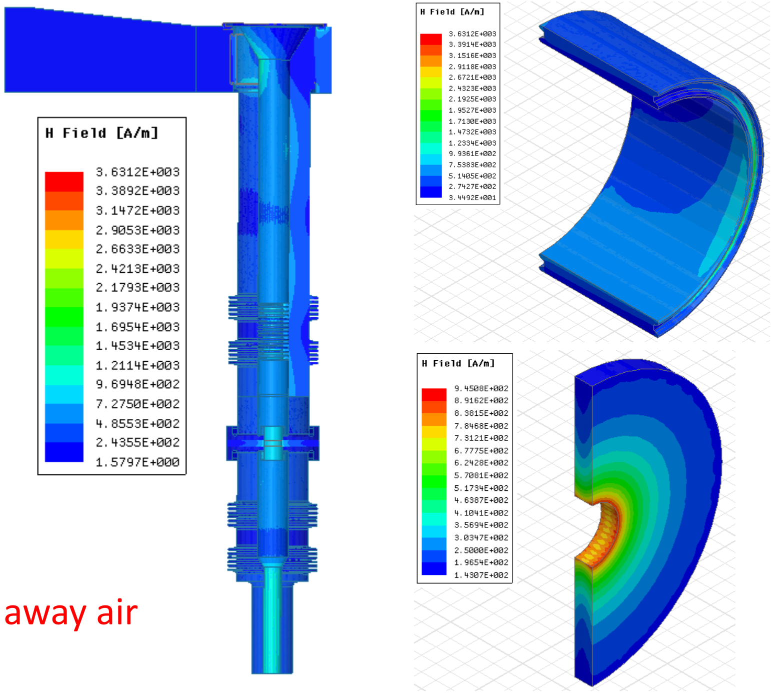
- The measured **S11=-45.4 dB @1.2989** GHz;
- The measured **S21=0.166 dB@1.3** GHz

E-H field distribution at CW 75kW,TW

- The E-H field distribution at CW 75kW in TW mode was calculated. And the peak E-field is one forth of the air break value.

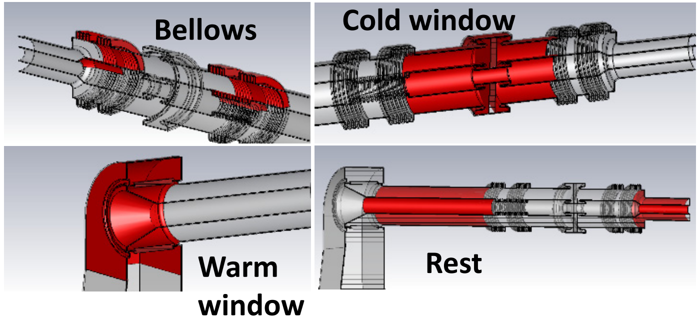


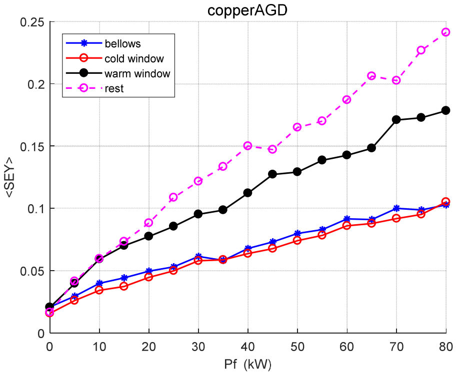
- Emax =7e5 → far away air break → safe!

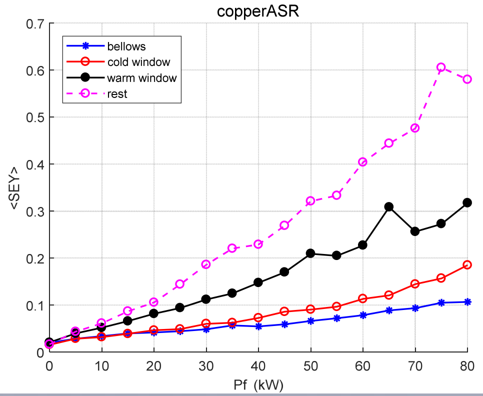


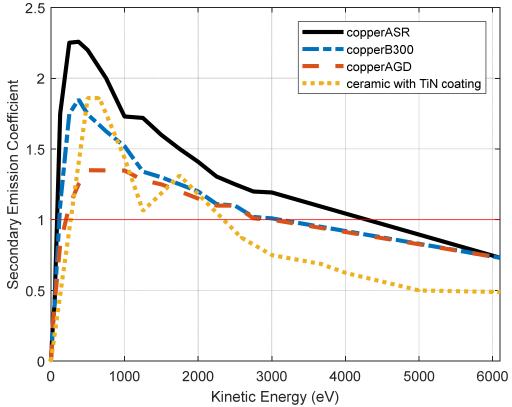
Multipacting Simulation

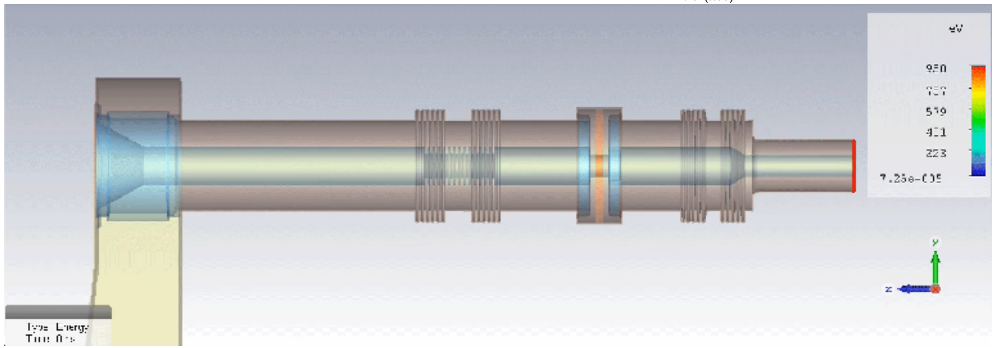
- **Free of MP** at the power range of 0~80kW!





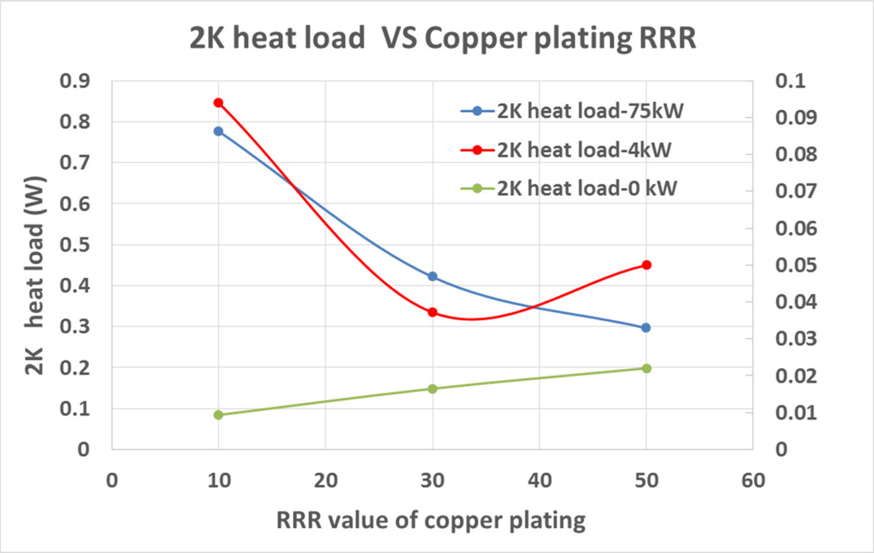






Thickness and RRR of copper plating

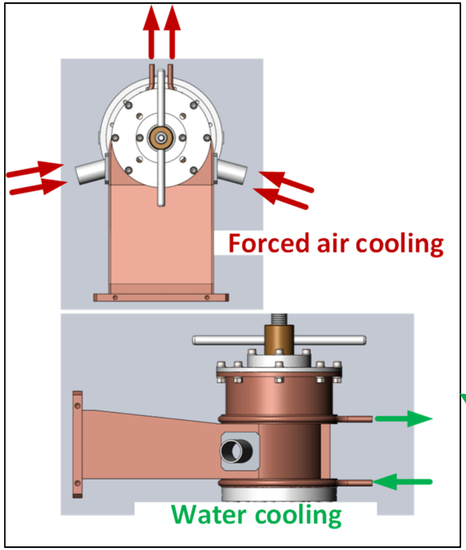
- The thickness and RRR of copper plating were determined to minimum the cryogenic heat load.
- Final decisions:
  - Copper plating thickness:
    - Cold OC: 5um
    - Warm OC : 30um
    - Warm IC: 150um
  - Optimum RRR value:
    - **RRR=30 for average 4kW**
    - **RRR=50 for CW 75kW**



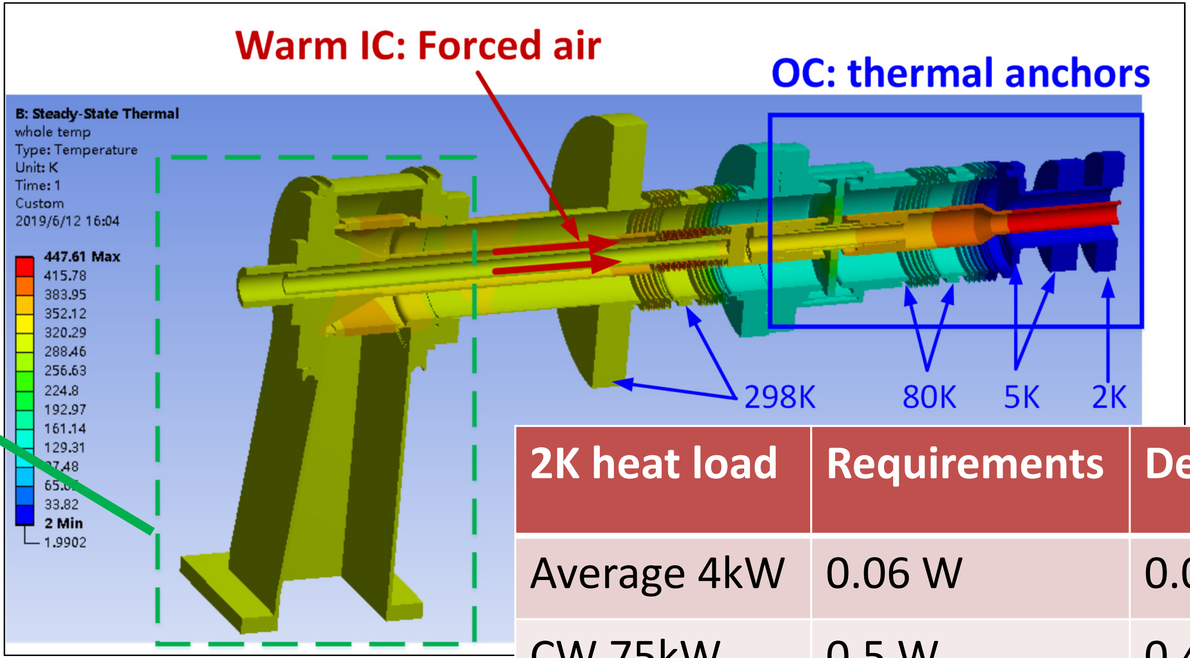
2K heat load at different RRR values

Cooling design

- The cooling was optimized based on the required heat load and temperature rise.

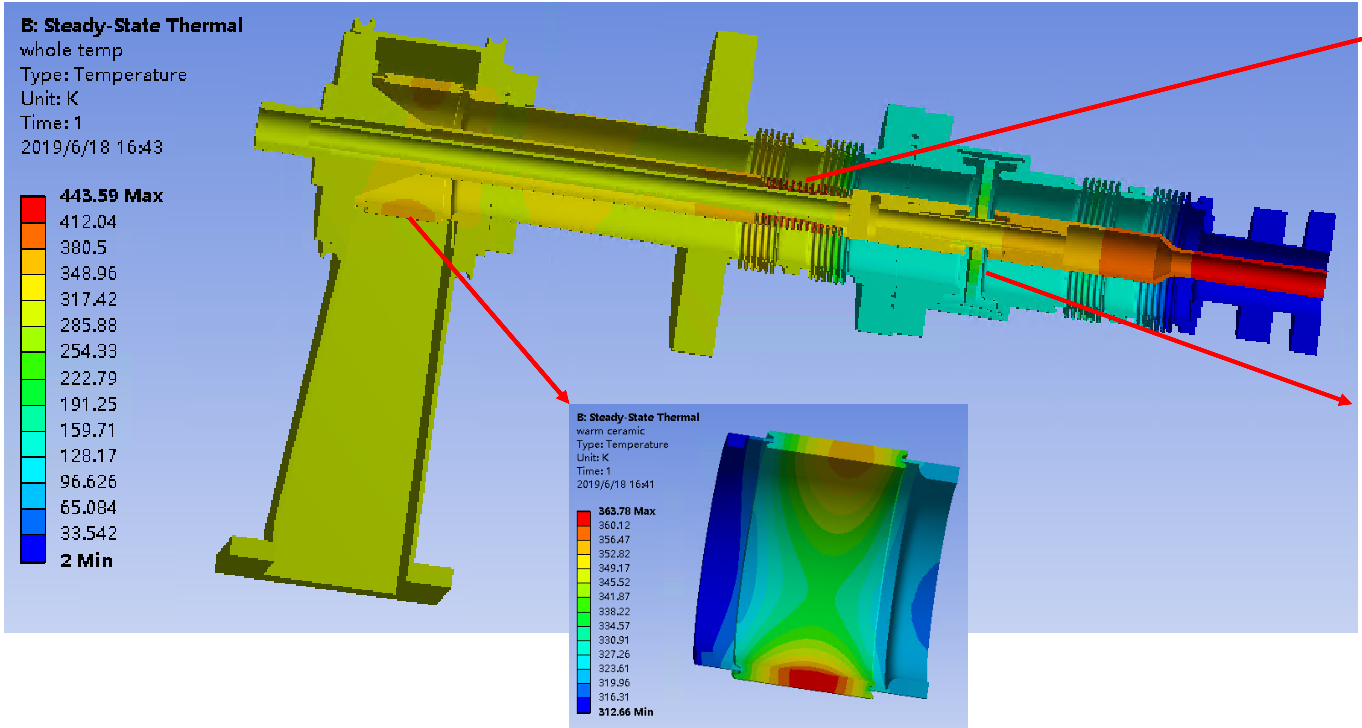


Doorknob and warm window
(Forced air and water)

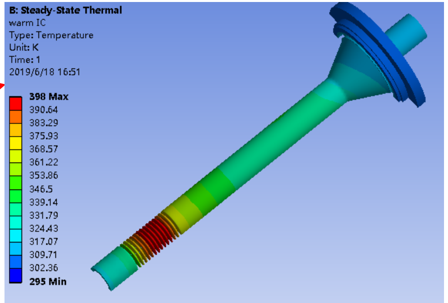


2K heat load	Requirements	Design
Average 4kW	0.06 W	0.04 W
CW 75kW	0.5 W	0.4 W

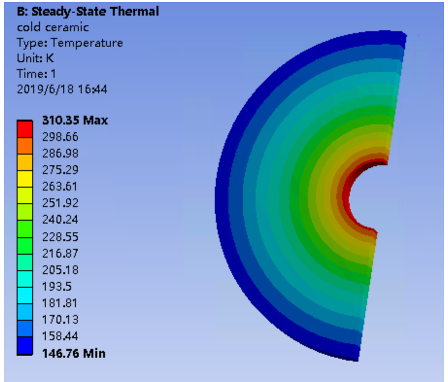
Temperature distribution at CW 75kW,TW



Warm window: 90°C



Warm IC: 125°C

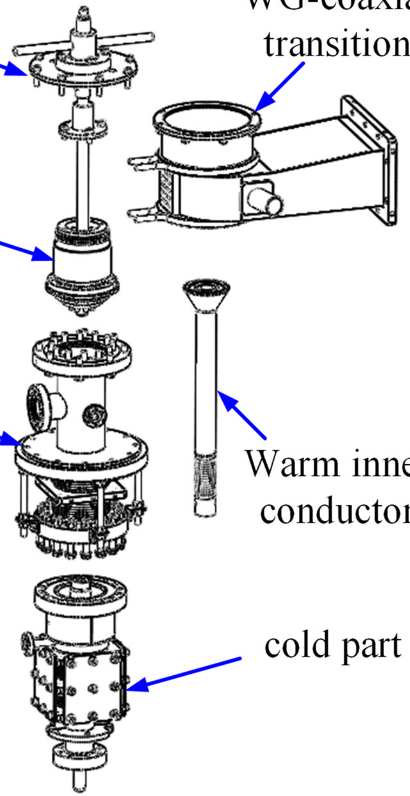


Cold window : 37°C

Mechanical design

- Divided into six sub-assemblies:
  - Cold part: cold window, cold IC, cold OC
  - Warm OC
  - Warm IC
  - Warm window
  - Doorknob
  - Tuning unit
- Warm window is demountable: easy to be replaced once damaged.

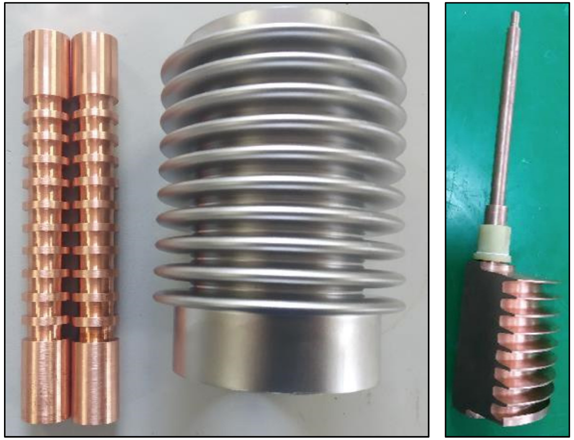
Demountable window



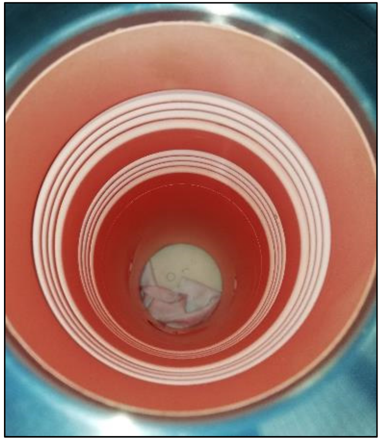
Fabrication issues of the FPC

Copper plating

- **Challenges**
  - Uniform copper plating on bellows
  - Very thick (~150um) plating on warm inner conductor
  - High RRR required (RRR>30)
- Copper plating after brazing or welding



Electrodes optimization



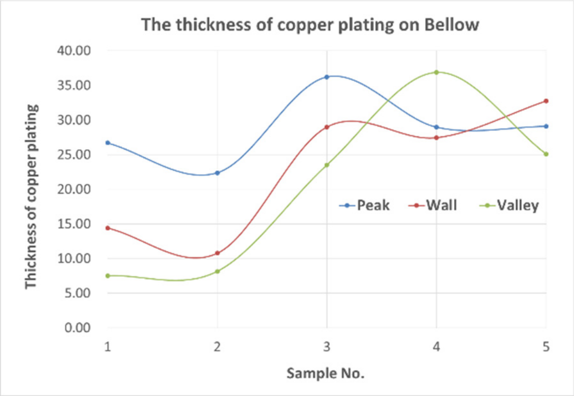
Warm OC: 30um copper plating

Warm IC: 150um copper plating

Very difficult!

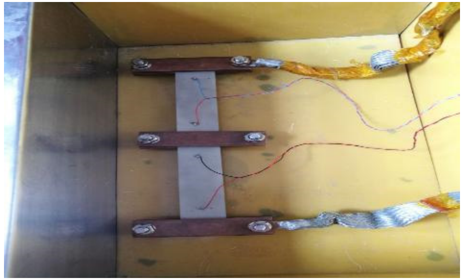
Copper plating quality test

Thickness



- Thickness tolerance < 20% achieved

RRR



Bath condition	Annealing T	thickness	RRR
Original electroplating bath (low purity)	400°C	20 μm	<10
		10 μm	<10
New electroplating bath (high purity)	400°C	20 μm	34
		10 μm	13
	350°C	20 μm	50
		10 μm	40

- RRR was largely improved by using purer electroplating bath and reducing the annealing temperature (400°C → 350°C).

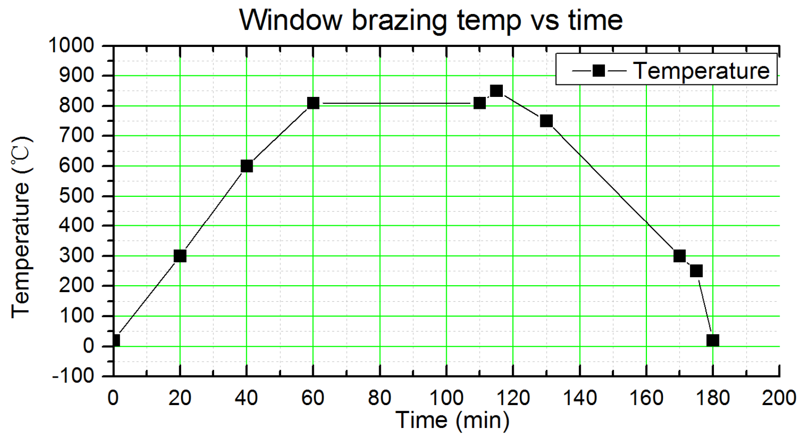
Adhesiveness

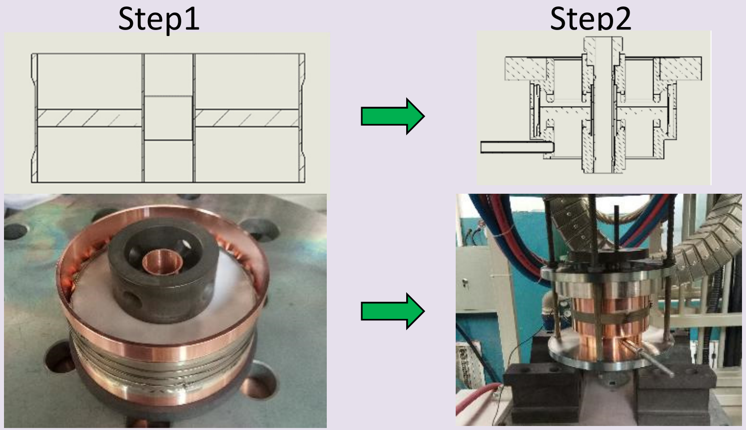
Liquid Nitrogen shocking

- The adhesiveness was tested by liquid nitrogen shocking and ultrasonic cleaning.
- No bubbles and peeling！

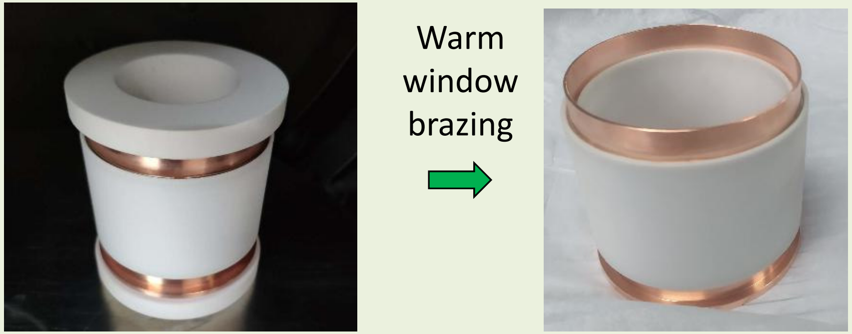
Window brazing

- Vacuum furnace, Ag72Cu28
- Optimize the temperature evolution curve
- Special fixture for support
- The cold window brazing processes were reduced from 3 steps to 2 steps. It greatly increased the success rate of cold window brazing.





Cold window brazing


Warm window brazing

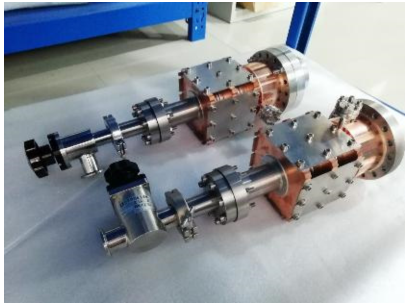
The fabricated components

Warm window

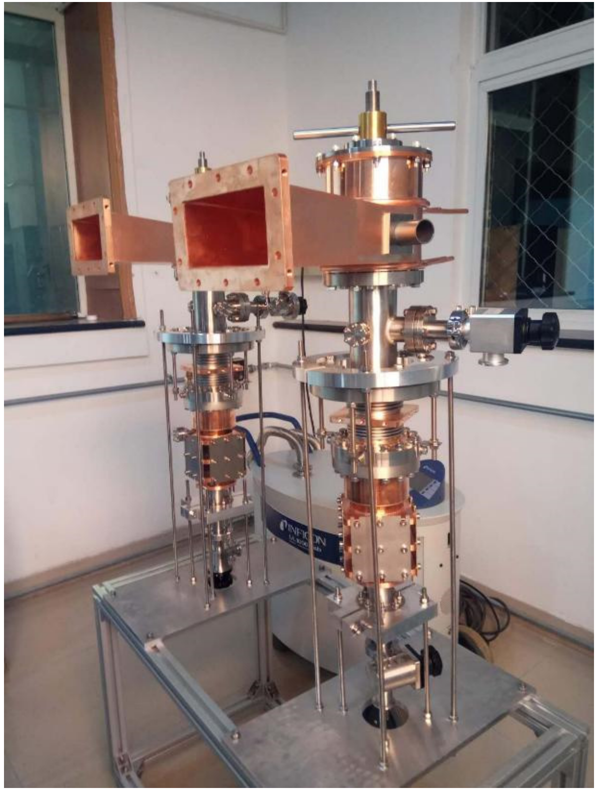
Warm OC

Doorknob

Warm IC



Cold part



Whole assembly

High power test of the FPC

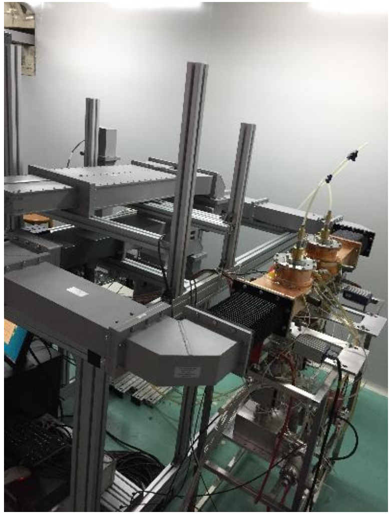
Cleaning, assembly, baking and on site installation

- Cleaning: ultra-sonic cleaning with detergent at 50 ℃→ pure water rinsing → pure N2 blowing
- Assembly： processed at class 10 clean room
- Baking: 120 ℃ for 48 hours

Ultra-sonic cleaning

Clean assembly and vacuum leak check

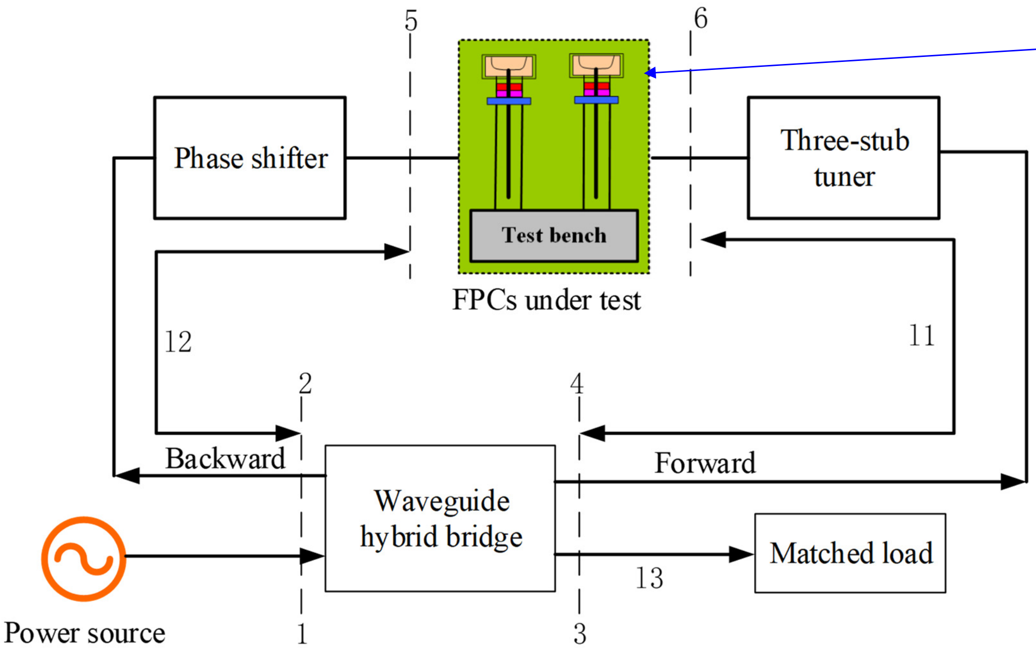
Baking

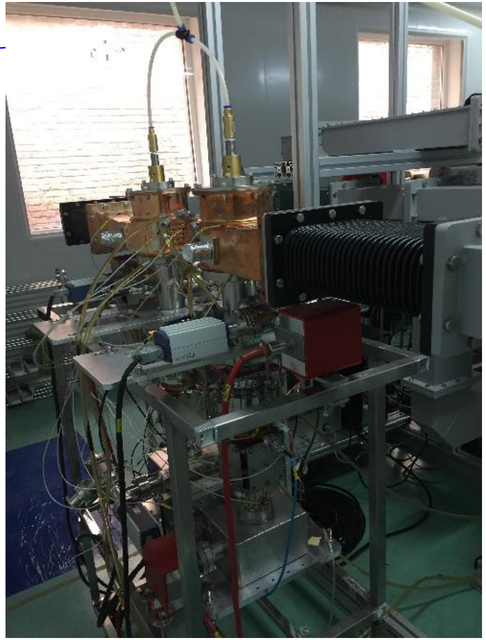


On site installation

Setup for high power test

- The high power test has been processed at a resonant ring platform developed at **Peking University*.**
- Power source: 10kW SSA; The input power can be amplified about 5~8 times.

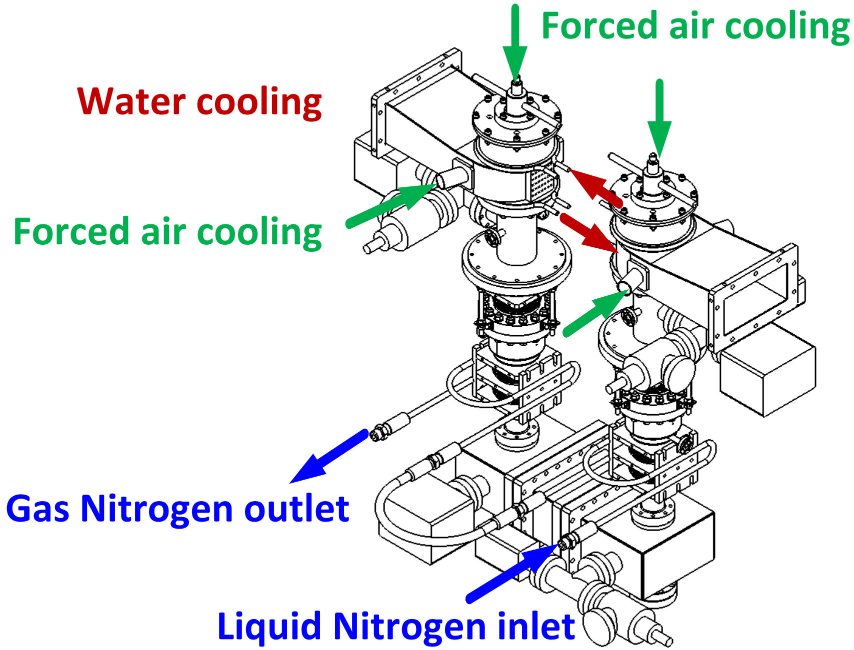




“An alternative way to increase the power gain of resonant rings”, REVIEW OF SCIENTIFIC INSTRUMENTS 89, 034702 (2018)

Cooling setup

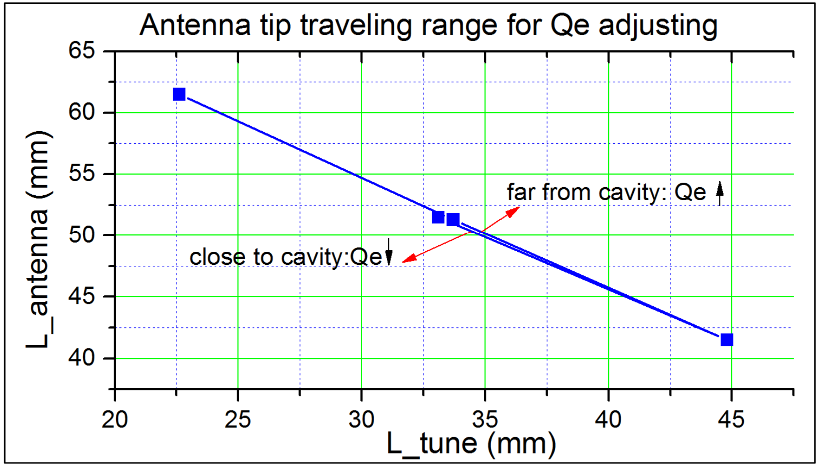
- The cold OC was cooled by the thermal intercepts connected to liquid Nitrogen cooled copper plates.

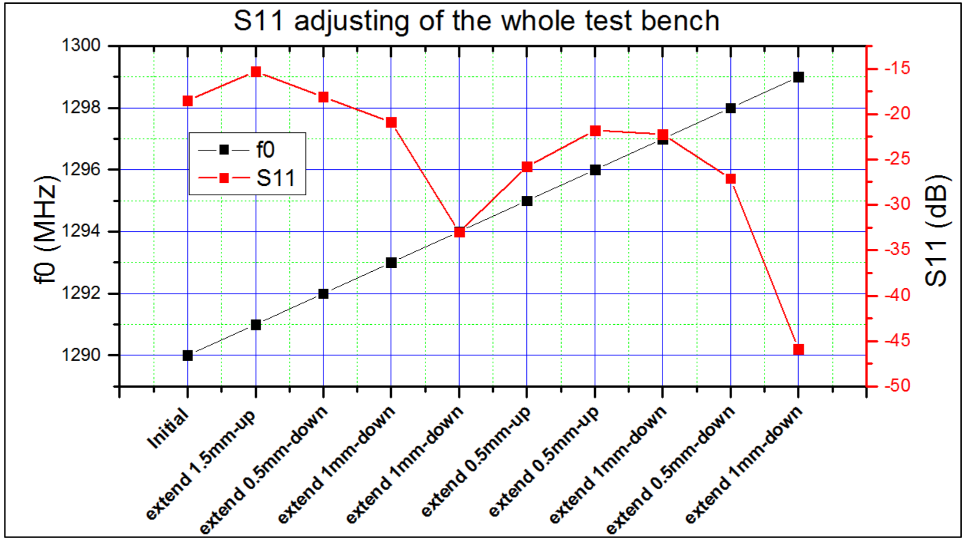


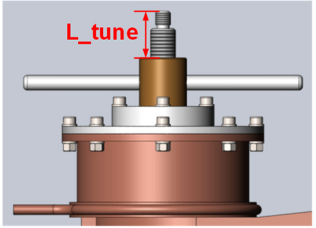
Components	Cooling method
Doorknob and warm window	Forced air and water
Warm inner conductor	Forced air
Cold outer conductor	Thermal anchors connected to LN cooled copper plate

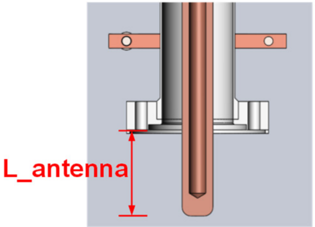
Antenna excursion test

- The antenna excursion tested: ±10mm → Qe variable range: 1.5E6~1E8 (Spec: 4E6~1E7);
- Before high power test, S11 of the whole test bench was adjusted by tuning the penetration depth of the antenna tip into the connecting test box.





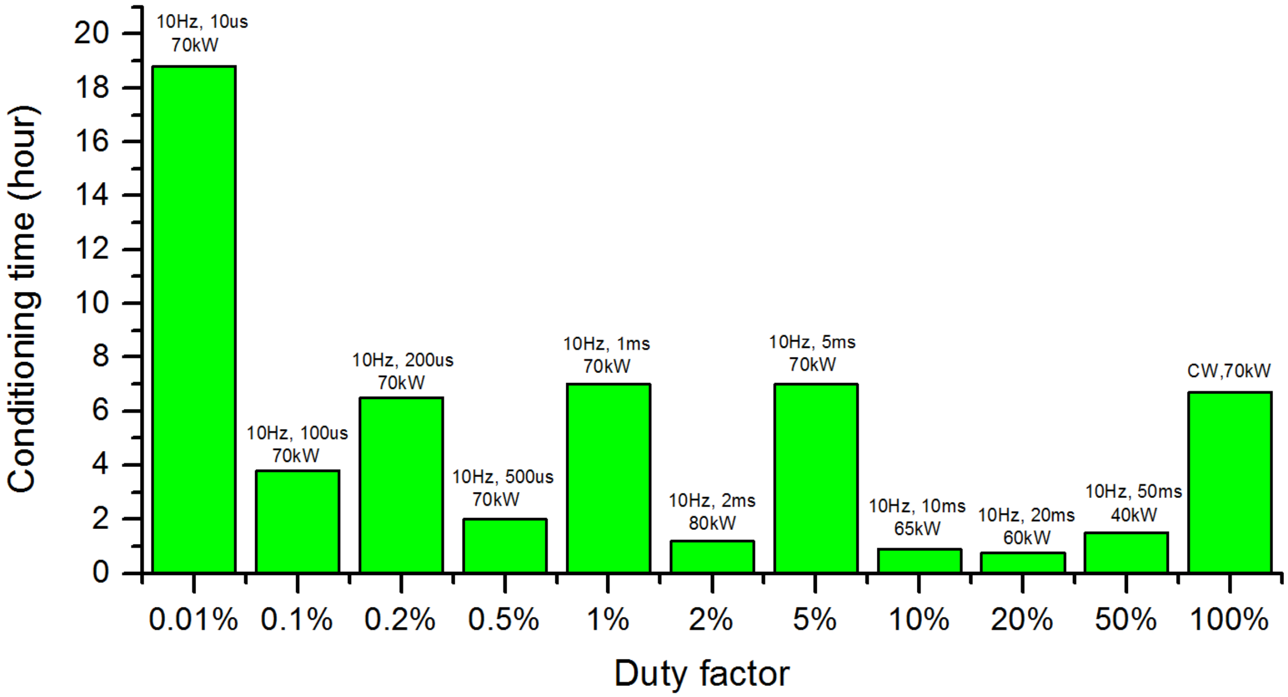




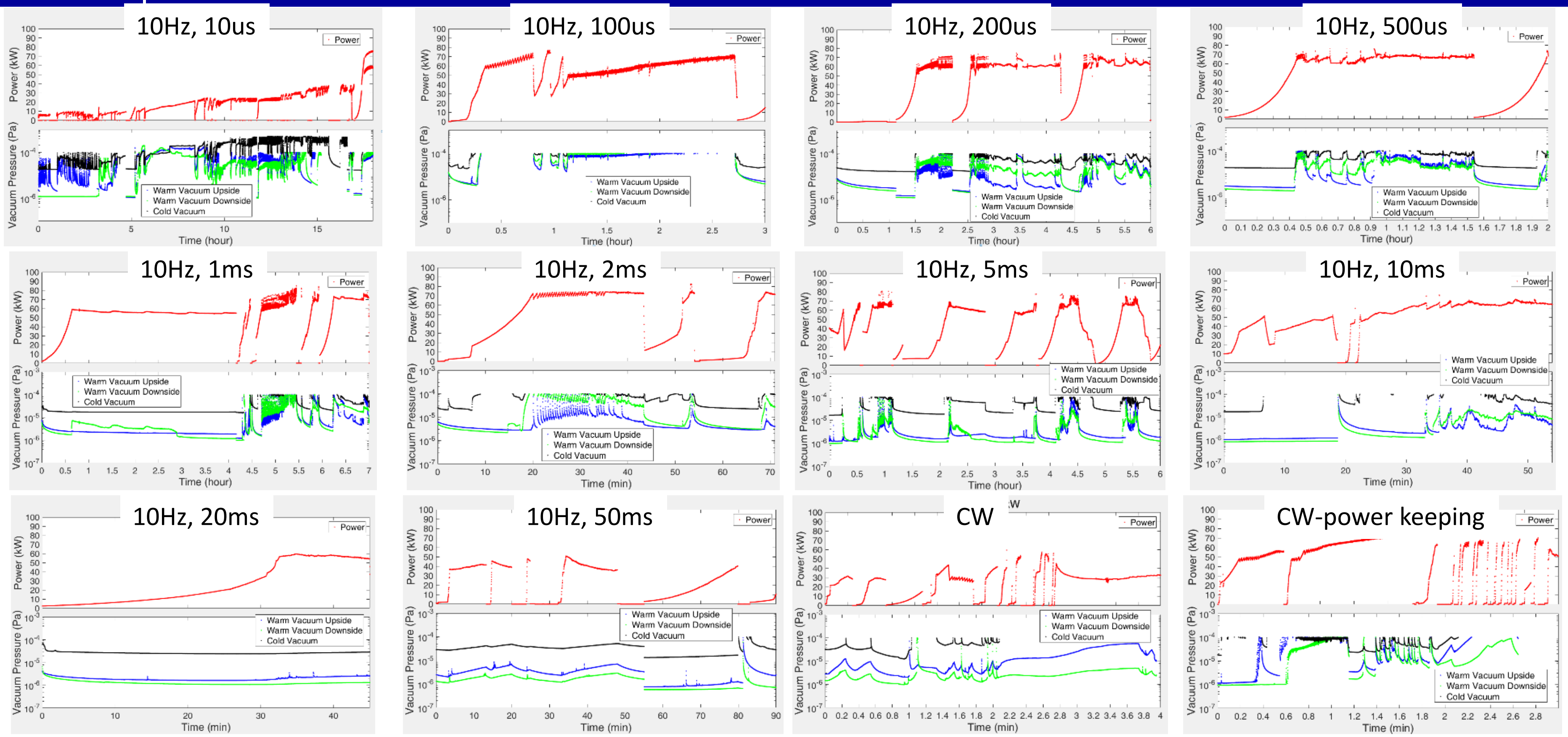
S11 adjusting before high power test
(After tuning: -45.4dB@1.2989GHz)

Conditioning time

- After **60 hours** conditioning, two prototypes reached **CW 70kW**.

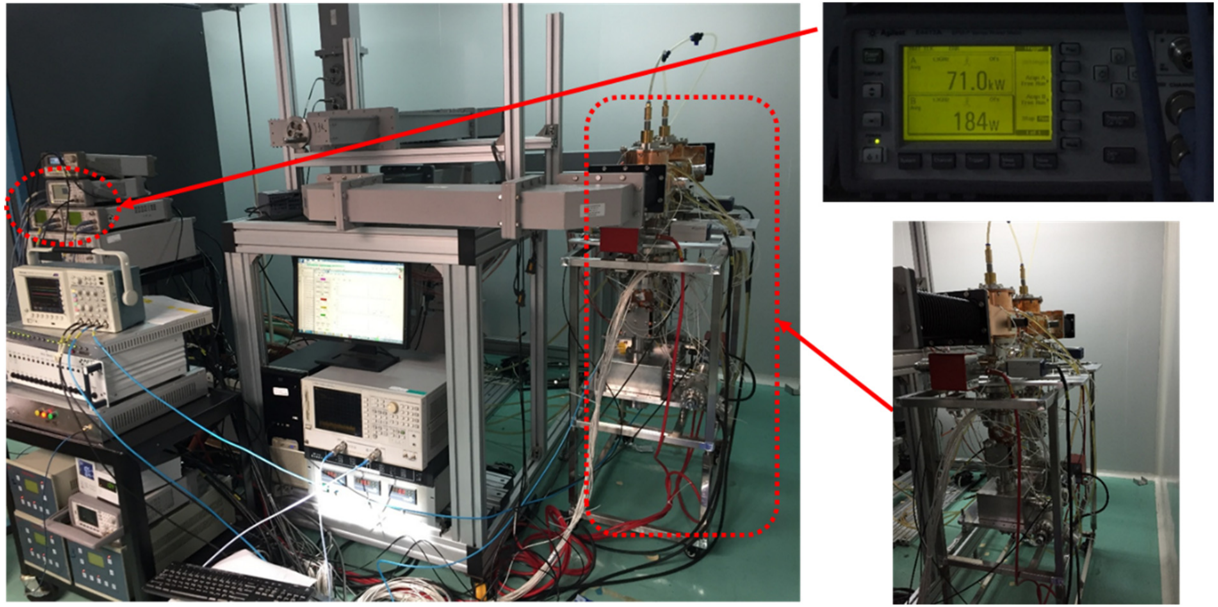


Conditioning process



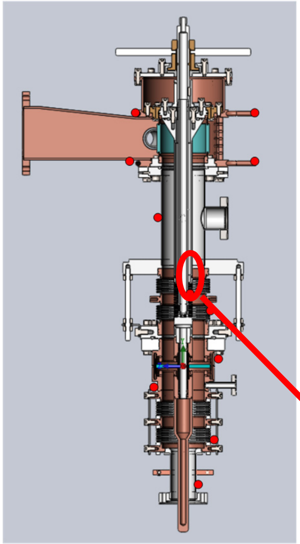
High power test result

- It's difficult to keep the resonant ring tuned for more than 30 minutes as the power above CW 50kW due to thermal drift.
- So we lowered the RF power below 50kW for power keeping test: stayed at 30kW for 60 minutes ; stayed at 40kW for 30 minutes.



Temperature rise at CW 40kW

- A high warm IC temperature observed during test:
  - Test result: 100 ℃
  - Simulation result: 72 ℃
  - Poor copper plating or insufficient cooling?



Pt100 distribution

Location	Equilibrium T up./down. (℃)
Inlet water	21.1/22.5
Outlet water	21.7/23.7
Doorknob WG up	25.2/27.2
Doorknob WG down	24.7/25.3
Warm inner conductor	**97.2/102.7**
Warm outer conductor	19.1/30.0
Warm outer bellow	58/74.2

Location	Equilibrium T up./down. (℃)
Cold window up	18.9/-24.6
Cold window down	15.6/-35.4
Cold outer bellow	14.4/-35.5
Connecting box	52.5/50.7

Summary

- 1.3GHz variable, double-window, CW 75kW coupler developed at IHEP

  - Demountable cylindrical warm window + Tristan-type cold window

- Two prototypes fabricated and high-power tested on test bench
- CW 70kW RF power reached on both couplers
- Warm-part inner conductor overheating observed (30^{o}C higher than simulation)
- FPCs fulfill CEPC booster cavity requirements
- Further optimization foreseen: cooling of warm inner conductor

Acknowledgement

Thanks for your attention

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