中国科学院高能物理研究所

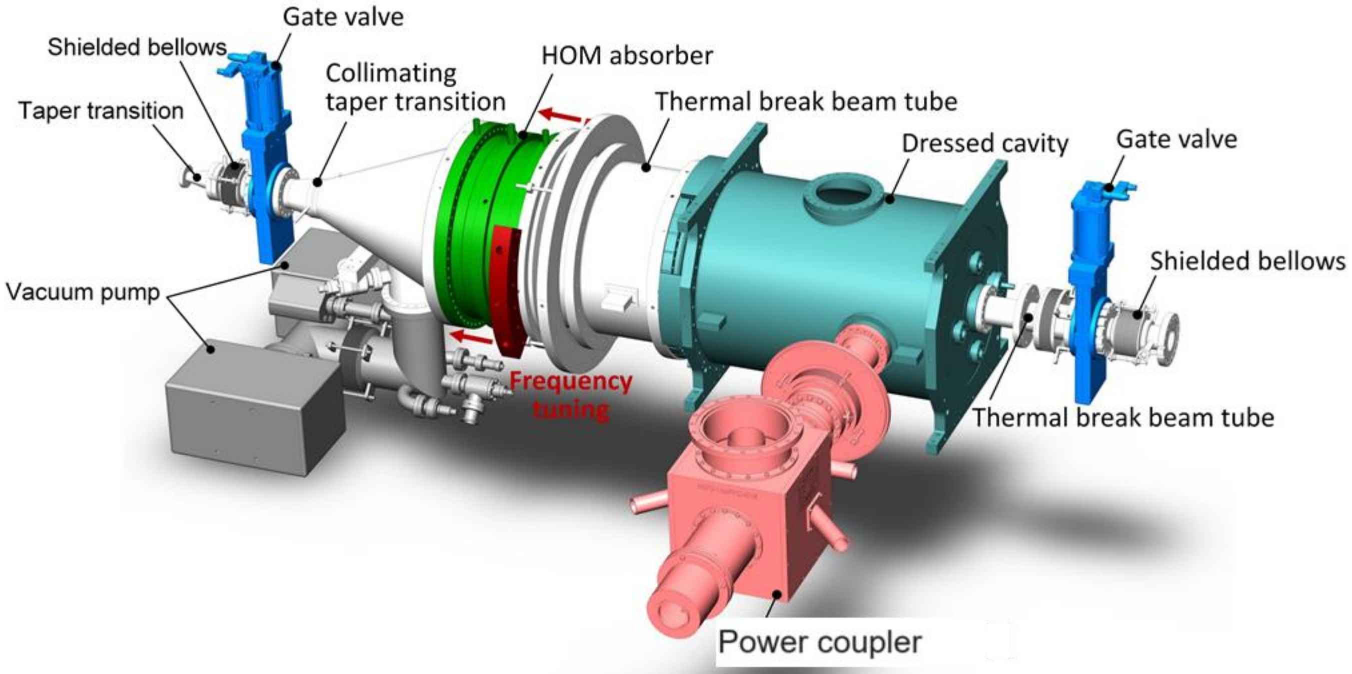
INSTITUTE OF HIGH ENERGY PHYSICS

Chinese Academy of Sciences

Power coupler activities at IHEP

T.M. Huang

(RF group, IHEP)



WWFPC #6 meeting, July 2024, CERN, Switzerland

Outline

Overview of FPCs at IHEP

Summary sheet

Project	Cavity type	Frequency	Coupler type	Power	Status	Time
BEPCII	Single-cell elliptical (SCC)	500 MHz	Coax, fixed, capacitive, single-window	Test: CW 420 kW (TW & SW) Op: CW 150 kW	Beam operation	2006-2012
ILC R&D	9-cell elliptical (SCC)	1300 MHz	Coax, fixed, capacitive, double-window	Test: 1MW,1.5ms,5Hz(avg:7.5kW) Op: 300kW,1.5ms,5Hz(avg:2.25kW)	HPT and Cavity integration	2010-2012
CADS	RFQ (NC)	325 MHz	Coax, fixed, inductive, single-window	Test: CW 105 kW (TW & SW) Op: 100 kW	Beam operation	2011-2016
	RFQ (NC)	162.5 MHz	Coax, fixed, inductive, single-window	Test: Not done on test bench Op: 80 kW	Beam operation	
	HWR (SCC)	162.5 MHz	Coax, fixed, capacitive, single-window	Test: CW 20 kW (TW & SW) Op: CW 15 kW	Beam operation	
	Spoke (SCC)	325 MHz	Coax, fixed, capacitive, single-window	Test: CW 10 kW (TW & SW) Op: CW 10 kW	Beam operation	
	5-cell elliptical β=0.82 (SCC)	650 MHz	Coax, fixed, capacitive, single-window	Test: CW 150 kW (TW & SW) Op: Not yet specified	HPT	2014-2016
HEPS-TF	QWR β=1 (SCC)	166.6 MHz	Coax, fixed, capacitive, single-window	Test: CW 50 kW (TW & SW) Op: CW 200 kW	HPT	2016-2018
R&D	Multi-cell elliptical (SCC)	1300 MHz	Coax, variable, capacitive, double-window	Test: CW 71 kW (TW & SW) Op: Not yet specified	HPT	2016-2019
CEPC R&D	2-cell elliptical (SCC)	650 MHz	Coax, variable, capacitive, single-window	Test: CW 150 kW (TW & SW) Op: CW 300 kW	HPT and Cavity integration	2017-2019
HEPS	**QWR β=1 (SCC)**	**166.6 MHz**	**Coax, fixed, capacitive, single-window**	**Test: CW, TW 250 kW, SW 100kW** **Op: CW TW 200 kW**	**HPT and Cavity integration**	**2020-now**

Development history

- Tested: CW, 420kW
- Operate with beam stably over 8 years

500MHz-BEPCII

2006

- Tested at KEK: 1MW,1.5ms,5Hz

1300MHz-ILC

2010

- Operate stably during the beam commission
- Tested power: CW,100kW

162.5/325MHz-RFQ

2012

- Operate stably during the beam commission
- Tested power: CW,25kW

325MHz-Spoke
162.5MHz-HWR

2014~15

- Tested power: CW,150kW
- Clean assembly with cavity is available

650MHz-Elliptical

2016

- Double-window, adjustable
- Tested power: CW,70kW

1300MHz Elliptical

2017~18

- Tested power: CW,150kW
- Adjustable, clean assembly

650MHz Elliptical

2019

- Coax, fixed, capacitive, single-window
- Clean assembly
- Attended cavity HT

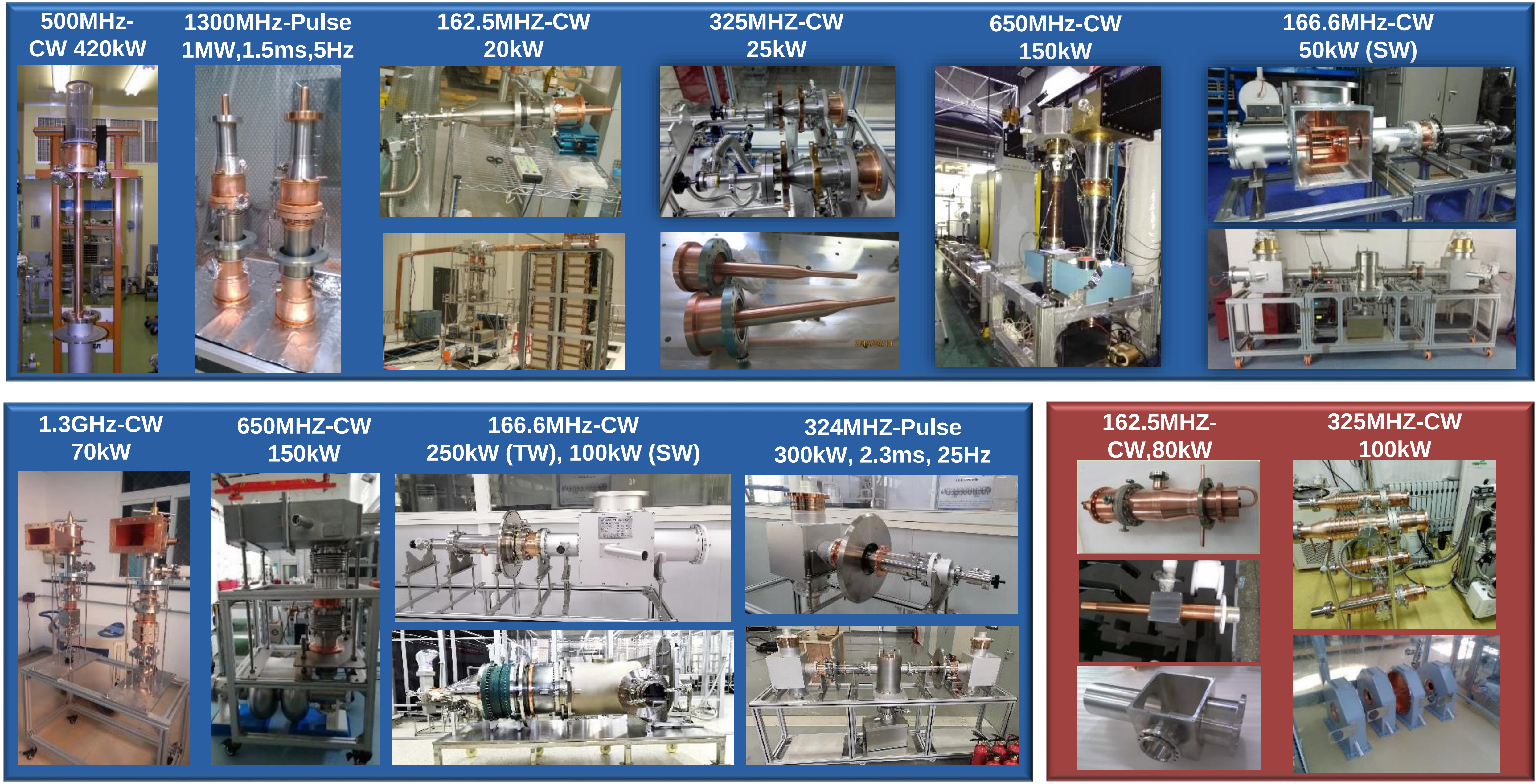
Test: CW, TW 250kW, SW 100kW
Op: CW TW 200kW

HEPS 166MHz SCC
Beta=1, QWR

2020~now

IHEP Input coupler gallery

SCC
NC



Power coupler for HEPS 166MHz SCC

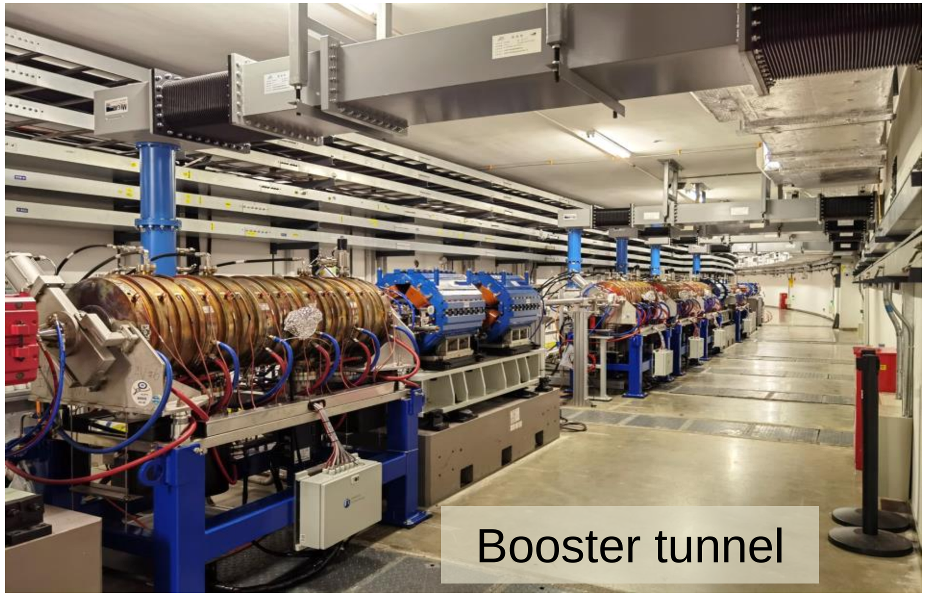
HEPS in Huairou Science City (Beijing)

- **High Energy Photon Source (HEPS)**

  - A diffraction-limited SR light source (4th-gen), 1st high-energy SR light source in China
  - **Main parameters:** 1360.4m circumference, linac + booster + SR, 6 GeV, 200 mA
  - **Construction time**: 06.2019 – 12.2025, **Location**: Huairou Science City, Beijing
  - **Budget**: 4.76 B CNY (~652 M USD)(incl. materials, civil constr. & commissioning, excl. labor costs)

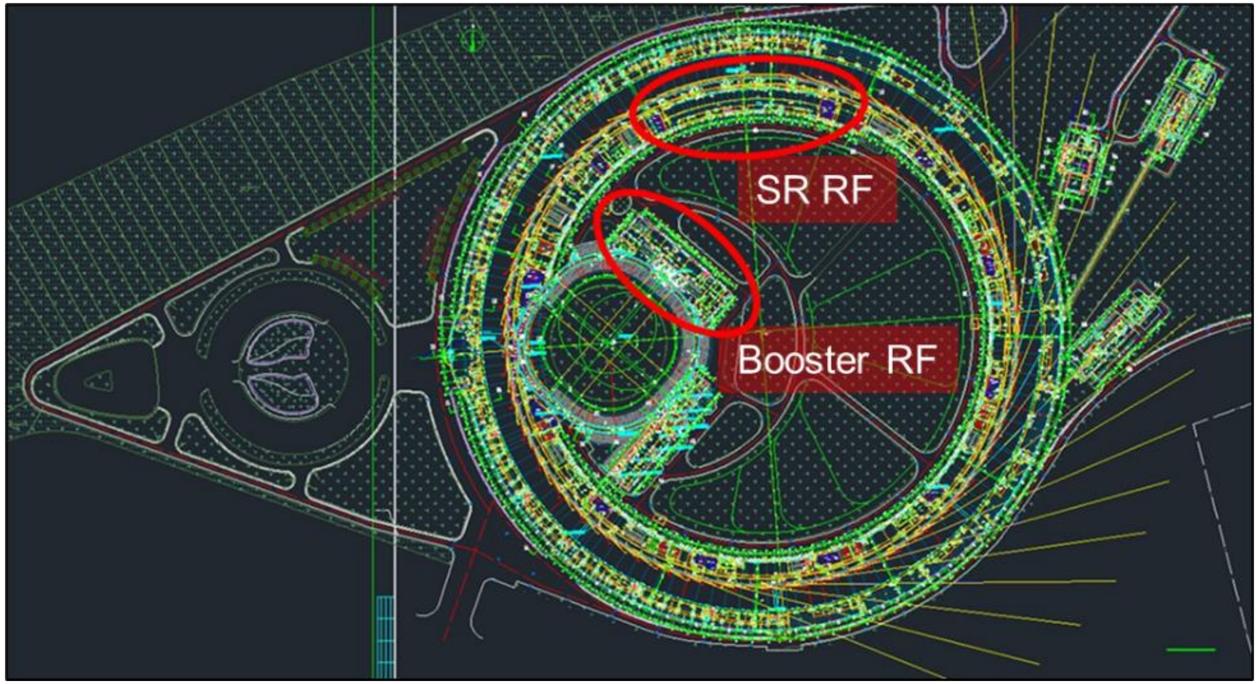
Milestones of HEPS

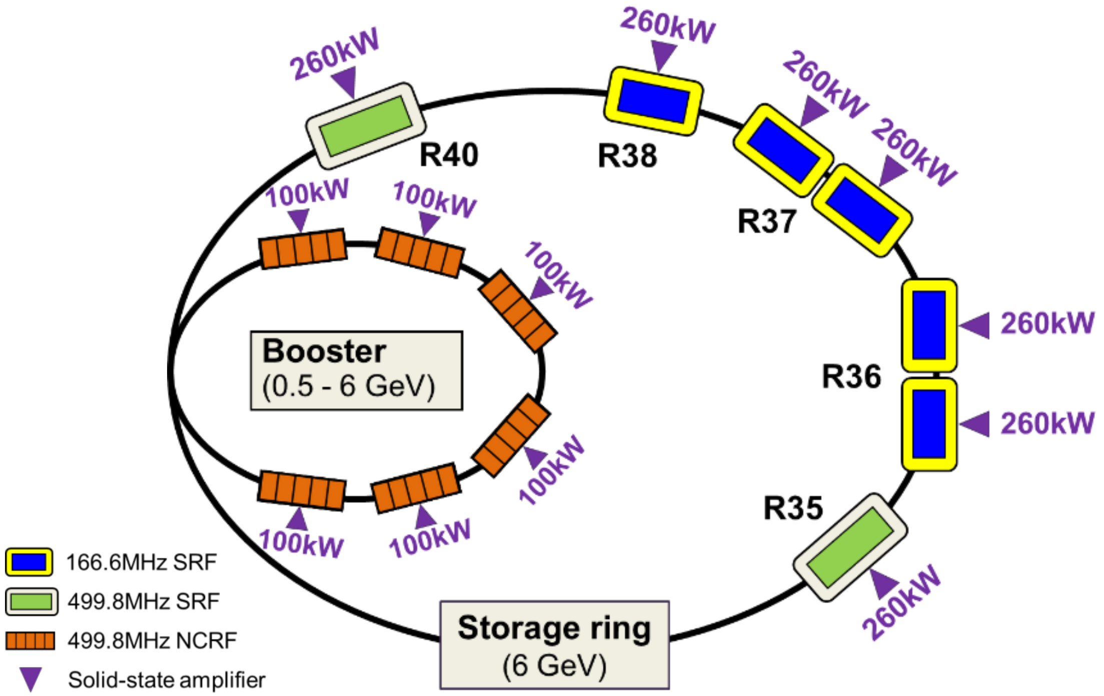
- **Groundbreaking in Jun 2019**
- Civil construction completed in Nov 2021
- PAPS completed in May 2021, currently in operation
- Booster installation completed in Jan 2023
- Storage-ring installation started in Feb 2023
- **Linac commissioned in Mar 2023**
- **Booster commissioned in Nov 2023**
- Storage-ring commissioning to be started in summer 2024



Main features of the RF system

- Double-frequency RF system: **166.6 MHz** + 499.8 MHz
- Active harmonic RF compatible for on-axis swap-out & on-axis accumulation injection schemes
- **SRF for the storage ring, normal-conducting RF for the booster**
- Heavy damping of higher order modes for storage-ring SRF cavities
- Solid-state power amplifiers for ring-RF transmitters, digital low-level RF control





Main RF parameters

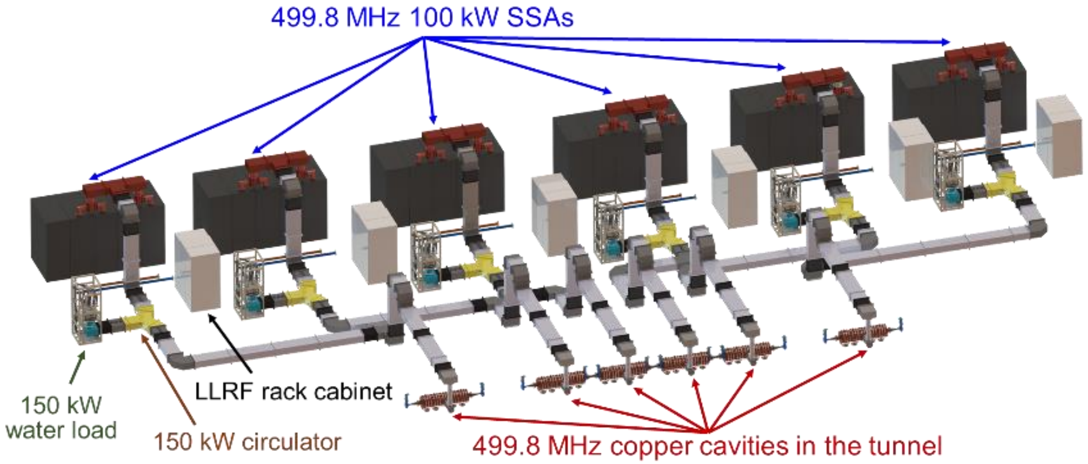
	BS	SR (main)	SR (HC)	Unit
RF frequency	499.8	166.6	499.8	MHz
Total RF voltage	2 – 8	5.4	0.91	MV
Cavity technology	Normal-conducting	Superconducting	Superconducting	-
Cavity type	5-cell	β=1 quarter-wave	1-cell elliptical	-
Technology readiness	Mature product	In-house new dev.	In-house exp.	-
No. of cavities	6	5	2	-
RF voltage per cavity	1.35 (op.) 1.9 (design)	1.2 (op.) 1.5 (design)	0.91 (op.) 1.75 (design)	MV
RF power per cavity (max)	70 (61 cav + 9 beam)	170	105	kW
Power spec. of FPC	100	250	250	kW
No. of transmitters	6	5	2	-
RF power per transmitter	100 (c.w.)	260 (c.w.)	260 (c.w.)	kW
Transmitter technology	SSA	SSA	SSA	-
LLRF control stability (p-p)	±1%, ±1°	±0.1%, ±0.1°	±0.1%, ±0.1°	-

High-power RF

Two frequencies; Two power levels;
Total RF power ~2.4MW

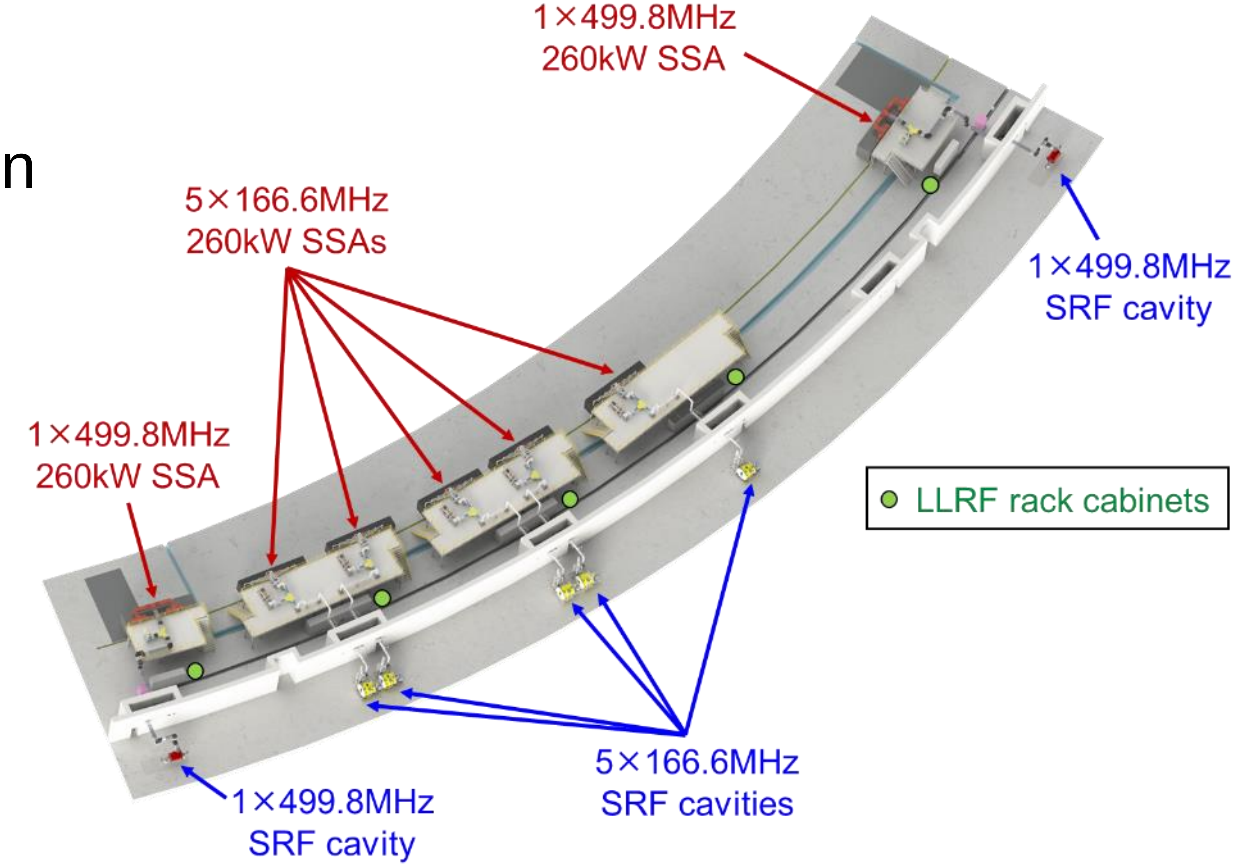
- Transmitter type: SSA
- Power transmission
  - 9-3/16” coaxial rigid lines for 166MHz
  - WR1800 rectangular waveguide for 500MHz
- High-power circulator for each RF station

Booster RF



RF hall surface area: 1600 m^2

Storage-ring RF



RF hall surface area: 2400 m^2

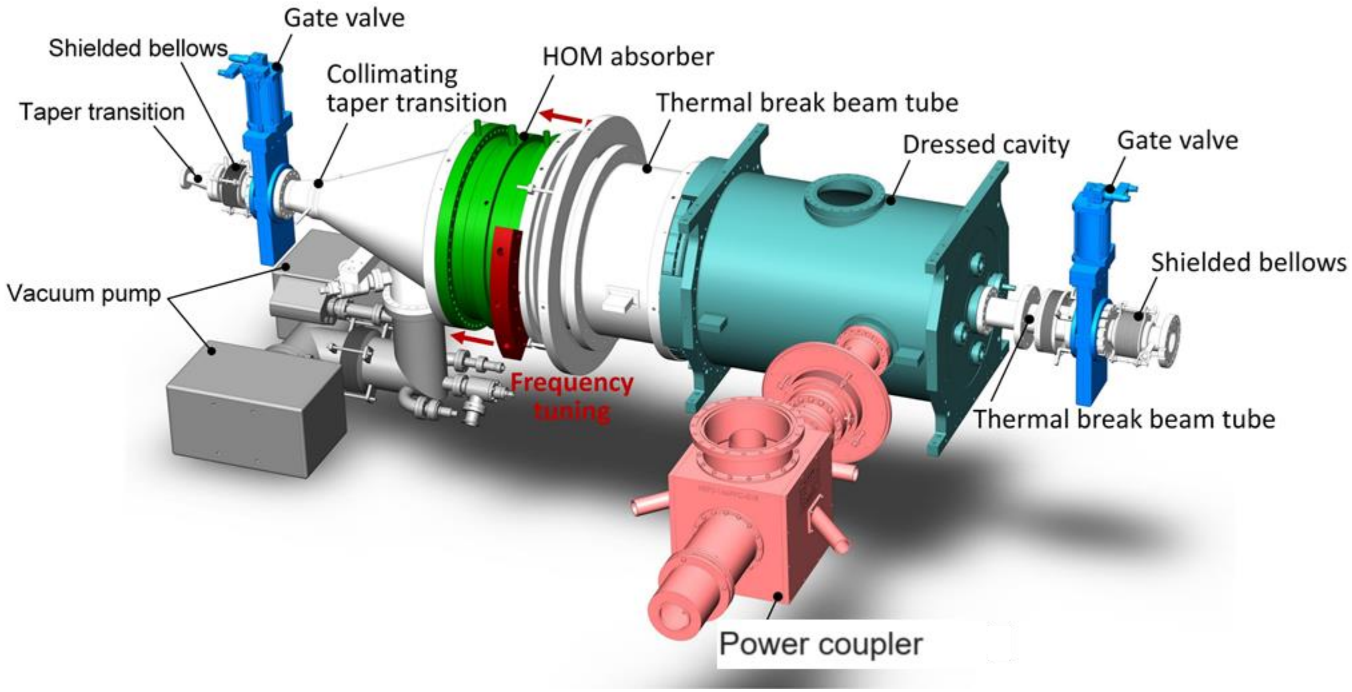
RF system Development

SR RF:
- SSA installed in Mar 2024,
- Commissioned in June 2024,
- Vacuum cleaning operation to be started in this month.

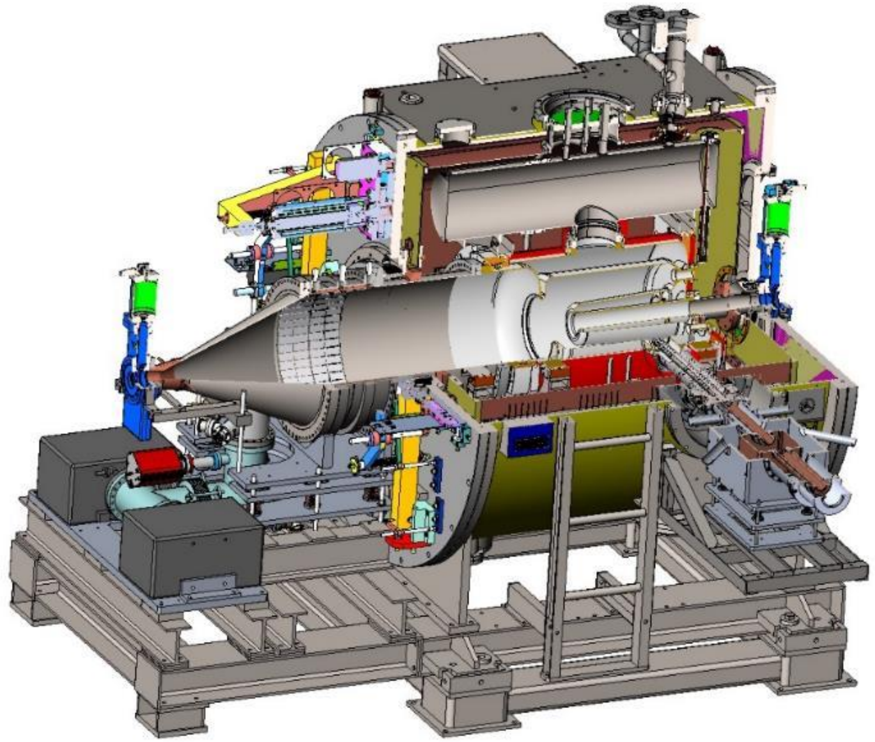
Booster RF:
- SSAs (100 kW * 5) installed in Jan 2023,
- Commissioned in Apr. 2023
- In operation since Jul. 2023, routinely at ~80 kW per SSA.

HEPS 166.6MHz SCC

The first low-frequency(166.6MHz), high-power(CW,170kW) **active** QWR SCC used to accelerate **Beta≈1** particles



166.6MHz SCC string



166.6MHz SCC cryomodule

Requirements and design criteria of FPC

Requirement	Design criteria
RF frequency: 166.6 MHz	- Coupler geometry: co-axial type - Interface with power source: coaxial rigid line, 9-3/16” - Difficult to avoid MP zones below nominal power → MP suppression
Power: 250 kW, CW	- Sufficient cooling to remove high RF power dissipation - Electric coupling instead of magnetic coupling - Single window
External Q: fixed, 5.0E4 (strong coupling)	- Position the coupler on cavity body instead of beam pipe → less insertion - Optimize location of the coupler port and the ceramic to avoid window damage by electron bombardment due to cavity field emission
Minimum contamination from power coupler to SRF cavity	- Coupler’s vacuum part assembling with cavity in the same clean room - Vacuum part geometry: as simple as possible
Reasonable cryogenic heat load	- Delicate cooling design - Careful optimization of copper plating: thickness, RRR
Multipacting free	- TiN coating for ceramic - Adopt DC bias between inner and outer conductor
Safe operation	Sufficient diagnostics: vacuum, arc, electrons, temperatures, flow

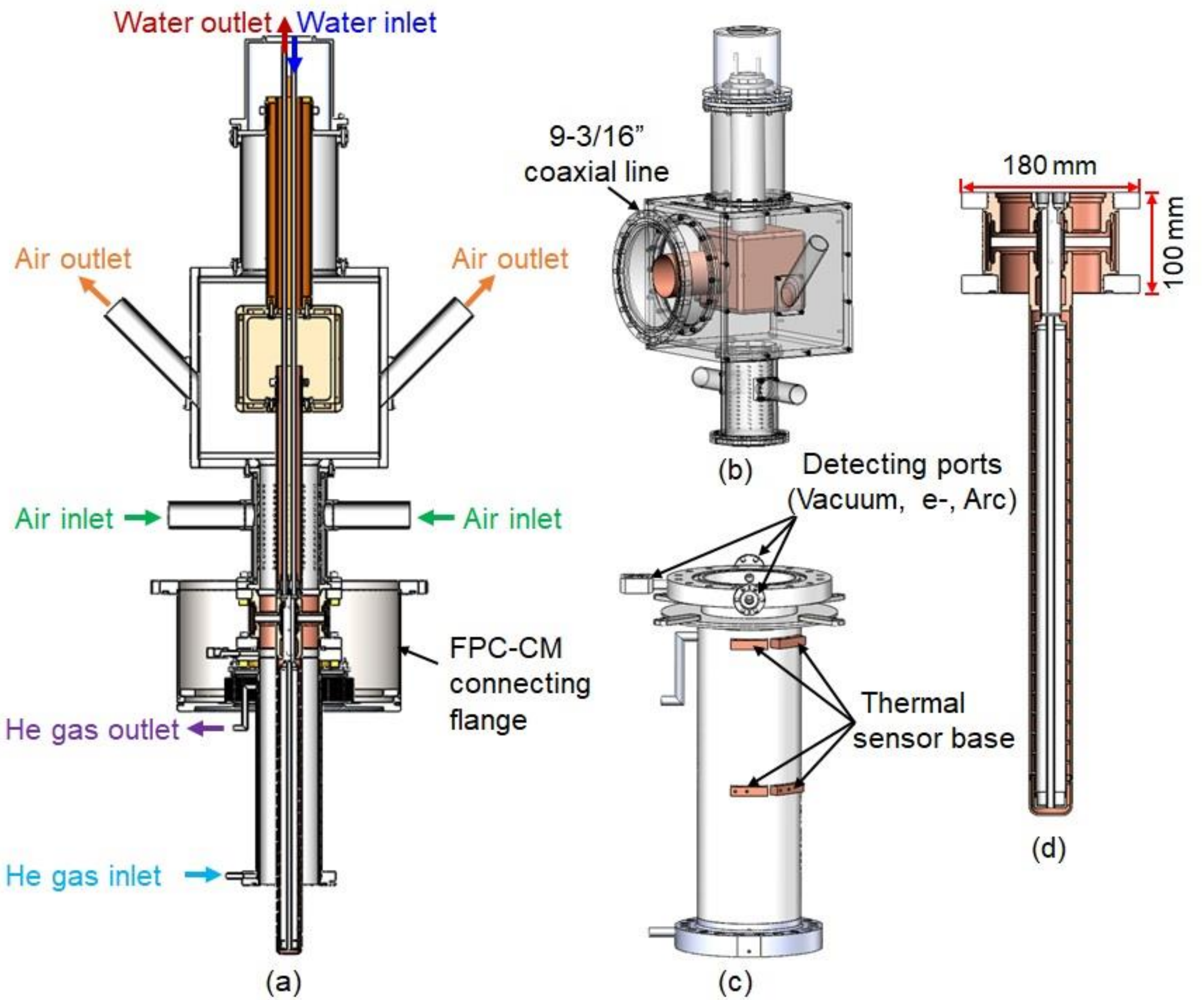
Challenges (compromise)

- High power level (CW 200kW) + On-cavity body location
- Potential window damage from cavity field-emitted electrons

High power level	Minimum FE damage risk	Low cryogenic heat load	Cleanroom assembly
↓	↓	↓	↓
High RF power dissipation and **high dynamic heat load**	Coupler's desired location **close to** cavity's H-end	Coupler's desired location **far away** from cavity's H-end	**Shorter** outer conductor and **limited** by cryostat size
	Large magnetic field leakage → **High dynamic heat load**	**Longer** outer conductor	

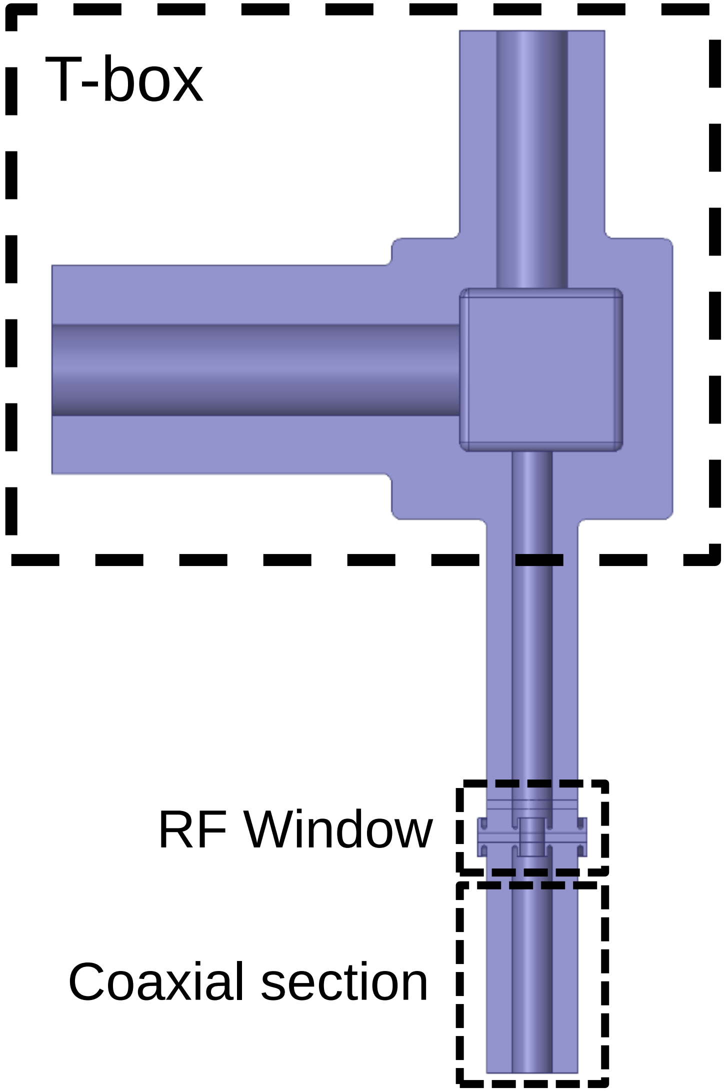
Main features

- **RF window**
  - Single window (Tristan-type)
  - Ceramic size: 27.4*120*10 mm
  - Ceramic material: 97.6% Al_2O_3 (Morgan AL-300)
- **Coaxial section**
  - OC: Double-wall structure
    - Φ: 100mm, length: 402 mm, Zc: 50 Ω
    - Thickness: 1mm SS + 20μm RRR30 copper plating
  - IC: Made of copper (OFHC)
- **Transition component**
  - T-box structure
  - Outer T-box dimension: 340*340*340 mm
  - DC bias: ±2000V
- **Cooling**
  - Inner conductor (vacuum part): water
  - Outer conductor (vacuum part): cold helium gas
  - Inner conductor (air part): forced air
  - Inner T-box (air part): forced air
- **Detector**
  - Vacuum, electron current, arc

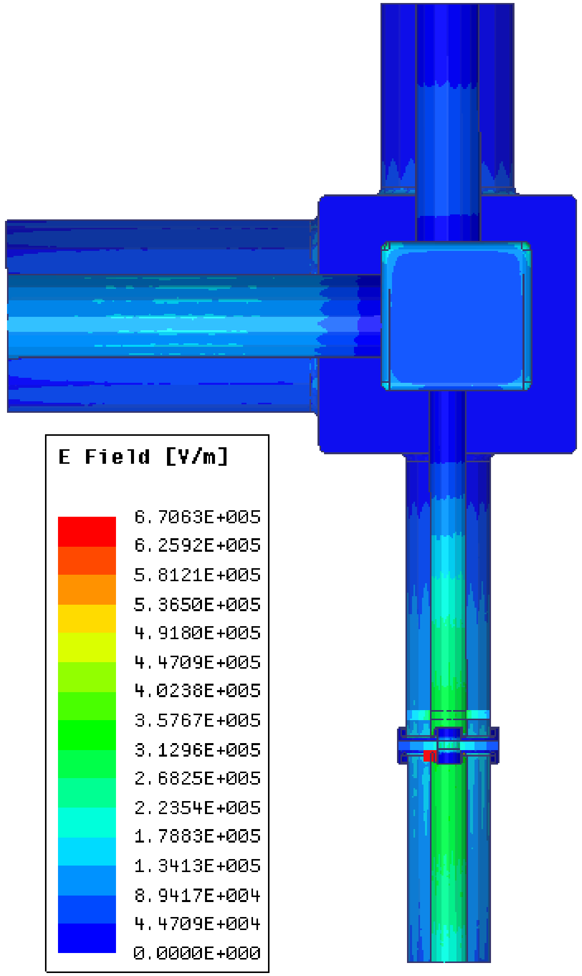


Power transmission optimization

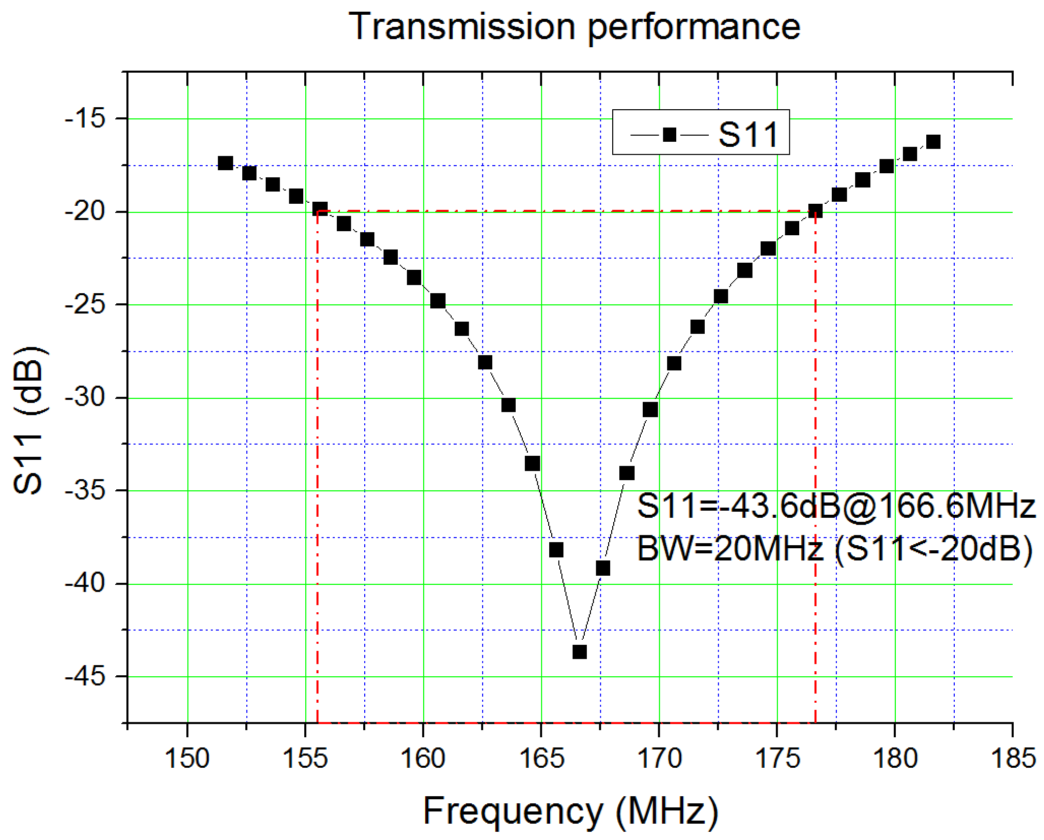
TW: travelling wave



Half RF structure



Emax=6.7E5 V/m at 300kW (TW)
Located at the inner choke tip

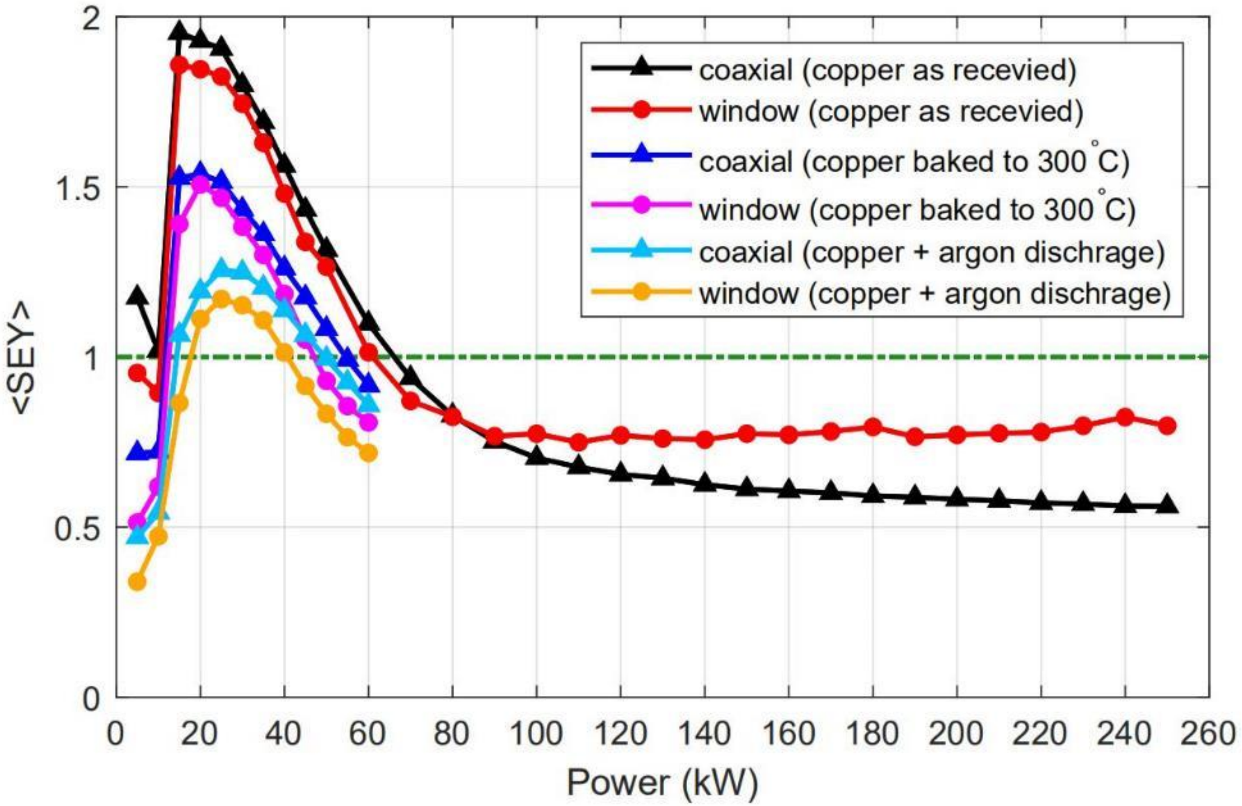


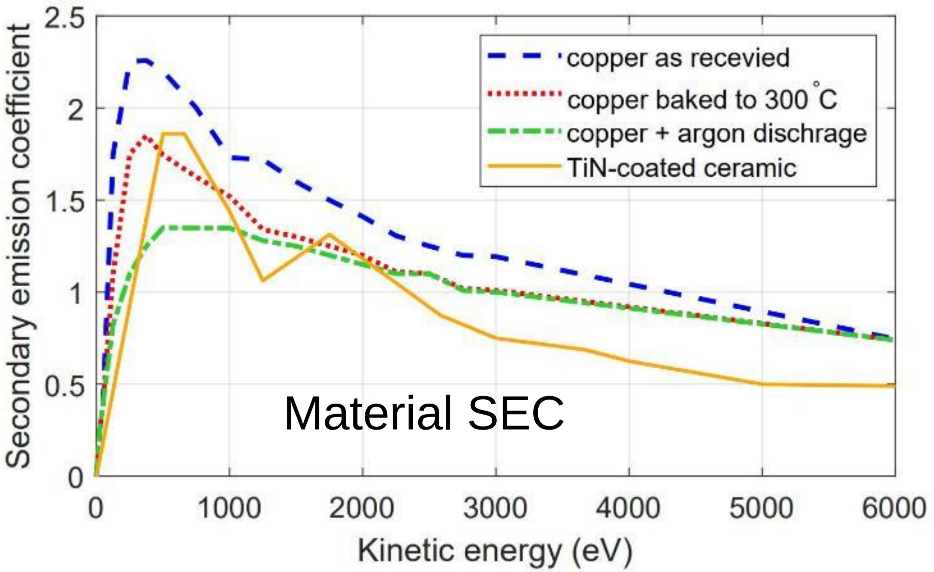
Calculated S11 vs frequency curve

Multipacting simulation

- Multipacting simulations carried out by using CST
- Hard multipacting barriers: 10 kW ~ 50 kW

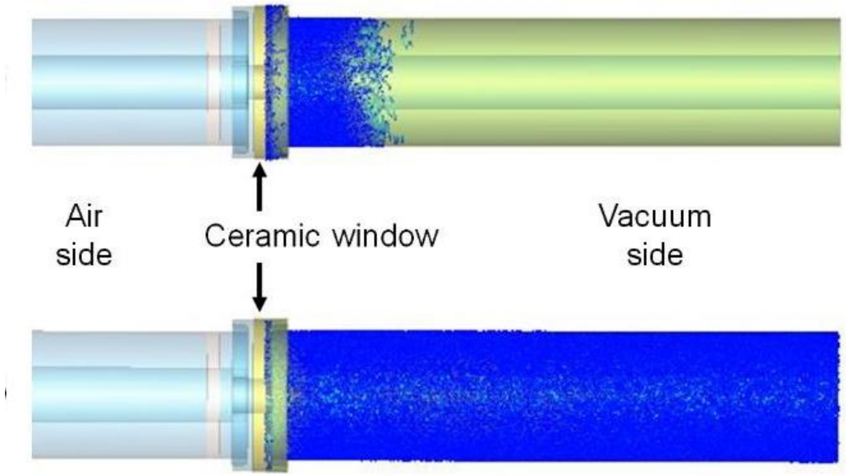
Normalized SEY curve





Material SEC

Electron trajectory



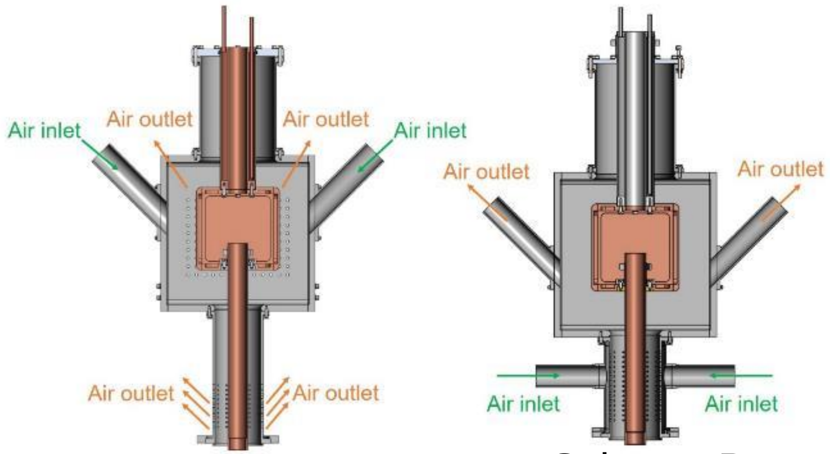
Cooling design: air part

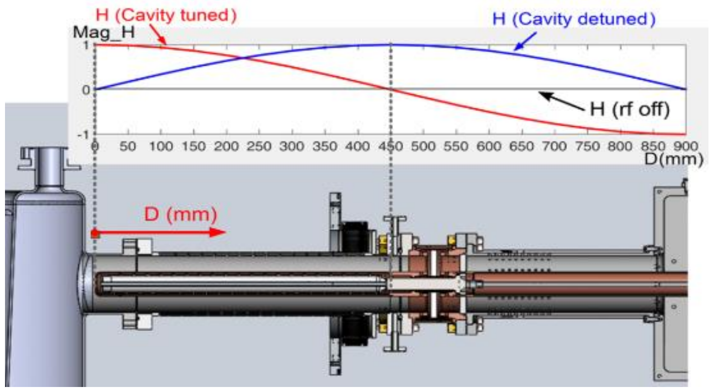
- Forced air cooling adopted: **100 m³/h**
- Two cooling schemes explored

 - On-cavity SW: Scheme A is better

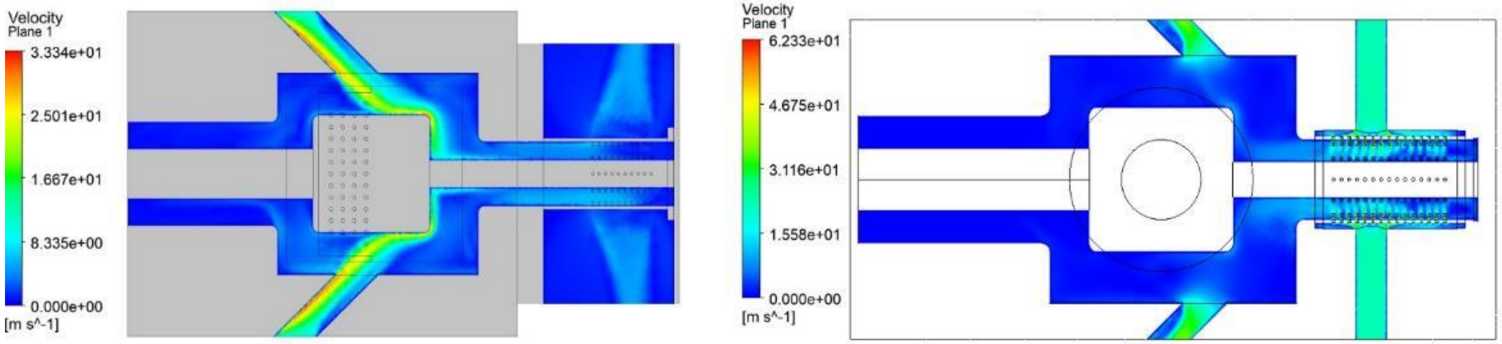
 - TW: Scheme B is better

The cooling scheme selection principle: making the "fresh" airflow firstly reaching the area with the largest power density.





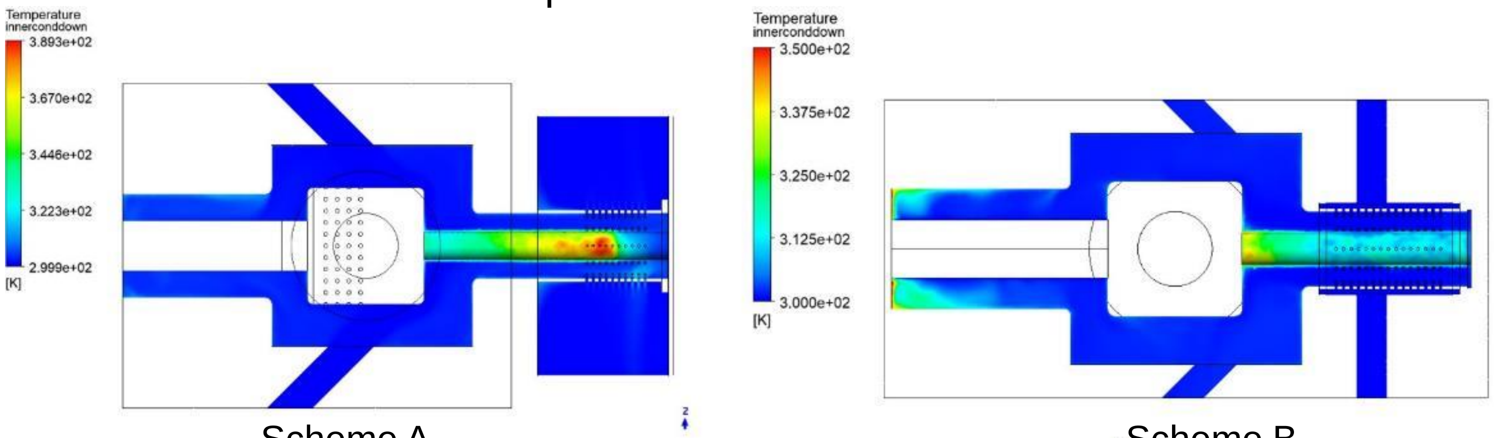
Simulated air velocity with a flow of 100 l/min



Scheme A

Scheme B

Simulated temperature at CW 200kW in TW mode



Scheme A

Scheme B

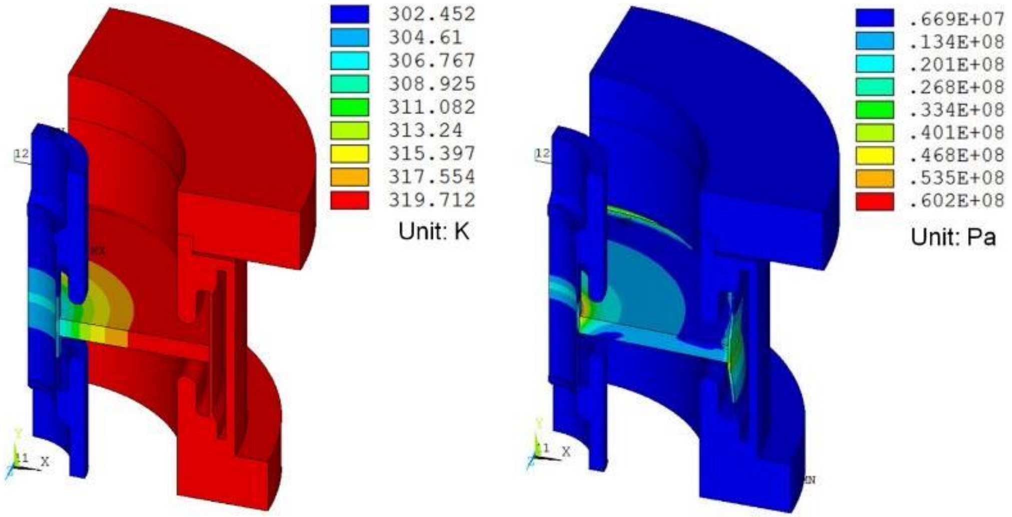
Cooling design: window

- Cooling water flow rate: 1.5~3.0 l/min
- Max. temperature reached **47°C** in TW-400kW, located on the ceramic close to the outer window
- Max. stress reads **60.2MPa** on the window joint: well below the specified flexural strength of alumina ceramic (296 MPa)

AL-300 properties

Parameters	Value
Content	97.6% Al_2O_3
Flexural strength	**296 MPa**
Thermal conductivity	26.8 W/m.K
Tan δ	4E-4 @10MHz, 25°C

Parameter	Cal. by HFSS	Cal. by ANSYS
S11 at 166.6 MHz	-28.4 dB	-28.4dB
S21 at 166.6 MHz	-0.0067 dB	-0.0064 dB
Ceramic dissipation at 400kW, TW	33 W	33 W
Inner window dissipation at 400kW, TW	38.6 W	53.7 W
Outer window dissipation at 400kW, TW	13.4 W	



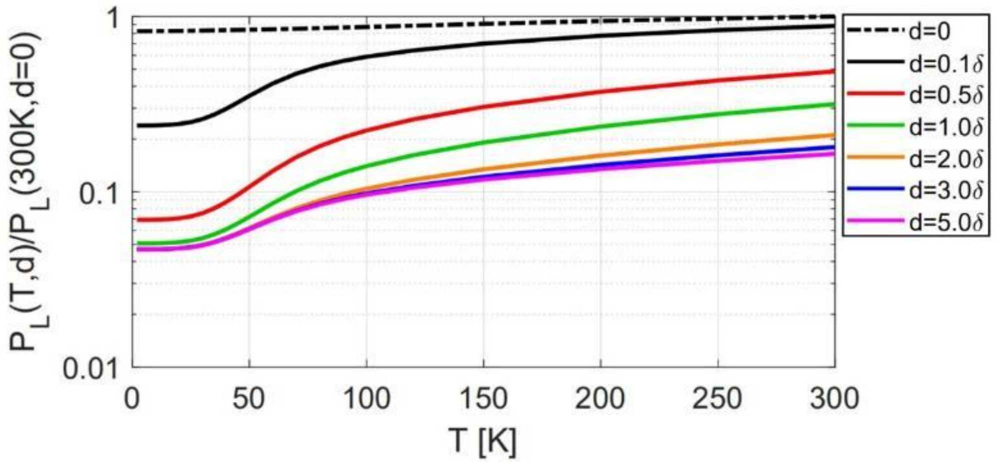
(a) Temperature (b) Stress

Cooling design: outer conductor

- Outer conductor: only 400 mm long, located close to high H-field area → **high cryogenic heat load, quench risk**
- Copper plating: thickness(>3δ,20um); RRR(30)
- Cooling method: thermal anchor or cold helium gas?

- After careful analysis, cold helium gas cooling (50 sl/min, 7 K) chosen to obtain less cryogenic heat load

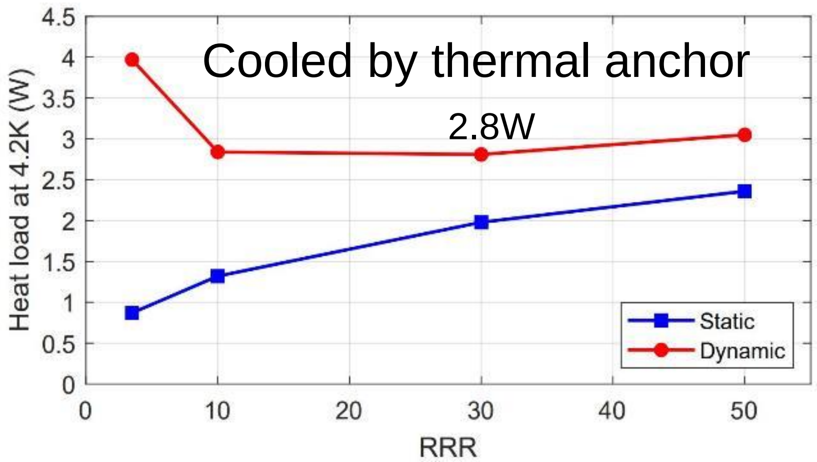
Power dissipation on the copper-plated surface with different thicknesses from 2 K to 300 K (RRR = 10).



The calculated heat load cooled by GHe

GHe flow rate (sl/min)	4K heat load (W)
0	17.7
5	5.8
15	2.0
30	1.5
50	**1.2**

Heat loads at 4.2 K of the FPC outer conductor with optimized 80 K thermal interception (copper plating thickness: 3*δ,* CW 200kW in TW)



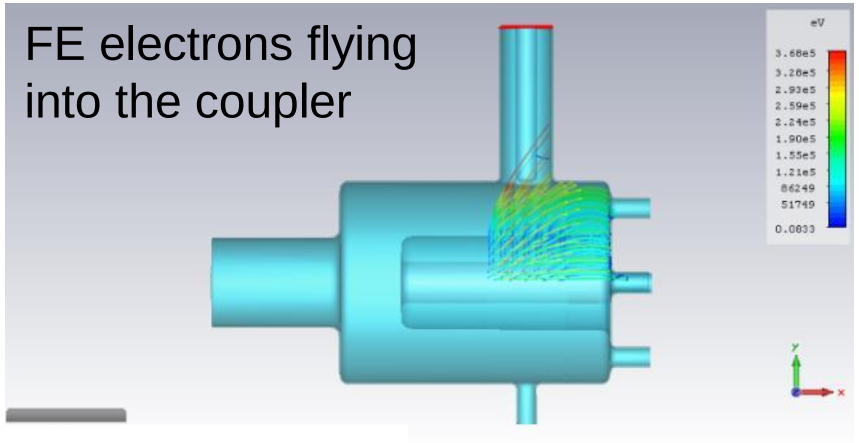
Coupler and window position optimization

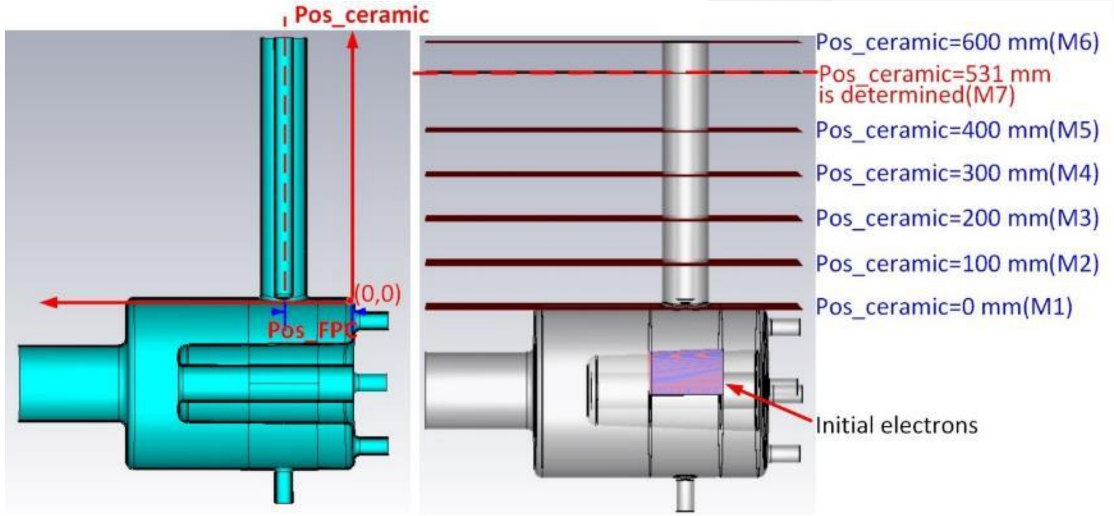
- FE electrons accelerated by transverse E-field may hit the ceramic → **Ceramic crack**
- Trajectories of FE electrons were tracked and recorded

Final choice

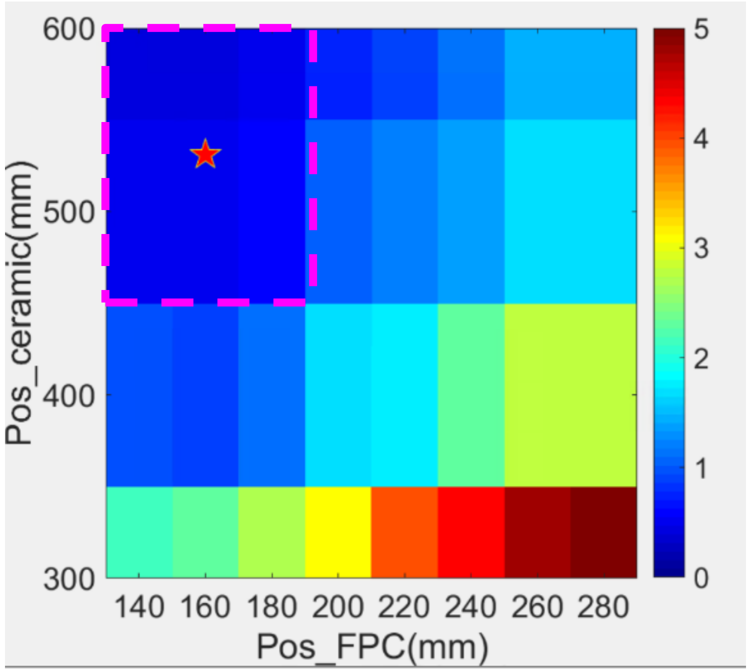
Pos_FPC = 160 mm

Pos_ceramic = 531 mm





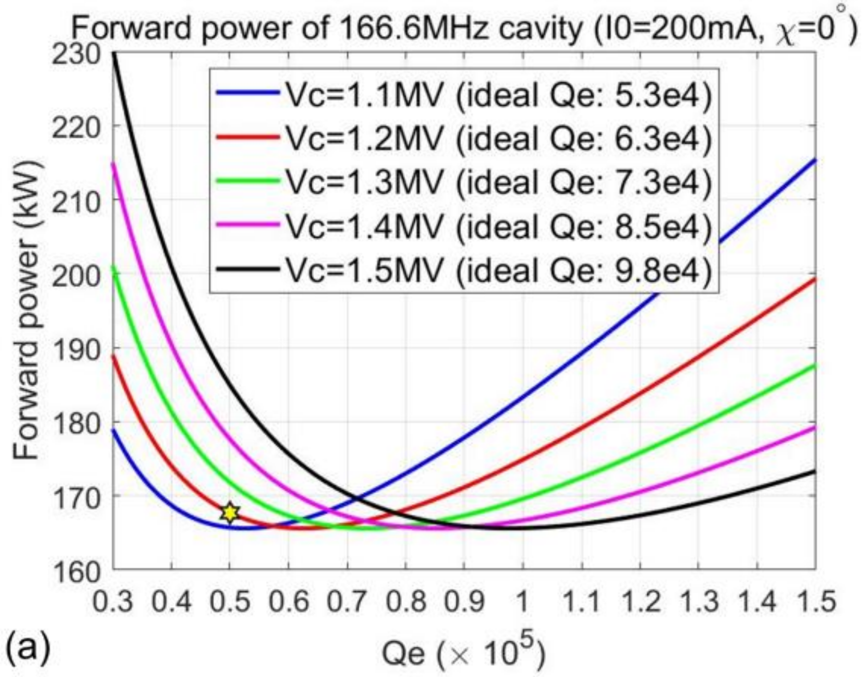
Average electron numbers

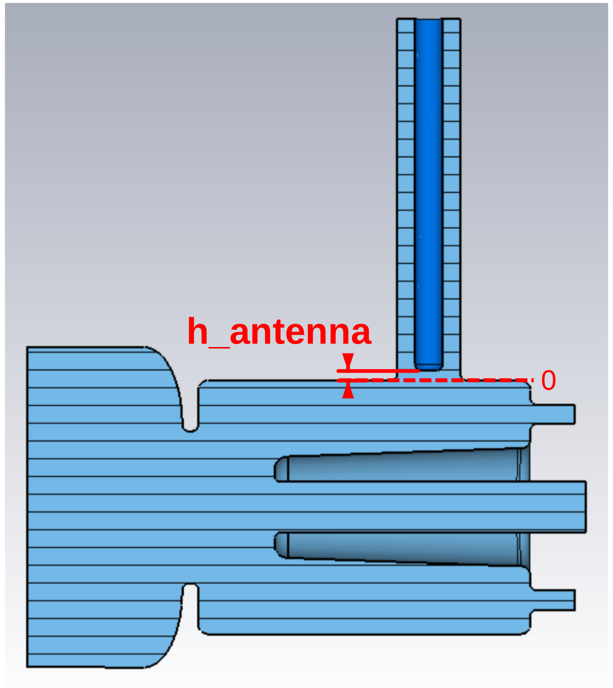


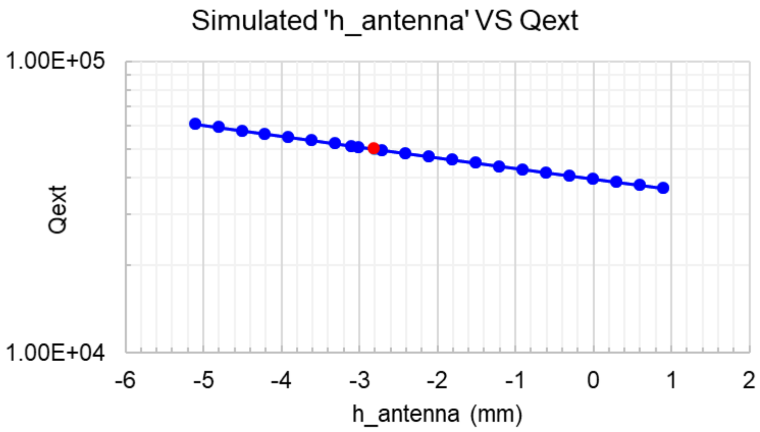
The ceramic window shall be arranged inside the area marked by pink dashed lines.

Coupling (Q_{ext})

- Coupling was chosen to be 5.0E4 instead of 6.3E4 (ideal coupling)
  - To achieve a higher Robinson-limited beam current：250mA (>200mA)
  - For low Vc operation (<1.2MV) in case of cavity degradation
- Insertion (h_antenna) determined based on simulation





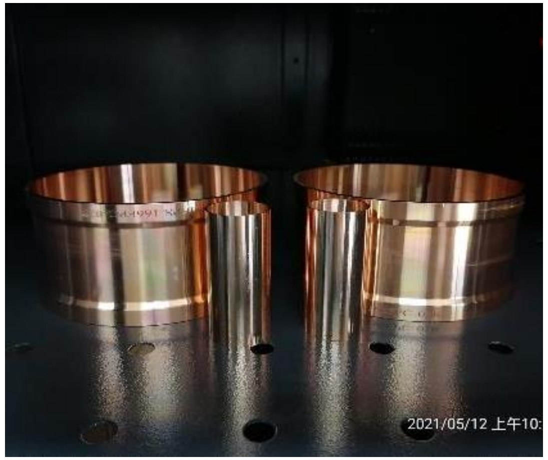


Simulated Qext		Measured Qext	
h-antenna -2.81mm*	h-antenna -3.11mm**	Before cooling	After cooling
5.02E4	5.15E4	5.14E4	5.21E4

*: AlMg gasket: compressed by 0.3mm
**: AlMg gasket: no compression
Negative means no insertion into the cavity inner volume

Fabrication

- Two 166MHz prototype couplers were fabricated at Beijing HE-Racing Technology (HERT) in 01.2022.



Window frame

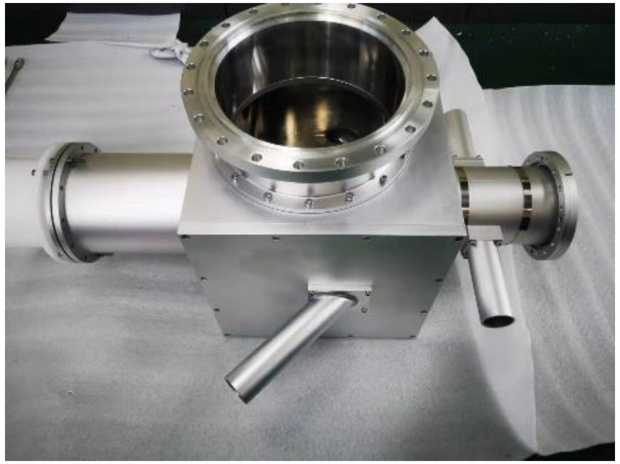
Window after 1st brazing


Outer conductor


Coupler during assembly


Window


Window-IC assembly


T-box


Whole coupler

High-power test record

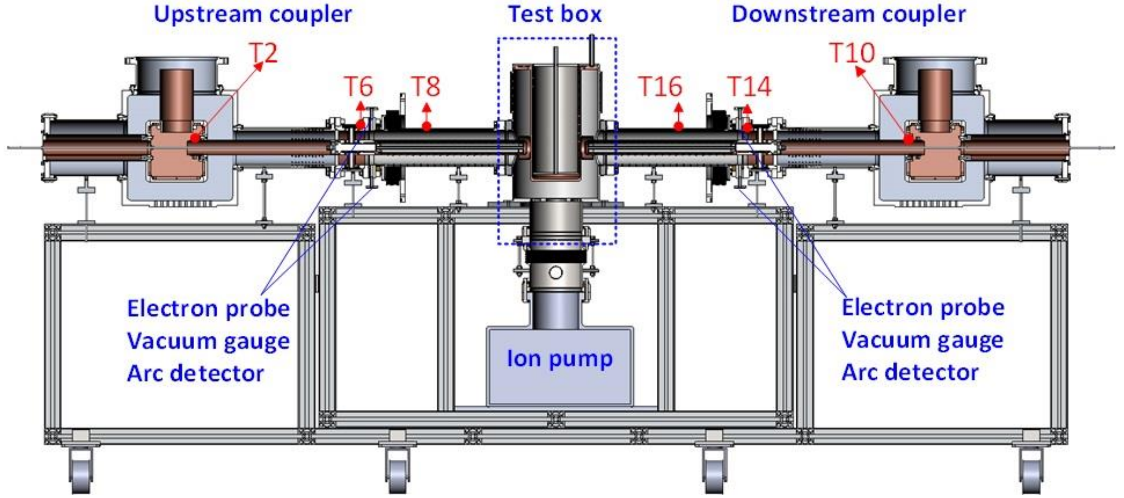
Coupler	Stage	Power source	Mode	Max. power reached	Description
PoP (2017~2018)	Stage I (2017.09)	166.6MHz 50kW SSA	TW & SW	CW, 50 kW	**On test box** Power limited by SSA
	Stage II (2018.04)	650MHz 150kW SSA	TW	CW, 150 kW	**On test box** Use a modified test stand
	Stage III (2018.12)	166.6MHz 50kW SSA	SW	CW, 50 kW	**On SC cavity at 4K and 2K** Horizontal test of 166MHz PoP cavity
Prototype (2019~2023)	Stage IV (2022.02)	166.6MHz 260kW SSA	TW & SW	TW: CW 250 kW SW: CW 100 kW	**On test box** SW phase moved in a step of 1/16 λ over 1/2 λ
	Stage IV (2023.11)	166.6MHz 260kW SSA	SW	CW, 100 kW	**On SC cavity at 4K** Horizontal test of 166MHz HOM-damped cavity

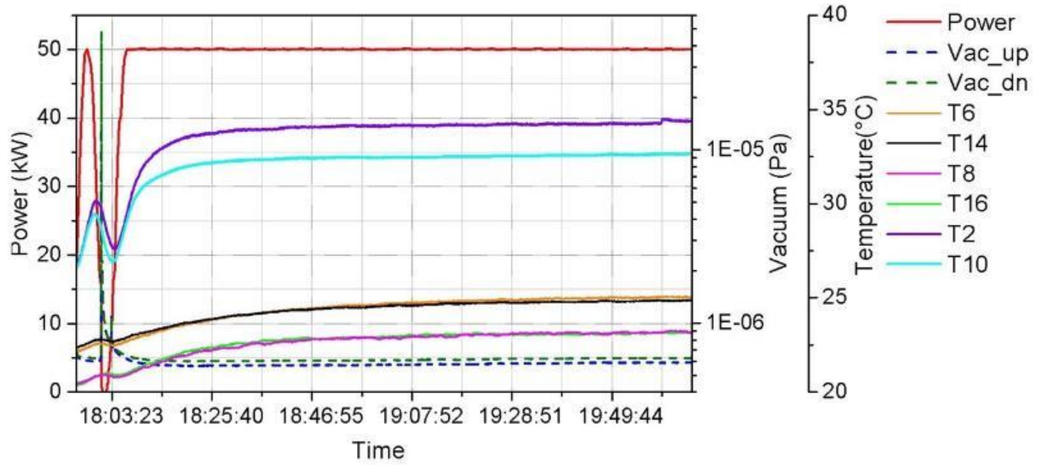
SW: standing wave, TW: travelling wave

PoP: 166.6MHz-50kW on test box

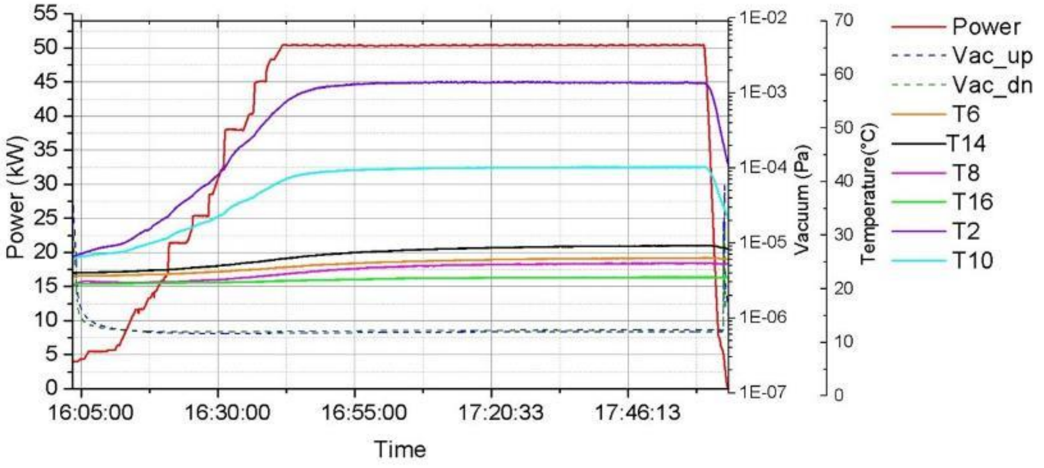
2017.09

- **Travelling wave (TW) mode**
  - Conditioned up to CW 50kW took **78 hours**
  - Temp. rise of window: **0.6°C/10kW (simu.: 0.5°C/10kW)**
- **Standing wave (SW) mode**
  - Phase shift: **1/8λ (step) * 4 positions** (over 1/2λ range)
  - Power keeping with Epeak positioned on ceramic window
  - Temp. rise of window: **1.0°C/10kW**
- **During 50kW power keeping (TW & SW)**
  - Vacuum **< 7E-7Pa**
  - No MP induced electrons or Arc discharging observed





(a) 166.6MHz 50kW cw power keep in travelling wave mode



(b) 166.6MHz 50kW cw power keep in standing wave mode

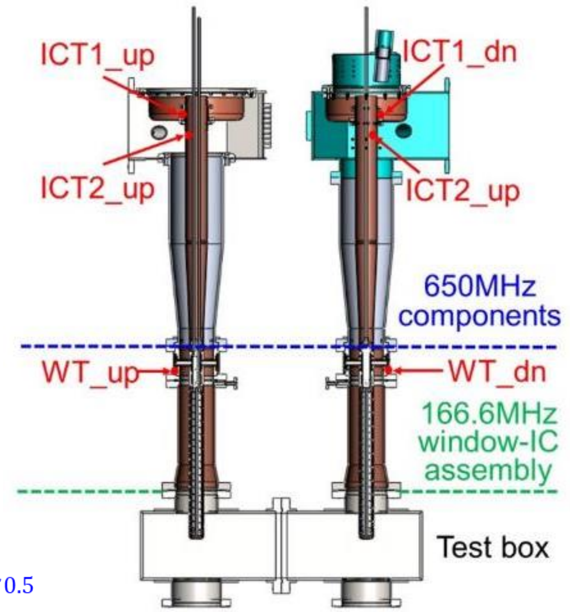
T. Huang *et al.*, *Rev. Sci. Instrum.* 91, 063301 (2020).

PoP: 650MHz-150kW on test box

2018.04

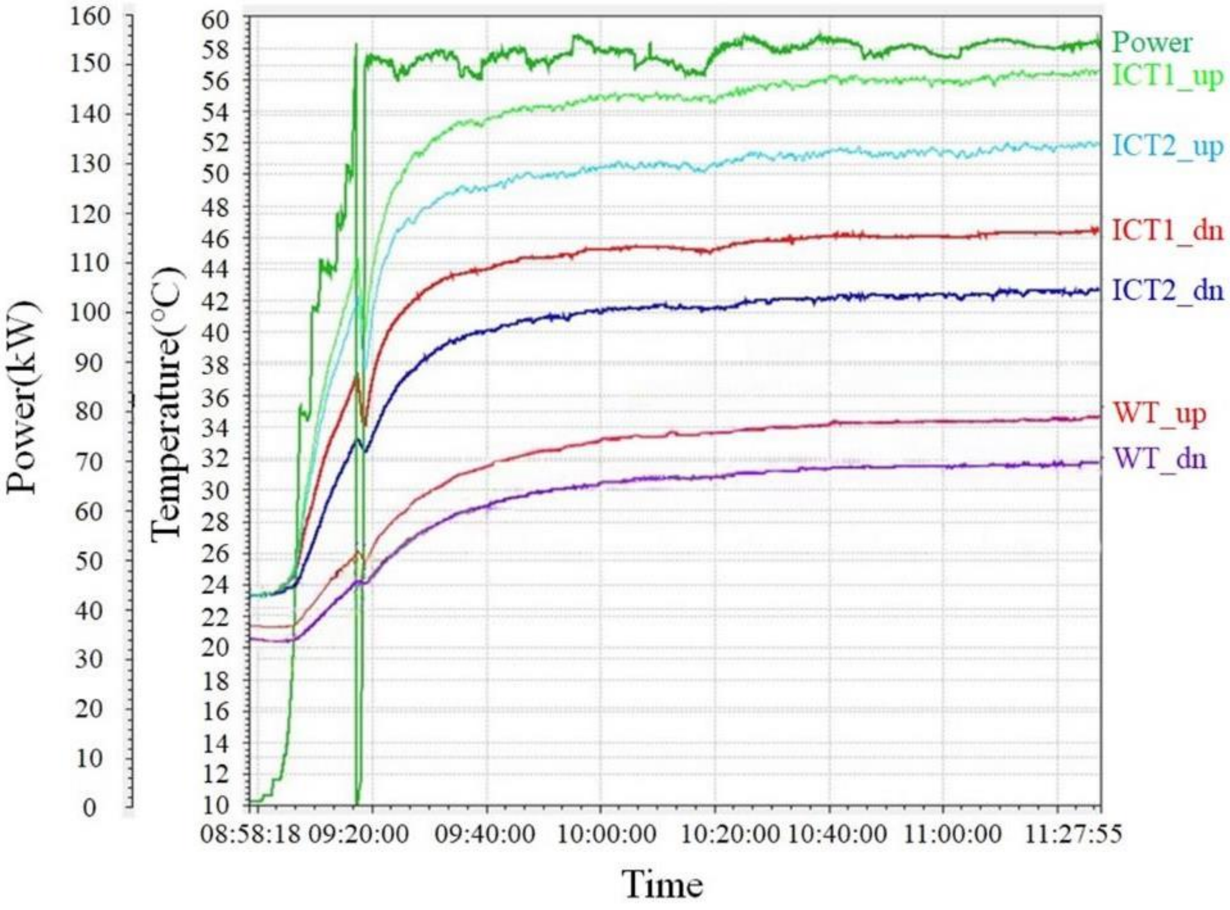
- Conditioning went smoothly and took only 23 hours to reach 150 kW CW power in traveling wave mode
- Temperature rise of window: **1.2°C/10kW**

Hybrid test bench



Dielectric loss: $\sim f$
Metal surface loss: $\sim f^{0.5}$

Test results during power keeping at 650 MHz CW 150 kW in traveling wave mode



Scaled to 166.6MHz

	166.6MHz 50kW SSPA [kW]	650MHz 150kW SSPA [kW]
Ceramic window	50	585
Metal part	50	296

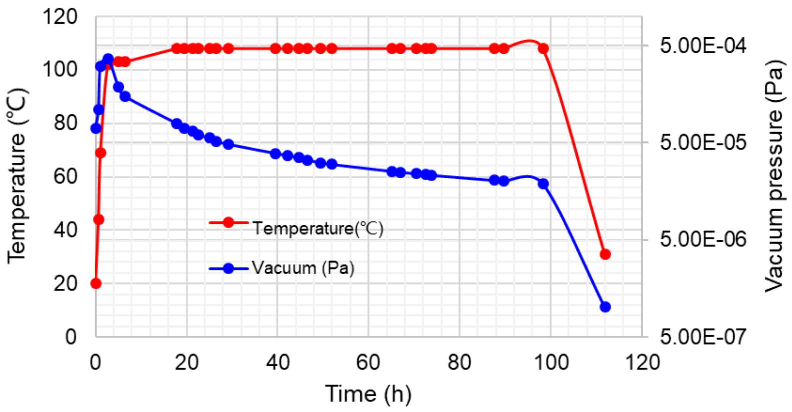
Prototype: 166.6MHz-250kW on test box 2022.02

- Entire test bench assembled and high-power tested in clean room
  - Reception: Class 10000 (ISO 7)
  - Cleaning: Class 100 (ISO 5)
  - Bake out: custom-made baking oven, Class 100 (ISO5)
  - Vacuum part assembly: Class 10 (ISO 4)
  - High-power test: Class 100 (ISO 5)
  - Vacuum part disassembled after conditioning: Class 10 (ISO 4)
  - Storage after conditioning: N2 cabinet in Class 100 (ISO5) clean room

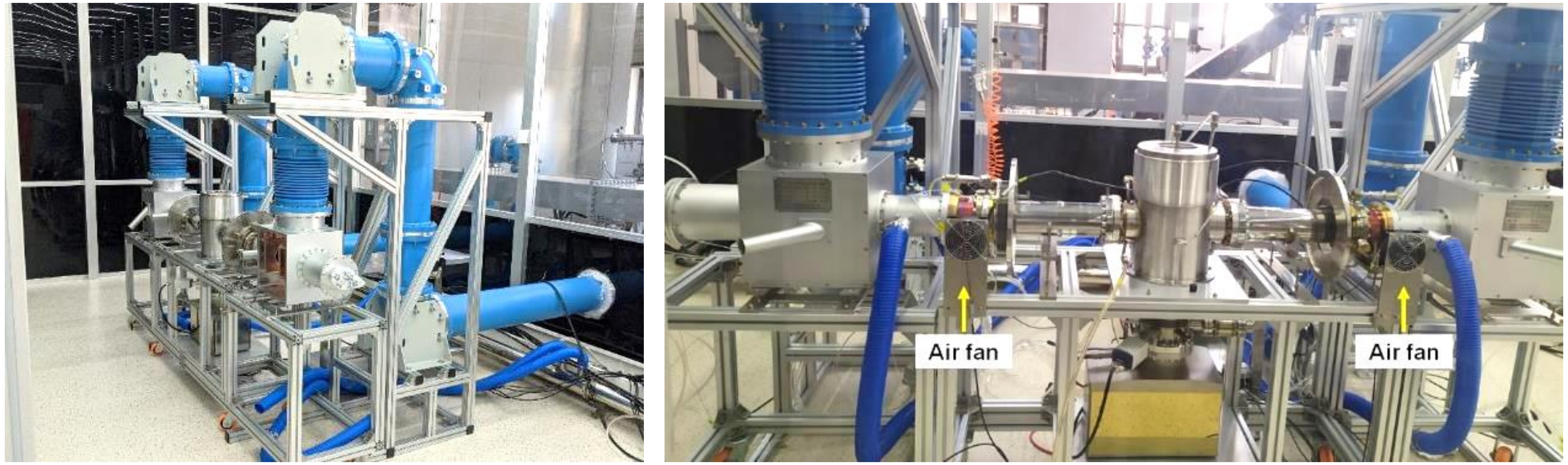
Maximum cleanliness is ensured !

Baking oven
(in Class 100 clean room)

The baking process of the 1# & 2# 166MHz FPC



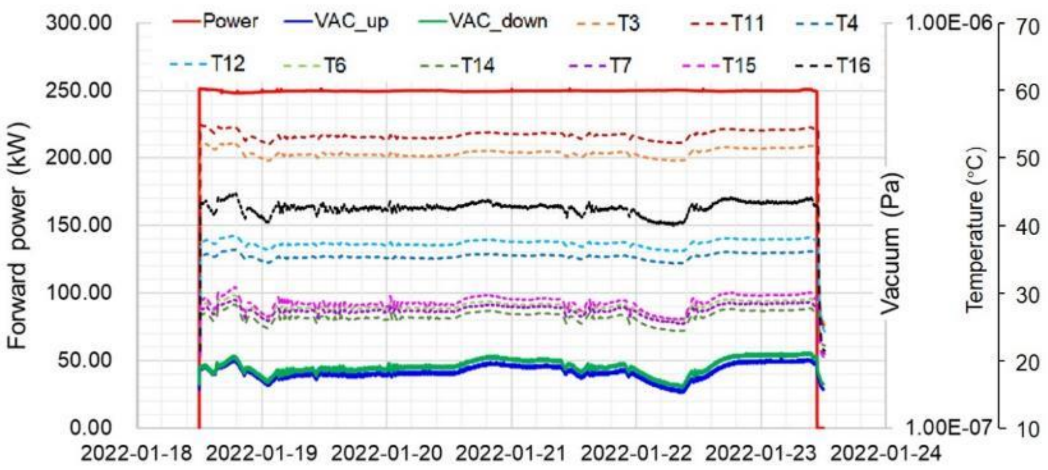
110°C, 112 hours



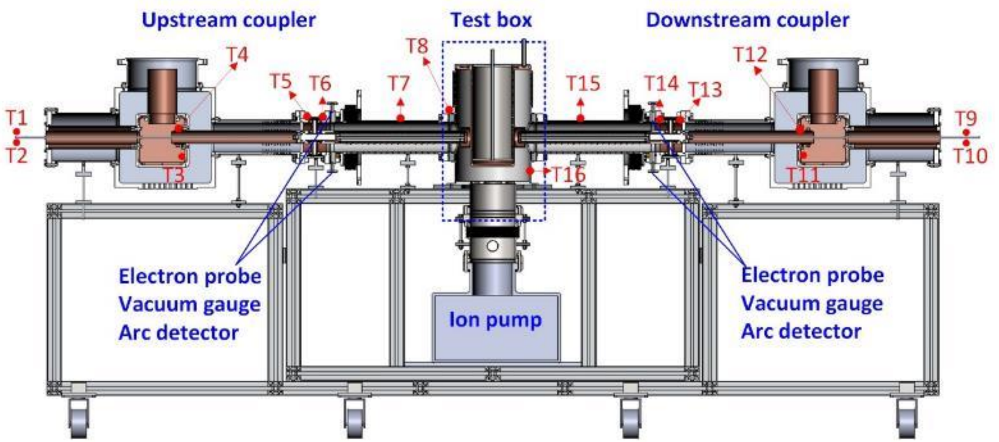
Test bench setup in Class 100 clean room (ISO 5)

Prototype: 166.6MHz-250kW on test box 2022.02

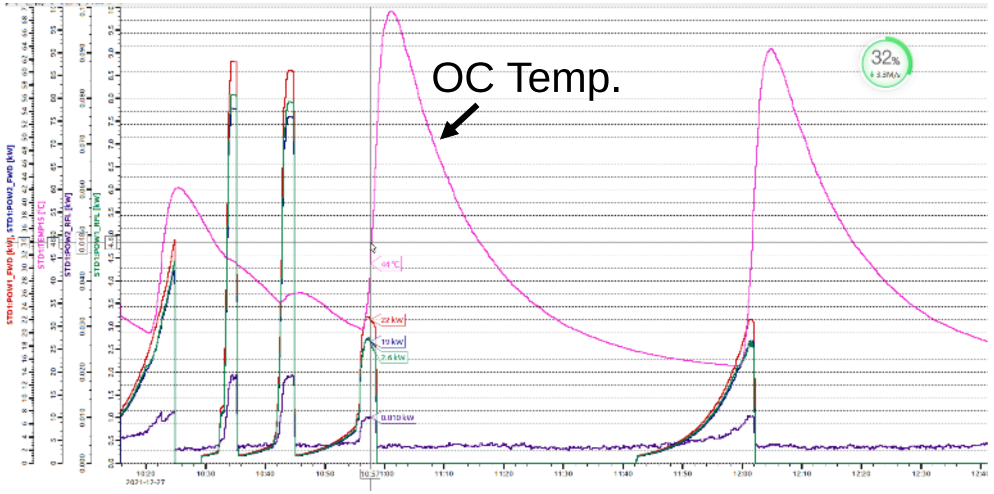
- **TW mode**
  - Conditioned up to CW 250kW took **100 hours**
  - Initial conditioning: sharp temp. rise on OC observed (no cooling)
  - Power keeping at CW 250kW for 120 hours
  - Max. T of window: **29 °C** (Ambient T: 22 °C)
- **SW mode**
  - Phase shift: **1/16λ (step) * 8 positions** (over 1/2λ range)
  - Conditioned up to CW 100 kW
  - Power keeping for 1 hour at each phase
  - Max. T of window: **35 °C** (Ambient T: 17 °C)



Vacuum and temperatures during power keeping at CW 250 kW in TW mode for 120 hours



Temperature sensor location



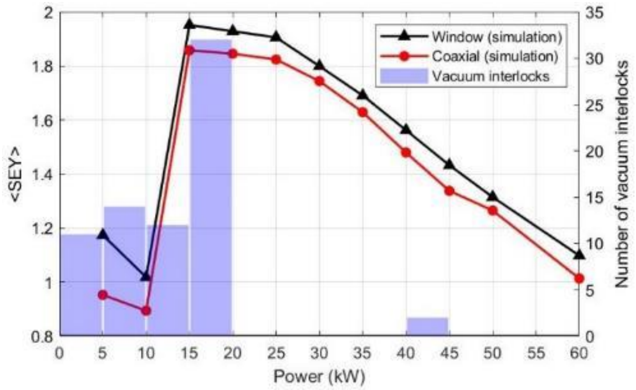
Sharp temperature rise on OC caused by MP

Multipacting validation (on test box)

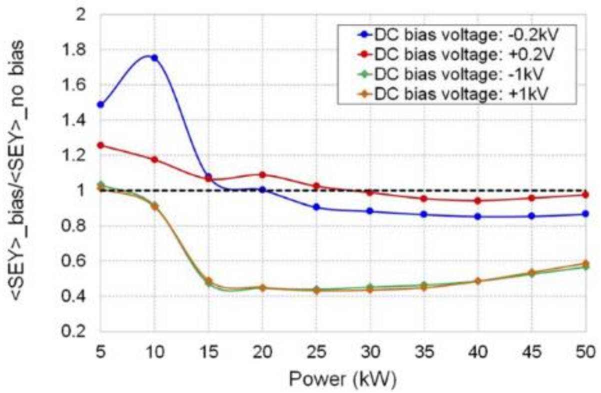
166MHz 50kW (on test box)

Agree well with simulation!

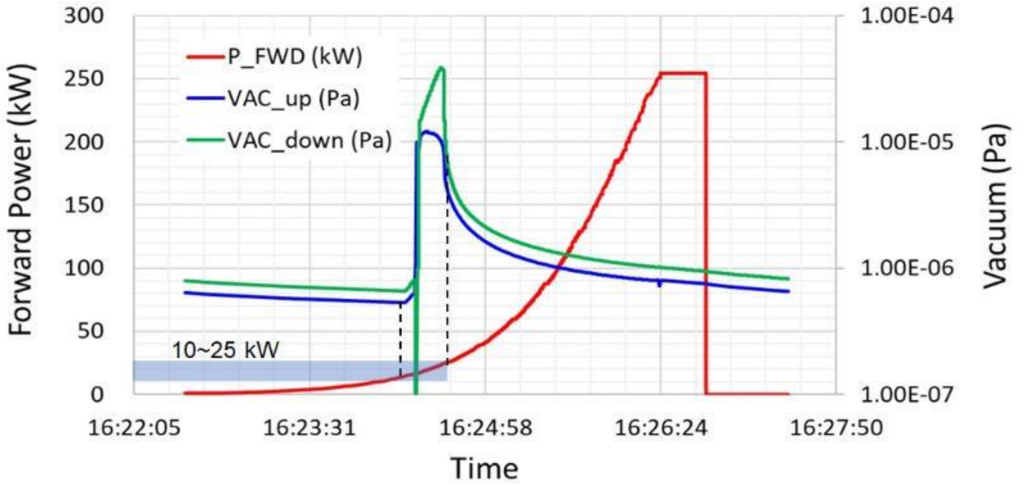
166MHz 250kW (on test box)



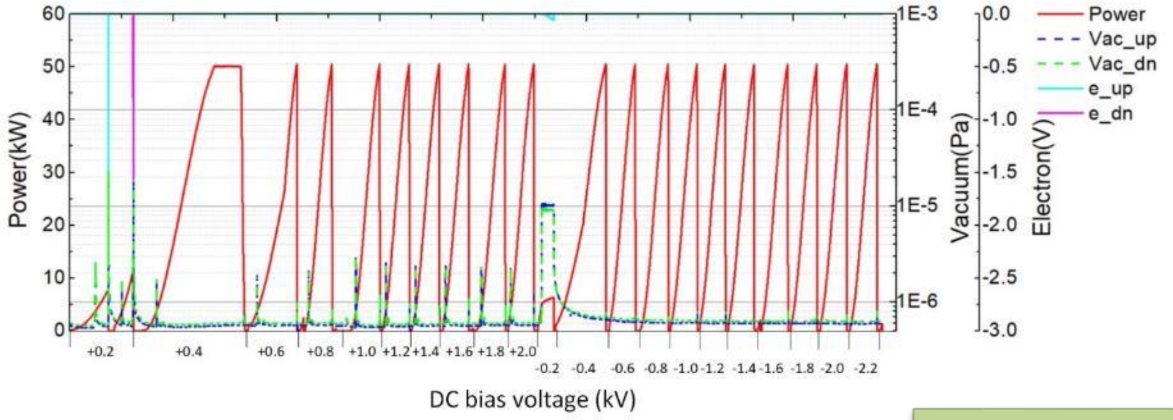
MP band observed: 15~20 kW



MP with DC bias simulated ±0.2kV → exciting new MP

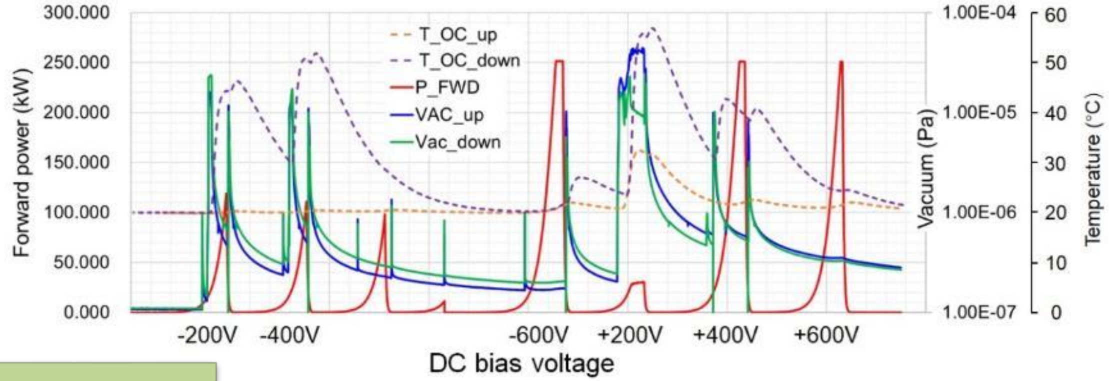


Hard MP band observed: 10~25 kW



MP with DC bias observed:
+0.2kV → fresh MP at 8kW,11kW
-0.2 kV → new MP at 5.5 kW

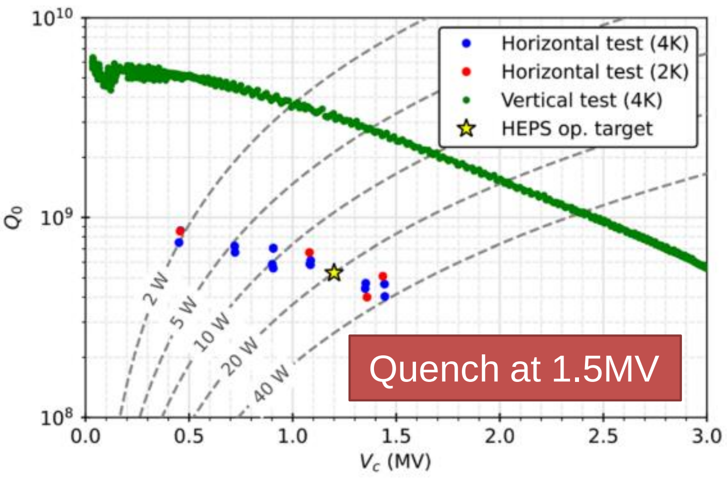
Operation with DC bias of +1.0~1.2kV is suggested.



MP-induced outgassing observed with DC bias between -0.6 kV and +0.4kV

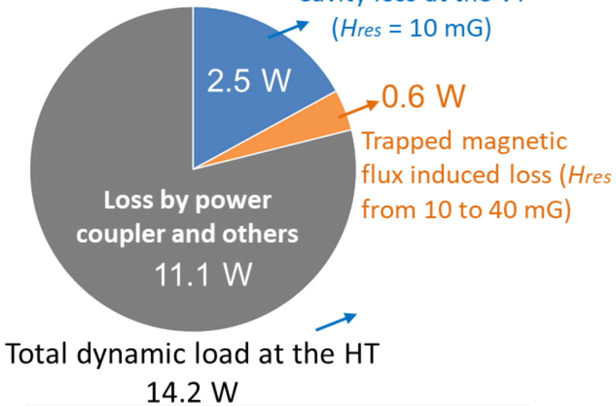
PoP coupler exception: overheating issue

2018.12



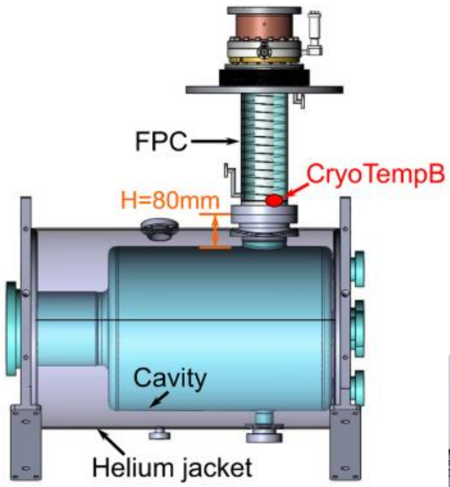
Large performance degradation

Vc=1.1 MV

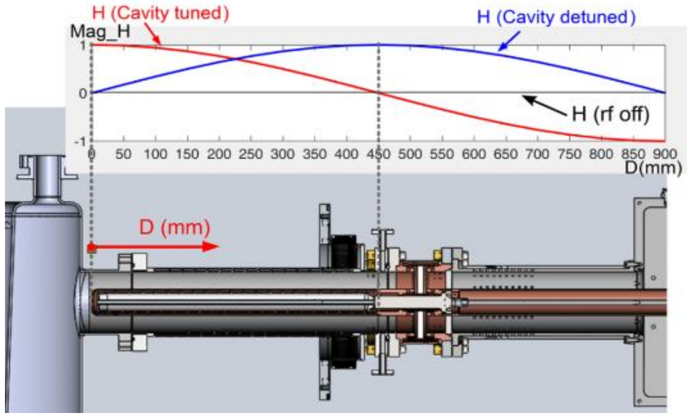


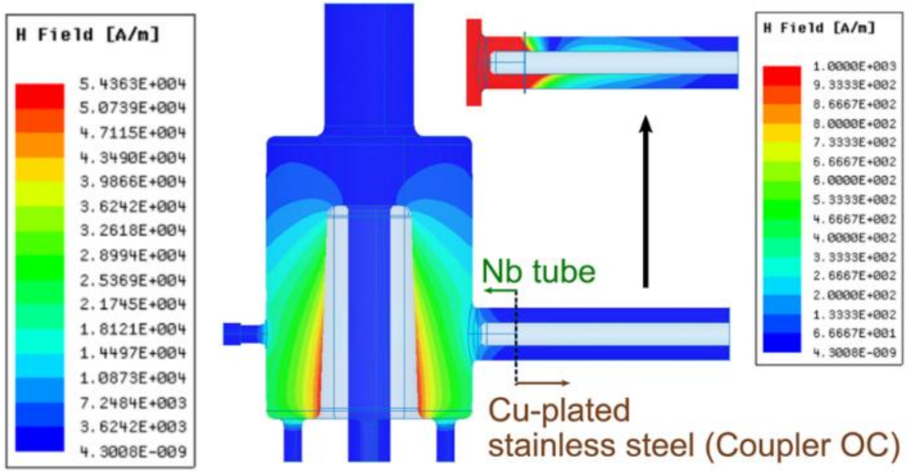
11.1W may be attributed to power coupler and others

Increased temperature and heat load was observed.

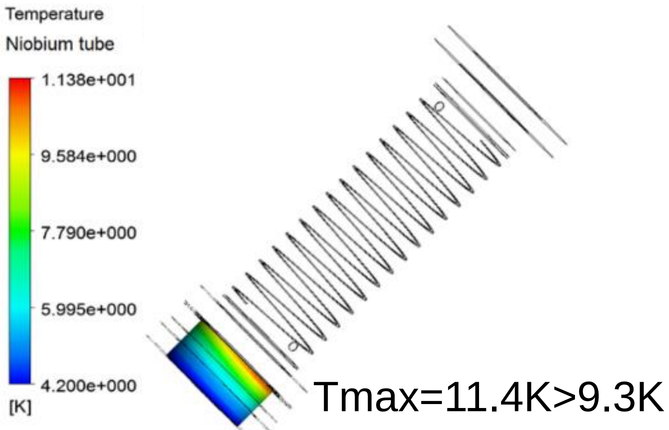


Operation mode	Pf (kW)	Vc (MV)	CryoTempB (K)	Ptot (W)
RF off	0	0	6.5	12.2
Cavity detuned	13.2	0	6.5	12.8
Cavity tuned	13.3	1.09	35.0	28.3





H-field > 1000 A/m in the cavity-coupler interface region (at 1.5MV)



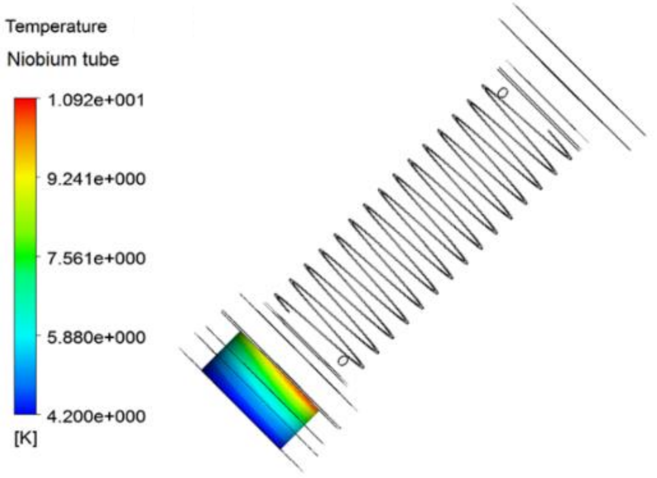
Tmax=11.4K>9.3K

Simulated temperature of the Nb extension tube at 1.5 MV with a helium gas flow rate of 14.4 standard l/min (slm).

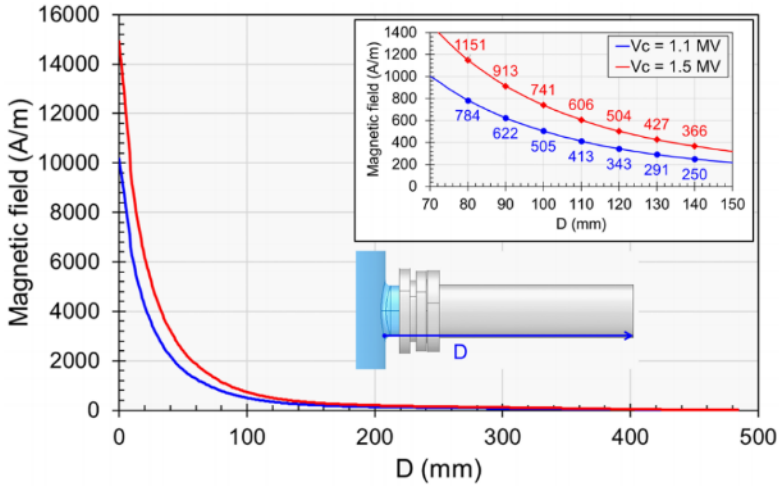
- **Overheating** observed in the cavity-coupler interface region caused a “thermal runaway” and eventually quenched the cavity
- Both test and simulation indicated a **quenching** at 1.5MV!

T. Huang *et al.*, *AIP Advances* 11, 045024 (2021).

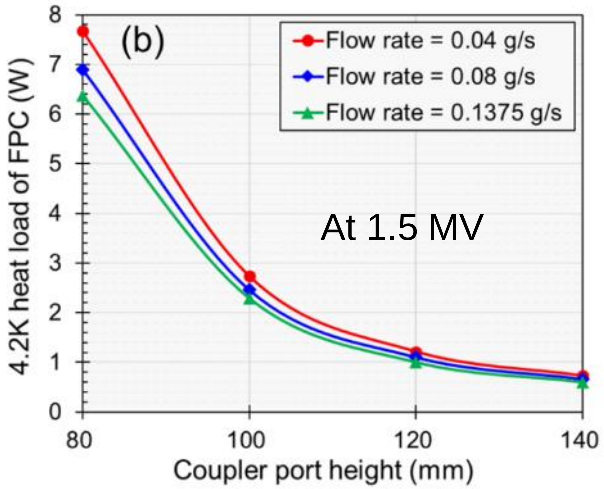
Solution: PoP coupler overheating



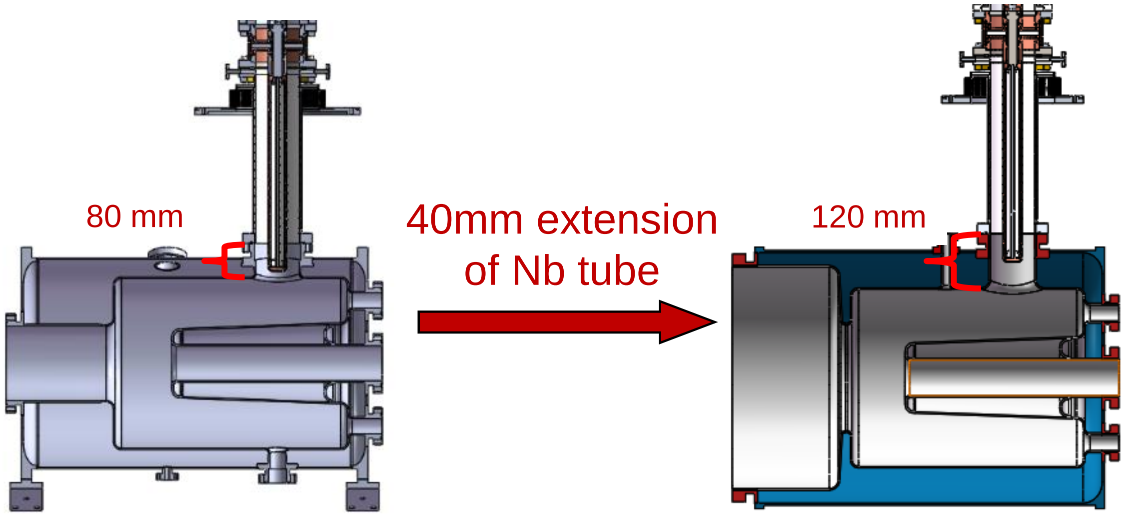
Simulated temperature of the Nb extension tube at 1.5 MV with a helium gas flow rate of 50 slm.



Magnetic field along the power coupler’s outer conductor

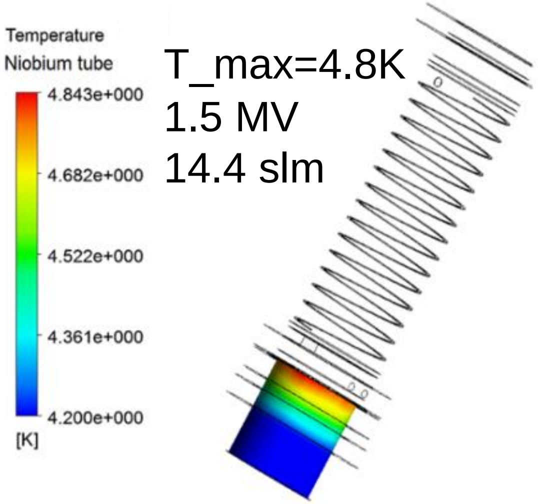


Simulated 4.2K heat loss of the coupler at various coupler port heights and different helium gas flow rates



PoP cavity

HOM-damped cavity

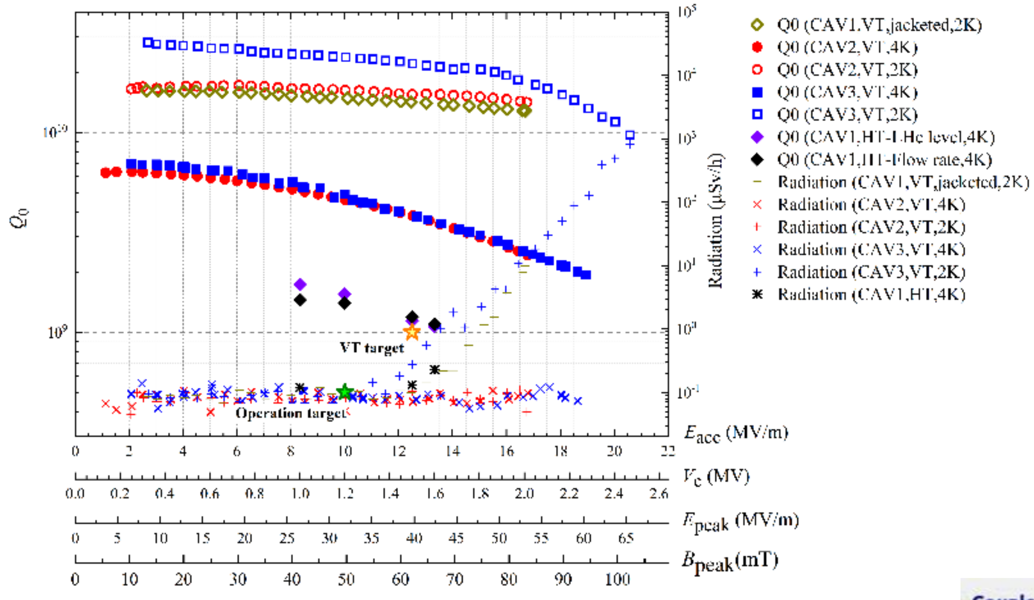


Simulated temperature of the Nb tube after extended to 120mm

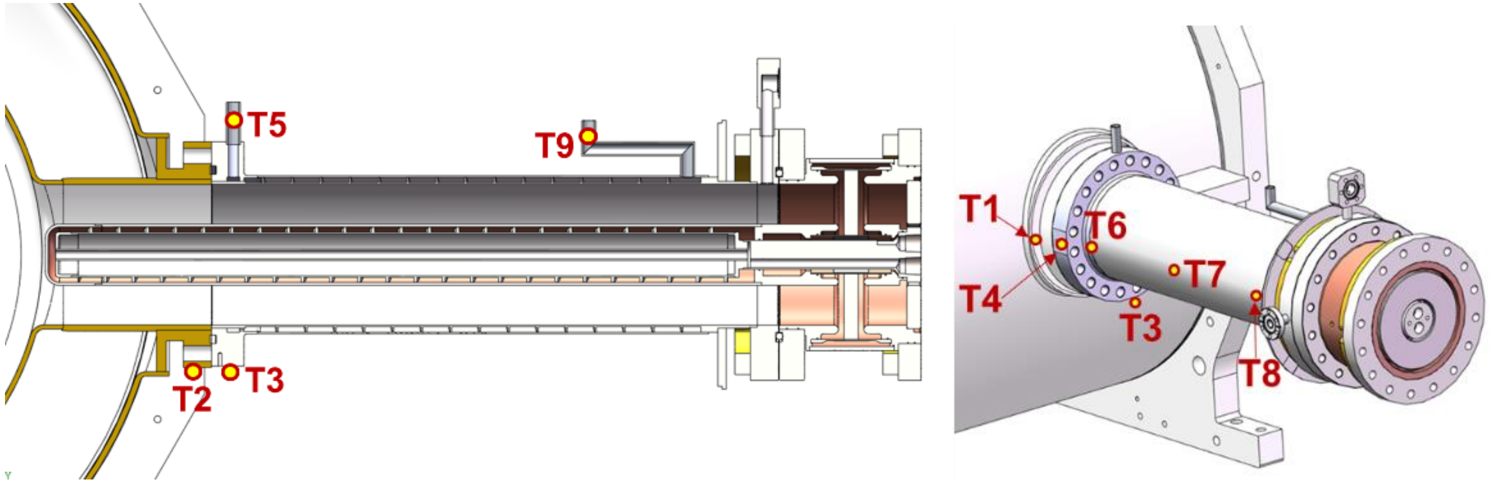
- Elongate the Nb ext. tube at the coupler port from 80mm to 120mm
- After mod. (1.5MV, 14.4 slm)
  - 4K heat load of coupler: 7.7W → 1.8W
  - T_max of Nb: 11.4K → 4.8K

T. Huang *et al.*, *AIP Advances* 11, 045024 (2021).

Prototype coupler on HOM-damped cavity HT 2023.11



Additional loss observed



Coupler Monitor (14 slm static)

T1 (TI6750)	4.798 K
T2 (TI6751)	4.835 K
T3 (TI6752)	4.512 K
T4 (TI6753)	4.628 K
T5 (TI6754)	4.394 K
T6 (TI6755)	5.471 K
T7 (TI6756)	7.994 K
T8 (TI6757)	206.872 K
T9 (TI6758)	187.930 K

14 slm static

Coupler Monitor (40 slm 1.2 MV)

T1 (TI6750)	7.052 K
T2 (TI6751)	14.896 K
T3 (TI6752)	9.061 K
T4 (TI6753)	6.542 K
T5 (TI6754)	4.329 K
T6 (TI6755)	9.248 K
T7 (TI6756)	9.209 K
T8 (TI6757)	172.379 K
T9 (TI6758)	118.091 K

40 slm 1.2 MV

40slm

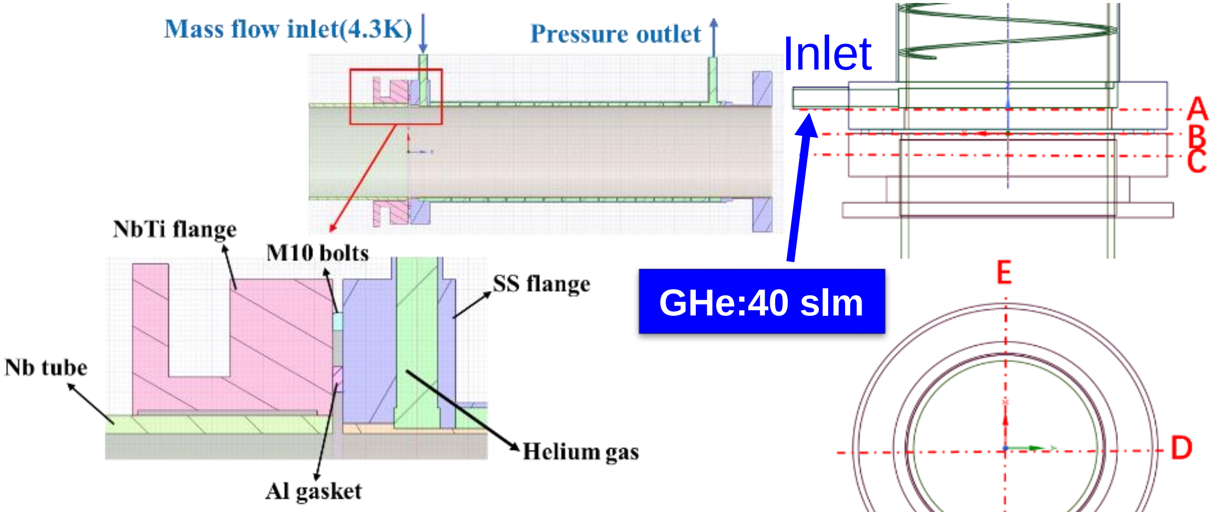
- Q lower than VT → Additional **5.1W** dynamic loss
- Contributed by (Vc=1.2MV)
  - Power coupler: **~4.1 W (Too large)**
  - Beam pipes: ~0.8W
  - Trapped magnetic induced loss: 0.22W
  - Others: ?

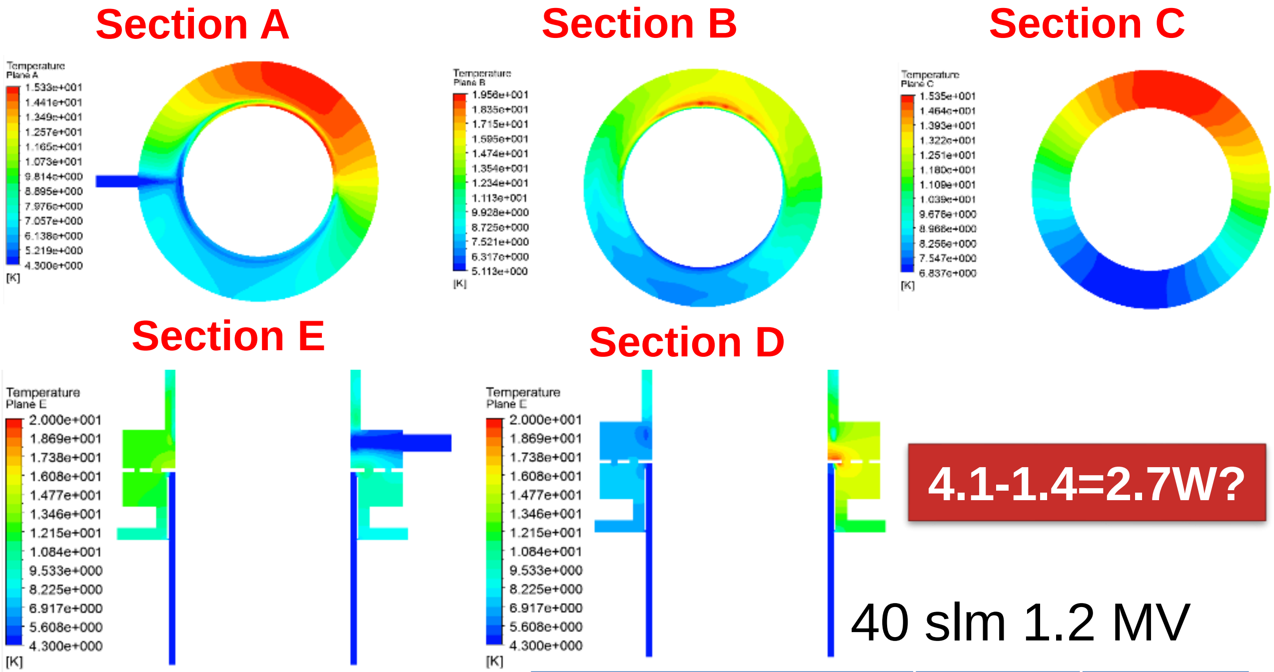
NbTi flange overheating

- T2 increased up to 14.9 K when Vc reached 1.2 MV
- No quench observed at Vc=1.6MV
- Vc ↑: Quench risk?

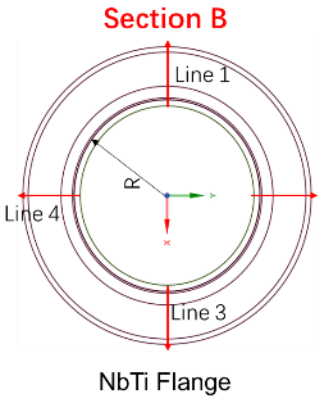
Prototype coupler： Simulation vs Measurement

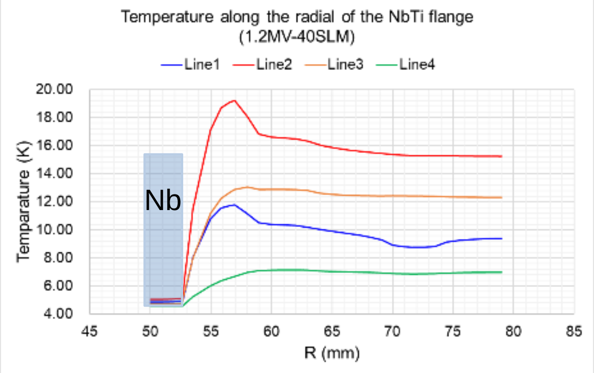
- Both the simulated Max_T on NbTi flange and heat load contributed by the coupler are lower than the measurement. An unpredictable heating load of 2.7 W was still not found. Confused!





At 1.2MV	RF surface loss (W)
OC	1.79
SS flange	1.55
NbTi flange	1.35
Al gasket	0.08
Total	**4.77**

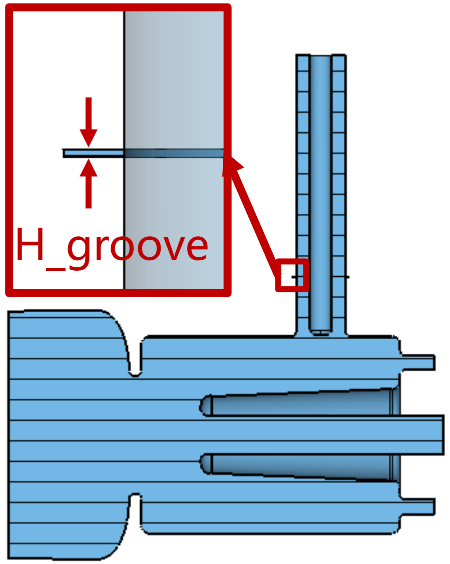




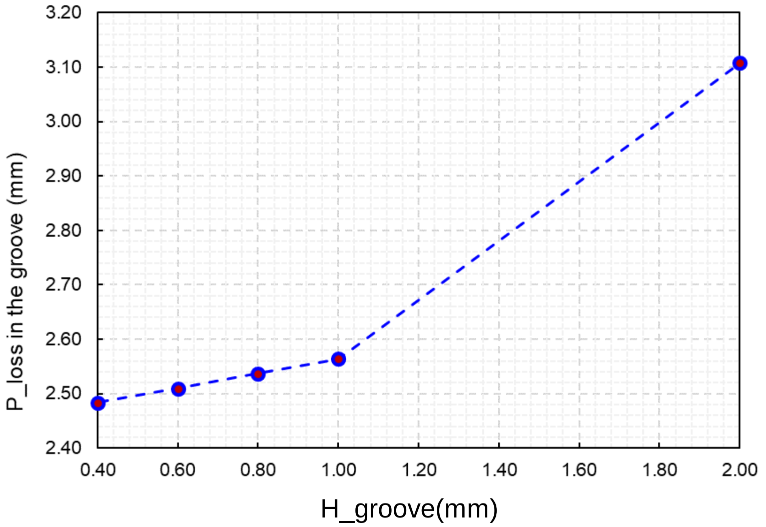
	Cal.	Meas.
T1 (K) at NbTi flange	7.03	7.05
T2 (K) at NbTi flange	**12.26**	**14.90**
T3 (K) at SS flange	**12.39**	**9.06**
T4 (K) at SS flange	6.68	6.54
4K heat load (W)	**1.38**	**4.10**

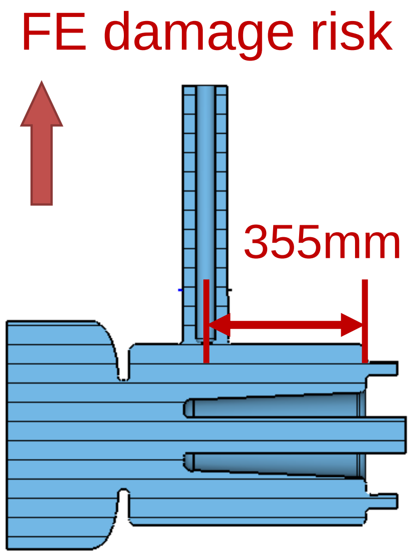
Field leakage in FPC vacuum sealing groove

- One of the main heat loss may be contributed by the RF power dissipation on the vacuum sealing groove at the cavity-coupler connecting flanges
  - Total power dissipation on the sealing groove at 1.2MV: ~2.5W, σ(20K) was used
  - Hard to reduce the gap loss by decreasing the sealing gap 'H_groove'
  - Gap loss decreased significantly by moving the coupler port far away from the cavity H-end
    - ✓ Pos_FPC=160mm, gap RF loss=2.56W
    - ✓ Pos_FPC=355mm, gap RF loss=0.53W

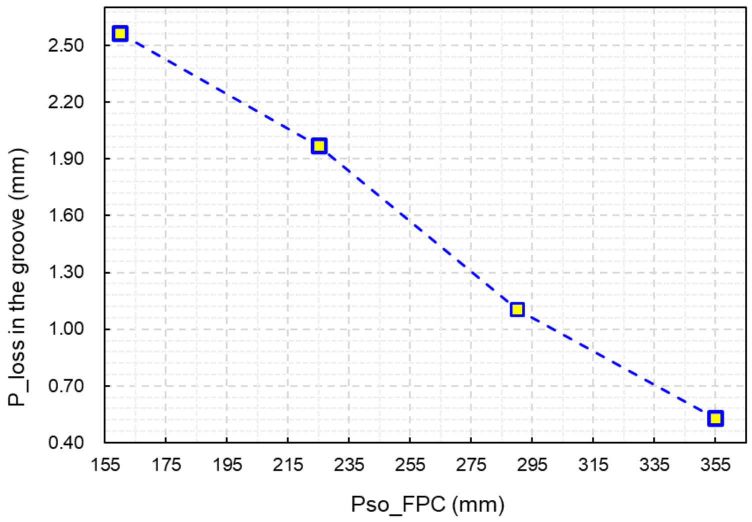


E-end H-end





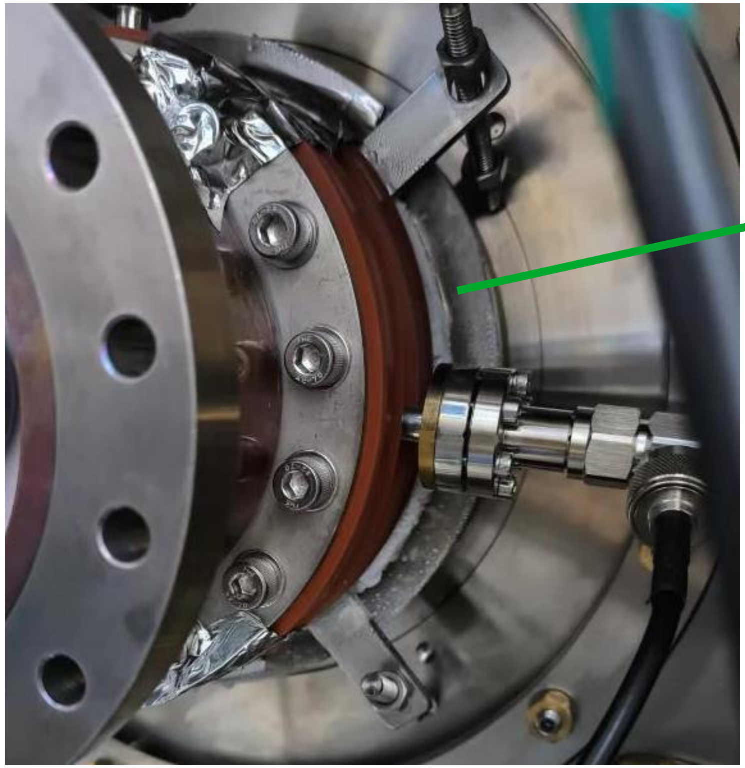
E-end H-end

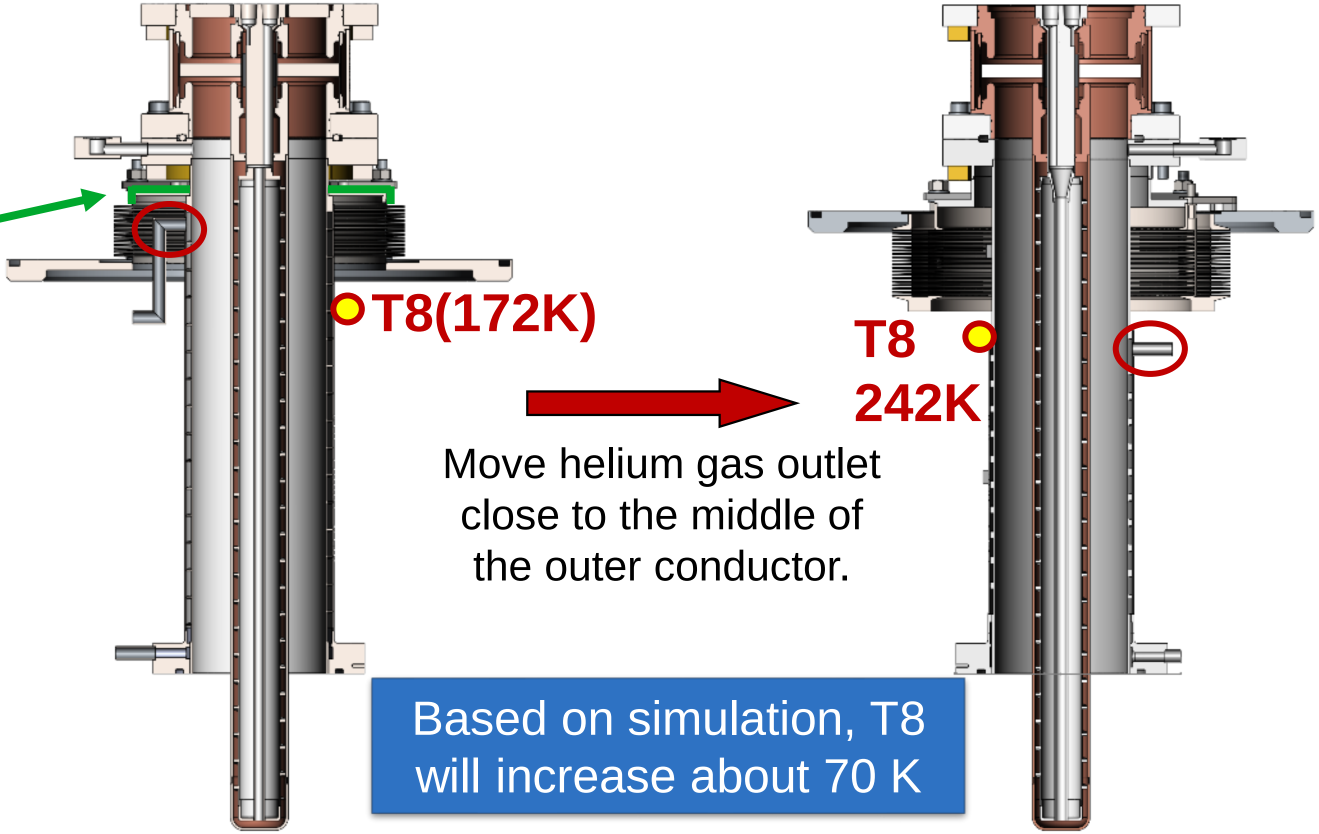


HT exception: frosting

- As the gas helium flow rate increased up to 30 slm, serious frosting observed close to the bellow of the coupler-cryostat connecting flange
- **Proposed solution**

  - Increase the power of the heating wrap: effective but limited.
  - Move the helium gas outlet (OC cooling) from top to the middle of the outer conductor.





HT exception: RF dissipation on IC

- RF power dissipations on vacuum part of the inner conductor & inner window have huge difference among three scenarios: on test box, on-cavity detuned and on-cavity tuned
- Once the cavity is tuned, cavity field leak in FPC & RF field distribution changed → RF dissipations on IC and inner window increase significantly

Conditions	Simulation	Measurement		
	Loss (W)	Water flow (l/min)	Water T-rise (°C)	Loss (W)
On test box: TW-200kW	95	1.6	1.0	112
On test box: SW-100kW	190	1.6	2.0	224
On-cavity detuned: SW-90kW	65~110*	1.6	0.8	90
On-cavity tuned: SW-56kW-1.2MV	750	1.6	8.0	896

Excessive RF IC loss！ How to solve the problem?

*: Depending on the frequency difference to f0

Solution: excessive RF dissipation on IC

Solution: Increase the cooling water flow from 1.6 l/min to 3.2 l/min

- **Simulation**

- Maximum temperature at the antenna tip decreased from **77.5°C** to **62.5°C**;
- The temperature rise of the cooling water decreased from **6.7°C** to **3.3°C**

- **Measurement**

- The temperature rise of the cooling water decreased from **8.0°C** to **3.6°C**

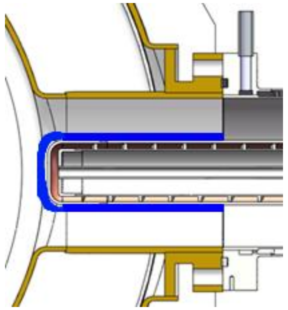
- **IC thermal radiation estimation**

$P_{\text{radiaiton}} = \varepsilon * \text{A} * \sigma * (T_h^4 - T_c^4)$

ε: 0.5~1; σ: 5.67E-8 W/(m^2.K^4);

T_h: Tmax of IC was used; T_c: 4.2K

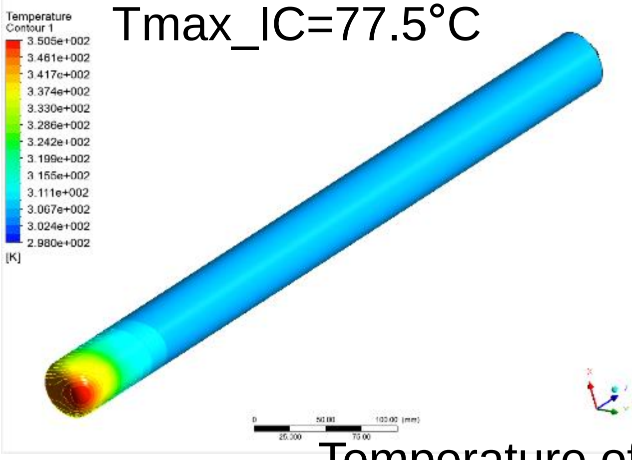
A: The area of the IC inserted into the FPC port (highlighted with blue).



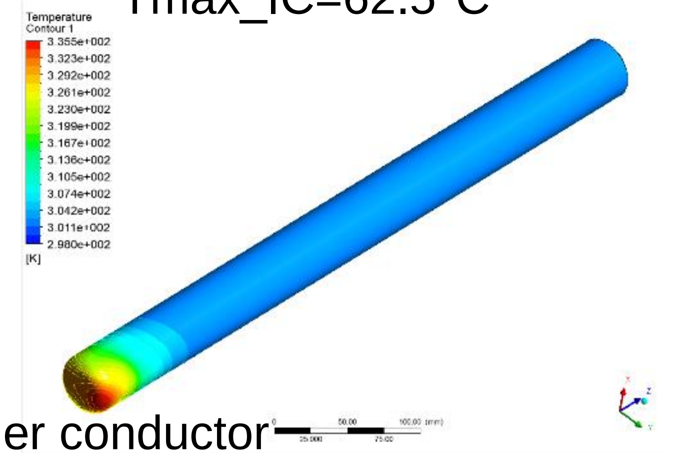
Estimated thermal radiation from IC: 0.6~1.2W

Cooling water flow: 1.6 l/min | **Cooling water flow: 3.2 l/min**

Tmax_IC=77.5°C

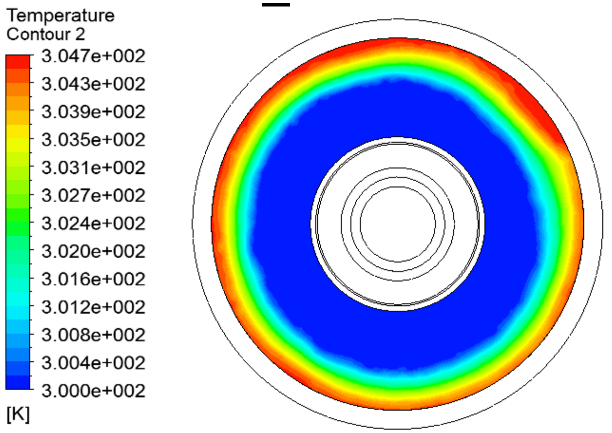


Tmax_IC=62.5°C

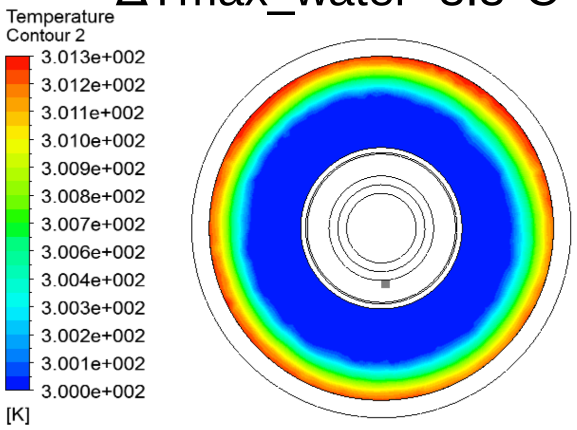


Temperature of inner conductor

ΔTmax_water=6.7°C



ΔTmax_water=3.3°C



Temperature of outlet water

Modification validation (PoP -> Prototype)

Q0 increased obviously.

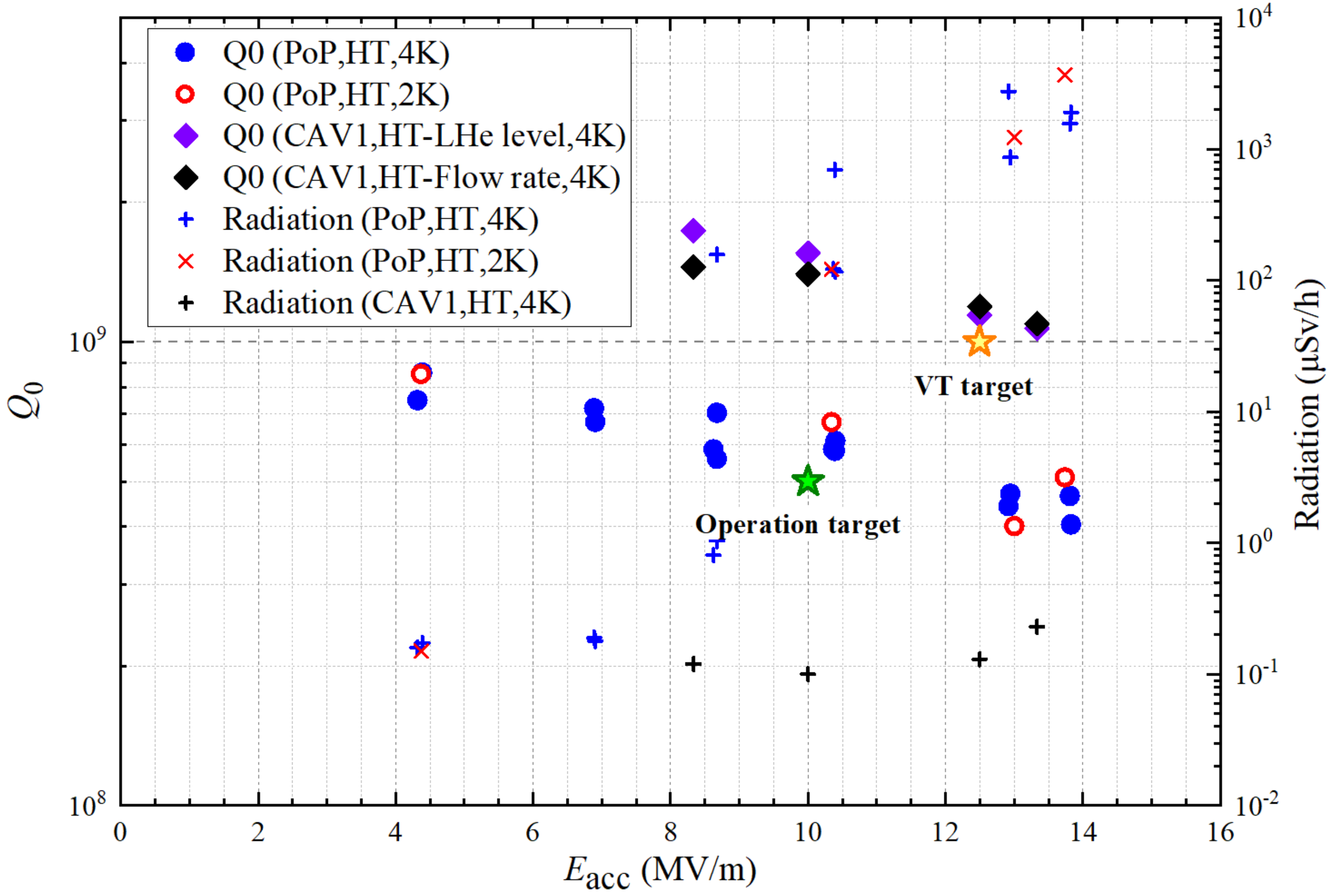
↓

Coupler port extension is successful.

Radiation dose decreased significantly.

↓

All the measures of improving the cleanliness is proved to be effective.

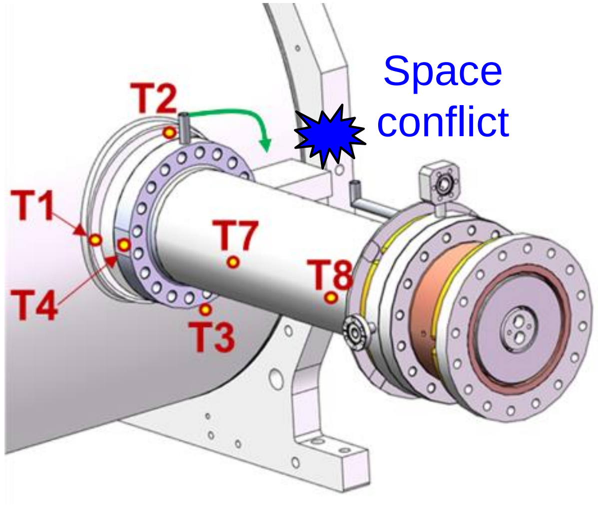


Further modifications (Prototype->Formal)

① Change the inlet of the helium gas from current 12 o'clock to 3 o'clock position

↓

Reduce the maximum temperature on the NbTi flange

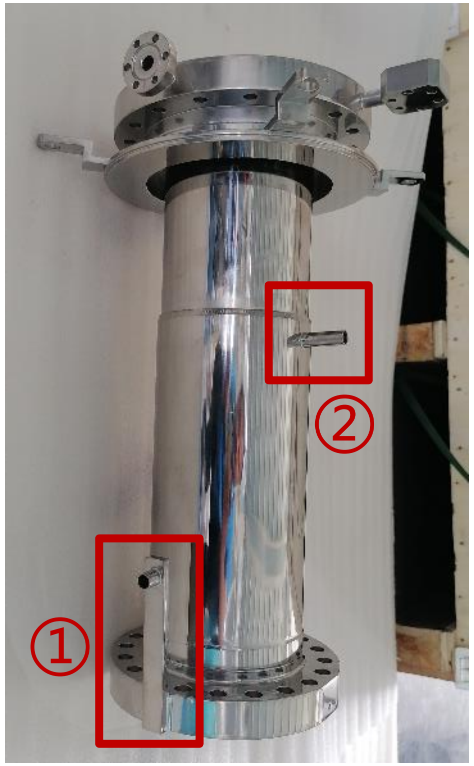


② Move the helium gas outlet (OC cooling) closer to the cold part

↓

Alleviate the frosting near the window

Prototype OC



Formal OC

Now, since both cavity and cryomodule have entered the manufacturing stage, what we can do is quite limited.

Modification validation (PoP -> Prototype->Formal)

Parameter	PoP (Measurement)	Prototype (Measurement)	Future modification (Simulation)	Comments
GHe flow rate	14.4 slm	40 slm	40 slm	/
OC Temp. close to coupler cold flange(T6)	35K @ 1.1MV	9.2K @ 1.2MV	6.8K@1.2MV	Overheating alleviated ✓
Temp. on NbTi flange(T1,T2)	Not measured	**7.1K / 14.9K**	6.5K/12.0 K	Overheating alleviated ✓
4K heat load from by FPC	11.1W @ 1.1MV	4.1W @ 1.2MV	2.3W@1.2MV	Heat load reduced ✓
Cavity quenching	Quenched at 1.5MV	No quench at 1.6MV	Shall not quench at 1.6MV	Quench risk reduced ✓
OC Temp. close to coupler warm flange(T8)	Not measured	172K	242K	Frosting near the window alleviated ✓
Temp. at the GHe outlet(T9)	Not measured	118K	47K	Icing more severe ✗

Future modifications

Try **new sealing way** with rf shielding between the cavity-coupler connecting flanges.

→

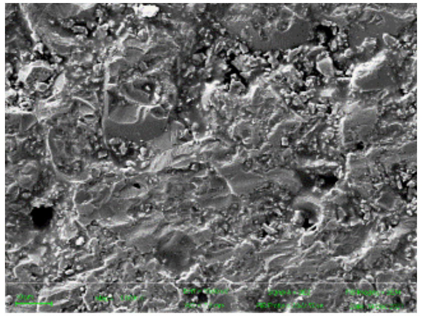
Reduce rf power dissipation on the sealing groove to alleviate the overheating in further.

Any other suggestions for this coupler?

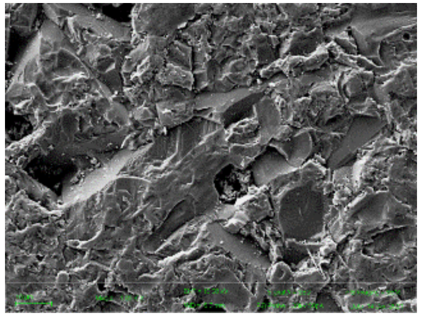
Miscellaneous: Some FPC related issues

Analysis of the damaged window ceramic

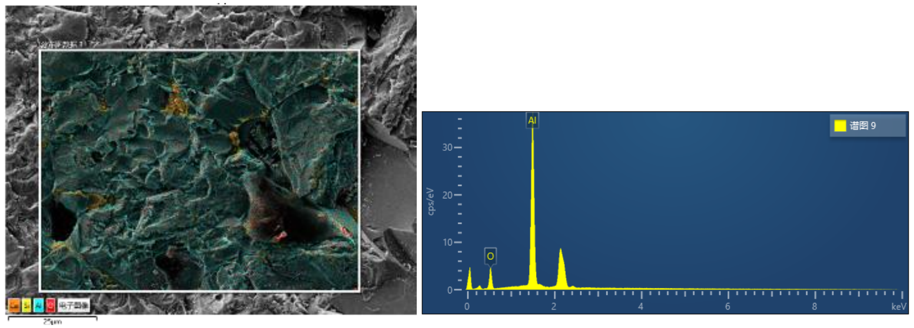
1#: Window cracked due to FE (Spoke021 SCC for CADS)



SEM*: air side



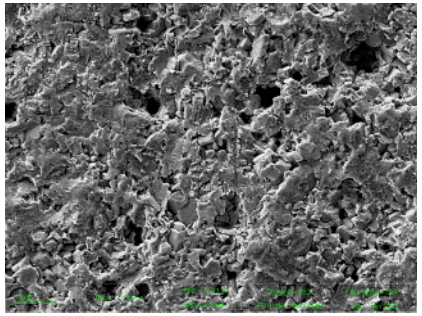
SEM: vacuum side



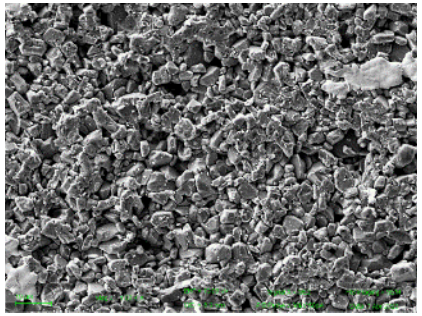
EDS: No Ti element.

*: scanning electron microscope

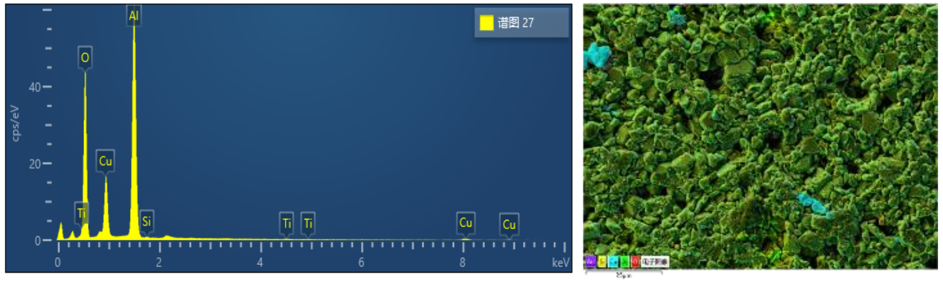
2#: Window cracked due to disabled ARC interlock (BEPCII 500MHz SCC)



SEM: air side



SEM: vacuum side



EDS**: Cu element existed.

**: Energy the Dispersive Spectroscopy

The measurement results of Rs on the damaged window ceramic

	1#	2#
Rs (Ω)	2.4E14	7.7E6

Conclusions:

- FE induced e- bombardment might damage the TiN coating
- Arc may result in copper sputtering and the increasing of the surface resistivity.

Vacuum sealing failure

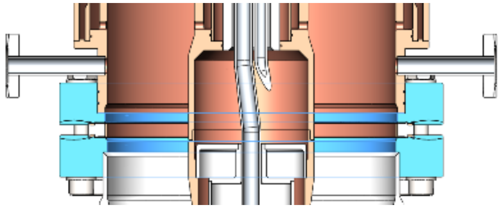
Q: Hardness requirement of sealing flange?

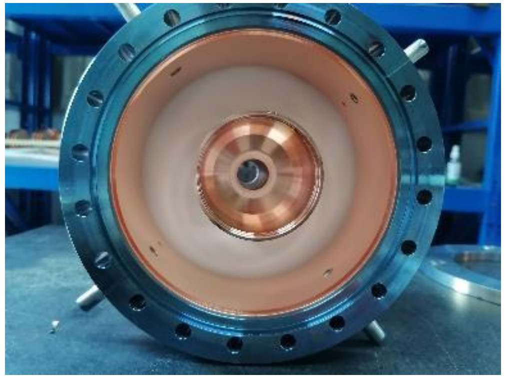
- Recently, we continuously encountered failed vacuum sealing due to the poor hardness of the stainless steel flanges: both knife sealing used copper gasket and flat sealing adopted aluminum gasket.

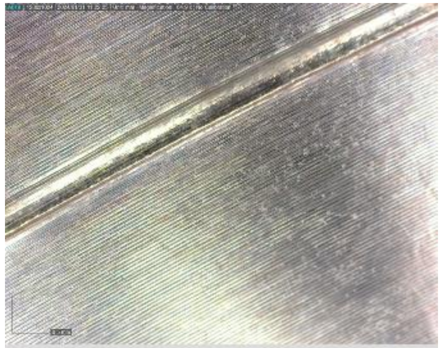
FPC for HEPS 500SCC

Knife copper gasket sealing

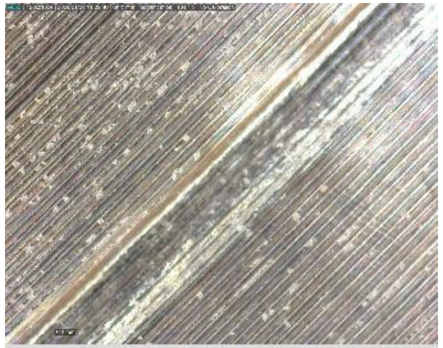
Torque 25 N.m
Leak rate: 1e-7 mbar.L/s
Gasket hardness: 60 (HV)







Gasket indentation: OC side



Wider gasket indentation: window side→ sealing knife of the window flange too soft

- CF150 flange
- Flange material: 316L SS
- Thermal cycle of flange: 1st 900 °C; 2nd 800 °C

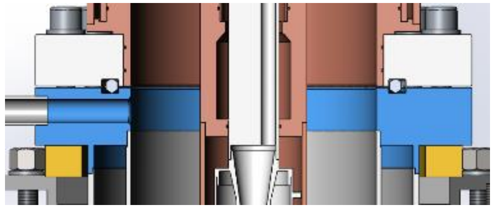
Sealing knife getting soft

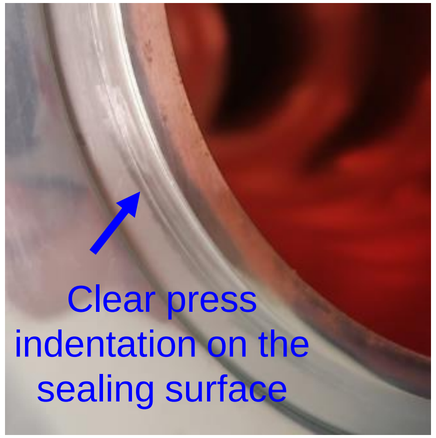
- **Confused:** same fabrication technic and never happened before; Material problem?
- **Final solution:** change to flat sealing using Al gasket

FPC for HEPS 166SCC

Flat Al gasket sealing：

sealing flange too soft





Plan to change flanges

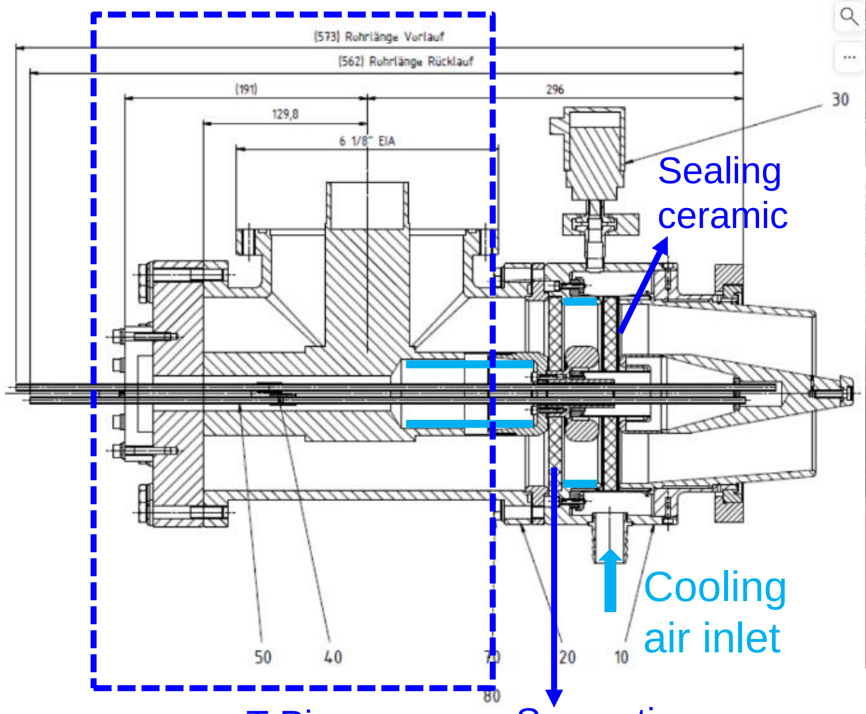
Any suggestion?

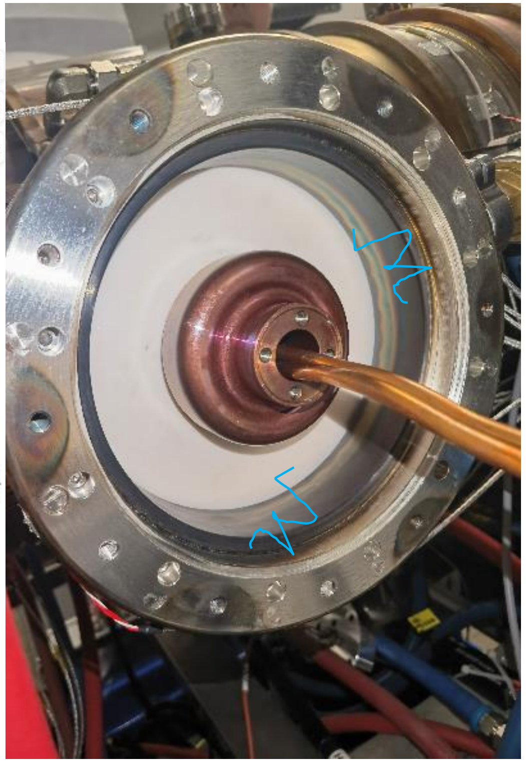
	Prototype	Formal
Hardness(HV)	113	103
Sealing	Success	Risk

Oxidation related discolor of the coupler air side

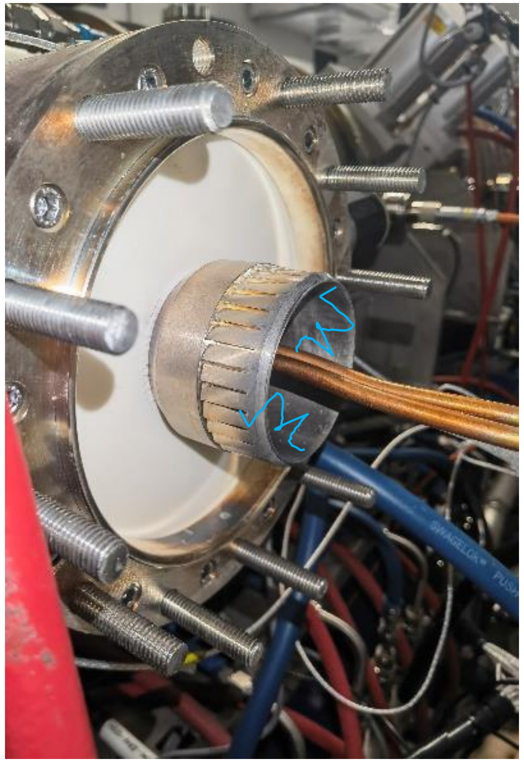
- High power operation (CW 120kW):
- Vacuum side of the coupler: operate normally (vacuum, temperature rise)
- Air side of the coupler: the area contacted directly with the cooling air turned black due to possible oxidation under high temperature and excessive humid conditions. Any risk?

FPC for Petra 5-cell 500NCC (ordered from RI)





Area near the vacuum sealing ceramic



Area near the supporting ceramic

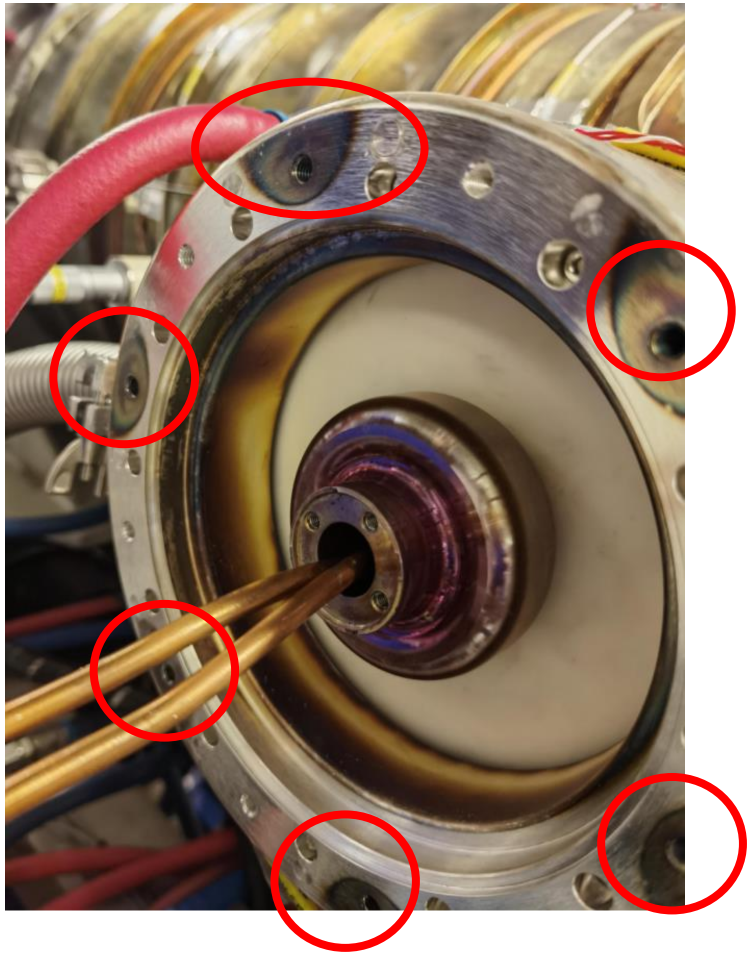
T-Piece

Bad RF connecting induced discharging

- Temperature of the outlet cooling air (Cp_T01) showed an excessive heating of the coupler for CAV02
- Obvious discharging traces observed at the flanges of the air side of the ceramic window
- **Cause**: Flexible flange deformation -> poor RF contact between window and T-piece
- **Solution**: Replaced the flexible flange

CAV No.	120kW@PAPS (°C)	100kW@HEPS-BST (°C)
CAV01	33.9	35
CAV02	54*	45.4**
CAV03	44.3	42.8

* bad flexible flange   ** good flexible flange



Thank you!