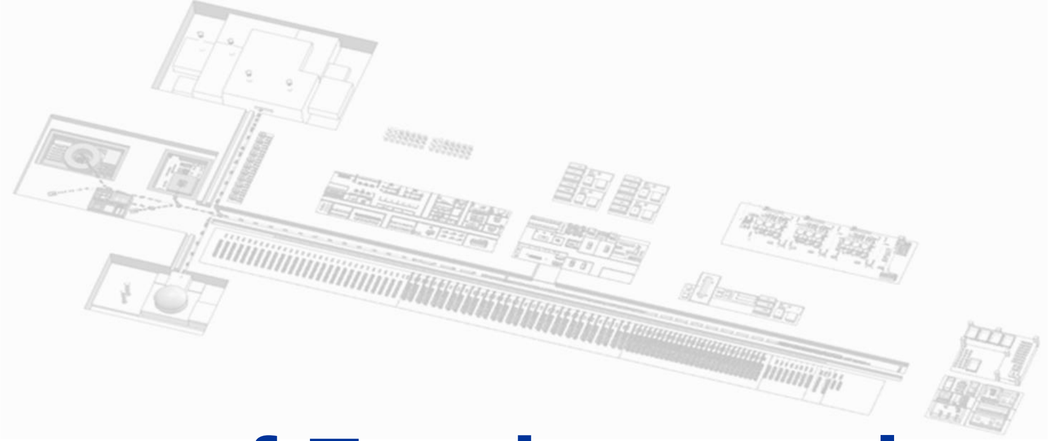

Recent progress of Fundamental power couplers at IMP

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Linear Accelerator Center
Institute of Modern Physics

2024.7.2

Outline

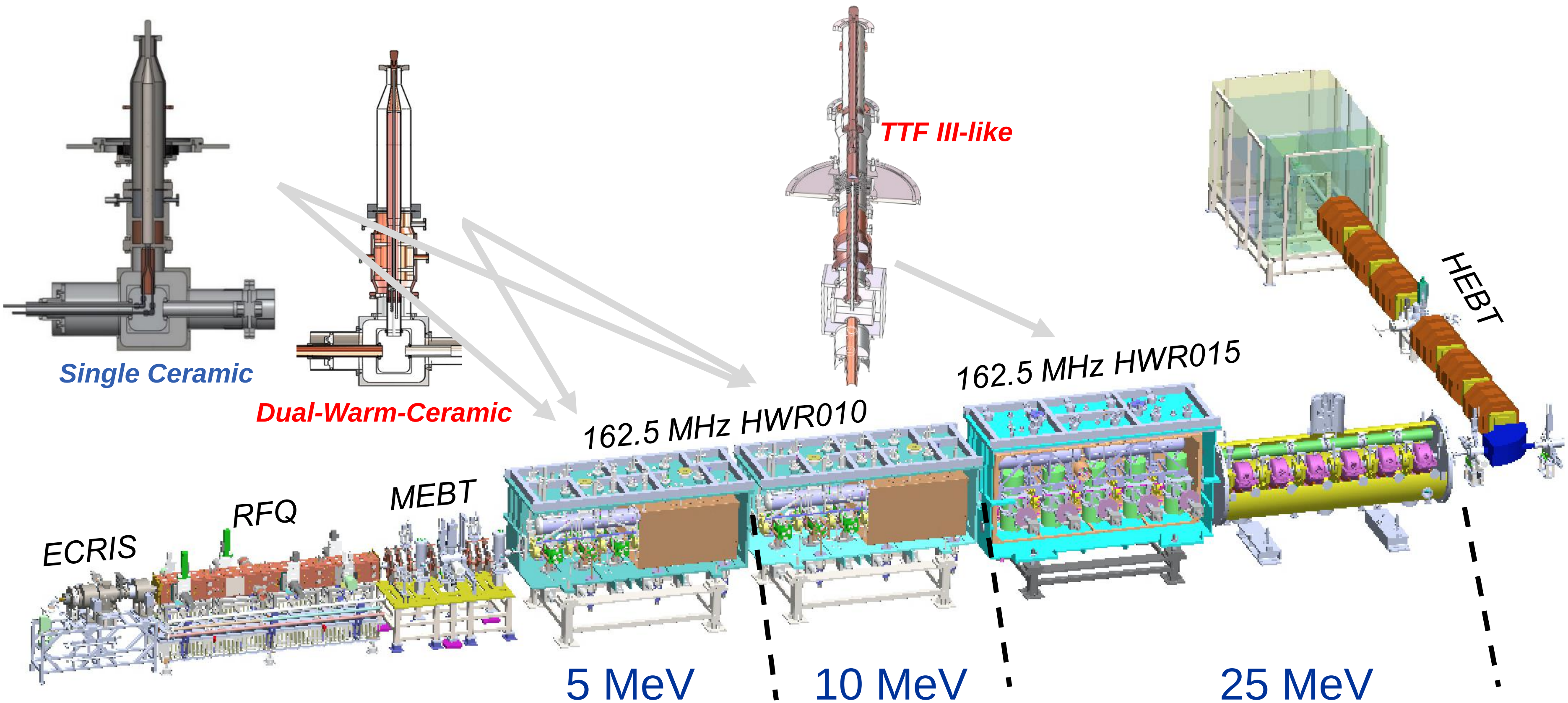
1 Operational experience in CAFe

2 Power coupler for CiADS & HIAF

3 Resonant test bench and test result

CAFe/CAFeII

CAFe: Chinese ADS front-end demo superconducting linac
CAFeII: Chinese Accelerator Facility for superheavy Elements



Goal: to demonstrate the technology of 10 mA CW beam of superconducting front-end Linac for CiADS project.

CAFe – coupler failure

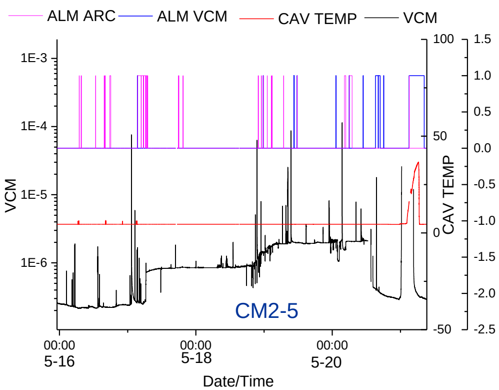
History of SC Cavity and Couplers

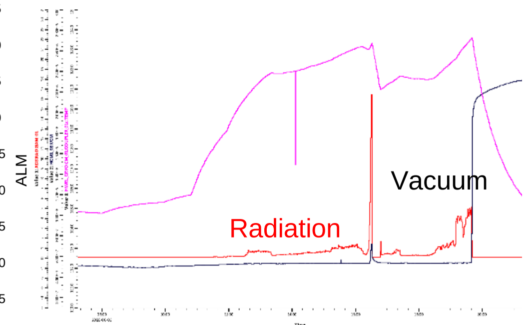
Normal temp. Coupler condition	Cooling down	Cavity Pulse condition
4.13—4.24	4.23- 5.2	5.3—5.5

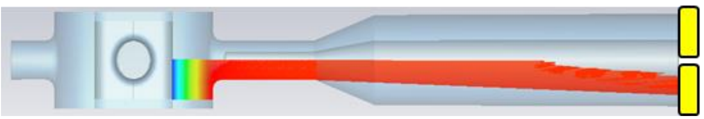
CW > 10 kW

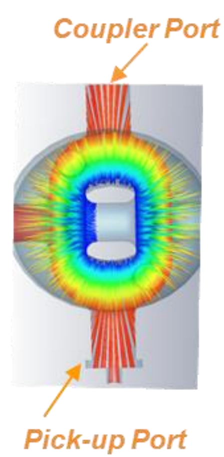
CW condition，May-7, 2 couplers Vacuum degradation	Warm up, May 14, leak check and repair)	Pulse condition，May-20, another 2 couplers were leaking
5.6-5.11	5.12-5.15	5.9-5.24

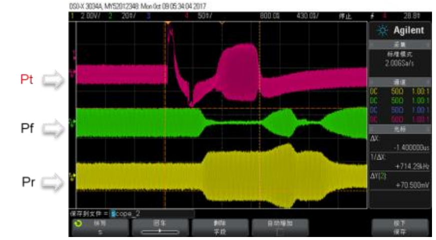
Cavity CW >20MV/m

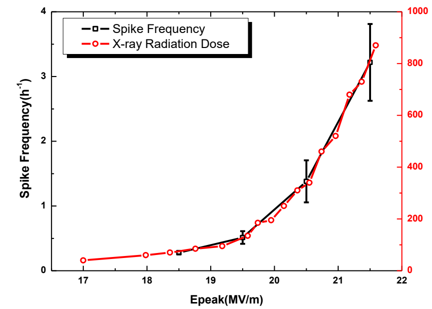


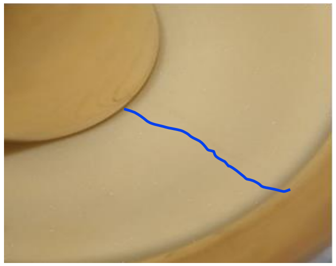


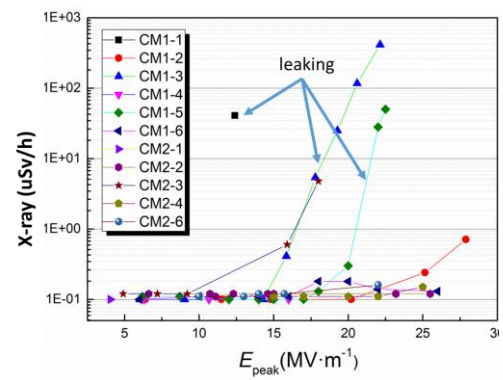








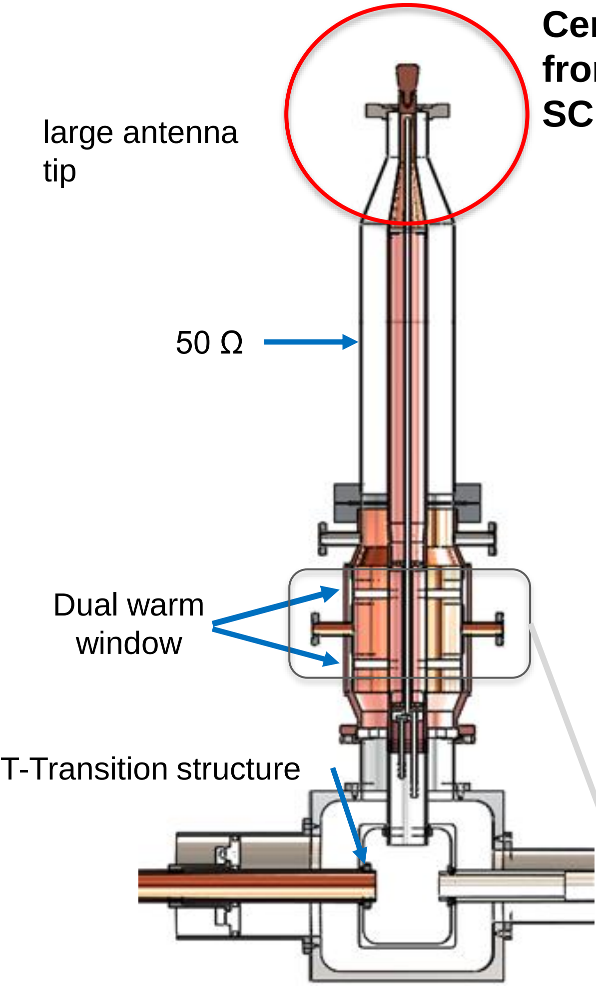




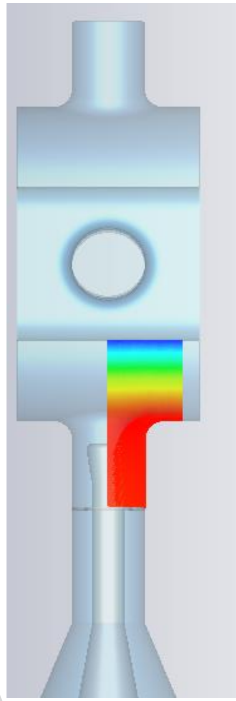
- Pickup port and coupler port is symmetric
- Electron from the cavity can hit on the ceramic

Electron activity can cause failure, 7 of 19 single window couplers failures since commissioning.

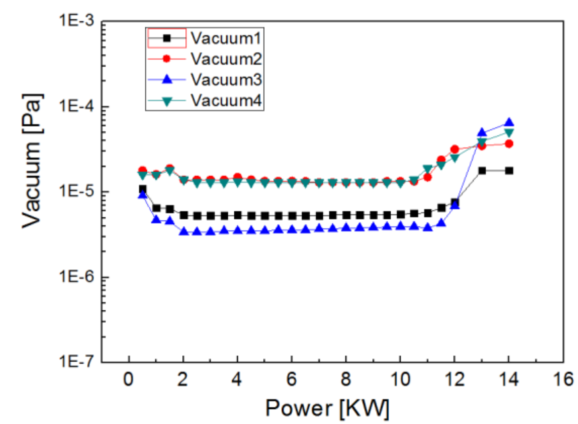
CAFe - dual warm window coupler



Ceramic sheilded from the electron of SC



- About 14 kW CW power can reach the couplers (power source limited)
- TW & SW high power conditioning
- Several MP barrier (0.5, 1.7, 13 kW)



- Vacuum between the two ceramics
- Difficult to braze and clean

- Reliability as two windows, compact as single window
- Any one crack is not fatal for SRF accelerator

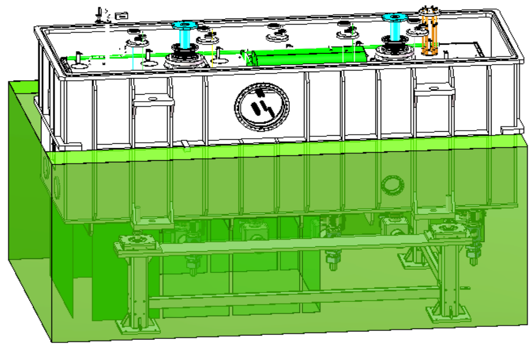
CAFe Operational Experience

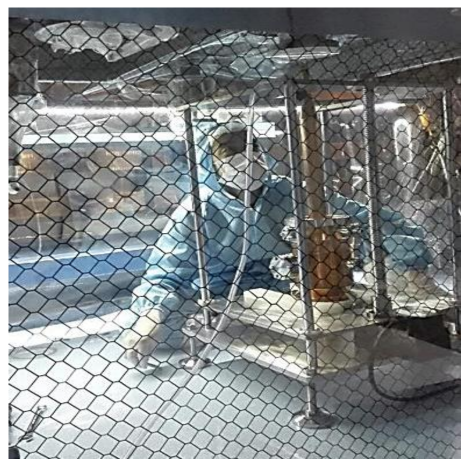
in-situ repair

Vacuum sealant

- It was absolutely catastrophic:
  - The accelerating gradient was degraded
  - We had to completely dismantle everything
  - All the components were polluted
  - It took six months to repair it
- The leak was repaired
- In-situ repair with high gradient cavities is forbidden
- Must have spare modules for exchange

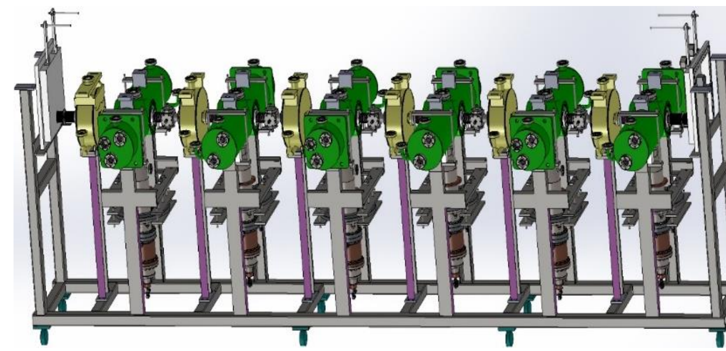
coupler repaired in tunnel





- Time saving
- Convenience
- Cavity performance is acceptable

coupler replaced in clean room



- Time consuming
- Easy accessibility
- Recovered full performance

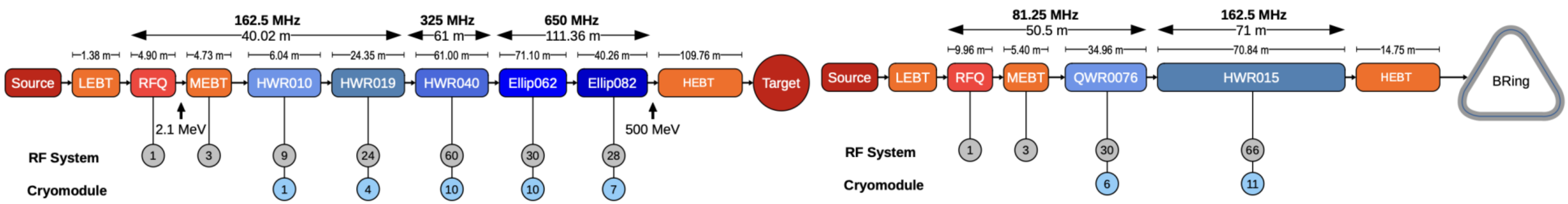
Dual-warm-window couplers have worked for around 8 years, there is no leak matter.

CiADS & HIAF Project

Location: Huizhou, Guangdong Province, 140km from Hong Kong

CiADS & HIAF Linear Accelerator

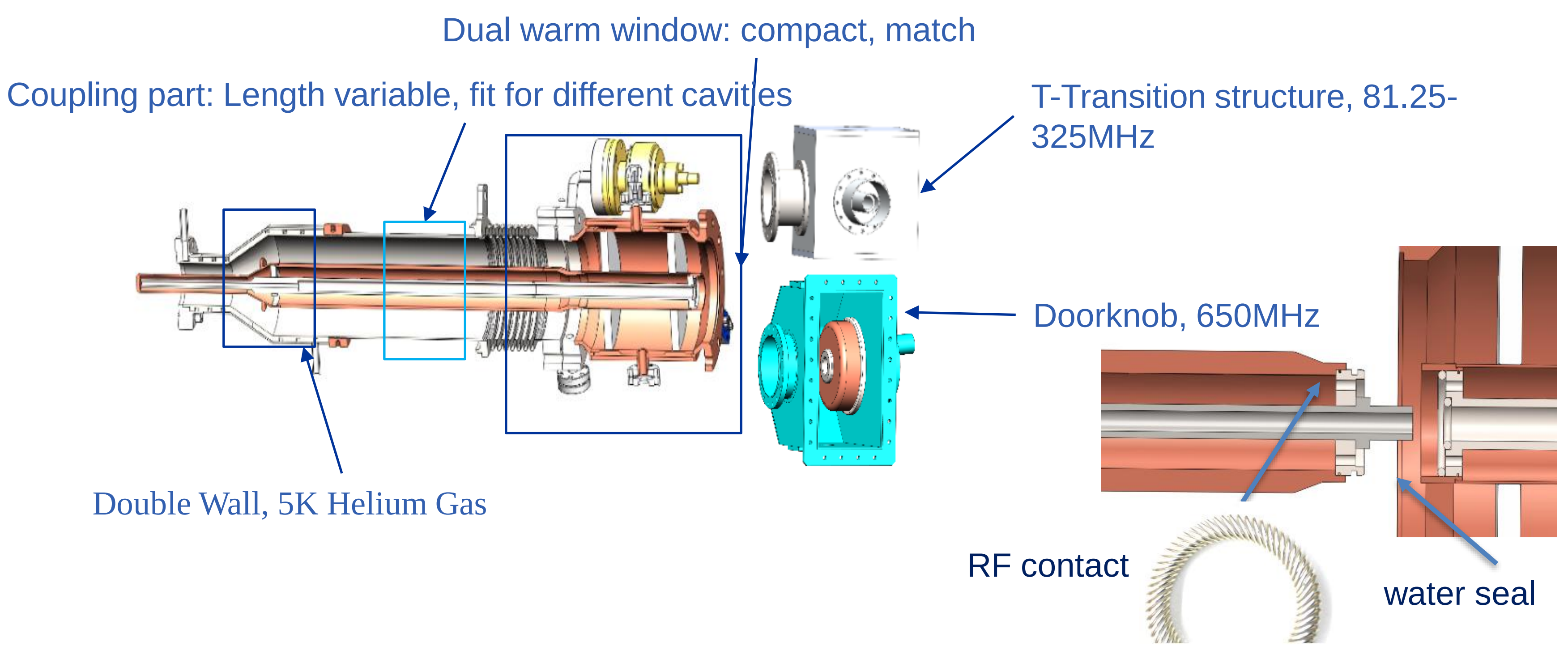
CiADS(170 FPCs) HIAF(107 FPCs)



Cavity	QWR007	HWR015	HWR010	HWR019	HWR040	Ellip062	Ellip082
Frequency(MHz)	81.25	162.5	162.5	162.5	325	650	650
Amount	30+5	66+6	9	24+6	60+6	30+3	28+4
Qe (10^6)	0.18~0.41	0.36~0.82	0.36~0.82	0.54~1.08	1.08~2.17	2.17~4.64	2.95~3.61
Power (kW)	6	6	10	24	32	64	100

- Various types of superconducting cavity, Wide frequency range
- Couplers have to allow make assembling superconducting cavities with coupler in clean room and to be installed in cryomodules.
- High reliability requirement

Dual warm window coupler

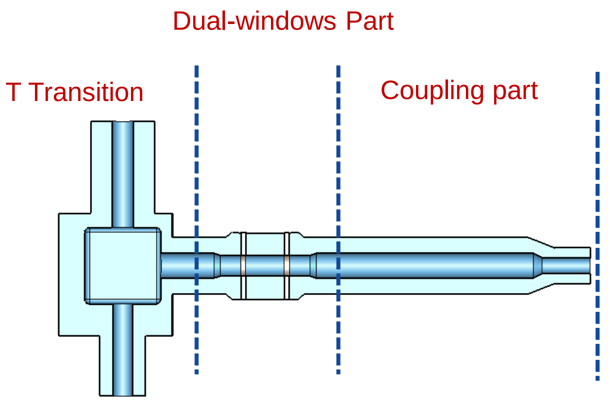


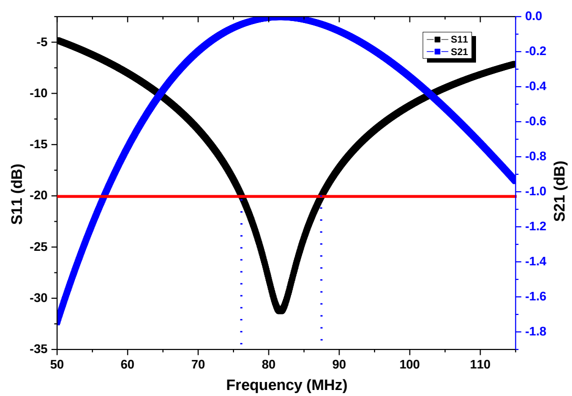
Unification:

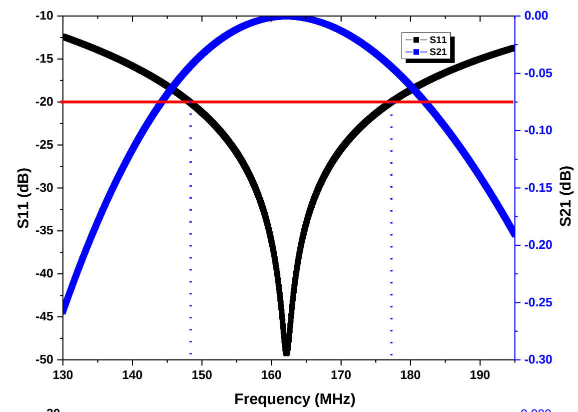
- ❑**Similar dual-warm-window and OC part**
  - ✓**Similar fabrication technology**
  - ✓**Water cooling systems, RF contact and water seal within the same screw**
  - ✓**Arrangements to provides contacts between IC and waveguides/coaxial**
- ❑**162.5 MHz and 325 MHz coupler have the same diameters inner/outer conductors**
- ❑**HV bias system**

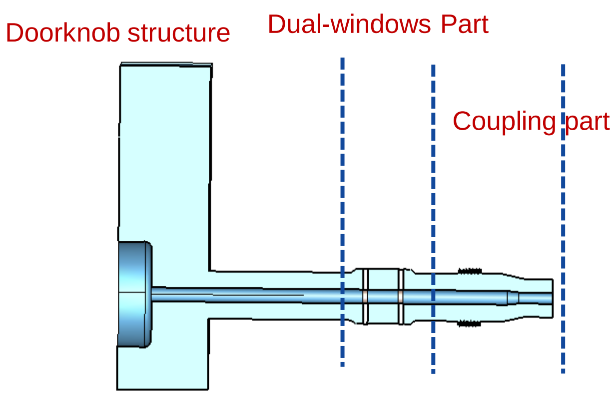
Dual warm window coupler

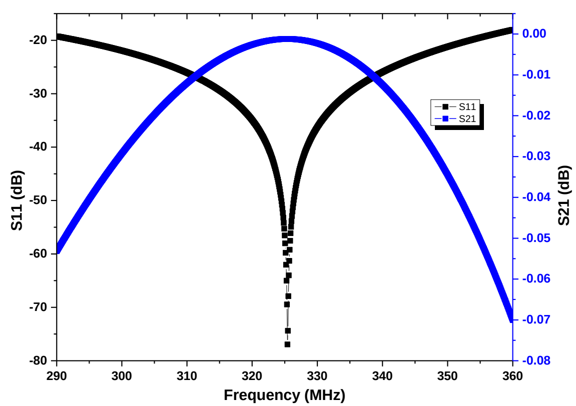
Operation frequency(MHz)	81.25	162.5	325	650
Passband (S11 < -20 dB) (MHz)	11	29	60	100
Power (kW)	6	24	32	100
Maximum power density through window (kW/cm^2)	5.33	7.91	8.52	15.33

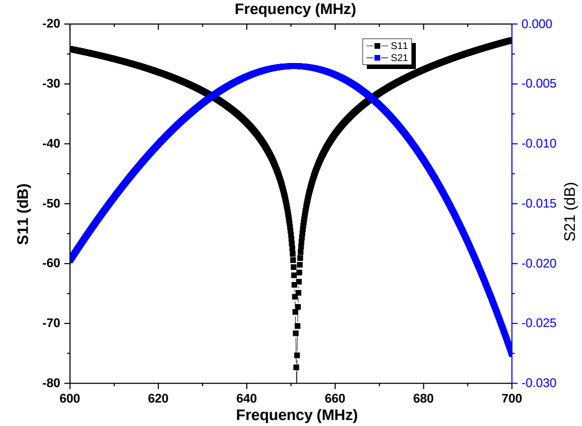




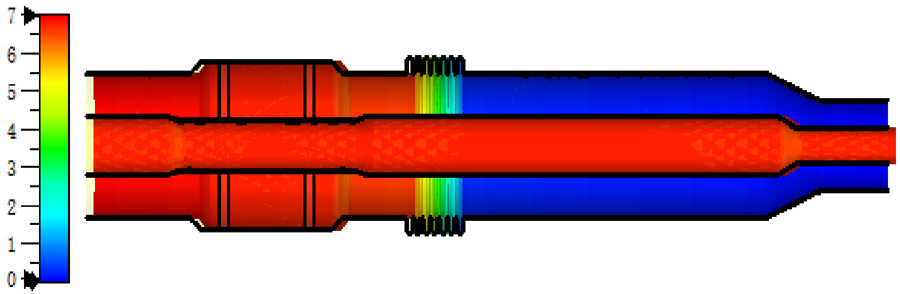


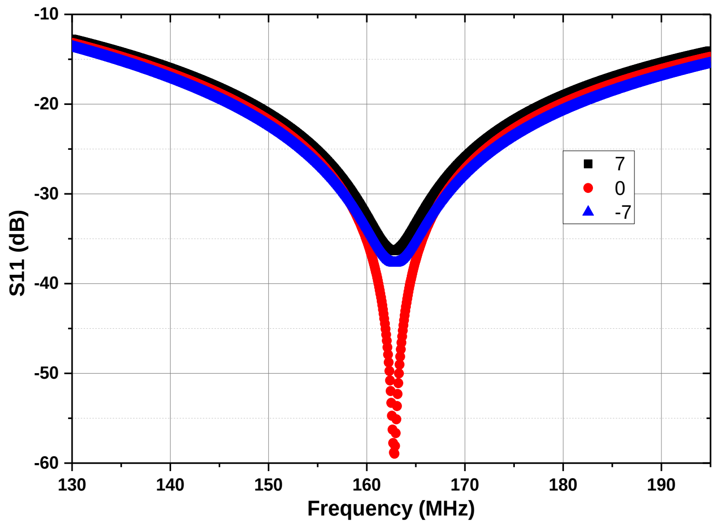




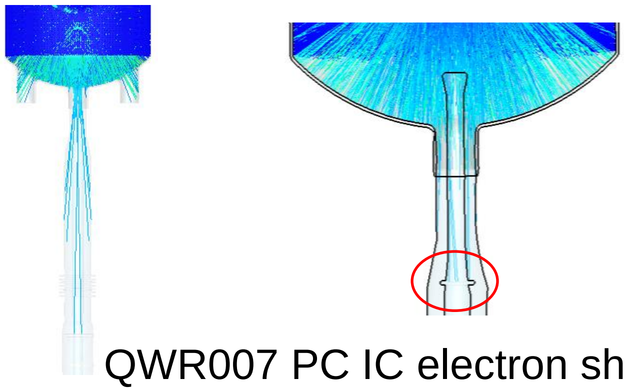


Dual warm window coupler

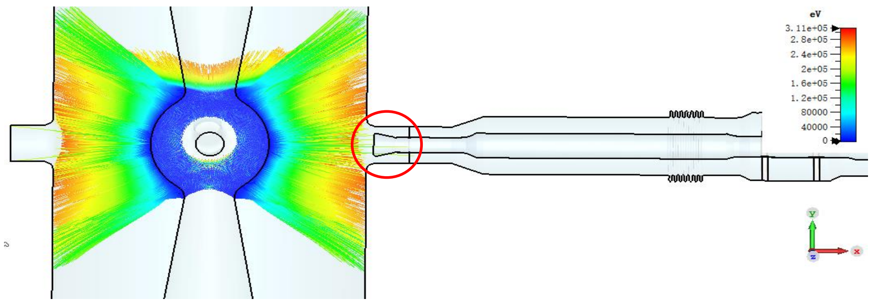




Adjusting bellows will not influence the transmission efficiency



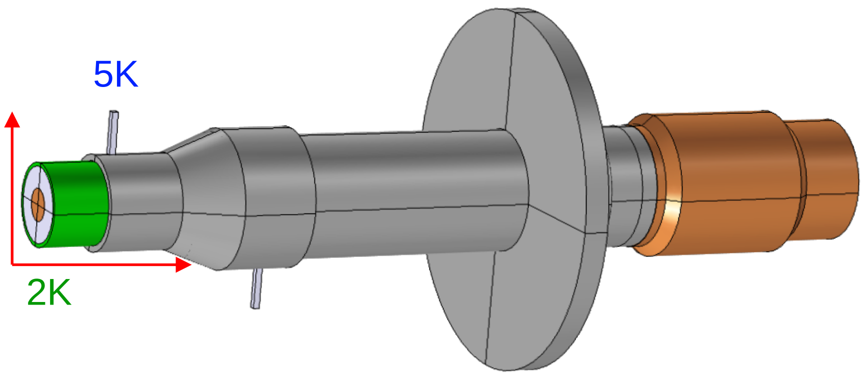
QWR007 PC IC electron shield structure

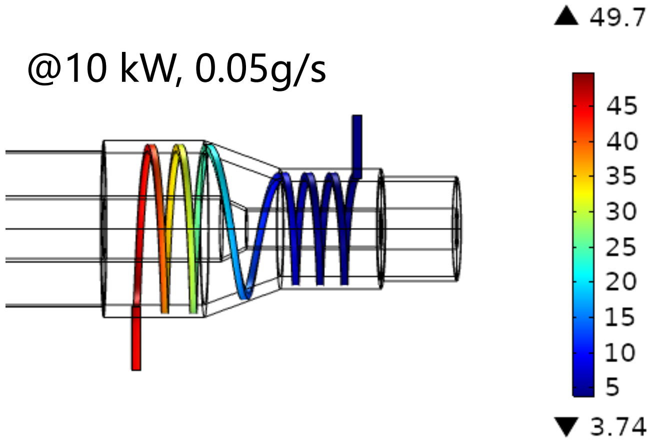


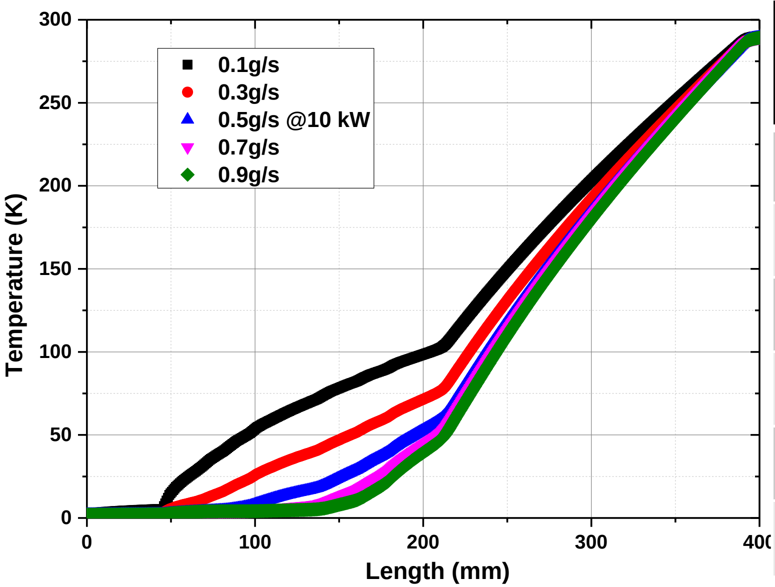
HWR015 PC big antenna tip

E-shield on IC and big tip protect ceramic windows from electron

Thermal simulation of OC



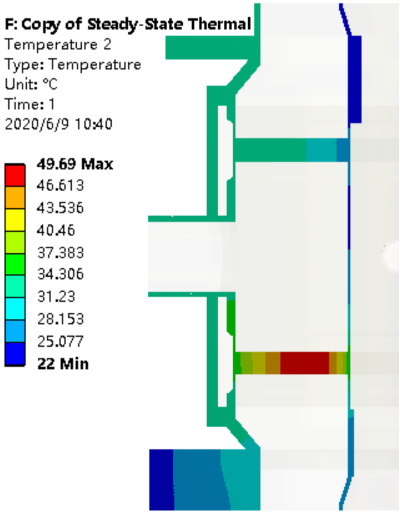




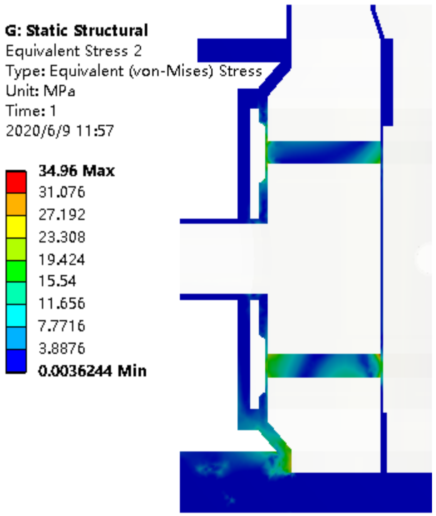
Power(kW)	2K Heat Load (W)	Mass flow (g/s)	Temp. of output gas (K)
0	4.153	0.01	95
10	4.358	0.01	96.6
0	0.378	0.03	67.8
10	0.438	0.03	69.1
0	**0.071**	**0.05**	**48.8**
10	**0.085**	**0.05**	**49.7**

Dual Warm Window

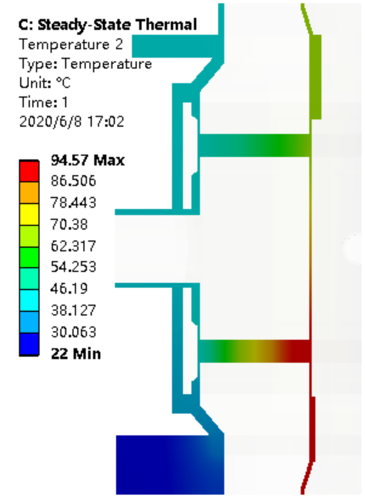
Loss in ceramic window, ceramic heating



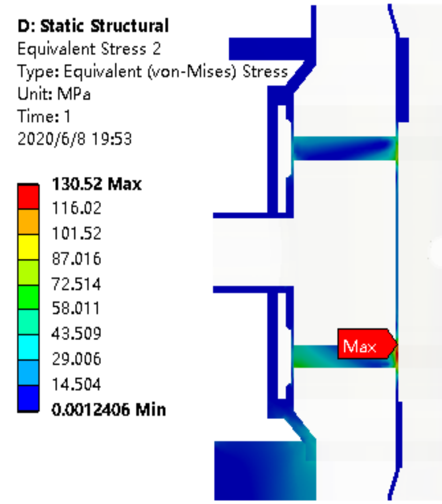
tanδ 4E-4



Frequency	650	MHz
P (avg)	100	kW
tanδ	4E-4 / 4E-3	
σ	5.8E7	S/m
h_air	5	$W/m^2 \cdot K$
h_air_canal	0.1	$W/m^2 \cdot K$
h_IC	2000	$W/m^2 \cdot K$
λ_Cu	400	W/m·K
λ_Ceramic	26.8	W/m·K
Thermal Expansion Coefficient	7.8E-6	K^{-1}
Flexural Strength	296	MPa
Pdiss_ceramic	2.5 / 18.2	W
Max ΔT	27.6 / 72.6	deg C
Max VM ceramic	35 / 130	Mpa



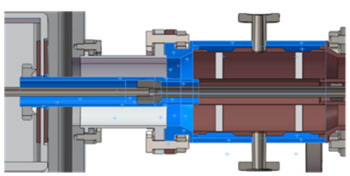
tanδ 4E-3



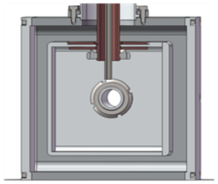
It seems we have no problem with ceramic window in case of good ceramic

Manufacture process

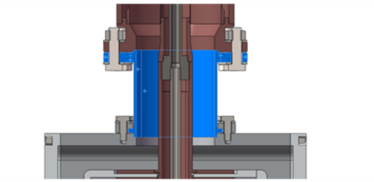
➢ Material selection



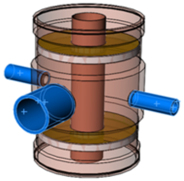
The diagram emphasizes the use of oxygen-free copper.



The T-transition structure utilizes aluminum alloy 6061. **Reduce weight**



The diagram emphasizes the use of aluminum alloy 6061. **Reduced weight, less heat generation.**



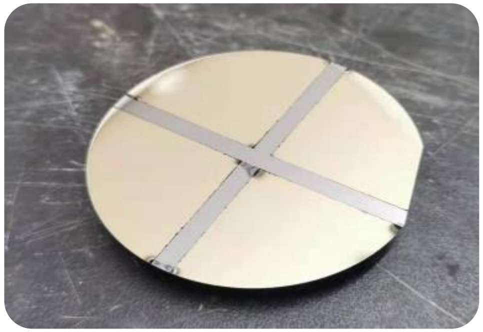
The flange connecting pipes are made of 304 stainless steel. **Facilitates vacuum brazing of ceramic windows.**

Structure name	Raw Material Categories	Brand Number
Dual warm Window component	Oxygen-Free Copper	C10100
Vacuum part Outer Conductor	Stainless Steel	304
Connecting Cavity Flange	Stainless steel	316L
Outer Conductor Bellows	Stainless Steel	304
T-transition structure	Aluminum Alloy	6061
Ceramic window	Alumina	Morgan Al300

- **Performance Integrity**: Ensuring the adjustments do not compromise the overall performance of the coupler.
- **Manufacturing Convenience**: Enhancing ease and efficiency in the manufacturing process.
- **Reliability: I**mproving the reliability of the coupler.
- **Cost Efficiency**: Addressing the need to reduce costs effectively while making material adjustments.

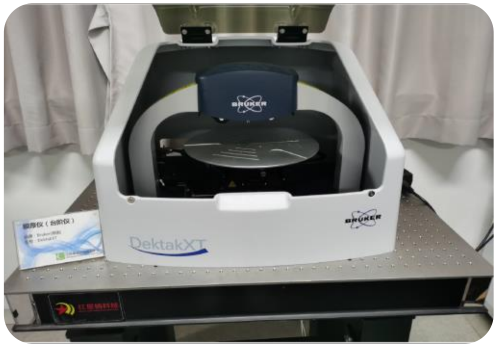
Manufacture process

➢ TiN coating



After 1 hour of coating on a single crystal silicon wafer.

Magnetron sputtering coating machine



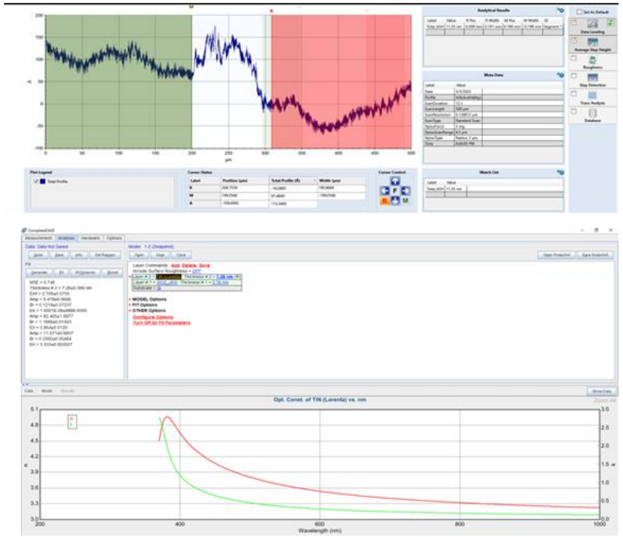
Film thickness testing step gauge

Here are the summarized key points based on the experiment:

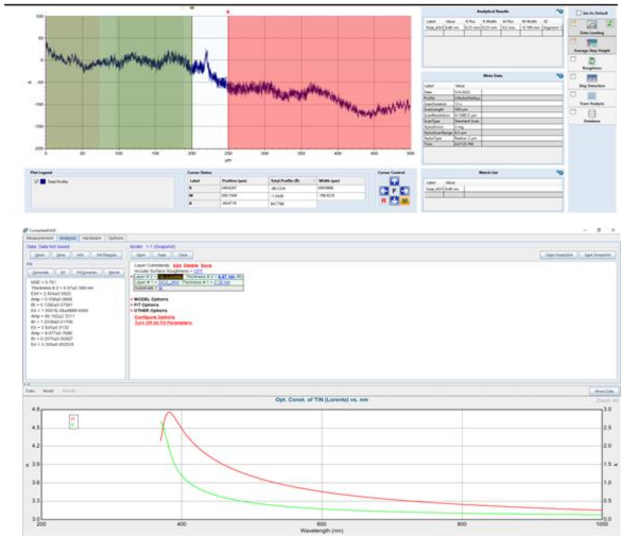
- Method: Used DC reactive magnetron sputtering on single crystal silicon wafers for TiN coating.
- Parameters Adjusted: Gas flow rate, target-to-substrate distance, coating power, rotation speed, and pressure were optimized.
- Objective: Adjusted coating time to achieve desired film thickness.

Manufacture process

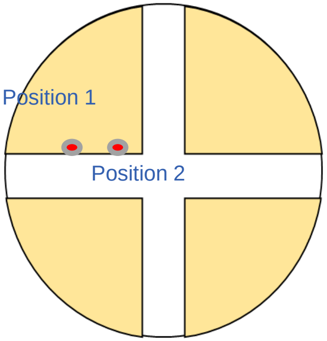
➢ TiN coating



Position 1



Position 2



Number	Substrate diameter	Substrate surface roughness	Testing instrument	Ion source cleaning	Test results (in nanometers)
1	76.2 mm	0.5 nm	Step gauge	No	11.35
2	76.2 mm	0.5 nm	Step gauge	No	8.48

Manufacture process

Copper plating the inner surface of bellows is crucial for the copper plating process of the coupler.!!!

Copper plating process several steps:

- Brush-on adhesive protection
- Cleaning and degreasing
- Hydrochloric acid activation
- Electroless nickel plating
- Pure water rinsing
- Sulfuric acid activation
- Copper plating in a copper sulfate bath
- Pure water rinsing
- Nitrogen gas drying

Protection of the outer surface of bellows after copper plating

The assessment of the quality of copper plating on bellows mainly involves the following four aspects:

Outer Surface Protection: Ensuring the protection of the outer surface after copper plating to prevent oxidation or damage.

Appearance of Copper Plating Layer: Evaluating the visual appearance of the copper plating layer for uniformity and absence of defects.

Adhesion of Copper Plating: Checking the adhesion strength between the copper plating and the substrate to ensure it remains firmly bonded.

Uniformity of Copper Plating Thickness: Verifying the consistency and uniformity of the copper plating layer thickness across the entire inner surface.

Manufacture process

The appearance of the copper plating layer on the inner surface of bellows

bellows copper plating (inner surface)

Observation of the copper plating layer on the inner surface of bellows using an endoscope

Industrial endoscope

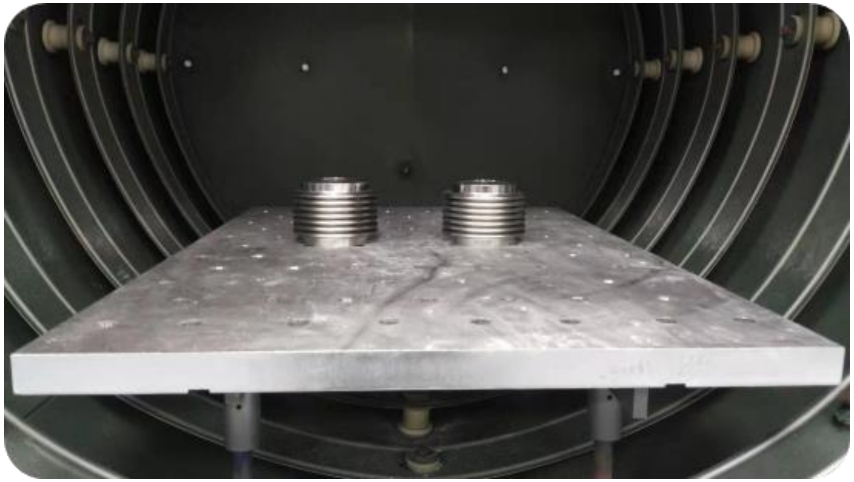
- Visually inspect the inner surface of the bellows to ensure the copper plating is uniform in color, with no discoloration or obvious plating gaps.
- Using the endoscope, examine the inner surface of the bellows to confirm the coating is even, with no significant plating defects such as gaps, impurities, or peeling.

Manufacture process

Three methods to test the adhesion of the copper plating on the inner surface of the bellows are:

- Vacuum annealing
- Continuous drawing
- Liquid nitrogen thermal shock

Adhesion of copper plating layer on the inner surface of bellows
- **vacuum annealing**



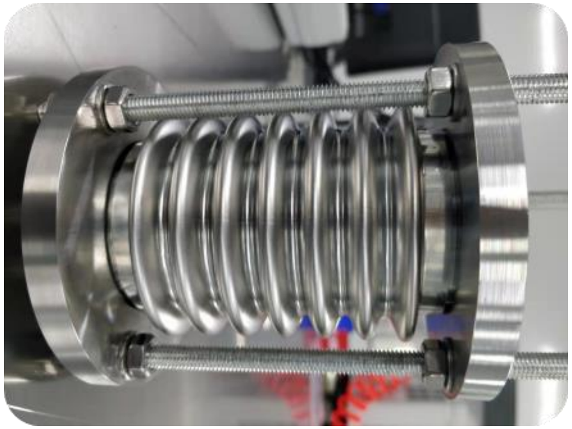
Vacuum heat treatment of bellows after inner surface copper plating

Copper-plated inner surface of bellows after vacuum heat treatment

- Vacuum heat treatment at 400°C for 1.5 hours,
- The copper-plated inner surface of the bellows shows no significant wrinkles, peeling, blistering, or delamination.

Manufacture process

Adhesion of copper plating layer on the inner surface of bellows
- **Continuous drawing**



Copper-plated bellows (in stretched state)

Copper-plated bellows(in compressed state)

Copper-plated inner surface of bellows after continuous drawing.

Continuous Drawing Parameters:
- Compression Stroke: 8mm
- Tension Stroke: 8mm
- Number of Drawing Cycles: 10

- After vacuum heat treatment, the custom drawing fixtures are used to perform continuous drawing within the stroke range.
- The inner surface of the bellows shows no significant wrinkles, peeling, blistering, or delamination.

Manufacture process

Adhesion of copper plating layer on the inner surface of bellows
- Liquid nitrogen thermal shock

Liquid nitrogen tank

Liquid nitrogen thermal shock test (liquid nitrogen to air) - one cycle

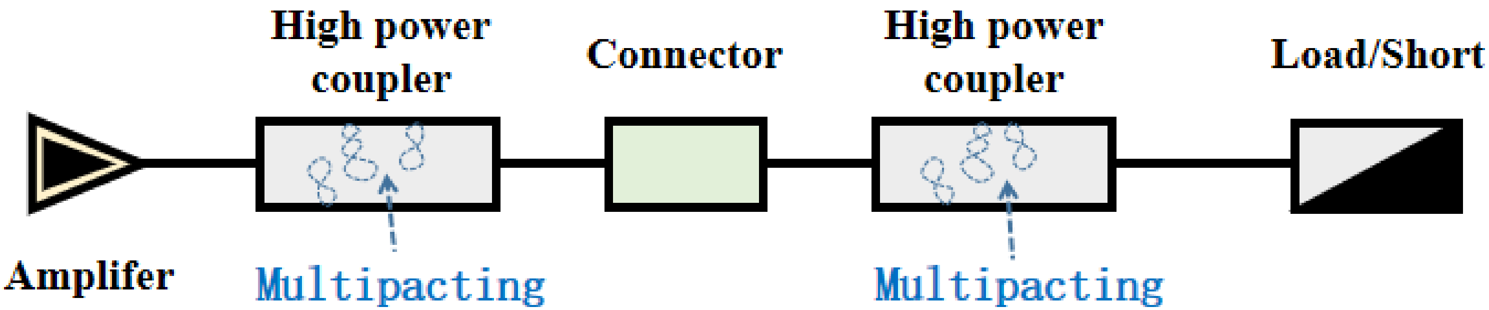
Liquid nitrogen thermal shock test (liquid nitrogen to warm water) - three cycles

Thermal Shock Tests:

- 1 Cycle of Liquid Nitrogen to Air: The bellows is immersed in liquid nitrogen, then placed in air.
- 3 Cycles of Liquid Nitrogen to Warm Water (40°C):The bellows is immersed in liquid nitrogen, then placed in warm water at 40°C.

Resonant Testing bench

- High-power coupler tests are needed as an acceptance test and for preconditioning prior to the on-line operation on the SC cavities.
- RF conditioning, also called ageing of a PC, is the controlled desorption of absorbed gases by accelerated ions and electrons from the RF surfaces.
- Travelling waves clean the entire RF surfaces, with standing waves only the high field part is conditioned.
- To condition all the part of couplers, the reflected phase must be changed 90° for SW configuration.

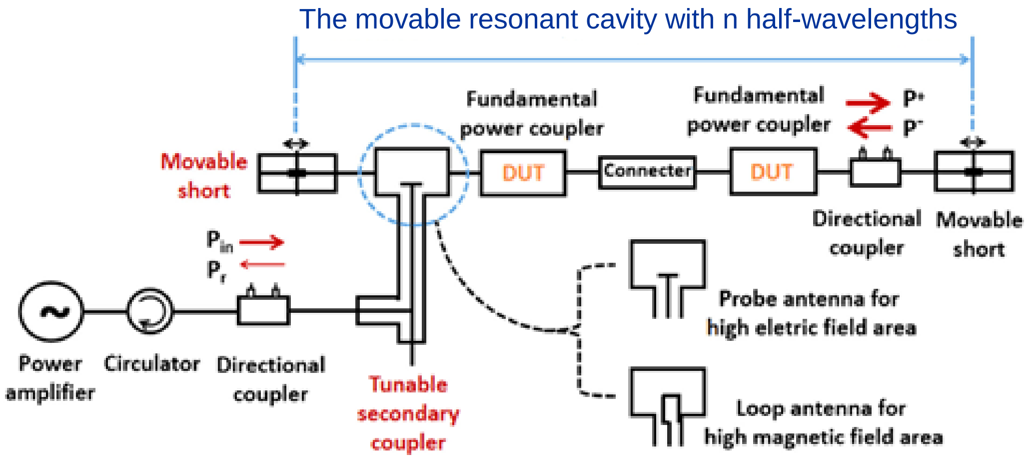


- The construction and operation cost is high for 100-kW-level coupler

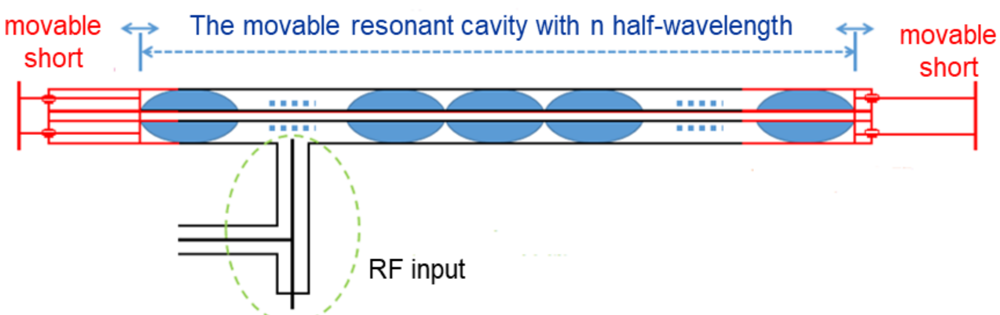
More than 200 couplers, RF conditioning should be with efficiency and productivity

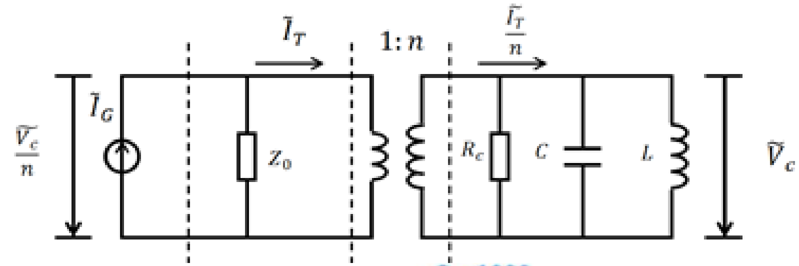
Resonant mode is an efficient way to reduce the cost

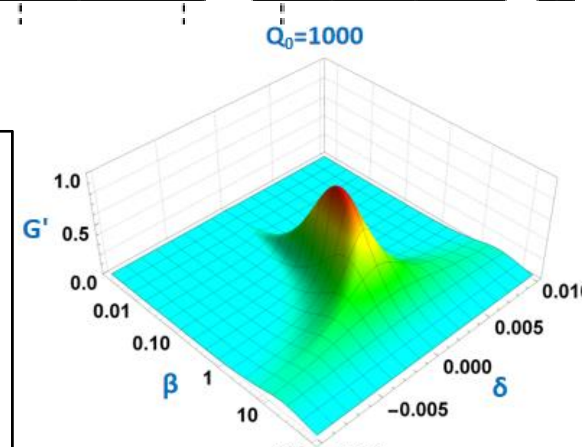
Movable SW Resonant Test bench



- Tunable input coupler, minimizing the reflected power, high power gain
- The node of SW resonant field can be shifted for a distance more than half a wavelength
- Power saving, cost reduction



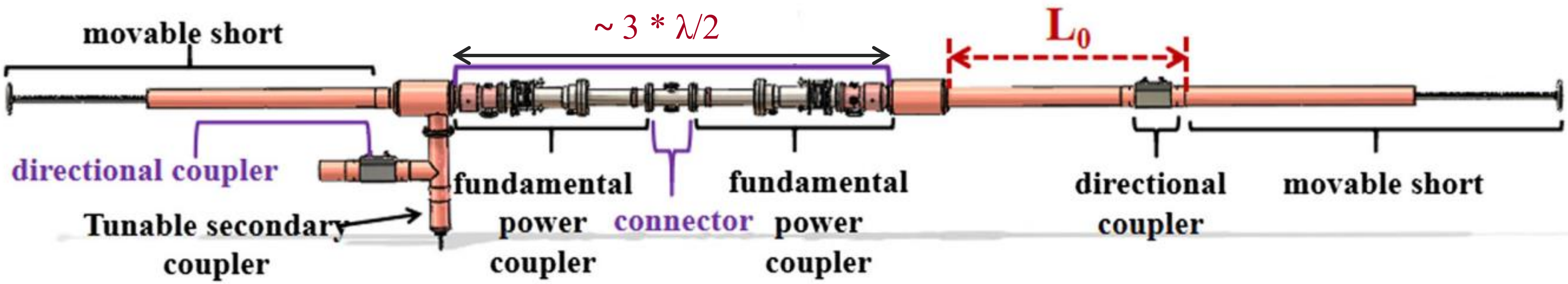




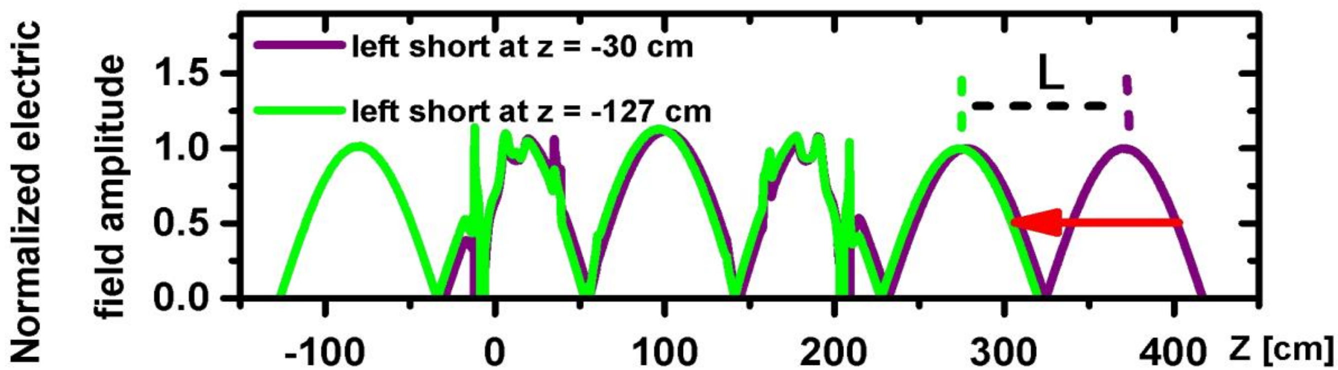
Power Gain $G = \frac{P^+}{P_{in}} \approx \frac{4\beta Q_0}{\omega k[(\beta+1)^2 + 4(Q_0\delta)^2]}$ $\quad k = \frac{U}{p^+}$

Maximum Power Gain $G = \frac{Q_0}{\omega k} = \frac{Q_0}{2\pi \cdot n}$

The proof-of-principle structure



n=5

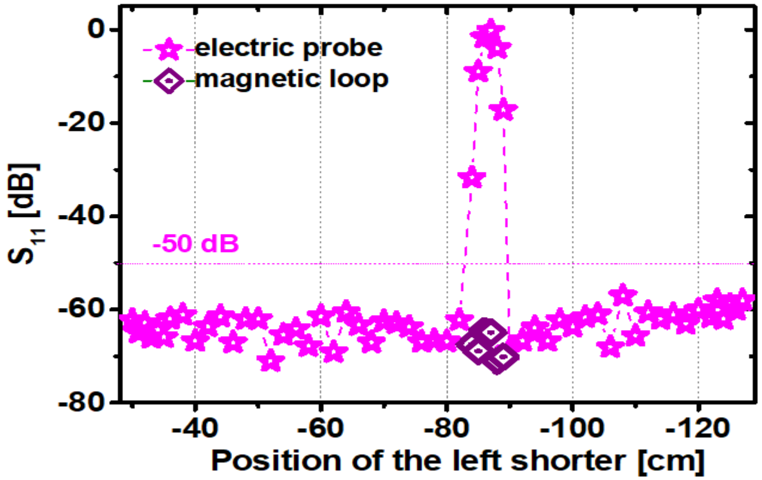


n=5

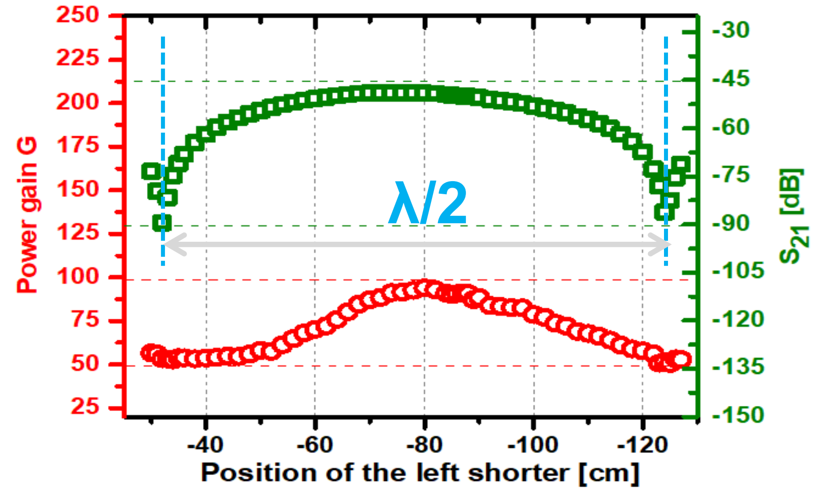
Five electric field antinodes is chosen for the movable SW resonant test system.

Low Power Tests

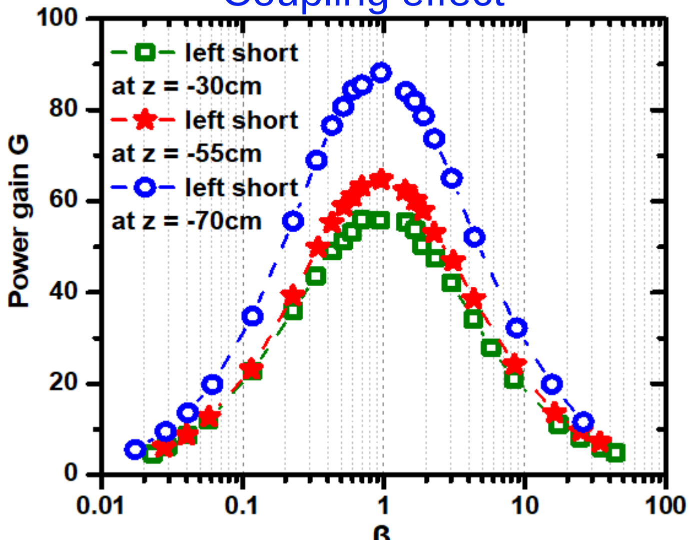
Power coupling efficiency



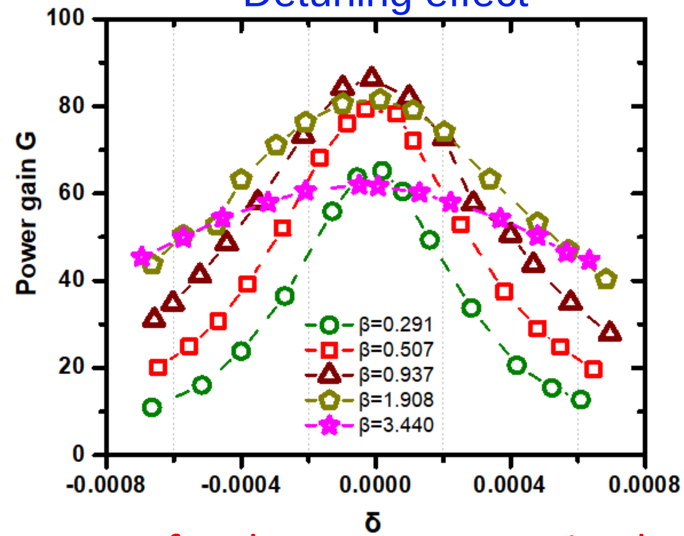
Gain and SW node



Coupling effect

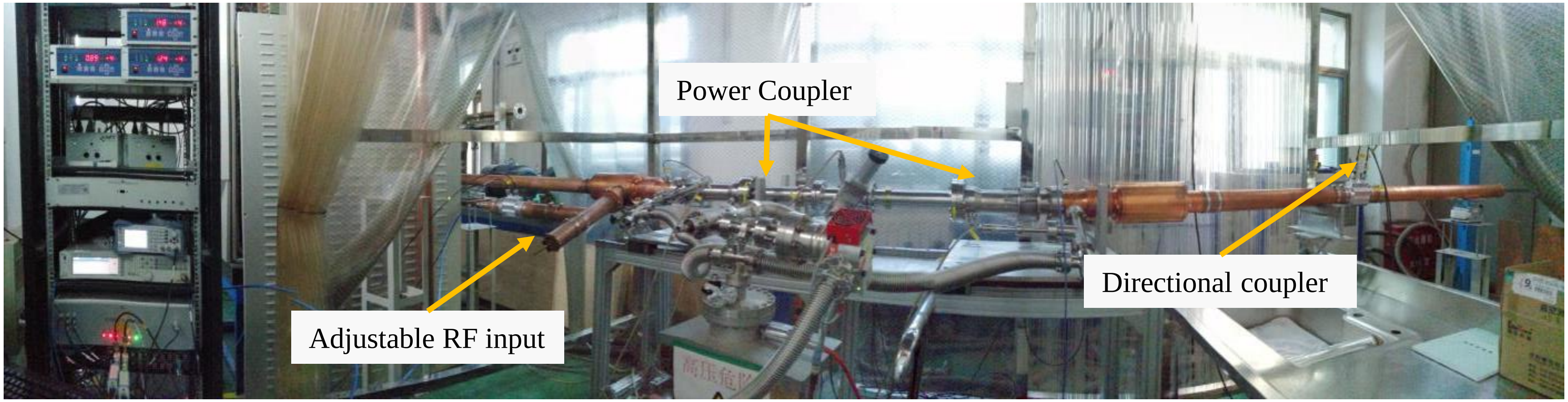


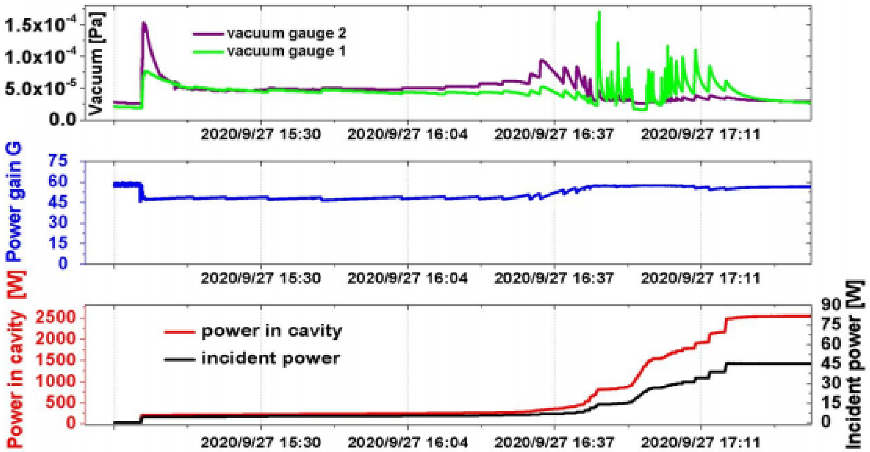
Detuning effect



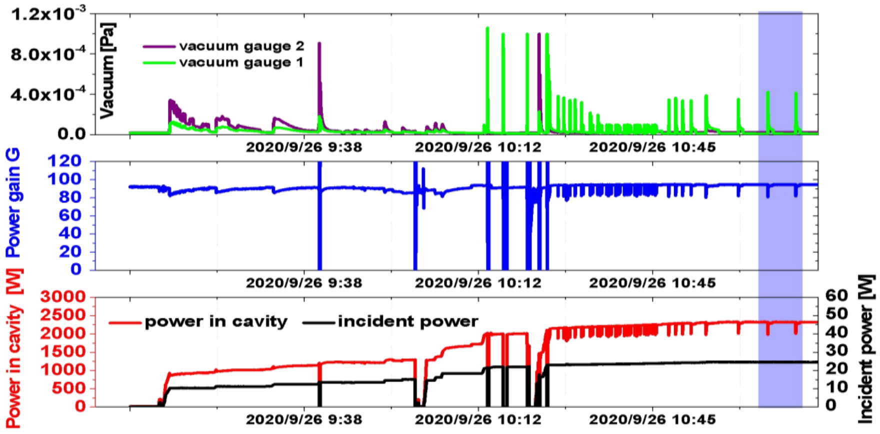
Low-power test results of the proof-of-principle structure for the resonant testing bench

High power Tests



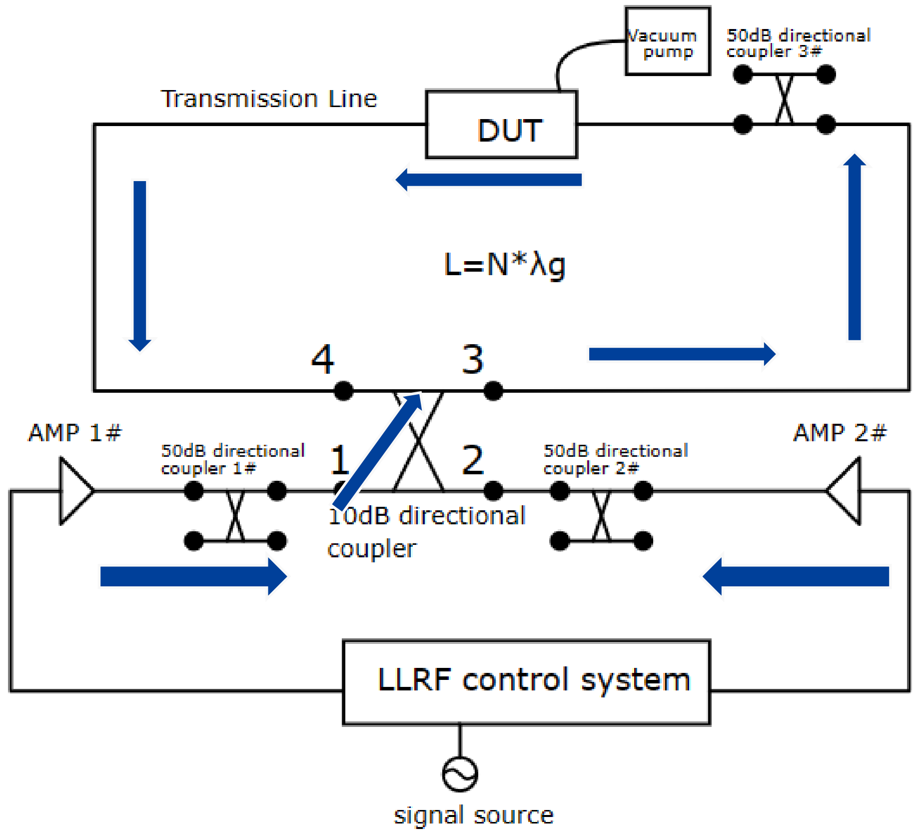


High-power test results with the left short at z = −30 cm



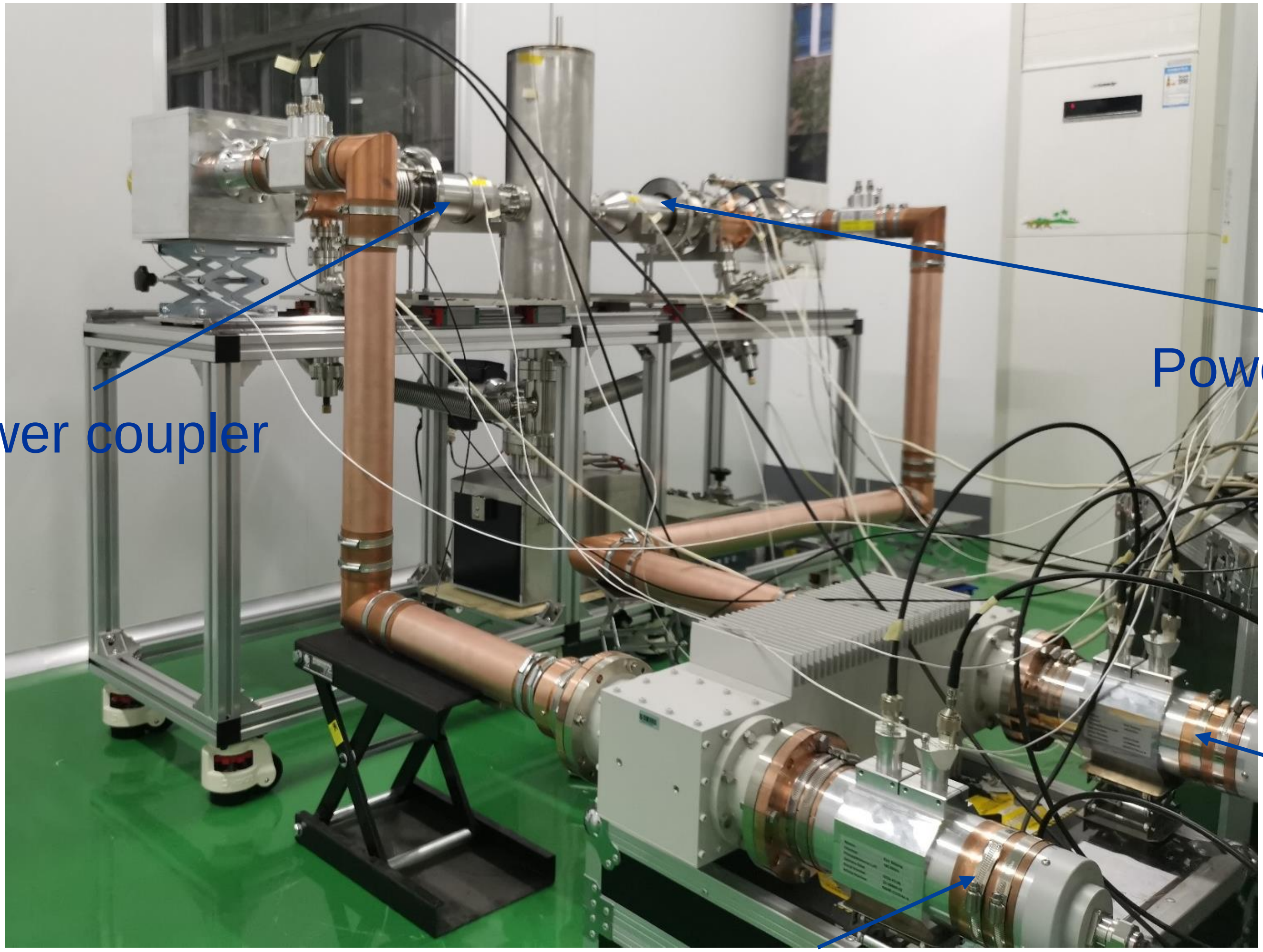
High-power test results with the left short at z = −76 cm

SW Resonant Ring



- high power directional coupler, power accumulating, high power gain
- the node of SW resonant field can be shifted for a distance more than half a wavelength by changing the phase between the two input wave
- Power saving, cost reduction
- No movable short, reliable

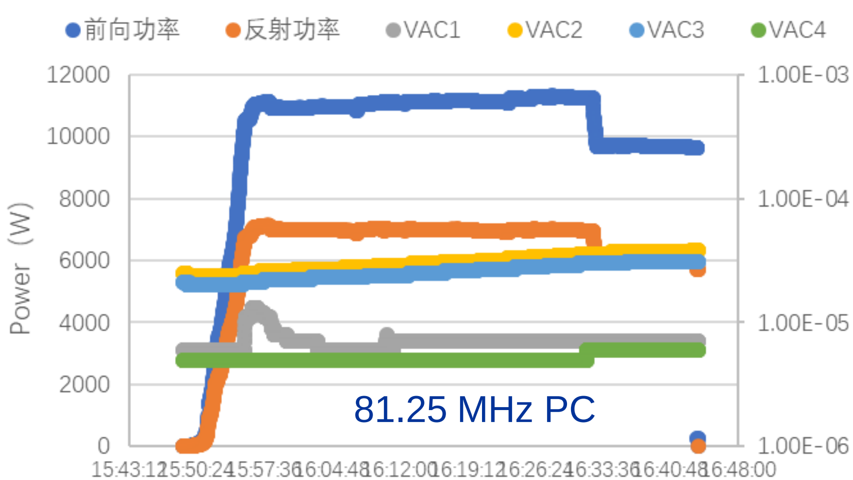
SW Resonant Ring

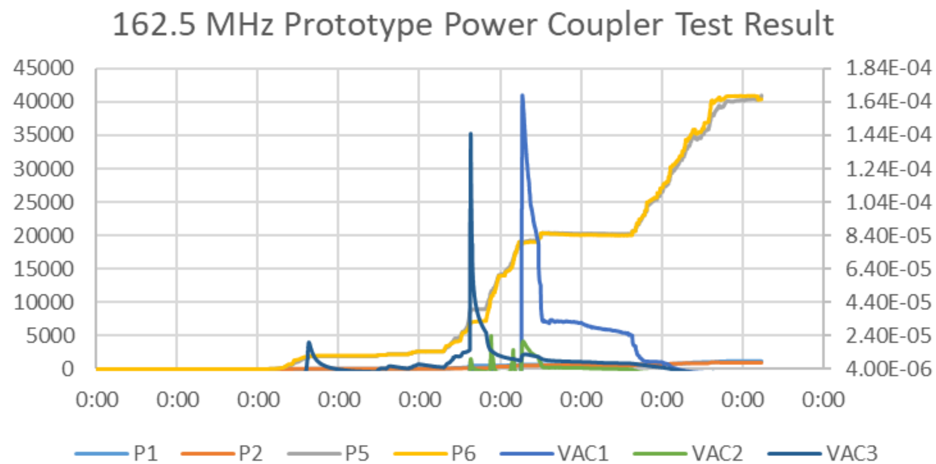


Prototype Coupler Test Result

81.25 MHz PC

162.5 MHz PC





- 81.25 MHz prototype PC can reach around CW 12 kW (TW & SW)
- 162.5 MHz prototype PC can reach around CW 40 kW (TW & SW)

Thanks for your attention