A Universal Power Coupler Developed for Three Superconducting Linear Accelerators at IMP

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Outline

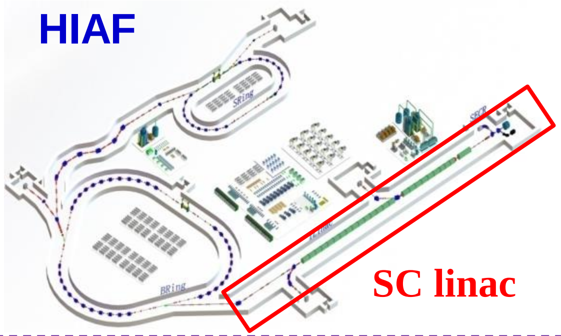
- Motivation
- Universal dual-warm-window coupler
- Exploration of key manufacturing processes
- Prototypes result
- A dual-source excited resonant ring for RF processing
- Mass production
- Summary

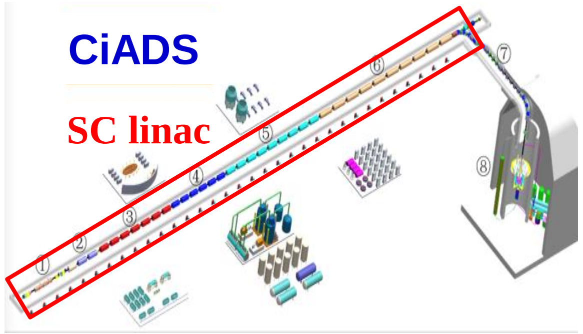
Motivation

HIAF IP-SAFE

- **High-power couplers are the most failure-prone components of SRF systems and play a vital role in their stable operation.**

Power coupler	HIAF		CiADS and upgrade					IP-SAFE and upgrade		
	QWR007	HWR015	HWR010	HWR019	HWR040	Ellip062	Ellip082	HWR010	HWR015	HWR040
Frequency(MHz)	81.25	162.5	162.5	162.5	325	650	650	162.5	162.5	325
Quantity	30	66	9	24	60	30	28+28	18	18	24+18
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	0.56	2.1	1.8
Stroke (mm)	7	5	5	5	5	6	8	-	-	-
Power (kW)	6	6	10	24	32	64	120	6	6	8





Challenge

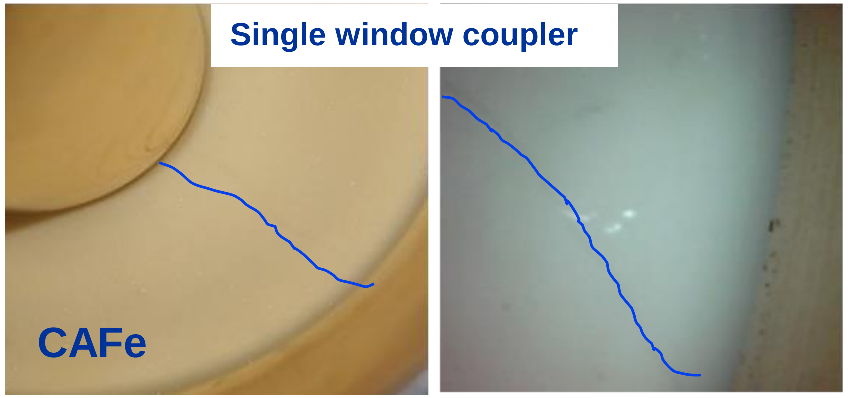
- Various types of resonator
- Wide operating frequency range
- Tight schedule

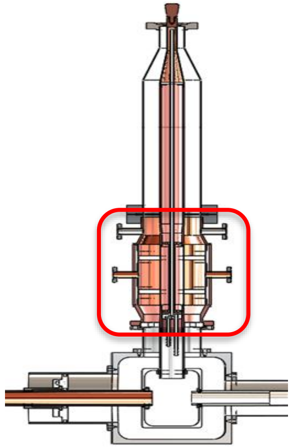
Solution

- Maximum unification of coupler part
- Similar design to use the same solutions and technology
- A dual-source excited resonant ring for RF processing

Dual-warm-window coupler

The dual-warm-window couplers developed for the CAFe facility have maintained reliable online operation for over a decade.



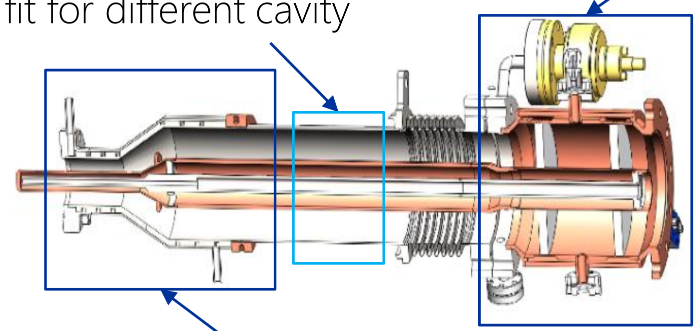


A universal dual-warm-window coupler

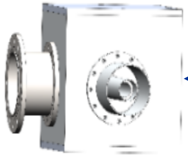
Design Approach

Dual warm window: compact, match

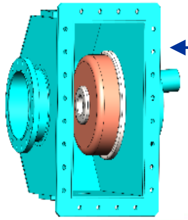
Coupling part: Length variable, fit for different cavity



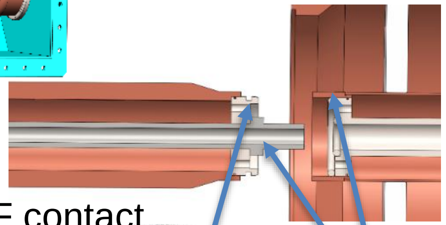
Double Wall, 4.5K Helium Gas inlet 75K outlet / thermal intercept



T-Transition structure, 81.25-325MHz



Doorknob, 650MHz



RF contact

water seal

Challenge

- Match, diverse resonator geometries across a wide operating frequency range
- Compact, Couplers have to allow make assembling accelerating cavities with coupler in clean room and to be installed in cryomodules then
- Compatible, various cooling schemes

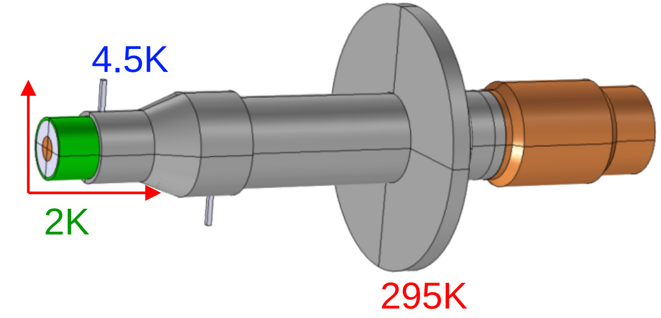
Unification:

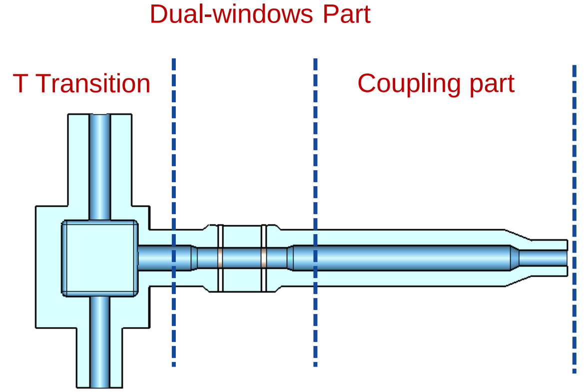
❑ **Similar dual-warm-window and OC part**
  - ✓ **Similar fabrication technology**
  - ✓ **Water cooling systems, RF contact and water seal within the same screw**
  - ✓ **Arrangements to provides contacts between IC and outer**

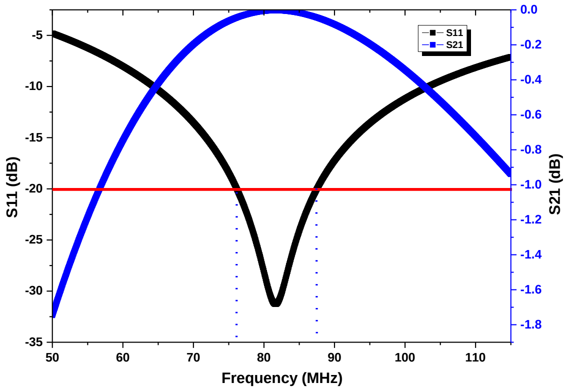
❑ **HV bias system**

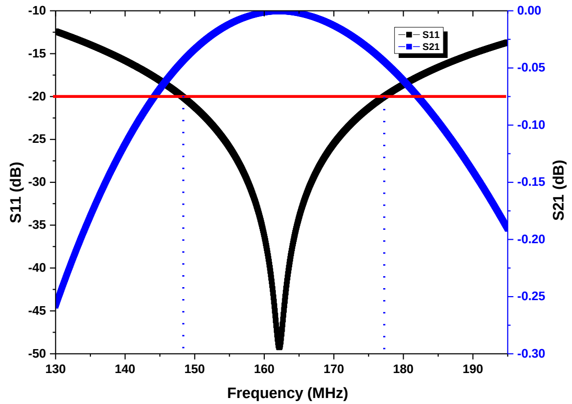
Dual-warm-window coupler-design

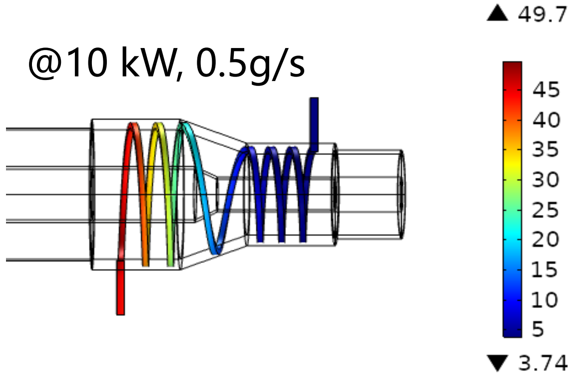
Operation frequency(MHz)	81.25	162.5	325	650
Passband (S11 < -20 dB) (MHz)	11	29	60	100
Power (kW)	6	24	32	100
Maximum power density through window (kW/cm^2)	5.33	7.91	8.52	15.33

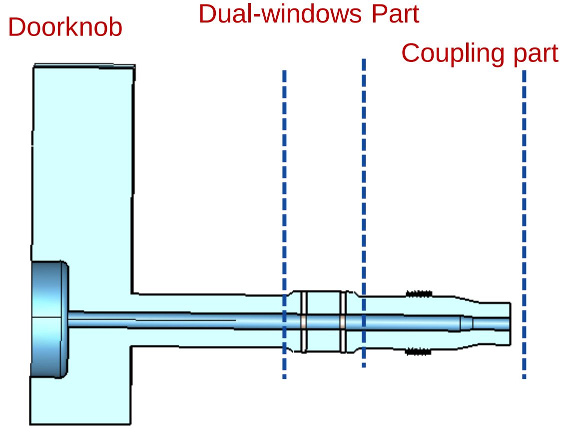


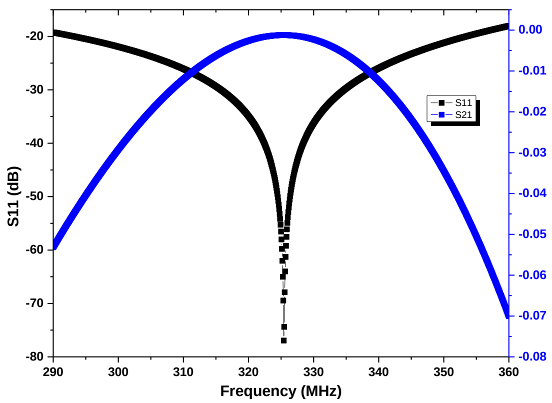


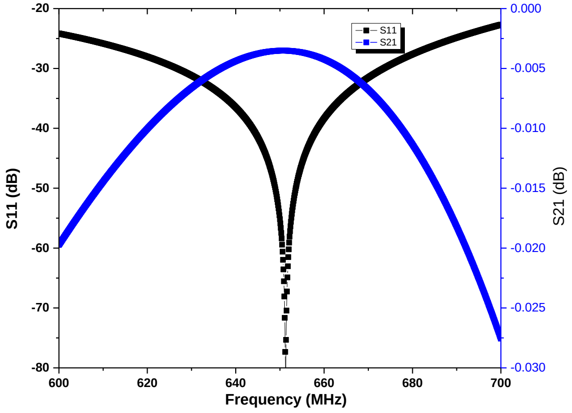


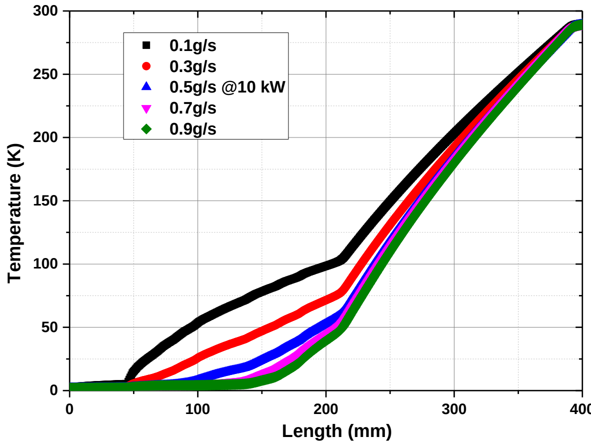




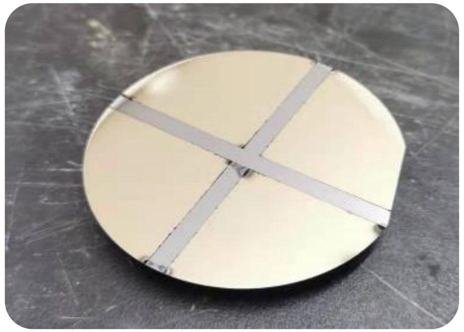




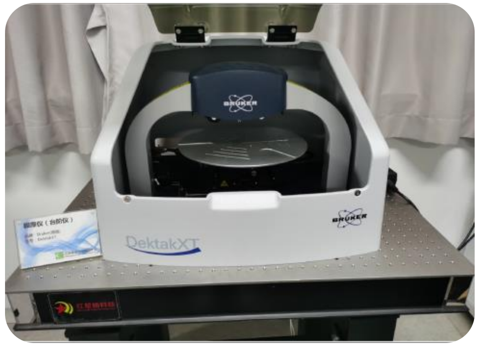


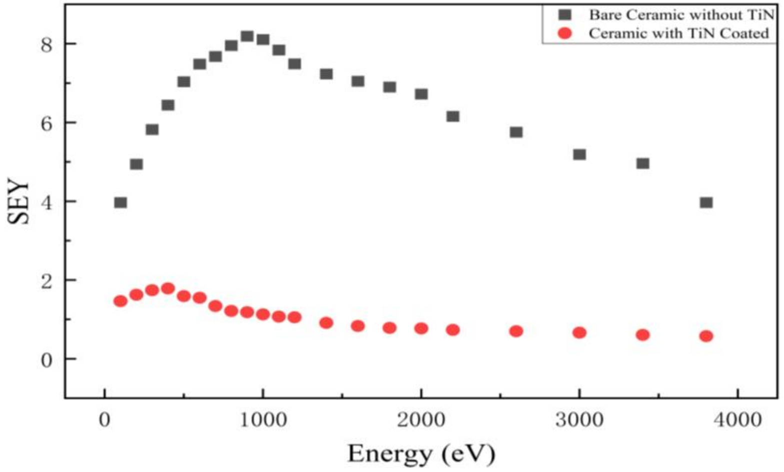


Dual-warm-window coupler-key process

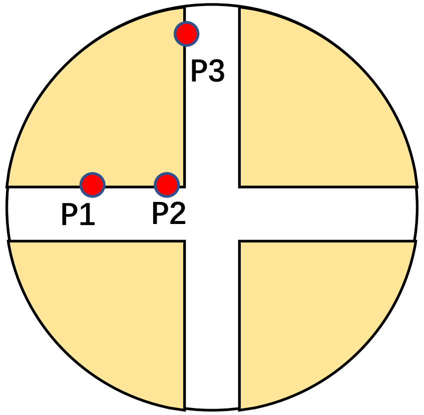

After 1 hour of coating on a single crystal silicon wafer.

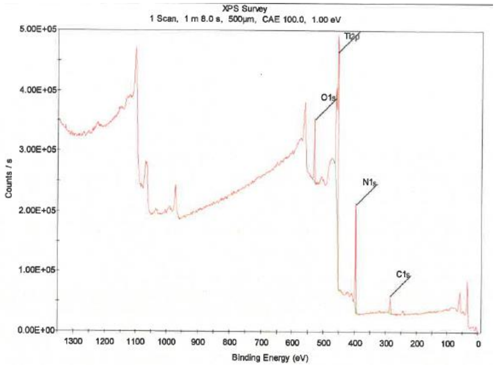

Magnetron sputtering coating machine


Film thickness testing step gauge



- Method: DC reactive magnetron sputtering
- Parameters: gas flow ratio, target-to-substrate distance, coating power, rotation speed, and pressure
- Results: obtaining the desired thickness, Ti:N-1.05





	Diameter of wafer	Coating Time/s	Testing Instrument	Ion Source Cleaning	positio1/ nm	position2/ nm	position3/ nm	Average Thickness/nm	uniformity
1	56mm	35	Step Profile	No	11.06	9.78	11.2	10.68	91.57%
2	56mm	38	Step Profile	No	12.66	14.56	11.71	12.98	92.20%
3	56mm	300	Step Profile	No	70.36	72.54	65.66	69.52	95.45%

Dual-warm-window coupler-key process

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

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

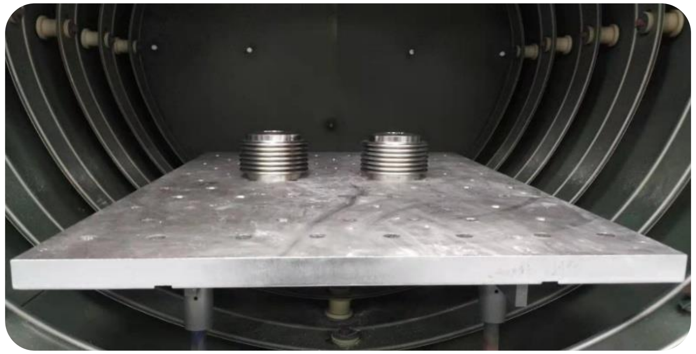
Appearance of Copper Plating Layer: Evaluating the visual appearance of the copper plating layer for uniformity and absence of defects.

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

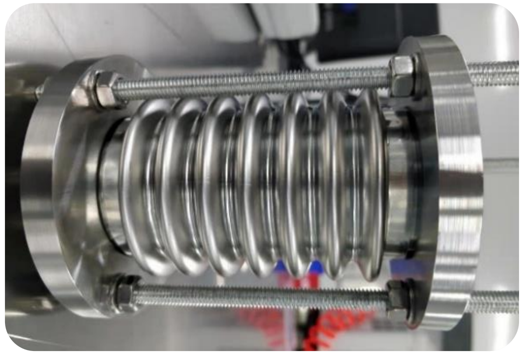
Uniformity of Copper Plating Thickness: Verifying the consistency and uniformity of the copper plating layer thickness across the entire surface.

Copper plating test route

Cleaning and degreasing
↓
Electroless nickel plating
↓
Copper plating in a copper sulfate bath
↓
Visual & airtight inspection
↓
Vacuum annealing
tension-compression cycling
thermal shock cycling
↓
RRR test
Thickness test

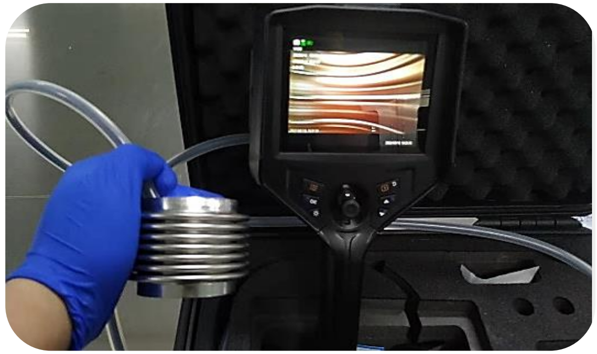


vacuum annealing



tensile-compressive

Thermal shock cycling



visual inspection

Dual-warm-window coupler-key process

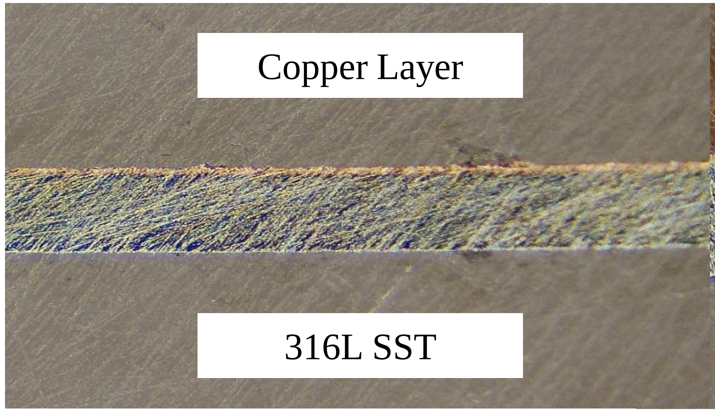
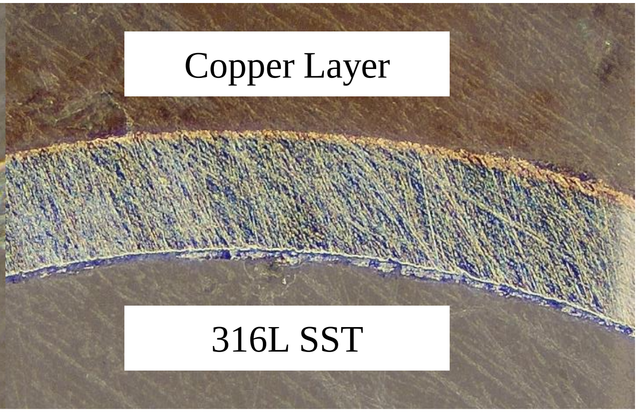


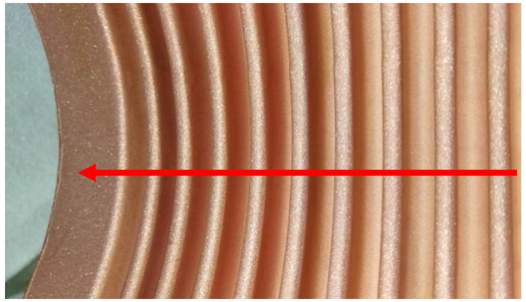
Plate Copper Plating



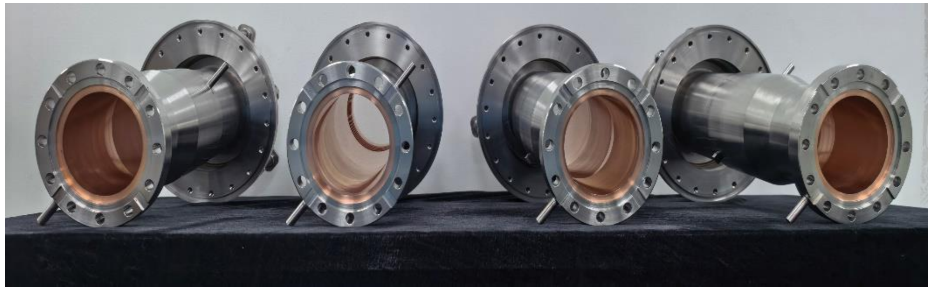
Bellow Copper Plating

RRR test instrument

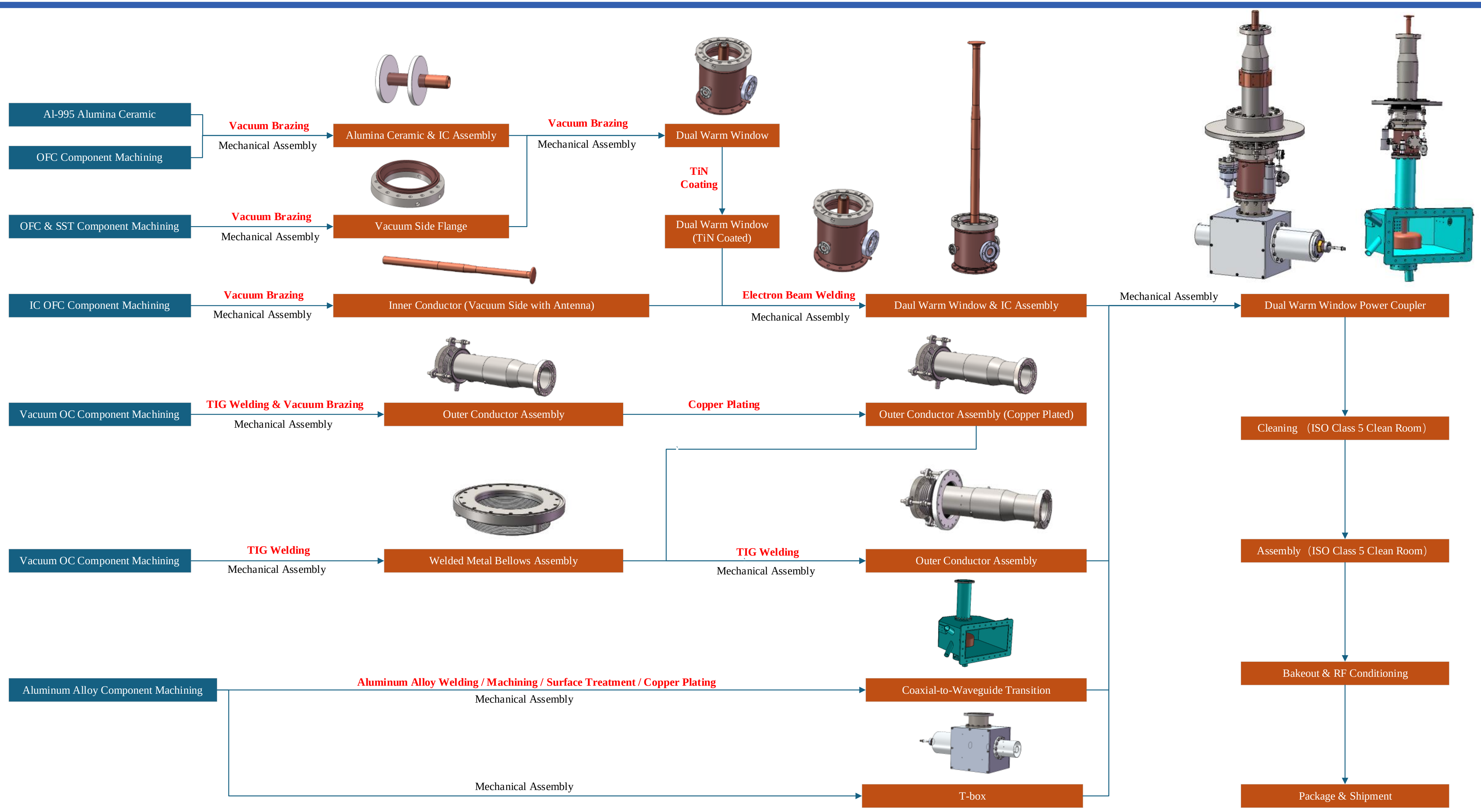
Copper Layer		Heat treatment	RRR
Target Thickness / um	Actual Thickness / um		
10	9.62	Vacuum 400°C 2h	27.91
20	20.65	Vacuum 400°C 2h	53.66
30	30.28	Vacuum 400°C 2h	80.75



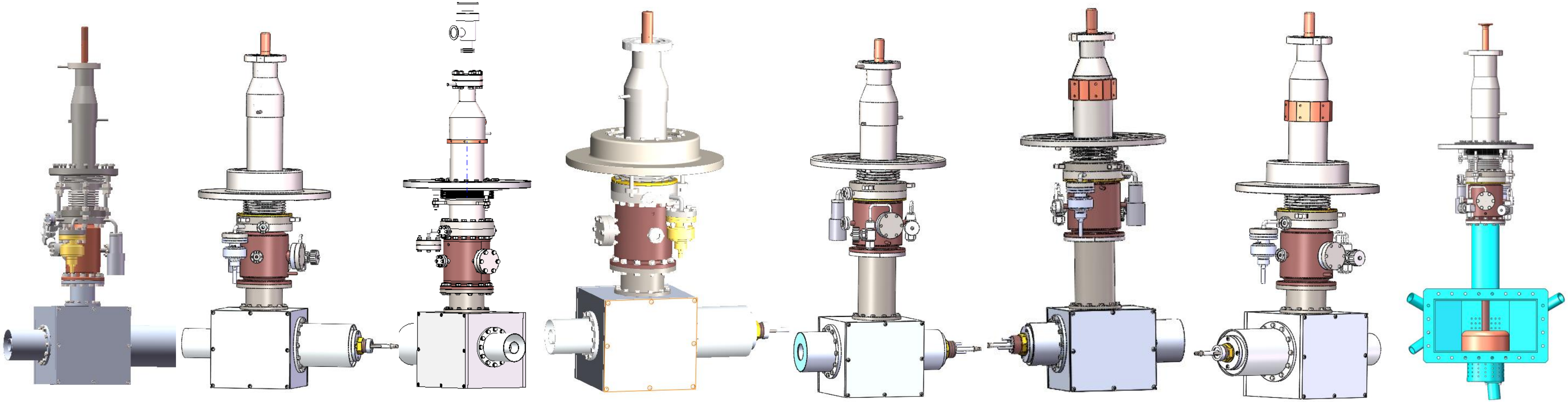
Test result	um
Average thickness	19.38
Standard error	0.214
Thickness range	0.56
Maximum	19.7
Minimum	19.14
RRR	**32**

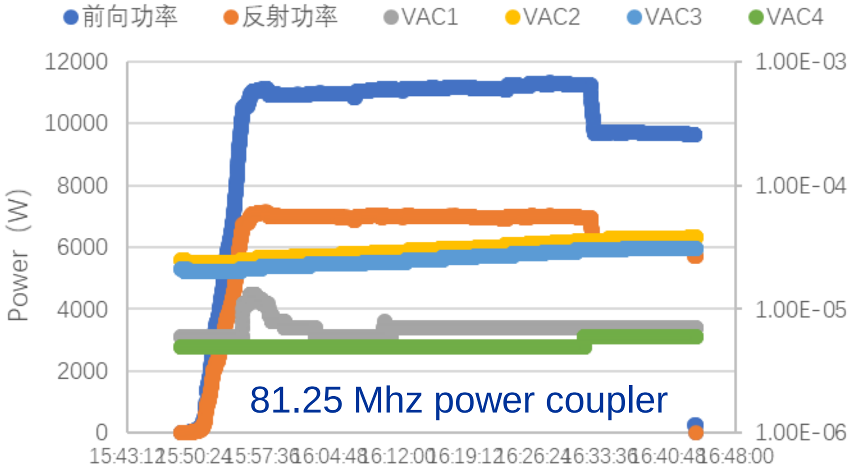


Dual-warm-window coupler-key process

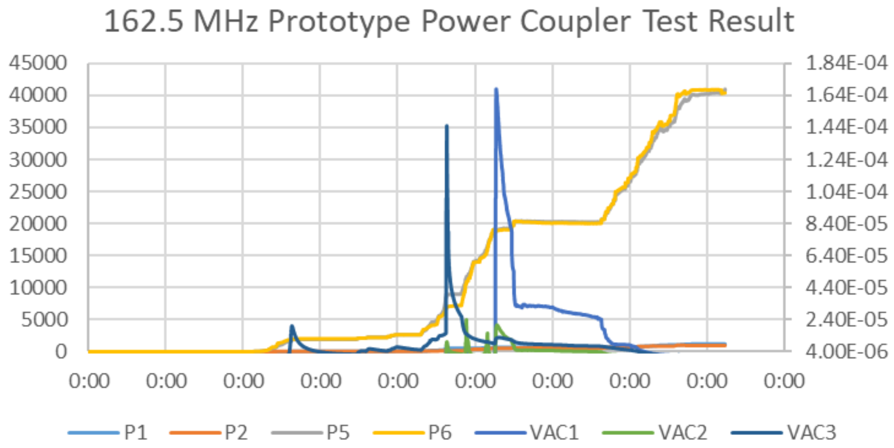


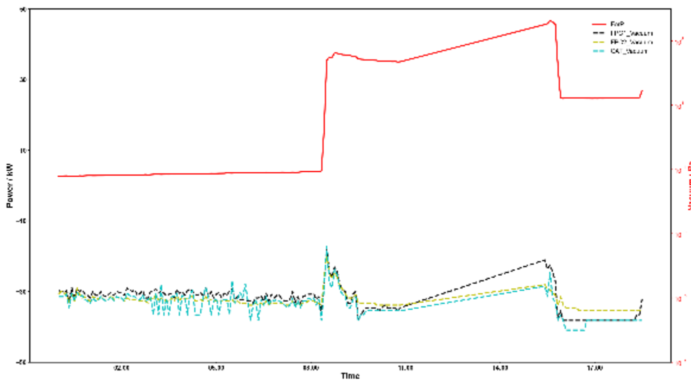
Dual-warm-window coupler-Protypes





81.25 Mhz power coupler



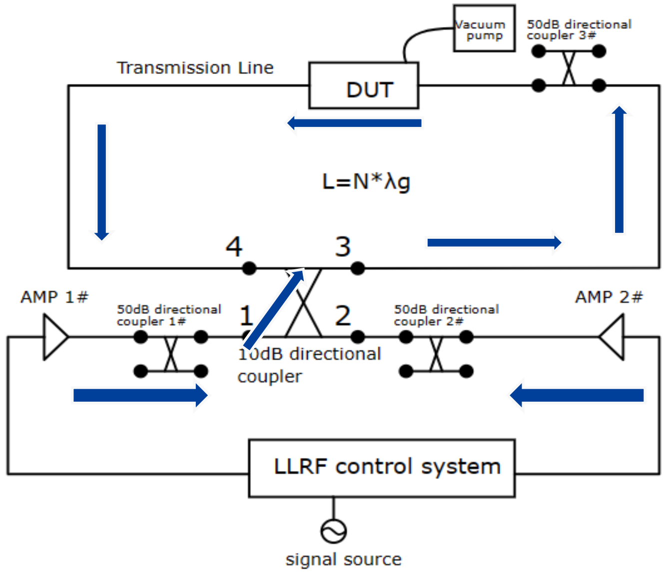


325 MHz power coupler

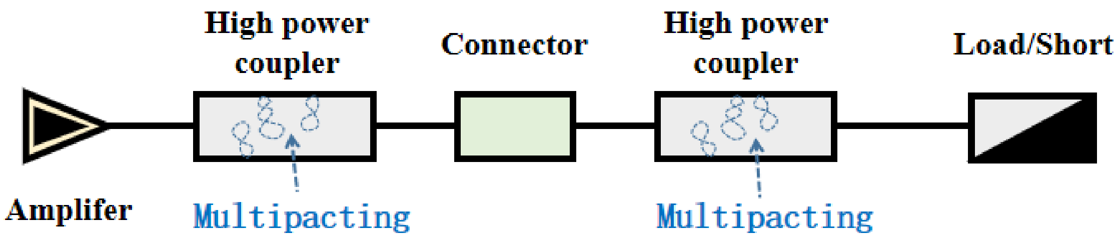
Dual source excited resonant ring

- High power conditioning: a necessary step prior to the operation of input power couplers for SC acclerator
- Traditional conditioning platforms: high demands on power sources and hardware infrastructure
- A dual source excitation resonant ring: high power gain, multimode

A dual source excitation resonant ring



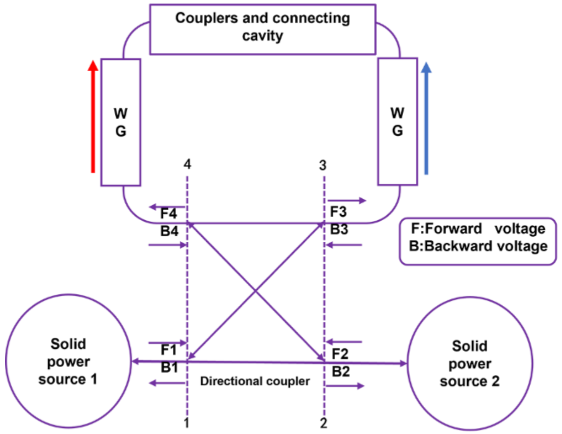
Traditional condition platform



- Directional coupler
- Solid state power source
- Rigid coaxial line and waveguide
- DUT(input power couplers and connecting cavity)

- High power directional coupler, electromagnetic field accumulating, high power gain
- 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 with LLRF
- Power saving, cost reduction
- No movable short component, reliable for high power

Dual source excited resonant ring



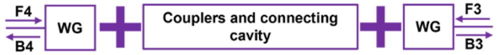
(a)

$$F_3 = \frac{1}{A}\left[S_{31} + \frac{(S_{33}S'_{12} + S_{34}S'_{22})S_{41}}{1 - S'_{12}S_{43} - S_{44}S'_{22}}\right]F_1 + \frac{1}{A}\left[S_{32} + \frac{(S_{33}S'_{12} + S_{34}S'_{22})S_{42}}{1 - S'_{12}S_{43} - S_{44}S'_{22}}\right]F_2$$

$$F_4 = \frac{1}{B}\left[S_{41} + \frac{(S_{43}S'_{11} + S_{44}S'_{21})S_{31}}{1 - S'_{11}S_{33} - S_{34}S'_{21}}\right]F_1 + \frac{1}{B}\left[S_{42} + \frac{(S_{43}S'_{11} + S_{44}S'_{21})S_{32}}{1 - S'_{11}S_{33} - S_{34}S'_{21}}\right]F_2$$

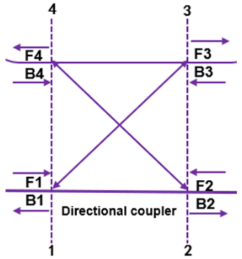
$$A = 1 - S_{33}S'_{11} - S_{34}S'_{21} - \frac{(S_{33}S'_{12} + S_{34}S'_{22})(S_{43}S'_{11} + S_{44}S'_{21})}{1 - S'_{12}S_{43} - S'_{22}S_{44}}.$$

$$B = 1 - S_{43}S'_{12} - S_{44}S'_{22} - \frac{(S_{43}S'_{11} + S_{44}S'_{21})(S_{33}S'_{12} + S_{34}S'_{22})}{1 - S'_{11}S_{33} - S_{34}S'_{21}}$$



$$\begin{bmatrix} B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} \begin{bmatrix} F_3 \\ F_4 \end{bmatrix}$$

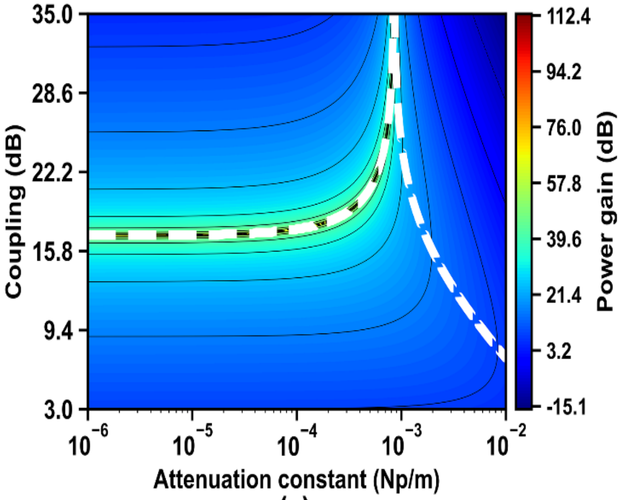
(b)



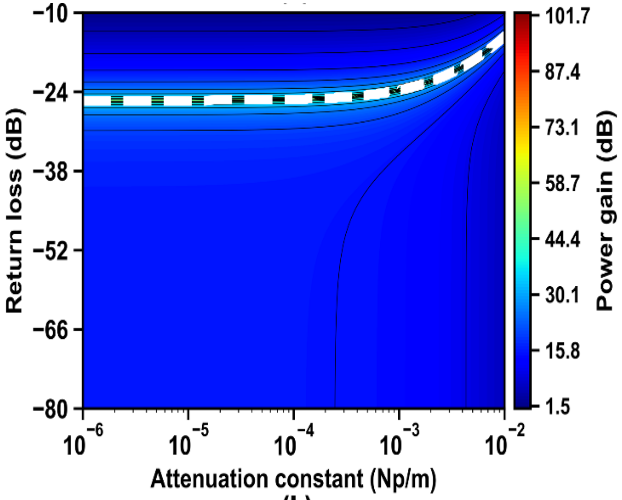
$$\begin{bmatrix} B_1 \\ B_2 \\ F_3 \\ F_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ B_3 \\ B_4 \end{bmatrix}$$

(c)

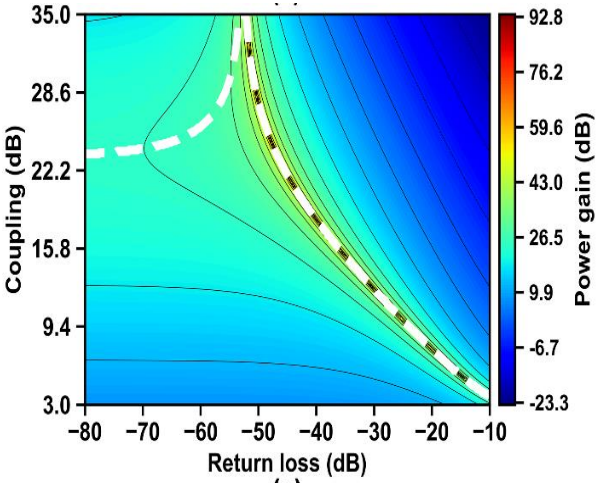
- **Power gain:** influenced by the **directional coupler** (coupling, return loss and isolation) and the **transmission of the DUT**.
- **Wave mode:** adjust the **phase** difference between the two power sources and their operating **frequency** to achieve a transition between operating modes.



(a)



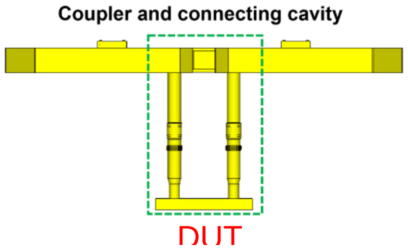
(b)



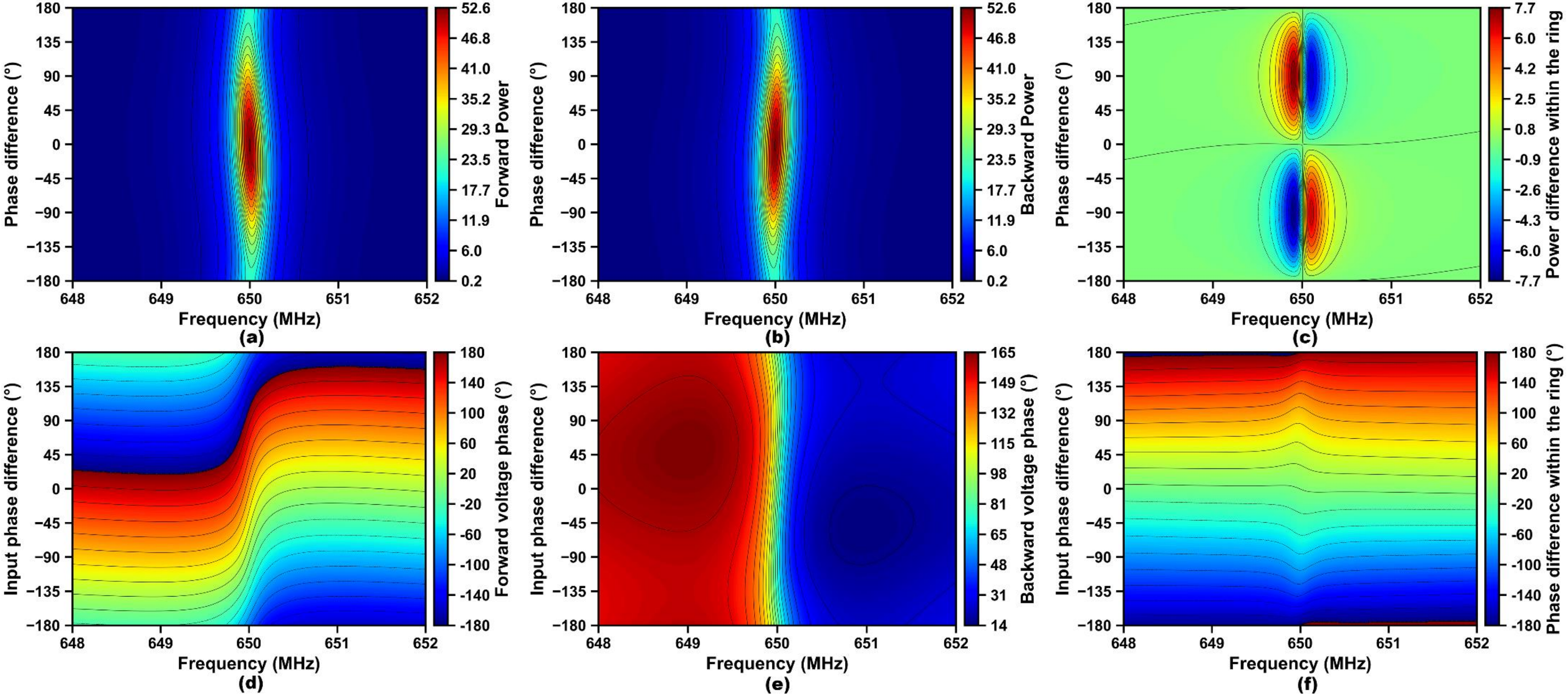
(c)

Dual source excited resonant ring

- When the DUT is symmetrically impedance-matched, both the forward and backward power in the ring increase significantly.
- Mode switching by adjusting the phase difference and operating frequency.



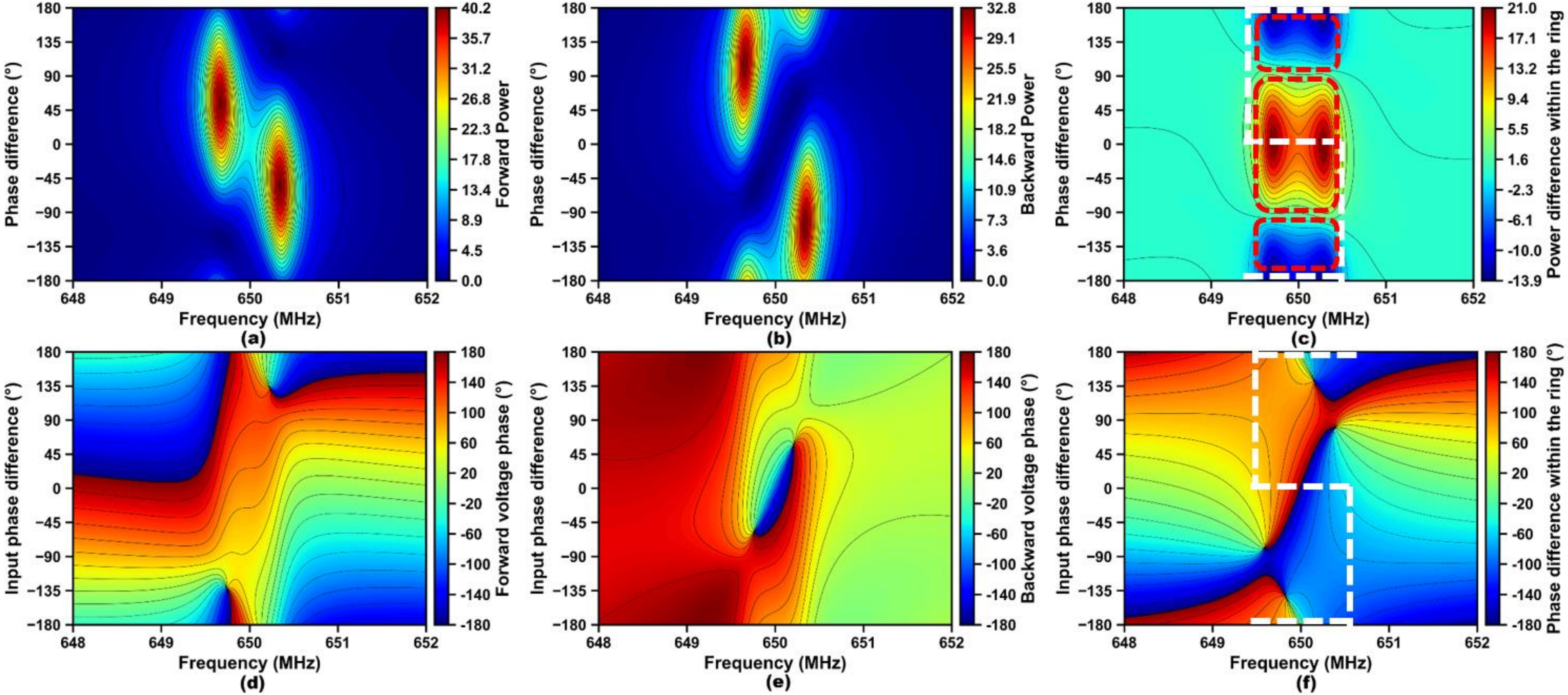
Adjusting the impedance matching of the DUT by adjusting the coupler's antenna.



C:10dB,I:60dB,R:-40dB; The white line indicates the standing wave mode operating point, and the red box indicates the traveling wave operating region.

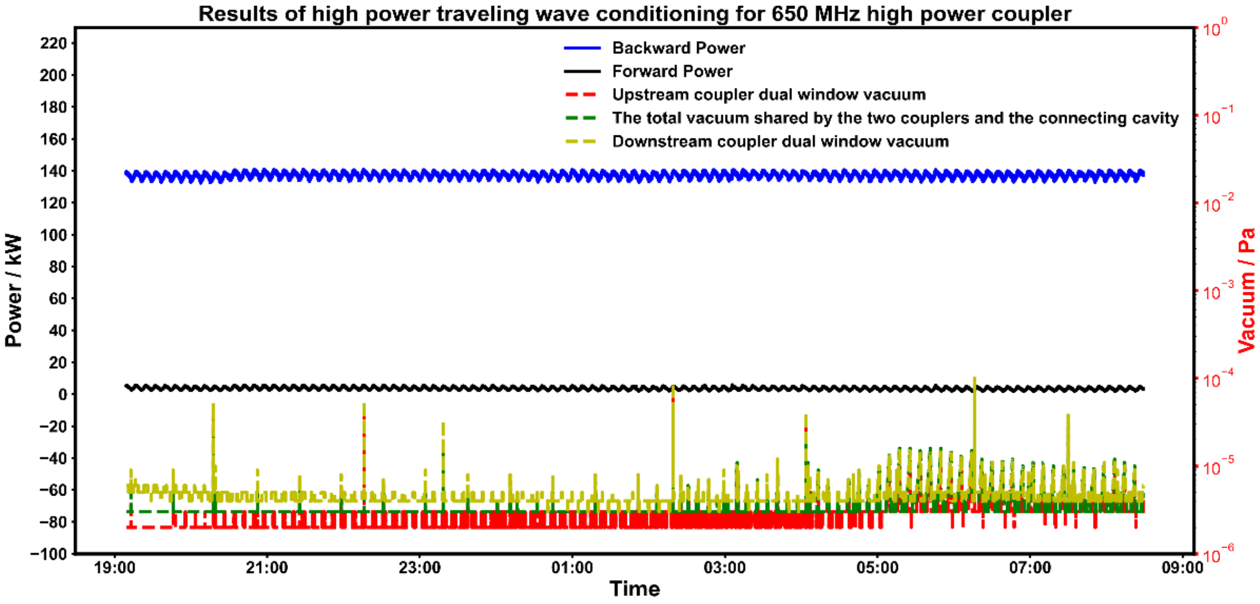
Dual source excited resonant ring

- When the DUT impedance is mismatched, the frequency distribution and magnitude of the forward and backward power in the ring change.
- The operating point in standing-wave mode and the operating region in traveling-wave mode also change accordingly.



C:10dB,I:60dB,R:-40dB; The white line indicates the standing wave mode operating point, and the red box indicates the traveling wave operating region.

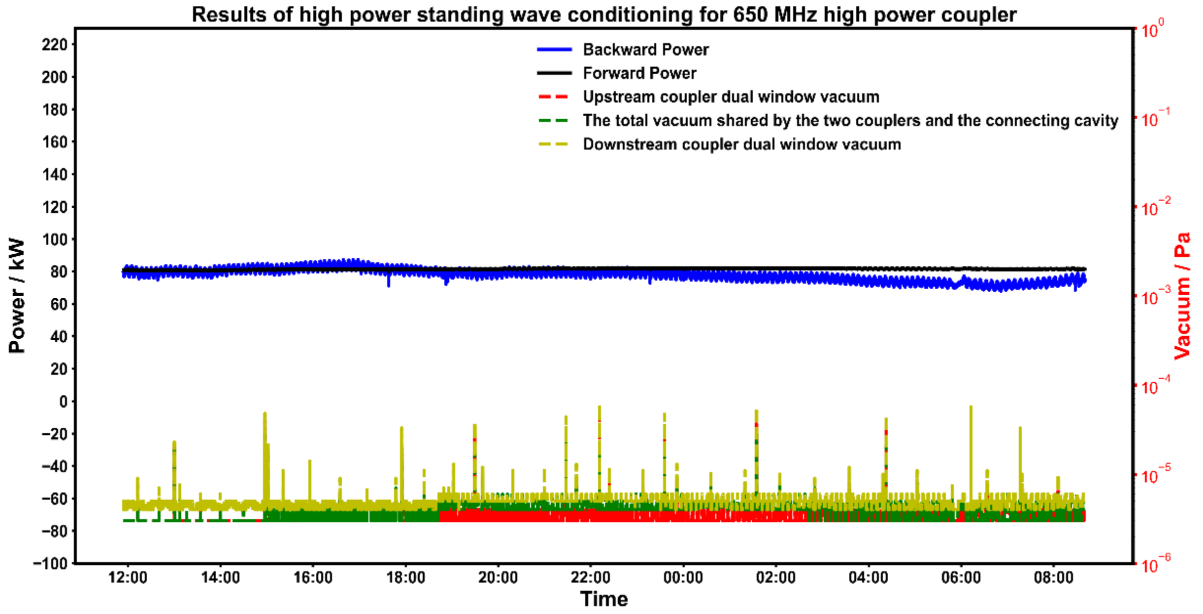
Dual source excited resonant ring



High-Power Traveling-Wave Testing of a 650 MHz Input Power Coupler.

- Traveling-wave mode operating point: Operating frequency of 650.65 MHz, power source 1 output power of 5.4 kW, power source 2 output power of 5.0 kW, and a phase difference of -25°
- The backward power within the ring was 138.5 kW, and the forward power was 4 kW. The traveling-wave test lasted more than 10 hours

- By continuously adjusting the phase difference and operating frequency of the power source, the standing wave node is shifted by 180°
- The forward and backward power within the ring are 80 kW, and the standing wave mode test lasted more than 10 hours



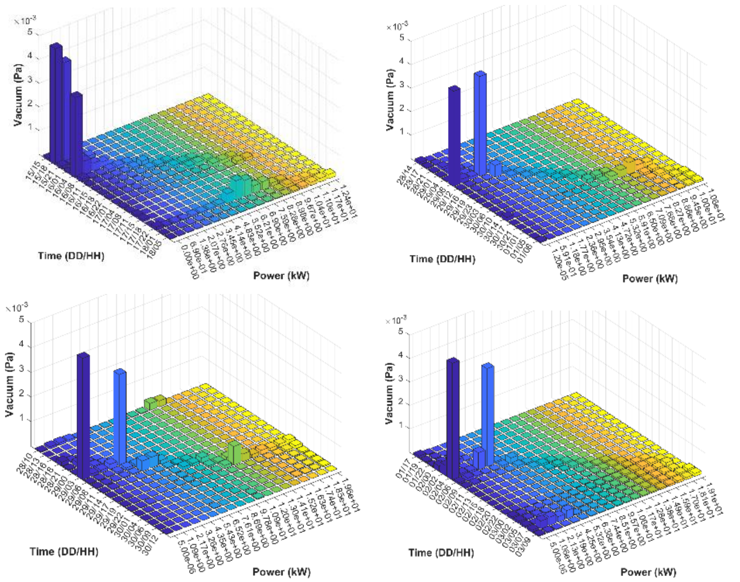
High-Power Standing-Wave Testing of a 650 MHz Input Power Coupler.

Mass production

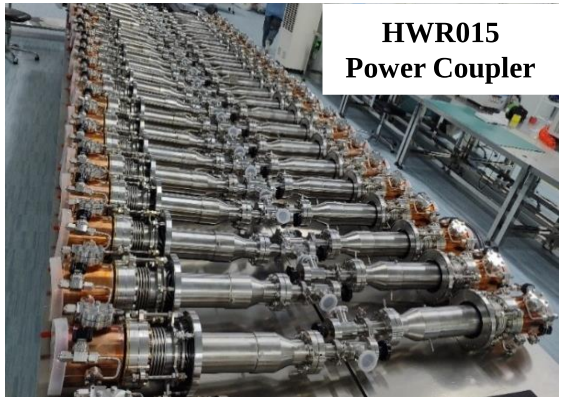
Mass Production Quality Consistency:

- **Mechanical Structural**
- **Assembly Orientation**
- **Performance (Outgassing Point, Vacuum Level)**

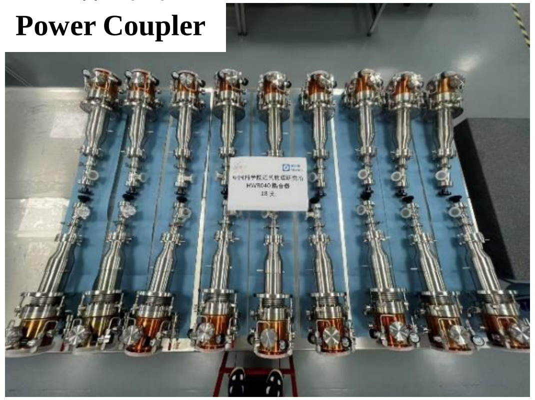
Key Manufacturing Processes	Critical Performance Consistency	Assurance Measures
Brazing	Dimensional accuracy / GD&T Process parameters / Process flow	•High-precision welding jigs and fixtures ; •Standardization of critical welding parameters • regular calibration of equipment
TIG		
Copper coating	Thickness RRR value	•Precision fixturing for copper electroplating •Regular monitoring and adjustment of copper electroplating solution
Cleanroom assembly	Clean assembly	•Cleanliness verification •Standardization and verification of assembly orientation ;
RF conditioning	Effectiveness of the aging process	•Standardization of baking time/temperature •Data logging of critical parameters during high-power conditioning



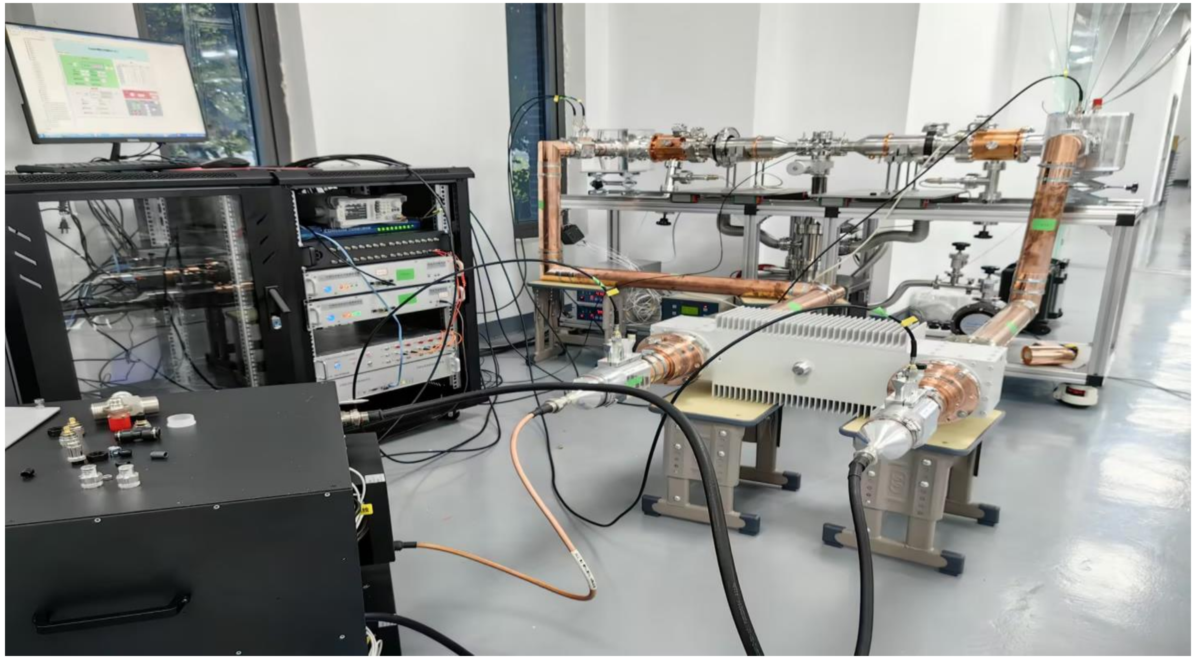

QWR007 Power Coupler


HWR015 Power Coupler

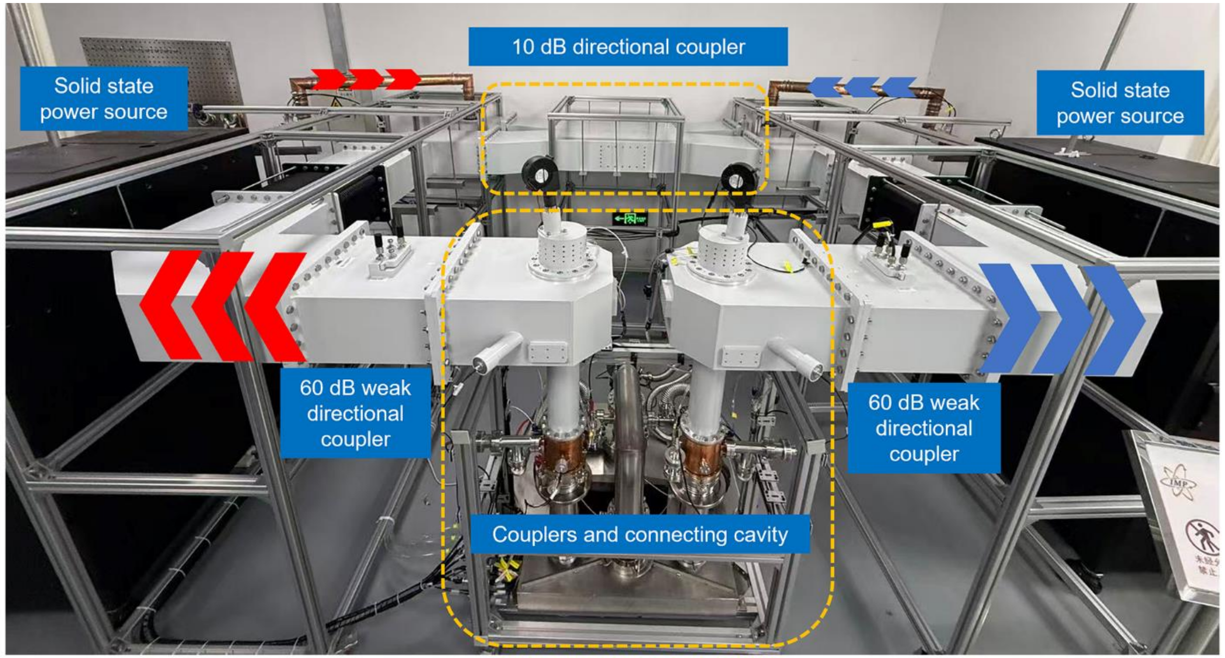

HWR019 Power Coupler

HWR040 Power Coupler


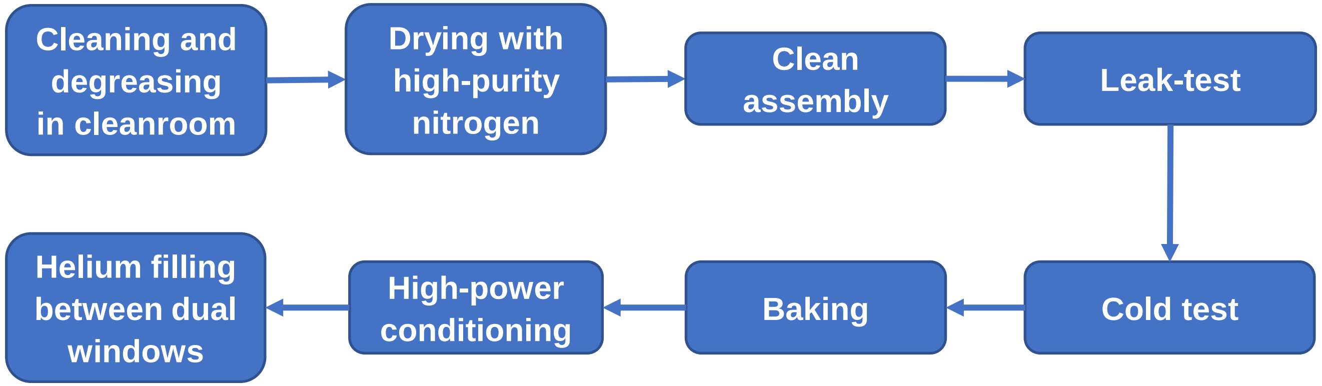
Mass production

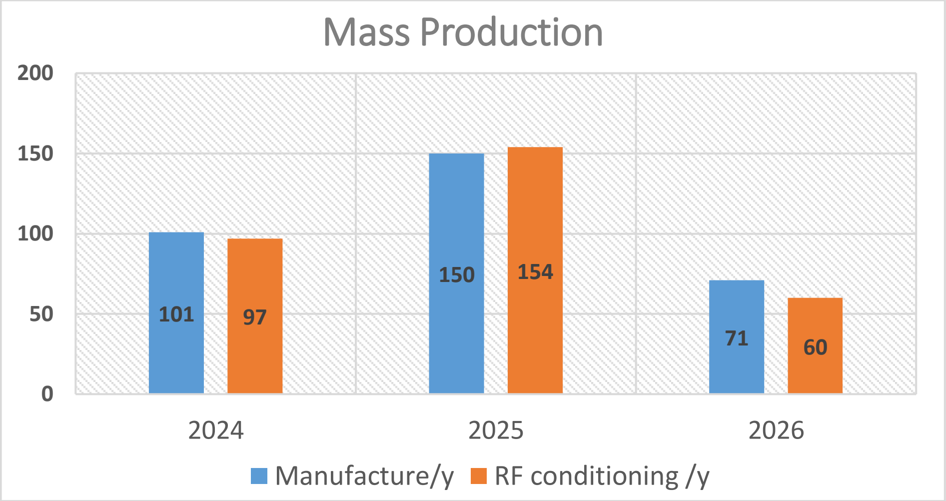


81.25-325MHz RF processing platform



650MHz RF processing platform





Over the past 31 months, 322 couplers were manufactured, 311 of them having completed RF conditioning. 174 couplers are operating well on-site.

Summary

- A universal dual-warm-window coupler technology has been developed to establish a unified technical route for superconducting cavity couplers of HIAF, CiADS and IP-SAFE.
- Several variants of power couplers are derived from this universal architecture, enabling the standardization of all critical manufacturing processes. One round of R&D delivers coupler solutions for multiple facilities, significantly shortening the R&D cycle.
- A novel high-gain resonant conditioning system has been developed, which enables timely batch delivery of high-power couplers for all three accelerator facilities.
- Hundreds of couplers have been engineered and delivered, achieving good consistency in fabrication, assembly and RF performance.

Thanks for your attention!