北京大学
PEKING UNIVERSITY

Progress of FPCs development at Peking University

Fang Wang

on behalf of our SRF group

July 2, 2024

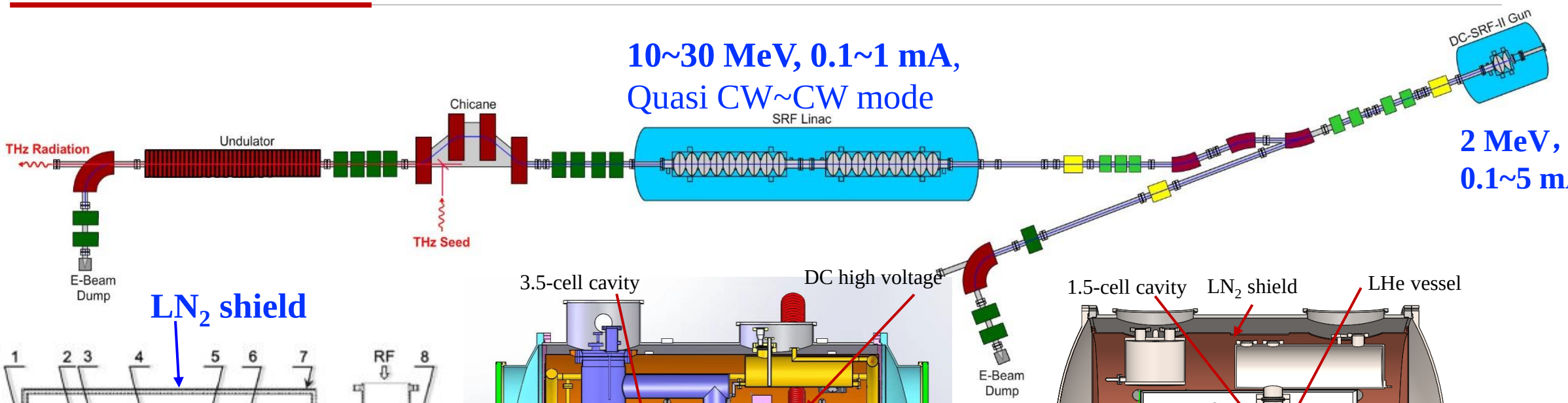
The 6th worldwide meeting on Fundamental RF Power Coupler (2024)

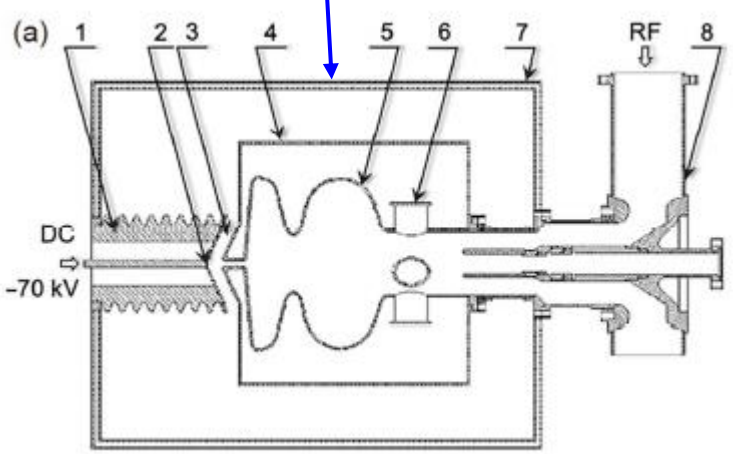
CONTENTS

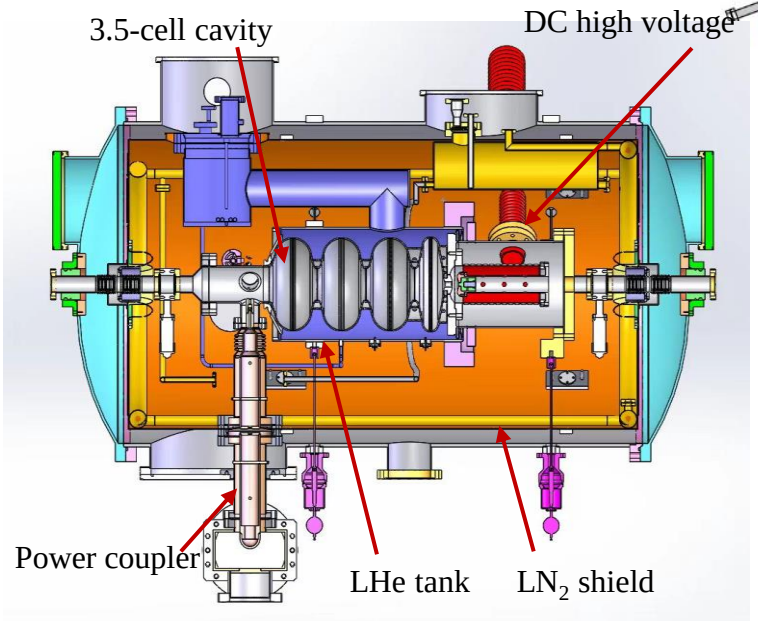
1.1 The facility

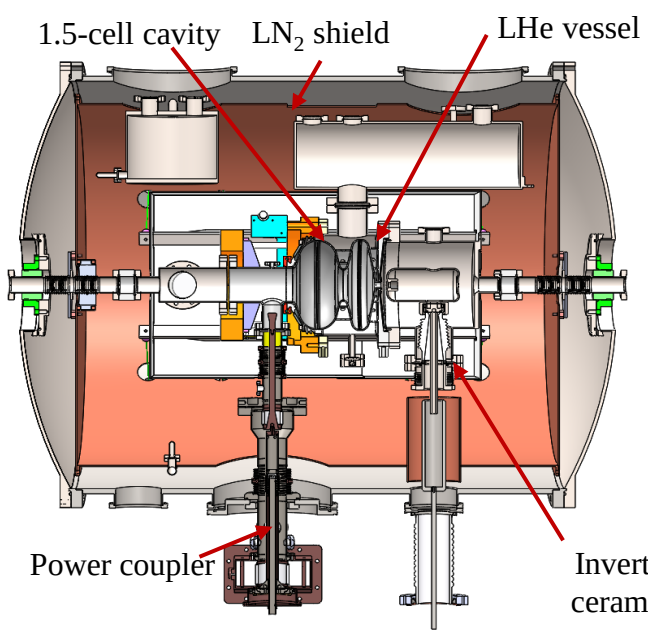
10~30 MeV, 0.1~1 mA,
Quasi CW~CW mode

2 MeV,
0.1~5 mA









DC-SRF prototype (2001-2004)

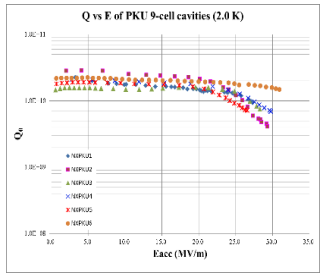
DC-SRF-I 2007-2011,2012-2016，2020-

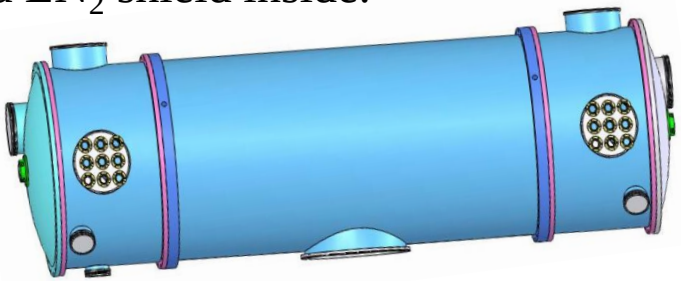
DC-SRF-II 2016-2020，2021-

1.2 The 2 × 9-cell cryomodule

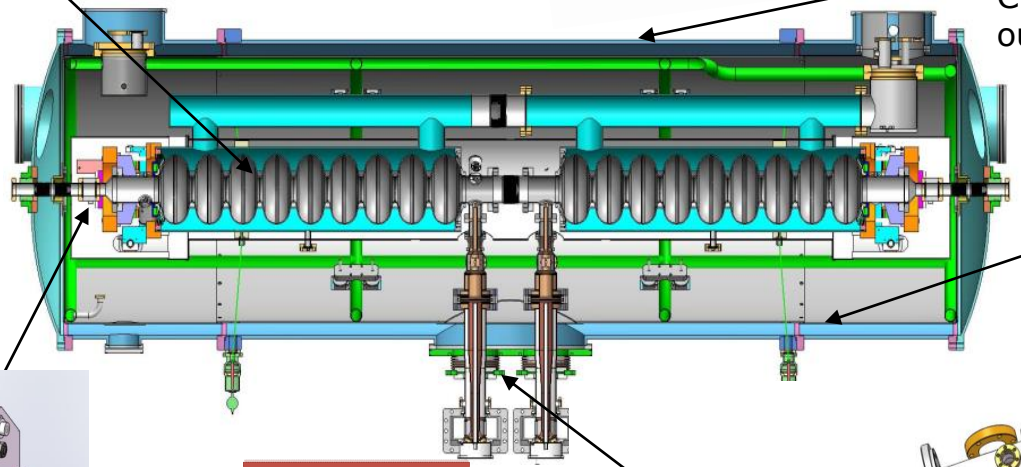
It can accelerate the electron beam to 10 ~ 30 MeV, also uses a LN_2 shield inside.

9-cell cavity

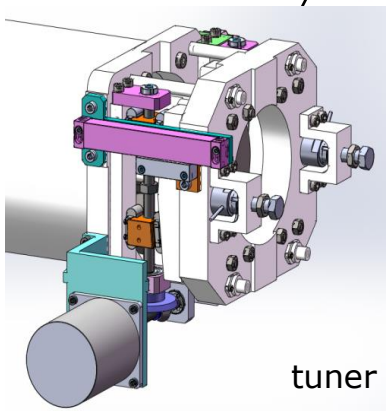




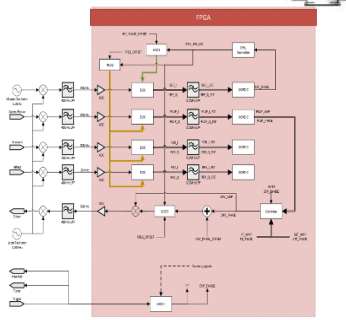
Cryomodule outer barrel



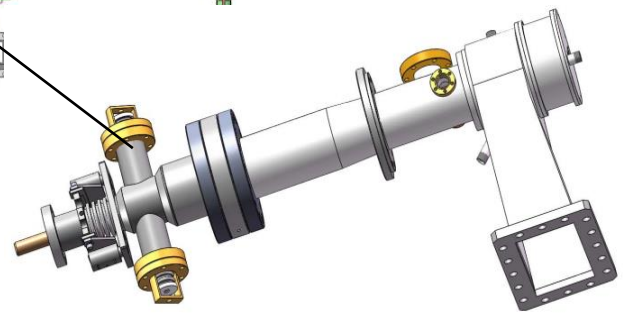
LN_2 shield



tuner



LLRF



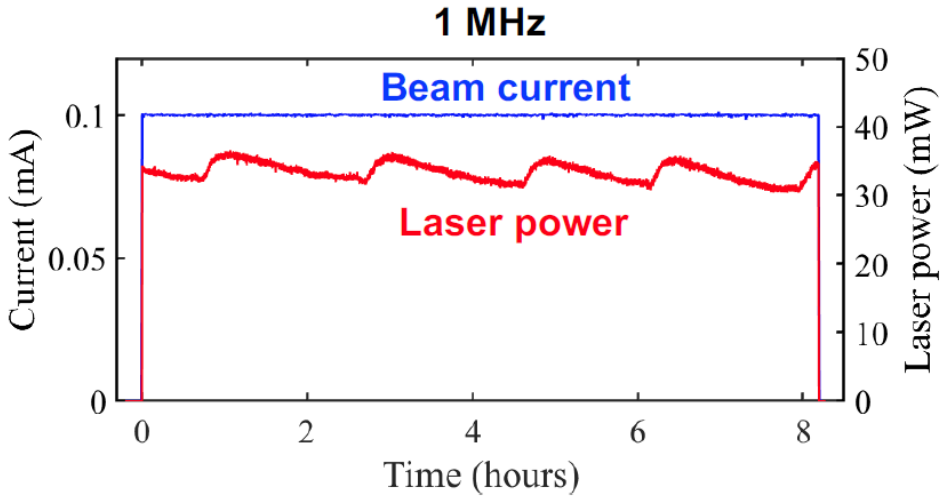
Power coupler

1.4 The CW operation of DC-SRF-II

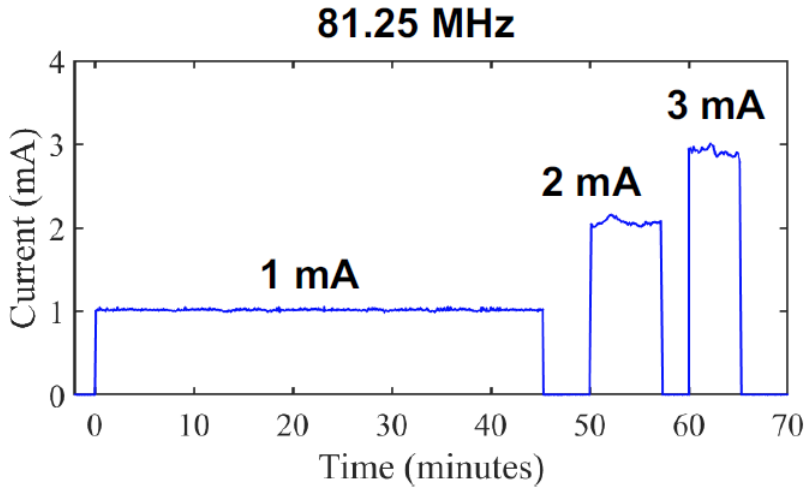
DC-SRF-II gun and beam line

Table I. Measured emittance and relevant parameters.

Parameters	100 pC	50 pC	20 pC	Units
SRF cavity gradient	14.4	14	14	MV/m
Drive laser size (σ_0)	1.0	1.0	0.8	mm
Electron beam energy	2.42	2.35	2.35	MeV
Normalized emittance	0.54	0.40	0.28	mm-mrad
Core emittance	0.28	0.25	0.19	mm-mrad
Core fraction	70%	75%	77%	



Beam current feedback was applied to maintain a constant current



Short-term tests were performed with a current up to 3mA and at the energy of 1.7 MeV.

2. The development of the FPCs

2.1 Resonant ring for coupler conditioning

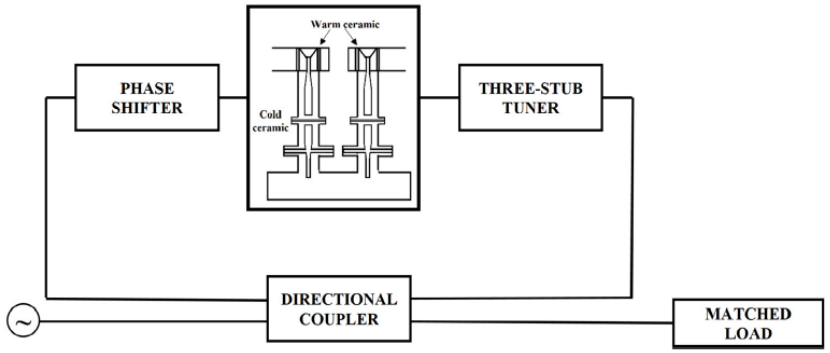
2.2 Couplers for DC-SRF-I gun

2.3 Couplers for 2 × 9-cell cryomodule

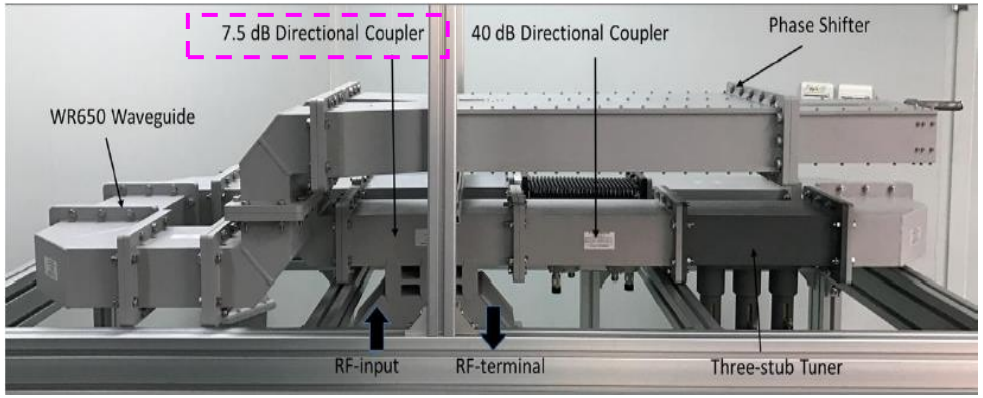
2.4 Couplers for DC-SRF-II gun

2.5 Couplers for DALS injector CM00

2.1 Resonant ring for coupler conditioning

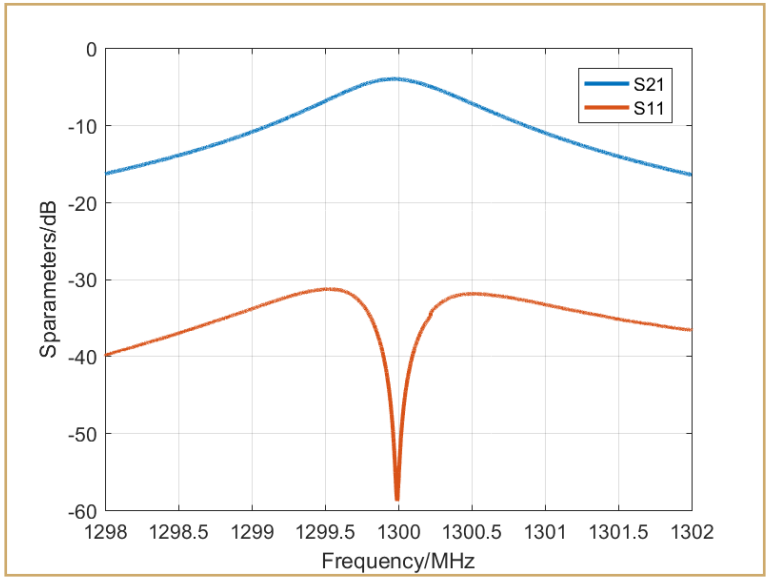


Schematics of the resonant ring used for power coupler conditioning



Test bench of the resonant ring

≥200 kW in 10 Hz 5 ms, ≥70 kW in CW



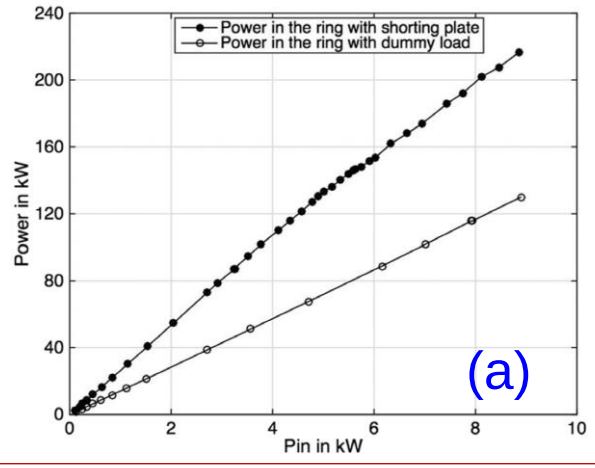
Measured resonance curve of the ring with a pair of power couplers.

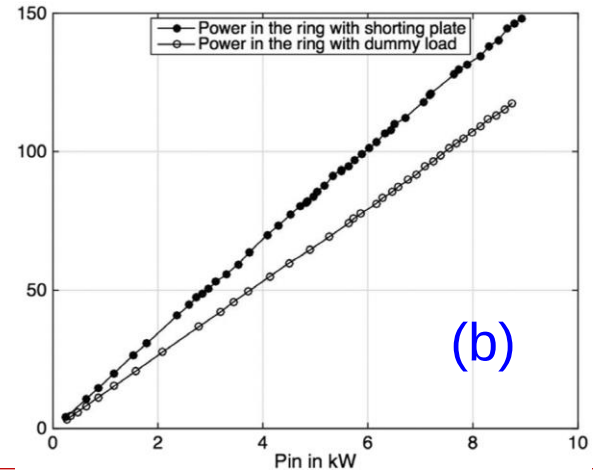
f =1.3 GHz

f_{3dB} =0.9953 MHz

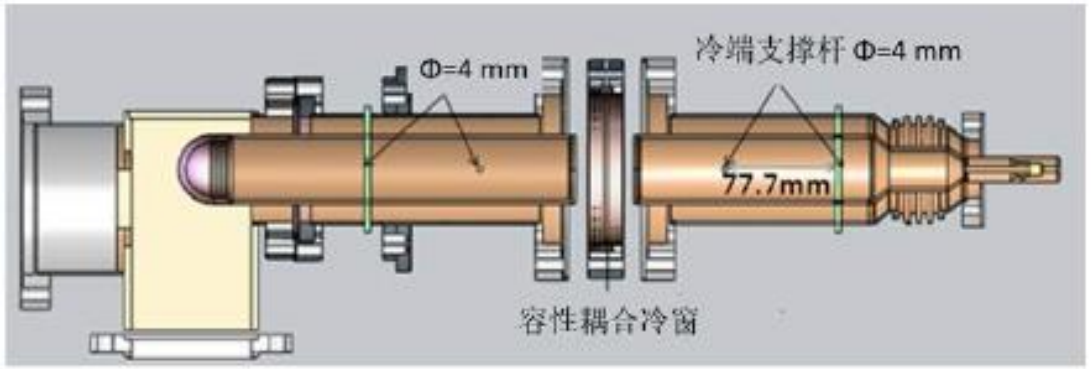
Q =1306

Powers in the ring: (a)Without insertions, (b)With a pair of couplers



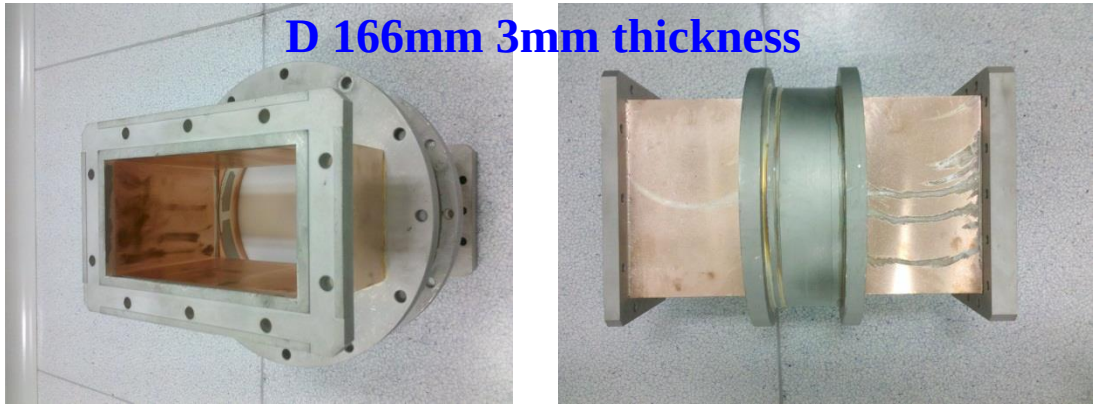


2.2 The coupler with capacitive coupling



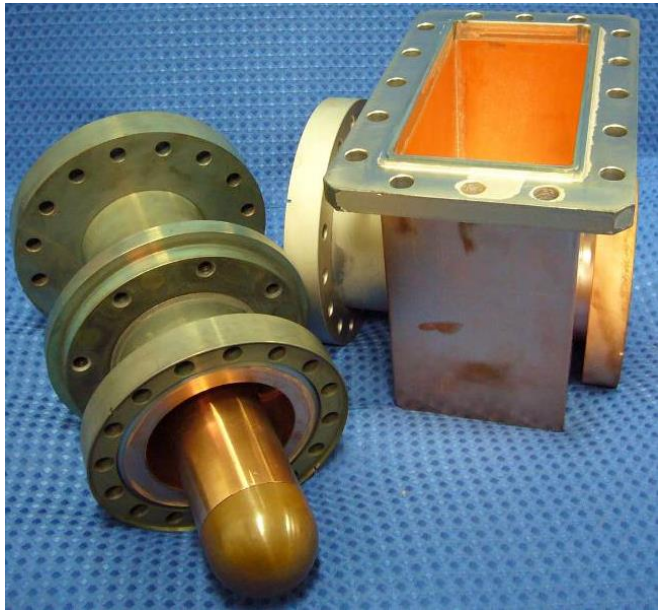
The coupler for DC-SRF-I gun

D 166mm 3mm thickness

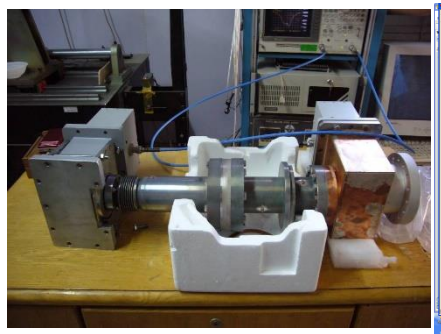


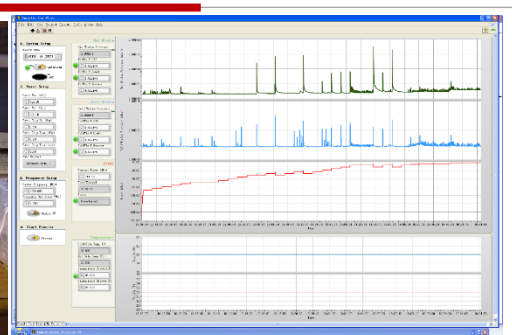
The warm ceramic window of waveguide type

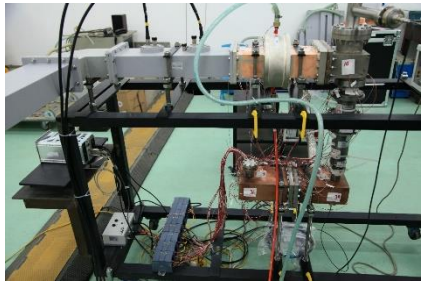
D 103mm 3mm thickness

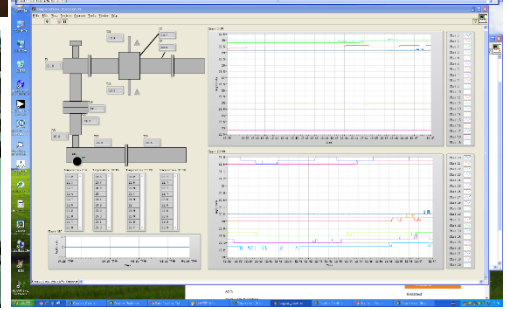


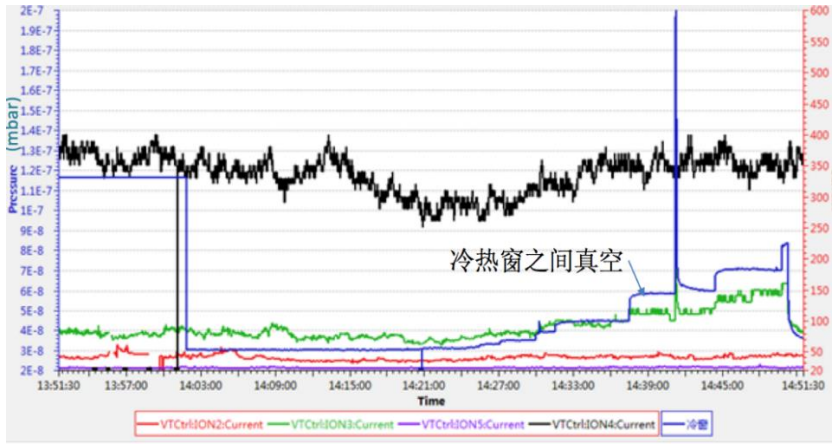
2.2 The performance of the capacitive coupling couplers

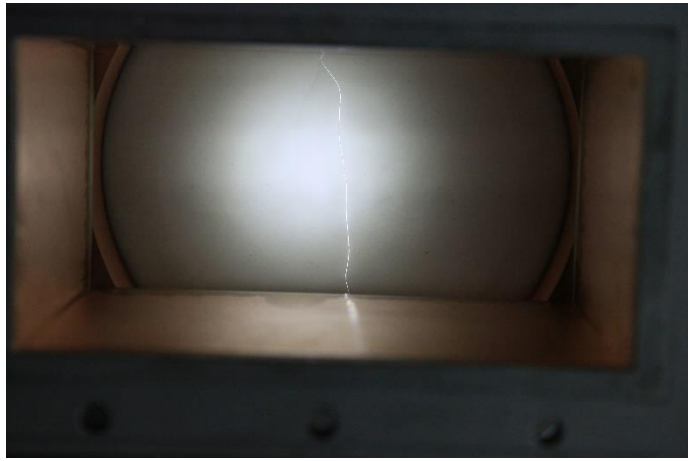












Cold test using vector network analyzer:

- VSWR=1.07@1.3GHz, the bandwidth with VSWR < 1.1 is 30 MHz.

RF conditioning on the test stand

- Up to 17 kW in SW with 10Hz 40%, which was limited by the power amplifier.

Warm off-resonance RF conditioning on the DC-SRF-I gun

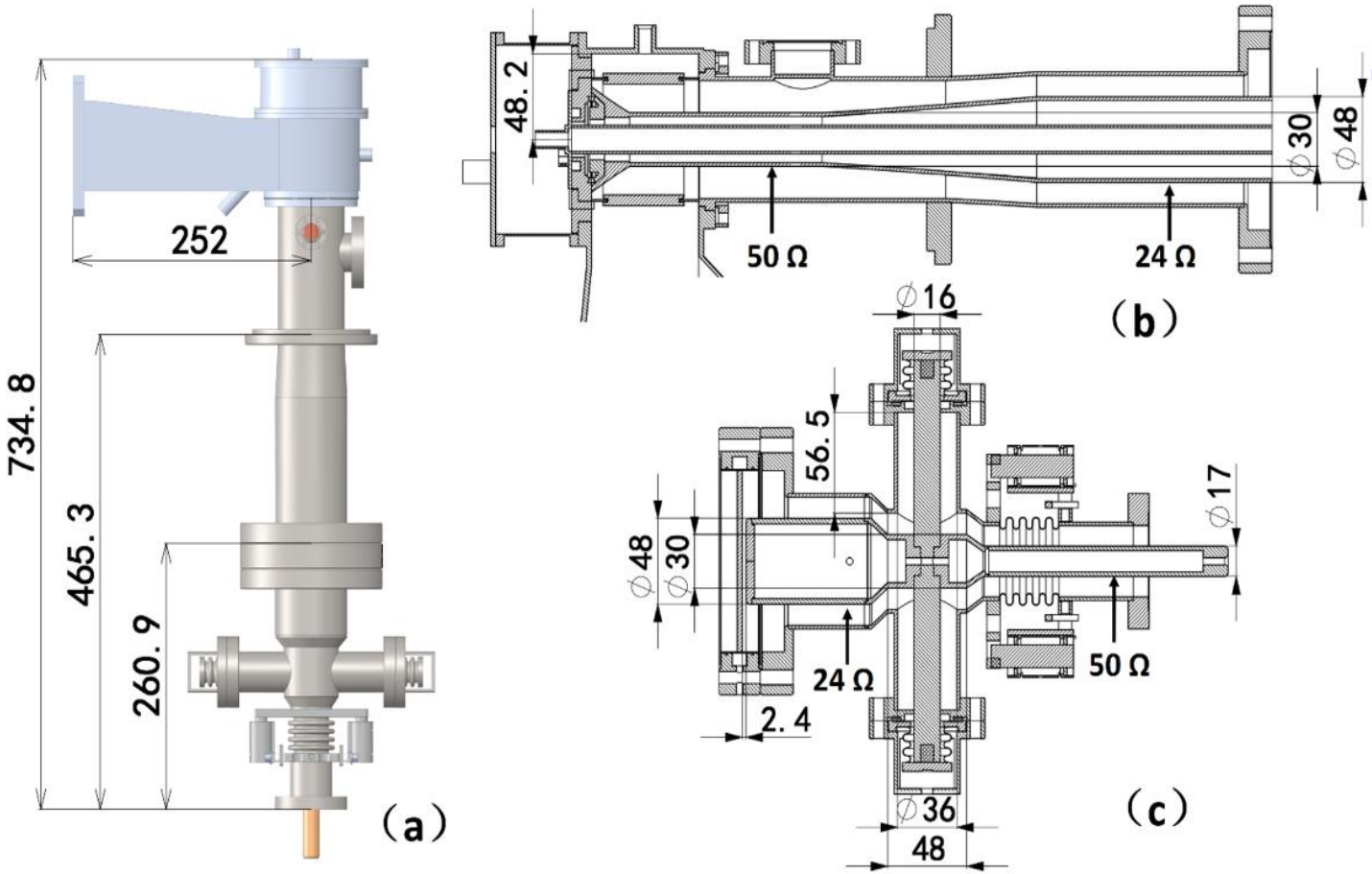
- Up to 17 kW in SW with 10Hz 40%

Long-term operation on the DC-SRF-I

- The cracking of the warm widow occurred sometimes.
- In CW mode, for safety consideration, the power was limited to 5 kW.

2.3 The hybrid coupler for 2×9-cell SRF linac

investigate the CW capacity of the capacitive coupling coupler and develop power couplers for the 2 9-cell cavities



The structure of upgraded type of power coupler with capacitive coupling:
(a) overall layout, (b) warm section, and (c) cold section

The improved structure design

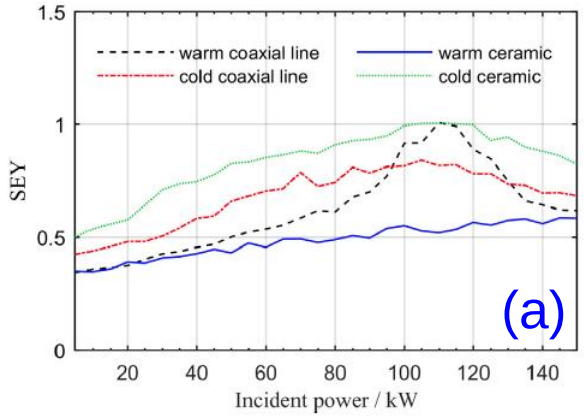
① A cylindrical ceramic warm window

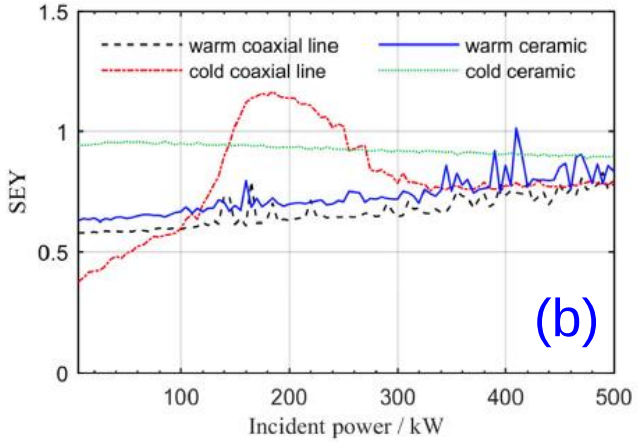
- More robust.
- DC bias can be applied.

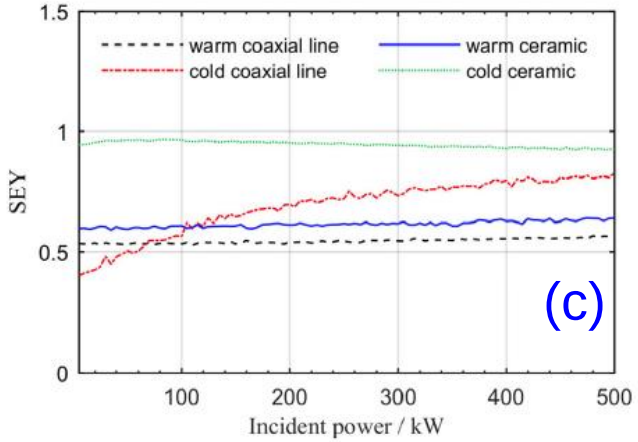
② A thick T-stub

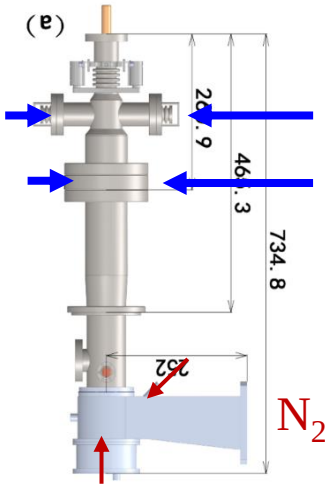
- A much shorter length of the cold section.
- The heat conduction can be improved.

2.3 Multipacting and thermal analysis simulation



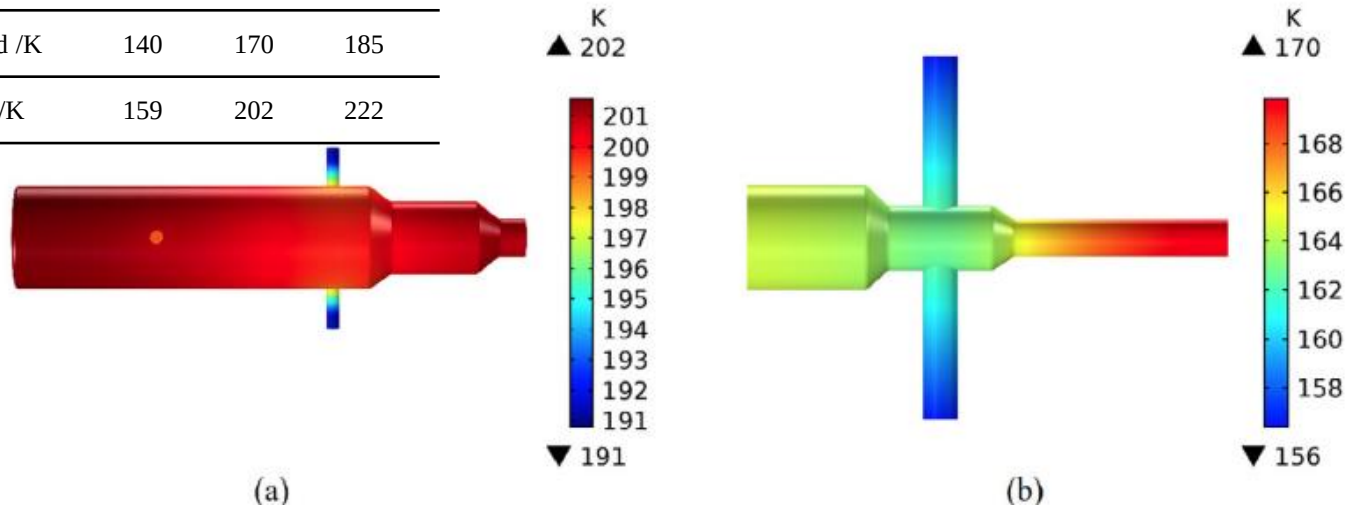




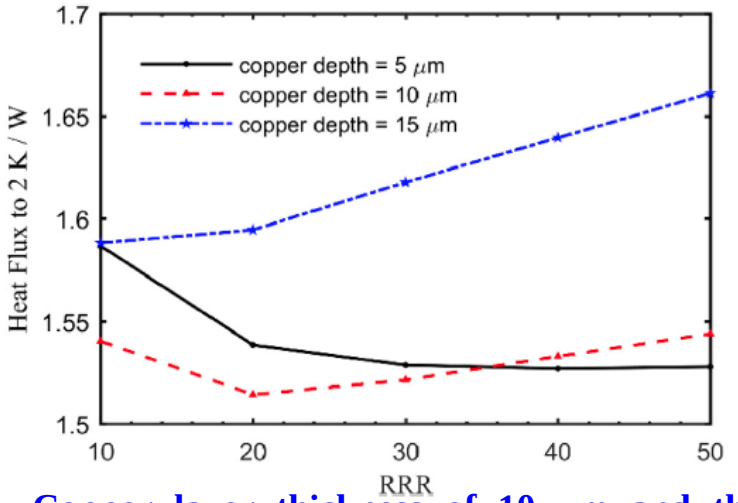


Normalized SEY curve of all four regions with different DC bias :(a) no bias; (b) 1 kV; (c) 2 kV

Power/kW	10	15	20
Improved /K	140	170	185
Previous/K	159	202	222

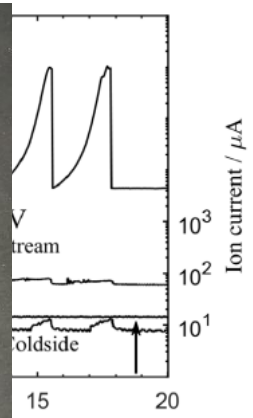


Temperature distribution of the cold inner conductor with the incident power of 15 kW. (a) original design and (b) upgraded design.



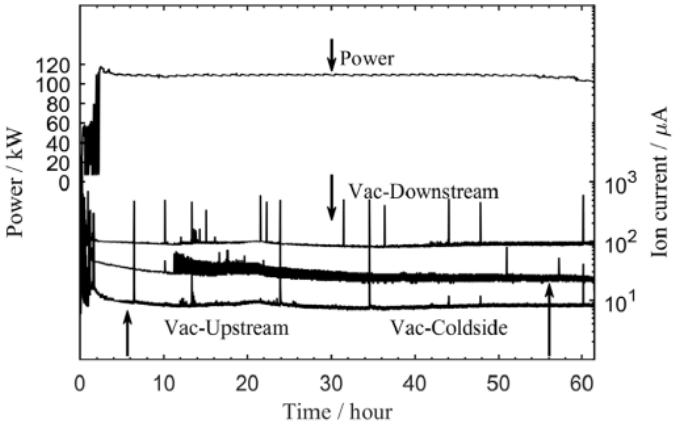
Copper layer thickness of 10 μm and the RRR value of 20 is the best choice for power level of 15 kW.

2.3 Results from the high power test

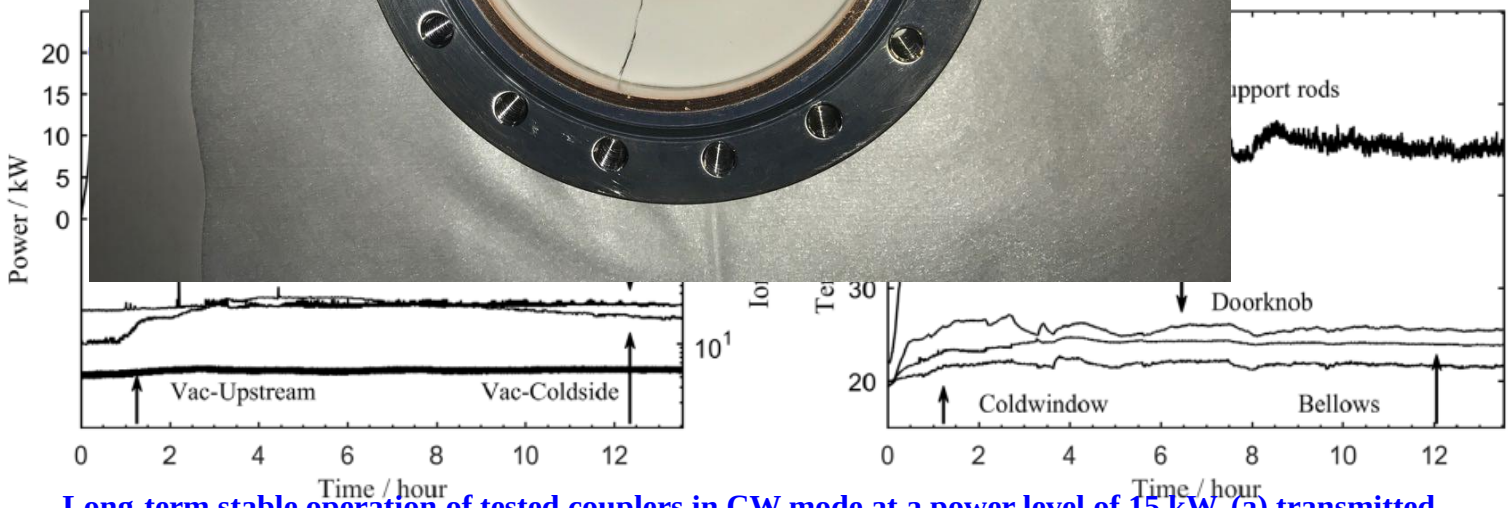


Vacuum
up to 1

g suppression
ltages.



Long-term stable operation, 10Hz 5ms
Up to 110 kW with a duty factor of 5%



Long-term stable operation of tested couplers in CW mode at a power level of 15 kW. (a) transmitted RF power and ion current; (b) monitored temperature.

- 2 kV DC bias could overcome the multipacting barrier.
- CW RF power up to 15 kW could be transmitted steadily in the coupler by using the resonant ring for the test.
- Further tests in CW mode for power up to 20 kW made the ceramic disk at risk.
- Assembled to 2x9-cell linac, the couplers were operated in 8 kW, 5 Hz, 2 ms.

2.4 the power coupler for DC-SRF-II gun

The improvements to enhance cooling

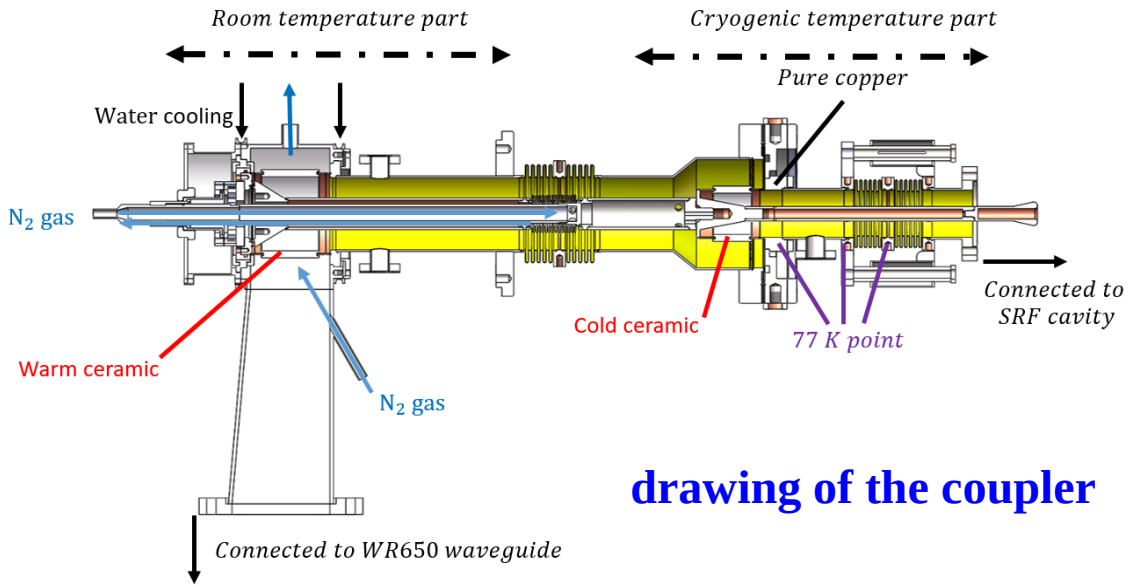
①Forced N_2 gas cooling for the warm inner conductor

②Forced N_2 gas cooling for the warm ceramic

③Forced water cooling for the doorknob transition

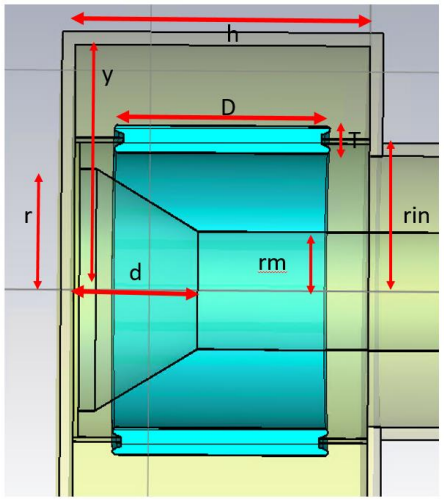
④A OFHC copper block is connected to the cold ceramic

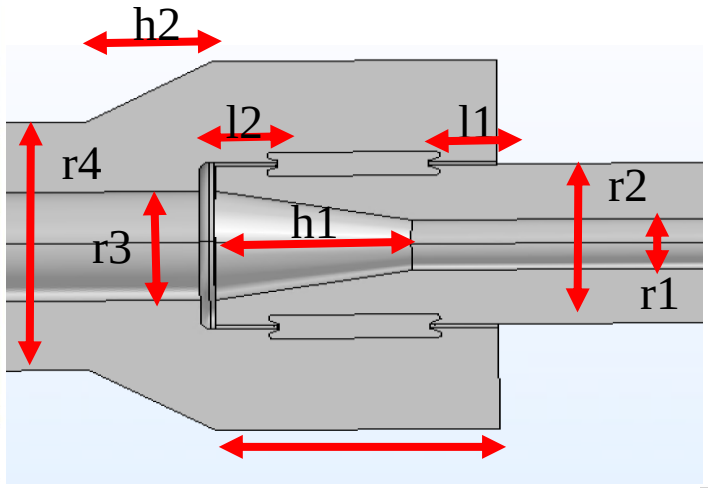
⑤Intercepts are added in the bellows

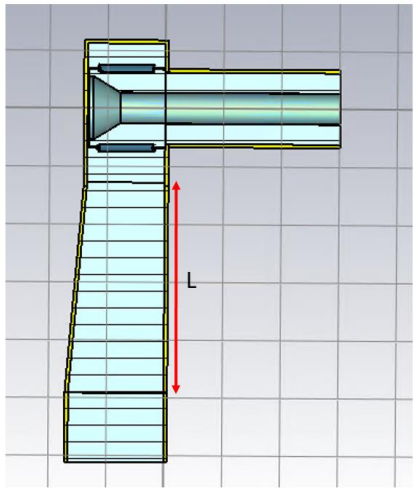


drawing of the coupler

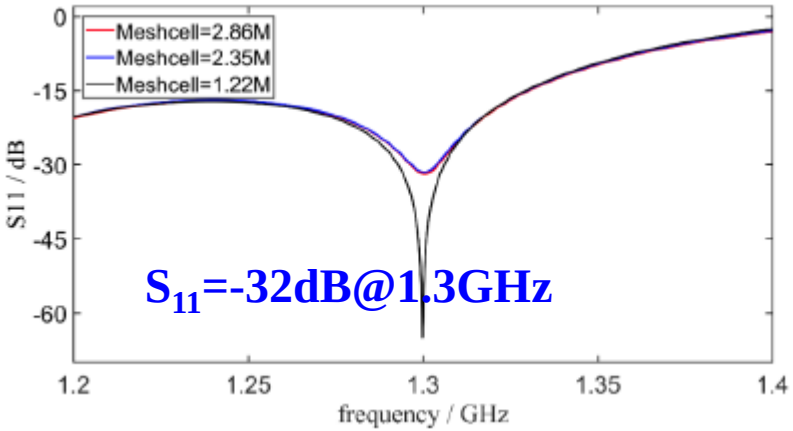
Microwave design simulation





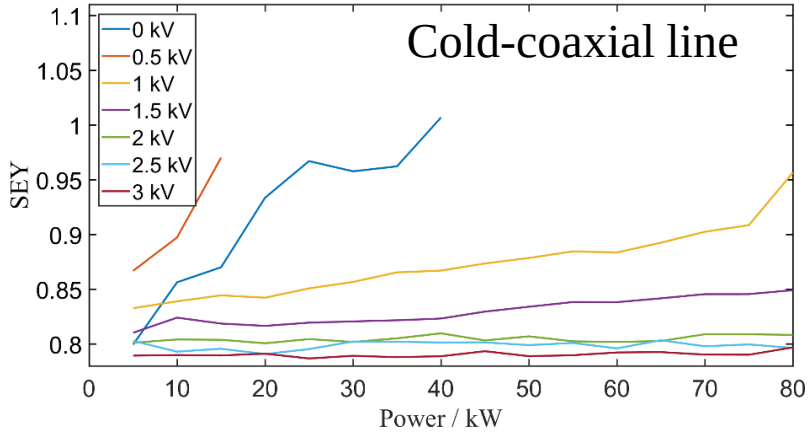


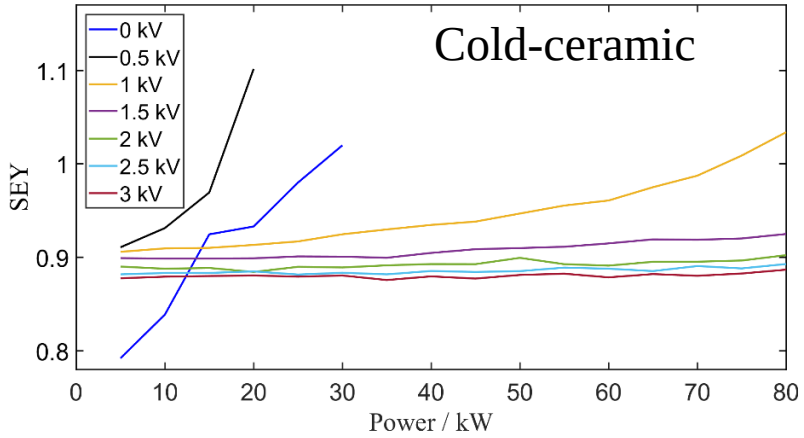
S_{11} of the coupler in the COMSOL simulation with different number of mesh cells

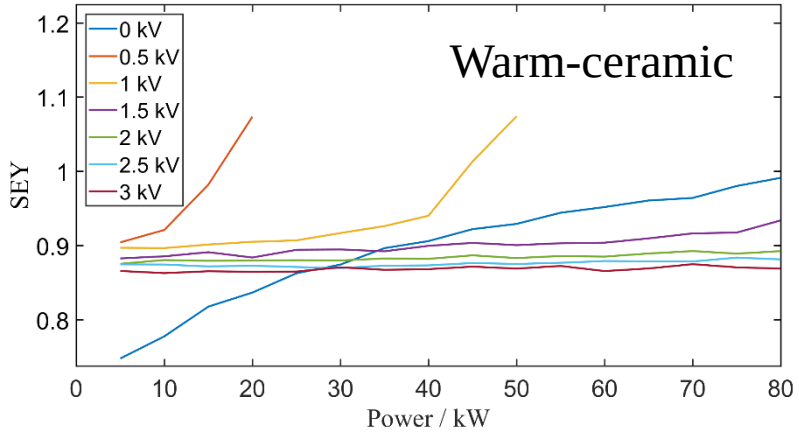


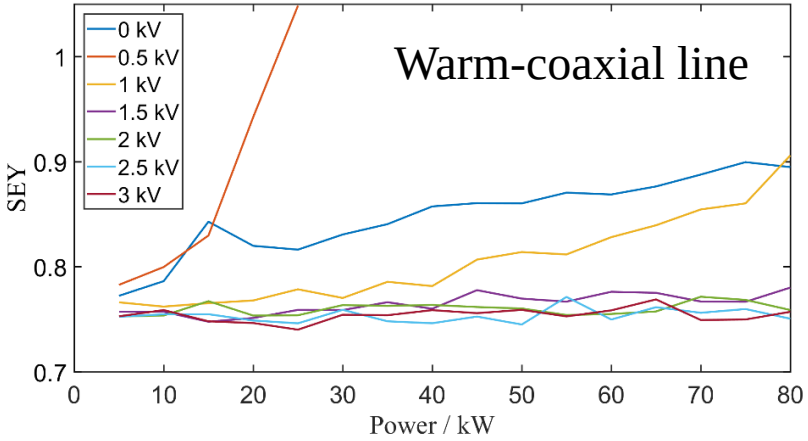
2.4 Multipacting simulation of the coupler

Normalized SEY curve of all four regions with different DC bias applied on inner conductor









0 kV
≤25 kW
cold-ceramic

0.5 kV
≤15 kW
cold-ceramic
warm-ceramic

1 kV
≤45 kW
warm-ceramic

≥1.5 kV
80 kW

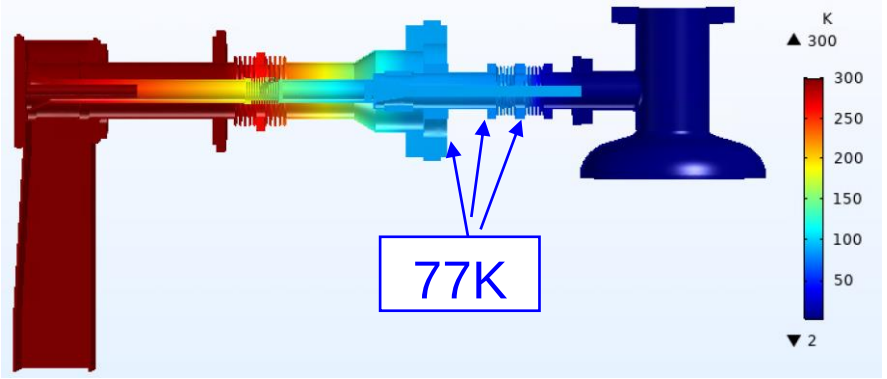
- 25 kW is OK without DC bias.
- Voltage higher than 1.5 kV is good for power up to 80 kW.
- DC bias of 0.5 kV and 1 kV is not good for the multipacting suppressing.

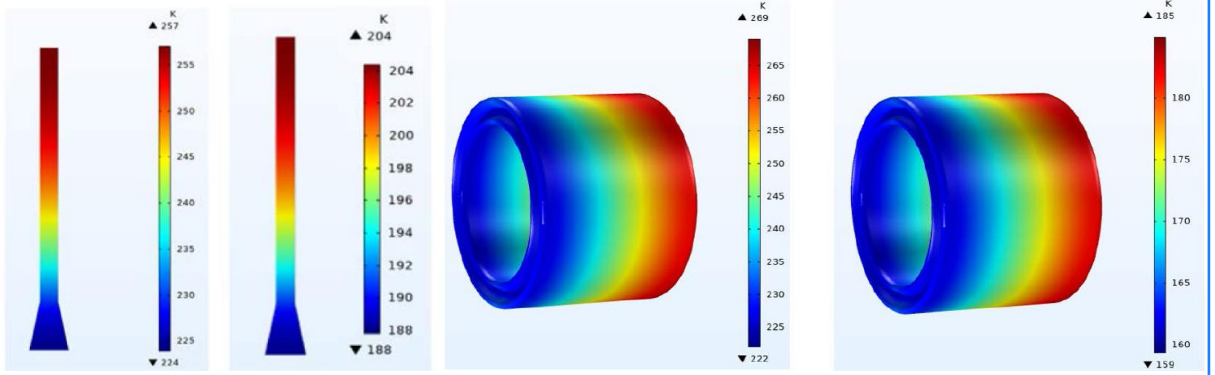
2.4 thermal analysis

Static and total heat load with RRR=30. **Considering the uniformity of the copper layer， the thickness are 15 μm and 50 μm, respectively.**

Copper depth/μm	Heat load to 2 K / W	Heat load to 77 K / W	10 kW		20 kW	
			2 K/ W	77 K/ W	2 K/ W	77 K/ W
5	0.053	2.47	0.75	11.90	1.32	22.8
10	0.062	2.56	0.79	11.55	1.28	21.97
15	0.07	2.64	0.88	11.61	1.36	21.96
20	0.08	2.72	0.97	11.69	1.45	22

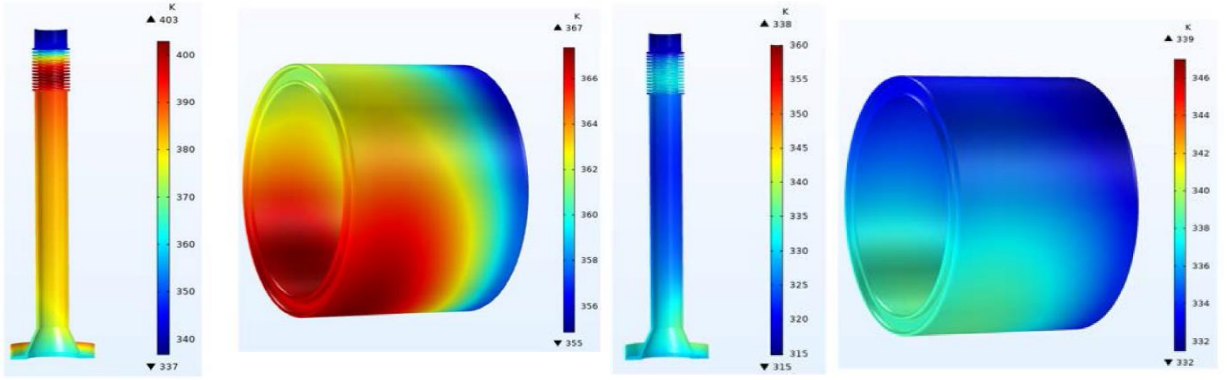
Temperature distribution without RF power





Effects of the SS block with copper plating vs. the OFHC copper @20 kW

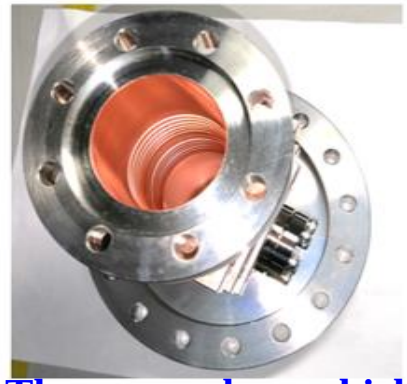
With the OFHC copper block, the highest temperatures of the cold inner conductor and the cold ceramic decrease significantly, from 257K to 200K, from 269K to 185K, respectively.

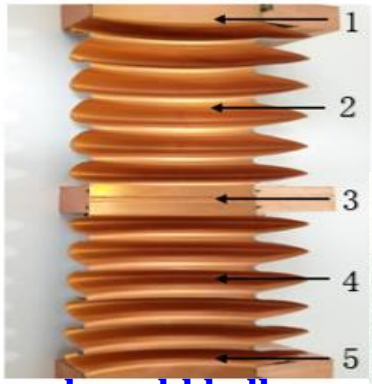


Effects of the forced N_2 gas cooling: none vs. 20L/min @20 kW

The gas cooling is needed. Without cooling, the highest temperature is up to 403 K in the bellow part, and 367K on the warm ceramic. With 20L/min N_2 cooling, the temperatures both decrease to 339K.

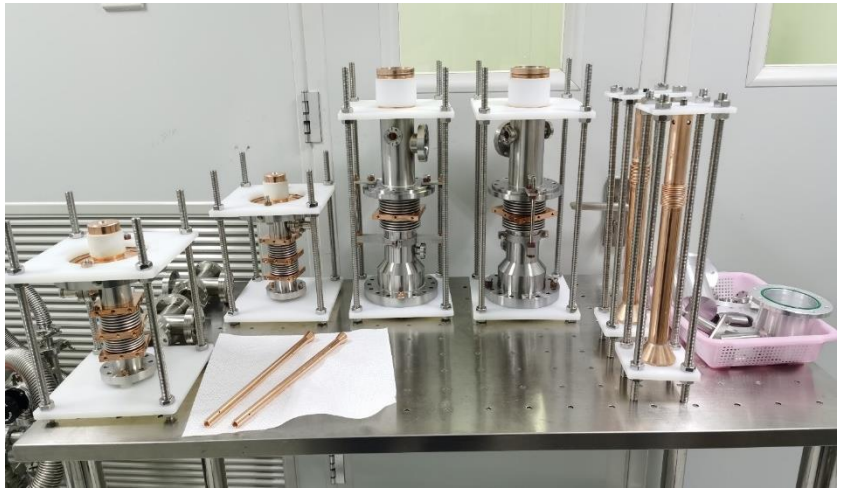
2.4 from fabrication to assembly

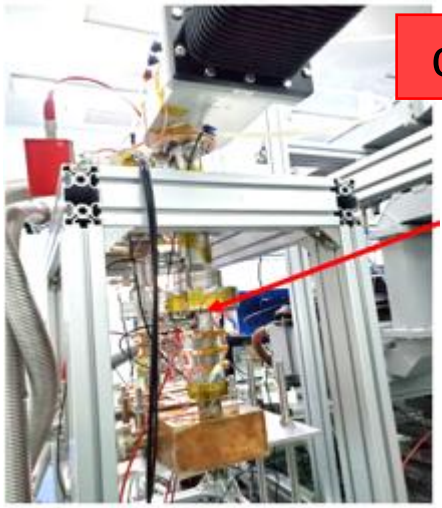




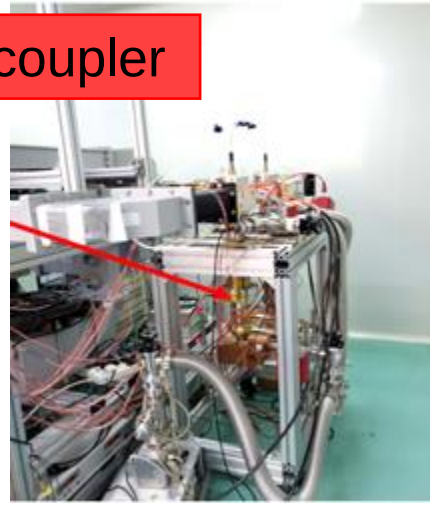
The copper layer thickness on the cold bellows

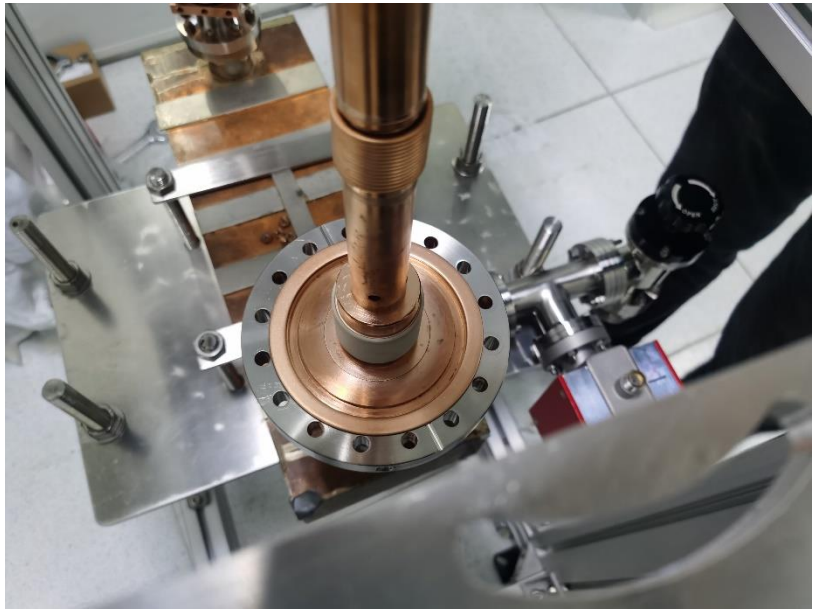
Position	1	2	3	4	5
μm	17.04	16.01	15.33	12.69	15.32



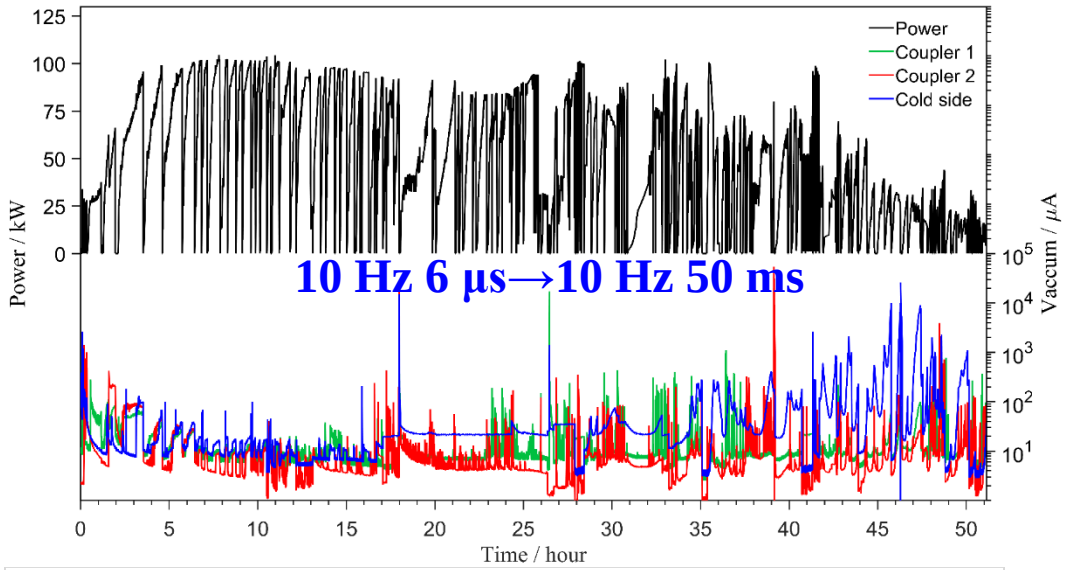


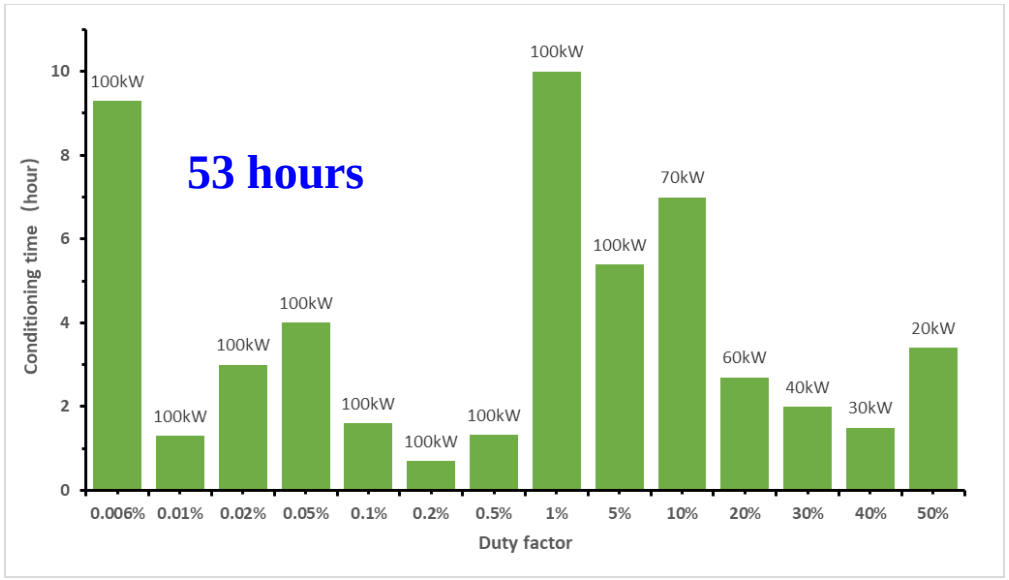
coupler

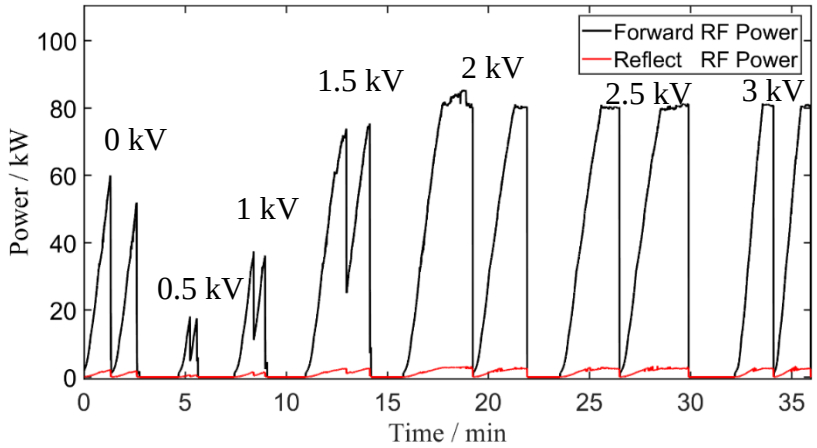


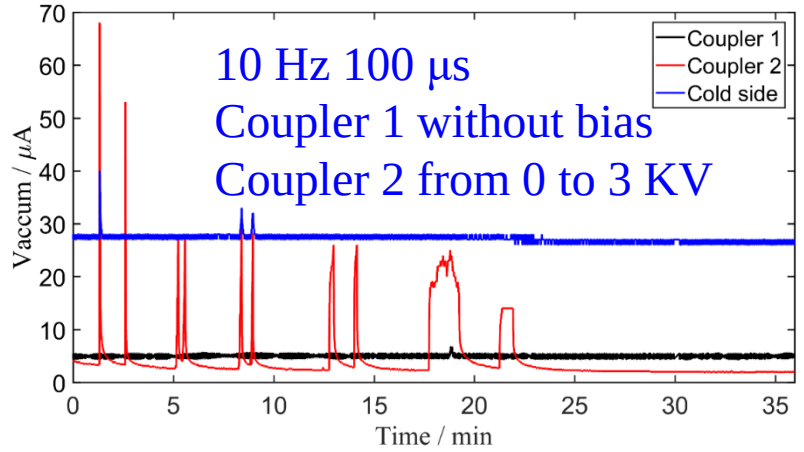


2.4 the conditioning of the coupler at pulse mode



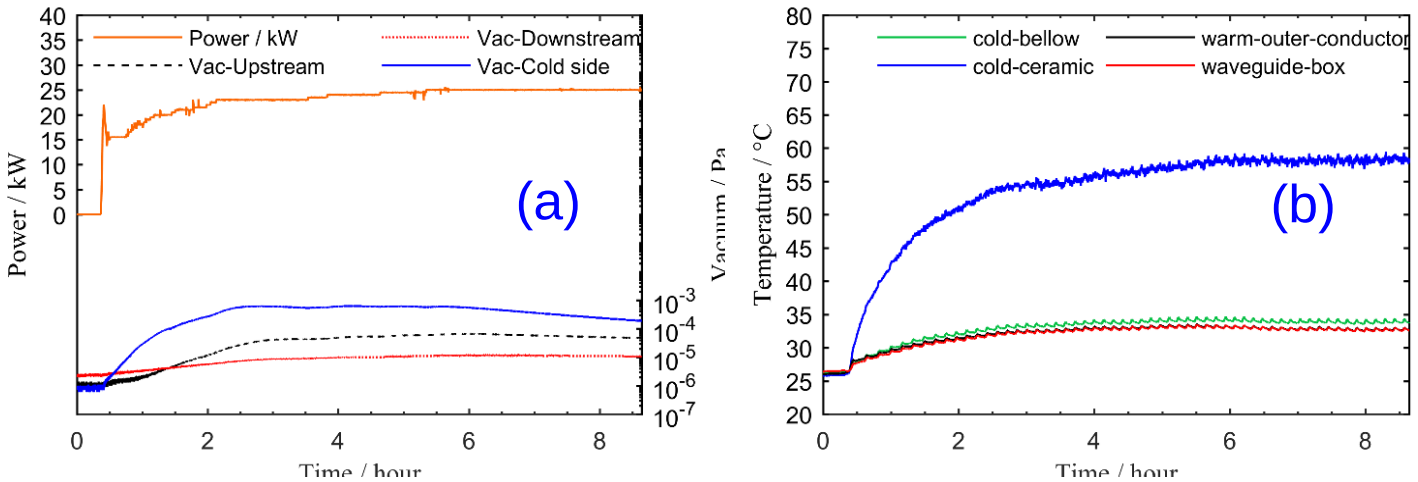




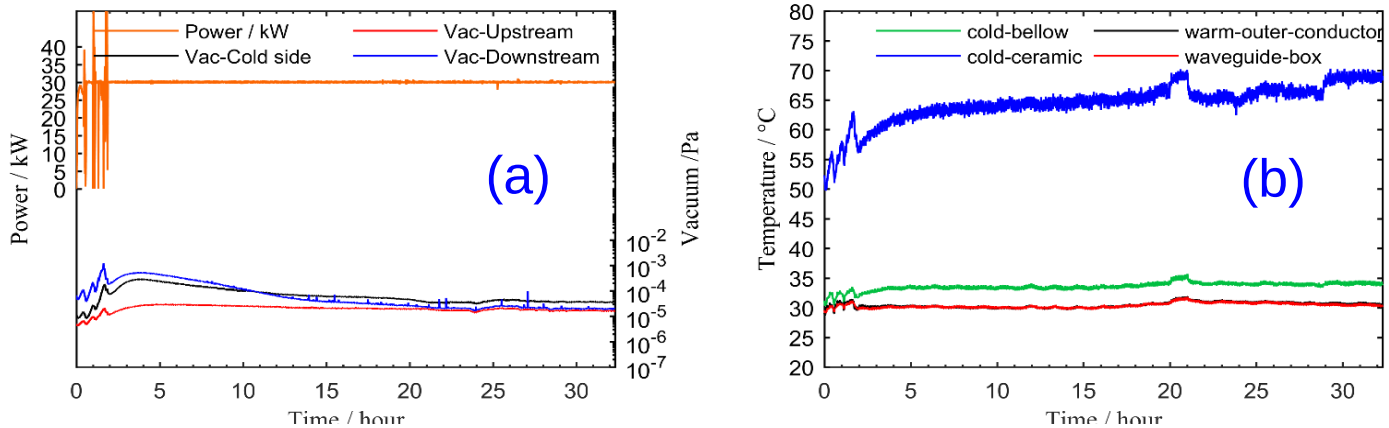


- DC bias of 0.5 kV and 1 kV is worse than no bias.
- Over 2.5 kV is effective.
- The result is partly consistent with the simulation.

2.4 Re-conditioning of the coupler



8 h CW TW 25 kW without DC bias (a)Power and vacuum, (b)temperature



30 h CW TW30 kW with 3 kV DC bias (a)Power and vacuum, (b)temperature

- The couplers were brought back to the clean room.
- All the parts were cleaned from the ultrasonic bath to filtered high-purity nitrogen gas blowing.
- With reliable clean assembly, the power can be raised sharply.

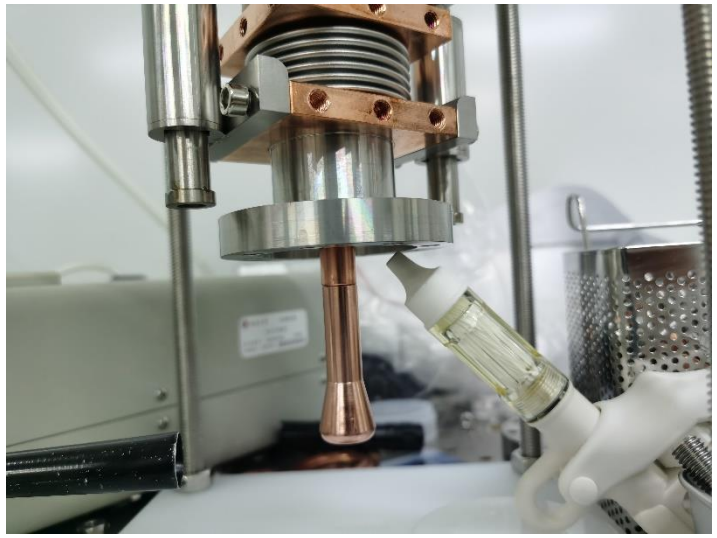
Pt100 sensors stuck to the outside of OFHC copper block

58°C@25kW

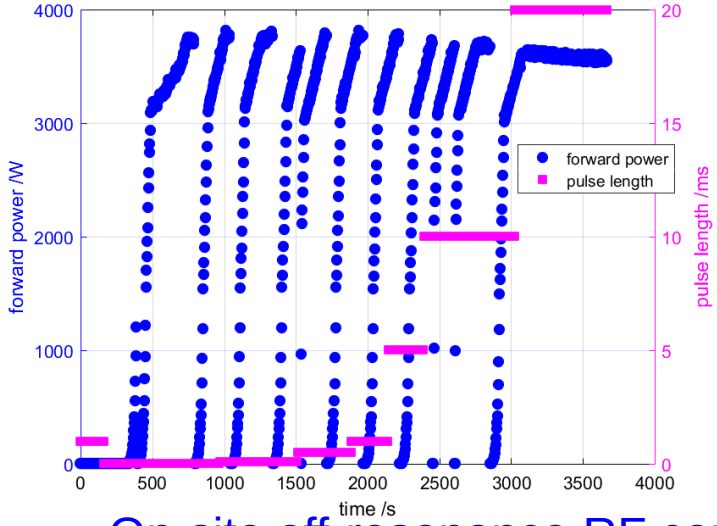
70°C@30kW

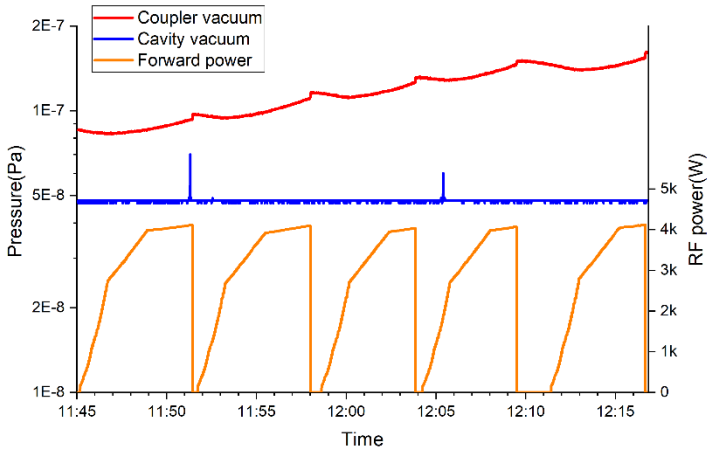
This result gave us much confidence on the power operation under 25 kW.

2.4 the coupler on the DC-SRF-II gun



Assemble to the DC-SRF-II gun



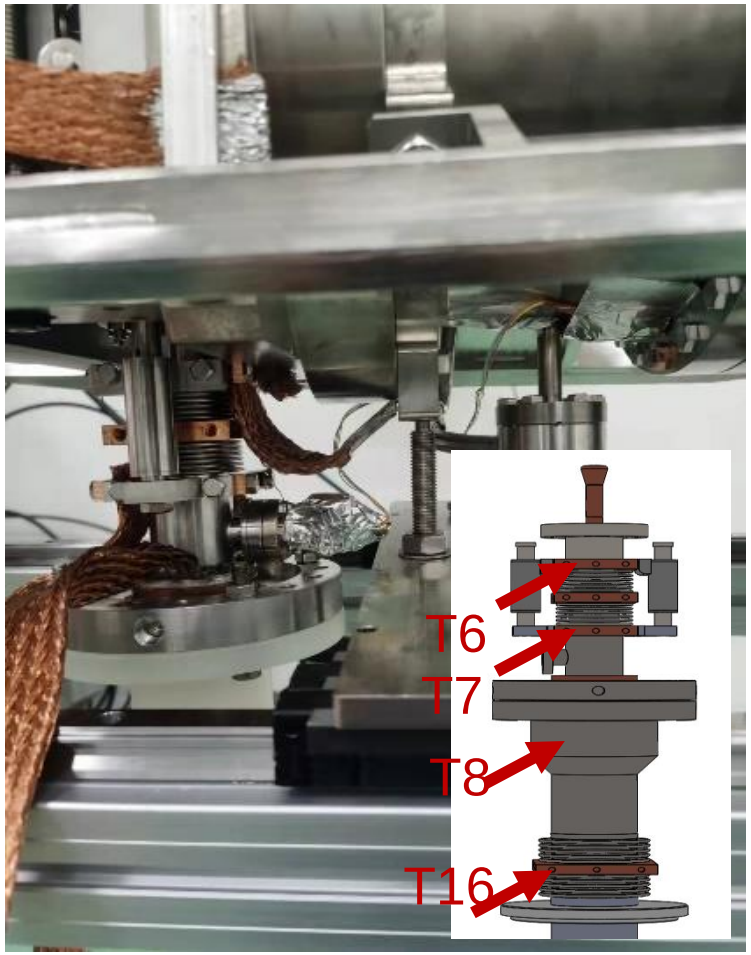


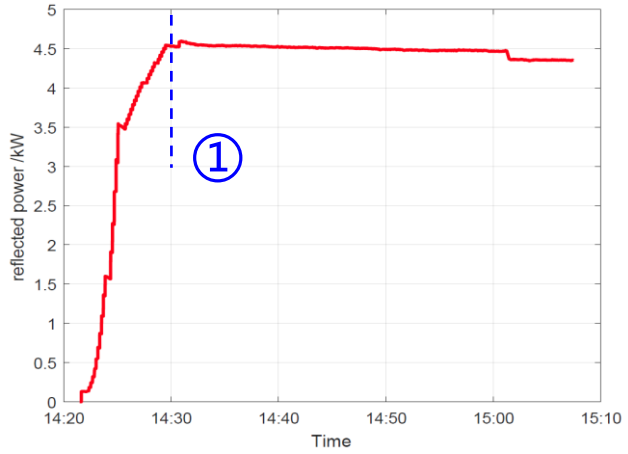
On-site off-resonance RF conditioning during the cooldown

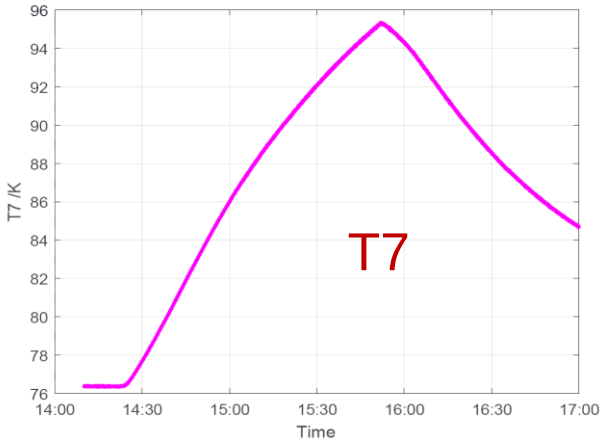
- The initial forward power was limited to 4 kW for safety reason.
- During the test of the 1.5-cell cavity
  - pulsed mode,10Hz 7ms,forward power is 6 kW. Eacc= 9.3 MV/m
  - CW mode, forward power is 3 kW. Eacc= 8.2 MV/m

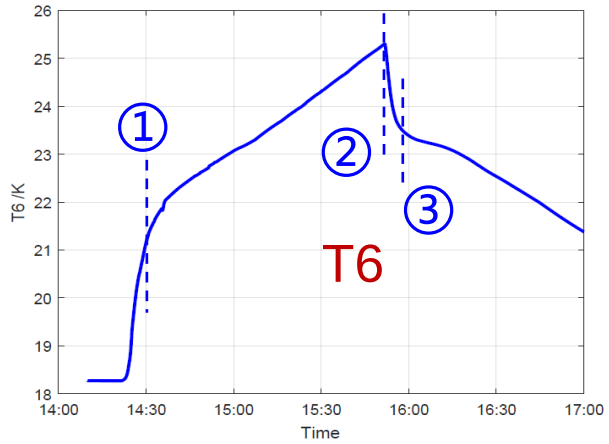
2.4 the coupler on the DC-SRF-II gun

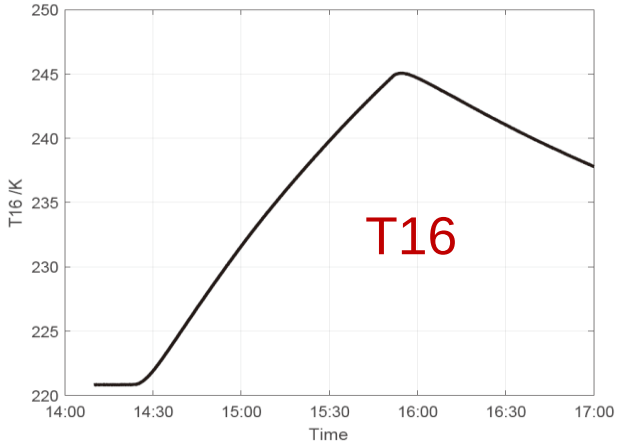
Before the disassembly of the DC-SRF-II, a cold off-resonance conditioning at 2 K was conducted. A CW 4.5 kW forward power was applied for one and half hour. It can be seen it needs a long time to get thermal balance.





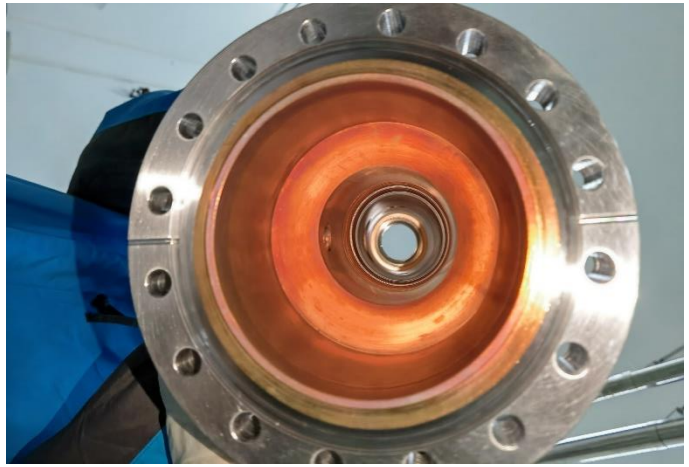


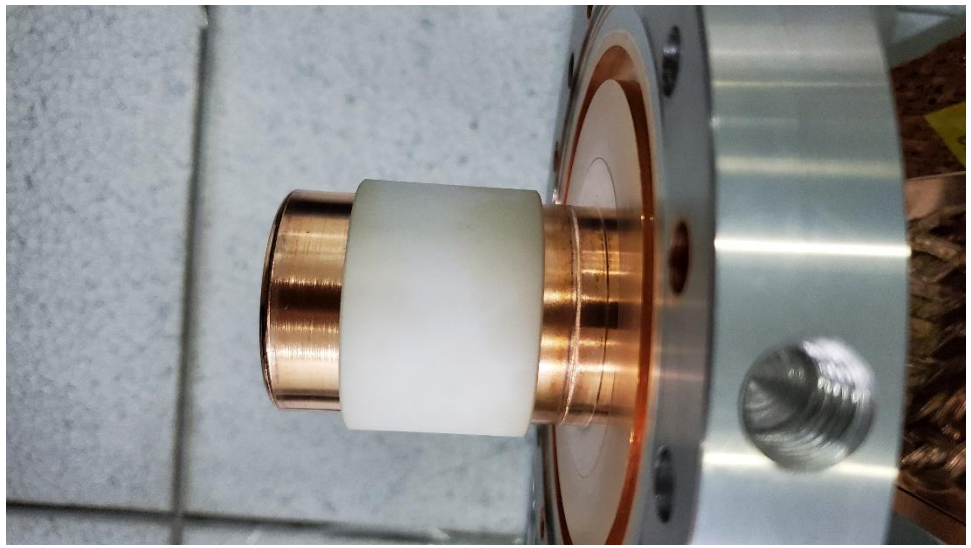
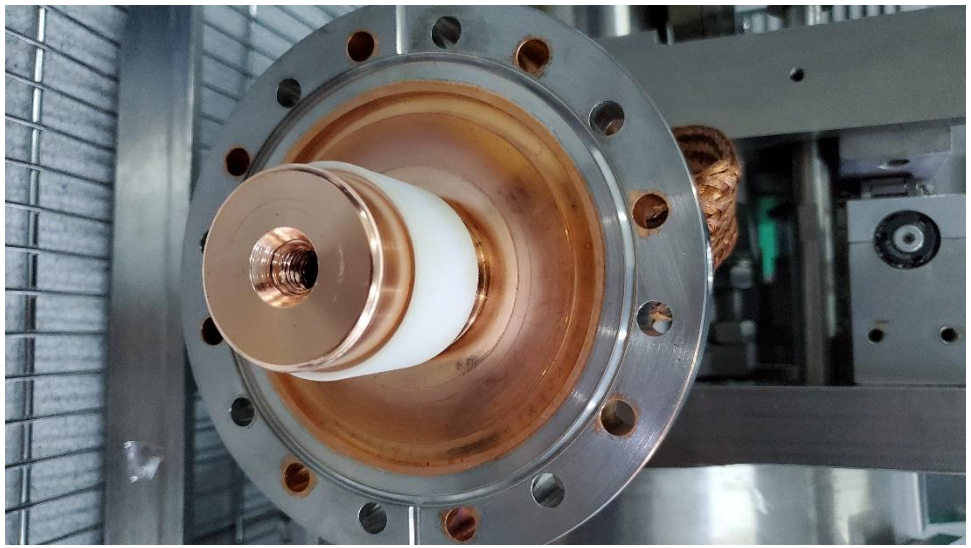




① incident power kept at about CW 4.5 kW; ② turn off the incident power; ③ turn off the 2 K cooling

2.4 the coupler on the DC-SRF-II gun



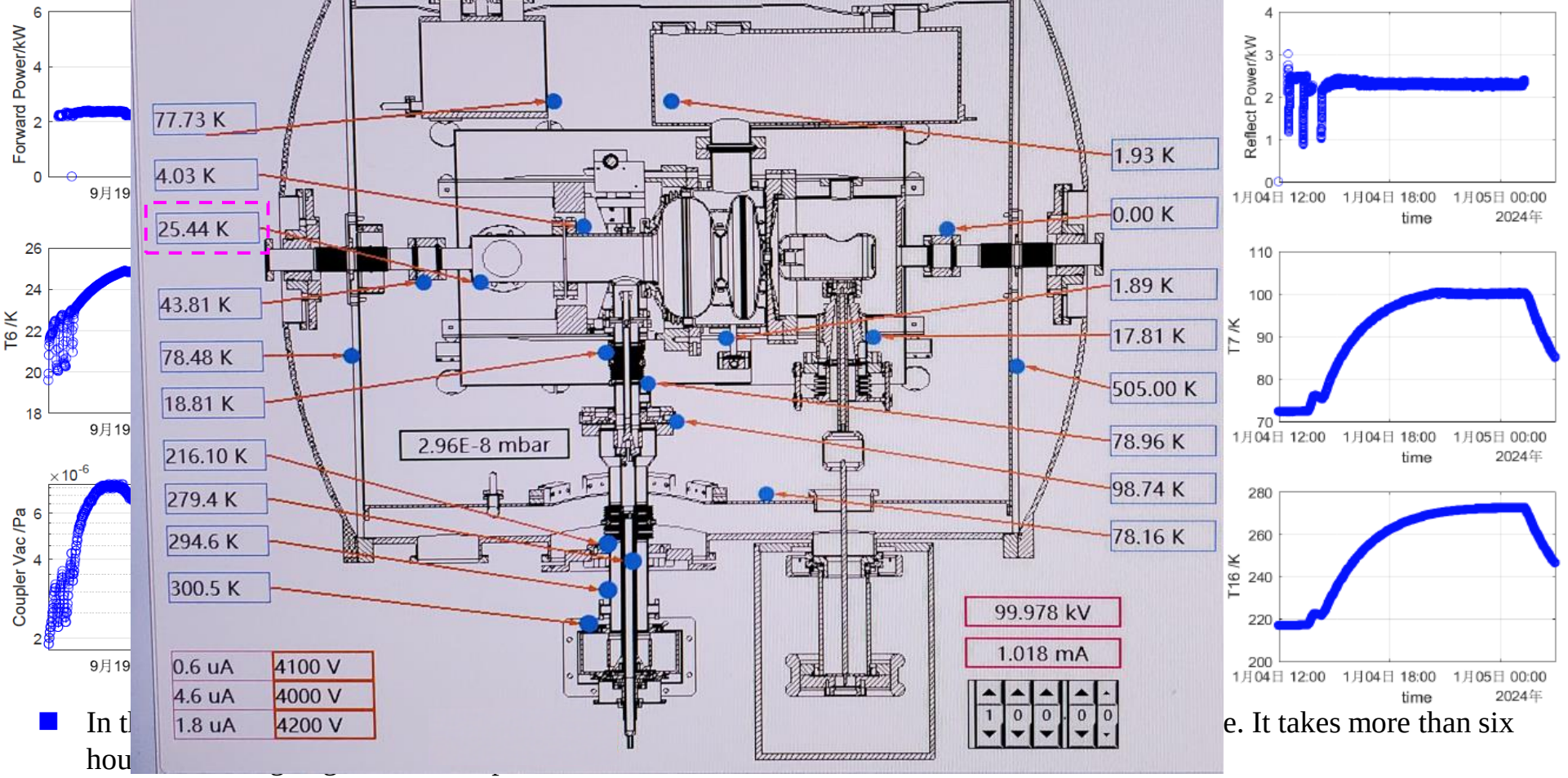




Disassembling from the DC-SRF-II injector after three months tests

The coupler parts were only blown with filtered high-purity nitrogen gas again, and then assembled to the gun.

2.4 the coupler on the DC-SRF-II gun---beam operation

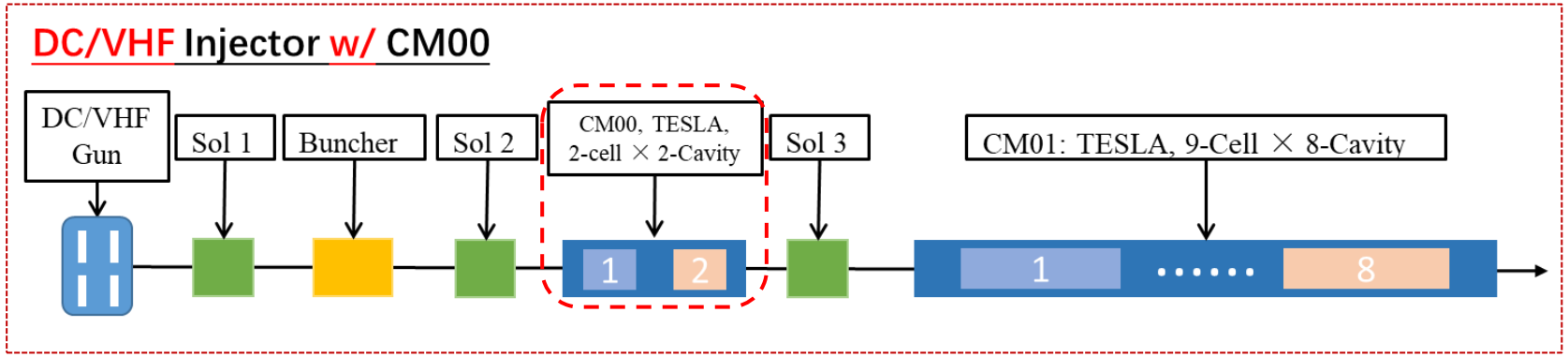
0.1mA: rward power is 3 kW

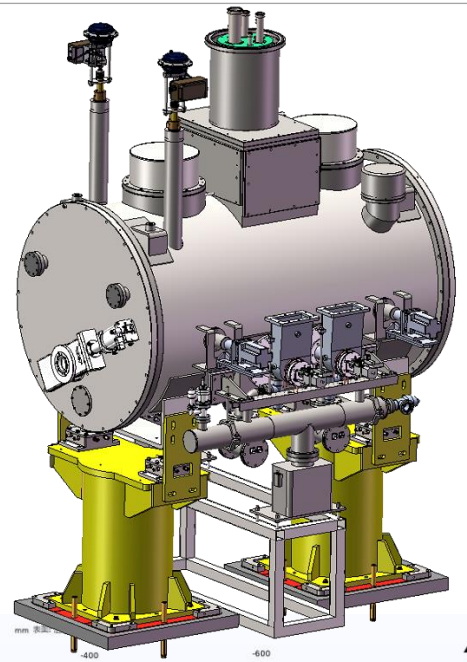


- In t e. It takes more than six hou
- In the 1mA to 3mA beam test, the gun encountered some other problem, only short-term tests were available, it was quite short for the coupler to get thermal balance.

Heat load at cryogenic temperature needs to be further investigated.

2.5 Power couplers for DALS injector CM00





CM00 Beam Design Parameters

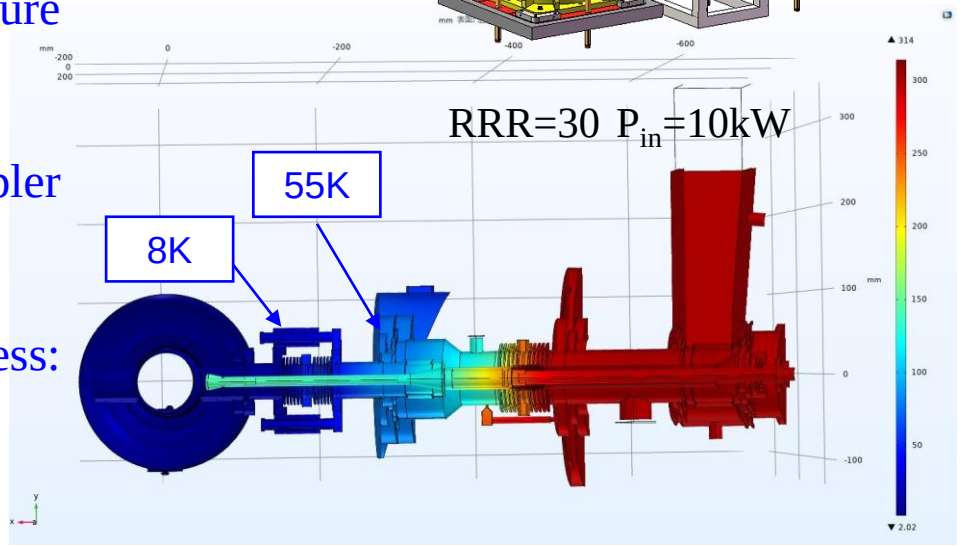
Parameter	Values	Unit
Q_b	100	pC
f_b	1	MHz
Entrance E_0	300(DC)-750(VHF)	keV
Export E_0	2-4	MeV
Normalized emittance ε_n	0.56	mm-mrad
I_0	0.1	mA
Longitudinal bunch length σ_z	1(VHF)-2(DC)	mm

Heat load with RF power of 10 kW

Temperature zone	2 K	8 K	55 K
heat load	0.15 W	5.67 W	26.38 W

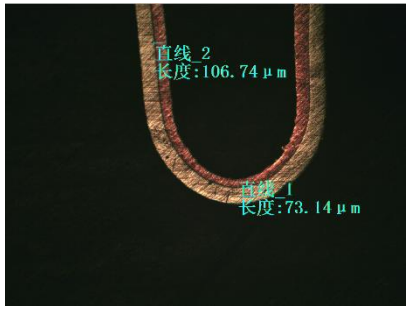
Four couplers are needed, six ones are made.

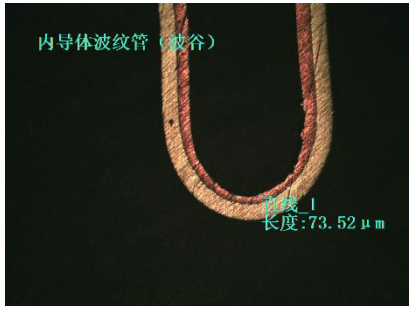
- A twin coaxial couplers
- CW power: ≥10 kW at room temperature conditioning
- Q_{ext} of a single coupler 6E6-1.6E7
- Copper layer thickness: 150 μm for the inner 30 μm for the outer

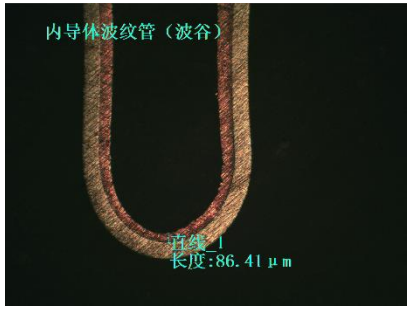


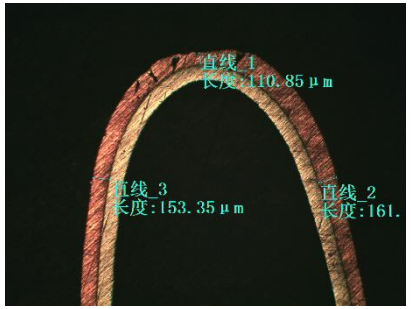
2.5 thickness measurements

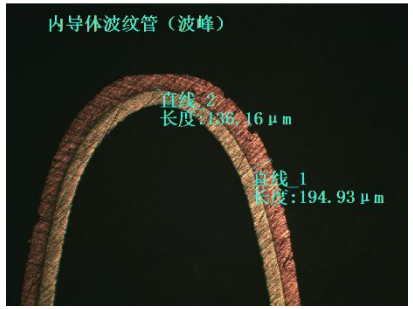
- The warm inner conductor was firstly welded and then made copper plating.
- In order to measure the thickness and RRR, one sample was cut.

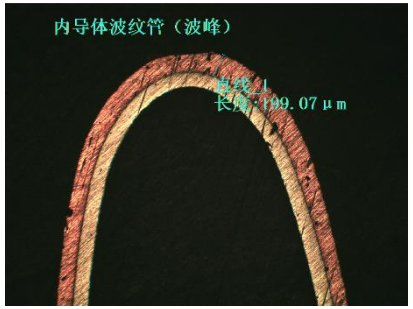


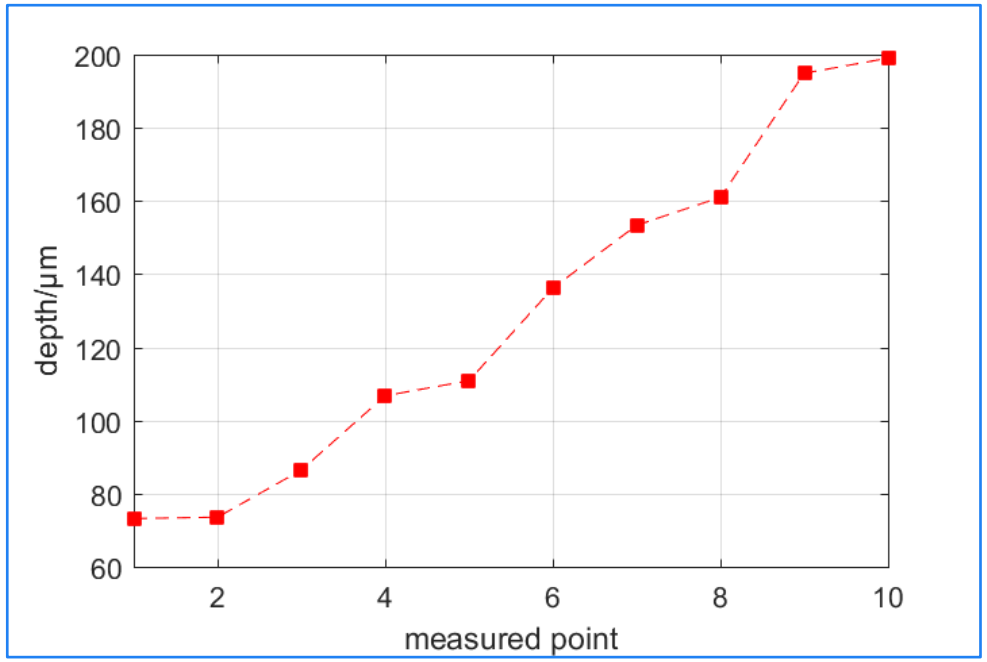




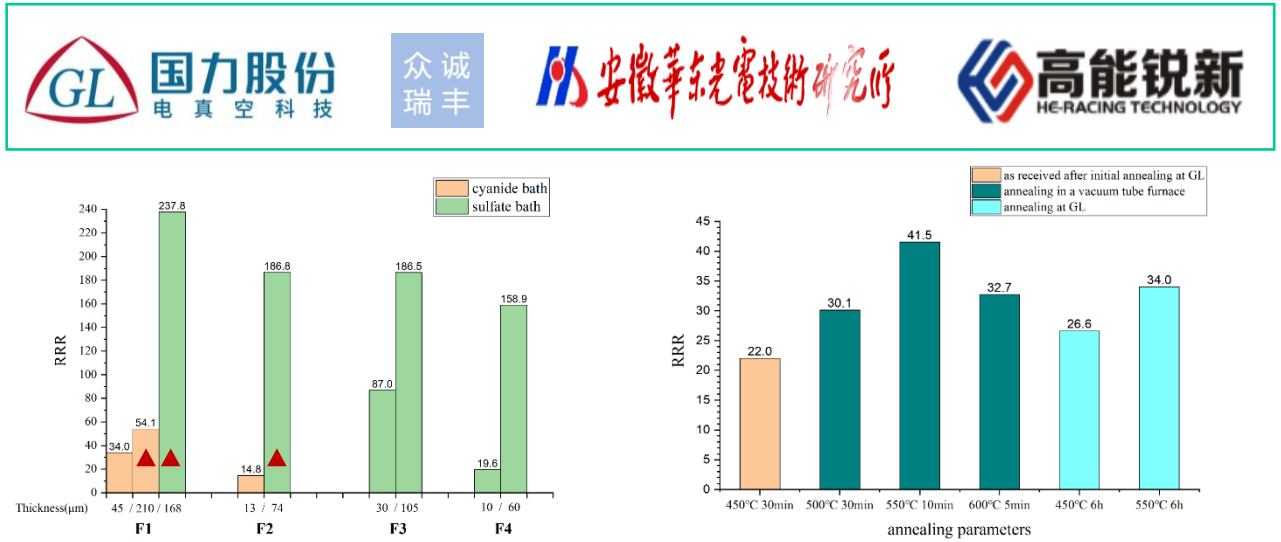






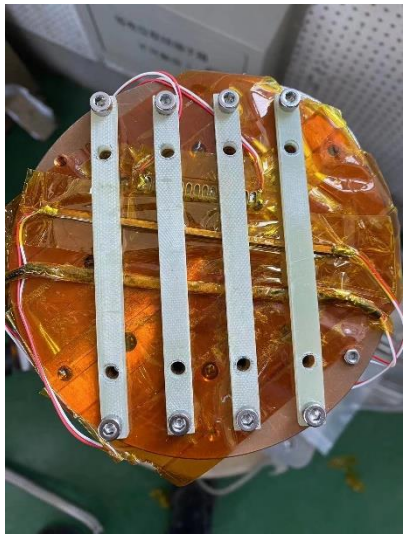


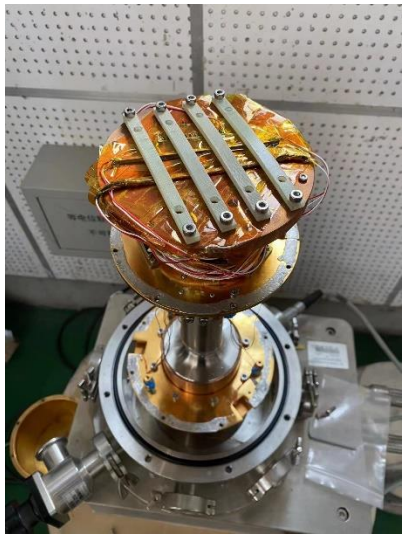
2.5 RRR measurements

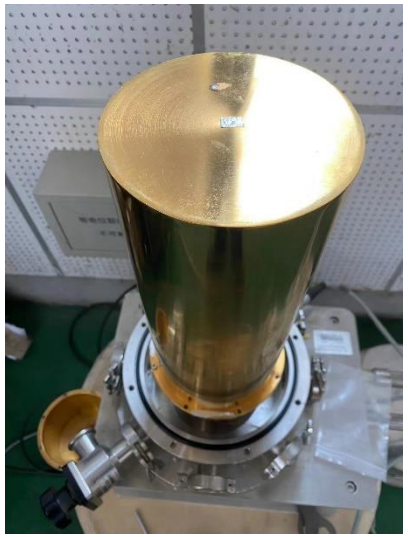


Results of RRR measurements

RRR of samples with heat-treatment

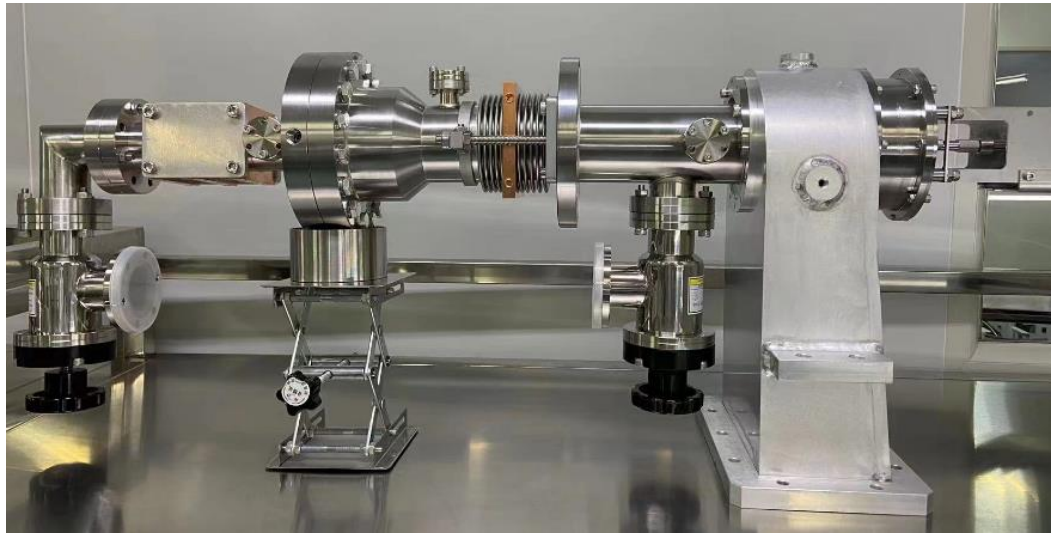






- Measure the RRR of the samples from four domestic venders. Two of them provided samples both from cyanide bath and sulfate bath.
- For the GL cyanide bath samples, the heat-treatment parameters are modified to improve the RRR.

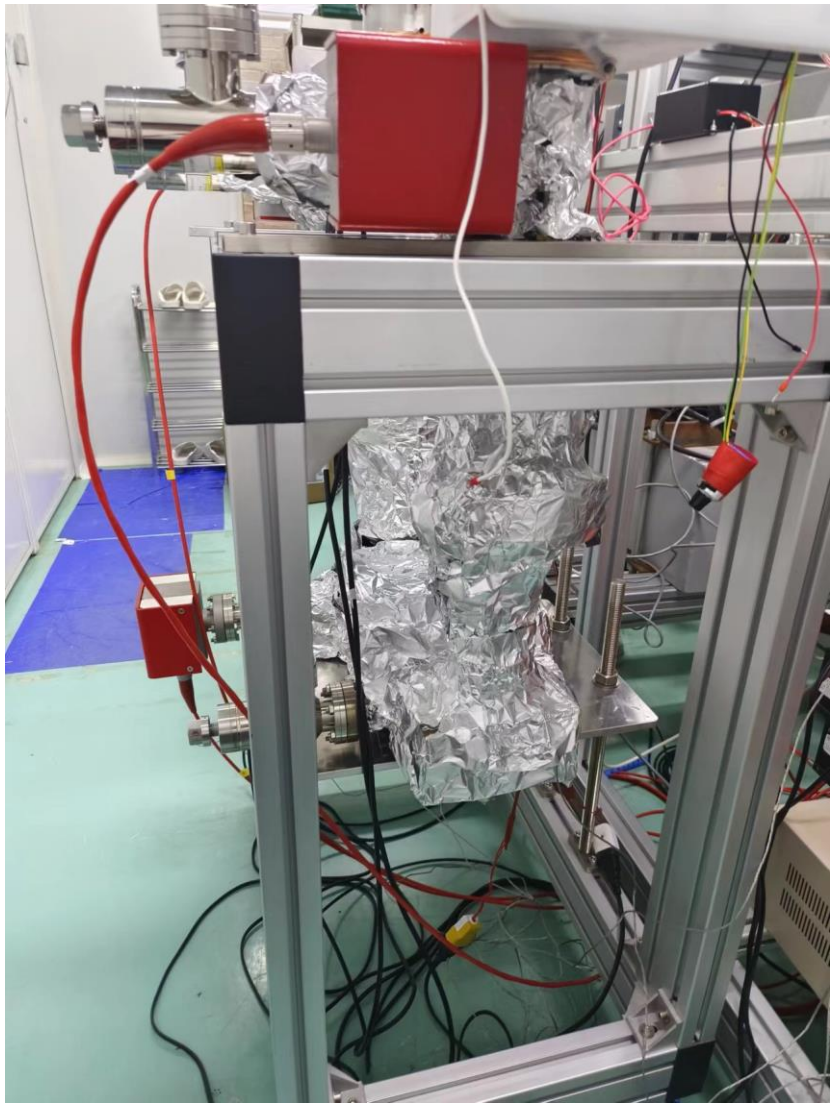
2.5 The power couplers as received and during cleaning

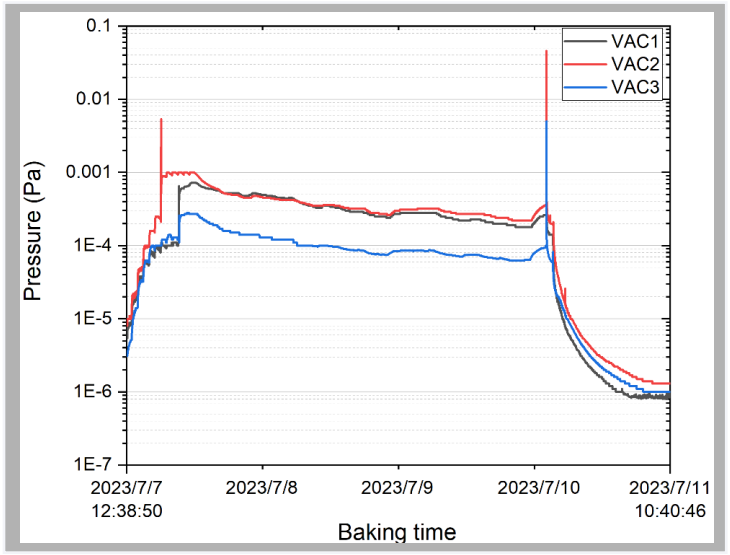


As received

cleaning

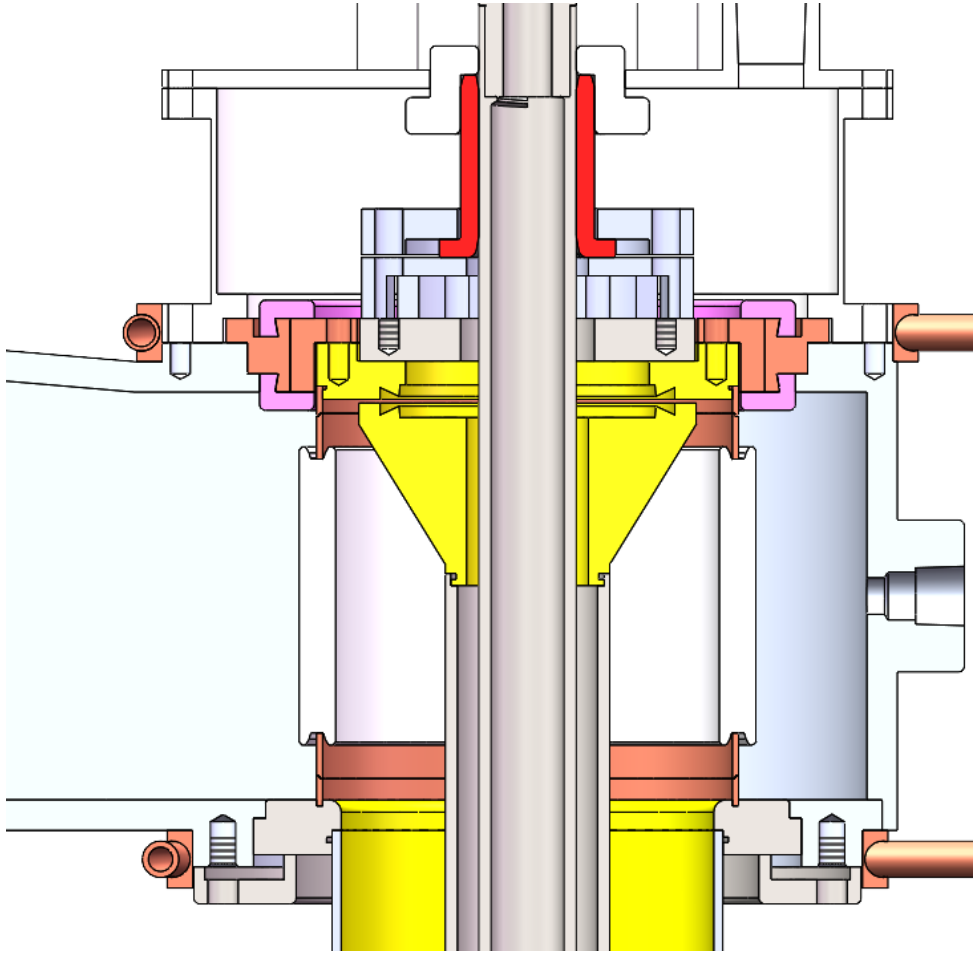
2.5 The baking

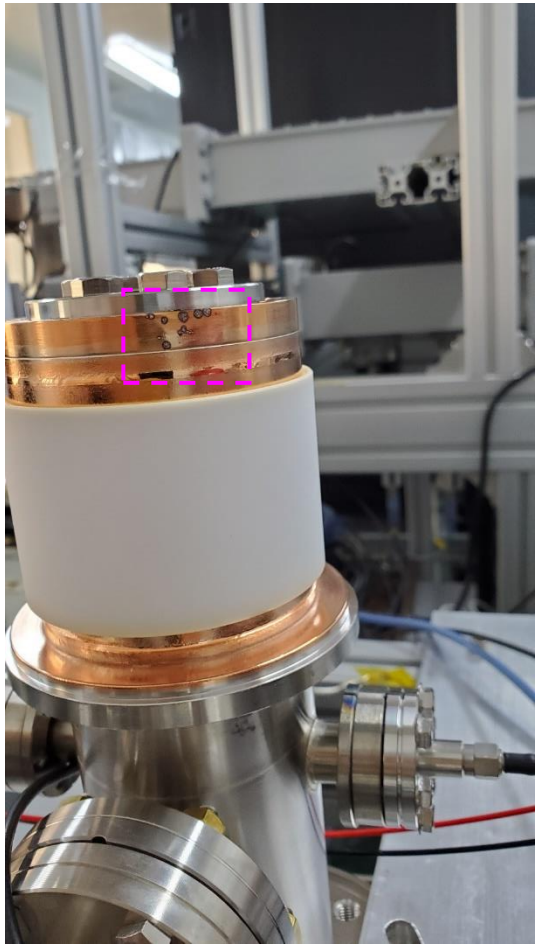


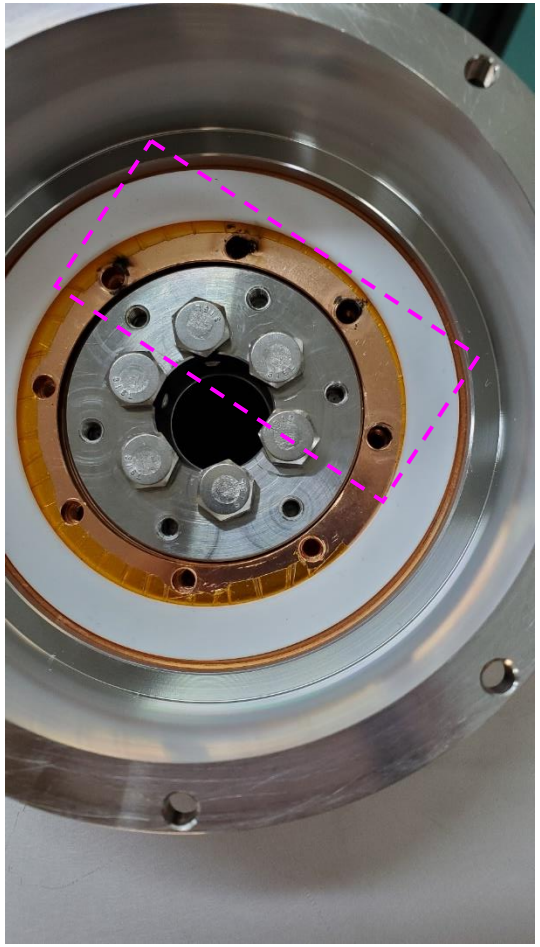


- The baking procedure: increasing the temperature with a gradient of 10℃/h, and maintaining a temperature of 150℃ for 48h.
- All ion pumps are shut off when the temperature reaches 150℃.
- Defects: As the baking was carried out by using heating tapes in air, and the heating is not uniform. The outer surfaces of the OFHC copper intercept blocks had different colors.
- Tightly wrap the silicone rubber tapes around the couplers afterwards.

2.5 arcing outside the vacuum during RF conditioning

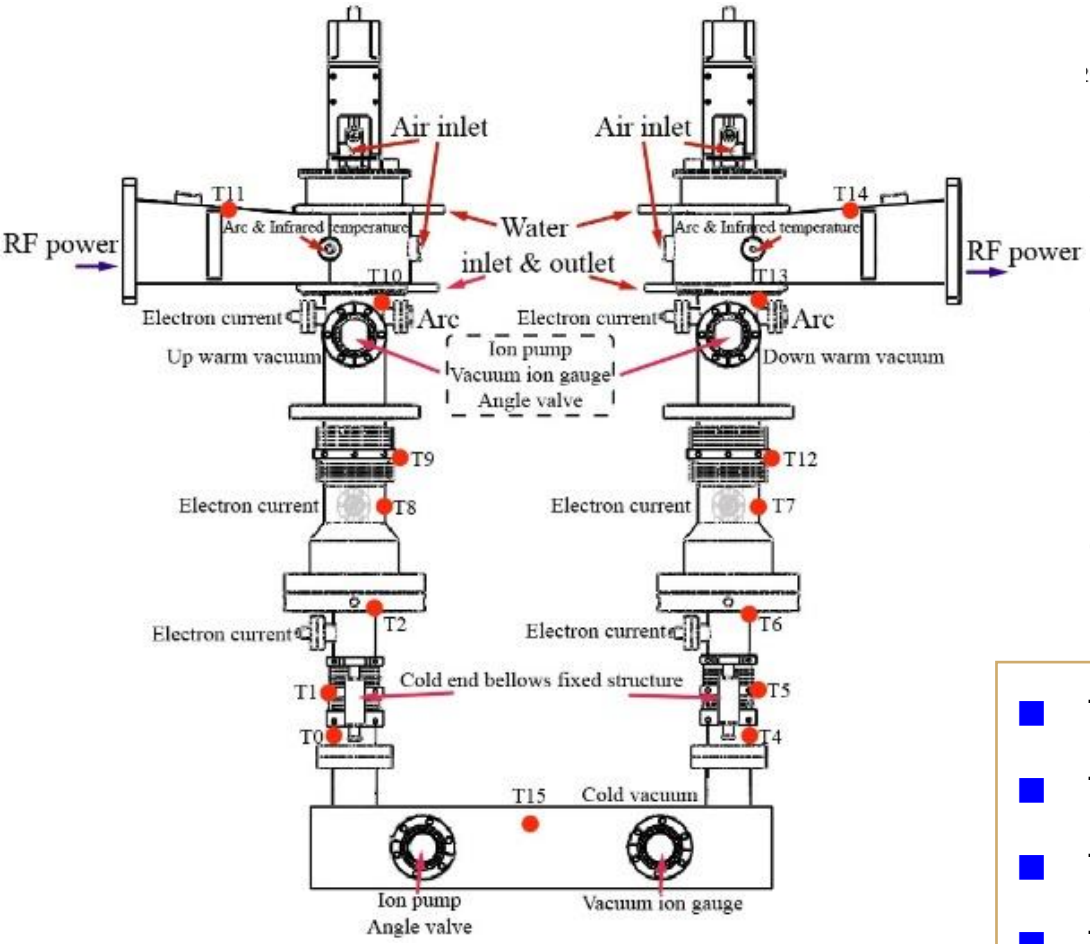


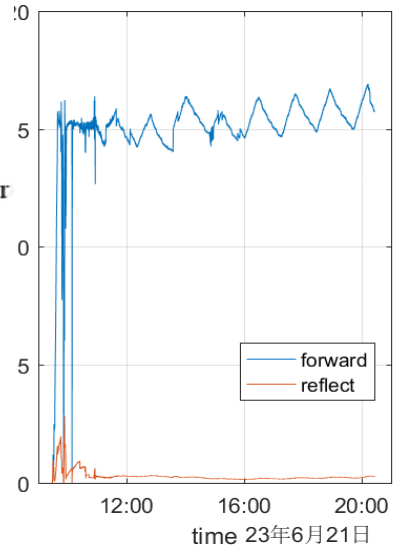


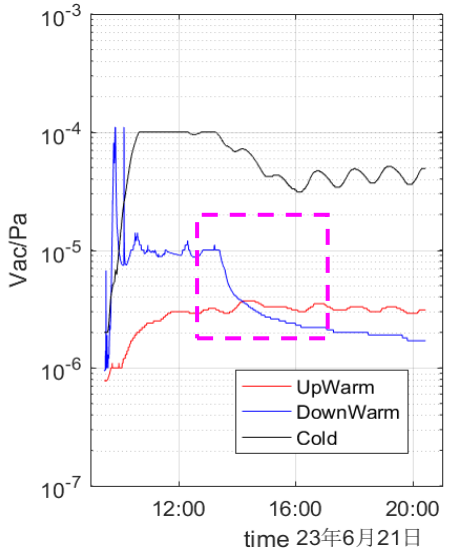


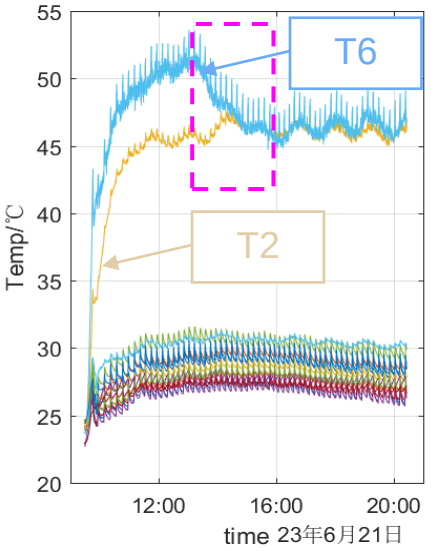
Burnout due to some improper assembly

2.5 The 1st pair of power couplers for DALS injector CM00



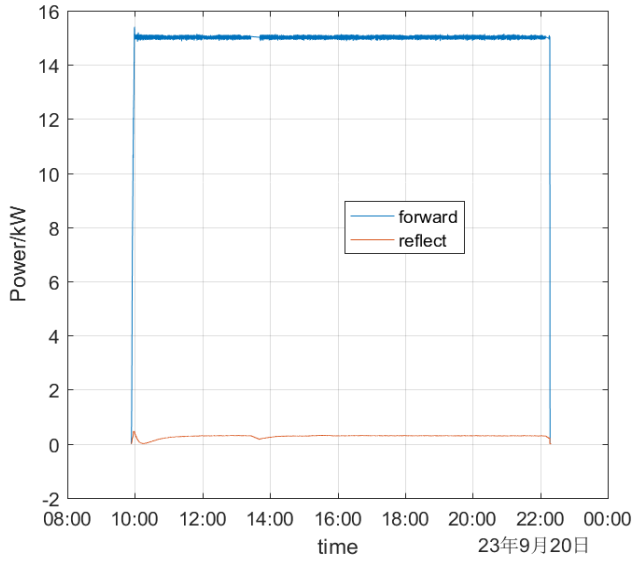


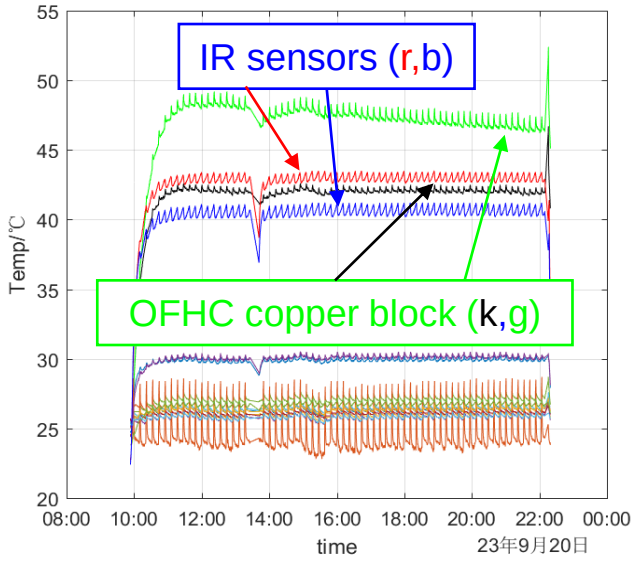


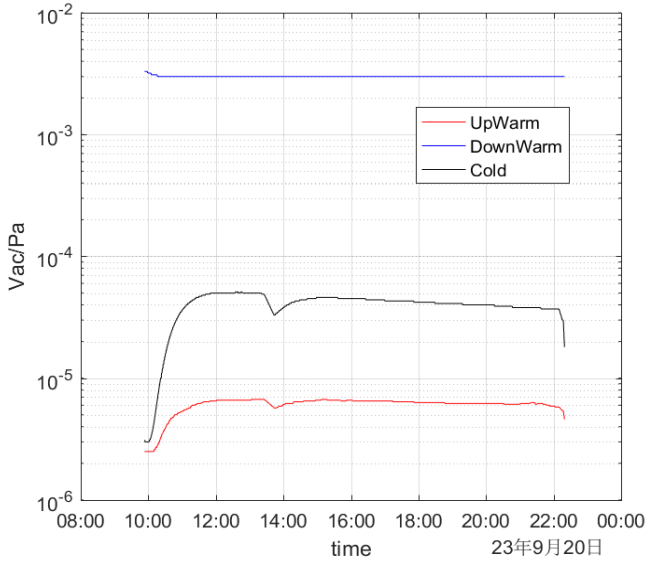


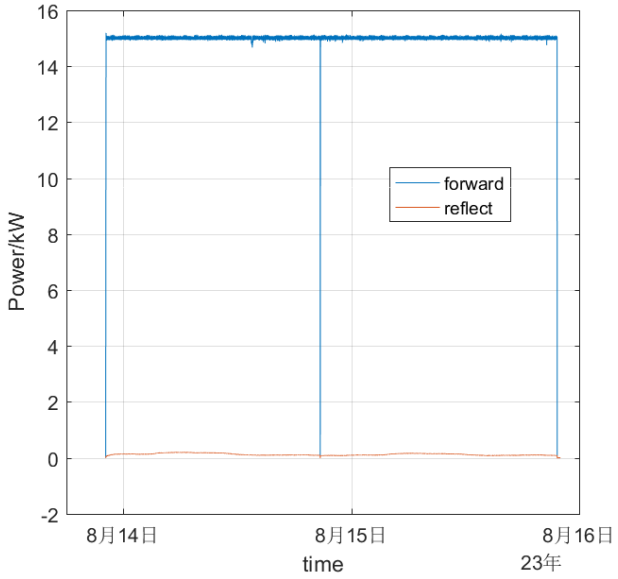
- The conditioning effect was captured directly once.
- The vacuum of the downstream coupler suddenly improved
- T6 decreased to the same value as T2.
- The vacuum between the two cold ceramic window also decreased.

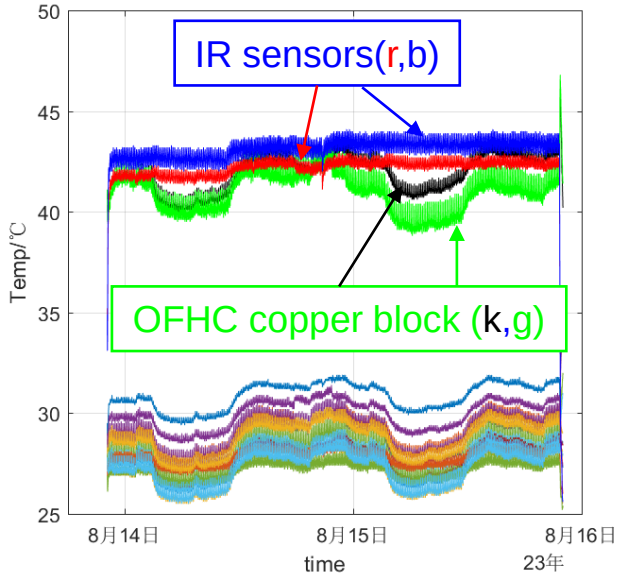
2.5 The 2nd&3rd pair of power couplers for DALS injector CM00

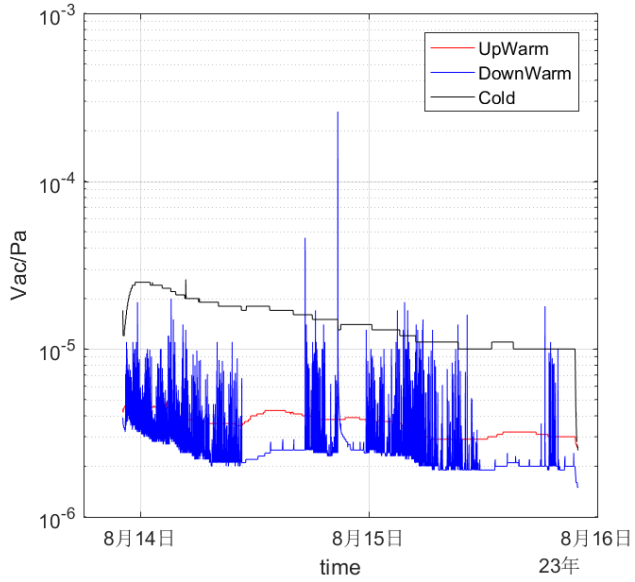










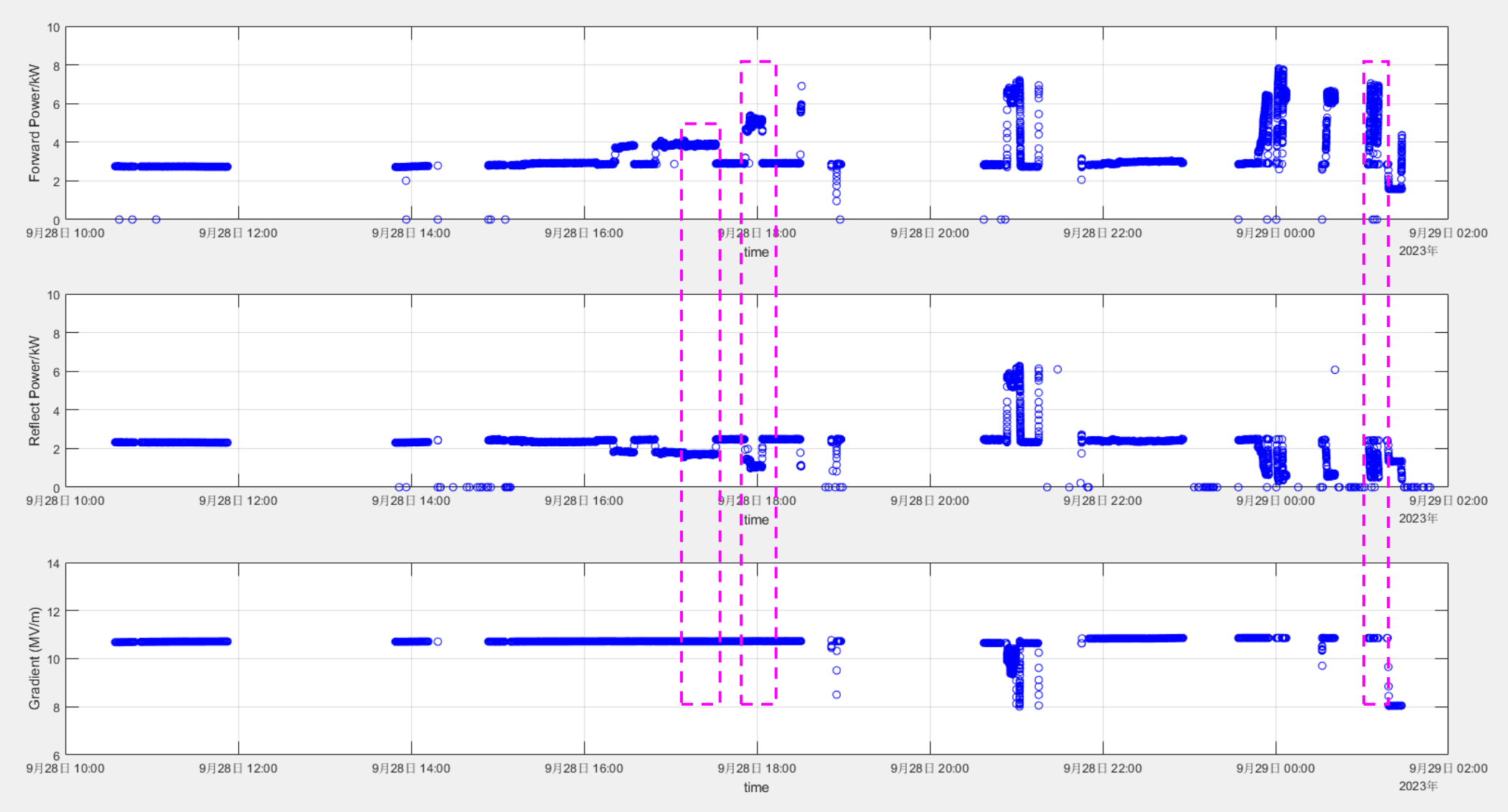


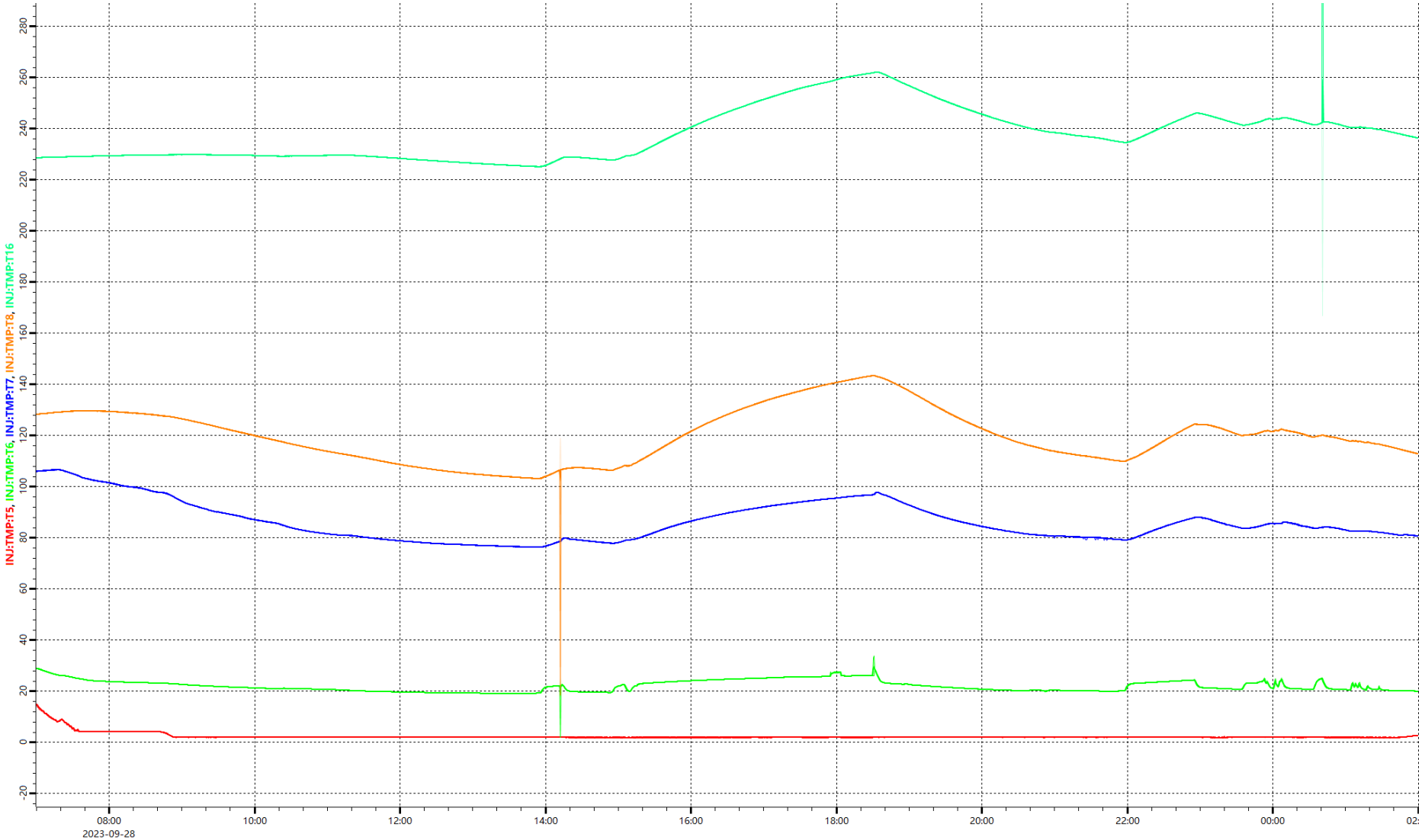
3 Summary

Time	2007-2016	2013-2019	2015-2017	2018-now	2020-now
Structure	Capacitive coupling	Hybrid coupler	Resonant ring	TTF-III like	TTF-III like
Project	DC-SRF-I gun	2x9-cell		DC-SRF-II gun	DALS 2 × 2-cell cryomodule
Tested Power	20kW 10Hz 40ms 5kW CW	110kW 10Hz 5ms 15kW CW	200 kW 10Hz 5ms 70 kW CW	100 kW 10Hz 5ms 30kW CW	15kW CW
Status	Beam operation (2011-2016)	Beam operation (2019-now)	Operation (2017-now)	Beam operation (2021-now)	High power tested
Operation Power	5kW CW max	8kW, 5Hz, 2ms		7kW CW max 3kW CW typ.	

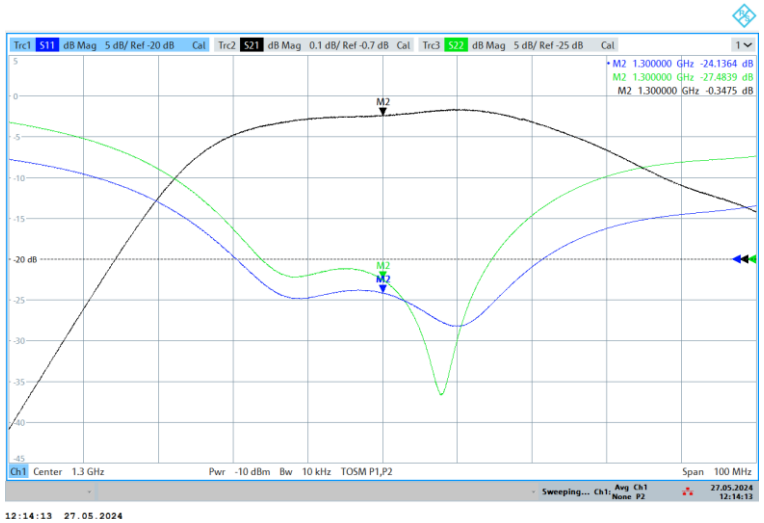
- Three types of power couplers have been developed during the facility construction. The heat load will be further investigated at cryogenic temperature with higher power.
- After nearly 20 years of efforts, DC-SRF photocathode gun has gradually developed from concept design to a stable operation device.

Thanks for your attention


Forward Power/kW
Reflect Power/kW
Gradient (MV/m)
9月28日 10:00
9月28日 12:00
9月28日 14:00
9月28日 16:00
9月28日 18:00
9月28日 20:00
9月28日 22:00
9月29日 00:00
9月29日 02:00
time
2023年

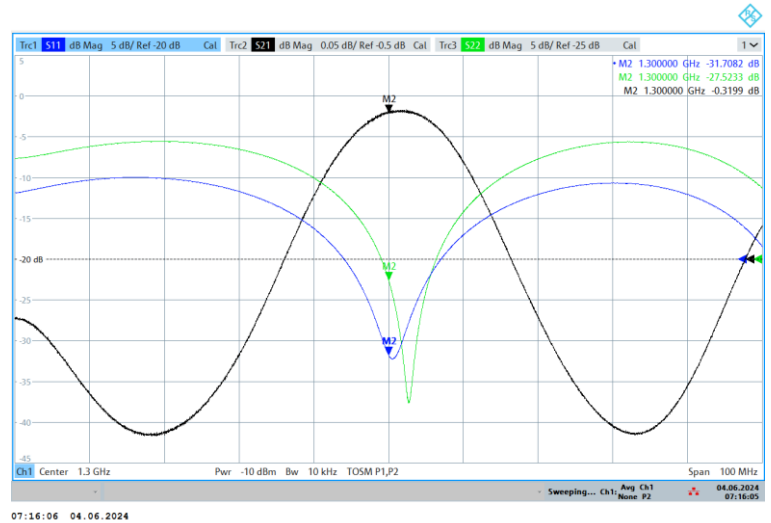

INJ:TMP:T5, INJ:TMP:T6, INJ:TMP:T7, INJ:TMP:T8, INJ:TMP:T16
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-20
08:00
2023-09-28
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00

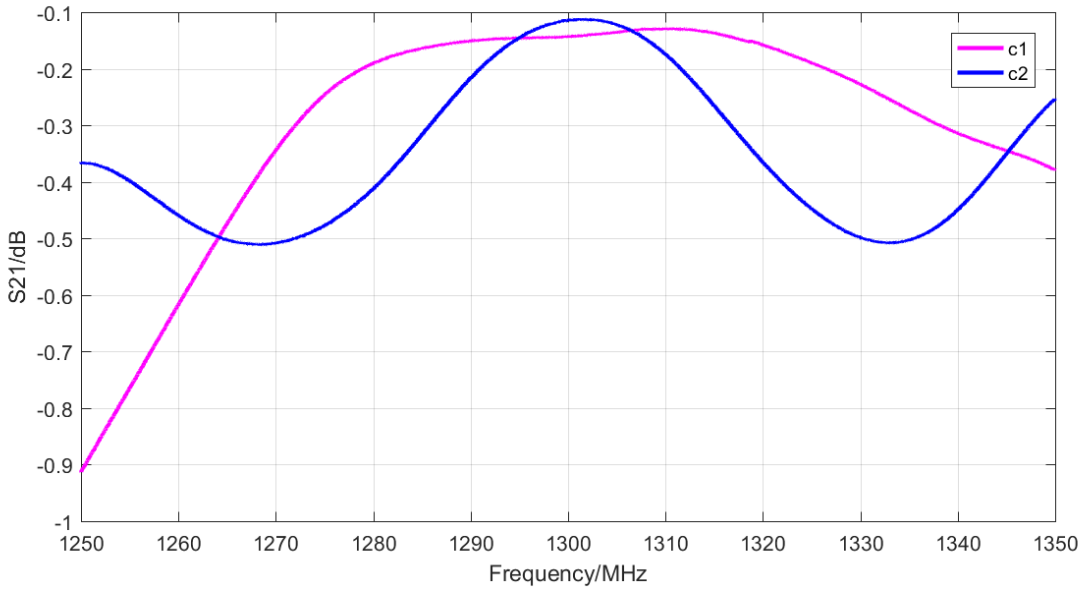
2.5 Typical S curves of the coupler-pair

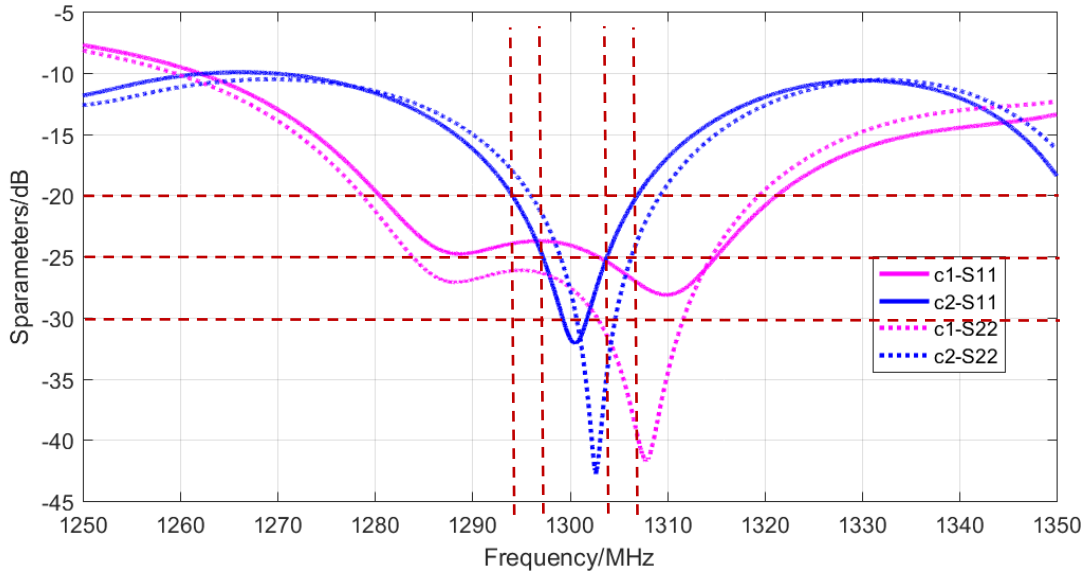


c1@f =1.3 GHz
S21=-0.15dB
S11=-24.14dB
S22=-27.48dB

c2@f =1.3 GHz
S21= -0.12 dB
S11= -31.71 dB
S22= -27.52 dB







The refrigerant compressor operates periodically

The heat is expelled via a fan.