Coupler operation and R&D activities at IMP

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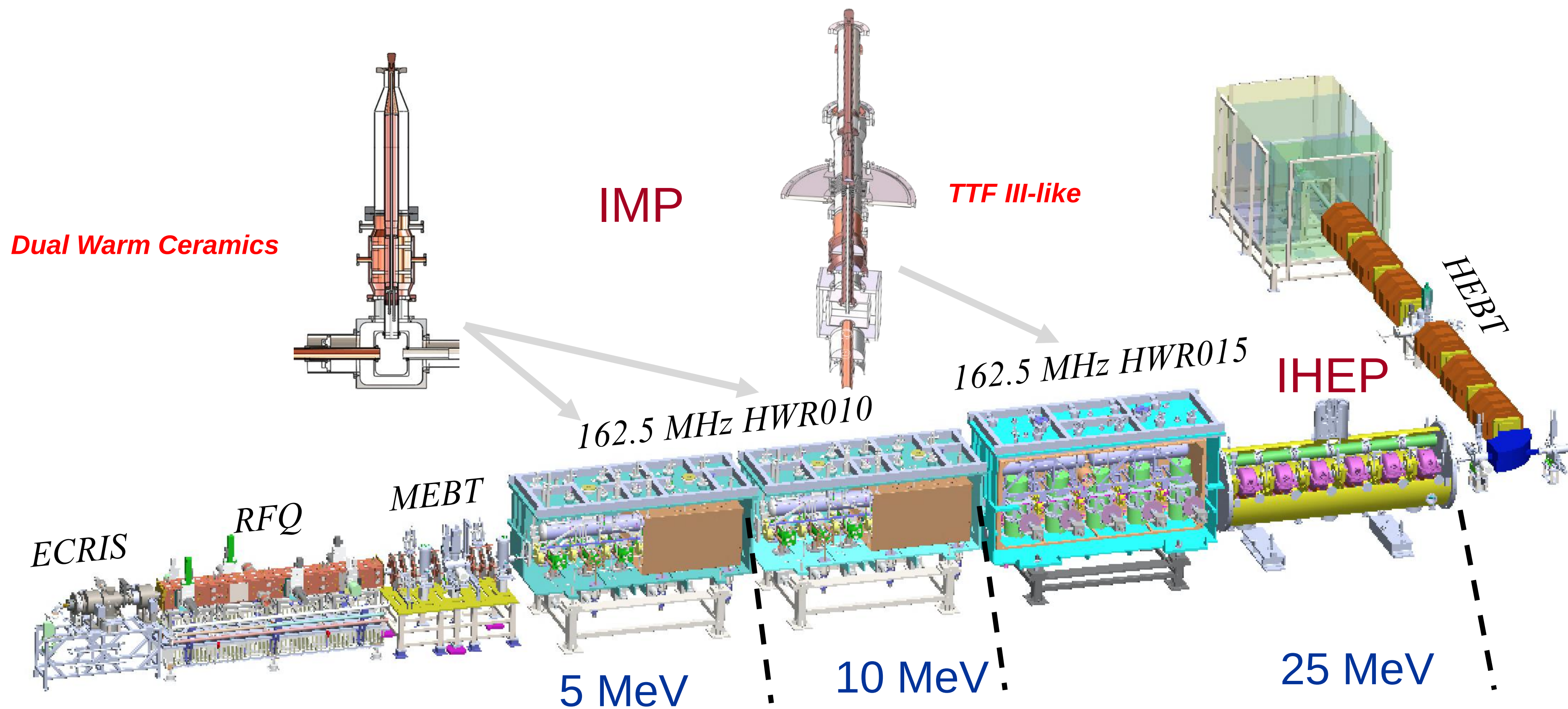
Outline

- **Power coupler operation experience**
  - Overview of the power coupler for CAFe
  - HV DC Biasing
- **Power couplers for CiADS**
  - Requirement
  - Primary Design
  - RF conditioning consideration

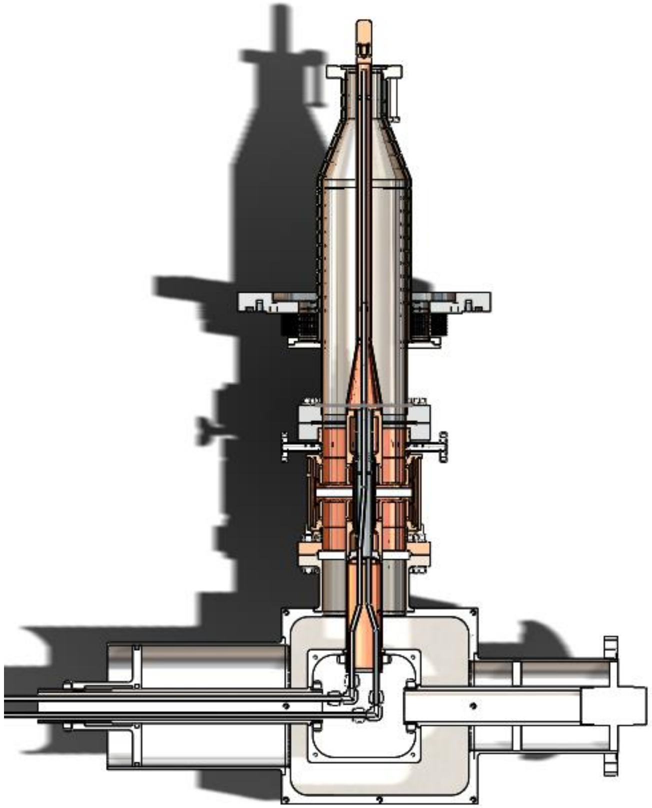
CAFe

CAFe: Chinese ADS front-end demo superconducting linac



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

IHEP Couplers for HWR010

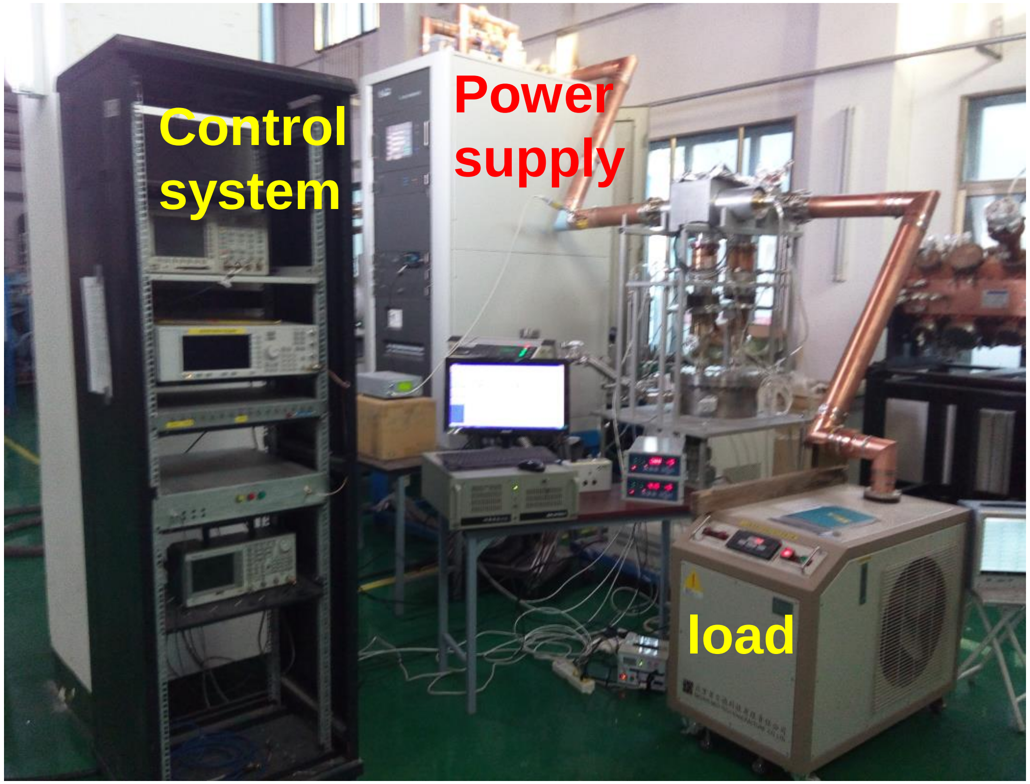


Design & Built by IHEP

f (MHz)	162.5
Pf (kW)	15
Pref (kW)	8
Qe	6E5
Heat Load (W) (4.5K) 15kW	0.18
Heat Load (W) (80 K) 15kW	14.2

- Single ceramic window
- Helium cooling (OC)
- Water cooling (IC)
- Short piston
- No bias

Coupler RF Test Stand



Test procedure

1.ARC: AFT
2.Vacuum interlock: 5E-5Pa
3. T rise: < 20°
4. MP voltage: <1V

1. Travelling Wave
Duty Factor: 1%, 10%, 50%, 75%, CW
Repetition: 100Hz

2. Standing Wave
Duty factor: 10%, 50%, CW
Freq. 100Hz
Phase shift: 10° / time
Total shift: 90°

Travelling Wave: 20 kW, Standing Wave: 8 kW (phase shifter)

History of SC Cavity and Couplers

10 MeV operation for 2 months, ceramic windows of 4 couplers in two cryomodules were leaking.

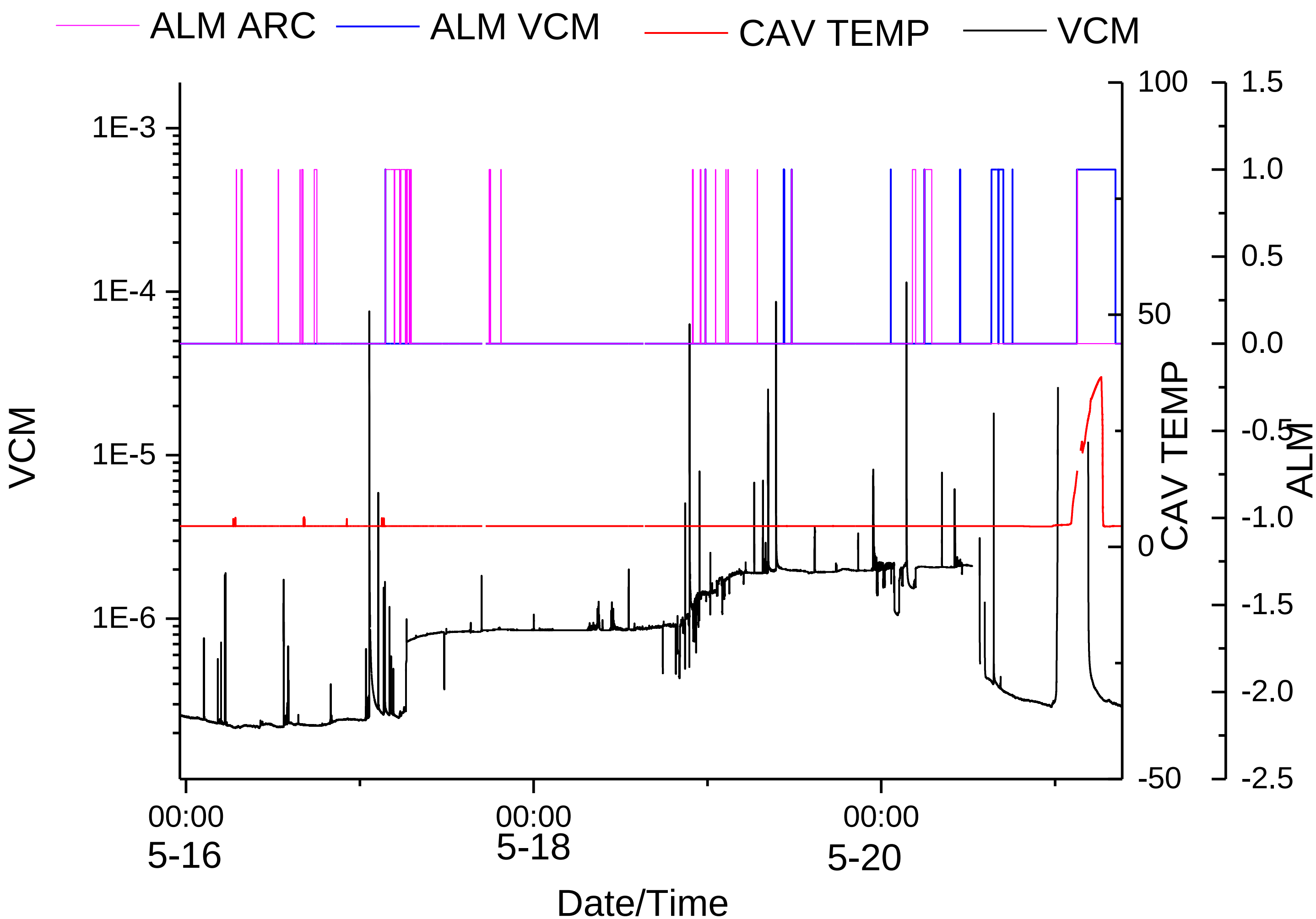
Normal temp. Coupler condition	Cooling down	Cavity Pulse condition
4.13—4.24	4.23- 5.2	5.3—5.5
CW > 10 kW		

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		

10 MeV Coupler Operation

10 MeV operation for 2 months, ceramic windows of 4 couplers in two cryomodules were leaking.

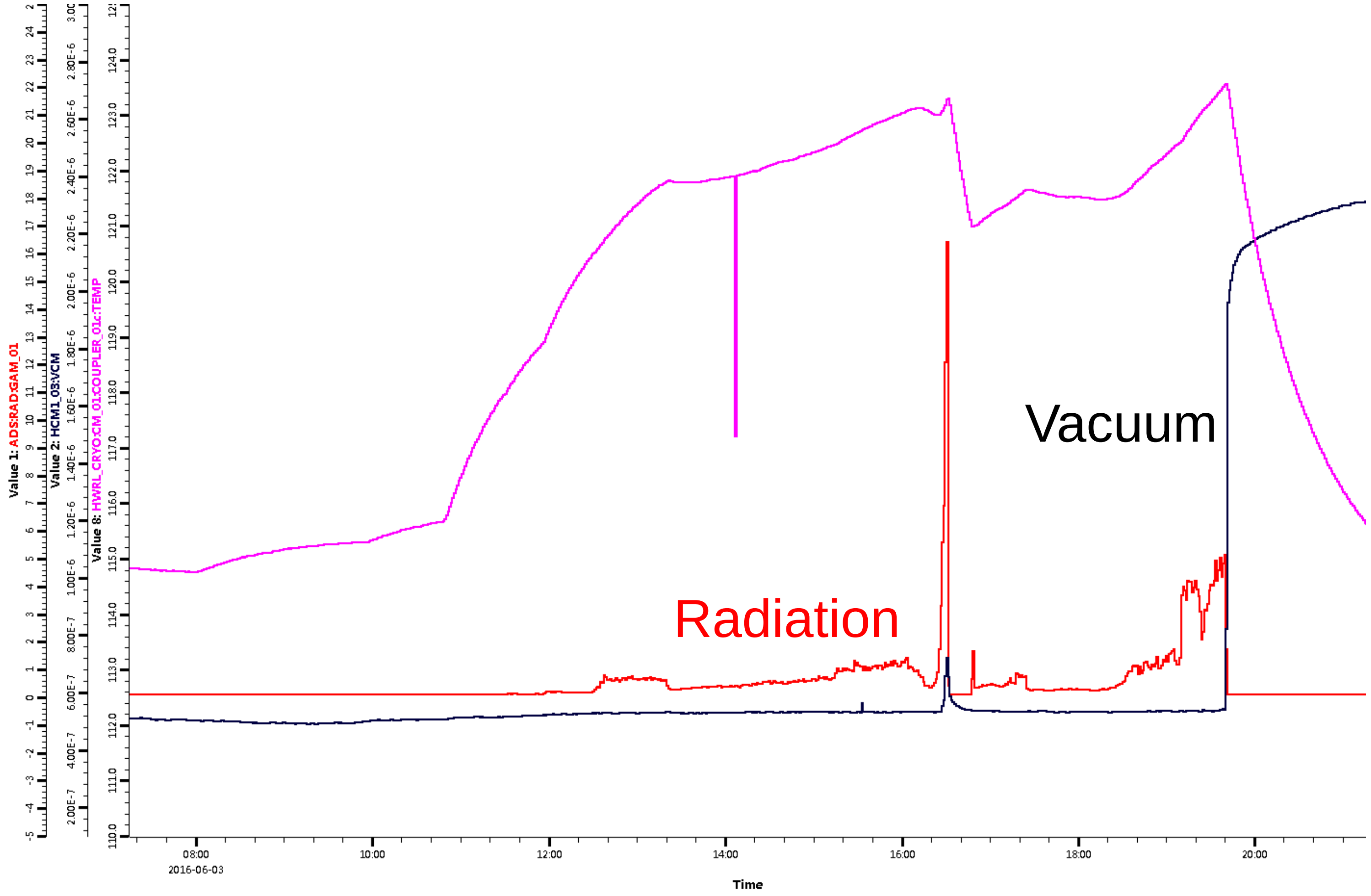
CM1-3



10 MeV Coupler Operation

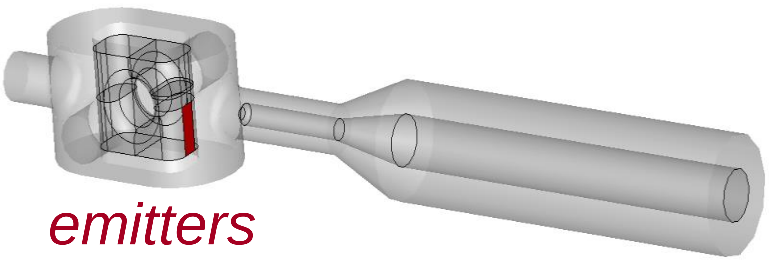
10 MeV operation for 2 months, ceramic windows of 4 couplers in two cryomodules were leaking.

CM2-5

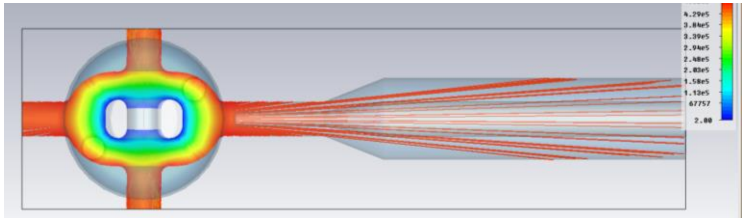


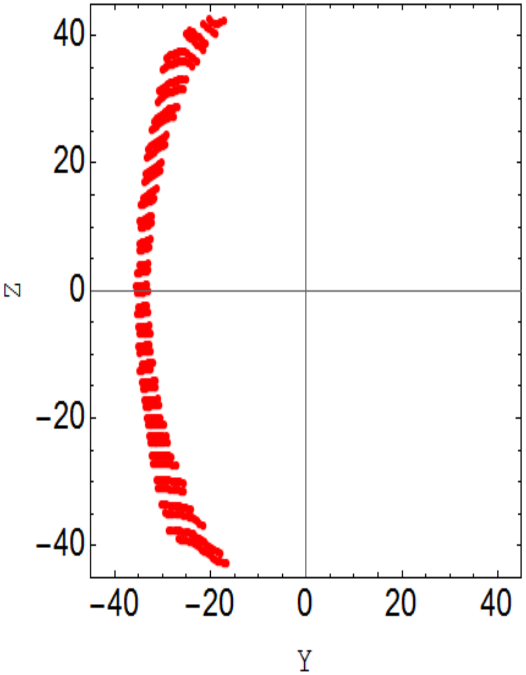
Field Emission on Coupler





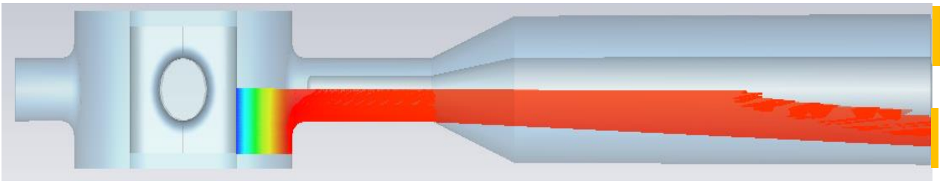
emitters





FE hitting on Window

Cavity Ep 25MV/m
Local Ep 15MV/m

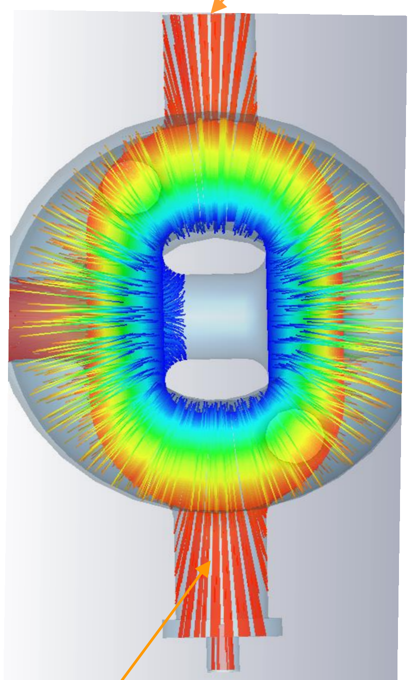


Energy of FE ~ 400 keV

Trajectory of FE ***window***

Field Emission on Pick-up

Coupler Port

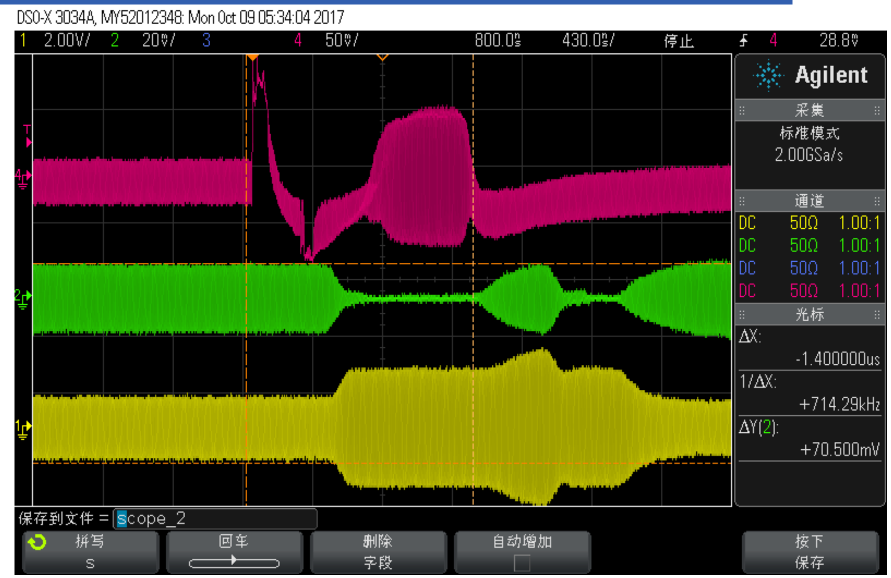


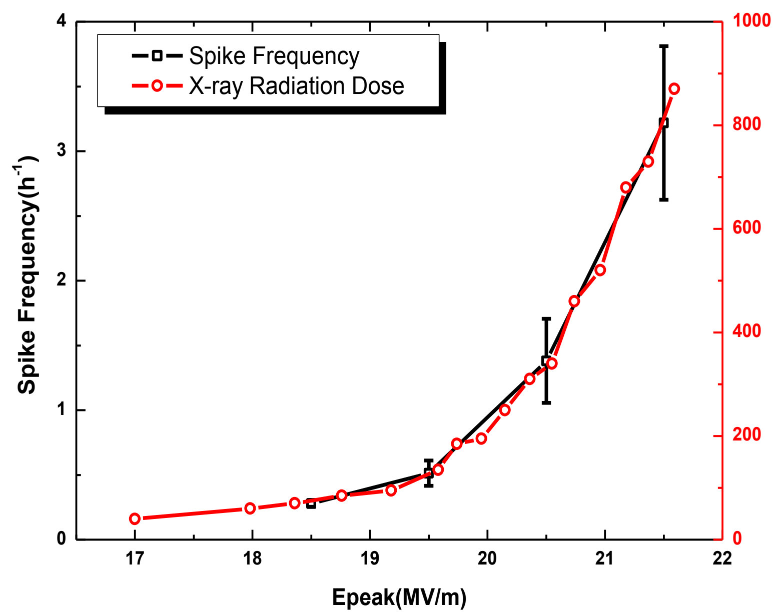
Pick-up Port

Pick-up from cavity

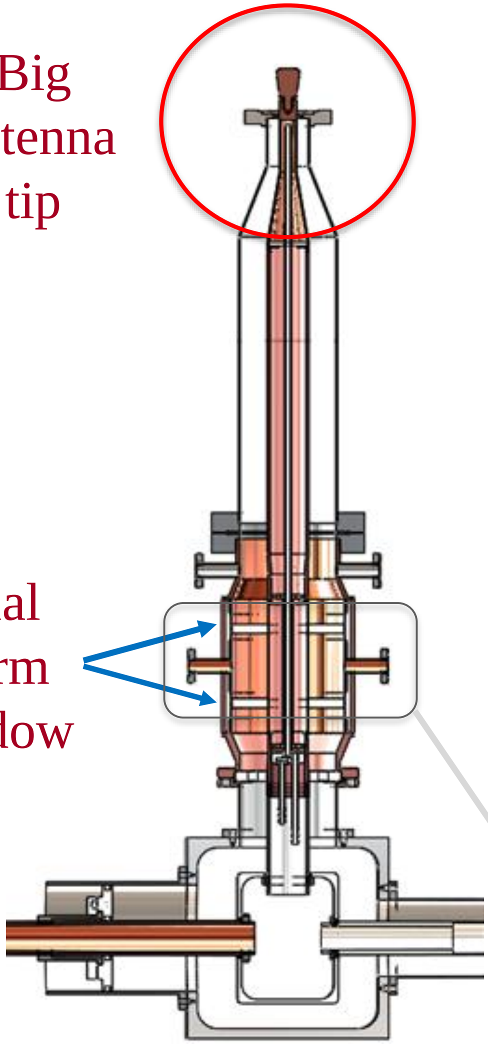
Forward RF signal

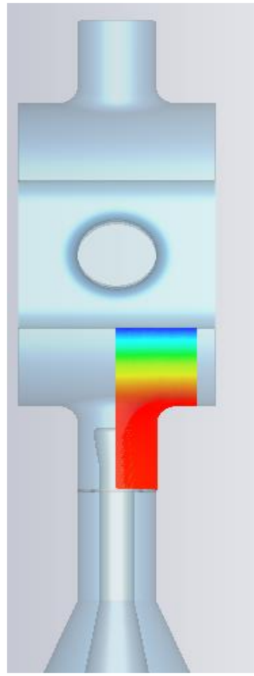
Reflected RF signal



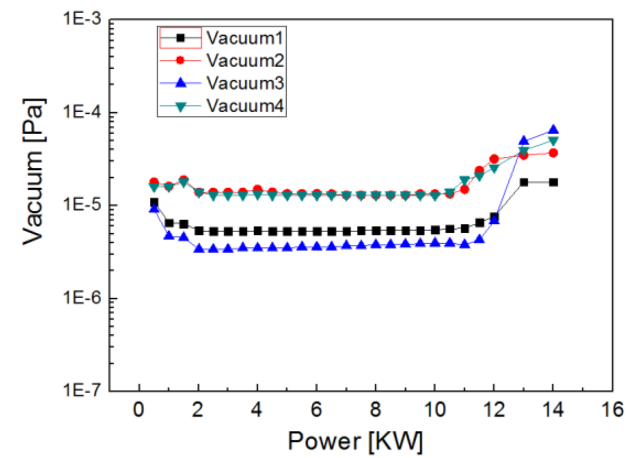


Solutions





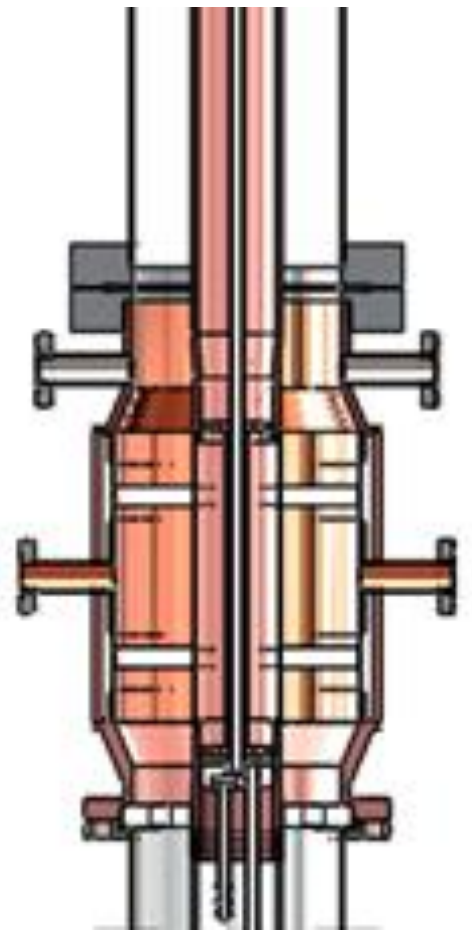
FE simulation



Couplers passed the power test.

- Difficult to braze
- Not easy for the clean of the space between the dual windows

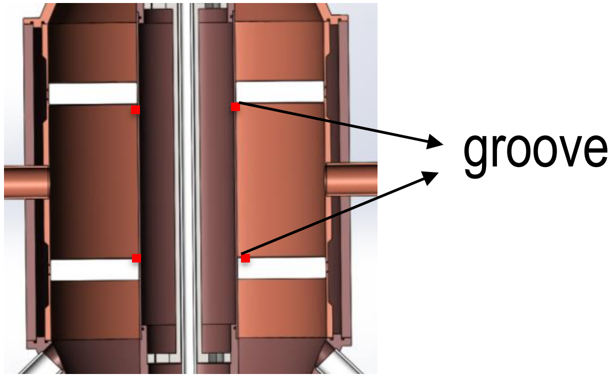
Dual Warm Window

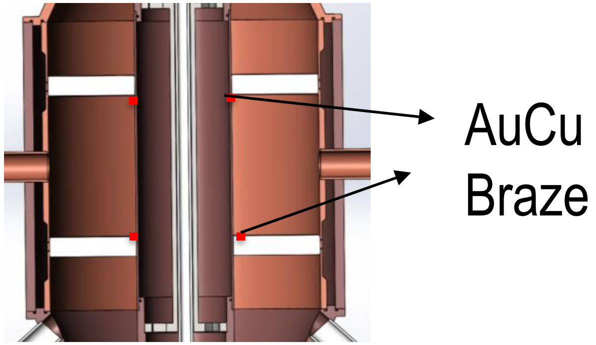


Braze for the windows

Arcing during the condition of the coupler.

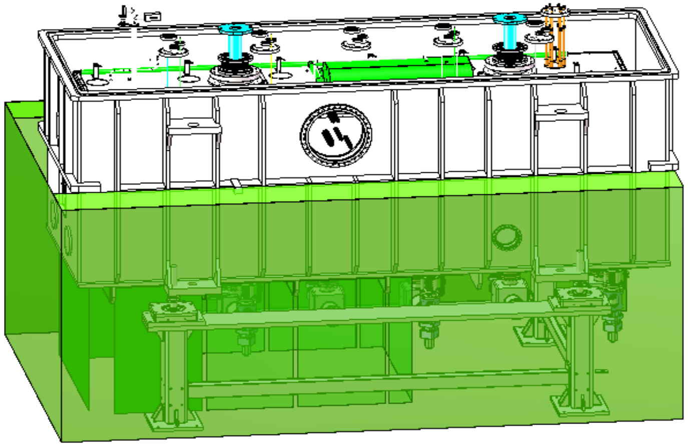
Solve

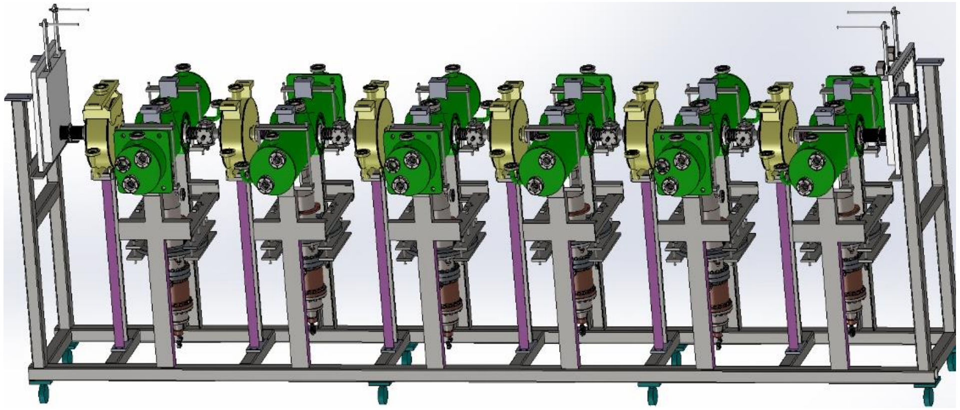


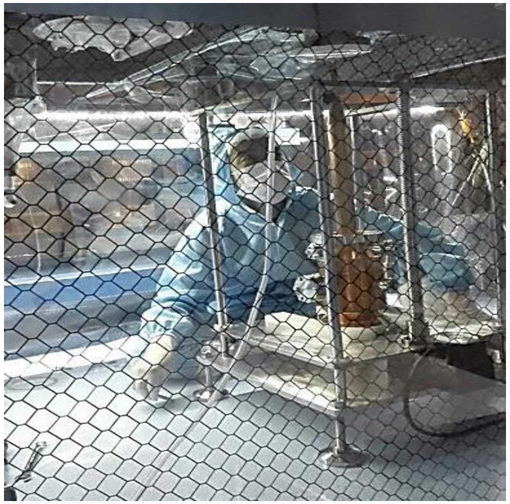


Both of the two ways solve the problem.

HWR010 Coupler Replacement





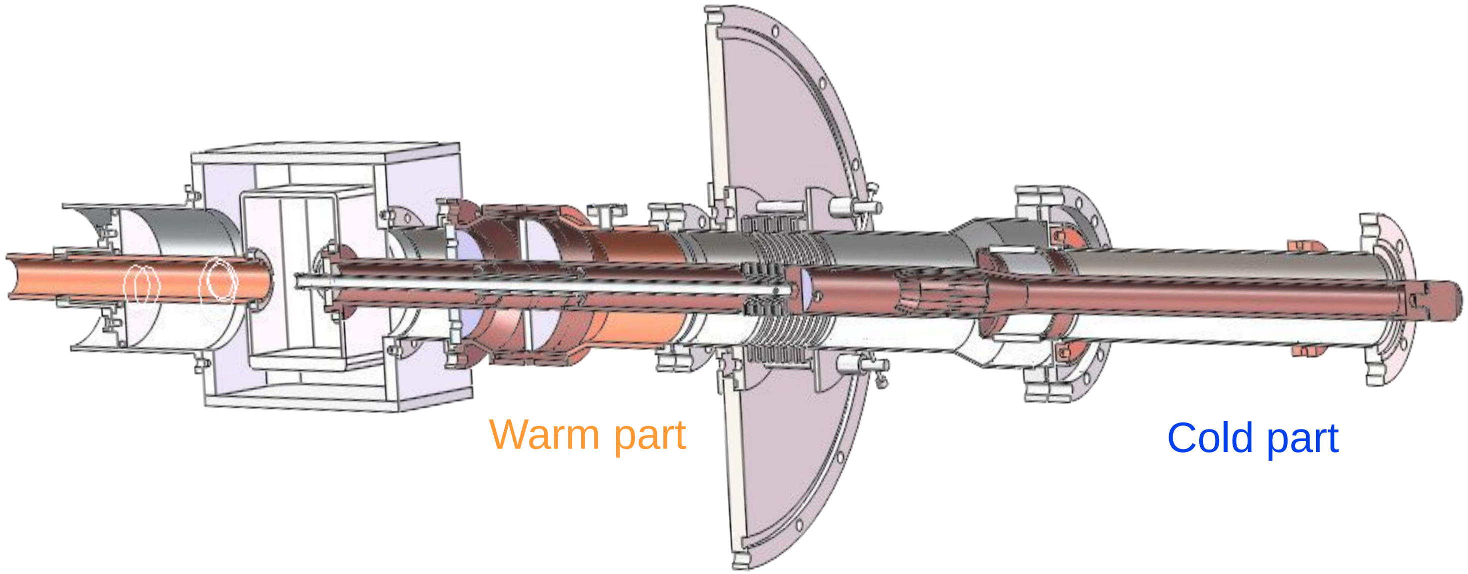


coupler replaced in tunnel

coupler assembled in clean room

New couplers have worked for around 3 years, no leak was found, and the new couplers work very well.

Power Couplers for HWR015



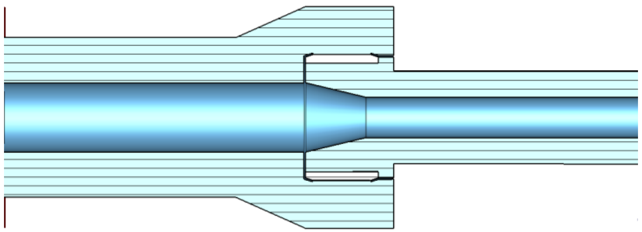
Pros：

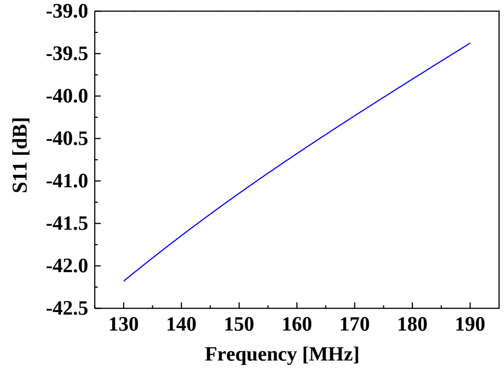
- Two windows more reliable
- Easy for assembling
- Reduce the size of the cryomodule

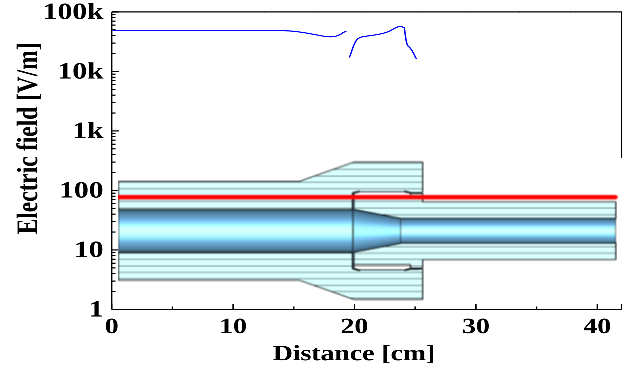
Cons：

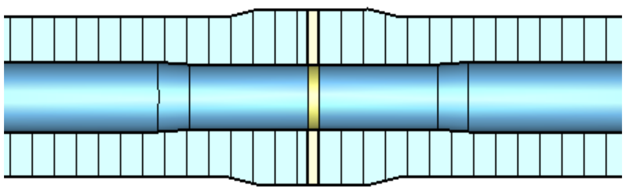
- Difficult to monitor the vacuum activity around the cold window
- Complexity and price
- Low average power

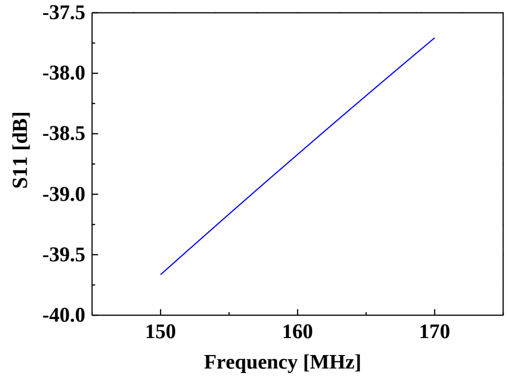
RF Design

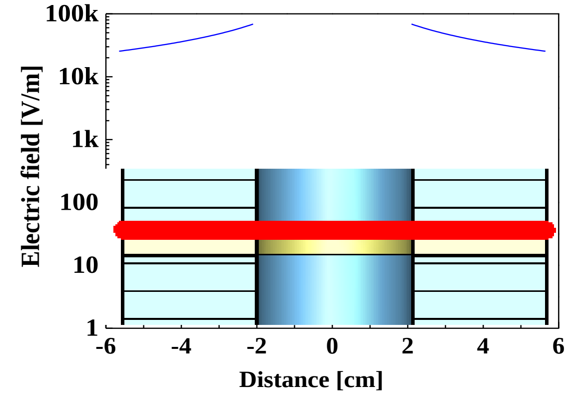


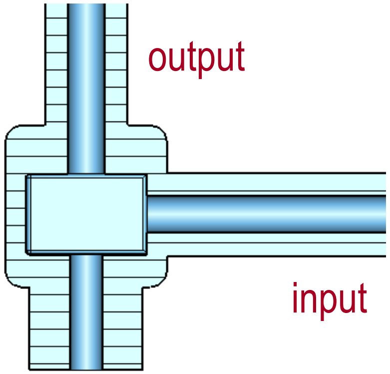

S11 [dB]
-39.0
-39.5
-40.0
-40.5
-41.0
-41.5
-42.0
-42.5
130 140 150 160 170 180 190
Frequency [MHz]

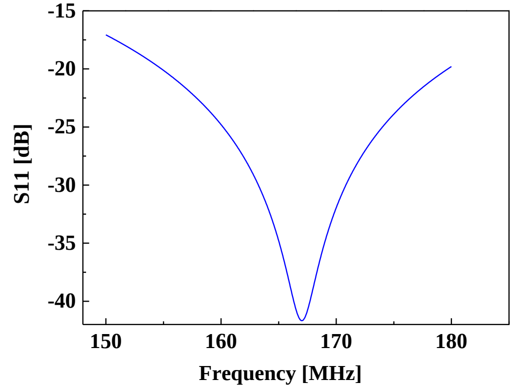

Electric field [V/m]
100k
10k
1k
100
10
1
0 10 20 30 40
Distance [cm]

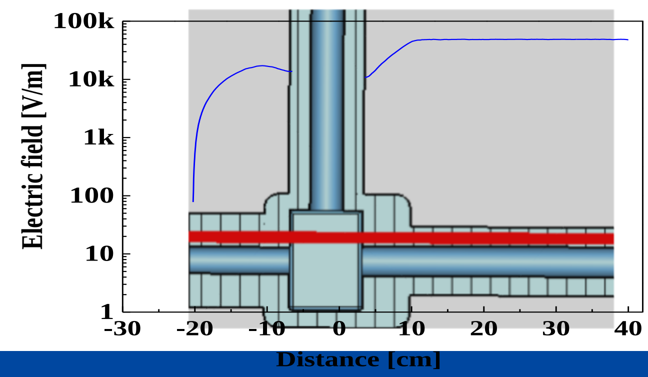



S11 [dB]
-37.5
-38.0
-38.5
-39.0
-39.5
-40.0
150 160 170
Frequency [MHz]

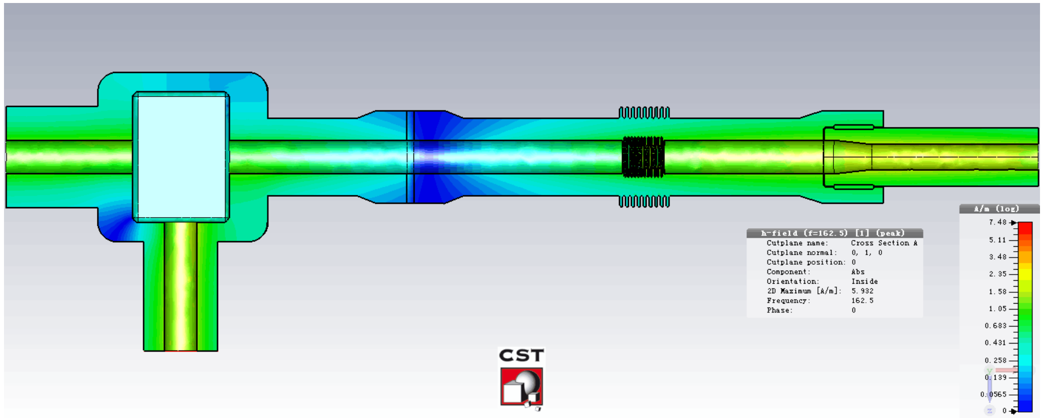

Electric field [V/m]
100k
10k
1k
100
10
1
-6 -4 -2 0 2 4 6
Distance [cm]


output
input

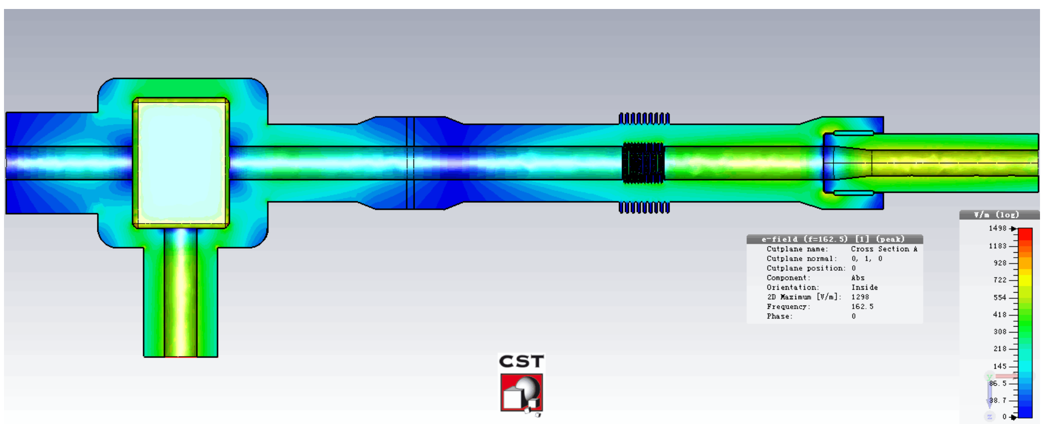

S11 [dB]
-15
-20
-25
-30
-35
-40
150 160 170 180
Frequency [MHz]


Electric field [V/m]
100k
10k
1k
100
10
1
-30 -20 -10 0 10 20 30 40
Distance [cm]

RF Design

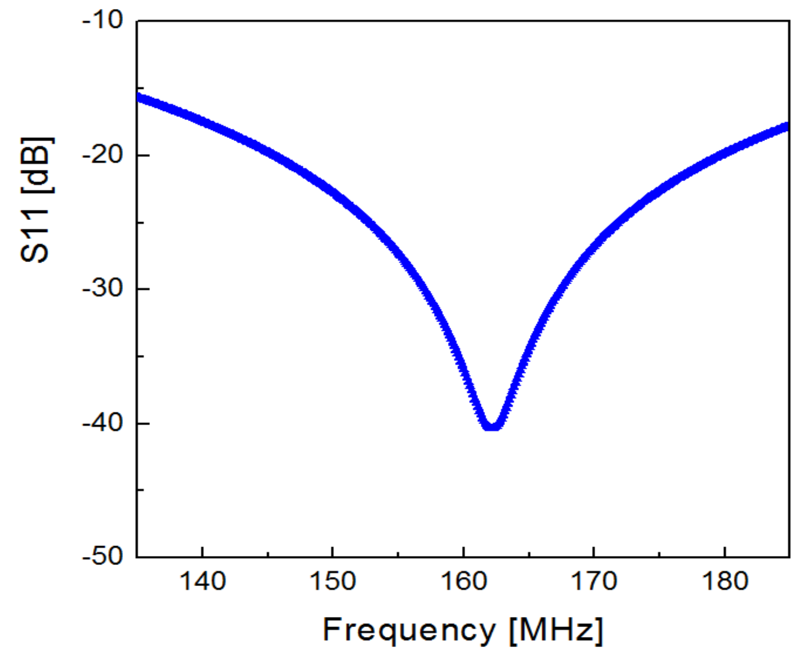


Travelling mode (H_field)



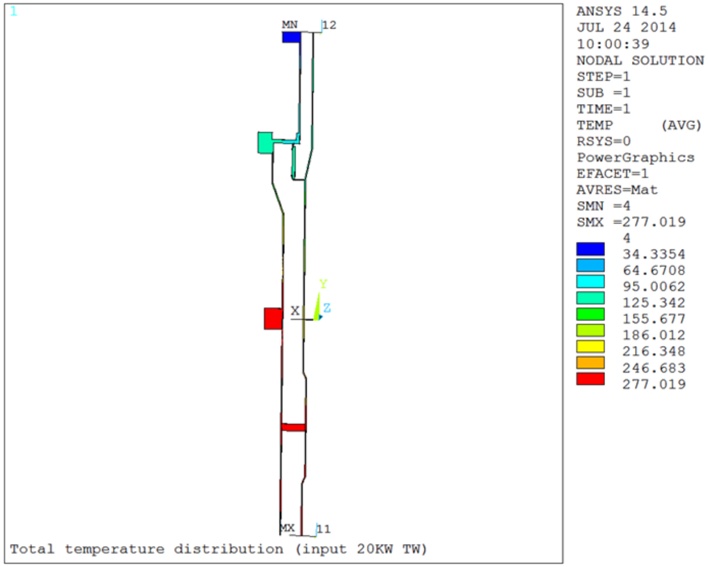
Travelling mode (E_field)

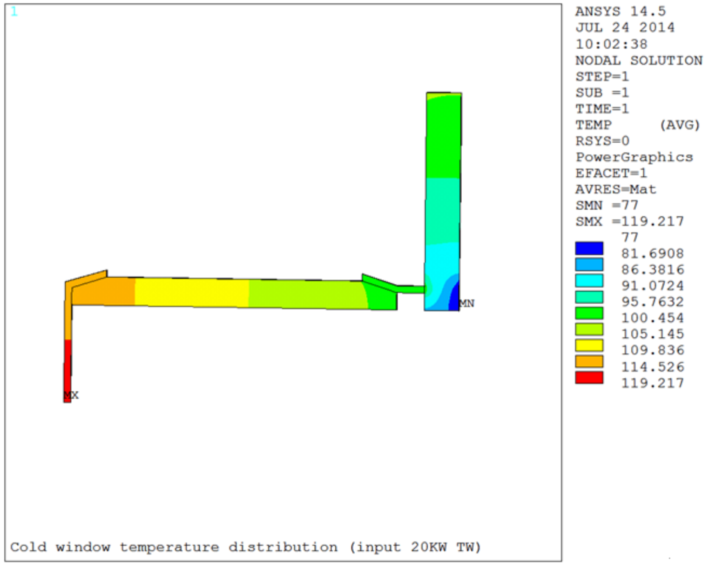
Power transmission



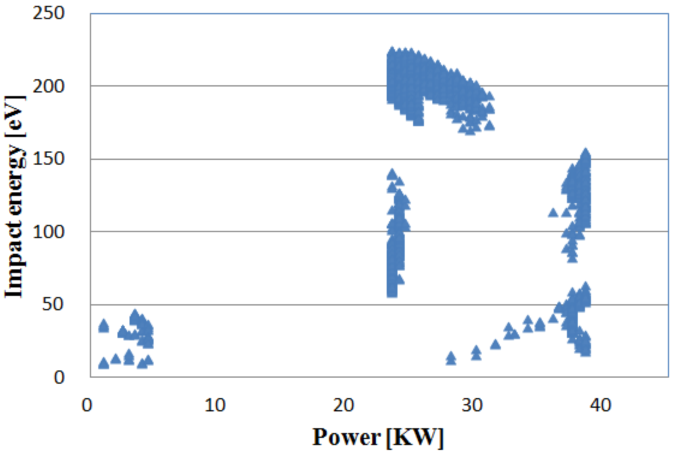
S11<-35dB@162.5MHz

Thermal & MP Simulation



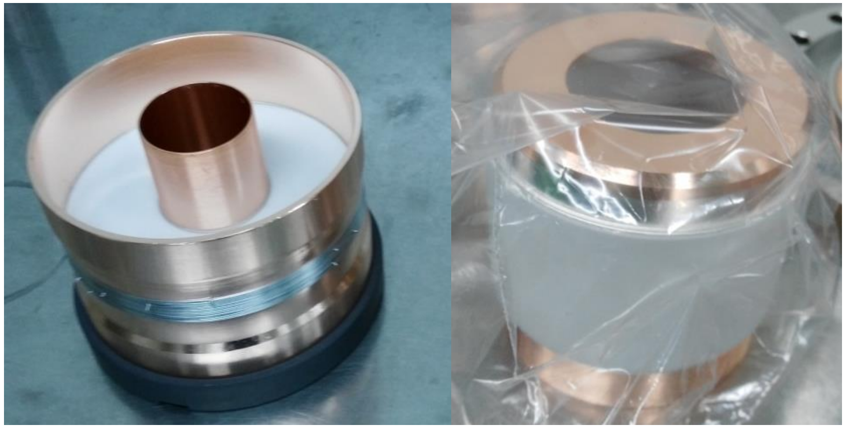


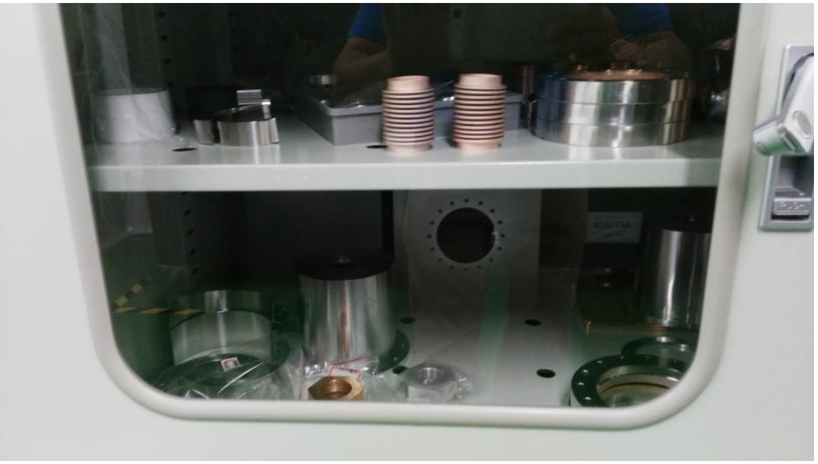
Heat Loss	4K (W)	80K (W)
static	0.1	10
20 KW (travelling)	0.5	15



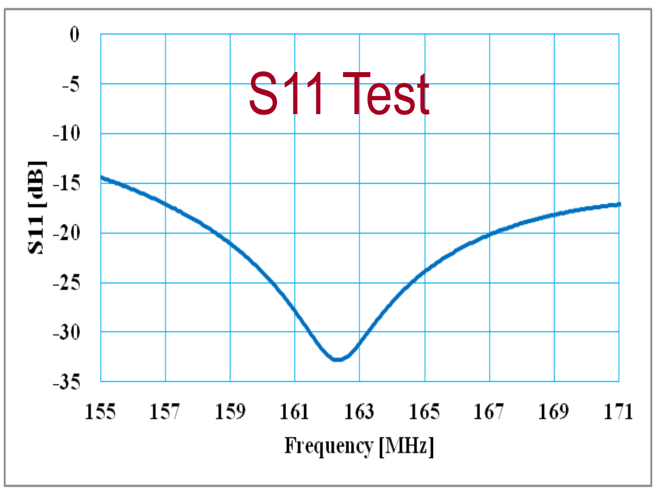
MP Simulation

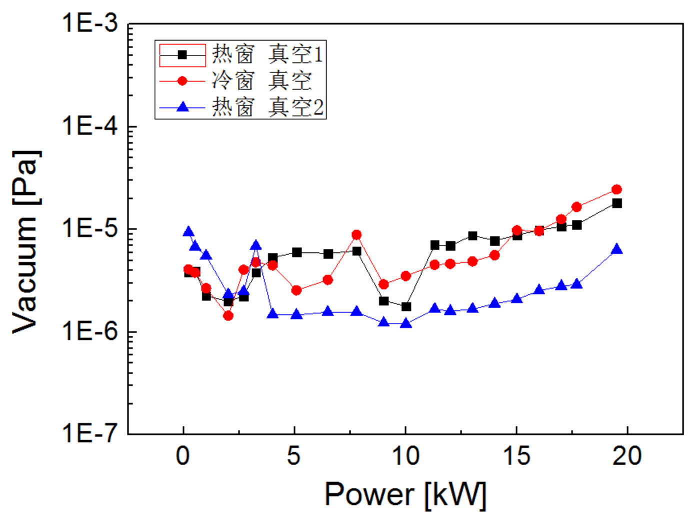
Fabrication





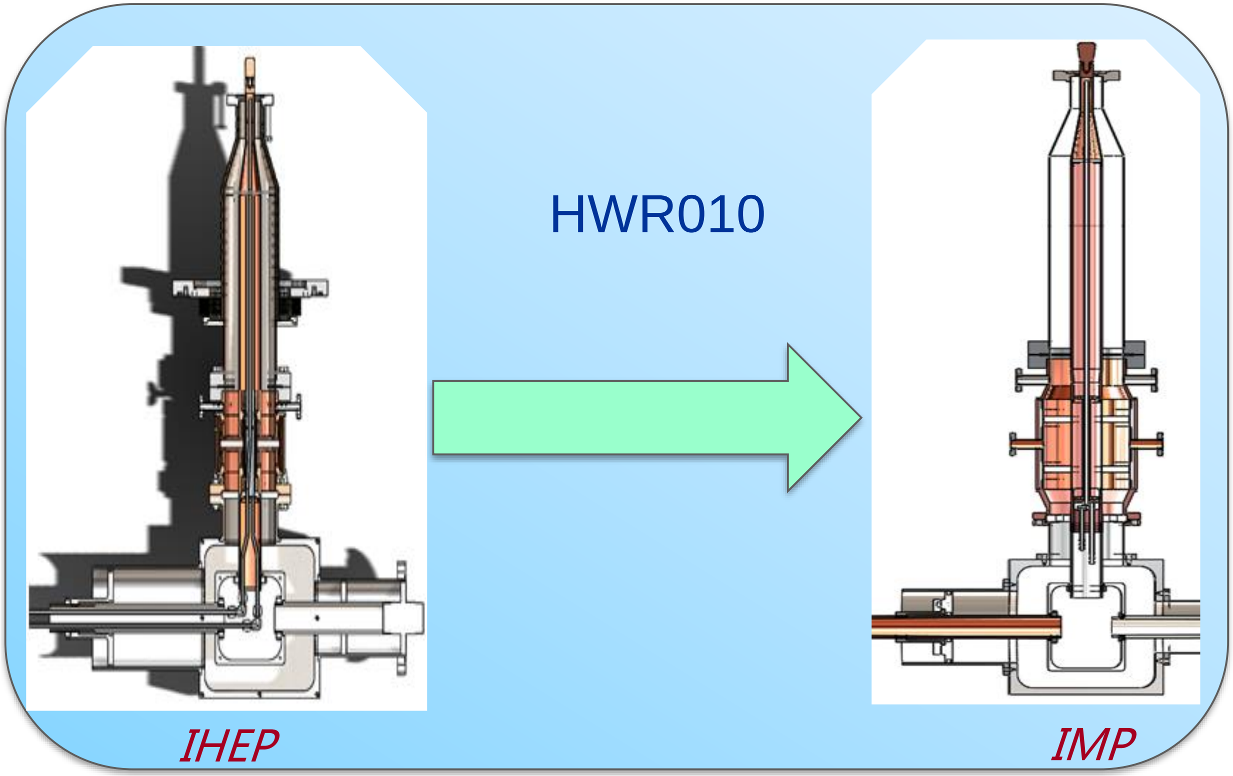
Test

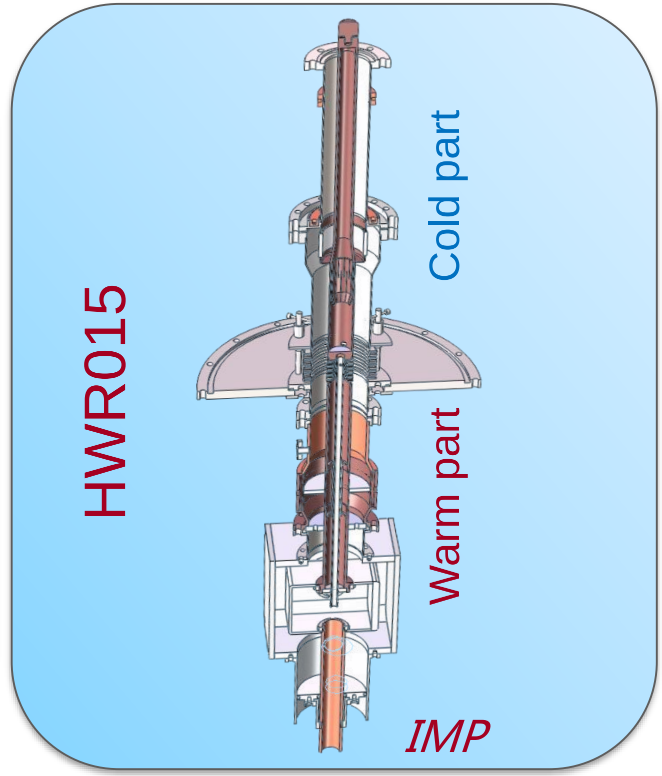




20 kW for both travelling and standing wave modes

Power Couplers at IMP

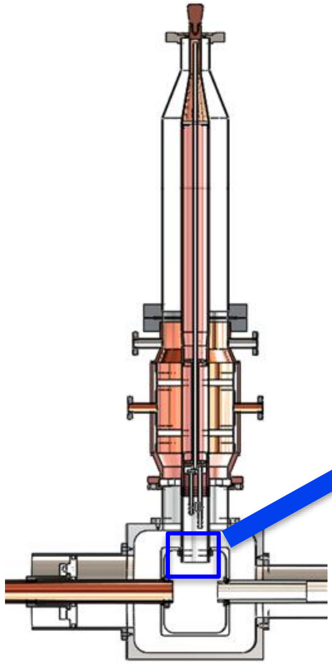




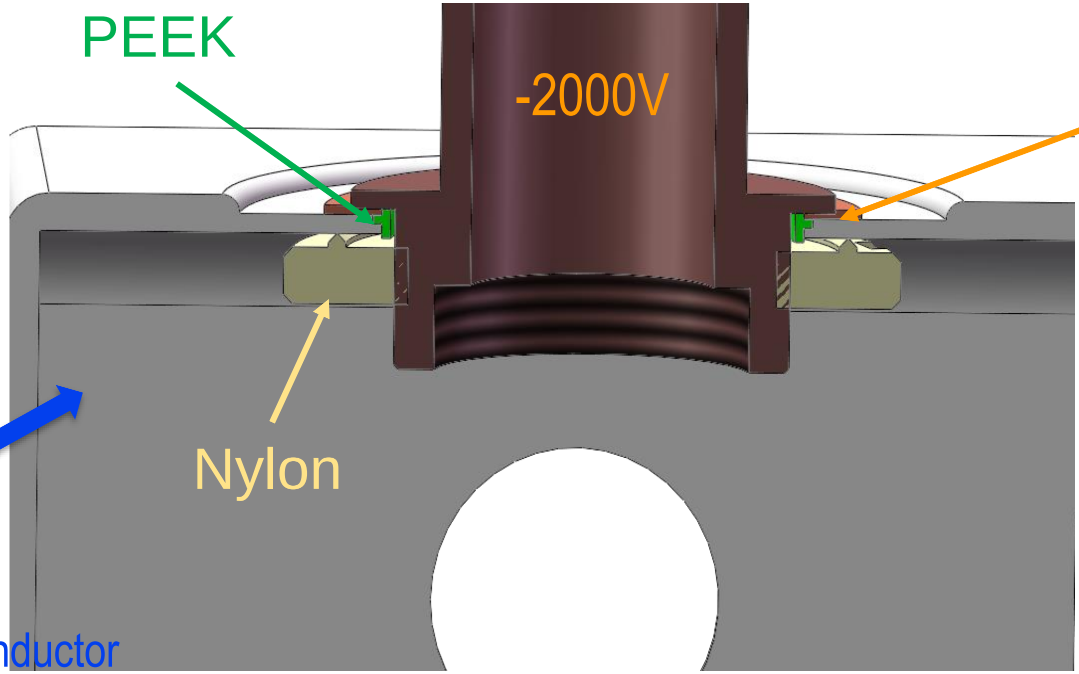
- 16 IHEP couplers passed the off-line test, 13 operate online, 5 leak
- 17 dual warm couplers passed the off-line test, 15 operate online, no leak
- 10 TTF III like couplers passed the off-line test, 10 operate online, no leak

No obvious degradation of characteristic over 1~3 years.

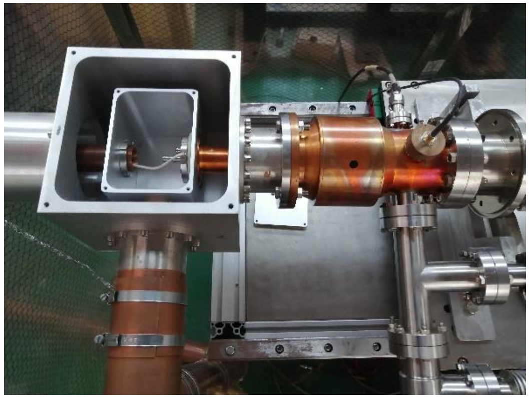
Bias Structure

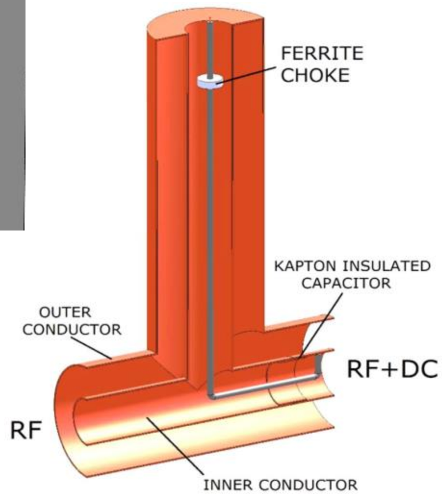


Bias for the inner conductor



Kapton film



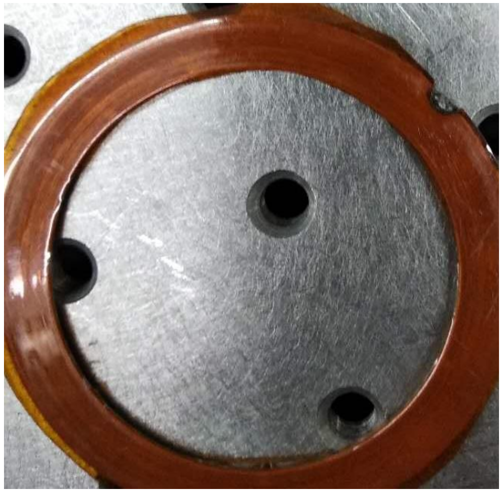


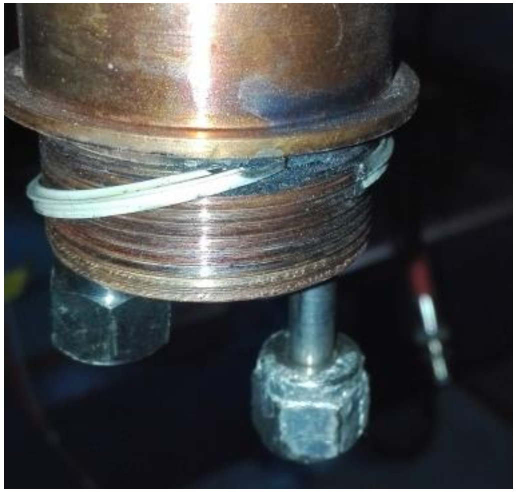
- T Transition with bias structure
- Bias T is dispensable
- Qe is adjustable with the short piston

(Ostroumov, Kazakov)

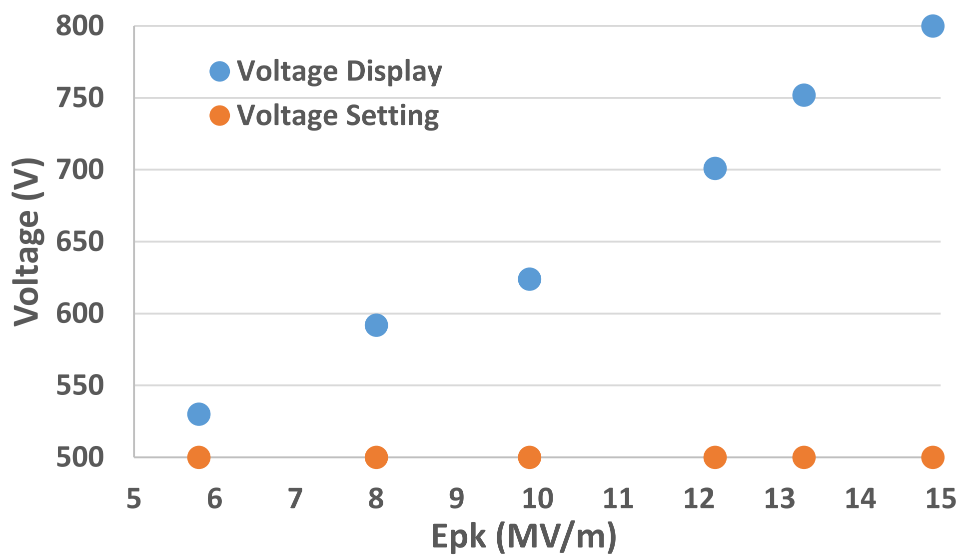
Bursting out of gas is avoided unless the bias unworked.

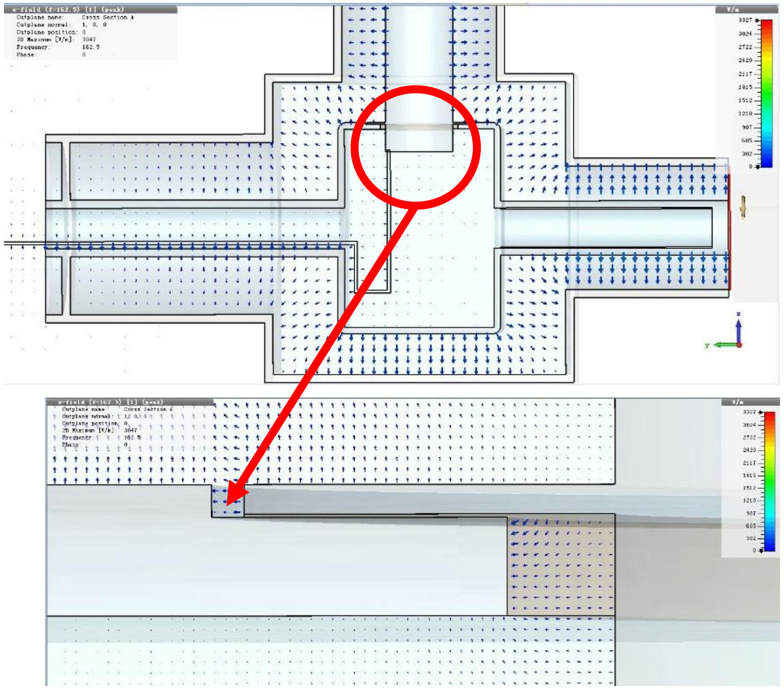
Burning

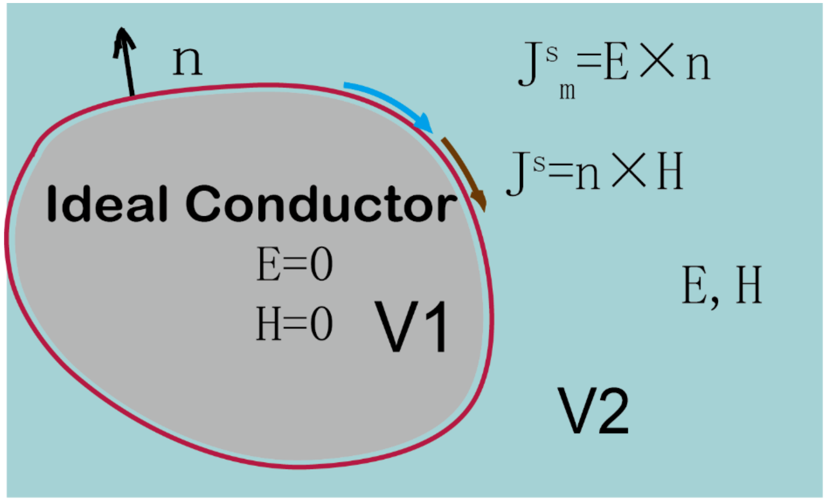




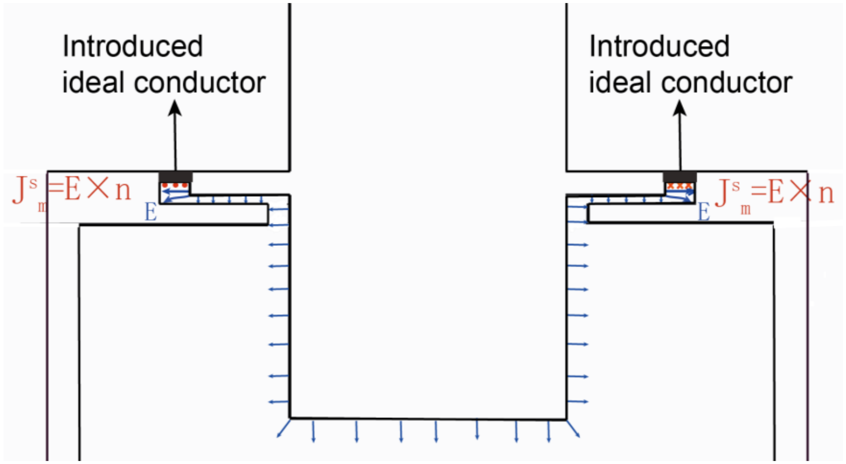
EMI on the DC Bias Power Supply







the principle of Schelkunoff



Bias Structure Improvement

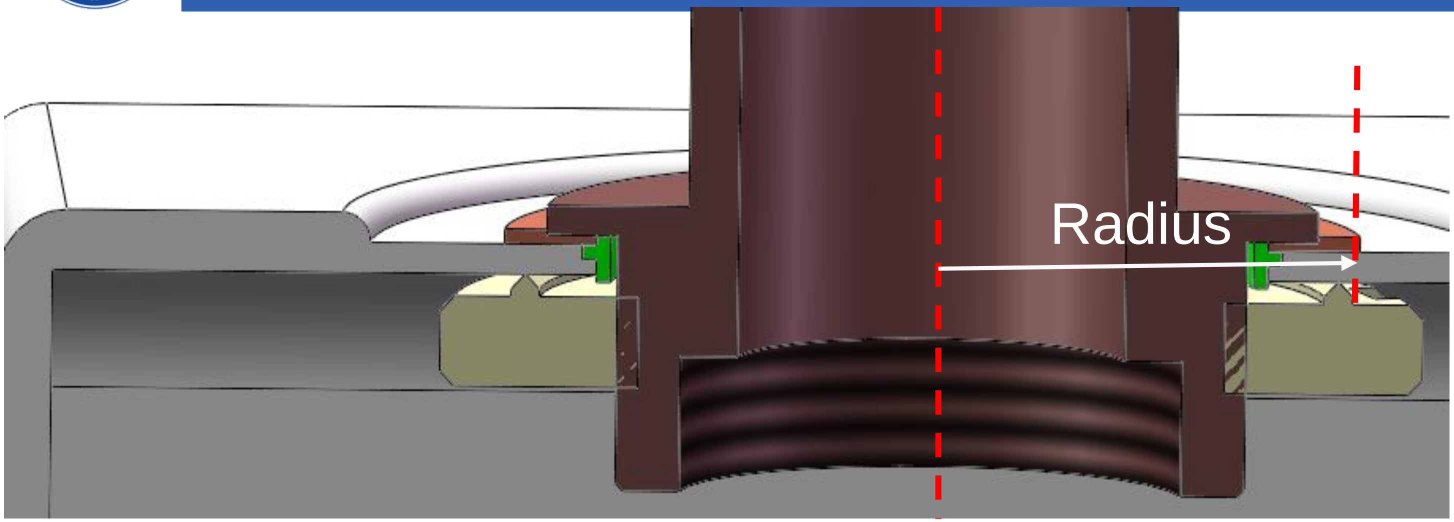
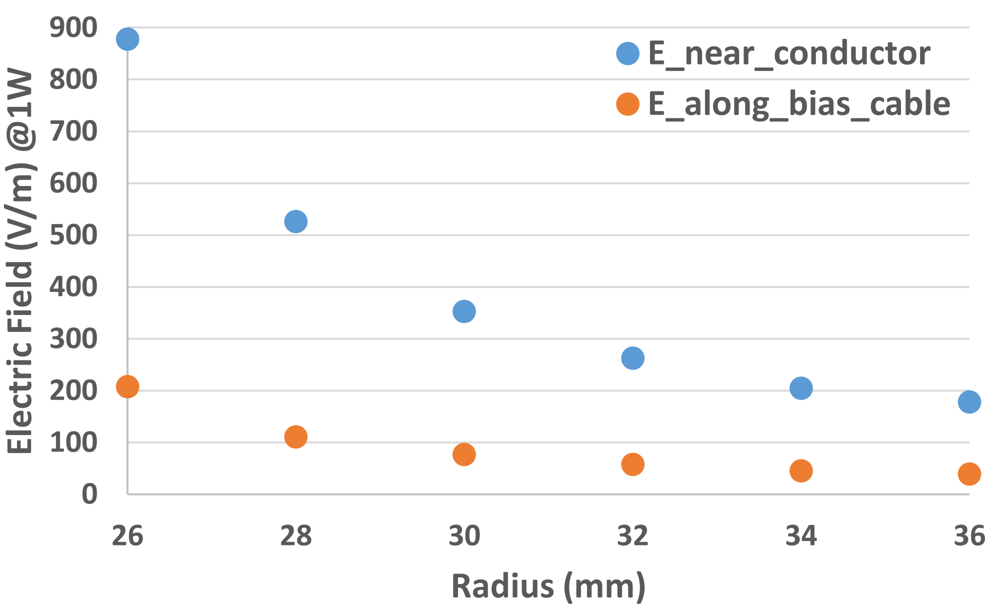
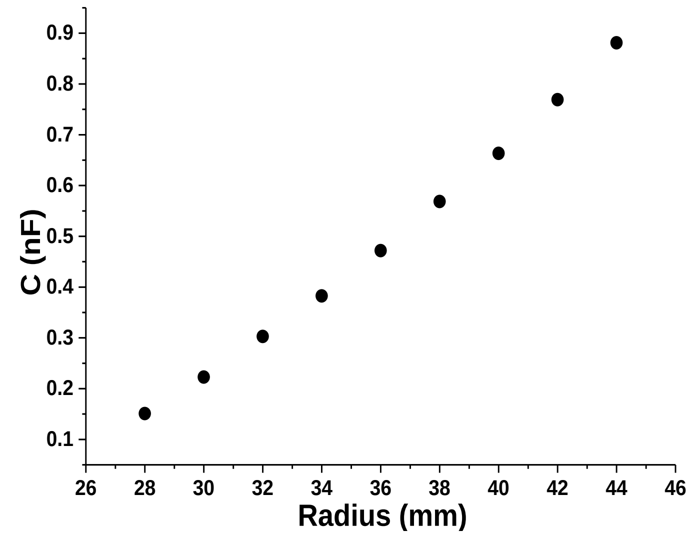


plate capacitor

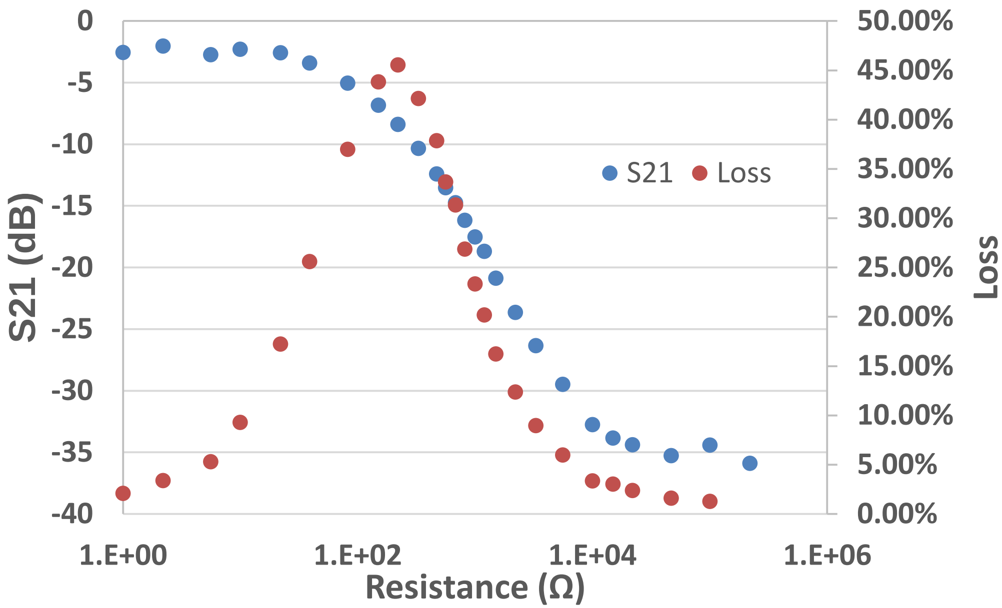
$$C = \frac{\varepsilon \varepsilon_0 S}{d}$$

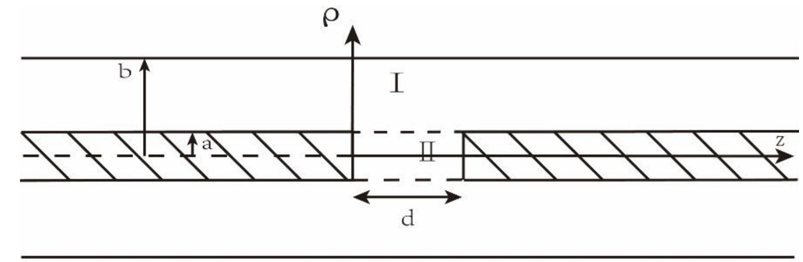


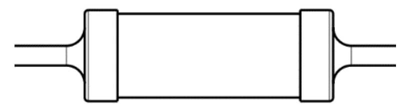


The leaking field can be reduced by increasing the capacitor.

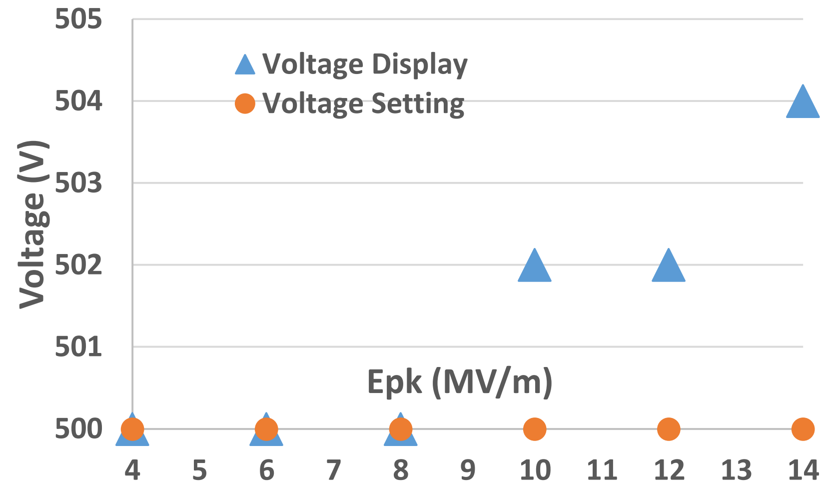
Bias Cable Improvement

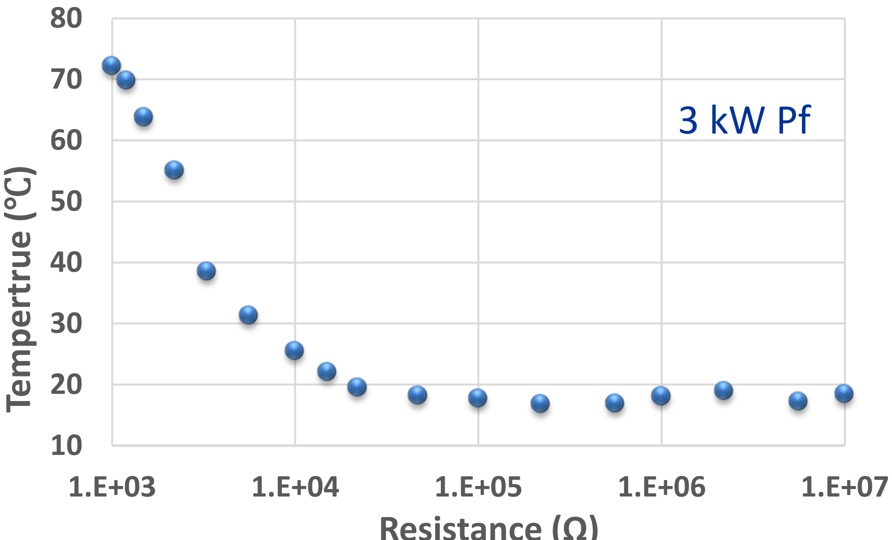






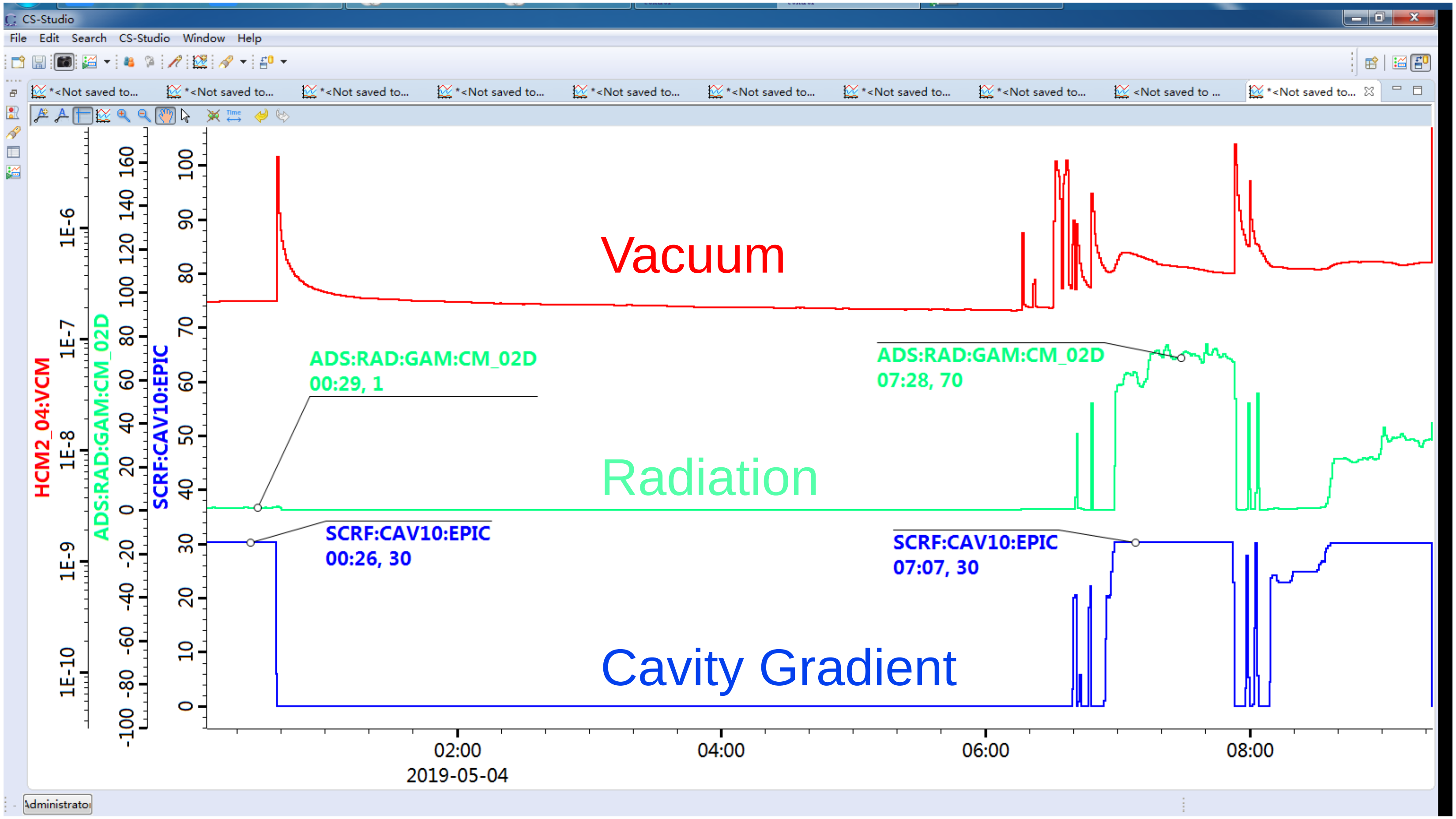
TE Connectivity
CFR25_Resistance





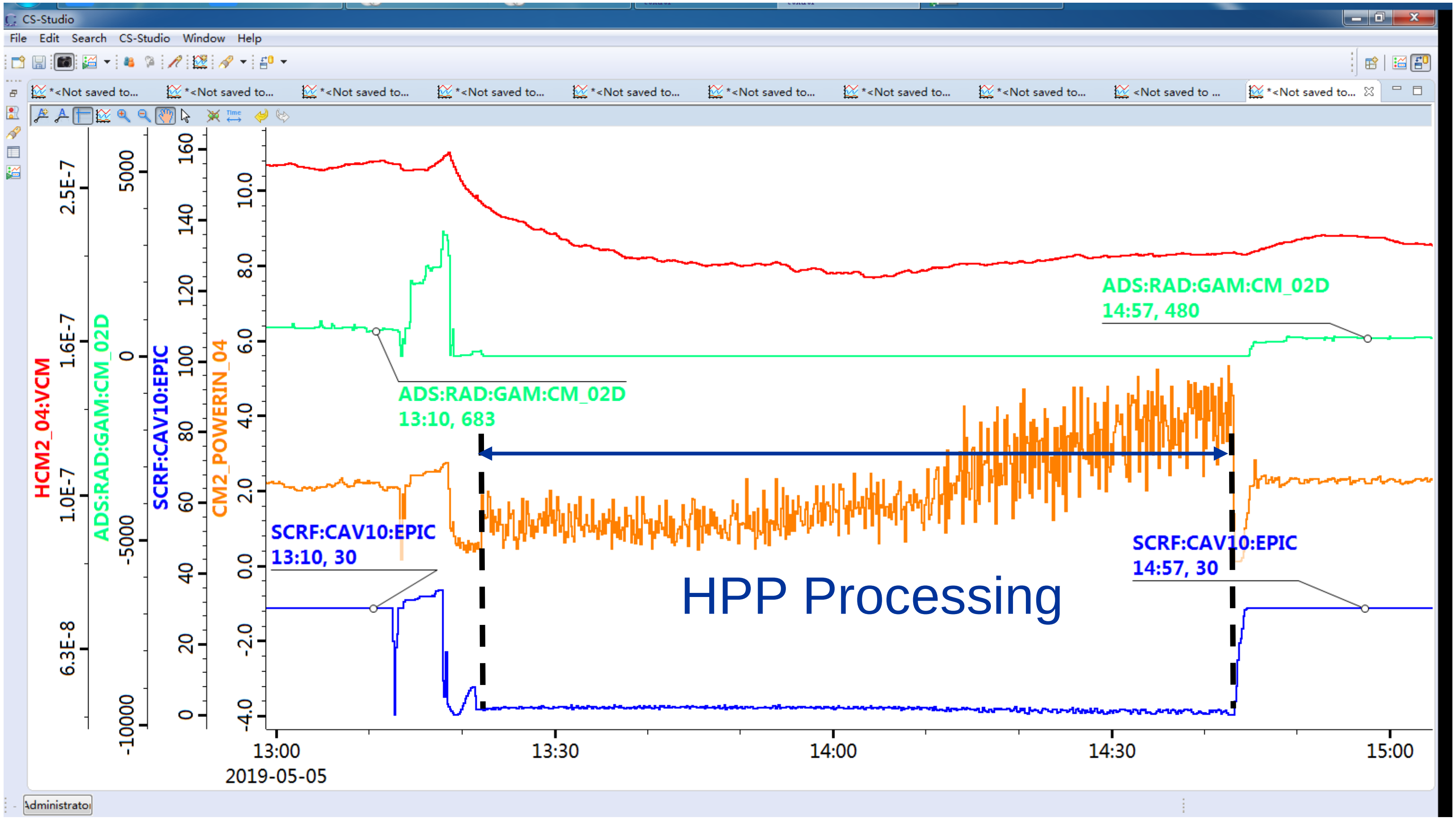
	CW Beam Commissioning Test Time (h)	Vacuum Interlock	ARC Interlock
2017	67.5	21	5
2018	125.9	4	1

Contamination



Gas desorption from coupler might be a field emitter of the SC cavity.

HPP Processing

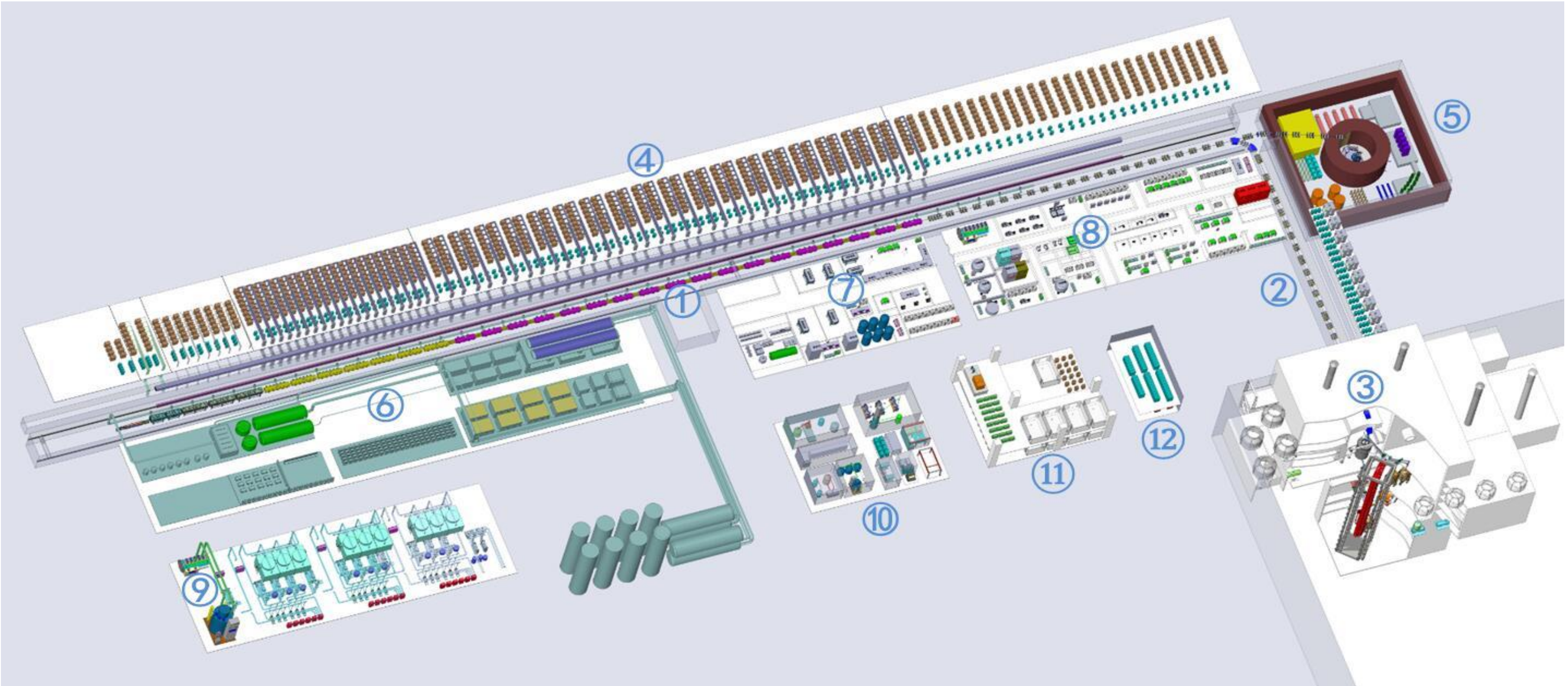


$$E_p(t_{RF}) = E_{EQM}(1 - e^{\frac{t_{RF}}{2\tau}}) = k_e \frac{2\beta}{1+\beta}\sqrt{P_{\mathrm{RF}}\frac{Q_{ext}}{\omega}}(1 - e^{\frac{t_{RF}}{2\tau}})$$

Pulse length ~ τ

High power short pulse processing is effective.

CiADS



Overall Arrangement of CiADS

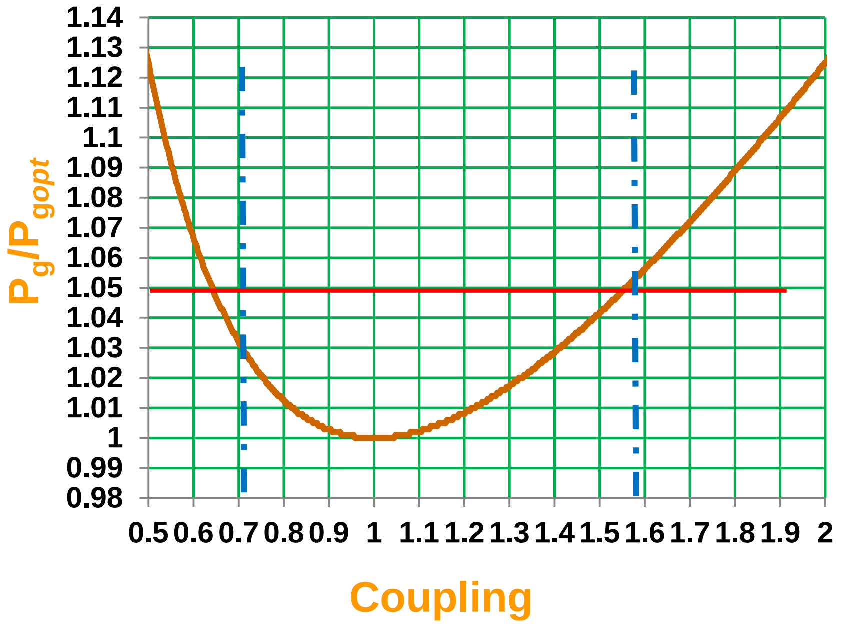
Cavity	HWR010 162.5 MHz	HWR019 162.5 MHz	Spoke042 325 MHz	Ellip062 650 MHz	Ellip082 650 MHz	Total
Quantity	9	24	40	40	24	**137**

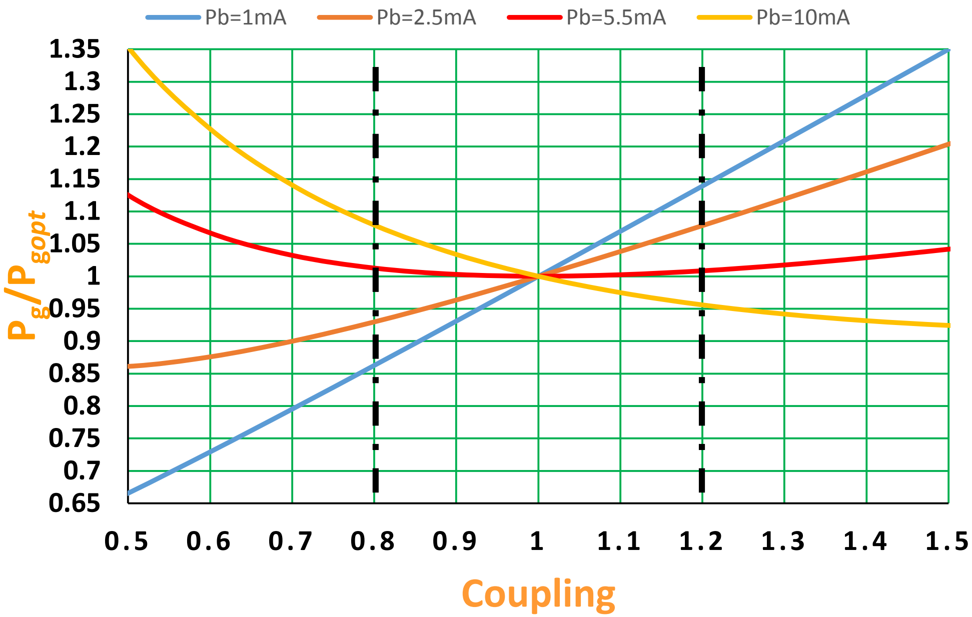
Power coupler requirements

*CiADS	162.5	325	650
Maximum Beam Current, mA	10	10	10
Maximum Operation Power (CW, any reflection), kW @10mA	28	48	130
Acceptance Testing Power (CW, any reflection), kW	40	60	160
Operating $Q_L(10^6)$ @5.5 mA	1.12/1.22	2.12	4.96/5.19
β uncertainty, %	±20	±20	±20
2K Heat Load (TW 28/48/130 kW), W	< 0.5	< 0.8	< 1.5
5K Heat Load (TW 28/48/130 kW), W	< 3	< 5	< 6
80K Heat Load (TW 28/48/130 kW), W	< 10	< 12	< 30

*CiADS : 1 mA → 2.5 mA → 5 mA → 10 mA

Upgrade Consideration





$0.64 \le \beta \le 1.56$

$\beta \approx 1.6$

Beam Current is 2.4 time(1.56/0.64 = 2.4)

5% additional power

CiADS Phase I:

Qe → 5.5mA

Fixed coupling, coupling error±20%

Constraints to RF coupler for CiADS

❑Clean constraint. Couplers have to allow make assembling accelerating cavities with coupler in clean room and to be installed in cryomodules then.

- The main limit of performance is field emission

❑Couplers should not increase noticeably the heat load of cavity.

HWR010	2.77W		(2742W, cryo-plant)
HWR019	4.43W		(4386W, cryo-plant)
DSR042	11.44W	@2K	(11326W, cryo-plant)
MB062	15.92W		(15761W, cryo-plant)
HB082	16.73W		(16563W, cryo-plant)

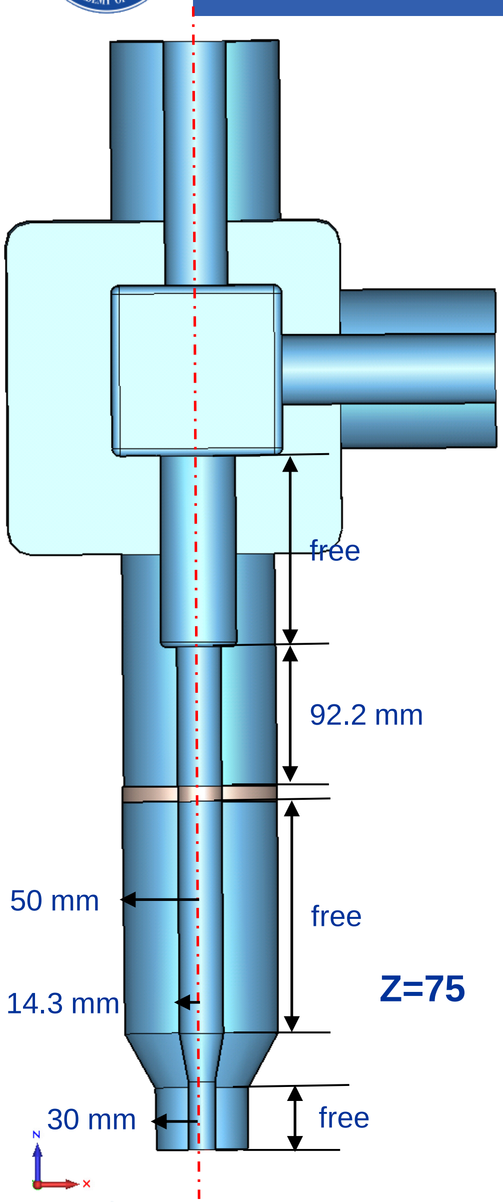
❑Cooling of the couplers has to be air-type.

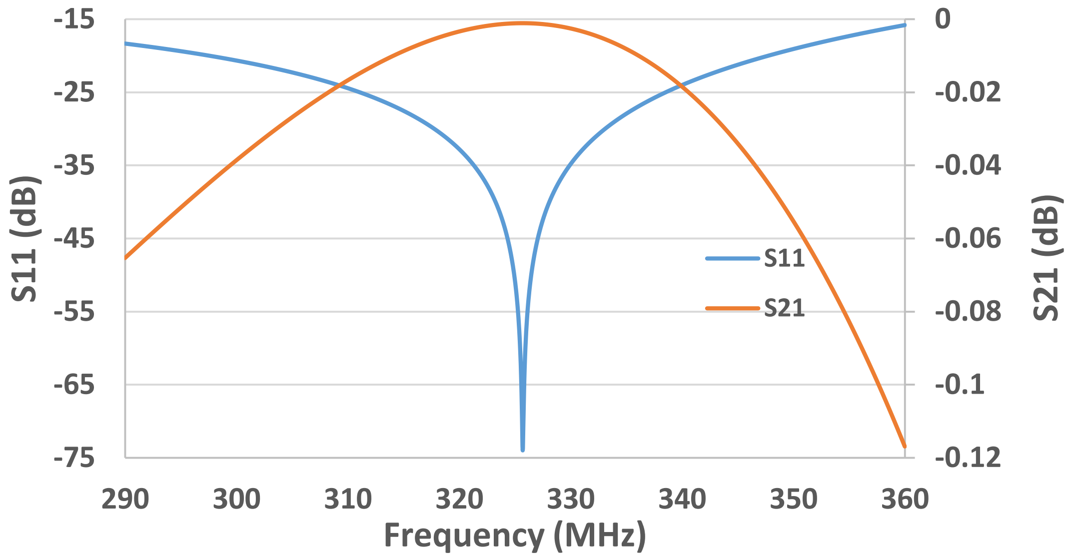
- Air cooling is preferred (mandatory when possible) to water cooling in order to ease vacuum leak detection in case of failure

❑Having the possibility to apply HV DC biasing.

- DC biasing is an effective method to suppress multipacting.

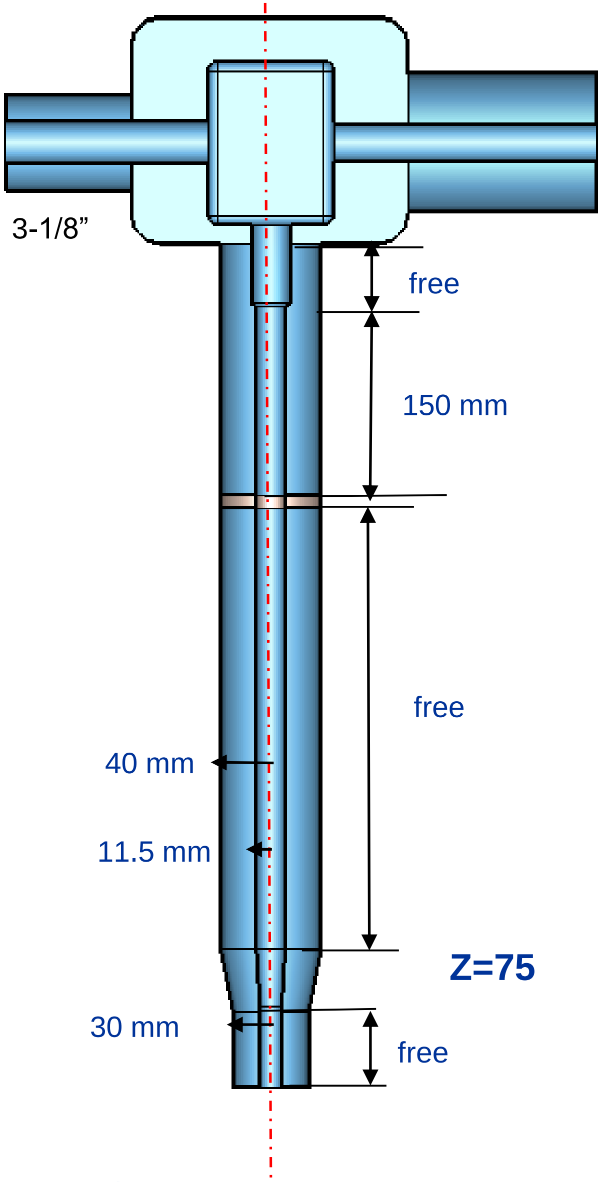
RF Design—325MHz

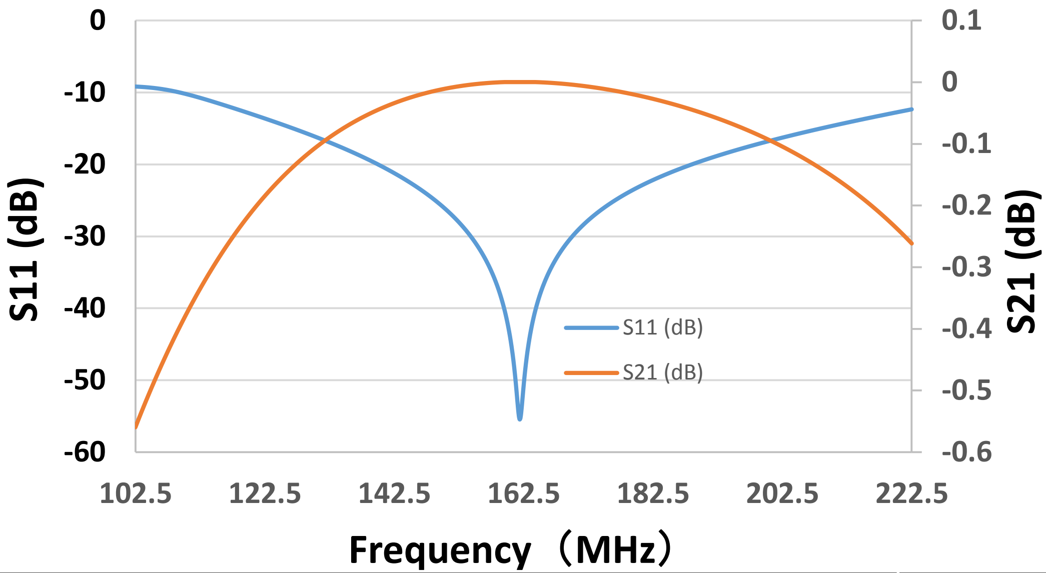




Parameters	Value
Operation Frequency	325 MHz
Bandwith (S11 < -20 dB)	50 MHz
Maximum Power	60 kW
Maximum Electric Field in Air (60 kW, TW)	2.6 kV/cm
Allowed maximum Pulse Power (TW, 20 kV/cm)	3.3 MW
Average Power Density of Ceramic (60 kW, TW)	0.83 kW/cm^2
Maximum Power Density of Ceramic (60 kW, TW)	3.69 kW/cm^2

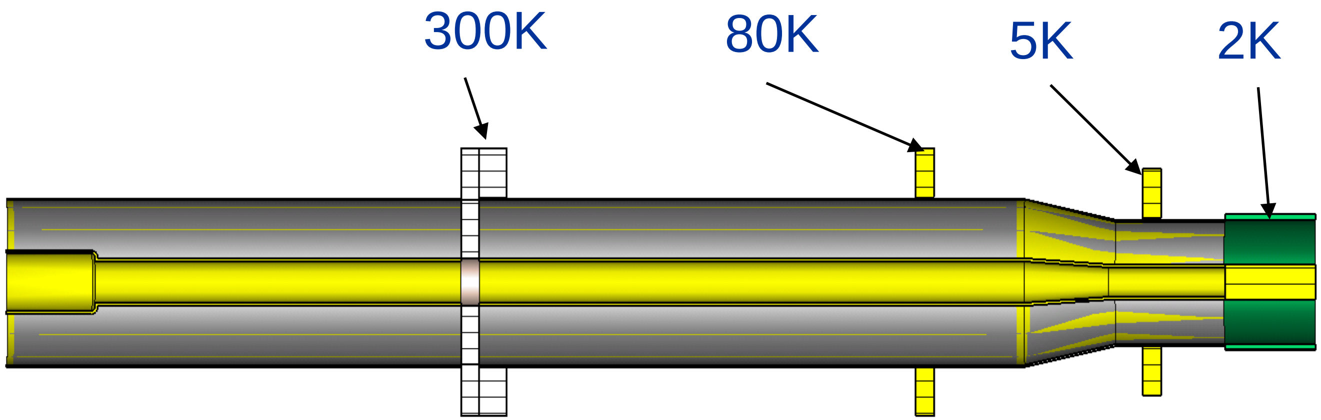
RF Design—162.5MHz





Parameters	
Operation Frequency	162.5 MHz
Bandwith (S11 < -20 dB)	48 MHz
Maximum Power	40 kW
Maximum Electric Field in Air (40 kW, TW)	2.7 kV/cm
Allowed maximum Pulse Power (TW, 20 kV/cm)	2.1 MW
Average Power Density of Ceramic (40 kW, TW)	0.86 kW/cm^2
Maximum Power Density of Ceramic (40 kW, TW)	3.91 kW/cm^2

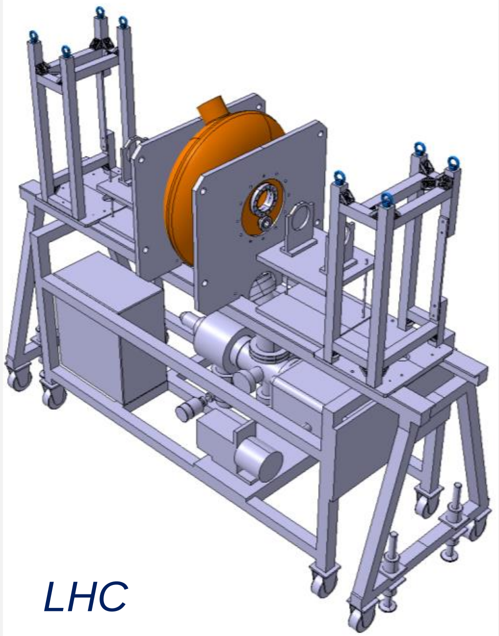
Thermal

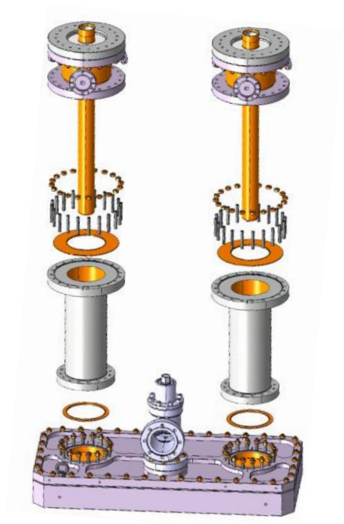


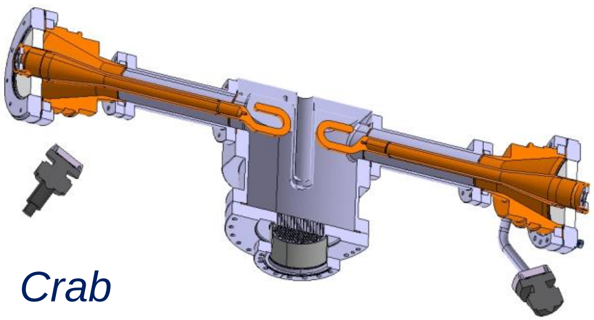
162.5 MHz	2K (Flow/Plant),W	5K(Flow/Plant), W	80K(Flow/Plant), W	Total plant, W	
RF = 0kW	0.05/49.5	0.56/117.6	5.99/95.8	262.9	Static
RF = 7kW	0.11/108.9	0.98/205.8	6.62/105.9	420.6	2.5mA
RF = 12kW	0.15/148.5	1.30/273.0	7.10/113.6	535.1	5mA
RF=28kW	0.28/277.2	2.28/478.8	8.54/136.6	892.6	10mA

325 MHz	2K (Flow/Plant),W	5K(Flow/Plant), W	80K(Flow/Plant), W	Total plant, W	
RF = 0kW	0.06/59.4	0.58/121.8	6.02/96.3	277.5	Static
RF = 15kW	0.27/267.3	1.73/363.3	7.69/123.0	753.6	2.5mA
RF = 23kW	0.37/366.3	2.36/495.6	8.59/137.4	935.3	5 mA
RF = 48kW	0.72/712.8	4.29/900.9	11.35/181.6	1795.3	10 mA

RF Conditioning at Test Stand


LHC

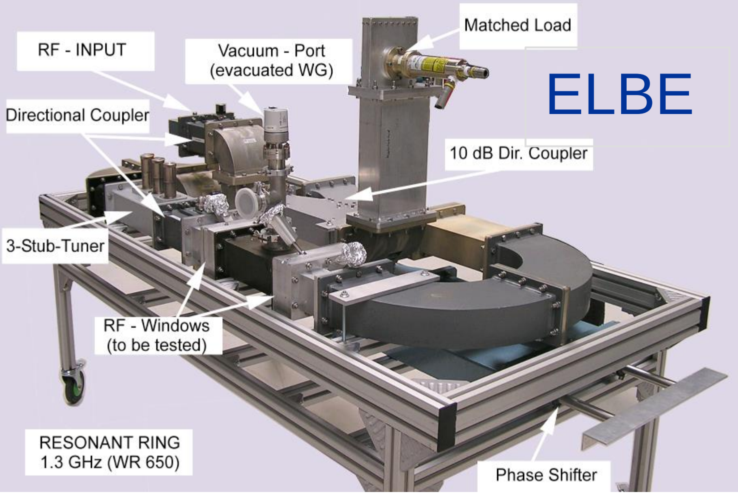

HG

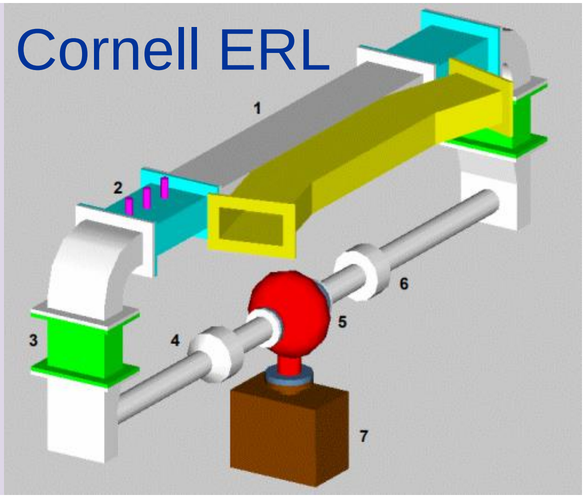

Crab

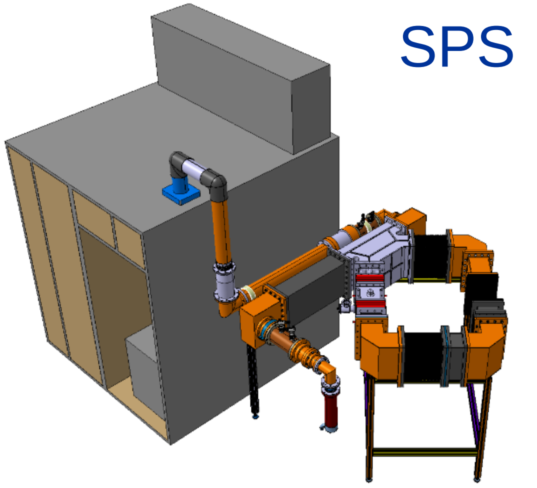
- ➢ Controlled desorption of absorbed gases by accelerated ions and electrons from the RF surfaces
- ➢ TW, no power gain, field and MP is homogeneous, cleaning the entire RF surfaces
- ➢ SW, power gain is 4, field and MP is inhomogeneous, only the high field part is conditioned

- Different positions of reflection plane
- Using bias to increase MP area (KEK)

Resonant Ring

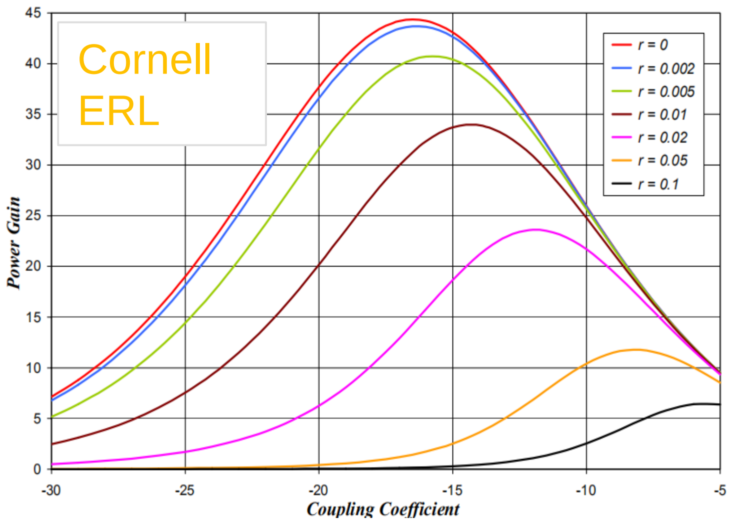




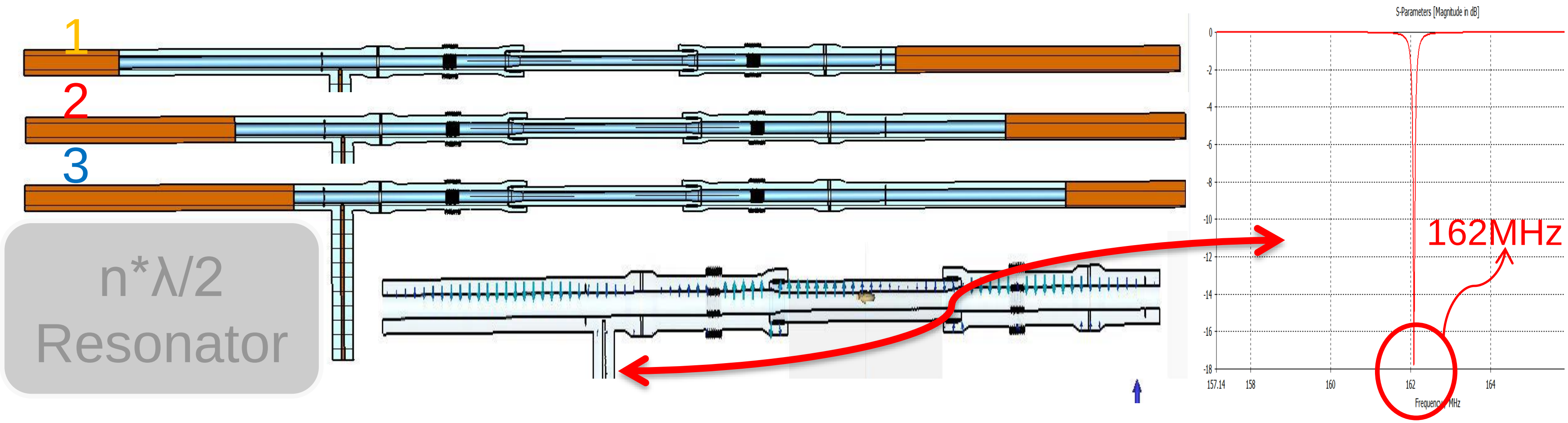


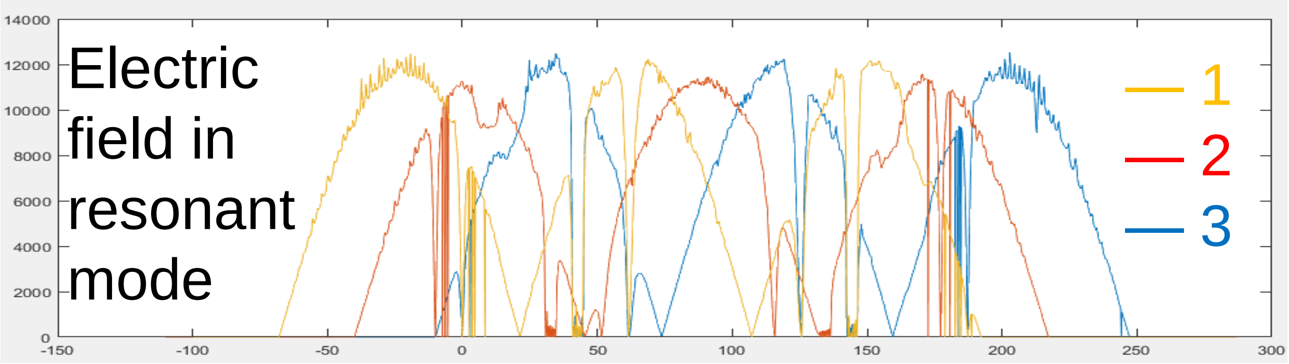
Power gain, field and MP is homogeneous.

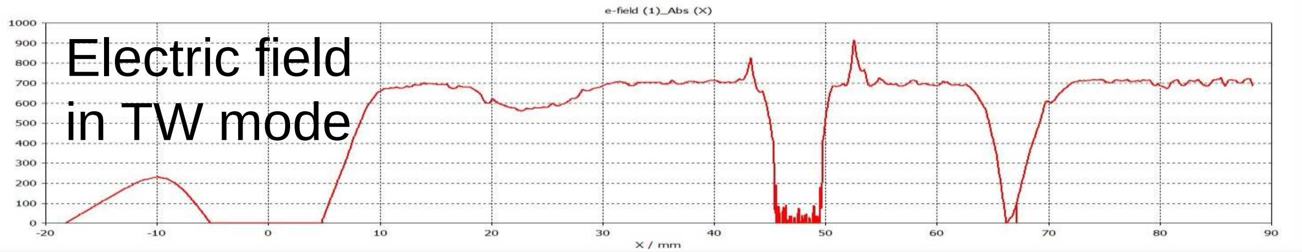
- Complexity, high price
- Gain is limited
- High sensitivity to high power, dependence of temperature



Resonant Conditioning



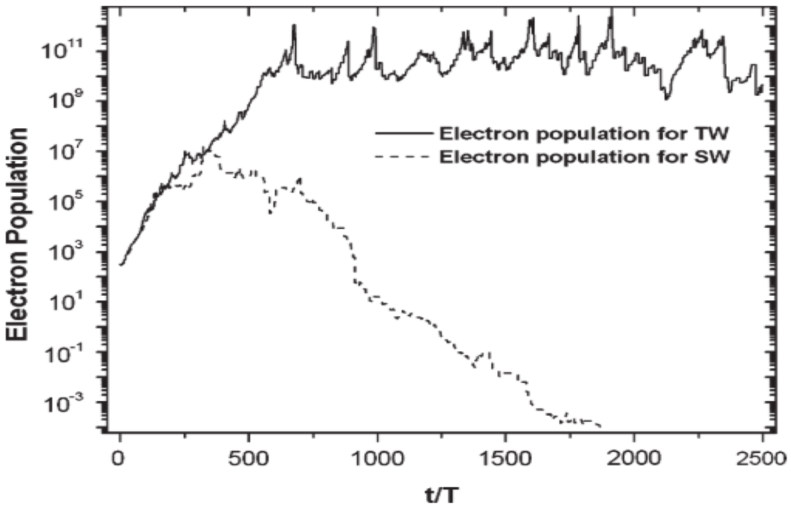


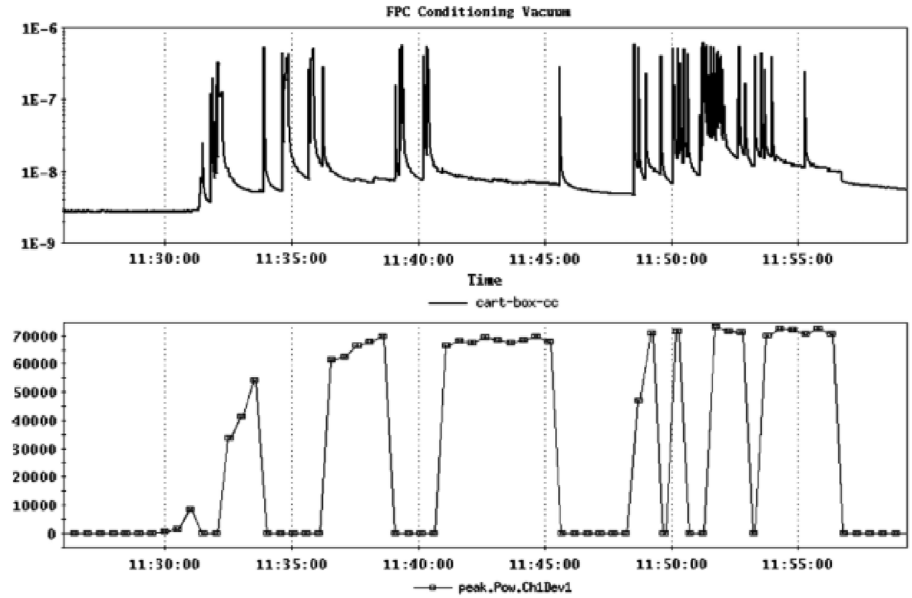


- High Power Gain, ~100
- Dummy Load is not required
- Cost reduction

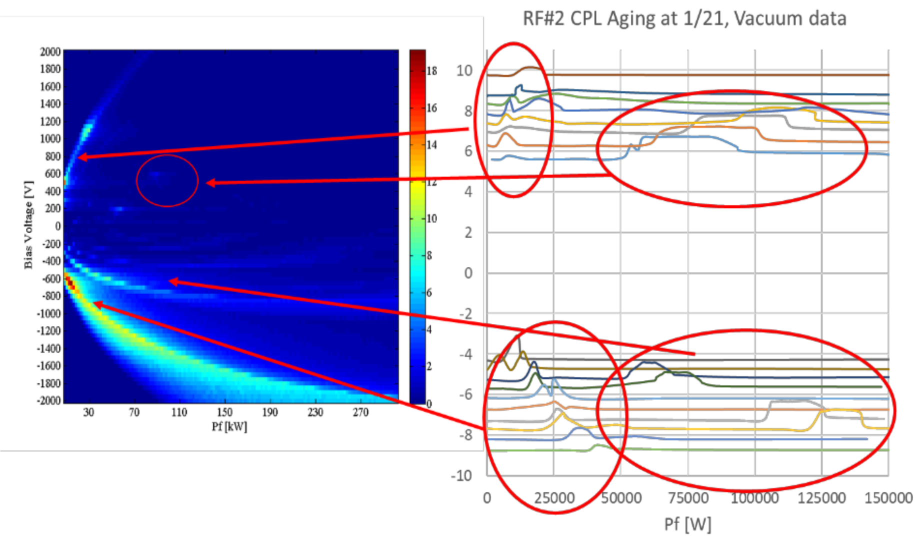
- MP is very complex in real world
- Ceramic may be the weakest link

Resonant Conditioning Expection



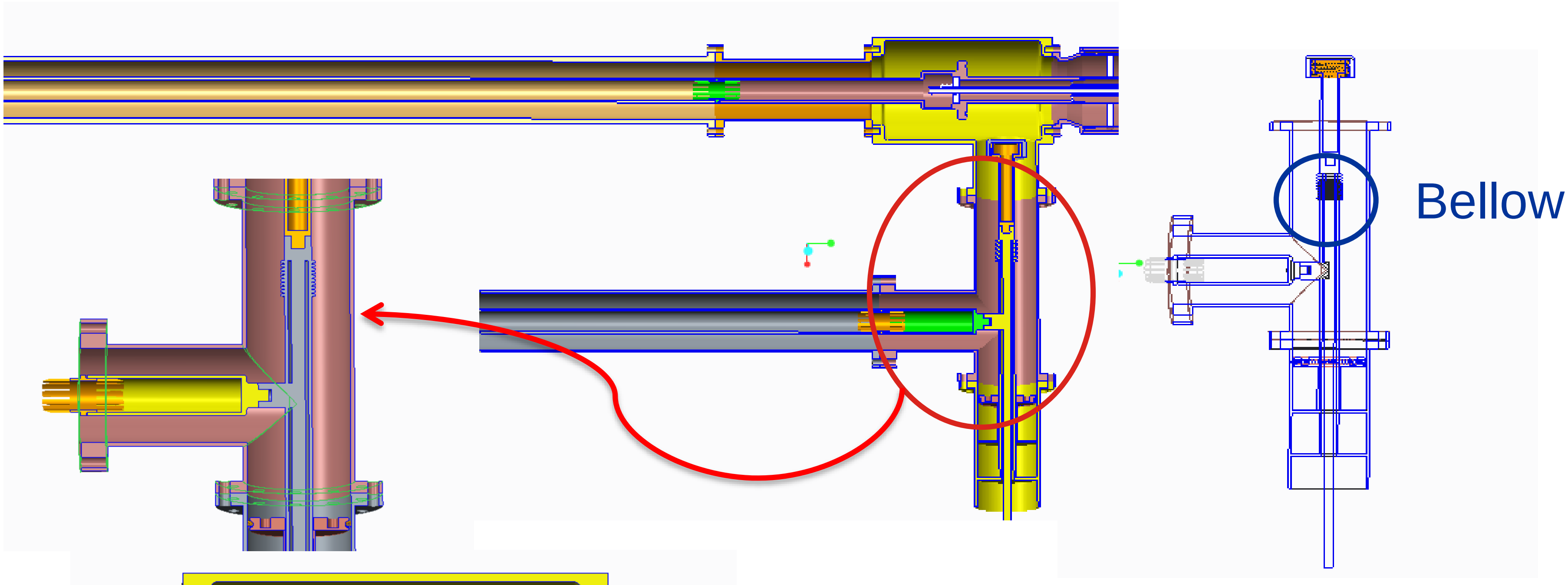


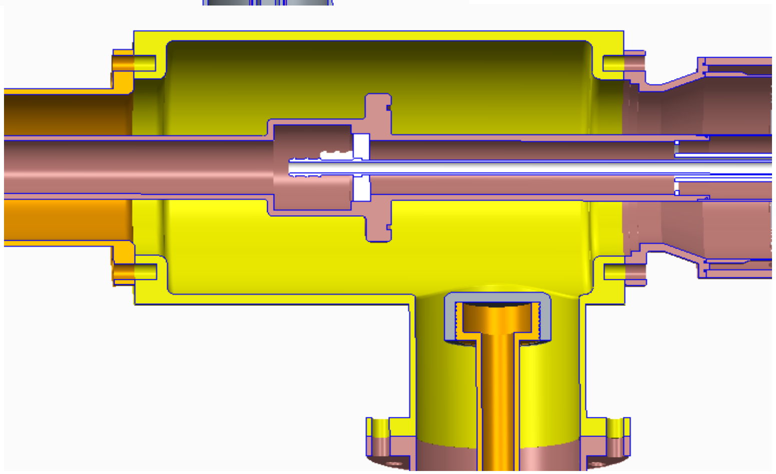
(a) MP processing from about 40 to 70 kW: top plot – vacuum in Torr; bottom plot – RF power in watt.



- ➢ Field distribution is similar to SW
- ➢ SW mode with phase shifter is efficient (BNL)
- ➢ DC biasing can be used to broad MP area

Resonant Structure





- Resonance can be easily achieved
- Atmospheric part can be replaced

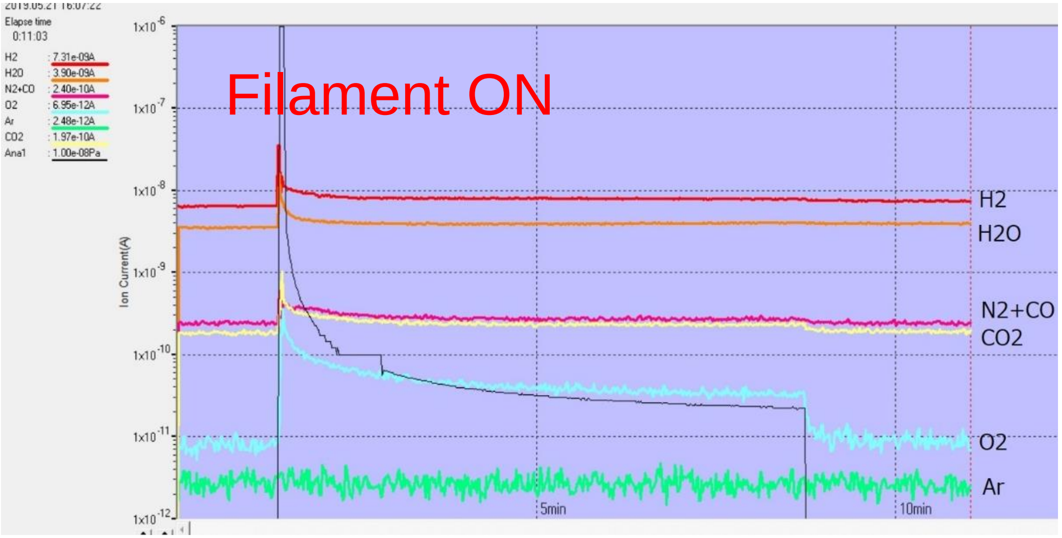
Vacuum Gauge

Cold Cathode Gauge

- Easily handling
- Low outgassing
- Universal interface, Ethernet

Hot Cathode Gauge

- High precision
- Small size
- High vacuum



Thanks for your attention