Development of HOM-damped 166.6MHz SRF cavities for HEPS in Beijing

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Outline

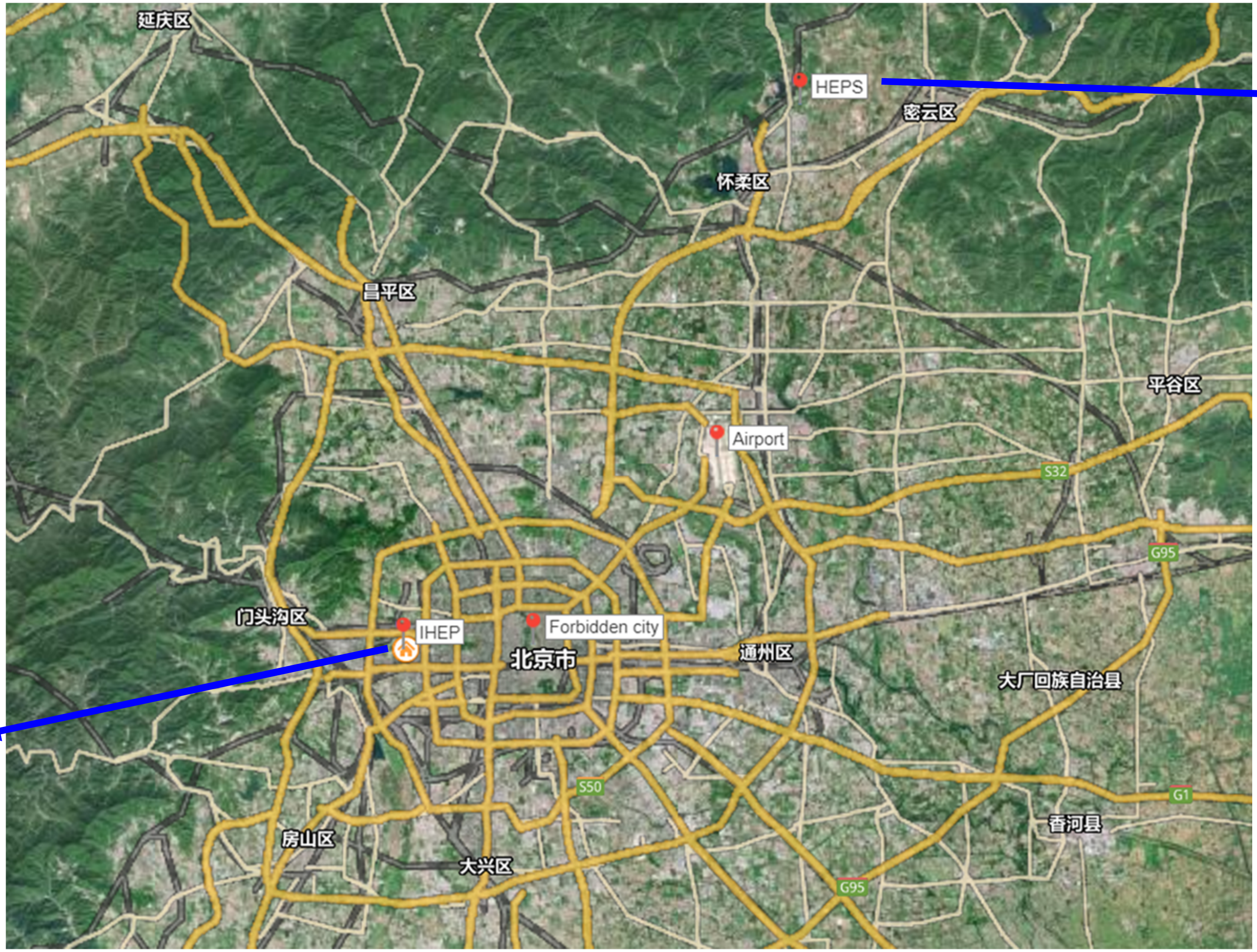
- Introduction to HEPS
- Introduction to HEPS RF system
- 166.6MHz proof-of-principle cavity
- 166.6MHz prototype cavity
- Summary

HEPS

HEPS in 6.5 years (2025)

High Energy Photon Source (**HEPS**)

Huairou scientific city



HEPS

IHEP

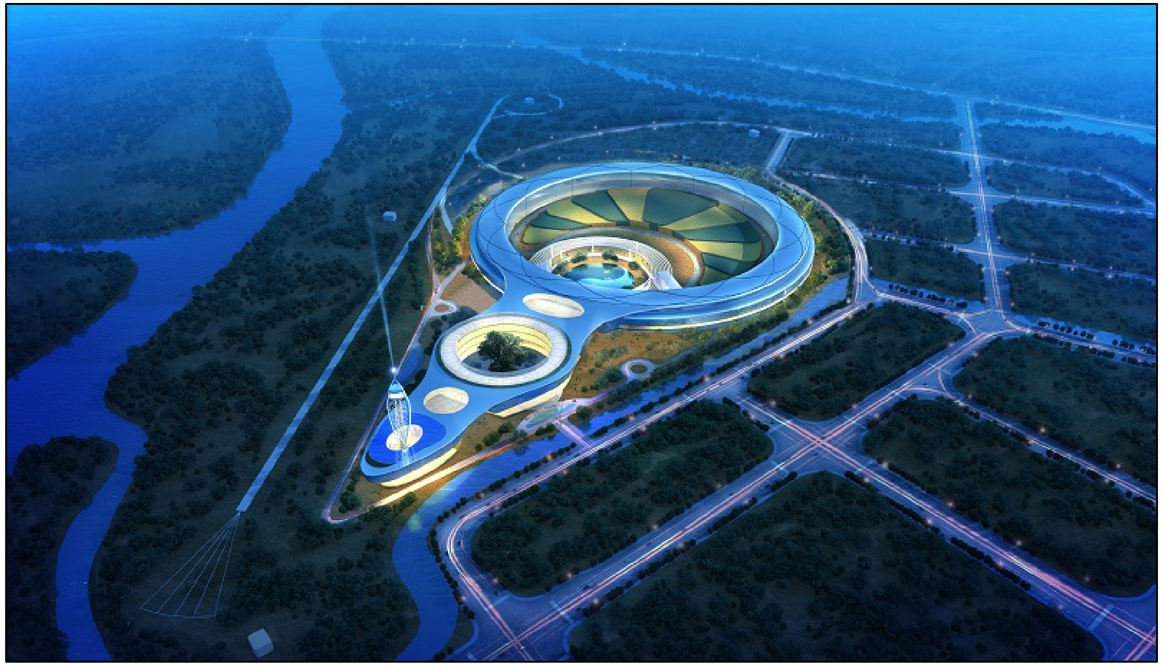
Huairou scientific city

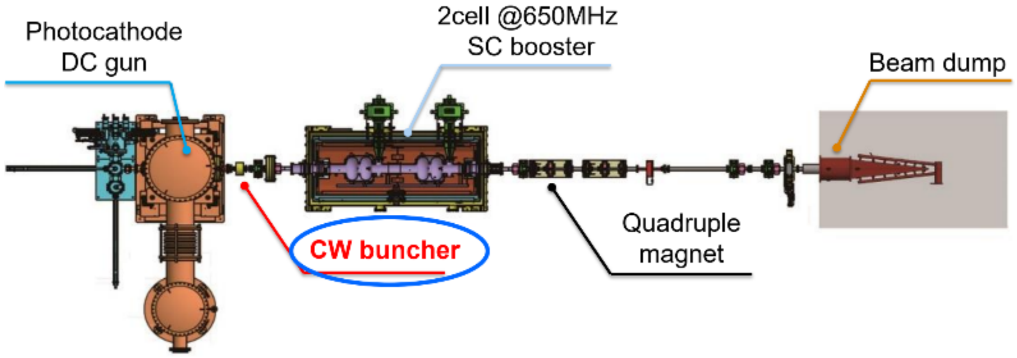
HEPS

IHEP

ERL conceived

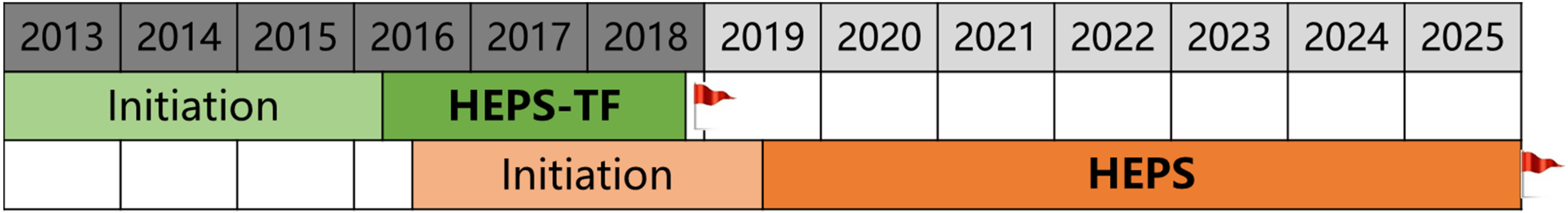
Place reserved for ERL light source





ERL test facility planned

HEPS schedule



- **HEPS test facility (HEPS-TF)**
  - R&D program from 2016 to 2018

- **HEPS project**
  - Ground breaking on 29.06.2019
  - Construction period: 6.5 years

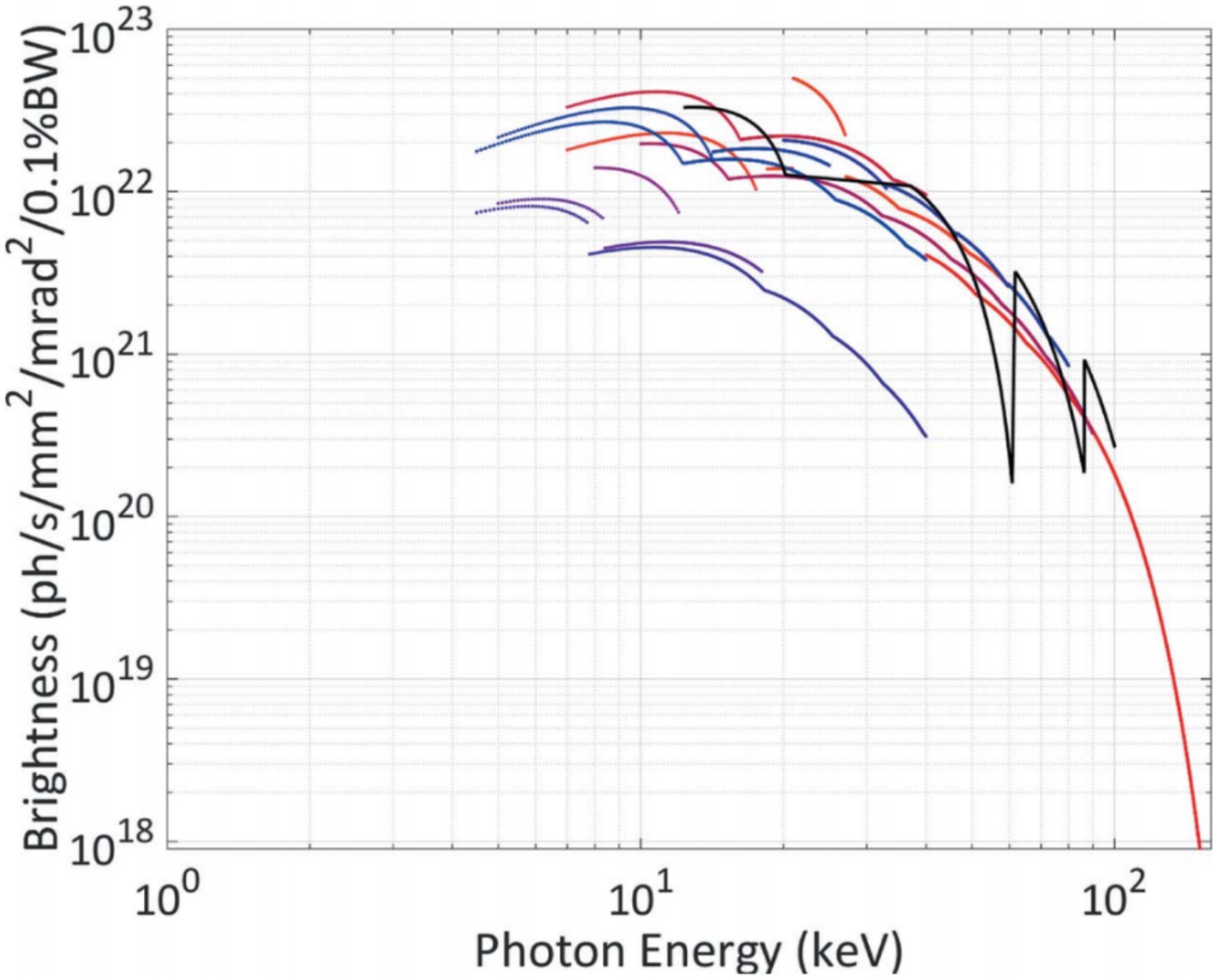
HEPS main parameters

Diffraction-limited light source

Parameter	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Natural emittance	< 60	pm·rad
Energy loss per turn	4.4	MeV
Beam power (w/ IDs)	900	kW

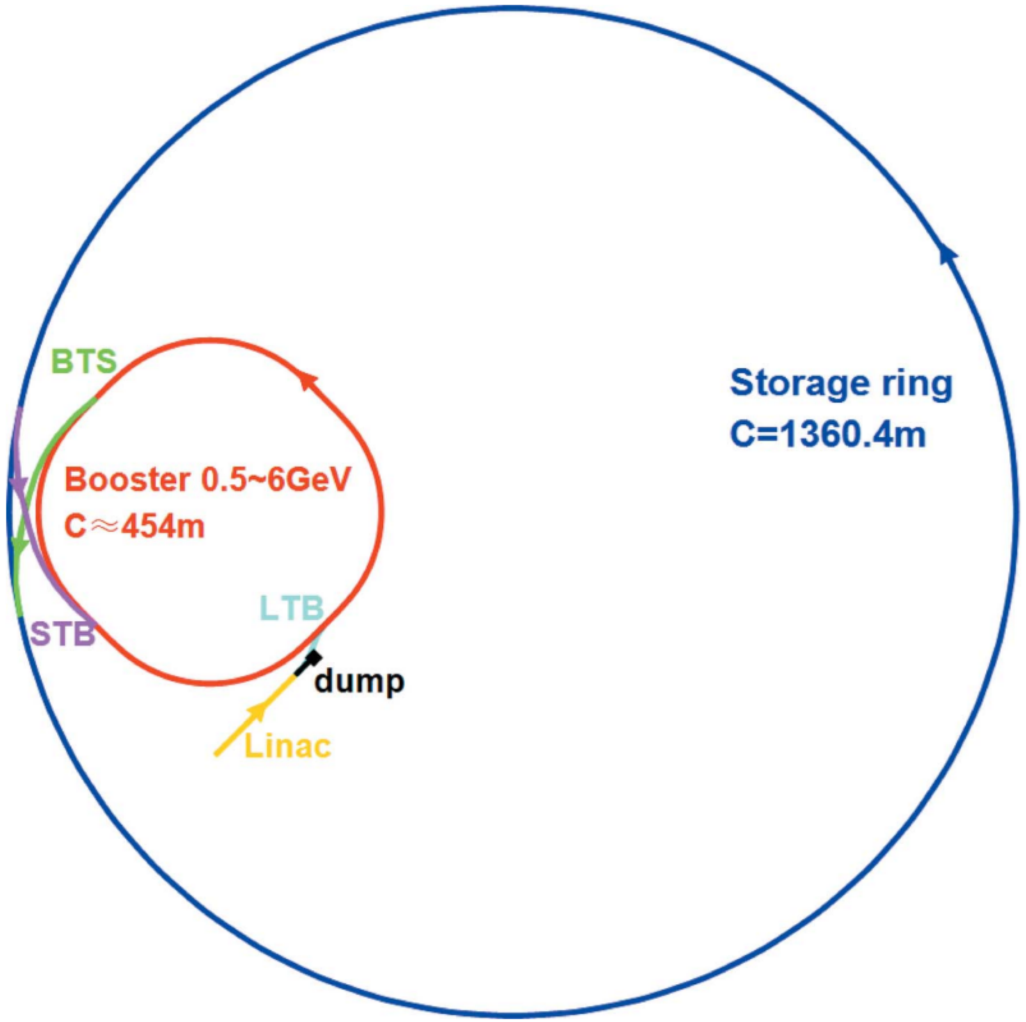
Y. Jiao *et al.*, *J. Synchrotron Rad.* **25** (2018) 1611.

HEPS main parameters



Y. Jiao *et al.*, *J. Synchrotron Rad.* **25** (2018) 1611.

Linac + Booster + Ring

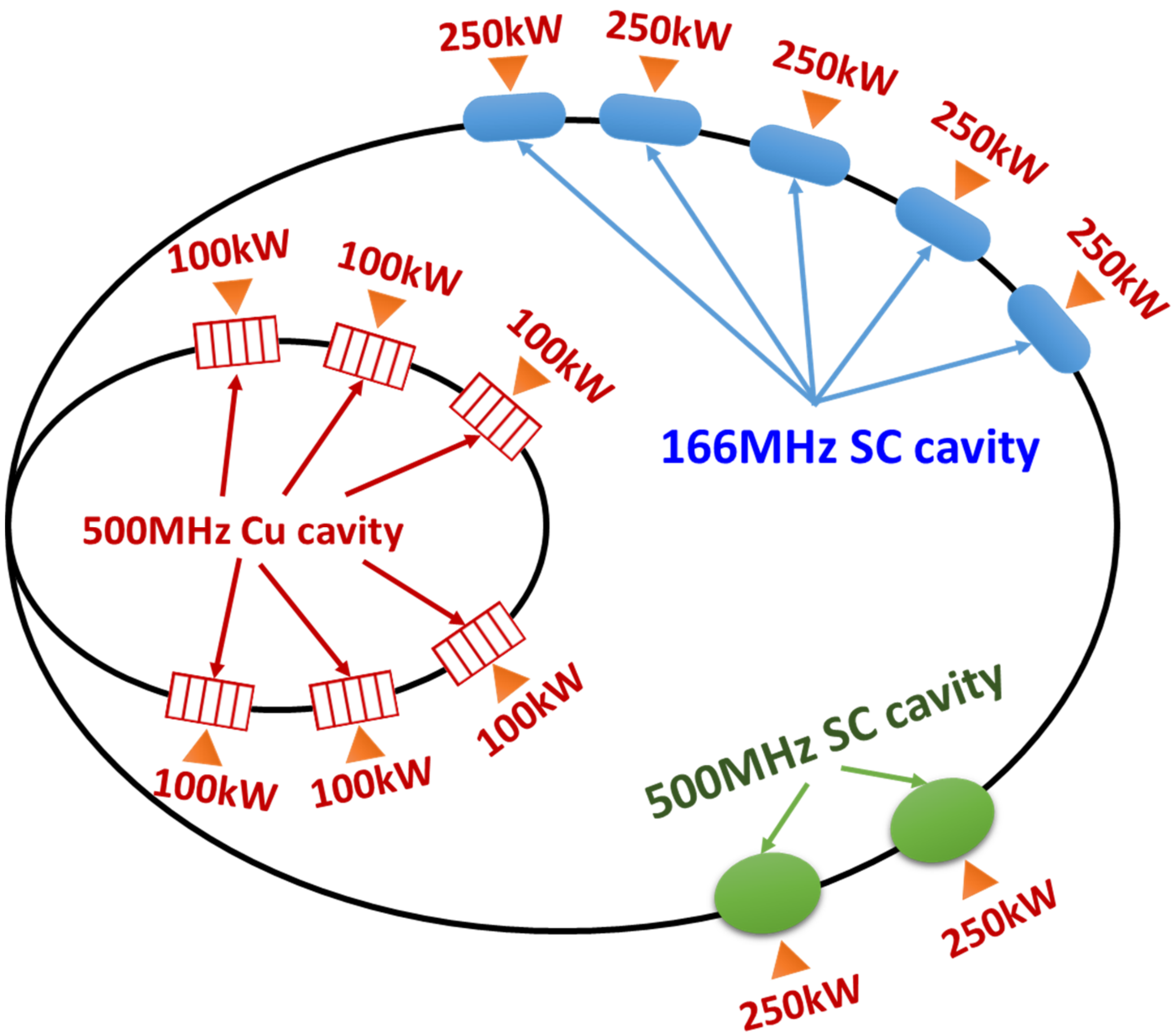


Y. Jiao *et al.*, *J. Synchrotron Rad.* **25** (2018) 1611.

Linac	
Output energy	500 MeV
Booster	
Beam energy (inj./ext.)	500MeV/6GeV
Beam current (ext.)	13 mA
Circumference	454.1 m
Storage ring	
Beam energy	6 GeV
Beam current	200 mA
Circumference	1360.4 m
Injection	Top-up (on-axis)

HEPS RF system

RF system



Main RF (Storage ring)

- RF frequency: 166.6 MHz
- Cavity voltage: 1.1 MV
- Min. power per cavity: 180 kW

Harmonic RF (Storage ring)

- RF frequency: 499.8 MHz
- Cavity voltage: 1.7 MV
- Min. power per cavity: 200 kW

Booster RF

- RF frequency: 499.8 MHz
- Total RF voltage: ≥8 MV
- Min. power per cavity: 80 kW

Frequency choice

Main RF frequency: 166.6MHz

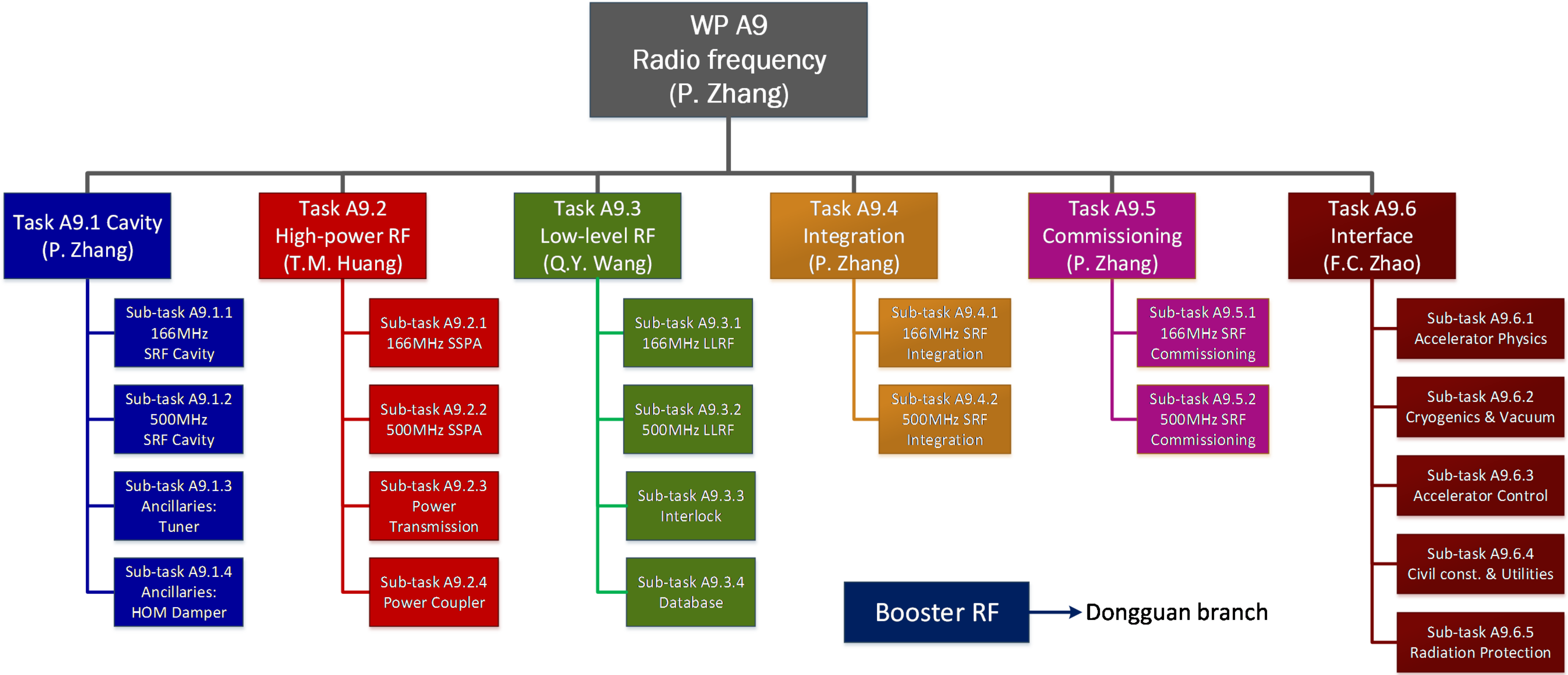
- Driven by physics design (on-axis accumulation injection scheme)
- A compromise between kicker and RF technologies
- Technology readiness (500MHz SRF, 500MHz NCRF)

[1] G. Xu *et al.*, "On-axis Beam Accumulation Enabled by Phase Adjustment of a Double-frequency RF System for …", IPAC2016, WEOAA02.
[2] D. Zhe et al., "Top-up injection schemes for HEPS", eeFACT2016, TUT2H4.
[2] S.C. Jiang and G. Xu, "On-axis injection scheme based on a triple-frequency rf system for …", *Phys. Rev. Accel. Beams* **21** (110701) 2018.

RF parameters

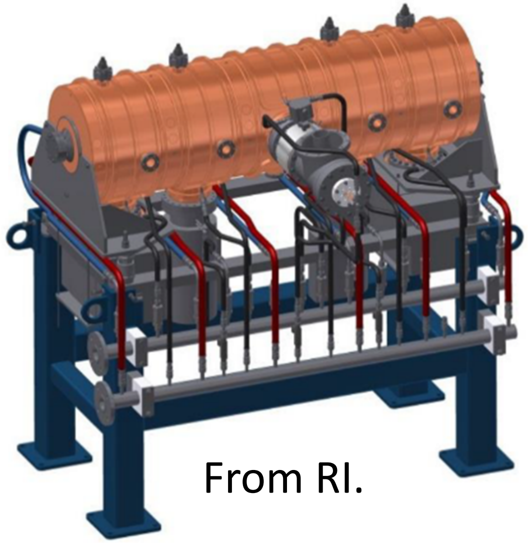
	Booster	Storage ring	
Beam energy [GeV]	0.5-6	6	
Beam current [mA]	11-13	200	
Energy loss/turn [MeV]	4.0	4.4	
Beam power [kW]	52	900	
RF frequency [MHz]	499.8	166.6	499.8
Cavity type	5-cell	QW-type	1-cell elliptical
Cavity technology	Normal conducting	Superconducting	
Number of cavities	6	5	2
Total RF voltage [MV]	≥8	5.4	3.2
RF power/cavity [kW]	70	180	200
Power source type	Solid-state power amplifier		
RF power/station [kW]	100	250	250
LLRF technology	Digital LLRF		
RF field control stability (rms)	0.3%, 0.3°	0.03%, 0.03°	

RF working package

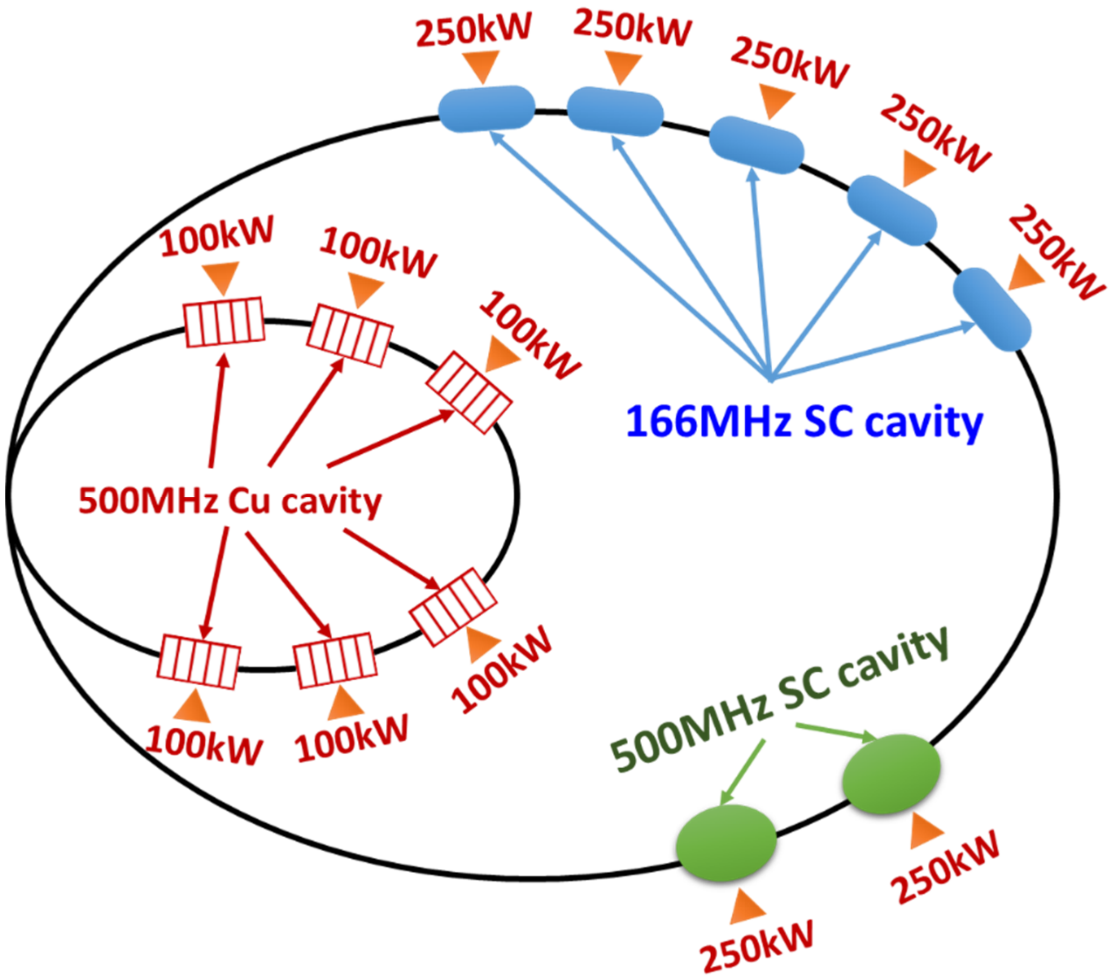


RF: Radio Frequency, **SRF**: Superconducting RF, **HOM**: Higher Order Mode
SSPA: Solid-State Power Amplifier, **LLRF**: Low-level RF

HEPS RF cavities

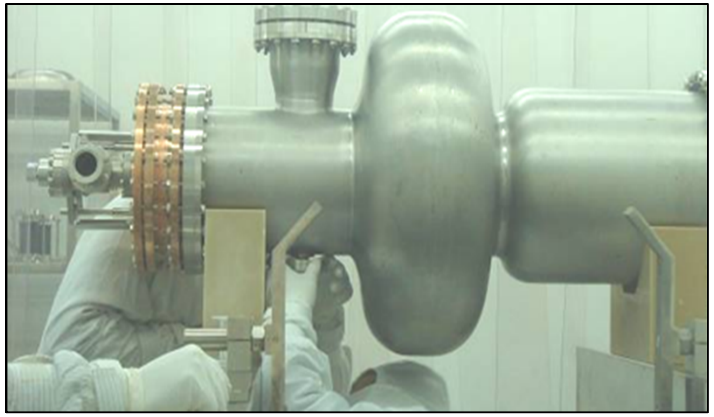


PETRA-type 5-cell 500MHz NCRF cavity



QW-type 166.6MHz SRF cavity (PoP cavity)

KEK-B type 1-cell 500MHz SRF cavity



166.6MHz PoP cavity

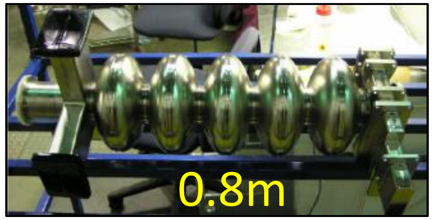
Cavity design features

- **Low frequency**: 166.6MHz, **β=1**
- High current: 200mA → **heavy HOM damping**: Q_L<1000
- **High RF power**: 200kW per cavity
- **Compactness**: limited space of the linear section (6m)
- Stable operation (user facility): **large margin** in RF parameters

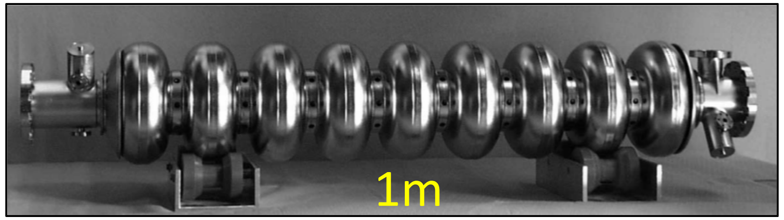
β=1 elliptical cavities

3.9GHz

1.5GHz

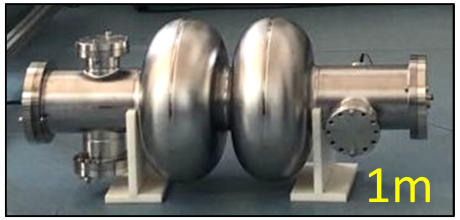


1.3GHz

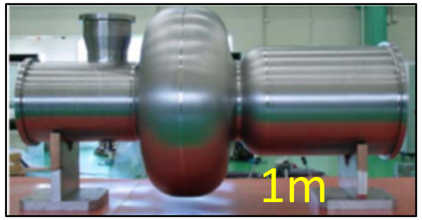


704MHz

650MHz

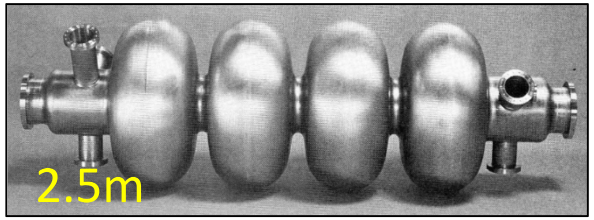


500MHz

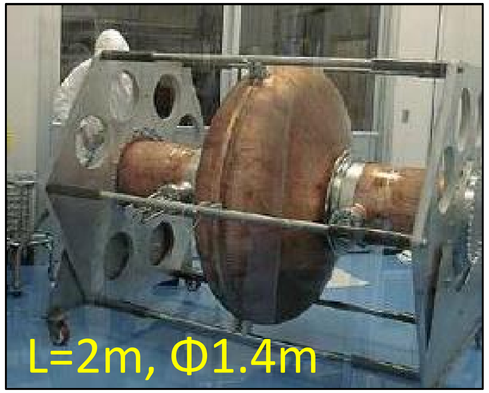


400MHz

352MHz



200MHz



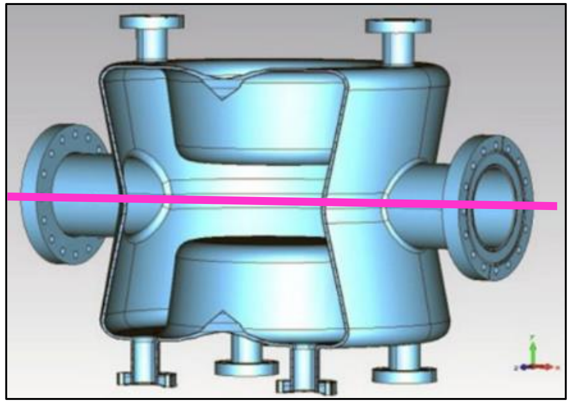
Elliptical cavity length: $\sim\lambda = \frac{c}{f}$

λ of 166.6MHz: ~1.8m

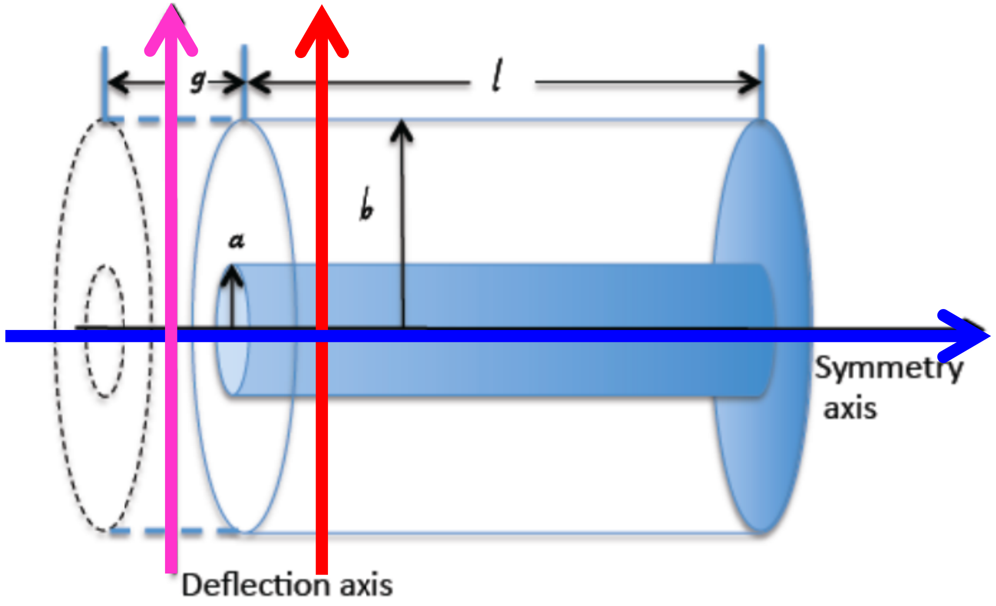
- Elliptical cavity of 166.6MHz becomes prohibitively large
- QW-type β=1 cavity looks promising

QWR

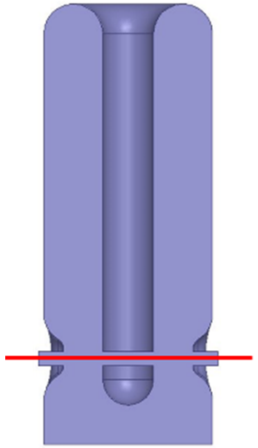
BNL 400MHz crab cavity



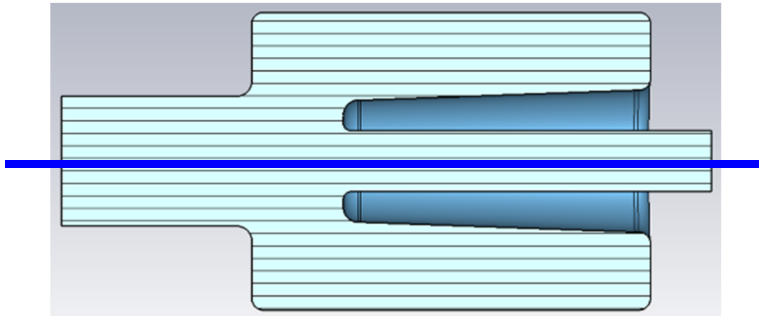
B.P. Xiao *et al.*, PRST-AB **18** (2015) 041004.



HIE-ISOLDE 101.28MHz β=0.11 QWR



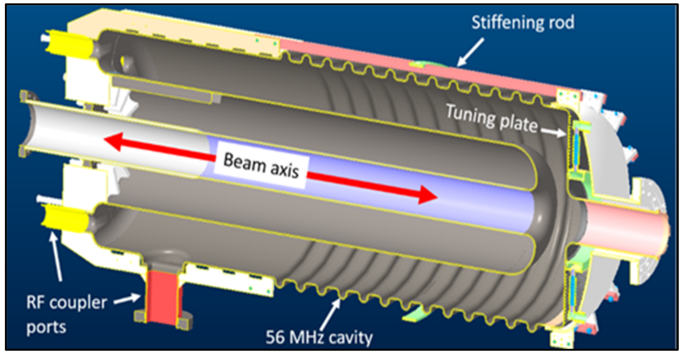
A. D'Elia *et al.*, SRF2009, THPPO027.

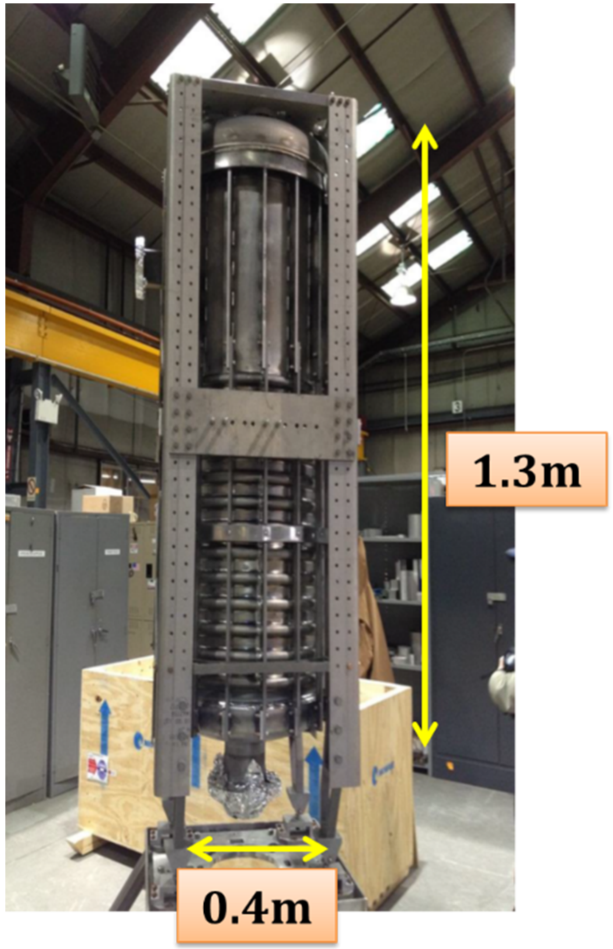


Ilan Ben-Zvi, Quarter-wave resonators for beta~1 accelerators, SRF2011, THIOA04

QWR (β=1)

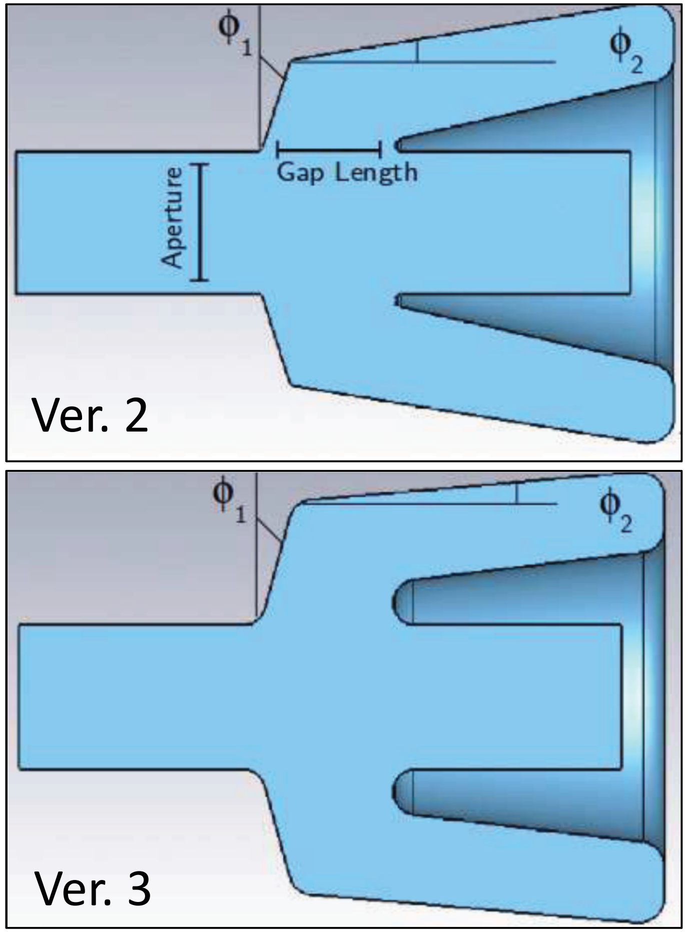
BNL 56MHz QW cavity





Q. Wu *et al.*, SRF2015, WEBA07.
Q. Wu *et al.*, IPAC2019, MOPMP051.

CERN 200MHz QW for HL-LHC



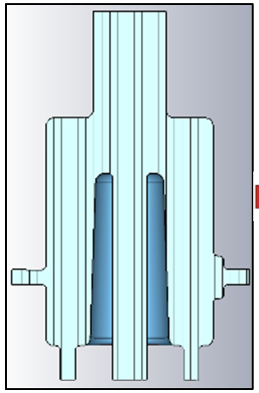
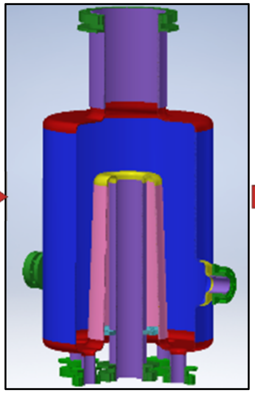
R. Calaga *et al.*, IPAC2016, TUPMW034.

166.6MHz SRF cavity

Two-step approach:

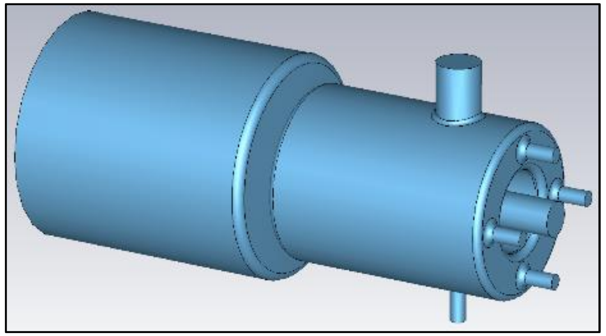
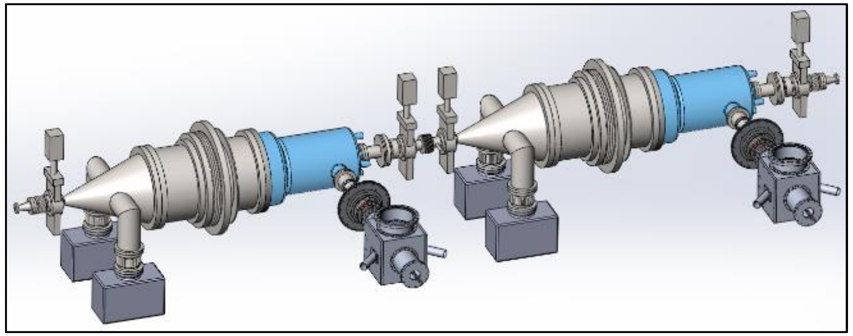
1. Proof-of-Principle (PoP) cavity: production technics, surface treatment, maximize learning
2. Prototype cavity: including higher order mode coupler/absorber

PoP cavity



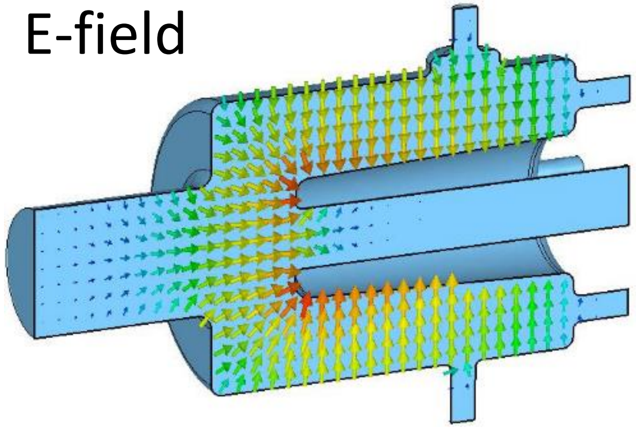
Prototype cavity

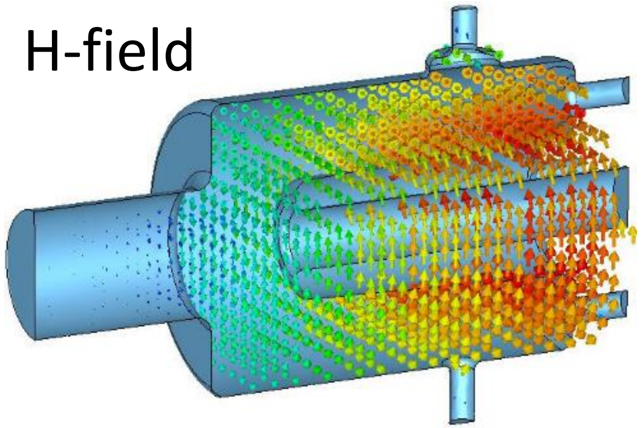
…

RF design

E-field



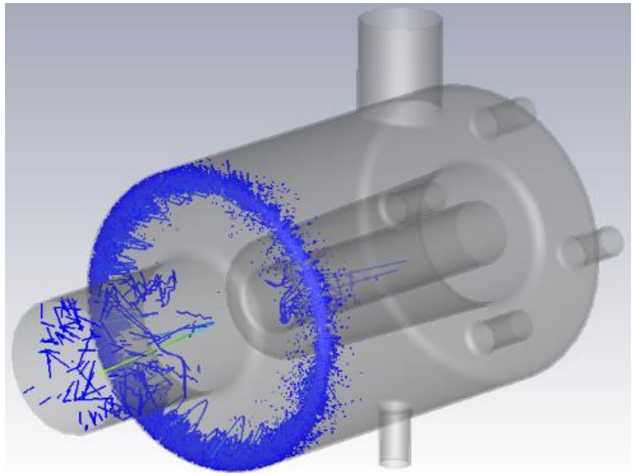
H-field

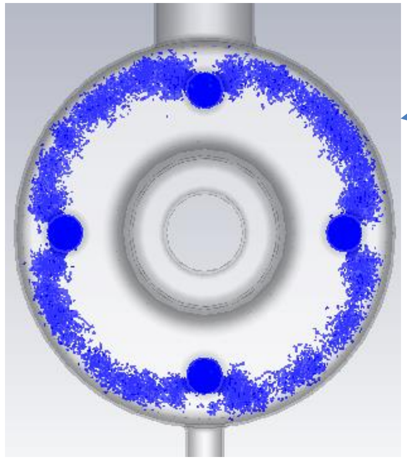


P. Zhang *et al.*, *Rev. Sci. Instrum.* **90** (2019) 084705.

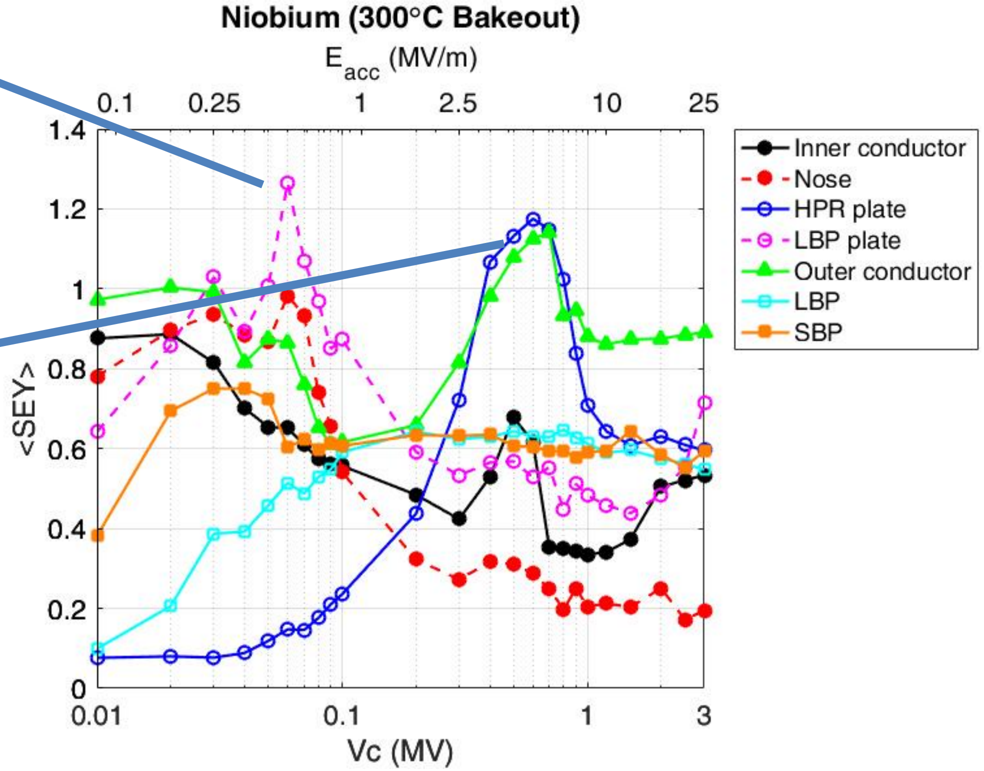
Parameter	Value	Unit
Frequency (f_0)	166.6	MHz
Frequency of nearest mode	433	MHz
$\lambda/4$ of π mode	449.9	mm
Cavity length (main body)	530	mm
Cavity diameter (no ports)	397	mm
Aperture diameter (small side)	80	mm
Operating temperature	4.2	K
Accelerating voltage (V_c)	1.5	MV
Accelerating gradient (E_{acc})	12.5	MV/m
Peak surface electric field (E_p)	40.1	MV/m
Peak surface magnetic field (B_p)	63.9	mT
B_p/E_p	1.59	mT/(MV/m)
Stored energy (U)	15.8	J
R/Q ($=\vert V_c\vert^2/\omega U$)	136.0	Ω
Geometry factor ($G = R_s \cdot Q_0$)	54.5	Ω

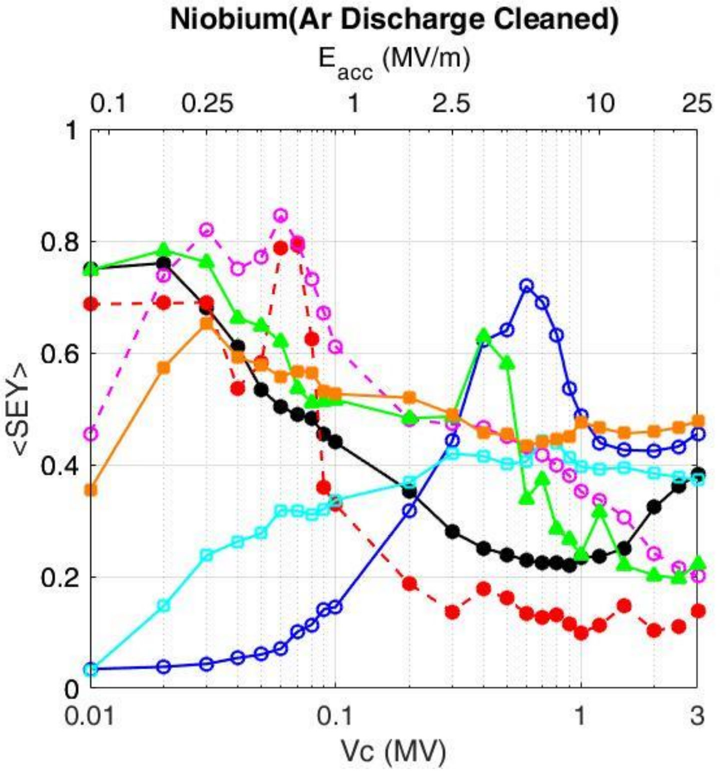
Multipacting





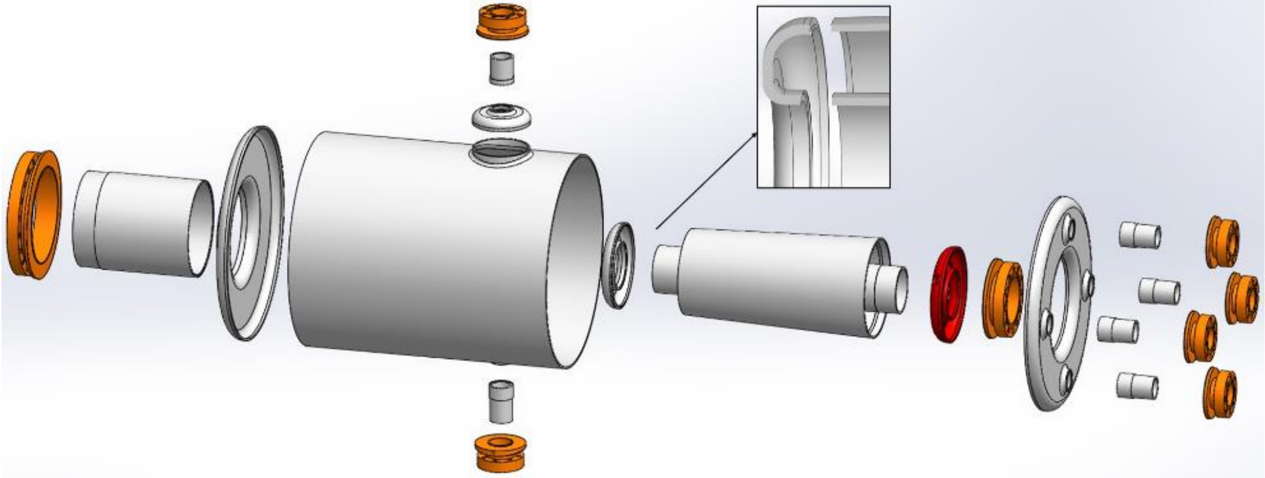
- No hard barriers
- Easy to process during VT (10')





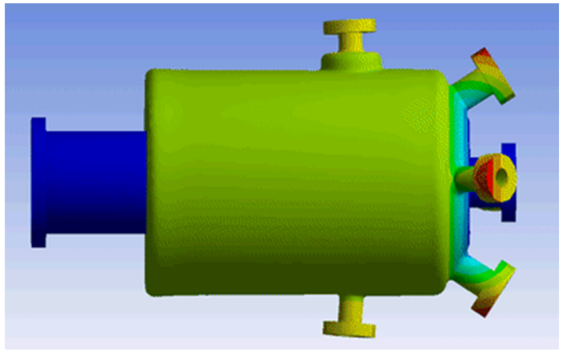
P. Zhang *et al., Rev. Sci. Instrum.* **90** (2019) 084705.

Mechanical design

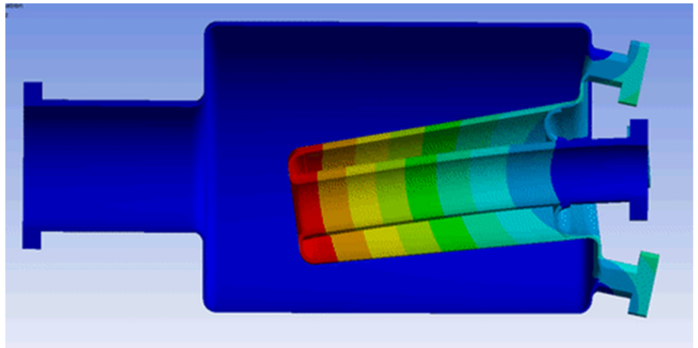


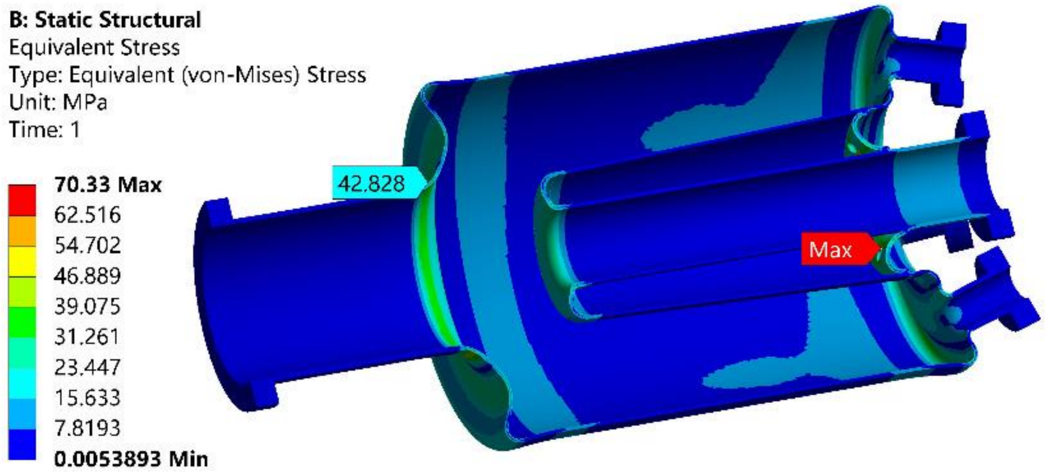
- Peak stress on cavity: 42.8MPa (1.5atm)
- Lorentz coefficient: 2~5 Hz/(MV/m)^2
- Tuning sensitivity: 101.5kHz/mm
- Microphonics: 113Hz, 147Hz

113Hz



147Hz





X.Y. Zhang and P. Zhang *et al.*, accepted by NIM-A.

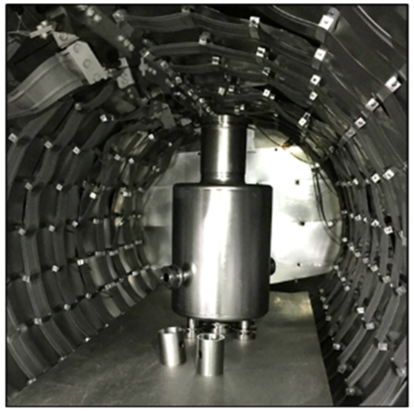
Fabrication & processing

Cavity fabrication

Cavity surface treatment

BCP

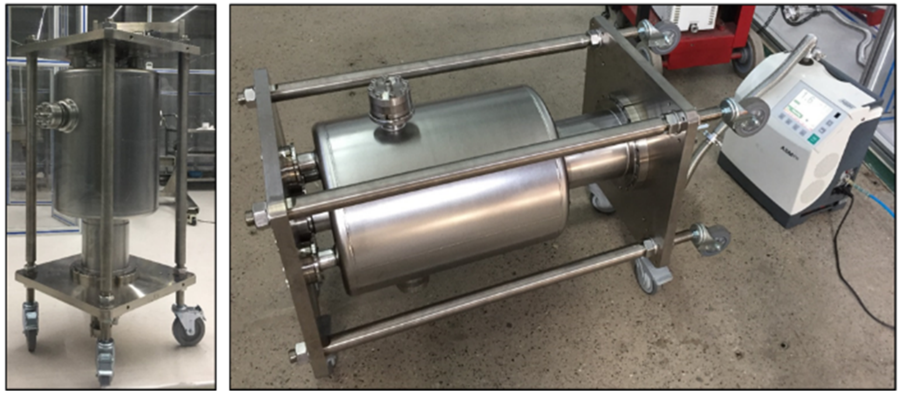
750°C annealing



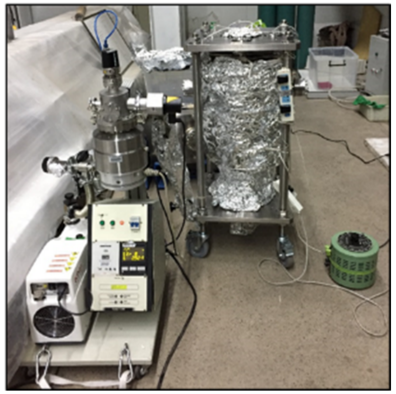
HPR

Clean assembly

Leak check & frequency pre-tuning



120°C bake



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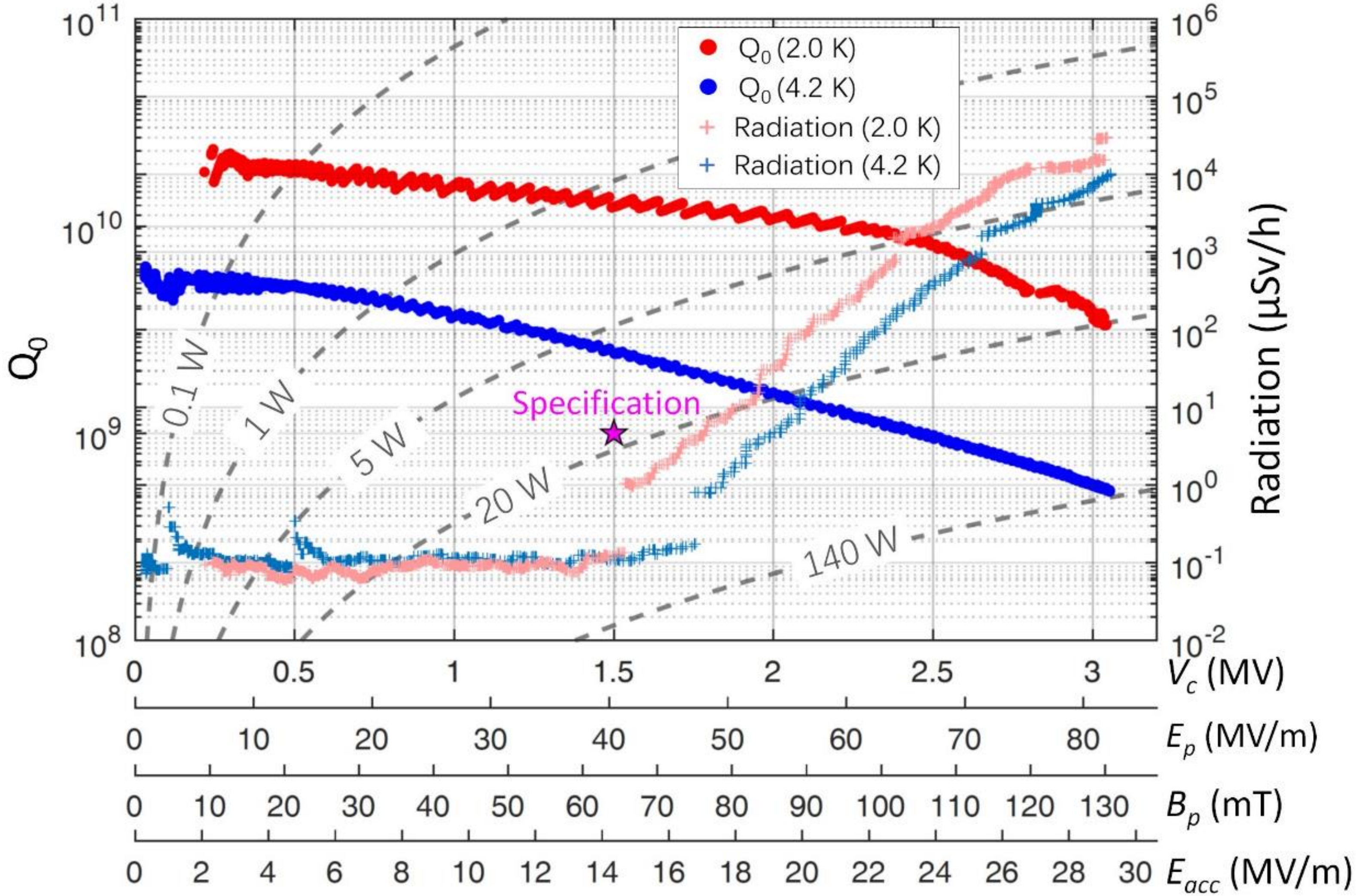
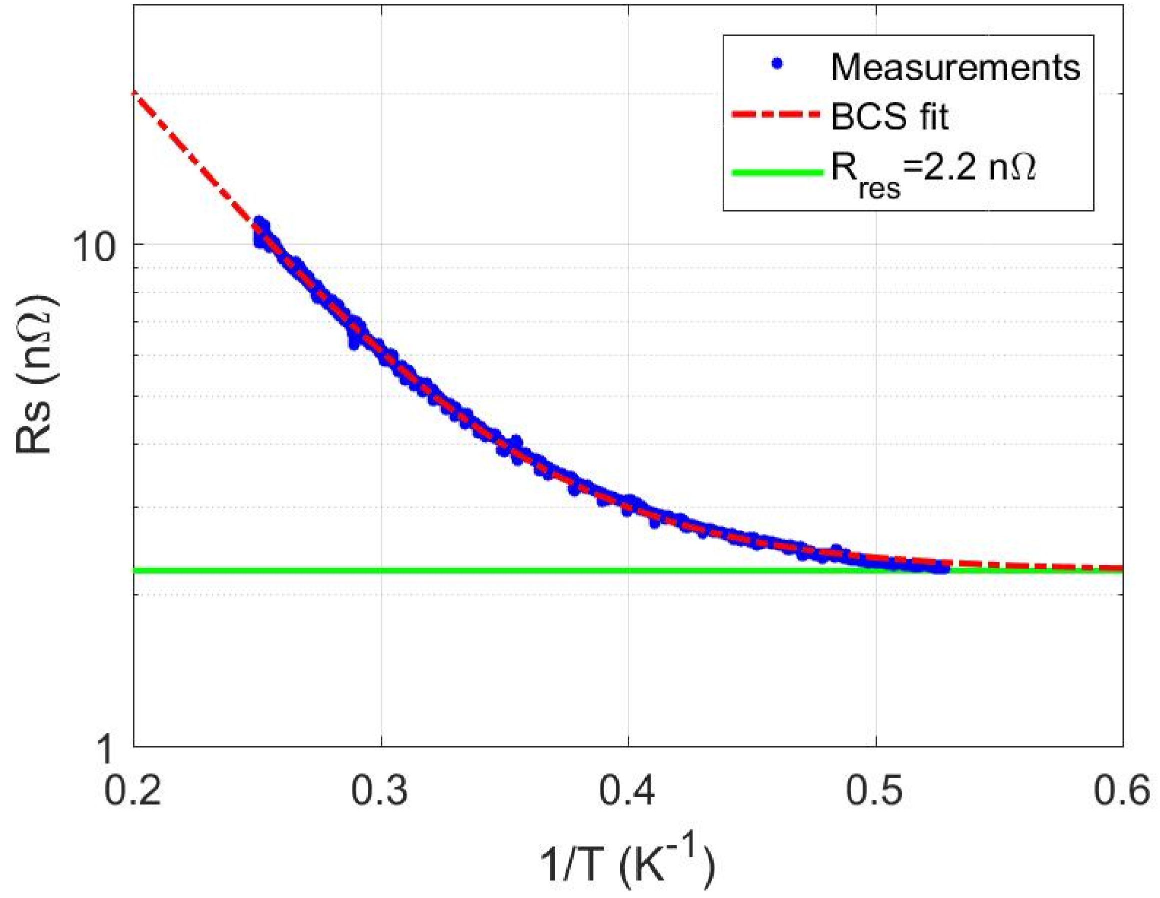
Vertical test



P. Zhang *et al.*, *Rev. Sci. Instrum.* **90** (2019) 084705.

RF performance

Residual resistance : 2.2 nΩ

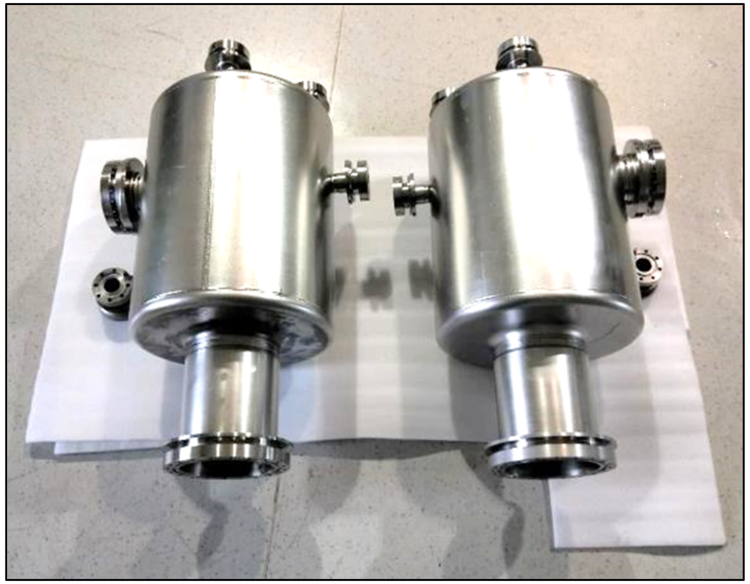


- Designed Vc: 1.5MV
- Maximum Vc reached: 3.1MV
- Q0 (4K) at designed Vc: 2.4×10^{9}
- Maximum Ep: 82MV/m
- Maximum Bp: 130mT
- FE onset: 1.84MV

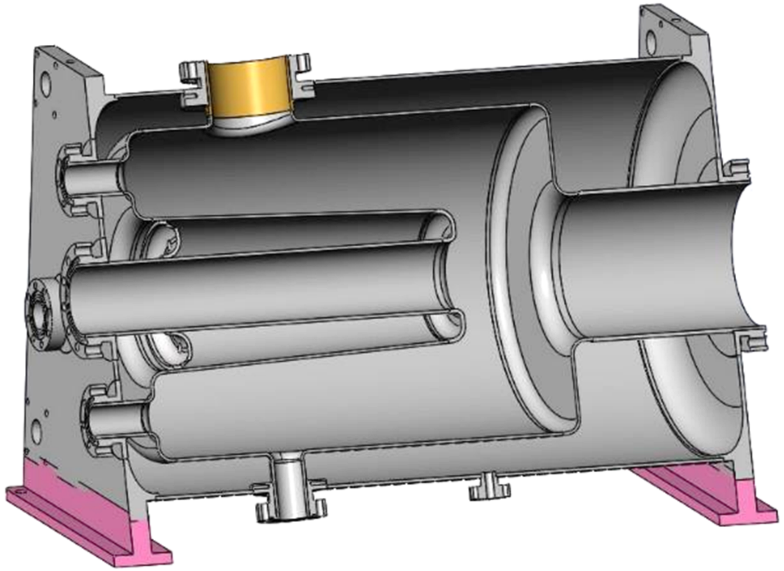
P. Zhang *et al., Rev. Sci. Instrum.* **90** (2019) 084705.

Helium vessel

FPC port modified



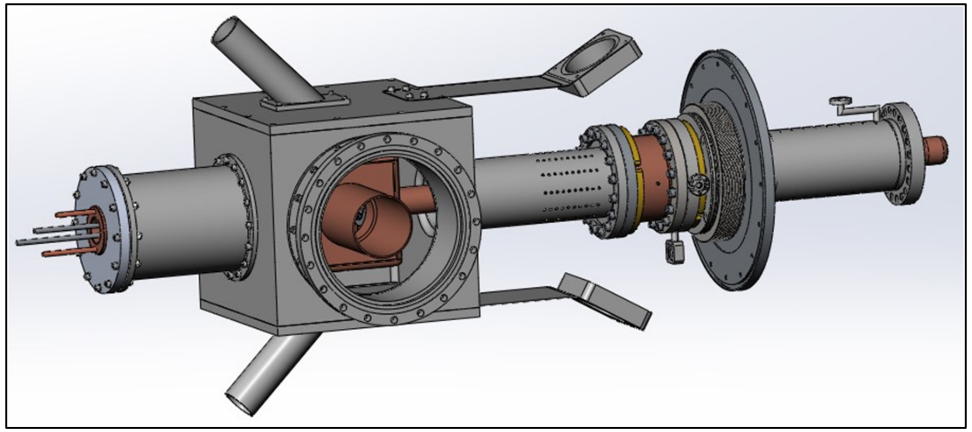
Helium vessel

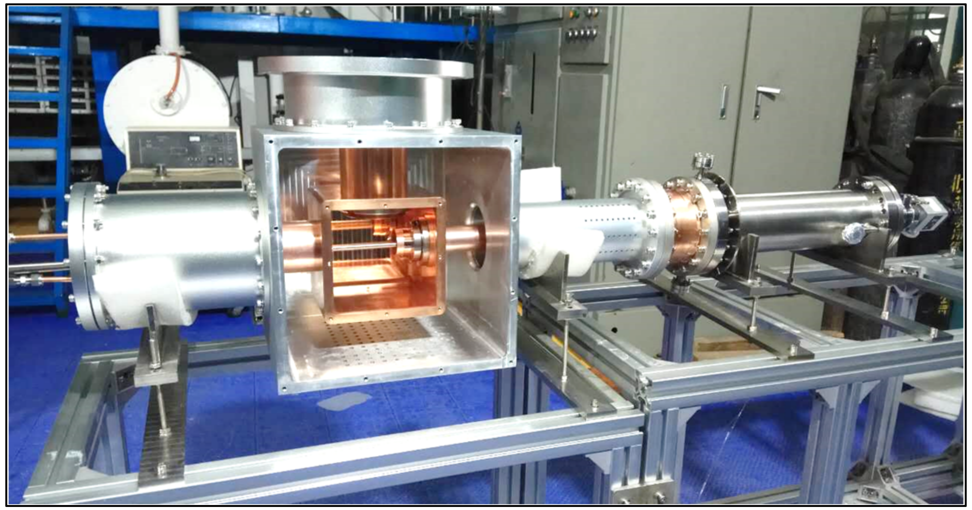


He vessel welded

Fundamental power coupler

Design & fabrication





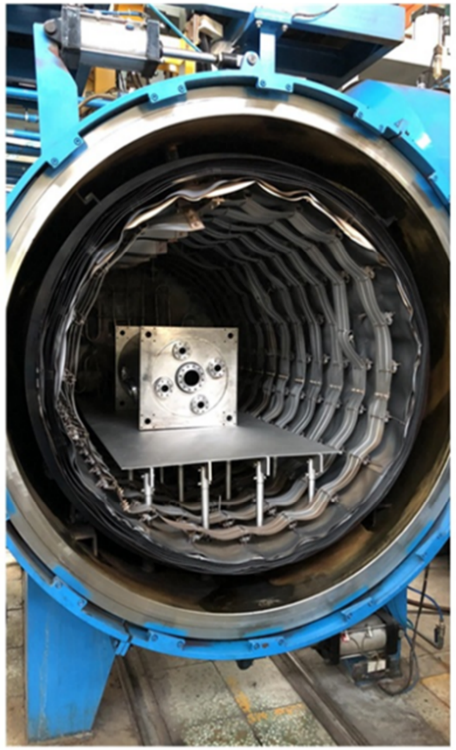
High-power test

Cavity processing

BCP

Ningxia

750°C annealing



Ningxia

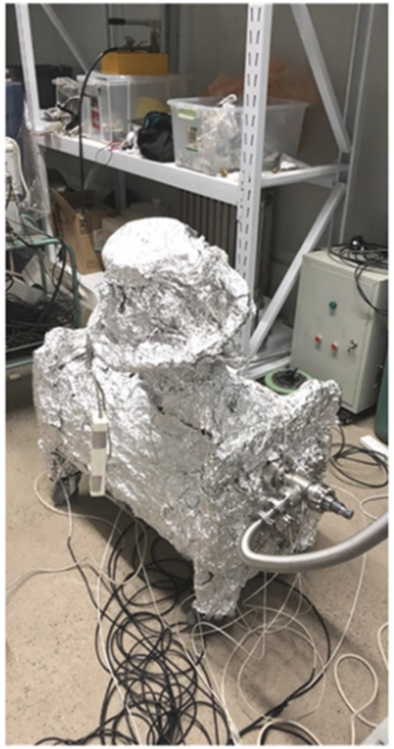
HPR

IHEP

Clean assembly (ISO 4)

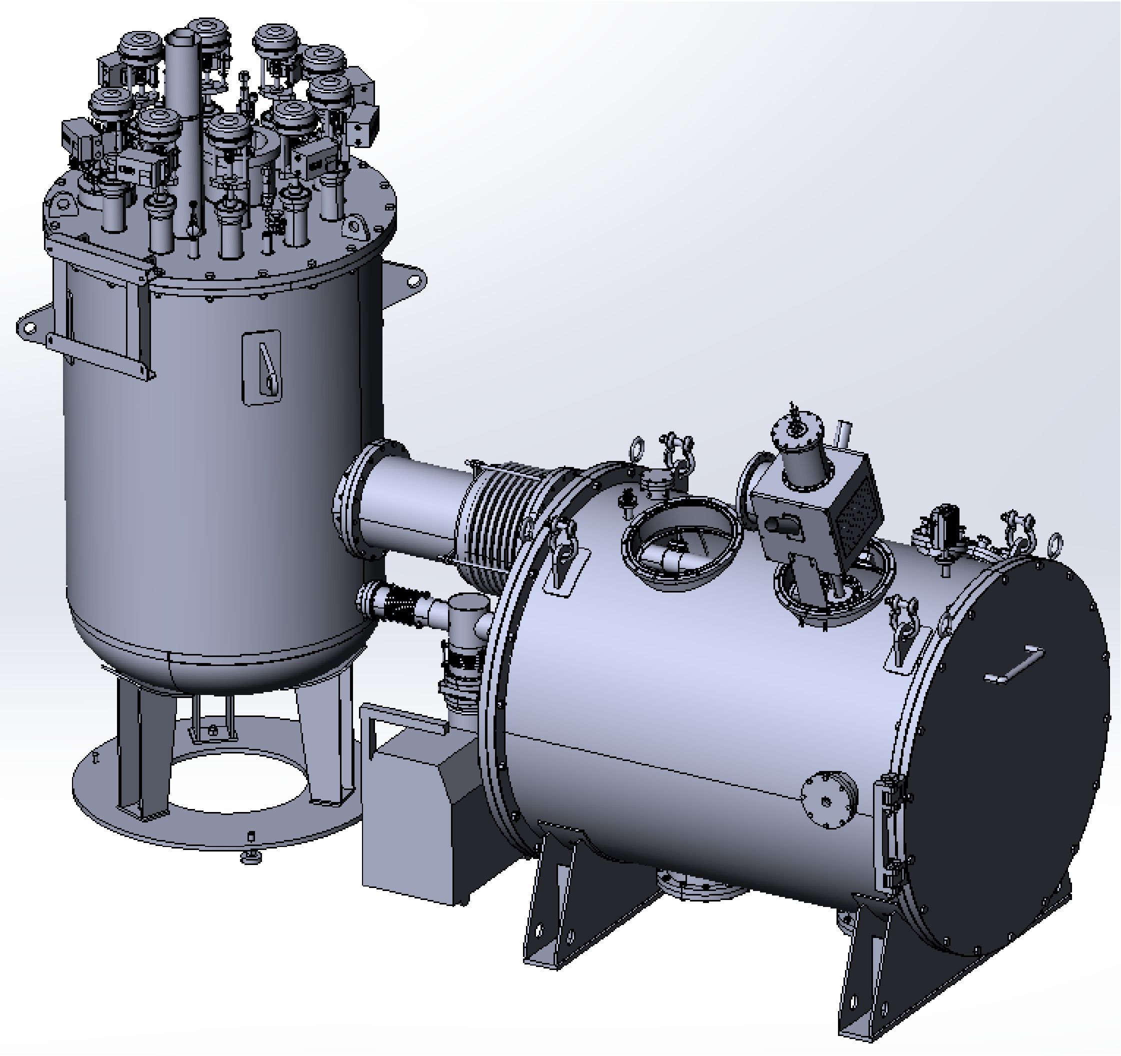
IHEP

120°C bake



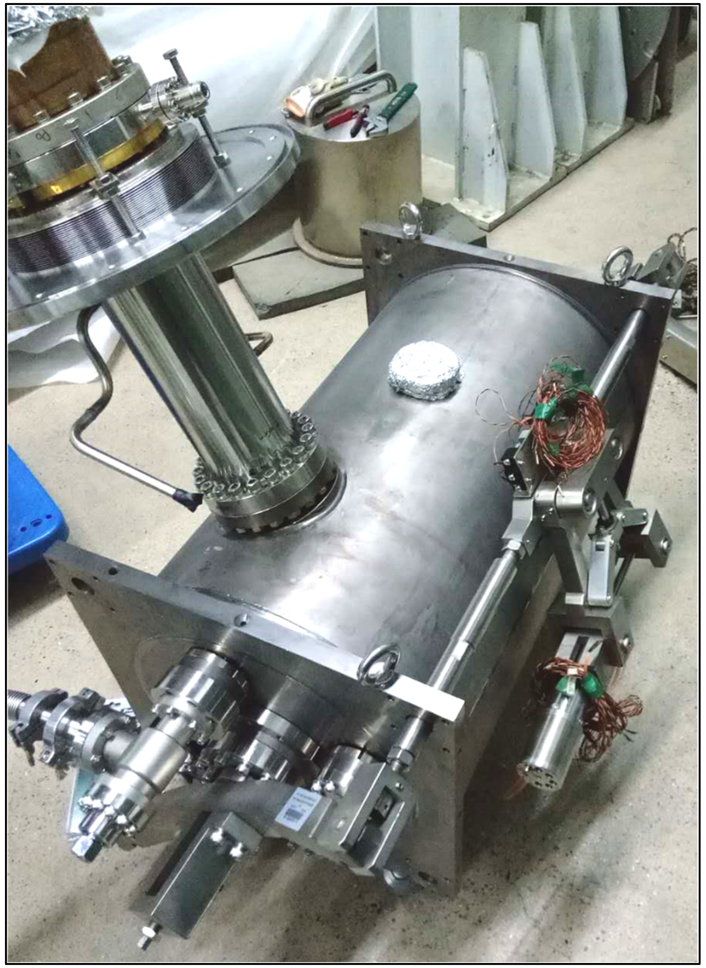
IHEP

Test cryomodule



Modify the existing 325MHz Spoke cavity module for ADS project

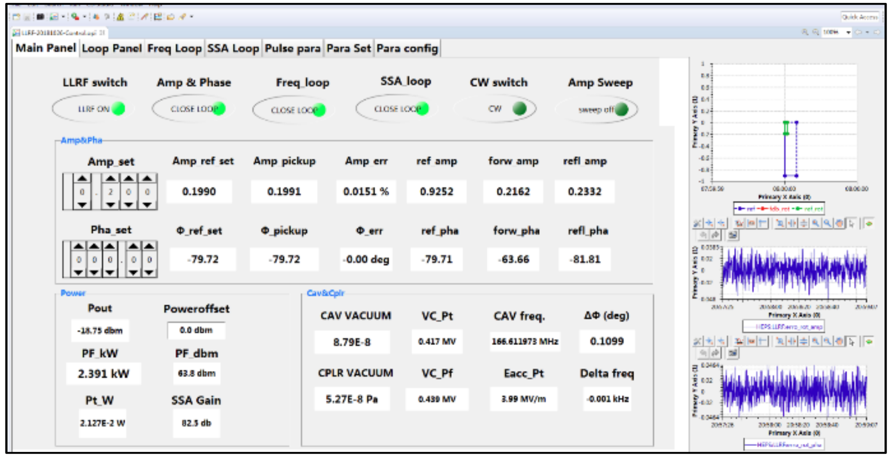
CM assembly

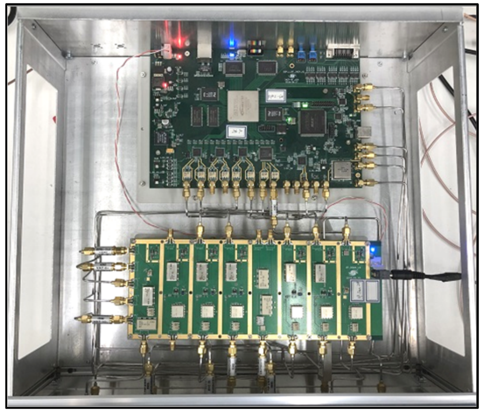


Measurement system

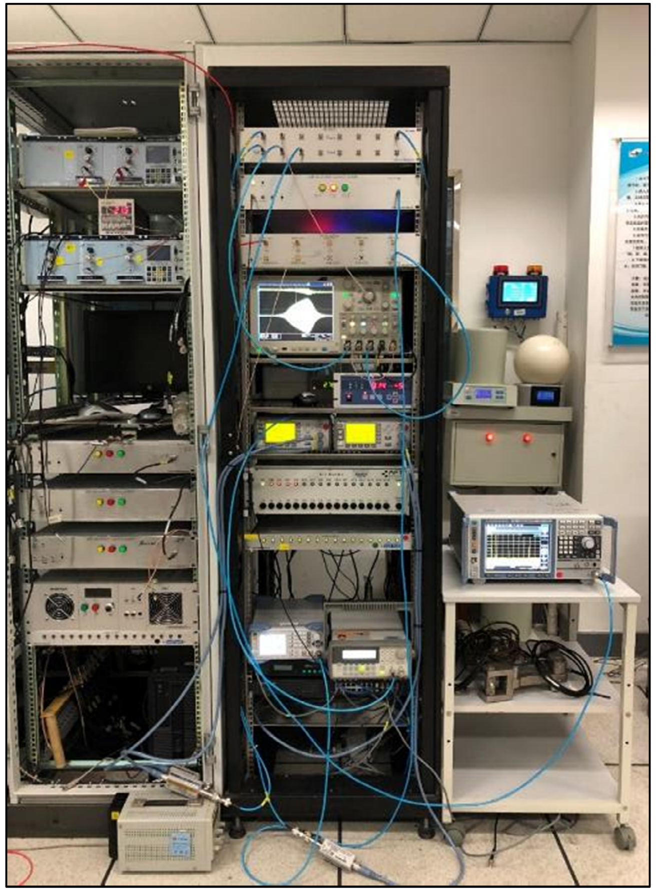
166.6MHz 50kW SSPA

In-house developed LLRF



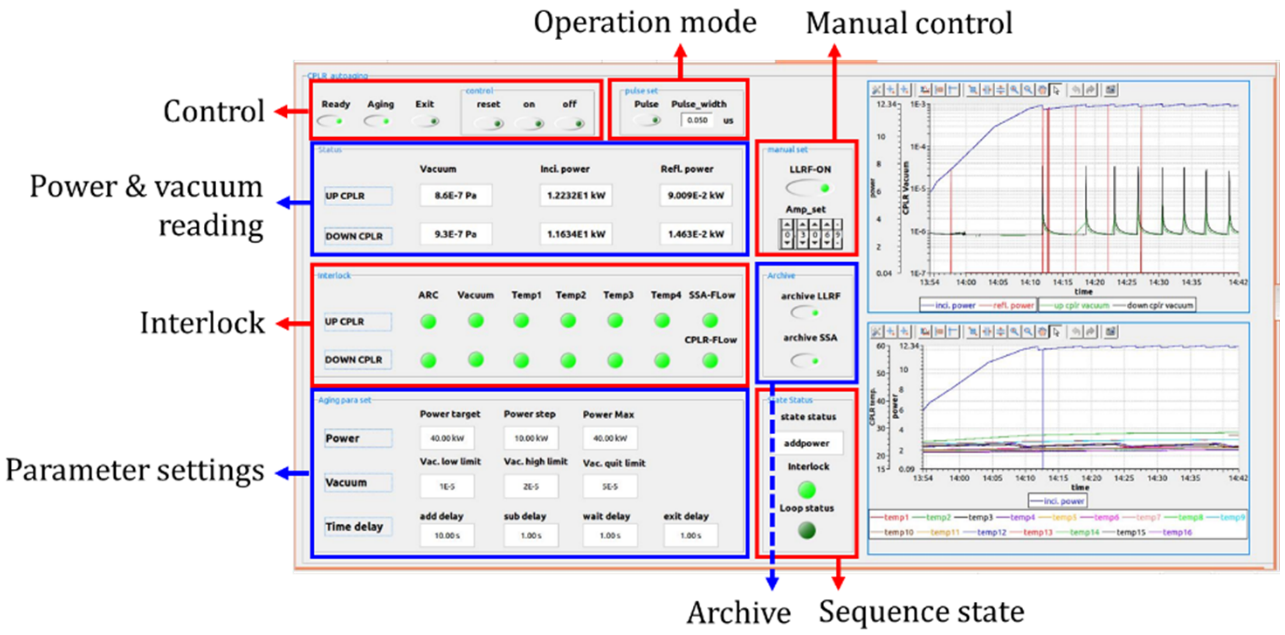


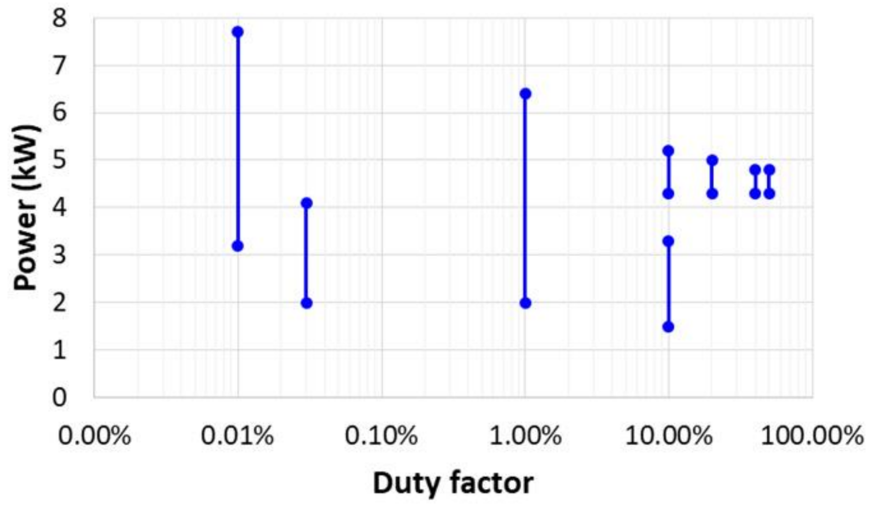
Measurement system



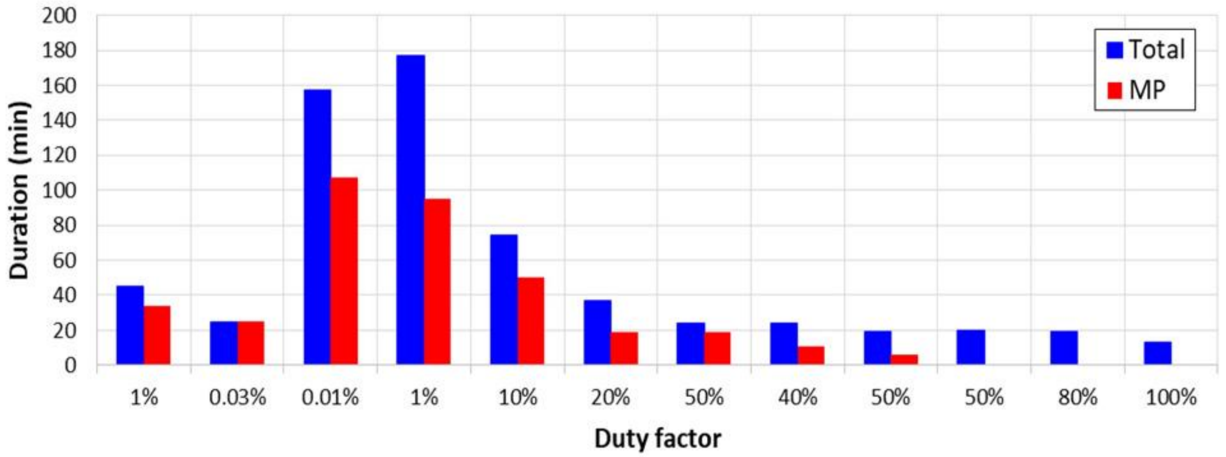
FPC conditioning

Automatic conditioning system





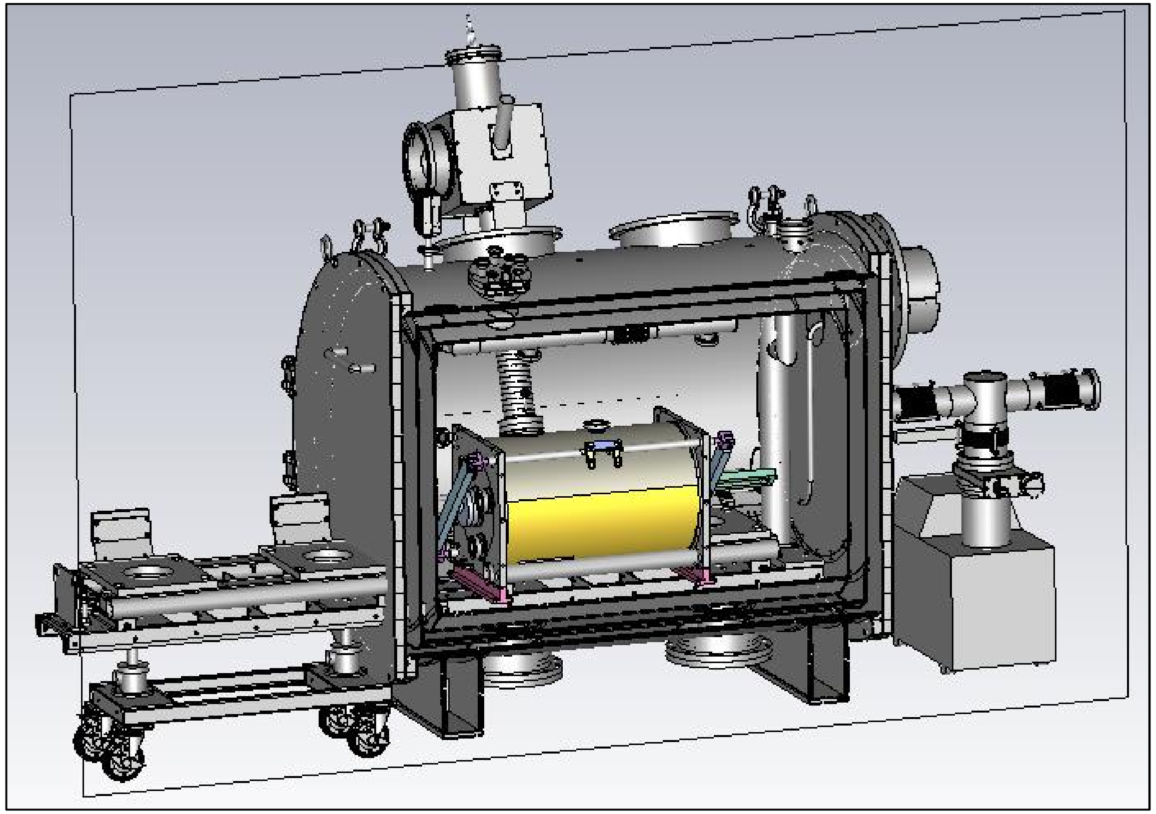
11-hour conditioning

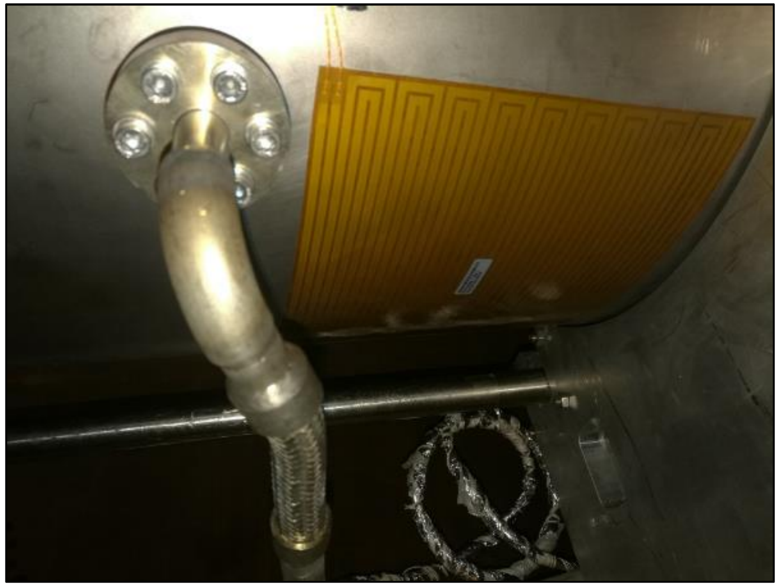


- FPC conditioning went smoothly
- MP was expected and can be conditioned
- Bias applied during cold tests (OC: 0V, IC: +1kV)

Static loss

Measured static loss: 12W

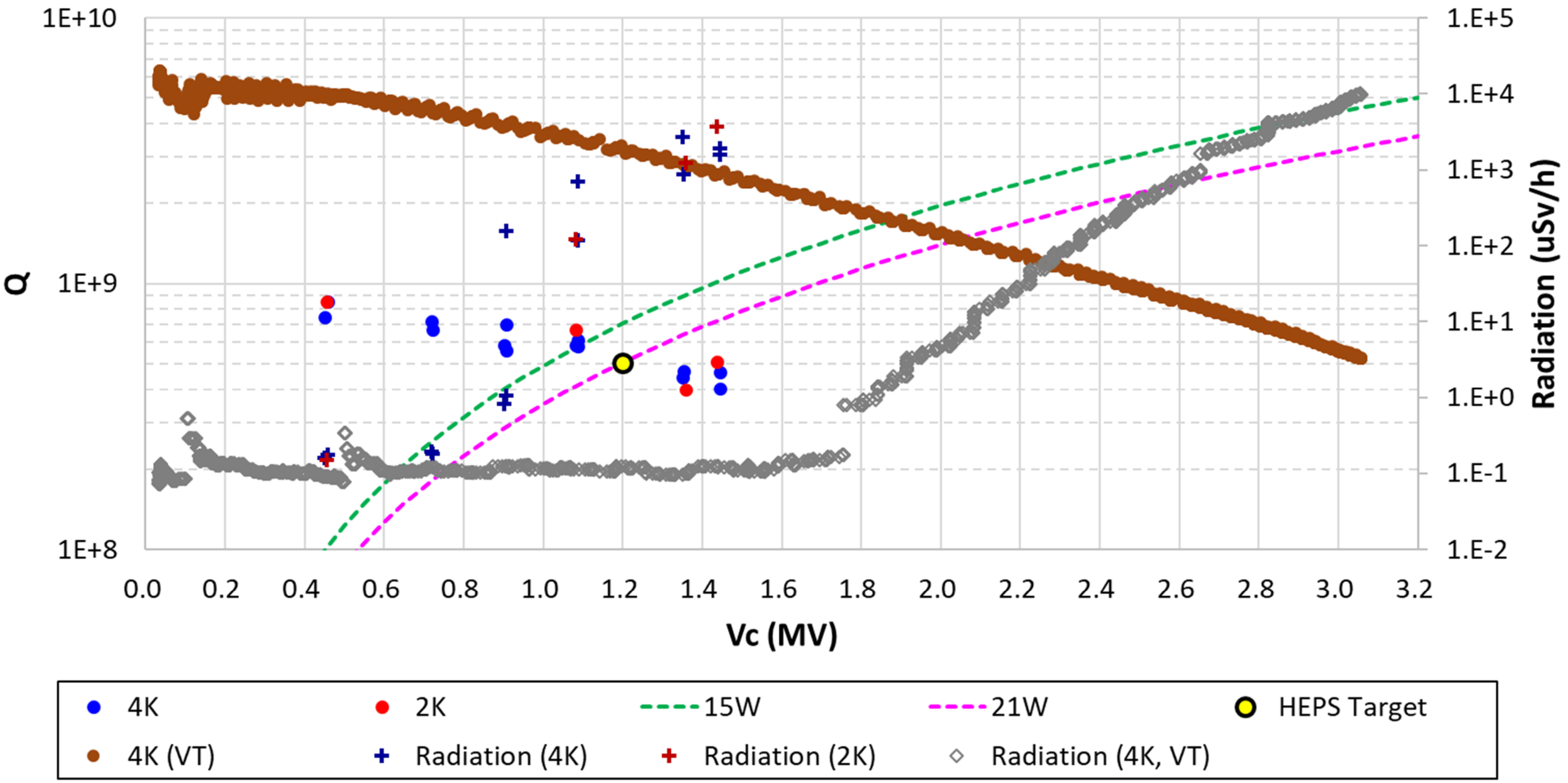




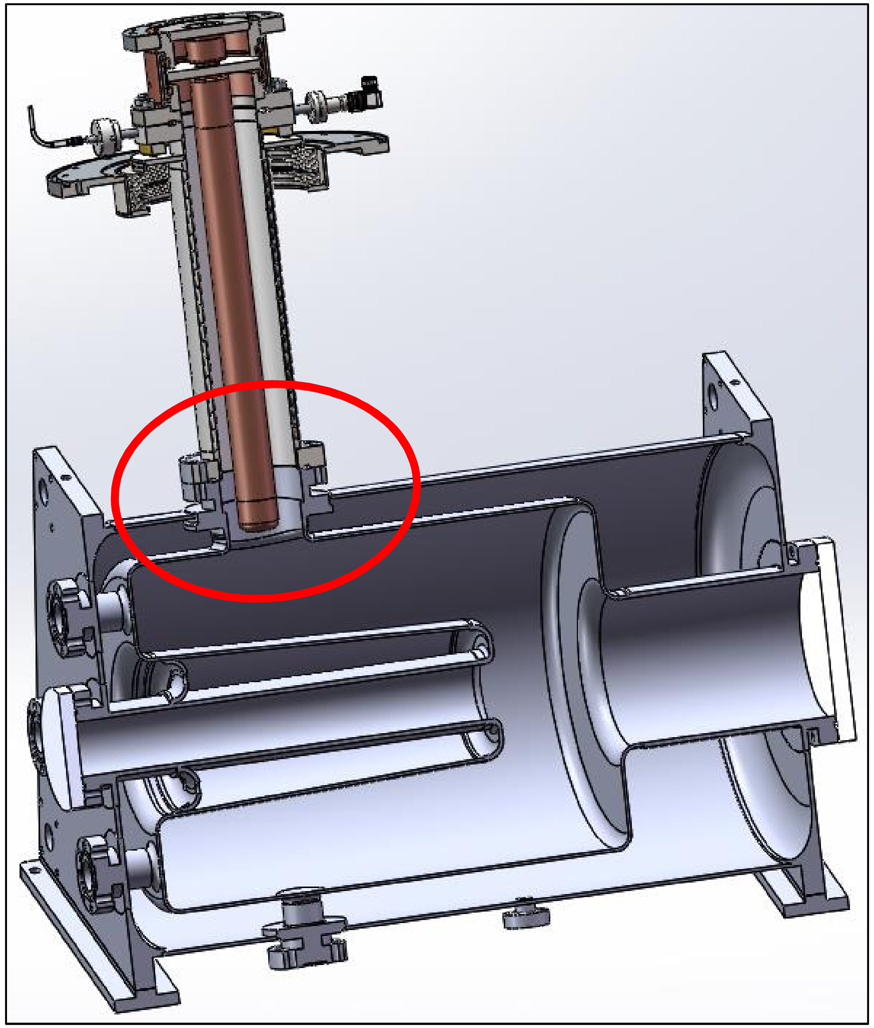
Benchmark with heater

Parameter	4.2 K	2.0 K	Unit
Power generated by heater	12.7	12.7	W
Static loss measured	12.1	12.0	W
Total loss of heater and static	24.8	24.7	W
Total loss measured	25.6	26.5	W
ΔPower	0.8 (3%)	1.8 (7%)	W

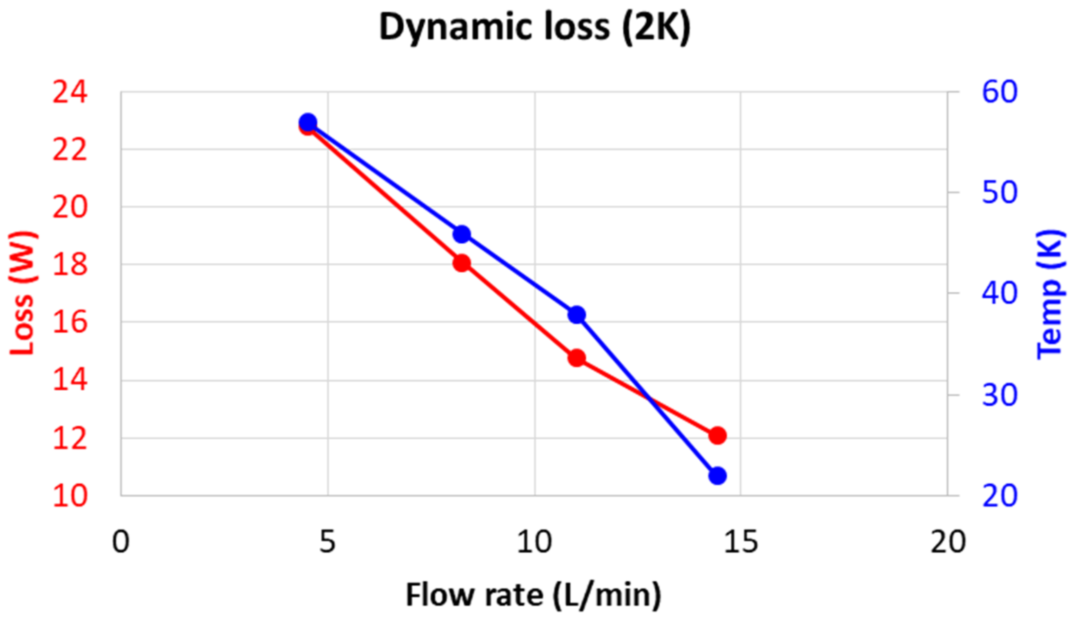
Quality factor



Cavity field leakage



- Cavity RF field leak on FPC port
- Cure
  - Elongate the Nb tube of the FPC port
  - Improve the He gas cooling of FPC outer conductor



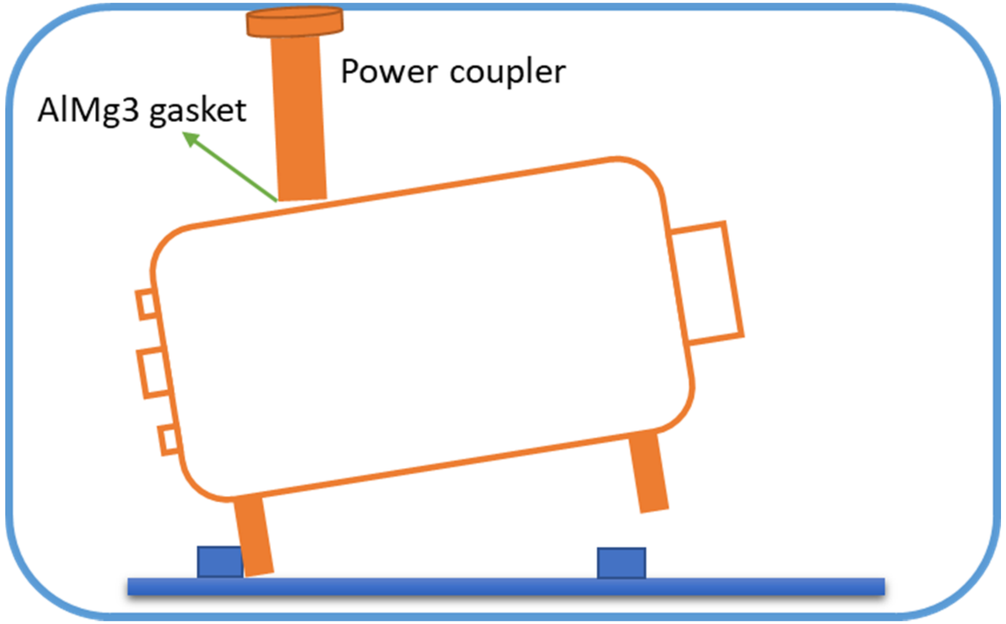
Early field emission onset

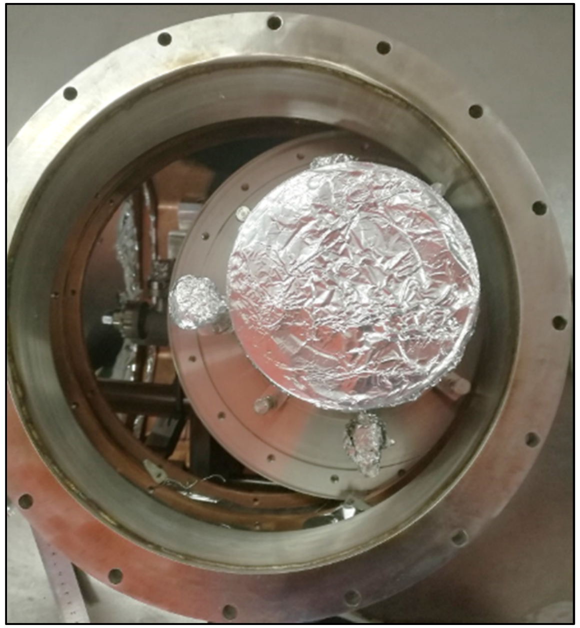
- Accident during cryomodule assembly

  - Leak rate: 1e-7 mbar·l/s (after tightening: 1e-10 mbar·l/s)

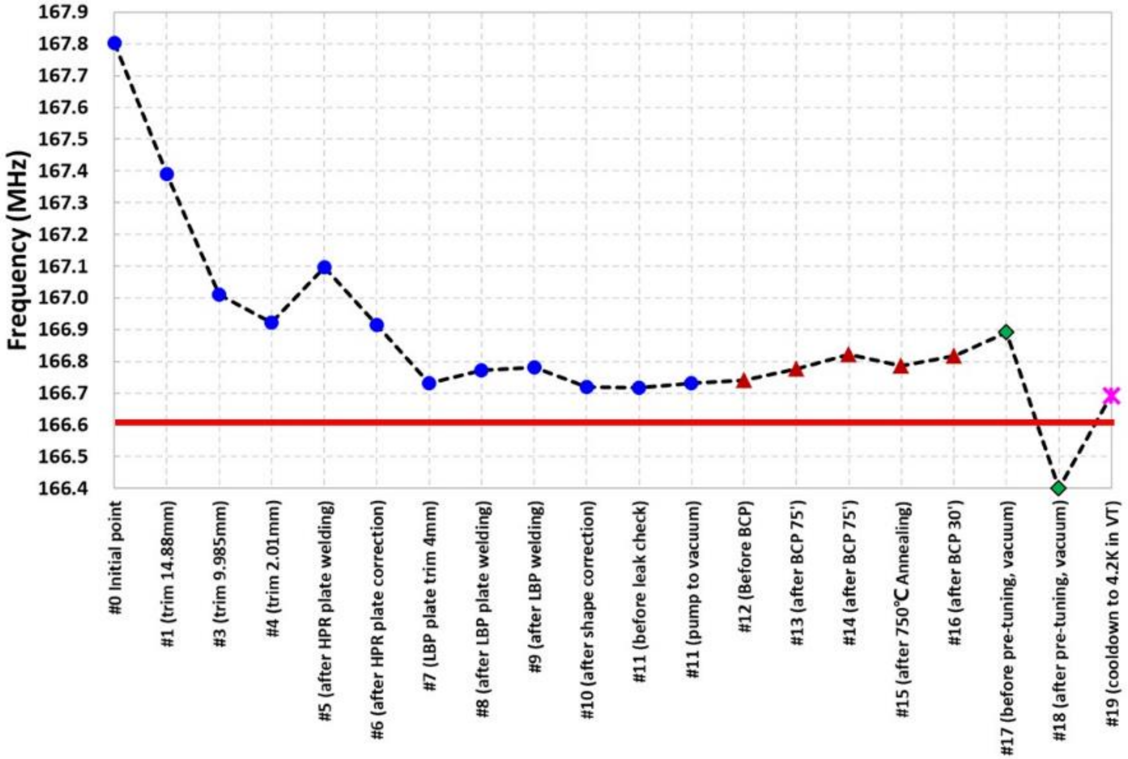
  - Speculations: particles shaken out of FPC

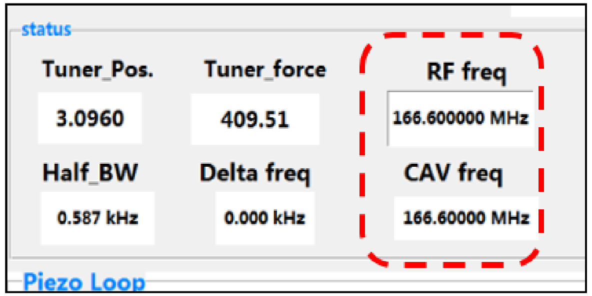
- Early field emission onset: ~1MV (VT: 1.8MV)

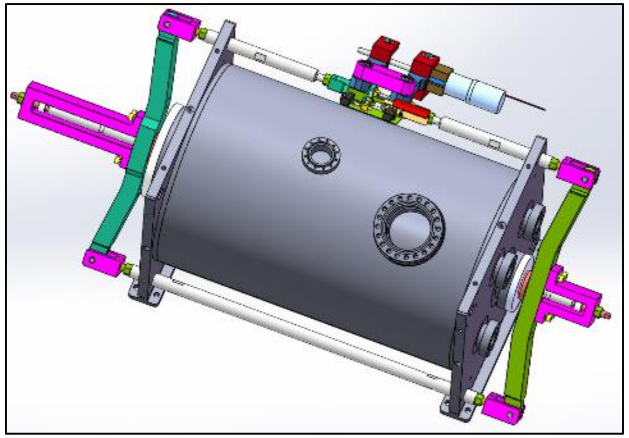


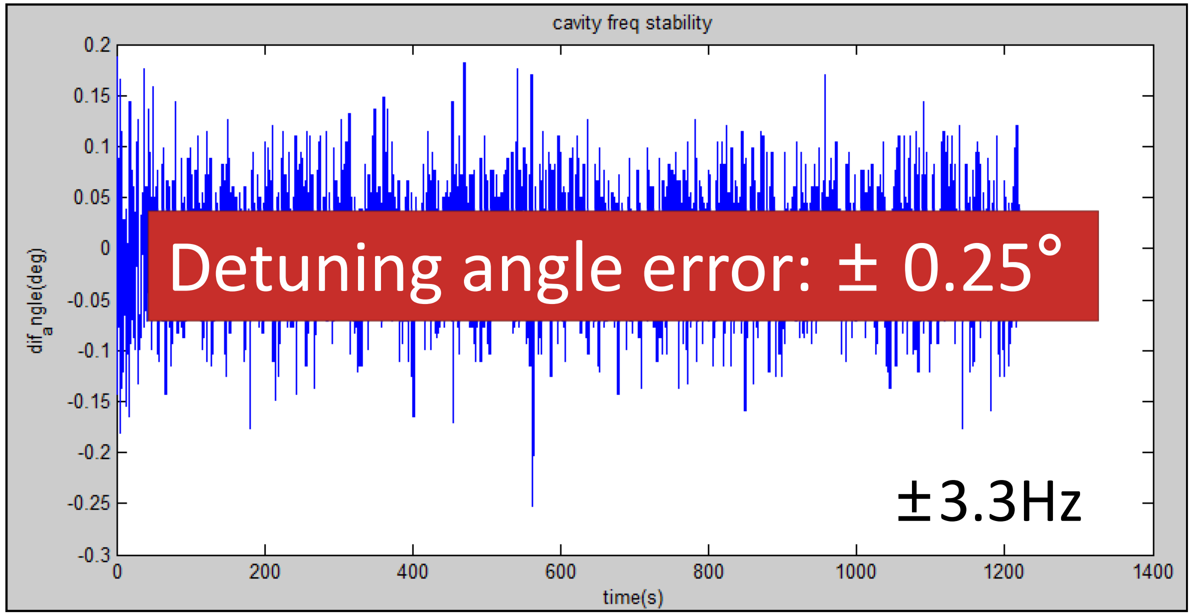


Frequency control





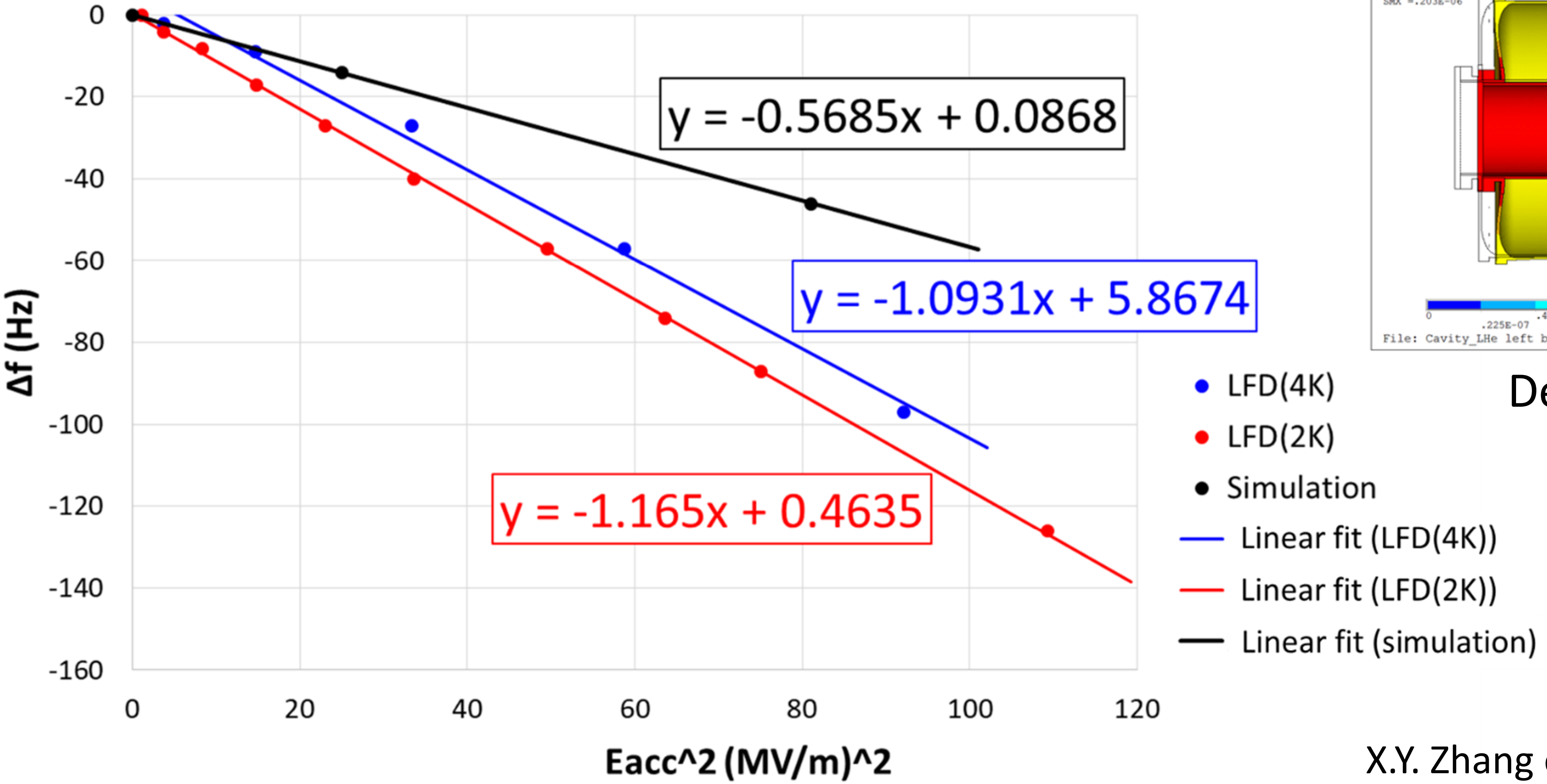


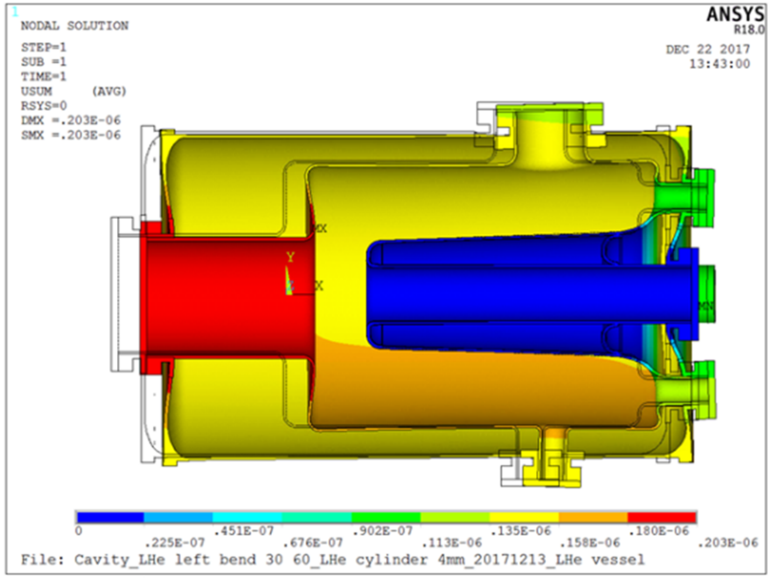


166MHz HT at 4.2K, Vc=1.2MV
freq. loop closed (motor + piezo)

[1] P. Zhang et al., SRF2017, TUPB035.
[2] Z.H. Mi et al., SRF2019, TUP080.

Lorentz force detuning



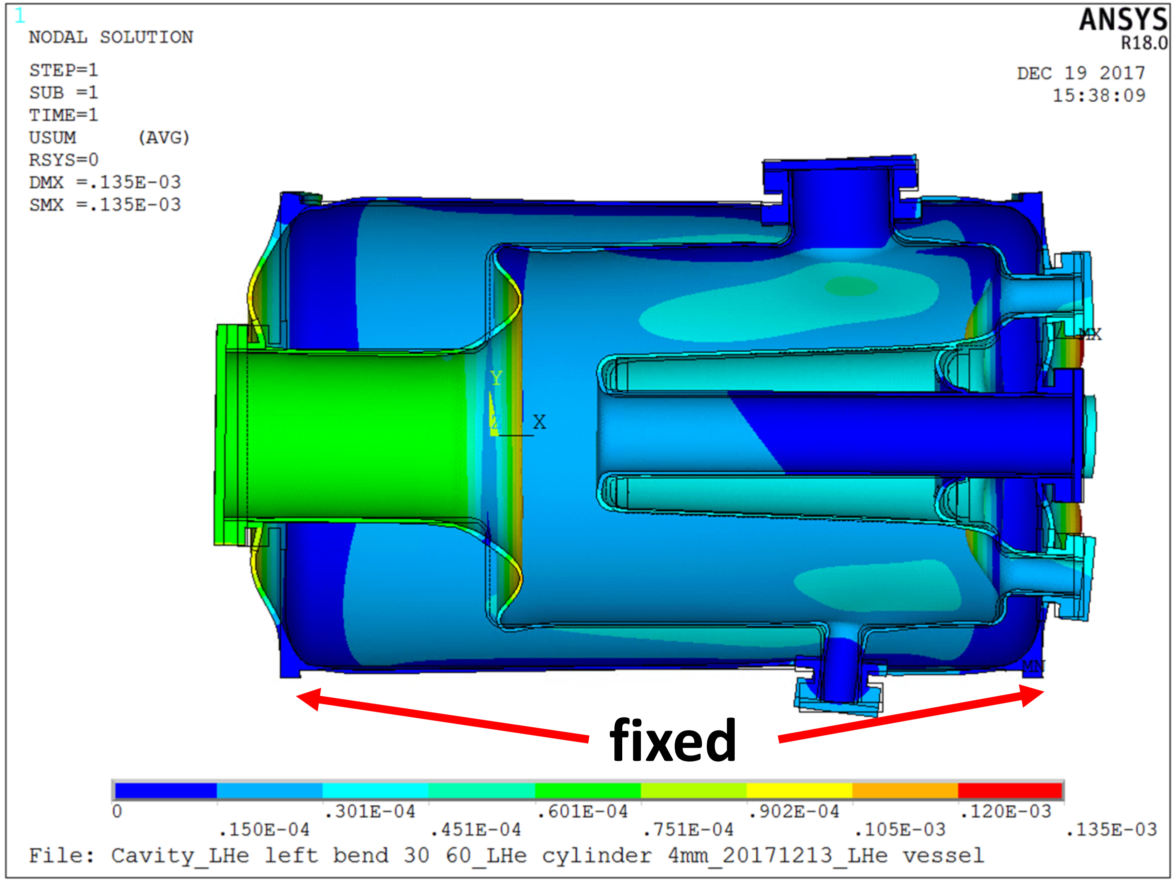


Deformation when Vc=1MV

X.Y. Zhang et al., SRF2019, TUP010.

Pressure sensitivity (df/dp)

1.5bar LHe pressure



Simulation: -1.5 Hz/mbar

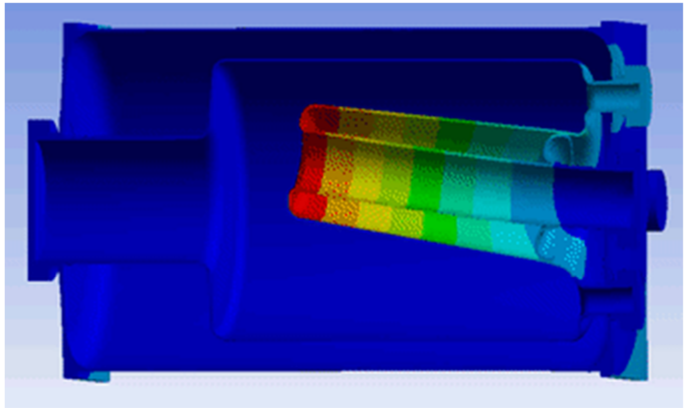
Measurement: -1.3 Hz/mbar

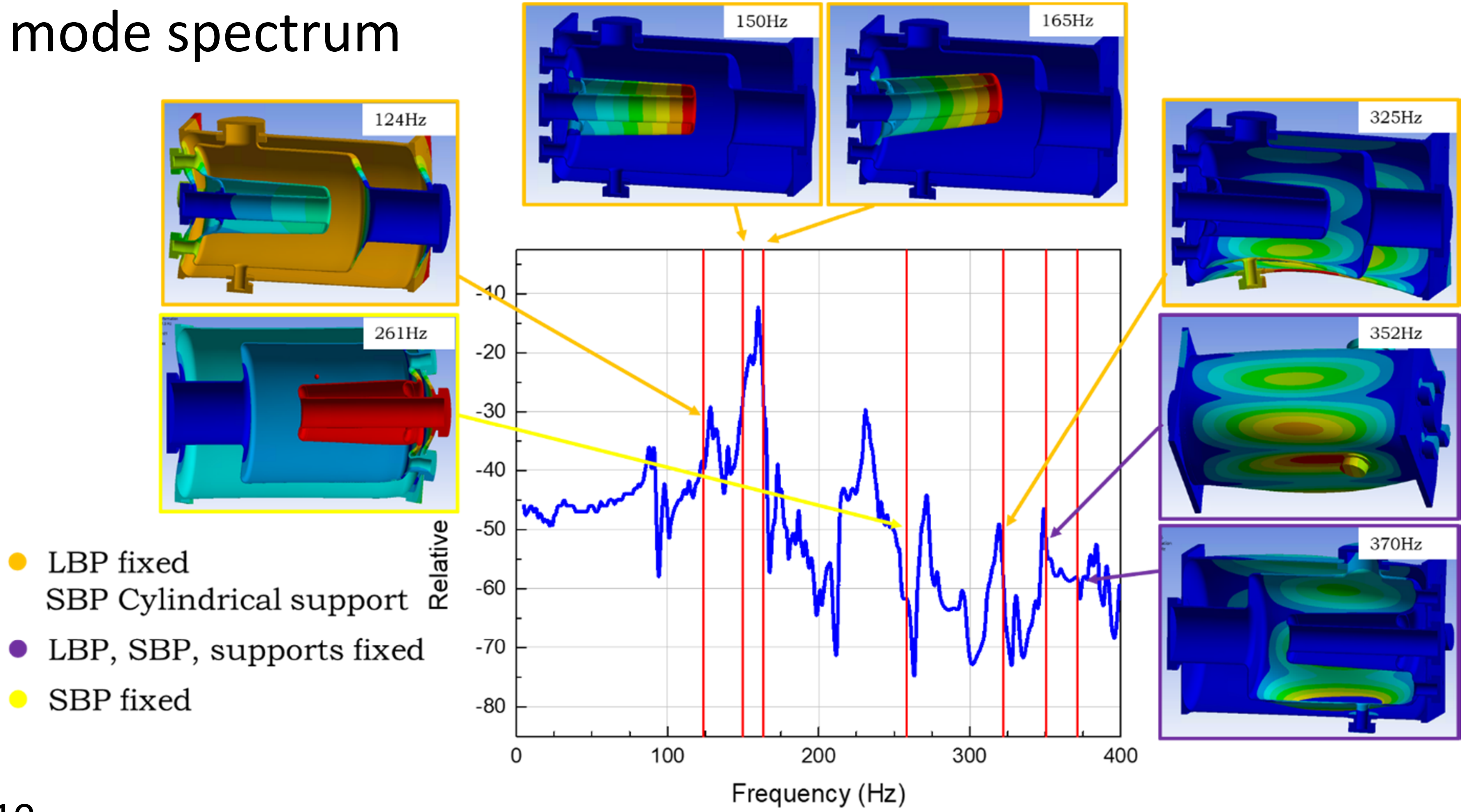
X.Y. Zhang et al., SRF2019, TUP010.

Microphonics

Use one piezo knocking on the cavity to sweep the mechanical mode spectrum

165Hz

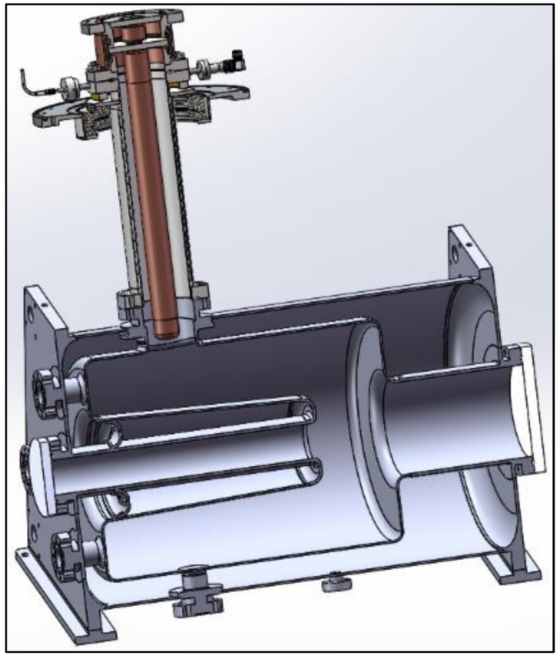




X.Y. Zhang et al., SRF2019, TUP010.

Lessons learnt

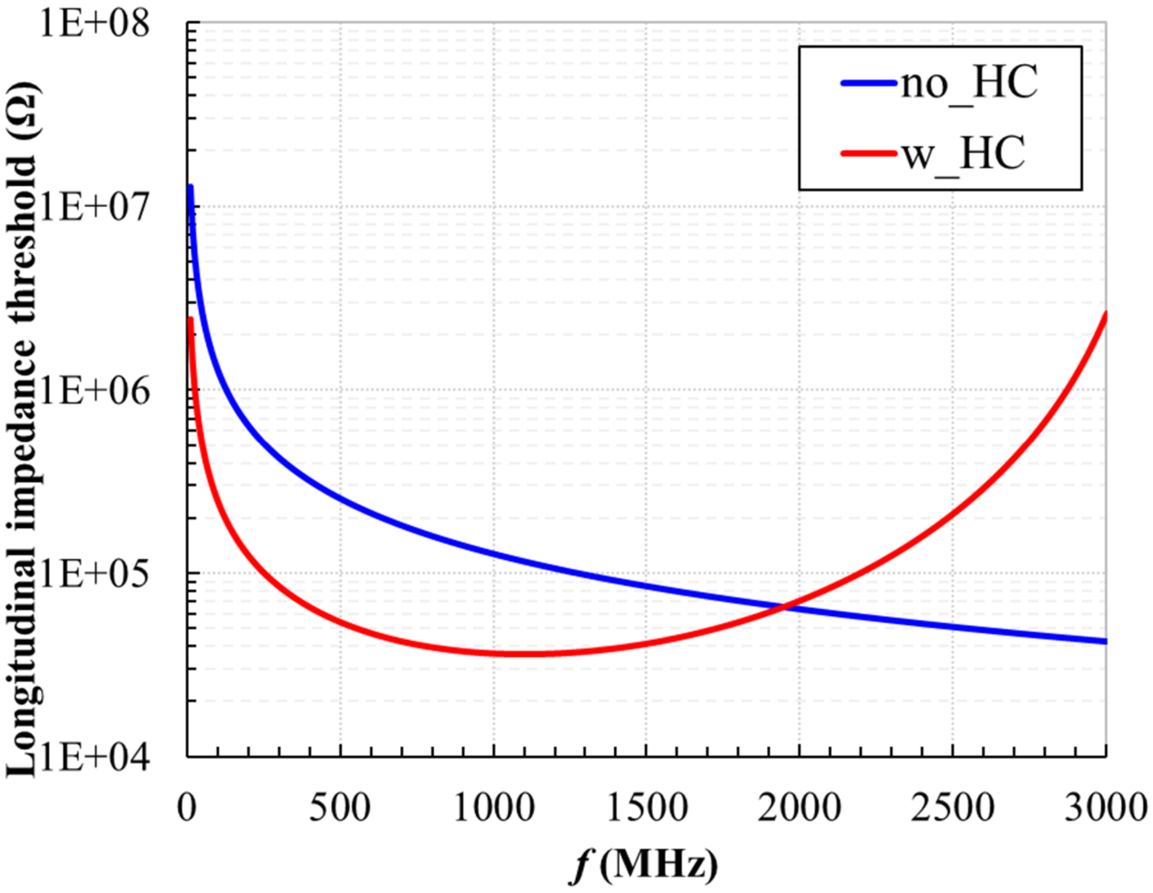
- Longer Nb tube of FPC port to reduce dynamic loss
- Improve FPC outer conductor cooling
- Larger helium vessel for stable 4K operation



166.6MHz HOM-damped cavity

HOM damping

Threshold due to coupled-bunch instabilities



Transverse impedance threshold

- Synchrotron radiation damping (SRD)

  - x: 3.4E6 Ω/m

  - y: 1.9E6 Ω/m

- SRD + Landau damping (LD)

  - y: 2.5E8 Ω/m

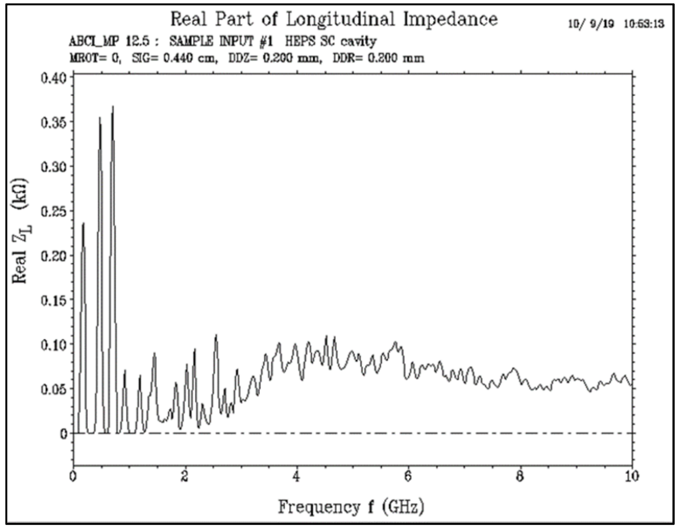
- **HOM damping requirements**

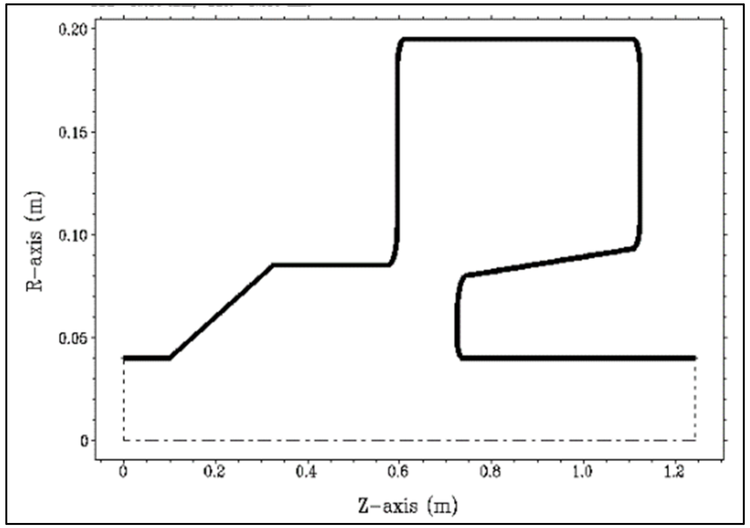
  - Q_L ~ **10^2 – 10^3** (monopole, w/ HC)

  - Q_L ~ **10^3** (dipole, SRD)

  - Q_L ~ 10^5 (dipole, SRD+LD)

HOM power

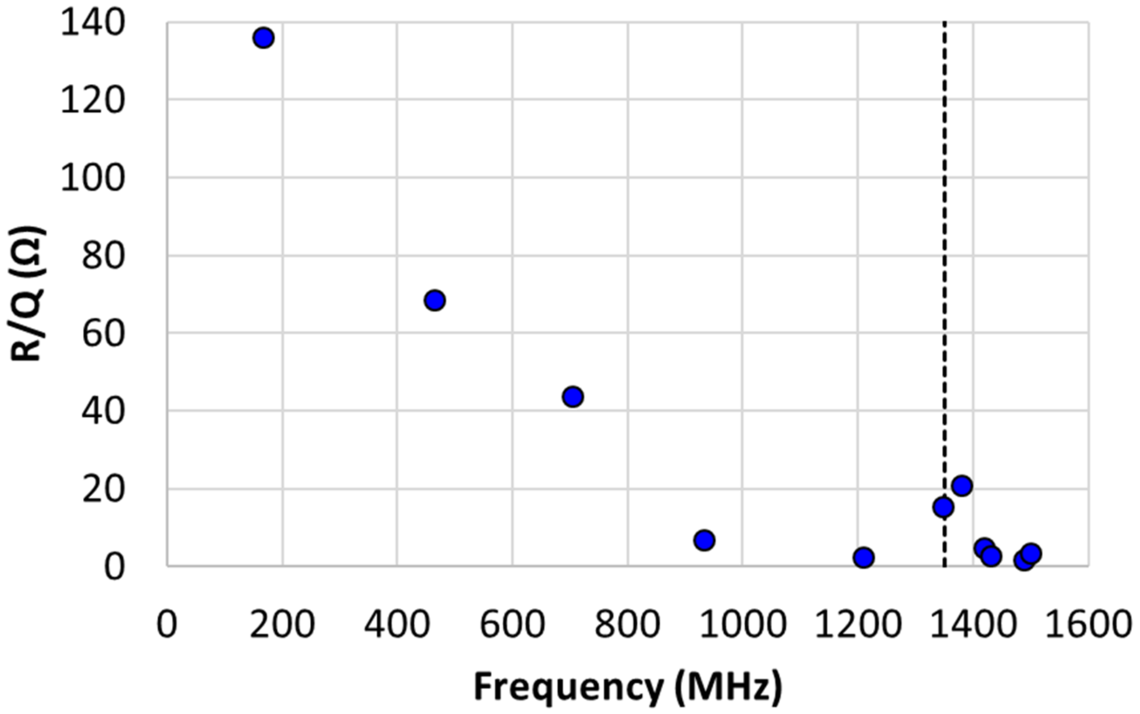




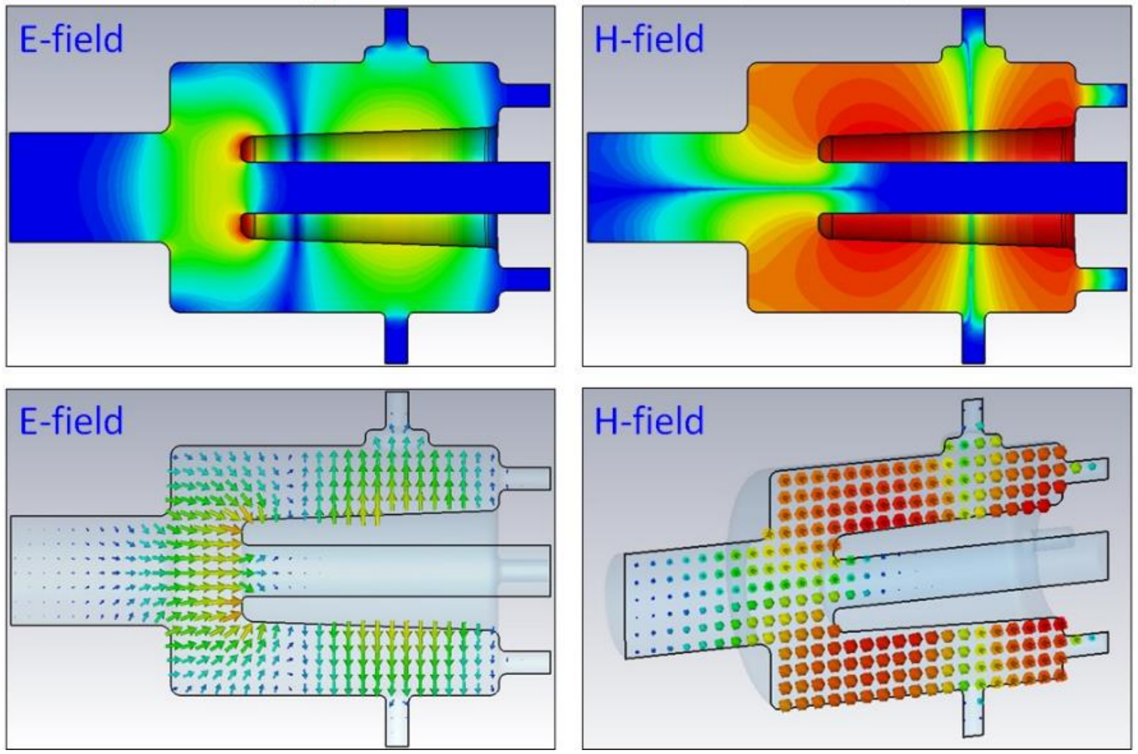
PoP cavity

Parameter	High-brightness mode	High-bunch-charge mode
Bunch length [mm]	4.4	
Bunch charge (q) [nC]	1.3	14.4
Beam current (I) [mA]	200	
Loss factor (k) [V/pC]	-1.136 (1 cavity)	
HOM power (=-k·q·I) [W]	295 (1 cavity)	3272 (1 cavity)

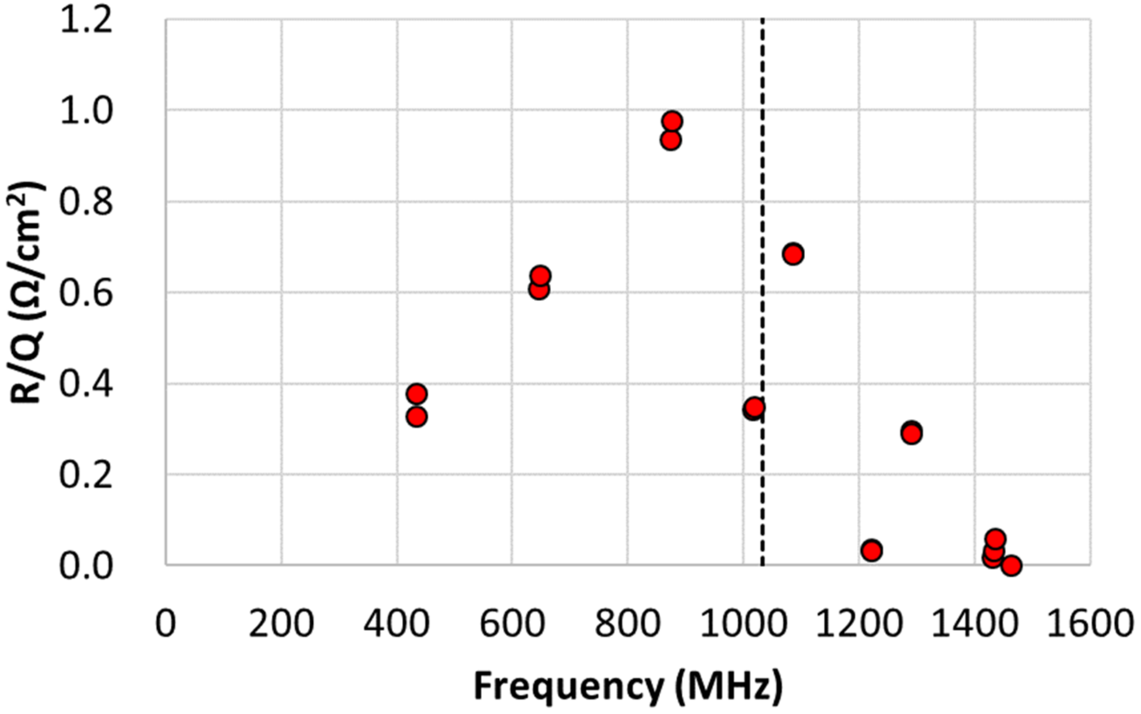
Monopole



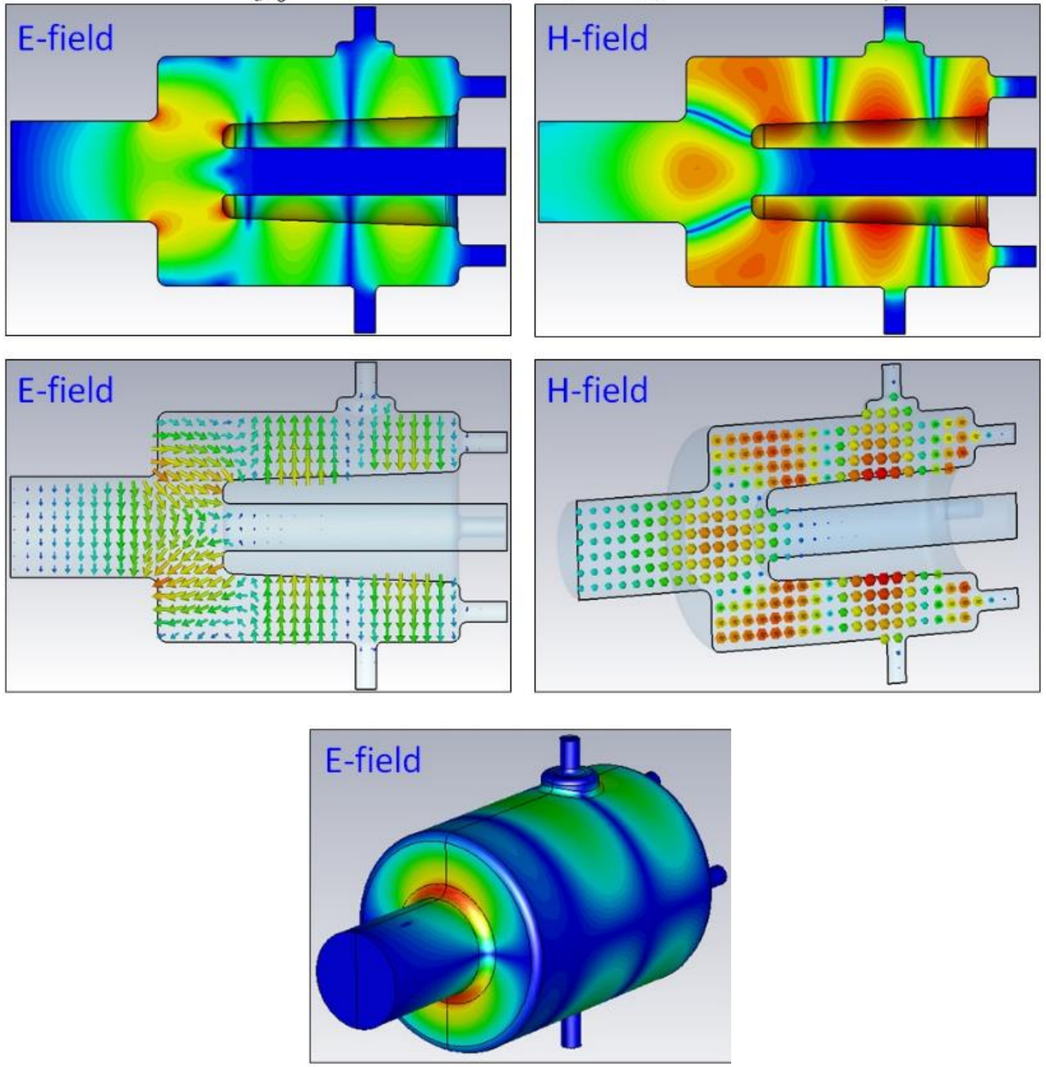
M2 (f_0: 464.009 MHz, R/Q: 68.5 Ω)



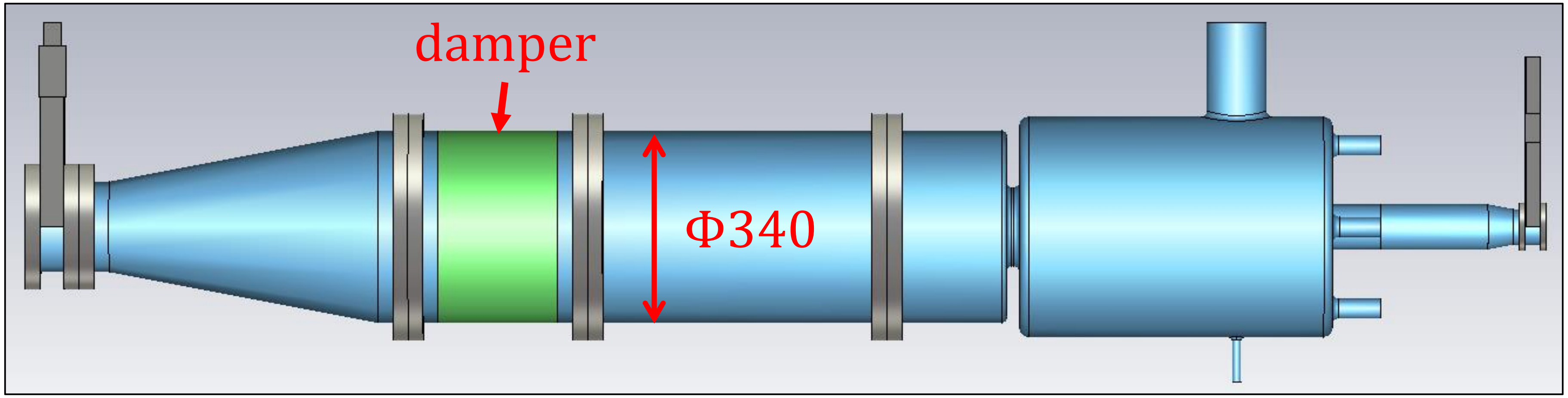
Dipole



D3.1 (f_0: 873.909 MHz, R/Q: 0.94 Ω/cm²)



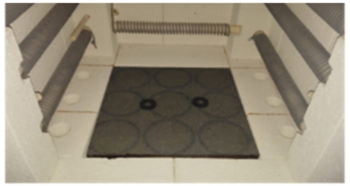
Hybrid damping



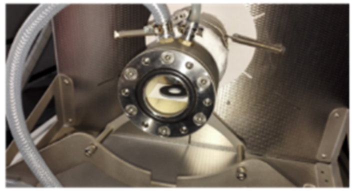
Beam-pipe cutoff frequency: 675MHz (monopole), 517MHz (dipole)

- **Below f_{cutoff} (localized modes)**
  - M2 (464MHz) and D1 (433MHz)
  - HOM coupler
- **Above f_{cutoff} (propagating modes)**
  - Beam-pipe HOM damper

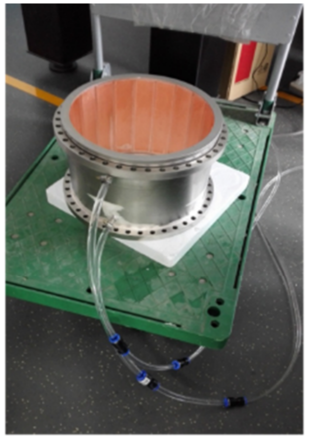
Beampipe HOM damper



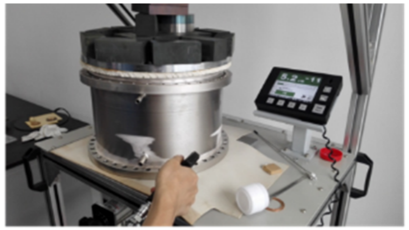
Metallization temperature



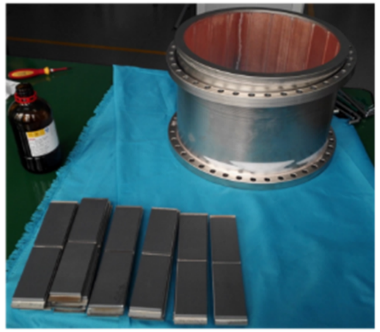
Brazing temperature



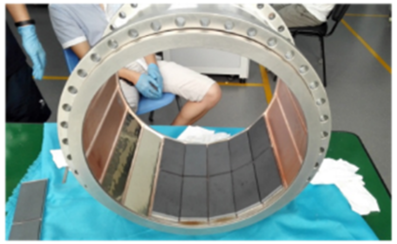
Hydrostatic test



Vacuum leak detection

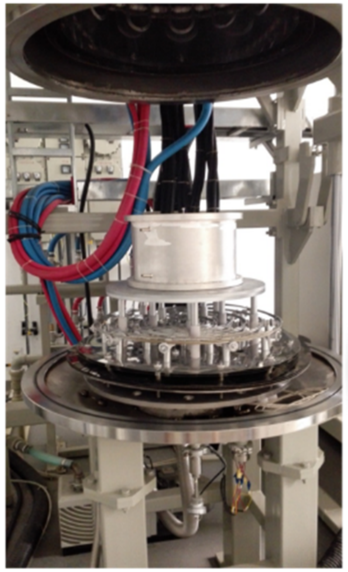


Ferrite and outer pipe

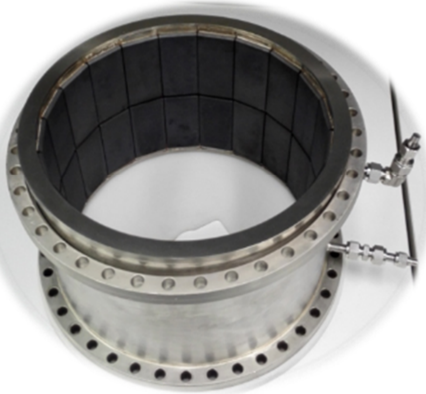


Assembly

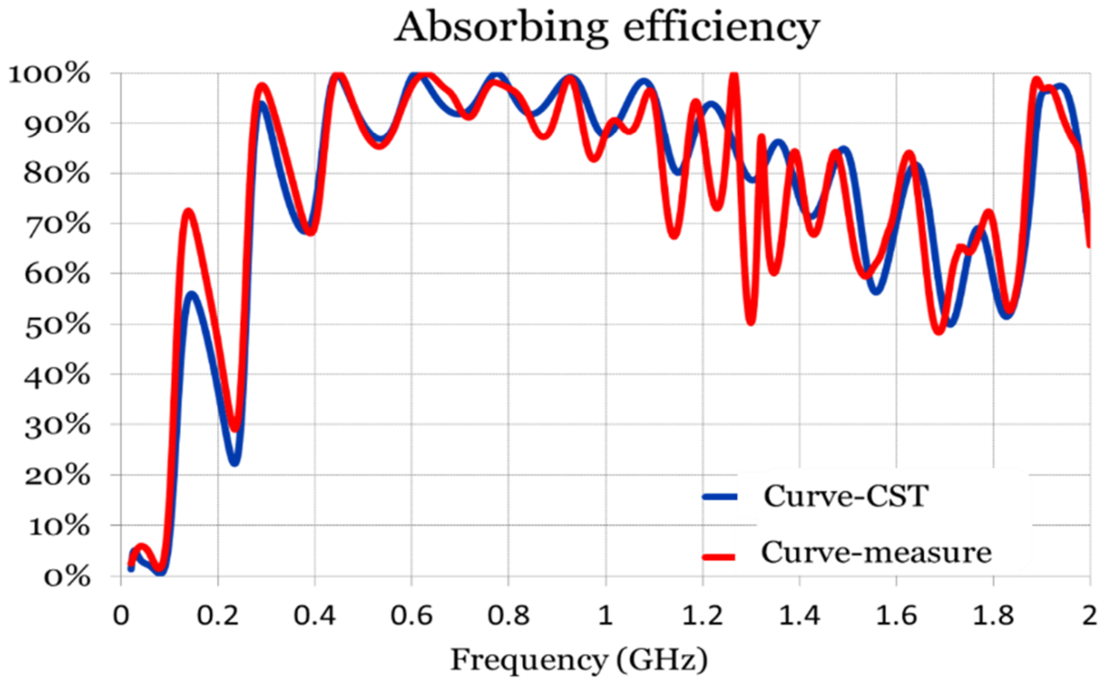
Fixation



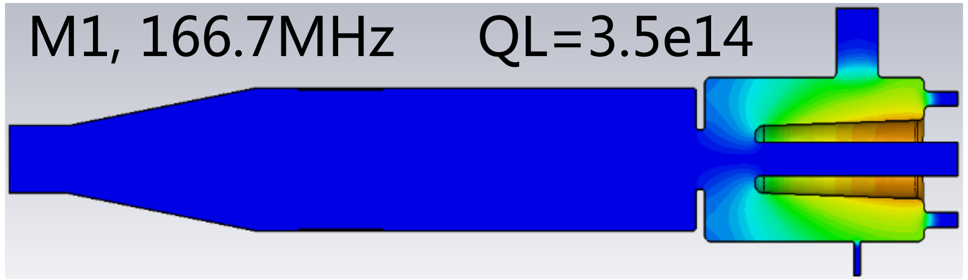
Brazing

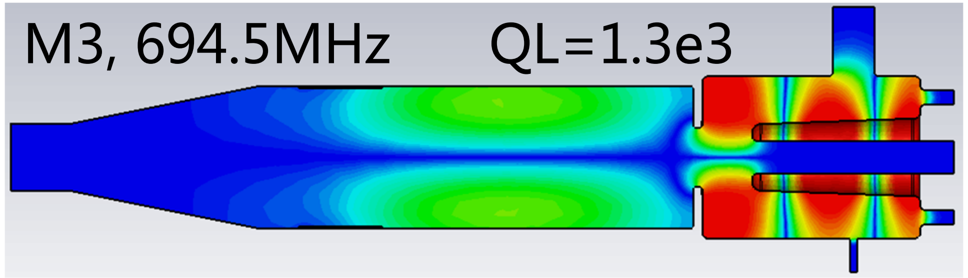


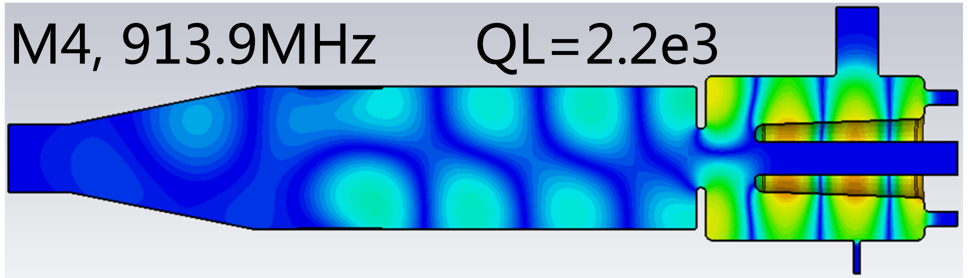
Prototype



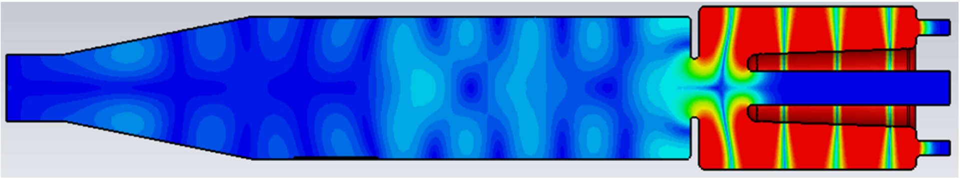
Propagating HOMs

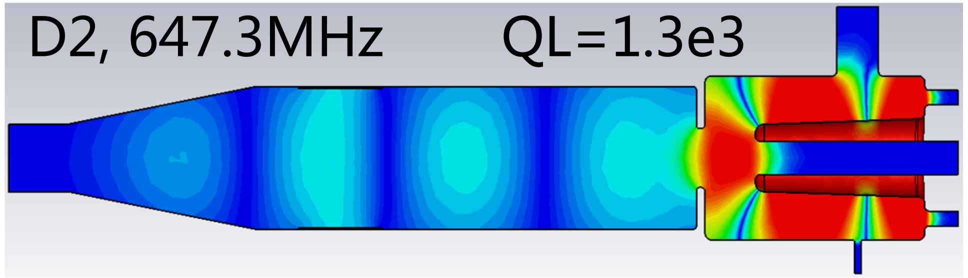


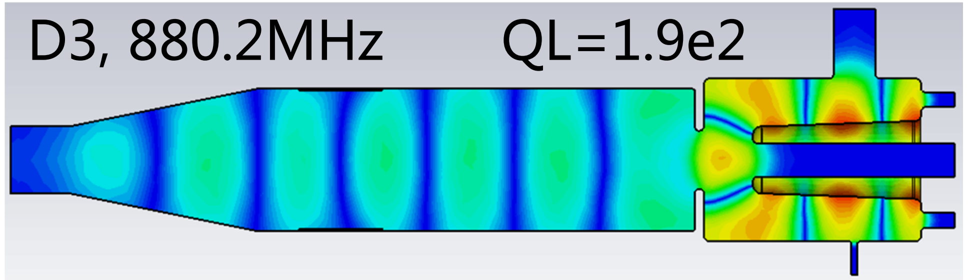


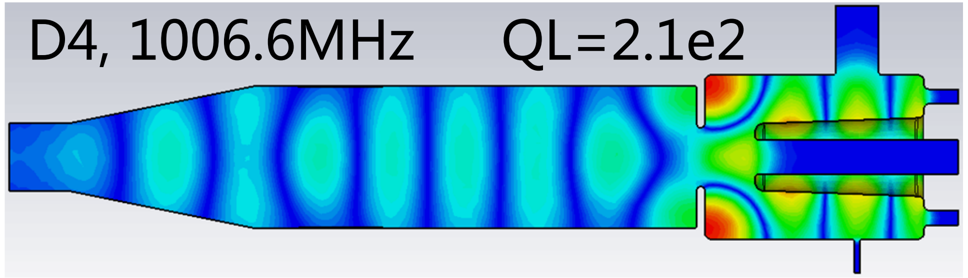


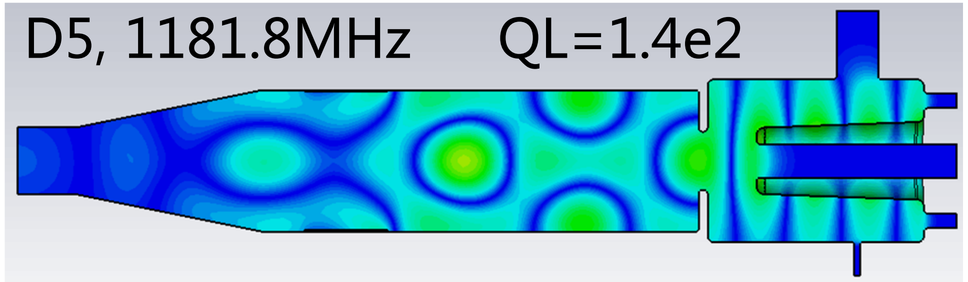
M5, 1189.4MHz QL=1.06e4



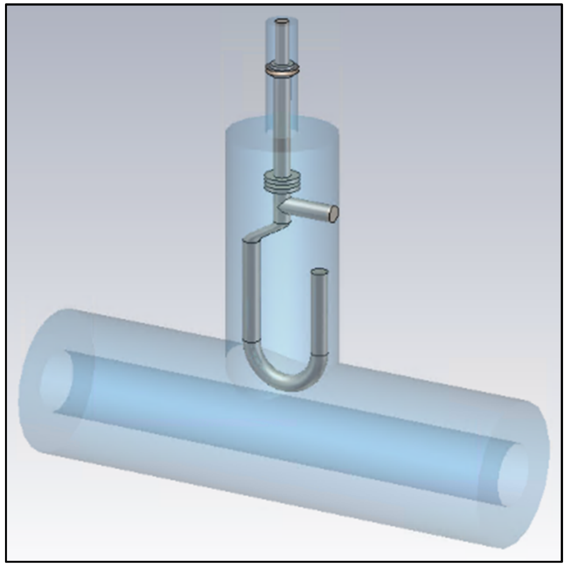


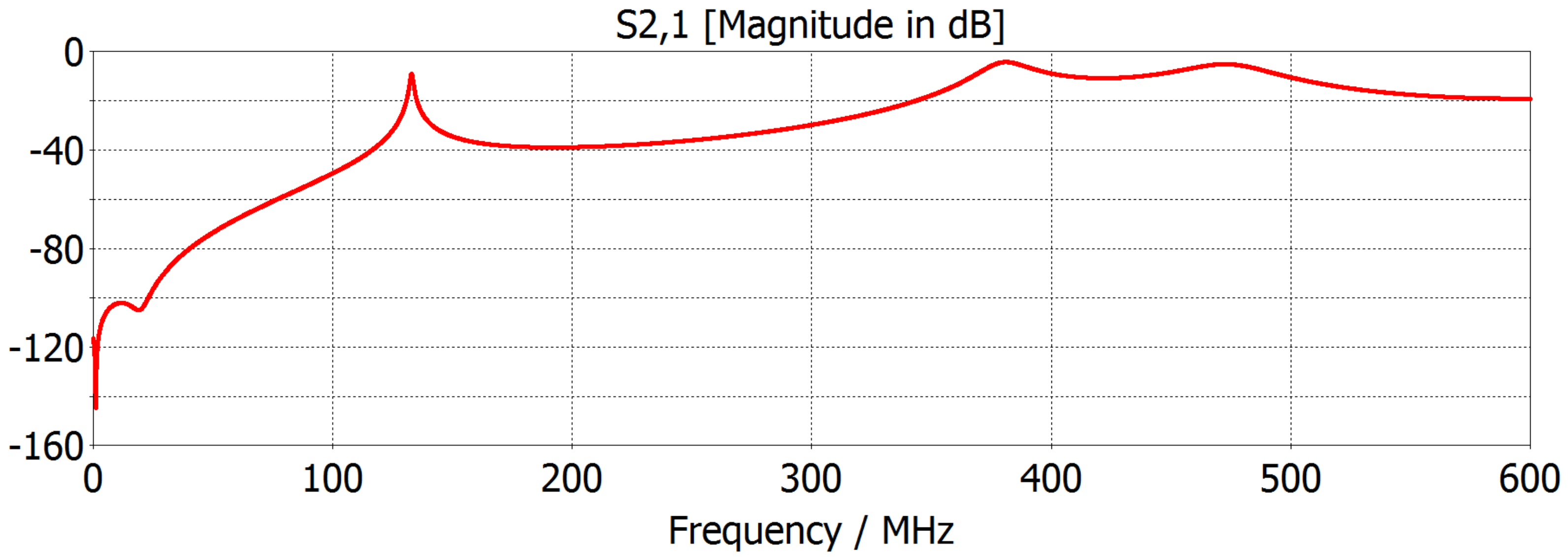


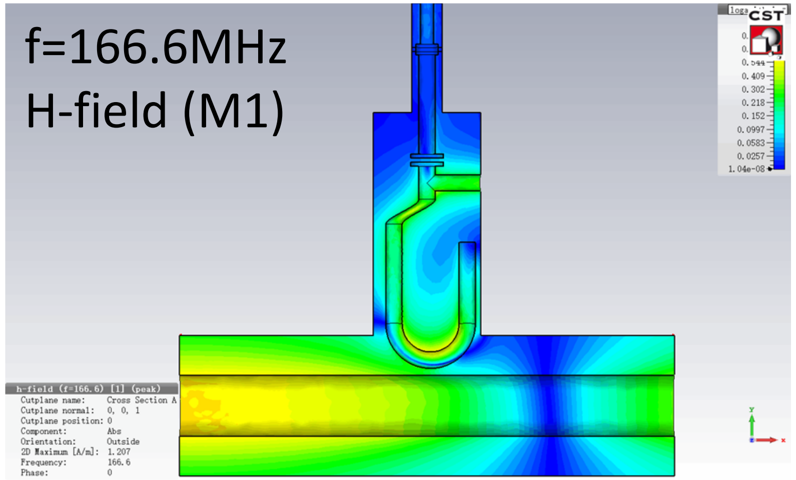


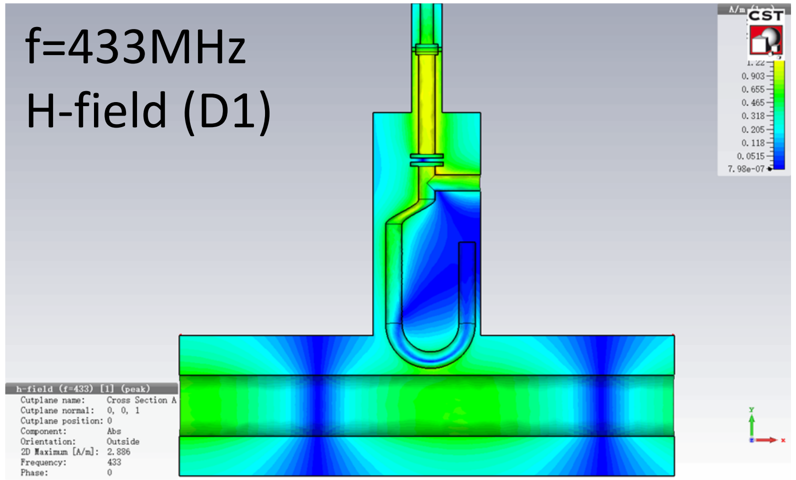


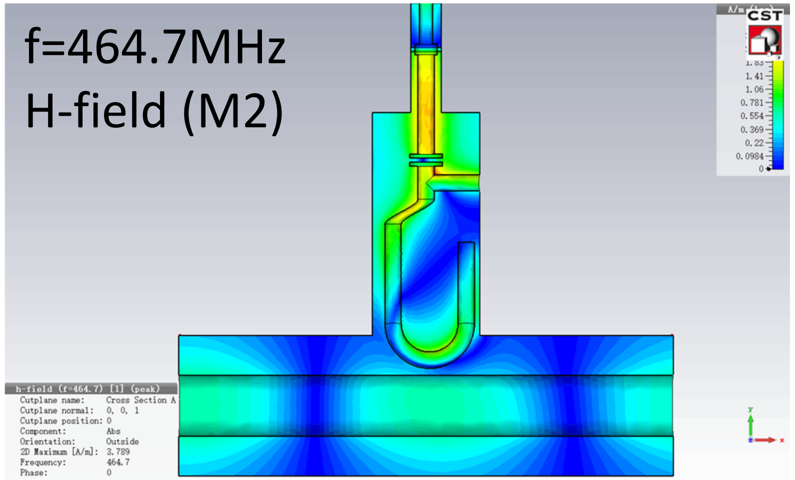
HOM coupler



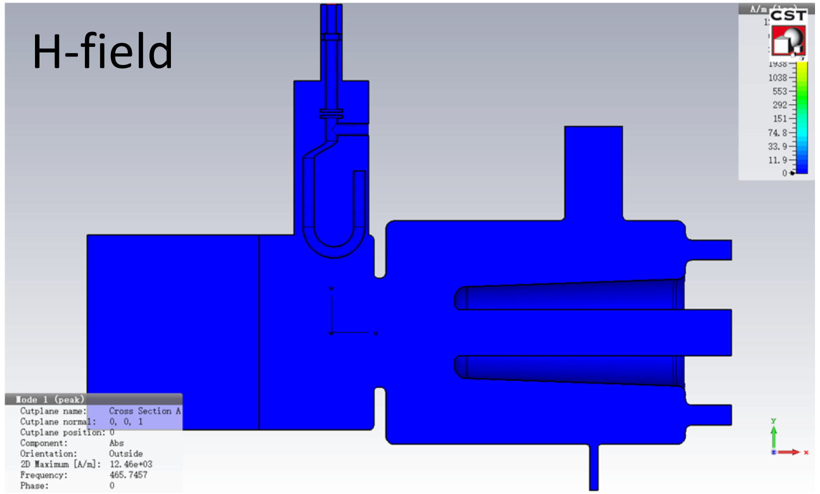

S2,1 [Magnitude in dB]
0
-40
-80
-120
-160
0
100
200
300
400
500
600
Frequency / MHz


f=166.6MHz
H-field (M1)
CST


f=433MHz
H-field (D1)
CST

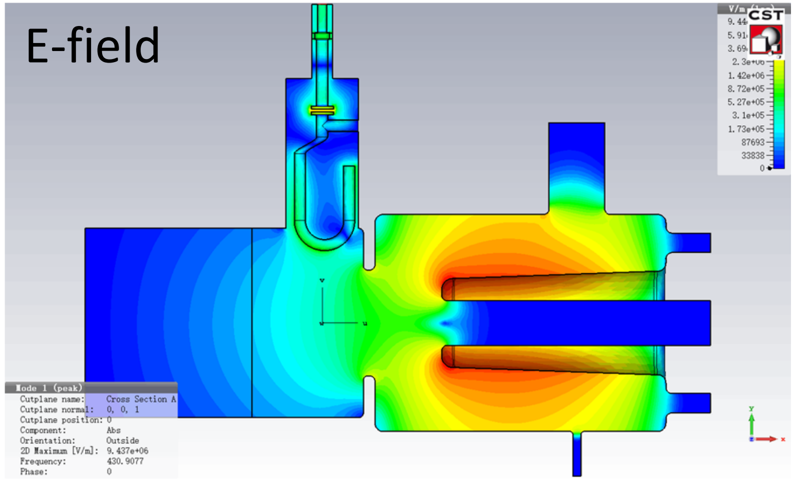

f=464.7MHz
H-field (M2)
CST

HOM coupler



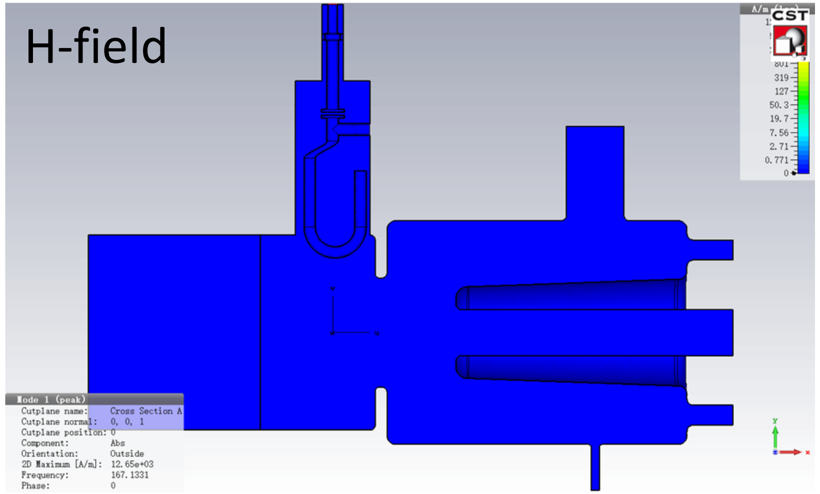
M2

Freq: 465.746 MHz
R/Q: 66.0 Ω
Qe: 4.8e4
Qe_th: 3.5e2



D1

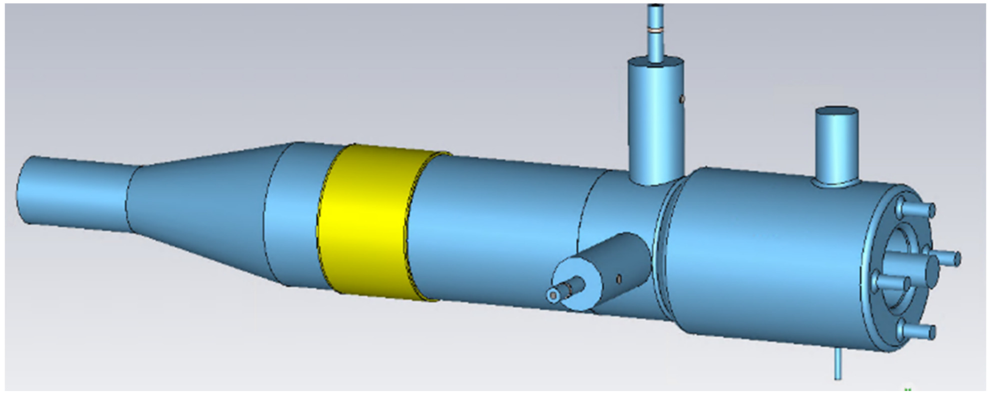
Freq: 430.908 MHz
R/Q: 474.9 Ω/m
Qe: 4.3e4
Qe_th: 1.6e3

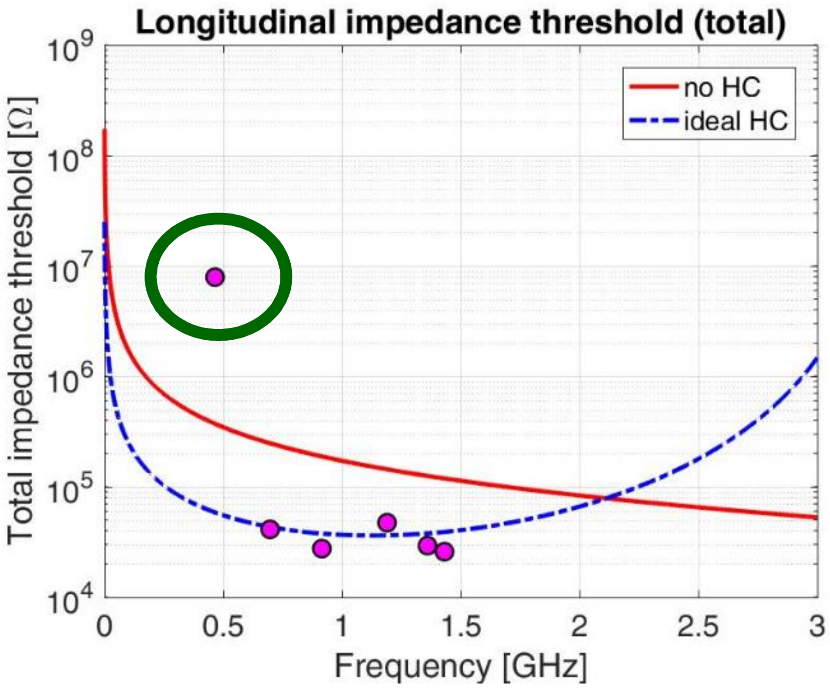


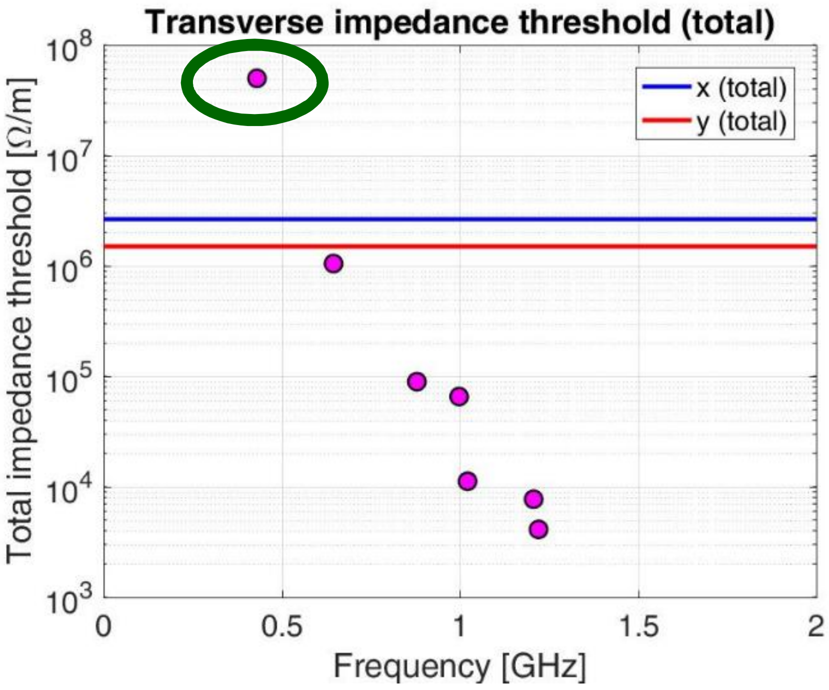
Fundamental mode

Freq: 167.133 MHz
R/Q: 134.9 Ω
Qe: 2.1e8
Qe_th: >1e10

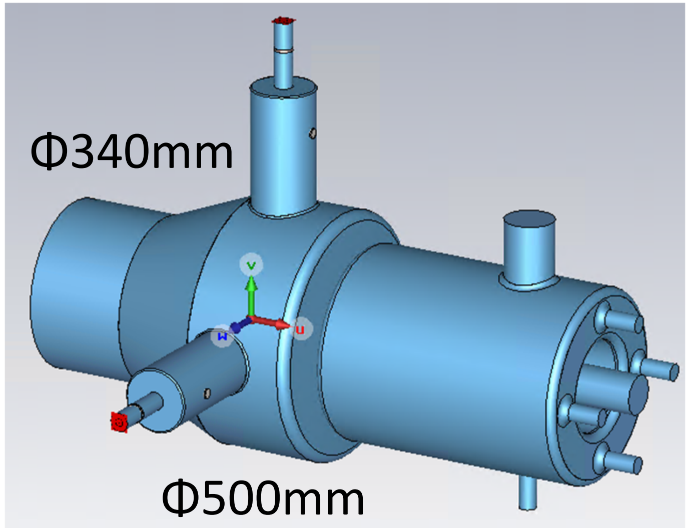
HOM coupler + damper

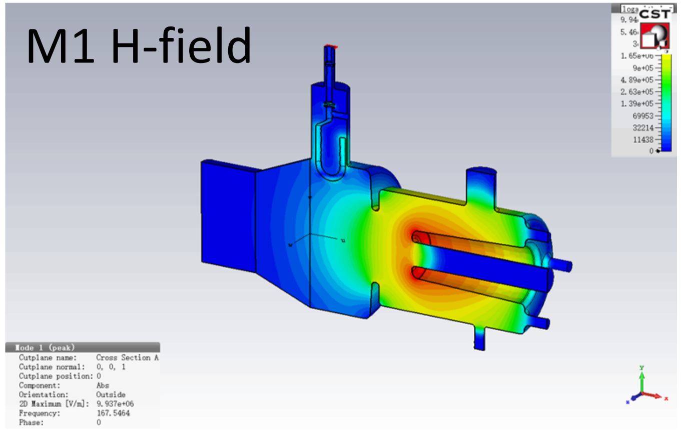




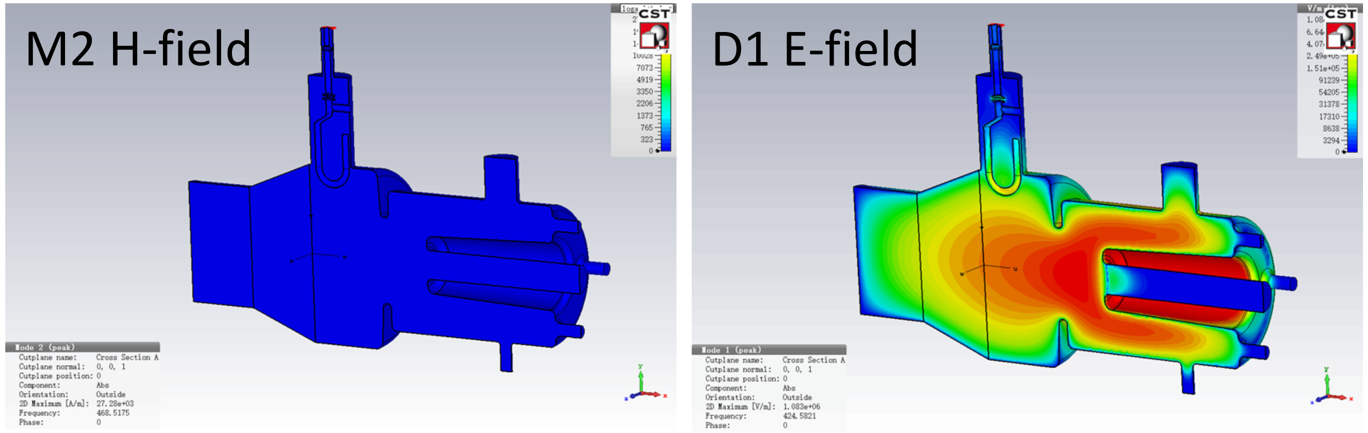


HOM coupler





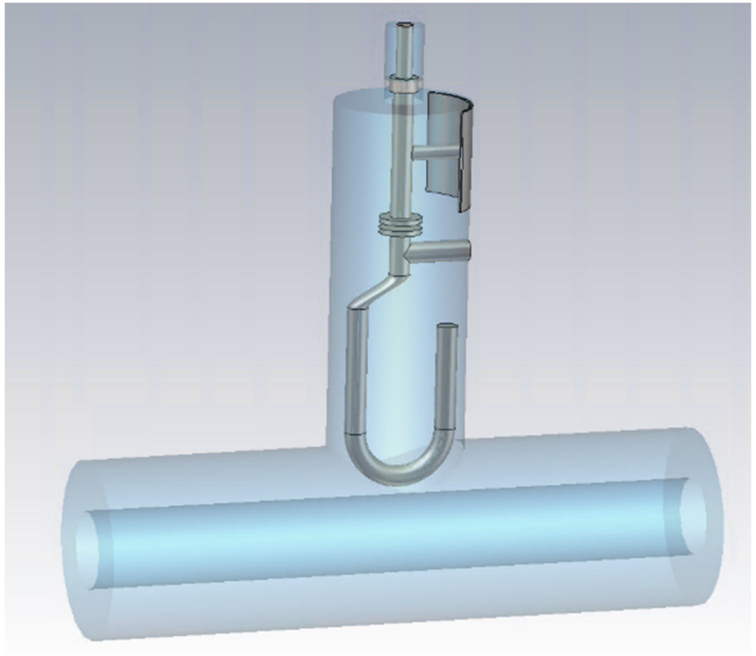
Mode	Freq. (MHz)	R/Q (Ω)	Q_{ext}	Z (Ω)	Zth_HC _1C (Ω)
M1	167.546	133.5	8.8e7	/	/
M2_1	465.792	12.0	1.4e3	8.7e3	1.2e4
M2_2	468.518	36.3	6.3e2	1.1e4	1.2e4

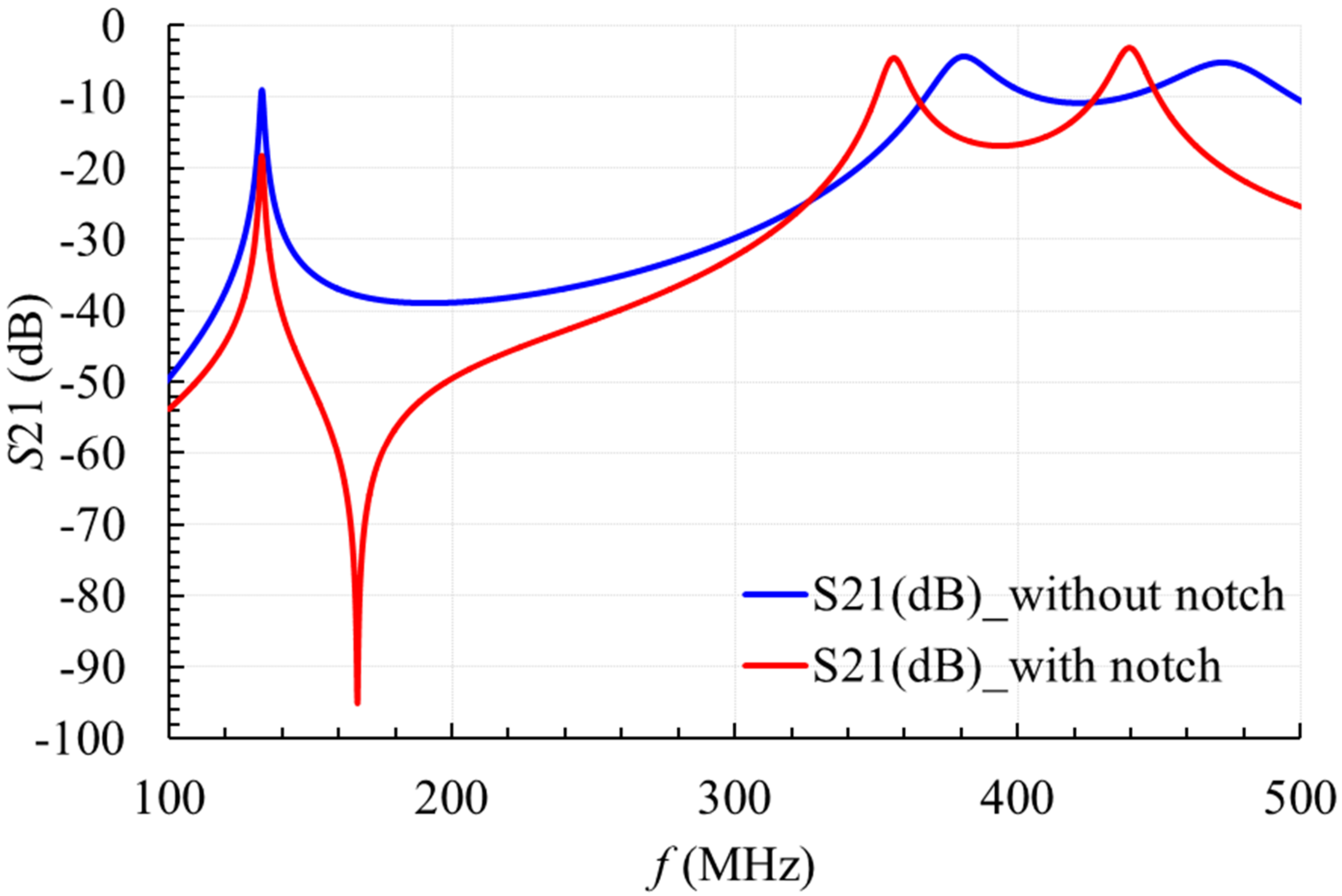


Mode	Freq. (MHz)	R/Q (Ω/m)	Q_{ext}	Z (Ω/m)	Zth_1C (Ω/m)
D1.1	424.582	376.7	2.5e4	4.6e6	3.8e5
D1.2	425.609	445.4	2.3e4	5.2e6	3.8e5

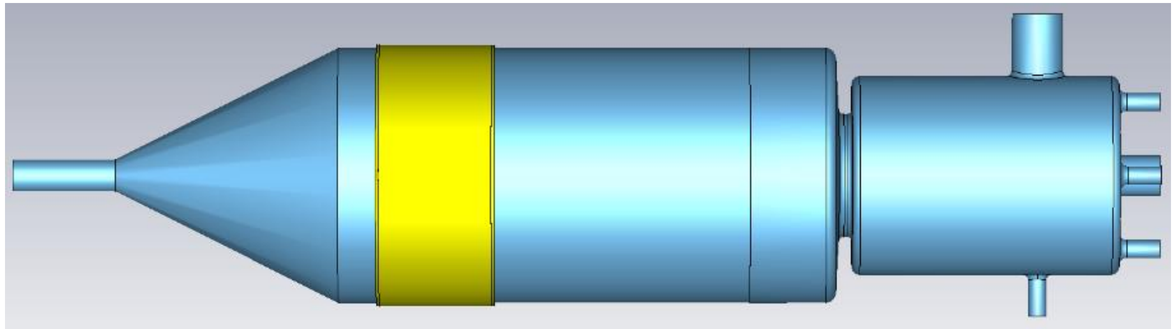
Loss factor: -1.528V/pC (400W, 4.4kW)

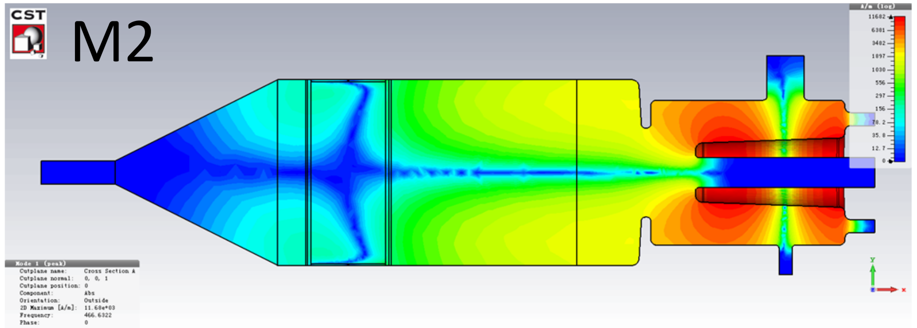
HOM coupler w/ notch

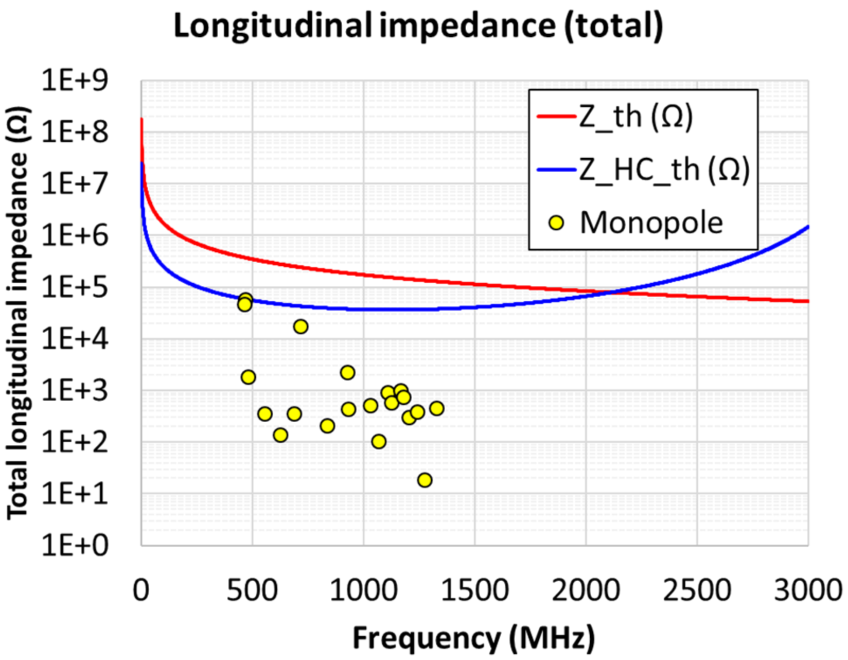


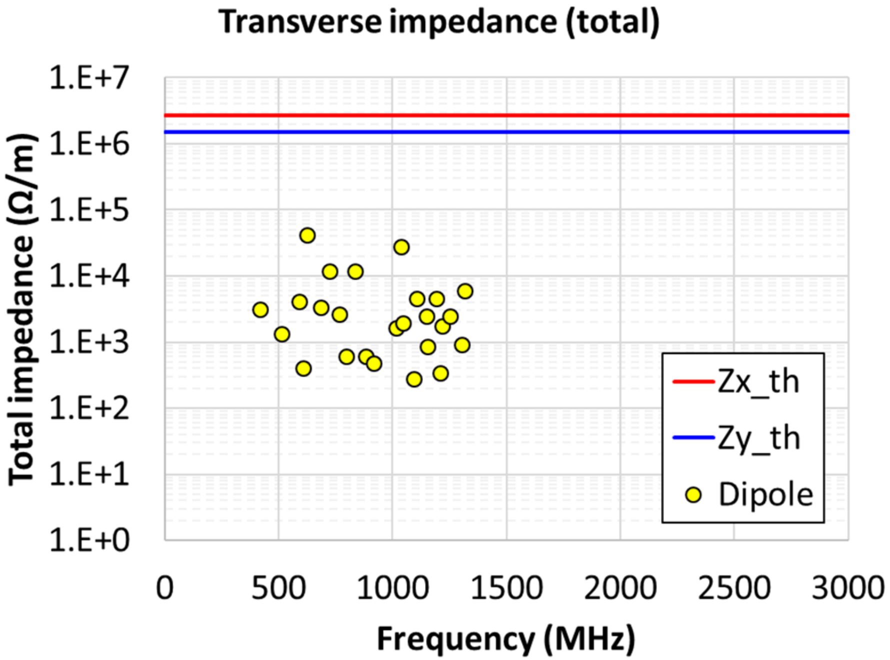


Enlarged beam pipe



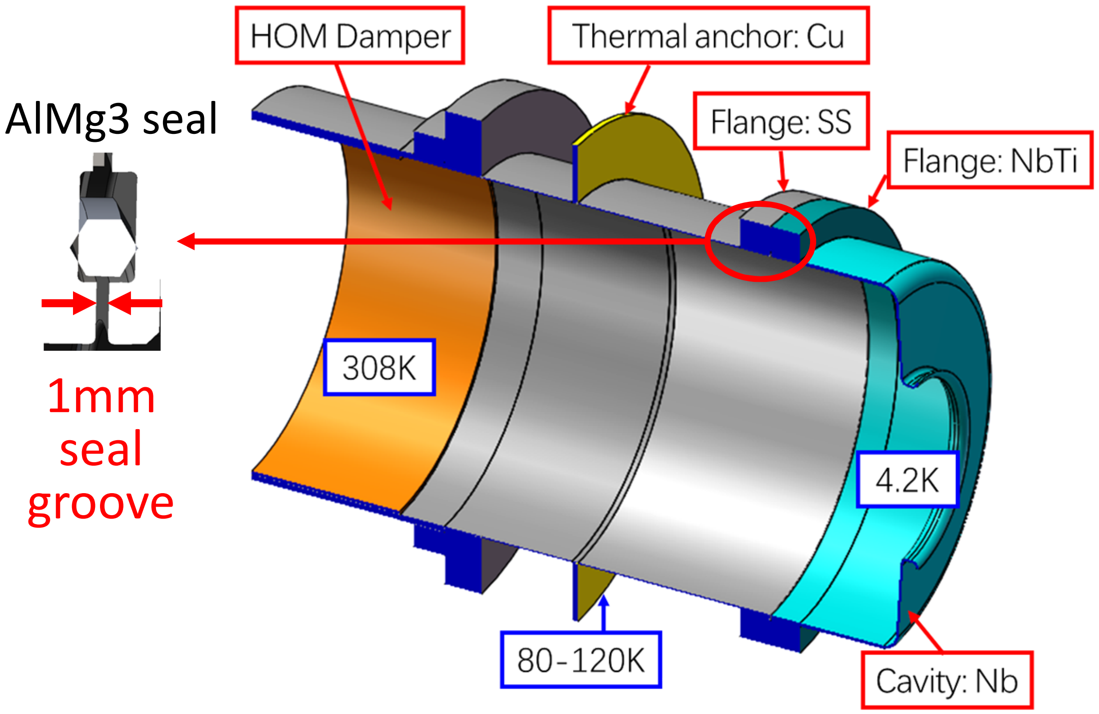






Loss factor: -2.697 V/pC (700W, 7.8kW)

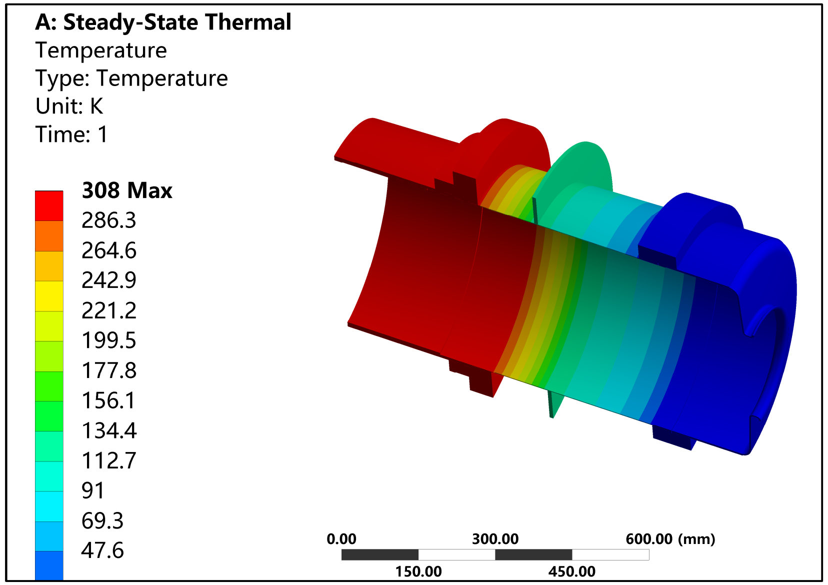
RF heating on seal

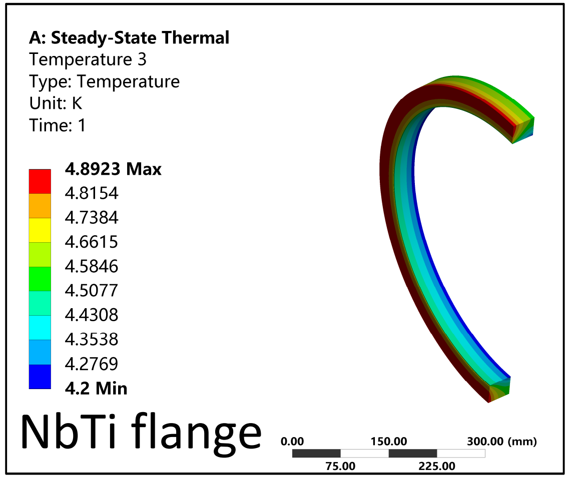


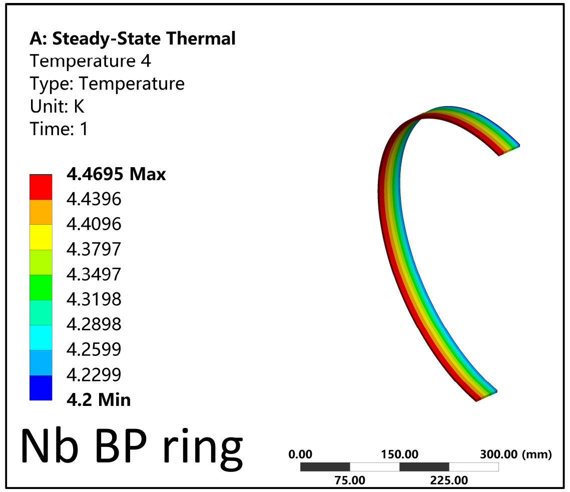
- **RF loss (Vc=1.5MV)**
  - Seal_NbTi: 0.18 W
  - Seal_SS: 0.65 W
  - Seal_AlMg3: 0.013W
  - Seal_Nb: 0.03 W

- Max temperature (Vc=1.5MV)
  - NbTi: 4.9K
  - Nb: 4.5K

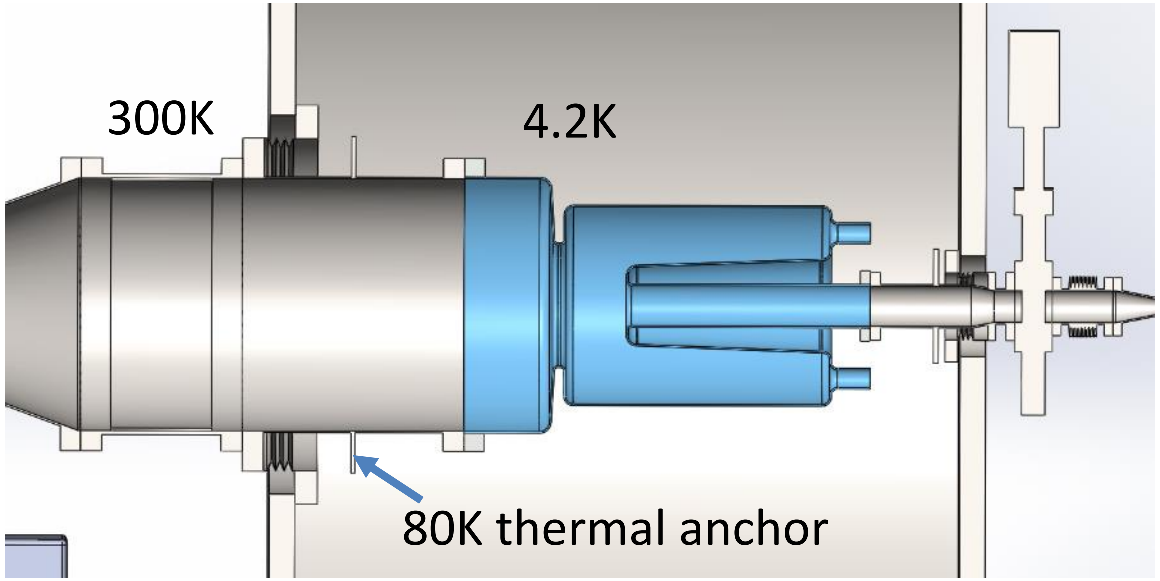
Need to be double-checked with other simulation codes.







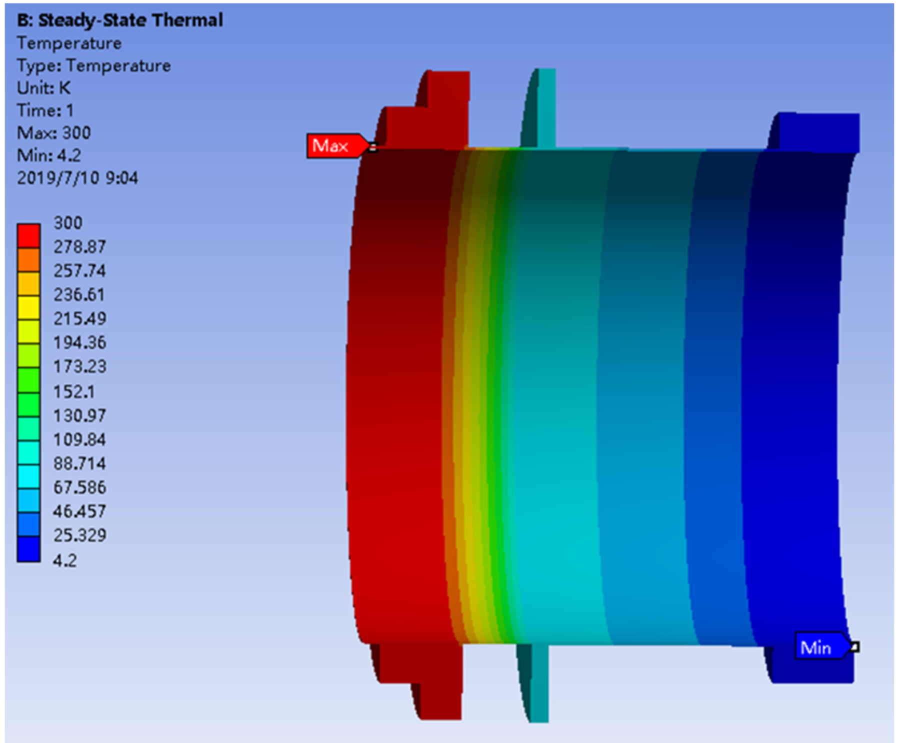
Transition tube



- Thickness: 2mm
- Length: 440mm
- Material: stainless steel

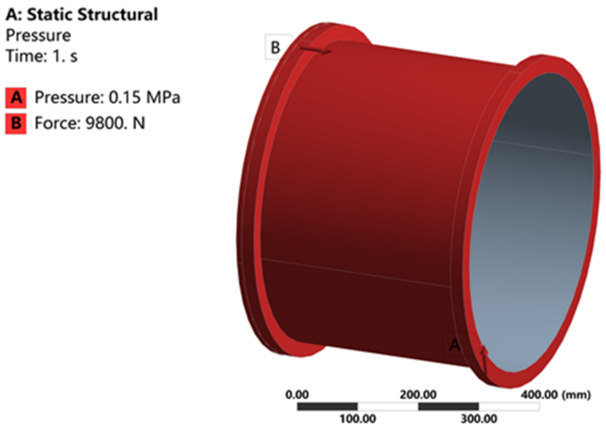
- Tunnel: 25±0.1°C, 30-70% humidity
- Dew point: 6°C (30%) - **19°C** (70%)

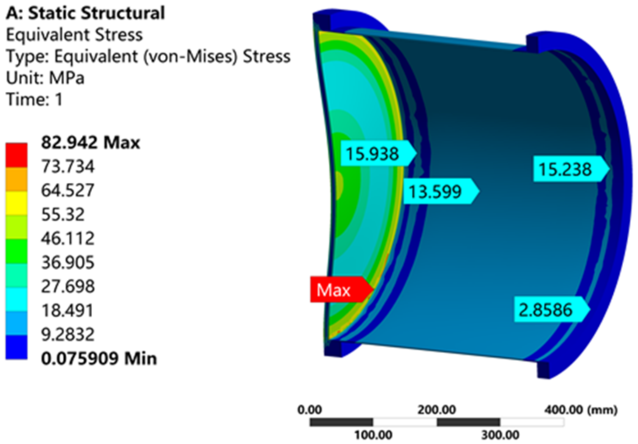
- **Static loss**
  - 4.2K: 5W
  - 80K: 60W
  - Cavity warm flange T: **19.3°C**



Transition tube

1.5atm external surface + 1000kgf tuning force + 1.5atm on blind flange

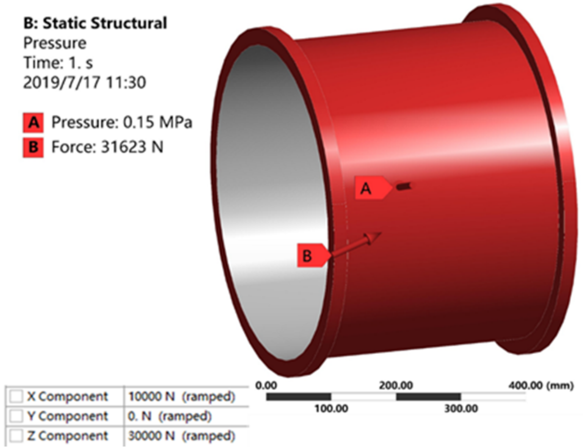


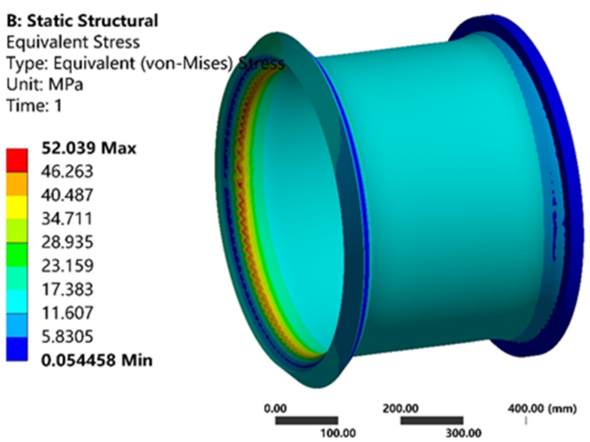


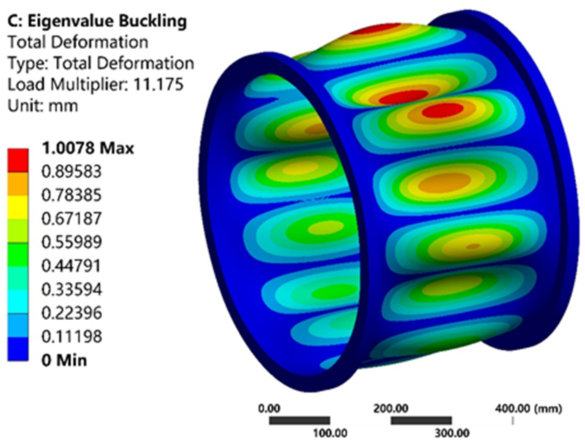
- Allowable stress for SS
  - 114MPa (293K)
  - 373MPa (4K)

- Mechanically stable from simulations
- Tests has been planned

External stress + tuning force + shearing force



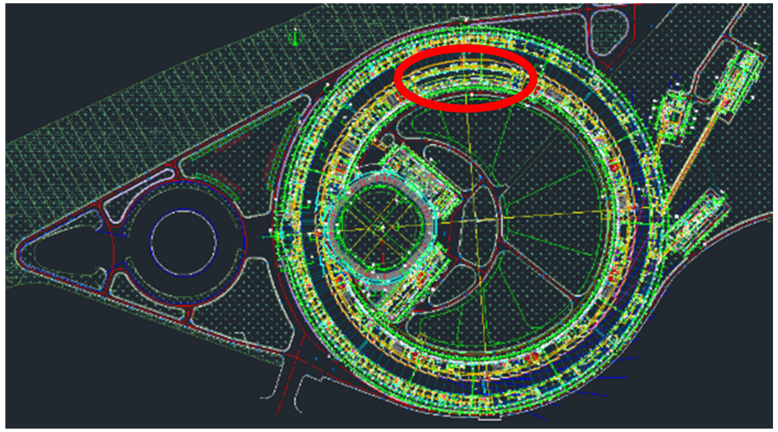


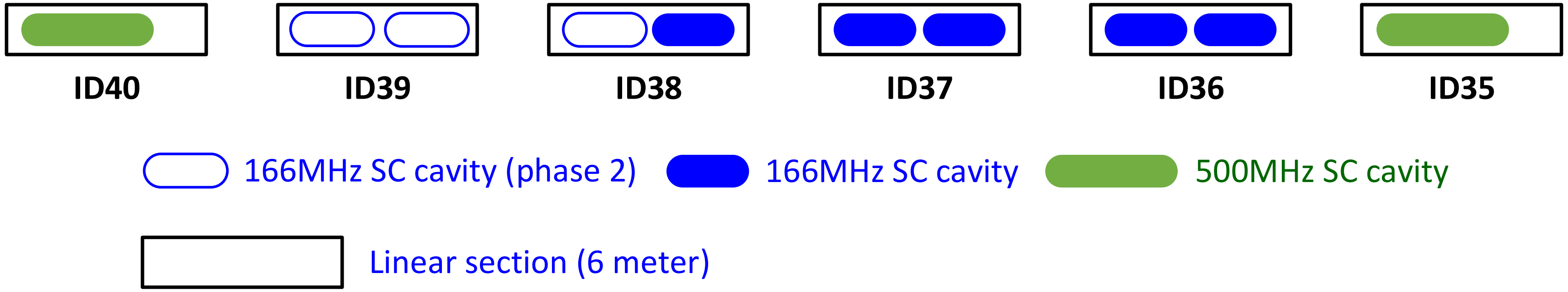


Lowest mode

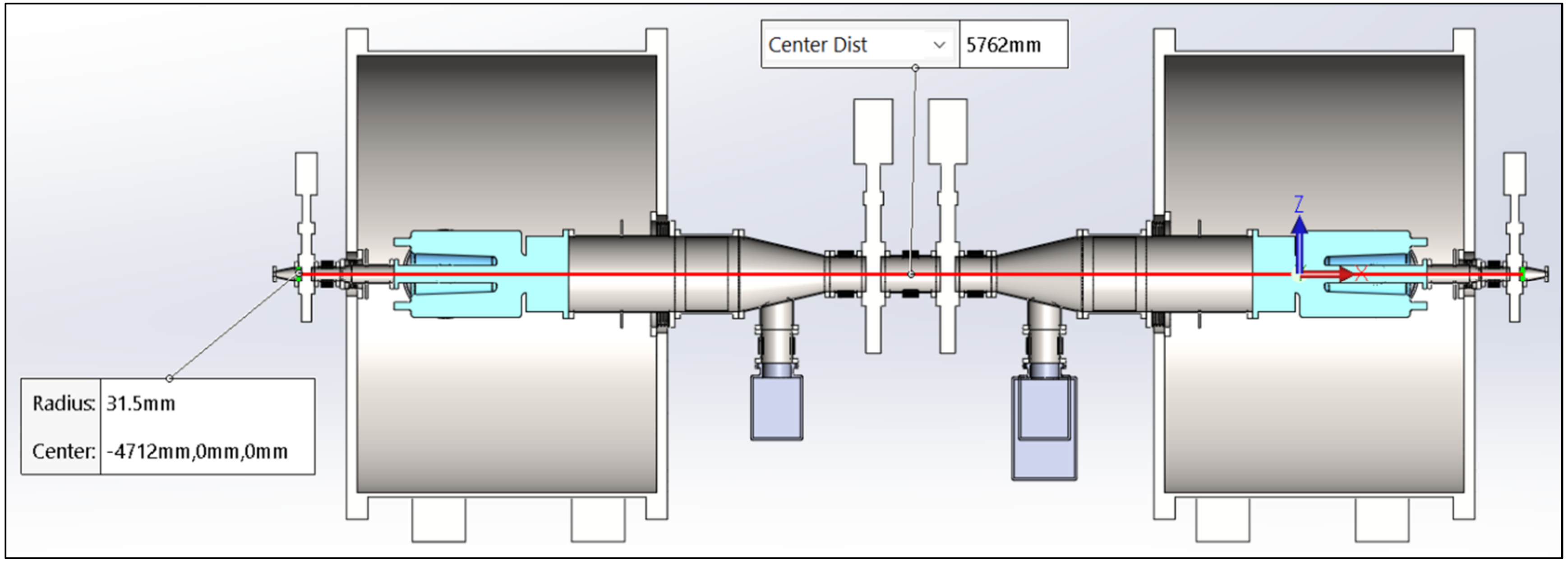
- Load multiplier: 11.2
- Critical load
  - Pressure: 1.68 MPa
  - Tuning force: 335kN

Space

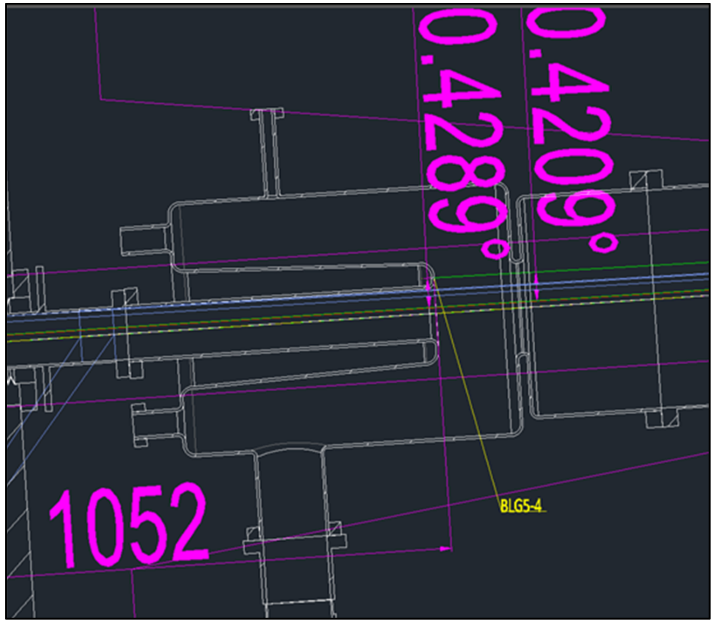




ID40
ID39
ID38
ID37
ID36
ID35
166MHz SC cavity (phase 2)
166MHz SC cavity
500MHz SC cavity
Linear section (6 meter)

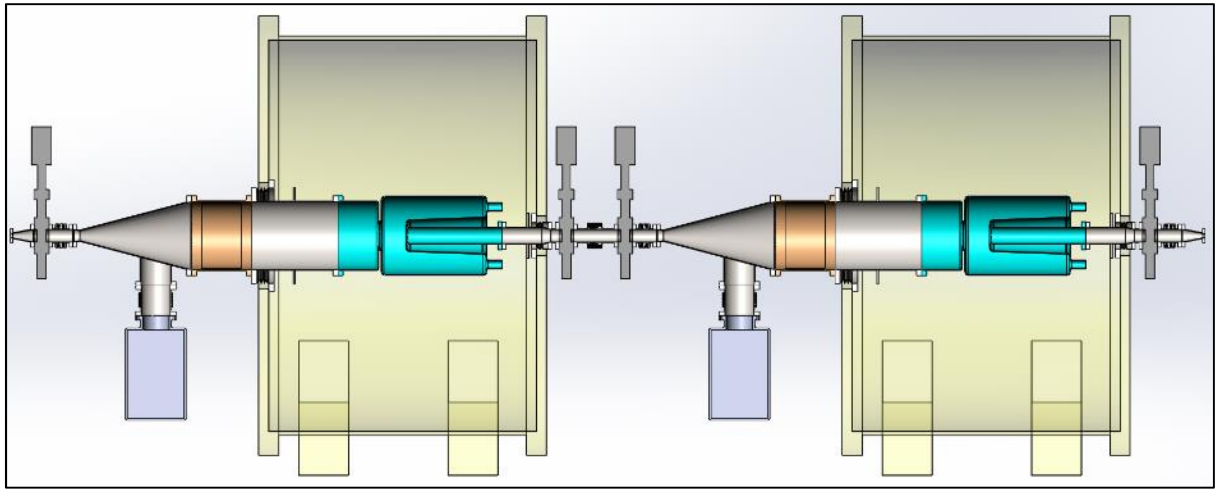


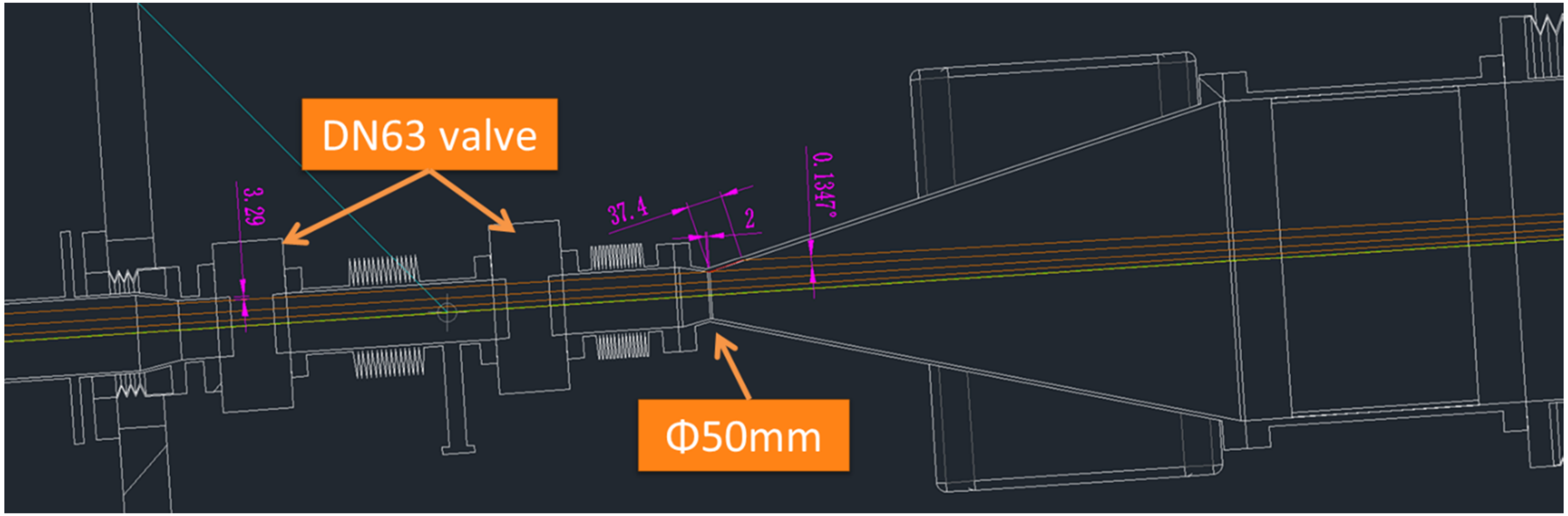
Center Dist
5762mm
Radius: 31.5mm
Center: -4712mm,0mm,0mm



0.4289°
0.4209°
1052

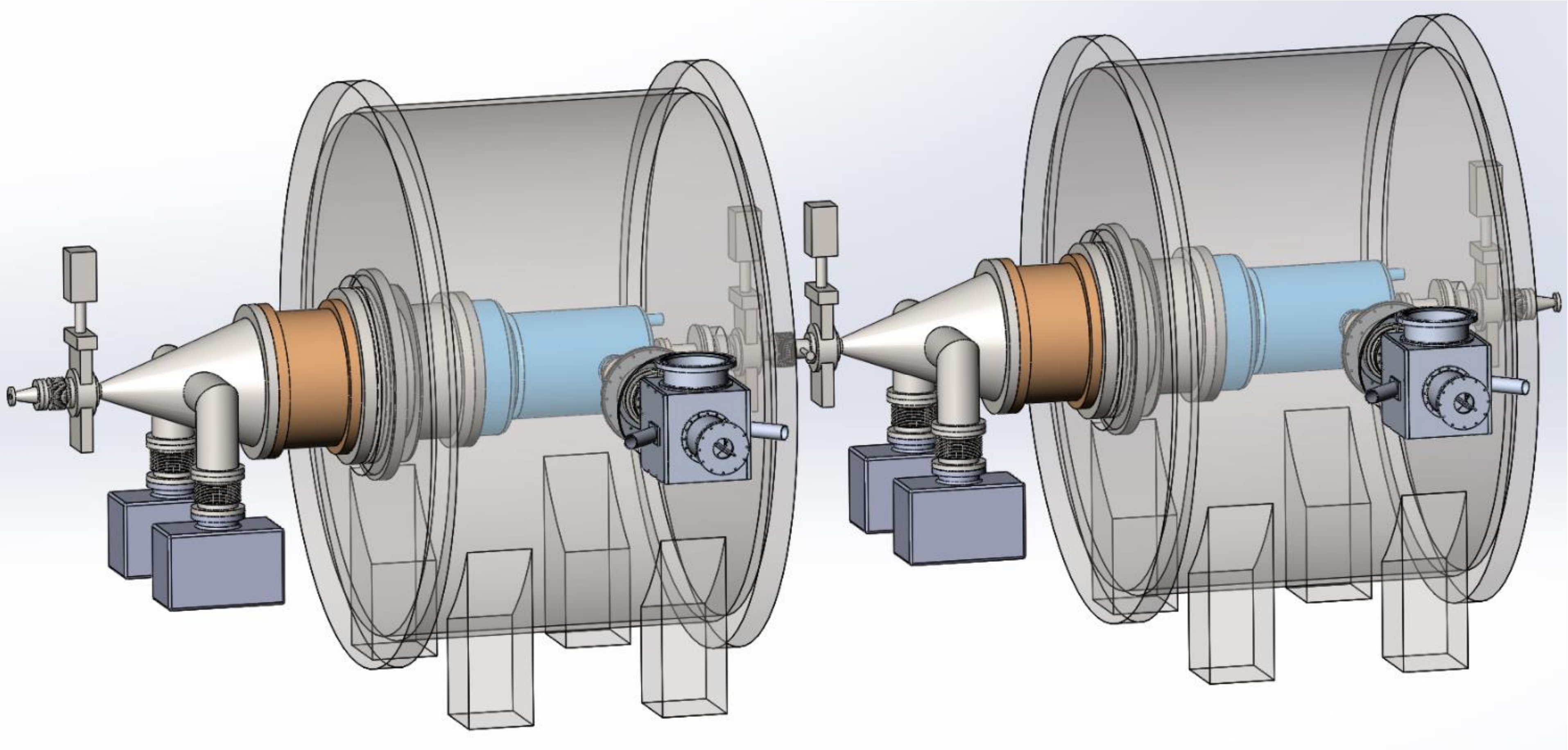
Synchrotron light





Enlarged beam pipe

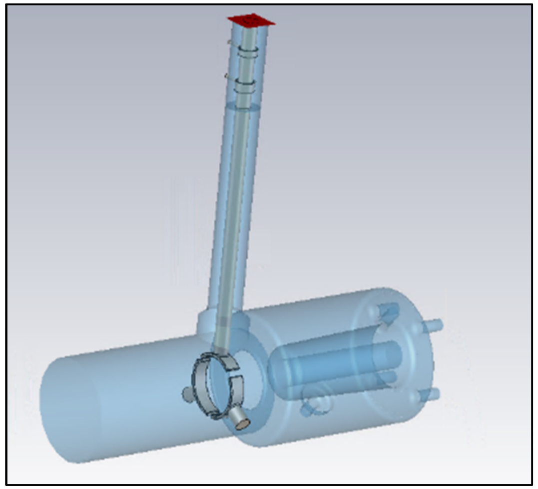
Cryomodule to be designed



Loss factor: -5.379 V/pC (2 cavity string)

Various design trials

Petal + HOMC



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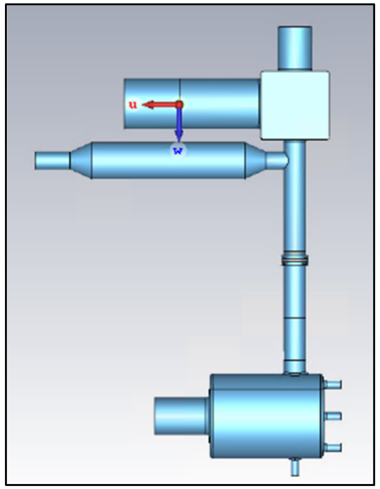
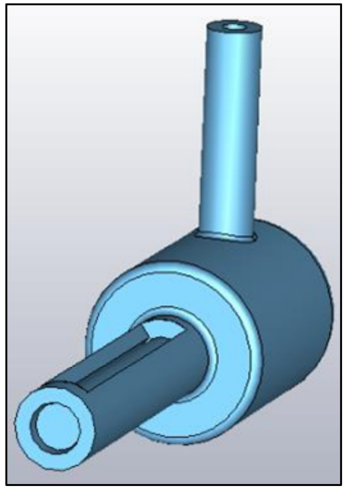
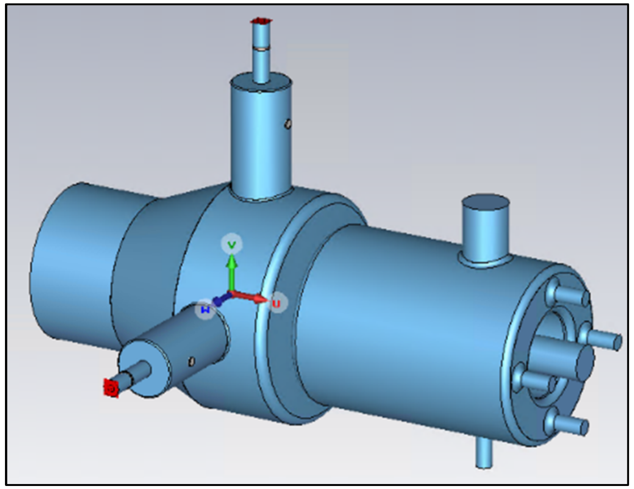
CWG + FPC



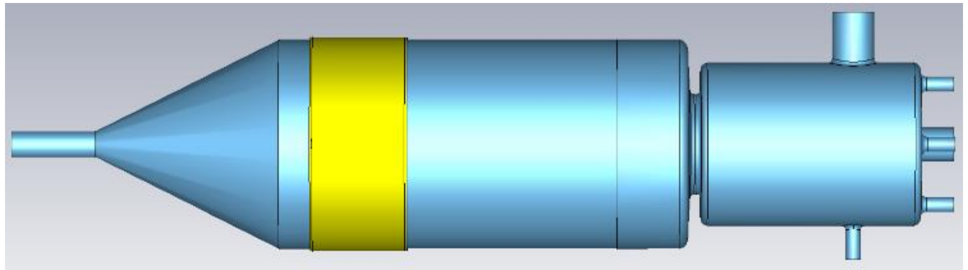
CWG



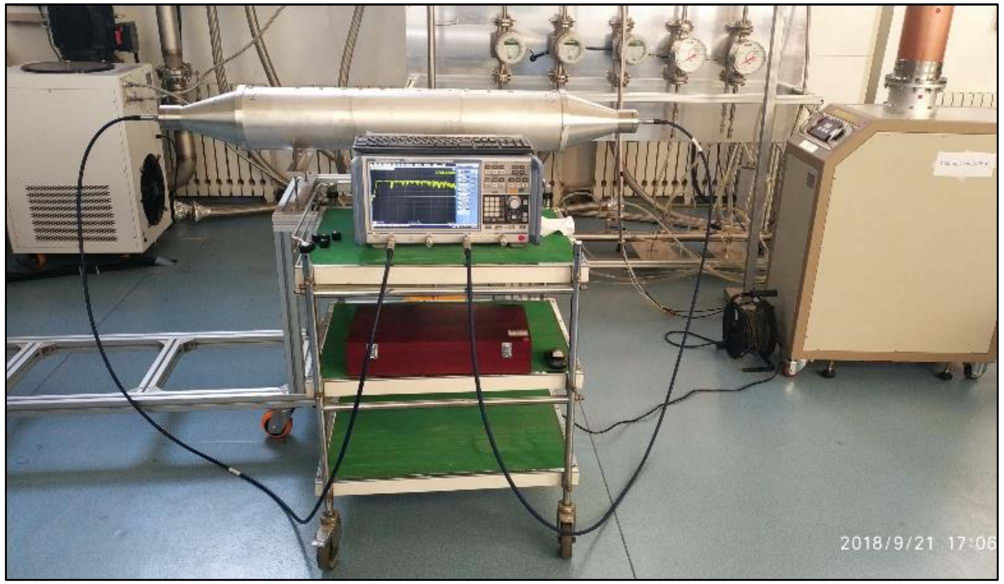
Damper + HOMC

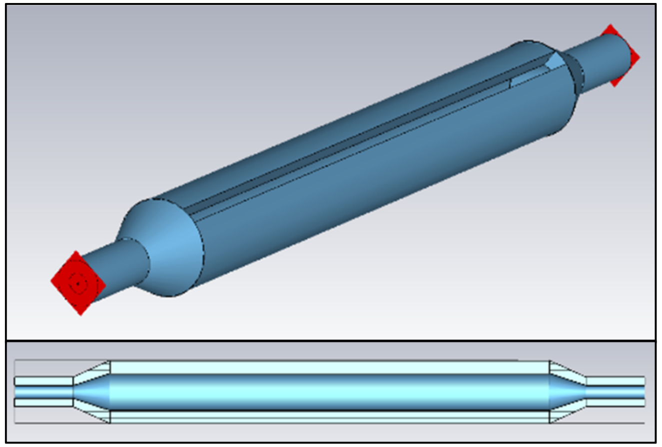


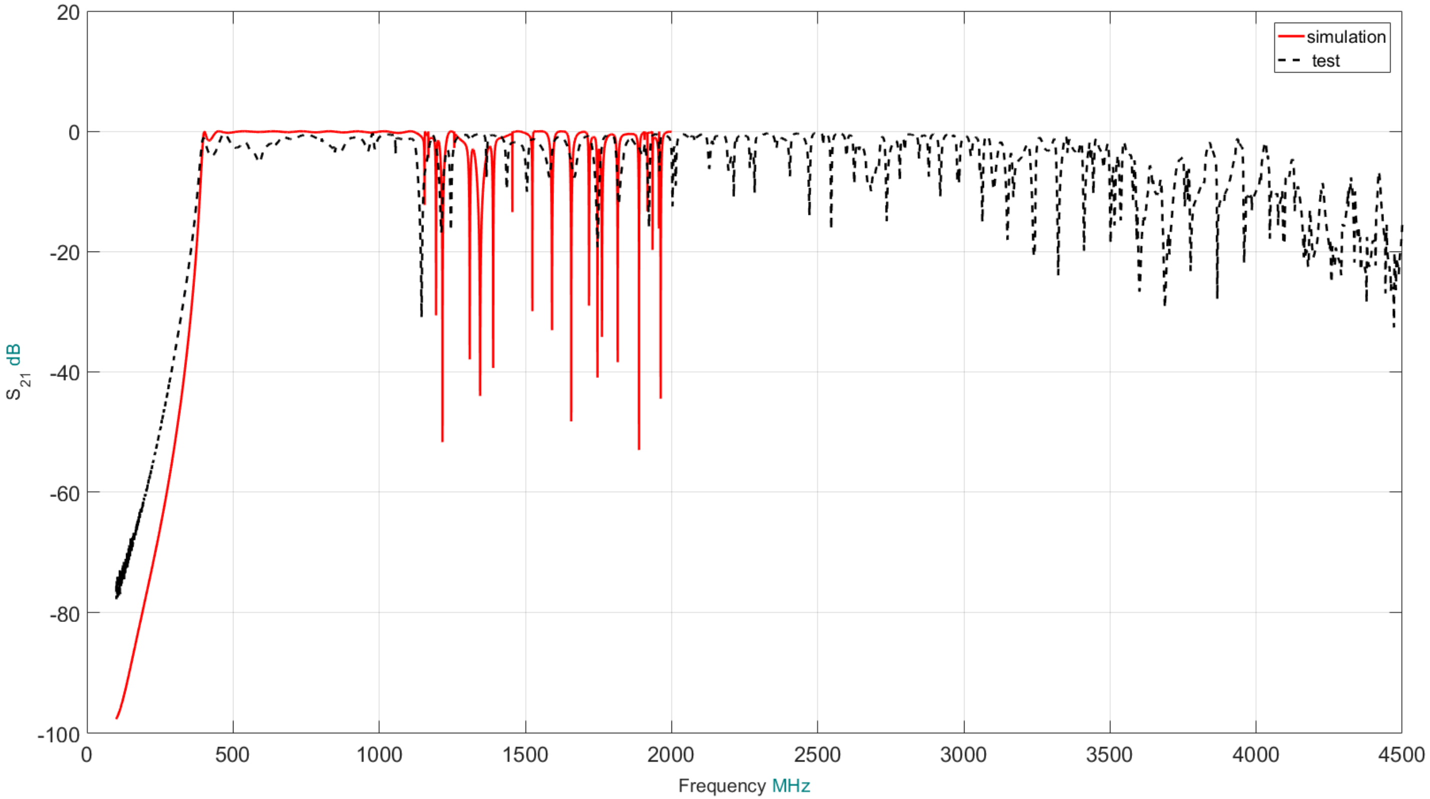
Damper



C-shaped waveguide

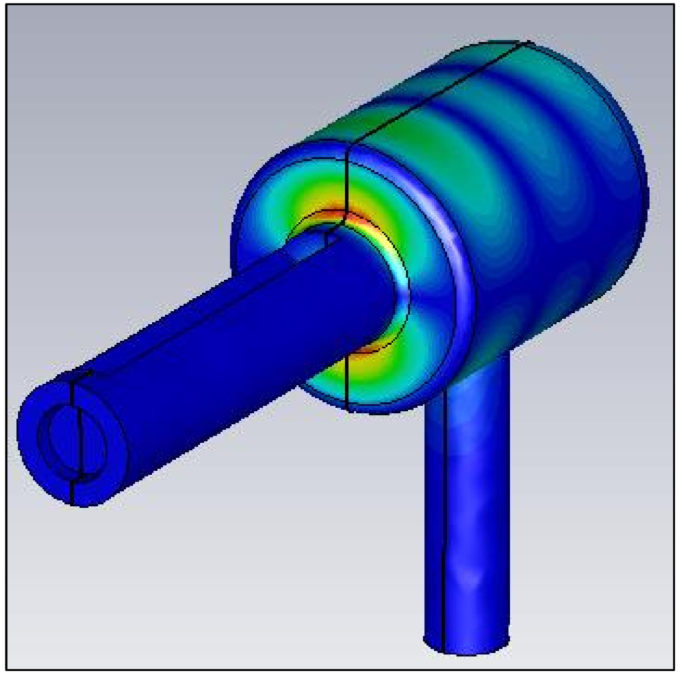


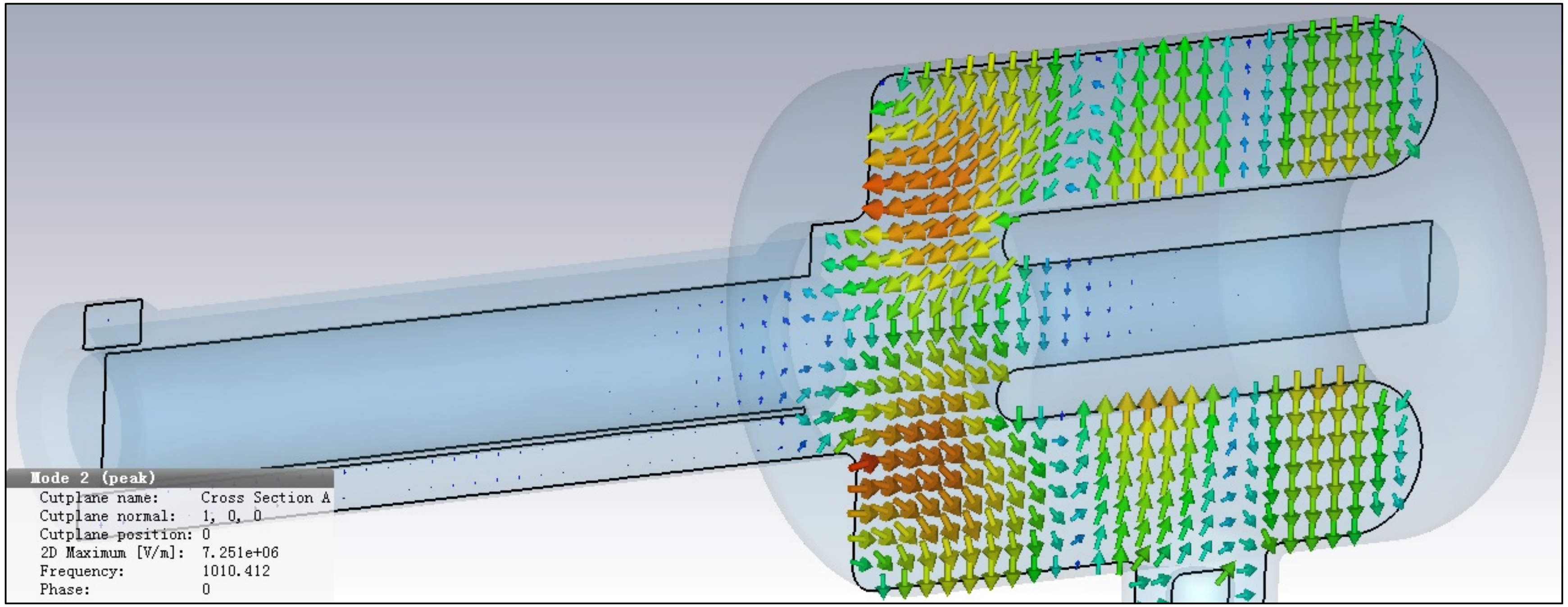




- CWG is an ideal high-pass filter
- The reflection (400-1000MHz) is small

C-shaped waveguide

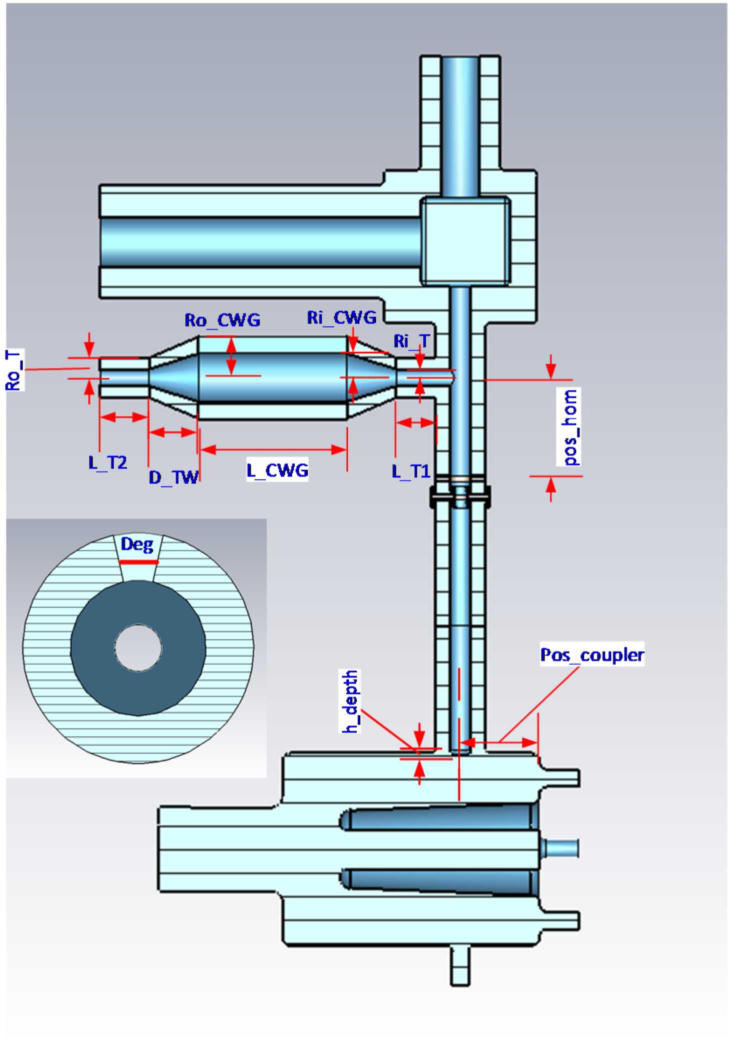




Freq: 1010MHz
R/Q: 236 Ω/m
Qext: 5.9e5
Qth: 3.2e3

Trapped mode

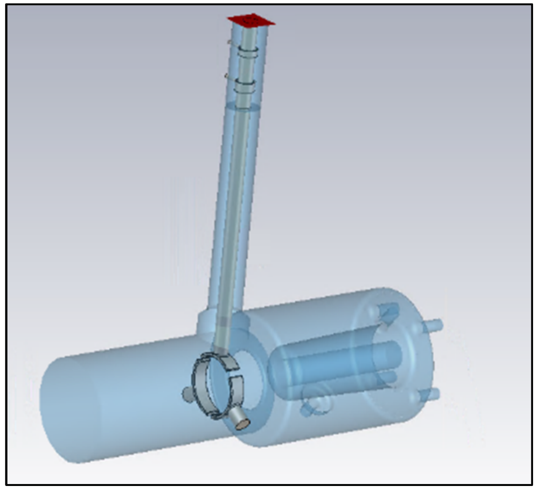
CWG + FPC



Mode	f_0 (MHz)	Q_L^{th} (with HC)	Q_{ext}
M2	464.502	343	2354 ✘
M3	698.545	393	4728 ✘
D1.1	431.781	2.9E+03	4.1E13 ✘
D1.2	432.841	2.2E+03	3.2E4 ✘

Various design trials

Petal + HOMC



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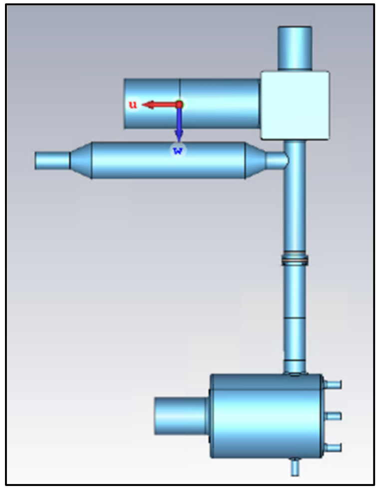
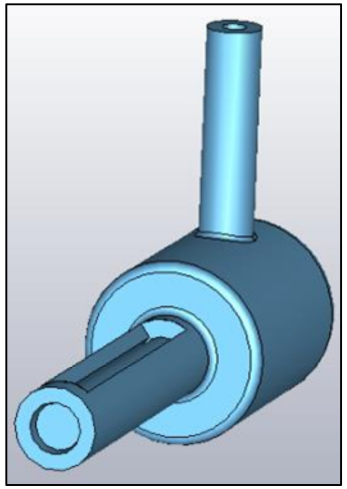
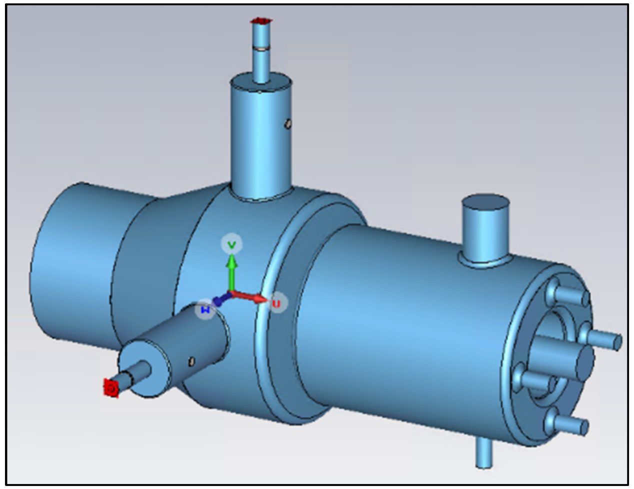
CWG + FPC

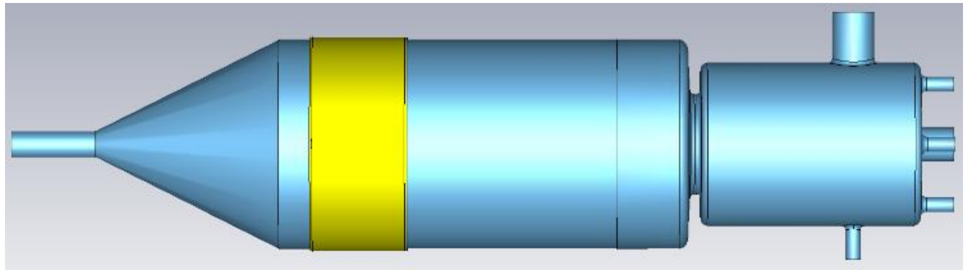


CWG



Damper + HOMC





Summary

- HEPS SR RF system: 166.6MHz SRF + 499.8MHz SRF
- Proof-of-principle 166.6MHz cavity was developed
- HOM-damped 166.6MHz cavity was under design