Development of Low-Frequency Superconducting Cavities for High Energy Photon Source

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on behalf of the 166 MHz Cavity Development Team

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Outline

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

HEPS

High Energy Photon Source (HEPS)

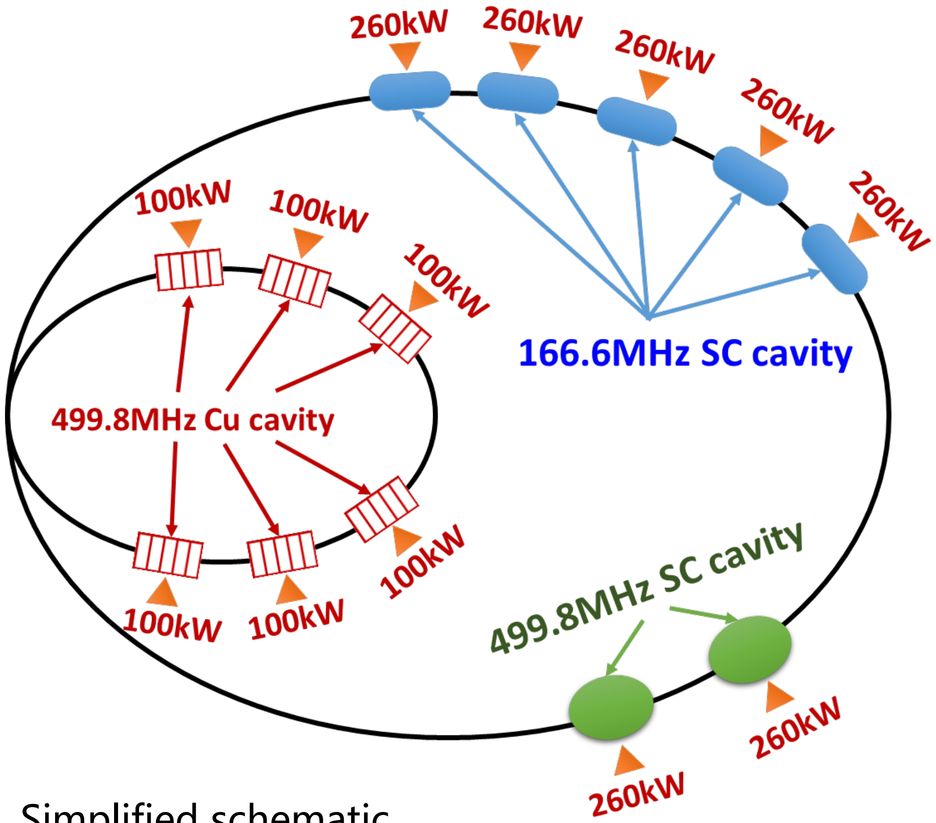
Located in the north of Beijing

Diffraction-limited synchrotron light source

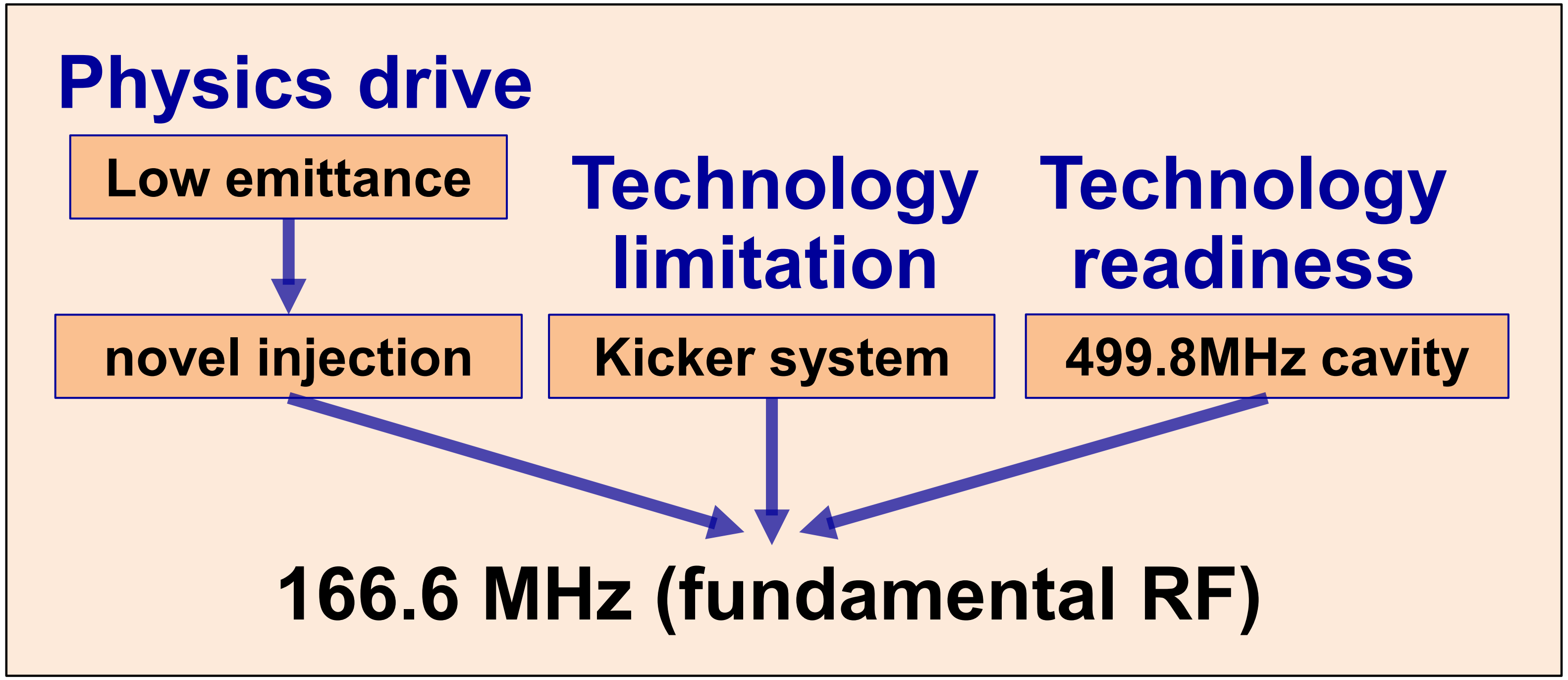
Parameter	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Natural emittance	< 60	pm·rad
Energy loss per turn	4.14	MeV
Beam power (w/ IDs)	850	kW

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

Why 166MHz?



Simplified schematic.



- Five 166.6MHz SRF cavities will be installed in the storage ring as main accelerating cavities
- Two 499.8MHz SRF cavities will be used as third harmonic cavities

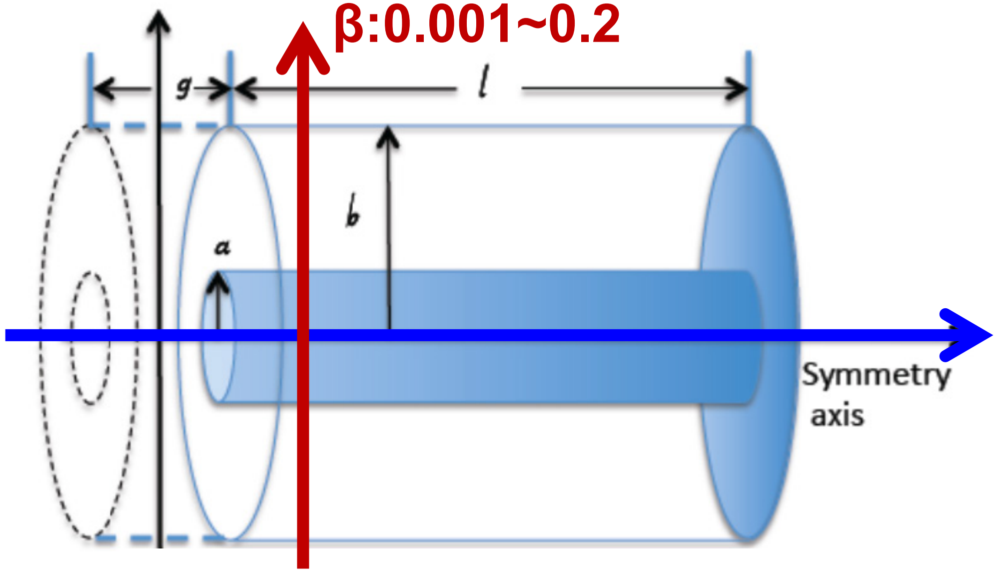
[1] Zhang, Pei *et al.*, *RDTM.* 7 (2022).
[2] G. Xu *et al.*, *IPAC2016*, WEOAA02.
[3] D. Zhe *et al.*, *eeFACT2016*, TUT2H4.

Cavity geometry

β=v/c (relativistic particles)

β=1 elliptical cavities

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



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

λ of 166.6MHz: ~1.8m

[1] Padamsee, Hasan. “Design Topics for Superconducting RF Cavities and Ancillaries”. (2015).
[2] I. Ben-Zvi, “Quarter-wave resonators for beta~1 accelerators”, SRF2011, THIOA04.

Requirements & Challenges

- **Low frequency**: 166.6MHz, **β=1** (relativistic particles)
- High current: 200mA -> **Heavy HOM damping**: Q_L< 1000
- **High RF power**: 180kW cw power per cavity
- **Compactness**: limited space of the straight section (< 6m)
- Stable operation (user facility): **large margin** in RF parameters

Development of 166.6MHz cavity

Two-step approach

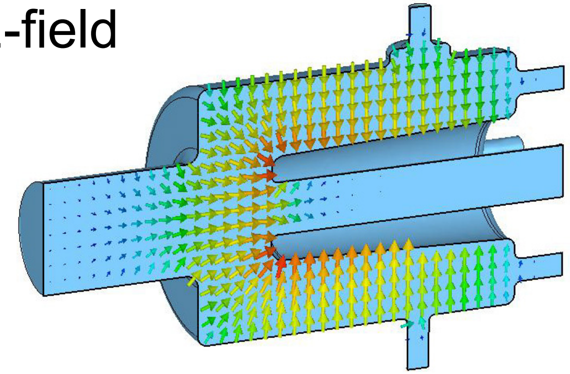
1. Proof-of-Principle (PoP) cavity: without HOM
2. HOM-damped cavity

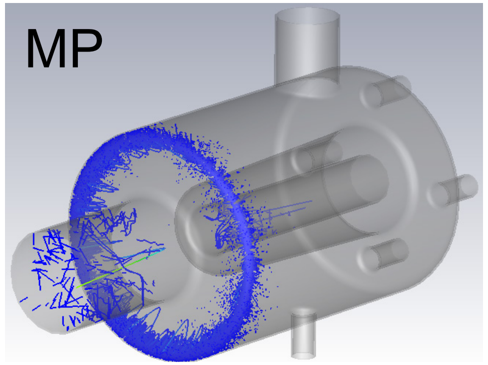
Type	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
PoP cavity	Bare cavity	Dressed cavity								
HOM-damped cavity				Prototype cavity and module					Series production	

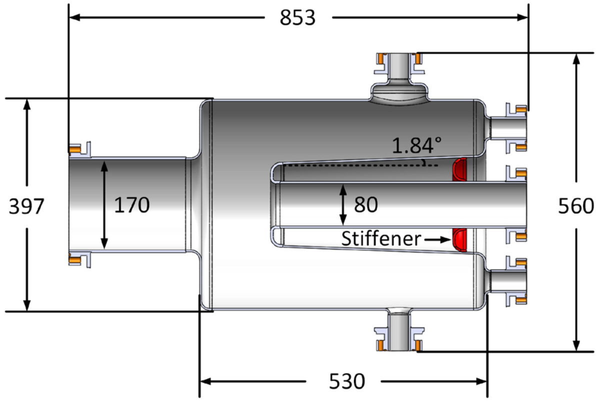
Proof-of-Principle cavity

Bare cavity design

E-field

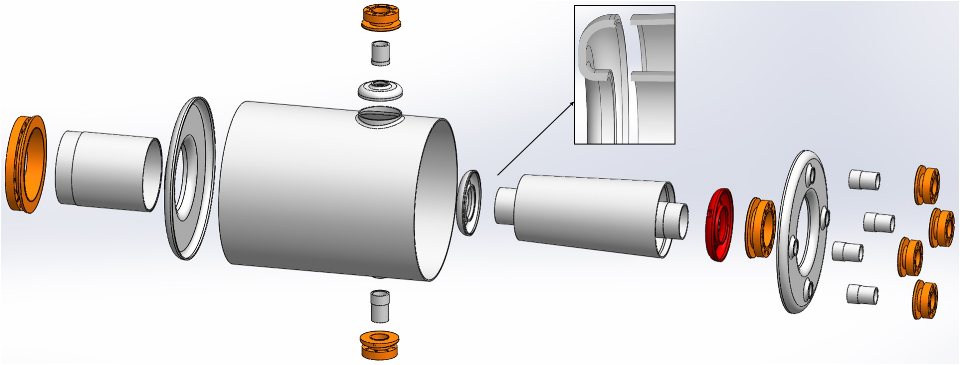




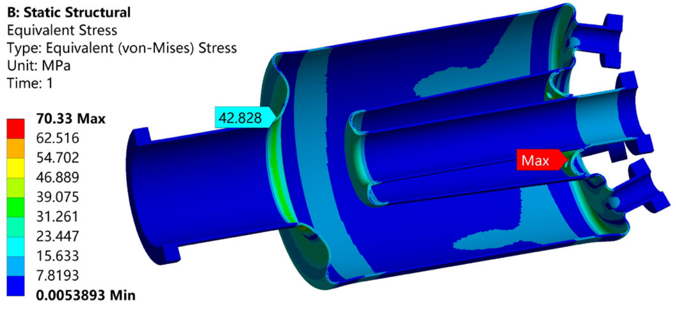


Main parameters

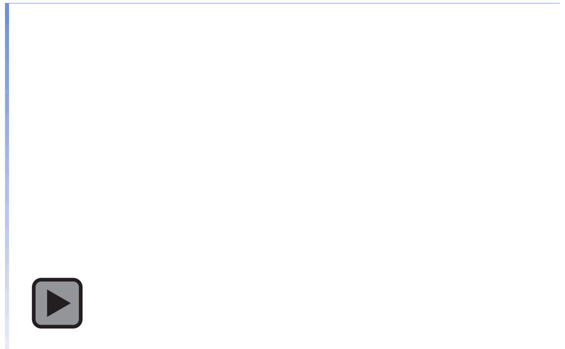
Parameter	Value	Unit
Frequency (f_0)	166.6	MHz
Frequency of nearest mode	433	MHz
$\lambda/4$ of π mode	449.9	mm
Cavity length (main body)	530	mm
Cavity diameter (no ports)	397	mm
Aperture diameter (small side)	80	mm
Operating temperature	4.2	K
Accelerating voltage (V_c)	1.5	MV
Accelerating gradient (E_{acc})	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 ($=\lvert V_c\rvert^2/\omega U$)	136.0	Ω
Geometry factor ($G = R_s \cdot Q_0$)	54.5	Ω



Stress



113Hz



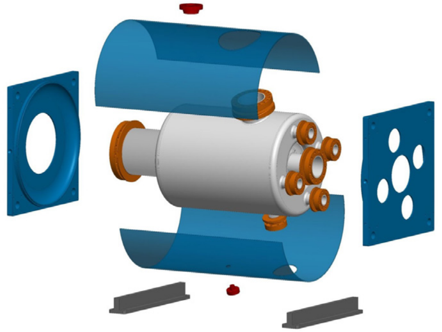
[1] P. Zhang *et al.*, *Rev. Sci. Instrum.* **90**, 084705 (2019).

[2] X.Y. Zhang *et al.*, *NIM-A* **947**, 162770 (2019).

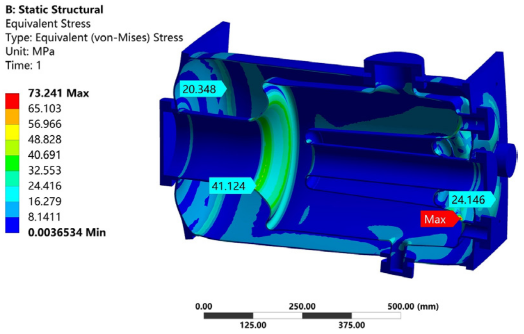
[3] P. Zhang *et al.*, *SRF2017*, TUPB035.

Dressed cavity development

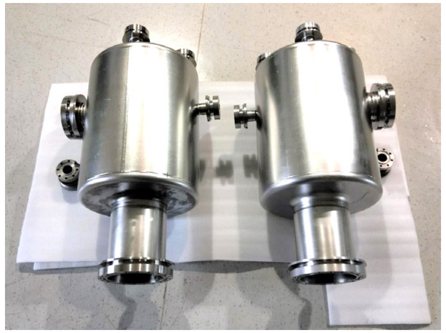
Helium vessel



Stress

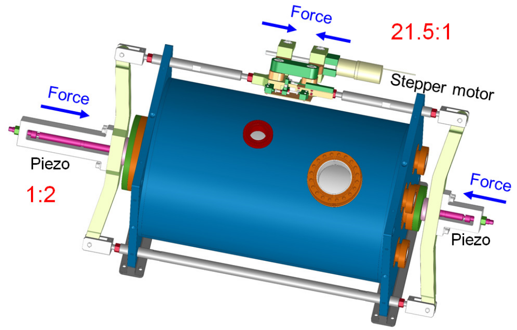


FPC port modified

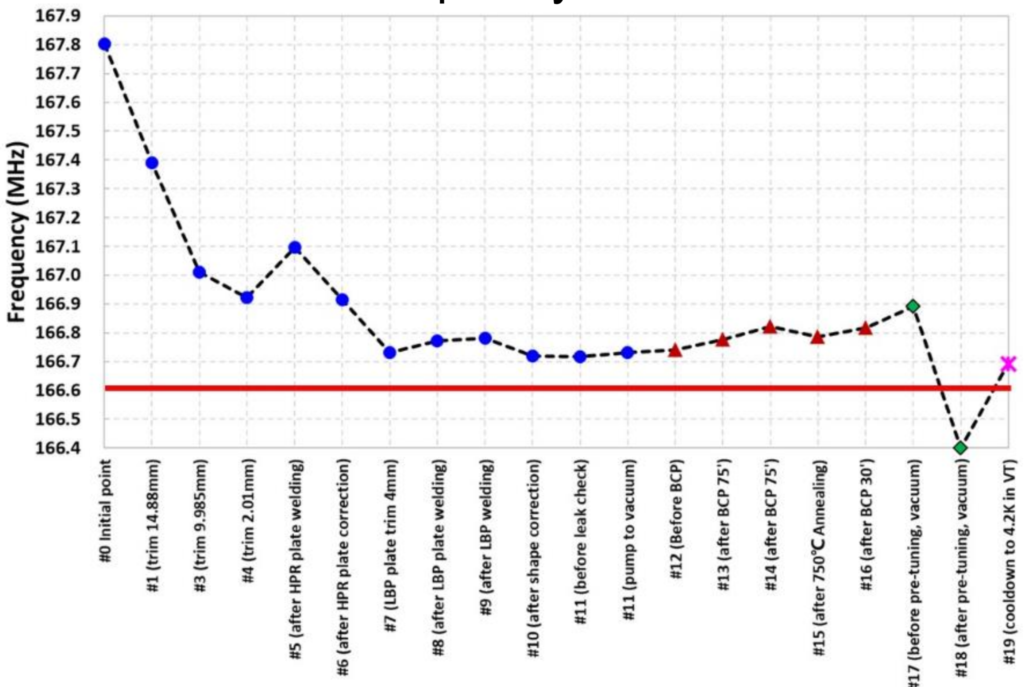


He vessel welded

Tuner



Frequency control



X.Y. Zhang *et al.*, *IEEE TAS* **30**, 3500208 (2020).

Main parameters

Parameter	Value	Unit
Cavity length (flange to flange)	853	mm
Cavity diameter (flange to flange)	550	mm
df/dp	-0.9	Hz/mbar
Max stress on cavity	73.2	MPa
Max stress on cavity	24.1	MPa
Lorentz coefficient	-0.58	$Hz/(MV/m)^2$
Tuning range(4.2K)	169.3	kHz
The lowest mechanical mode	124	Hz

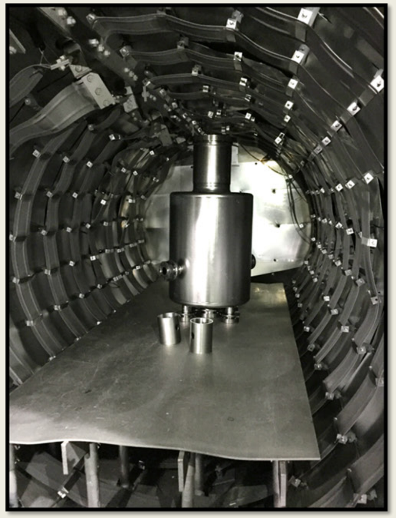
In-house development

Bare cavity

Welded cavity

Chemical polishing

750°C Annealing



High-pressure water rinsing

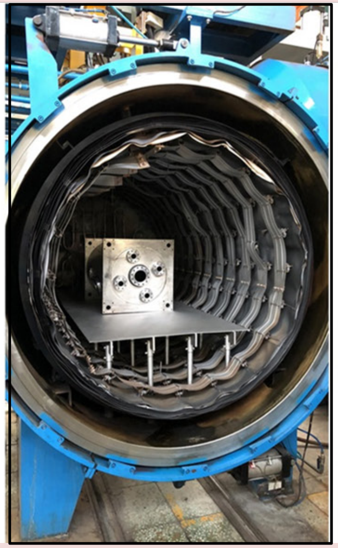
ISO4 clean assembly

Vacuum leak check

Dressed cavity

BCP

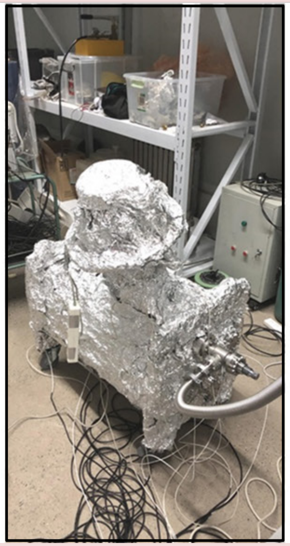
750°C annealing



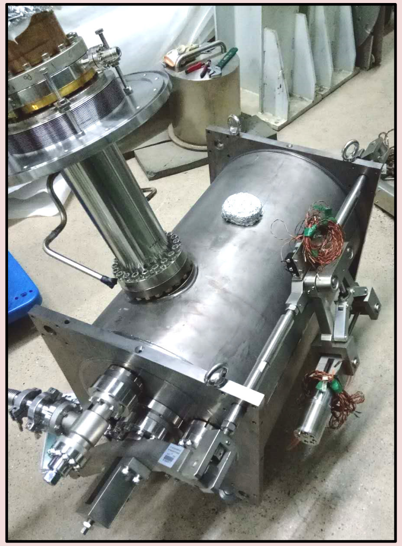
HPR

Clean assembly (ISO 4)

120°C bake



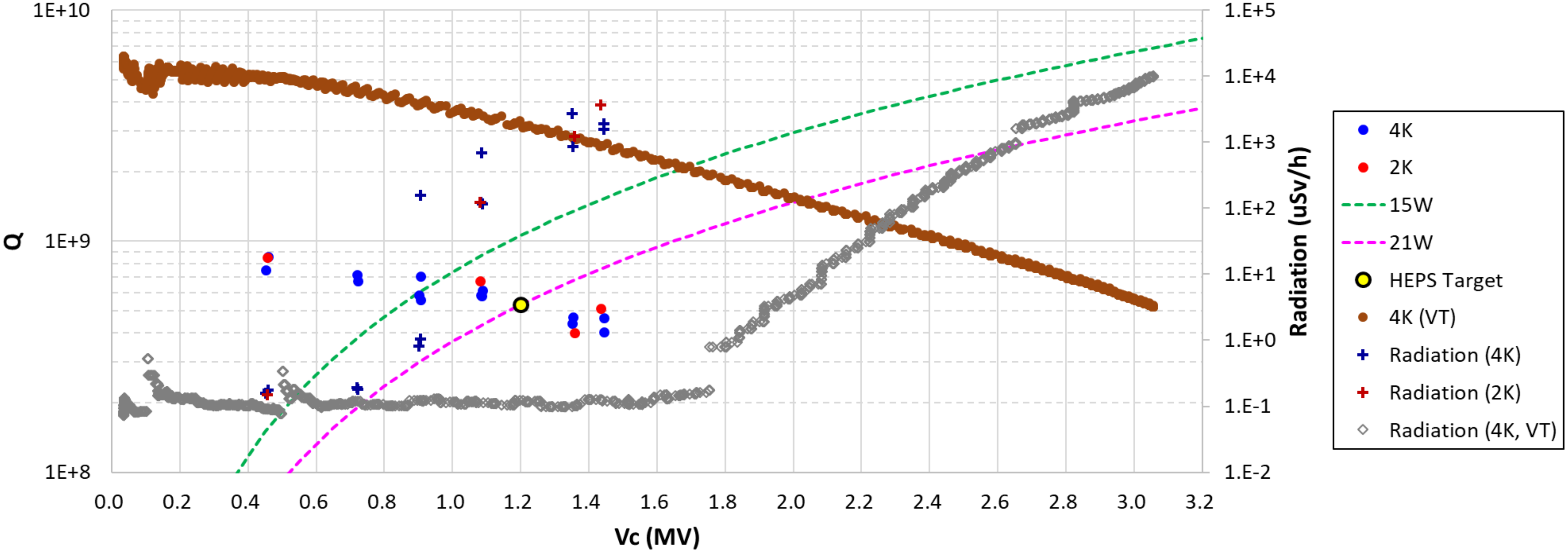
Fully dressed



Cryogenic test

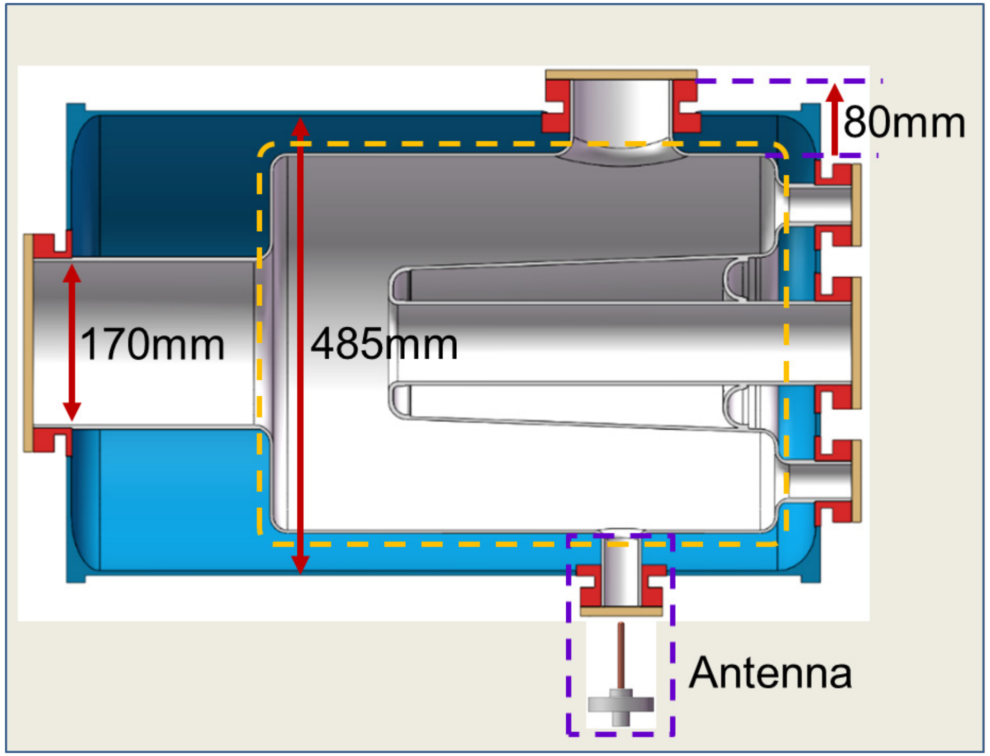
[1] P. Zhang *et al.*, *Rev. Sci. Instrum.* **90**, 084705 (2019).
[2] X.Y. Zhang *et al.*, *IEEE TAS* **30**, 3500208 (2020).
[3] P. Zhang, *et al.*, *AIP Advances* **11**, 045024 (2021).

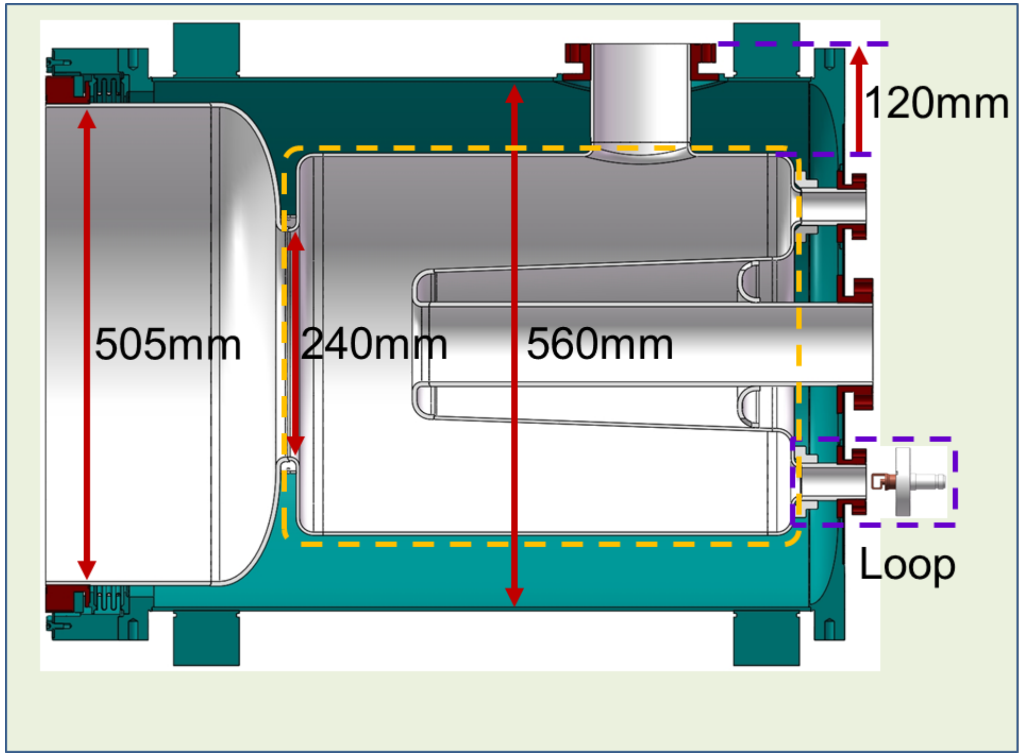
- **Excellent cryogenic performance obtained in vertical tests**
  - Validated cavity design, fabrication techniques, surface treatment and assembly process
- **Large Q degradation, early field emission onset from VT to HT**
  - Longer Nb tube of FPC port & better FPC outer conductor cooling to reduce dynamic loss



166.6MHz HOM-damped cavity

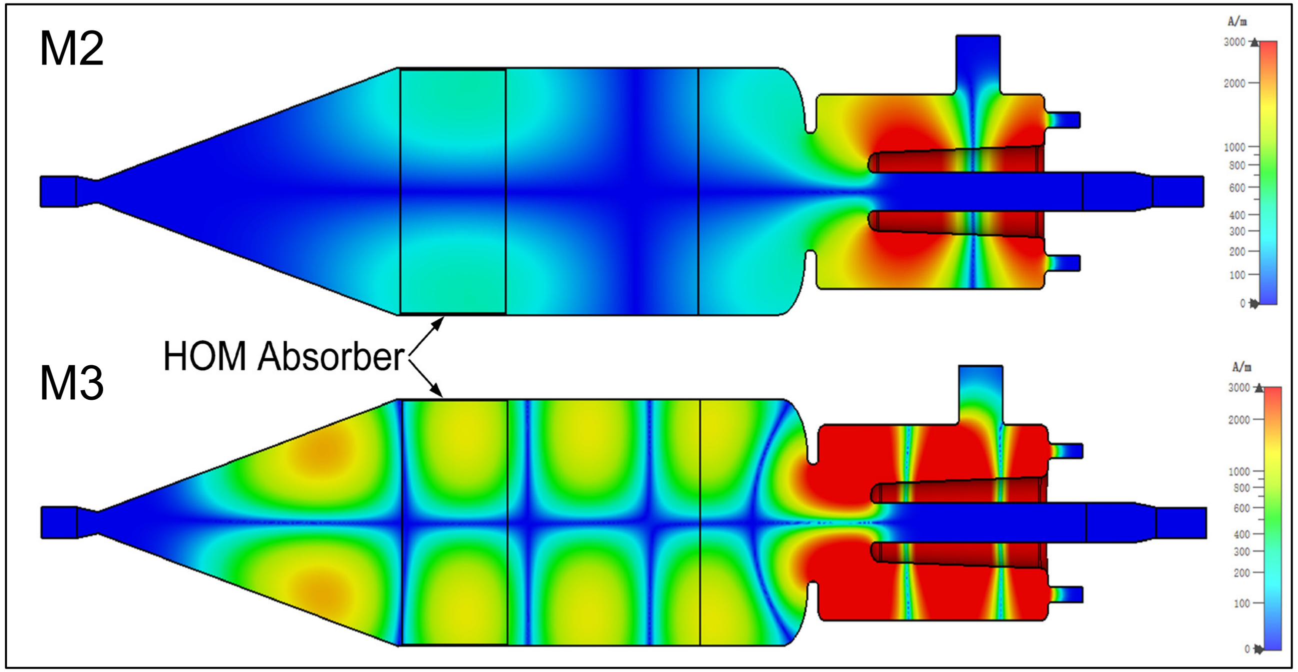
HOM-damped cavity



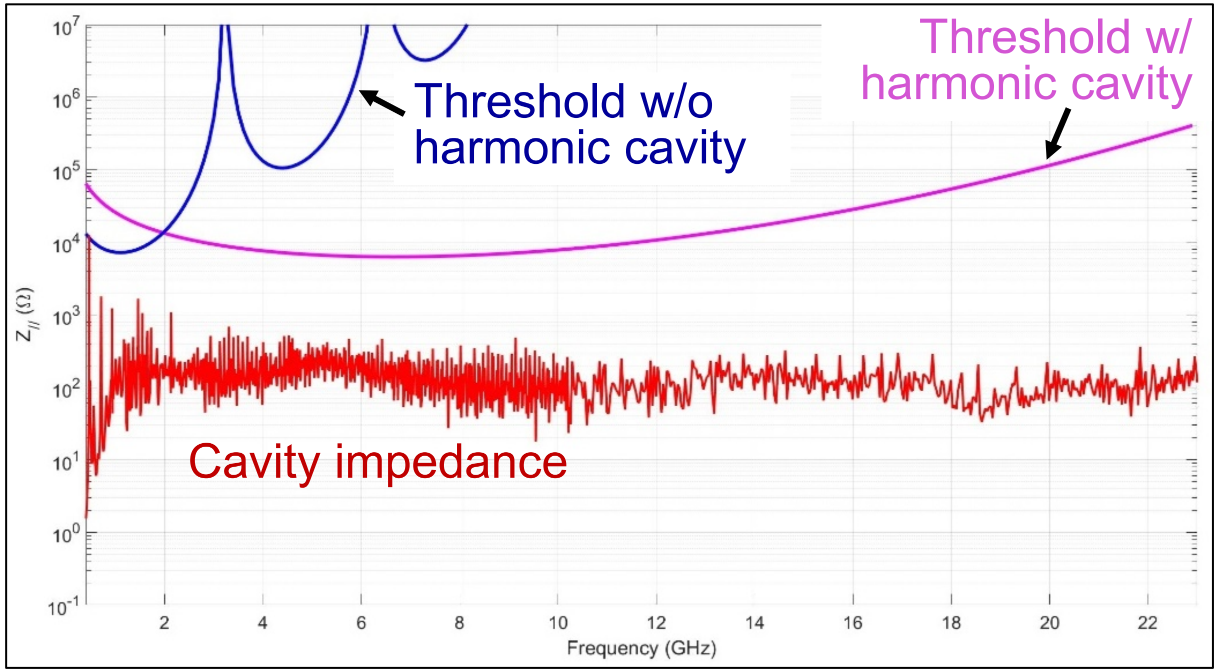


- **Largely inherited from the PoP cavity**
  - main structure, excellent EM design, techniques…
- **Enlarged beam pipe and iris**
  - HOM propagation & damping by absorber
- **Coupler port: extended Nb tube**
  - alleviate overheating by cavity field
- **Pickup re-designed: Antenna->Loop**
  - simplified helium jacket w/ less ports

HOM damping scheme



Magnetic field distribution of M2 and M3

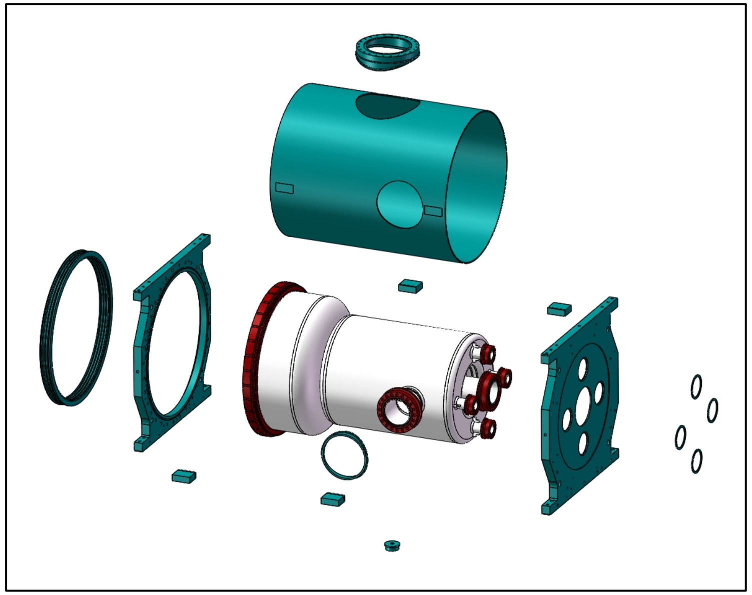


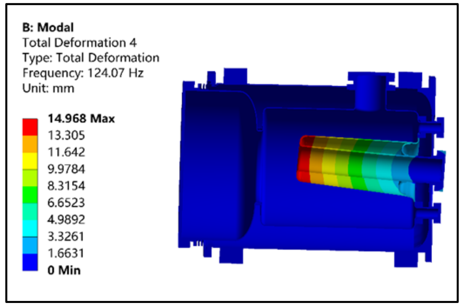
Impedance of the 166MHz SRF cavity and the impedance threshold per cavity

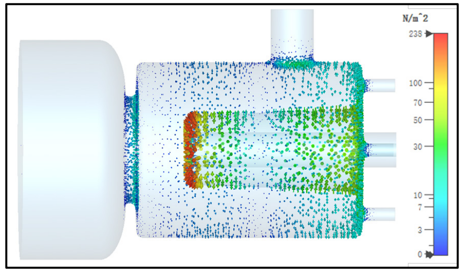
Damping requirements are fulfilled (w/ and w/o harmonic cavities).
Loss factor: -2.54 V/pC (680W@high-luminosity mode, 7kW@high-charge mode)

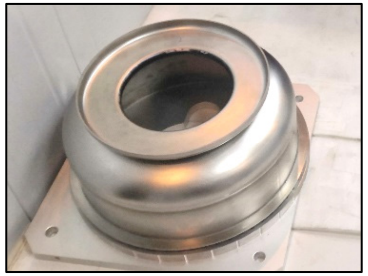
H.J. Zheng, *et al.*, IPAC2021, WEPAB090.

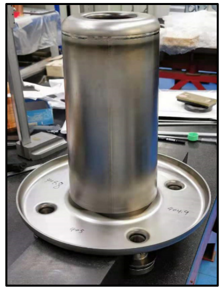
Cavity main parameters

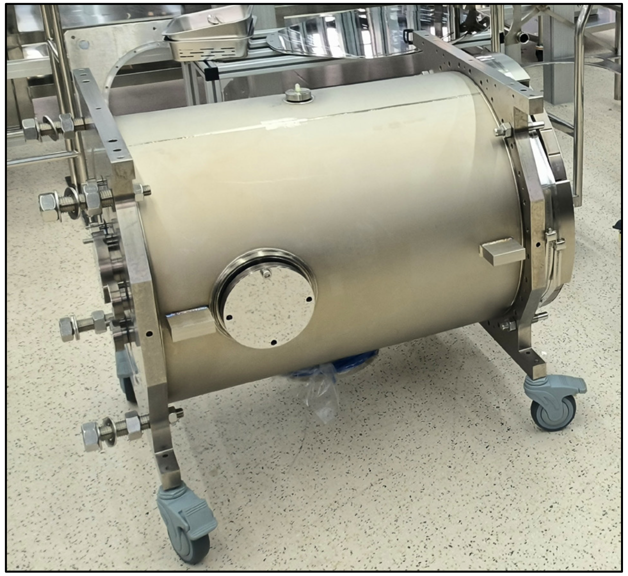












Parameter	Value	Unit
RF frequency	166.6	MHz
Cavity length	880	mm
Aperture diameter(LBP/SBP)	505/80	mm
Q_0 at designed voltage (Vd=1.5MV)	1×10^9	-
Q_0at designed voltage(Vop=1.2MV)	5×10^8	-
R/Q	139	Ω
G(=Rs×Q0)	56	Ω
Epeak at Vd	40	MV/m
Bpeak at Vd	62	mT
Operating temperature	4.4	K
Operating LHe pressure	1230±3	mbar
Peak stress on cavity/bellows	78/119	MPa
Pressure sensitivity (df/dp)	-18	kHz/mbar
Longitudinal stiffness	9.7	kN/mm
Tuning range at 4.2 K	67	kHz
LFD coefficient	-1.1	$Hz/(MV/m)^2$
The lowest mechanical mode	110	Hz

post-process of the prototype cavity

120℃ bake

HPR

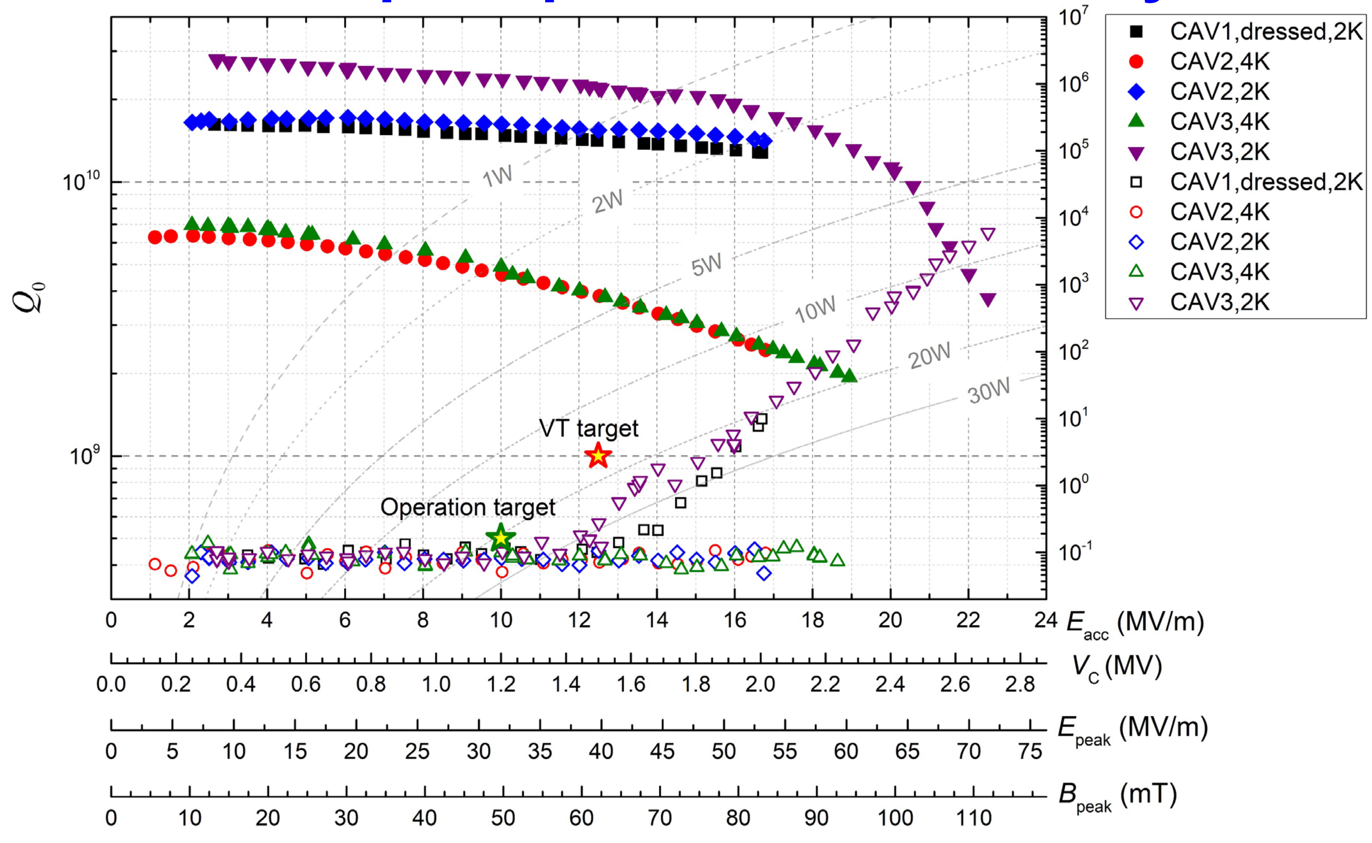
Assembly (class 10)

Leak check

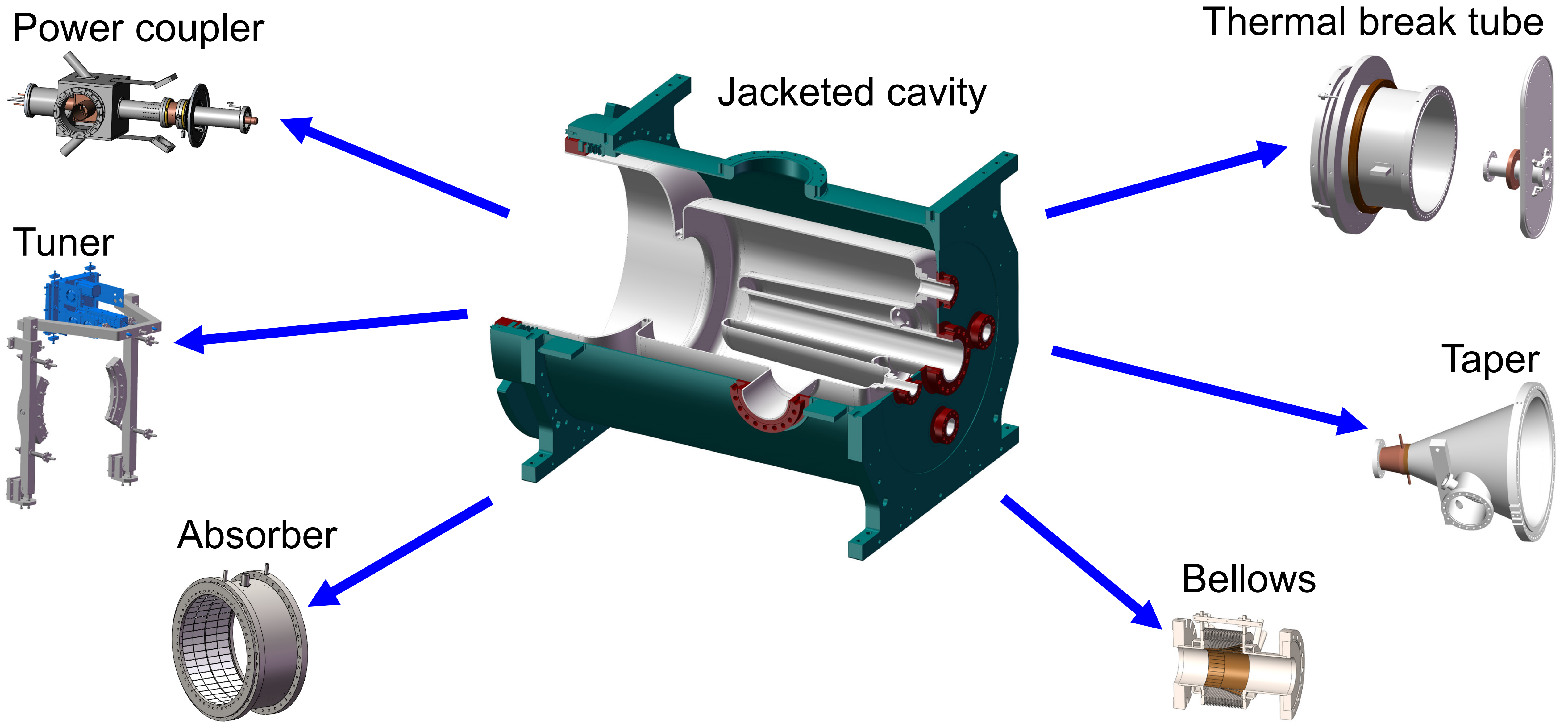
follows the verified treatment procedures of PoP cavity

Vertical test

- **Excellent cryogenic performance obtained in vertical tests**
  - Bare cavity: $Q_0=3.83\times10^9$@V_d(4K), largely surpassing the HEPS specification.
  - Jacketed cavity: $Q_0=1.42\times10^{10}$@V_d(2K), comparable to bare cavity.
- **Validated design, fabrication techniques, process of the cavity**

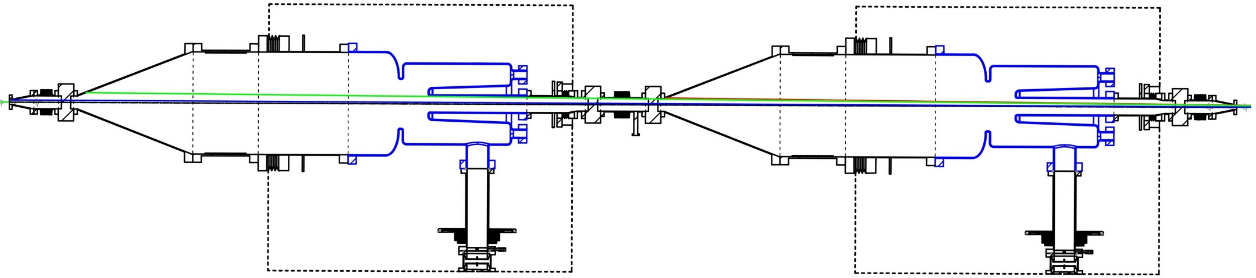


Cavity system

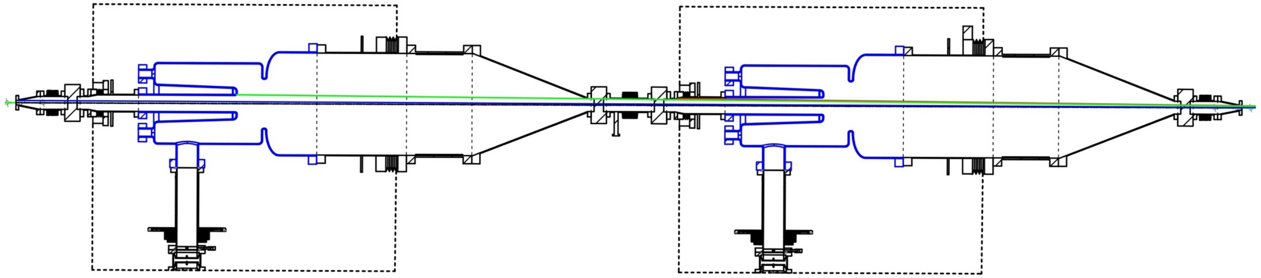


Design of the cavity string

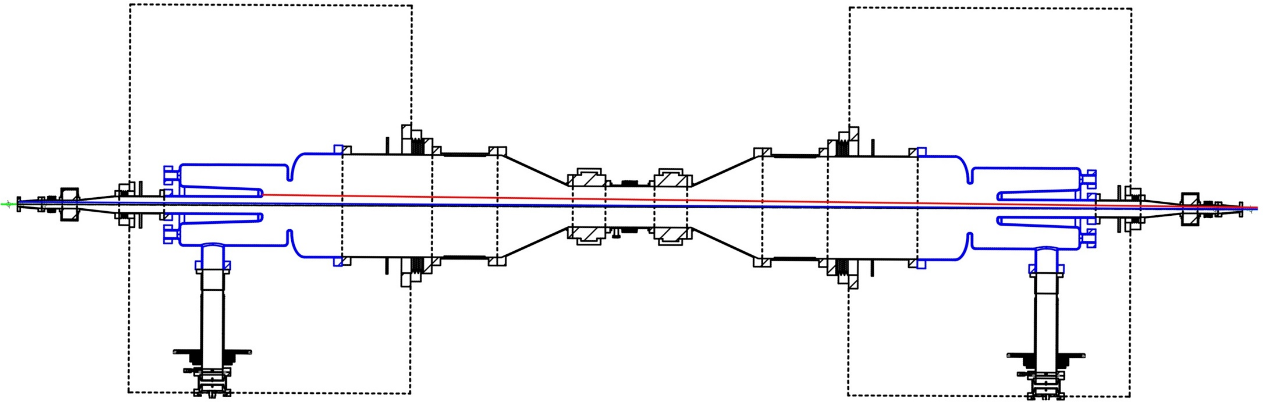
A total of four layouts for the cavity string were analyzed. Based on the location of synchrotron light, loss factor, replaceability, and risk resistance, layout1 was selected as the baseline.



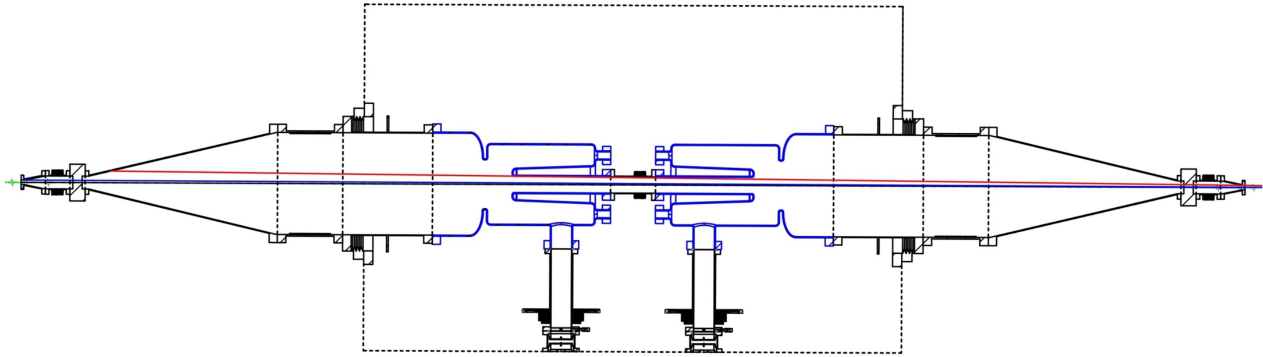
layout1: Synchrotron light hits the taper and bellows, $k_{//}$=5.090 V/Pc.



layout2: Synchrotron light hits the cavity and bellows, $k_{//}$=5.089 V/Pc.

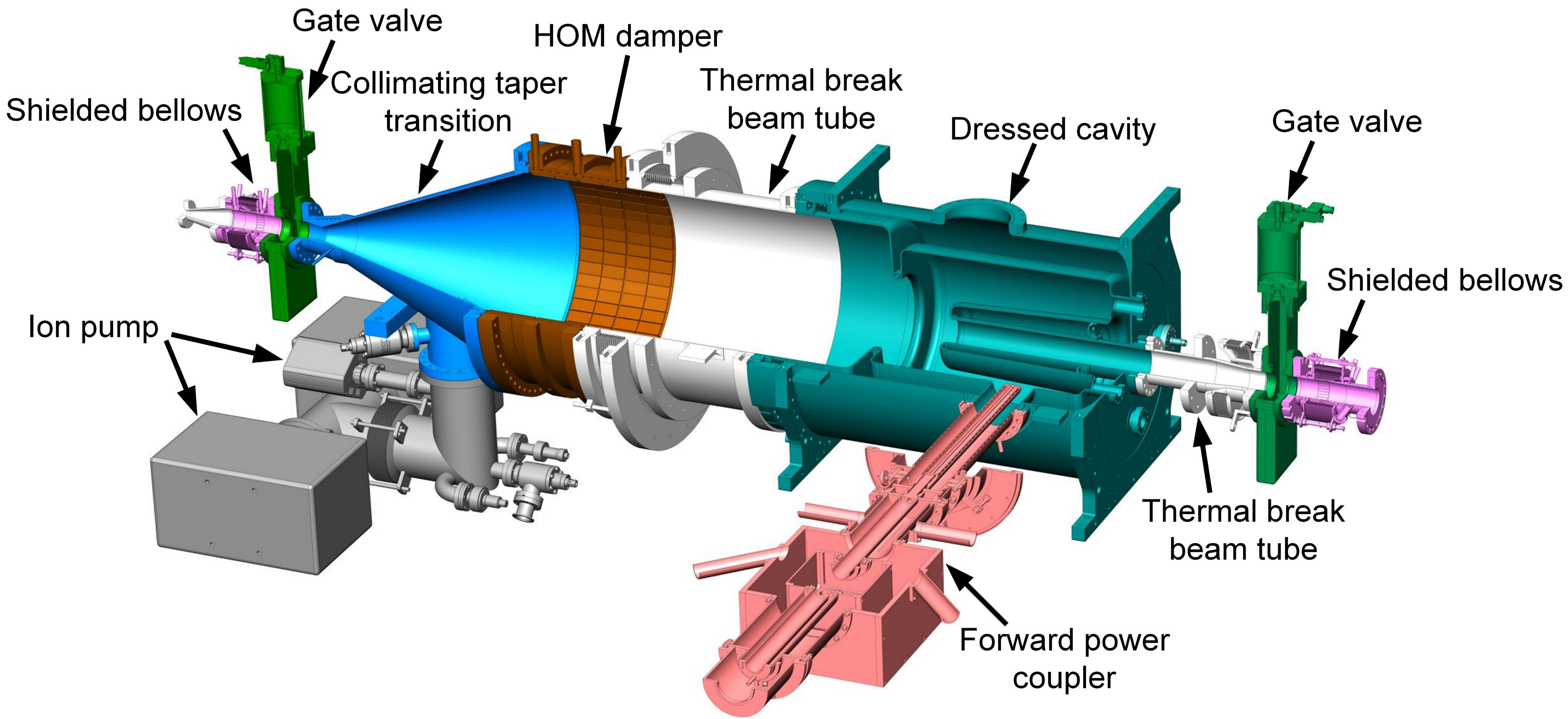


layout3: Synchrotron light hits the cavity and bellow, $k_{//}$=3.447 V/Pc.



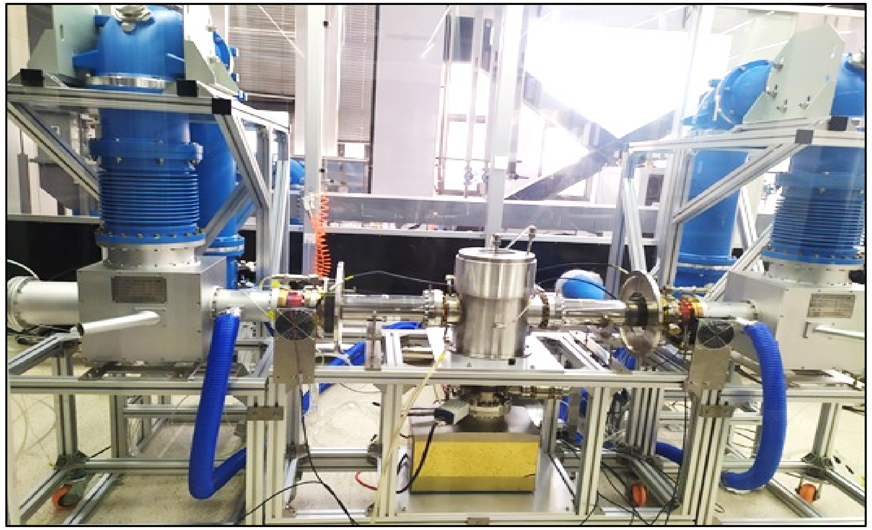
layout4: Synchrotron light hits the taper and bellows, $k_{//}$=4.911 V/Pc.

Model of the cavity string



Power coupler

High-power test on test bench



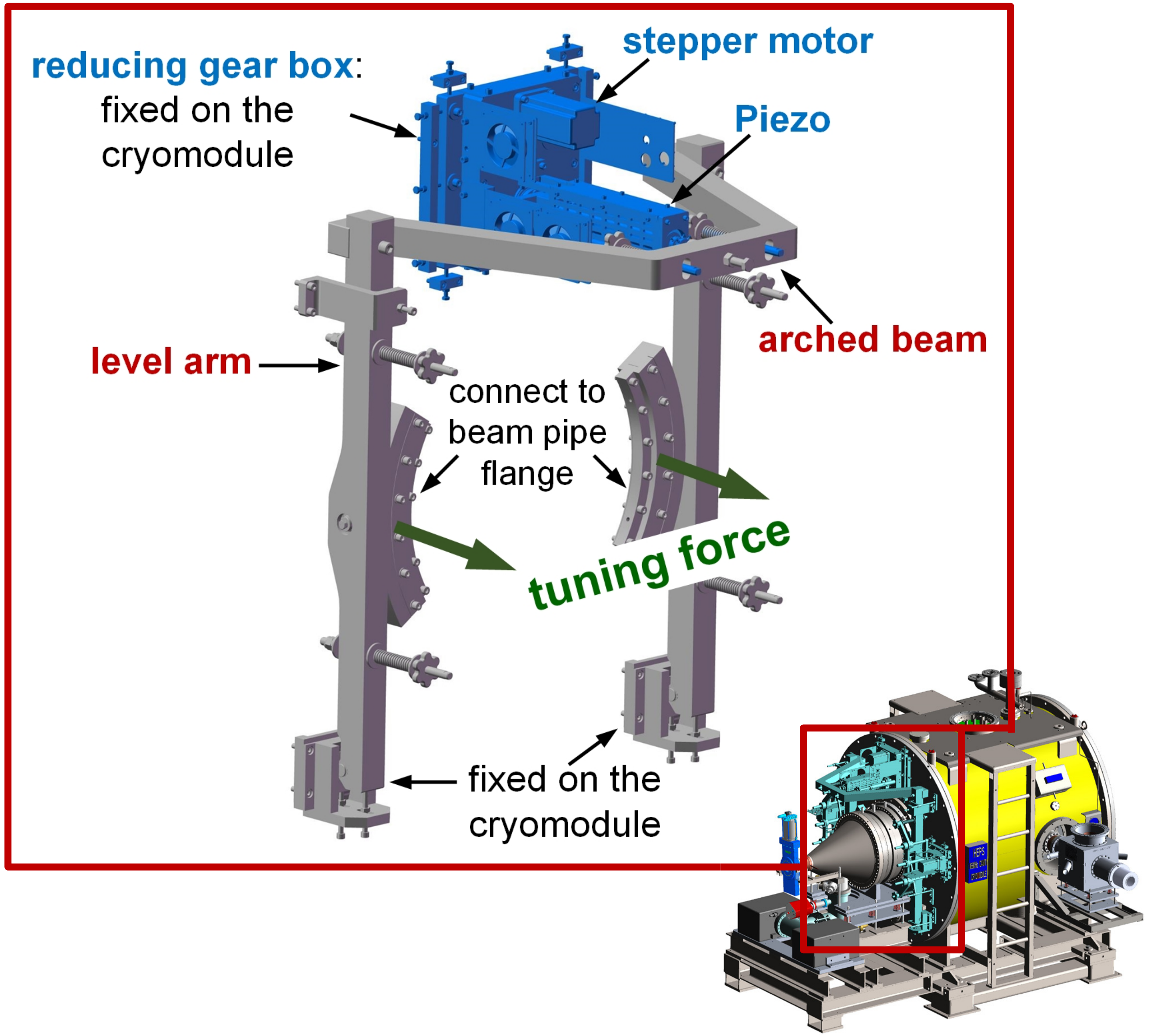
Main parameters

Parameter	Value
Max. power per FPC	200 kW (c.w.)
External Q	5×10^4
FPC type	Coaxial, single window
Window type	Coaxial disk with choke
Coupling type	Electric

in-house development

T. Huang et al., IPAC'23, MOPA185.

Frequency tuner

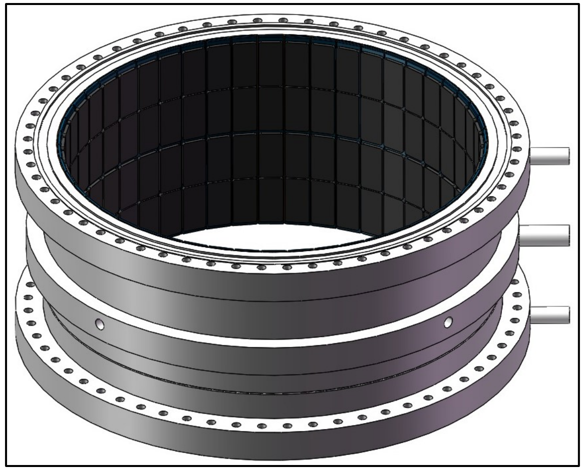


Main parameters

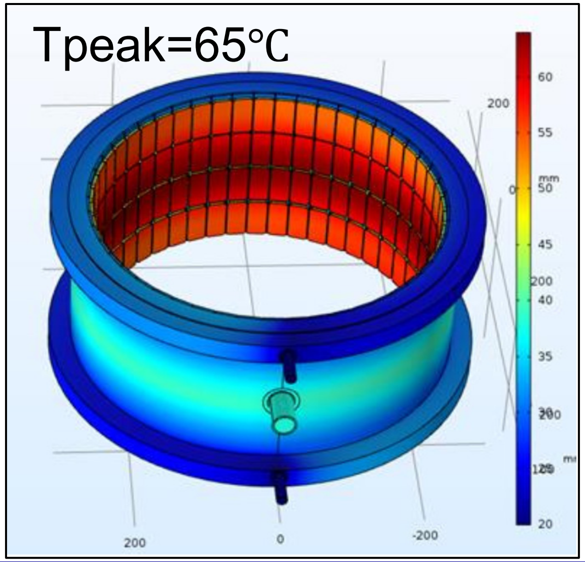
Parameter	Value	Unit
Tuner stiffness	32	kN
Coarse (slow) tuner frequency range	>50	kHz
Coarse tuner frequency resolution	<5	Hz
Fine (fast) tuner frequency range	>1	kHz
Fine tuner frequency resolution	1	Hz
Number of Motor/Piezo	1/1	-
Working temperature	298	K

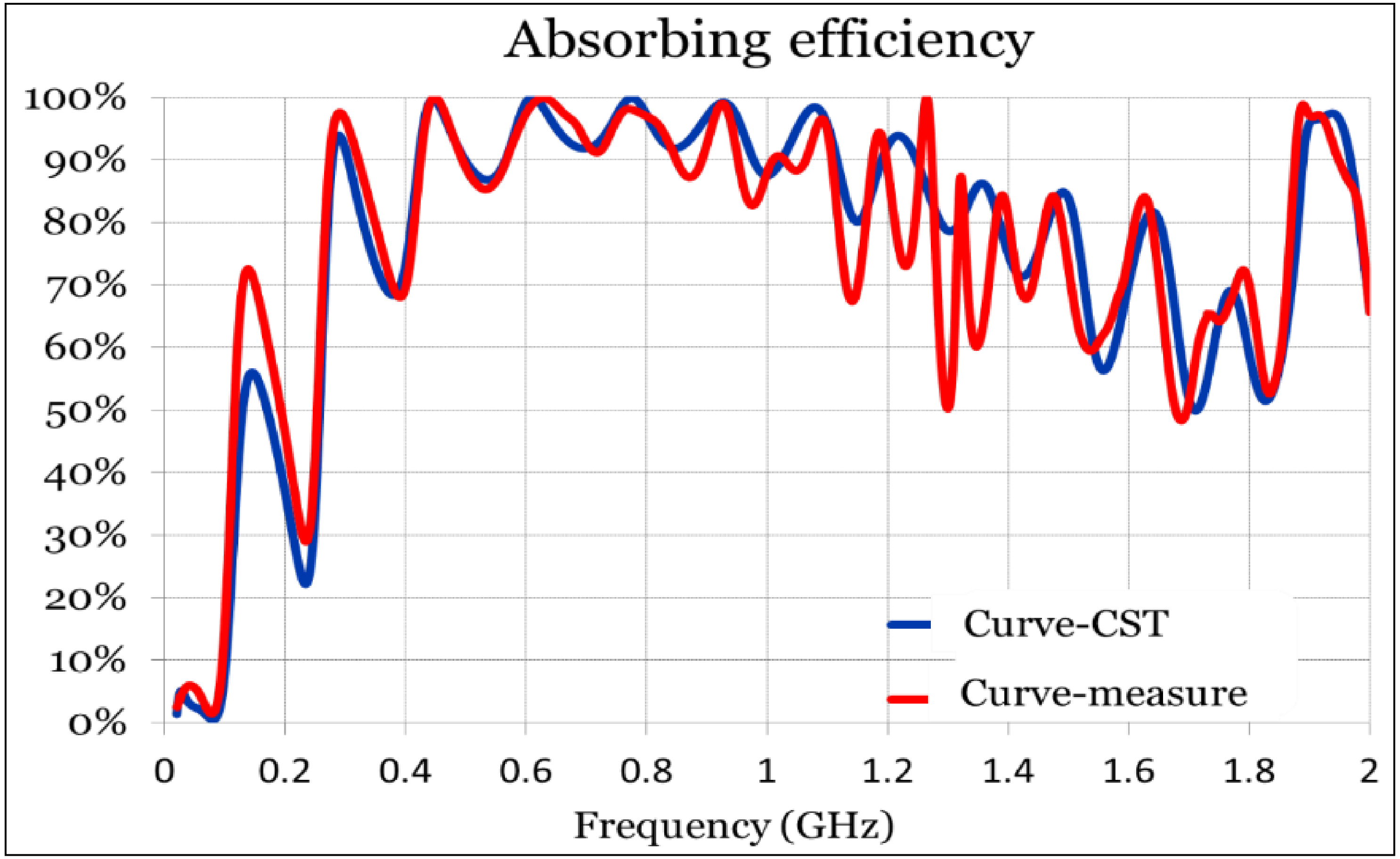
Higher-Order-Mode absorber

Model of the HOM absorber



Temp. distribution@10kW HOM power





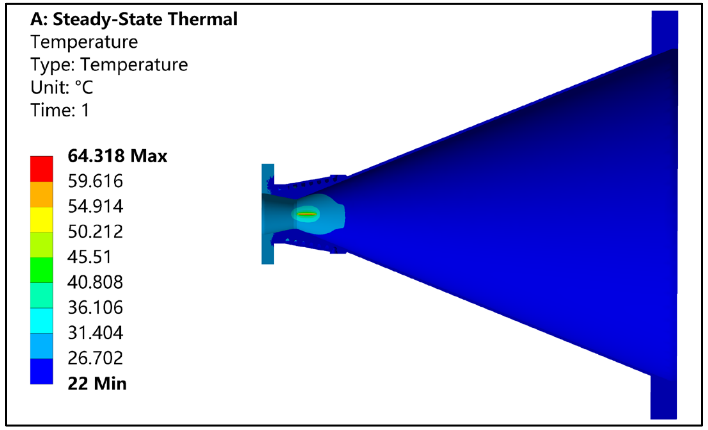
in-house development

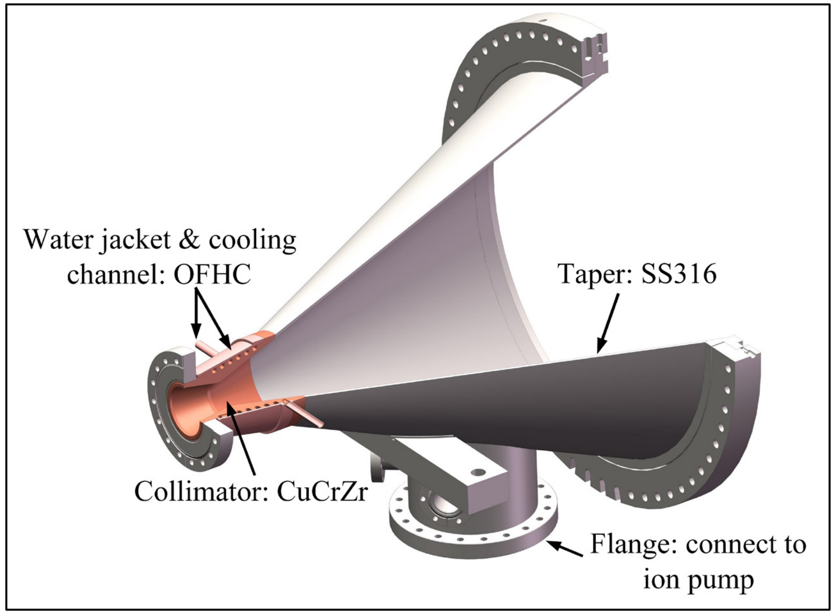
F. Meng *et al.*, *SRF'17*, MOPB071.

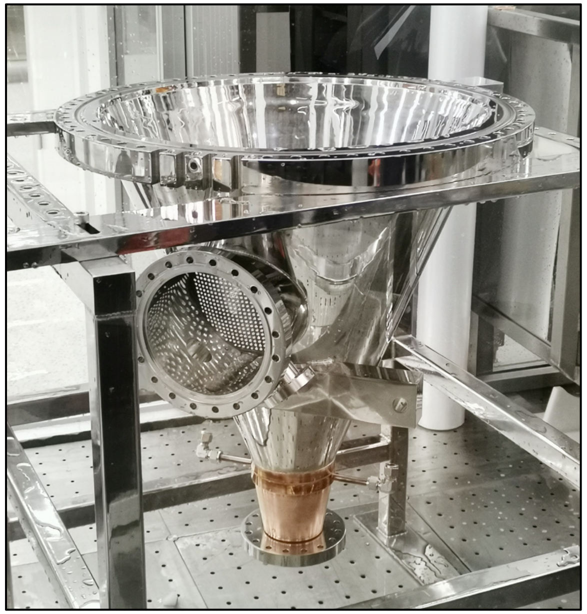
Collimating taper transition

Light incidence(235W, 11.75w/mm^2)

temperature distribution



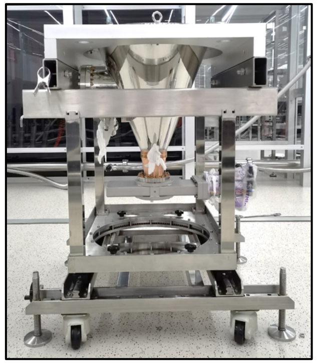


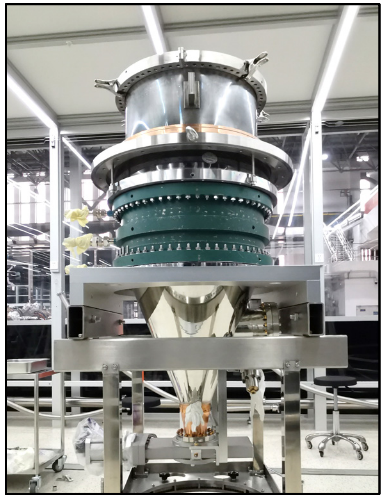


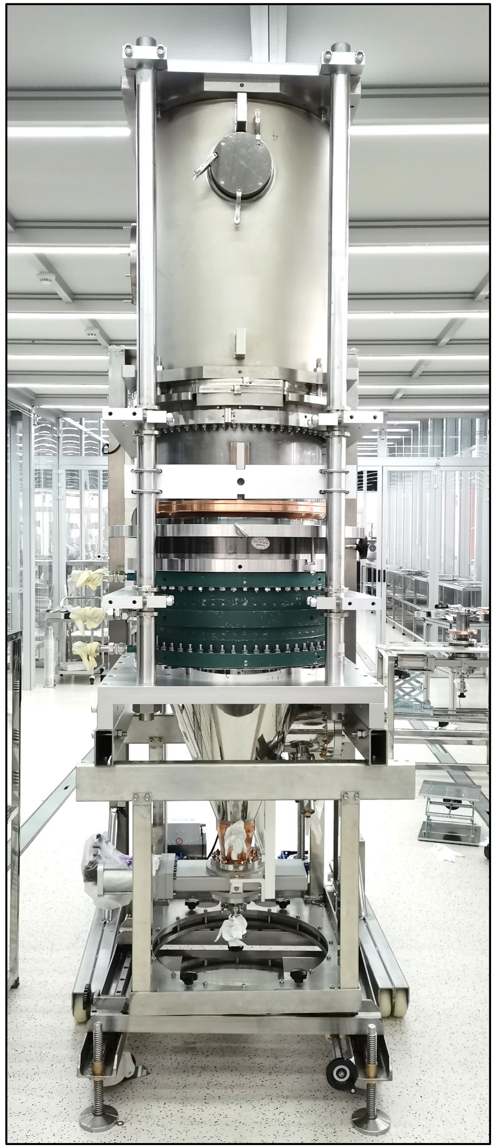
Main parameters

Parameter	Value	Unit
material	CuCrZr/ SS316	-
Aperture transition	505->63	mm
Max Temp. on CuCrZr/SS316	64/29	°C
Peak stress on CuCrZr/SS316	57/40	MPa
safety margin	6.5	mm
e-beam lateral orbit deviation	±1.34	mm
accumulated installation error	±1	mm

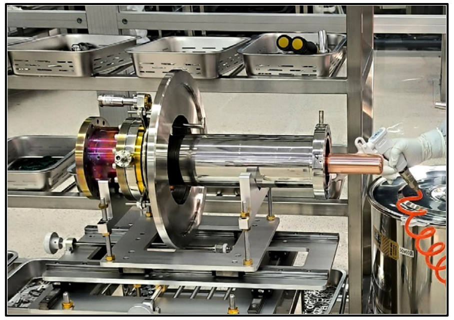
Cavity string assembly

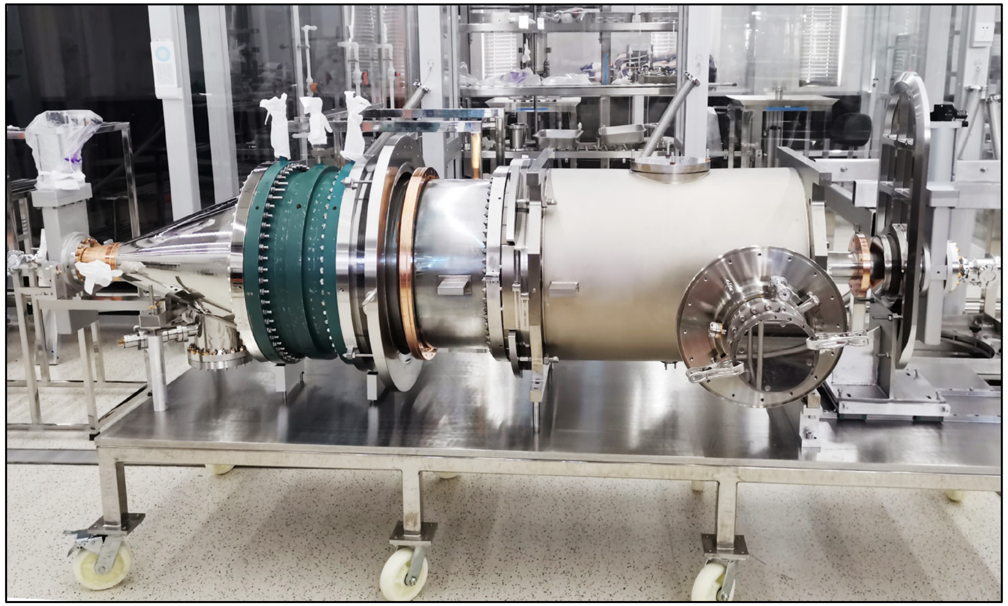




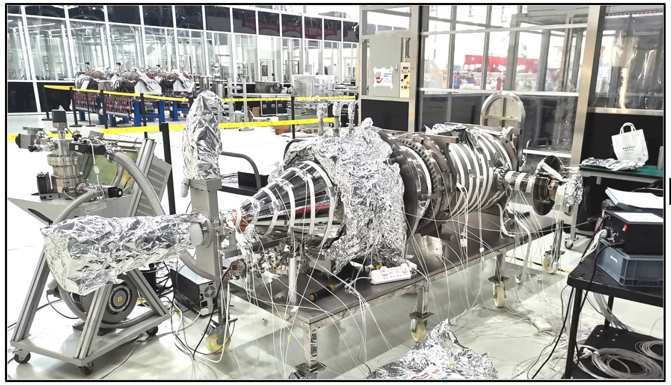


Assembly in class 10 (ISO4) cleanroom

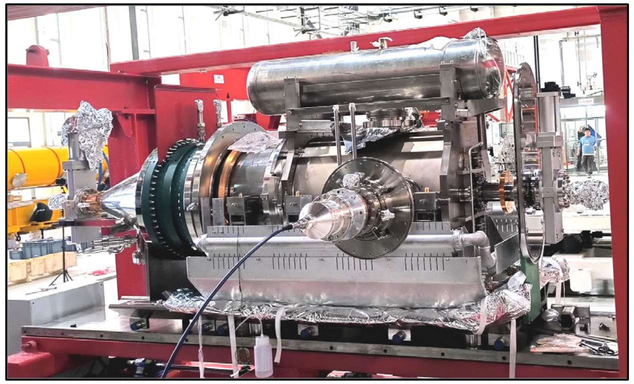




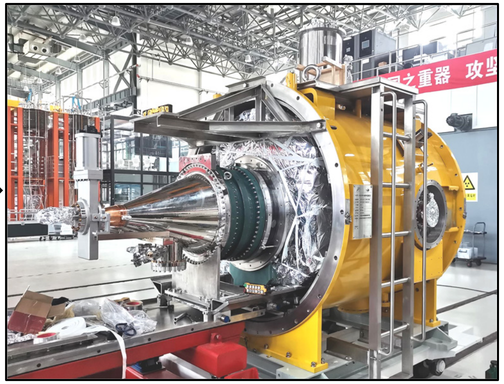
Cryomodule assembly



Baking



Assembly and alignment



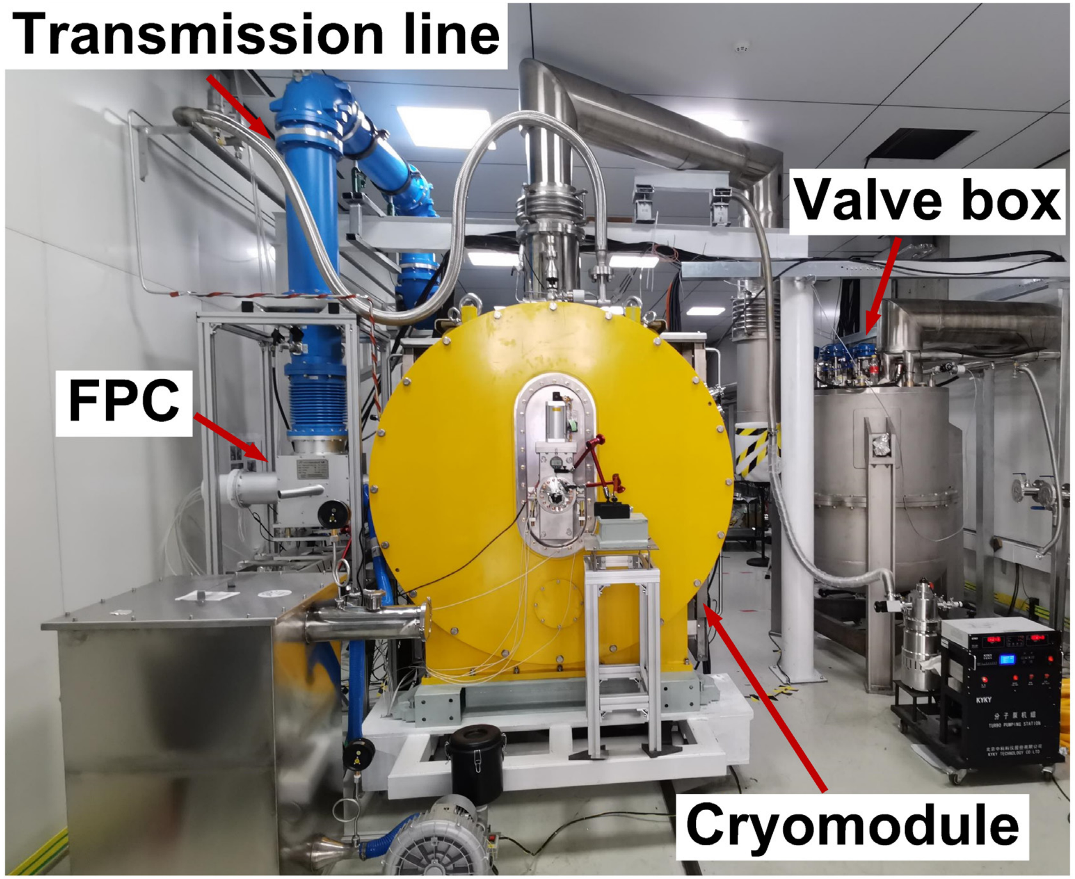
Assembly into cryostat

Ion-pump installation

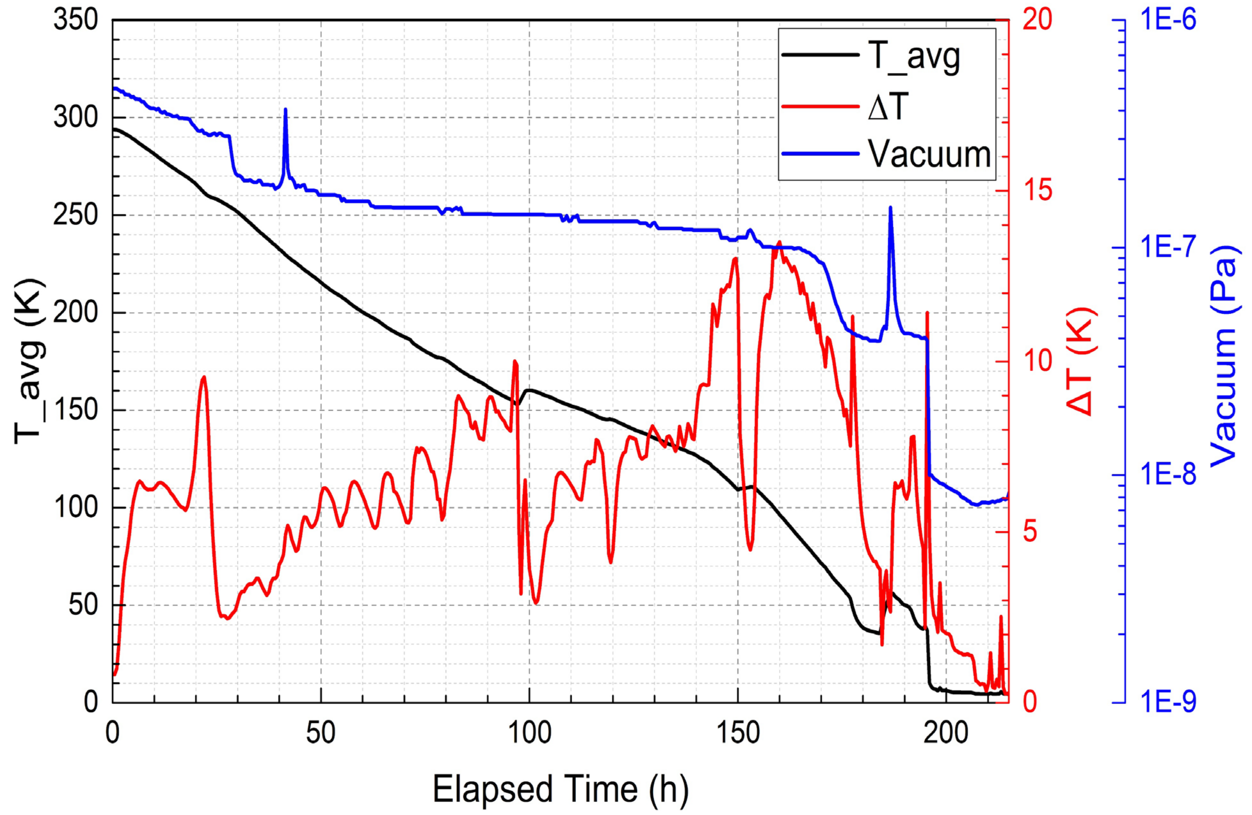
Tuner installation

Assembly completed

Preparation for horizontal test



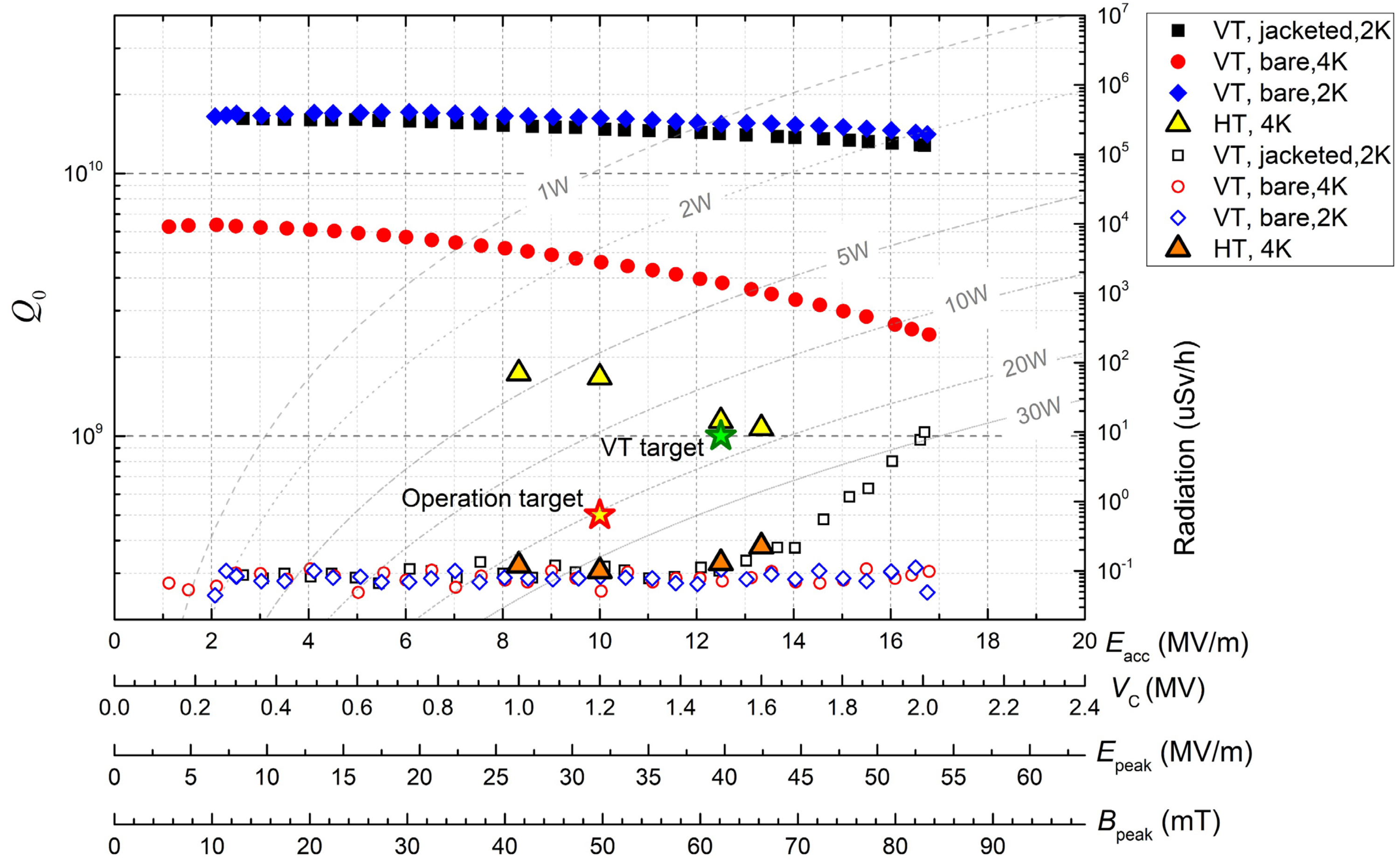
Horizontal test stand



- **300K ~ 40K (slow cooldown)**
  - ΔT<10K (300K ~ 120K), ΔT<15K (120K ~ 40K)
- **40K ~ 4K (fast cooldown)**

Horizontal test

- $Q_0=1.7\times10^9$@1.2MV
- Dynamic heat loss is 6.2W@1.2MV
- No early field emission
- Little Q degradation



Summary

- Following the success of the PoP cavity, HOM-damped 166.6MHz SRF cavities have been developed for HEPS storage ring
- 166MHz cavity string were developed, and the cryomodule were assembled
- Excellent cryogenic performance of the prototype cavity and module were obtained in vertical tests and horizontal tests
- 166MHz cavity system successfully verified by the horizontal test, and the series production will be launched soon

Thank you for your attention!