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69th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

The 1.3 GHz 3-cell superconducting cavity for high current beam acceleration

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2024.09.26

Outline

- Motivation
- Design of the cavity
- Fabrication of the cavity
- Tests of the cavity
- Summary

High current acceleration

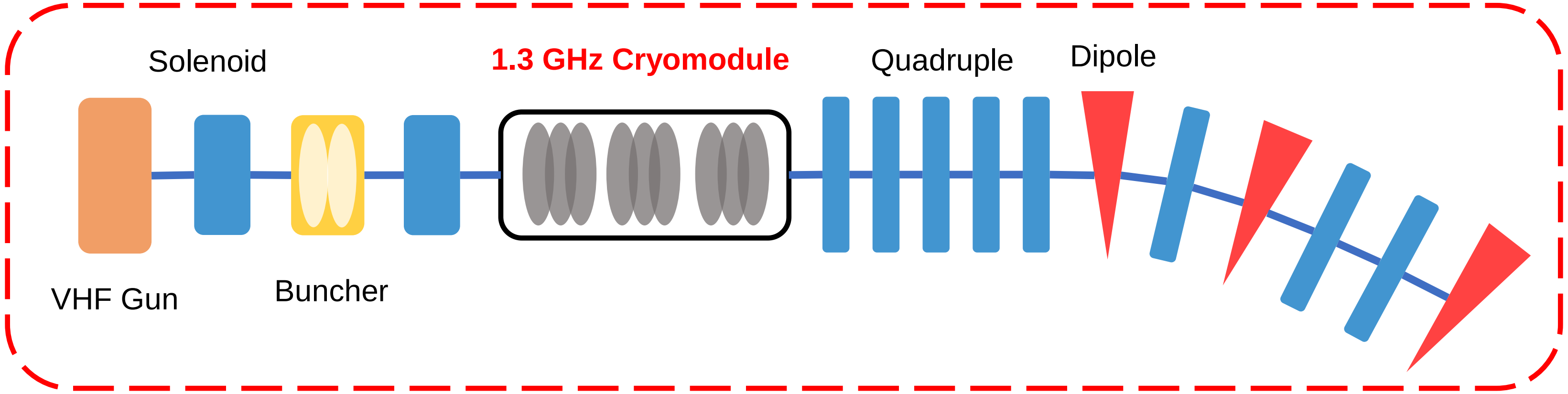
SHINE
- Average current: 0.3 mA
- Repetition: 1 MHz

High average power FEL

Lower beam dump power

ERL-FEL
- Average current: **10 mA**
- Repetition: 100 MHz

- The High-brightness ERL-FEL injector based on VHF gun.
- Three 1.3 GHz 3-cell cavities were required to accelerate a 10 mA electron beam to 10 MeV.

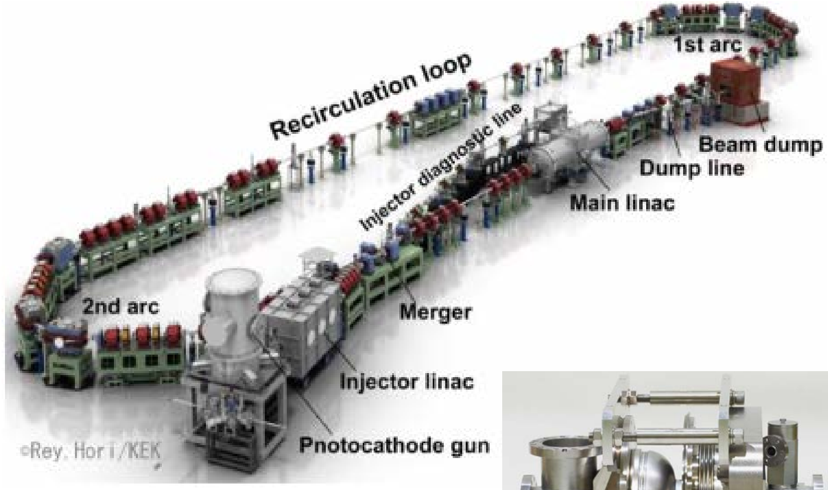


The layout of ERL-FEL injector

Parameters	Value
Injector energy	**10 MeV**
Beam energy	1 GeV
Average current	10 mA
Bunch charge	100 pC
Repetition	100 MHz
RF frequency	1.3 GHz

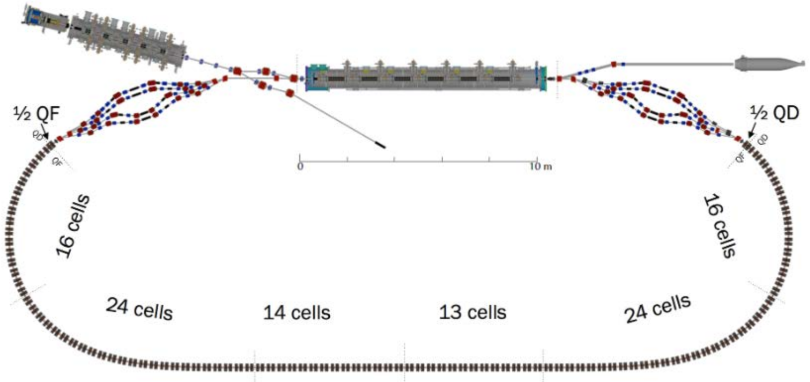
Worldwide injector cavities for ERL

cERL



2-cell cavity ×3

CBETA



2-cell cavity ×5

bERLinPro

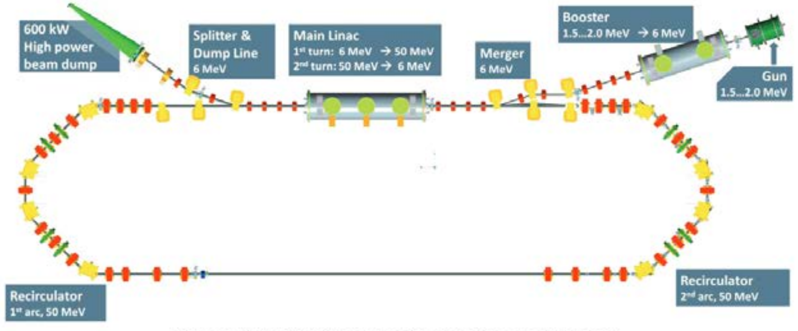


Figure 1: The bERLinPro Energy Recovery Linac machine layout.

2-cell cavity ×3

[1] K. Watanabe, et al., NIMA 714, 67 (2013).
[2] B. Dunham et al., Applied Physics Letters 102, 034105 (2013).
[3] A. Neumann, et al., Proceedings of IPAC2022.

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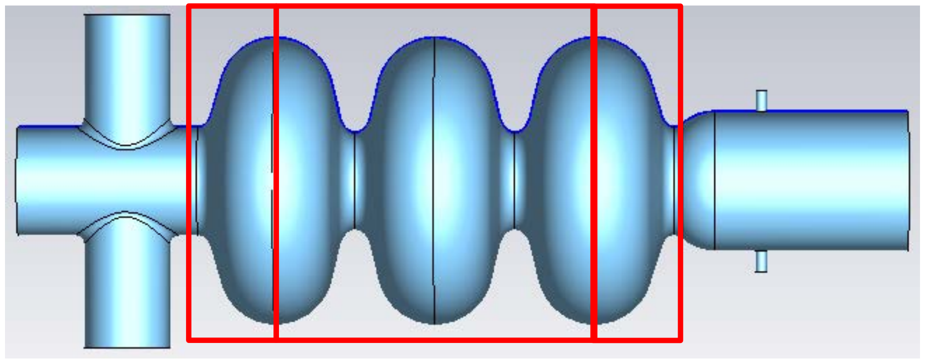
RF parameters of the 1.3 GHz 3-cell cavity

- Middle and end cells are the same as TESLA cavity design.
- Transitions between the end cell and beam tube are similar as cavities developed at Cornell and KEK.
- Enlarged beam tube for damping of HOMs.

Parameters	ERL-FEL	cERL	Cornell	bERLin pro	TESLA
End Iris diameter	78	88	78	70→88	78
Beam tube diameter (mm)	78→100	88	78→106	78→106	78
Cell number	3	2	2	2	9
R/Q (Ω)	329	208	222	217	1036
G (Ω)	272	288	261	261	270
Ep/Eacc	2	2.25	1.94	2.0	2
Bp/Eacc (mT/MV·m)	4.26	4.22	4.28	4.3	4.26

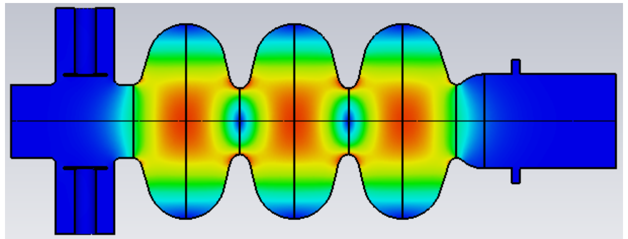


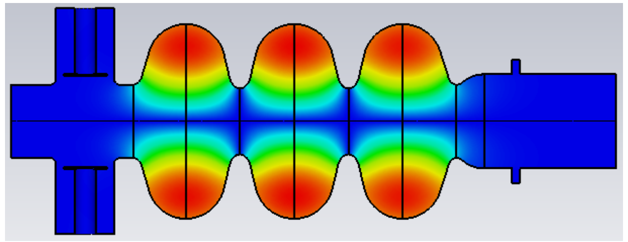
[1] B. Aune, et al., Phys. Rev. ST Accel. Beams 3, 092001 (2000).
[2] V. Shemelin, et al., Proceedings of SRF2003.
[3] Akai, K., et al., NIMA 499.1 (2003): 45-65.
[4] A. Neumann, et al., Proceedings of IPAC2014.

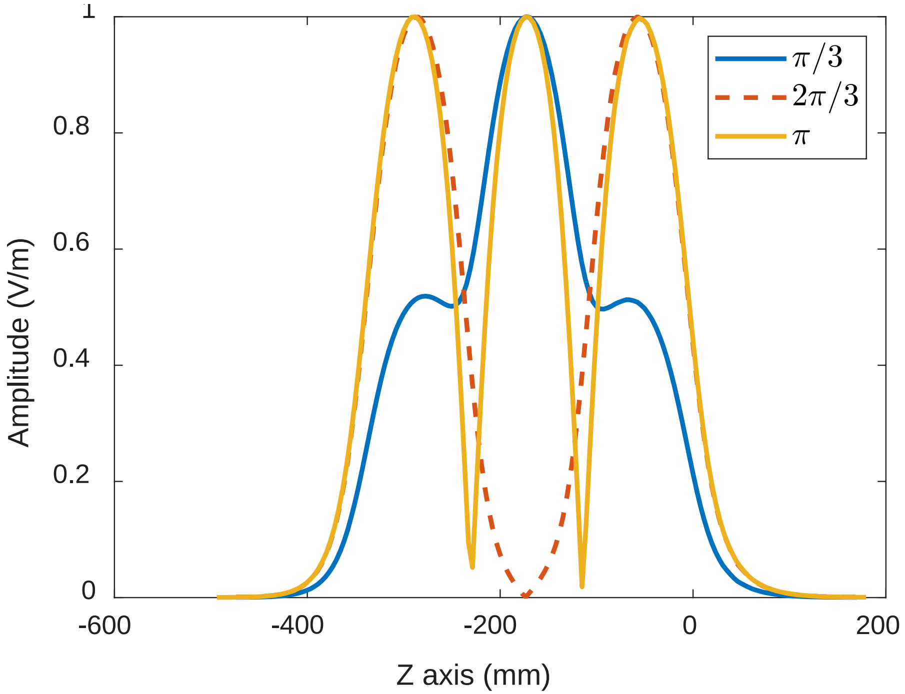
3 passband modes

Mode	Frequency (MHz)	R/Q (Ω)	Field flatness
$\pi/3$	1282	0.016	-
$2\pi/3$	1294	0.017	-
π	1300	329	99%

Pi mode field distribution

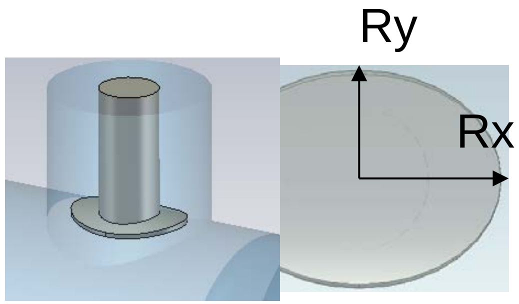


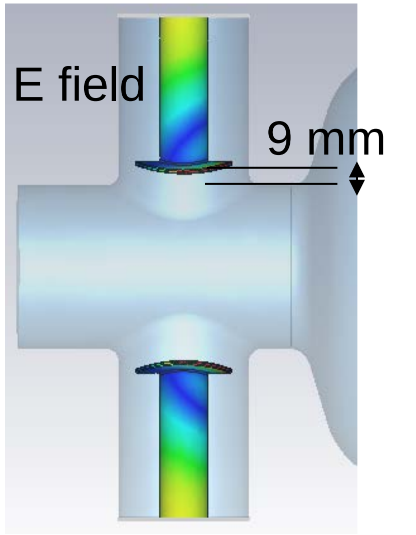


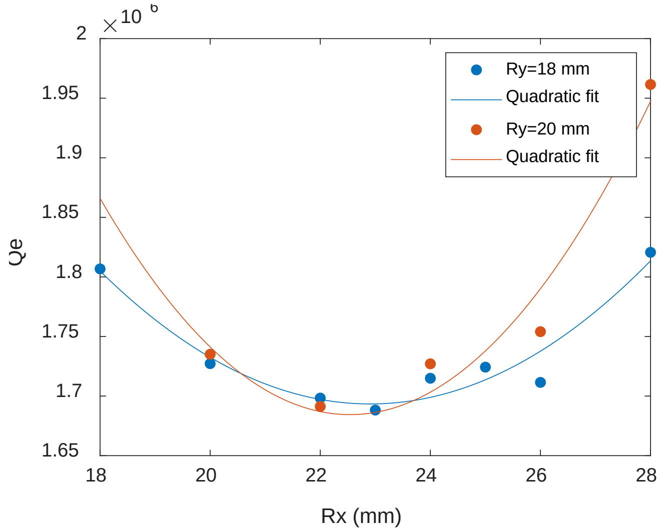


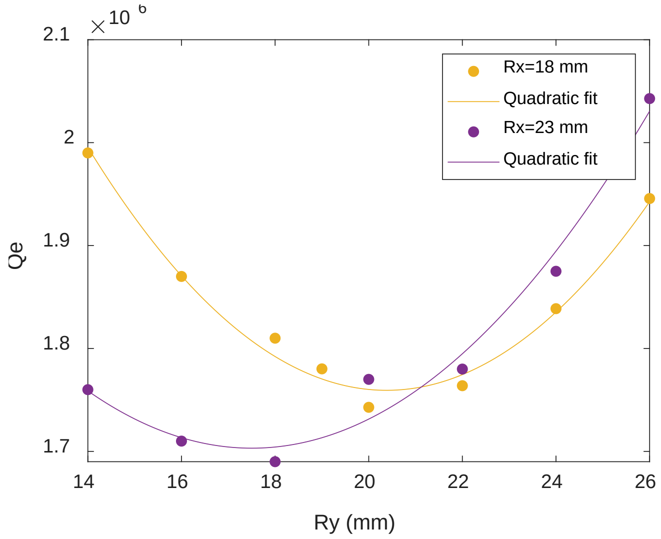
Twin couplers for high-power input

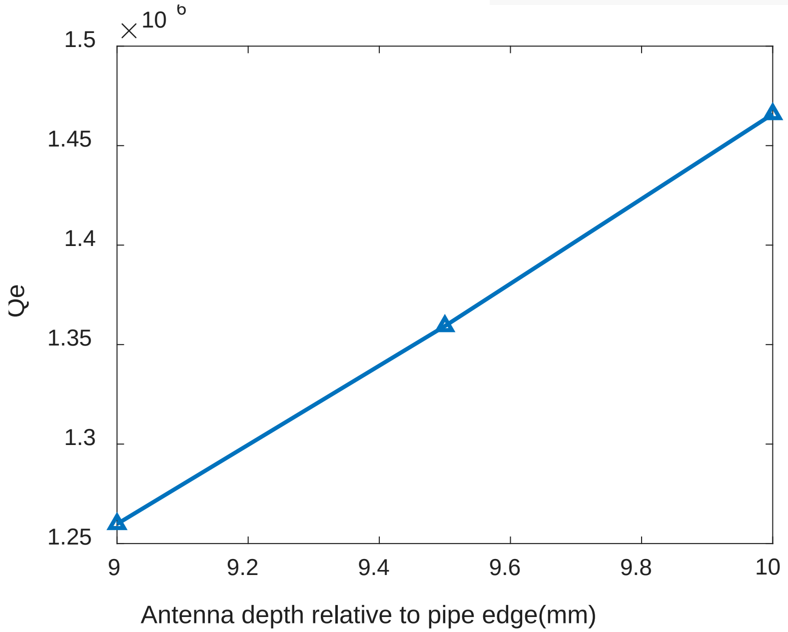
- The antenna optimization was based on Cornell design.
- Optimized elliptical dimensions of the tip (Rx, Ry).
- Qe=1.25E6 for Eacc=12 MV/m and I=10 mA, antenna depth relative to the pipe edge is 9 mm.





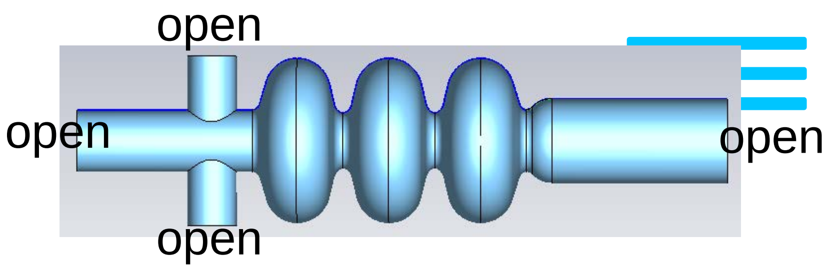




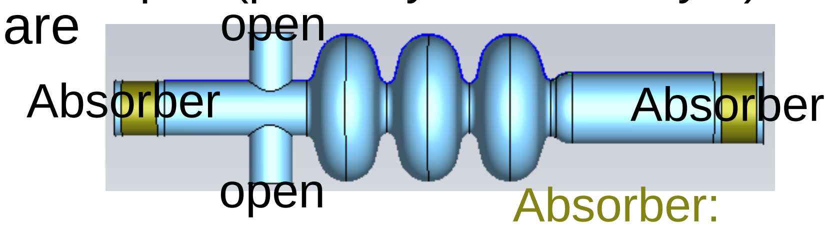


[1] V. Shemelin, et al., Proceedings of SRF2003

HOMs damping



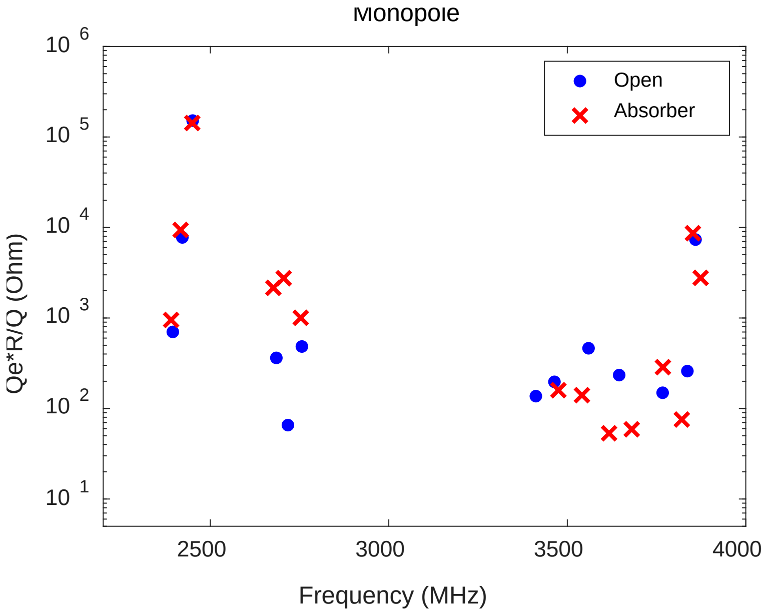
Open (perfectly matched layer)



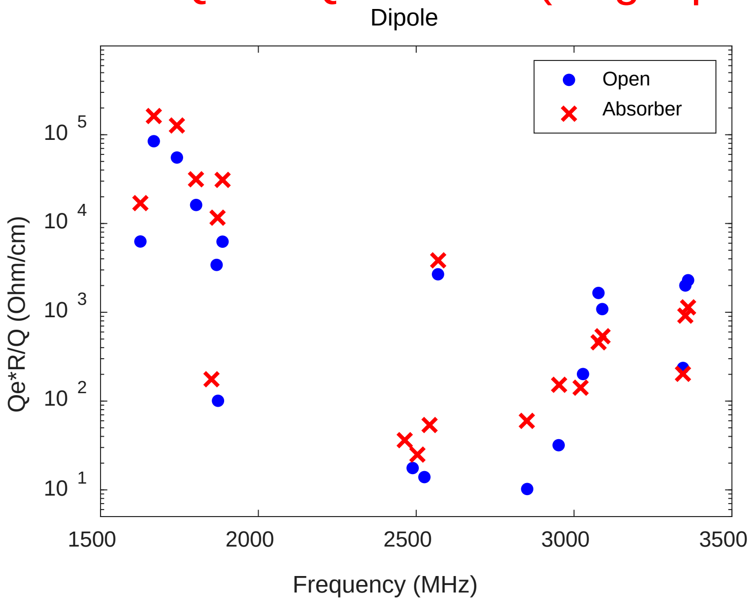
Absorber:
$\varepsilon' = 50, tangent = 0.1$

- MCs are under open boundary conditions (PML). Beam pipes are under PML or absorber.
- $P_{max} = I^2 \frac{R}{Q} Q_e < 100\ W;\ \ I = \frac{\pi^3 V_{beam}}{2\frac{R}{Q}_{\perp} Q_e L_{act}} F(x) = 10\ mA$
- HOMs impedances are below the limits.

Limits: Qe*R/Q < 1E6



Limits: Qe*R/Q < 7.5E7 (single pass)



[1] M. Liepe, Proceedings of SRF2003
[2] T. P. Wangler, Principles of RF Linear Accelerators (Wiley, New York, 1998).

HOMs power

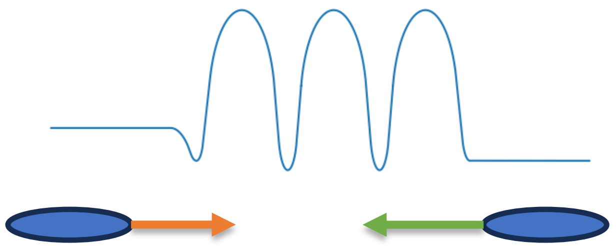
Parameters	Value
Average current	10 mA
Bunch charge	100 pC
Bunch length	0.6 mm

- Total Resonant power is 110.72 W.

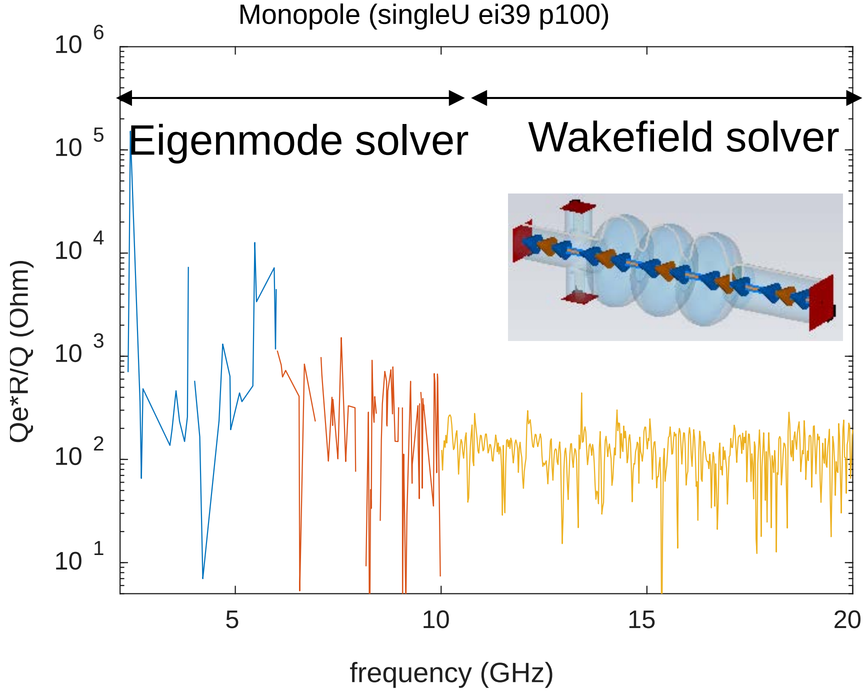
$$P_{L,M} = \sum_{\omega} I^2(\omega) Z(\omega) \qquad P_t = P_L + P_M + \frac{90}{4} P_M = 110.72\ W$$

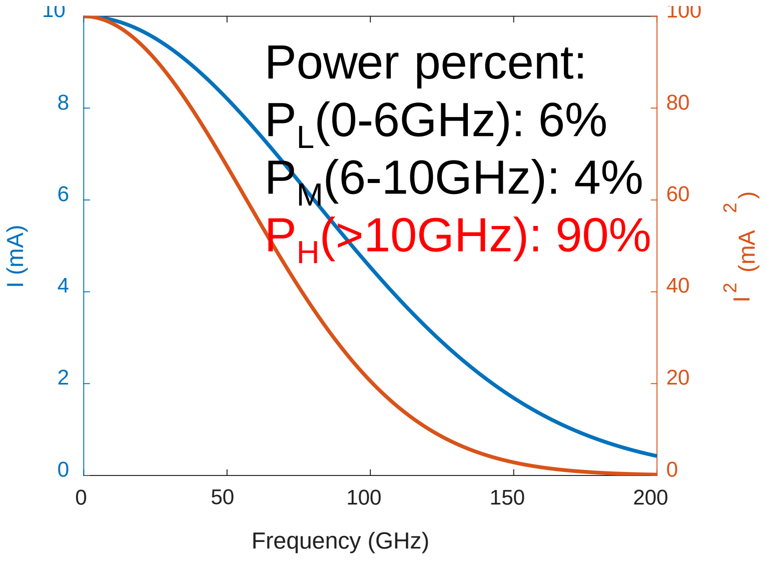
- Incoherent power is 4.95/9.11 W.

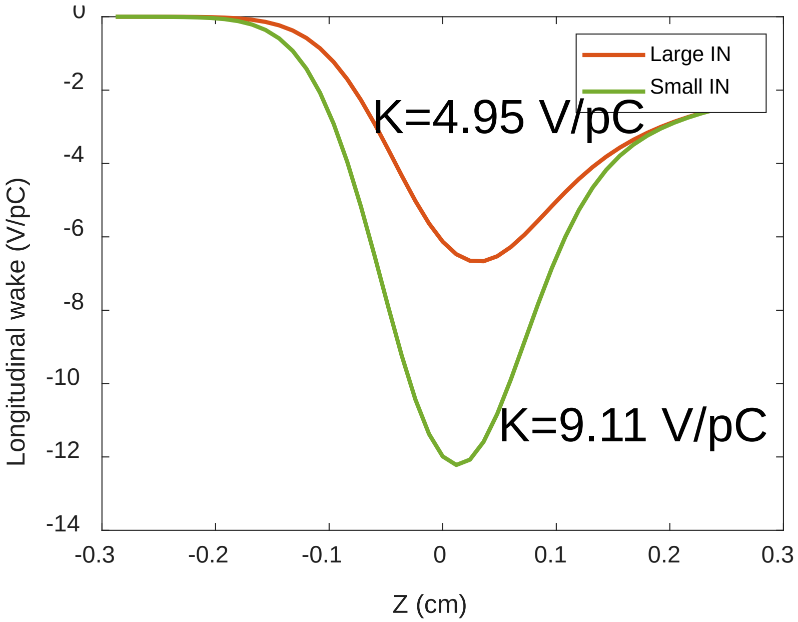
$$P_{inco} = KQI$$



Short-range wake (ECHO)



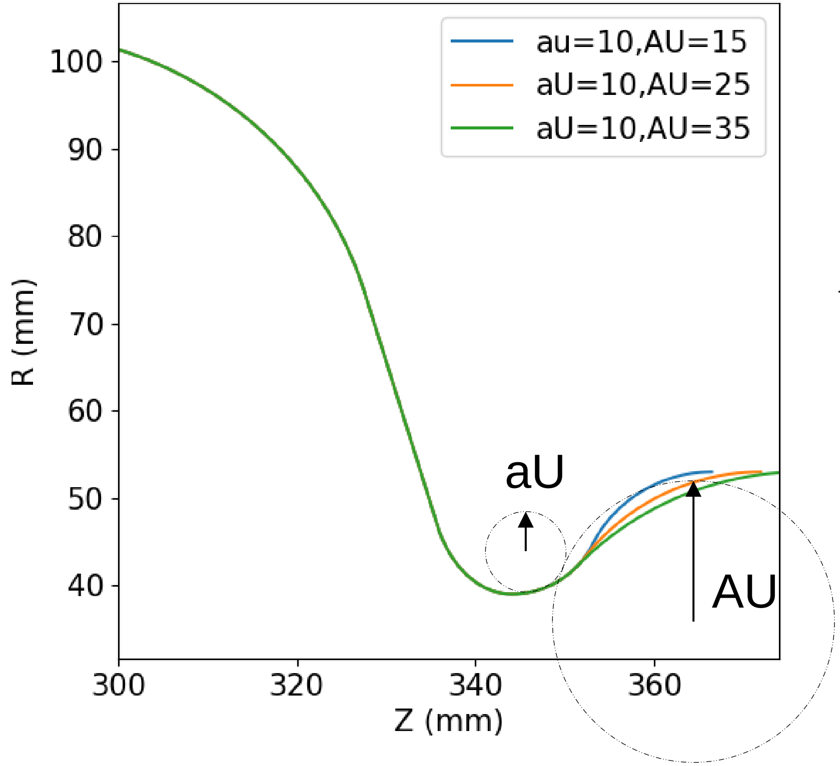




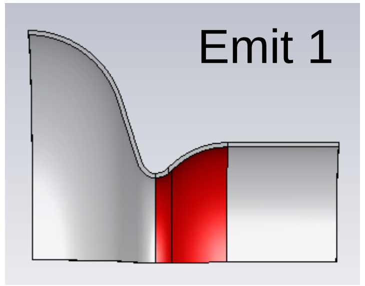
[1] A. Lunin, et al., Phys. Rev. Accel. Beams 21, 022001 (2018)
[2] S. Gorgi Zadeh, et al., Proceedings of IPAC2019.

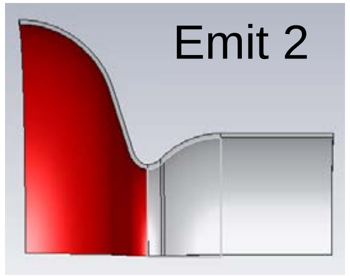
Multipacting in transitions

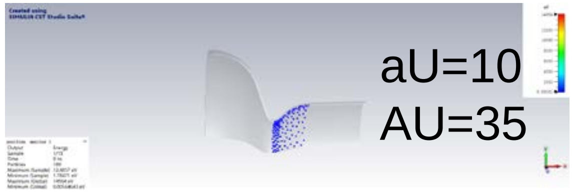
- Multipacting free at AU>12 for aU=10.

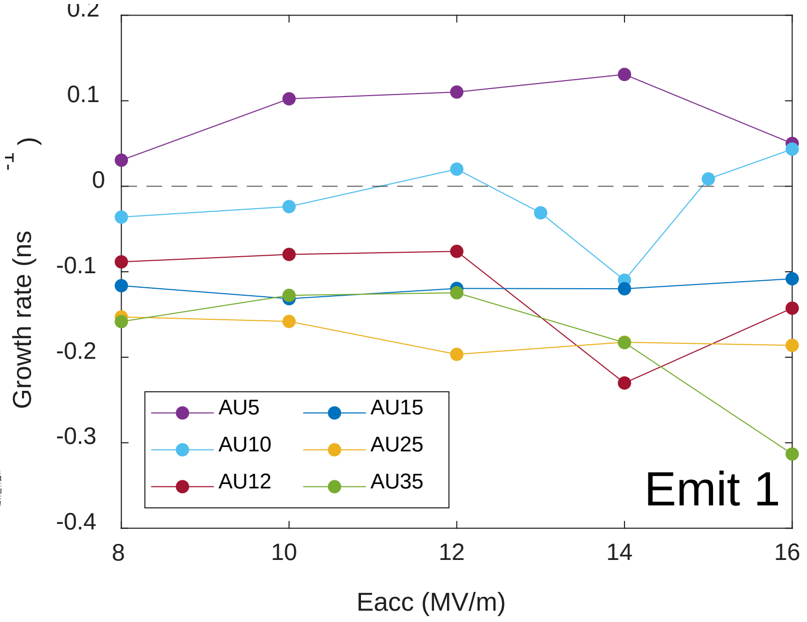


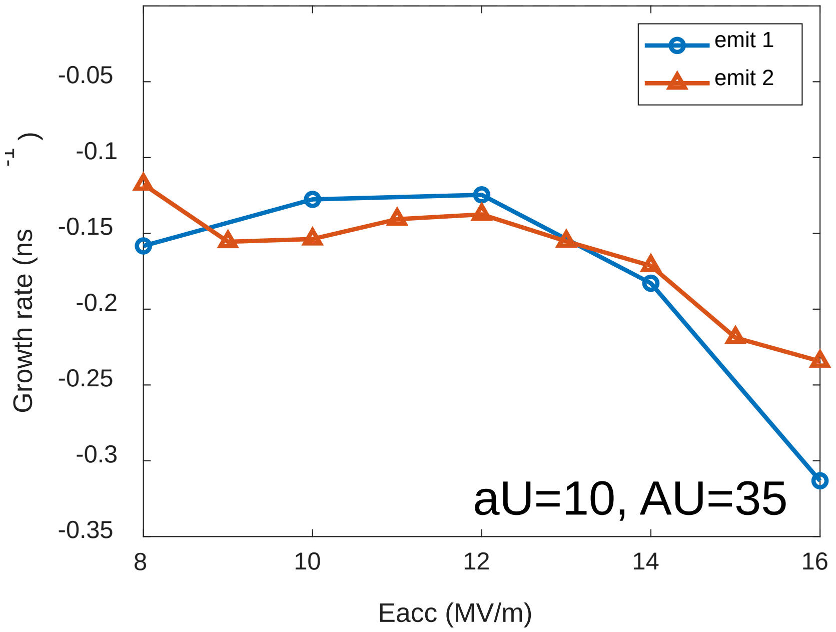
Particle Sources







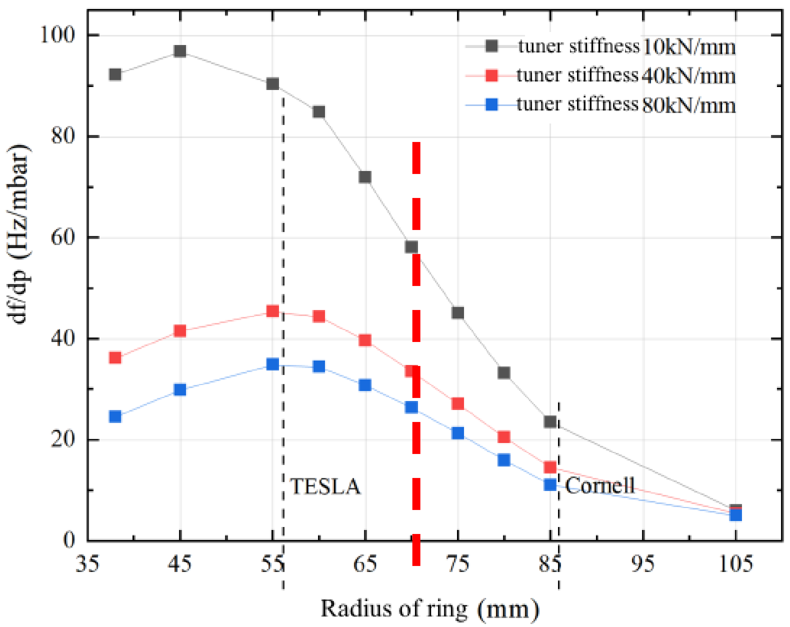


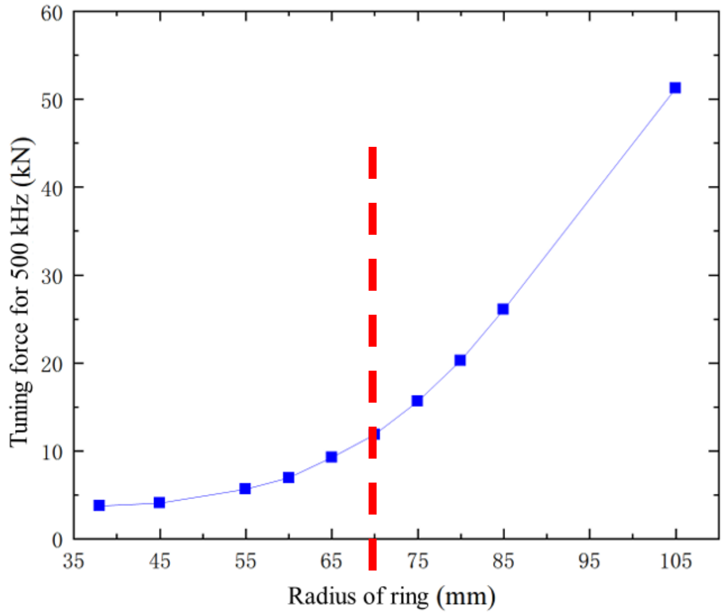


[1] S. Belomestnykh, et al., NIMA 595, 293 (2008).

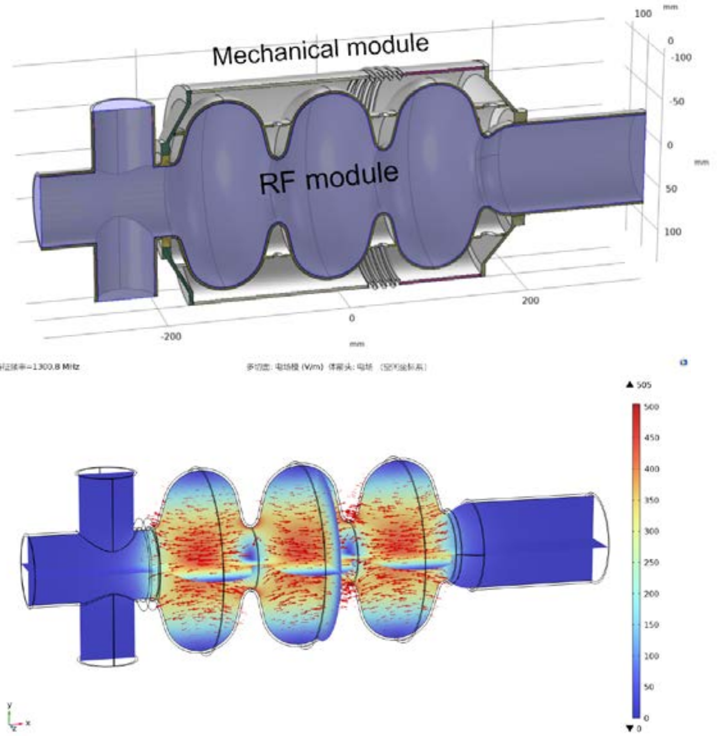
Helium pressure sensitivity

- Small beam pipe end is fixed, the other end is free to expand during the simulation.
- The radius of stiffening ring was selected as 70 mm for relatively low df/dp while not being particularly difficult to tune.





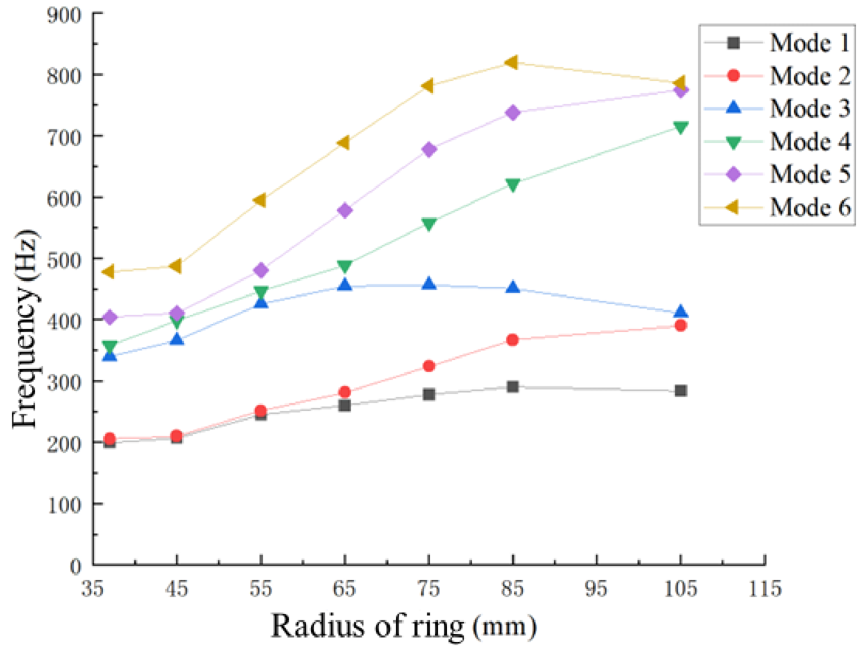
Fixed

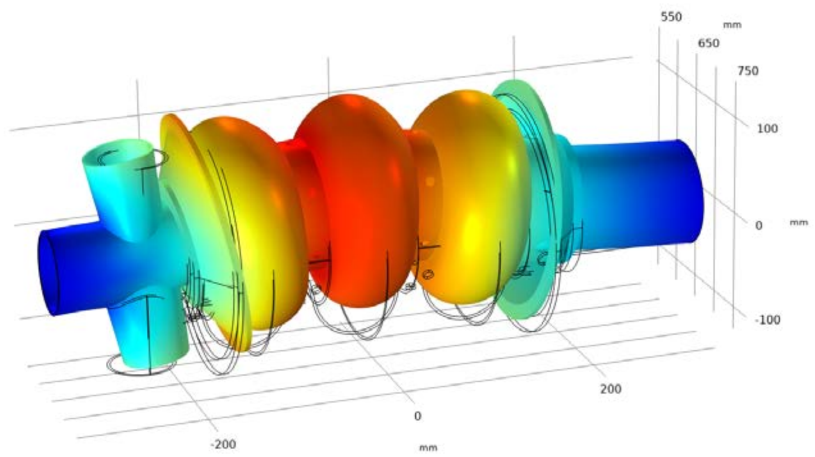


[1] S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 022002 (2012).

Mechanical modes

- The cavity is fixed at both ends for calculate the first six modes.
- The lowest modal frequency is up to 200 Hz. 70 mm radius of stiffening ring met requirements.





Outline

- Motivation
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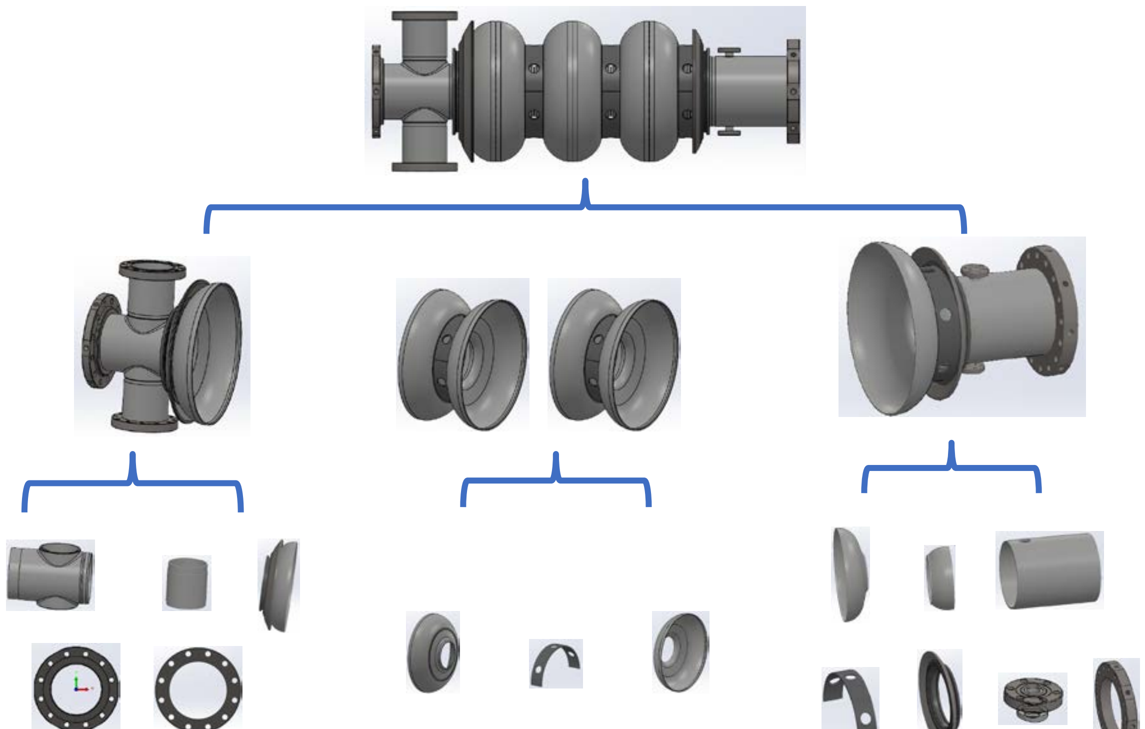
Fabrication of the prototype

- The prototype was fabricated by Beijing HE-racing Technology Co., Ltd.
- Materials provided by OTIC, NX.
- Followed by the standard fabrication procedures.
- Diameter reducing working method for transition section.



Middle cell

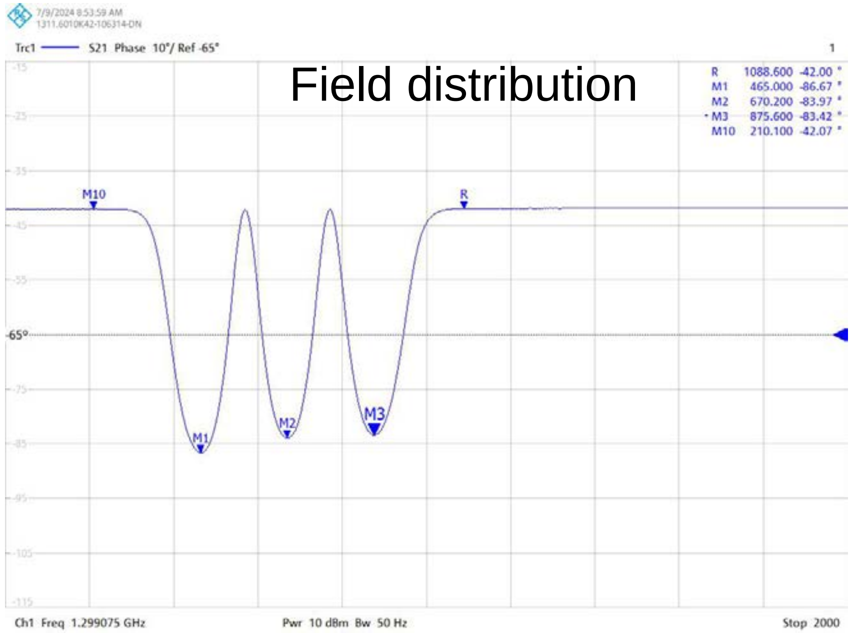
End group

transition section

Fabrication of the prototype

- The prototype was fabricated by Beijing HE-racing Technology Co., Ltd.
- Frequency/length met the goals.
- Field flatness is good after fabrication.

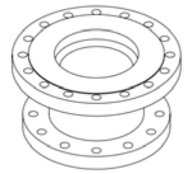
	Goals	#01
Length (mm)	643.23±3.0	642.36
Frequency (MHz)	1298.9±0.5	1299.077
Field flatness (%)	> 50	96



Surface treatment of #01

- Surface treatment was conducted at SHINE facility at Wuxi Creative.
- BCP and heat treatment.
  - 160 μm heavy BCP+900 °C
  - Based on SHINE BCP process
- No obvious defects.

BCP



New transfer tooling

Equator before BCP

Equator after BCP

Borescope system

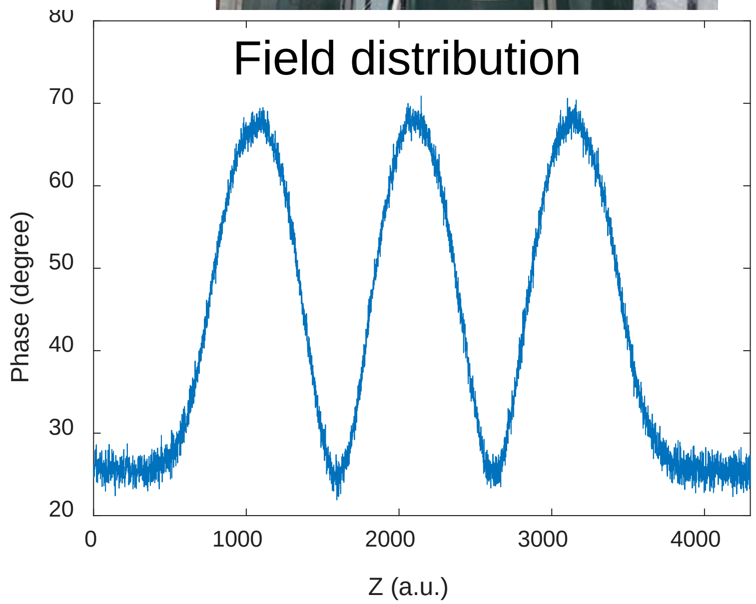
[1] Z. Wang, et al., Proceedings of IPAC2024.

Tuning of #01

- Frequency/length met the goals.
- Field flatness is good after tuning.
- Goals at room temperature and vacuum.

Tuning

	Goals	#01
Length (mm)	643.23±3.0	642.31
Frequency (MHz)	1298.33±0.1	1298.38
Field flatness (%)	> 96	99



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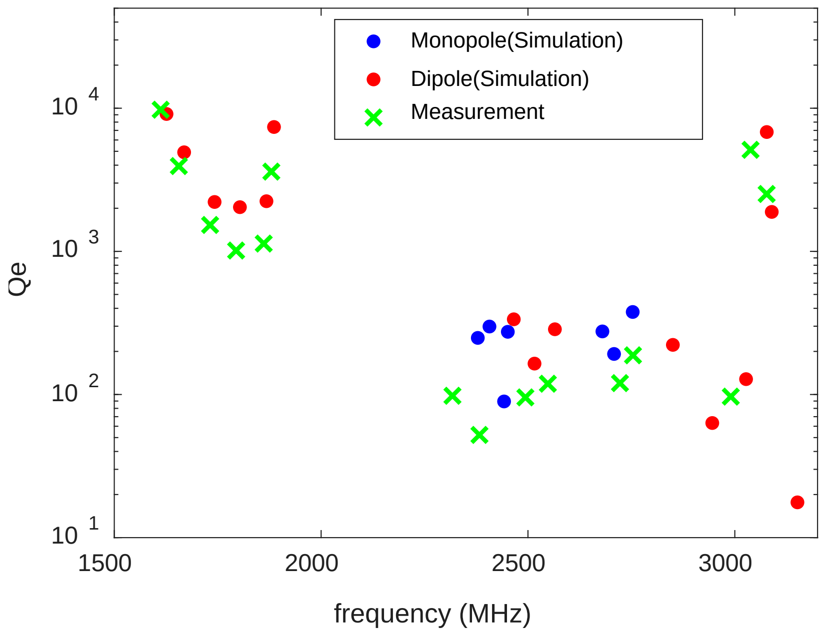
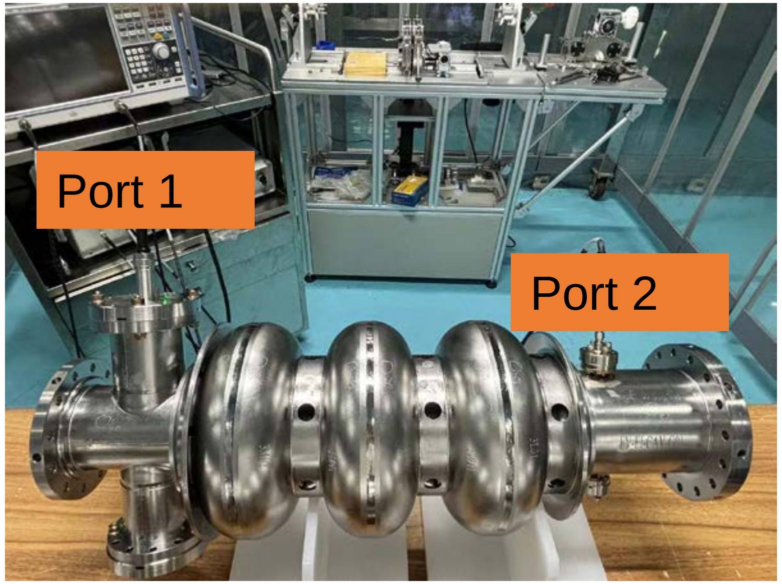
HOMs measurement at room temperature

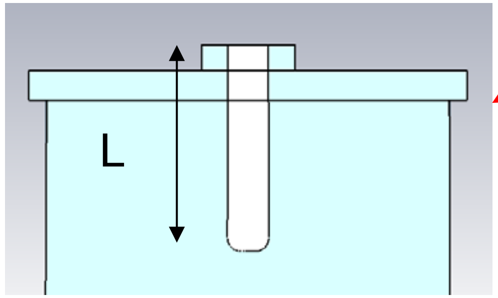
- Check damping of HOMs by measuring Qe with open beam pipe ends ('perfect absorber').
  - $\frac{1}{Q_e} = \frac{1}{Q_L} - \frac{1}{Q_0}$. Q0: closed beam pipe; QL: open beam pipe.
- Q-values were measured by -3dB method of S21.
- Measured results show the good propagation of HOMs.

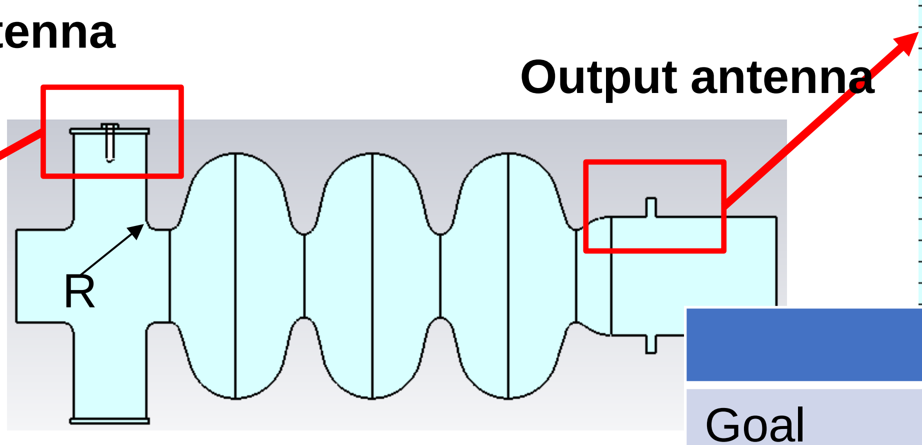


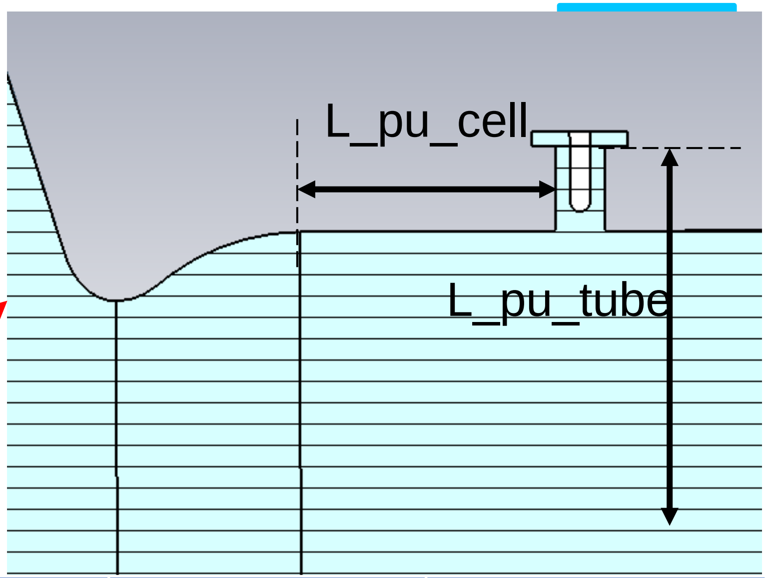


[1] W. Xu, et al., Proceedings of IPAC2012.

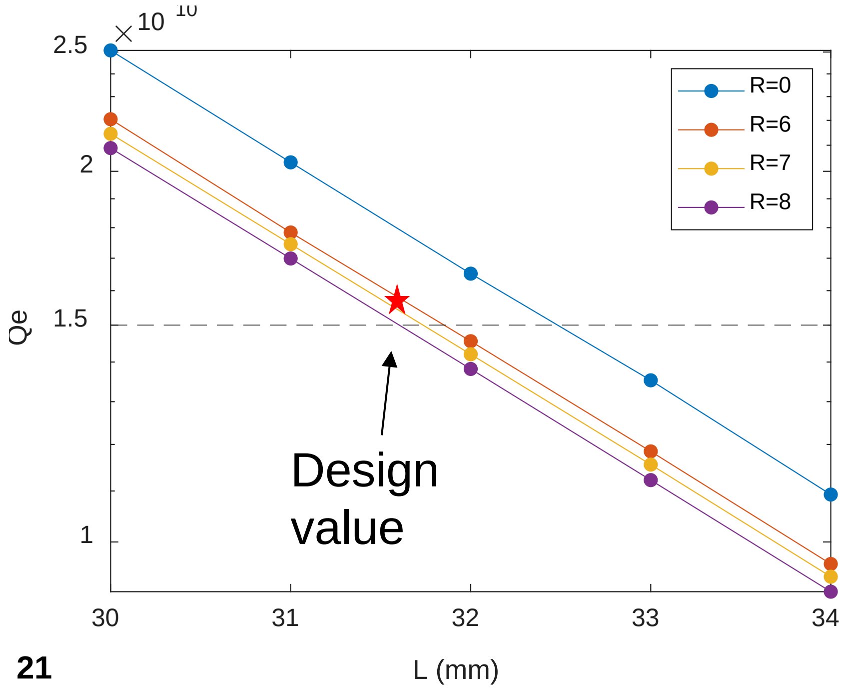
Antennas of vertical tests

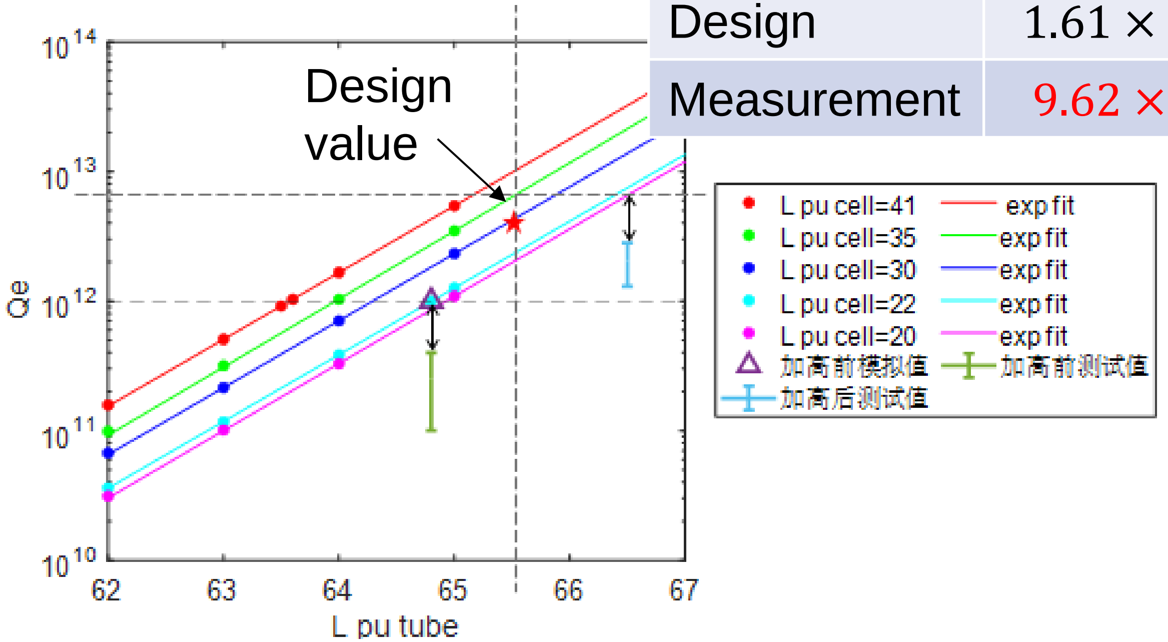






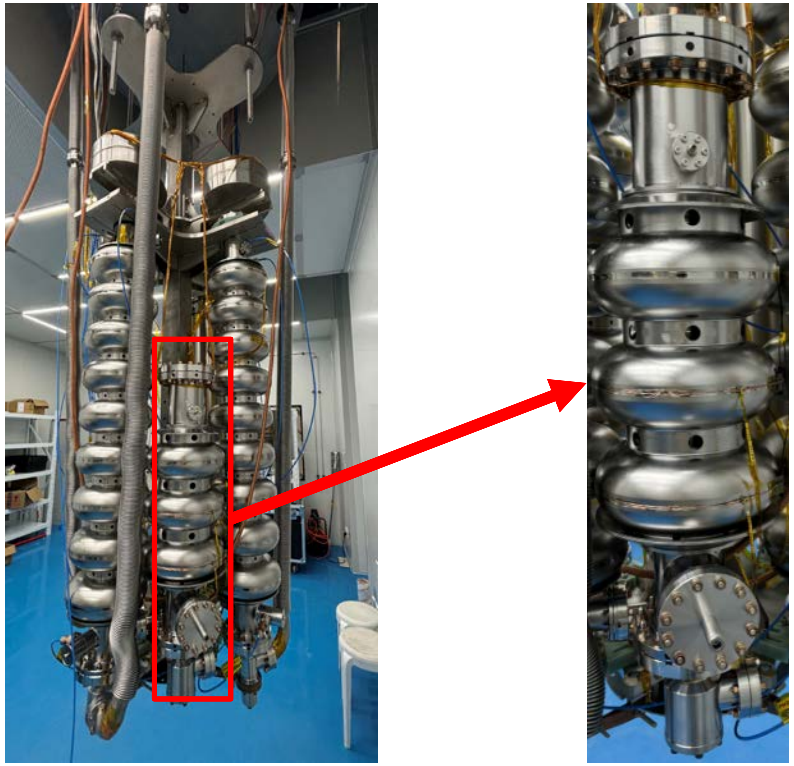
	Qe	Qt
Goal	1.5×10^{10}	1×10^{12}
Design	1.61×10^{10}	4.26×10^{12}
Measurement	9.62×10^{9}	1.62×10^{12}

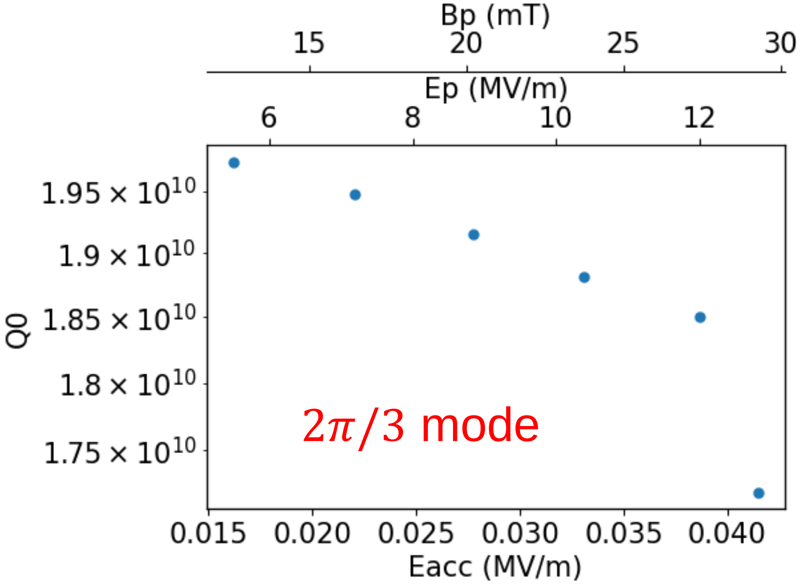


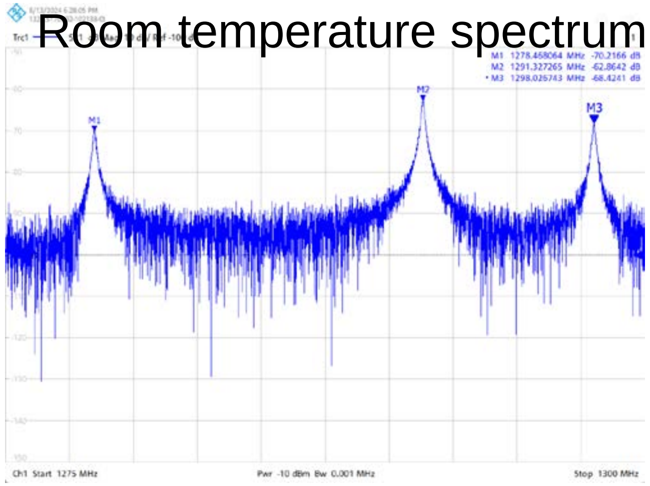


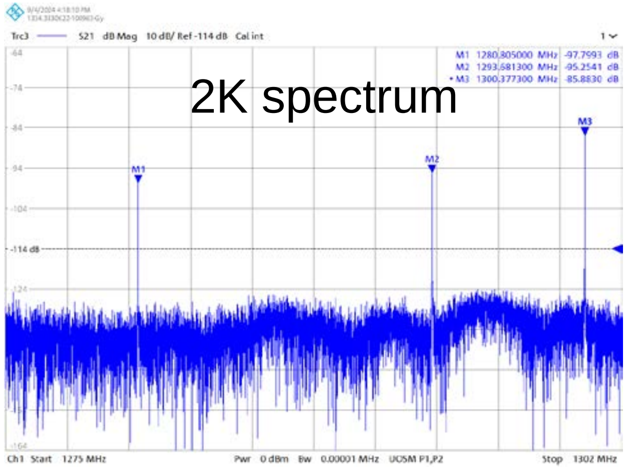
Vertical tests

- The cavity was tested at the vertical test stand at SHINE.
- The π-mode was unable to establish the cavity voltage.
- However, $2\pi/3$-mode can be established. The very low accelerating gradient is due to the small impedance.



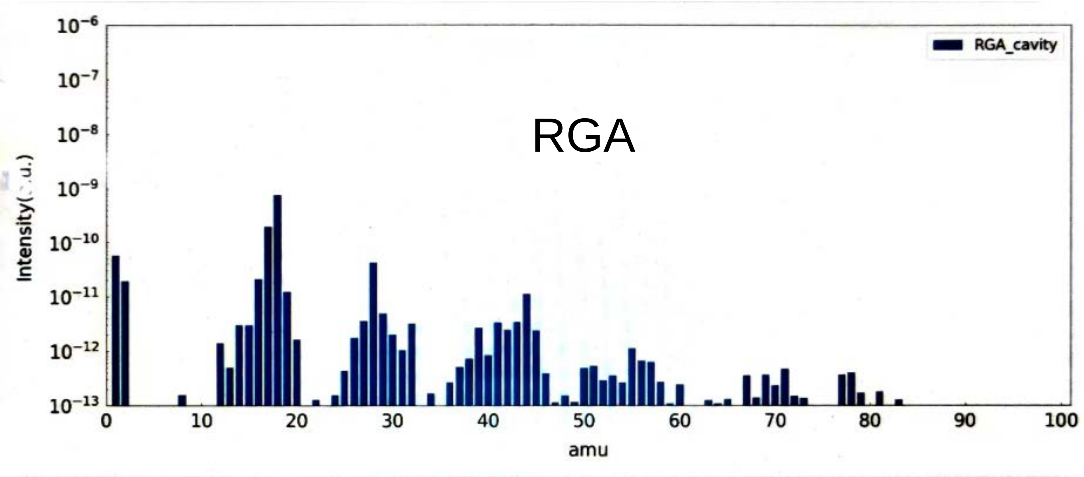


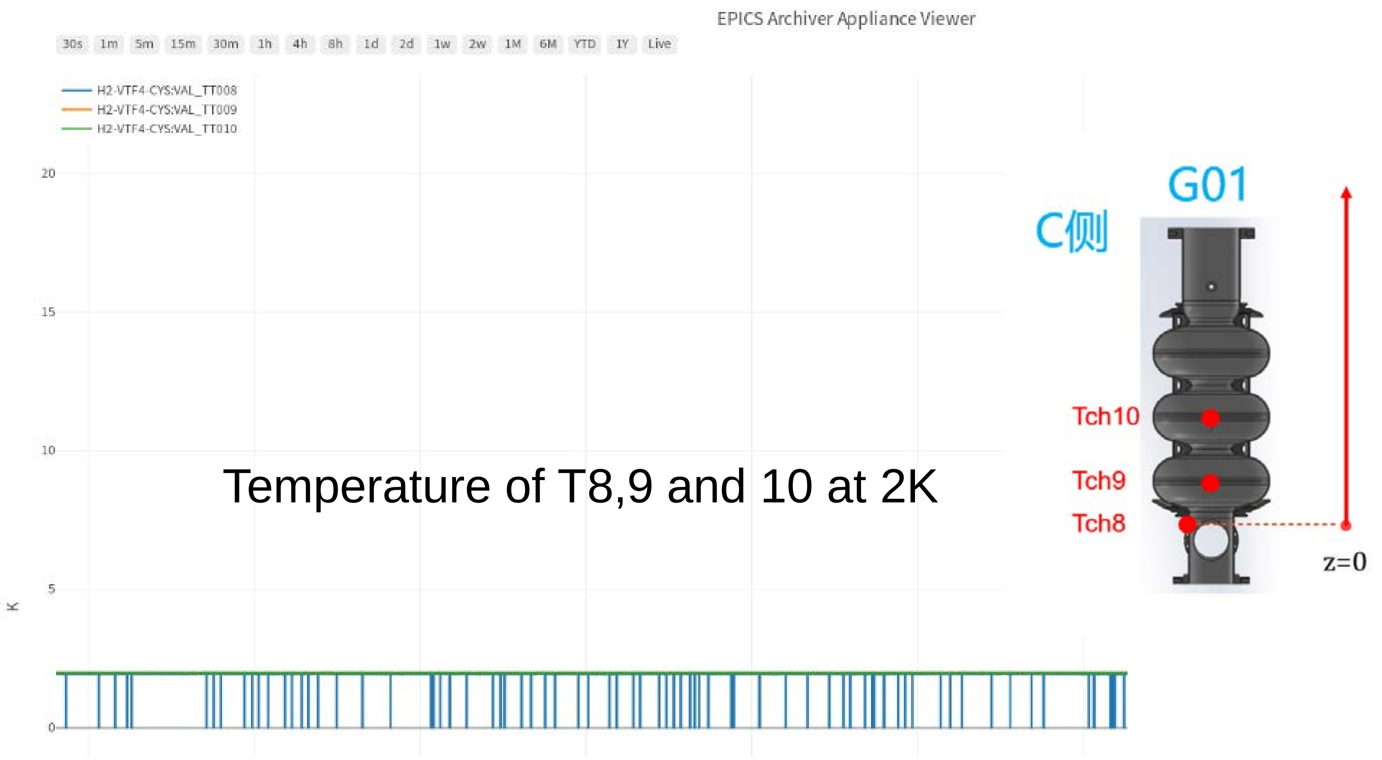




Vertical test issue analysis

- Data from the temperature probe during the vertical test indicated no temperature rise.
- The RGA data after the cavity was removed from the dewar indicated no liquid helium leakage into the cavity.
- A vacuum pipe will be connected with the cavity in the next vertical test to monitor the vacuum level.





Summary

- **The 1.3GHz 3-cell cavity has been designed for high current injector.**
  - RF parameter of fundamental mode met the goals.
  - Dimensions of the antenna tip were optimized for optimal coupling.
  - Beam tube was enlarged, and impedances of HOMs was below the limits.
  - The stiffening ring radius was optimized through helium pressure sensitivity and mechanical modes analysis.
- **The first prototype has been fabricated and tested.**
  - Measured results show the good propagation of HOMs.
  - Only $2\pi/3$-mode was established in the first vertical test.
- **Plan**
  - The second vertical test around October 2024.

Acknowledgments

- Many thanks to SHINE SRF cryomodule team.

- Collaboration of several institutes
  - J.F. Chen, P.C. Dong, Y. Zong, S. Xing, J.N. Wu, Z.Y. Ma, S.J. Zhao, X.M. Liu, X.H. Ouyang, S. Sun, L.J. Lu, Y.L. Zhao, H.T. Hou, D. Wang from SARI, CAS
  - Z. Wang from SINAP, CAS
  - X. Yan, X.H. He, M.Y.M. Zhao, Y.W. Huang from ShanghaiTech University

Thanks for your attention!