STCF常温高频腔预研进展

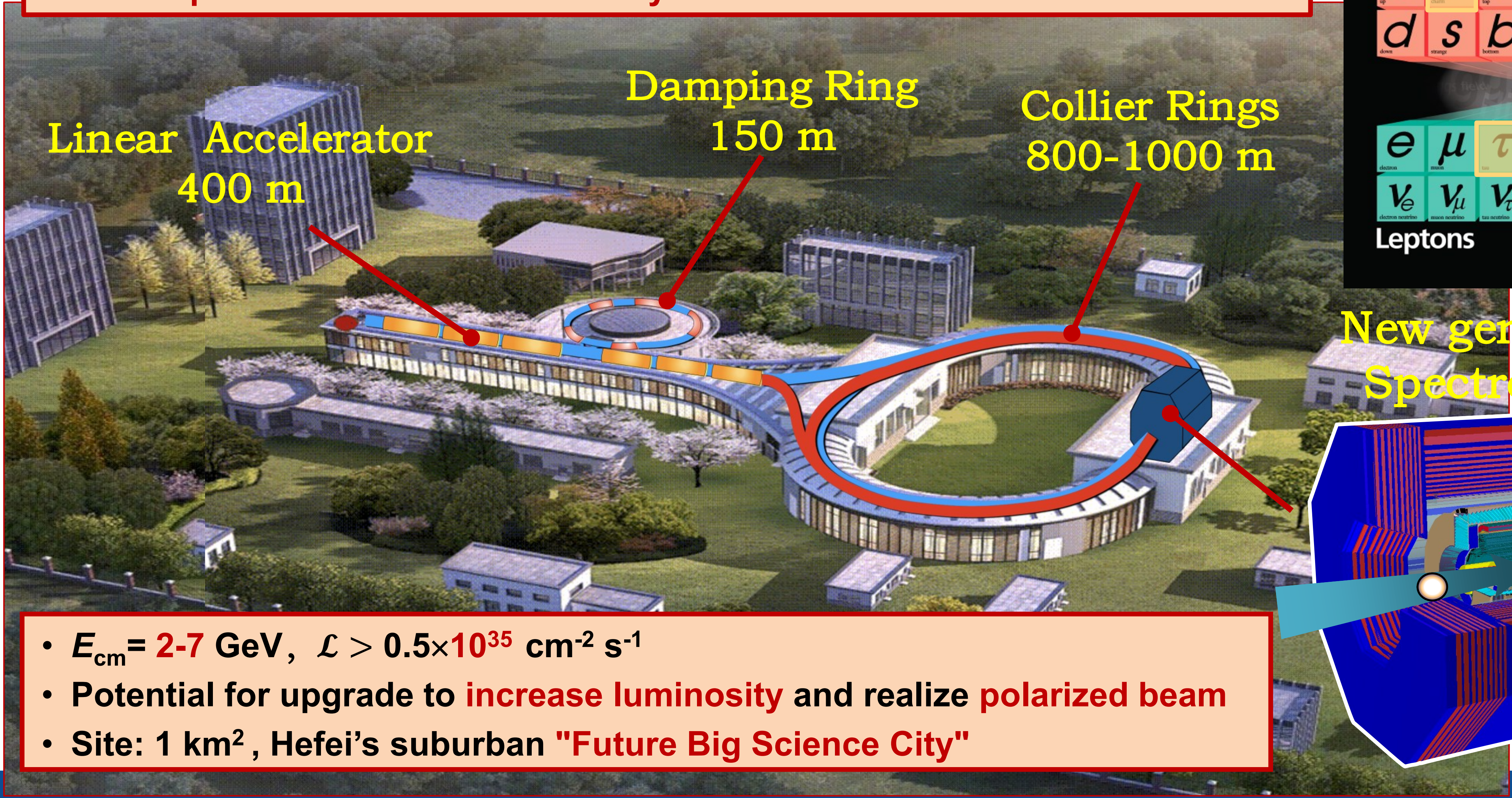
韦业龙

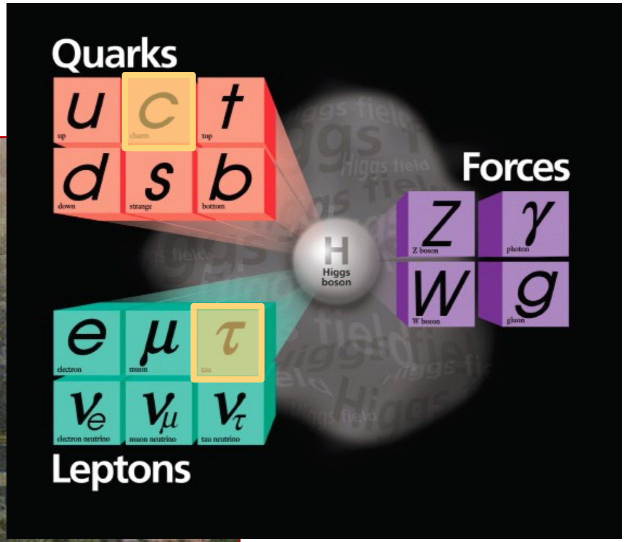
代表环高频系统

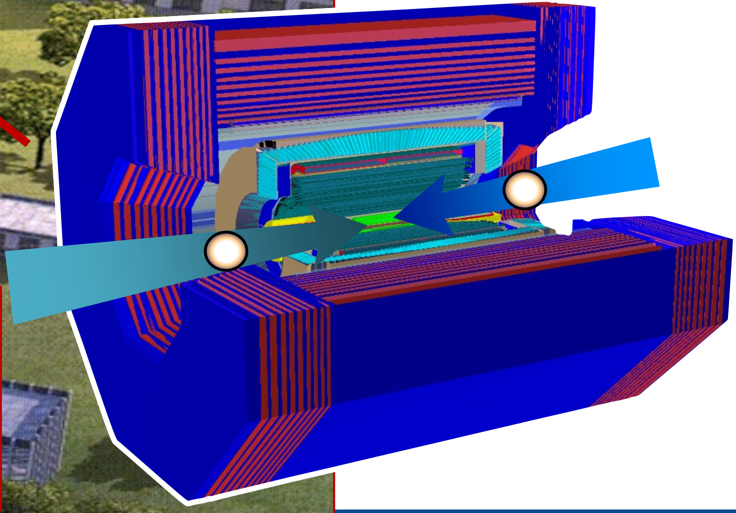
Outline

Super Tau Charm Facility (STCF)

A factory producing massive **tau lepton** and **hadrons**, to unravel the mystery of **how quarks form matter** and the **symmetries** of fundamental interactions







- E_{cm}= 2-7 GeV， $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential for upgrade to **increase luminosity** and realize **polarized beam**
- Site: 1 km^2 , Hefei's suburban **"Future Big Science City"**

STCF Collider Ring

	Values			
Beam Energy [GeV]	1.0	1.5	2.0	3.5
Circumference [m]	860.321			
Revolution frequency [kHz]	348.47			
RF Frequency [MHz]	499.7			
Harmonic Number	1434			
Number of Bunches	688			
Beam Current [A]	1.1	1.7	2	2
Momentum Compaction Factor	12.63×10^{-4}	13.24×10^{-4}	13.49×10^{-4}	13.73×10^{-4}
Total Energy Loss per Turn [keV]	106	267	543	1494
Total Beam SR Power [kW]	117	453	1086	**2988**
RF Voltage [MV]	0.75	1.2	2.5	**6**
Synchronous phase [°]	172	167	167	166

- Considering damping ring has a low beam current, so the RF system can be developed for both damping and collider ring.
- Key parameters for RF system：

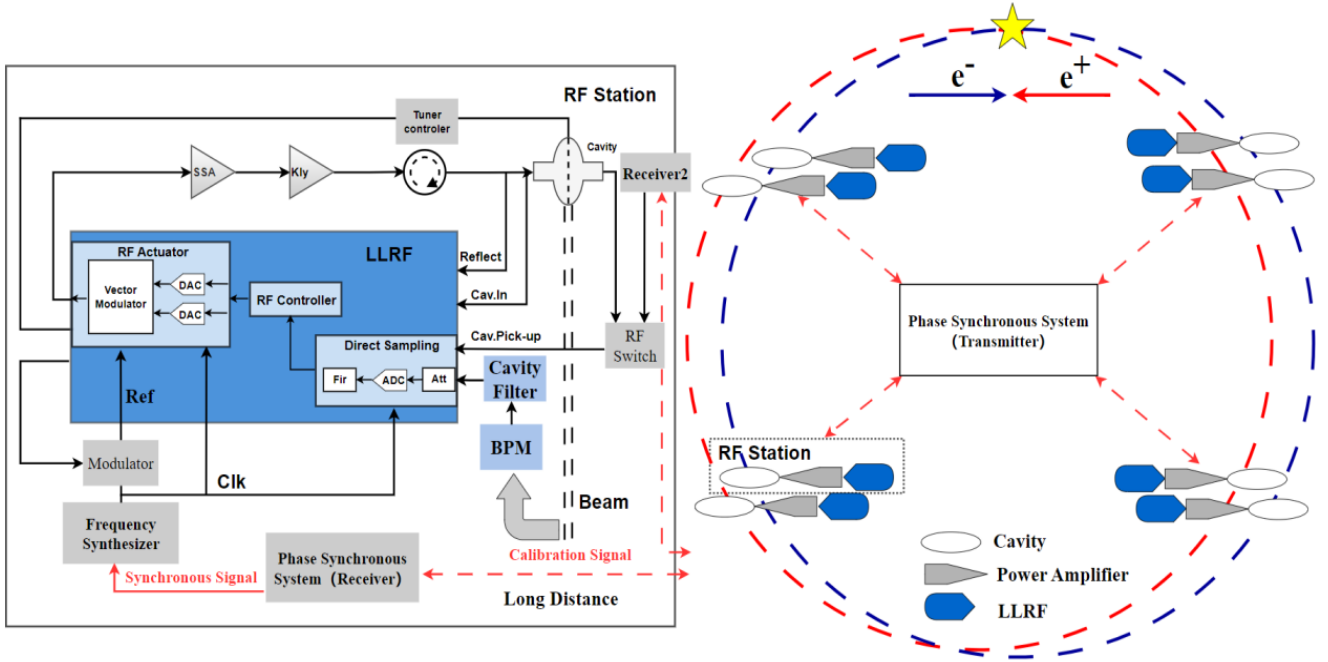
(1) Frequency: 499.7 MHz ;

(2) RF system has to provide a voltage of 6 MV and a beam power of 3 MW for each ring

STCF Ring RF System

Super Tau-Charm Facility Ring RF system

RF system
- RF Cavities
- RF Power Source
- Low-level RF Control System



- One of the most serious issue is that large beam currents to excite fast-growing longitudinal coupled-bunch instabilities (CBI) caused by the accelerating mode of detuned RF cavities which is needed to compensate for the reactive component of beam-loading.
- The other issue is to minimize the cavity higher-order mode (HOM) impedances which drive strong longitudinal and transverse CBI and bring the induced HOM power.

Outline

RF Systems for Different Colliders

- NC is more advantageous in terms of easy maintenance, running robust, low construction budget.

Colliders	Cavity Types	
PEP-II	NC（20 NC for electron ring, 6 NC for positron ring）	Closed-off at 2008
BEPCII	SC（1 SC for each ring）	Operation
SuperKEKB	SC+NC（8 NC and 8 SC for electron ring，32 NC for positron ring）	Operation
BINP-SCTF	NC（3 NC for each ring）	Under Design

	KEKB Achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 8th		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	0.129	0.090	0.0236	0.0219	0.0407 0.0565*	0.0279 0.0434*	0.0881	0.0807
Luminosity [10^{34}cm^{-2}s^{-1}]	2.11		1.57		4.65		80	
Integrate luminosity [ab^{-1}]	1.04		0.03		0.41		50	

PEP-II Records

Last update: April 8, 2008

Peak Luminosity

12.069×10^{33} cm^{-2}sec^{-1} — August 16, 2006

1722 bunches 2900 mA LER 1875 mA HER

Integration records of delivered luminosity

Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 pb^{-1}	Aug 16, 2006
Best 3 shifts in a row	910.7 pb^{-1}	Jul 2-3, 2006
Best day	858.4 pb^{-1}	Aug 19, 2007
Best 7 days (0:00 to 24:00)	5.411 fb^{-1}	Aug 14-Aug 20, 2007
Best week (Sun 0:00 to Sat 24:00)	5.137 fb^{-1}	Aug 12-Aug 18, 2007
Peak HER current	2069 mA	Feb 29, 2008
Peak LER current	3213 mA	Apr 7, 2008
Best 30 days	19.776 fb^{-1}	Aug 5 – Sep 3, 2007
Best month	19.732 fb^{-1}	August 2007

Total delivered 557 fb^{-1}

PEP-II turned off April 7, 2008

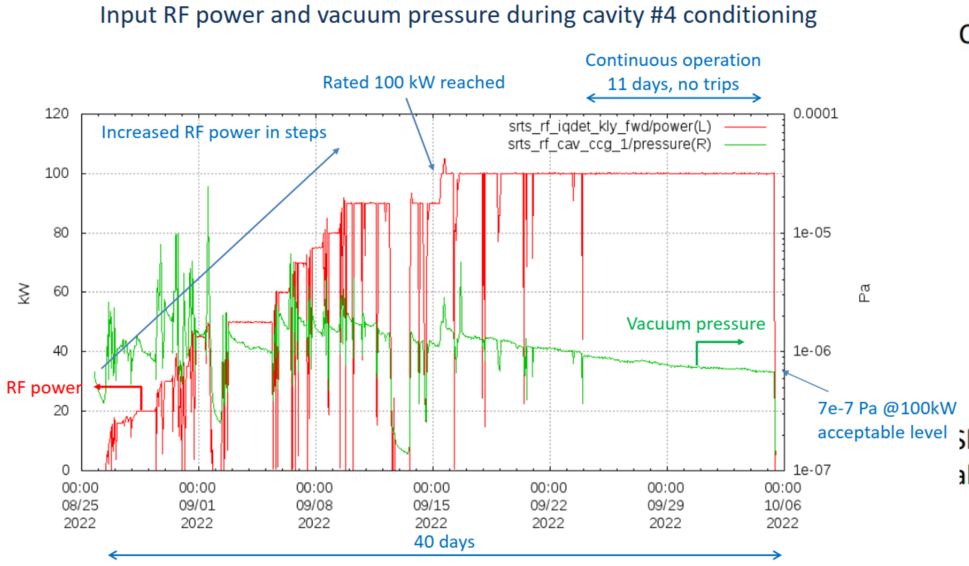
STCF Ring RF System

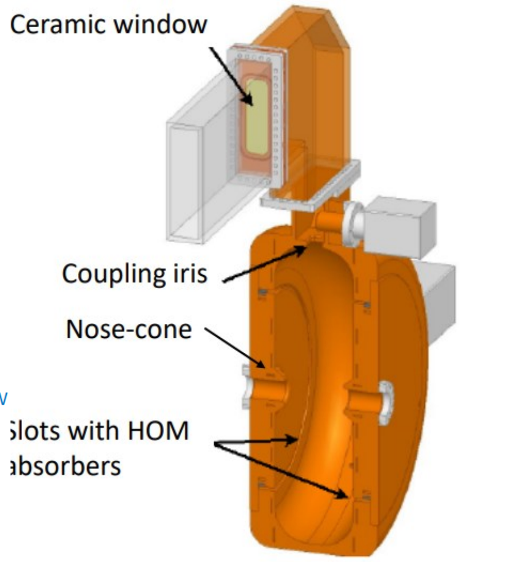
- ✓ **Due to relative lower accelerating voltage required, NC is preferred**
- ✓ **NC RF systems are chosen as a candidate for our STCF collider rings。**

	KEKB SC	**BEPCII SC**	**ARES NC(KEKB& SuperKEKB)**	**KEK-RIKEN TM020-mode NC**	**PEP-II NC**	**BESSY-II NC**
Beam power [kW]	3000	3000	3000	3000	3000	3000
Voltage [kV]	6000	6000	6000	6000	6000	6000
Number of cavities	10	20	10	12	15	30
Voltage per cavity [kV]	600	300	600	500	400	200
Shunt impedance per cavity –circuit Ω	46.5E9	46.5E9	8.625E5	2.5E6	3.5E6	3.4E6
Unloaded quality factor	1E9	1E9	1.15E5	6.5E4	3E4	2.96E4
Power poss per cavity [kW]	0.00387	0.00097	209	49.7	23	6
Beam power per cavity [kW]	300	150	300	250	200	100
Input power per cavity [kW]	300	150	509	299.7	223	106
Detuning frequency per cavity [kHz]	75	150	12	75	283	557

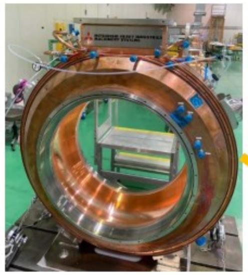
TM020-mode NC from KEK and RIKEN

RF Parameters	
Working mode	TM020
Working frequency	509 MHz
Unloaded quality factor Q_0	60000
Shunt impedance R_s	6.8 MΩ
Voltage per cavity	825 kV
Power per cavity	100 kW （no beam） 210 kW（400 mA）

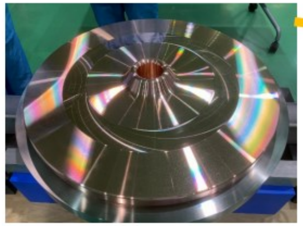


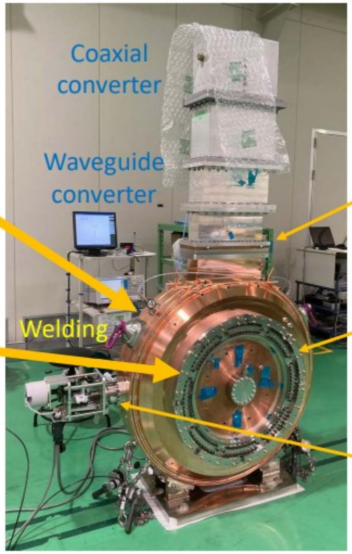


Cavity body



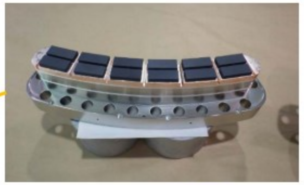
End plate



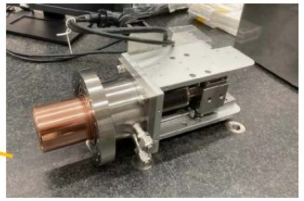


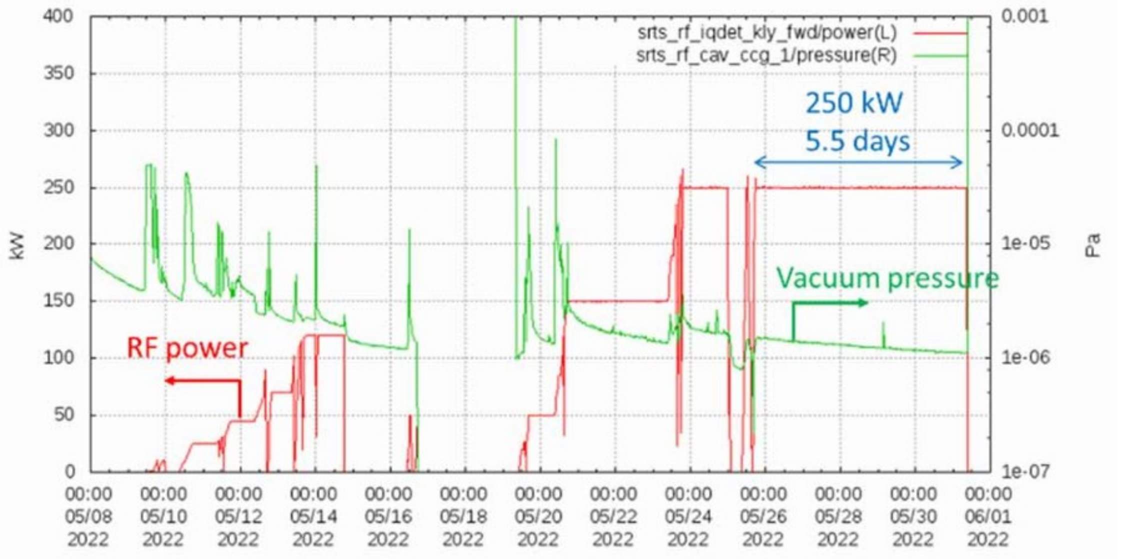
Ceramic window
(Kyocera)

Ferrite absorber



Tuner
(Meisyo kikou)





Technique Route Selected for STCF

	KEKB SC	BEPCII SC	ARES NC(KEKB& SuperKEKB)	KEK-RIKEN TM020-mode NC	PEP-II NC	BESSY-II NC
Beam power [kW]	3000	3000	3000	3000	3000	3000
Voltage [kV]	6000	6000	6000	6000	6000	6000
Number of cavities	10	20	10	12	15	30
Voltage per cavity [kV]	600	300	600	500	400	200
Shunt impedance per cavity –circuit Ω	46.5E9	46.5E9	8.625E5	2.5E6	3.5E6	3.4E6
Unloaded quality factor	1E9	1E9	1.15E5	6.5E4	3E4	2.96E4
Power poss per cavity [kW]	0.00387	0.00097	209	49.7	23	6
Beam power per cavity [kW]	300	150	300	250	200	100
Input power per cavity [kW]	300	150	509	299.7	223	106
Detuning frequency per cavity [kHz]	75	150	12	75	283	557

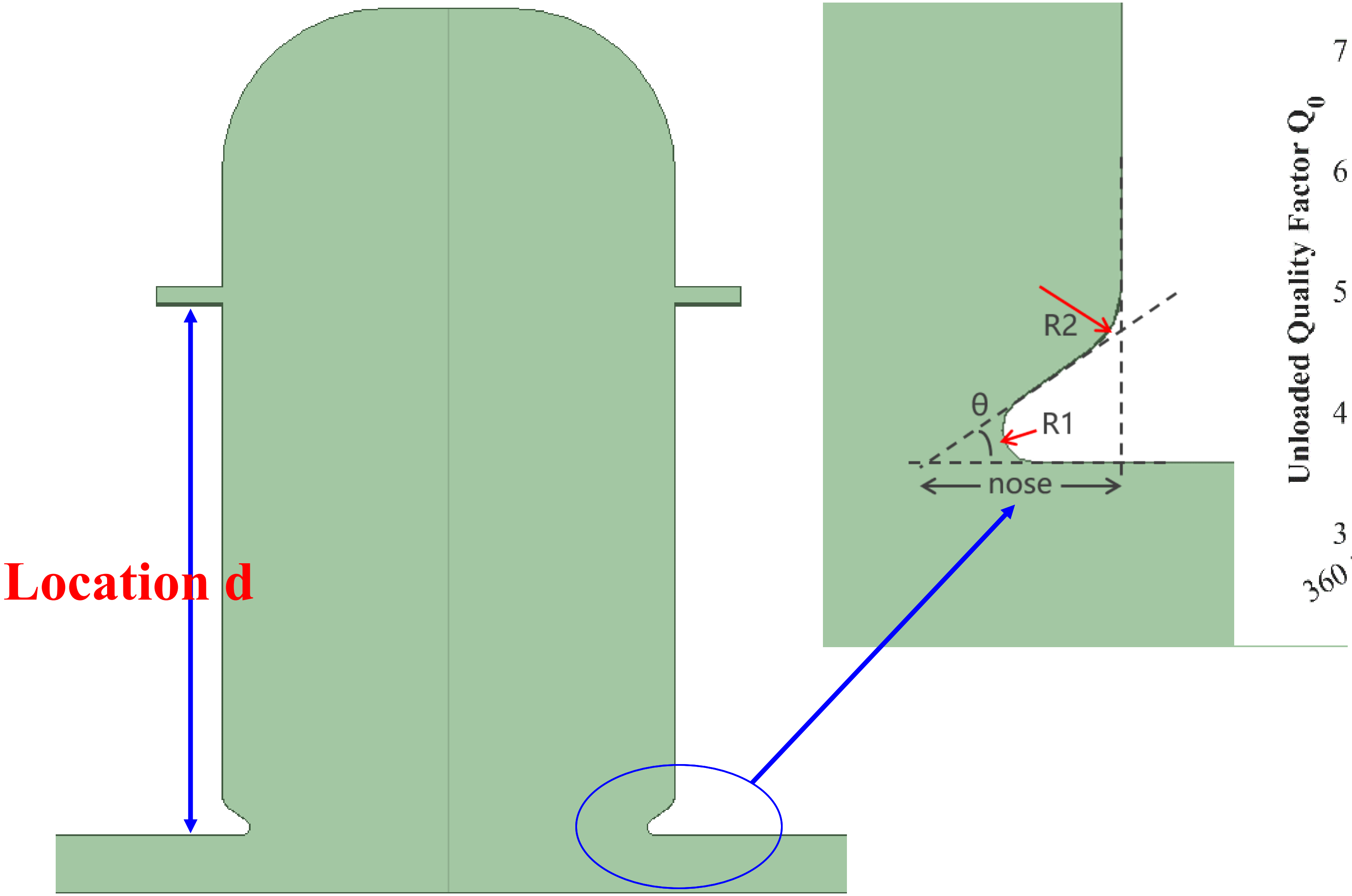
Considering the power losses due to other factors, such as vacuum impedances, so ≥ 12 cavities are required for each ring.

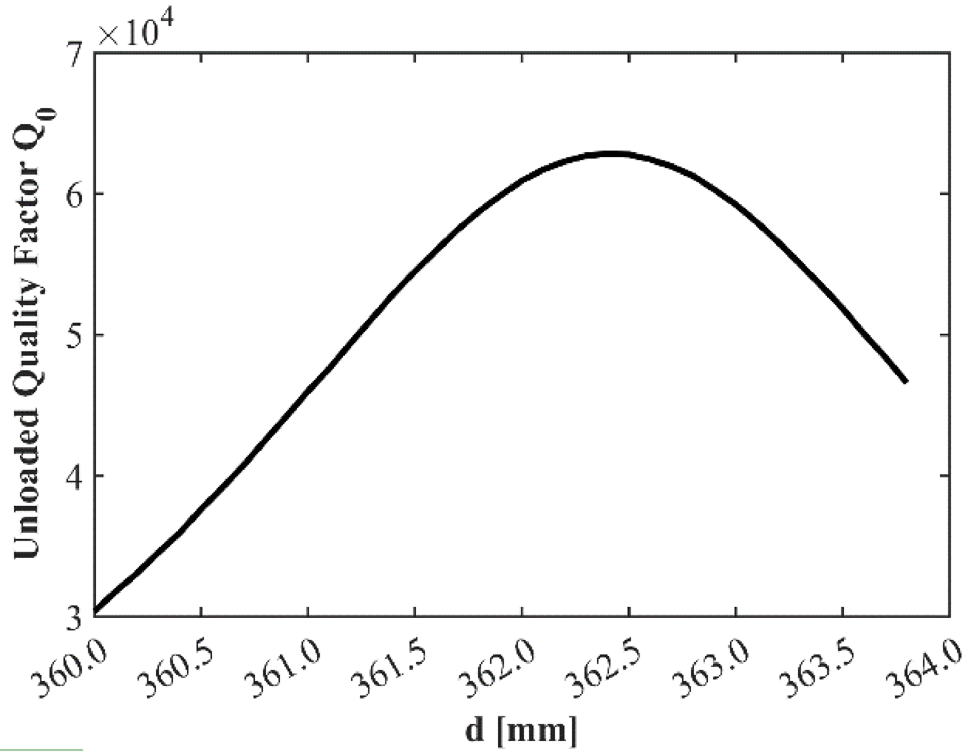
Technique Challenges

- Each NC has to provide a beam power of >200 kW and an accelerating voltage of >0.5 MV; Such a NC has not been realized beforehand in CHINA.

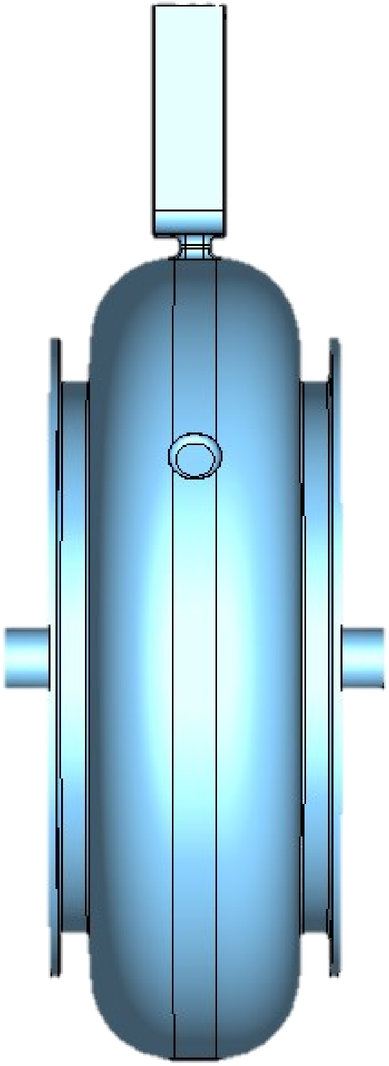
- All of harmful modes have to be strongly suppressed for each NC;

Cavity Geometry

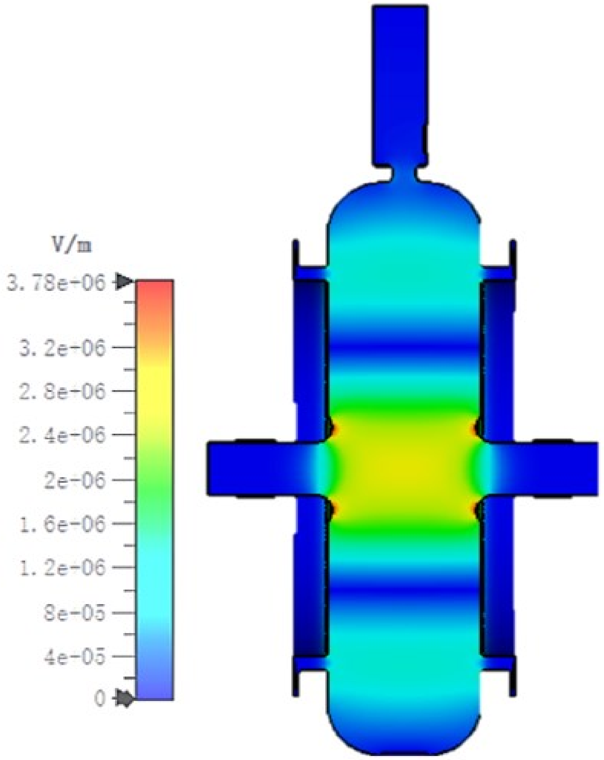


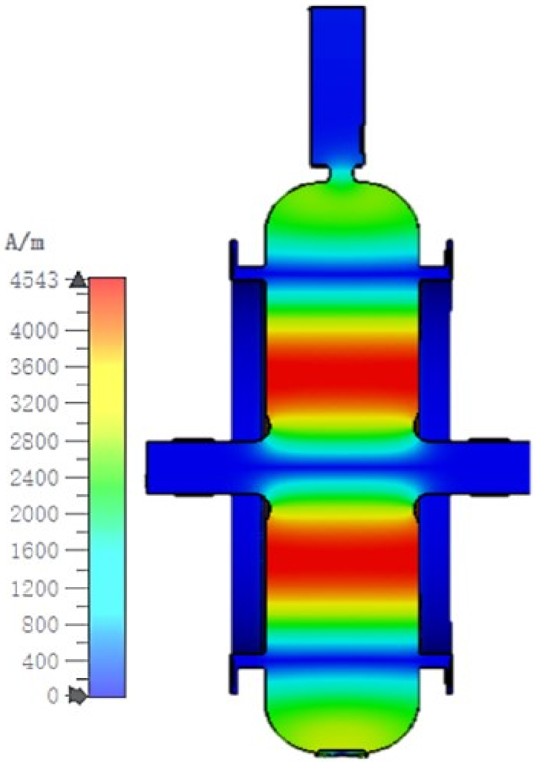


Optimized TM020-mode cavity



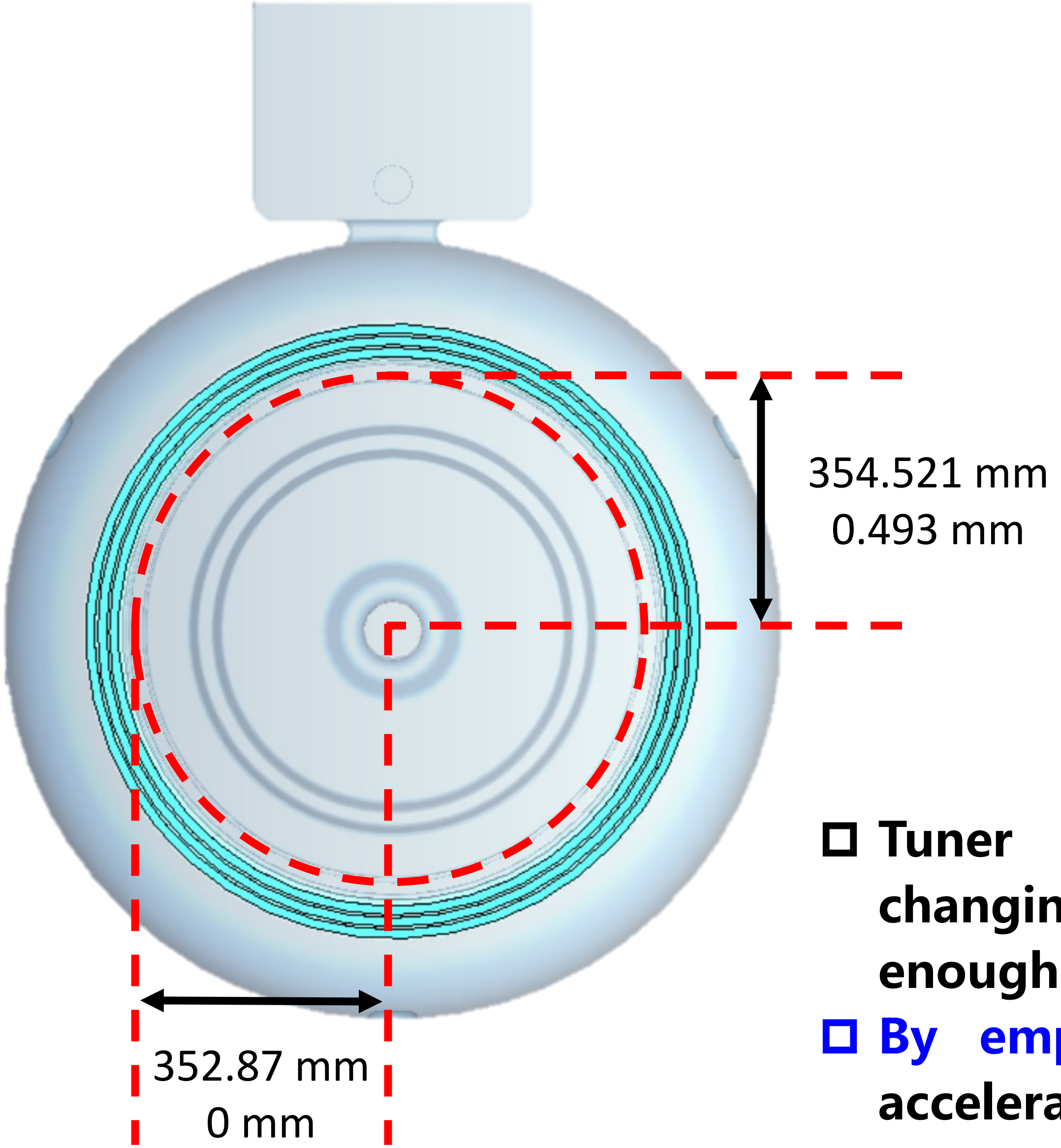
Electric fields **Magnetic fields**

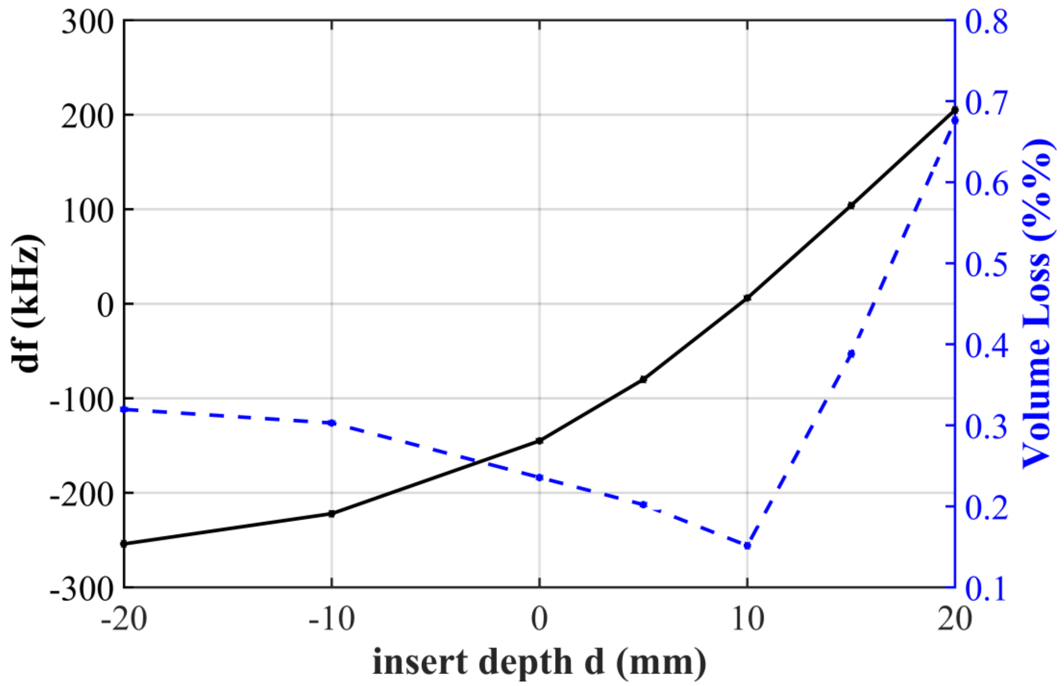




RF parameters	
Working mode	TM020
Frequency [MHz]	499.7
R/Q [Ω]	77.3
Unloaded quality factor	65110
E_p/E_{acc}	2.12
B_p/E_{acc} [mA/V]	2.55

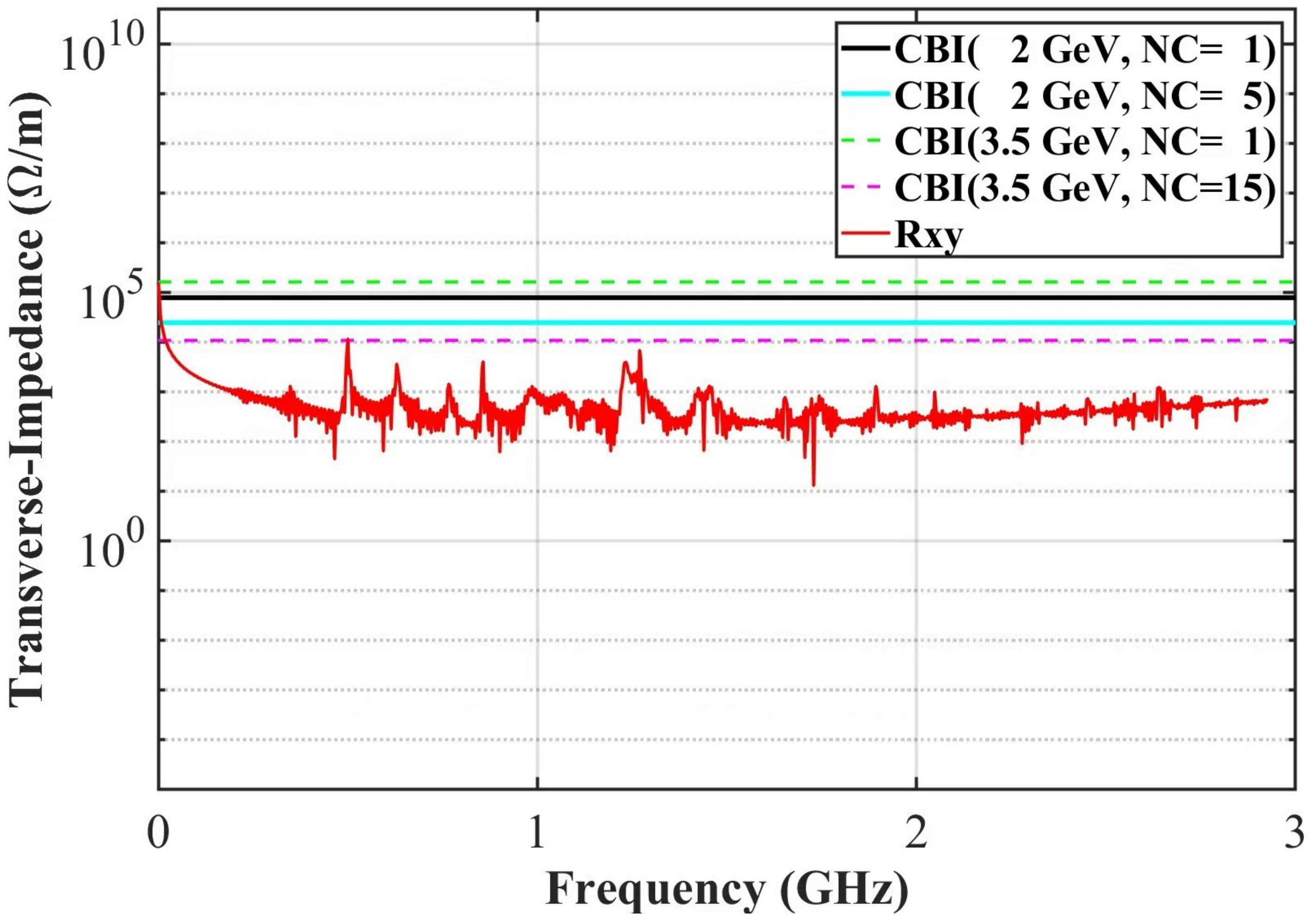
Tuner Range





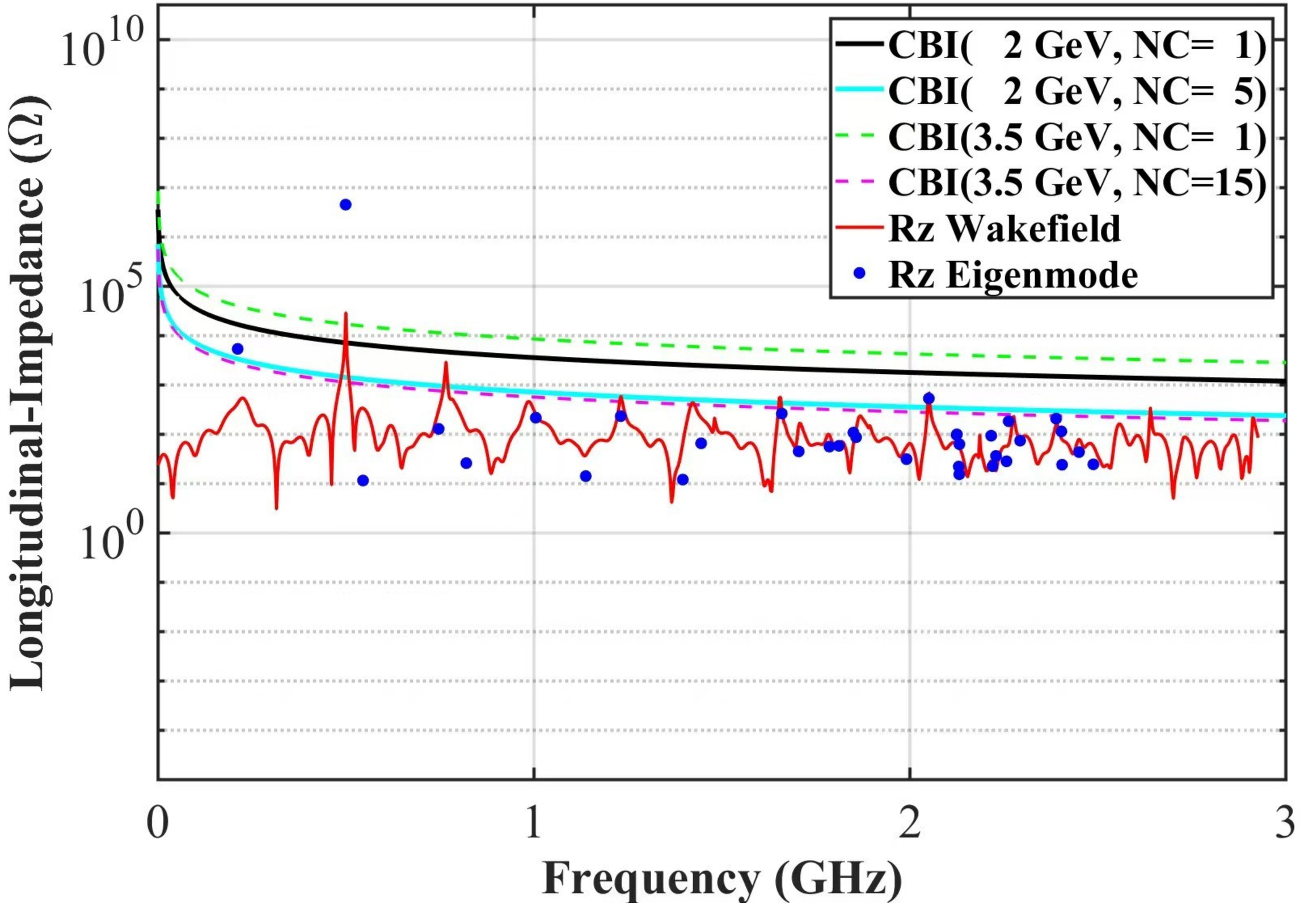
- ☐ Tuner moving range[-20mm, 20mm], Frequency changing range[499.45 MHz, 499.9 MHz], sufficient enough to cover a detuning frequency of 75 kHz.
- ☐ By employing elliptical slots, the leakage from the accelerating mode can be significantly reduced to be 1%。

HOM damping-Transverse modes



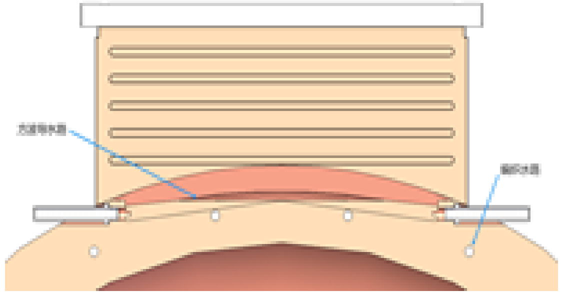
- All of dipole modes are strongly damper below CBI thresholds, so CBI due to harmful modes can't occur.

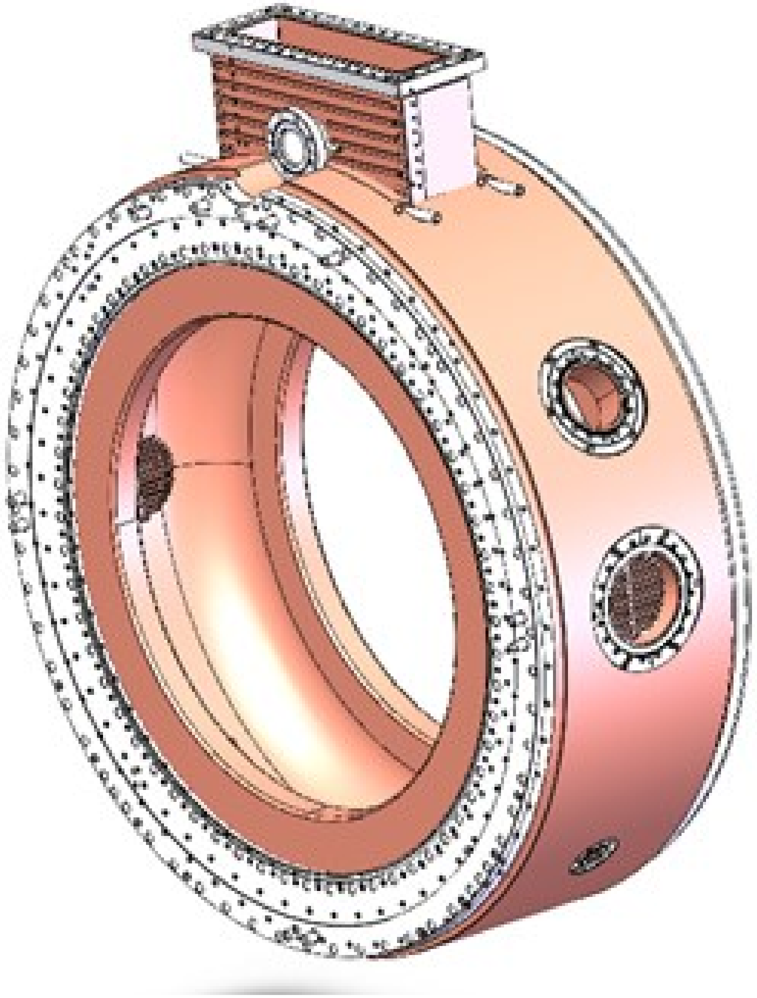
HOM damping-Longitudinal modes

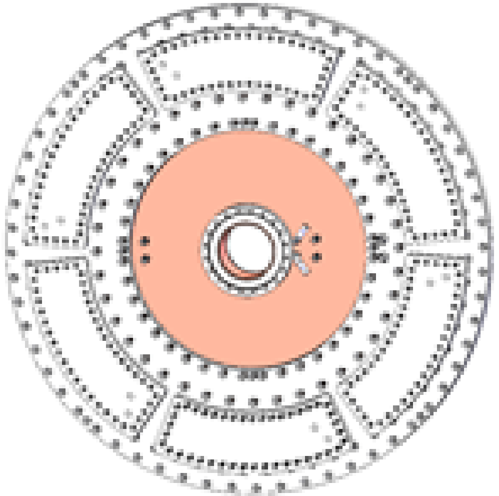


Mode	Frequency（GHz）	R/Q（Ω）-Circuit definition	R（Ω）-Circuit definition
TM010	0.211648	85.6	836.5056
TM021	0.762821	15.2	117.9846
TM051	1.46392	1.8	112.987
TM033	1.89493	1.4	108.1376
TM063	2.5092	1.9	80.3744

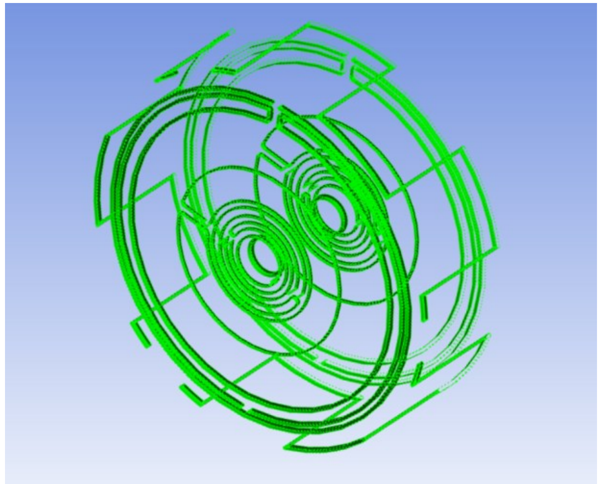
Thermal Analysis for Cavity



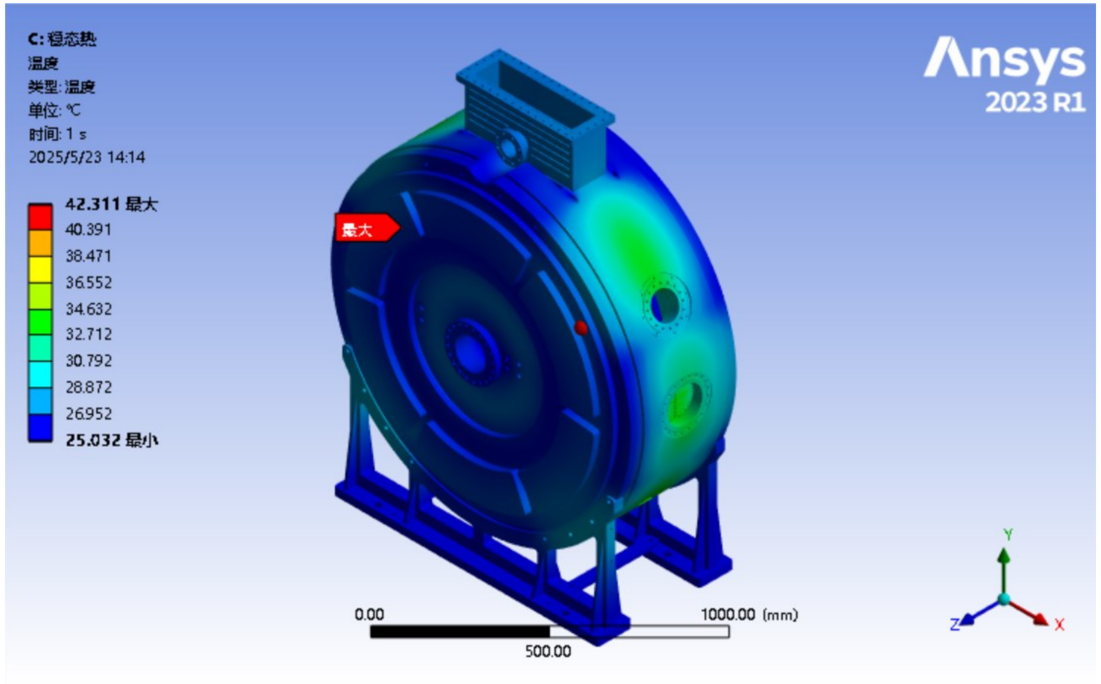


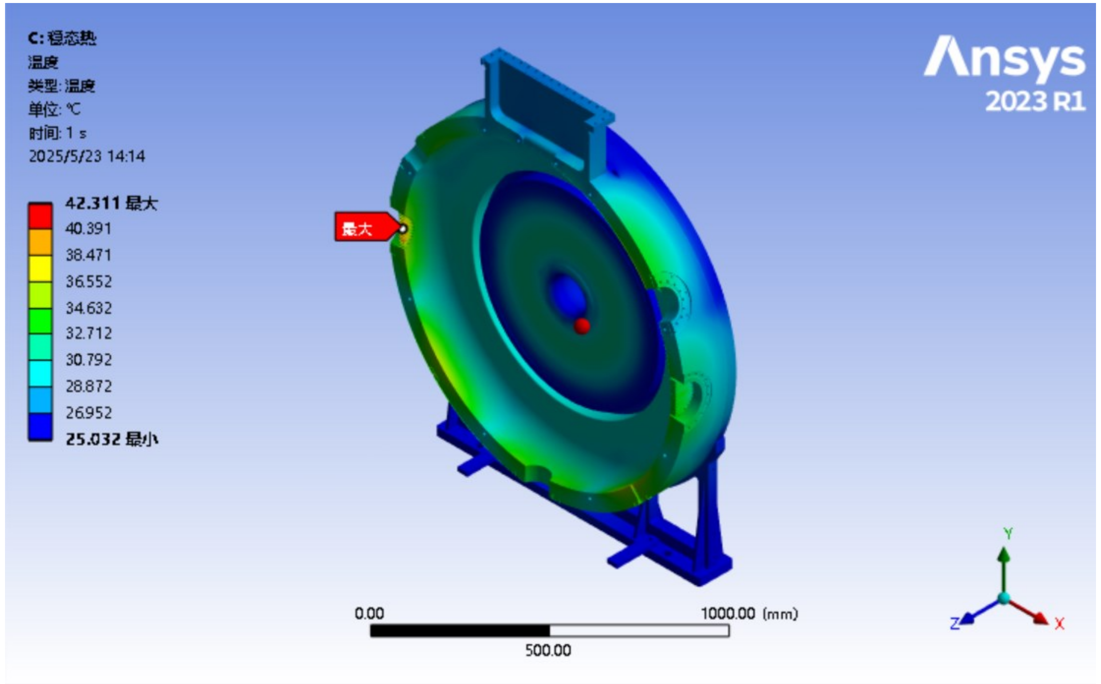


Thermal Analysis for Cavity



- Temperature distribution
  - Simulations setup: a power loss of 50kW on the surface
  - Cooling temperature is set to 24℃
  - Max temperature is located at inner surface, Max Tem: 42.3℃





Thermal Analysis for Cavity

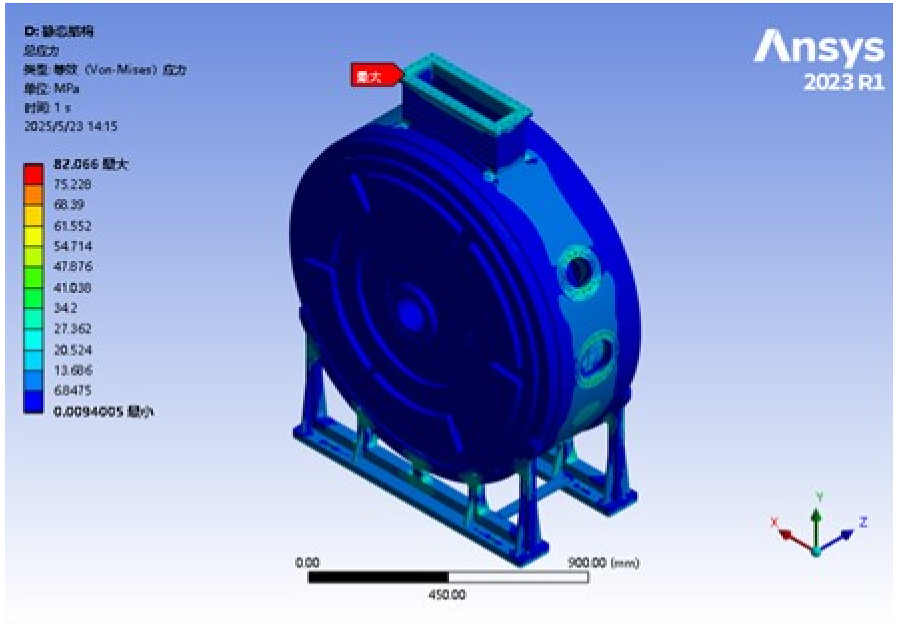
- ## Equivalent Stress
  - Stress location: cavity equator
  - Max stress location:

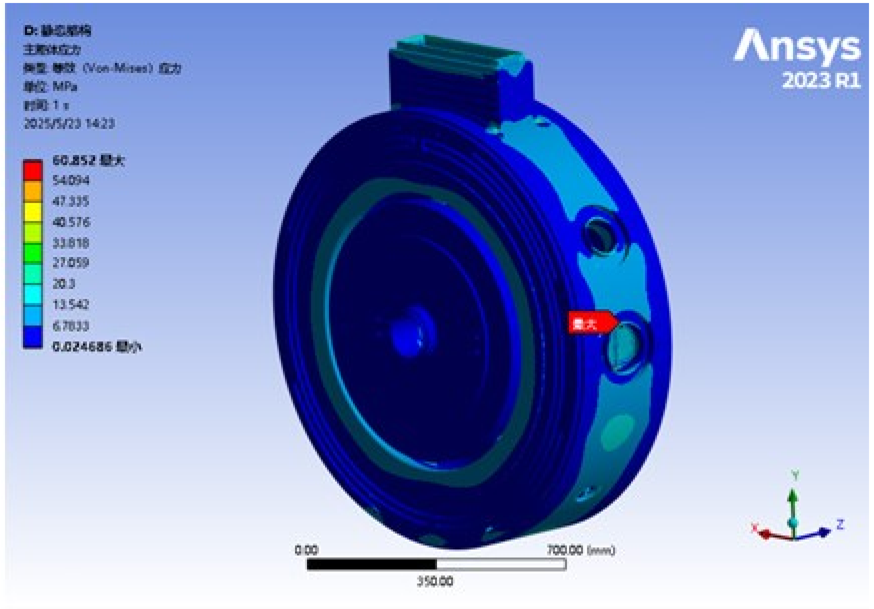
    stainless steel waveguide port, 82.07 MPa

    pumping port，60.85 MPa

Simulations setup:

- Standard atmospheric pressure: 0.1013MPa
- Standard Earth gravitational acceleration;
- End face support





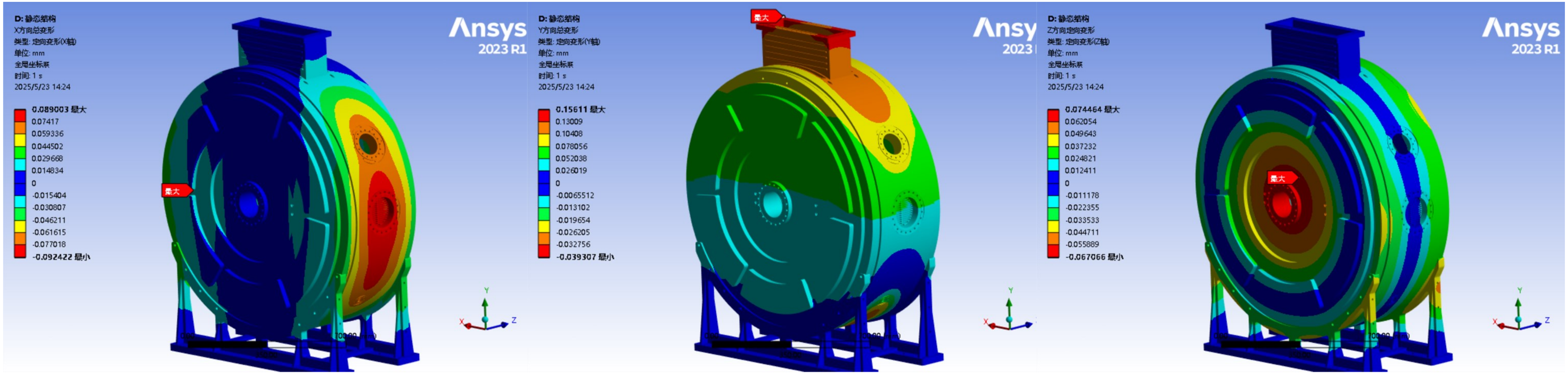
Thermal Analysis for Cavity

- Deformation
  - Primary deformation location: cavity equator outer surface
  - Max deformation: waveguide port, 0.156 mm

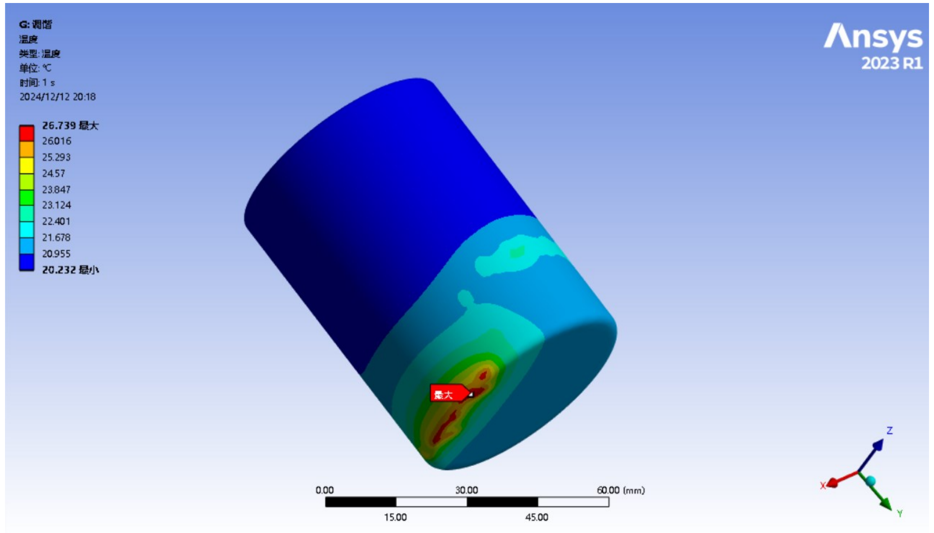
This deformation can be compensated by adjusting the input waveguide

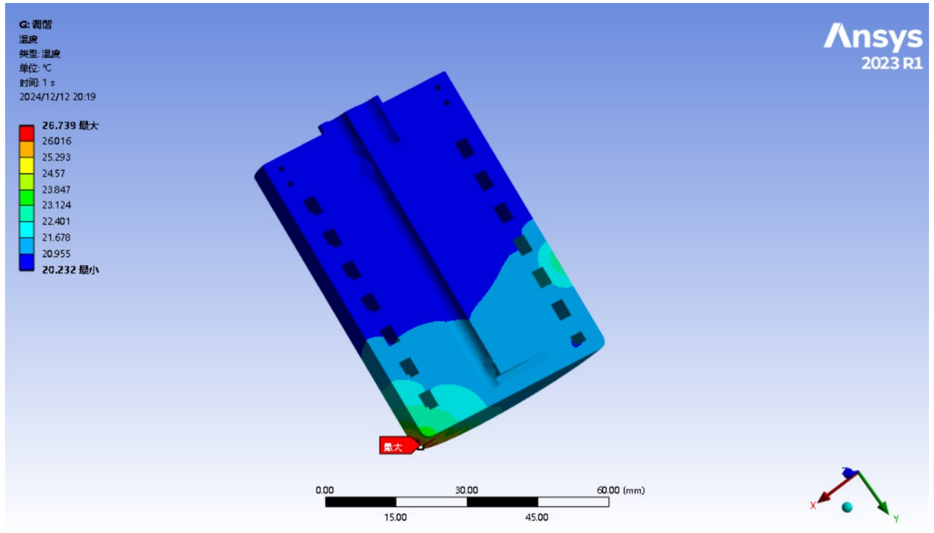
Simulations setup:

- Standard atmospheric pressure: 0.1013MPa
- Standard Earth gravitational acceleration;
- End face support

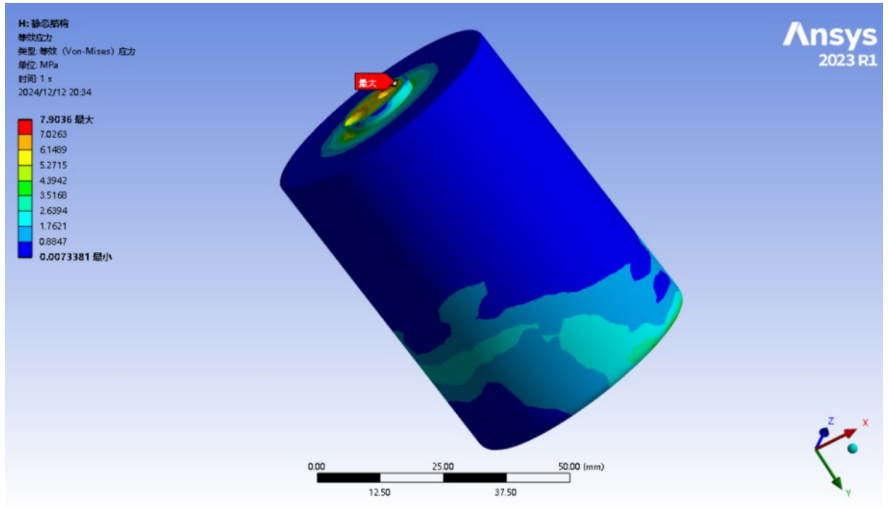


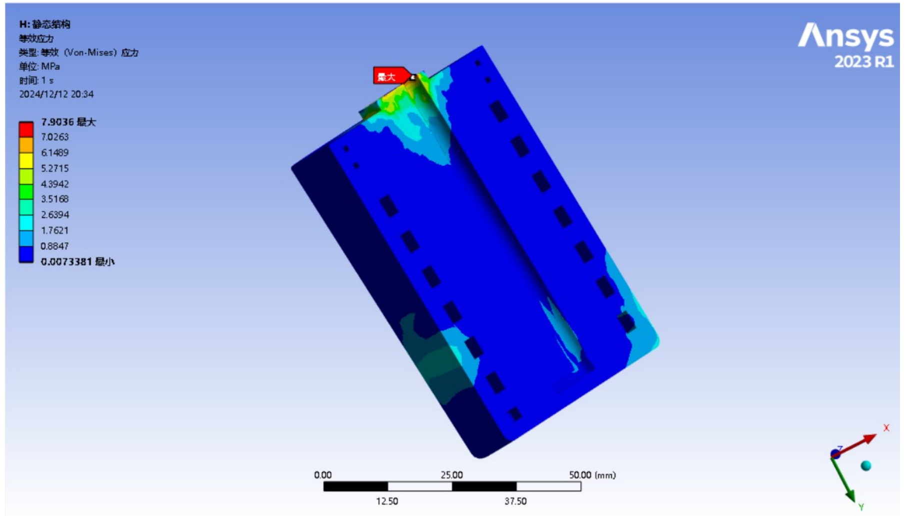
Thermal Analysis For Tuner





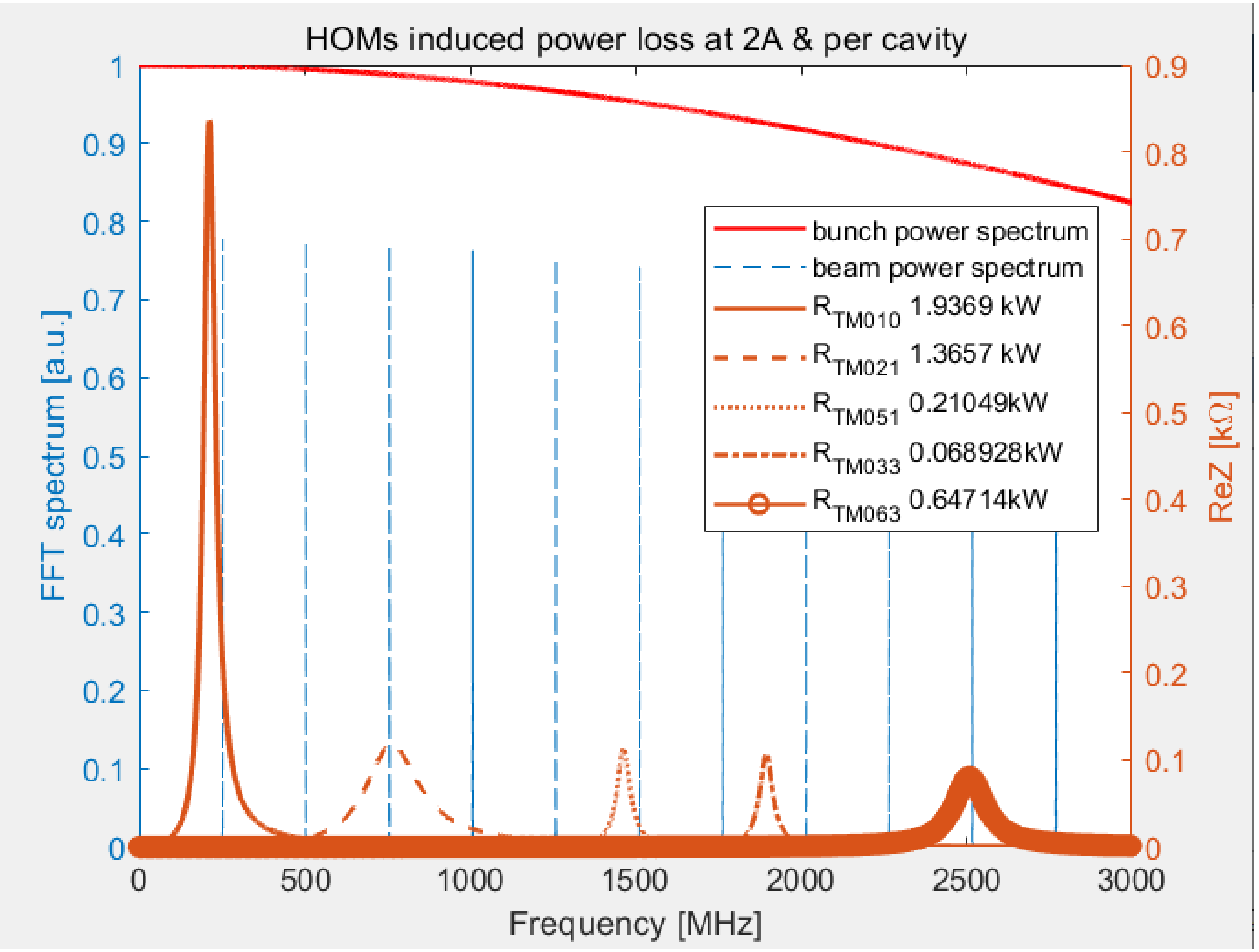
Max temperature 26.7℃





Max stress is 7.9MPa at upper supporting structure， Stress is much smaller than 70 MPa

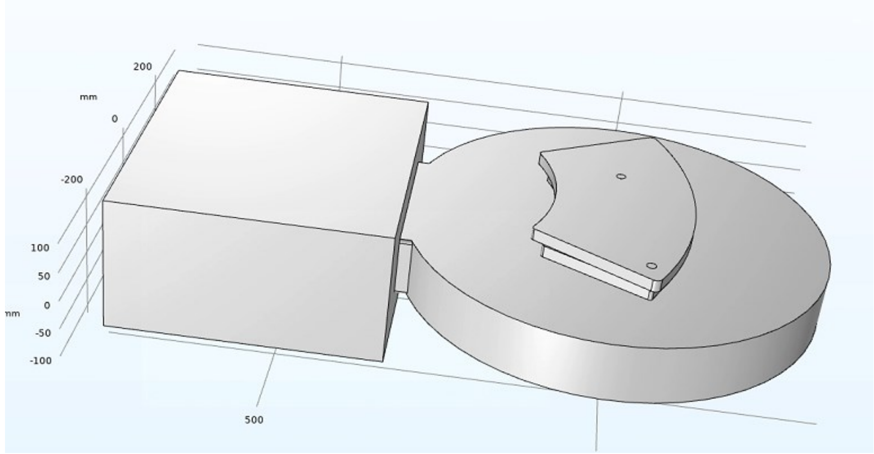
HOMs Induced Power Loss

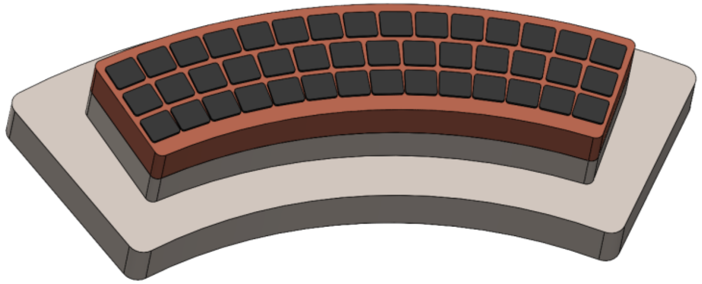


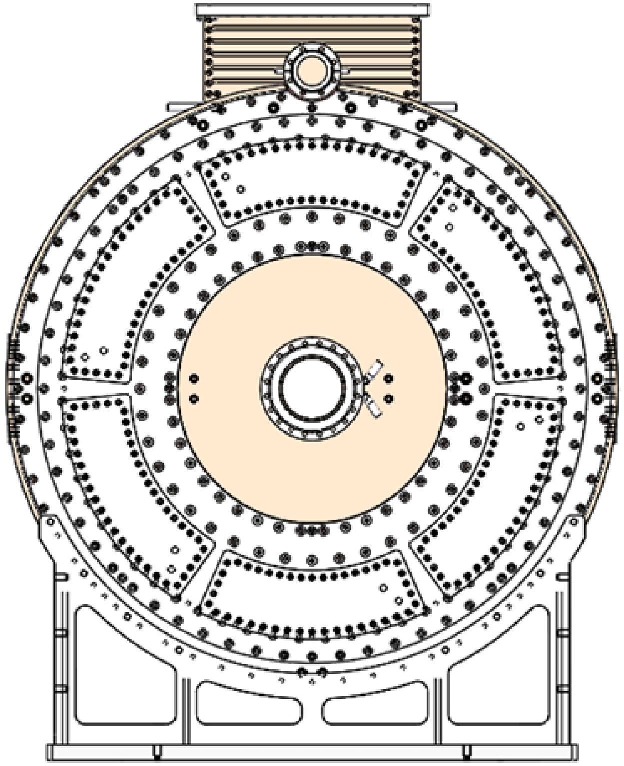
HOMs induced power loss for 5 longitudinal modes are calculated to be totally **4.3 kW**

Mechanical Design for HOMs Dampers

- Simulation modes： CW
- Absorption power capacity for each damper＞5 kW， each damper has 6 sections, each section has a power capacity＞833 W



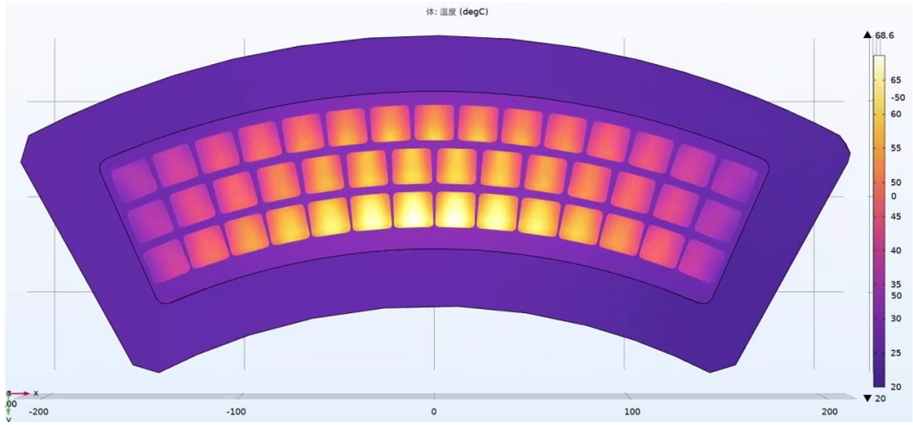




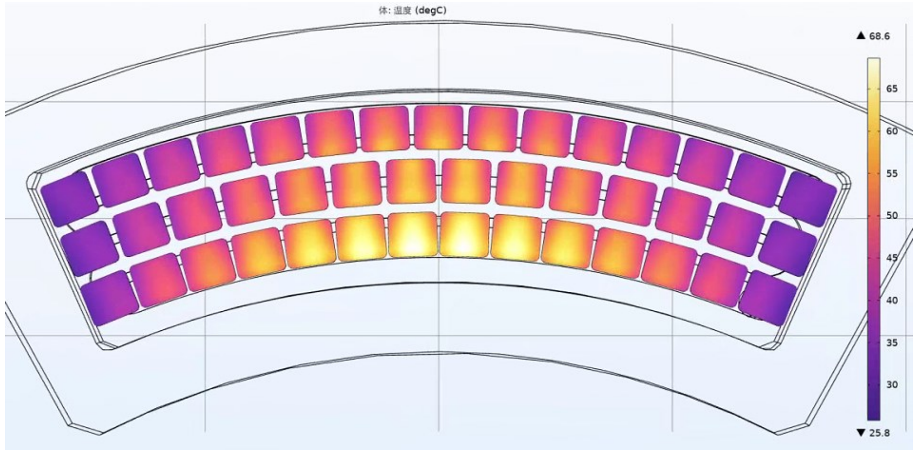
The thickness for ferrites is set to 2 mm， 3 rows of ferrites are arranged as a section within the ring width of 62 mm. A COMSOL model is established as shown in the figure. The thermal simulation was performed with a water flow rate of 4.5 L/min and an input power of 850 W (about 840 W of ferrite absorption power) at the rectangular waveguide port。

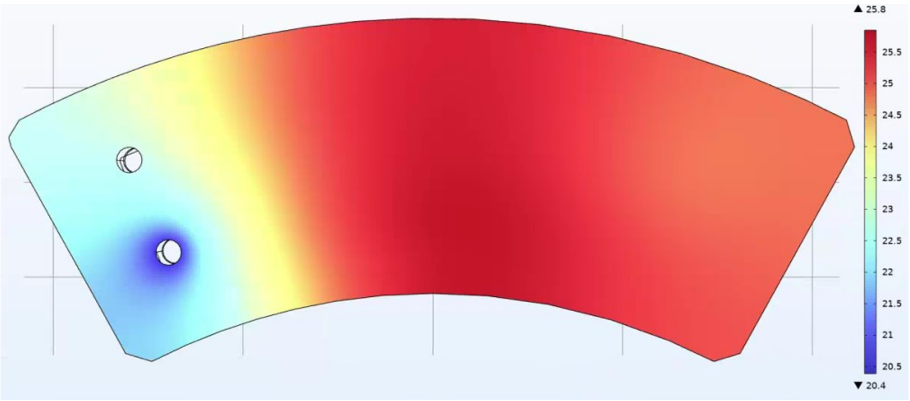
Thermal Analysis For HOMs Dampers

Temperature for ferrite dampers with outer surface

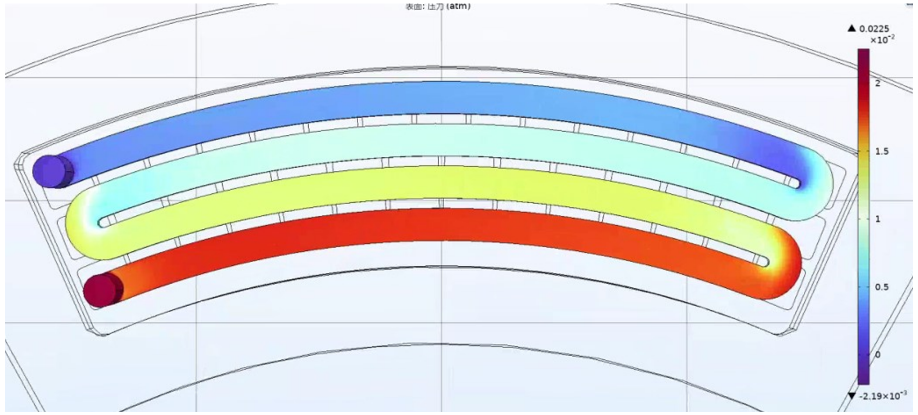


Temperature for ferrite dampers





Temperature at outer surface



Cooling pressure

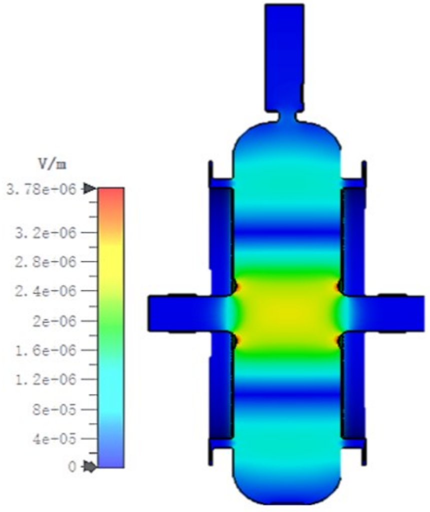
- Max temperature for a ferrite section is 68.6℃, temperature rise is 48.6℃。
- Max cooling pressure drop is 0.025atm for each section , total pressure drop is 0.15 atm for a single ferrite damper

Input Power Coupler

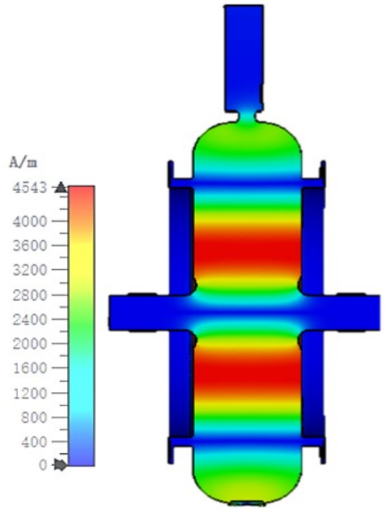
- Design Target
  - 499.7 MHz TM020-mode cavity

Mode	Frequency	Q0
TM020	499.70 MHz	65110

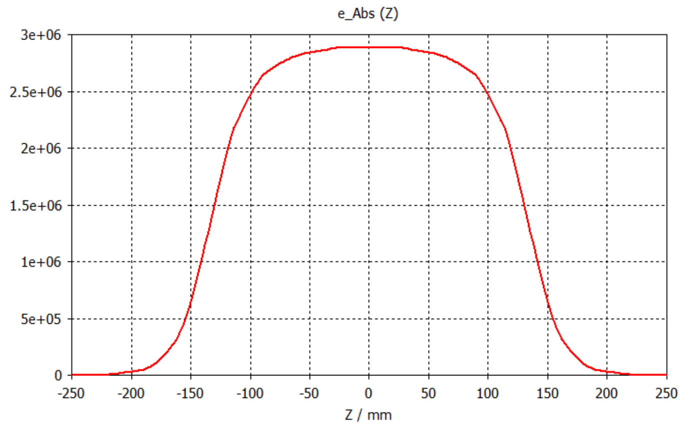
  - Waveguide-type input coupler，online tuning。



Electric fields



Magnetic fields

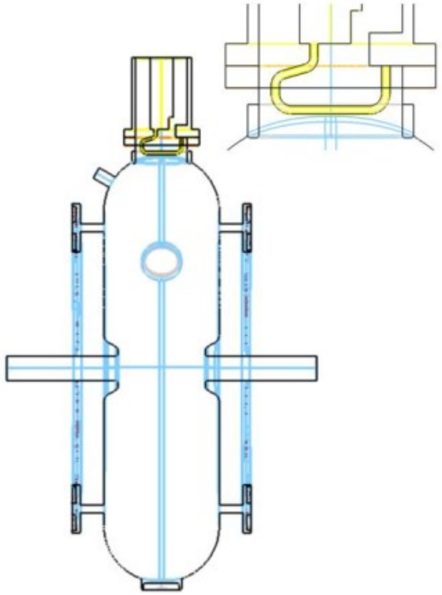


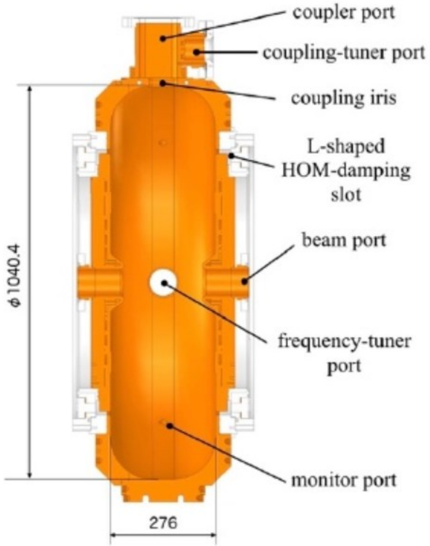
On-axis electric fields

Working frequency	499.7 MHz
Type	Waveguide type
Power capacity	CW 300 kW
Design coupling factor	1.0
Coupling factor	1~8
Coupling type	Magnetic Coupling
Vacuum leakage rate	<1e-10 mbar·l/s
Ultimate vacuum	<5e-7 Pa

Two Types of Input Coupler

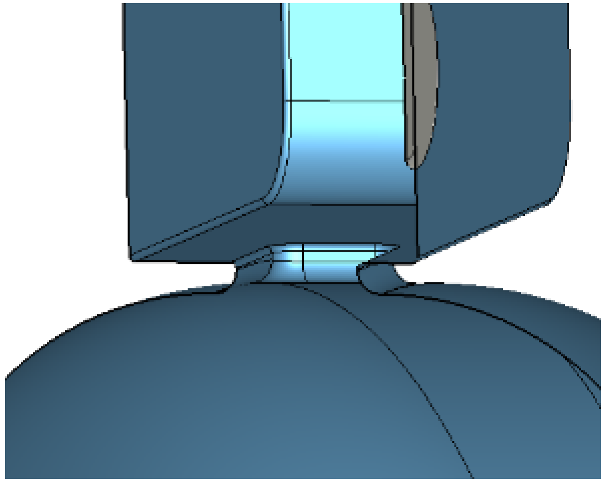
- Coupler types
  - Coaxial type：
    - Complicated
    - Fixed coupling factor, have large reflections for different beam currents
  - Waveguide type：
    - Simple geometry
    - Variable online tuning for different beam currents
    - High construction budget
  - After comparisons, we choose waveguide type input coupler



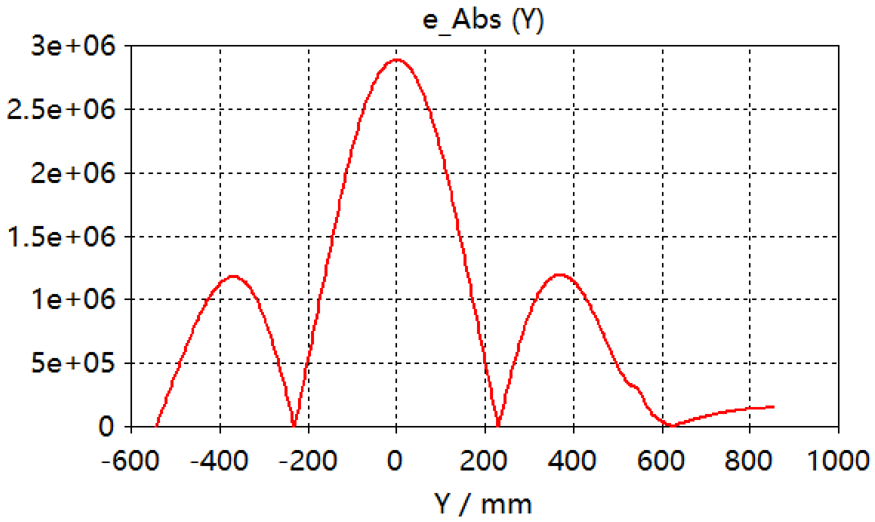


RF Design

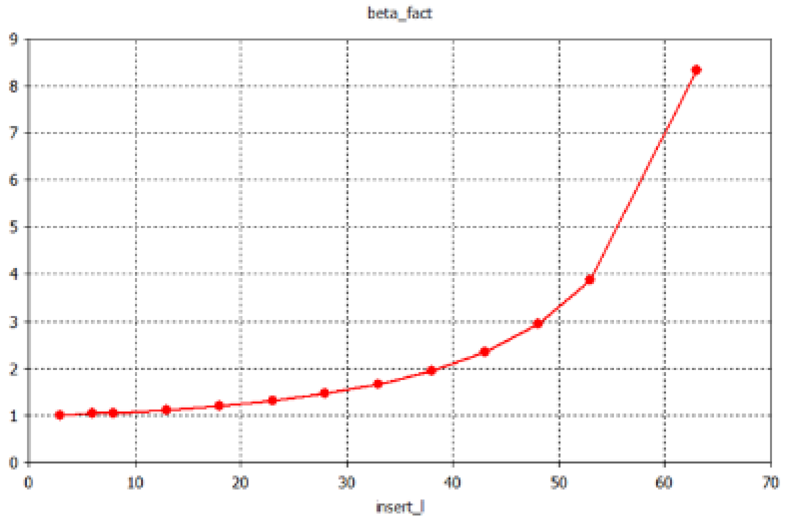
- Coupling port
  - Increasing the fillets to minimize the magnetic fields
  - Tuning range: Tuner insertion depth 3~63mm→0.9975~8
  - Frequency shift: -0.1564MHz
  - 50 kW→560 kV



Coupling port



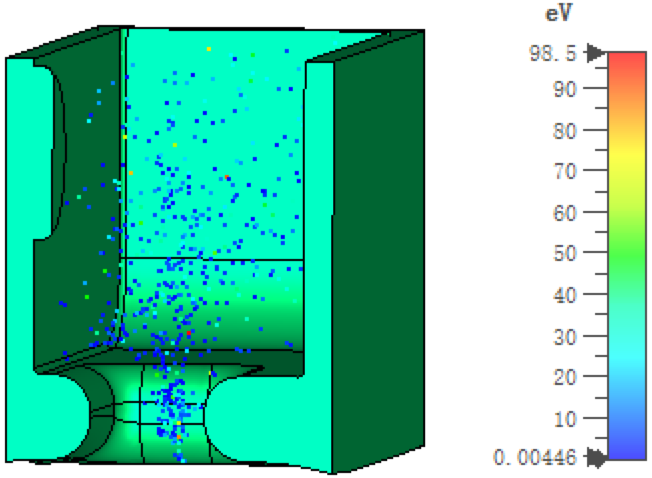
Electric fields distribution



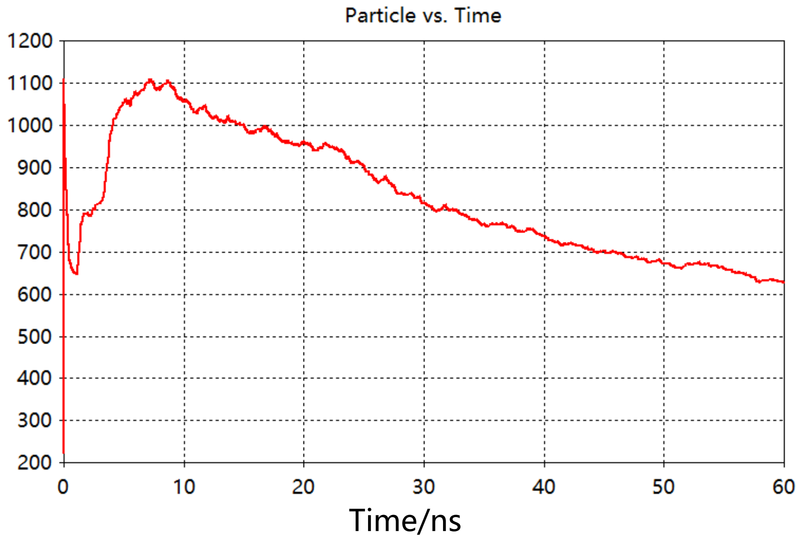
Coupling factor as a function of insertion depth of Tuner

MP For Coupling Port

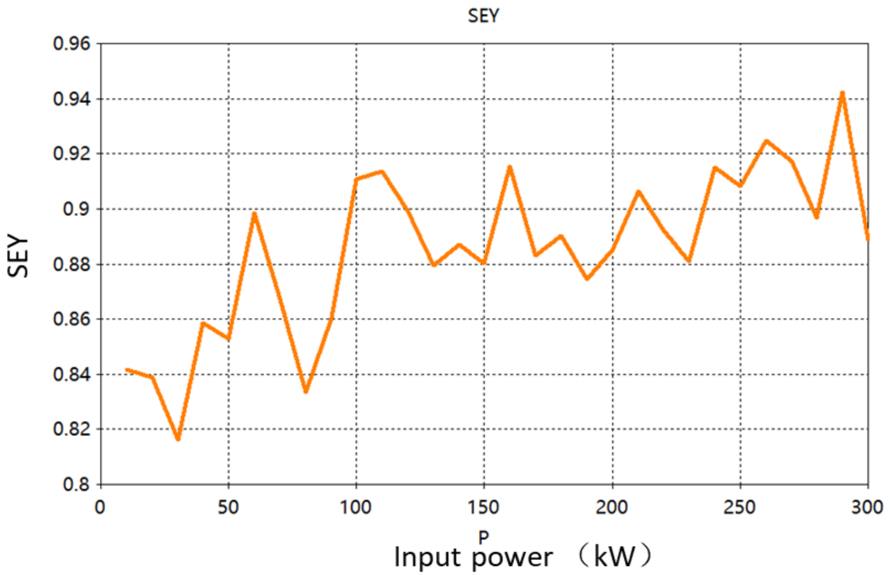
- MP for coupling port： No oscillating，the number of particles decreases with time
- For an input power：10~300 kW，No MP occur



Particles distribution at 100 kW@60ns



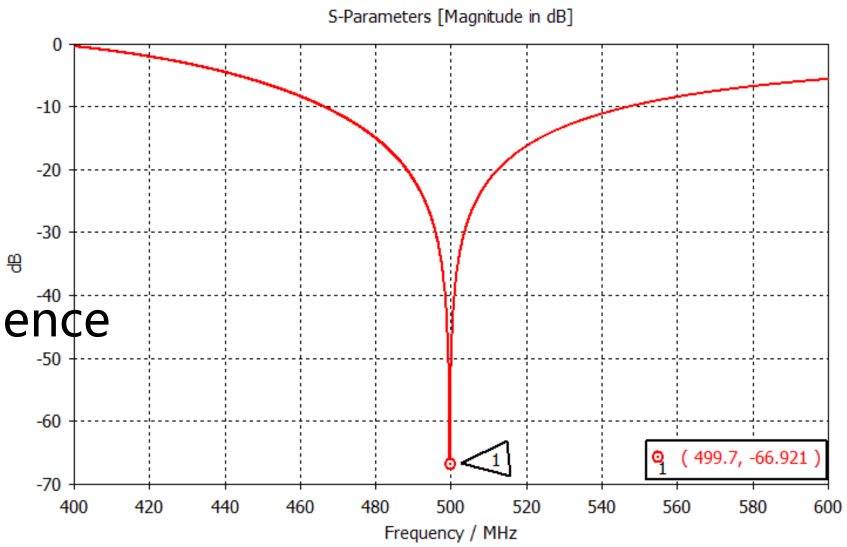
At 300 kW，the number of particles decreases with time



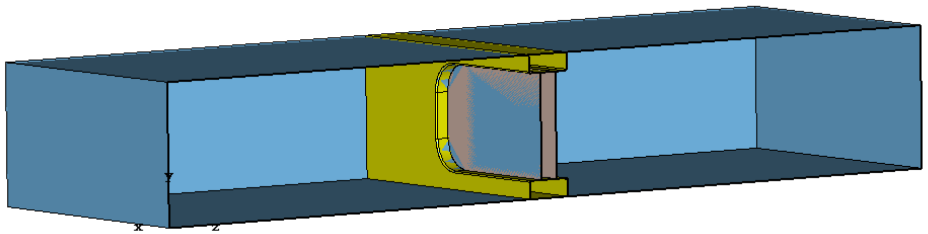
SEY

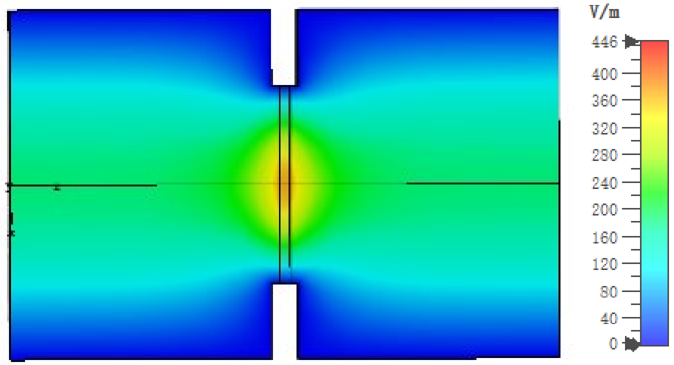
RF Design for Ceramic Window

- Ceramic Window
  - 99.5% Ceramic Window：aluminium oxide
    - Low loss tangent，low temperature，low BDR
    - No difficulty in welding，there are some existing experience
  - S11：499.7MHz@-66.921dB
  - WR1800 waveguide

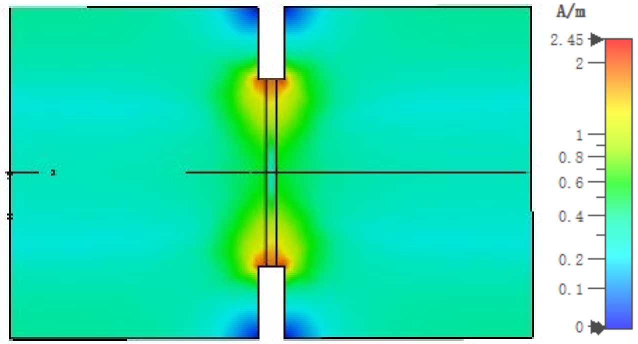


Optimized S11


Ceramic window geometry



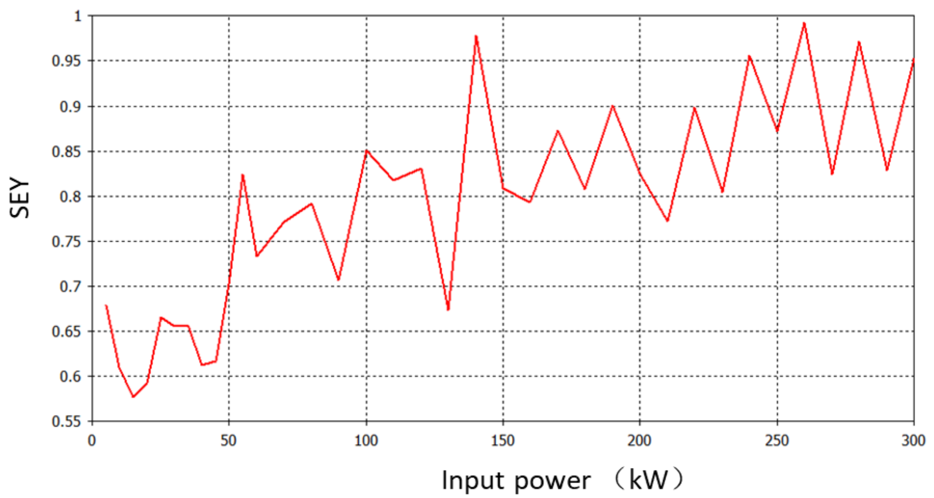
Electric fields



Magnetic fields

Ceramic Window

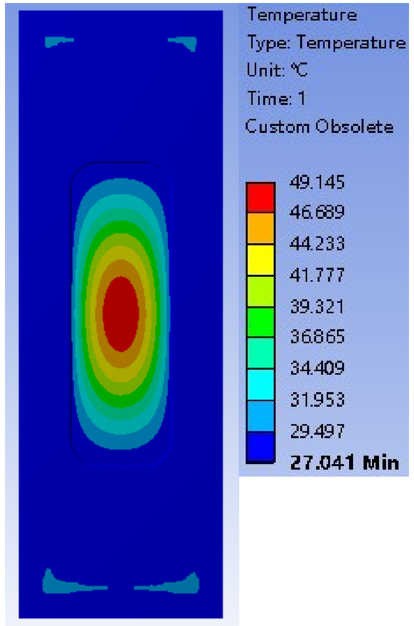
- MP simulations for ceramic window
  - It is fragile component, which is highly susceptible to secondary electron multiplication bombardment to cause overheating, and eventually lead to rupture.
  - Input power: 10-300 kW
  - No MP



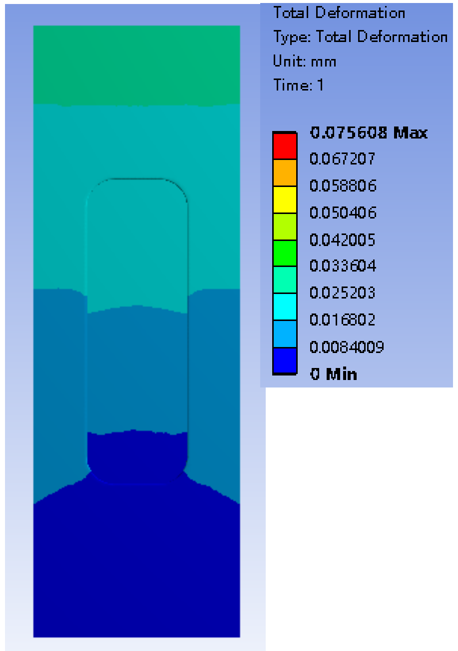
- Thermal analysis for ceramic window

Meet the requirements

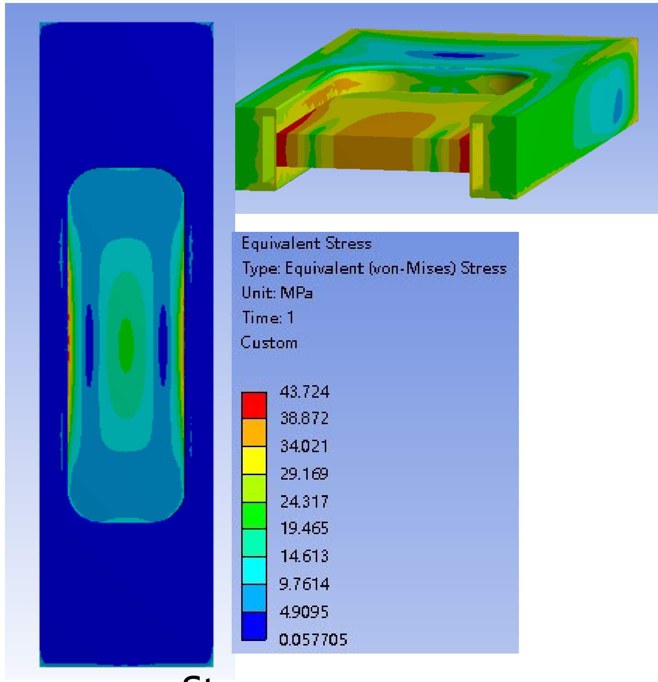
  - Input power: CW 300kW
  - Cooling has a flow velocity 7.5 L/min@25℃， pressure ≥0.4 MPa
  - Max Temp 49.15℃， Max stress is 43.724 MPa for copper



Temperature



Deformation

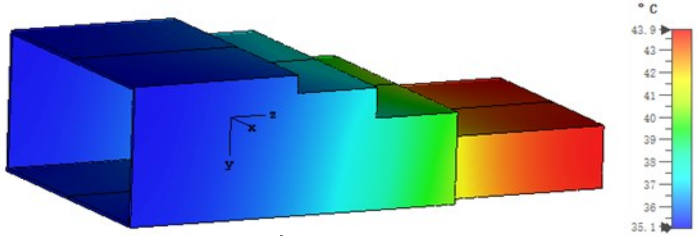


Stress

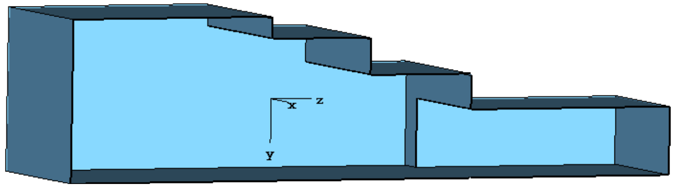
30

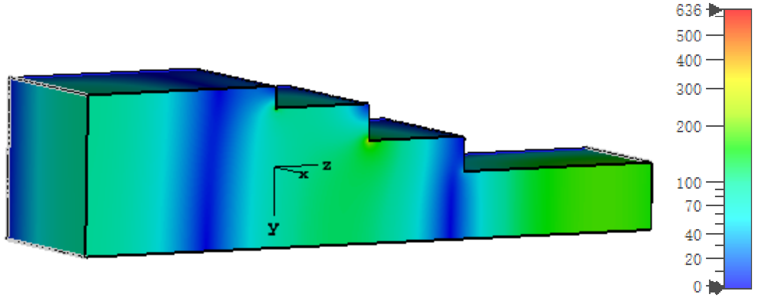
Connecting Waveguides

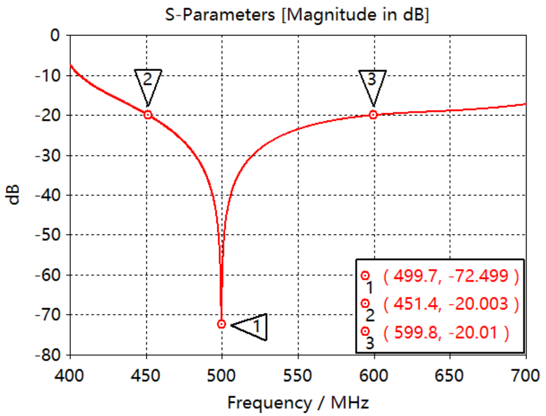
- WR1800-HFWR1500 converter
  - Stepped waveguide material：Aluminum alloy
  - Bandwidths：S11：499.7MHz@-71.638dB, -30dB@38.61MHz
  - Input power = 300kW，Emax<0.1 MV/m, much lower than breakdown
  - Max temperature: 43.9℃



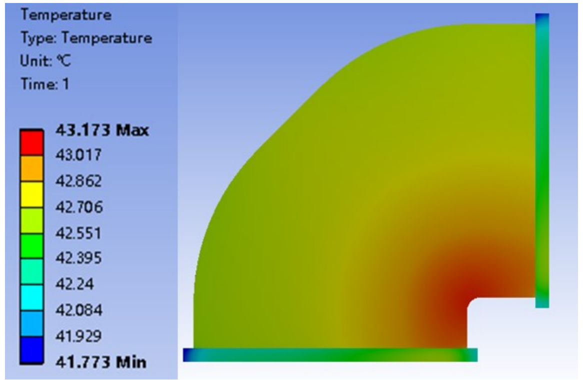
300kW CW RF power

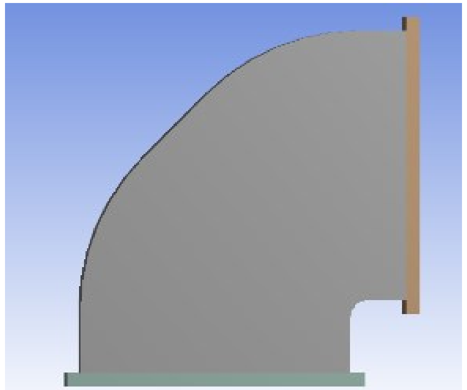




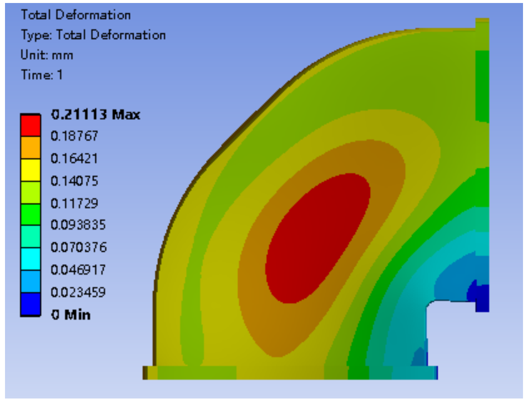


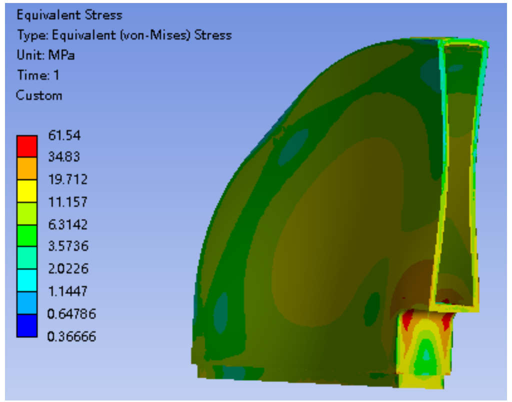
- Bending waveguide
  - 90° bending waveguide for connection between port





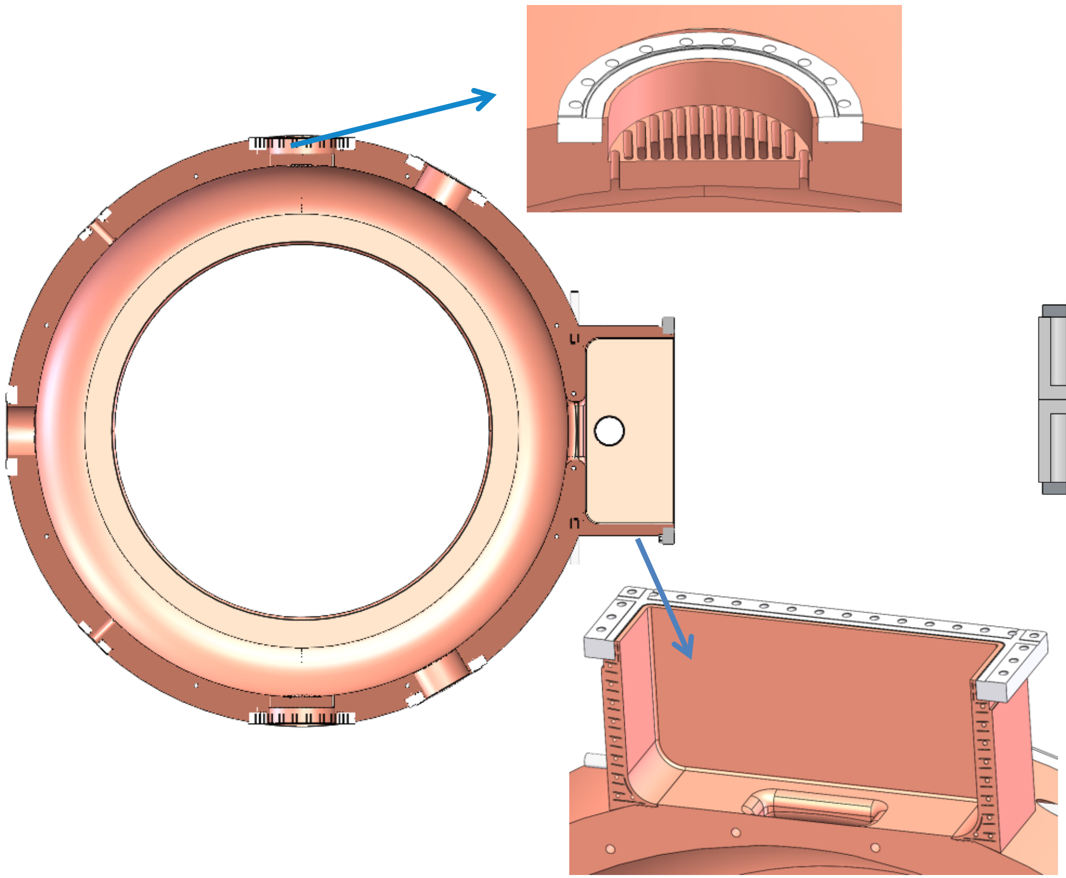
Mechanical modelling

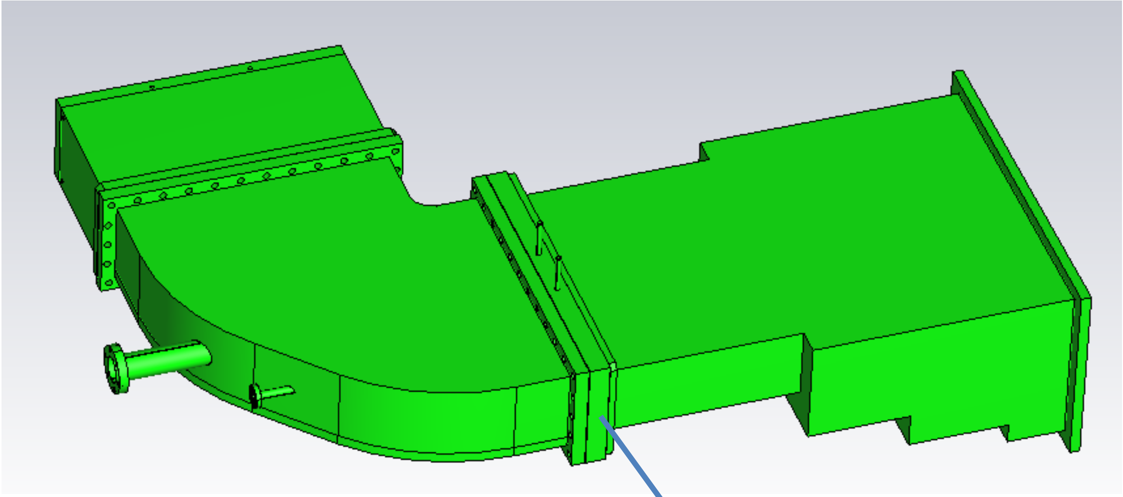


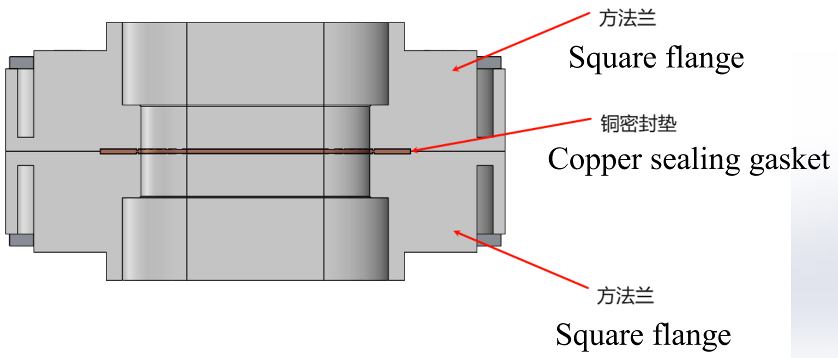


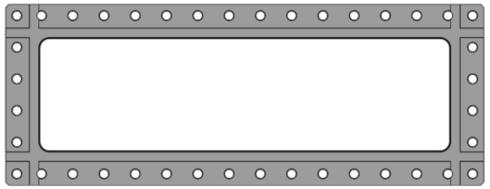
For an input power of CW 300kW，temperature, deformation and stress

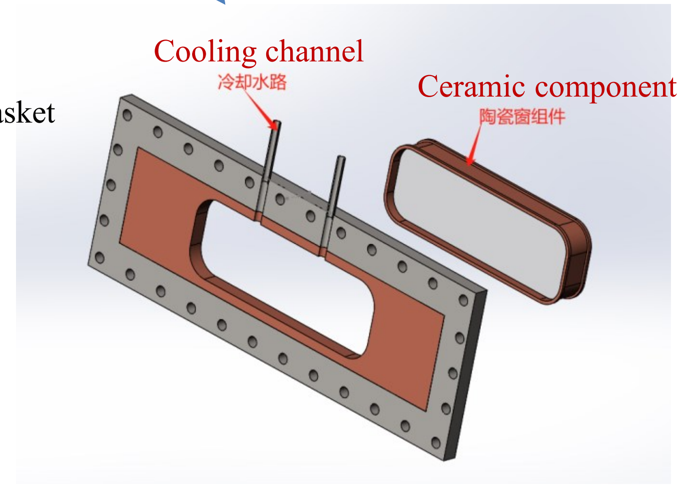
- Final Input coupler connected with WR1800 waveguides



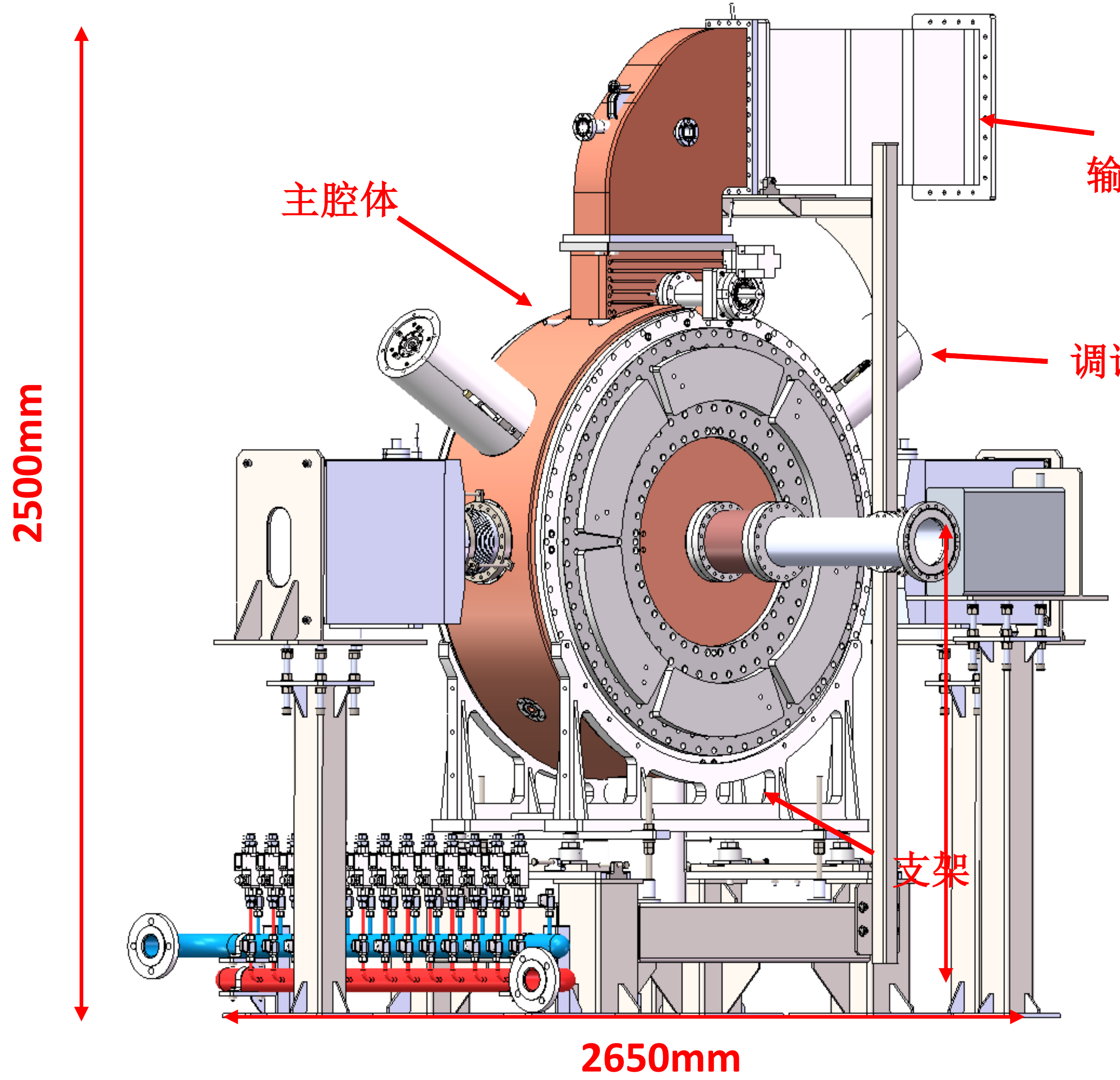


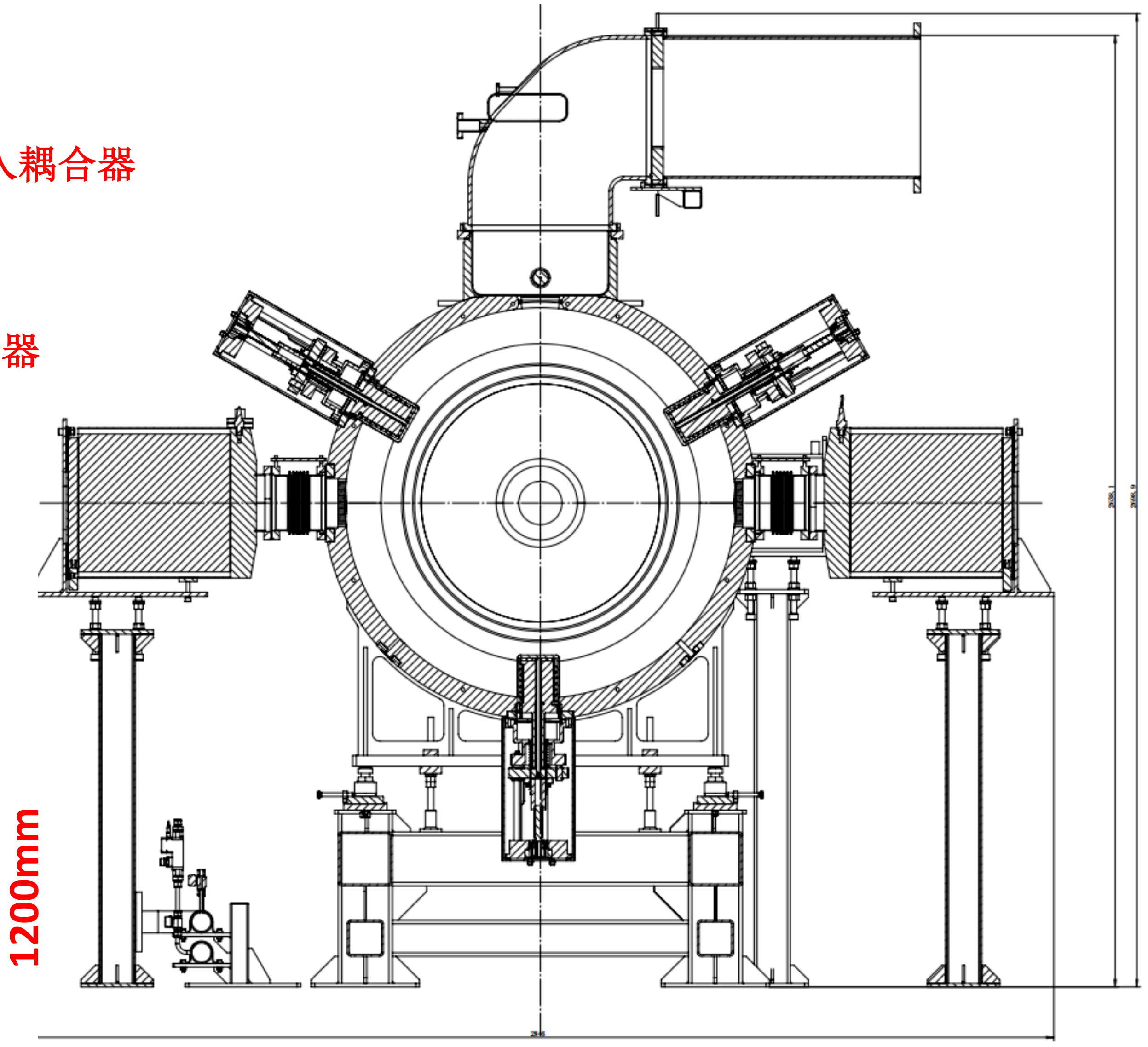




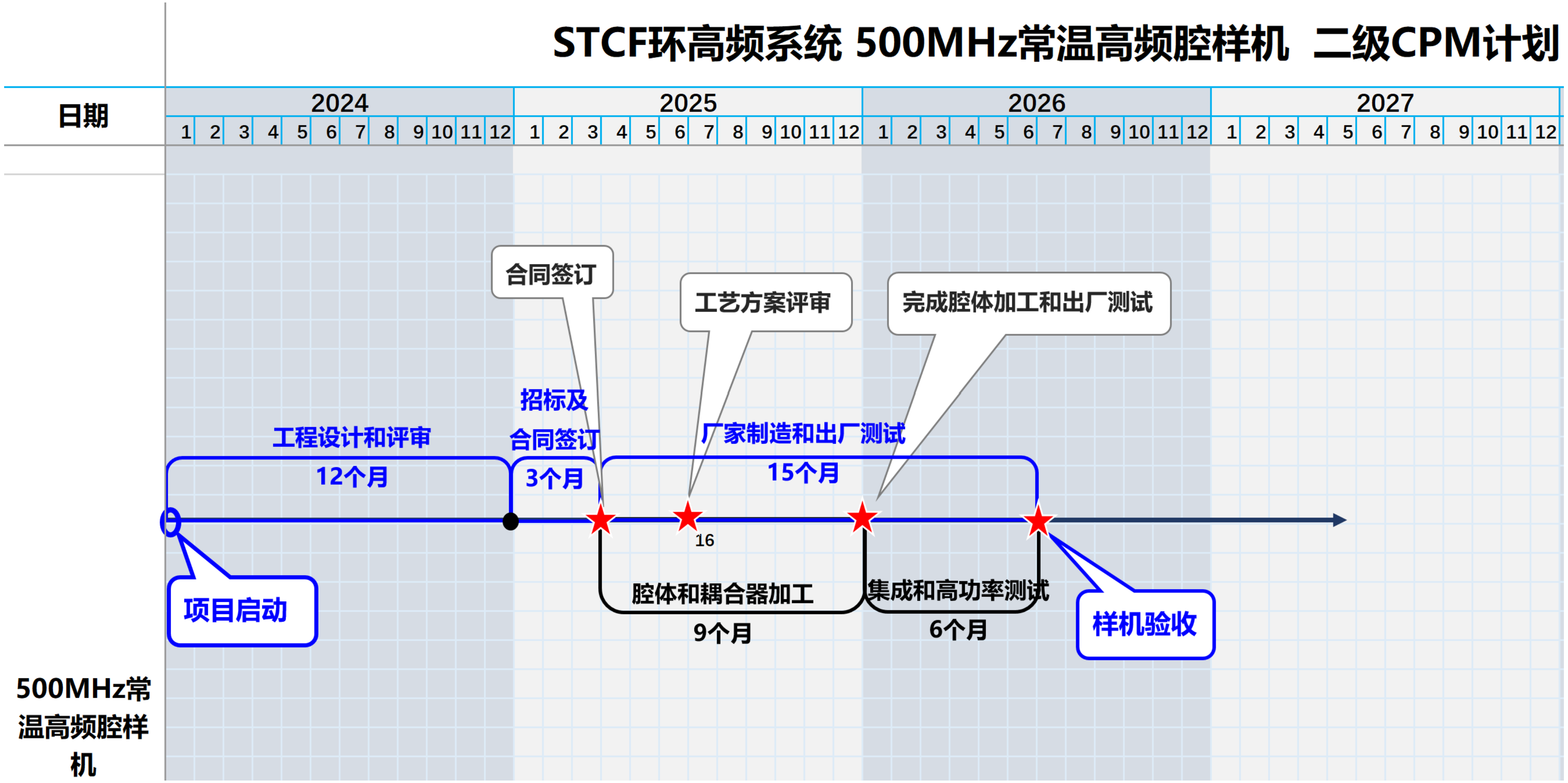


Mechanical Design for Whole Module





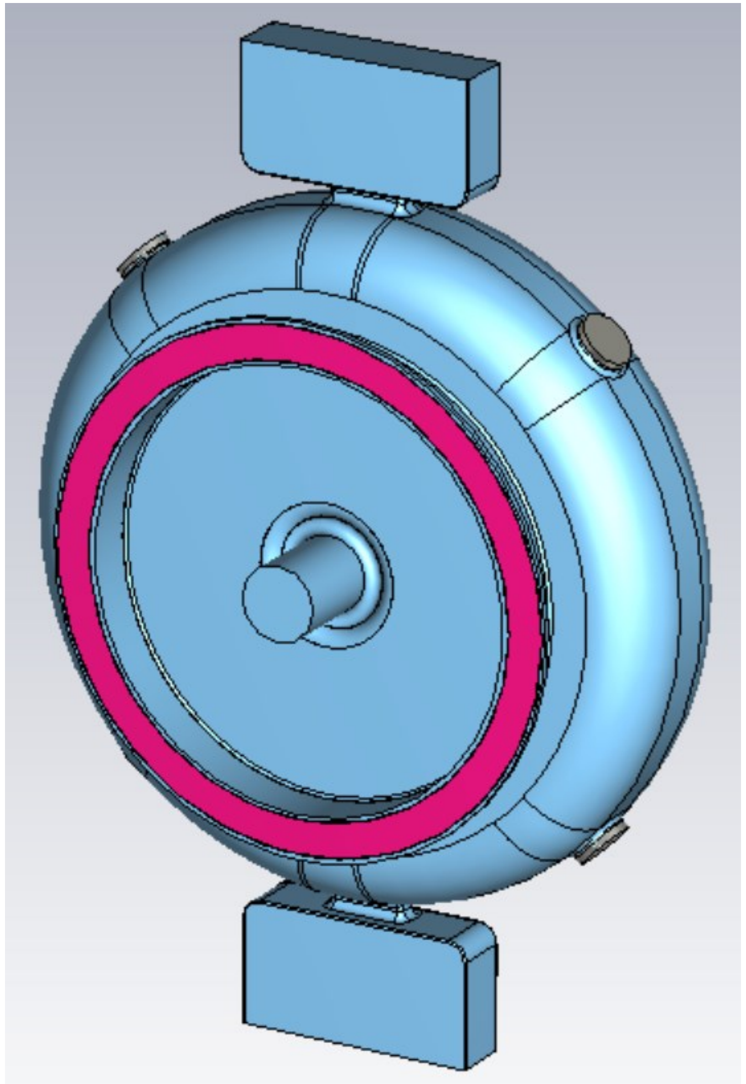
时间计划安排



样机研制路径长30个月

Outline

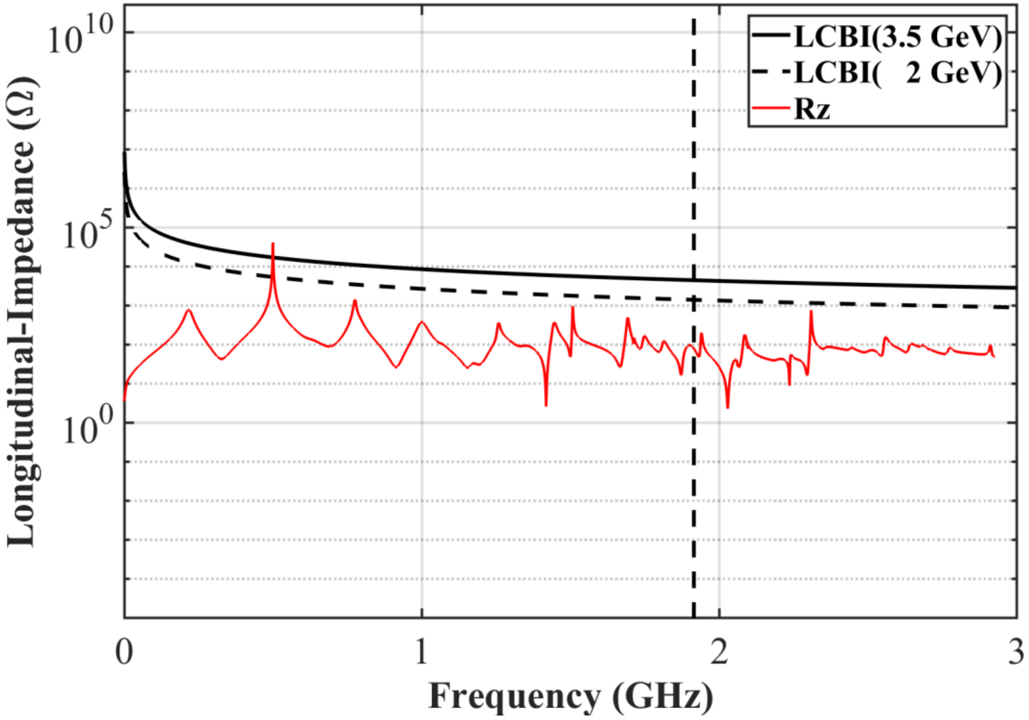
Symmetrically-powered Cavity



- Symmetrical power couplers are employed
  - ✓ **Greatly reduce the demand for the transmitted power for each coupler;**
  - ✓ **Improve the dipole field and leakage rate**

参数	单位	数值	参数	单位	数值
束管半径	mm	60	截止频率	GHz	1.914
工作频率	MHz	499.7	腔压	kV	511
无载品质因子	-	60607	平均加速梯度	MV/m	1.91
几何因子R/Q	ohm	83.36	峰值电场	MV/m	5.81
分路阻抗	Mohm	5.05	Ep/Eacc	-	3.04
Volume Loss	%	1.5	峰值磁场	A/m	5573.72
外部品质因子	-	60000	Hp/Eacc	mA/V	2.92

HOM damping-Longitudinal modes



- 纵向尾场300m情况下，尾势衰减趋于均匀，单腔阻抗谱满足阈值曲线要求

Summary & Outlook

- ✓ We have optimized a NC 499.7 MHz TM020-mode cavity with strong HOM damping to meet the requirement of 2 A for our STCF collider rings.
- ✓ RF design and mechanical design on this TM020-mode cavity have been completed ; Preliminary LLRF developments have been performed.
- ☐ The prototype fabrication is ongoing, it is expected to be completed by the end of 2025 and high-power conditioning is planned by June 2026.