The 24th meeting of the international collaboration of advanced neutron sources(ICANS XXIV)

Development of Dual-harmonic RF System for CSNS-II

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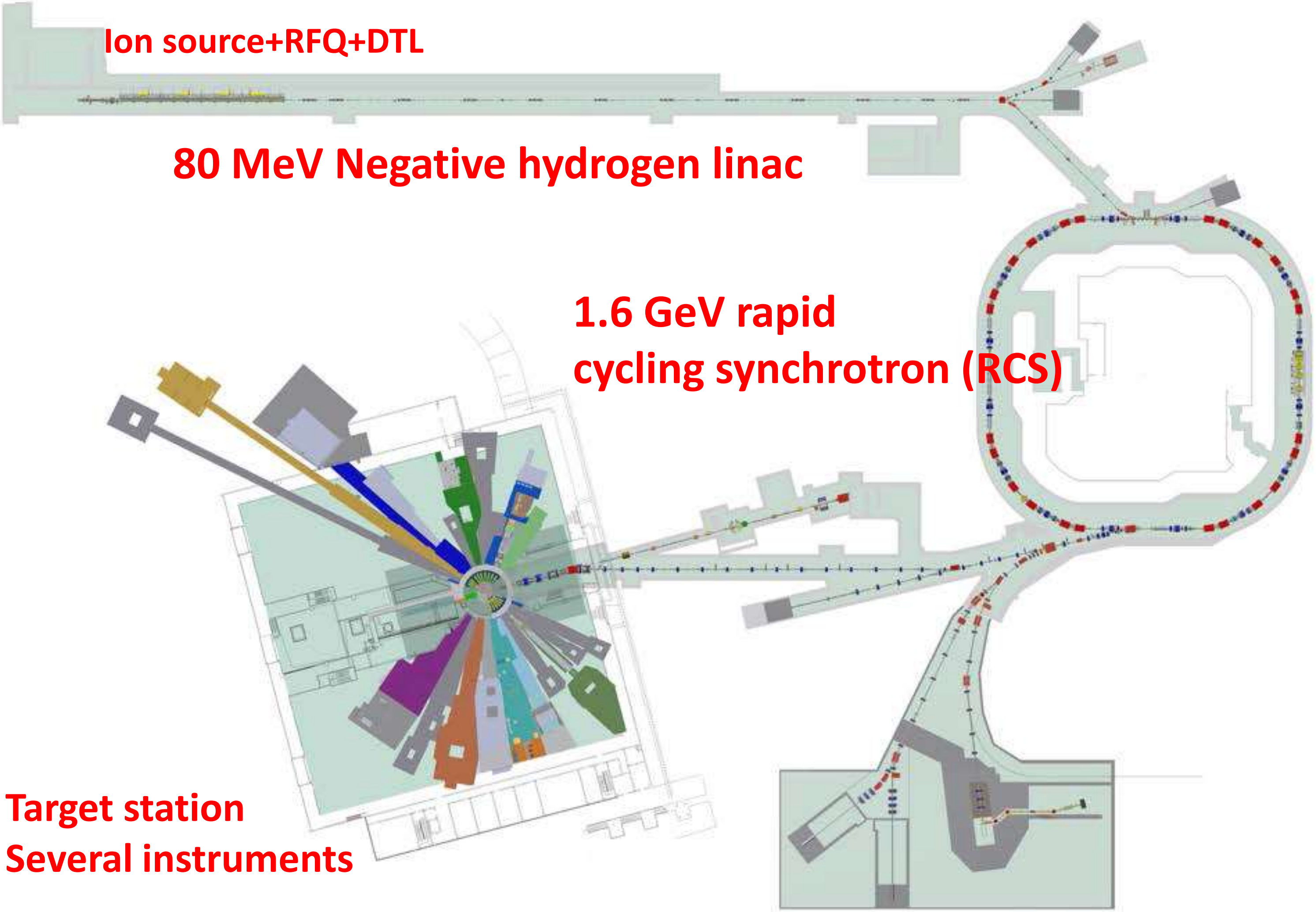
Content

China Spallation Neutron Source II（CSNS-II)



Ion source+RFQ+DTL

80 MeV Negative hydrogen linac

1.6 GeV rapid cycling synchrotron (RCS)

Target station
Several instruments

	CSNS-I	CSNS-II
Beam power (kW)	100	500
Repetition rate (Hz)	25	25
Extraction energy (GeV)	1.6	1.6
Injection energy(MeV)	80	300
Average Current (μA)	62.5	312

Facility	Beam power	ΔQ (Space charge effect)
CSNS-II (China)	500kW	**0.19**
J-PARC (JAPAN)	1MW	0.12
SNS (USA)	1MW	0.08

The space charge effect is heavy !

CSNS-II RCS power upgrade plan

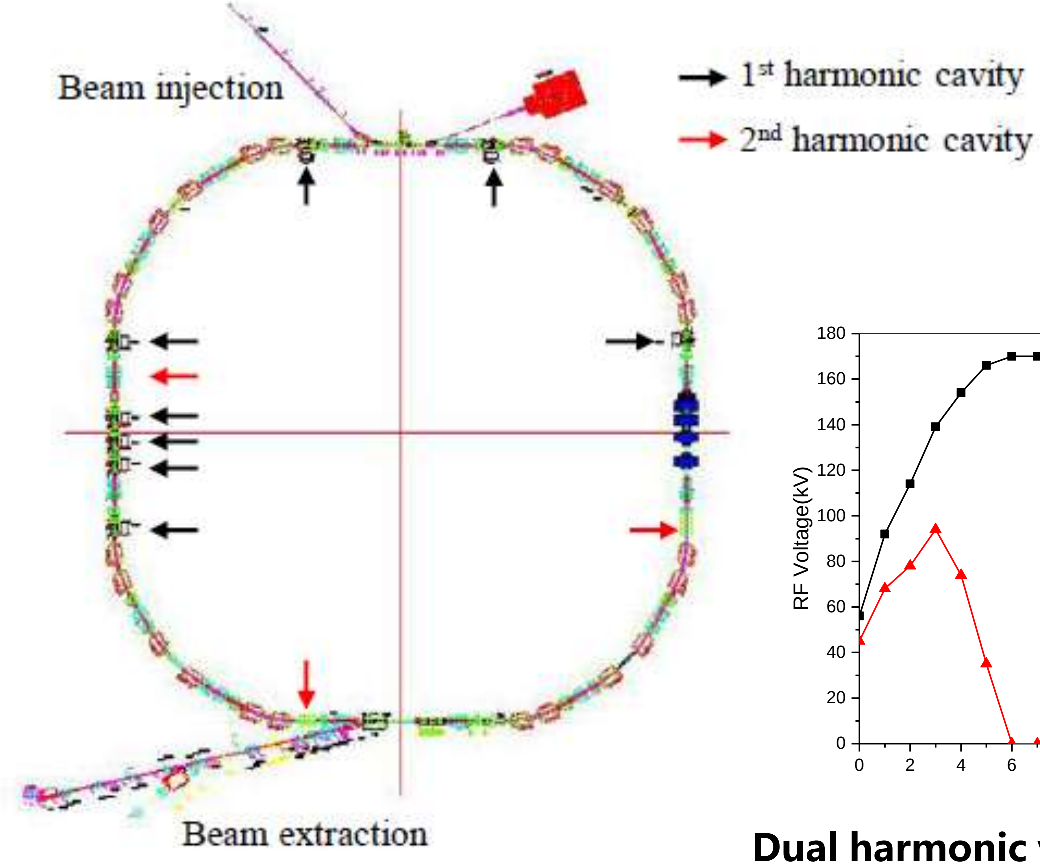
Dual-harmonic acceleration technique -> increase the acceptance and beam factor

8 ferrite loaded cavities （165kV）

3 2nd harmonic cavities （100kV）

↓

Dual harmonic RF SYSTEM



RCS power upgrade technical route：

1. Maintaining injection energy at 80 MeV

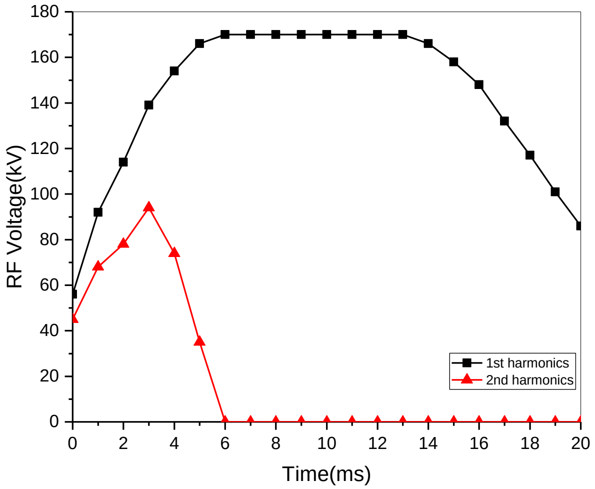
+2 2nd harmonic cavities **Beam power:100kW→200kW**

+ AC correction quadrupole/ sextupole/ octupole magnets, etc

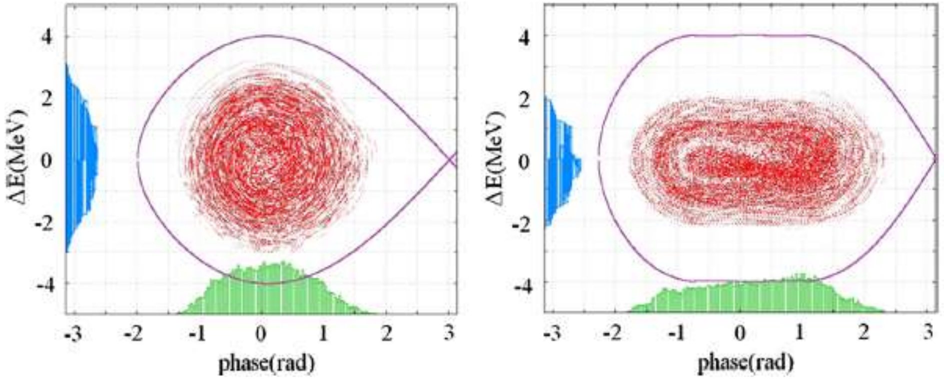
2. Increasing injection energy to 300 MeV

+1 2nd harmonic cavity **Beam power: 200kW→500kW**

New injection system and main magnet resonant power supply system



Dual harmonic voltage ramping curves



Dual harmonic beam acceleration technology to enhance beam bunching factor

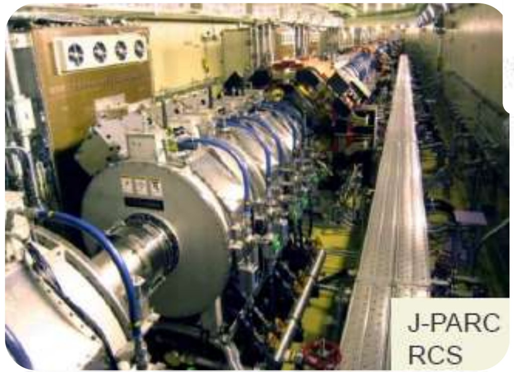
2nd harmonic cavity

CSNS-I/RCS
Ferrite cavity
L=2.7m
V=15kVx2Gap

→ Ferrite Material

Low Bs 0.31T
Low μ 400,1MHz
Low Tc 200°C
Nonlinearity
Complex tuning system

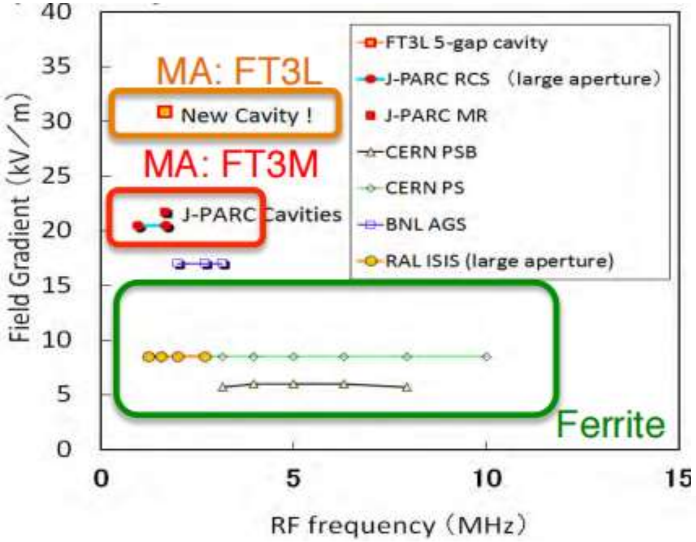
Accelerating Gradient≈11kV/m

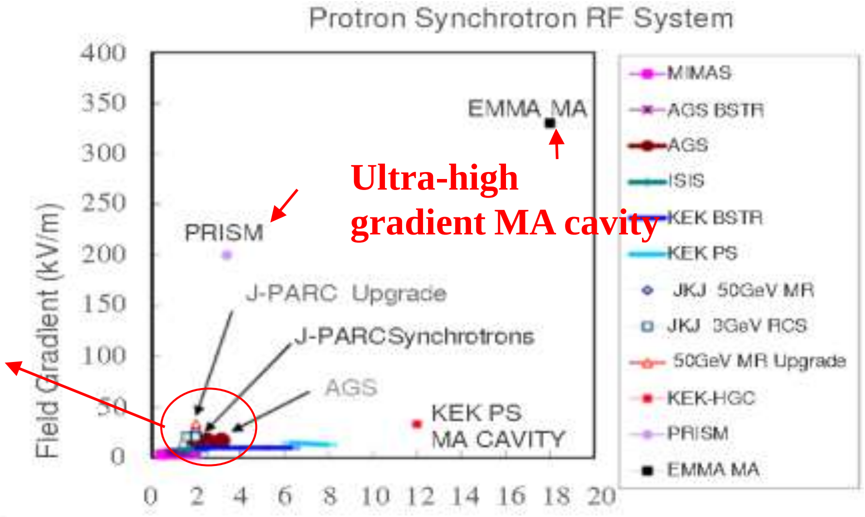


J-PARC
MA cavity
L=2.59m
V=15kVx5Gap

→ Nanocrystalline soft magnetic alloy (MA)
High Bs 1.2T
High μ 2400,1MHz
High Tc 570°C
Q<1
No tuning system

Accelerating Gradient≈29kV/m





Comparison of gradient in magnetic alloy-loaded cavities

The necessity of using MA-loaded cavities in CSNS-II RCS:

1, Limited space leaved in RCS tunnel

2, High RF voltage (100kV)

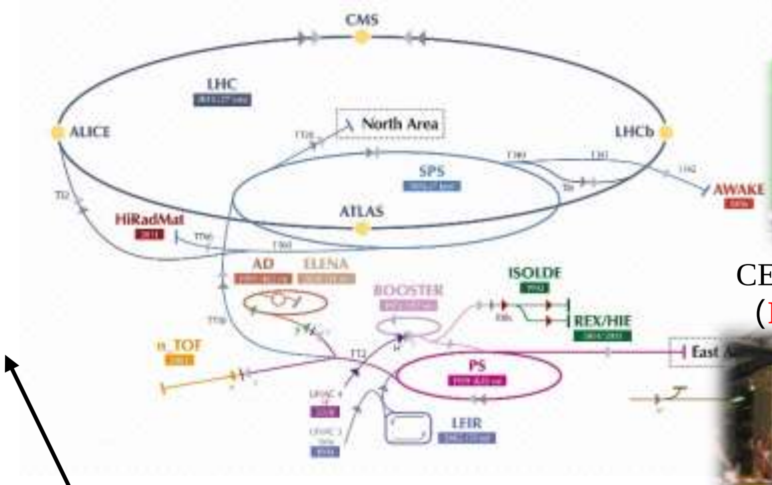
3, Multi-harmonic accelerating technique

The MA loaded cavity is the best choice !

The application of magnetic alloy-loaded cavities

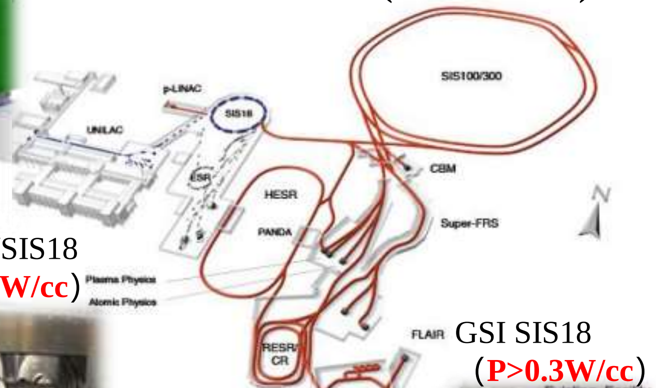
HIREL (**P<0.01W/cc**)

CERN

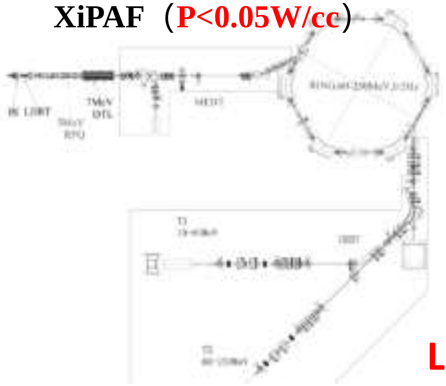


CERN PS Booster (P>0.15W/cc)

FIRA(Based on GSI)



XiPAF (**P<0.05W/cc**)



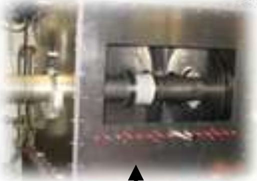
1k107B
(China)

Low average power density

Hospital in ShangHai (**P<0.05W/cc**)

CERN LEIR
(**P>0.15W/cc**)

GSI ESR/SIS18
(**P>0.15W/cc**)

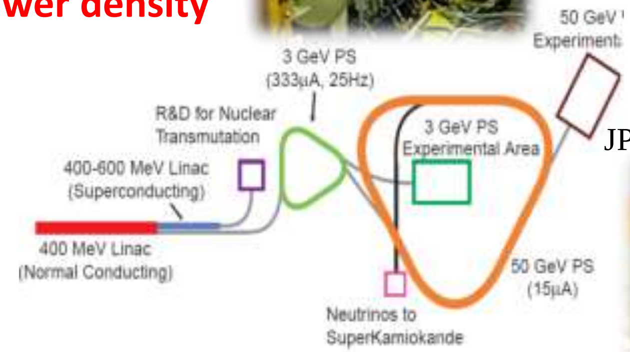


GSI SIS18
(**P>0.3W/cc**)

JPARC RCS (**P≈0.37W/cc**)

Nano-crystals Finemet
Hitachi Metal Ltd (JAPAN)

High average power density



J-PARC

JPARC MR (**P≈0.89W/cc**)

HIMAC RCS
(**P>0.15W/cc**)

HIMAC

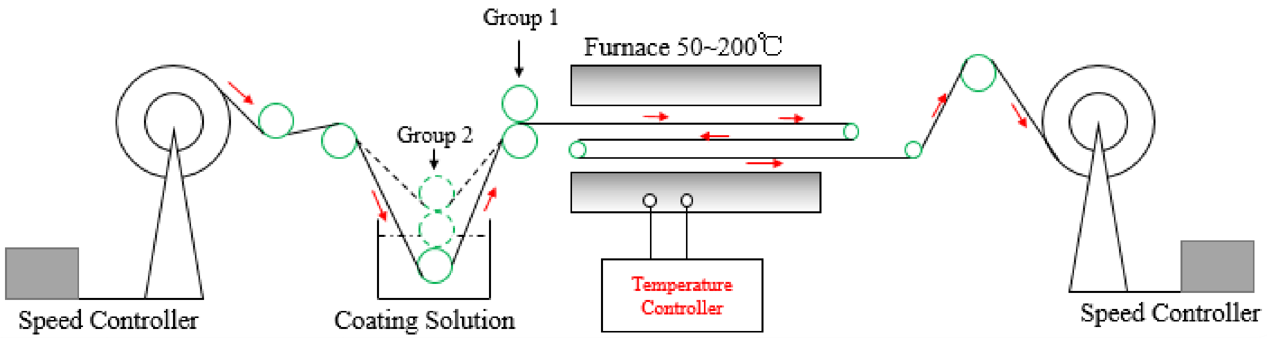
The challenges in the development of high power MA-loaded cavities

- ☐ **Surface insulation and low-stress coating treatment of magnetic alloy ribbons**
- ➢ **Insulation breakdown between magnetic core inter-layers under high electric field gradients**
- ➢ **Significant eddy current losses under high power operation**
- ➢ **The MA ribbons are stress-sensitive and require low stress and can bear high temperatures(400℃~600℃).**
- ☐ **Large size MA core winding and high-temperature annealing**
- ➢ **Insulation breakdown between layers and deformation of large-sized MA core during winding**
- ➢ **Excessive or insufficient transition crystallization of large-size MA core**
- ☐ **Encapsulation of large-sized MA cores**
- ➢ **The solidification layer causes an increase in thermal stress and deformation of the MA core**
- ➢ **The stress induced by the solidification layer leads to a decrease in the performance of the MA core**
- ☐ **Design of cavity structure with high cooling efficiency**
- ➢ **The average thermal power of the magnetic ring exceeds 0.3W/cc**
- ➢ **The power distribution of the magnetic ring is not uniform.**

Technologies for high-performance MA core fabrication

■ Key process flow

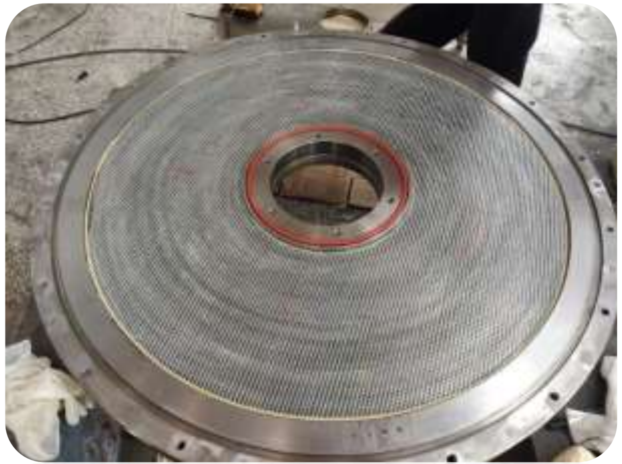
Nanocrystalline ribbon with 18μm
1k107B (Fe-Cu-Nb-Si-B)



Low-stress insulation coating

Constant tension level winding

Transverse magnetic annealing

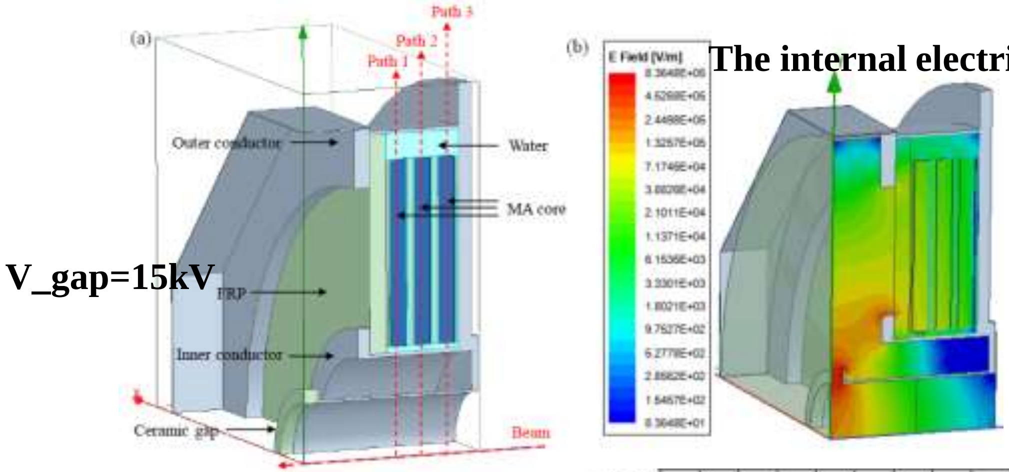


Encapsulation

Product

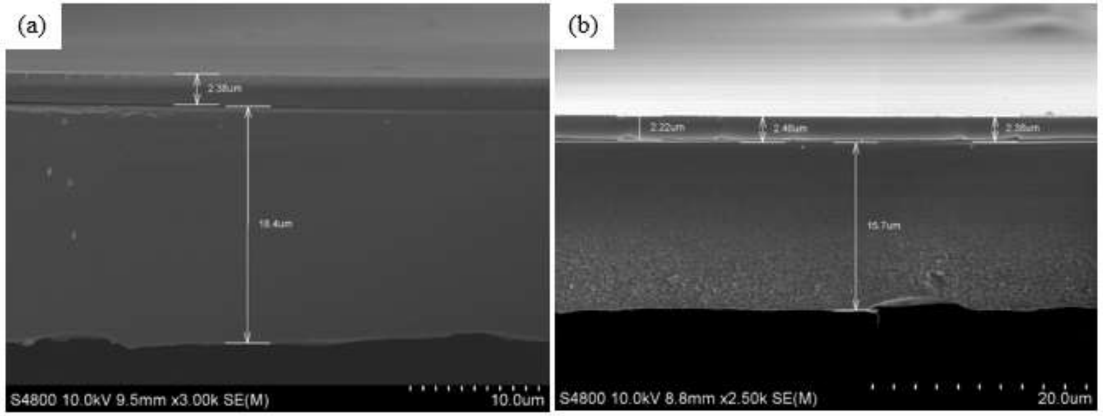
Low-stress insulation coating

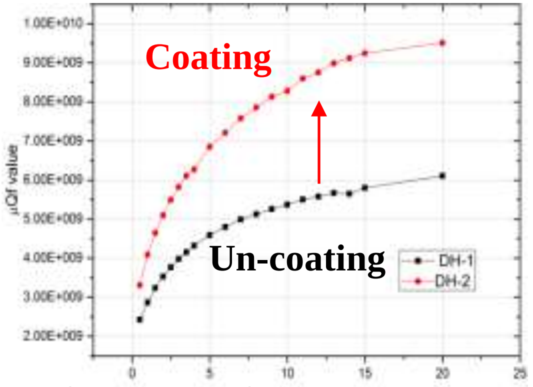
- ■ To reduce eddy current losses and interlayer sparking → Coating on the MA ribbon is necessary
- ■ An inorganic coating with a thickness of about 2μm by using the sol-gel process.
- ➢ low stress ,high temperature resistance(>700℃)
- ➢ Single layer withstand voltage of up to 270VDc



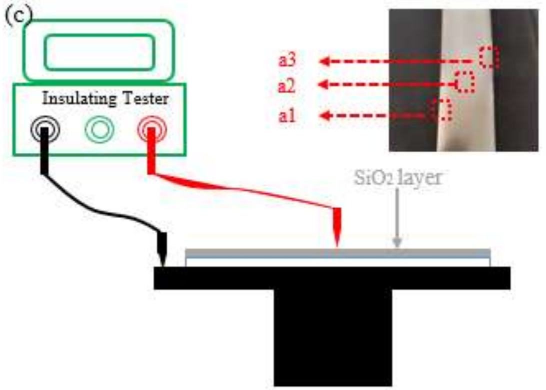
The internal electric field

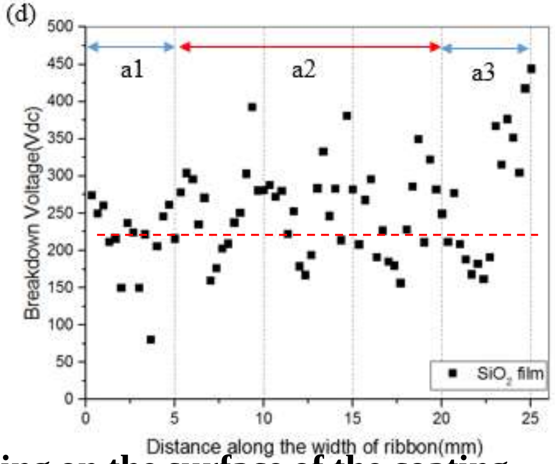
Cross-sectional electron microscopy of the coating.





Testing the impact of the coating to the performance of small MA cores.



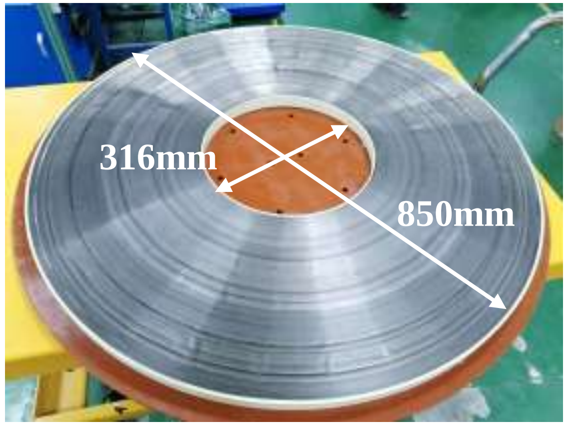


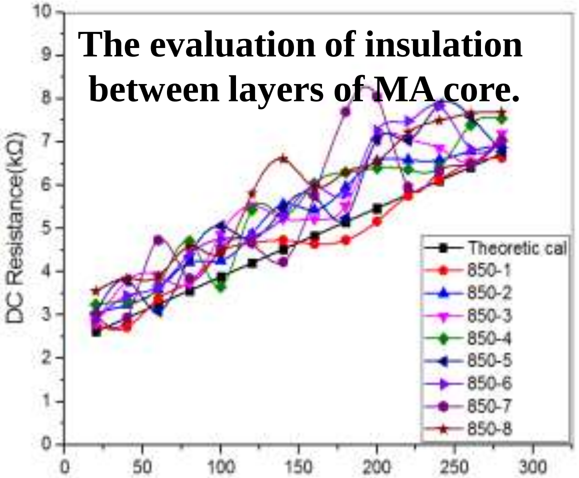
270Vdc

Insulation breakdown testing on the surface of the coating.

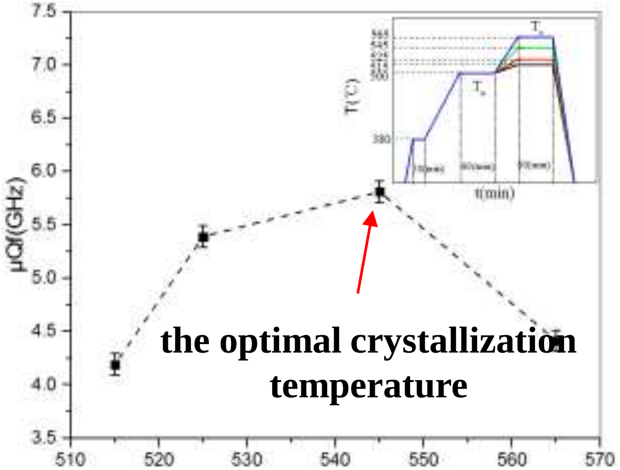
Winding and annealing for large-sized MA core

- High shunt impedance for the cavity, large size core->insulation detachment and the core deformation
- A multi-ring overlapping and horizontal winding process were conducted on the core with Φ850mm.
- In-house developed transverse magnetic annealing furnace -3000Gs

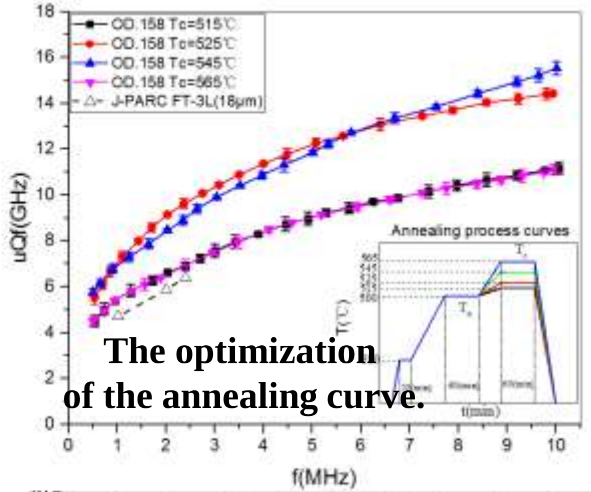




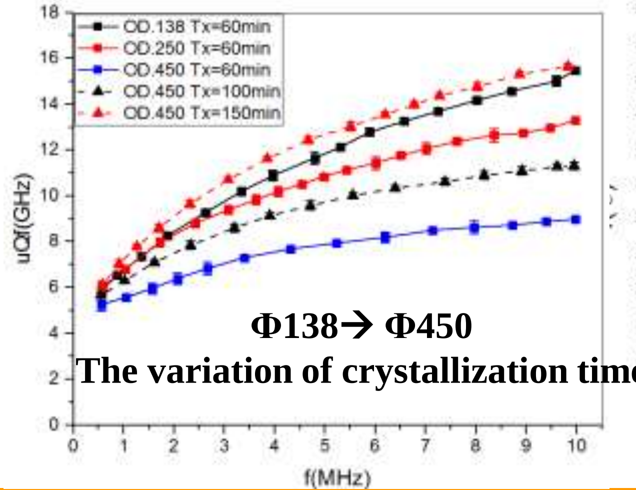
The evaluation of insulation between layers of MA core.



the optimal crystallization temperature

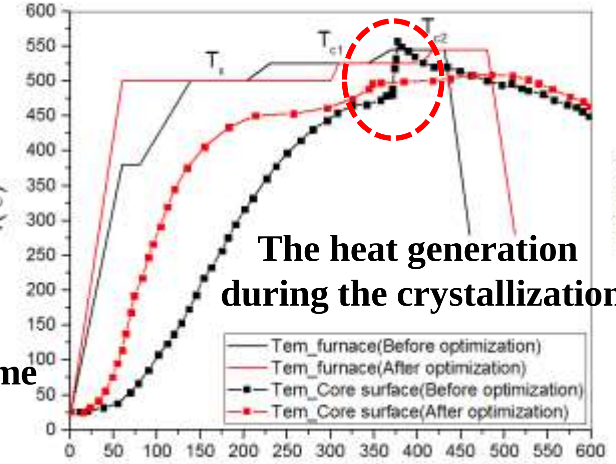


The optimization of the annealing curve.

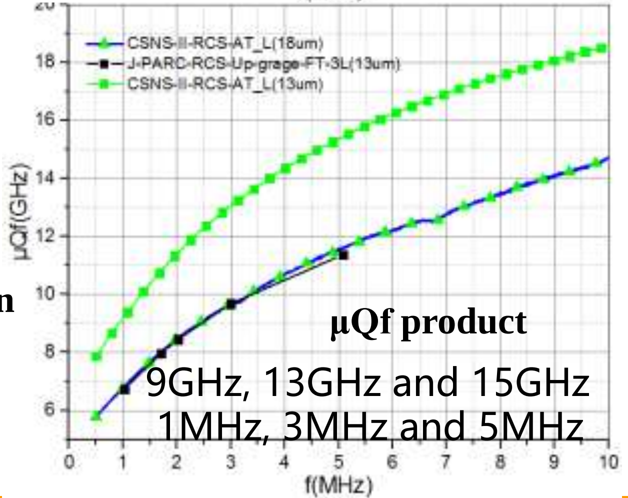


Φ138→ Φ450

The variation of crystallization time



The heat generation during the crystallization



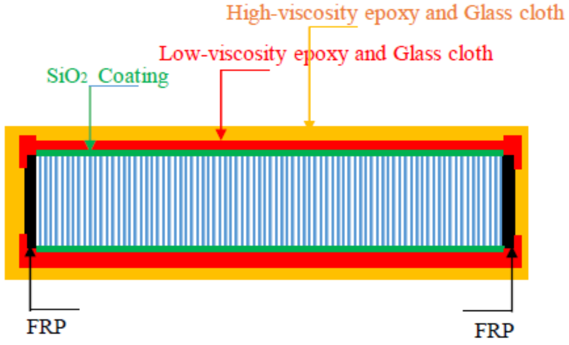
μQf product

9GHz, 13GHz and 15GHz

1MHz, 3MHz and 5MHz

Low-stress solidification packaging process

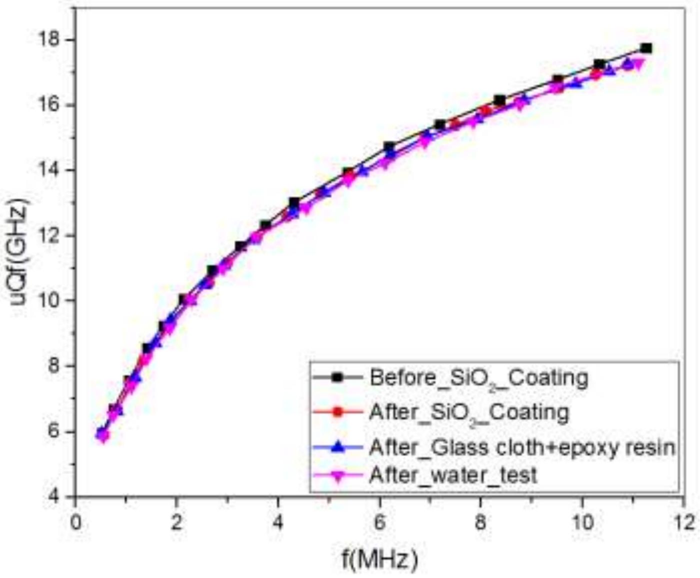
- ■ A direct water cooling method is adopted for the MA core in CSNS-II as the high power density.
- ➢ Waterproof the MA core and ensure that they have sufficient hardness are necessary.
- ◻ A waterproof packaging structure and curing process to prevent epoxy resin from infiltrating into the core.
- ➢ No thermal stress deformation after long time high-power test, MA cores are in mass production



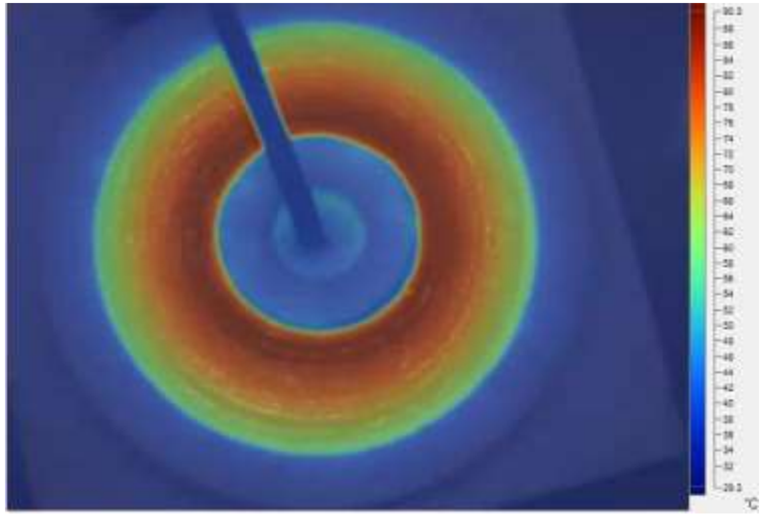
Curing fixture

Low vacuum environment + fixture

The impact of each curing process step on the performance of the core

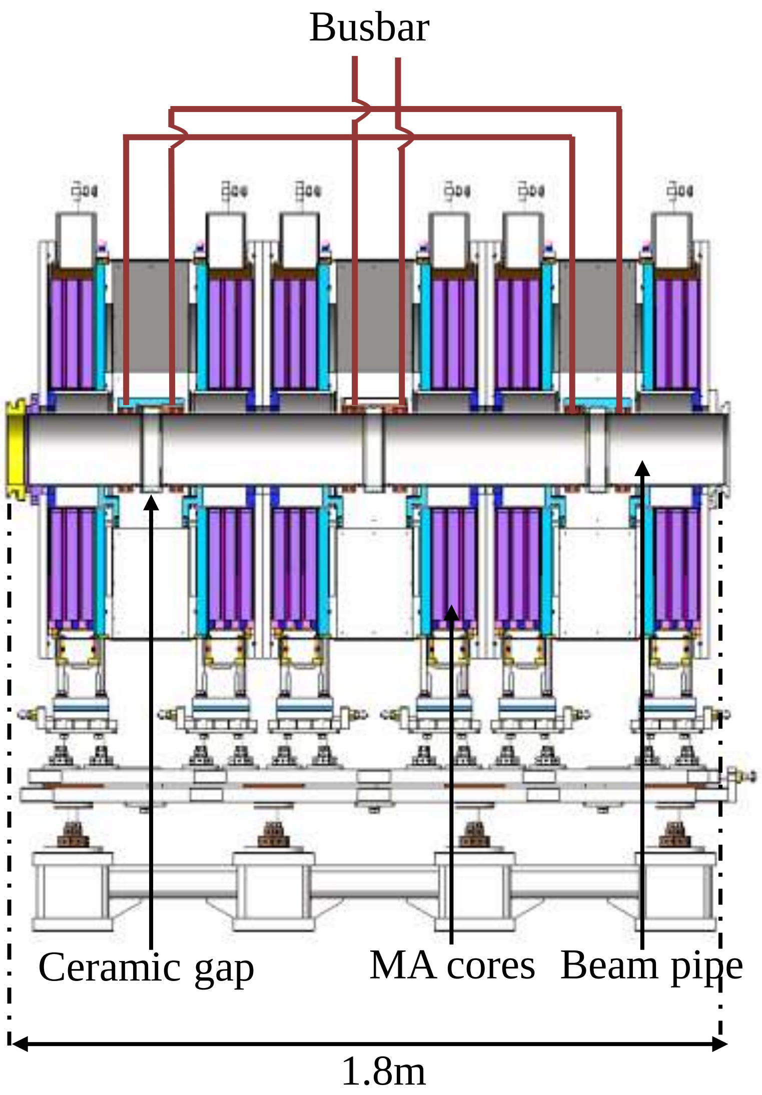


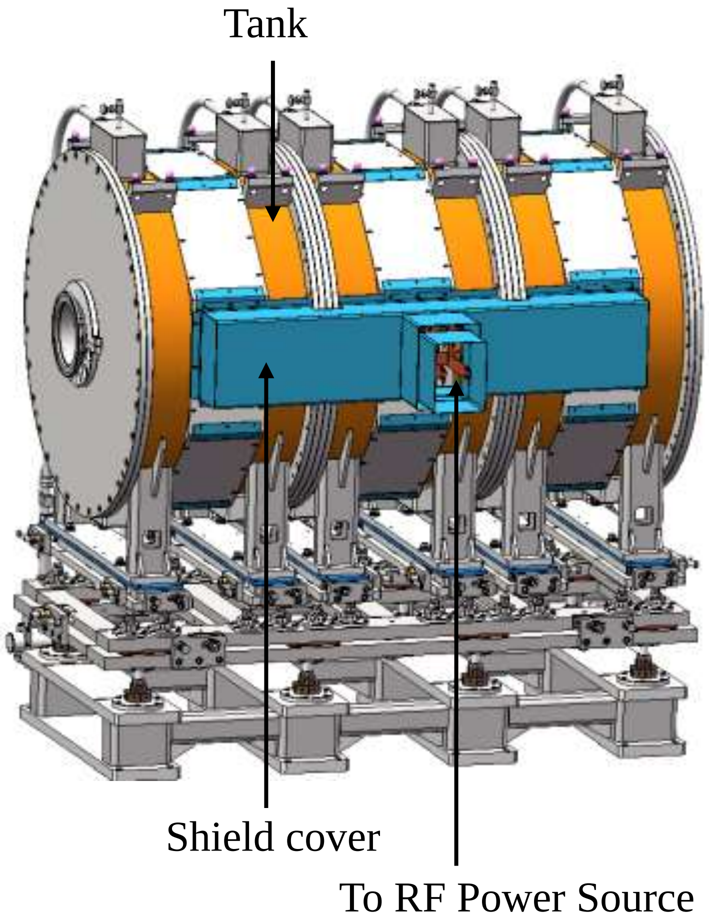
>1000hr high power test



MA loaded cavity design

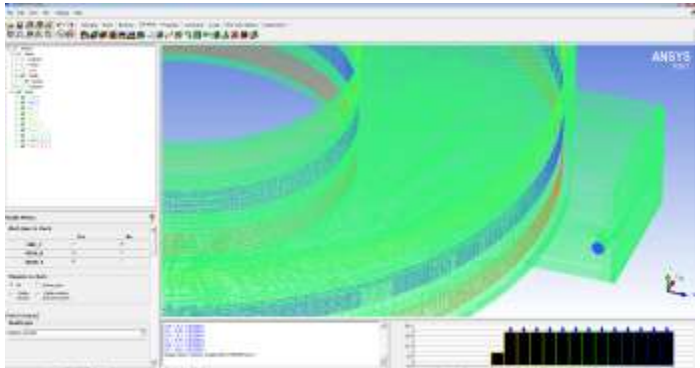
Frequency range (MHz)	**1~8**
Length of Cav（m）	1.8
Number of gaps	3
Number of cores	18
Peak RF voltage（kV）	36(72kV@test)
Size of core（mm）	O.D850×I.D316×H25mm
Type of MA material	1k107B
Thickness of MA ribbon（μm）	18
Annealing type	Transverse magnetic annealing
uQf（@1MHz）（GHz）	> 6.5
uQf（@3MHz）（GHz）	>9.5
uQf（@5MHz）（GHz）	>11
Average power density（W/cm^3）	0.33
Cooling method	Direct water cooling
Water flow/Tank（L/min）	45



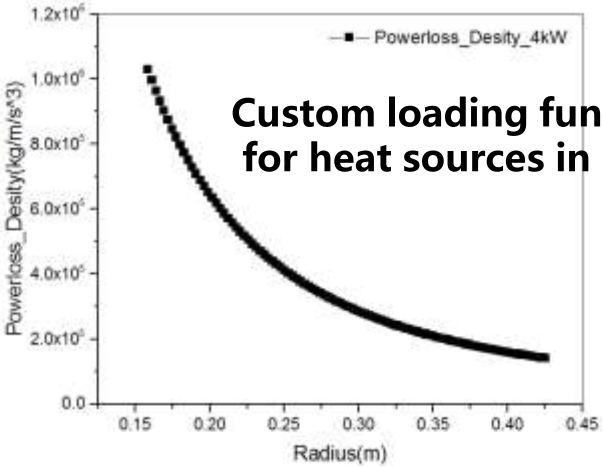


Fluid thermodynamic simulation and validation

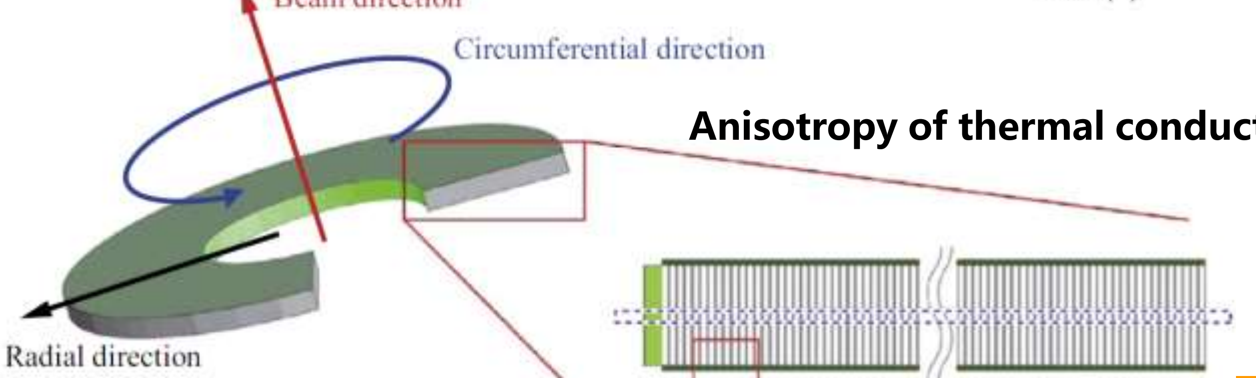
- Low Q value of the cavity, almost all the losses in core
- The accuracy of simulation results → Two specific characteristics
  - Thermal load varies with radius
  - Thermal conductivity exhibits anisotropic properties



Hexahedral mesh using ICEM



Custom loading function for heat sources in CFX



Anisotropy of thermal conductivity →

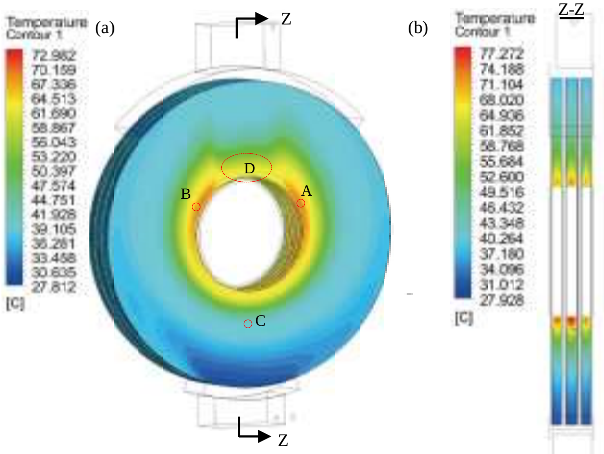
Key parameters for simulation

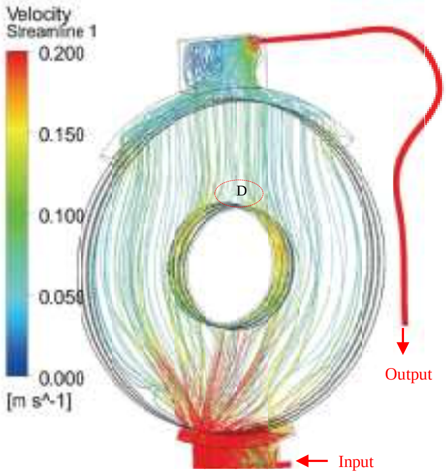
Parameters	Values	
Liquid	Deionized Water	
Input Temp[℃]	24.4	
Flow rate[L/min]	40	
Specific Heat capacity[J/kg/k]	4181.7	
Dynamic Viscosity[kg/m/s]	8.9E-4	
Reynolds number	153~256(Laminar)	
Turbulence Mode	SST-k-w	
Thermal conductivity(Water) [W/m/K]	0.6	
Thermal conductivity(MA) [W/m/K]	**Z**	**7.1**
	Θ	**7.1**
	r	**0.2**
Thermal conductivity(FRP) [W/m/K]	0.2	

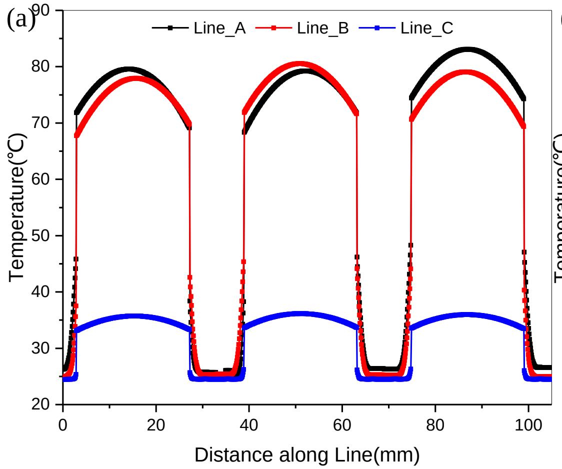
Fluid thermodynamic simulation and validation

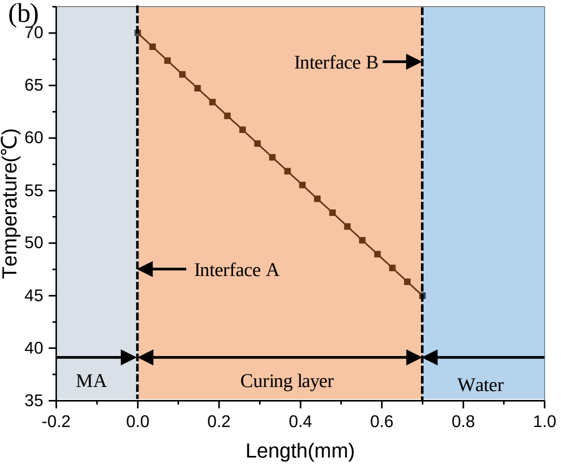
- **Surface temperature of the core < 41℃, a maximum temperature of the solidification layer < 72℃, which is significantly lower than the maximum operating temperature of 120℃**

$0.4W/m^3$
(5kW/core
40L/min)

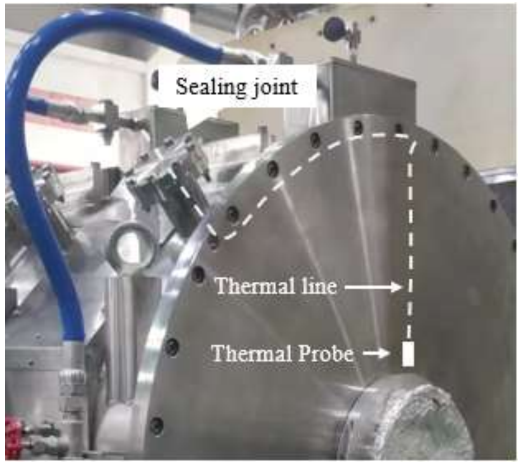


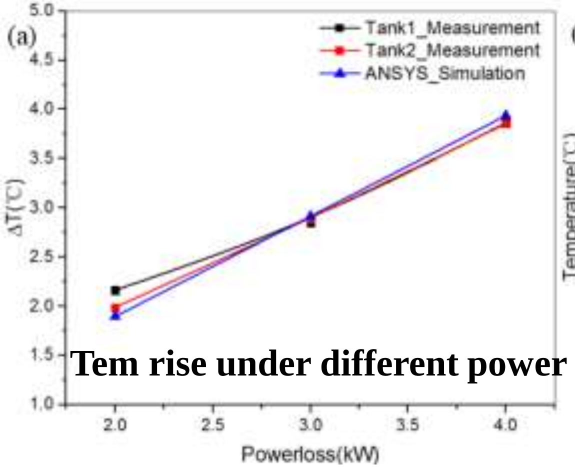




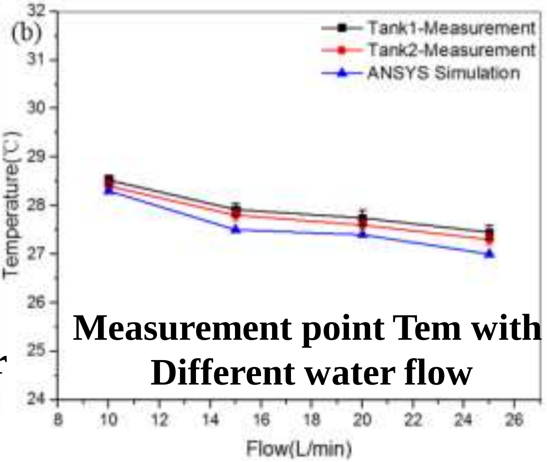


- **The test results are well consistent with the simulation results**

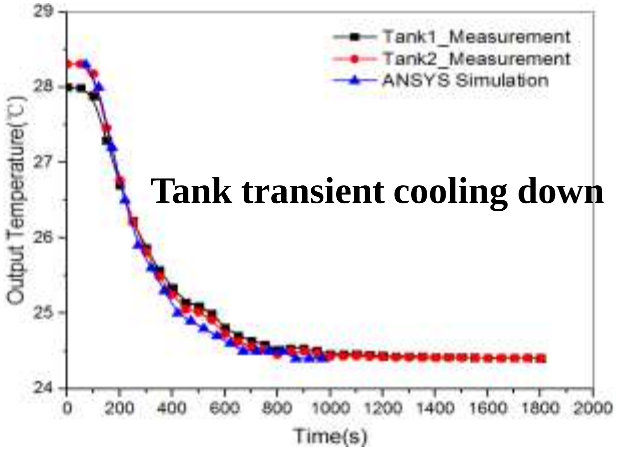




Tem rise under different power



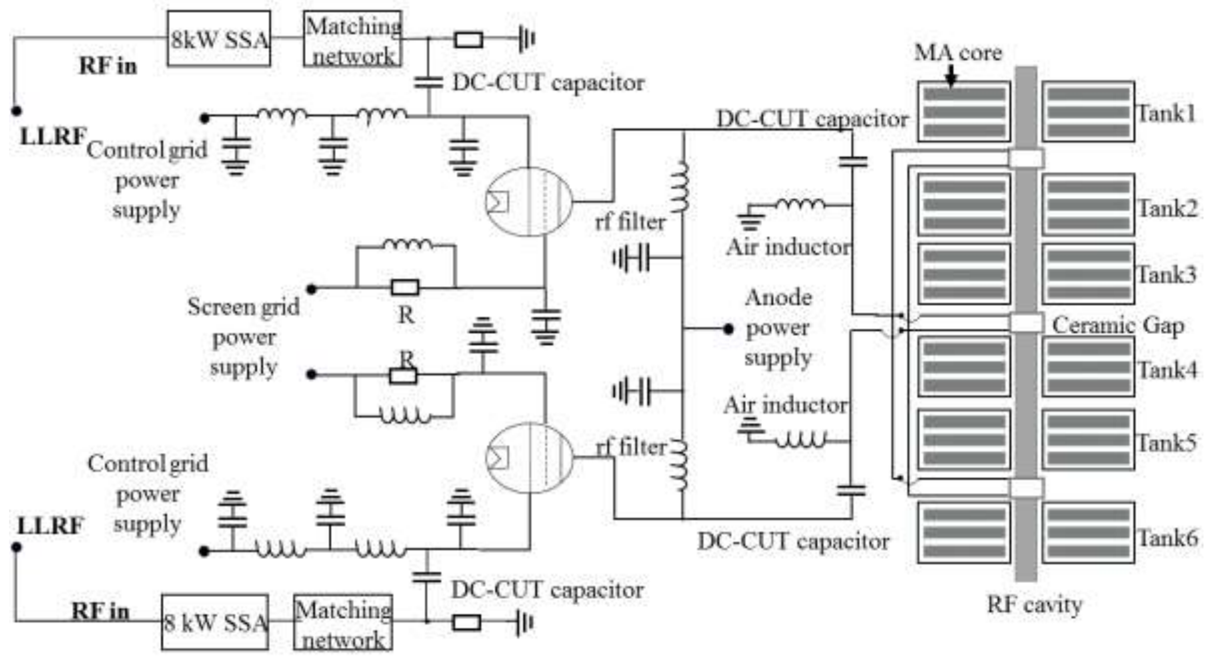
Measurement point Tem with Different water flow



Tank transient cooling down

RF power system

- **Two high-power tetrode tubes operated in class AB1 and PUSH-PULL mode**
- **Each three tanks are connected in parallel for direct electrical coupling with the anode of the tube**
- **Each tube is driven by an 8 kW solid-state amplifier (SSA)**
- **A broadband matching network is inserted to minimize power reflection from the SSA**

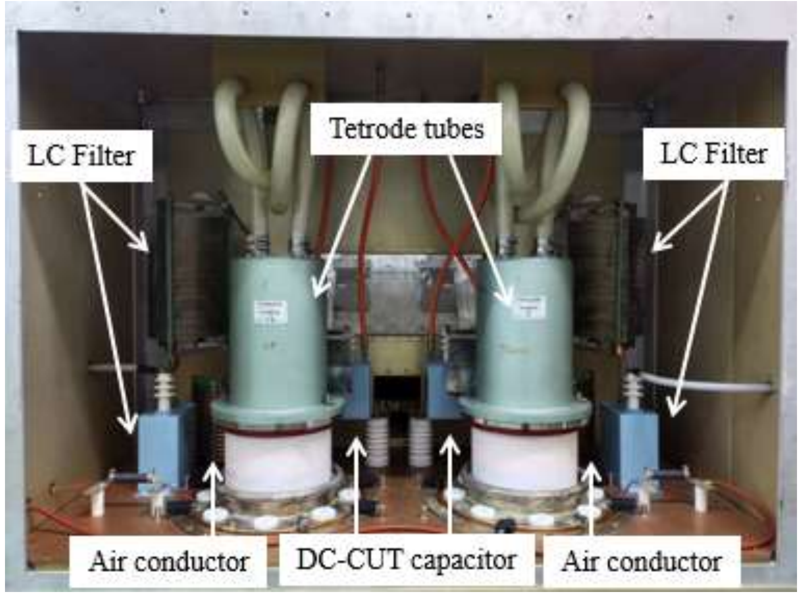


the schematic of RF amplifier system for the MA loaded cavity

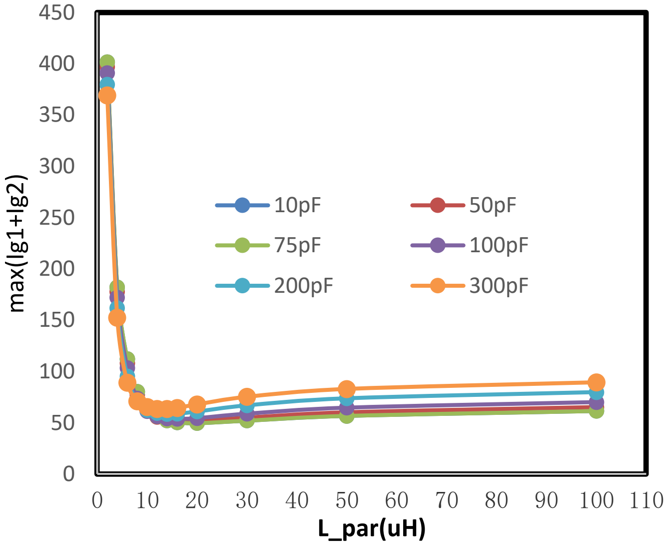
Frequency range	**1 MHz~8 MHz**
Final stage amplifier	Tetrode tube (TH558)
Repetition frequency	25 Hz
Duty cycle	50%
Anode dissipation	500 kW
Screen grid dissipation	8 kW
Control grid dissipation	3 kW
DC anode voltage	15 kV
DC screen grid voltage	1500 V
DC control grid voltage	-340 V

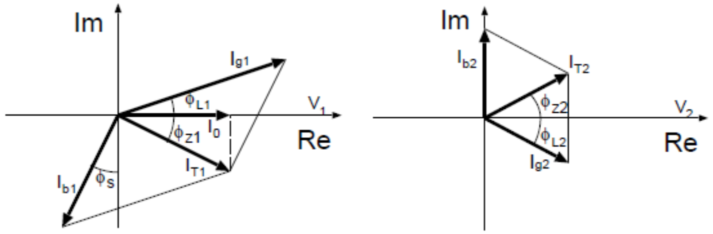
RF amplifier system for MA loaded cavity

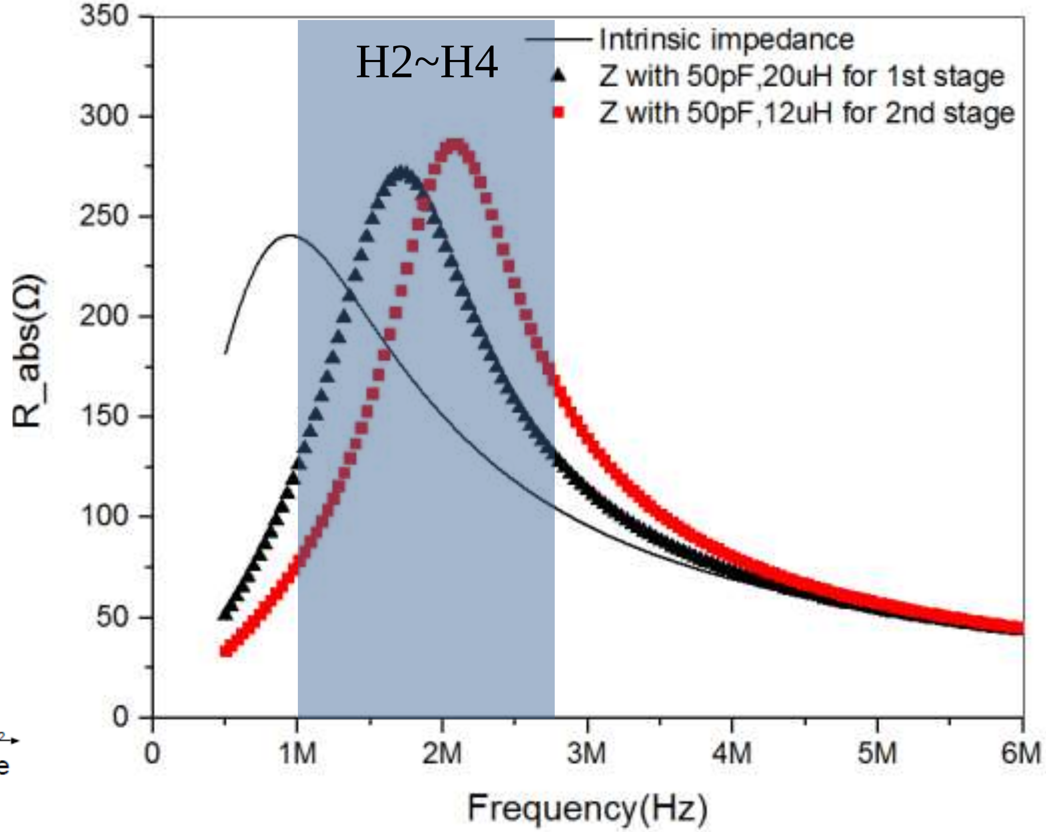
- **Two air inductors (20μH) are connected at each end of the cavity gap to adjust the center frequency and Q value of the cavity, improving the output efficiency of the RF power source.**



Anode current Vs （Lpar, Cpar）

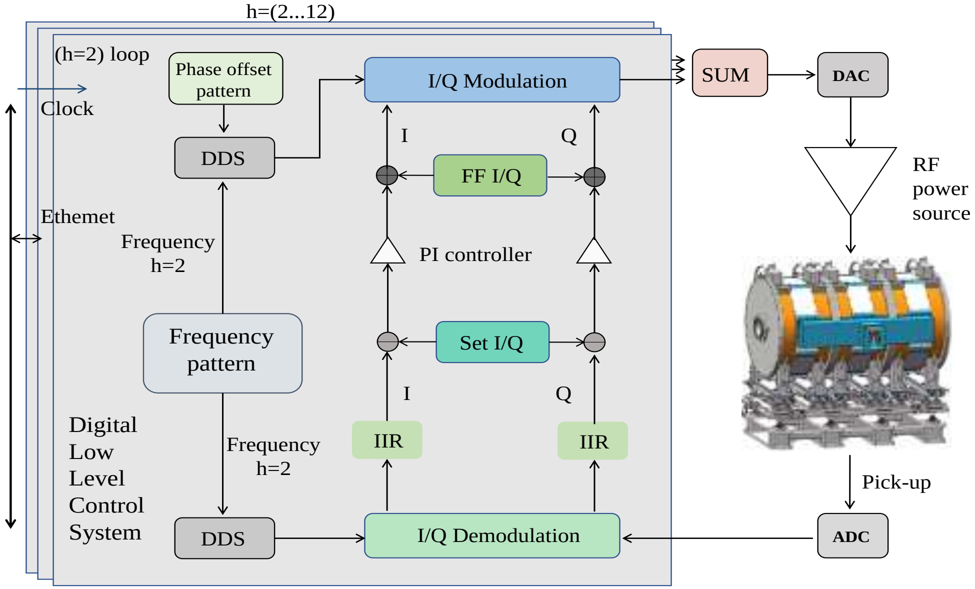


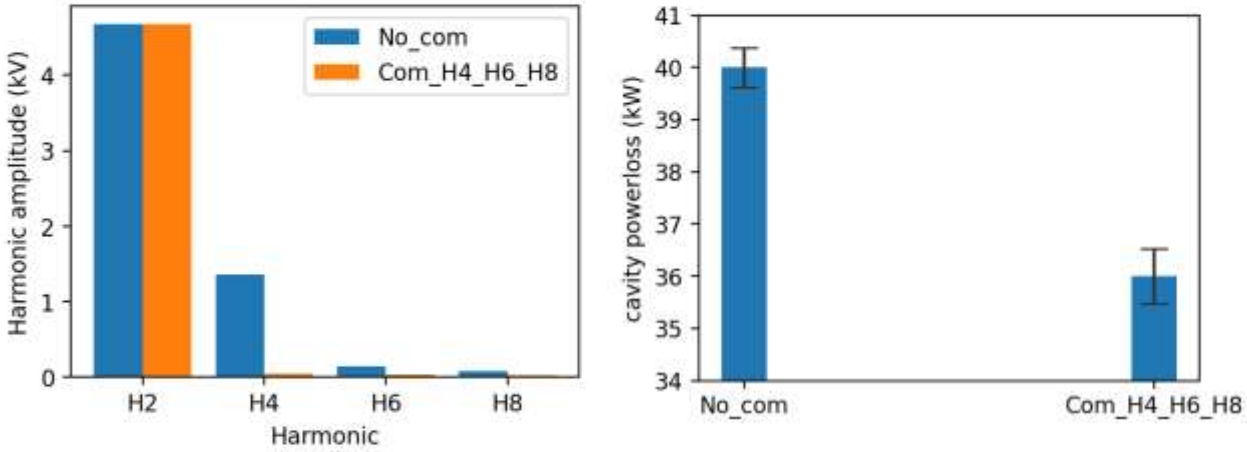


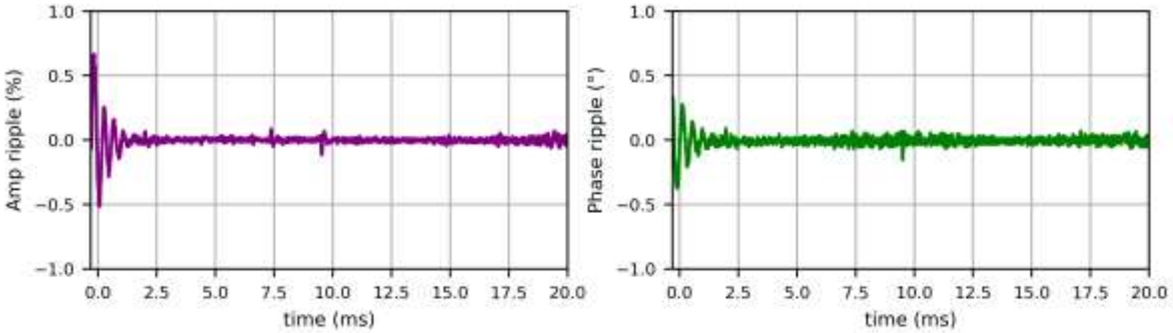


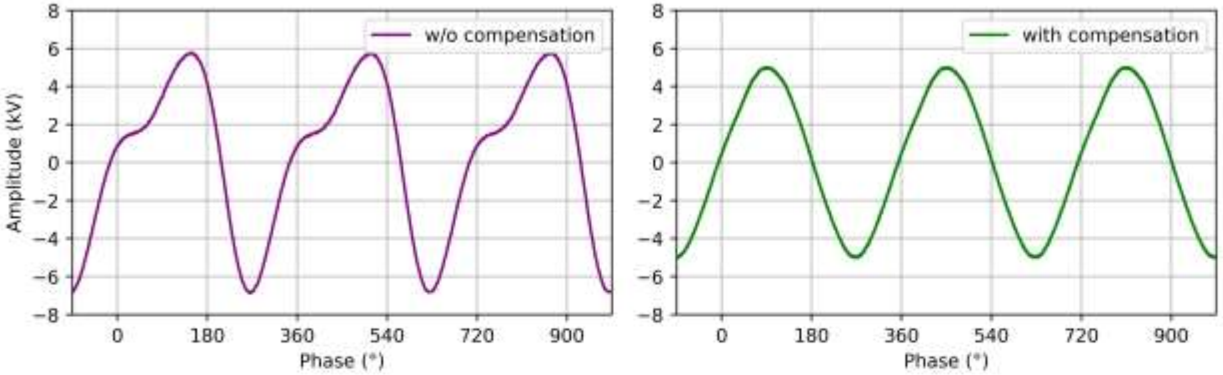
LLRF system

- Low Q-value of the MA load cavity, rich higher-order harmonics are excited by tubes and beam
- A multi-harmonic feedback control algorithm to suppress the higher harmonics, higher-order harmonic components < -30dB, the amplitude and phase ripple are controlled to ±1.0% and ±1°



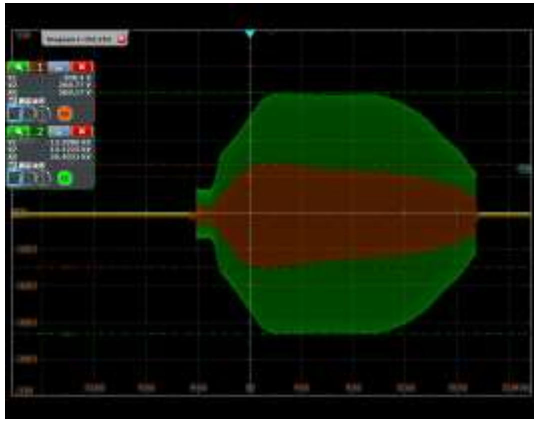


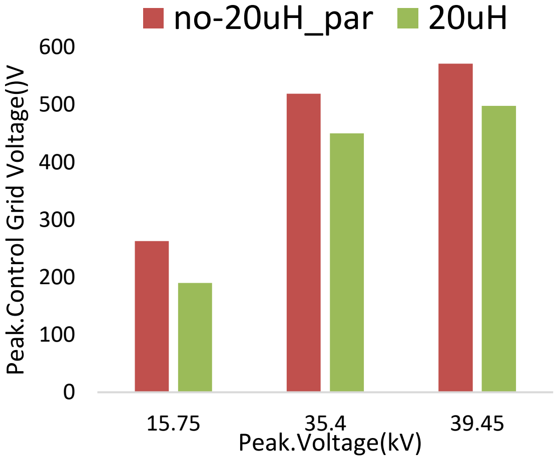


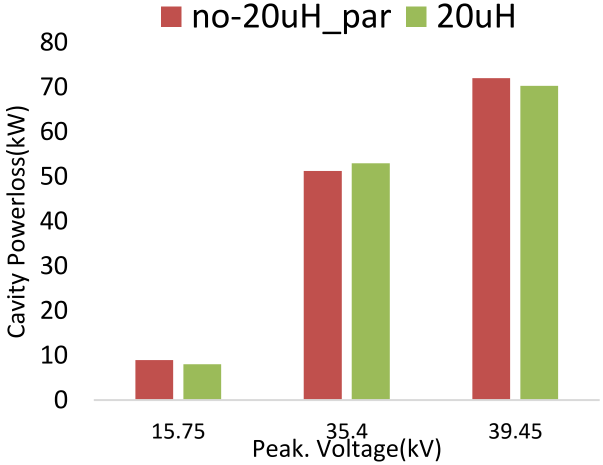


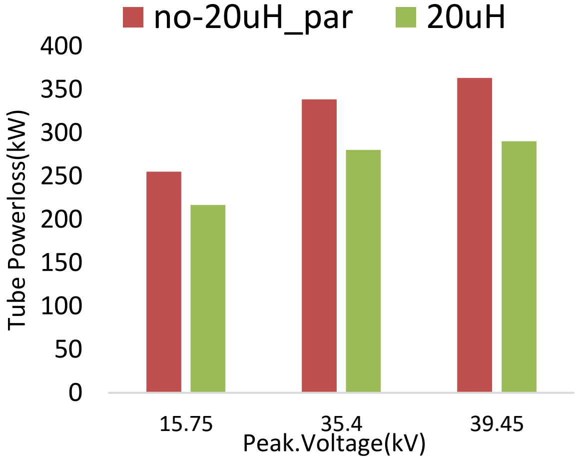
High power and high gradient testing

- **Fundamental model（1.02MHz~2.4MHz，Duty:50%），Peak gradient: 26kV/m，Cavity power loss:72kW**

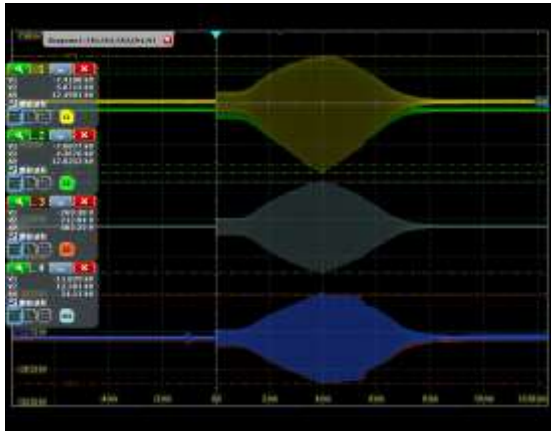


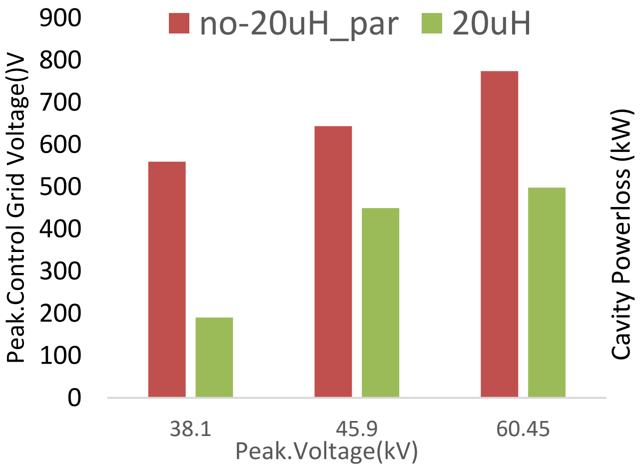


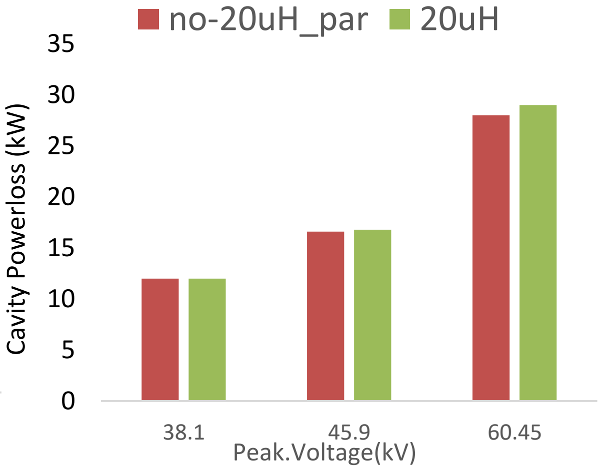


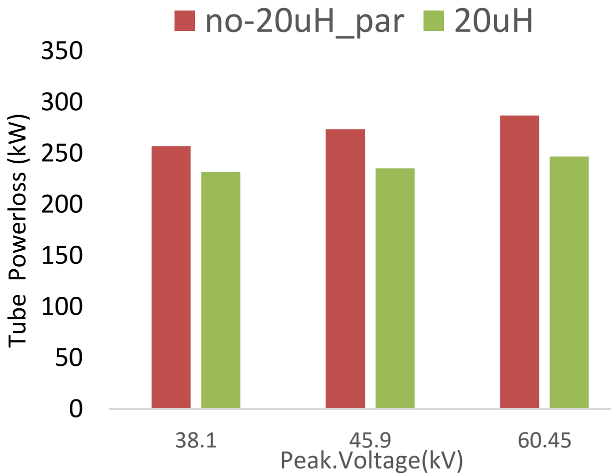


- **2nd harmonic model（2MHz~3MHz，Duty:15%），Peak gradient: 40kV/m，Cavity power loss: 30kW**



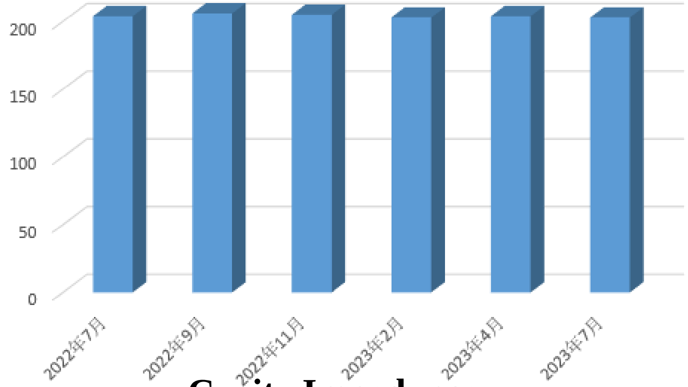




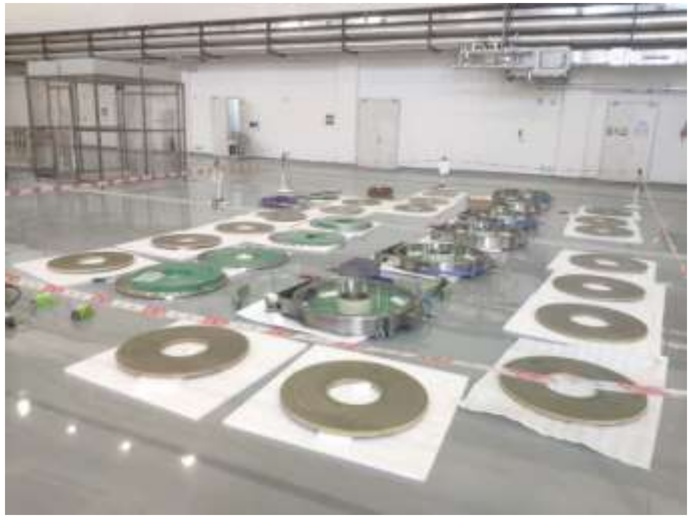


MA loaded cavity operation in CSNS RCS

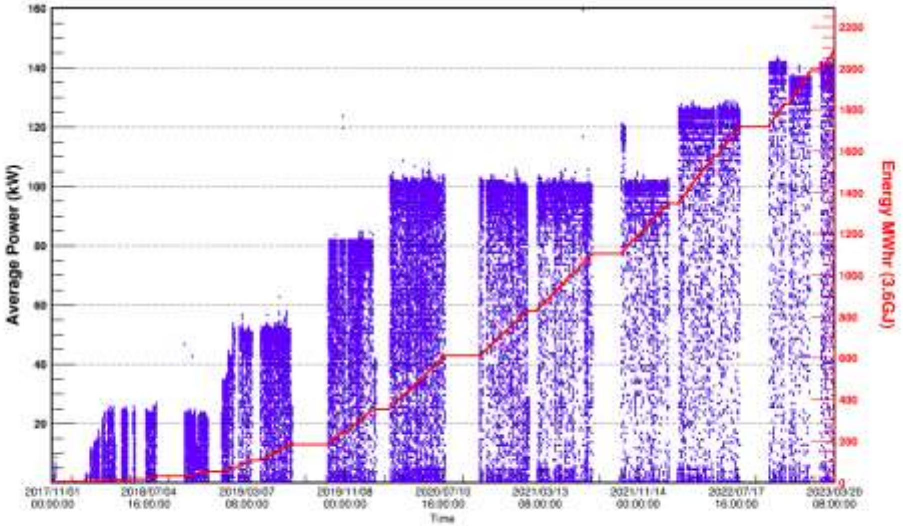
- In August 2022, the installation of the first MA loaded cavity in the RCS tunnel was completed.
- The cavity accumulated an operating time of over 9600 hours at a gradient of 40 kV/m, the cavity impedance variation rate is less than 3%.



Cavity Impedance



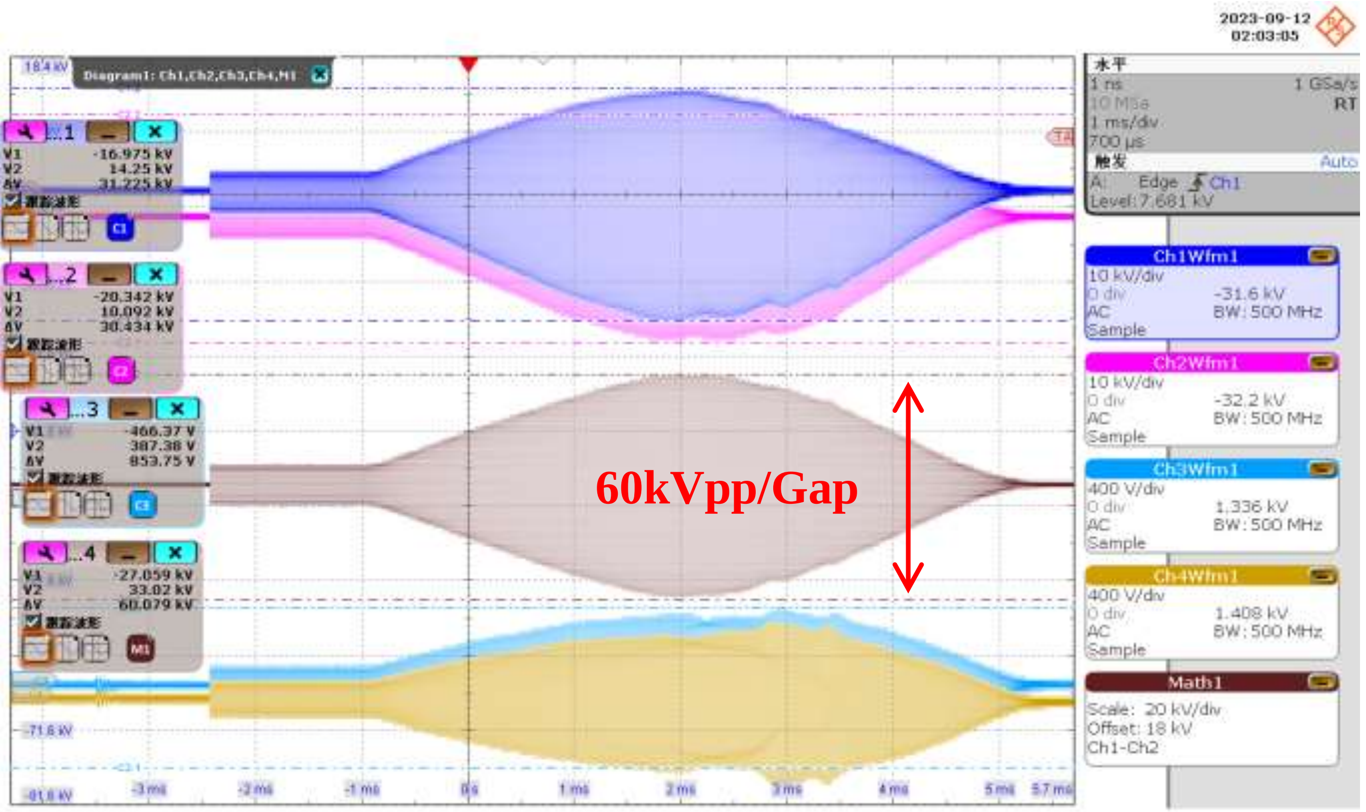
In February 2023,
the cavity was
disassembled and all cores
were inspected.
no damage, and the performance is stable.



In October 2022,
the beam power reached 140 kW.

MA loaded cavity operation in CSNS RCS

- **In August 2023, the installation of the second MA loaded cavity in the RCS tunnel was completed. After optimizing the cavity gap ceramic structure and power source operating point, the cavity achieved a gradient of 50 kV/m (total voltage of 90 kV) under the second harmonic mode.**



2023-09-12
02:03:05

...1
V1 -16.975 kV
V2 14.25 kV
ΔV 31.225 kV
☑ 跟踪波形

...2
V1 -20.342 kV
V2 10.092 kV
ΔV 30.434 kV
☑ 跟踪波形

...3
V1 -466.37 V
V2 387.38 V
ΔV 853.75 V
☑ 跟踪波形

...4
V1 -27.059 kV
V2 33.02 kV
ΔV 60.079 kV
☑ 跟踪波形

60kVpp/Gap

水平
1 ns 1 GSa/s
10 MSa RT
1 ms/div
700 µs
触发 Auto
A: Edge Ch1
Level: 7.681 kV

Ch1Wfm1
10 kV/div
0 div -31.6 kV
AC BW: 500 MHz
Sample

Ch2Wfm1
10 kV/div
0 div -32.2 kV
AC BW: 500 MHz
Sample

Ch3Wfm1
400 V/div
0 div 1.336 kV
AC BW: 500 MHz
Sample

Ch4Wfm1
400 V/div
0 div 1.408 kV
AC BW: 500 MHz
Sample

Math1
Scale: 20 kV/div
Offset: 18 kV
Ch1-Ch2

Summary

- The performance of the MA cores has exceeded our expectations, and we will continue to monitor the performance during longer cavity operation.
- In the face of future higher gradients and higher power density operation, there is still significant room for improvement in the performance of the MA core and cavities.
- Using thinner MA ribbon materials to improve the performance of the MA core
- Further optimizing the cooling structure of the cavities to enhance cooling efficiency
- Optimizing the accelerator gap structure to improve the threshold for gap breakdown

Thank you for your attention