TTC meeting 2025

Developments of Nb_3Sn cavities and conduction-cooled cryostat at PKU

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Outline

- Preparation of Nb_3Sn cavities
  - Single tin source method
  - Three tin source method
  - Annealing study
- Conduction cooling experiments with SRF cavities
  - Conduction cooling cryostat
  - Conduction cooling researches
  - Coating of copper by cold-spray
  - DC-SRF electron gun with conduction cooling technology
- Summary

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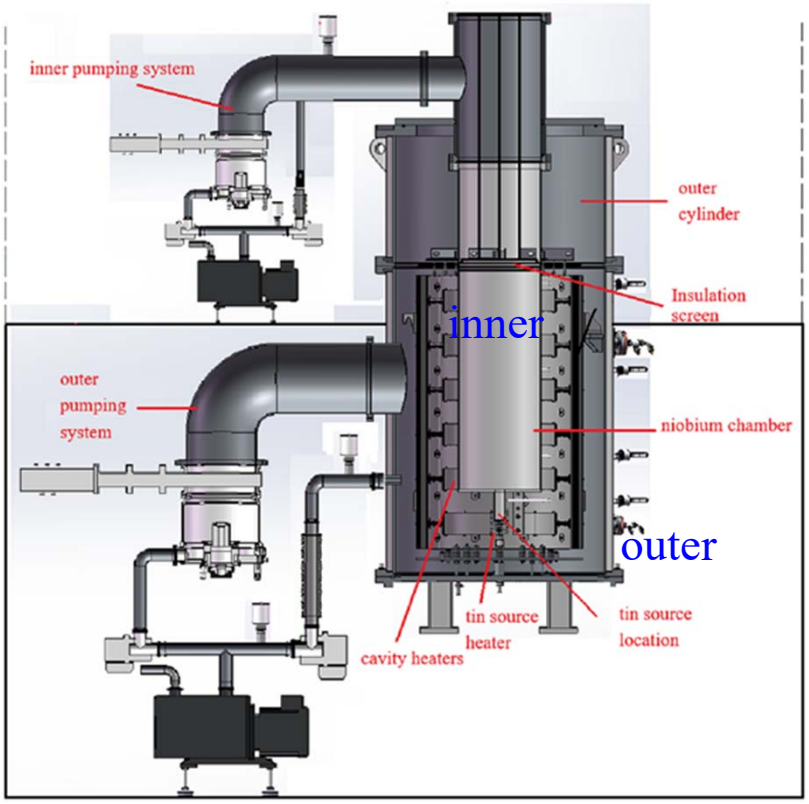
Preparation of Nb_3Sn cavities with tin vapor diffusion method

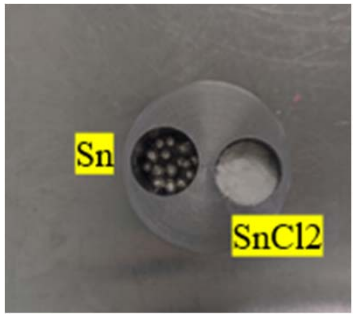
high temperature furnace

- For 1.3 GHz 1-cell / 1.5-cell cavities
- Constant T area:
  diameter 300 mm
  height 600 mm
- Temperature stability
  $<\pm 5$℃
- Temperature ramp
  ≥ 10℃/min
- background vacuum
  $\leq 5\times10^{-5}$ Pa



single-tin-source method

tin source

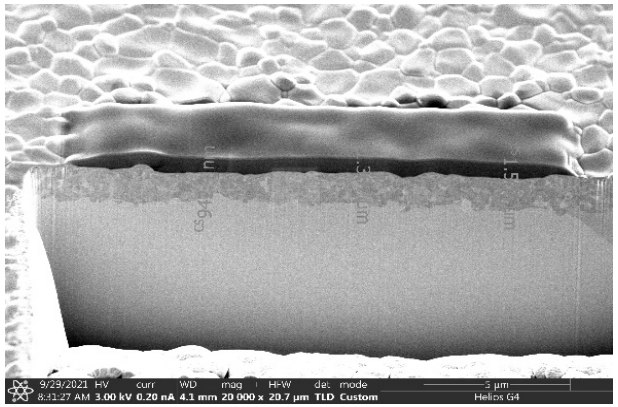


evaporation boats

Pre-processing

BCP/EP, 800 ℃ 3 h

US cleaning, HPR



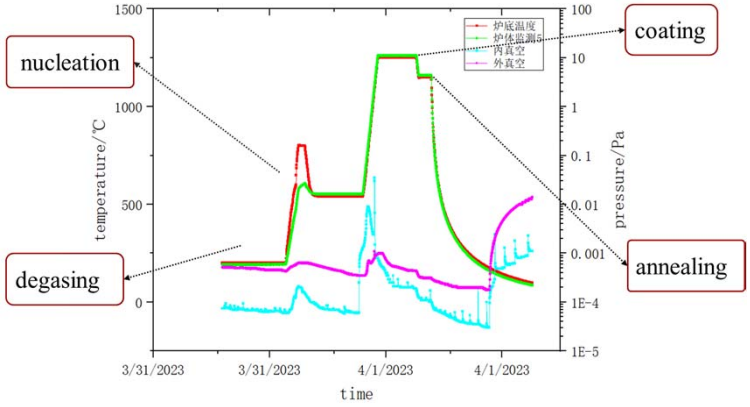
Thickness 1~2μm (TEM)

Coating Procedure

200℃ 48 h degas

Coating process

samples

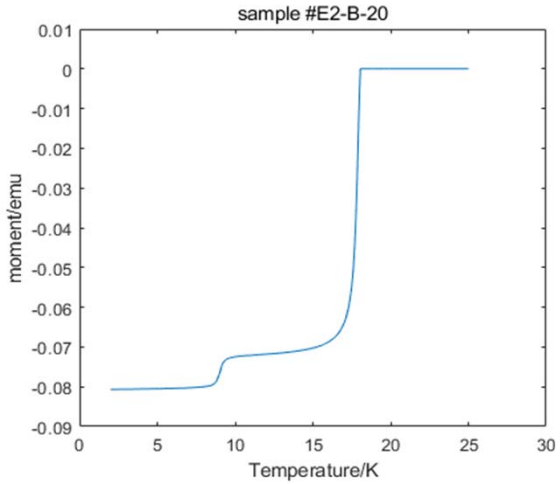


temperature

Test

Sample: SEM, TEM, EDS, XRD

Cavities: vertical test



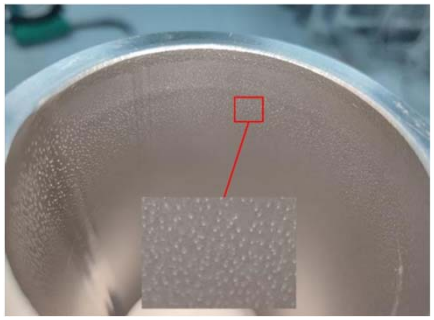
T_c(M-T) =18.08 K

single-tin-source method

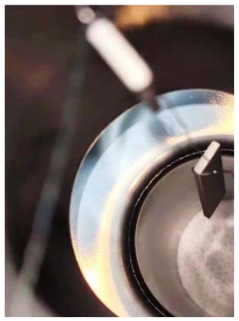
Basic recipe:

- 3 g Sn
- Nucleation: 525℃ 300 min
- Coating:1315℃ 1100 ℃ 90 min
- Annealing: 1150 ℃ 100 min

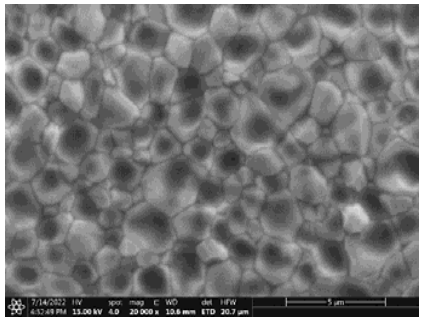
Basic: Sn condensation



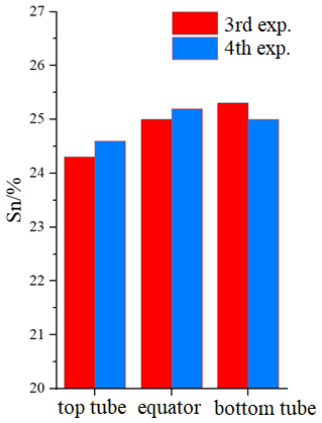
Sn->2.8 g, upper side open



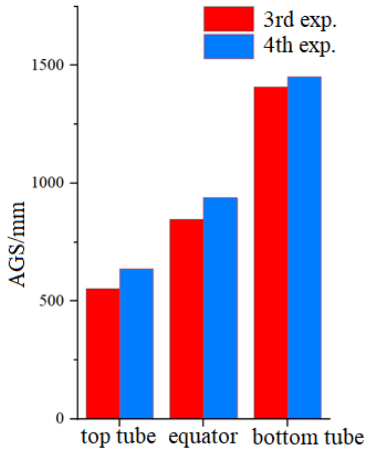
Sn->1.5 g, increase distance of cavity and Sn source



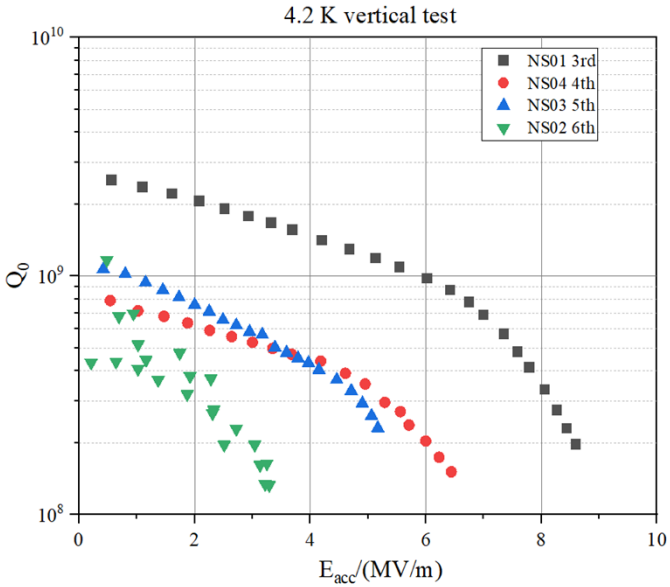
tungsten cover on top (20000×)



Sn content (EDS)



Grain size (SEM)



Veritcal test (4.2 K)

- 0.1-0.2 K/min through T_c
- Q_0~2×10^9 at low field, Q-slope
- Sn/%: 24.1~26.5%
- Nb_3Sn film thickness: 1~2μm
- T_c: ~18.1 K

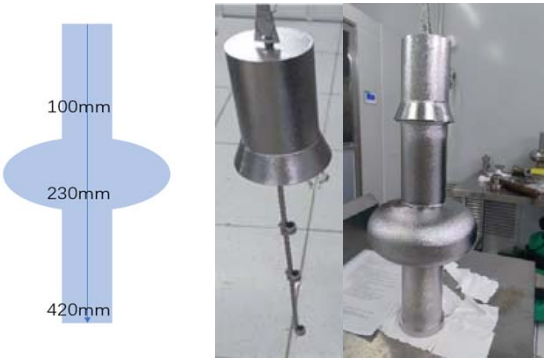
three-tin-source method

Purpose of three-tin-source

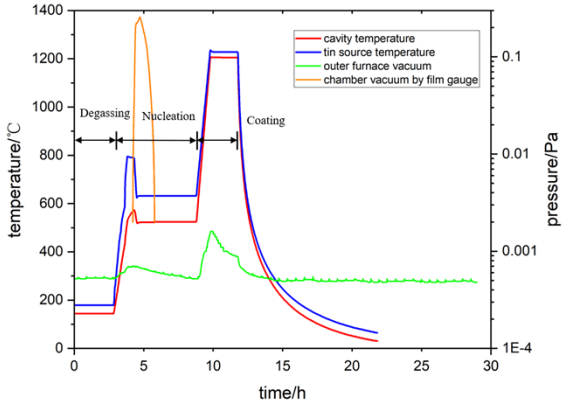
- Improve tin vapor uniformity
- Avoid tin condensation
- Multi-cell cavity coating

Disadvantage

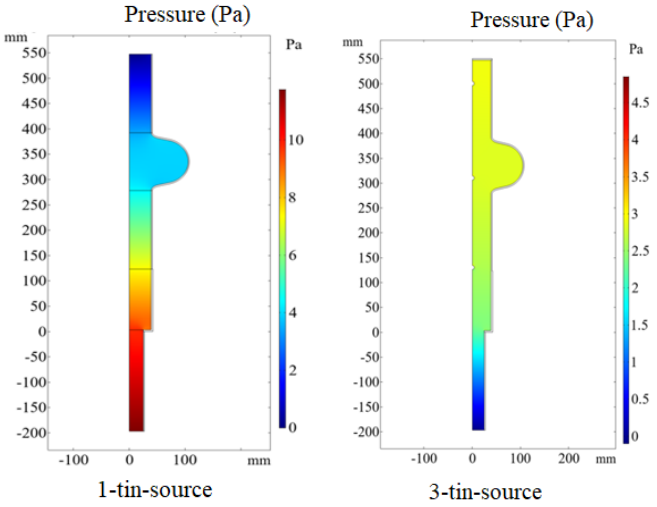
- Temperature of tin sources cannot be controlled separately



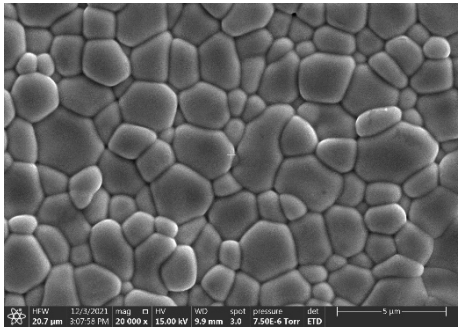
Three-tin-source coating design



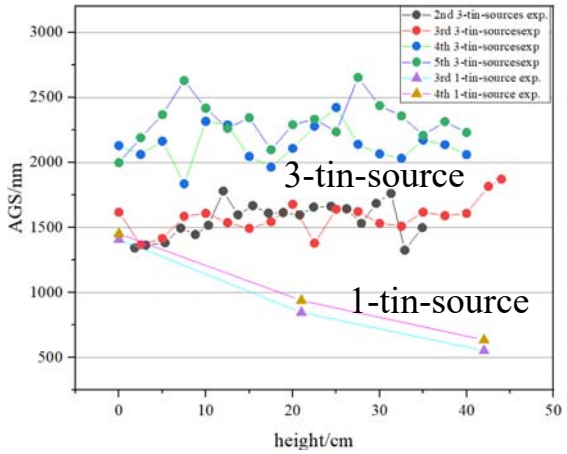
Temperature and vacuum profile



Sn vapor pressure simulation

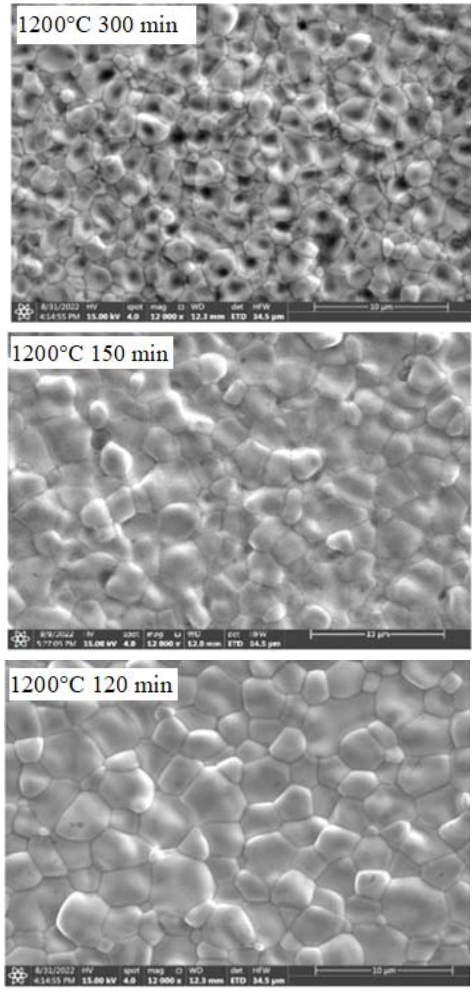


Nb_3Sn grain
Sn%: 24.8%~26.1%

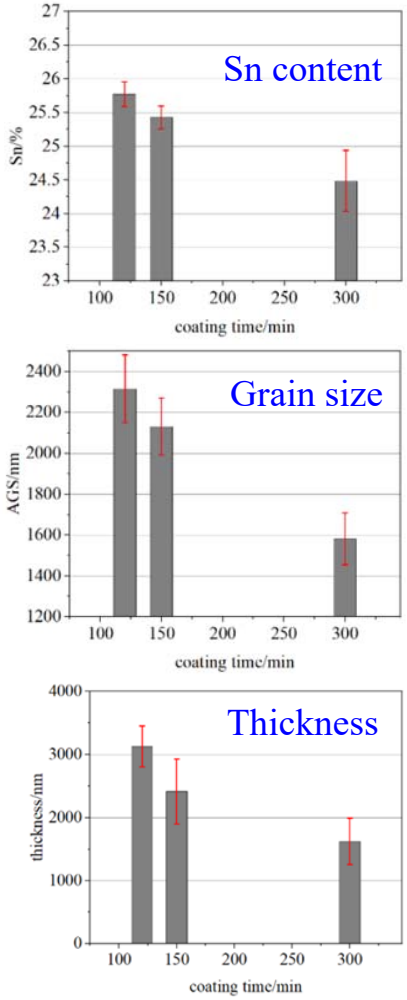


Grain size comparison

Sn loss problem

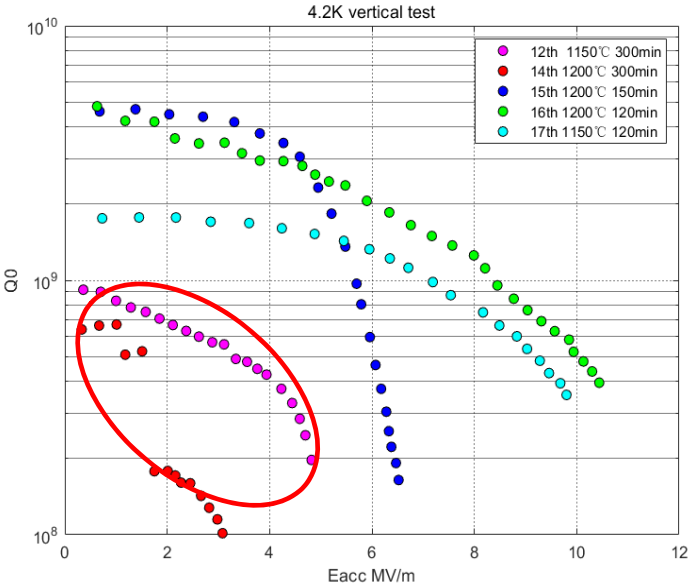


SEM (12000×)



Sn loss

- Pit in the center of grain
- Decrease
  - Grain size
  - Sn content
  - Thickness
- Reason
  - Sn not enough
  - Coating time too long
- Low Q_0 of Nb_3Sn cavity



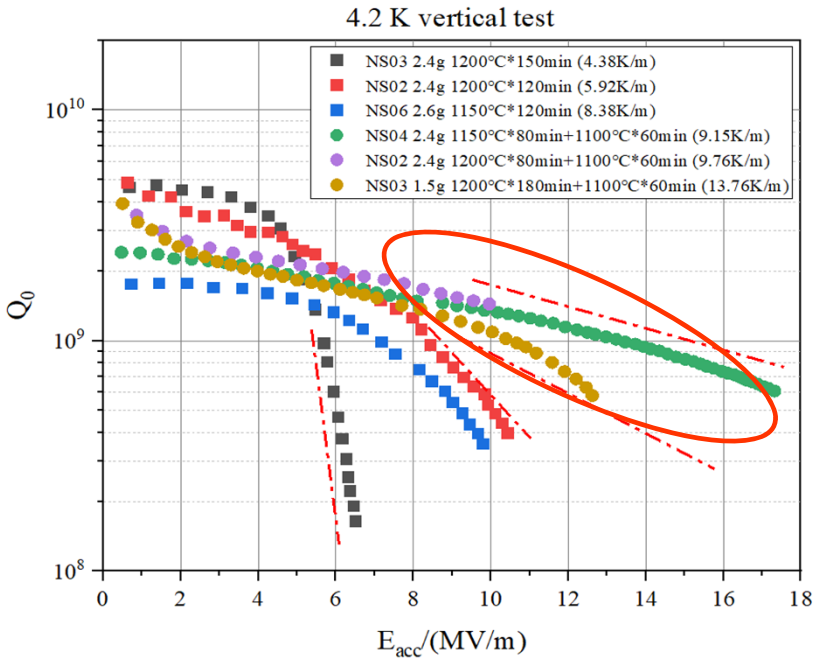
Solution: lower coating time

- $Q_0 \sim 5\times10^9$ at low field
- Obvious Q-slope

Q-slop improvement

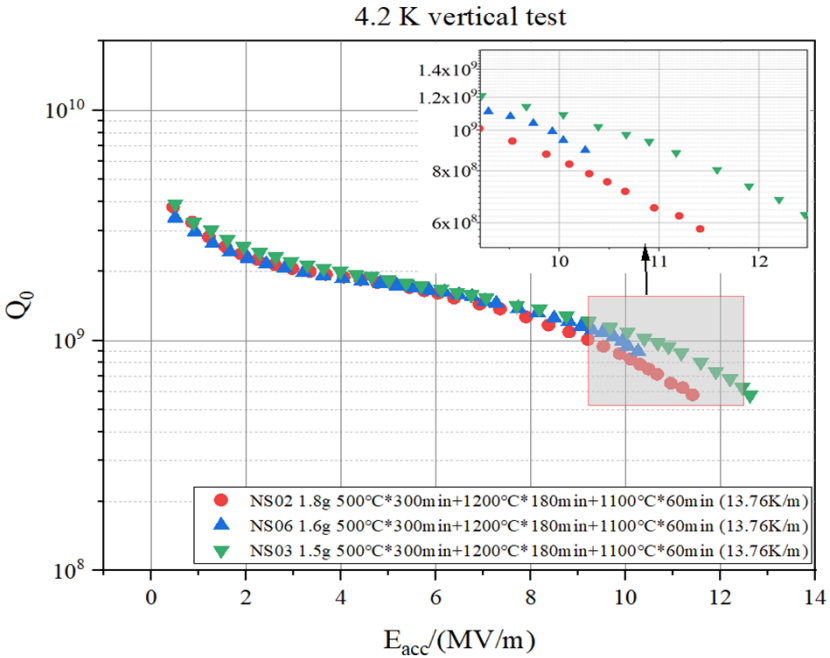
1100℃ 60 min annealing

- Lower the evaporation rate of Sn to match the consumption



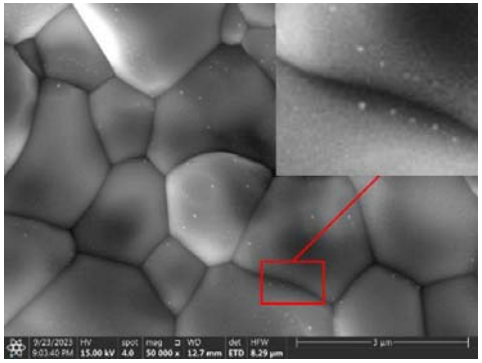
Lower Sn source

	top/g	middle/g	bottom/g	total/g	Sn%	AGS/nm
NS02	0.3	0.6	0.9	1.8	26.3	1591.2
NS06	0.2	0.5	0.9	1.6	26.0	1569.9
NS03	0.2	0.5	0.8	1.5	25.5	1562.3



New problem

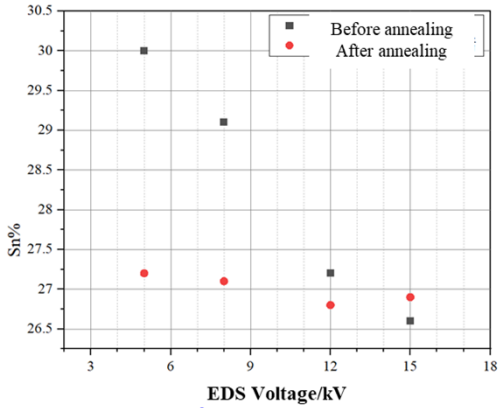
adsorption of small Sn particle



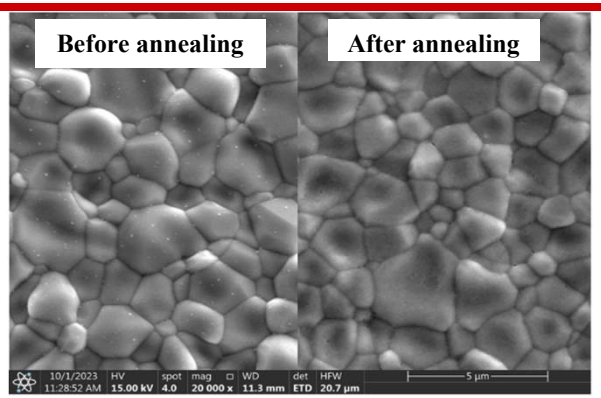
Sn particle elimination

ex-situ annealing

- 950℃ 1 h (after vertical test)
- All ports covered with Nb foil
- Surface Sn% decrease (EDS)



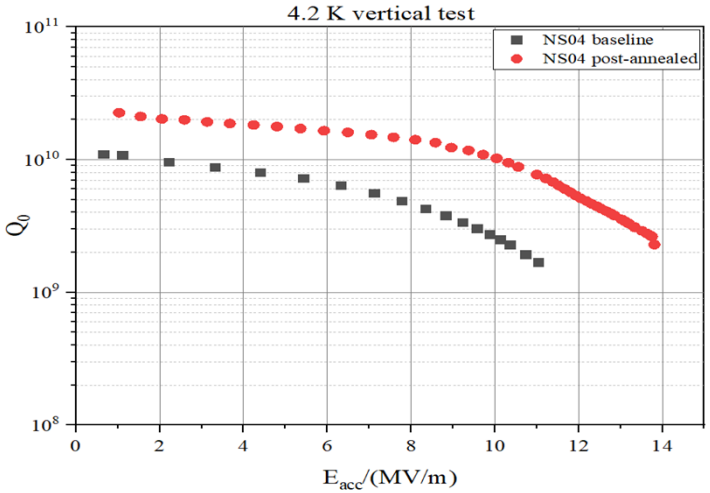
Surface Sn content

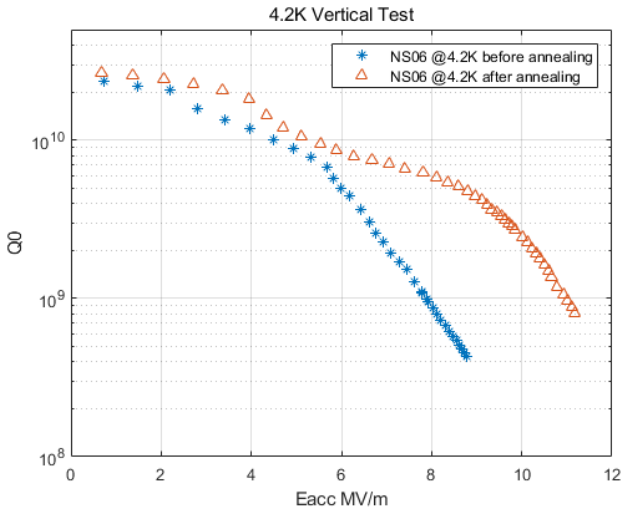


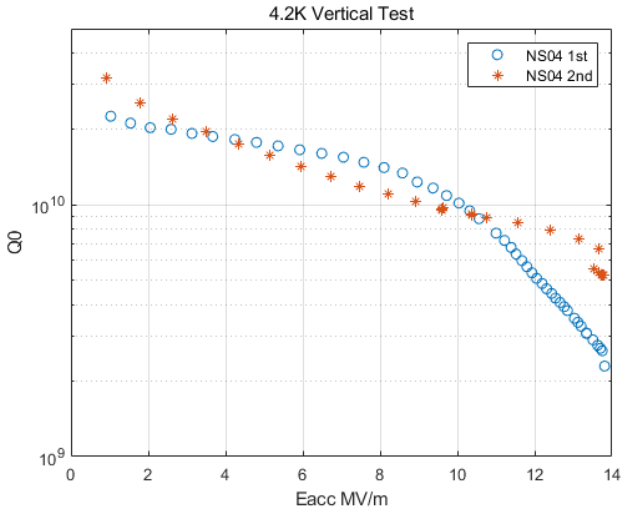
Adsorbed Sn disappeared

After annealing

- Q_0>2.2×10^{10} @ 1 MV/m
- Q_0>1.0×10^{10} @10 MV/m
- Eacc~13.8 MV/m







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  - Annealing study
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Conduction cooling test cryostat

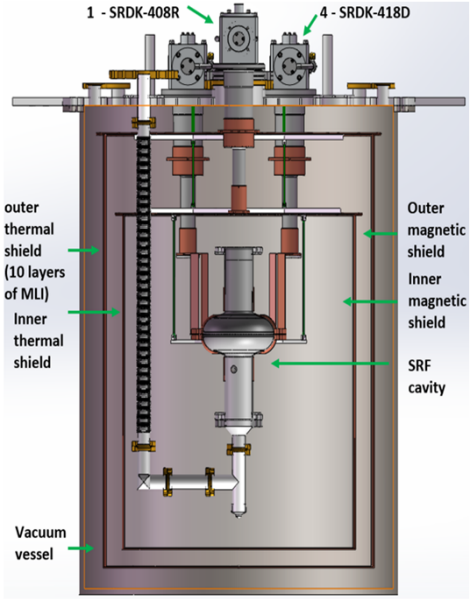
Cryostat design

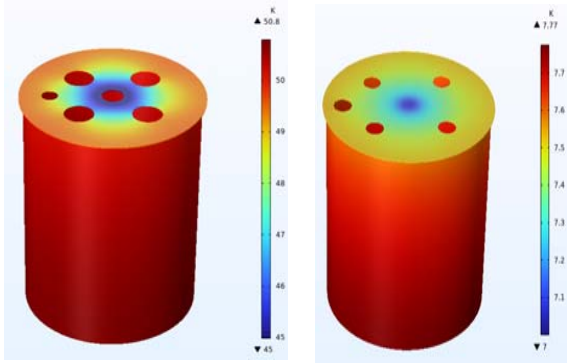
- For 1.3GHz/650MHz 1-cell cavity
- Conduction cooling, helium free
- 5 Sumitomo cryocooler

  4K: SRDK-418D*4 1.8W@4 K

  10K&50K: SRDK-408R 5.4W@10 K
- G-10 connection
- Double magnetic shield
- Double thermal shield

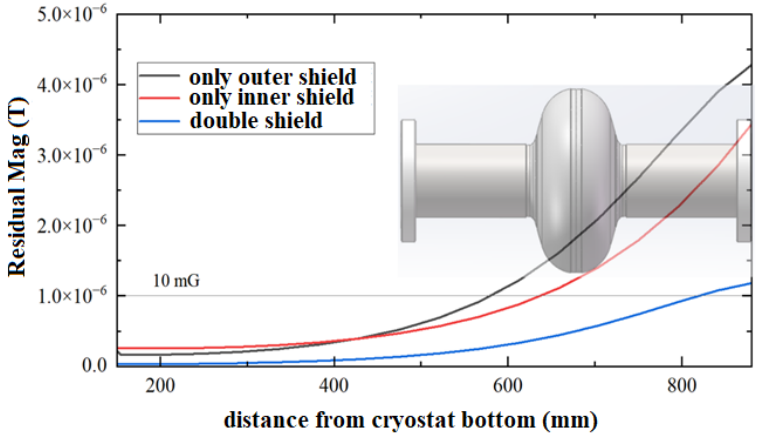
Heat loss	50 K	10 K	4 K
Radiation (W)	42.4	0.39	0.001
Conduction (W)	1.5	0.46	0.056
Total (W)	43.9	0.85	0.057





thermal shield (50 K) thermal shield (10 K)

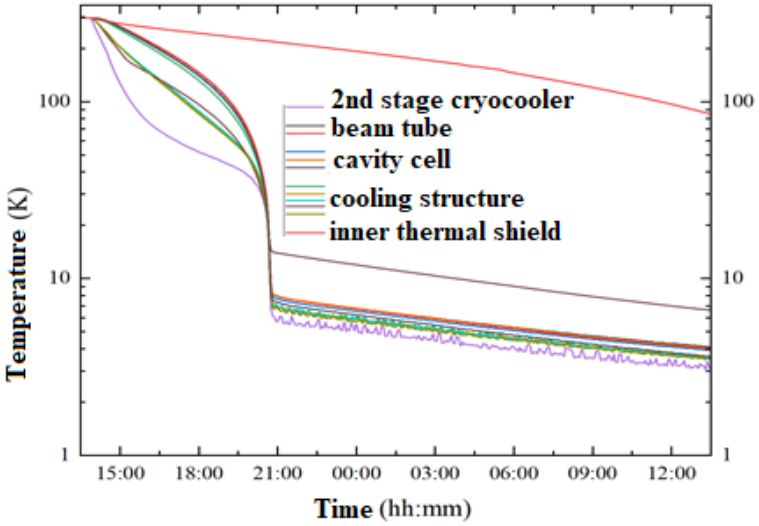
Conduction cooling test cryostat



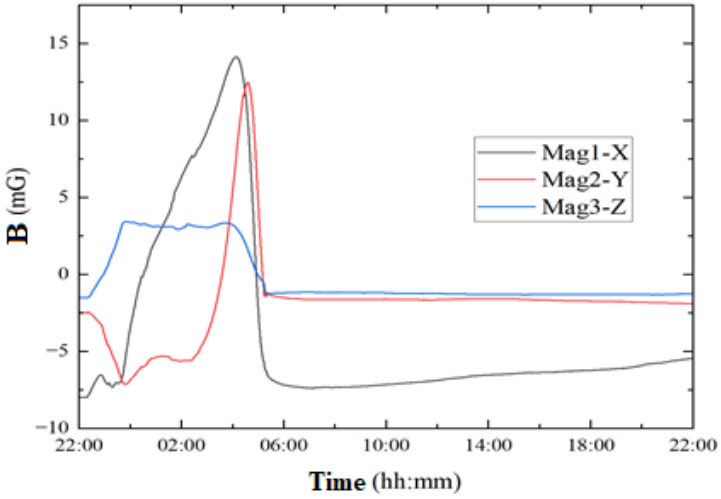
Residual magnet shield simulation

Cryostat cooling down

- Down to 2.5 K within 48 h
- Residual magnetic field
  < 10 mG at cavity area
- Q_0-T measurement of cavities
  2.5~15 K



Temperature during cooling

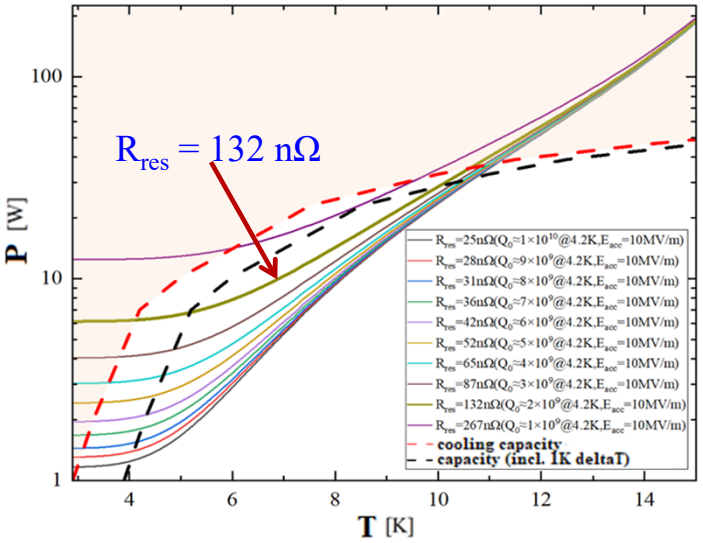


Residual magnet shield during cooling

Conduction cooling of Nb_3Sn cavity

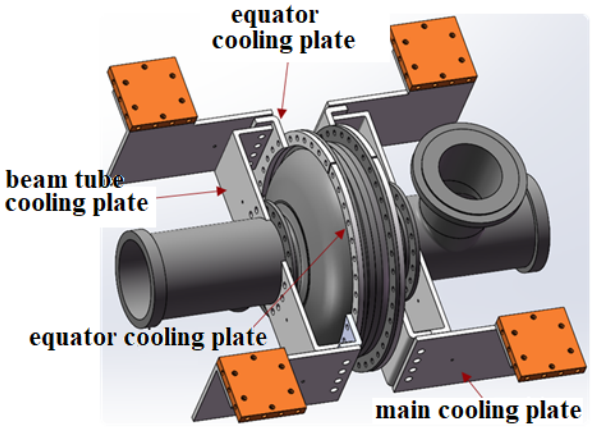
Design goal

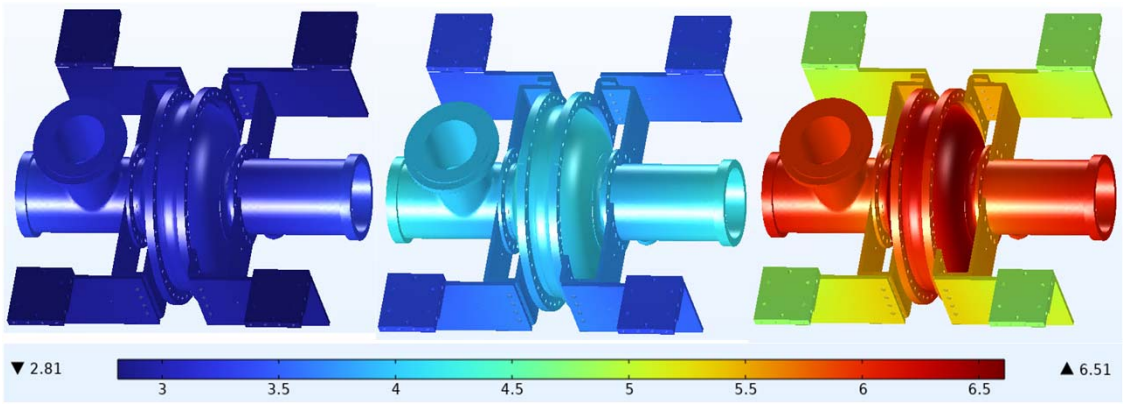
- Operation gradient: 10 MV/m
- Nb_3Sn cavity: $R_{res} < 132n\Omega$
- Operation temperature: 5-10K
- $T_{cavity} < 6.5$ K



Conduction ring structure

- Nb rings: near equator and iris
- High pure Al ring connection to Nb equator ring
- Al plate connection between Nb ring and cryocooler
- Main cooling plate: connection between equator/tube plate and cryocooler



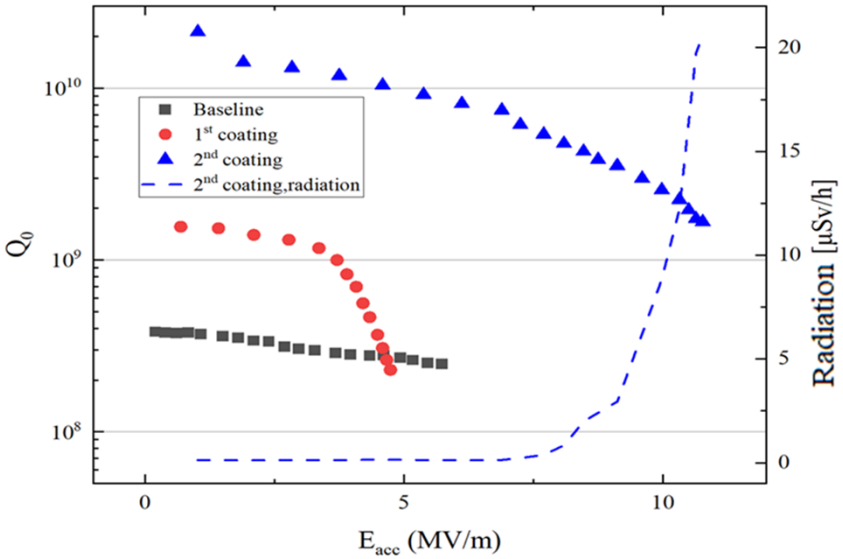


Temperature simulation: 10 MV/m, R_{res} = 25, 65, 132 nΩ

P_{cav}=8.15W (R_{res}=132nΩ), $T_{average}$=6.01K, T_{equaor}=6.14K, T_{max}=6.51 K

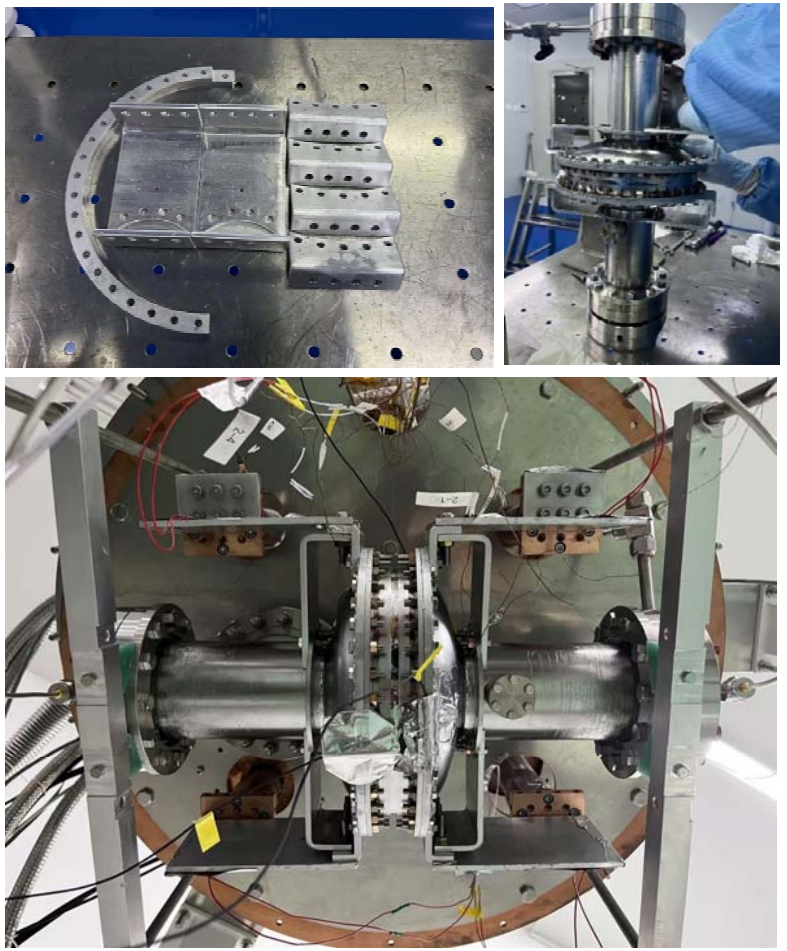
Nb_3Sn cavity with Nb ring

NR01: 1-cell cavity with Nb ring



Vertical test (2^{nd} coating)

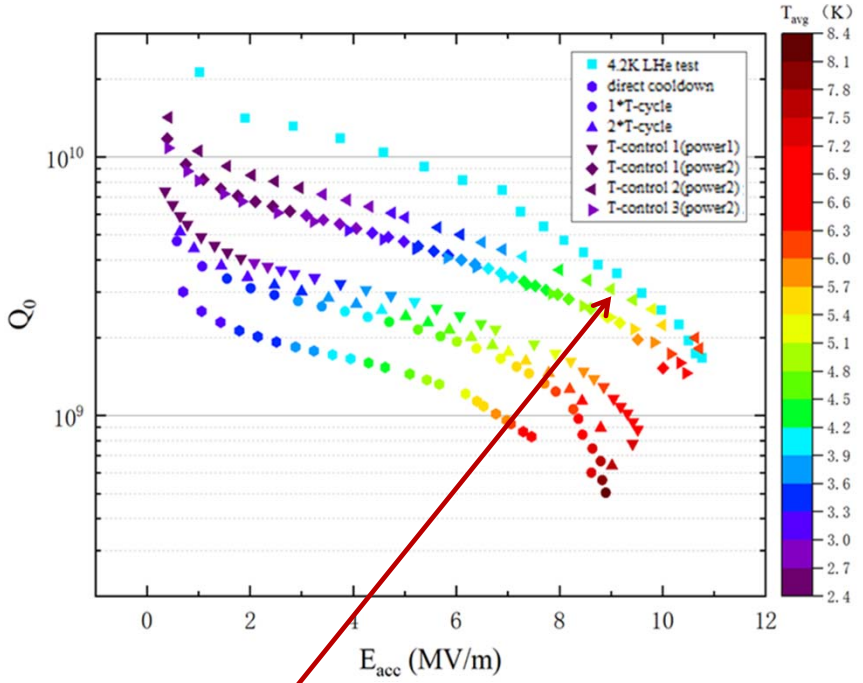
$Q_0 > 1\times10^{10}$ at low field, $Q_0 = 2.5\times10^9$ @ E_{acc}=10 MV/m



NR01: conduction cooling structure

Conduction cooling of Nb_3Sn cavity with Nb ring

NR01 conduction cooling

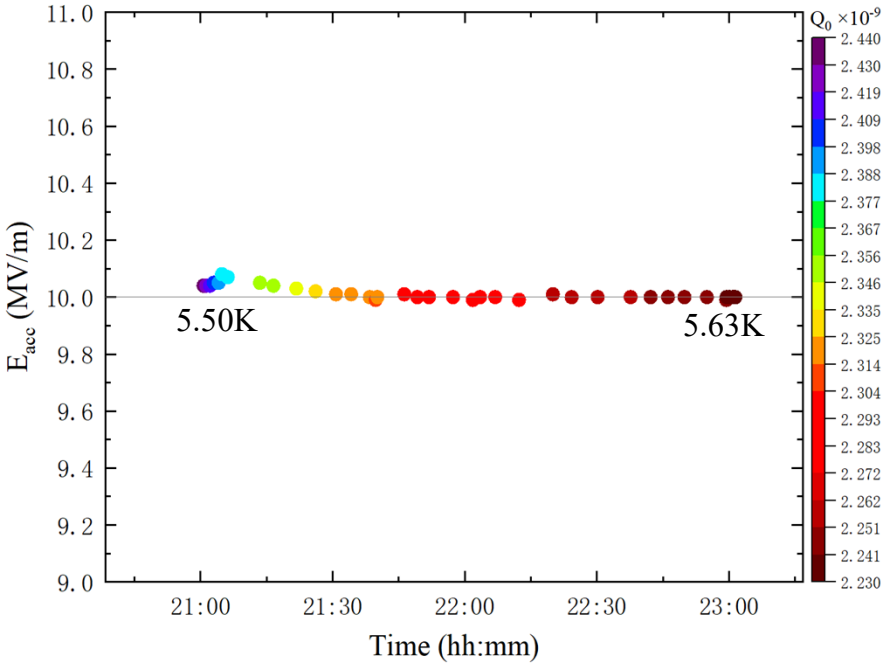


Cooling method: direct cooldown, T-cycle(warmup above T_c and cooldown), temperature control by heater

Best result: T-control (~0.3K/min, ΔT~0.5K@cell)

Q_0 >1×10^{10} at low field, Q_0 = 2.0 ×10^9 @ E_{acc}=10.7 MV/m

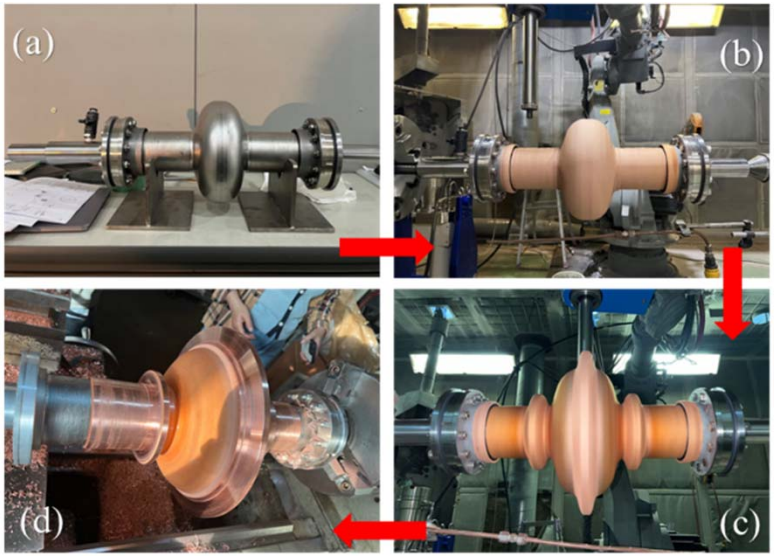
NR01 stability



- E_{acc}=10MV/m, CW running 2 h
- Reflected power~0.4 W, cable~0.2W, cavity temperature increase
- Forward power 5.6W->6.0W, heat loss 5.2W->5.6W
- T(cell) increased by 0.13K, Q_0:2.4 ×10^9 -> 2.2 ×10^9

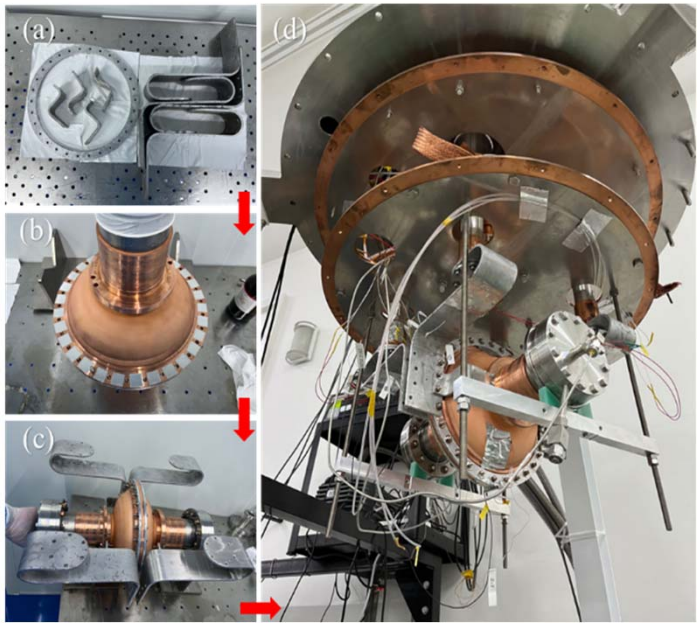
Copper plating by cold-spray

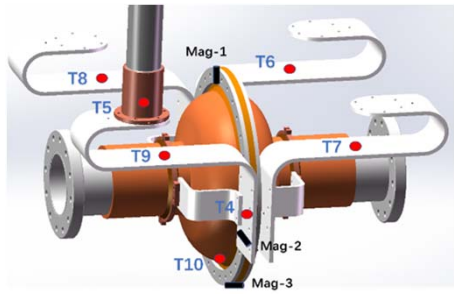
Cu outer layer by cold spray (NS03）

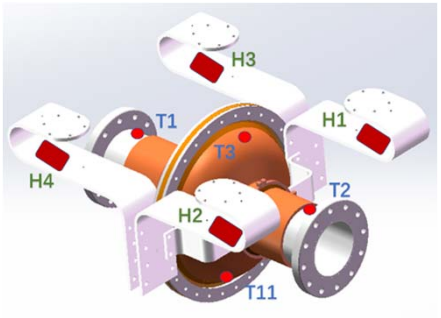


- Cu layer1: 0.3 mm, He as carrier gas
- Cu layer2: 3.2 mm, N_2 as carrier gas
- 3 Cu flanges sprayed: equator and both tubes
- Machining, polishing, and drilling
- T < 100°C by N_2 cooling during spraying process

Installation to cryostat

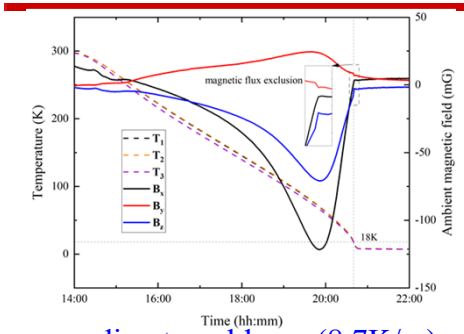




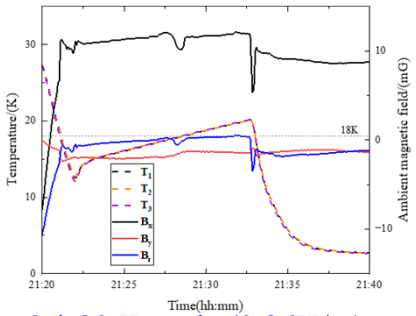


- Al plates connect 2nd stages of cryocoolers to the Cu flanges
- In foils (0.1 mm thick) on the contact surface
- Apiezon N grease between 2nd stages and Al plates
- Temperature sensor, magnet fluxgate, heater

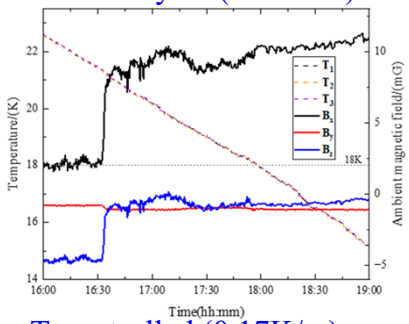
Conduction cooling of Cu-sprayed Nb_3Sn cavity



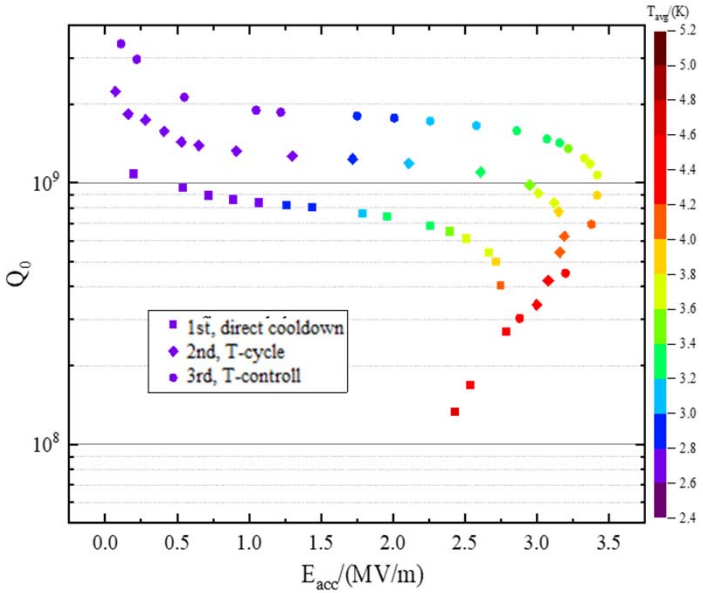
direct cooldown (8.7K/m)



2 * 20 K cycle (0.86K/m)

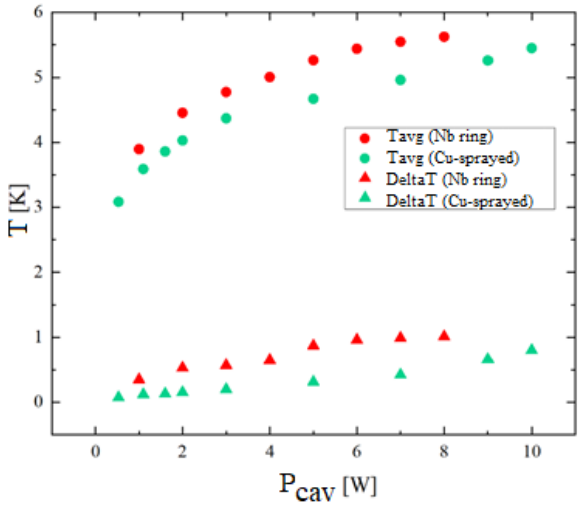


T-controlled (0.17K/m)



Q-E of conductiong cooldown (NS03)

- T-controlled cooling is best
- $Q_0 \sim 3.0 \times 10^9$ at low gradient
- $Q_0 = 1.1 \times 10^9$ @ $E_{acc,max} = 3.4$ MV/m
- $P_c = 1.37$ W, $T_{avg} = 3.86$ K

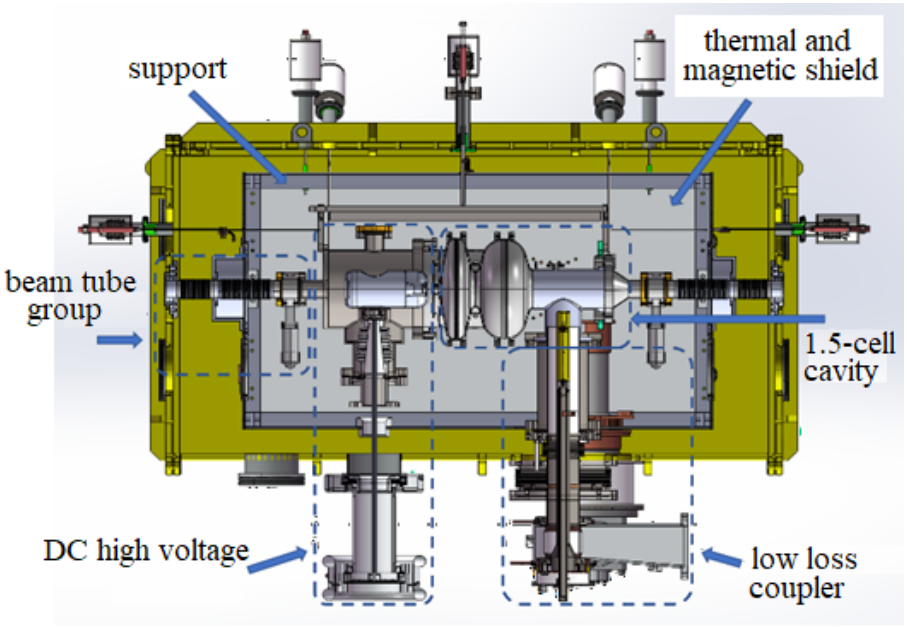


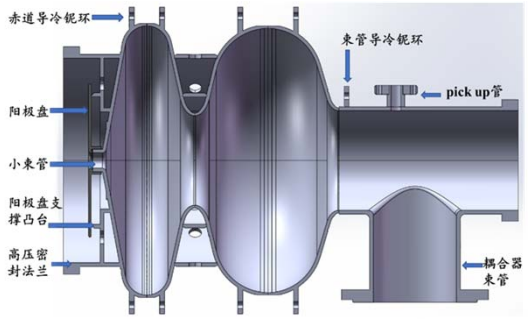
Comparison of Nb ring and Cu-sprayed

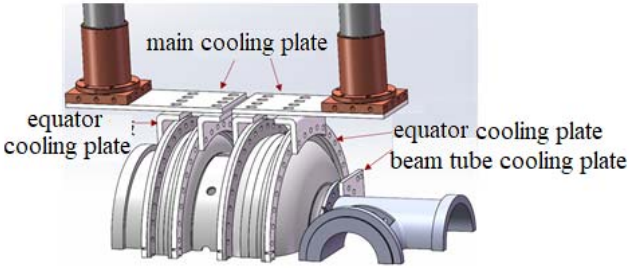
	Cu-sprayed	Nb ring
Stability	4.67K@5W	5.26K@5W
Uniformity	0.3K@5W	0.9K@5W
Freq. shift	$f_0 \pm 8$Hz	$f_0 \pm 13$Hz
T control	<0.1K (cavity)	<0.2 K (cell)

Conduction-cooled DC-SRF electron gun

Conduction-cooled DC-SRF gun







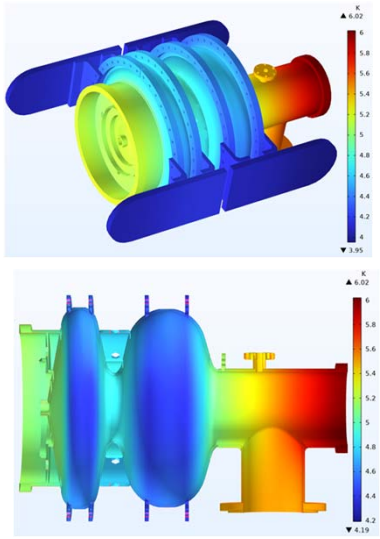
Design goal

- Compact structure with conduction cooling
- Running gradient: 10 MV/m
- Beam current: ~ mA

- Running at 10MV/m with $Q_0 > 4\times 10^9$

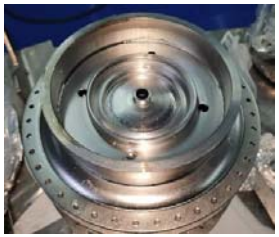
Parameters of 1.5-cell cavity

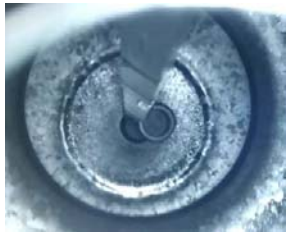
Parameters	Value
frequency	1.3 GHz
R/Q	191.5 Ω
Geometry factor G	212.5 Ω
TTF	0.709
E_0/E_{acc}	1.8
E_{peak}/E_{acc}	2.16
B_{peak}/E_{acc}	5.03 mT/(MV/m)

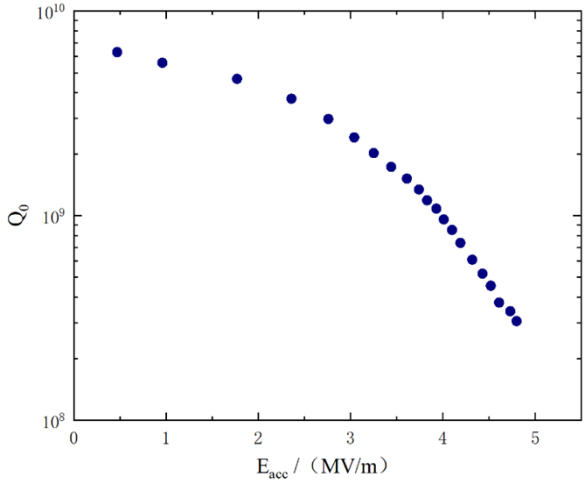


Simulation: 10MV/m, R_{res}=50.1nΩ

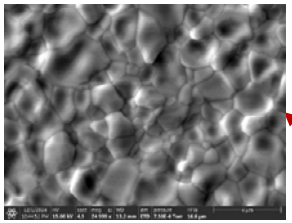
Nb_3Sn film coating of 1.5-cell cavity (NR02)



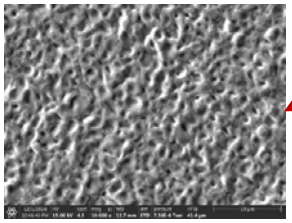




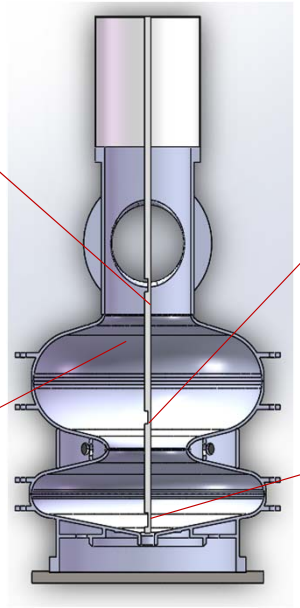
- Q_0~6× 10^9 at 1MV/m

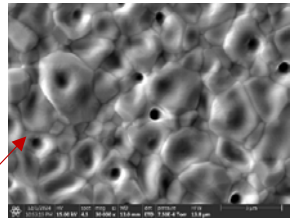


Top Sn%=26.0

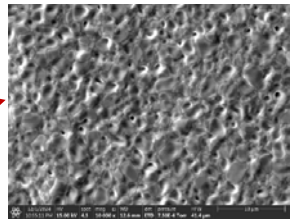


1-cell top Sn%=25.6

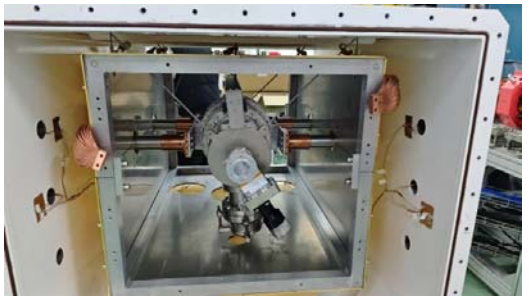




1-cell bottom Sn%=25.9



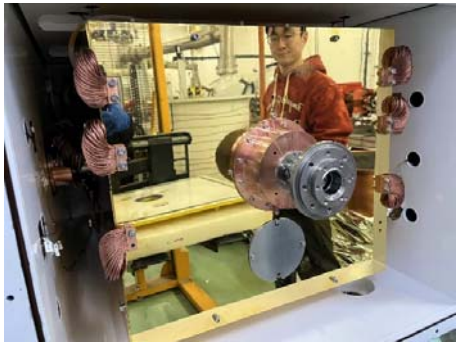
half-cell Sn%=25.7

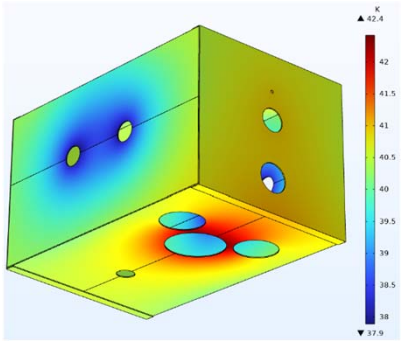


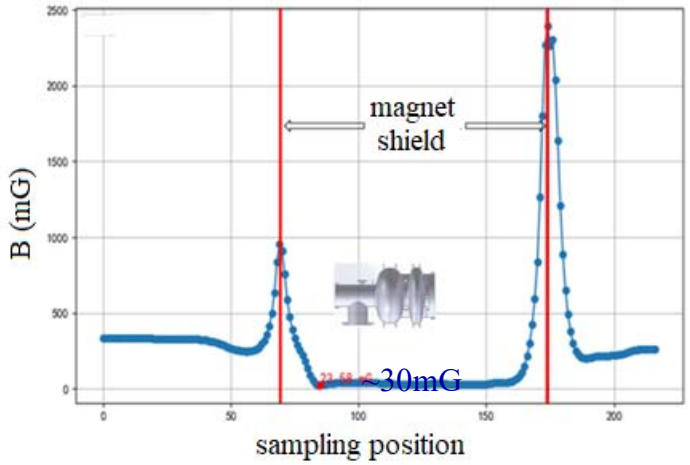
Assemble for cryostat test

Installation of conduction-cooled DC-SRF electron gun

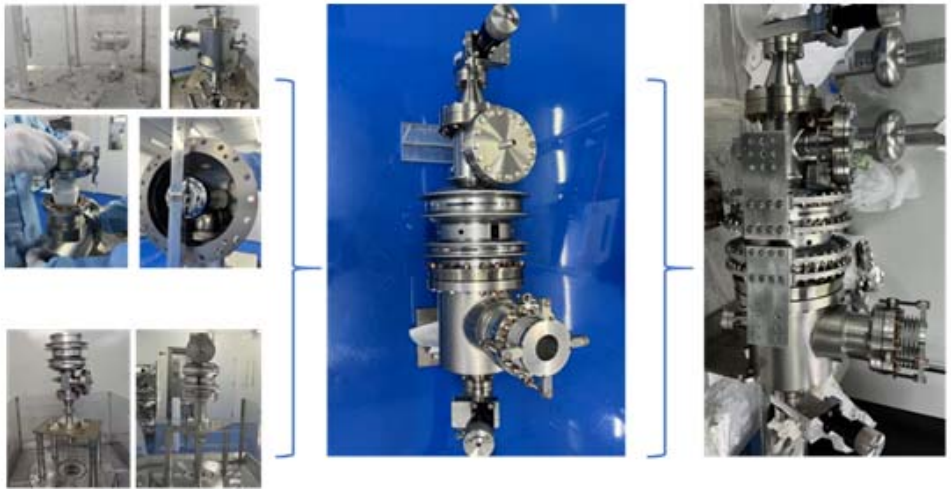
Copper shield plated with Au



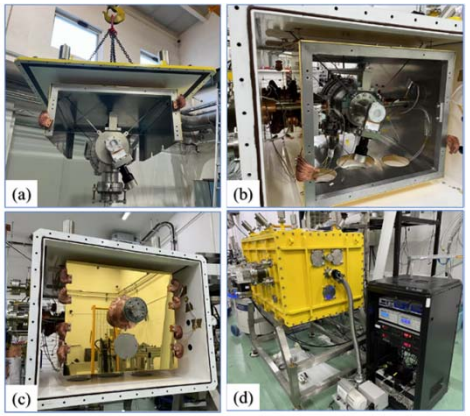




Measured residual mag. field at cavity area: ~30mG



Cleaning and assembling of cavity, HV, conduction cooling structure



Installation of cryostat

Installation of test beamline

Summary and outlook

- Progresses have been made on Nb_3Sn cavities and conduction cooling cryostat
  - ✓ $Q_0>1.0\times10^{10}$ at 10 MV/m is achieved by tin vapor diffusion with 3-tin-source method
  - ✓ Nb_3Sn cavities are successfully cooled down in a conduction cooling cryostat
  - ✓ E_{acc}=10 MV/m is obtained with $Q_0=2.0\times10^9$ by conduction cooling
  - ✓ Copper-spray method is promising for conduction cooling of Nb_3Sn cavities
  - ✓ Conduction cooling based DC-SRF electron gun is manufactured and the preliminary experiments are in progress
- Researches in the future
  - ✓ Gradient improvement of Nb_3Sn cavities
  - ✓ Re-coating of 1.5-cell DC-SRF gun cavity
  - ✓ Further optimization conduction cooling structure of DC-SRF cryostat

Acknowledgements

- Efforts from Peking University SRF group

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- Guangdong Institute of Laser Plasma Accelerator Technology

Thank you for your attention !