Preparation and conduction cooling test of Nb_3Sn SRF cavities at PKU

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(on behalf of SRF group at PKU)

TFSRF2024

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Background

SRF cavity

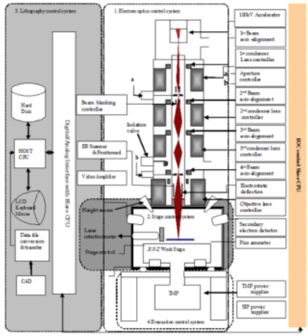
- High Q and low microwave loss
- Ability to work in CW mode
- Large beam aperture with good beam quality

applied in accelerators for high-energy physics, nuclear physics, and free-electron lasers……

Potential applications： Irradiation, processing, imaging



Treatment of industrial wastewater, flue gas, and medical waste through irradiation


Utilizing electron beams for processing, lithography, imaging……

SRF： advantages in cost, efficiency, or beam quality.

SRF accelerator for basic science → **SRF accelerator for society**

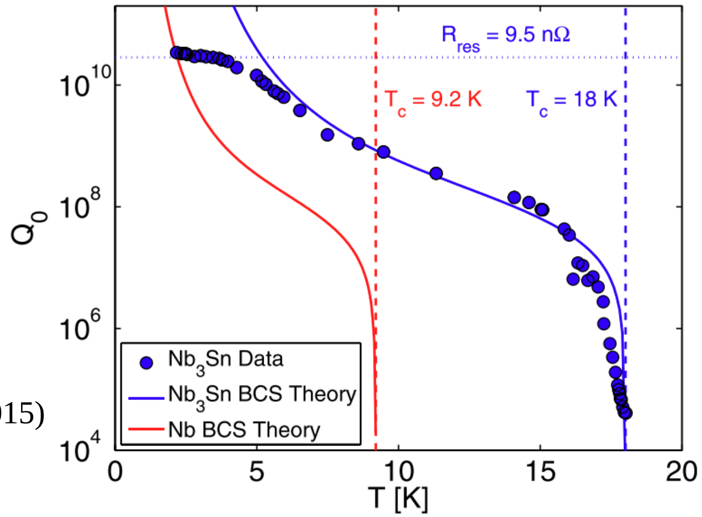
Simplifying SRF cryogenics

Workshop on Energy and Environmental Applications of Accelerators(2015).
Chmielewski, A.G. Electron Accelerators for Environmental Protection. Rev. Accl. Sci. Tech.(2011)

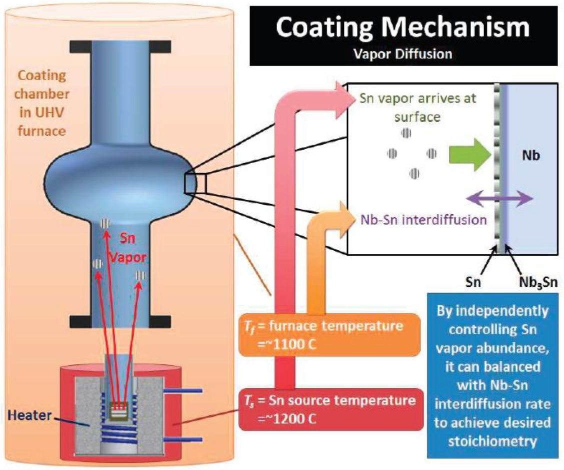
Background

Key technologies: cavity materials with high T_c and high Q_0, Cryocooler Conduction Cooling, Low-loss copuler, Low-cost RF power system, Compact cryomodule......

Nb_3Sn



(S. Posen, 2015)



(S. Posen, 2012)

- 1953 ✓ Matthias Nb_3Sn superconductivity；
- 1970s ✓ Siemens AG、Wuppertal、Cornell、CERN, Q-slope；
- 1980~1990s
- 2009 ✓ Cornell，Optimize the nucleation process；
- 2014 ✓ Cornell：**Q_0 > 10^{10}**@14 MV/m(1.3GHz)；
- 2015 ✓ Jlab, Preliminary experiment；
- 2018 ✓ IMP, Preliminary experiment；
- 2019 ✓ Jlab,'Two cavities coating', Q_0 > 10^{10}@**15** MV/m (1.5GHz)，5-cell Q_0 > 10^{10}@10 MV/m；
- 2020 ✓ Cornell, Fabricated in 2.6 GHz and 3.9 GHz cavities；
- 2021 ✓ KEK, Preliminary experiment；
  ✓ FNAL, 'shiny procedure'，Q_0 > 10^{10}@20 MV/m, **22.5 MV/m** (1.3GHz)，9-cell Q_0 > 10^{10}@10 MV/m
- 2022 ✓ PKU、IHEP, Preliminary experiment；
- 2023 ✓ IMP, 'Hanging ceramic pieces and temperature control'：Q_0 > 10^{10} @12MV/m (1.3GHz)；
- 2024 ✓ **PKU**: 'Three-tin-source', Q_0 > 10^{10} @10MV/m (1.3GHz);
  IHEP: Q_0 > 10^{10} @10MV/m (1.3GHz)
  SARI, Preliminary experiment

Key technologies: cavity materials with high T_c and high Q_0, Cryocooler Conduction Cooling, Low-loss copuler, Low-cost RF power system, Compact cryomodule......

Conduction cooling

high thermal conductivity: 5N Al, OFHC...

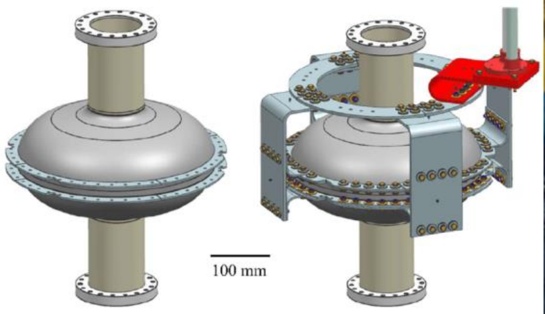
avoid vibration transmission: flexible links

reduce heat leakage: thermal insulation design

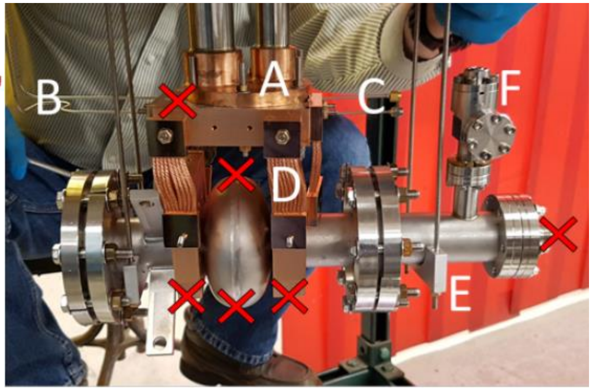
cryocoolers with high capacity: GM-JT, PT450...

……

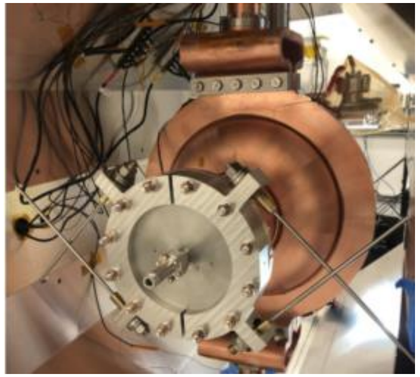
institution	cavity	E_{max}	$Q_0@E_{max}$	connection
FNAL	650MHz,1-cell	10	2e10	Nb rings, 5N Al plates
Cornell	2.6GHz,1-cell	10.3	4e9	Cu clamps and straps
Jlab	952.6MHz,1-cell	**12.4**	2e9	Cu plating, Cu links
IMP	1.3GHz,1-cell	6.6	4e9	Cu clamps and straps
KEK	1.3GHz,1-cell	6	1e9	Cu rings and bars



FNAL,2020

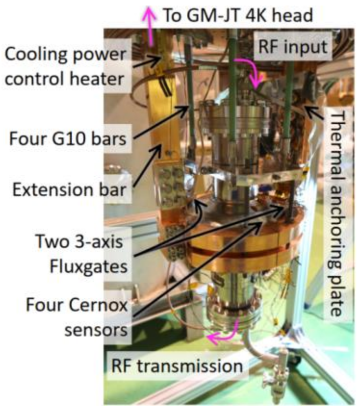


Cornell,2020



Jlab,2023

IMP,2023

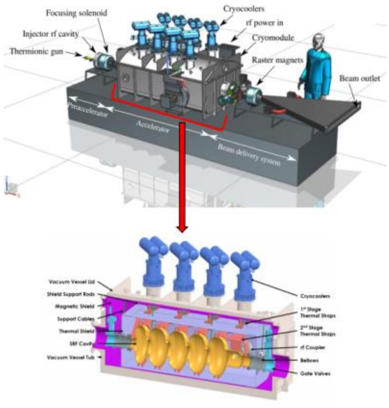


KEK,2023

PEKING UNIVERSITY

Compact accelerator design

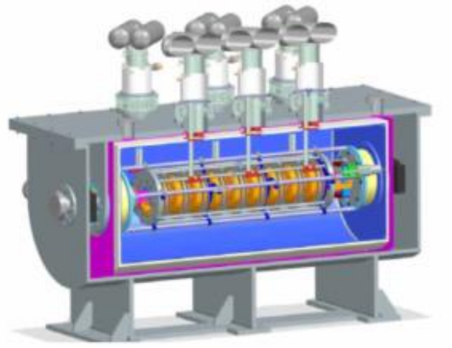
1MW



wastewater treatment

(FNAL, R. C. Dhuley, 2022)

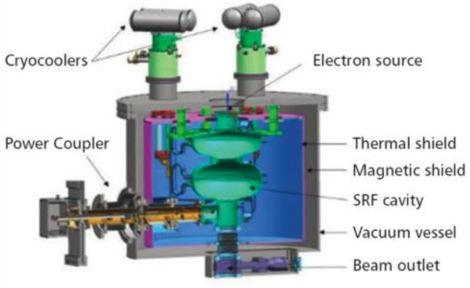
200kW



asphalt pavement renovation

(FNAL, J. Thangaraj, 2023)

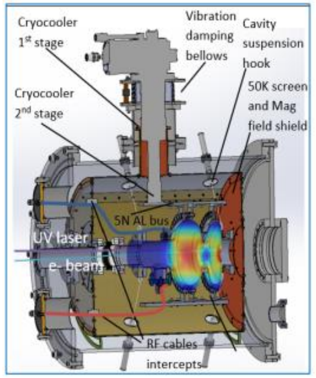
20kW



additive manufacturing

(FNAL, T. Kroc, 2022)

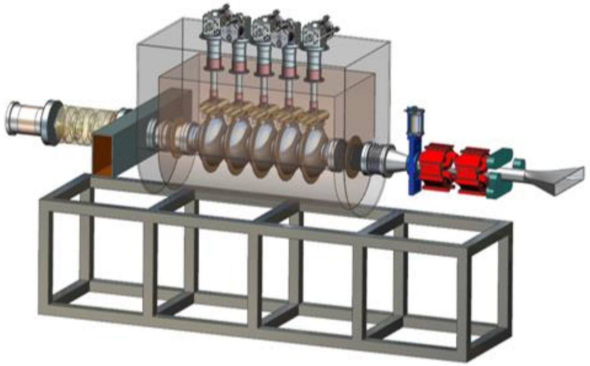
RF cable



UED/UEM

(Euclid Beamlabs, R. Kostin, 2021)

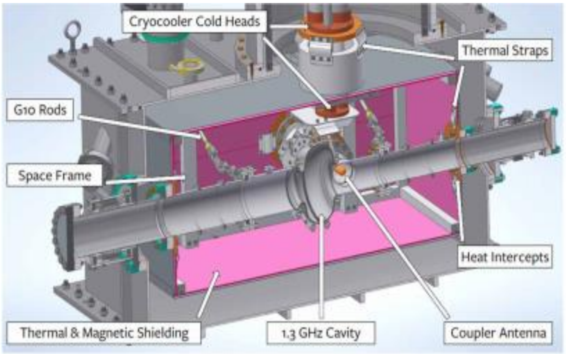
1MW



wastewater treatment

(Jlab, J. Vennekate , 2024)

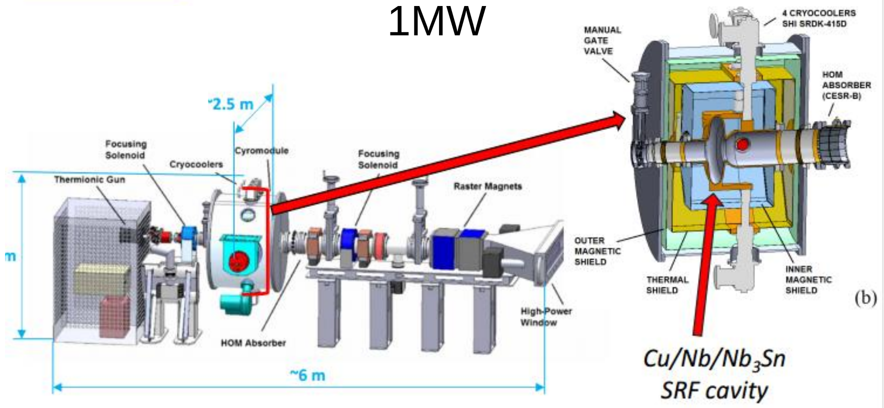
100kW



module prototype

(Cornell, N. A. Stilin, 2023)

1MW



wastewater treatment

(Jlab, G. Ciovati, 2018)

5kW

Accelerator prototype-**beam-loaded operation**

(IMP, Z. Yang, 2024)

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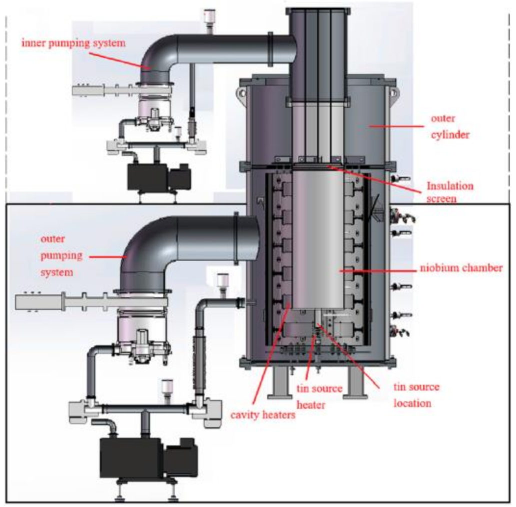
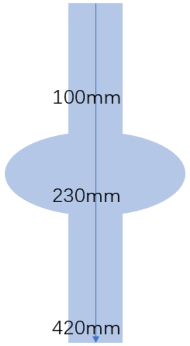
Nb_3Sn preparation

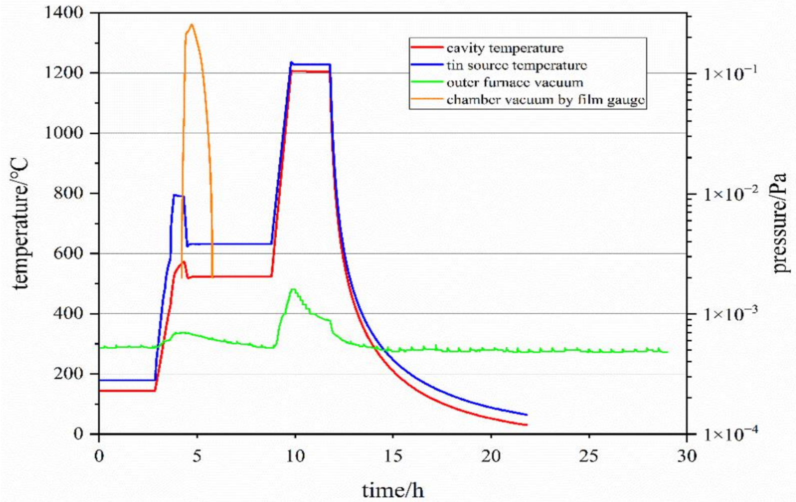
The furnace for Nb_3Sn coating at PKU



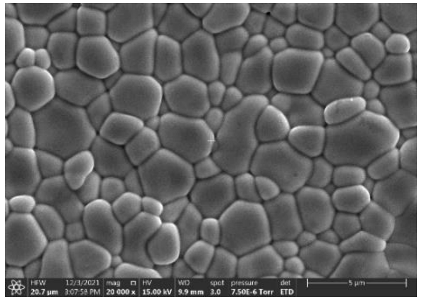


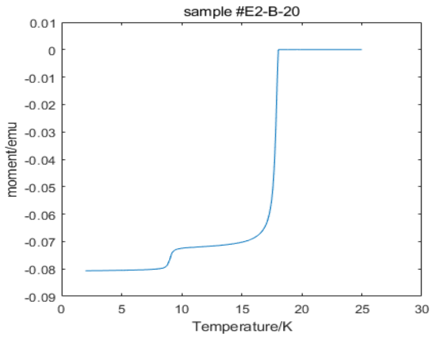
Advantages of three-tin-source:

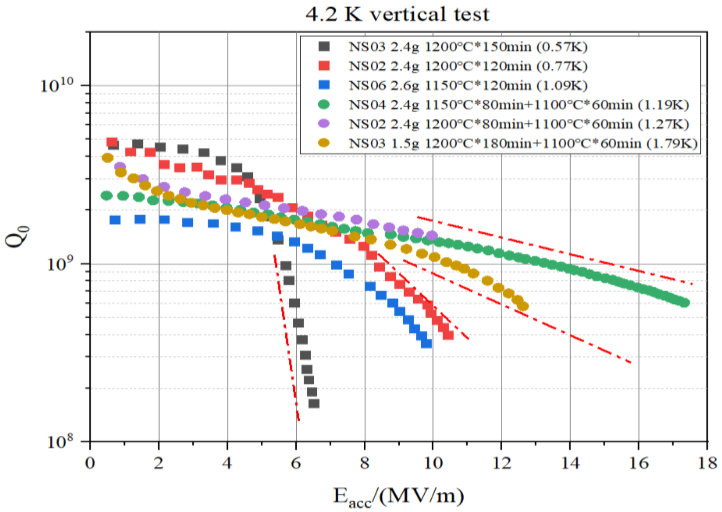
- ✓ Improve the uniformity of tin vapor
- ✓ Reduce the risk of tin condensation
- ✓ multi-cell cavities coating



Temperature profile







Nb_3Sn grain

Sn%: 24.8%~26.1%

Tc(M-T) =18.08K

E_{acc}=17MV/m

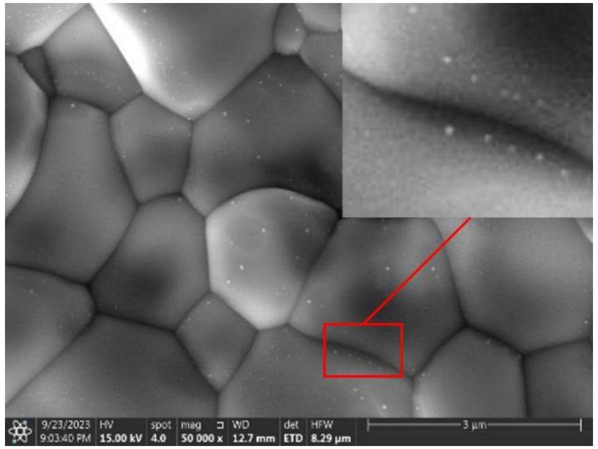
Nb_3Sn preparation

Tin particles attached to the film：

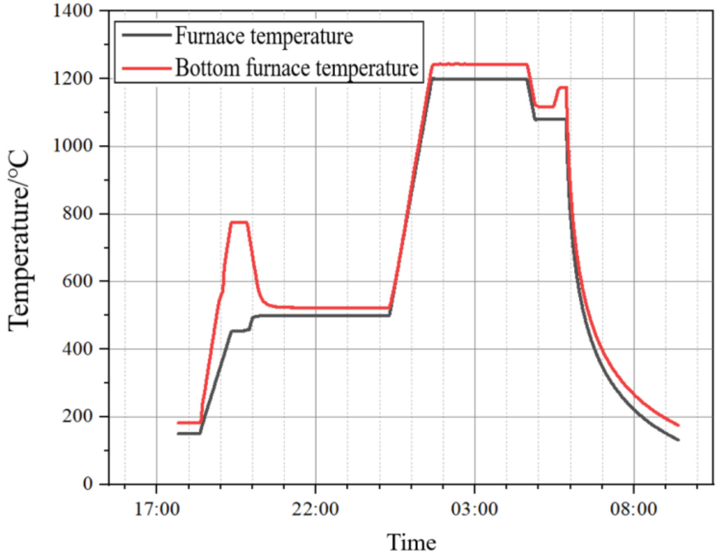
The furnace evaporation boat area is heated during annealing.

The temperature difference from the bottom to the top of the cavity is 75 °C. The annealing time of is 30 mins.

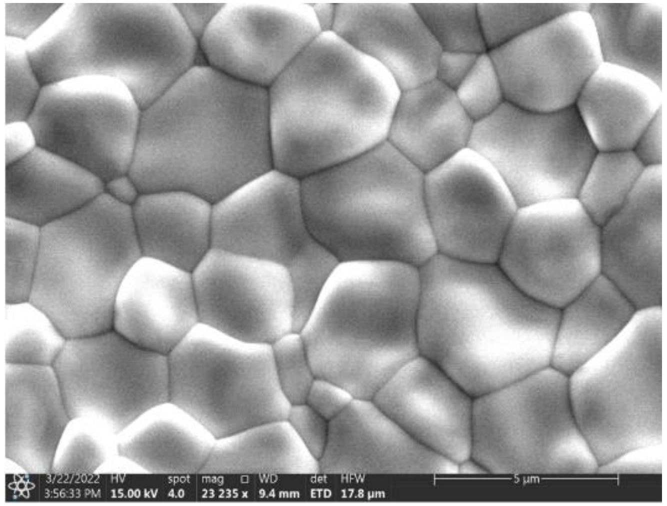
Annealing to deposit excess tin vapor onto the top cover.



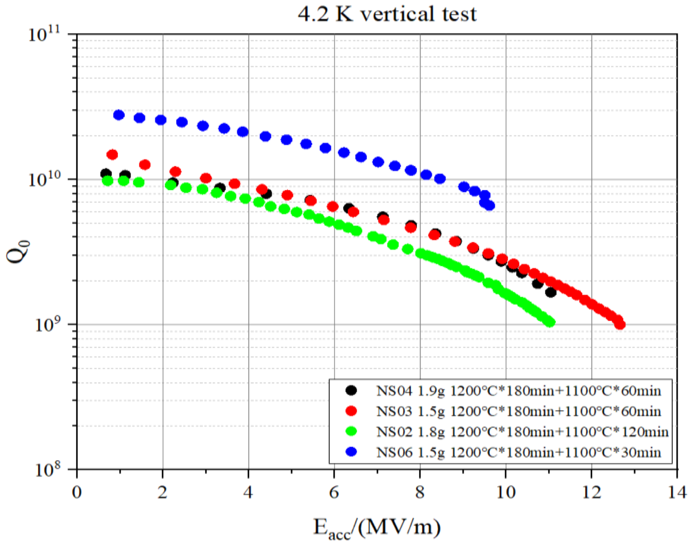
Tin particles attached



Temperature profile with temperature gradient



Nb_3Sn grain



Q-E curve comparison

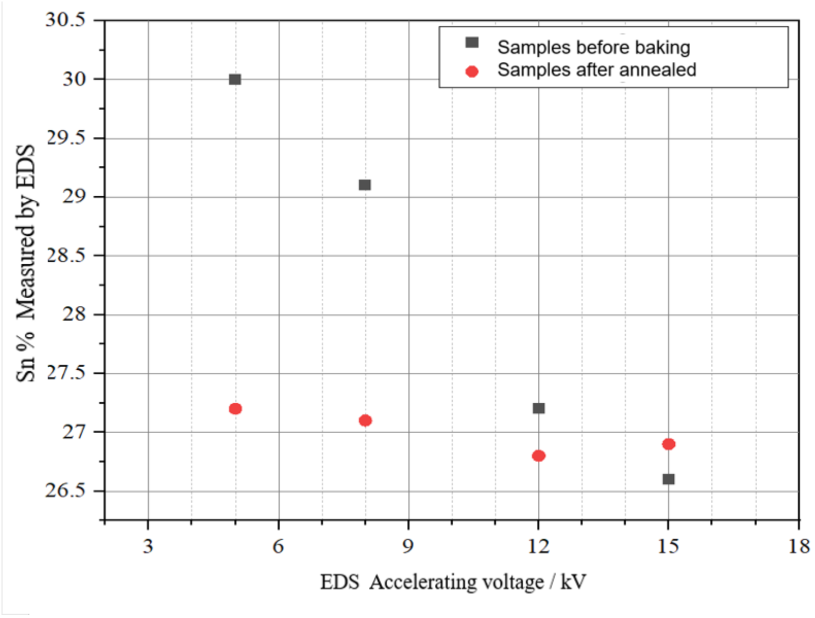
Q_0: 2.78×10^{10}@0.97 MV/m

Nb_3Sn preparation

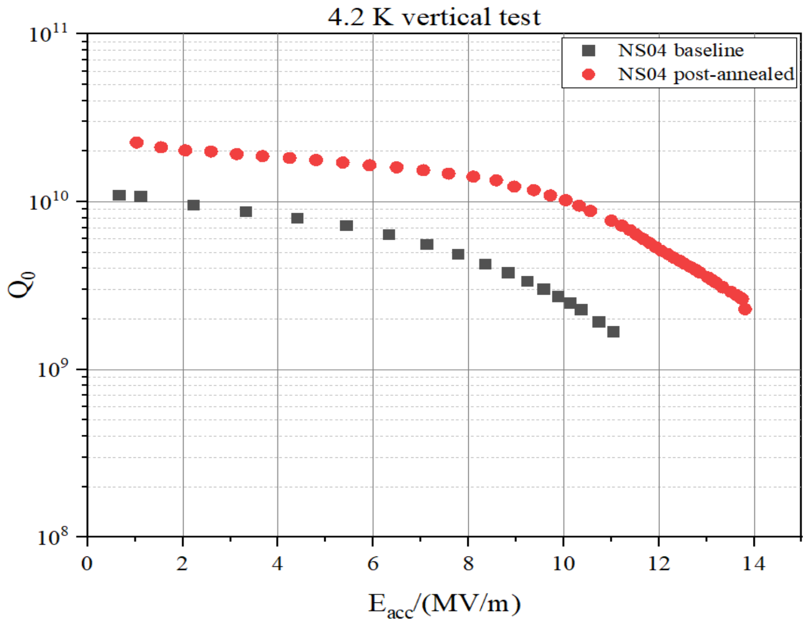
The Sn% is not evenly distributed within the film:

① Post-annealed (ex situ)： 950℃ 1 h;

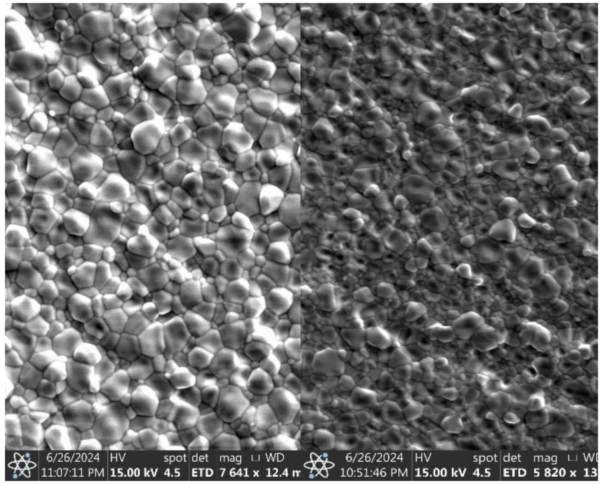
② After the post-annealed, the Sn% decrease in the surface (EDS);



Sn% varies with the acceleration voltage



Q-E curve after Post-annealed



Before and after post-annealed

Q_0: 2.25×10^{10}@ 1MV/m

Q_0 > 10^{10}@ 10MV/m

Quench field: 13.8 MV/m

CONTENTS

Conduction cooling test

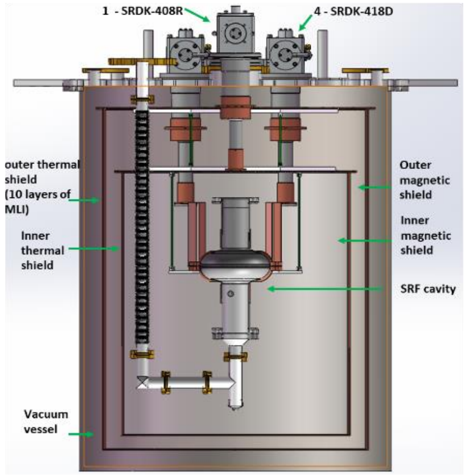
Liquid helium bath —— Conduction cooling

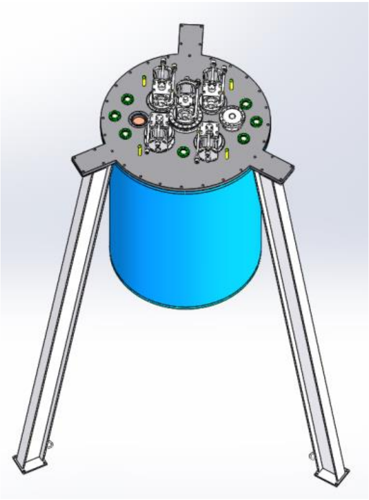
- allocating limited cooling capacity to the superconducting cavity

  ——proper cavity treatment and thermal connection

- reducing heat leakage in the cavity temperature region

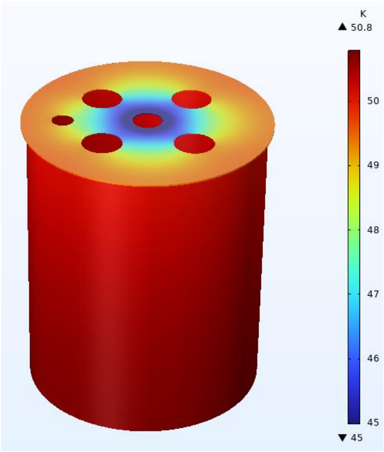
  ——appropriate low heat leakage design



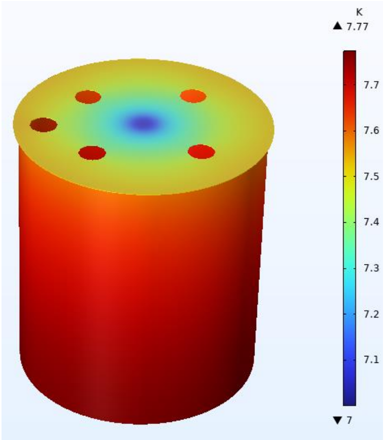


✓ A helium-free cryostat has been developed for studying conduction cooling technology.

✓ For RF testing of 1.3 GHz and 650 MHz single-cell cavities.



thermal shield - 50 K



thermal shield - 10 K

Simulation temperature distribution of the two shields

Equipped with a double-layer thermal and magnetic shielding

Cryogenic source：

4 K： Sumitomo SRDK-418D*4 1.8 W@4 K

10 K & 50 K ： Sumitomo SRDK-408R*1 5.4 W@10 K

Heat leakage is less than 0.02 W at 4 K. (simulation)

Residual ambient magnetic field is below 5 mG at low temperatures

Conduction cooling test

Installation process of the cryostat：

Test equipment and components:

thermometers： 13 * DT-670-CU， Lakeshore

fluxgates： 3*Probe F， Bartington

heaters： 4*polyimide film heater

RF cables: 2*semi-rigid cable， HUBER+SUHNER

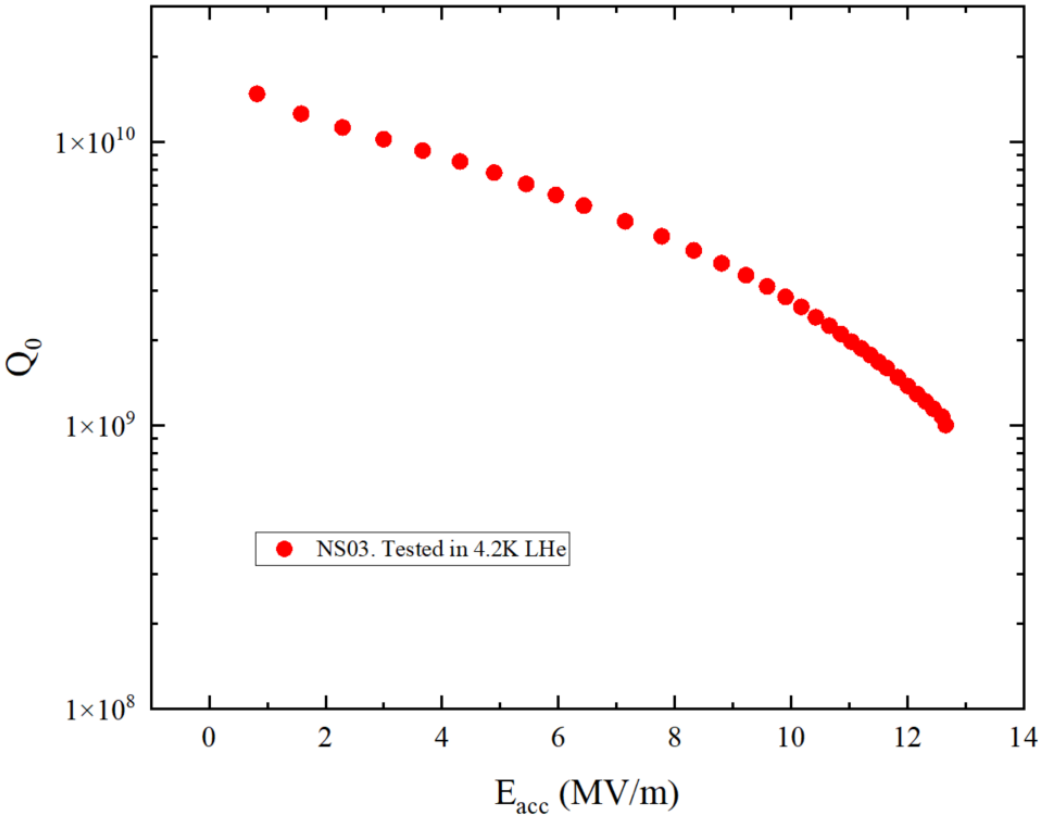
microwave testing and signal acquisition： vertical test system at PKU

the actual testing process

Conduction cooling test

A Nb_3Sn cavity was selected for conduction cooling test

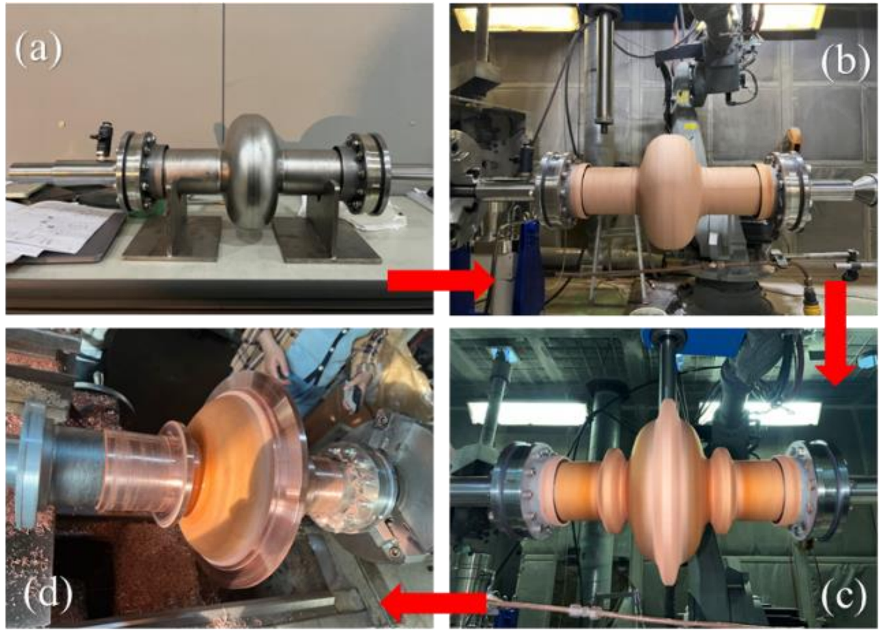
Test result at 4.2 K in liquid helium



$$Q_0 > 1 \times 10^{10} \text{ @ low gradient}$$

$$Q_0 \approx 2.5 \times 10^9 \text{ @} E_{acc} = 10 \text{ MV/m}$$

Preparation of a Cu outer layer using cold spray technology

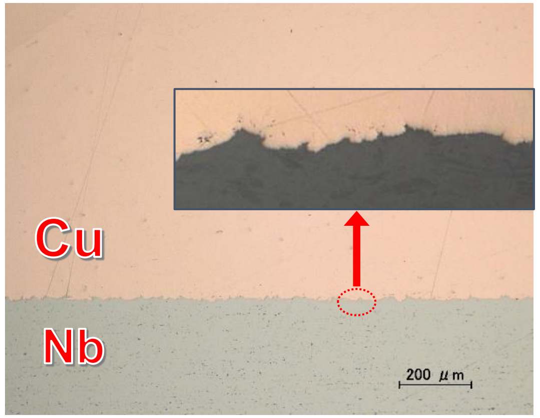


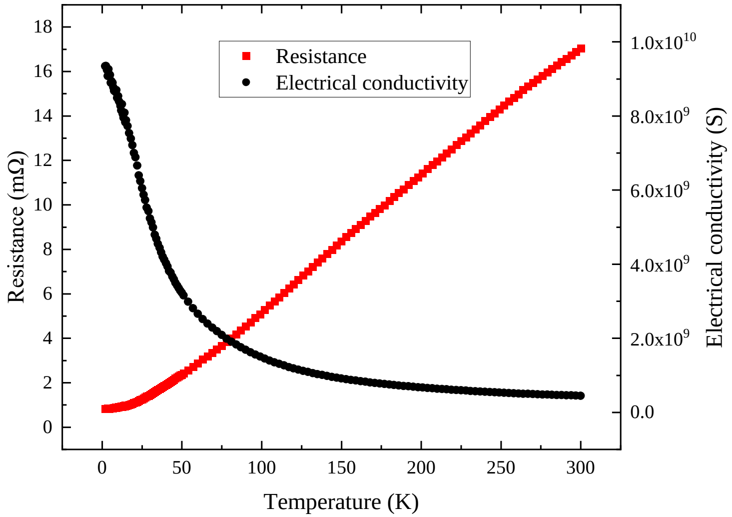
- ✓ Cu layer 1: 0.3 mm thick, He as the carrier gas.
- ✓ Cu layer 2: 3.2 mm thick, N_2 as the carrier gas.
- ✓ 3 Cu flanges were sprayed at the equator and both beam tubes.
- ✓ Machining, polishing, and drilling

N_2 cooling was applied during spraying process keeping the cavity temperature below 100°C.

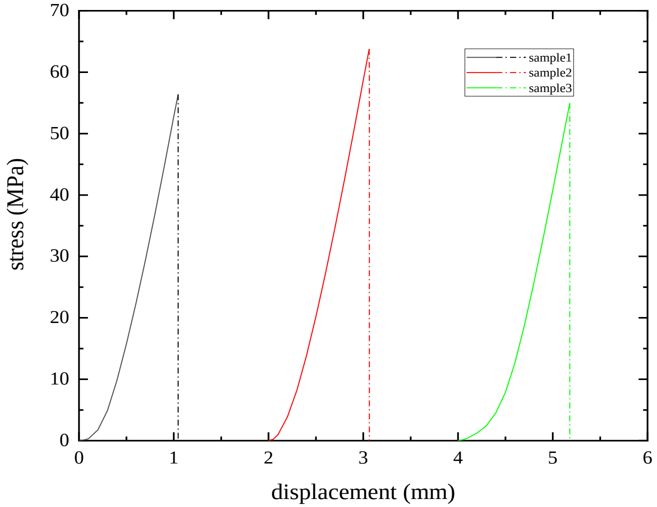
Conduction cooling test

Performance of Cu samples from nitrogen gas cold spraying.



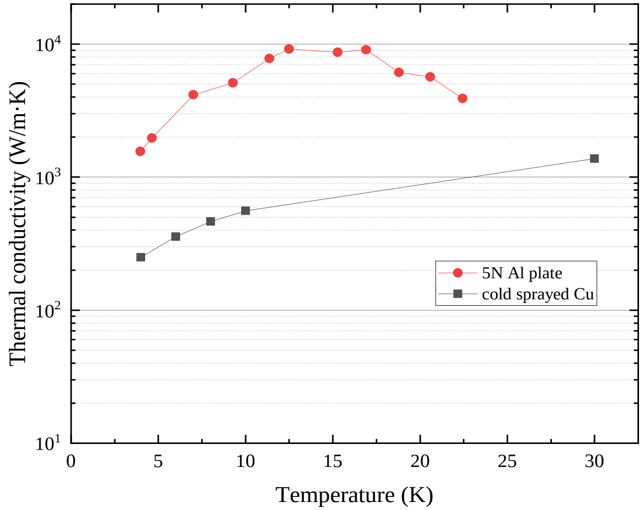


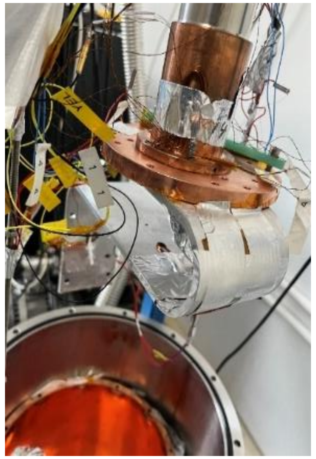
The RRR is 21, and the thermal conductivity is 250W/(m·K) @ 4K



3 Nb-Cu sample, Ø25mm

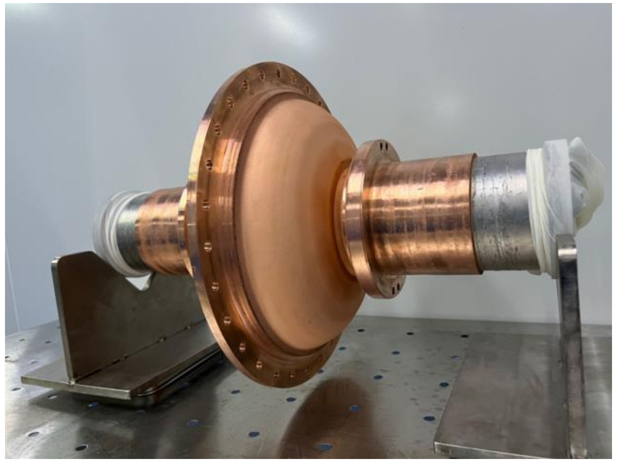
Average maximum tensile stress: 58.4MPa (colloidal cracking)





The Al plates used for thermal links has a thermal conductivity exceeding 1500 W/(m·K) @ 4K

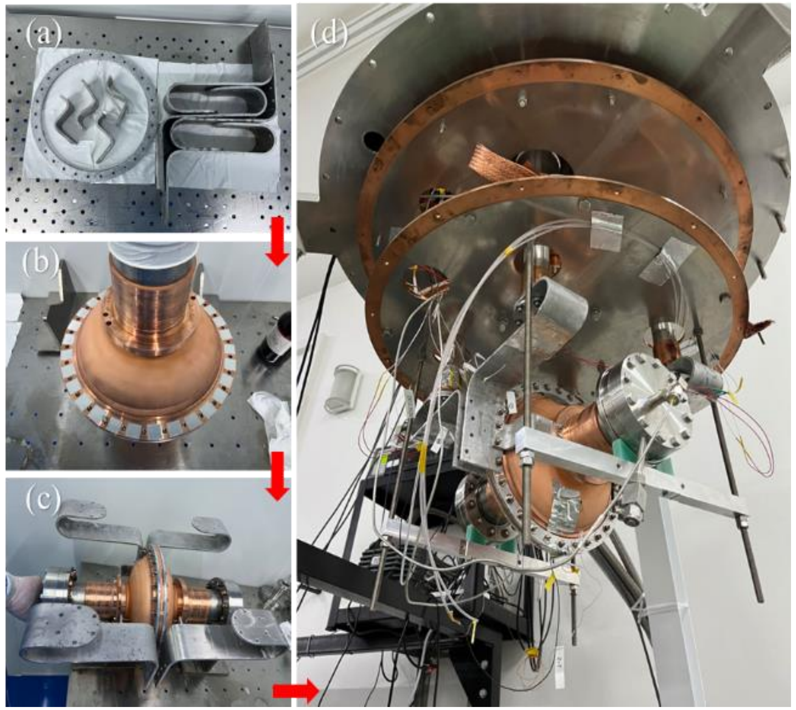
Conduction cooling test

Drilling holes in the flange and cleaning the cavity.


Ultrasonic cleaning with acetone and HPR
Suspected contaminant did not be fully removed

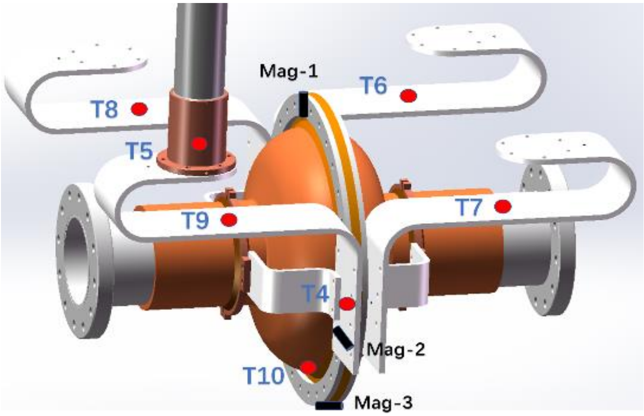
Thermal links assembly and cavity installation

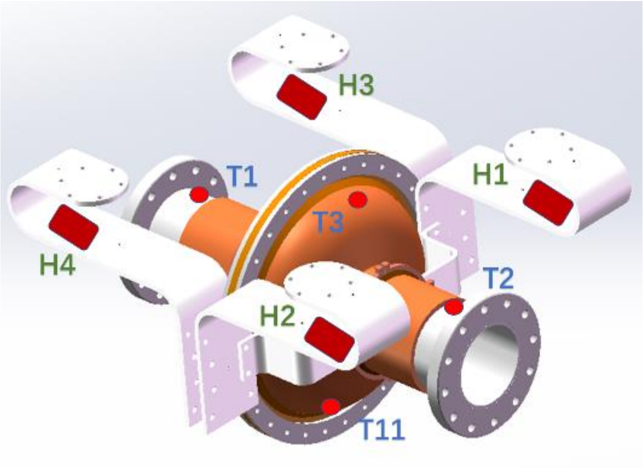


- ✓ Al plates connect the 2nd stages to the Cu flange, and also used to connect the 3 flanges.
- ✓ 0.1 mm thick In foils were padded on the contact surface. The preloading force of the bolts was 10 N·m
- ✓ Apply Apiezon N grease between the 2nd stages and the Al plates

NS03腔水平测试

Installation locations of the thermometers(T1-T11), fluxgates(Mag1-Mag3), heaters(H1-H4)

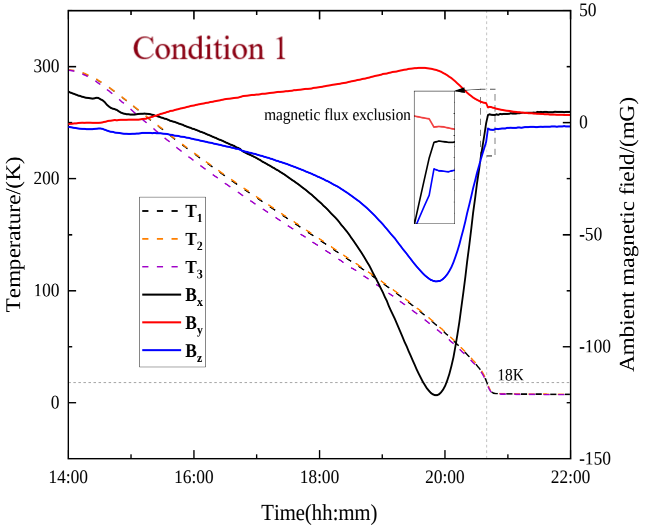


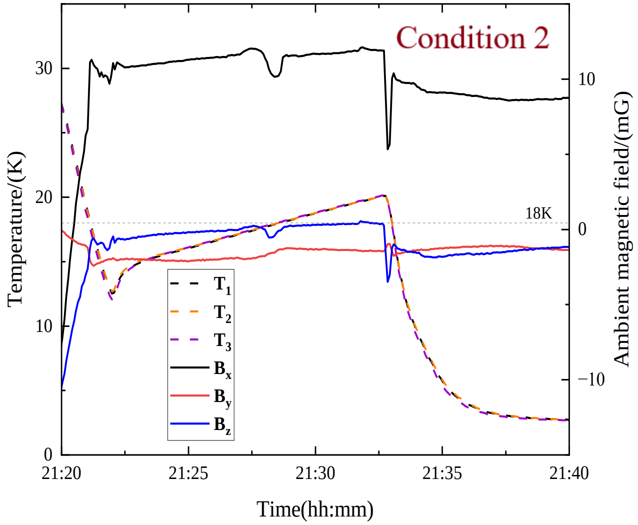


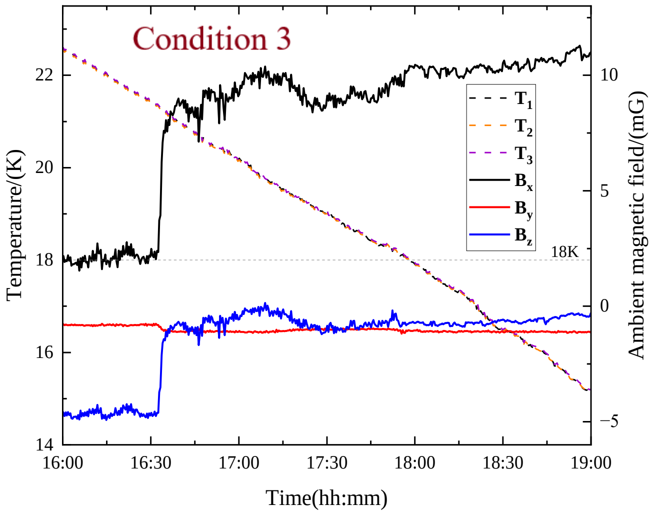
The heaters were placed on the side of the Al plates farther from the cavity

RF tests under three cooling conditions:

- ✓ direct cooling without controlling the cooling rate
- ✓ two T-cycles by switching the cryocoolers on and off between 30 K and 12 K
- ✓ using the heaters to control the cooling rate







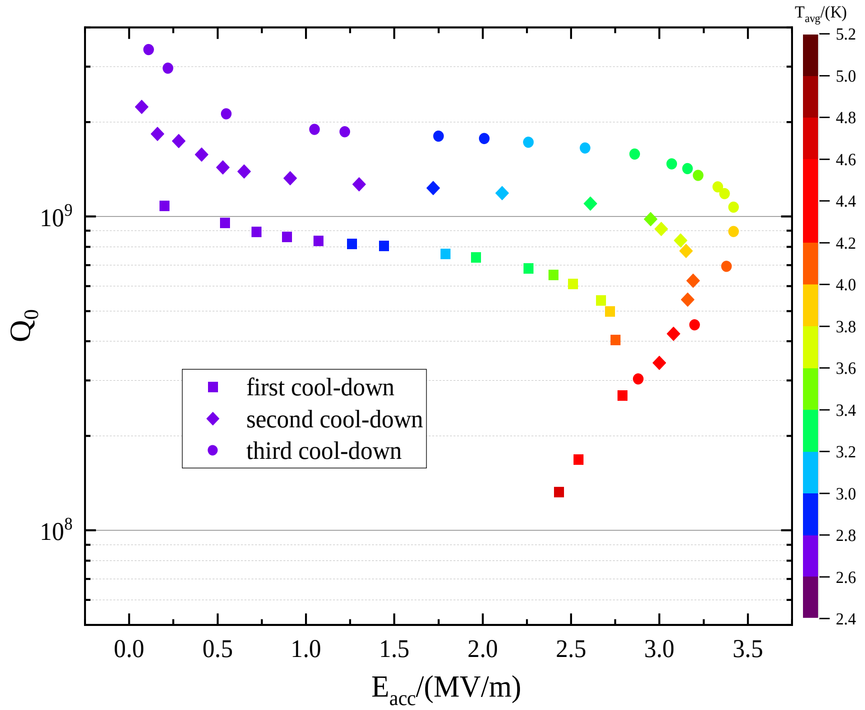
NS03腔水平测试

Cooling rate, cavity temperature gradient, and ambient magnetic field near 18 K under three cooling conditions.

cooldown	Cooling Rate K/min	Temperature Gradient K/m	B_x mG	B_y mG	B_z mG
1	2.55	8.72	4.04	6.71	-2.47
2	12.39	0.86	9.79	-1.60	-1.35
3	**0.06**	**0.17**	10.15	-1.08	-0.81

- ✓ The heating current did not generate a significant additional ambient magnetic field.
- ✓ The cooling rate was approximately 0.06 K/min near 18 K, and the thermal oscillations were controlled within 0.05 K.
- ✓ The temperature gradient on the cavity was 0.17 K/m.

Test results in CW mode (steady state).



The test results for cooling controlled by the heaters were relatively better.

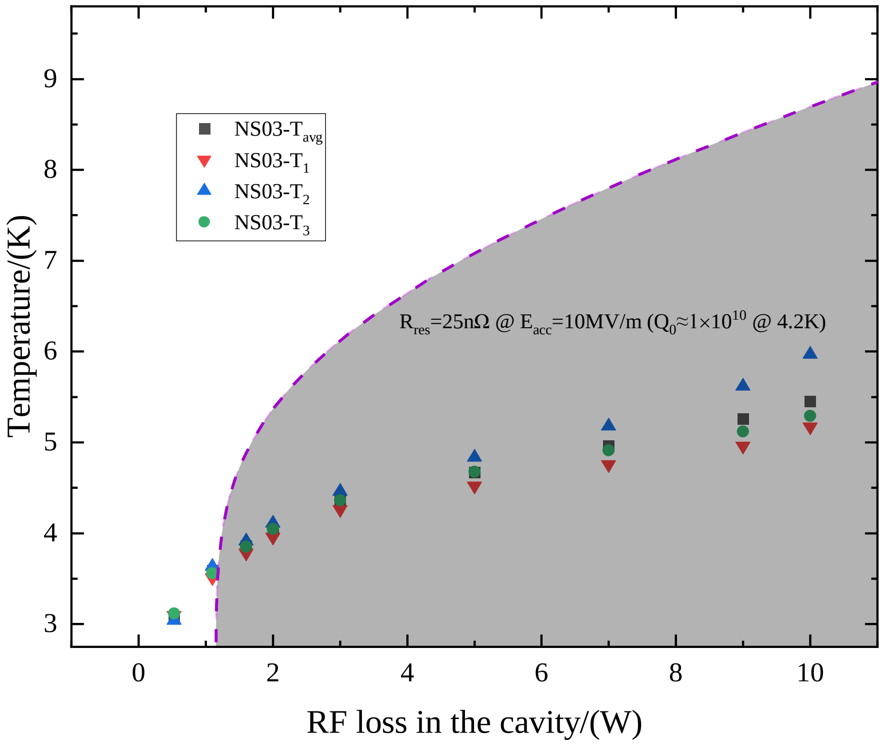
low gradient $Q_0 \approx 3 \times 10^9$

$Q_0 = 1.1 \times 10^9 \, @E_{acc,max} = 3.42 \text{ MV/m}, \;\; P_c = 1.4\text{W}$

Conduction cooling test

Thermal stability tests:

Temperature comparison under different cavity dissipation. (steady state):



Cavity dissipation: P_c

Temperature difference on the cavity: T_d

$P_c < 7$ W, $T_d < 0.5$K

$P_c = 10$ W, $T_{avg} \approx 5.5$K ($T_d \approx 0.8$K)

As P_c increases, the temperature rise on the defective side is significant.

dashed curve:

$$P_c = \frac{(E_{acc} \times L)^2}{\frac{R}{Q} \times Q_0} \qquad Q_0 = \frac{G}{R_s}$$

$$R_{BCS} = 9.4 \times 10^{-5} \frac{f^2}{T} e^{-\frac{2.2T_c}{T}}$$

where: $E_{acc} = 10$MV/m, R/Q=104.6Ω

When the cavity temperature is kept below the dashed curve, the cavity can operate at an E_{acc} of 10 MV/m

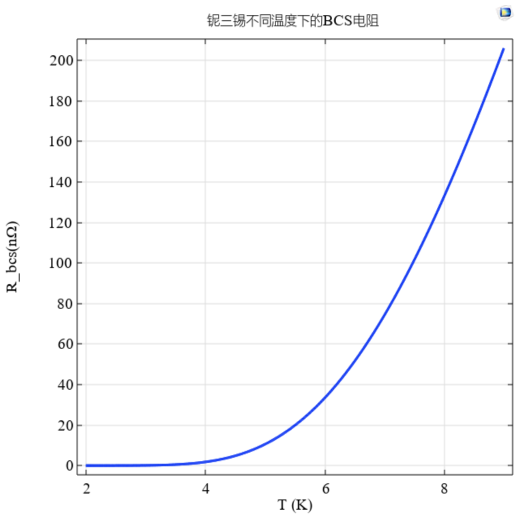
Cu coating on the exterior of the cavity significantly improves its thermal stability and uniformity.

Conduction cooling test

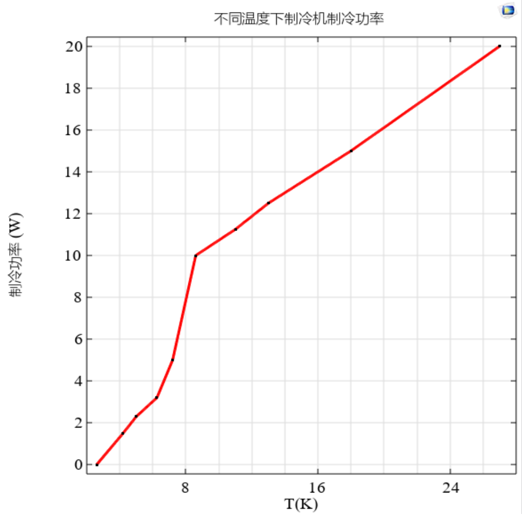
Electromagnetic-thermal coupling simulation：

$$R_S = 9.4\times10^{-5}\frac{f^2}{T}e^{\frac{-2.2T_c}{T}} + R_{res} = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}}$$

$$\sigma = \frac{5.1\times10^3}{\left(1.59\times10^{-4}\times\frac{e^{\frac{-39.6}{T}}}{T} + R_{res}\right)^2}$$

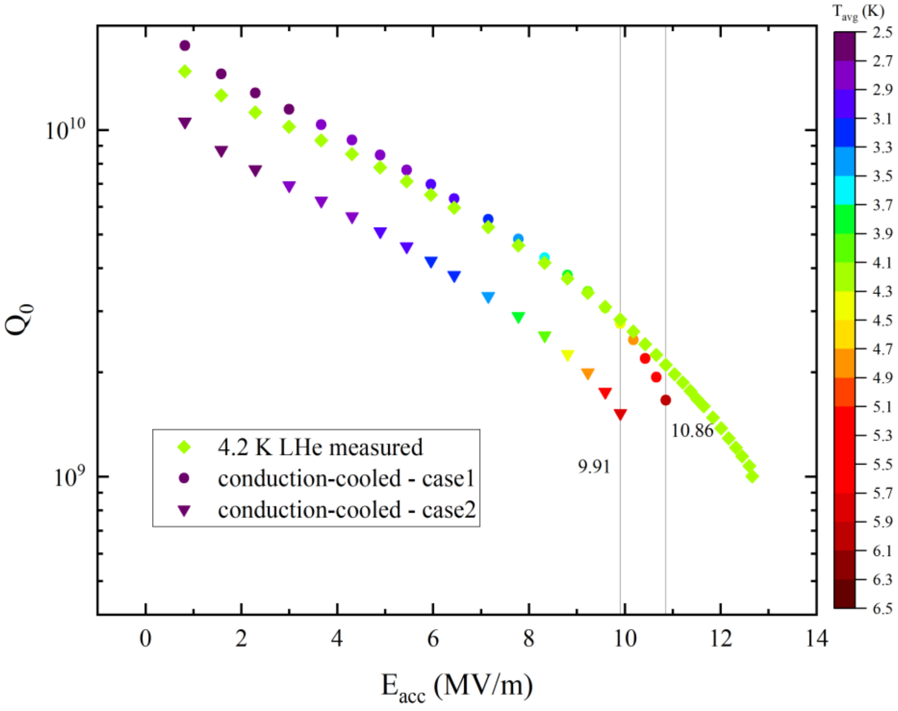


Variation of R_{BCS} of Nb_3Sn with temperature.



Variation of cooling capacity with temperature for the cryocooler.

Simulation of the performance curve under conduction cooling for undamaged Nb_3Sn cavity

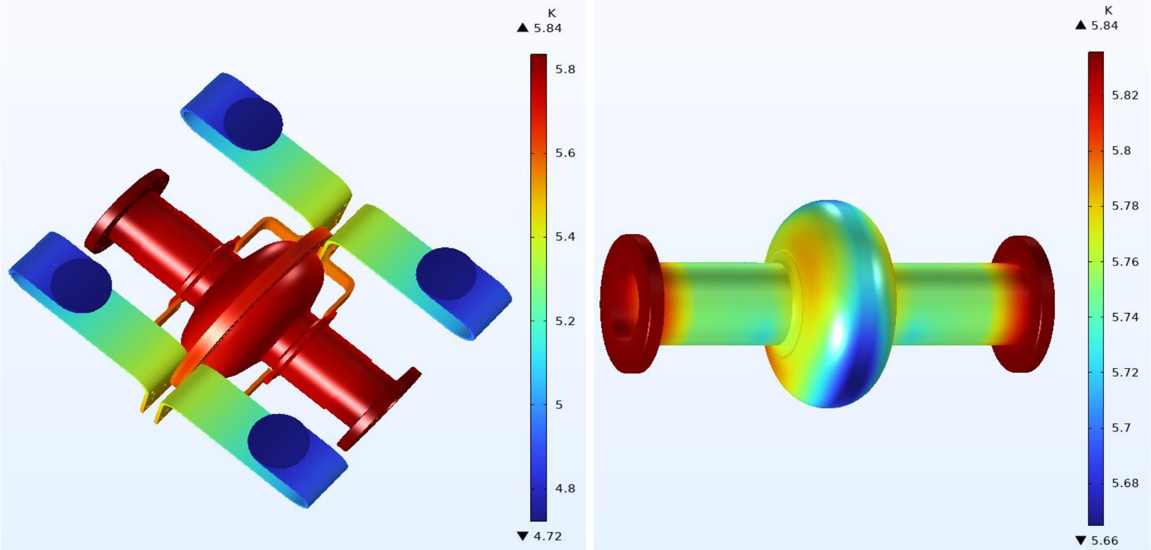


●： The Rres under conduction cooling is the same as in LHe. The maximum convergent value of E_{acc} is 10.86MV/m.

▲： The Rres under conduction cooling is twice that in LHe. The maximum convergent value of E_{acc} is 9.91MV/m.

Conduction cooling test

Electromagnetic-thermal coupling simulation：



Temperature distribution when E_{acc} = **9.91MV/m**

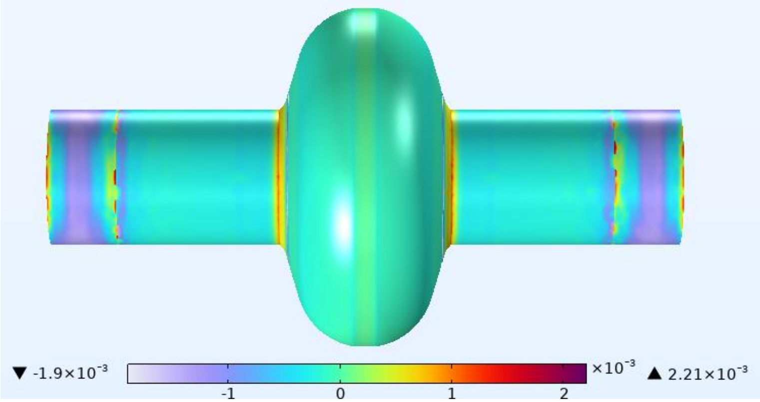
$P_c = 8.1$ W， $T_{avg} = 5.7$K （$T_d = 0.18$K)

The simulation is reasonably consistent with the experimental results

The reason for the deviation may be:

- The actual thermal conductivity of the Cu layer may be higher than the measured value.
- Due to localized damage to the film, the distribution of dissipation may be changed.

Cavity strain caused by the thermal contraction of the Cu layer.



Surface strain on the cavity is less than 0.3%.

Copper extrusion on niobium is not the primary cause of the reduced accelerating gradient.

Improper handling during the spraying and processing led to damage to the Nb_3Sn, which is the primary cause of the performance degradation.

CONTENTS

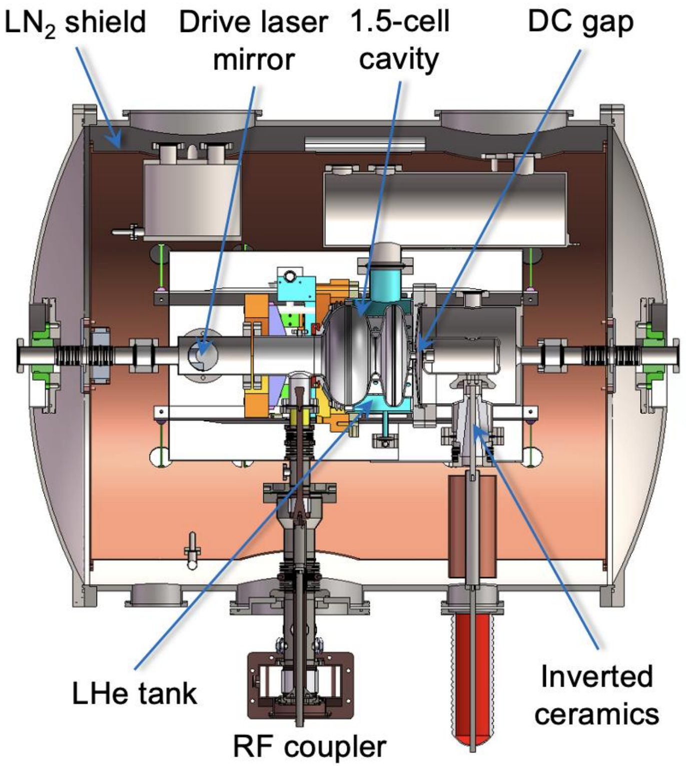
Conduction-cooled e-beam source

DC-SRF-Ⅰ (2007-2016)

Stable beam operation in quasi-CW mode in 2014

DC-SRF-Ⅱ (2021-)

Completed in 2021, and achieved 100 pC pulse charge and 1 MHz repetition frequency in CW mode in 2022.



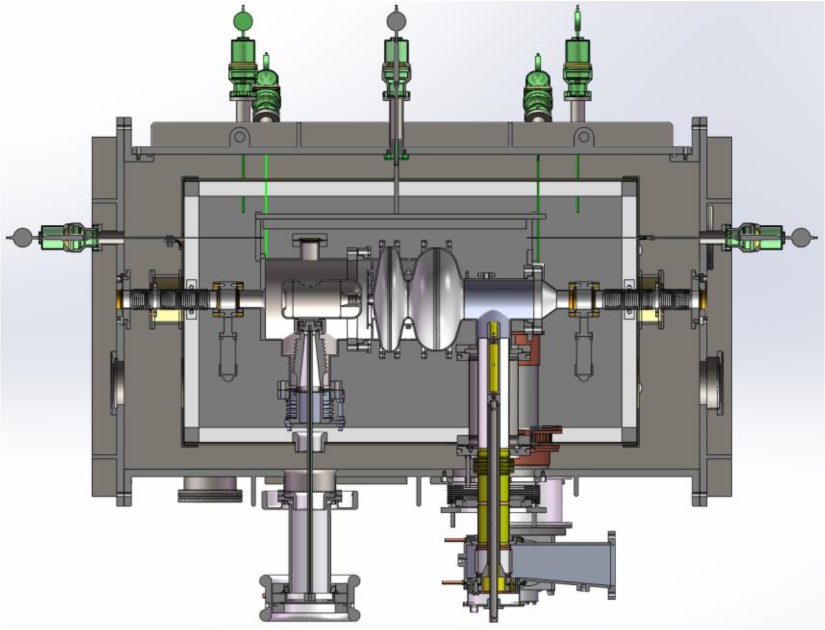
The DC-SRF photoinjector electron gun proposed by PKU can generate high repletion rate, low ennitance electron beams.

To enable the operation of the DC-SRF electron gun without LHe, a conduction-cooled electron gun was designed.

Conduction-cooled e-beam source

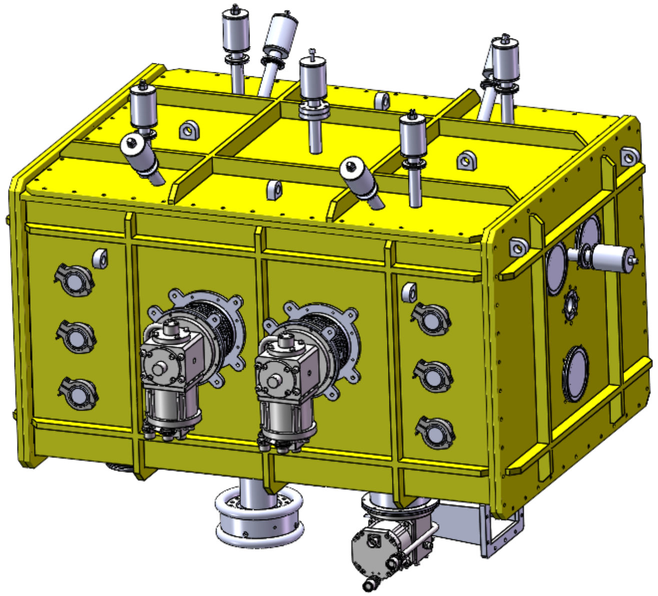
Design:

The electron gun primarily consists of a 1.3G Hz 1.5-cell Nb_3Sn cavity、DC high voltage component、Low heat leak coupler

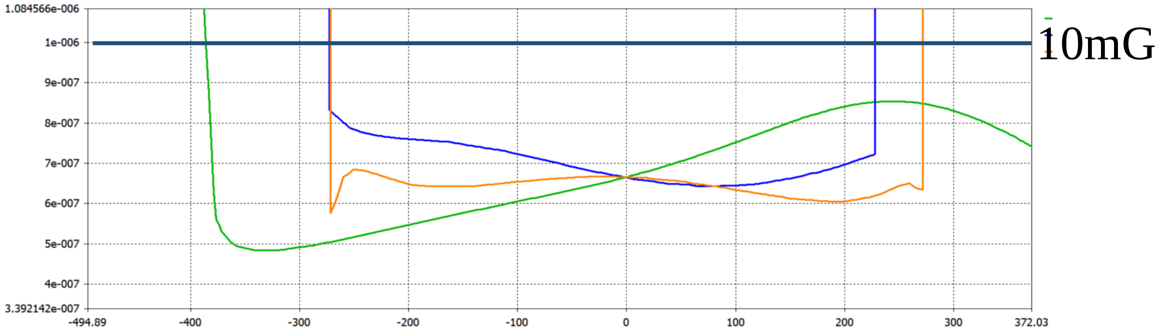


Temperature	4K/W	50K/W
Total	0.574	37.99

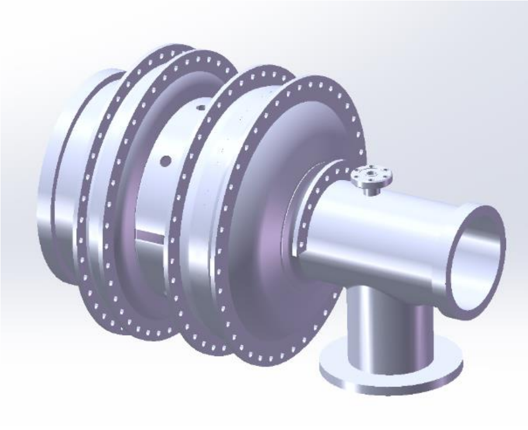
Total heat leakage: < 0.6W@4K



Residual ambient magnetic field: < 10mG

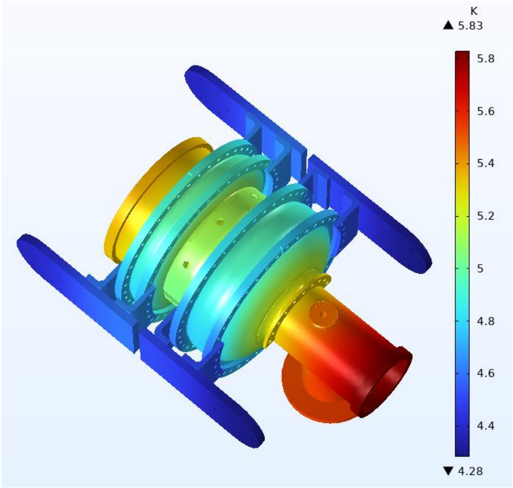


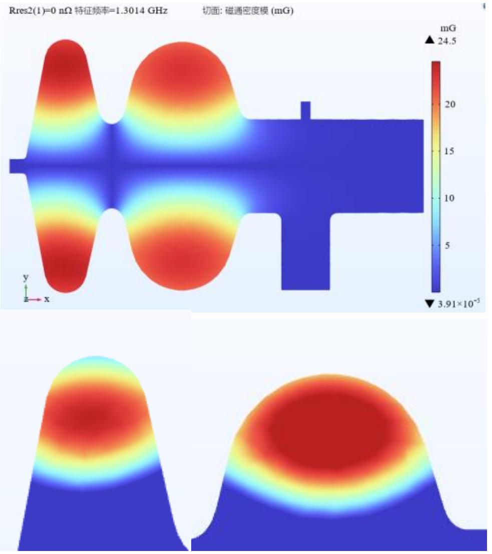
Superconducting cavity design:



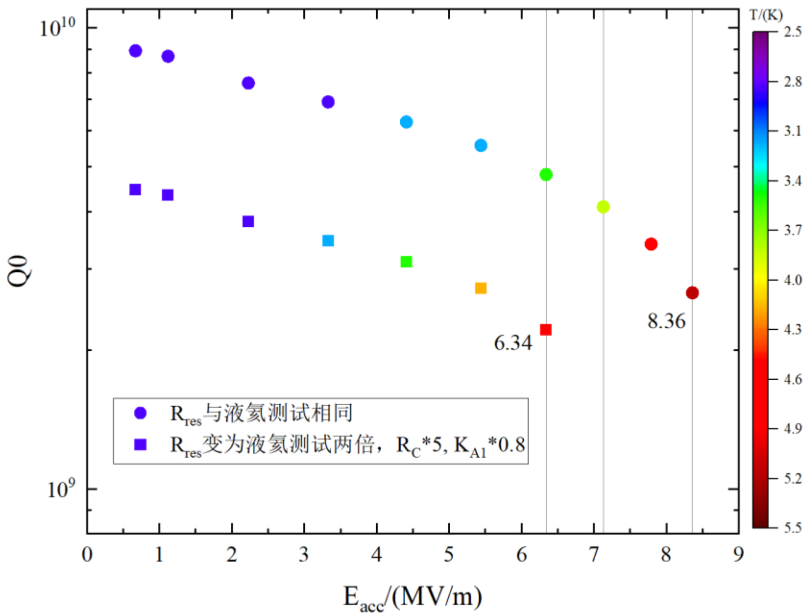
RF Parameters of the Cavity

Parameter	Value	Unit
Frequency	1300	MHz
Q_0	5×10^9	\
E_{acc}	8	MV/m
Effective Length	186.6	mm
G-factor	212	Ω
Shunt Impedance r/Q	203	\
E_{peak}/E_{acc}	2.07	\
B_{peak}/E_{acc}	4.86	mT/(MV/m)





Electron beam welding of niobium rings near B_{max}



Temperature distribution of the cavity at Eacc=8.4 MV/m.
The ellipsoidal section is at approximately 5 K, with Pc=5 W.

Nb rings were welded near the equator.
The cavity is currently being coated.

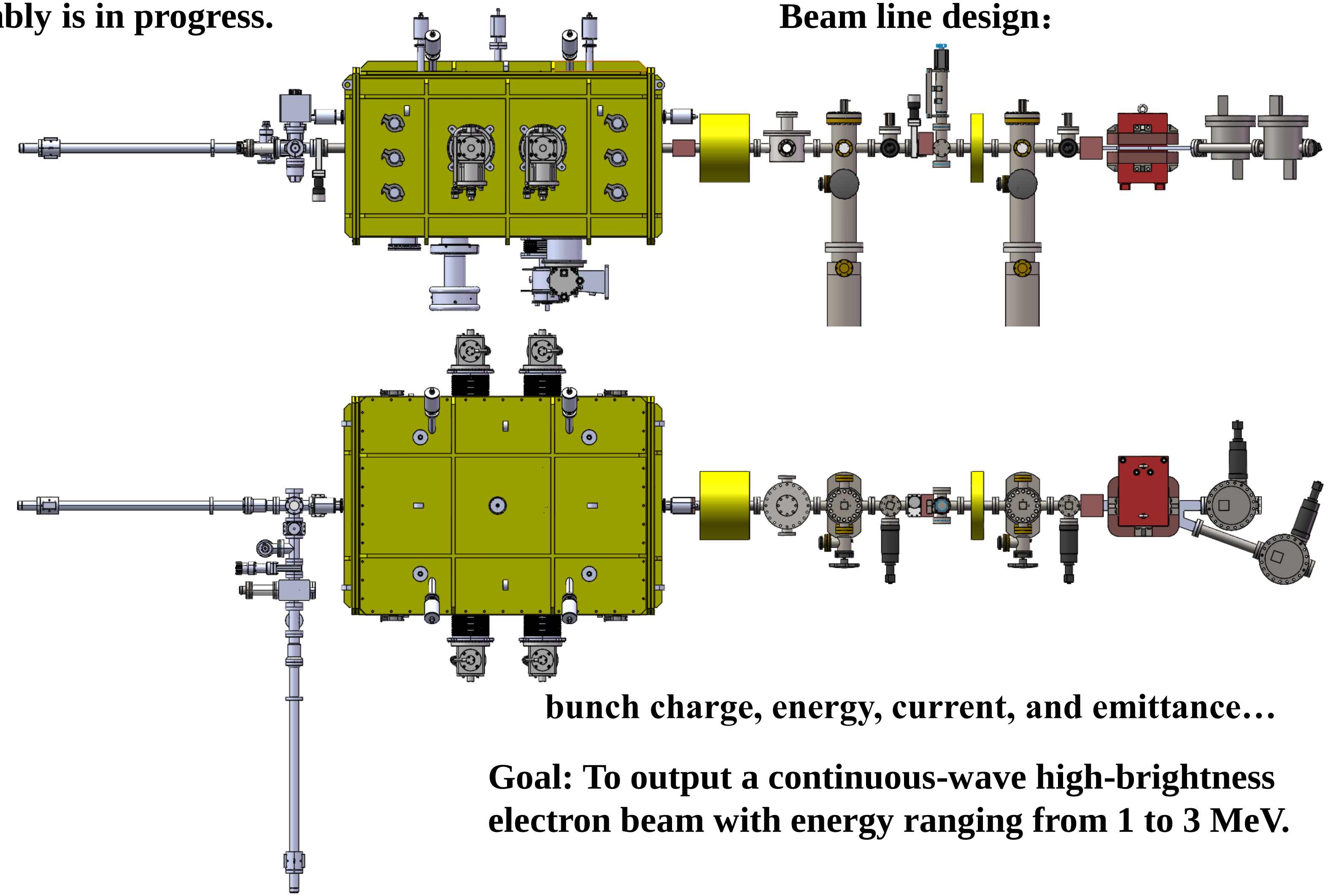
The goal is to achieve an E_{acc} of at least 6-8 MV/m under conduction cooling

Conduction-cooled e-beam source

Conduction-cooled DC-SRF photoinjector electron gun.

Manufacturing is complete and assembly is in progress.

Beam line design:



bunch charge, energy, current, and emittance…

Goal: To output a continuous-wave high-brightness electron beam with energy ranging from 1 to 3 MeV.

Summary

- 1.3 GHz single-cell Nb_3Sn cavities were prepared by tin vapor diffusion method, At present, the low field Q_0 reached 2.25×10^{10} , and Q_0 $>10^{10}$ @ 10 MV/m. We need to continue to improve the quality of the film.
- Cu coating on the exterior of the cavity by cold spraying can significantly improve the thermal stability and uniformity of the cavity, and can be prepared quickly. However, it is important to avoid contamination and damage to the Nb_3Sn film during the spraying and processing.
- The conduction-cooled DC-SRF photoinjector electron gun has been manufactured and is currently being assembled. The goal is to establish a superconducting photoinjector electron source that operates without liquid helium, generates high repetition rate MeV electron beams.

Thanks for your attention!