Development of Cu-Nb composite superconducting cavities for enhanced operational stability at IMP

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August 20, 2026

Outline

1. **Introduction**

2. **Cu-Nb composite cavities based on Cu-Nb composite sheet**

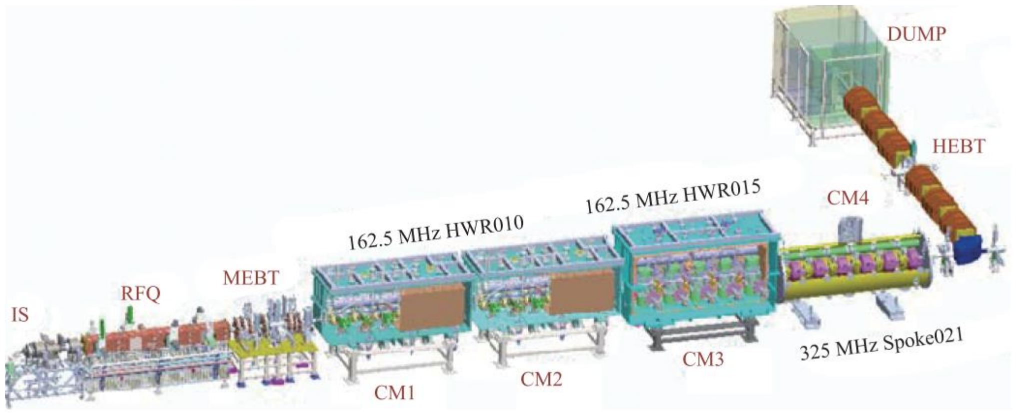
3. **Cu-Nb composite cavities based on electroforming copper**
    - Sample studies
    - Cu-Nb composite prototype cavity
    - HWR040 Cu-Nb composite cavity for engineering application

4. **Conclusions and plans**

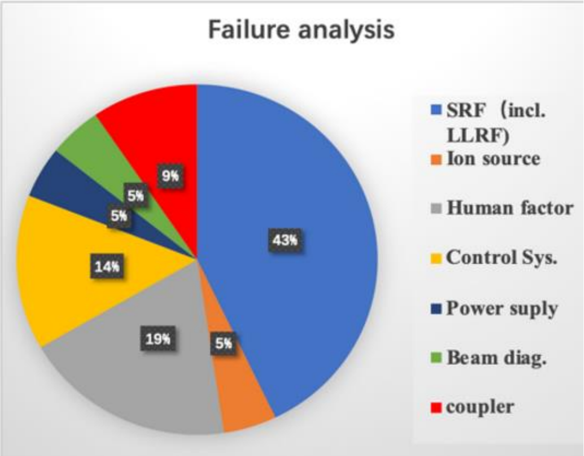
Introduction

Operation experience of the Chinese ADS Front-end Demo Linac(CAFe)

- **43%** of machine trips originated from SRF system



Layout of CAFe



Machine failure analysis
[Y. He, SRF2019]

Factors constrain the operational stability of the low-beta SRF cavities

- **Thermal stability:** thermal breakdown due to defects, field emission and multipacting electrons etc.
- **Mechanical stability:** helium pressure fluctuation detuning(*df/dp*), Lorentz force detuning(*LFD*) , environmental vibration etc.

Introduction

Cu-Nb composite cavity: thin-walled Nb cavity backed up with thick copper shell

- **Higher thermal stability**
  - **Nb thermal conductivity~ *60 W/(m*K)* at 4.2 K**
  - **Cu thermal conductivity *400 W(/m*K)* even more**
- **High mechanical stability** (*df/dp*, *LFD*, environment vibration etc.)
- **RF performance guaranteed-** high gradient recipes developed for the bulk Nb cavity
- **Low niobium cost**(3 mm to 1.5 mm or less)

Thin-Niobium cavity

1.5 mm Nb wall or Less

High-purity copper shell

Electroplating copper
Hot Isostatic Pressure Bonding…

Conducting cooling of partial surface or whole cavity

Partial surface cooled by thermal strips and/or pipe cooling

Improve

df/dp

LFD

Vibration influence

Thermal breakdown

…

4.2 K
Stable operation

Cu-Nb composite sheet – approach one

1.3 GHz single-cell Cu-Nb composite cavity made of Cu-Nb composite sheets

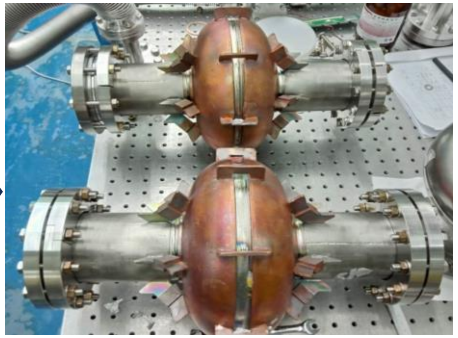
- Cu (6.8mm) and Nb (1.5mm)
- Cu-Nb composite sheets preparation by Hot isostatic pressure
- surface treatment: BCP and 600 °C /10 h

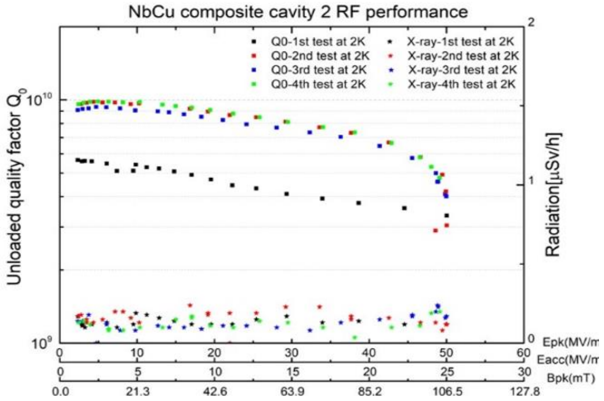
1) Nb-Cu composite sheet

2) Half cell cups deep drawing

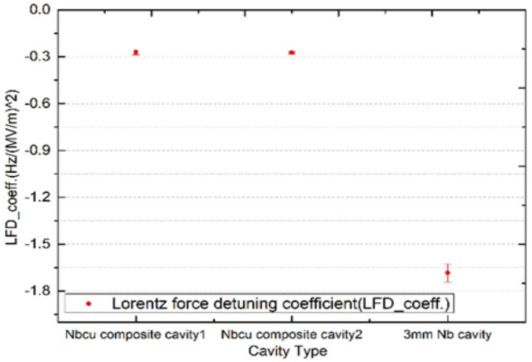
3) Removal of cu layer in welding zones

4) Welding





RF performance at in different cooling



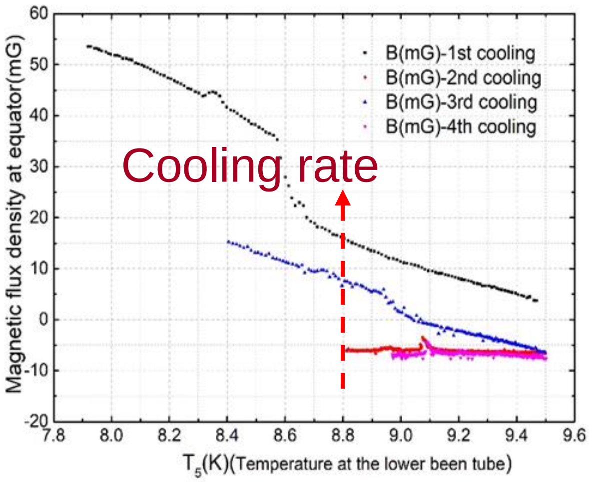
Comparison of LFD coeff. between Cu-Nb composite cavities and Nb cavity(3mm)

Test results

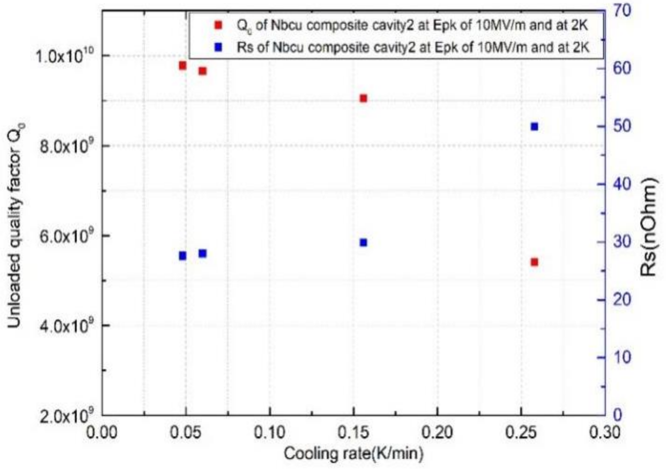
- RF performance: comparable to Nb cavity with similar surface treatment(BCP)
- Mechanical property(remarkable improvement)
  - ✓ *df/dp*: -17 (Cu-Nb) vs. ~ -106(Nb) Hz/mbar
  - ✓ *LFD coeff.*: ~-0.3 (Cu-Nb) vs. ~-1.7(Nb) Hz(MV/m)^-2

Cu-Nb composite sheet – approach one

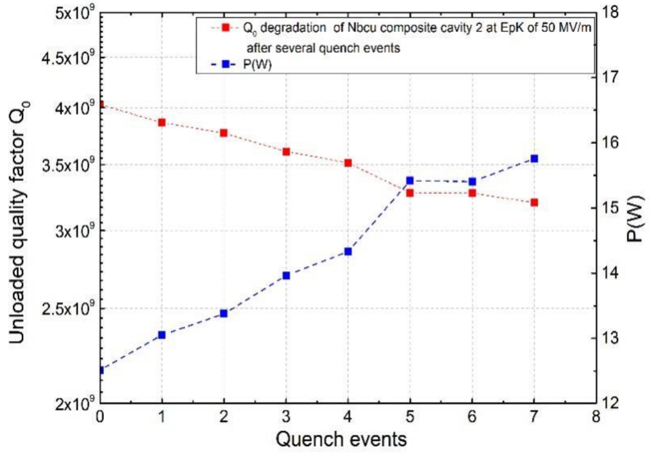
- **Cooling dynamics** significantly impacts the magnetic flux generation and trapping
- **Rs** exhibits saturations at a lower cooling rate
- **Quench related Q_0 degradation** tends to saturate after several quench events



B field at the equator during different cooling



Q_0 and R_s Vs. cooling rate
[E_{pk} =10 MV/m , 2 K]



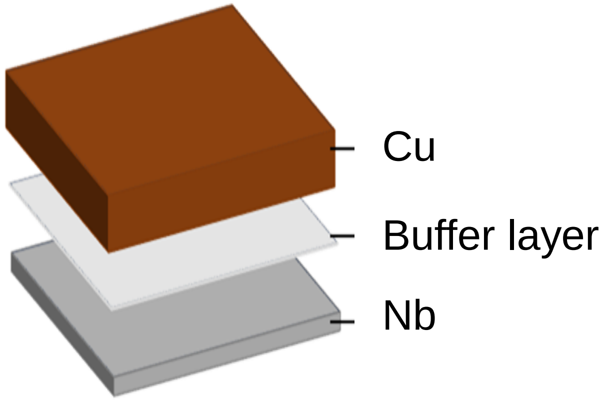
Quenches related Q_0 degradation
[E_{pk} =50 MV/m , 2 K]

- **Fabrication difficulties of complex superconducting cavities using Cu-Nb composite sheets**

Electroforming copper– approach two

Manufacturing procedures of the Cu/Nb composite cavity by electroplating copper technology

1. **Bulk Nb cavity fabrication**
2. **Electroplating a buffer layer and a copper layer**, sequentially on the outer surface of the bulk niobium cavity
3. **Heat treatment: 850 °C /70 mins**, to enhance the bonding strength and minimize the thermal resistance between the Nb and Cu layer
4. **Electroplate the thick copper layer** (e.g. 5 mm).



Challenges

- **Strong bonding between copper and niobium layer**
- **High copper thermal conductivity**
- **Suitable for high-temperature heat treatment**

Electroforming copper– approach two

Study the thermal and mechanical properties of Cu-Nb composite samples

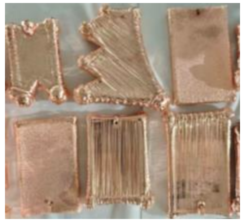
1)Pre-treatment by sandblasting

2) Electroplating thin silver layer and copper layer in sequence

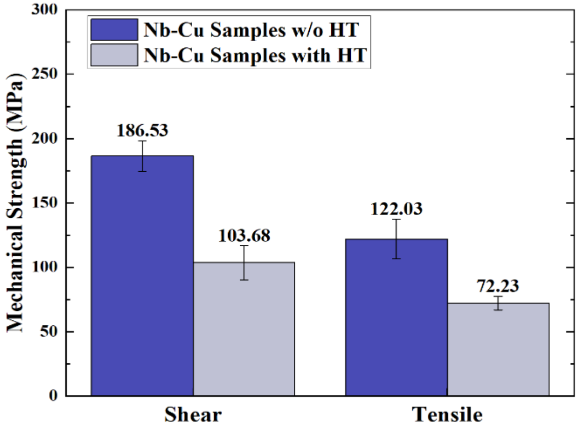
3) High temperature treatment

4) Electroforming thick copper layer

5) Post-treatment: HT or HIP

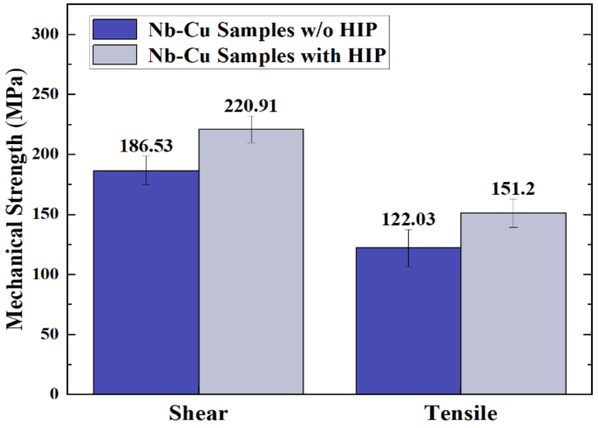


- **Mechanical properties**: tensile strength and shear strength



Mechanical properties of heat-treated samples

- Heat treatment(HT) may degrade mechanical properties
- Hot isostatic pressure(HIP) treatment enhance mechanical properties.

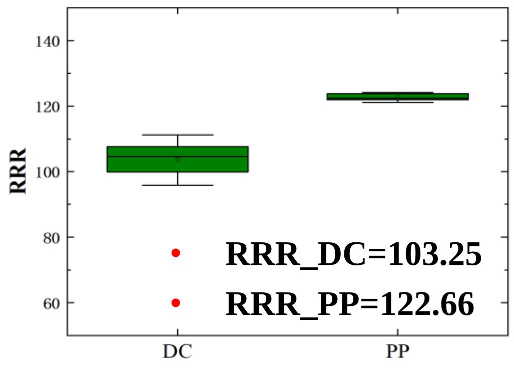


Mechanical properties of HIP treated samples

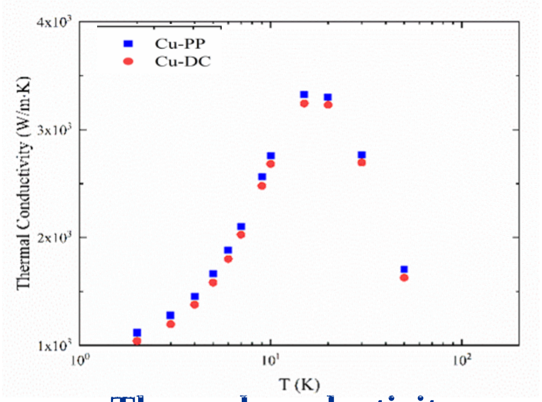
Electroforming copper– approach two

Thermal properties: direct current and pulse plating(PP) copper

- **Residual Resistivity Ratio(RRR) and thermal conductivity** of Cu



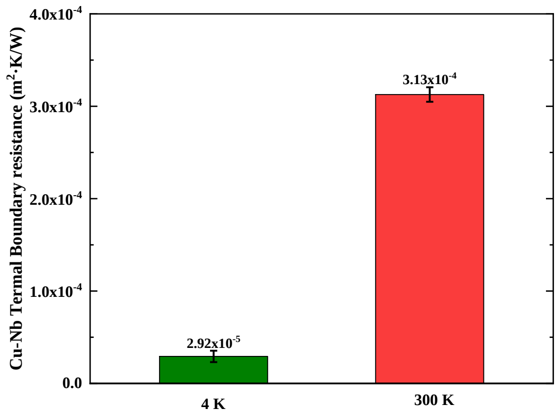
RRR



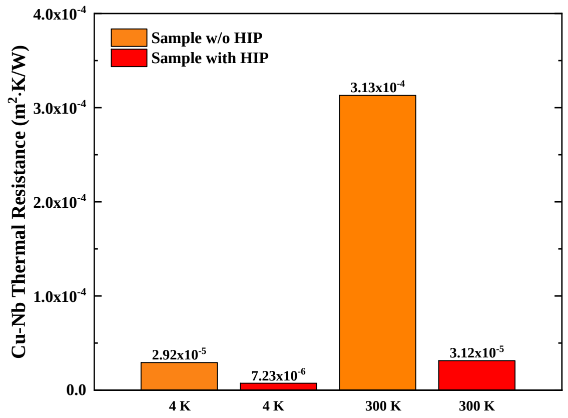
Thermal conductivity

- **RRR> 100**
- **Kcu >1000 W/(m*K),** [κ_{DC}= 1378, κ_{PP}=1451] @ 4 K
- RRR and K is superior to that of oxygen-free copper

- **Cu-Nb interface thermal resistance**
  - Hot isostatic pressure treatment substantially decrease Cu-Nb thermal resistance, ~75.2% decrease
  - All the data was used for Cu-Nb cavity design



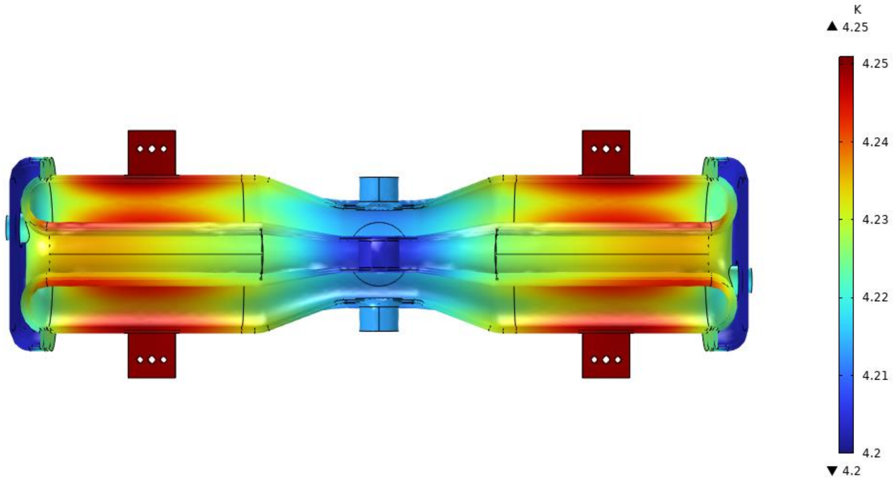
thermal resistance of heat-treated(HT) samples



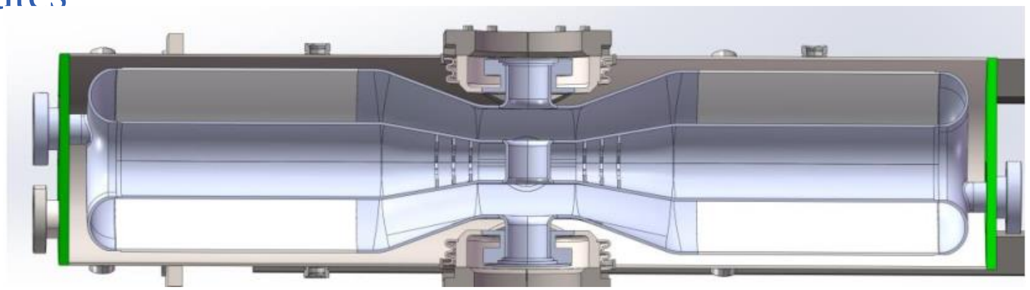
thermal resistance of HIP treated samples

Prototype Cu-Nb composite cavity

- **HWR010 Cu-Nb composite cavity design: aimed to improve the stability of low-beta cavity**
  - **Local area helium cooling** -inner conductor and short plates
  - **Pipes and conduction cooling-** outer conductor



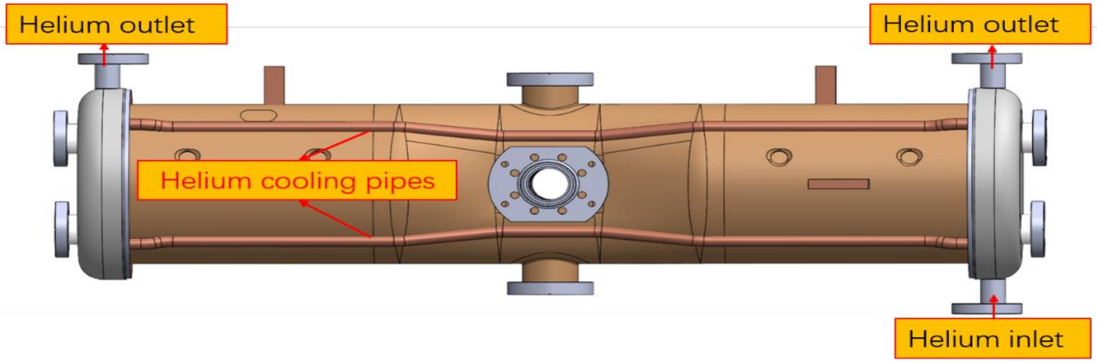
Temperature distribution at E_{pk} of 26 MV/m
Delta T max= 0.05 K



HWR010 bulk niobium cavity

df/dp=7 Hz/mbar
df/dp=-0.6 Hz/mbar

LFD coef.= -5.1 Hz/(MV/m)^2
LFD coef.= -1.7 Hz/(MV/m)^2



Cooling configuration of the HWR010 Cu-Nb cavity

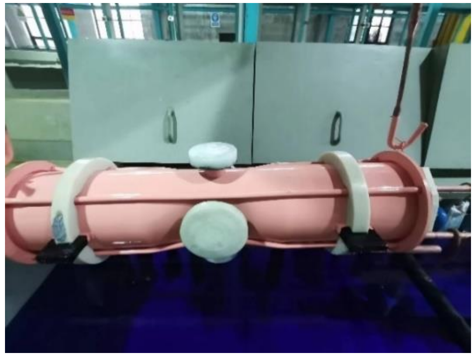
Prototype Cu-Nb composite cavity

Fabrication procedures

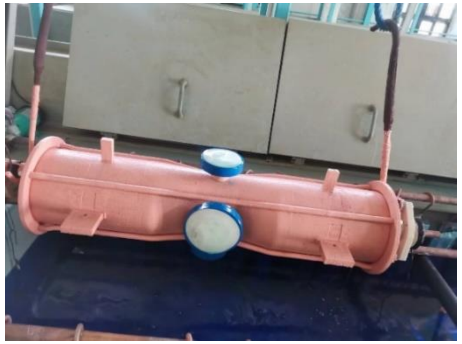
1) Nb cavities fabrication

2） Vacuum heat treatment of Nb-Ag-Cu layers

3） First 2 mm copper layer plating by pulse power supply



4） Last 3mm copper layer plating by DC power supply



5） Machining after electroplating copper

6） The finished HWR010 Cu-Nb cavity

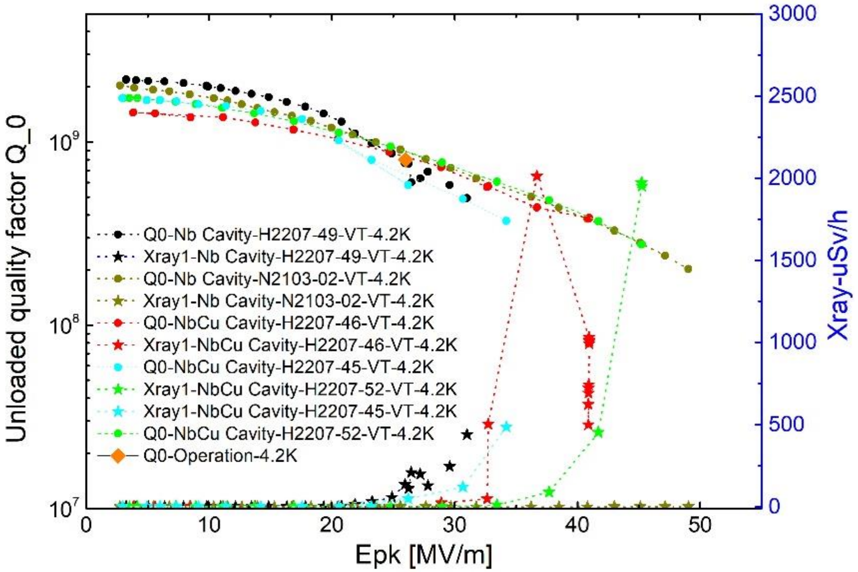
- **Surface treatment:** BCP~150 um and 600 °C/10 h furnace outgassing before electroplating copper
- Cavity was sealed and filled with high-purity water during electroplating process

Prototype Cu-Nb composite cavity

Cryogenic test results- vertical test

- **Surface treatment:** 30 μm BCP, 380°C/2.5 h heat treatment for stress relief of copper, 30 μm BCP
- **Slow cooling** at T_c crossing of niobium adopted, B field < 10 mG
- **RF performance:** Epk_av.= 40 MV/m, limited by field-emission induced thermal breakdown

HWR010 Cu/Nb cavity mounted on vertical test stand

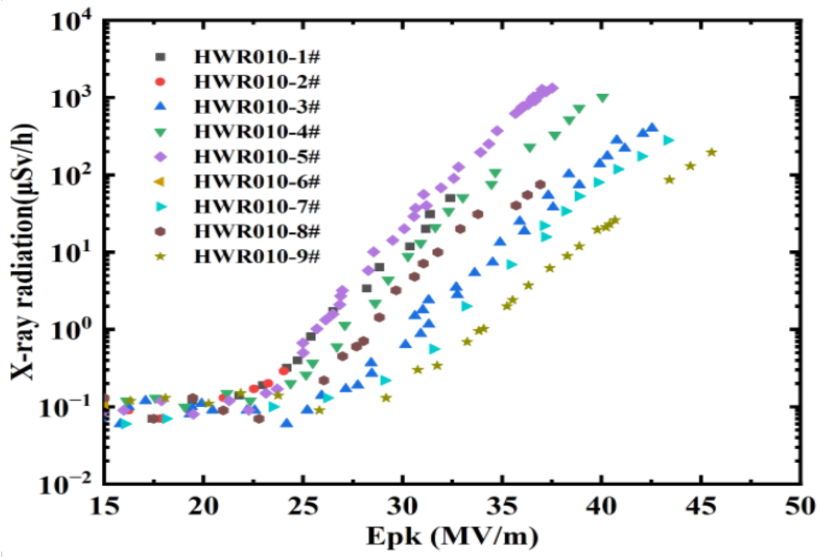


Q_0 vs. E_{pk} at 4.2 K

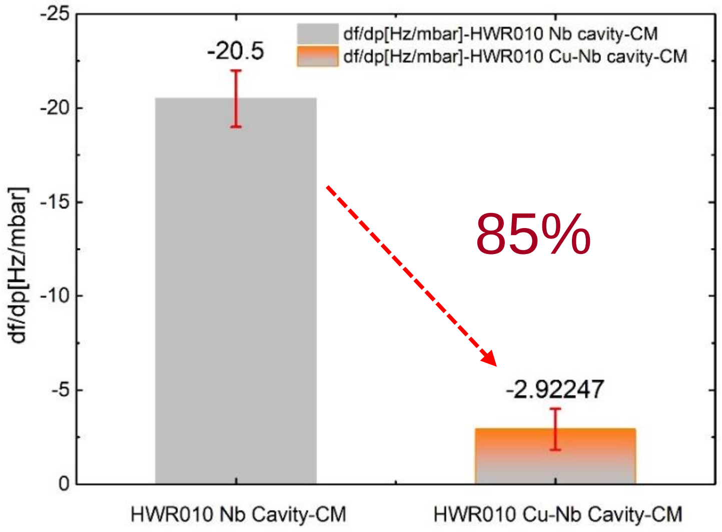
Prototype Cu-Nb composite cavity

- Cryogenic test results- horizontal test
  - ✓ 9 HWR010 Cu-Nb cavities in string
  - ✓ Average Epk ~35.3 MV/m, limited by FE
  - ✓ Q0=4.31E8@Epk=20 MV/m at 4.2 K
  - ✓ Mechanical performance: df/dp and LFD_coeff. improved 85% and 50%

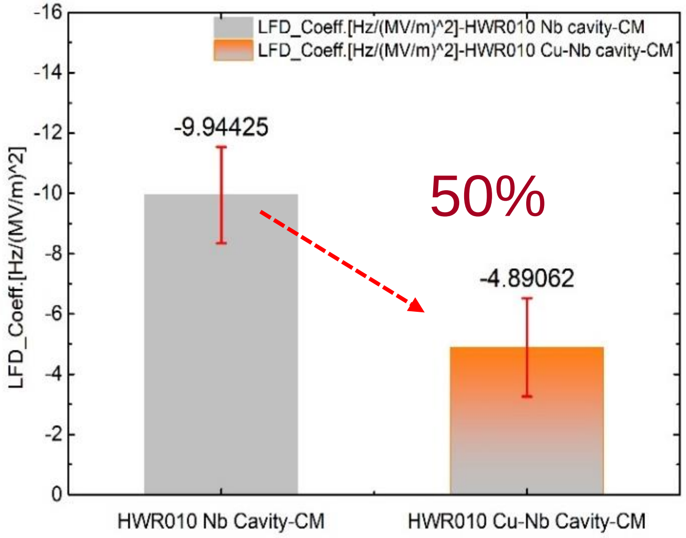
The assembled 9 HWR010 Cu/Nb cavities string



X-Ray vs. Epk



df/dp



LFD_coeff.

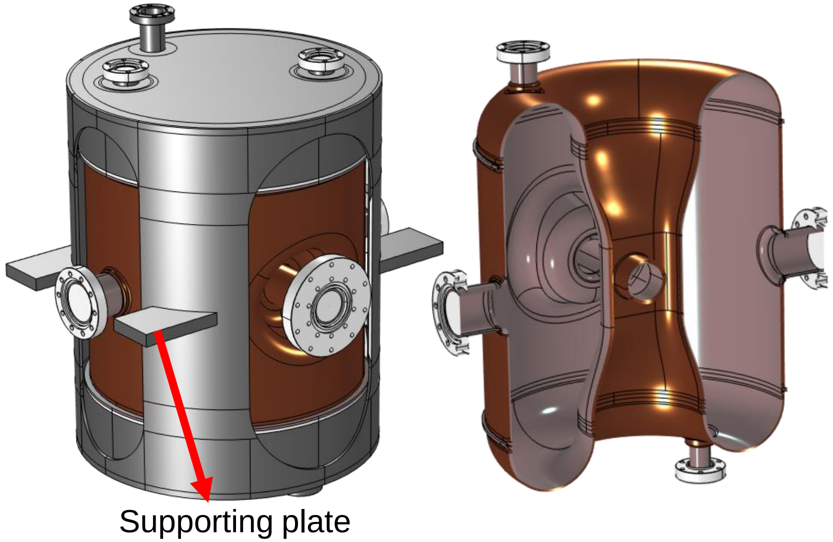
HWR040 Cu-Nb composite cavity

- 60 HWR040 Nb cavities are used in CiADS Linac, one cryomodule will be replaced by Cu-Nb cavities for the verification of Cu-Nb composite cavity technology on-line

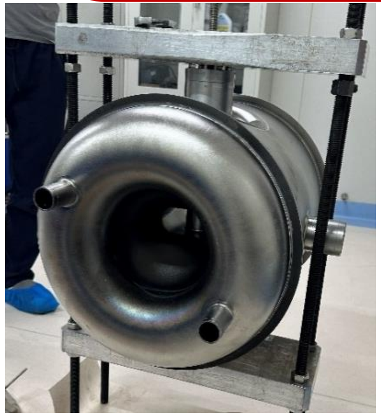
✓ **HWR040 Cu-Nb composite cavity design**

- **Local area helium cooling - inner conductor and short plates**
- **Conduction cooling - outer conductor**

✓ Two Nb cavities has been fabricated
✓ Buffer layer with thin Ag and Cu layer were plated
✓ The cavity will be ready for test in October



Final HWR040 model(left) and cutaway view(right)



Bulk niobium cavity

Cavities with buffer layer

Conclusions and plans

- **1.3 GHz single-cell Cu-Nb composite cavity made of Cu-Nb composite sheets**
  - **Verify the enhanced mechanical properties of Cu-Nb composite cavity**
  - **Slowing cooling crossing Tc is preferred for obtaining high-performance of the copper-niobium composite**
  - **Quench related Q0 degradation tends to saturate after several quench events**
- **Cu-Nb composite cavities based on electroforming copper technology have been explored**
- **HWR040 Cu-Nb composite cavities will be ready for vertical test in October, and proton beam acceleration next year**

Thanks for your attentions!