Researches of High Q Superconducting Cavities at Peking University

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Peking University

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Outline

- Introduction
- Nitrogen doping/infusion researches
- Medium temperature baking researches
- Nb_3Sn cavity and conduction cooling accelerator
- Summary

Introduction

- The development of high Q/high Gradient superconducting cavities is driven by large projects
  - High gradient: European XFEL, ILC
  - High Q: CEPC, LCLS-II, SHINE, S3FEL
- Technology to high Q
  - Nitrogen doping (high T)
  - Nitrogen infusion (low T)
  - Medium temperature baking (medium T)
  - Large grain cavity
  - Nb_3Sn cavity

Introduction

- Development of SRF cavities at PKU
  - Since 1988
  - 1st L-band cavity (1994), 1st QWR (2000), 1st 9-cell cavity (2008)
  - High Q researches
  - Nb_3Sn cavities and conduction cooling accelerator
  - Completion of SRF facilities

SRF lab

HPR

furnace

2K cryogenic system

VTS

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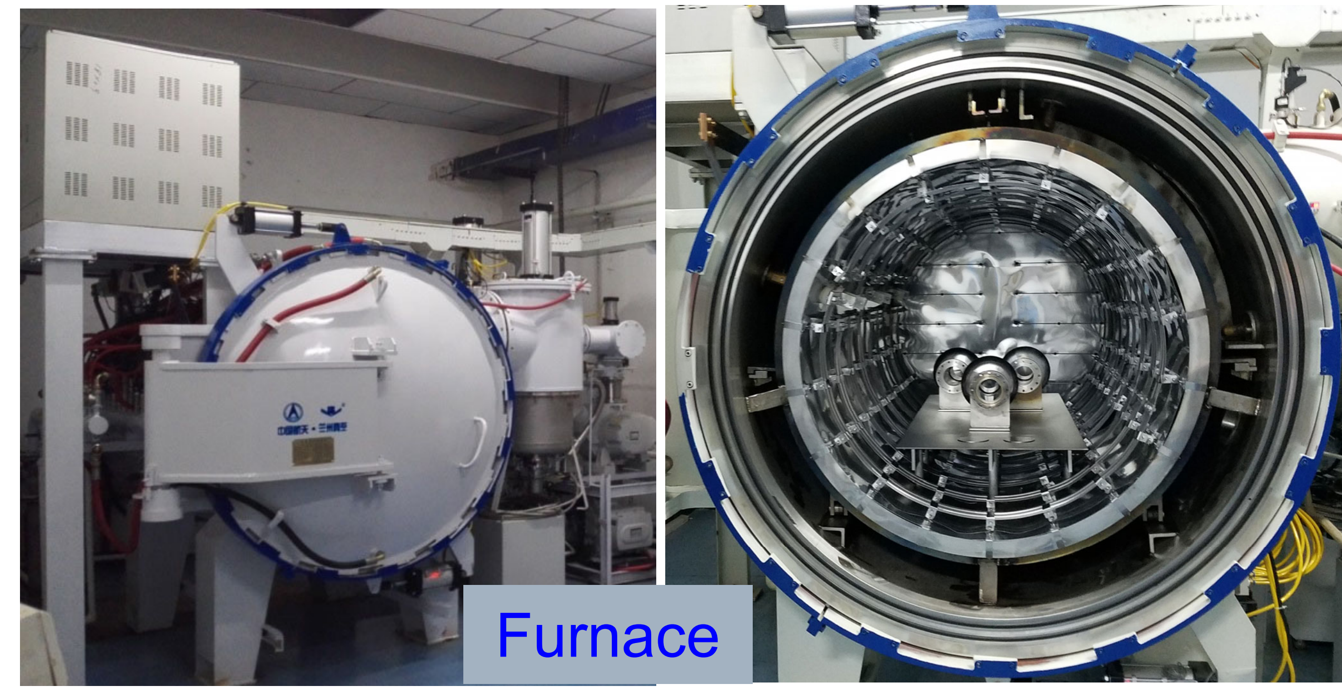
N-doping researches with single cell cavities

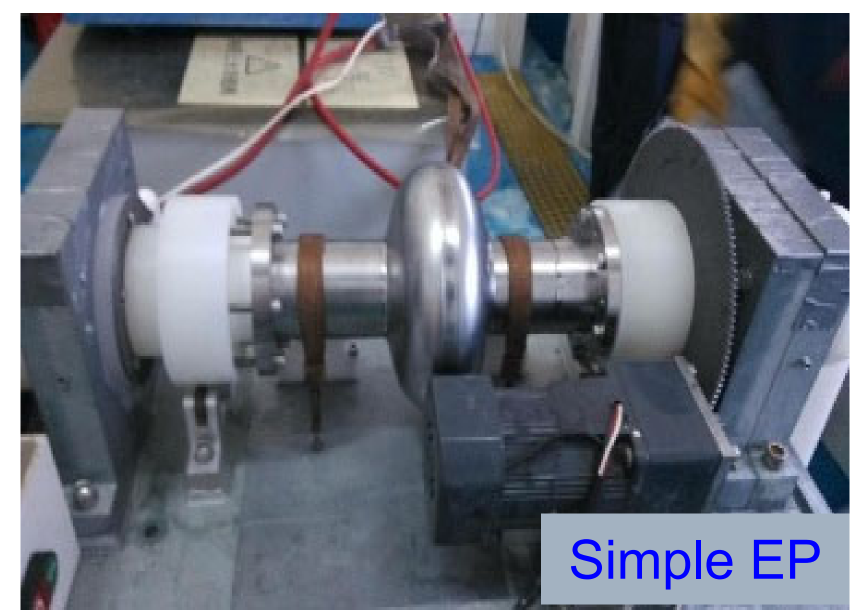
- Buffered Chemical Polishing (BCP) /Electropolishing(EP): refresh the surface
- High Pressure Rinsing (HPR)
- 800°C/900-950°C heat treatment: 3 h
- Nitrogen-doping at 2.7-4.0 Pa, 800°C

  Heavy doping: N-doping 20 min/Annealing 30 min (N20/A30)

  Light doping: N2/A6

  Mid doping: N10/A20
- EP: remove NbN on the surface
- Ethanol cleaning and Ultra sonic cleaning
- HPR and clean room assembling
- Vertical Test

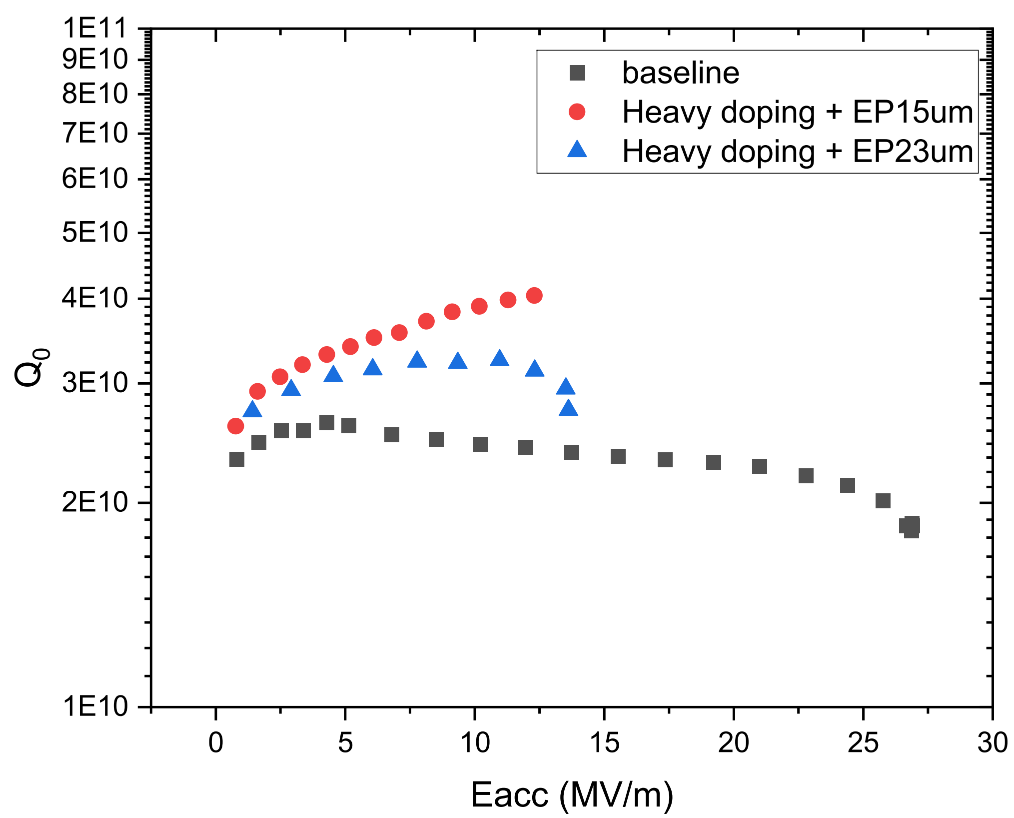




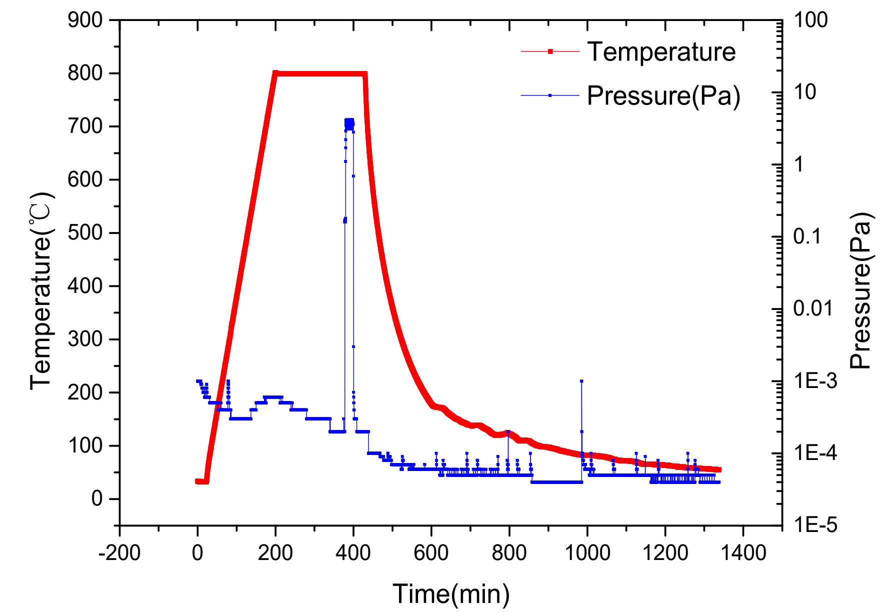
Heavy Doping

large grain cavity LG1

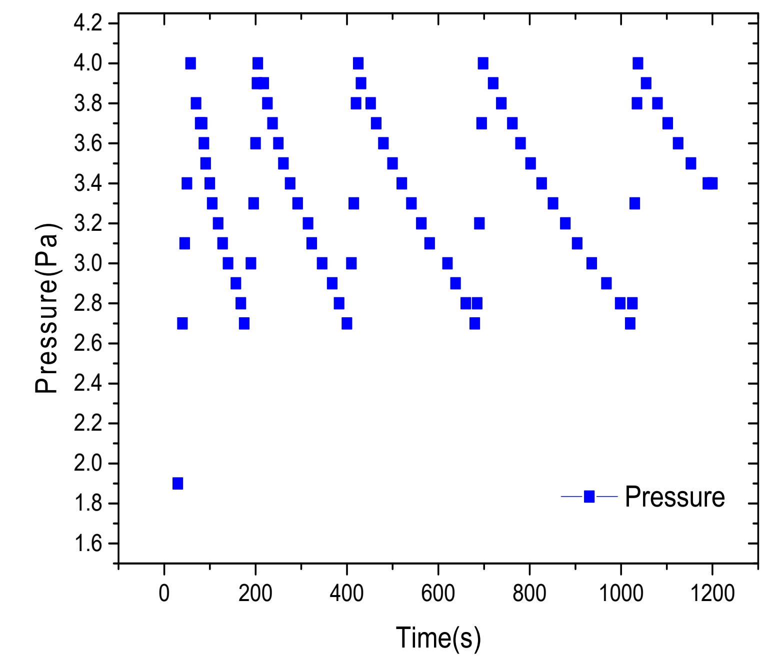
- BCP 250 μm, 800°C 3 h, N20/A30
- EP 15 μm, vertical test
- + EP 8 μm, vertical test



Vertical test



Temperature and Pressure



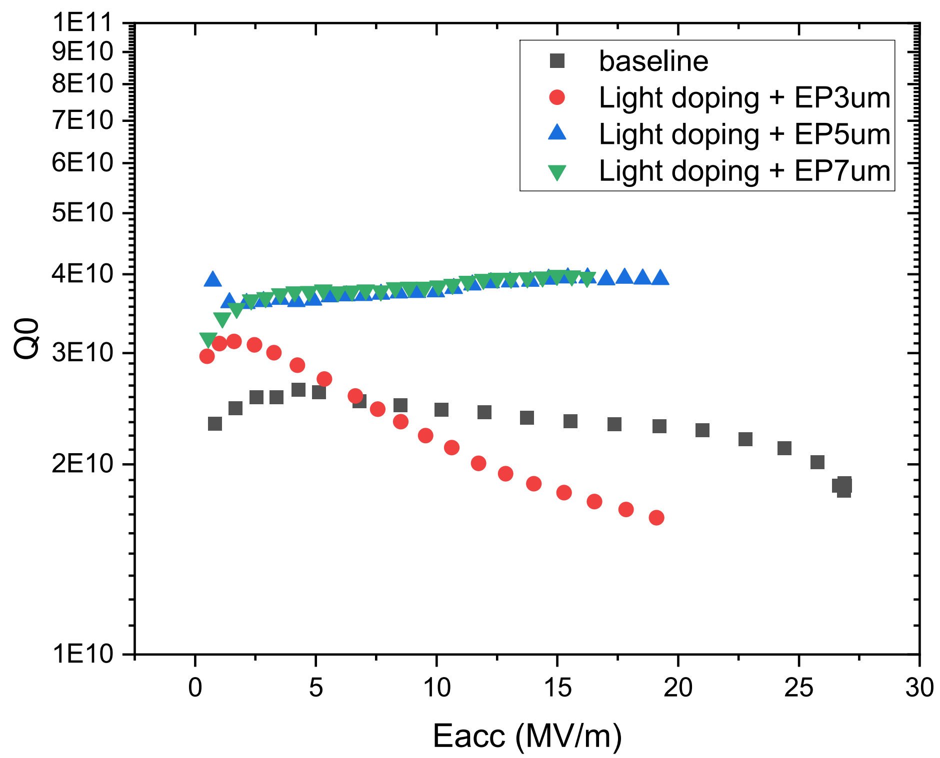
Pressure in doping

Treatment	Q_0 (2K)	E_{acc}(MV/m)
Baseline(BCP250+EP70)	2.4e10@12MV/m	27.0
Heavy doping + EP15	4.0e10@12MV/m	12.3
+EP8 (totally EP23)	3.2e10@12MV/m	13.6

Chin. Phys. Lett. 35(3):037401, 2018

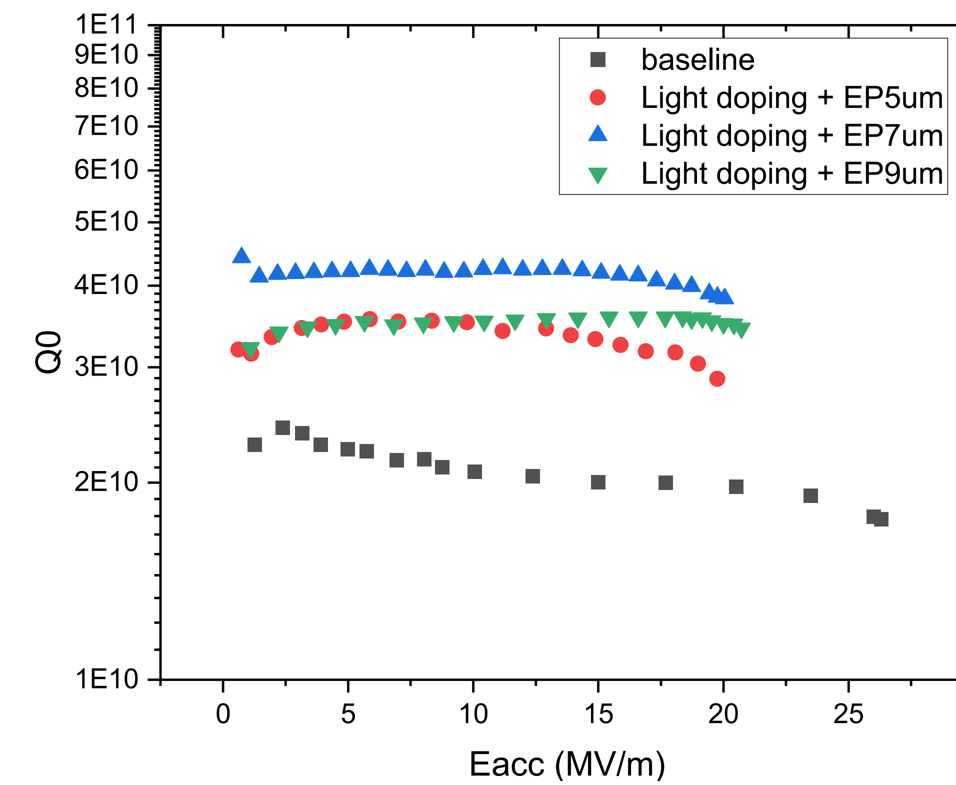
Light Doping

LG01



- BCP to remove the N-surface + HPR
- 800°C 3 h, N2/A6
- Light EP, vertical test
- + EP 2 μm, vertical test
- + EP 2 μm, vertical test

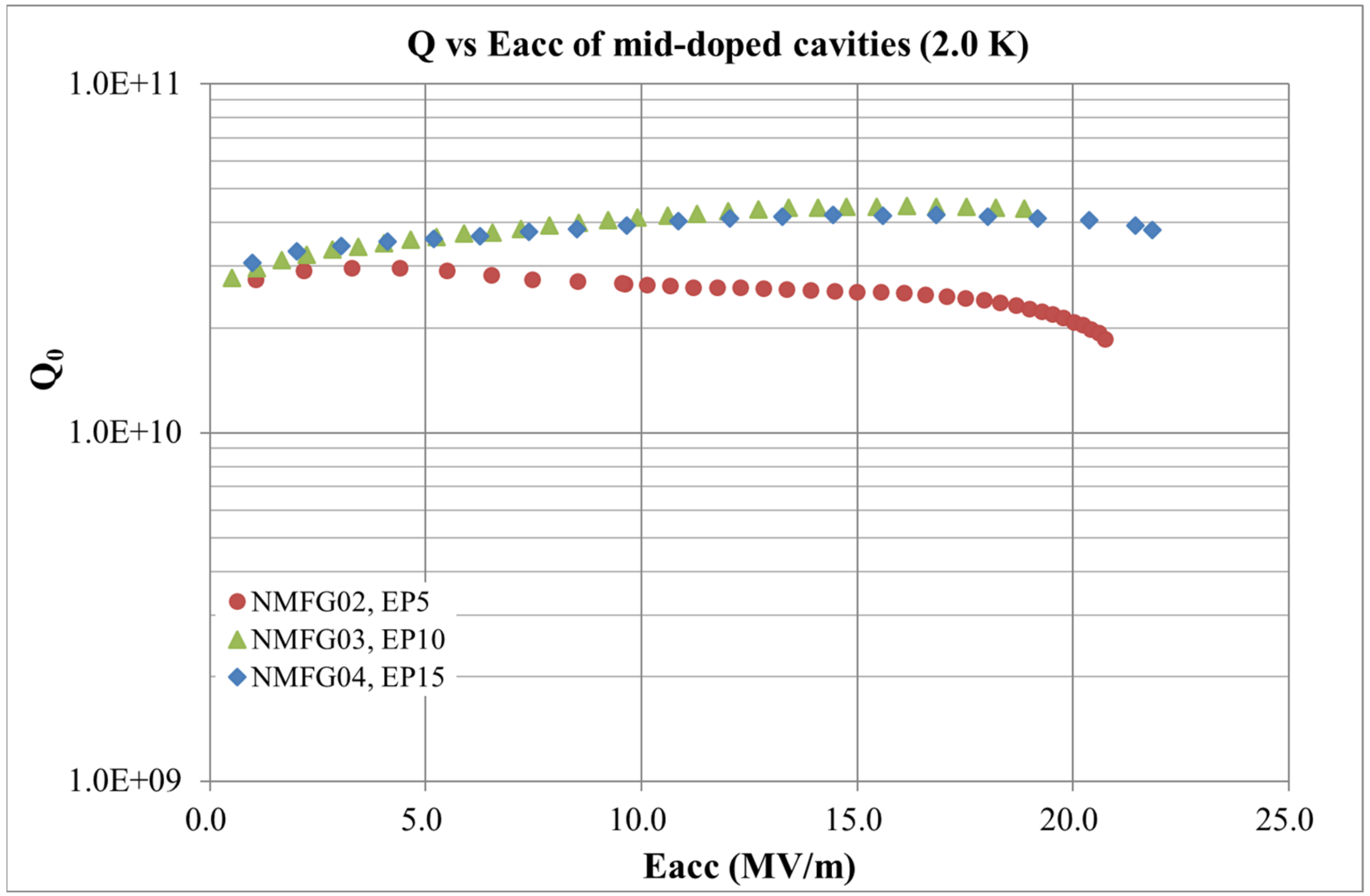
LG03



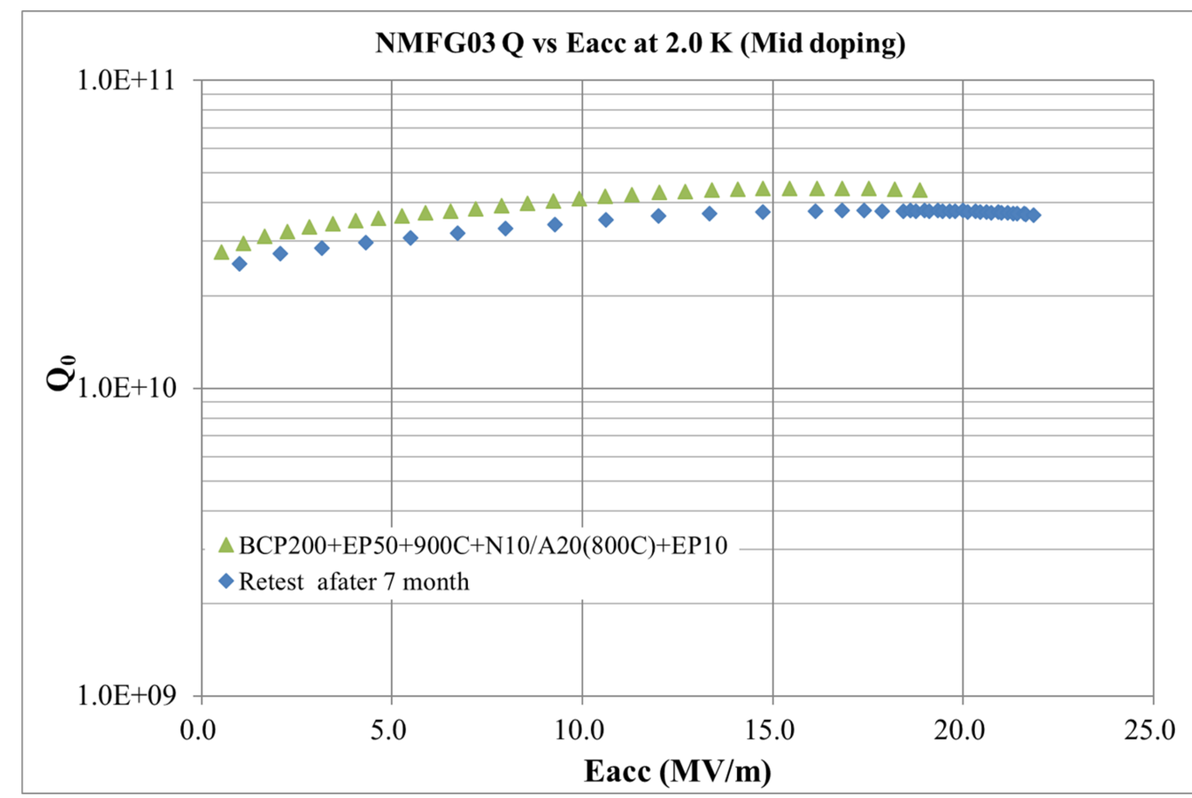
Treatment	Q_0 (2K,16MV/m)	E_{acc}(MV/m)
Baseline	2.4e10 (12MV/m)	27.0
BCP30+N2/A6+EP3	1.7e10	19.1
+ EP2 (totally EP5)	3.9e10	19.3
+ EP2 (totally EP7)	4.0e10	16.2

Treatment	Q_0 (2K,16MV/m)	E_{acc}(MV/m)
Baseline(BCP200+800C+EP6)	2.0e10	26.3
BCP30+N2/A6+ EP5	3.2e10	19.8
+ EP2(totally EP7)	4.1e10	20.0
+ EP2(totally EP9)	3.6e10	20.7

Medium Doping



- BCP 200 μm + EP 50 μm + 900°C 3 h
- N10/A20
- EP 5/10/15 μm, vertical test
- + EP 5 μm, vertical test

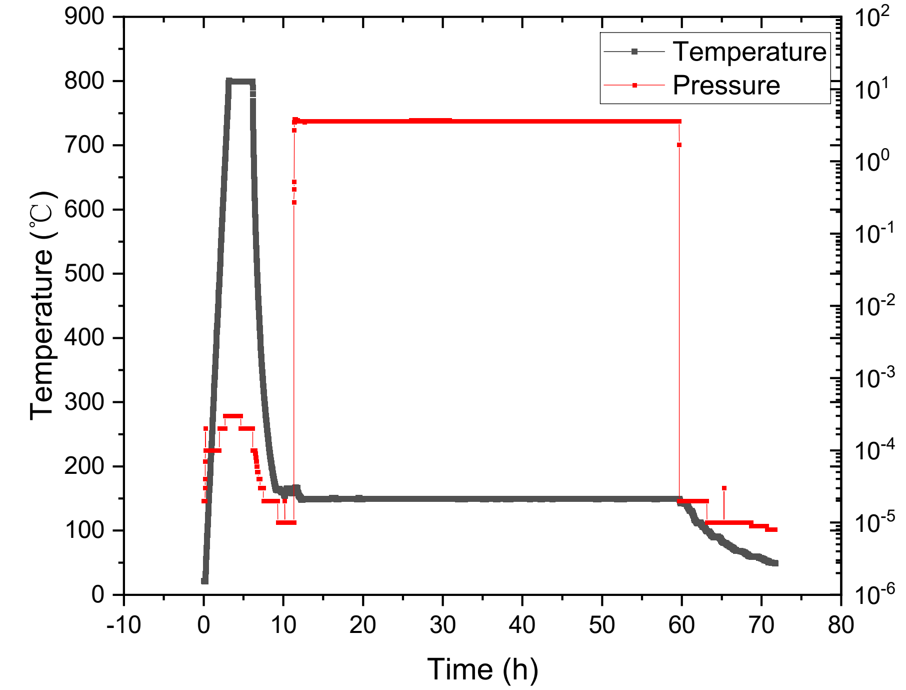


Treatment	Q_0 (2K,16MV/m)	E_{acc} (MV/m)
NMFG02, N10A20 + EP5	2.5e10	20.7
NMFG03, N10A20 + EP10	4.2e10	18.9
NMFG04, N10A20 + EP15	4.4e10	21.8

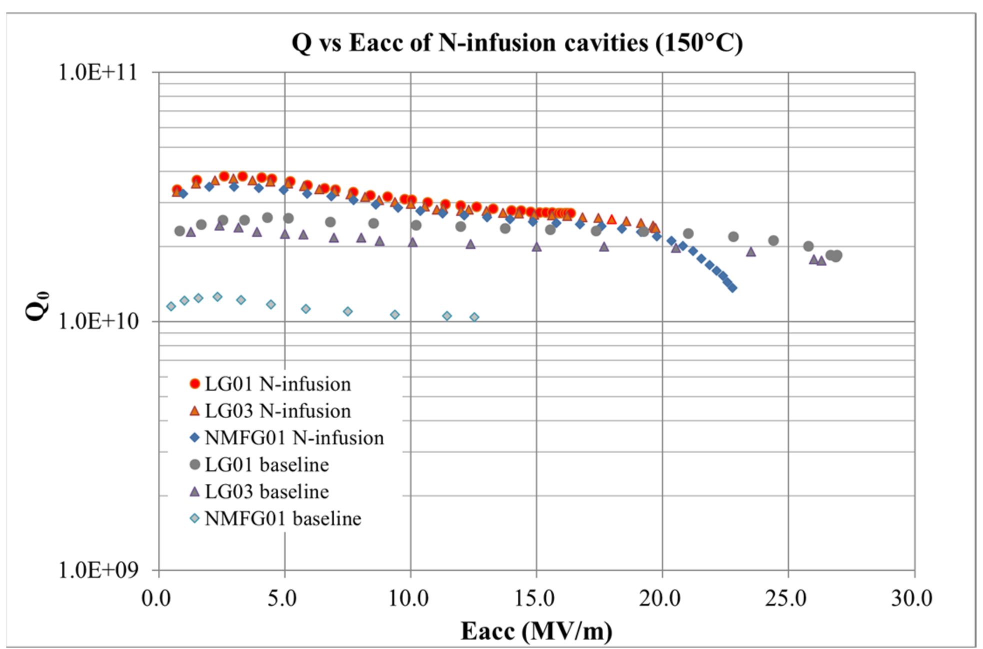
EP10, Q_0-4.2e10@16MV/m
After 7 month, Q_0-3.8e10@16MV/m

Nitrogen infusion

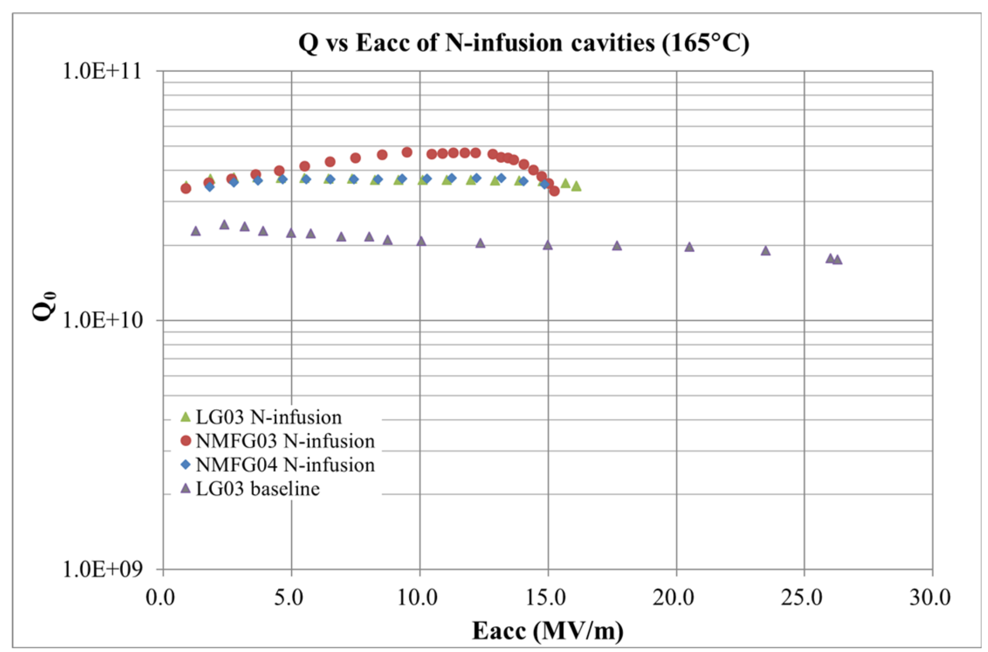
- BCP to remove the N-surface (if exist)+HPR
- 800°C 3 h (sealed with Nb cap)
- cool down to 150-180°C
- N-infusion at 3.5 Pa, 48 h
- Cavities: 1.3 GHz, 650 MHz, 162.5 MHz



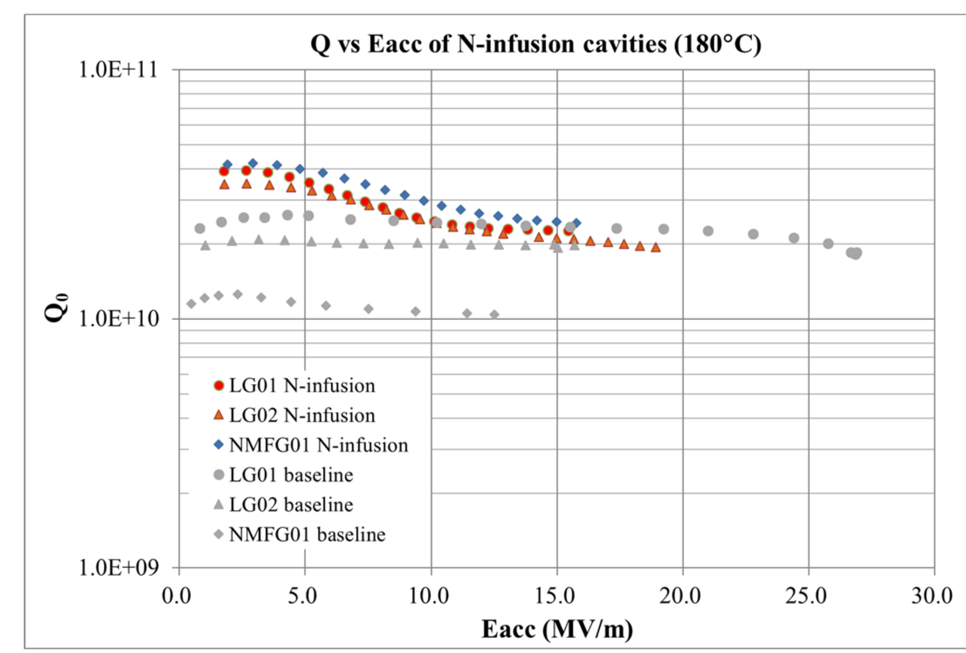
N-infusion of 1.3 GHz cavities



150°C

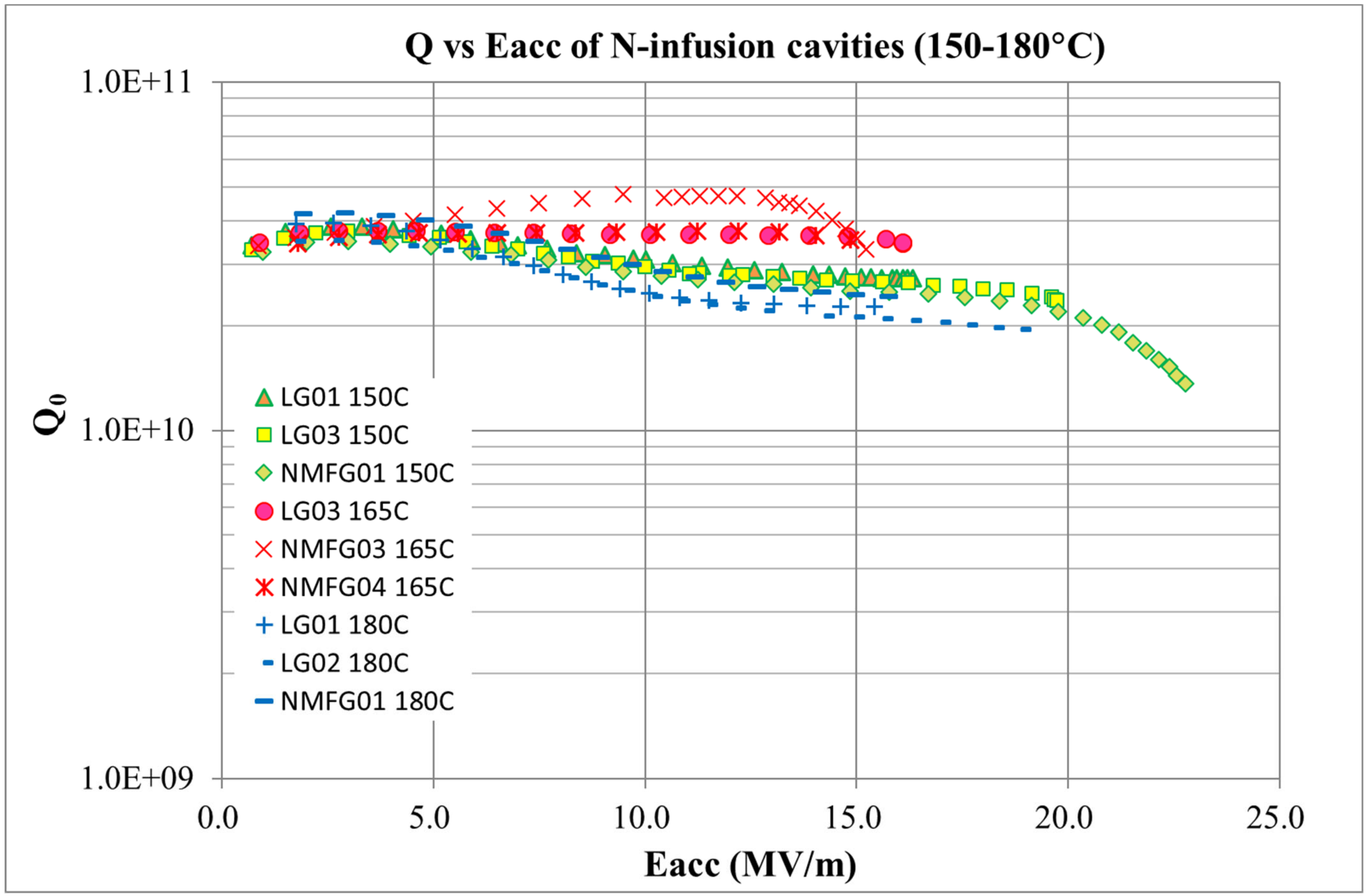


165°C



180°C

Nitrogen infusion



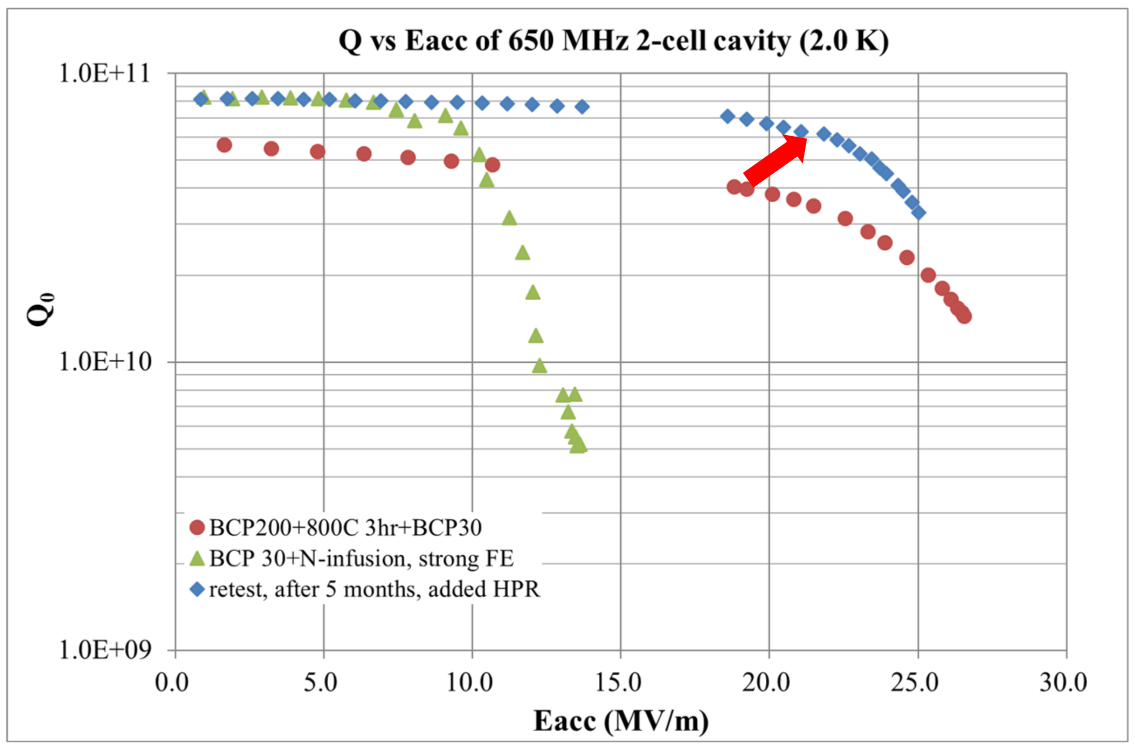
N-infusion of1.3GHz cavities

Treatment	Q_0(2K)
LG01, 150°C	2.7e10@16.0MV/m
LG03, 150°C	2.7e10@16.0MV/m
NMFG01, 150°C	2.5e10@16.0MV/m
LG03, 165°C	3.5e10@16.0MV/m
NMFG03, 165°C	3.3e10@15.2MV/m
NMFG04, 165°C	3.5e10@14.9MV/m
LG01, 180°C	2.3e10@15.5MV/m
LG02, 180°C	2.0e10@16.0MV/m
NMFG01, 180°C	2.4e10@15.8MV/m

Q improvement: 165°C > 150 °C > 180 °C

Nitrogen infusion

- 650 MHz 2-cell, CEPC cavity
- Nitrogen infusion, 165°C



Baseline, BCP200+800C+BCP30

$Q_0 \sim 3.8 \times 10^{10}$ (2.0 K, 20 MV/m)

BCP30+N-infusion

$Q_0 \sim 6.7 \times 10^{10}$ (2.0 K, 20 MV/m)

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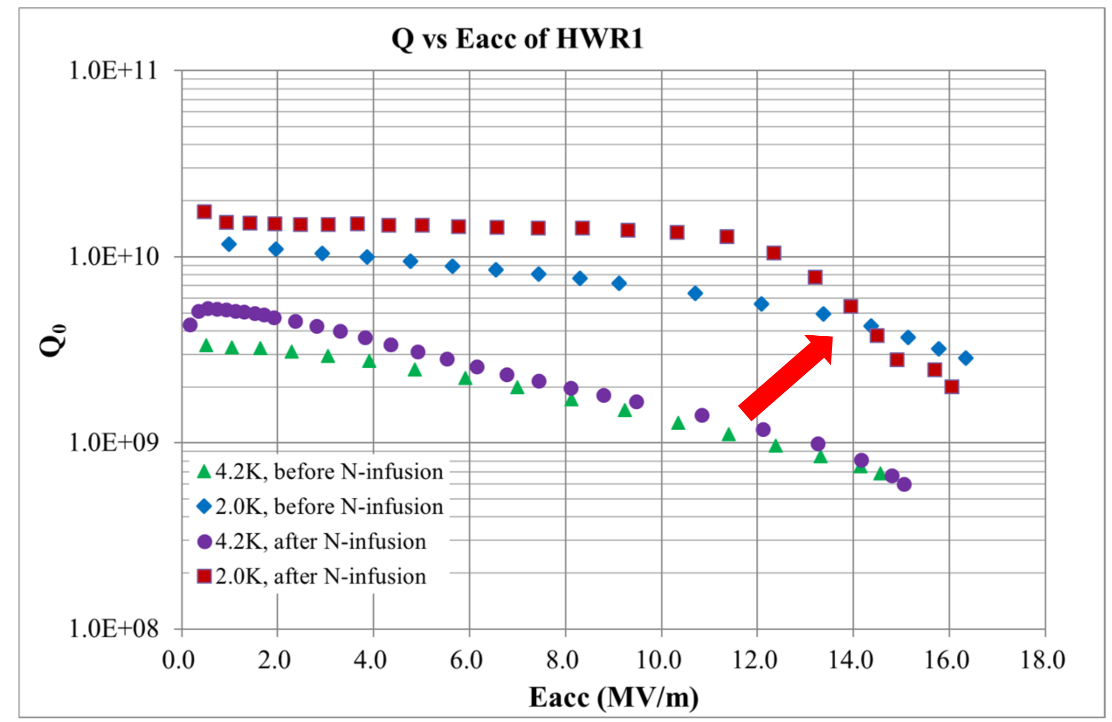
- 162.5 MHz HWR
- Nitrogen infusion, 160°C



Before infusion

$Q_0 \sim 7.9 \times 10^9$ (2.0K, 10 MV/m)

1.3×10^9 (4.2K, 10 MV/m)

After infusion

$Q_0 \sim 1.4 \times 10^{10}$ (2.0 K, 10 MV/m)

1.6×10^9 (4.2 K, 10 MV/m)

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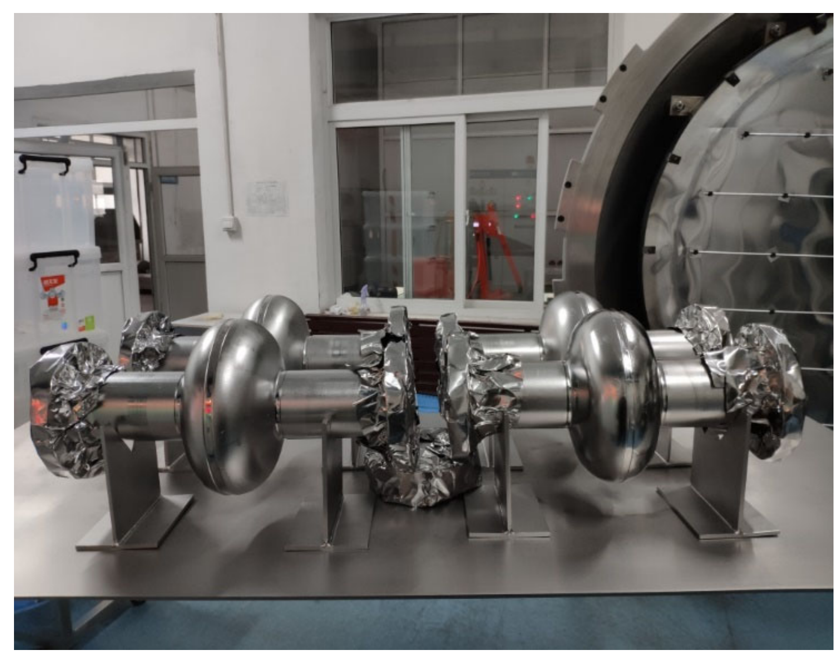
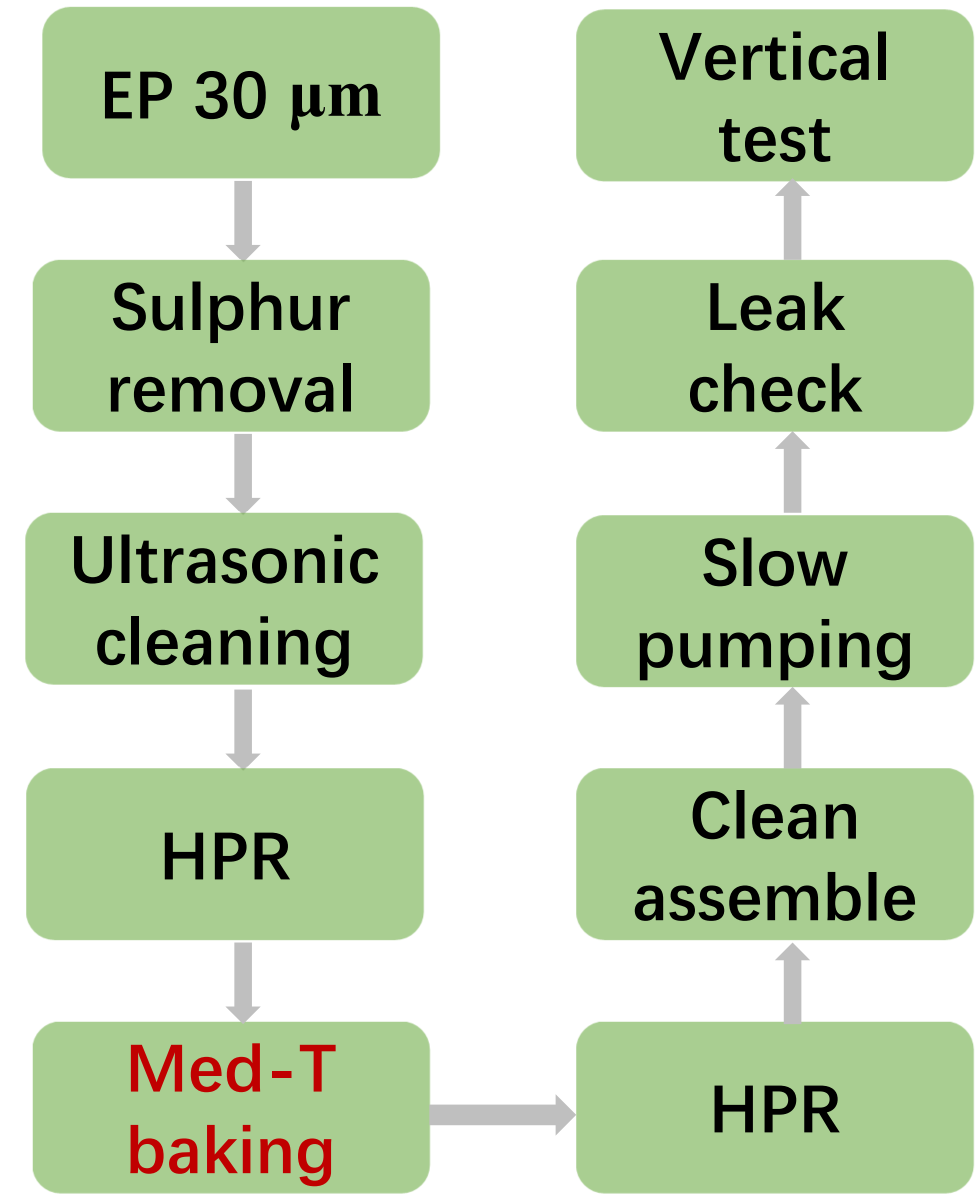
Medium temperature baking

- Advantages of medium temperature baking
  - N-doping: high Q, E_{acc} is limited, post-EP
  - N-infusion: high Q, high E_{acc}, no post-EP, long infusion time
  - Medium T baking, high Q, high E_{acc}, no post-EP
- Medium temperature baking
  - Proposed by FNAL
  - Developed at FNAL, IHEP, Jlab, Cornell, KEK, PKU, SARI…
- Med-T at PKU
  - 1-cell cavities
  - 9-cell cavities

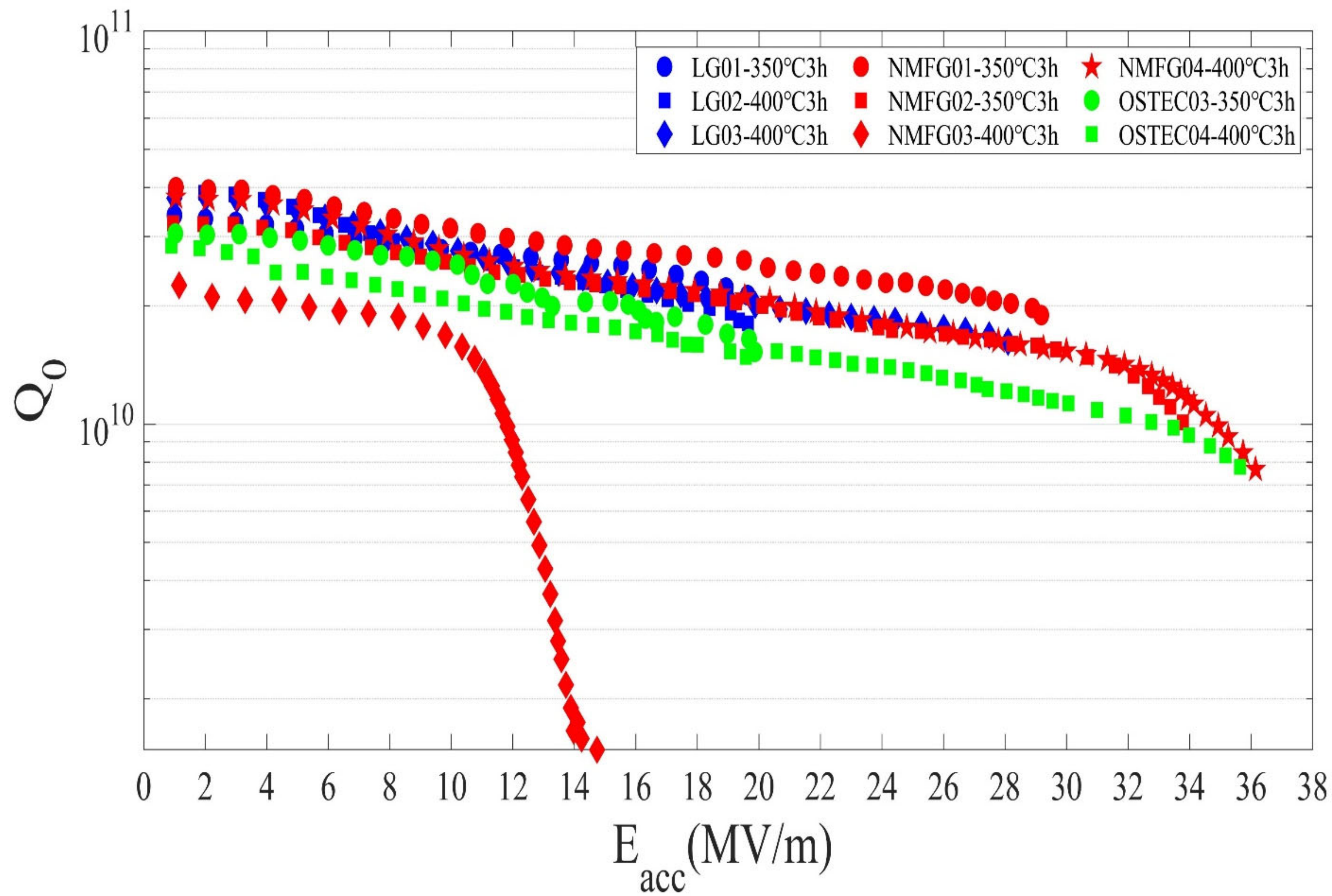
1-cell cavities
350-400°C 3h

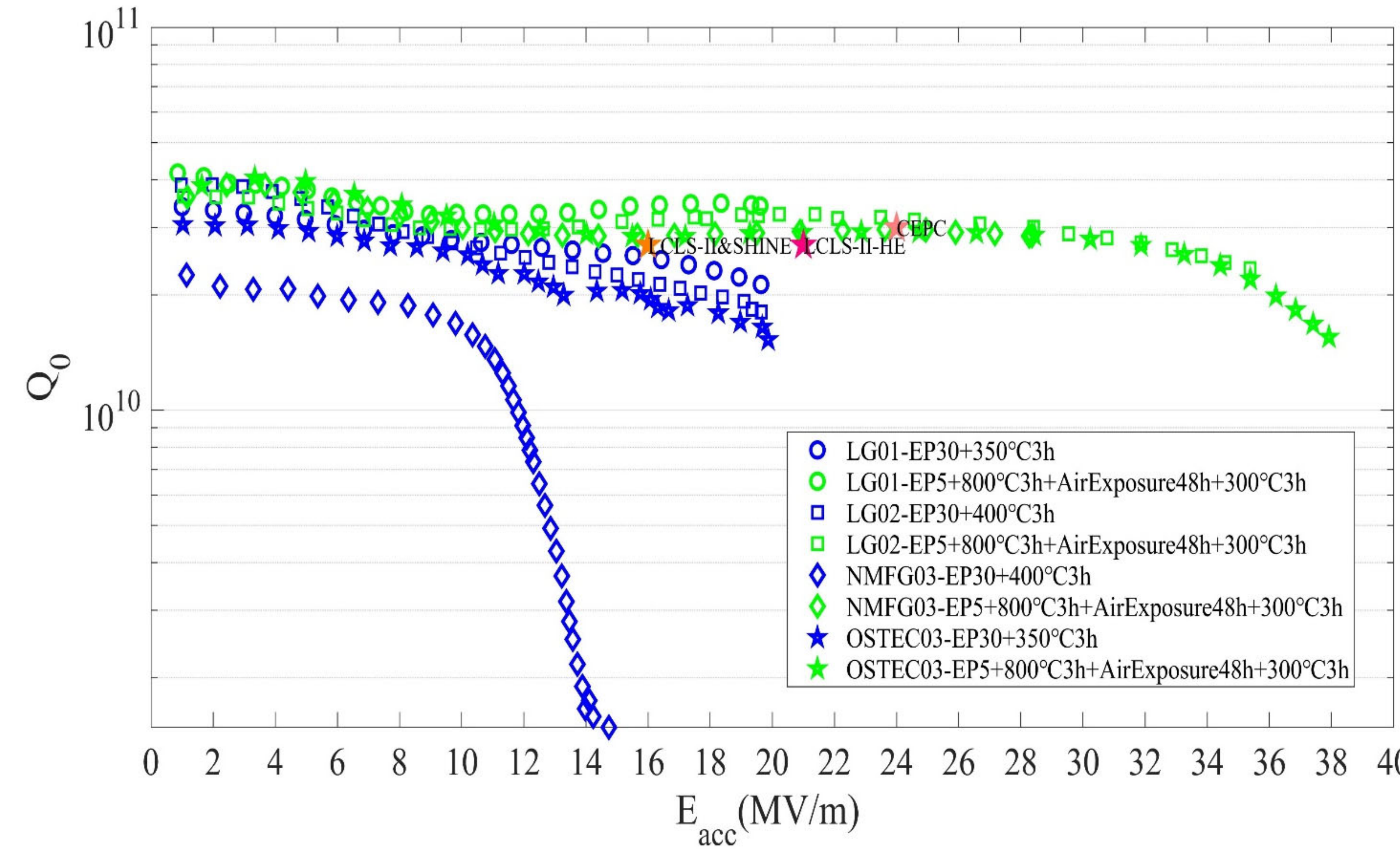




Med-T for 1-cell cavities

Med-T for 1-cell cavities





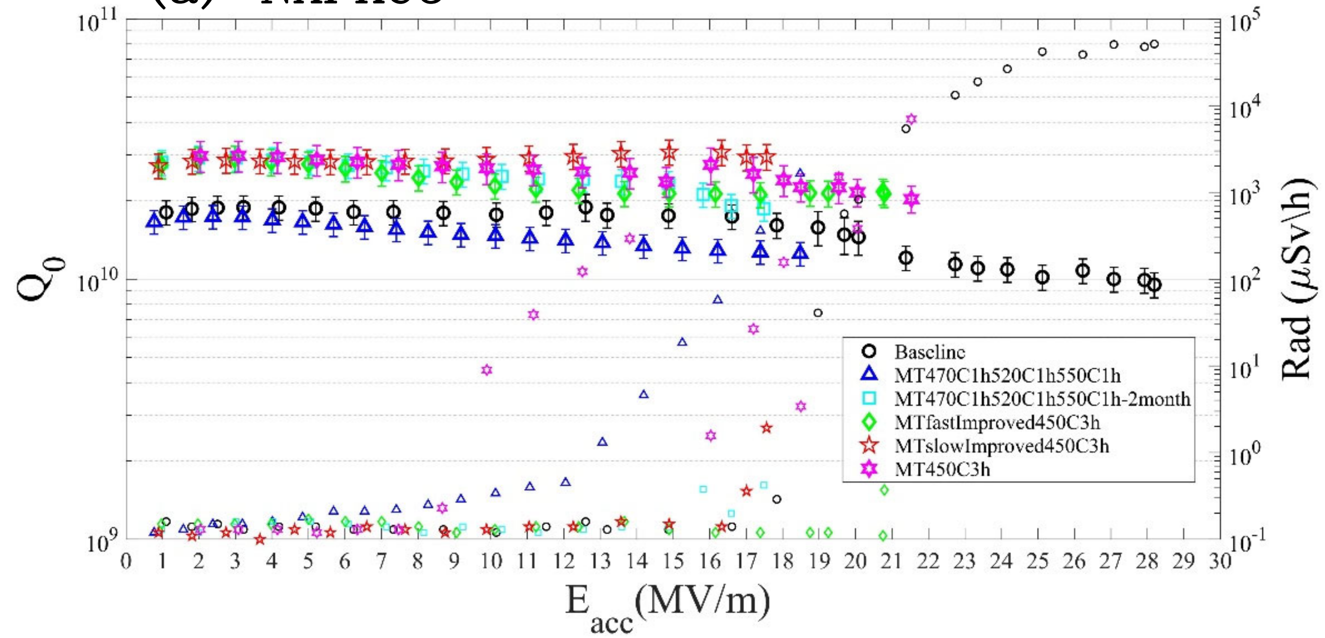
Preliminary Med-T, 350-400°C, continuous Q-slope

Improved Med-T: Q improved
800°C3h+AirExposure48h+300°C3h
Q_0: 2.8-3.4E10@16MV/m

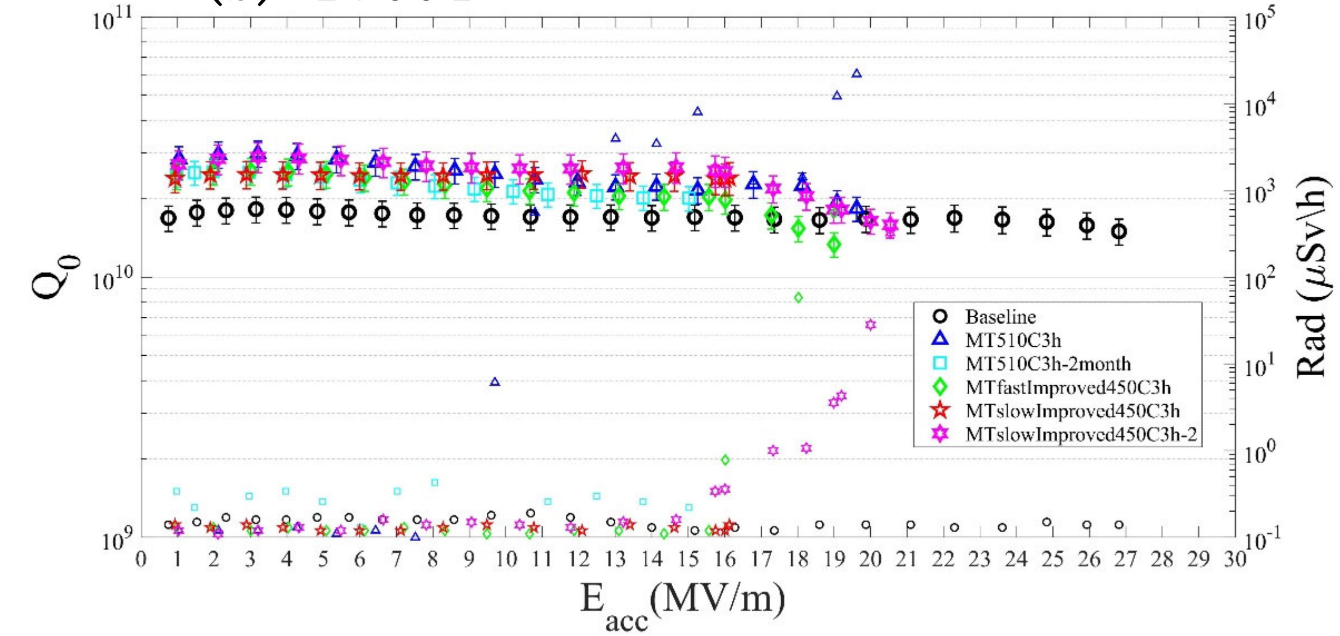
Physica C: Superconductivity and its applications 599 (2022) 1354092

Med-T for BCPed large grain 9-cell cavities

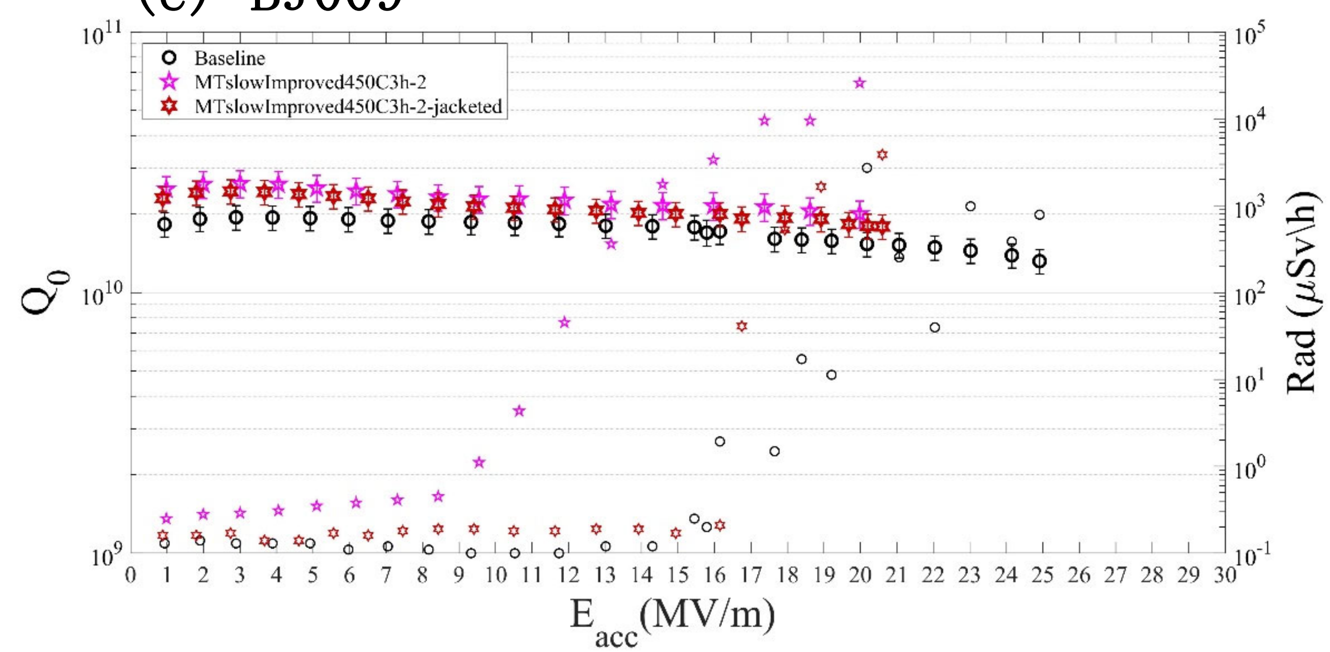
(a) NXPKU3



(b) BJ004



(c) BJ009



- Better parameters:

3 h 800℃ 3 h – Air Exposure 48 h – 2 h 450 ℃ 3 h

- $Q_0 \sim 2.7 \times 10^{10}$ @ 16 MV /m

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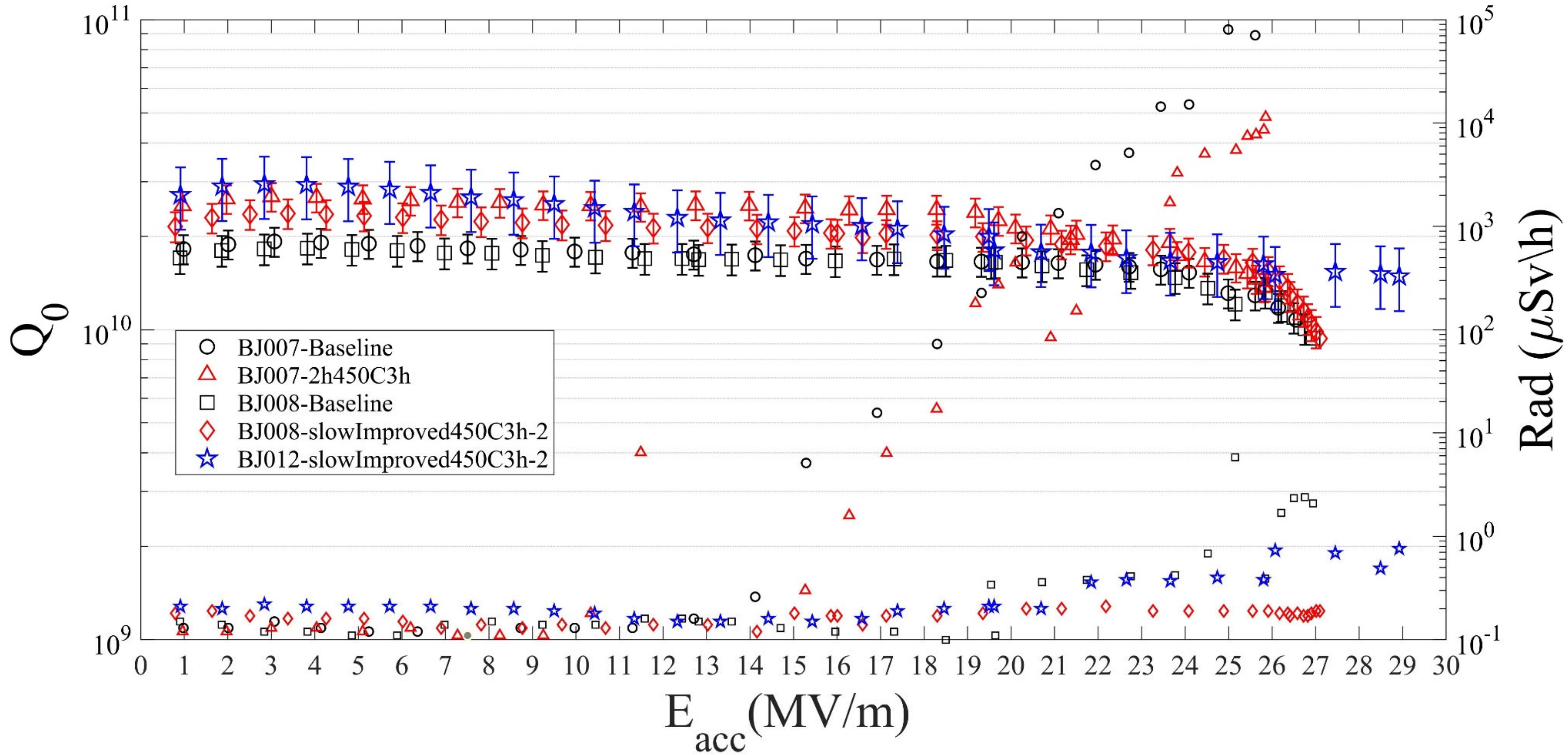
Med-T for EPed fine grain 9-cell cavities



- 3 h 800°C 3 h – Air Exposure 48 h – 2 h 450 °C 3 h
- $Q_0 \sim 2.3 \times 10^{10}$ @ 16 MV /m

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Compact electron accelerator

Application of electron beams

- **Scientific research**

  material detection, X-ray

- **Industrial application**

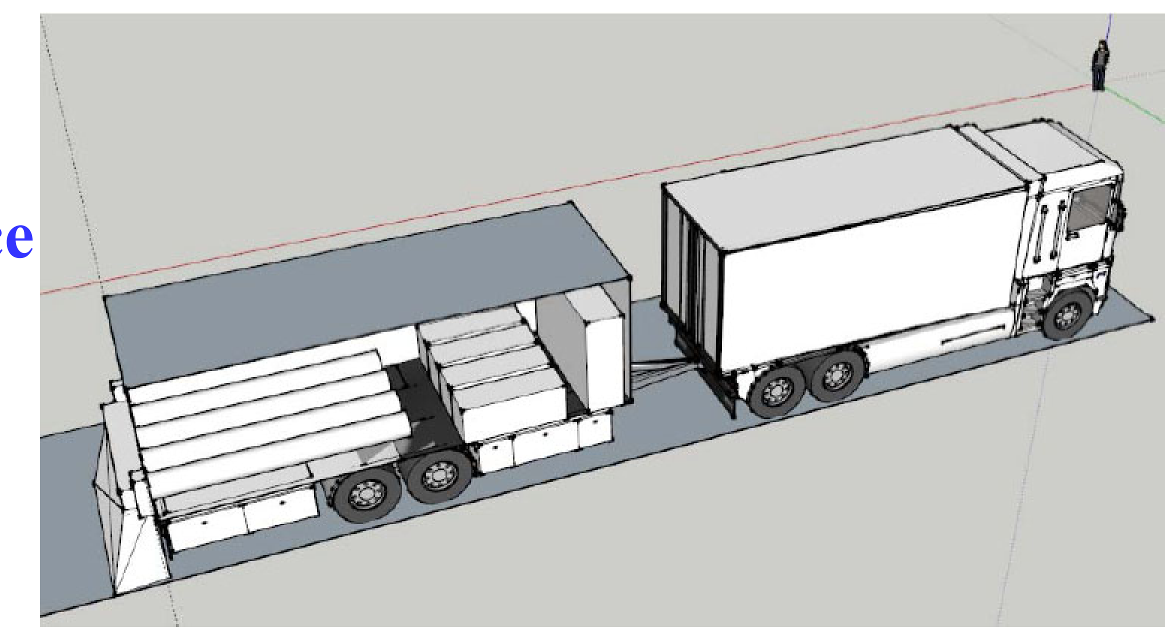
  imaging, iridation

- **Application in environmental fields**
  - Waste water 10MeV, 1MW
  - Flue gas desulfurization 1-2MeV, 1MW
  - Medical waste 10MeV，100kW

	Demo/ Small Scale	Medium Scale Low Energy	Medium Scale High Energy	Large Scale High Energy
Description	Demo and pilot-scale low-energy systems	MW-class, industrial-scale, low-energy systems based on DC technology	MW-class, industrial-scale, high-energy systems	10 MW-class, industrial-scale systems based on RF technology
Applicability to E&E Needs	Sterilization, R&D	Flue gas, wastewater	Wastewater, sludge, medical waste	Wastewater, sludge, medical waste
Electron Beam Energy	0.5–1.5 MeV	1–2 MeV	10 MeV	10 MeV
Electron Beam Power	>0.5 MW	>1 MW	>1 MW	>10 MW
Electron Beam Current	0.33–1.0 A	0.5–1.0 A	0.1 A	1 A

compact， portable，
low cost， high performance

Industrial application



Compact electron accelerator

Requirement for industrial application: MeV, MW

	MeV	MW
NC	√	×
SC	√	√

But for SRF accel.: large cryogenic

Solution:

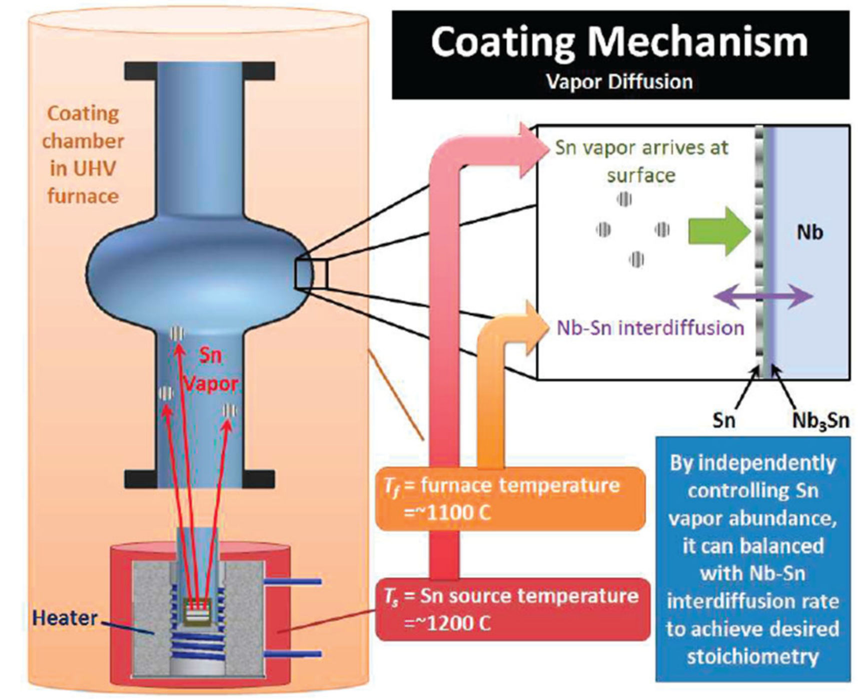
Higher T_c material: Nb_3Sn

Conduction cooling with cryocooler

} **compact**

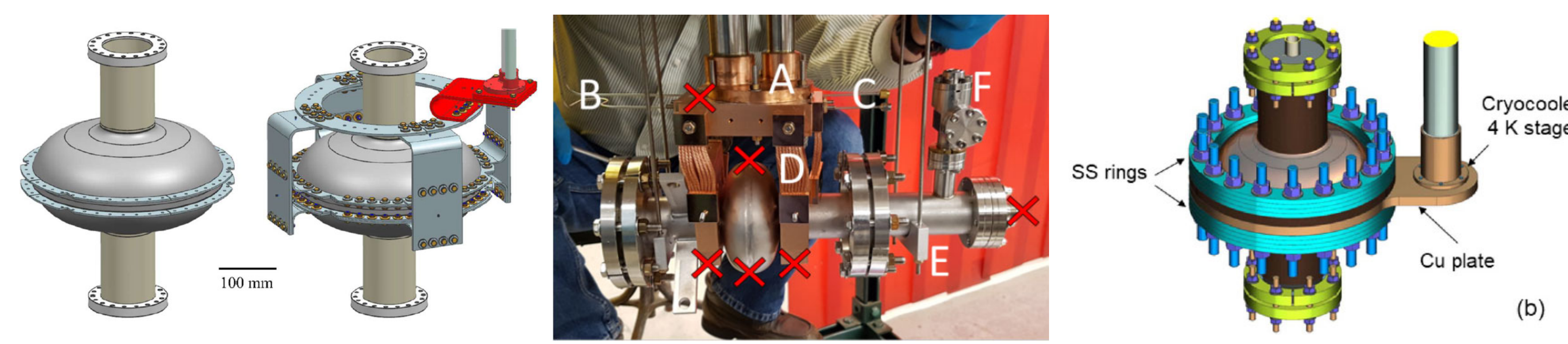
Nb_3Sn film preparation

- **Vapor diffusion**
- **Magnetron sputter**
- **Bronze method**
- **Electroplating**
- **……**



Tin vapor diffusion

Conduction cooling



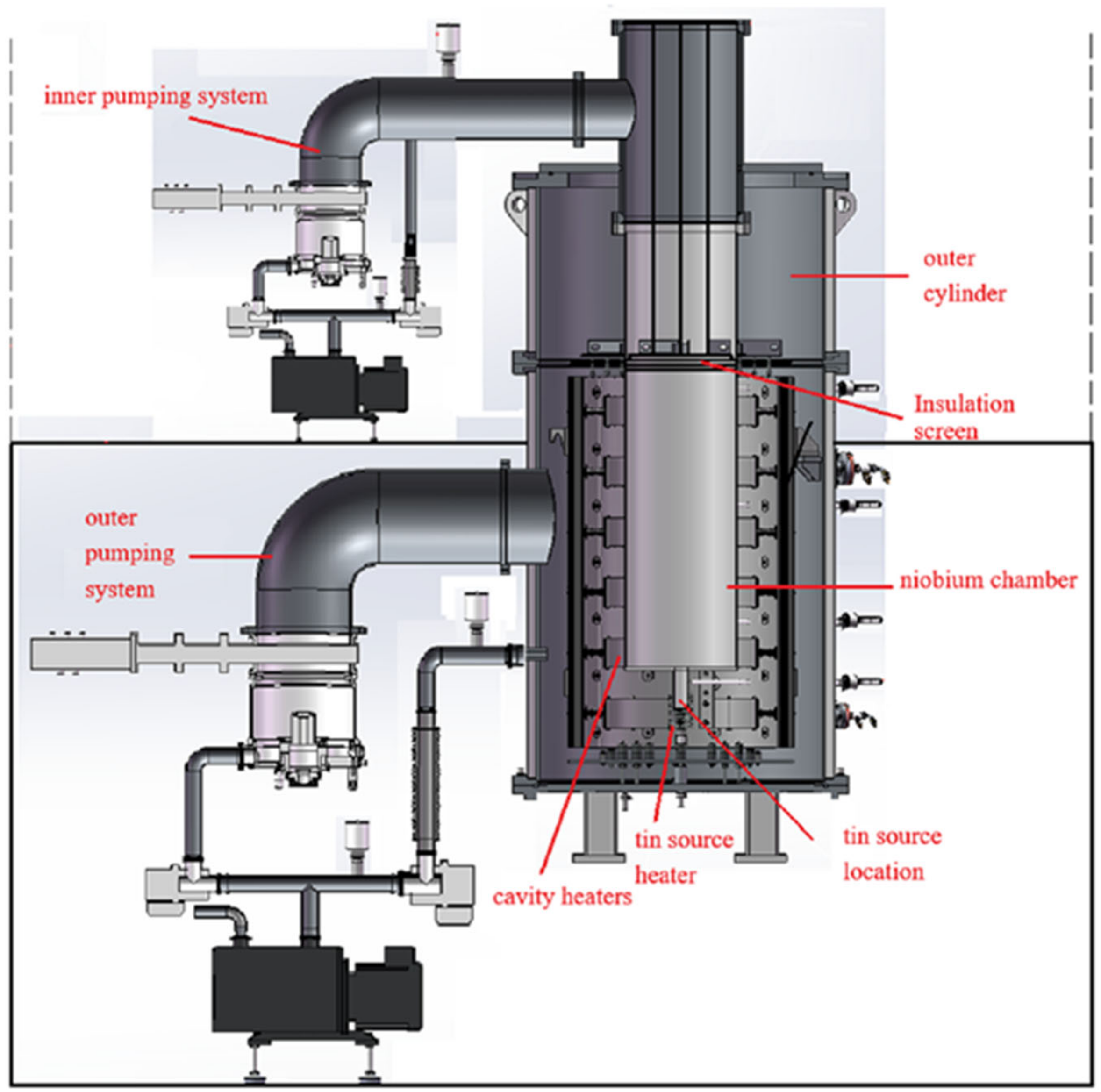
Conduction cooling structure

Nb_3Sn film cavities

Tin vapor diffusion method for Nb_3Sn coating on Nb cavities

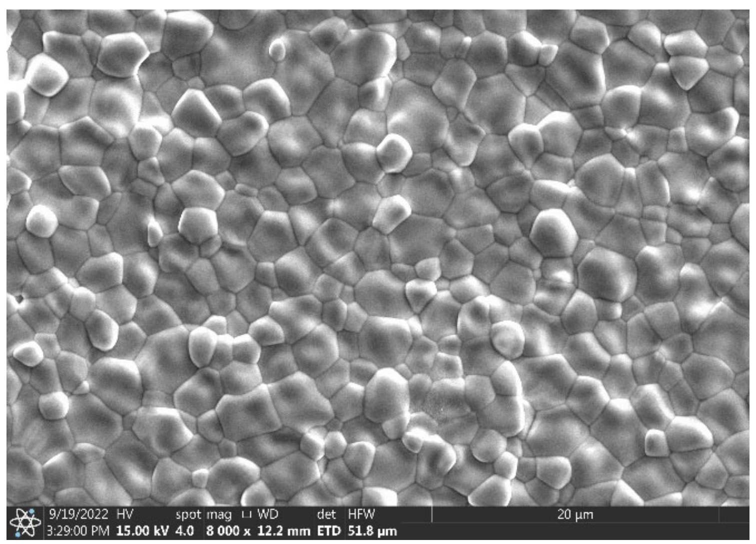
High T furnace

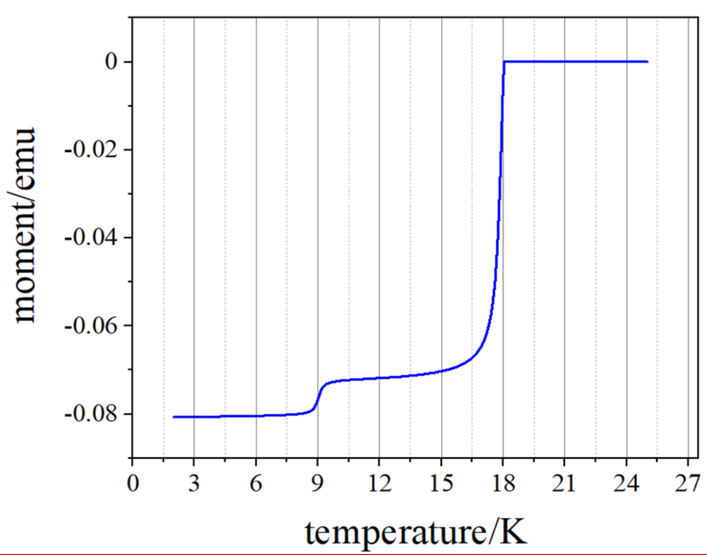
- Const T area:
  diameter 300mm
  height 600mm
- Temperature stability
  <±5°C
- Temperature ramp
  ≥10°C/min
- background vacuum
  ≤5×10^{-5} Pa

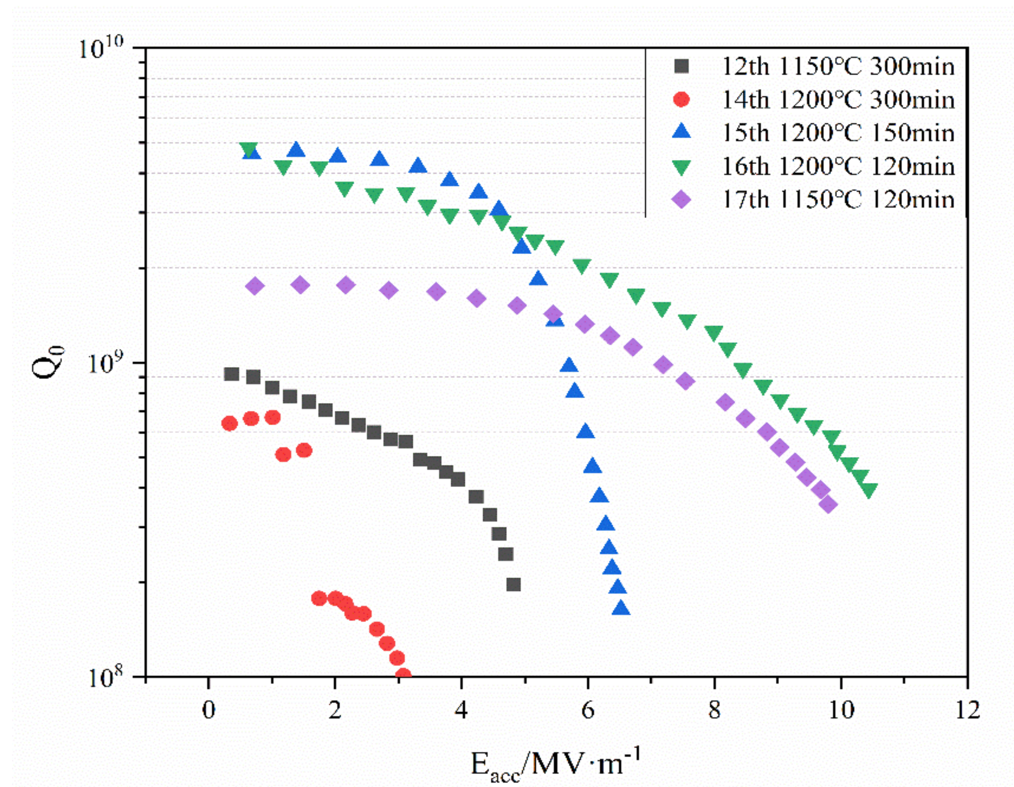


Nb_3Sn film cavities

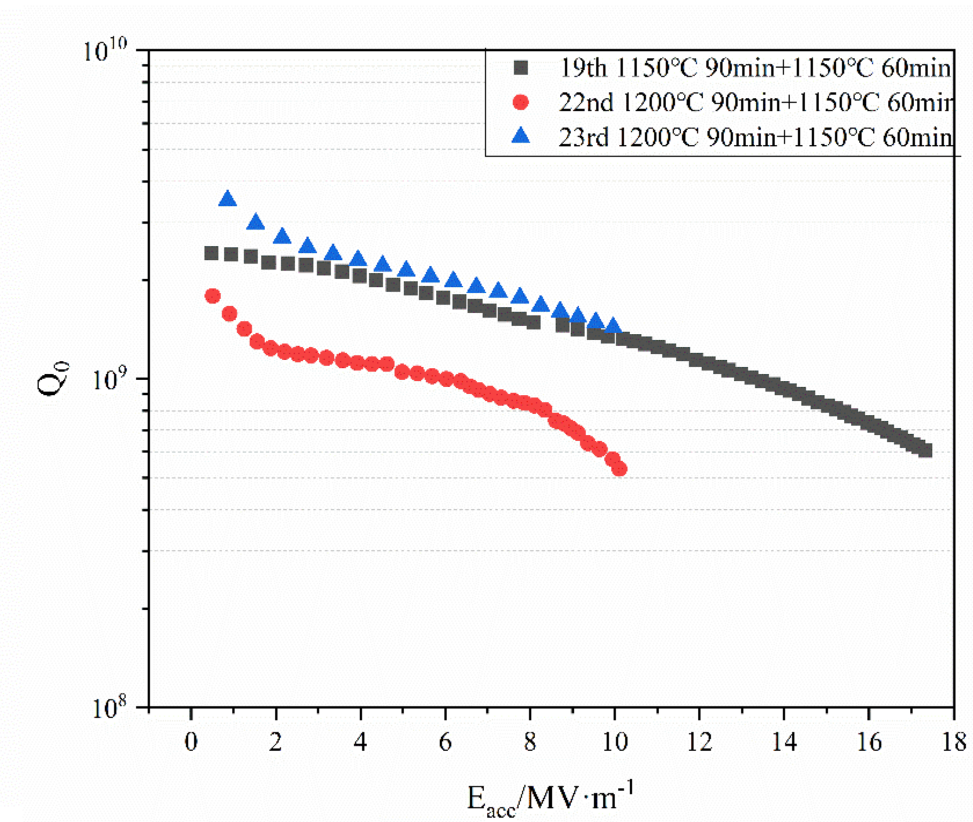
- T_c~18.1K
- Tin: 25-26%
- Thickness of Nb_3Sn film:1~2 μm







without annealing stage



with annealing

Vertical test at 4.2 K

Q_0 ~ 4.8×10^9 @ low field

max. E_{acc} ~ 17.3MV/m

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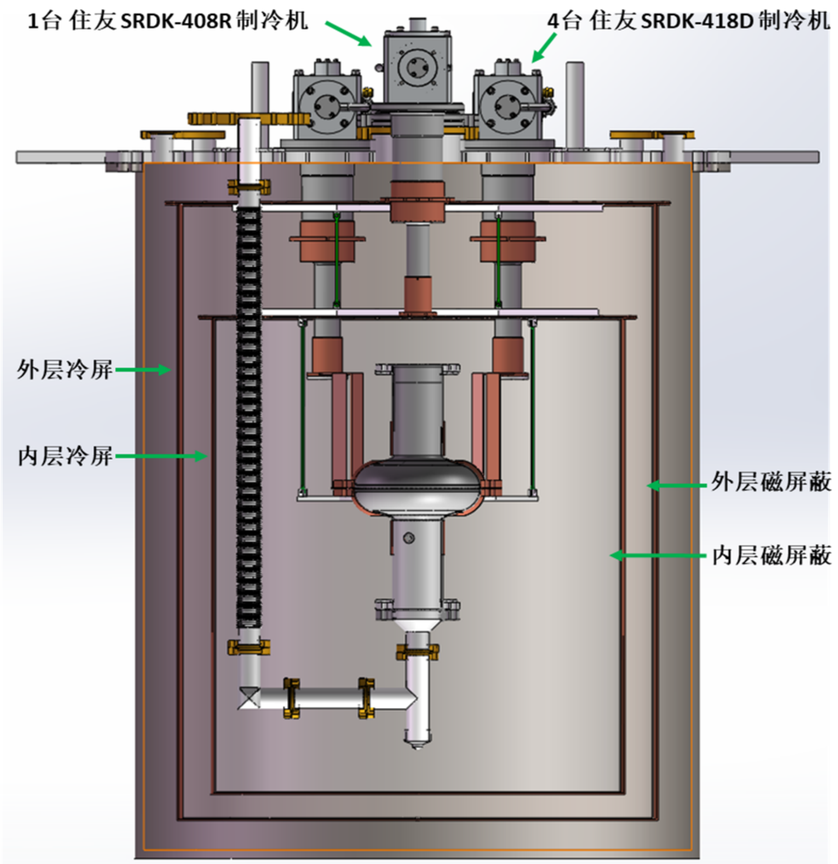
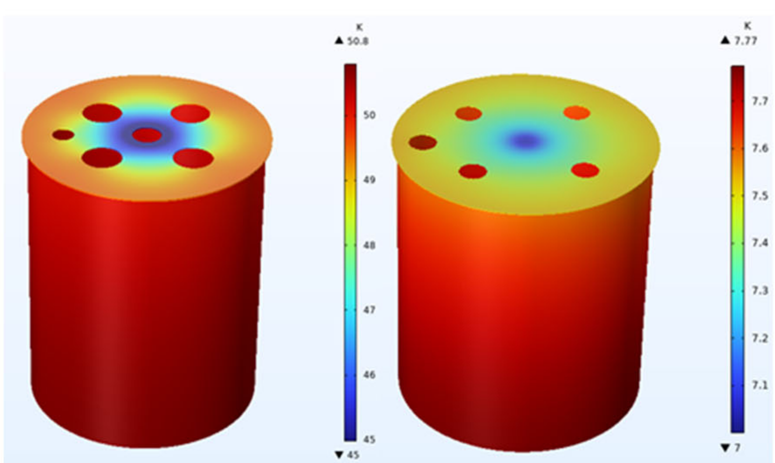
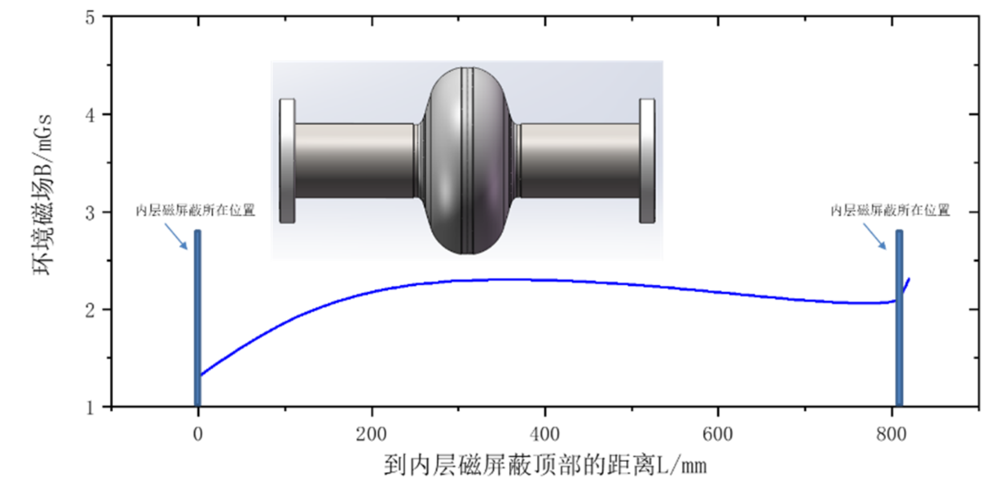
Conduction cooling test cryostat

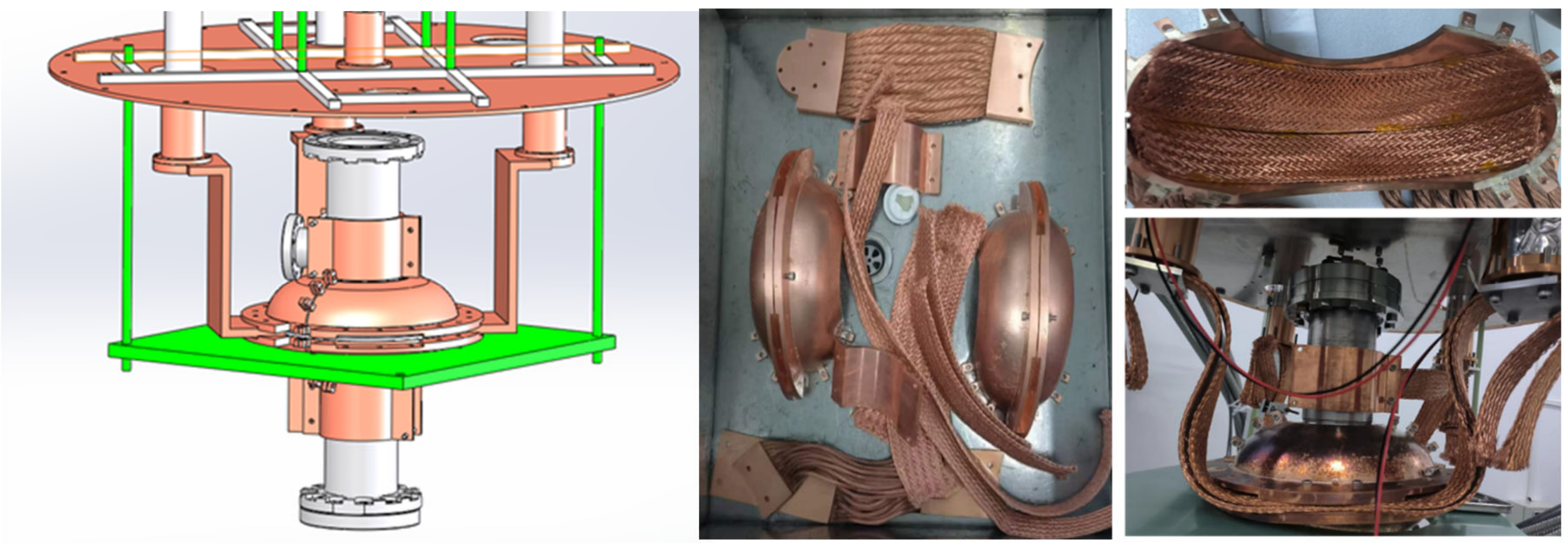




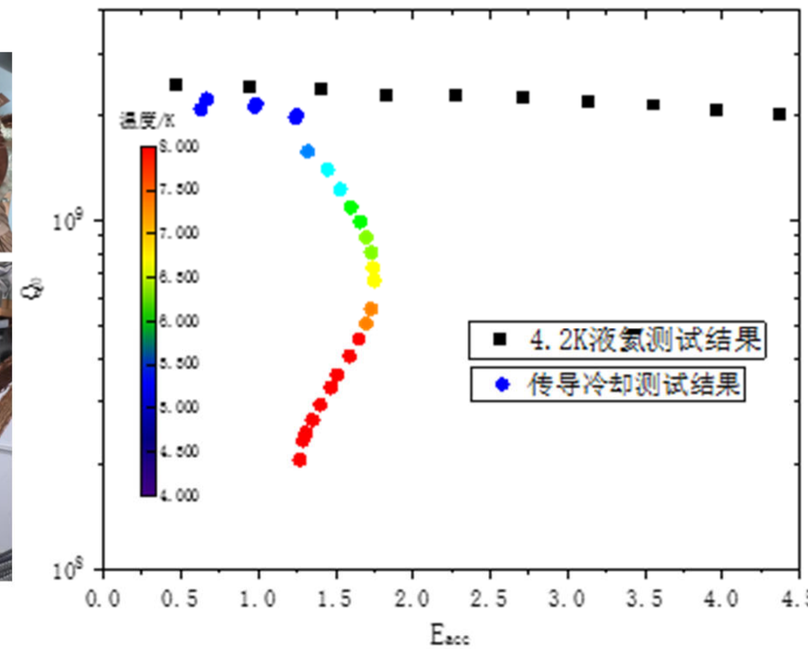


- For 1-cell 1.3 GHz cavity
- 5 Sumitomo cryocooler
  1 for thermal shield, 4 for cavity
- Heat loss@4K
  < 0.02 W
- Residual magnetic field
  < 3 mGs

Conduction cooling of SRF cavities



Connection with copper hoop and strip

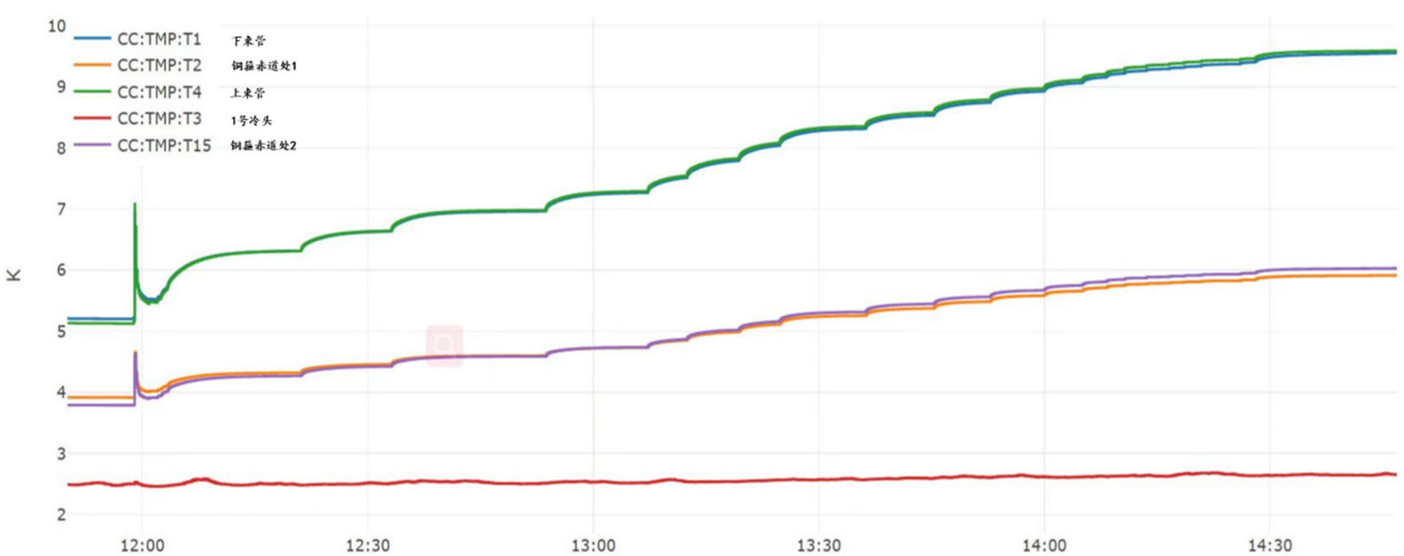


- CW running of Nb_3Sn cavity with conduction cooling

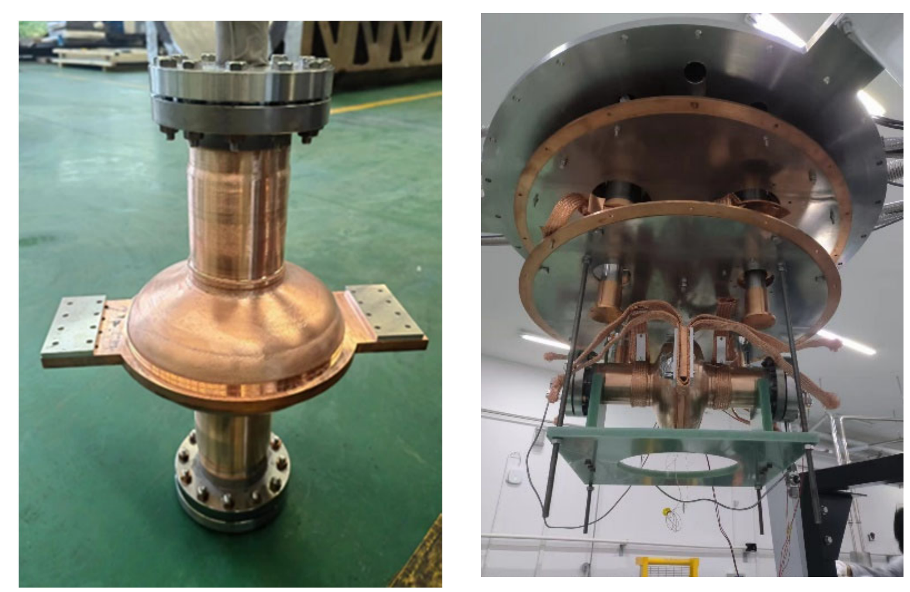
  $Q_0 = 6.7 \times 10^8$

  $@E_{acc,max} = 1.75MV/m$

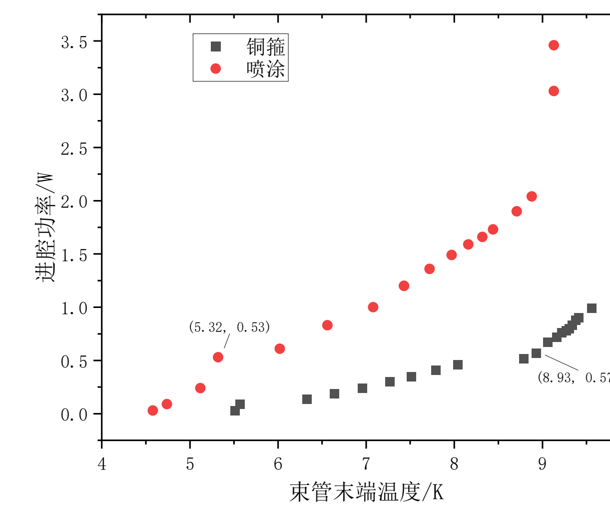
  - Cavity heat loss: 0.58W
  - Ave. T of cavity ~ 7K



Temperature during RF test



Cold spraying with copper



- Improvement by Cold spraying with copper
- Cavity T~5.5K @0.58W

Summary

- Q_0 of $> 3.0\times10^{10}$ @ 16 MV/m @ 2K is obtained with both N-doping and N-infusion for 1.3 GHz cavities
- N-infusion is also effective to improve Q_0 of cavities with lower frequencies and/or complicated shape
- Medium temperature baking is successfully used for 9-cell cavities to improve the Q_0
- Nb_3Sn cavities and conduction cooling experiments are successfully carried out, improvement of Q_0 of Nb_3Sn cavity is in process.

Acknowledgements

We give great thanks to

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Thank you for your attention !