Development of the Directly-Sliced Nb material for High Performance SRF Cavities

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- Introduction
- Mechanical characterization of large Grain and medium grain Niobium
- LG Nb 1.3 GHz SRF cavity study
- MG Nb 1.3 GHz SRF Cavity study

Introduction

- Directly-sliced Nb materials are referred to Large Grain and Medium Grain Nb.
- These materials are cost effective compared to Fine Grain Nb due to their manufacturing process.
- In this presentation, the results on mechanical characterization and cavity performance for directly-sliced Nb materials will be shown.

Mechanical Characterization of Nb

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz
Nb SRF Cavity

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz
Nb SRF Cavity

Fine Grain (FG) Nb

- Grain size < 50 µm
- Isotropic mechanical properties.
- Uniform and adequate properties.
- High Cost.

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz
Nb SRF Cavity

Conventional Material

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Niobium for 9-Cell 1.3 GHz SRF Cavity

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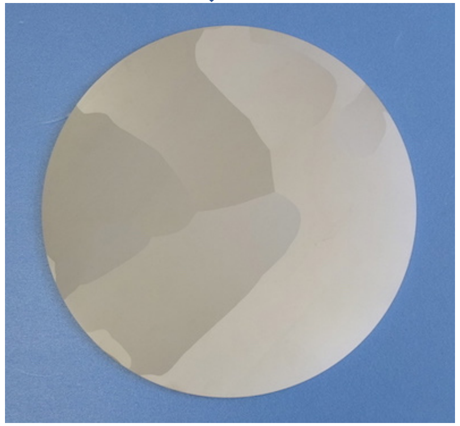
9-Cell 1.3 GHz Nb SRF Cavity

Conventional Material



Fine Grain (FG) Nb

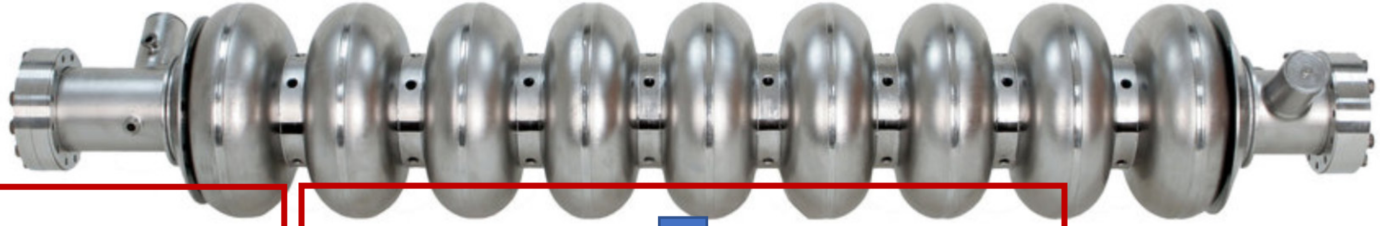
- Grain size < 50 µm
- Isotropic mechanical properties.
- Uniform and adequate properties.
- High Cost.

Large Grain (LG) Nb

- Grain size > 1 cm.
- Anisotropic mechanical properties.
- Issue with HPGS clearance
- Low Cost.

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz
Nb SRF Cavity



Conventional Material

Fine Grain (FG) Nb

- Grain size < 50 μm
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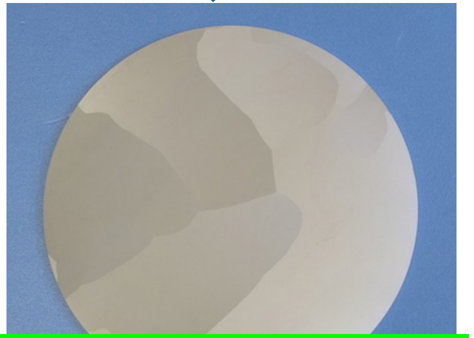
- High Cost.



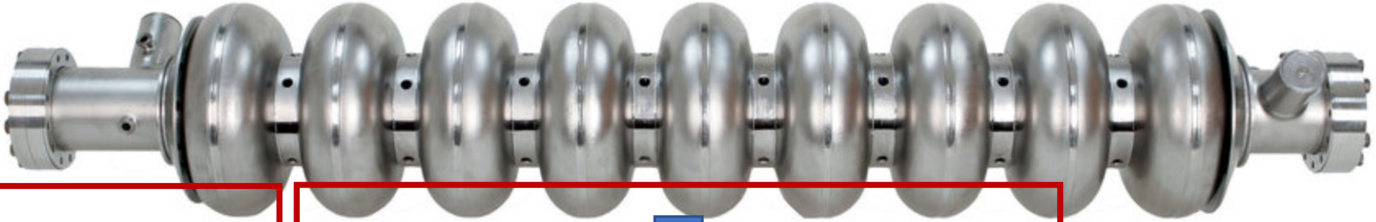
R & D Material

Large Grain (LG) Nb

- Grain size > 1 cm.
- Anisotropic mechanical properties.
- Issue with HPGS clearance
- Low Cost.

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz Nb SRF Cavity



Conventional Material

Fine Grain (FG) Nb

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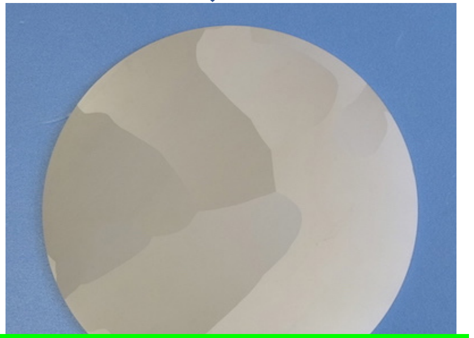

R & D Material

Large Grain (LG) Nb

- Grain size > 1 cm.
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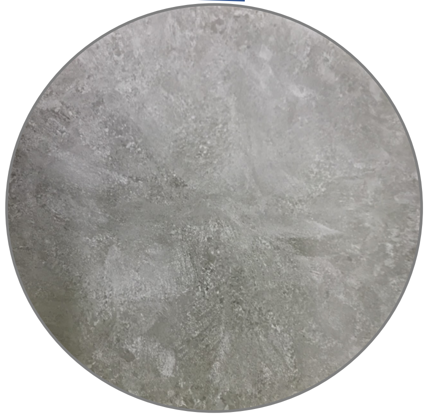
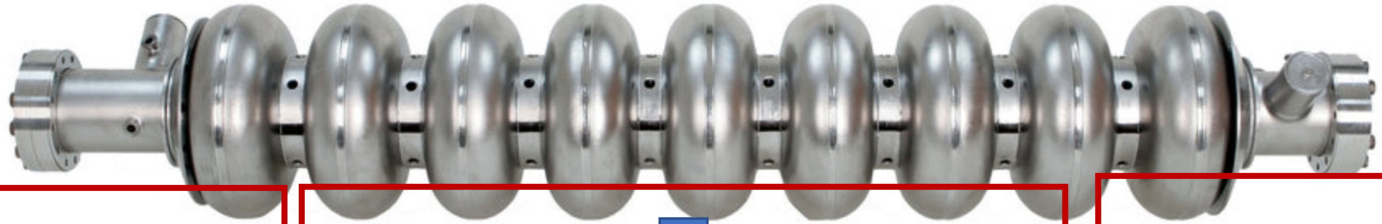


ATI Medium Grain (MG) Nb

- Grain size - 200-300 µm, occasional 1-2 mm grains
- Isotropic properties ✓
- Viable for SRF cavity ✓
- Cost reduction w.r.t FG Nb ✓

Niobium for 9-Cell 1.3 GHz SRF Cavity

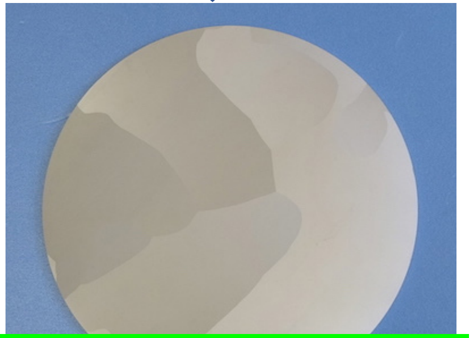
9-Cell 1.3 GHz Nb SRF Cavity



Conventional Material

Fine Grain (FG) Nb

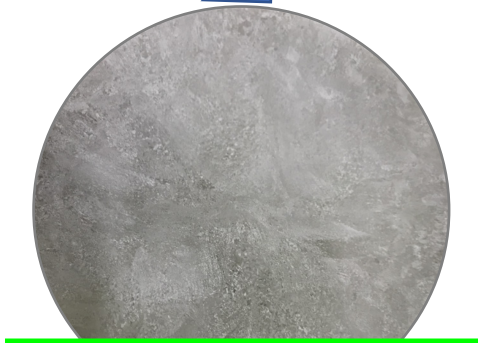
- Grain size < 50 µm
- Isotropic mechanical properties.
- Uniform and adequate properties.
- High Cost.



R & D Material

Large Grain (LG) Nb

- Grain size > 1 cm.
- Anisotropic mechanical properties.
- Issue with HPGS clearance
- Low Cost.

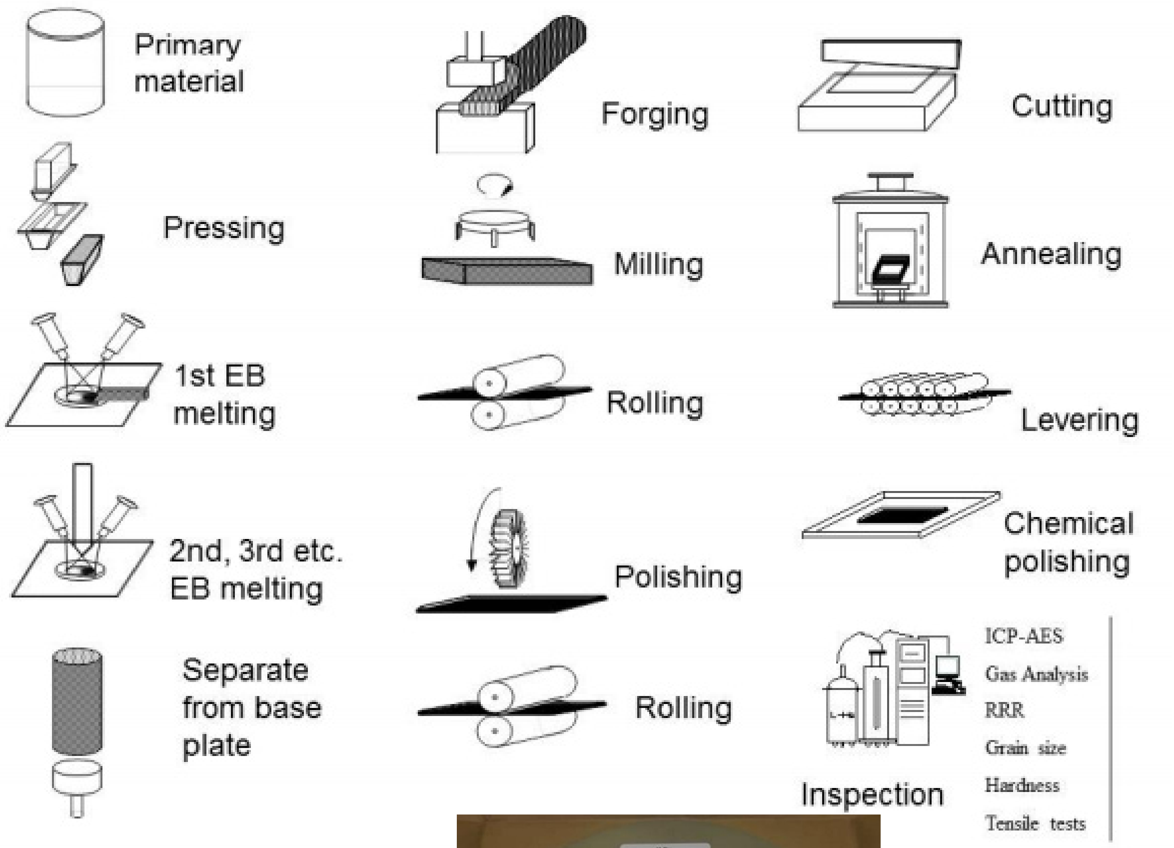


New Material

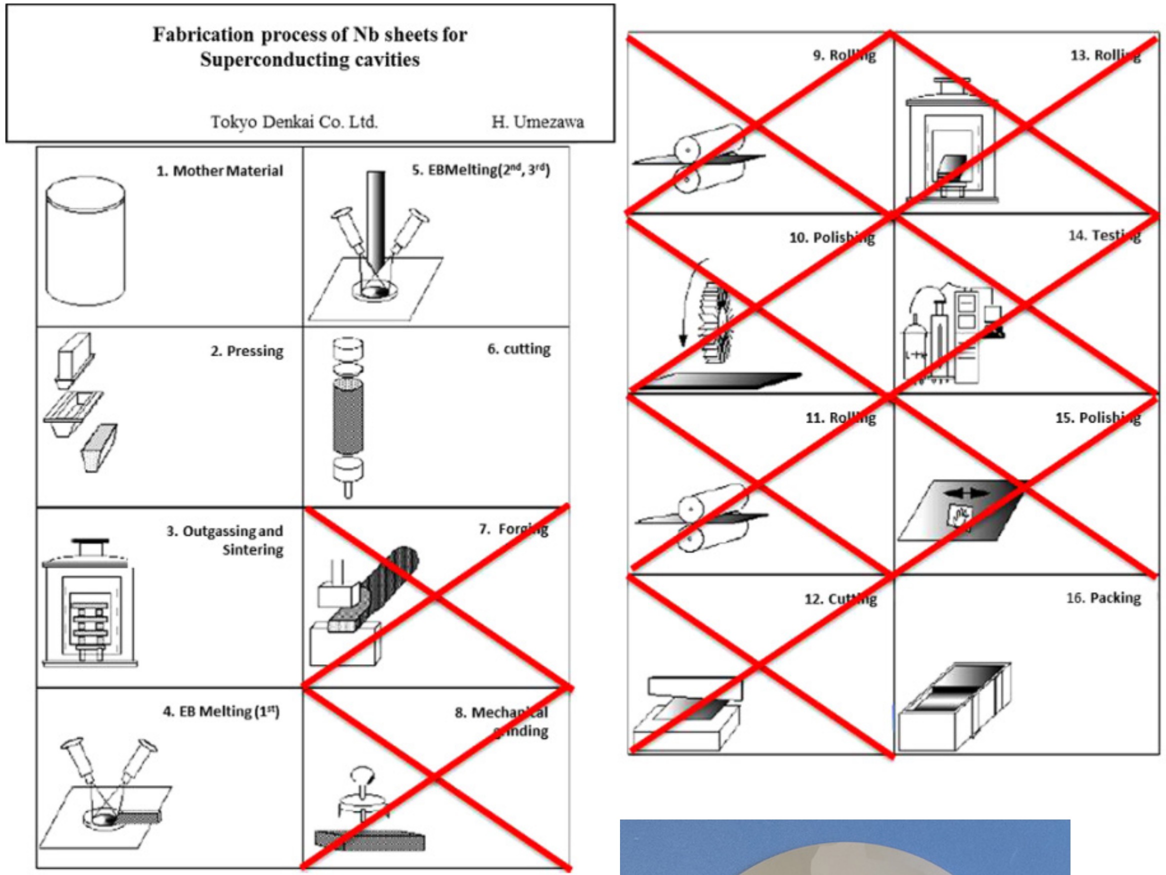
ATI Medium Grain (MG) Nb

- Grain size - 200-300 µm, occasional 1-2 mm grains
- Isotropic properties ✓
- Viable for SRF cavity ✓
- Cost reduction w.r.t FG Nb ✓

Nb Disk Manufacturing

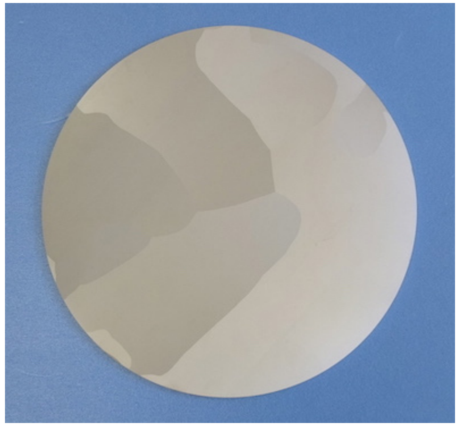


FG Nb



LG Nb

Cited from: Nuclear Instruments and Methods in Physics Research A 774 (2015) 133–150



Manufacturing of LG & MG Nb

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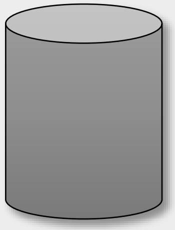
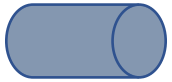
Nb melting

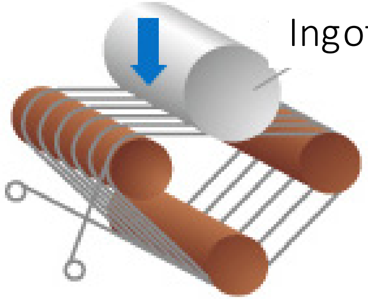


Niobium ingot
(Raw material)

Direct slice of LG ingot

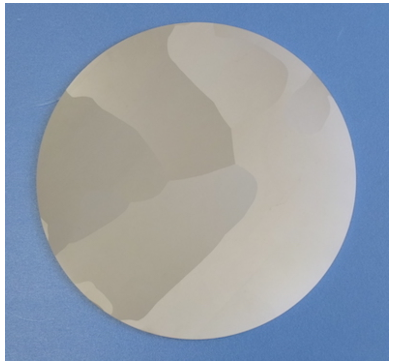


Ingot, as it is



Ingot

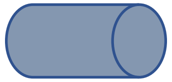
Slicing image
by wire-saw



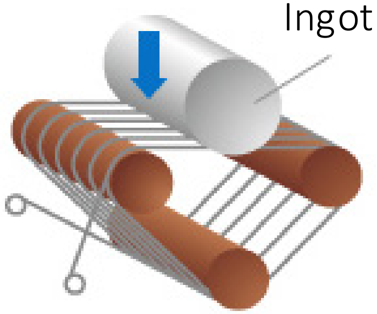
LG Nb

Large Grain (LG) Disc
Grain Size >> 1 cm

Direct slice of MG ingot

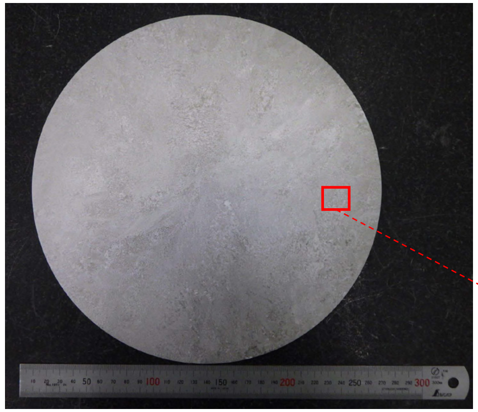


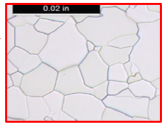
Ingot, forged
and annealed



Ingot

Slicing image
by wire-saw





MG Nb

* The "Nb forged ingot" technology originated by **ATI**, and SRF (GHz) cavities planned to be fabricated and RF tested by **KEK** and **JLab**, to qualify this approach, in collaboration of **ATI, ODU/BSCE, JLab, and KEK.**

Tensile Testing for Mechanical Properties

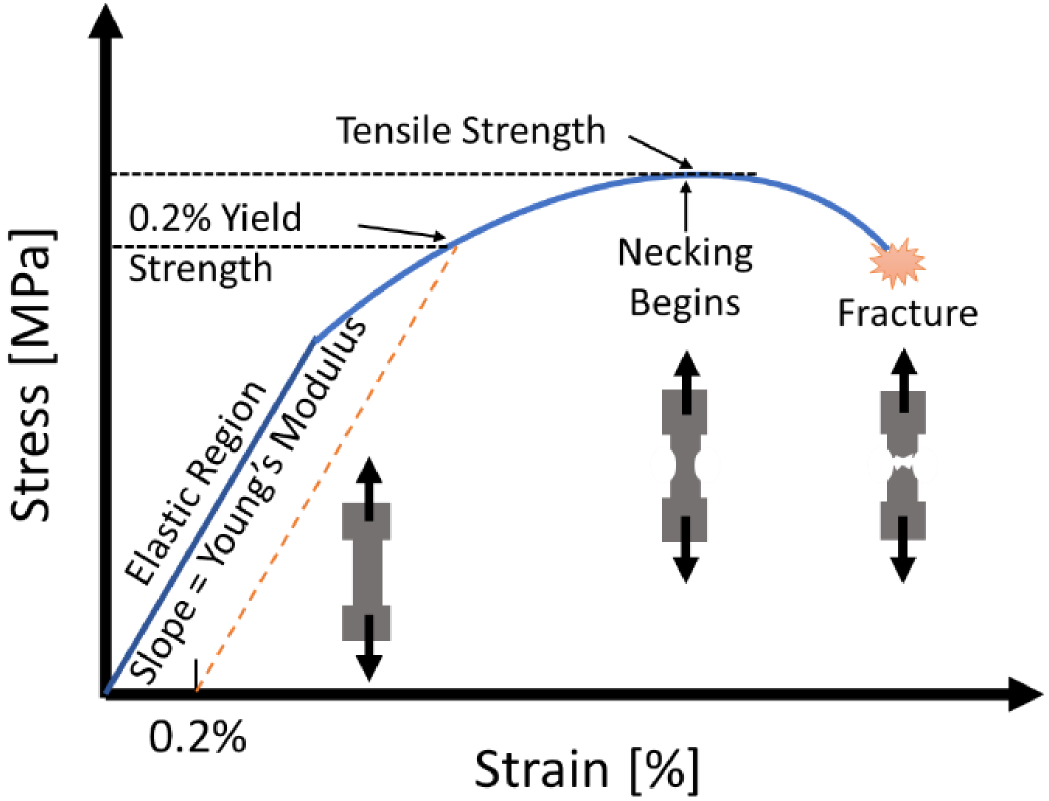
- Material is subjected to uni-axial tension until failure.

- Young's Modulus (E) – Stiffness of the material in tension

- 0.2% Proof Strength (0.2% P.S) – Stress at which strain is 0.2% after unloading

- Tensile Strength (T.S) – Maximum stress or stress before failure of the specimen

- Elongation – Measure of ductility of a material



$$\text{Elongation (\%)} = 100 \times \Delta L_f / L$$

Room Temperature Property Comparison

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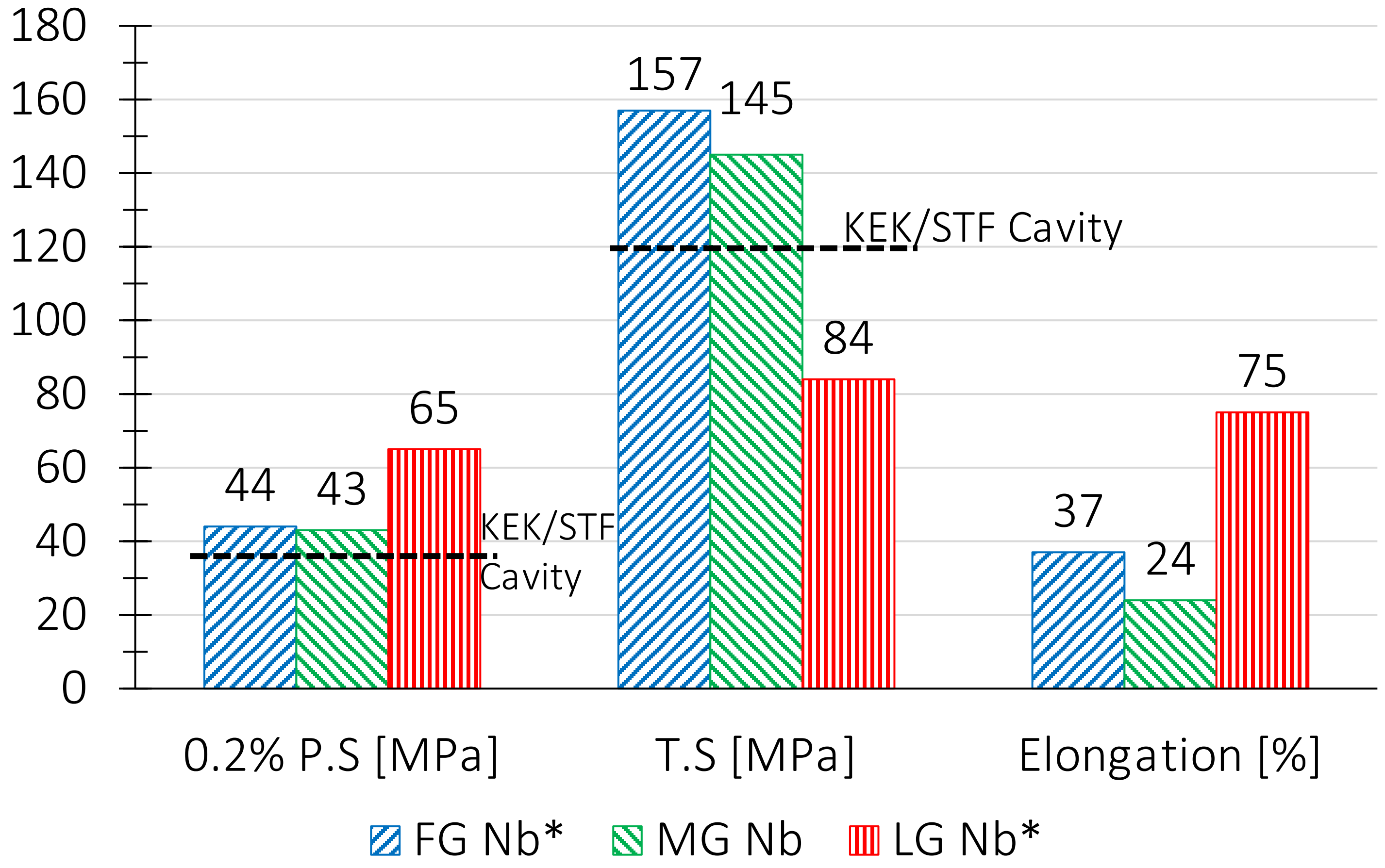


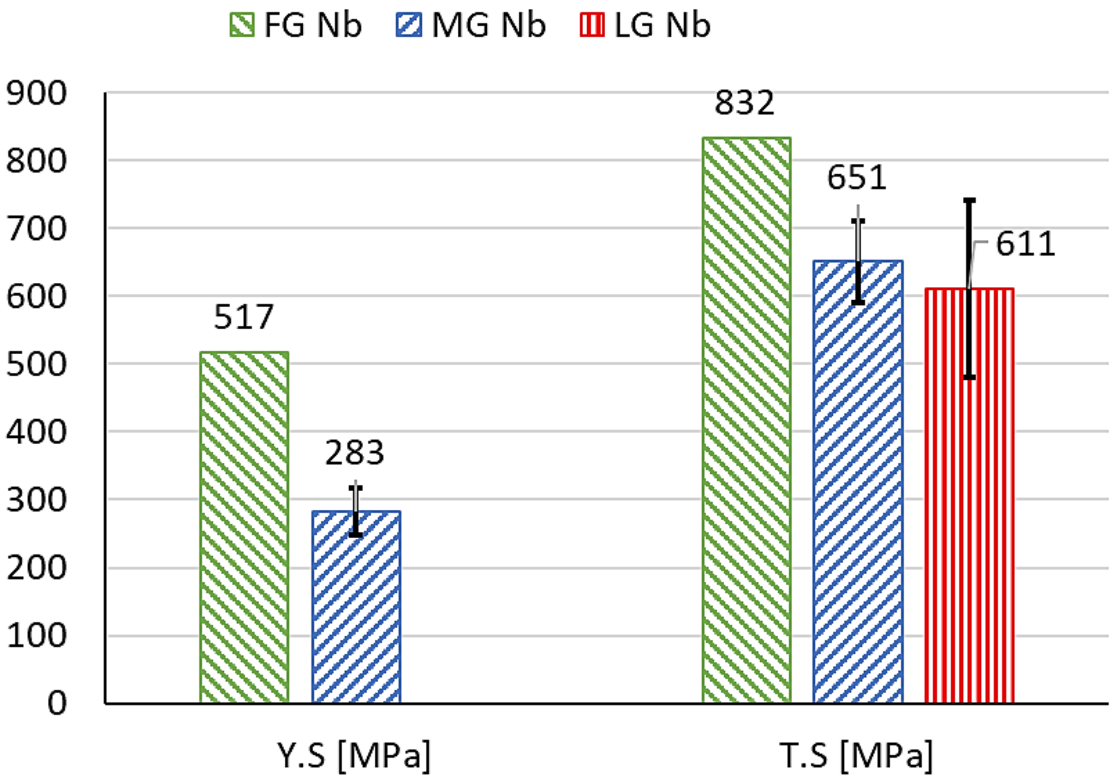
- MG Nb closer to FG Nb than LG Nb at room temperature.
- Elongation is lower than FG Nb but fine for HPGS
- High elongation necessary for press forming of half cells.

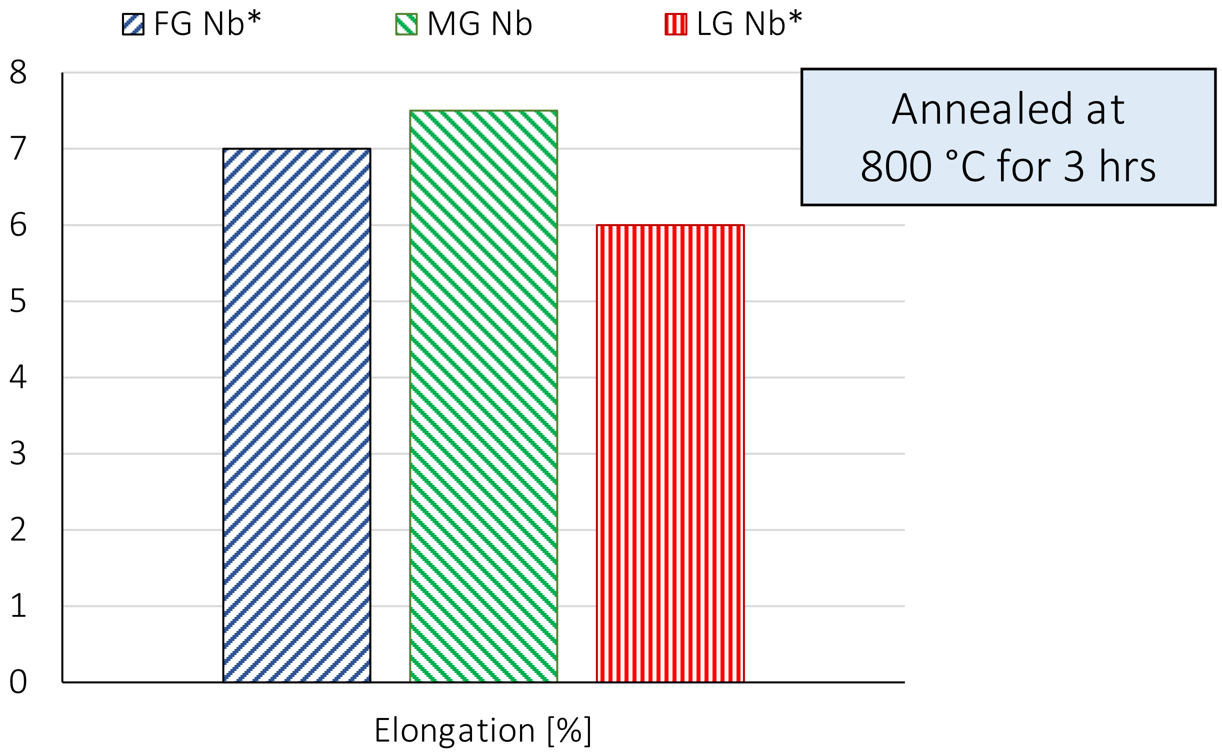
Mechanical strength of MG-Nb achieved the criteria of HPGS regulation for KEK/STF-Cavity

MG Nb data: A. Kumar et al. (July 2021), SRF2021 MOPCAV004

* FG Nb and LG Nb data is for middle RRR annealed material (M. Yamanaka et al., SRF'21 WEPFDV005).

Low Temperature Property Comparison



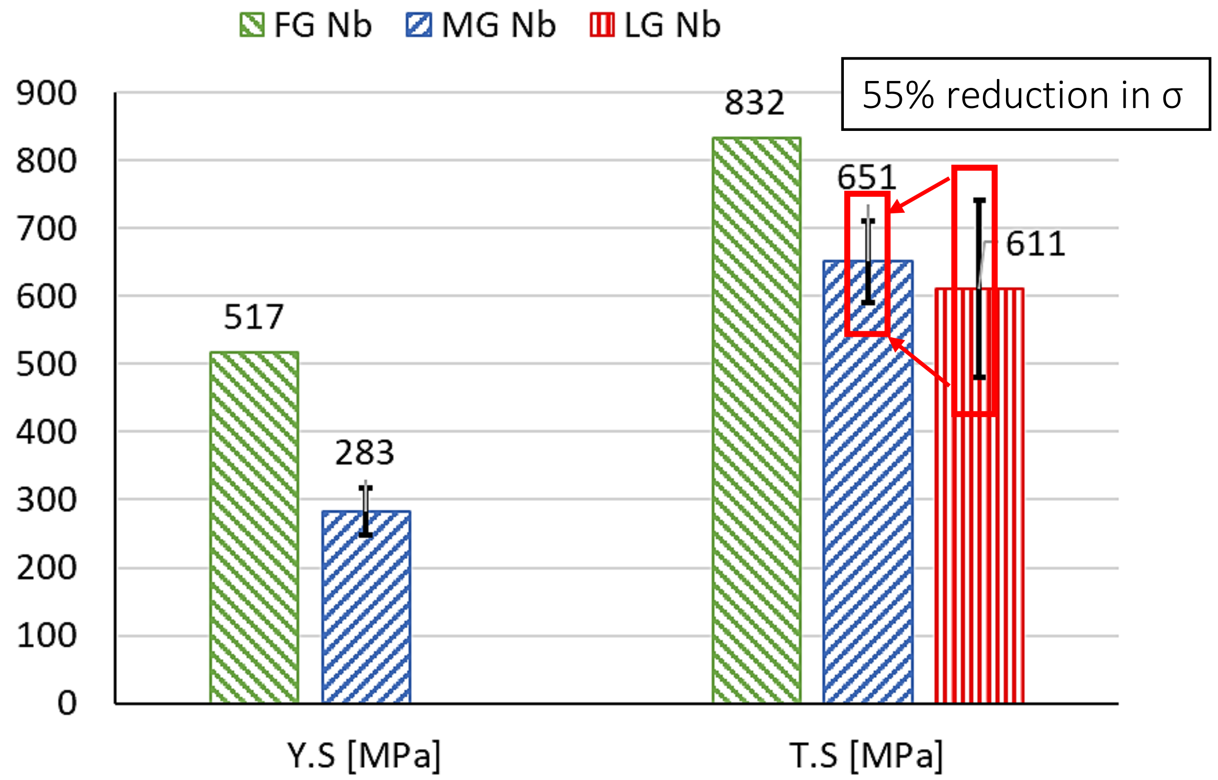


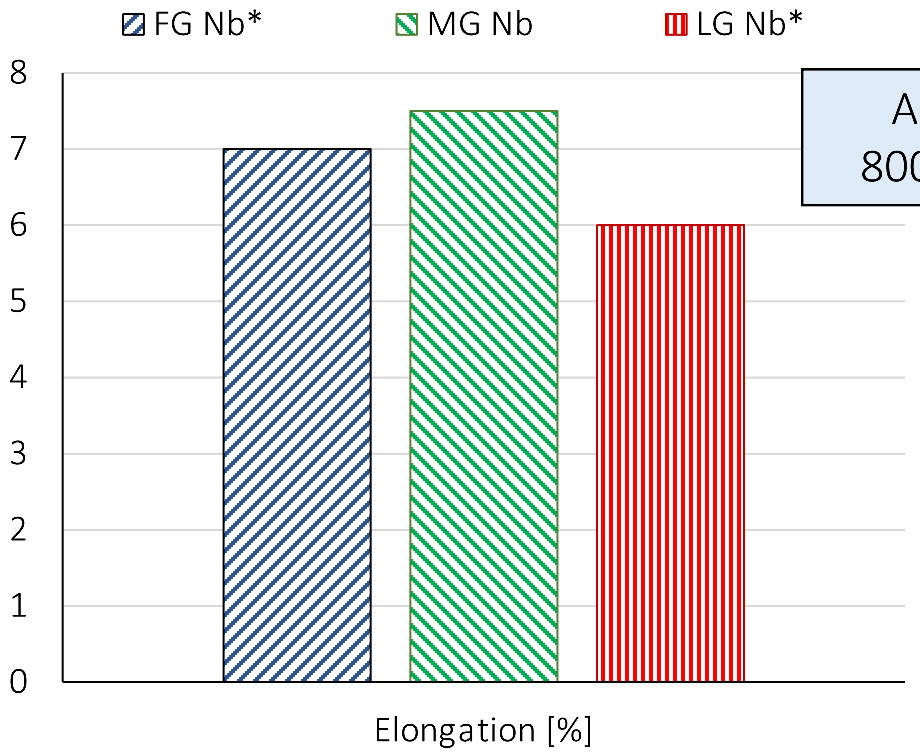
- Tensile Strength of MG-Nb at LHe-T is better than LG-Nb, with lower standard deviation.
- No issues with HPGS w.r.t mechanical strength in LHe (800 °C for 3 hrs).

* FG Nb and LG Nb data is for middle RRR annealed material (M. Yamanaka et al., SRF’21 WEPFDV005.

MG Nb data: A. Kumar et al., SRF2021 MOPCAV004

Low Temperature Property Comparison





Annealed at 800 °C for 3 hrs

- Tensile Strength of MG-Nb at LHe-T is better than LG-Nb, with lower standard deviation.
- No issues with HPGS w.r.t mechanical strength in LHe (800 °C for 3 hrs).

* FG Nb and LG Nb data is for middle RRR annealed material (M. Yamanaka et al., SRF’21 WEPFDV005.

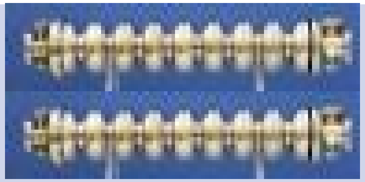
MG Nb data: A. Kumar et al., SRF2021 MOPCAV004

Performance of LG Nb Cavities

Credits:

LG Nb cavity results by Hayato ARAKI and Hayato Ito

Overview of Cavities and their Performance

Nb Materials	Cavities	Cavities	Vertical Test Results	ILC Specification
LG Nb (Mid-RRR, High-Ta)		Two 9-Cell	E_{acc} < 35 MV/m	✕ (Eacc = 32 MV/m)
LG Nb (High-RRR, Low-Ta)		Two 3-Cell	E_{acc} > 35 MV/m	✓
LG Nb (High-RRR, High-Ta)		Two 3-Cell (two 9-Cell under fabrication)	E_{acc} > 35 MV/m	✓
MG Nb (High-RRR, Low-Ta)		Two 1-Cell (One 9-Cell will be fabricated)	E_{acc} > 35 MV/m	✓

VT Parameters for LG Nb Cavity

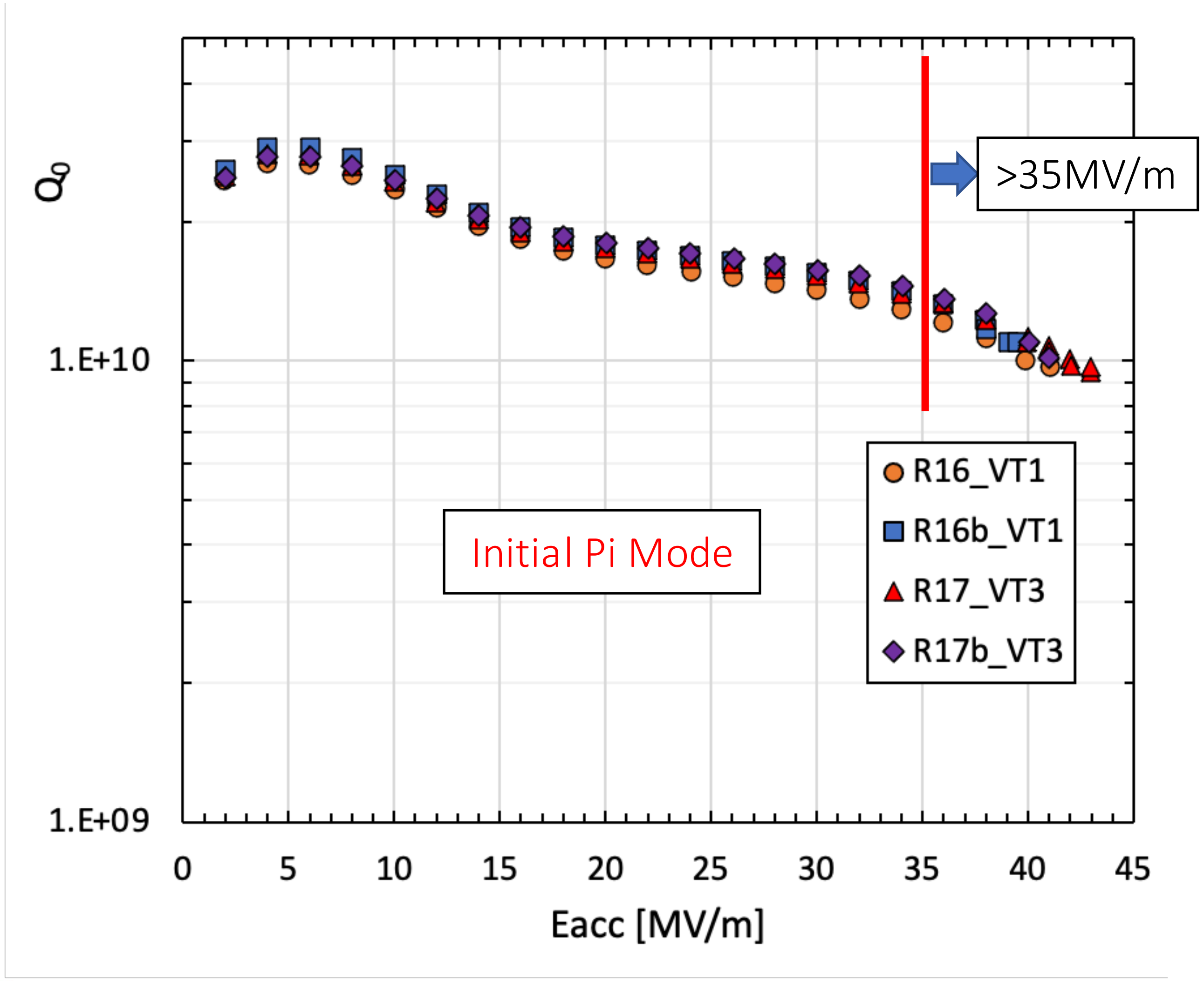
- Warm EP2 (5-30 µm) → HPR → Dry Assembly → Standard baking → VT
- Cold EP2 (10 µm) → HPR → Dry Assembly → 2-Step baking → VT
- Cold EP2 (10 µm) → HPR → Furnace baking → HPR → Dry Assembly → VT

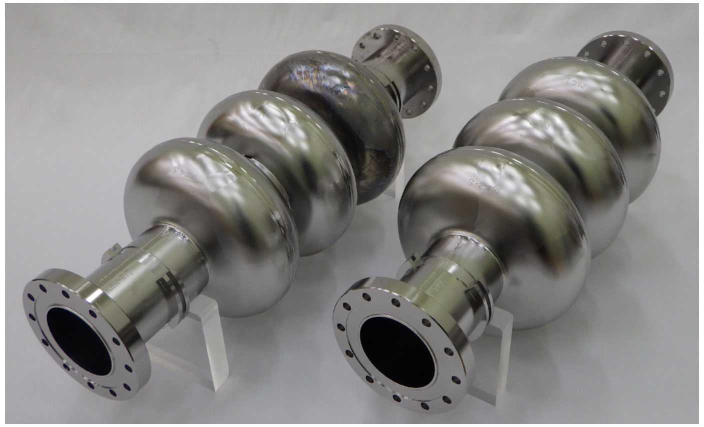
3-Cell LG Nb cavities manufactured at KEK-CFF

Standard or 2-step Baking

Furnace Baking

LG Nb 3-Cell Cavity VT





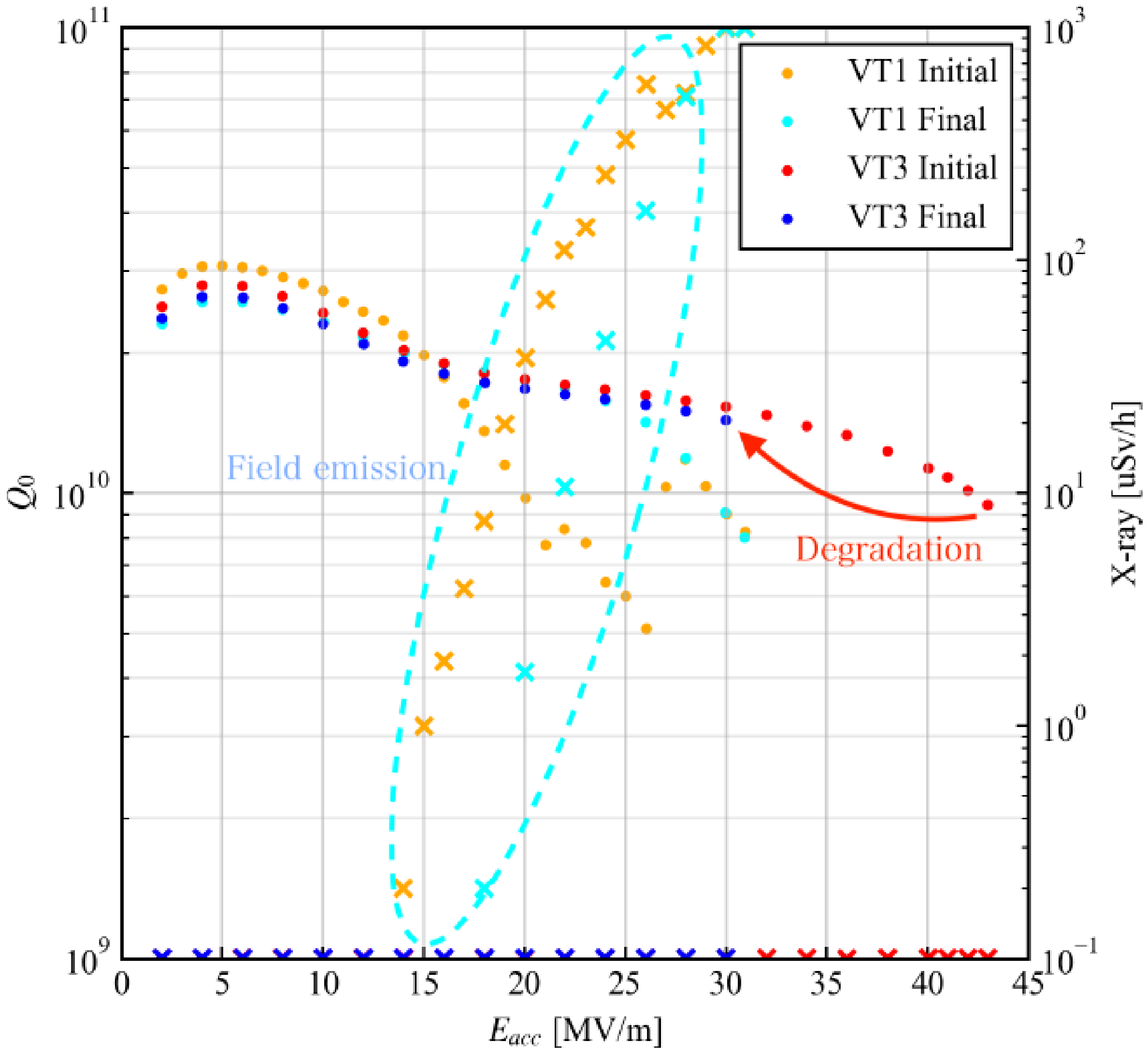
Comparison of Low-Ta vs High-Ta

Ta-fraction is not sensitive to the SRF performance if RRR > 300.

Difference of Q values are within the measurement error.

LG Nb cavity results by Hayato ARAKI

Performance Degradation in LG Nb Cavities

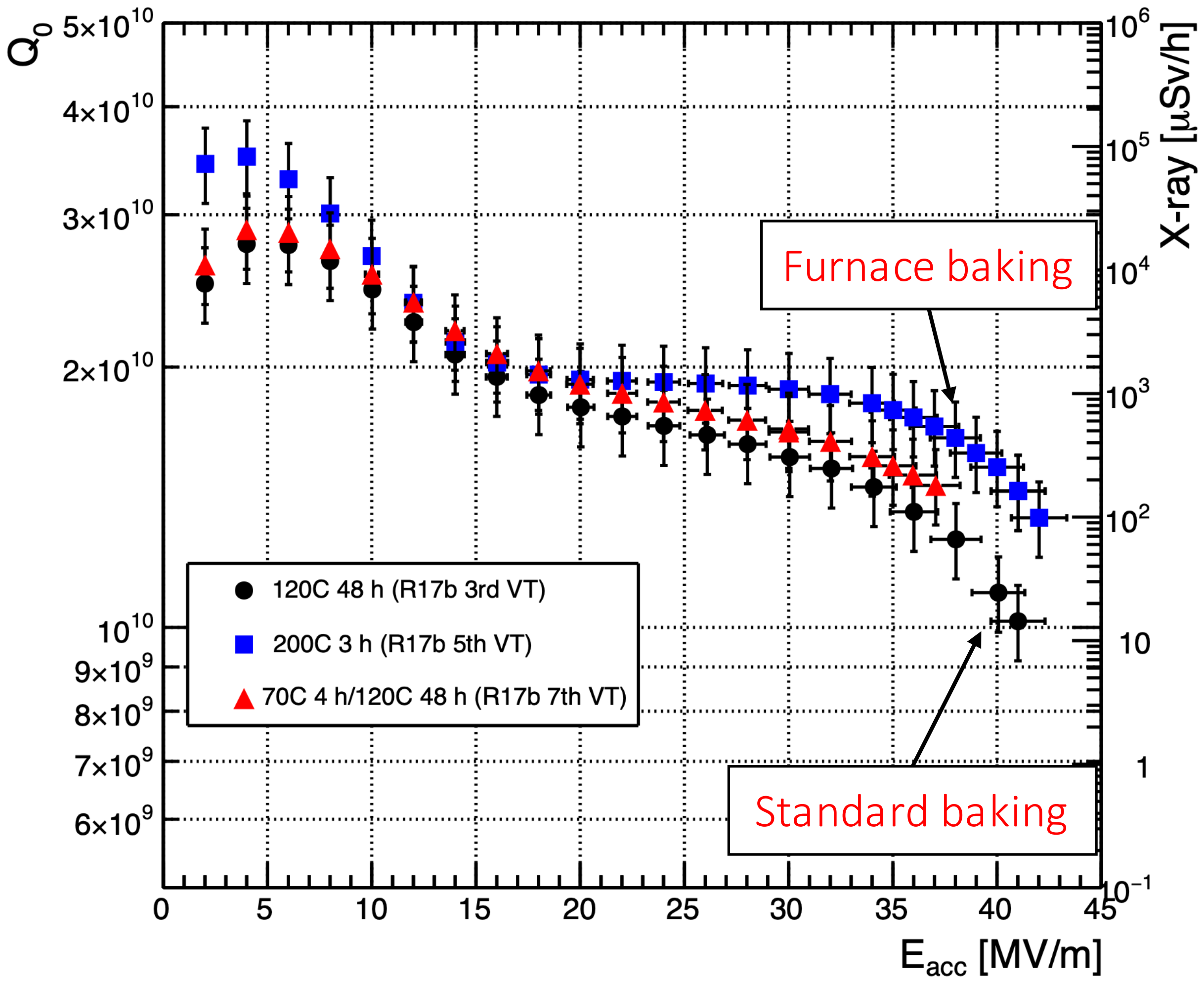


Cavity	Eacc Initial [MV/m]	Eacc Final [MV/m]	Delta
R16 VT1	41.4	37.2	-4.2
R16b VT1	39.7	39.5	-0.2
R16b VT2	41.7	35.4	-6.3
R16b VT3	40.6	34.7	-5.9
R17 VT3	43.1	30	-13.1
R17b VT3	41.9	36.6	-5.2

- Performance degradation in R17 was the highest.
- Cavity performance recovered after warmup for R17b.
- No degradation in Q_0 of the cavities.

LG Nb cavity results by H. ARAKI and H. Ito

LG Nb Material (High RRR, High Ta)

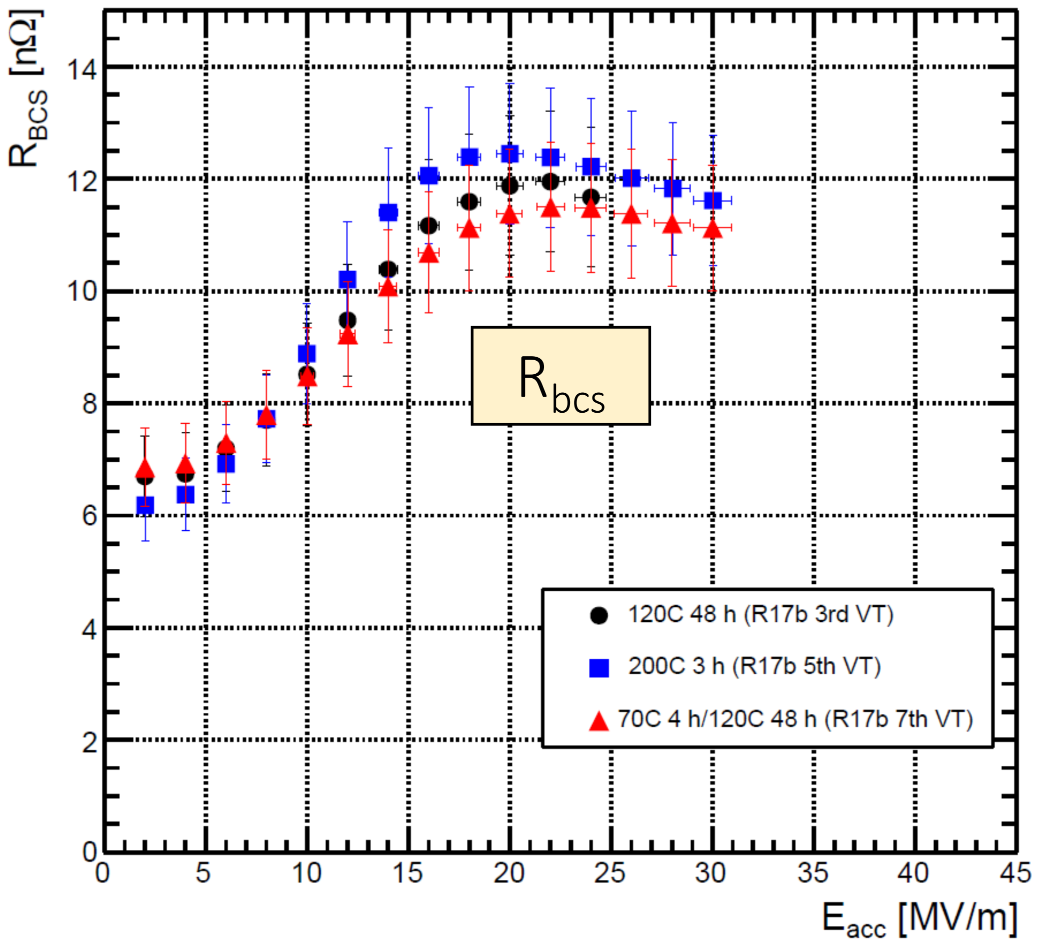


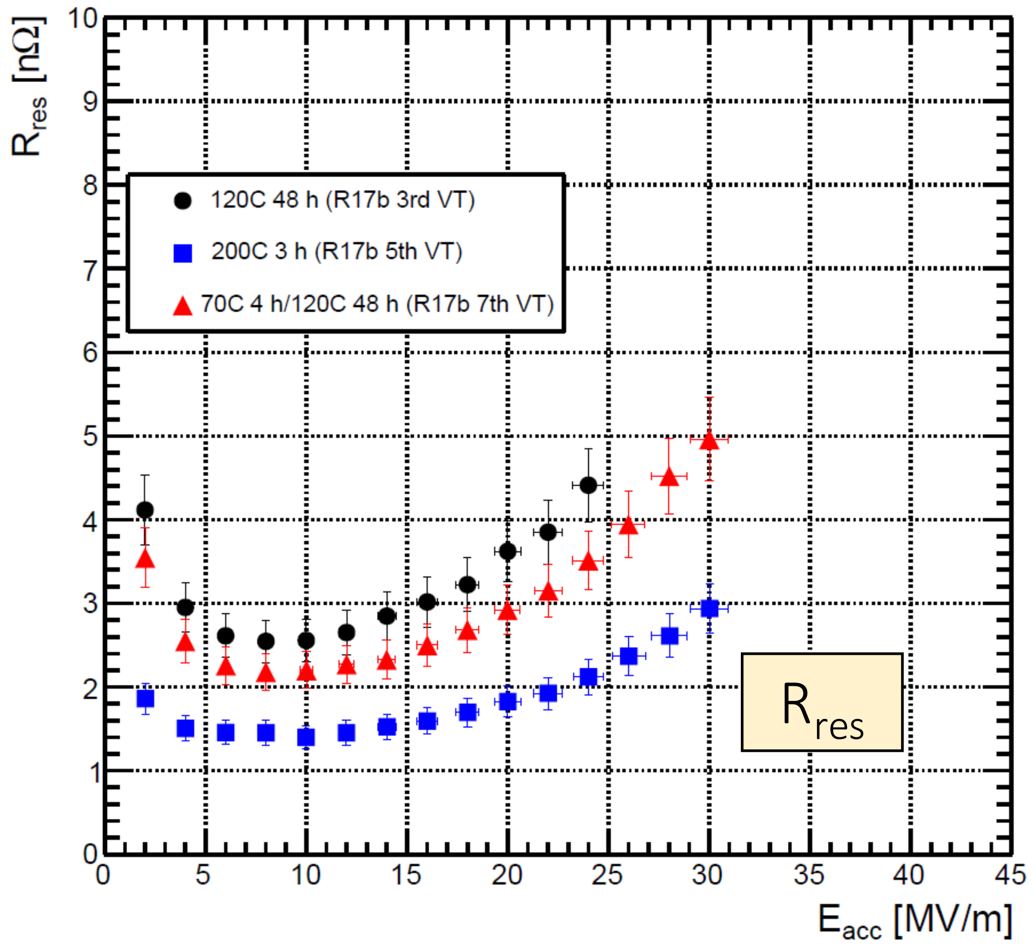
Parameters @ 2.0 K (R17b cavity)	E_{acc} max.	Q_0 @ E_{acc} = 36 MV/m	Q_0 max.
Standard Treatment (120 °C 48h)	41.9 MV/m	1.36E+10	3.06E+10
2-step baking (70°C 4h + 120°C 48h)	37.3 MV/m	1.50E+10	3.47E+10
Furnace baking (200 °C * 3hrs)	42 MV/m	1.75E+10	3.73E+10

- Clear improvement in performance with Furnace baking.
- Both Eacc and Q_0 improved with furnace baking.
- VT with 2-step baking within error range of standard treatment.

LG Nb cavity results by H. ARAKI and H. Ito

Resistance Deconvolution for LG Nb Cavity





- Lowest Rres with Furnace baking at 200 °C for 3 hrs

LG Nb cavity results by H. ARAKI and H. Ito

Furnace Baking on KEK-5 9-Cell LG Nb Cavity

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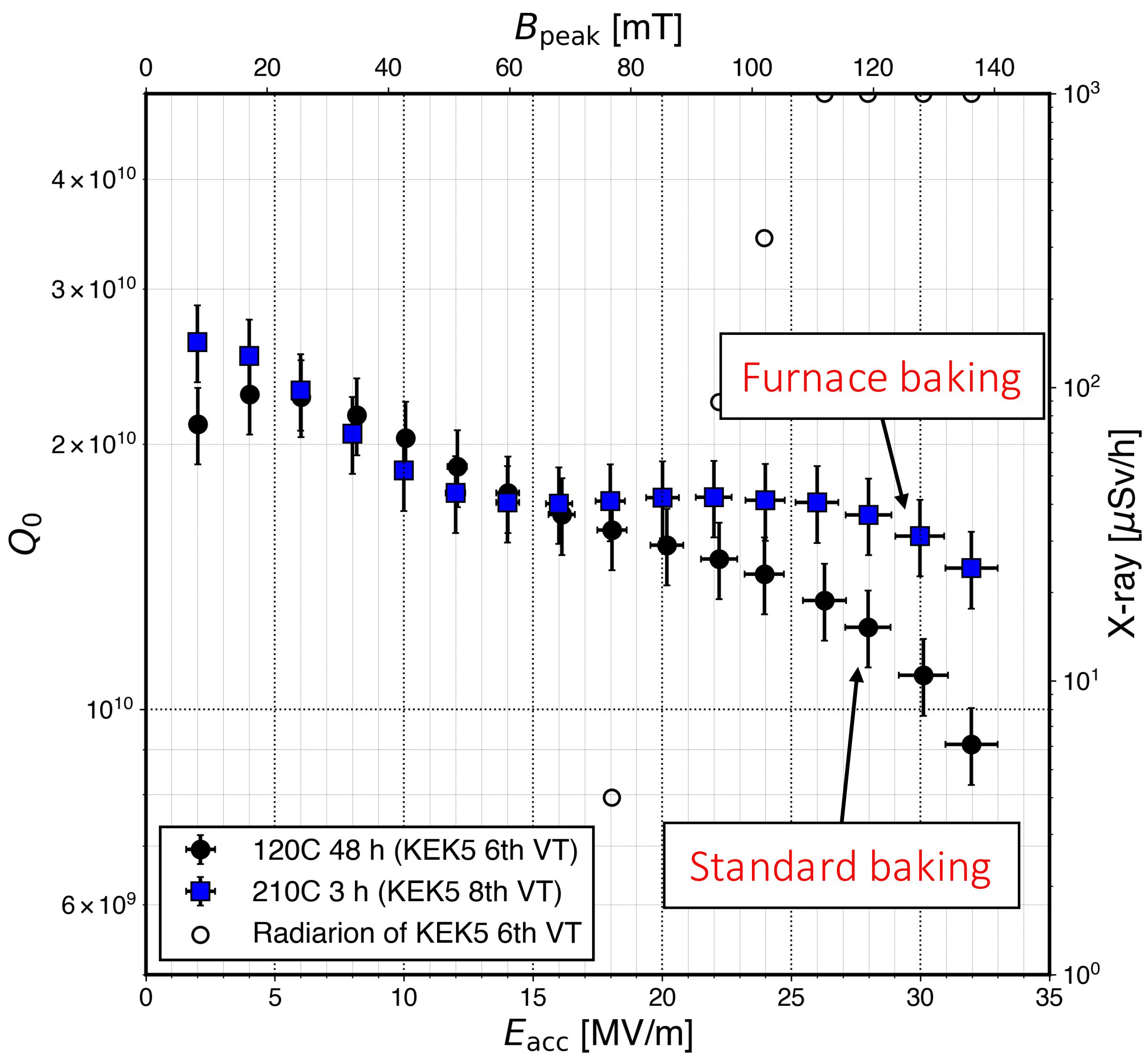


Parameters @ 2.0 K (KEK-5 cavity)	E_{acc} max.	Q_0 @ E_{acc} = 32 MV/m	Q_0 max.
Standard Treatment (120 °C 48h)	32 MV/m	7.69E+09	3.06E+10
Furnace baking (210 °C * 3hrs)	32 MV/m	1.45E+10	3.73E+10

- A 9-Cell LG Nb cavity KEK-5 was tested with Standard and Furnace baking.
- Clear improvement in Q_0 was observed with Furnace baking at 210 °C 3 hrs.

LG Nb cavity results by H. ARAKI and H. Ito

Progress in performance tests of MG Nb Cavities

Credits:

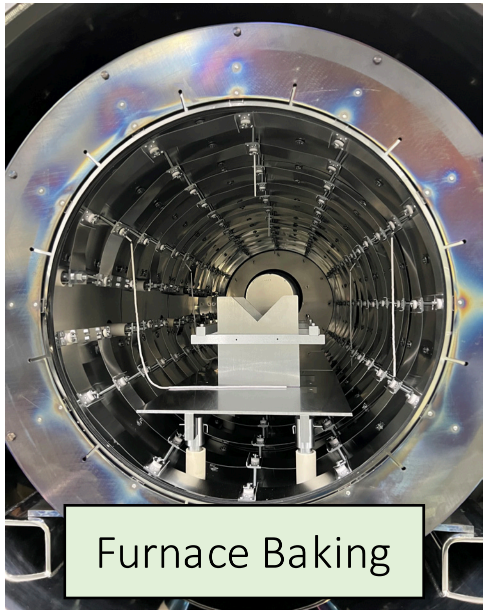
MG Nb cavity results by Ashish Kumar and Takeshi Dohmae

VT Parameters for HRRR MG Nb Cavity

Process 1	Process 2	Process 3
Warm EP2 (10 µm)	Cold EP2 (10 µm)	Cold EP2 (10 µm)
↓	↓	↓
HPR	HPR	HPR
↓	↓	↓
Dry Assembly	Dry Assembly	Furnace baking
↓	↓	↓
Standard baking	2-Step baking	HPR
↓	↓	↓
		Dry Assembly
		↓
VT	VT	VT

R18 & R18b HRRR MG Nb Tesla cavity manufactured at KEK-CFF

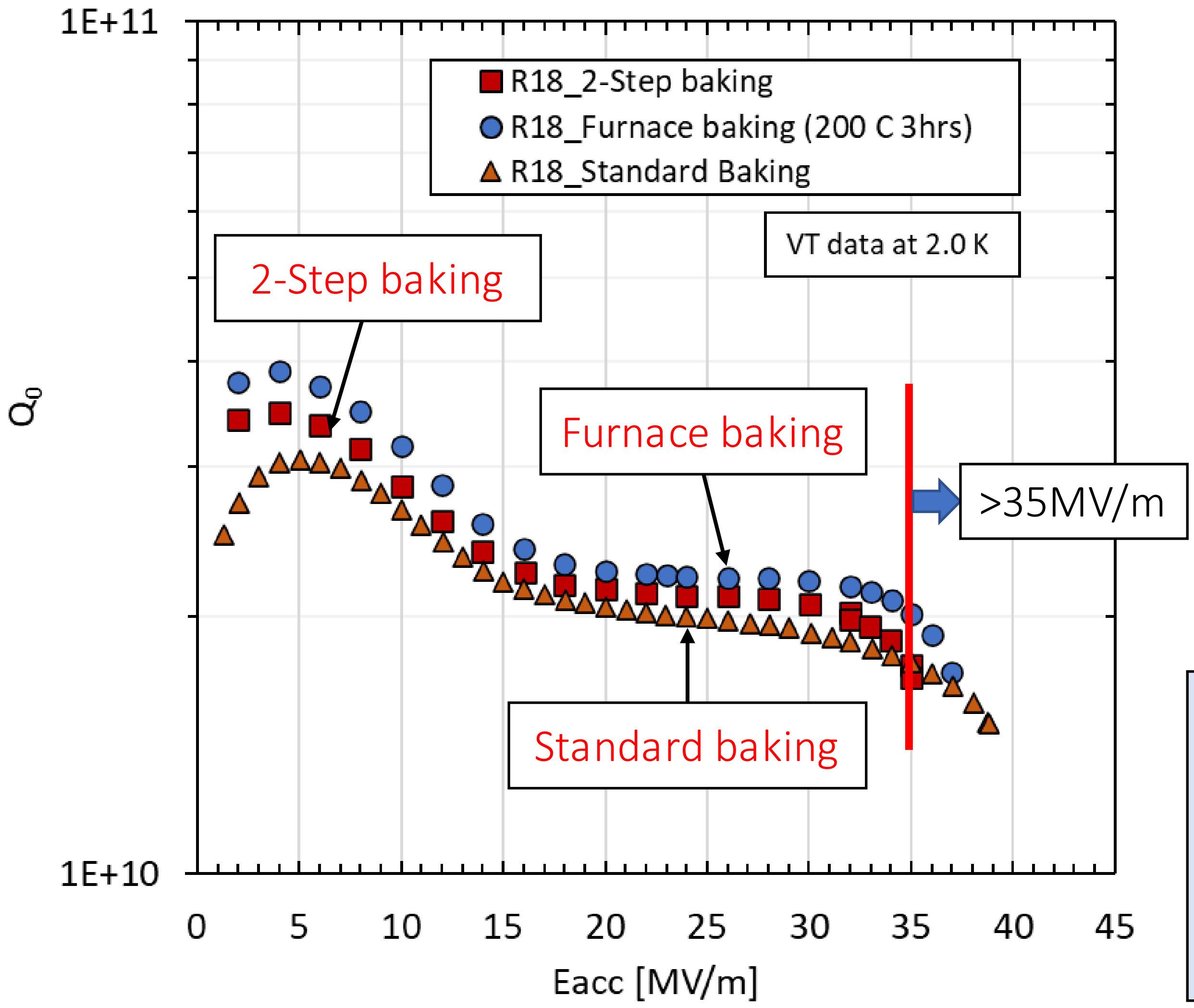
Standard or 2-step Baking



Furnace Baking

- For Flux sensitivity studies, 20 mG of flux is trapped using a solenoid coil.

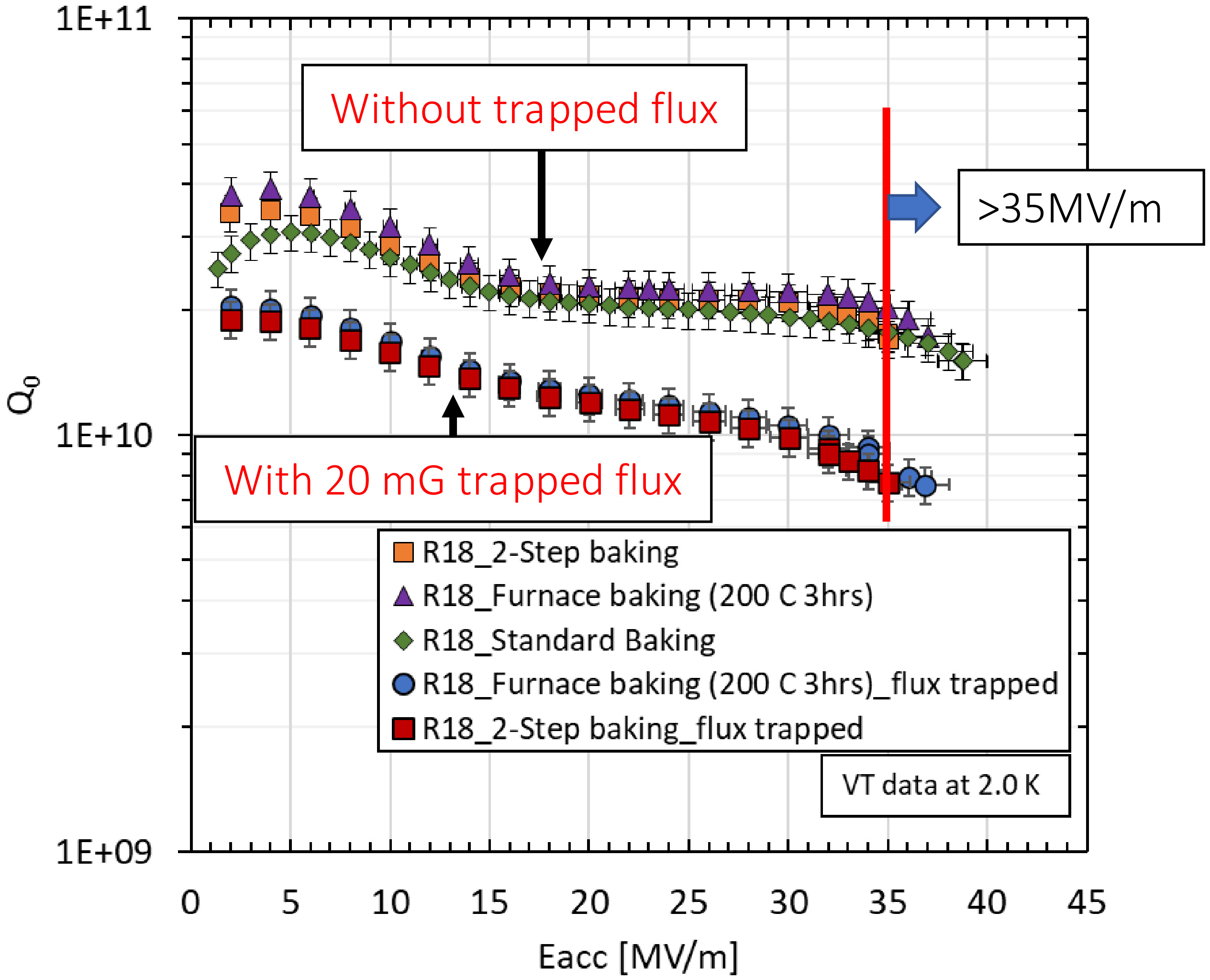
MG Nb 1-Cell Cavity High Q-High G Study



Parameters @ 2.0 K (R18 cavity)	E_{acc} max.	Q_0 @ E_{acc} = 35 MV/m	Q_0 max.
Standard Treatment (120 °C 48h)	38.8 MV/m	1.77E+10	3.06E+10
2-step baking (70°C 4h + 120°C 48h)	35 MV/m	1.75E+10	3.47E+10
Furnace baking (200 °C * 3hrs)	36.3 MV/m	1.87E+10	3.73E+10

- Clears ILC Specification.
- Highest Eacc for Standard surface treatment.
- Q_0 within error range
- No degradation in Eacc after quenching unlike LG Nb cavities.

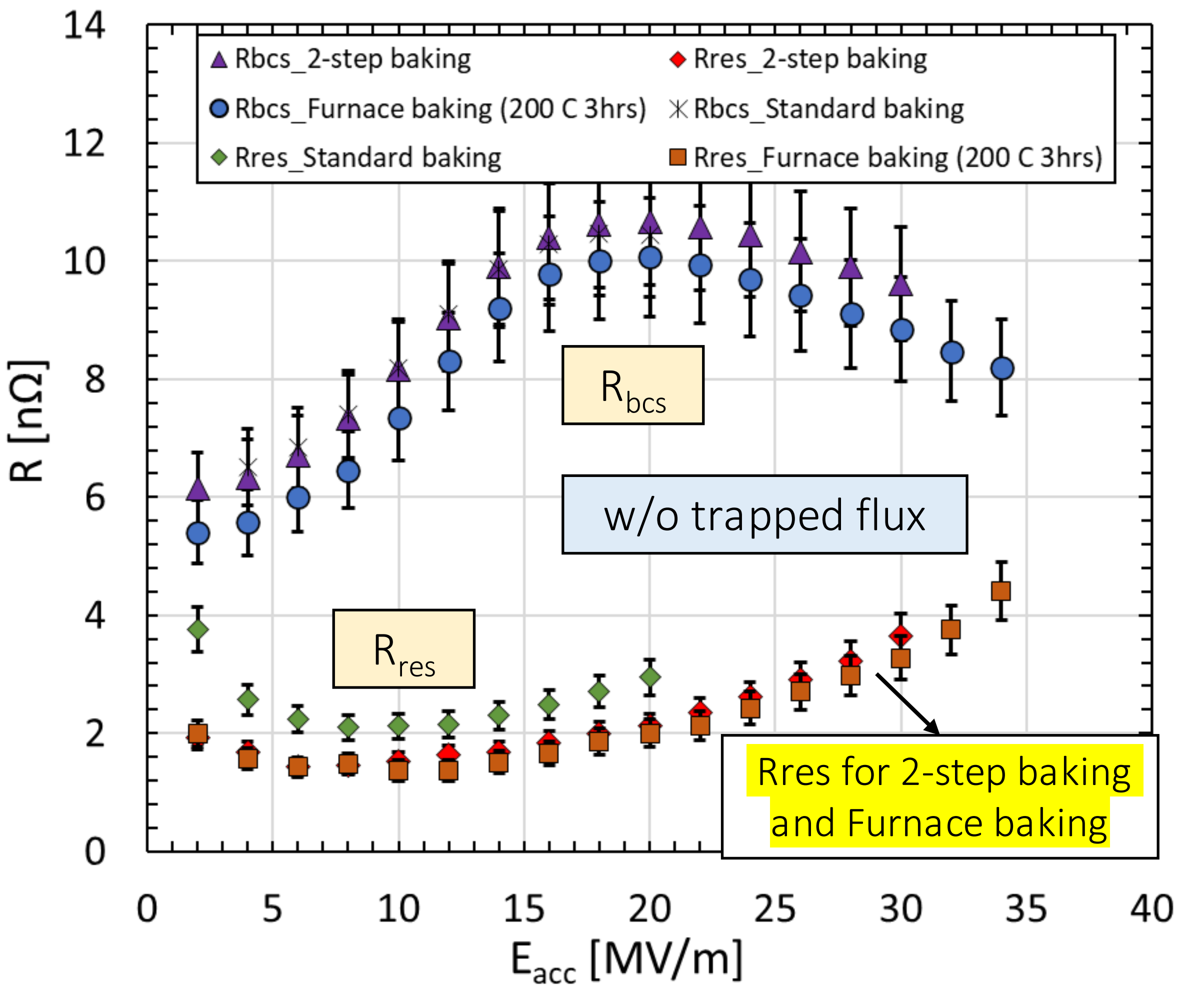
MG Nb 1-Cell Cavity High Q-High G with Flux Sensitivity Studies

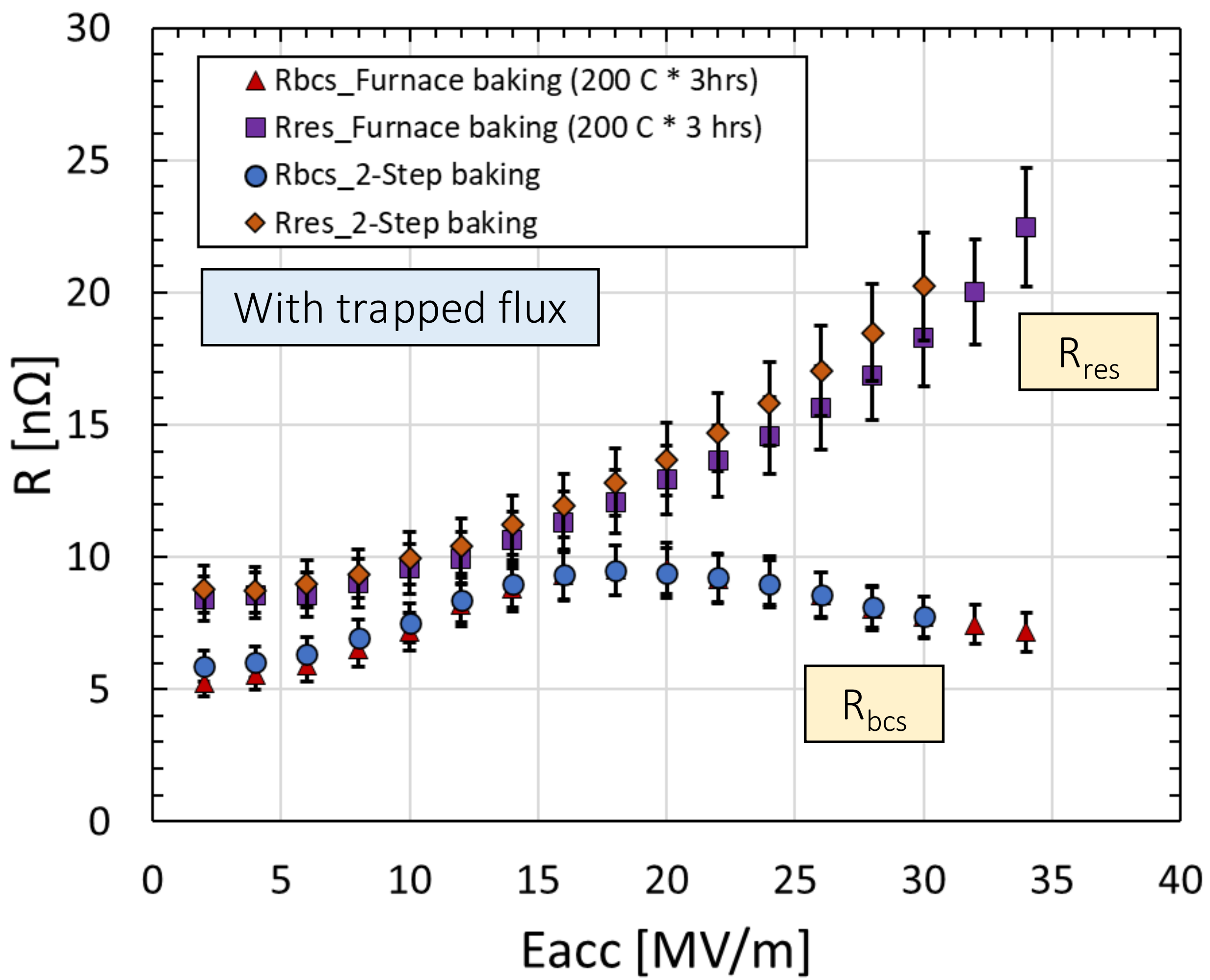


Parameters @ 2.0 K	E_{acc} max.	Q_0 @ E_{acc} = 35 MV/m	Q_0 max.
Standard Treatment (120 °C 48h)	38.8 MV/m	1.77E+10	3.06E+10
2-step baking (70°C 4h + 120°C 48h)	35 MV/m	1.75E+10	3.47E+10
2-step baking Flux Sensitivity test	35 MV/m	7.71E+09	1.89E+10
Furnace baking (200 °C * 3hrs)	36.3 MV/m	1.87E+10	3.73E+10
Furnace baking Flux Sensitivity test	37 MV/m	8.05E+09	2.03E+10

- No degradation in Eacc due to trapped flux.
- Degradation in Q_0 expected due trapped flux.

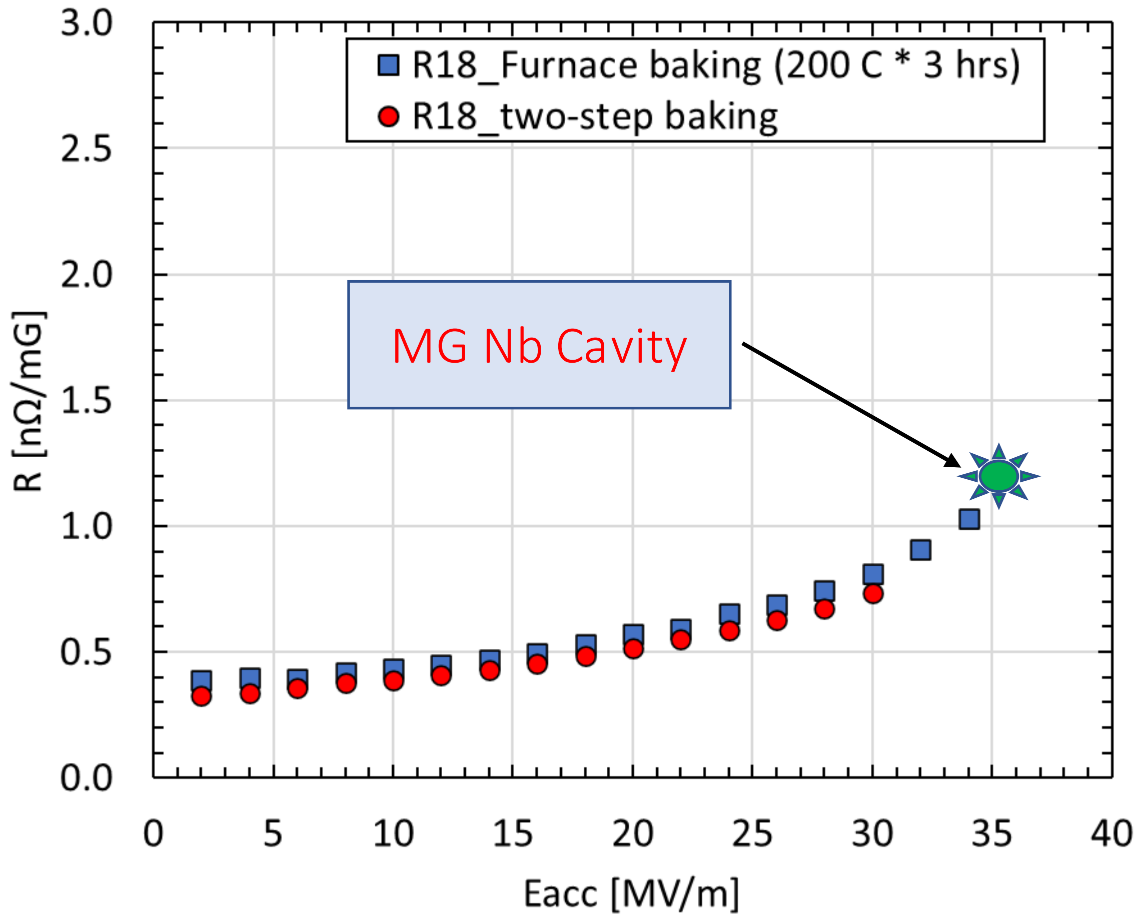
Resistance Deconvolution

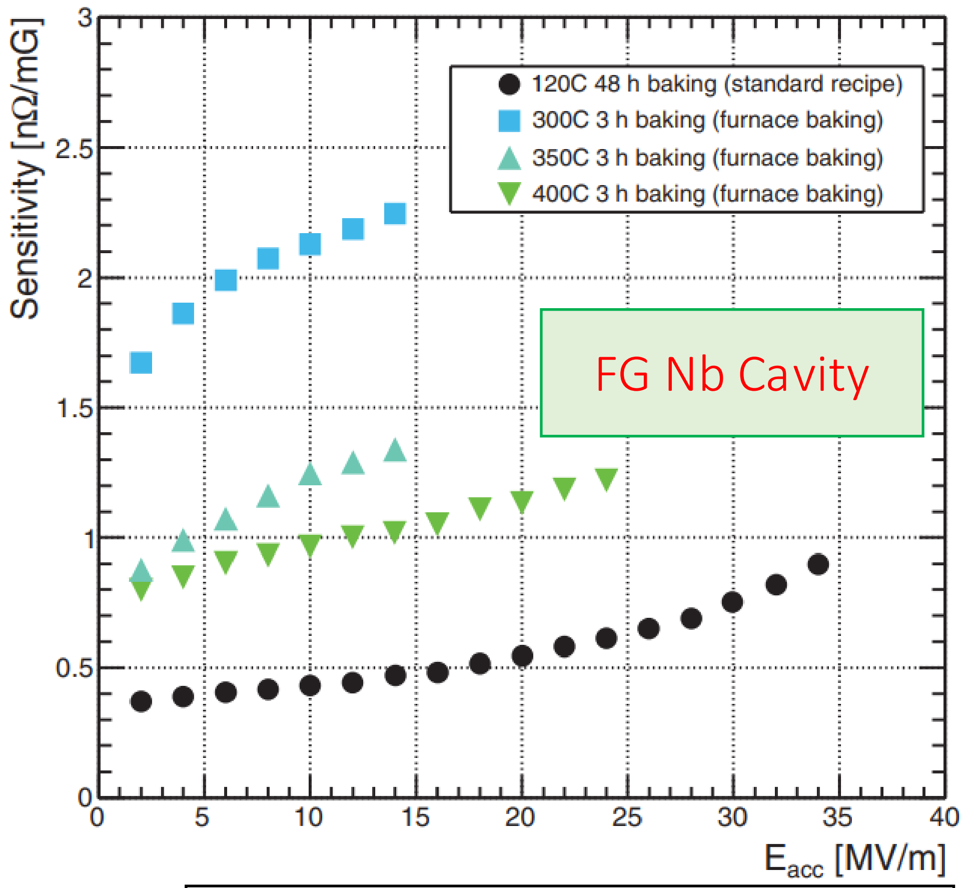




- Rres lowest and same for 2-step and Furnace baking

Flux Sensitivity for MG Nb





Cited from: H. Ito, Prog. Theor. Exp. Phys. 2021, 071G01

- Flux sensitivity of 1-Cell MG Nb cavity is similar to 1-Cell FG Nb standard baked cavity.
- It is approximately 1.2 nΩ/mG at Eacc = 35 MV/m.

Summary

- At KEK, extensive studies on directly-sliced Nb material is being carrying out.
- Mechanical properties of LG Nb and MG Nb has been determined from room to liquid helium temperatures.
- MG Nb is an exciting new cost-effective material with isotropic mechanical properties and its 1-Cell cavity performance clears ILC specification.
- LG Nb did not show any performance degradation due to high content of Ta.
- LG Nb did show some performance degradation after quenching but recovered after warmup.
- A jacketed 9-cell LG Nb cavity has reached ILC specification with horizontal testing (Eacc= 36 MV/m) -> See poster WEPWB114

Thank You for Your Attention!