New Nb Material for Cost Saving

Akira Yamamoto (KEK-CERN)

In cooperation with

A. Kumar, T. Dohmae, T. Saeki (**KEK**), G. Myneni (**BSCE**), G. Ciovati, P. Dhakal, R. Rimmer (**JLab**),

M. Carl, A. Fajardo, and N. Lannoy (**ATI**)

LCWS-2023, Acc. SR Session, at SLAC, **Sept. 16, 2023**

KEK BSCE SYSTEMS, INC. Jefferson Lab ATI

Motivations

- **The best cost-effective SRF cavity production:**
  - **Quality:**
    - **Clean** Nb and RF surface critically important,
  - **Cost:**
    - **Simple** production process inevitably required.
- **Efforts for a solution:**
  - Fine Grain (**FG**) :
    - Mechanically best, but contamination due to forging and rolling
  - → Large Grain (**LG**):
    - Best for cleanness and cost reduction, but mechanically not stable resulting in HPGS code not applicable
  - → **Medium Grain** (**MG**):
    - Optimized for cleanness, mechanical stability, cost reduction, and applicable to high pressure gas safety (**HPGS**) regulations.

References

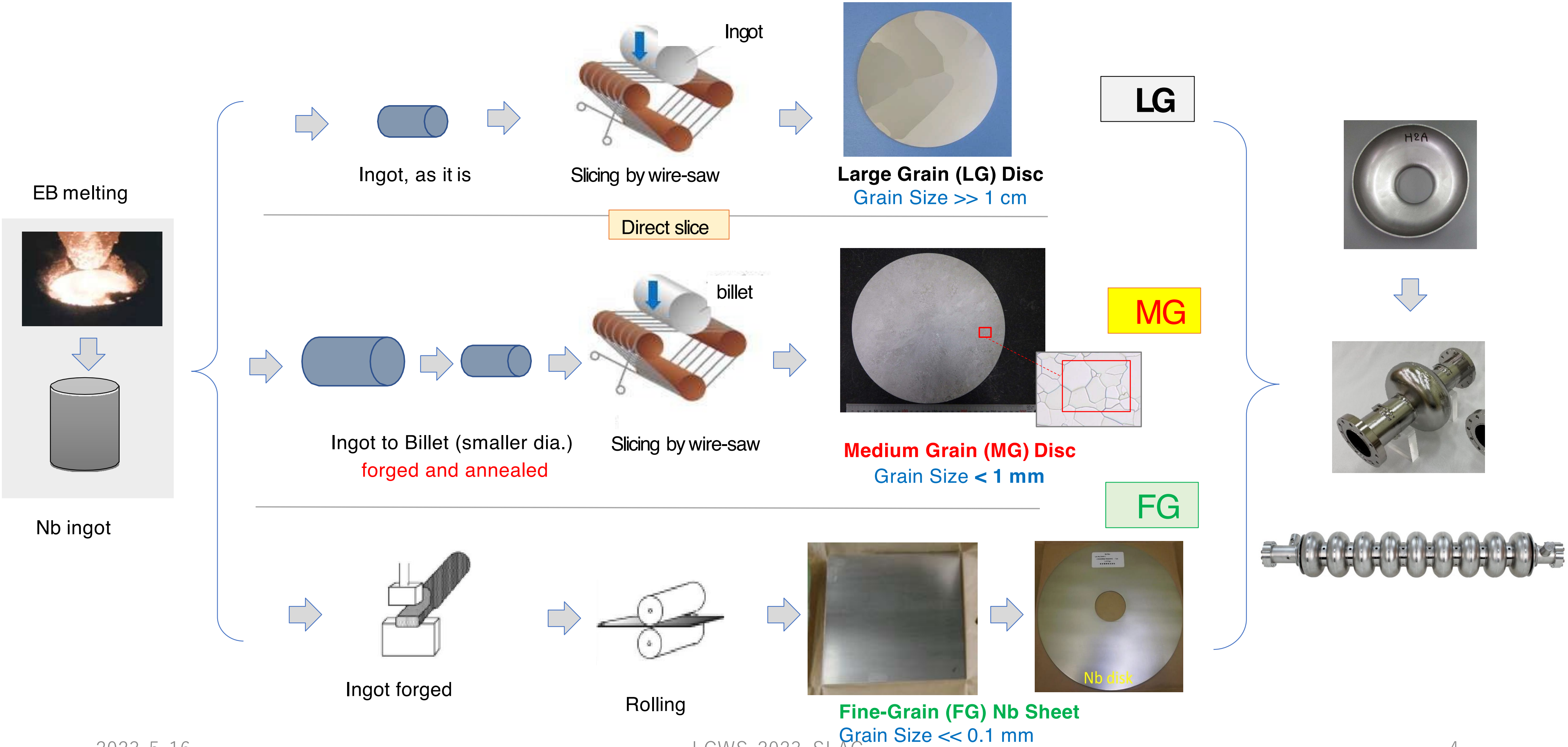
- **A. Yamamoto et al.,** “Ingot Nb based SRF Technology for the International Linear Collider”, in Proc. Science and Technol-ogy of Ingot Niobium for Superconducting Radio Frequency Applications, Virginia, USA, Dec. 2015, AIP Conf. Proc. 1687, 030005-1 – 03005-6.

- **A. Kumar et al.,** “Mechanical property of directly sliced me-dium grain niobium for 1.3 GHz SRF cavity”, JACOW-SRF-2021-MOPCAV004.

- **T. Dohmae et al.,** “FABRICATION OF 1.3GHz SRF CAVITIES USING MEDIUM GRAIN NIOBIUM DISCS DIRECTLY SLICED FROM FORGED INGOT*, JACoW-SRF2021-MOPCAV012.

- **G. Myneni et al,** “Medium Grain Niobium SRF Cavity Production Technology for Science Frontiers and Accelerator Applications”, presented at **SnowMass’21** AF-7, Sugroup RF,2022, and to be published in **JINST, 2023**.

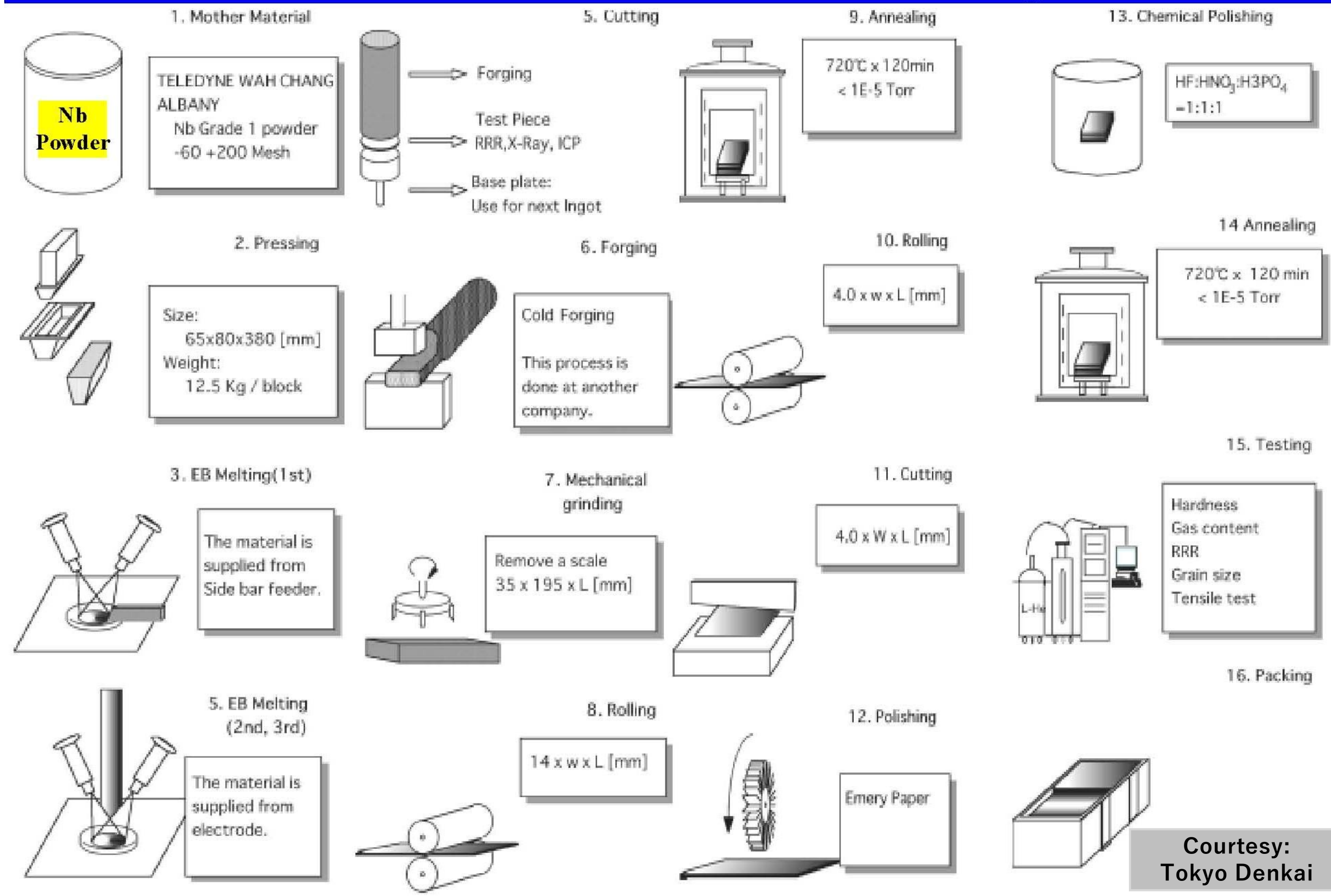
Production of Nb Discs/Sheets for 1.3 GHz SRF Cavities



Courtesy: Tokyo-Denkai

Process flow of the industrial Nb production

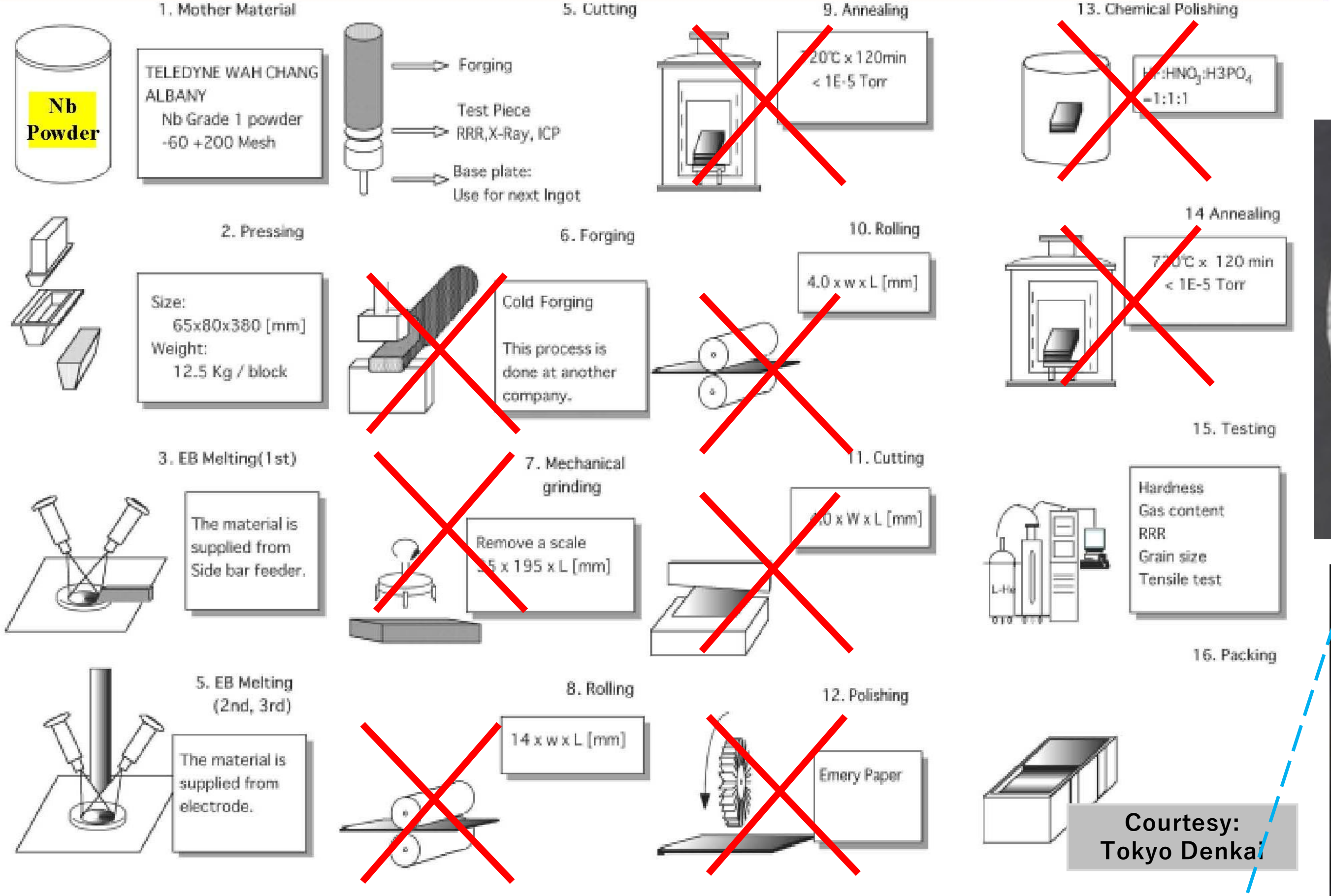
FG



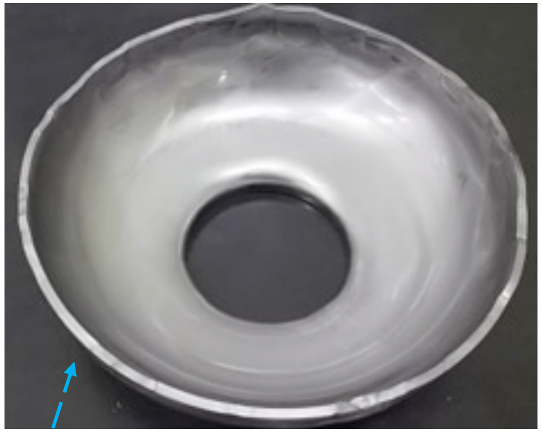
Courtesy:
Tokyo Denkai

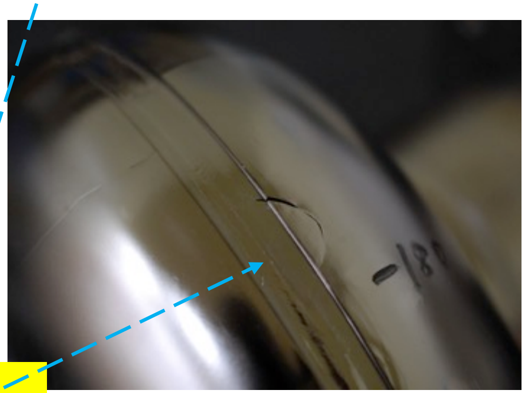
Process flow of the industrial Nb production

LG



Picture of half cup

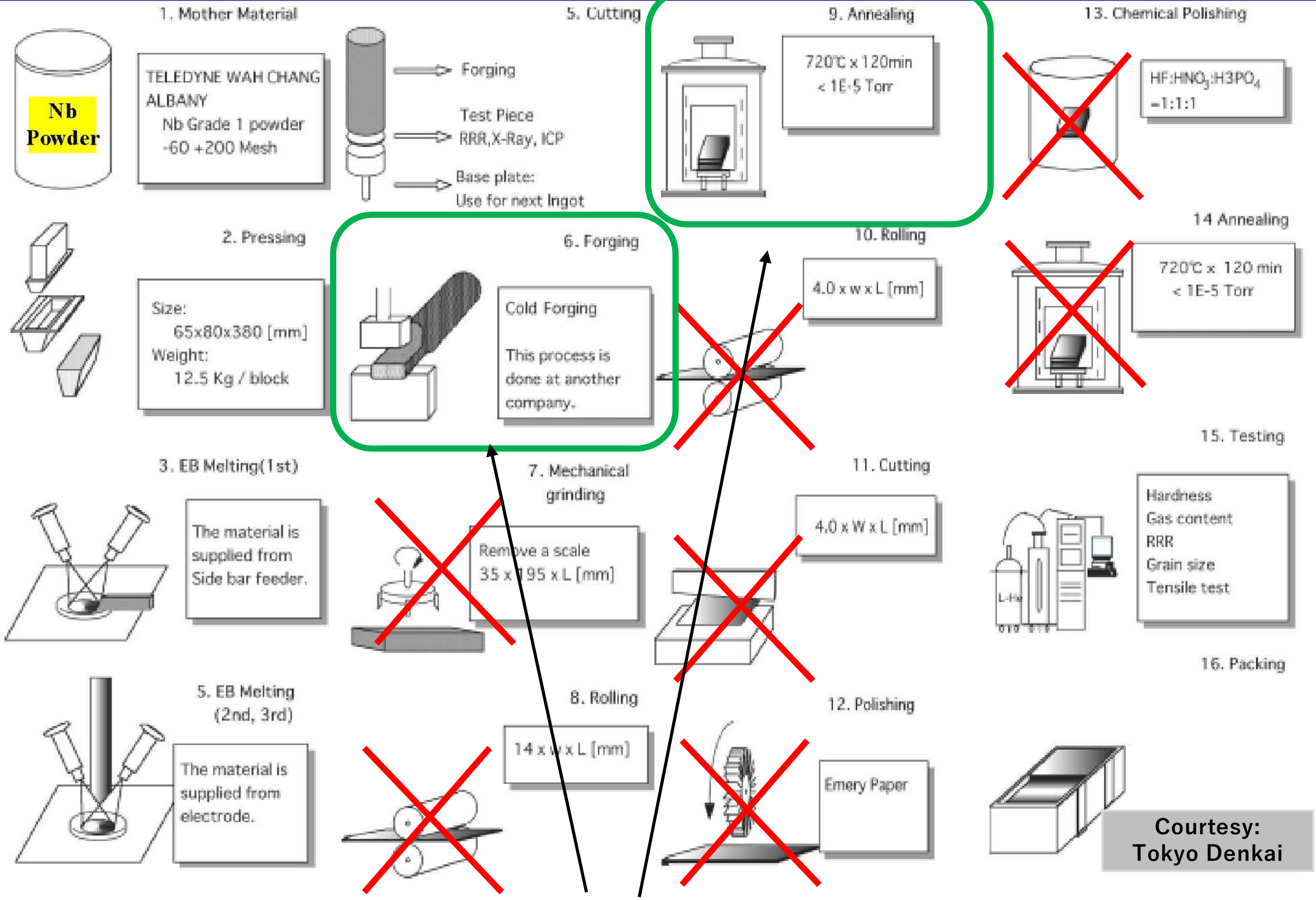




LG-Nb realized very good cost performance.
But LG-Nb material causes broad mechanical strength distribution (less uniformity).
(→ Minimum strength becomes low)

Process flow of the industrial Nb production

MG



Uniformity of Nb material is achieved by Medium-Grain (MG) structure.

Summary of Nb Sheet/Disc Fab.Technologies for SRF

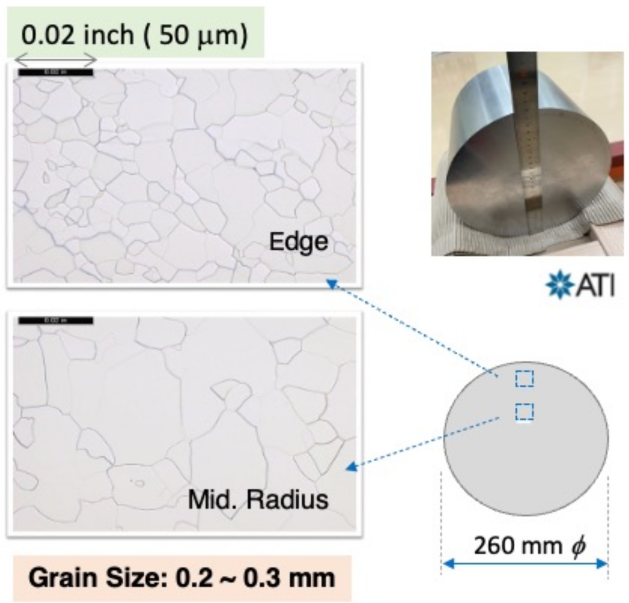
	Fine Grain (FG) Rolled Nb sheets	Medium Grain (MG) Forged Ingot Nb discs	Large Grain (LG) Ingot Nb discs
Fabrication process	Up to fourteen manufacturing steps	EB melted ingot w/ larger dia. Forging required dia to be sliced	EB melted ingot of required diam. to be sliced
ASTM Grade Grain size	~ 5 **~ < 50 μm**	0 – 3, (1~2 av.) **< 1 mm**	n/a **>1 cm**
Cleanness	Possible prone to contamination due to rolling	**clean surface** with direct slicing	Proven clean surface with no-forging and direct slicing
Mechanical properties	Very Uniform	**Reasonably uniform**	Non uniform, widely distributed
Cost	Expensive	**Cost advantage**	Best cost advantage

Courtesy: ATI

Properties of MG Nb disc realized in cooperation with ATI

Table 1. Material properties of MG Nb material produced by ATI.

Chemical Composition (%)	Other properties
Ta : < 0.01%	Dimensions: 260 m (dia.), 2,8 mm (t)
W : < 0.003 %	RRR : > 450
Ti, Si, Mo, Fe : < 0.003%	Recrystalization : 100 %
Ni : < 0.002 %	Grain size : 0.2 ~ 0.3 mm (ASTM: 1 ~ 2)
H_2 : < 0.003 %	Hardness (HV0.1) : 40 ~ 44
C : < 0.002 %	Mechanical Strength :
N_2 : < 0.002 %	Ultimate strength (RT) > 141-146 Nmm^{-2}
O_2 : < 0.004 %	Yield strength (RT) > 56-61 Nmm^{-2}



***Special Thanks* for the Cooperation by *ATI* !**

Courtesy: ATI and G. Myneni,

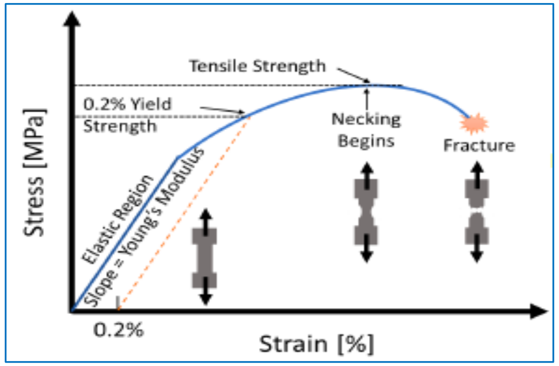
A Reference:
Comparison of NbGr1 & RRR Nb

Parameters	Nb Gr1 (MG) Measured	RRR Nb (MG) Measured
RRR	~ 100	450 523
Re-crystalization	100 %	100 %
Grain size (ASTM) Edge, Mid., Center	0.5 - 5	2 , 1, 1.5
Grain size (mm) Edge, Mid., Center	0.05 - 0.3	0.2, 0.25, 0.21
Y.S.-0.2% (RT)	~ 67 MPa	61 MPa
T.S. (RT)	> 147 MPa	141 MPa

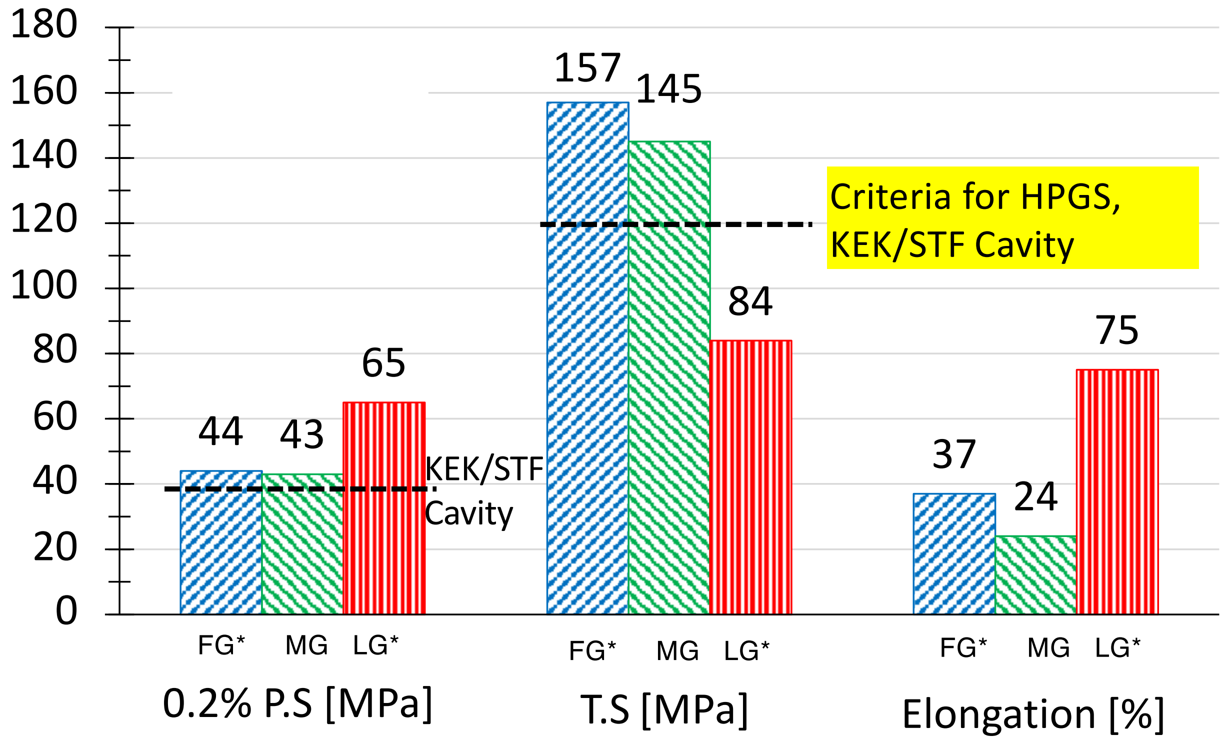
Courtesy: A. Kumar

Room temperature property Comparison

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



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

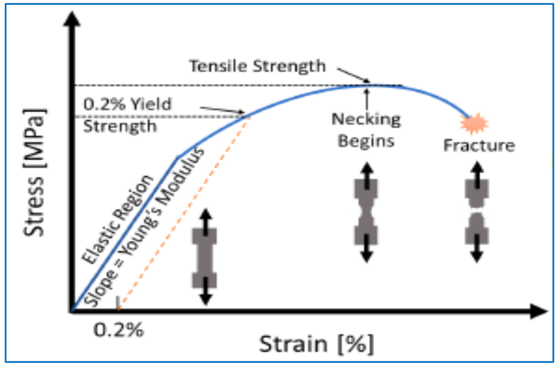


- MG Nb data: https://jacow.org/srf2021/papers/mopcav004.pdf
- FG Nb and LG Nb data is for Mid-RRR annealed material (M.Yamanaka et al., SRF'21 WEPFDV005).

Courtesy: A. Kumar

Room temperature property Comparison

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



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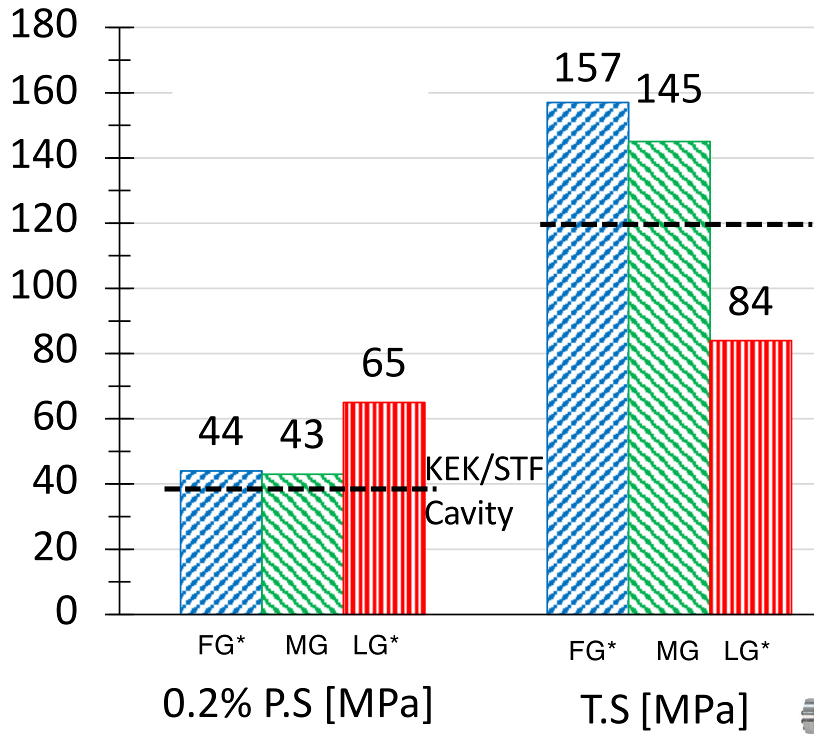
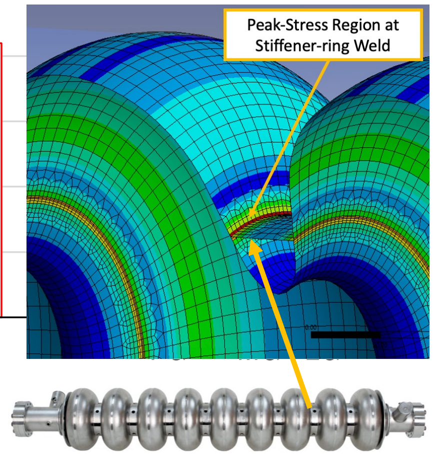


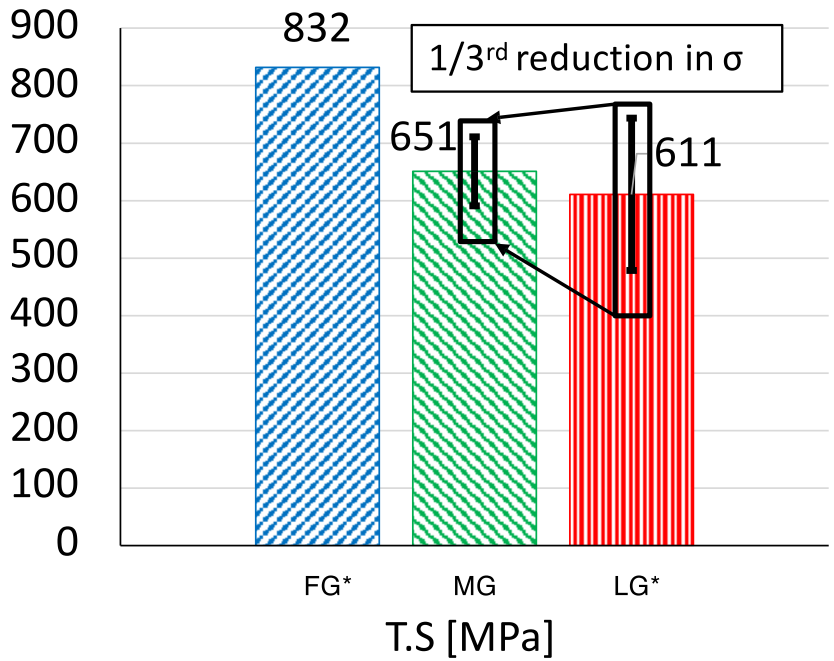


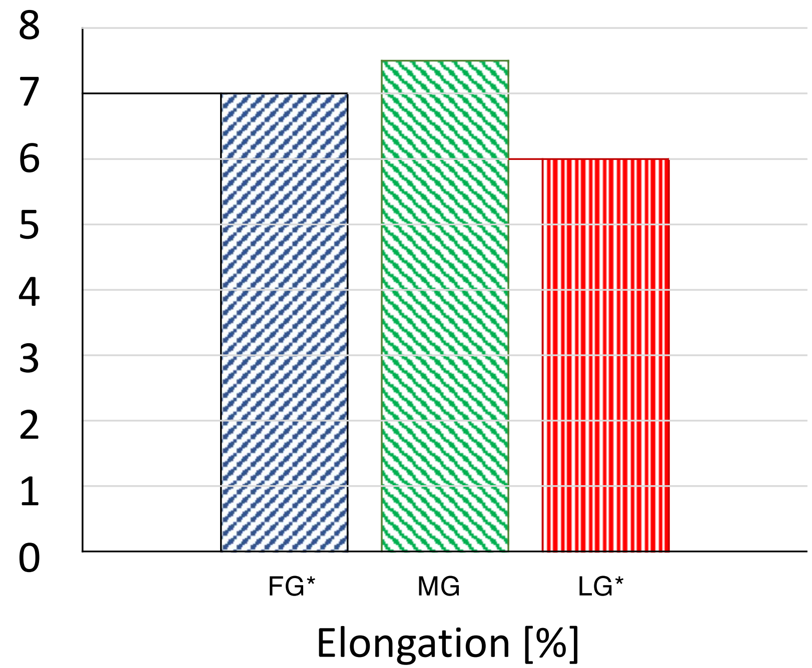
- MG Nb data: ht
- FG Nb and LG N PFDV005).

HPGS issues to be more discussed by K. Umemori, tomorrow, Wednesday !

Courtesy: A. Kumar

Low Temperature Property Comparison





- Tensile Strength of MG-Nb at LHe-T is better than LG-Nb.
- Brittleness and low elongation of MG-Nb are <u>not observed</u> at LHe-T after annealing.

Courtesy: A. Kumar

Summarized Results

ATI MG Nb Specimens

Temperature [K]	Sample Processing	Young's Modulus [GPa]	0.2% Proof Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
300	Annealed	88.7±9*	39±2	123±5	25.3 ± 3
300	ASR	89.7±6	43±4	145±7	23.9 ± 4
4.2	Annealed	114.0±11	283±34	651±60	7.5±2
4.2	ASR	115.4±14	284±22	351±28	1.8±1

* Error is standard deviation.

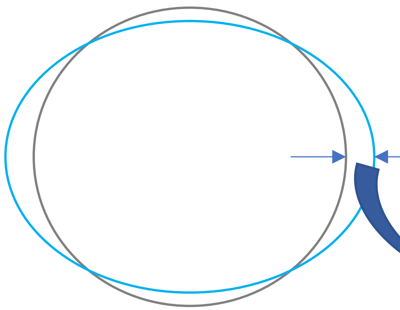
Courtesy: A. Kumar

Summary of Mechanical Test Results

- **ATI MG Nb's**_mechanical properties does **clear the mechanical strength criteris required for HPGS code** for KEK-STF SRF Cavity.
- **However,** elongation of the material needs to be improved for better yield with press forming.
- **MG Nb room temperature** properties are **closer to FG Nb**.
- **Low temperature** behavior of MG Nb is **closer to LG** Nb
- **Elongation** is same as FG and LG Nb at low temperature; however, **some** specimens did show lower elongation of **5-6%** too.
- **First Serration** usually starts at **250 to 300 MPa** stress.

Courtesy: T. Dohmae

MG Cavity Fabrication:
MG-Nb Disc successfully press formed to half-cells,



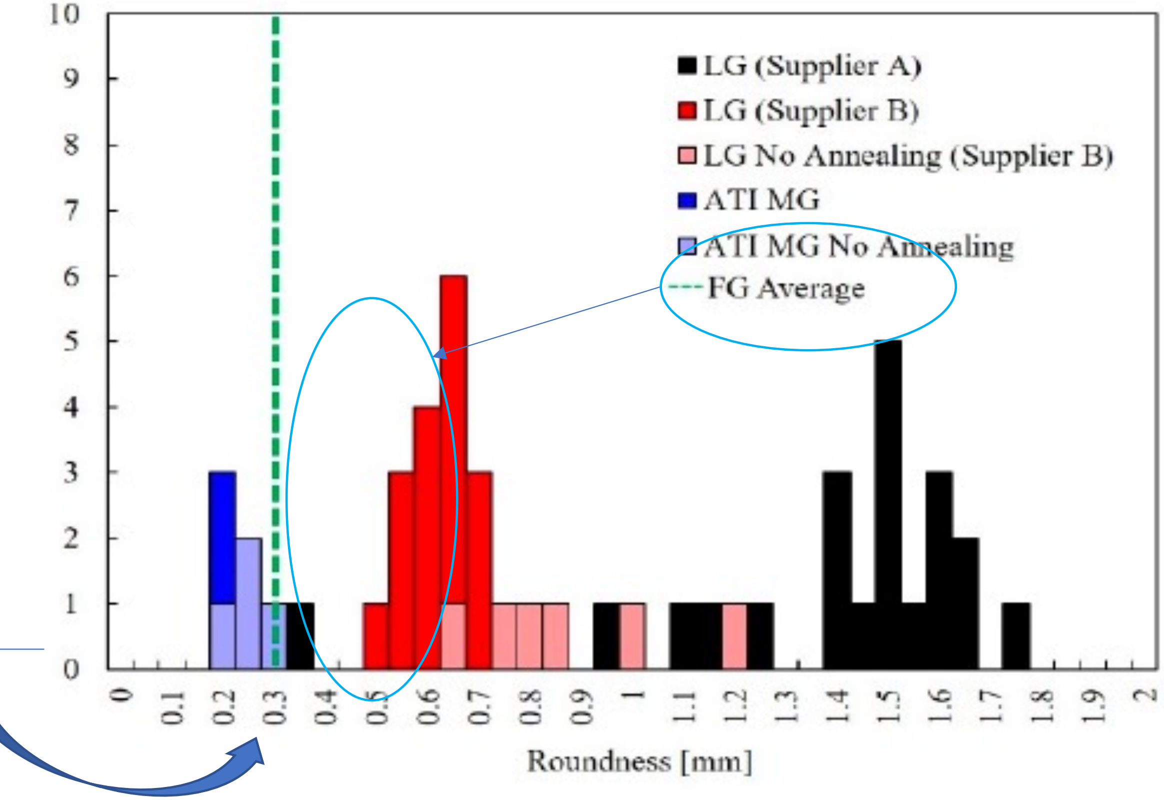
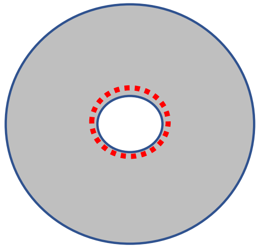


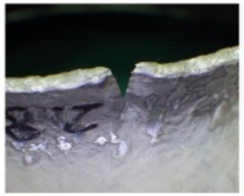
Figure 5: Histogram of measured roundness.

Courtesy: T. Dohmae

An Issue in Press-Forming Process

- settled with enlarging the disc, inner-hole diameter prior to press-forming



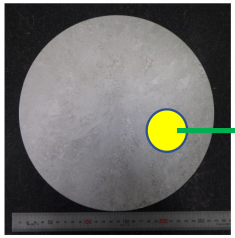


Disc #	Hole Diameter [mm]	Annealing	Forming Results	Purpose
#6	56	No	Light crack	R18
#7	56	No	Light crack	R18
#8	56	Yes	Deep crack	Test
#9	59	Yes	No crack	Test
#10	58	Yes	No crack	Test
#57	60	Yes	No crack	R18b
#58	58	No	Light crack	R18b
#59	56	No	Deep crack	Test
#60	58	No	Deep crack	Test

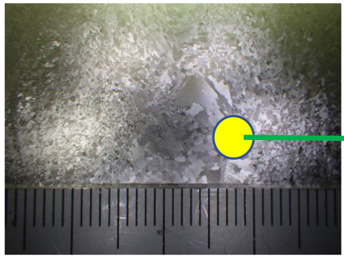
Courtesy: T. Dohmae

Evaluation of MG Surface Roughness Issue

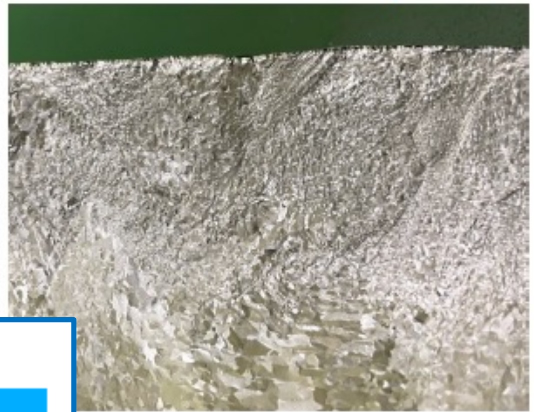
MG disc (ϕ260mm)



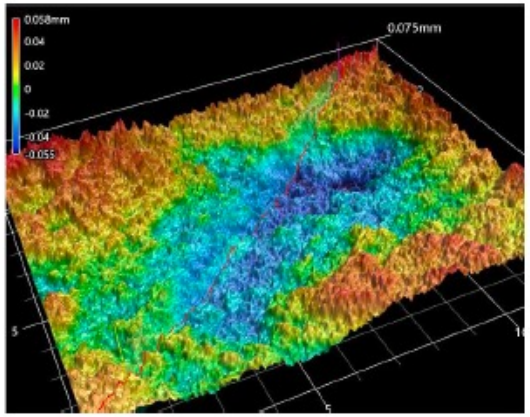
Zoomed view of MG disc



Inner surface around equator



3D data of surface



Surface roughness

	Ra [μm]	Rz [μm]
Disc	0.7	-
Formed	2.6 ~ 5.7	11 ~ 28
Polished	2.6 ~ 3.7	2.6 ~ 11
EP (100μm)	1.1 ~ 1.5	3.4 ~ 6.7

Surface

Became rough after forming.
(especially at curvature regions)

R18: Mechanically polished (equator)

Courtesy: T. Dohmae

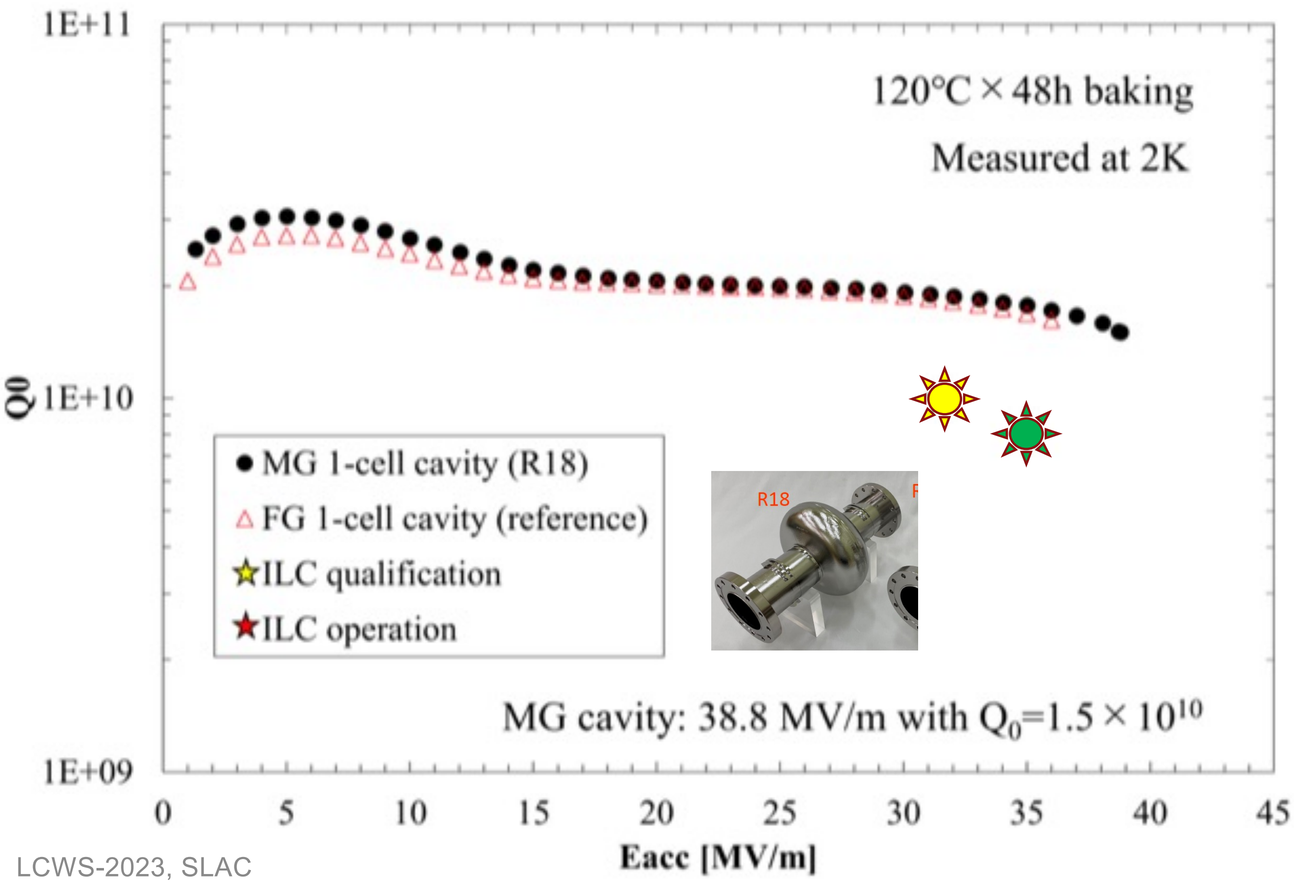
MG 1-Cell Cavity RF Performance
compared with FG 1-cell Cavity

RF Testing

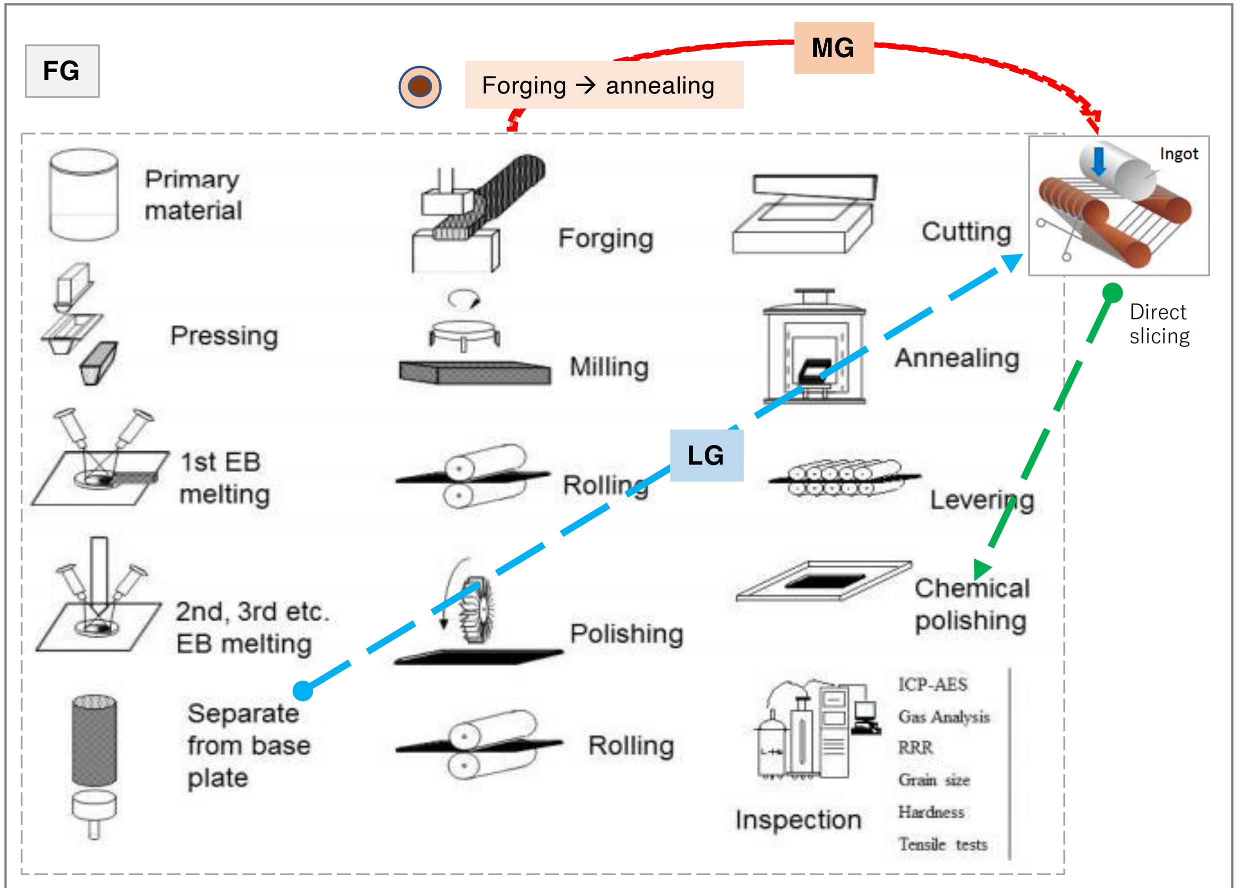
Surface treatment

1. Initial electropolishing of 100 µm
2. Annealing at 800 ℃ × 3 hours in a vacuum furnace
3. Second electropolishing of 20 µm
4. High pressure rinsing with ultra-pure water
5. Baking at 120 ℃ × 48 hours

Note: 9-cell MG Cavity fabrication **In progress**



Summary of Features for the FG, MG, LG Nb



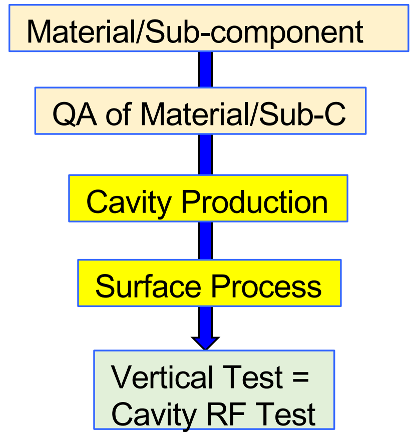
Nb sheet/disc production process for FG, MG, and LG.

	Process	FG	MG	LG
Refining	1. Primary material	✓	✓	✓
	2. Pressing	✓	✓	✓
	3, 4. EB Melting (multiple)	✅	✅	✅
Sheet/Disc forming	5. Separating Ingot	✅	✅	✅
	6. Forging to reduce (thickn. or dia.)	✅ (thick.)	✅ (diam.)	-
	7. Milling	✅	-	-
	8. Rolling	✅	-	-
	9. Polishing	✅	-	-
	* Annealing	✅	✅	-
	10. Rolling	✅	-	-
	11. Cutting (sheet)	✅	-	-
	* Direct Slicing (disc)	-	✅	✅
	12. Annealing	✅	✅	✅
Finishing	13. Leveling	✓	-	-
	14. Chemical polish.	✓	✓	✓
	15. Inspection	✓	✓	✓
Feature	**- Production cost**	**High (1)**	**Low (~2/3)**	**Lowest (<2/3)**
	- Cleanness	Modest	**Good**	Good
	- Mech. forming	Best	**Good**	Modest

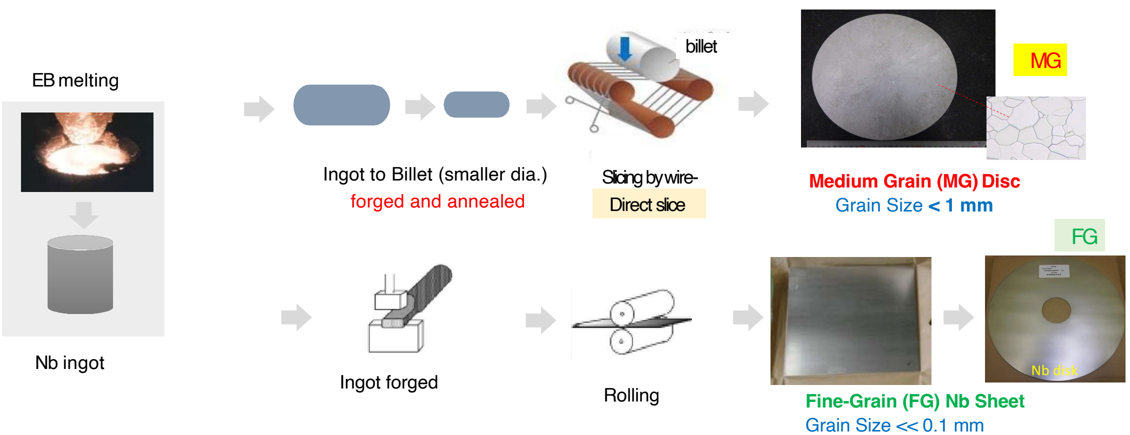
Courtesy: S. Michizono, Y. Yamamoto

ITN WPP-1 Plan: FG + MG Cavities, Indust. Product. Readiness

- **Pre-production** with 1-cell cavities to **establish the best process** including:
  - Nb sheet and SRF cavity production method
  - Inner surface treatment recipe
- **Production of > 20 (~3 x 8) x 9-cell cavities** for industrial-production readiness:
  - Globally common design with compatible High Pressure Gas Safety (HPGS) regulation
  - Best production process to be optimized in each region
  - Cavity performance expected: E_{acc} = <35 MV/m> (+/– 20%), $Q_0 = 1.0 \times 10^{10}$, Yield = ≥90%
- RF performance yield to be re-confirmed (including 2nd pass and further (3rd …)



Production process



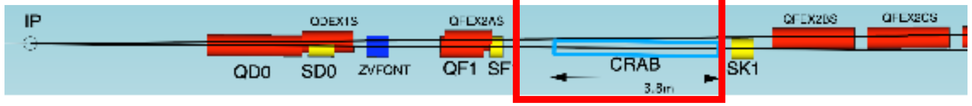
	# of cavities to be produced		
Region	Americas	Europe	JP/Asia
Type	FG + MG	FG + MG	FG + MG
1-cell	1 + 1	1 + 1	1 + 1, (+4)
9-cell	4 + 4	4 + 4	4 + 4, (+ 4)

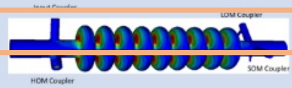
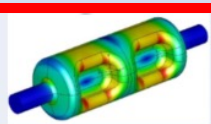
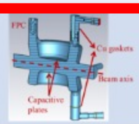
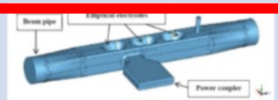
WP-prime 3: Crab Cavity Development

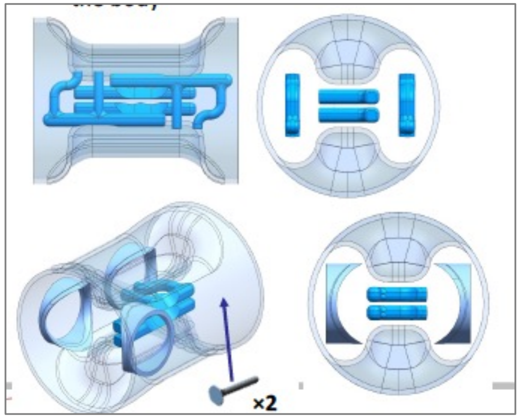
- Pre-down-selection review hosted by KEK chose two primary candidates on Apr/2023
  - RFD (1st), QMiR (2nd), Elliptical (3rd)
- Development and evaluation of two prototype cavities
  - KEK will provide for necessary Nb material to produce them
- RF property simulation to optimize cavity design
- Demonstration of synchronized operation with two prototypes
- Down-selection to choose final cavity design
- Cryomodule design based on final cavity design

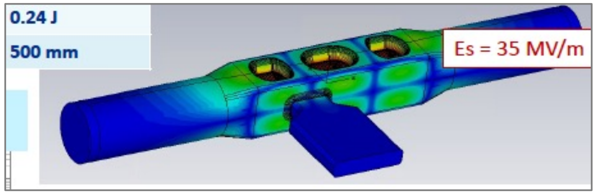
Both two candidates are from US!

two beamline distance
14.049m x 0.014rad = **197mm**

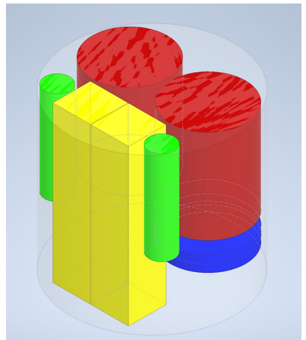


Elliptical/Racetrack (3.9 GHz)	Lanc. Univ.	
RF Dipole (RFD)	ODU	
Double Quarter Wave (DQW)	CERN	
Wide Open Waveguide (WOW)	BNL	
Quasi-waveguide MultIcell Resonator (QMIR)	FNAL	





Possible MG-Nb for Prototype



Summary

- **MG Nb** material has been **successfully developed** to qualify RF performance, qualified for 1.3 GHz SRF cavity application.
- **MG Nb** disc may **save the production cost to be ~ 2/3** of the FG Nb sheet production cost.
- The **RF performance** has been **demonstrated** with a **1-cell** 1.3 GHz SRF cavity satisfying the ILC SRF cavity specification. **9-cell in progress.**
- The **industrial production readiness** for 1.3 GHz 9-cell cavities is to be demonstrated in the **ILC-ITN global cooperation, and** .
- **For the future …**

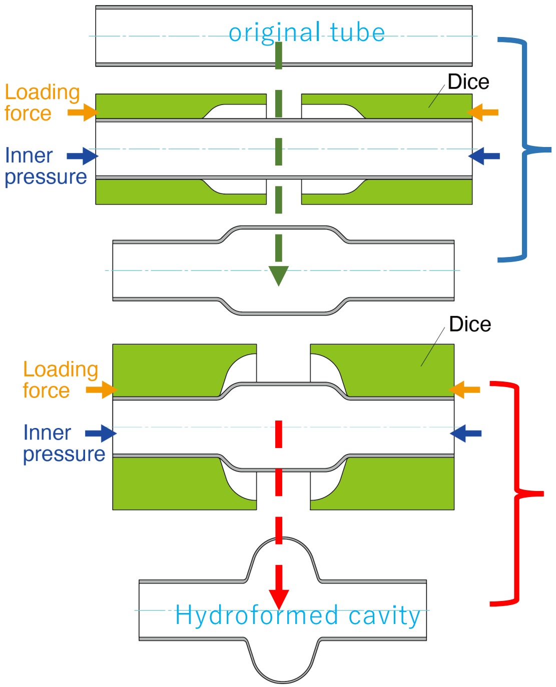
A Special Topic ! , toward the Future Cost Saving !

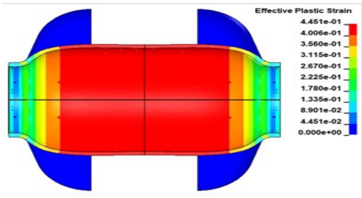
1.3 GHz, 1-cell Cu full-seamless cavity with new hydroforming

to be combined with thin **Nb/Nb3Sn** coating

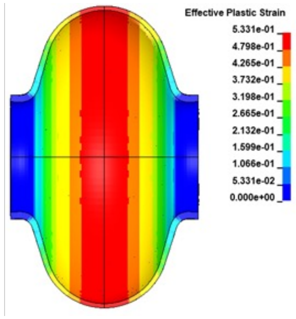
-- KEK-CERN Cooperation --

Courtesy:
- M. Yamamaka
- M. Carlasche

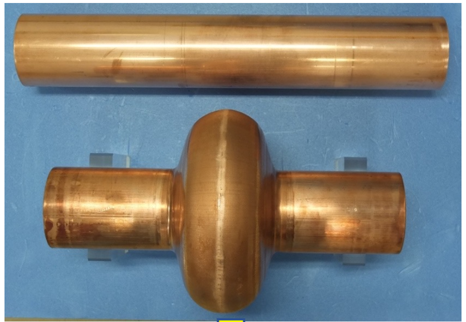




1st step



2nd step



← Succeeded, last week (in 2 days)

Seamless Cavity Hydroforming Process,
proposed by M.Y.

2023-5-16

Simulated by CERN and Realized by KEK

- Simulation and material characterization, by M. Garlashce et al. at **FCC-week** and at **SRF2023,**
- Hydroforming details will be presented by M. Yamanaka et al., at **SRF2023**