Forged Ingot Niobium Technology for Accelerators:
(Medium-Grain Nb disc directly sliced from forged ingot)

Takayuki SAEKI (KEK)

LCWS2021

SRF session, 17th (Wed.) Mar. 2021

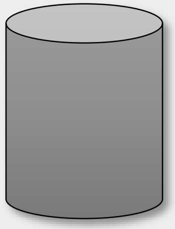
(Virtual Zoom conference)

Contents

- Manufacture method of Large-Grain (LG) Nb disc from Nb Ingot
- Advantage and key issues of directly sliced LG Nb discs
- Studies on directly sliced Nb-ingot at KEK
- Comparison of LG and Fine-Grain (FG) tensile strength
- High-pressure gas safety act
- Directly sliced Medium-Grain (MG) Nb discs from forged Nb ingot
- Press-forming of MG Nb disc (RRR~100)
- LOI of forged MG Nb ingot for Snowmass 2021.
- Sample Forged Nb Ingot (RRR>400) produced by ATI for 1.3 GHz SRF cavities to be fabricated at KEK
- Plan of studies of MG forged Nb ingot at KEK in 2021.
- Summary

Manufacture method of Large-Grain Nb disc from Nb ingot

Nb melting



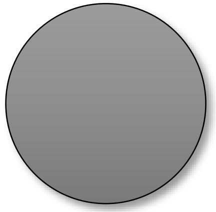
Niobium ingot
(Raw material)

Conventional method

Forging

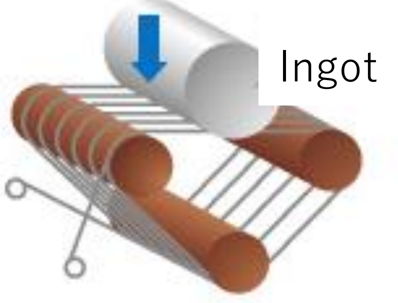
Rolling

Cutting

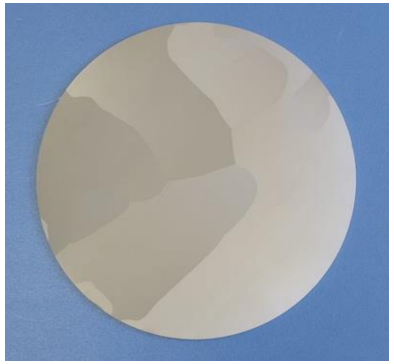


Finish
Fine-Grain Nb disc

Direct slice



Slicing image
by wire-saw



Sliced ingot
(260 mm Dia.)
Large-Grain Nb disc
Large grains are observed

Advantage and key issues of directly sliced LG Nb discs

Advantage:

- Direct slice method can omit the forging, rolling and turning processes compared with the conventional method.
- Direct slice method is cost effective than the conventional method.
- Direct slice disc is clean because the risk of contamination in the rolling process is avoided.

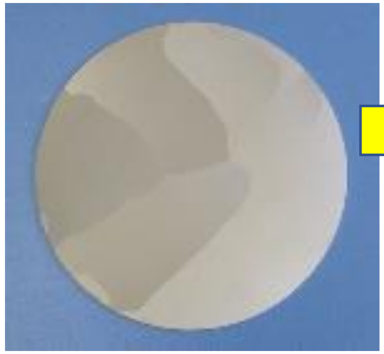
Key issues to be improved and confirmed:

- On the other hand, the tensile strength of the large-grain (LG) Nb material depends on the crystal orientation and has broader distribution compared with the fine-grain (FG) Nb material.
- It is still to be confirmed if more than nine thousand ILC 9-cell cavities made of LG material can be fabricated complying with the High-Pressure Gas (HPG) Safety Act.

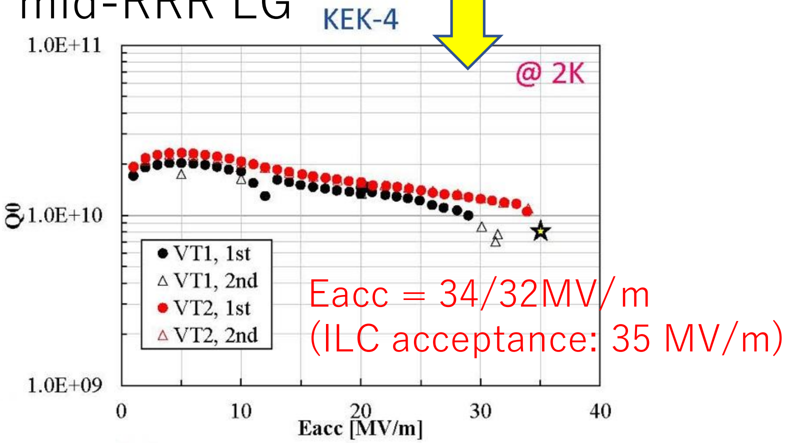
Studies on directly sliced Nb-ingot at KEK

- R&D for direct slice ingot Nb has performed for various Nb materials.
  - Nb ingot/disk fabrication
  - Mechanical test
  - RF performance test
- RF performance was evaluated for mid-RRR LG cavities. It was close to ILC specification, but bit lower than 35 MV/m.
- Tensile test machine at RT/4.2K was constructed and used for the tests.
- Test results become important input for high-pressure gas safety issue.

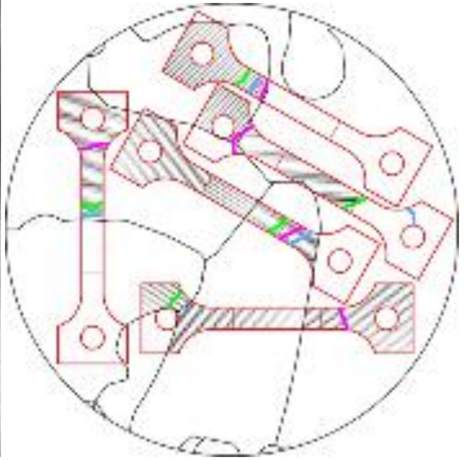
- Alternative Nb materials are developed with supports from companies
  - Cost effective high-RRR sliced LG disk (ULVAC)
  - MG disk from forged ingot (ATI)



KEK-4/5 cavities from mid-RRR LG



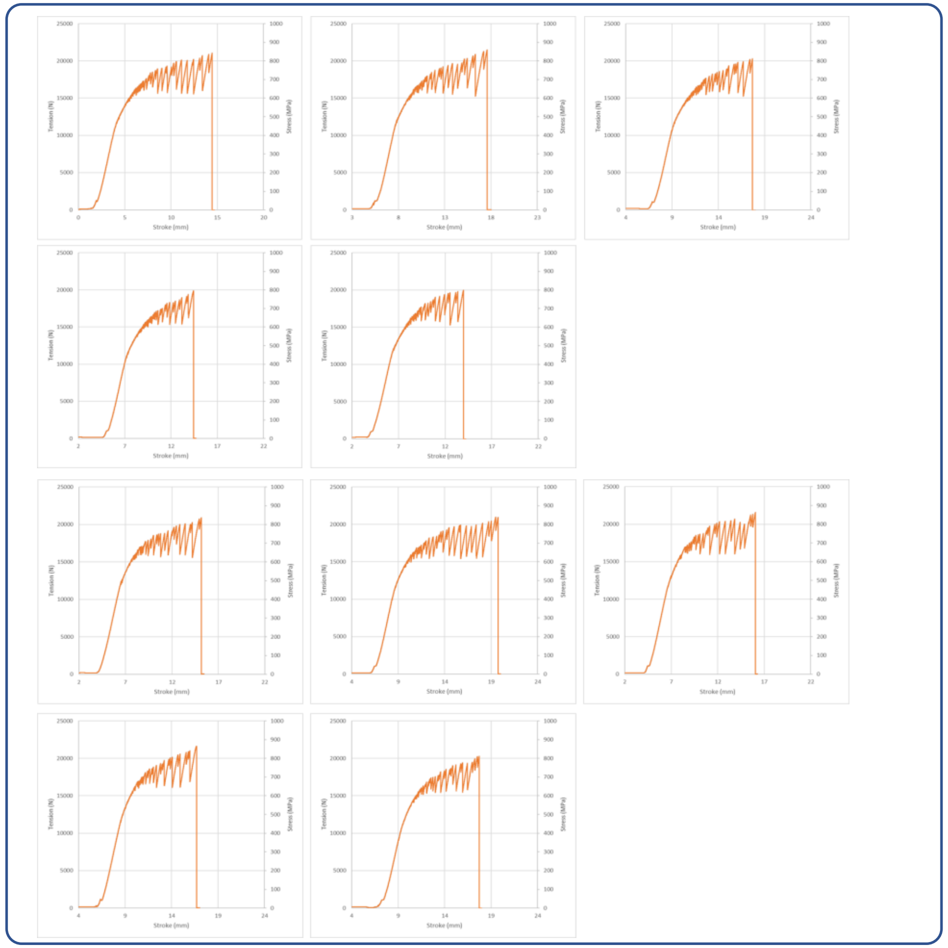
Tensile test machine for 4.2K



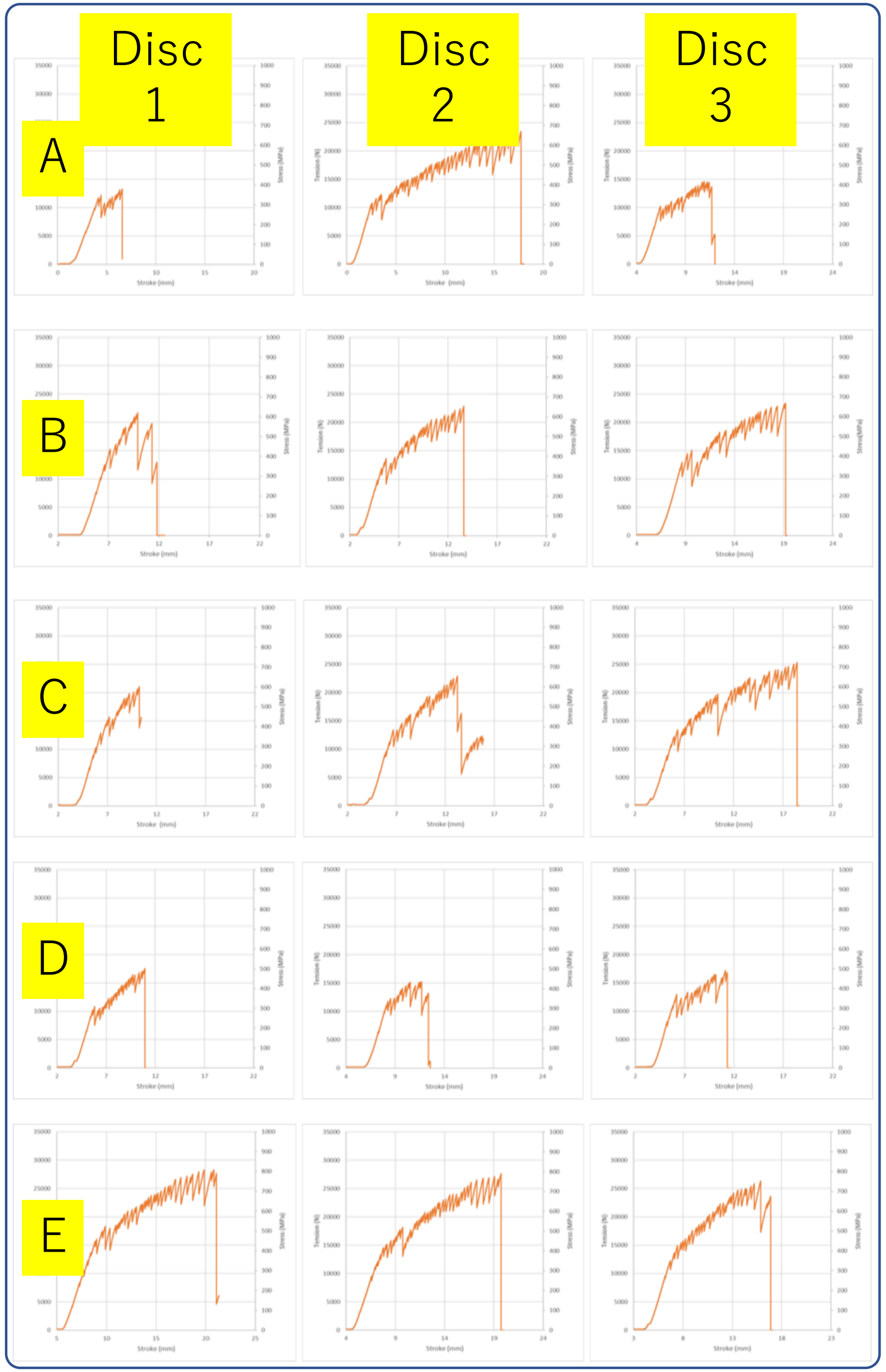
Comparison of LG and FG tensile strength

Tensile strength of LG Nb depends on the crystal orientation and has broad distribution.

FG



LG



Studied by K. Enami (KEK / Tsukuba Univ.)

High pressure gas safety act.

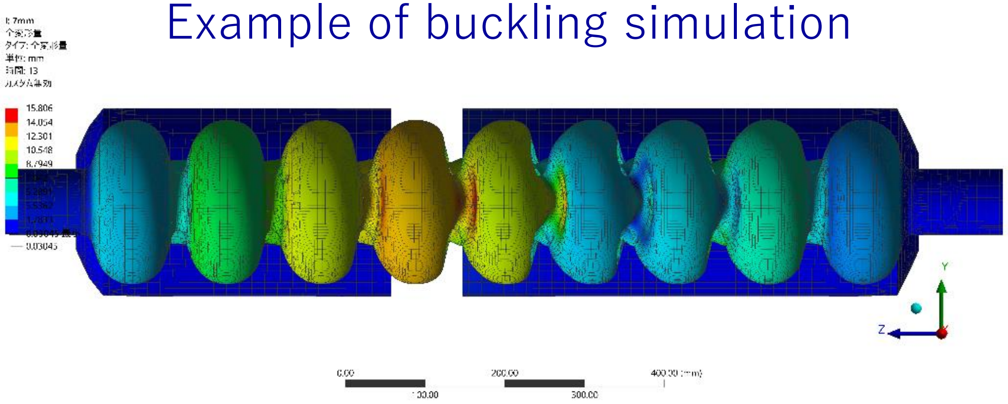
In order to pass the high-pressure gas safety act with the LG 9-cell cavity, following items are necessary.

- Stress and buckling simulation with the tensile strength values of LG Nb material.
- Welding procedure specification (WPS) with LG Nb material.

We (KEK) are trying to achieve this goal.

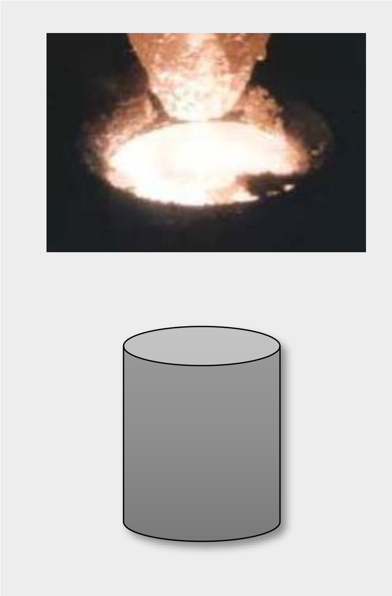
Example of WPS

Example of buckling simulation



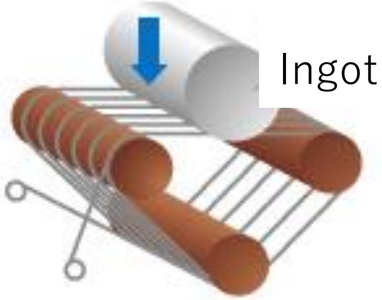
Manufacture method of Medium-Grain Nb discs from forged Nb ingot

Nb melting

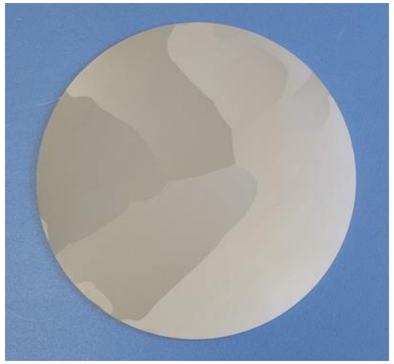


Niobium ingot
(Raw material)

Direct slice of LG ingot



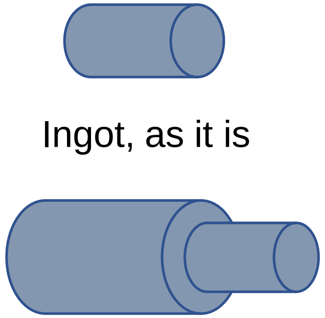
Slicing image
by wire-saw



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

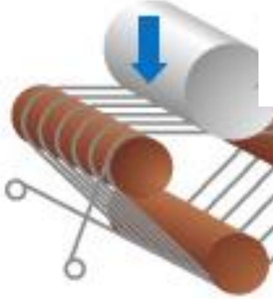
- Aiming for clean, mechanically stable, and cost-effective SRF cavity production.

Direct slice of MG ingot

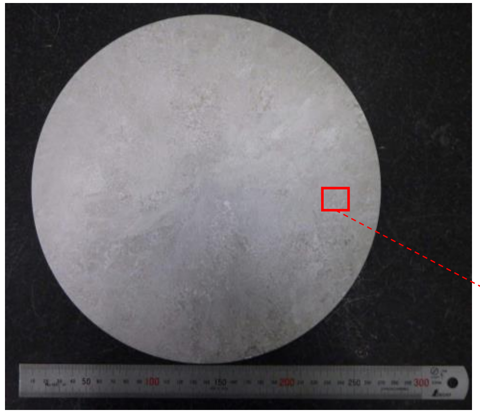


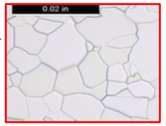
Ingot, as it is

Ingot, forged and annealed



Slicing image
by wire-saw





A New Approach:
Medium Grain (MG) Disc
Grain Size **< 1 mm**

* 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.**

Directly sliced MG Nb discs from forged Nb ingot

The cost of directly sliced Medium-Grain (MG) Nb disc is much lower than the rolled Fine-Grain (FG) Nb disc.
The advantage of cleanness from the direct slicing method is kept in the directly sliced MG Nb discs.
Medium-Grain (MG) Nb material is expected to have similar uniformity and tensile strength to the fine-Grain (FG) Nb material. To pass the HPG safety act, MG-Nb cavity might be more promising than LG-Nb cavity.

- Forged MG Nb ingot should be examined, if it could be applicable for the ILC SRF cavity, satisfying the cost-effective production and required RF performance.
- And it might be added as a technology of cost-effective Nb-disc production for the SRF cavities in the future (and for ILC).

Ref: A. Yamamoto, M. Yamanaka and G. Myneni, "Ingot Nb based SRF Technology for the ILC", AIP Conf. Proc. 1687, 030005-1 – 03005-6, (2015)

First step: Directly sliced Nb disc from forged MG Nb ingot (RRR~100) demonstrated in cooperation with ATI

Half-cup: press-formed MG Nb disc.

- ATI(US) provided directly sliced disc from forged MG Nb ingot.
- RRR ~ 100.
- Grain size: ASTM 3.5 – 5.5.
- Disc thickness: 3.1 mm.
- Forged MG Nb disc was appropriately heat-treated.
- The MG Nb disc was press-formed at KEK.

Note: ATI(US) is the company which supplied most of NbTi material for CERN-LHC superconducting magnets. For further information about ATI, please see the last slide (Appendix) of this presentation.

LOI submitted for Nb Disc sliced from forged Ingot

Development of High-efficiency and Cost-effective Forged Ingot Niobium Technology for Science Frontiers and Accelerator Applications

Snowmass 21 Contribution, August 28, 2020

Snowmass 2021

G. Myneni[1,2], G. Ciovati[3,5], P. Dhakal[3], Hani E. Elsayed-Ali[1], A. Fajardo[4], Md Obidul Islam[1], B. Khanal[5], N. Lannoy[4], F. Marhauser[3], P. O'Larey[4], R. A. Rimmer[3], T. Saeki[6], M. Yamanaka[6], T. Dohmae[6], K. Umemori[6], A. Yamamoto[6,7]

[1]Electrical and Computer Engineering, Old Dominion University, Norfolk, VA 23529
[2]BSCE Systems Inc., Yorktown, VA 23693
[3]Acclerator R&D, Jefferson Lab, Newport News, VA 23606
[4]ATI Specialty Alloys & Components, Albany, OR 97321
[5]Physics, Old Dominion University, Norfolk, VA 23529
[6]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan 305-0801
[7]European Organization for Nuclear Research (CERN), Geneva, Switzerland, CH-1211

Email: gmyneni@odu.edu

Development of Forged Ingot Niobium Technology:

Worlds science frontier programs and SRF accelerator applications ... performance and cost-effective SRF accelerator technology [1-8]. Fine-gra... (LG) ingot niobium technologies have been very well developed and imple... present-day accelerator projects. However, forged ingot niobium technolo... of this development proposal will be much more cost-effective and expect... technical advantages.

FG niobium sheet production is very complex involving more than ... making them prone to contamination. As a result, they are very expensive to produce and require stringent QA procedure to be ready for SRF cavity production. The accelerating cavity process steps are also numerous and require strict procedures in order to achieve high accelerating gradients and quality factors needed for science frontier progra...

LG niobium disc production, directly sliced from the ingot, is rela... forward to keep surface cleanness. The disc production cost is significan... niobium sheet production. However, there are (some) draw backs due t... the grain boundary distribution, resulting in non-uniform mechanical pro... cavity fabrication, although the LG cavities achieve the expected high-gr... goals with lower cost.

Medium-grain (MG) niobium disk production may be realized with a new approach/process, the disc directly sliced from the forged ingot, involves a simpler process steps contributing major production cost reduction [9]. These discs are expected to be superior as they tend to be homogenous with uniform sub millimeter grains and mechanical properties. We are eagerly looking forward to developing the forged ingot niobium SRF accelerator technology

for the benefit of the world-wide science frontier programs, green energy subcritical nuclear energy systems and a wide variety of industrial applications including the production of radio isotopes and nuclear transmutation applications.

References:

Forged Ingot Niobium Technology for Scientific Frontiers and Accelerator Applications

G. Myneni[1,2,3], G. Ciovati[3,5], P. Dhakal[3], Hani E. Elsayed-Ali[1], A. Fajardo[4], Md Obidul Islam[1],
B. Khanal[5], N. Lannoy[4], F. Marhouser[3], P. Olarey[4], R. A. Rimmer[3],T. Saeki[6], M. Yamanaka[6], T. Dohmae[6],
K. Umemori[6], A. Yamamoto[6,7]

[1]Electrical and Computer Engineering, Old Dominion University, Norfolk, VA 23529
[2]BSCE Systems Inc., Yorktown, VA 23693
[3]Accleratro R&D, Jefferson Lab, Newport News, VA 23606
[4]ATI Specialty Alloys & Components, Albany, OR 97321
[5]Physics, Old Dominion University, Norfolk, VA 23529
[6]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan 305-0801
[7]European Organization for Nuclear Research (CERN), Geneva, Switzerland, CH-1211

February 17th 2021, Virtual Snowmass mini-Workshop

Wednesday, February 17, 2021 Virtual SNOWMASS mini-Workshop on Cavity Performance Frontier
Myneni Ganapati rao@jlab.org

Jefferson Lab KEK BSCE SYSTEMS, INC. ATI U.S. DEPARTMENT OF ENERGY Office of Science JSA

Courtesy: **ATI**

Sample Nb-RRR Forged Ingot (RRR>400) produced by ATI for 1.3 GHz SRF cavities to be fabricated at KEK

“**Nb RRR**” Billet, annealed

RRR Test

Sample Location:	Top	Bot
RRR	525	450
	453	523

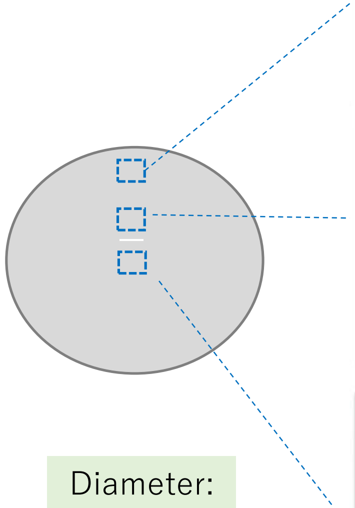
Metallography Test

Sample Location:		Top			Bot		
		Edge	Mid-Radius	Center	Edge	Mid-Radius	Center
Recrystallization:	%	100	100	100	100	100	100
Grain Size:	ASTM	0.5	2	1	2	1	1.5
Grain Size :	µm	300	200	250	200	250	210
Hardness:	HV 10	42.4	40.4	40.5	41.3	40.8	43.5

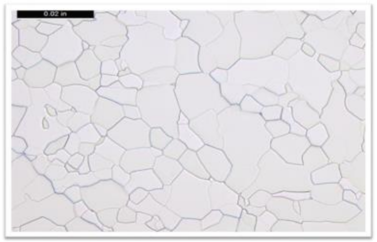
Room Temperature Tensile Test

Sample Location:		Top	Bot
Orientation:		Radial	Radial
0.2% Yield Point:	MPa	56	61
Ultimate Tensile Strength:	MPa	146	141

0.02 inch



Diameter: 260 mm



Edge

Mid. Radius

Center

Grain Size DIstribution: 200 ~ 300 μm

Mechanical homogeneity and stability, expected

Nb Forged Ingot produced by ATI for Demonstrating 1.3 GHz SRF Cavity Fabrication at KEK

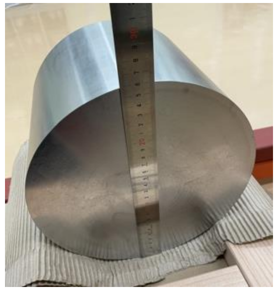
Courtesy: **ATI**

"**Nb RRR**" Billet, annealed

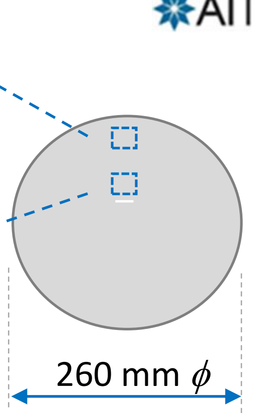
Sample location from forged ingot

Parameters	Nb sheet (FG) (Spec. Eu-XFEL as Reference)	Nb forged ingot (MG) Measured
RRR	$R_{RT}/R_{4.2K}$ ≥ 300	R_{RT}/R_{TC} 450 523
Re-crystallization	100 %	100 %
Grain size (ASTM) Edge, Mid., Center	4 ~ 6	2 , 1, 1.5
Grain size (mm) Edge, Mid.,Center	< 0.05	0.2, 0.25, 0.21
Y.S.-0.2% (RT)	≥ 50 MPa	61 MPa
T.S. (RT)	≥ 140 MPa	141 MPa

0.02 inch



ATI



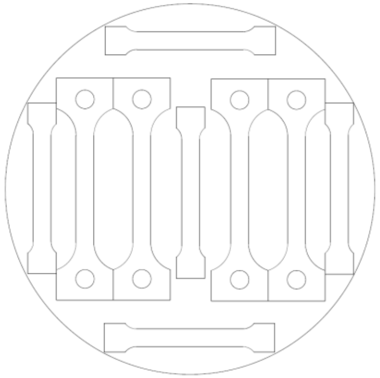
Grain Size: 0.2 ~ 0.3 mm
Mechanical stability may be expected

Directly sliced MG Nb discs from forged Nb ingot

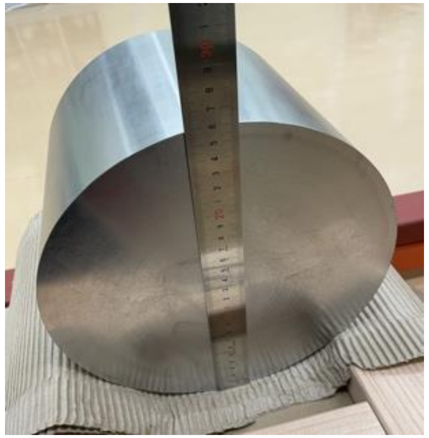
Plan of studies for MG Nb material at KEK in 2021.

Now cutting-out samples

- We (KEK) purchased the forged MG Nb ingot (D:260 mm, L: 200 mm, RRR > 400) from ATI (Delivery to KEK on 16th Feb. 2021).
- The forger MG Nb Ingot was sliced at a job-shop. (Delivery to KEK on 2^{nd} Mar. 2021)
- We are planning the tensile strength tests with forged MG Nb material.
- We are planning the fabrication of cavities with forged MG Nb material and RF performance tests of cavities (in cold vertical tests).



Delivery of ingot from ATI to KEK on 16^{th} Feb. 2021



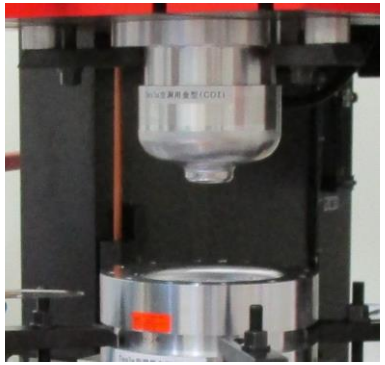
ATI

Ingot was sliced at a job-shop and delivered to KEK on 2^{nd} Mar. 2021, and BCP of several discs.

Tensile test at room T and liquid-He T.

Fabrication of two single-cell 1.3GHz cavities.
And RF performance tests at 2 K in vertical cryostat.

Now press-forming discs



Planning the fabrication of 9-cell 1.3GHz cavities, and RF performance tests at 2 K in vertical cryostat.

Nb Technologies for SRF

Fine Grain (FG) Rolled Nb sheets	Medium Grain (MG) Forged Ingot Nb discs	Large Grain (LG) Ingot Nb discs
Up to fourteen manufacturing steps Labor intensive	E-beam melted ingot of larger dia. forged to required dia and then sliced	E-beam melted ingot of required dia. is sliced
Grain Size ASTM 5 ~ 50 µm	ASTM 0 – 3, < 1 mm	Large non uniform grains >1 cm
Widely used complex technology prone to contamination	New kid on the block and very clean surfaces	Proven clean surface technology
Uniform & adequate mechanical properties	Superior uniform mechanical properties	Non uniform mechanical properties
Requires stringent QA & expensive	Cost advantage	Cost advantage

All of these Nb materials are available!

Summary

- Advantage of LG Nb disc: cost-down and cleanness.
- Key issues to be improved for LG Nb disc: broader distribution of tensile strength.
- Comparison of LG and FG tensile strength was done at KEK.
- Press-forming of ATI MG Nb disc (RRR~100) was done at KEK.
- The mechanical strength tests of LG, MG and FG Nb discs to be completed and established at KEK, to be well prepared for discussions on the HPG applications and regulations (worldwide).
- LOI of forged MG Nb ingot is submitted as Snowmass 2021 contribution.
- Sample Nb-RRR Forged Ingot (RRR>400) produced by ATI for 1.3 GHz SRF cavities to be fabricated at KEK
- Plan of studies with forged MG Nb ingot at KEK in cooperation with ATI in 2021: tensile tests and fabrication of 1.3-GHz cavities including RF performance tests at KEK.

Appendix: ATI (US) information

- LHC: Large Hadron Collider: 50k lbs of NbGr1 and Nb7.5Ta
- ITER: International Thermonuclear Experimental Reactor: 140k lbs of NbGr1
- RISP: Rare Isotope Science Project: 27k lbs of NbRRR
- FNAL: Fermi National Accelerator Laboratory: 10k lbs of NbRRR, 5k lbs of Nb55Ti
- Other projects: RHIC, Tevatron, Spallation Neutron Source (ORNL)

- For further information, please visit following ATI slides for SRF workshop for ILC in 2011.

https://agenda.linearcollider.org/event/5182/contributions/21998/attachments/18075/29035/ILC_workshop_presentation_-_ATI_Wahchang.pptm