Nb-Material Preparation Plan at KEK and High-Pressure-Gas-Safety (HPGS) Constraints in Japan

Akira Yamamoto

In cooperation with K. Umemori, T. Saeki, A. Kumar, and Y. Yamamoto

(ILC-IDT-WG2 and KEK)

To be presented at CC Design Meeting #6, 27 Jan. 2023

Outline

- **Nb (-FG and -MG) Material Preparation Plan for:**
  - 1.3 GHz Elliptical Cavities for ILC-ML Prototypes, on going, and
    Crab Cavity Prototypes for ILC-BDS, expected

- **High Pressure Gas Safety (HPGS) Constraints for:**
  - HPGS regulations in Japan, and a solution for the ILC-SRF
  - “Refrigeration Cycle Regulation” applied for IFMIF cavity fabricated in Europe
  - Requirements for SRF cavity fabrication, and experimental evaluation of the Nb (-FG and - MG) material properties

ILC-IDT Technical Preparation toward Pre-lab

2021 May

IDT-WG2 summarized the technical preparation as work packages (WPs) in the technical preparation document.

Actual cavity /CM manufacturing

ILC Pre-lab

- SRF ~41MILCU 285 FTE-yr
  - WP-1 Cavity production
  - WP-2 Cryomodule assembly
  - WP-3 Crab cavity
- e- source ~2.5MILCU, 6 FTE-yr
  - WP-4 Electron source
- e+ source ~6MILCU, 15FTE-yr
  - Undulator scheme
    - WP-5 Undulator
    - WP-6 Rotating target
    - WP-7 Magnetic focusing
  - e-Driven scheme
    - WP-8 Rotating target
    - WP-9 Magnetic focusing
    - WP-10 Capture cavity
    - WP-11 Target replacement
- DR ~2.5MILCU, 30FTE-yr
  - WP-12 System design
  - WP-13 Collective effect
  - WP-14 Injection/extraction
- BDS ~2MILCU, 16FTE-yr
  - WP-15 Final focus
  - WP-16 Final doublet
- Dump ~3MILCU, 12FTE-yr
  - WP-17 Main dump
  - WP-18 Photon dump

- The technical preparation document was reviewed by the international review committee (chair:Tor Raubenheimer (SLAC)).
- The total global cost of the project is about 60 MILCU* and about 360 FTE-year. (This does not include the cost of the infrastructure for the WPs.)
- The cost will be shared internationally as in-kind contribution.

1MILCU=1M$(2012)

2021 May

Ver-5: 2021/May/30

Technical Preparation and Work Packages (WPs) during ILC Pre-lab

IDT-WG2

Work Packages (WPs)

2022 June

Ver-8: 2022/June/10

Time-critical WPs for the ILC construction

IDT-WG2

Time Critical WPs
(~1/4 scale)

→ **WP-Prime**

http://doi.org/10.5281/zenodo.4742018

https://agenda.linearcollider.org/event/9735/contributions/50816/attachments/38190/59968/Time-Critical_WPsV8b.pdf

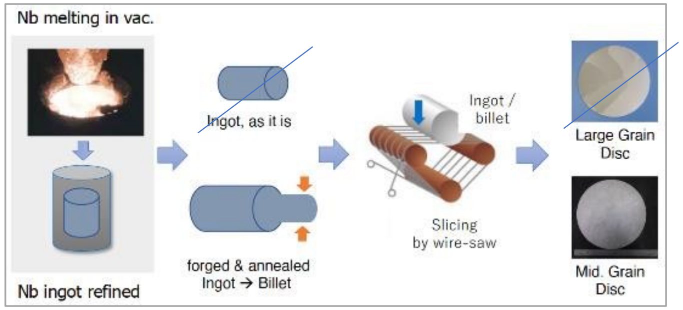
WP-prime 1: SRF Cavity

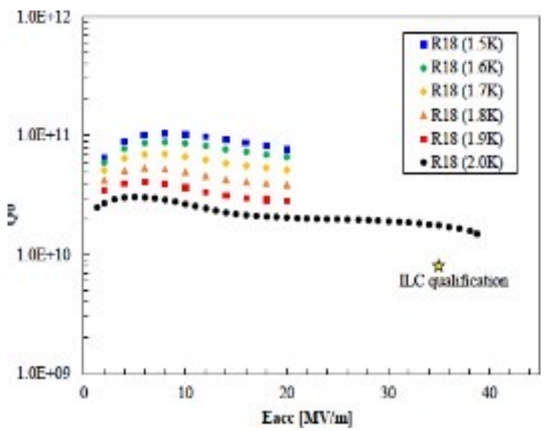
* Scoping the Industrial-Production Readiness

- ◆ Research with single-cell cavities to establish the best production process including:
  - ◆ Advanced Nb sheet production method
  - ◆ Advanced surface treatment recipe
- ◆ Globally common design with compatible High Pressure Gas Safety (HPGS) regulation
- ◆ 24 nine-cell cavities are to be developed for industrial-production readiness
  - ◆ 8 cavities (4 / batch) in each region
  - ◆ Production process encouraged to be optimized in each region
- ◆ RF performance/success yield to be examined (including 2^{nd} pass and further)
  - ◆ 3^{rd} pass to be examined if effective

Referring EuXFEL and LCLS-II experience

	Cavities to be produced		
	Americas	Europe	JP/Asia
single-cell	**2**	**2**	**2**
nine-cell	**8**	**8**	**8 (+ 12)**





Material/Sub-component

QA of Material/Sub-C

Cavity Production

Surface Process

Vertical Test = Cavity RF Test

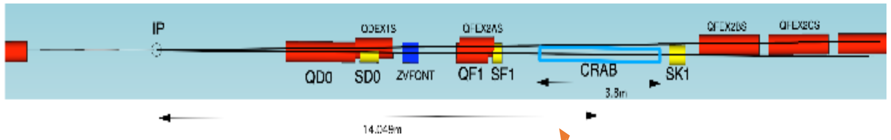
Production process

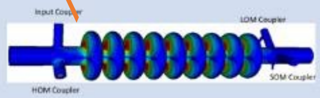
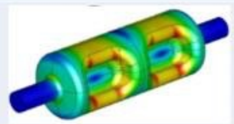
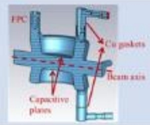
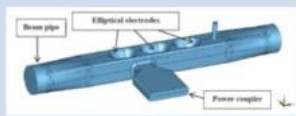
WP-prime 3: Crab Cavity Development with down-selection

- RF property simulation to optimize cavity design
- Pre-down-selection to choose two primary candidates
- Development and evaluation of two prototype cavities
- Demonstration of synchronized operation with two prototypes
- Down-selection to choose final cavity design
- Cryomodule design based on final cavity design

Item	Recent specification (after TDR)
Beam energy	125 GeV (e^-)
Crossing angle	**14 mrad**
Installation site	14 m from IP
RF repetition rate	5 Hz
Bunch train length	727 μsec
Bunch spacing	554 nsec
Operational temperature	2.0 K (?)
Cavity frequency	1.3/3.9 GHz
Total kick voltage	1.845/0.615 MV
Relative RF phase jitter	0.023/0.069 deg rms (49 fs rms)

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

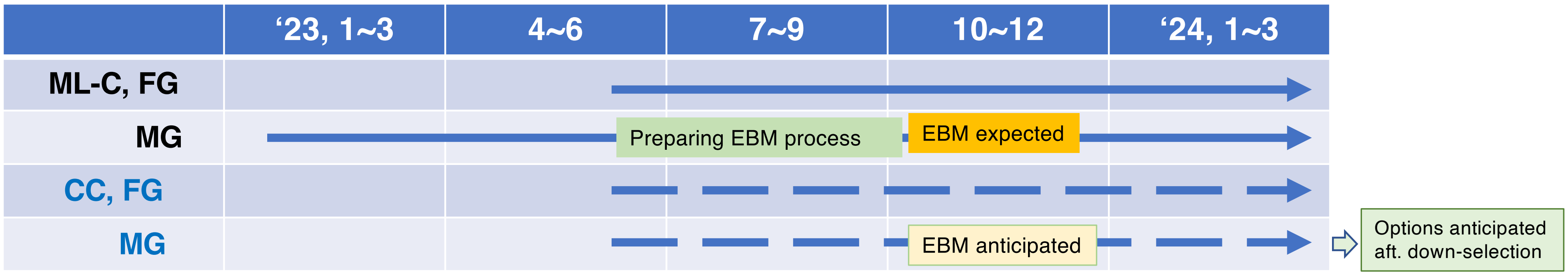


Elliptical/Racetrack (3.9 GHz)	Lanc. Univ.	
RF Dipole (RFD)	ODU	
Double Quarter Wave (DQW)	CERN	
Wide Open Waveguide (WOW)	BNL	
Quasi-waveguide MultIcell Resonator (QMIR)	FNAL	

Nb FG-sheets / MG-disks Fabrication expected in JFY2023

	Test	Prototype	Test	Prototype	Sum (FG+MG)
ML-Cavity AS AMs EU	FG 1-cell (1) (1) (1)	FG 9-cell [4 +6] +1 4 + 0.5 4 + 0.5	MG 1-cell (1) (1) (1)	MG 9-cell [4 +6] +1 4 + 0.5 4 + 0.5	9-cell 22 9 9
Procured (Bidding)	20 x (18+2) sheets (~1.5 m ingot -> 400 sheets (before Summer)		20 x (18+2) disks (~1.2 m billet → 400 disks) (process started)		40 Cavities
BDS-CC Type 1 Type-2	 TBD TBD	 TBD TBD	 TBD TBD	 TBD TBD	 TBD TBD

Procurement process expected



Requirements for Nb Material

Characteristics	FG	MG	Note
Chemical composition*	ASTM B393-09 Type5, EuXFEL, LCLS-II equiv.	Same	
Residual R. Ratio	≥ 250	Same	R(RT) / R(~4K)
Tensile Strength	≥ 120 MPa	Same	@ RT
Yield Strength	≥ 39 MPa	Same	@ RT
Grain Size	≤ 0.1 mm (av.)	≤ 1 mm (av,)	+ Re-crystalization (%)
Size	~ 280 x 280 mm2 2.8 mm, t	260 mmf x 1.5 m → ~ 500 disks (@ ~2.8 mm, t)	
Surface	(BCP aft. grinding)	(BCP aft. Slicing)	

*Remaining	C	N	O	H	Zr	Tn	Fe	Si	W	Ni	Mo	Hf	Ti	S
Upp. Limit [wt-ppm]	39	30	40	5	100	1000	50	50	70	30	50	50	50	10

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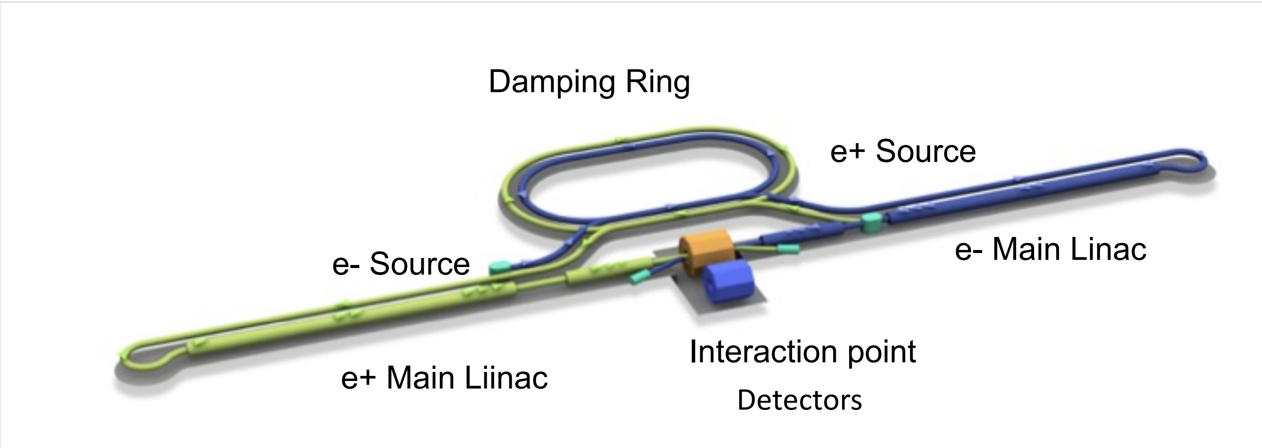
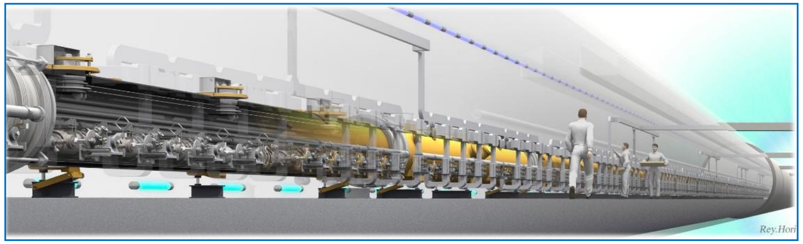
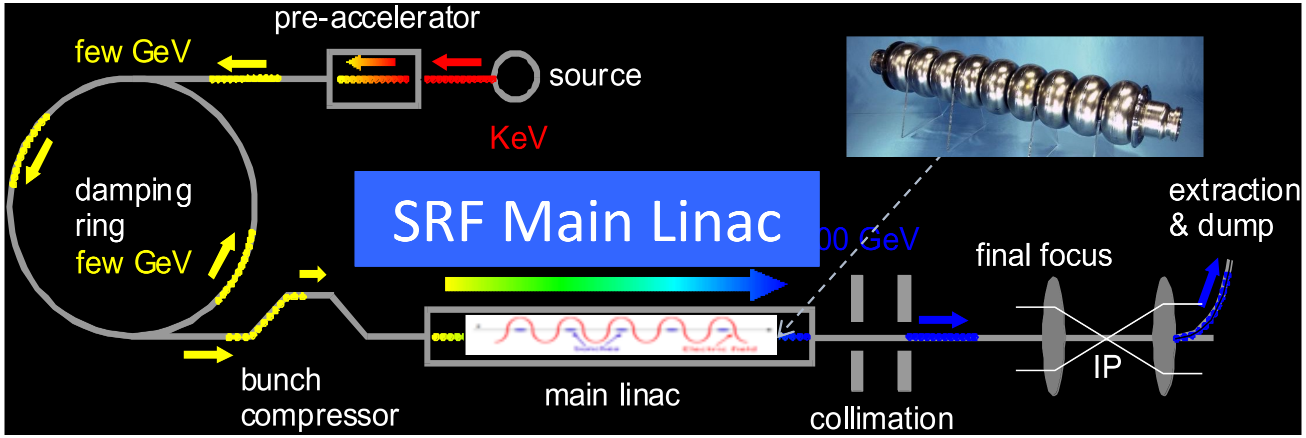
  - HPGS regulations in Japan, and a solution for the ILC-SRF
  - “Refrigeration Cycle Regulation” applied for IFMIF cavity fabricated in Europe
  - Requirements for SRF cavity fabrication, and experimental evaluation of the Nb (-FG and - MG) material properties

SRF: Key Technology at ILC:







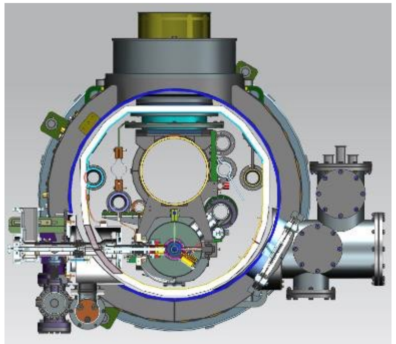
Parameters	Value
Beam Energy	125 GeV
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Av. field gradient	31.5 (35) MV/m +/- 20% Q_0 = 1E10 (1.6E10)
# 9-cell cavity (1.3 m)	~ 8,000 (x 1.1)
# cryomodule (12.m)	~ 900
# Klystron	~ 240

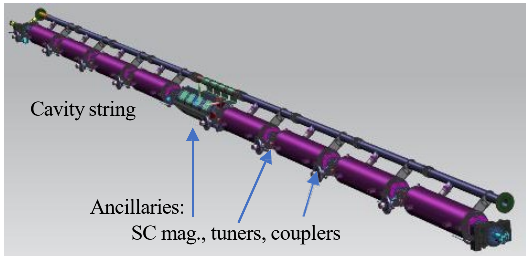
WP-prime 2: Cryomodule (CM) Design

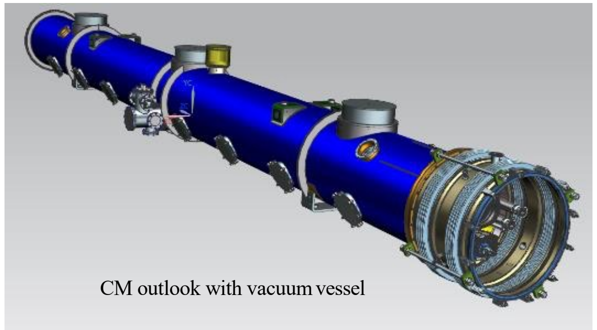
(Scoping the CM Global Transfer and Performance Assurance)

Referring LCLS-II experience,
FNAL-JLAB-SLAC-Cornell

- Unify cryomodule (CM) design with ancillaries, based on globally common engineering design, drawings & data-base, and
- Establish globally compatible safety design base to be approved/authorized by HPGS regulations individually in each region, most likely referring ASME guidelines to be compatible with Japanese regulations.







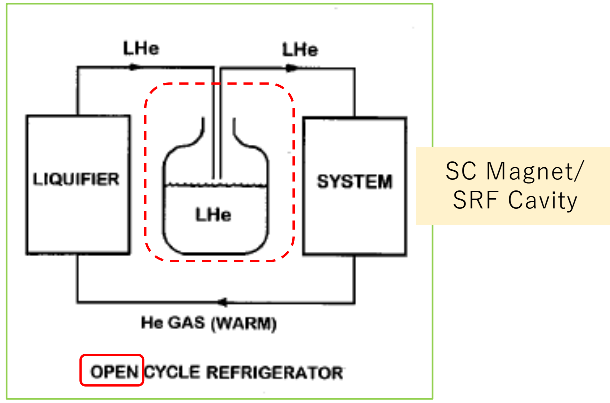
Region Regulation	Americas ASME	Europe Eu-EN, TUV	Japan/Asia JP-HPGS Act
CM tech. design base	LCLS-II	Euro-XFEL	KEK-STF, AST-IFMIF
ILC CM design	Common CM design globally compatible to HPGS regulation in all regions, and most likely ASME guidelines to be compatible with Japanese regulations.		

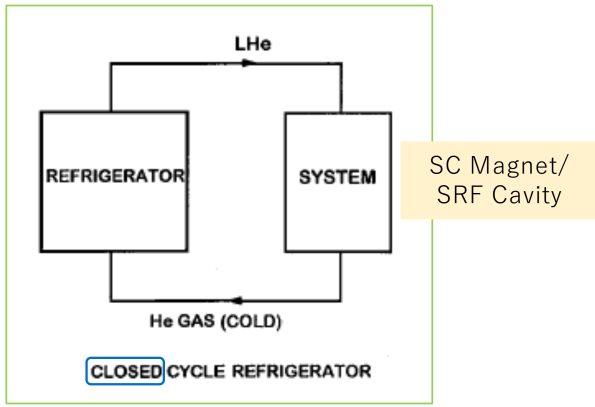
HPGS Act and Ordinance in Japan

- **Act (Law):**
  - **High Pressure Gas Safety Act,**

- **Ordinances (Regulations):**
  - **General HPG Safety Ordinance**
    - Main Applications:
      - Industrial-gas-plant systems
    - Features: Open Loop, enabling liquid/gas extraction/consumption,

  - **Refrigeration Safety Ordinance**
    - Main Applications:
      - Air-conditioning/refrigeration systems for building and Cold-Storage
    - Features: Closed-Loop, not allowing liquid/gas extraction/consumption,





Similarities in Technical Basis to be understood

in comparisons of HPG-RS (Japan), ASME (US), and PED (EU)

AY's personal understanding/questions

	Refrigeration Safety Japan	ASME US	PED EU
Material	SUS/Cu: specified Nb: not specified	SUS/Cu: specified Nb: not specified	SUS/Cu: specified Nb: not specified
Mechanical stress design – **σ-allowed**	≤ ¼ σ-tensile @ RT ≤ ¼ σ-tensile @ T-use ≤ 2/3 σ-0.2% @ RT ≤ 2/3 σ-0.2 % @ T-use	To be filled	To be filled
Non-standard	FE analysis, in particular for buckling	To be filled	To be filled
Fabrication process - **Structure** - **Welding**	Sample tests required	To be filled	To be filled
Pressure Test - **Hydr. Test** - **Pne. Test**	P(h)-test : 1.3~1.5 x WP (p)P-test : 1.1~1.25 x WP	To be filled	To be filled

Similar !

Similar !

Common criteria need to be established

Fabrication & design

Welding efficiency

This factor only applied for the refrigeration safety regulation, not for general gas high-pressure regulation.

- For butt welding, following welding efficiency factor is defined.

Fraction of radiation transmission test against total welding length	Welding efficiency factor
100 %	1.0
Less than 100 %, and more than 20 %	0.95
Less than 20 %	0.7

- Above welding efficiency factor is used as follows.

$$Pm \leqq S \times \text{(welding efficiency factor)}$$
$$PL \leqq 1.5 \times S \times \text{(welding efficiency factor)}$$
$$PL + Pb \leqq 1.5 \times S \times \text{(welding efficiency factor)}$$
$$PL + Pb + Q \leqq 3 \times S \times \text{(welding efficiency factor)}$$

Pm: Primary general membrane stress
PL: Primary local membrane stress
Pb: Primary bending stress
Q: Secondary stress
S: Design stress strength

Question

- Does welding efficiency applied also in ASME and/or EN?

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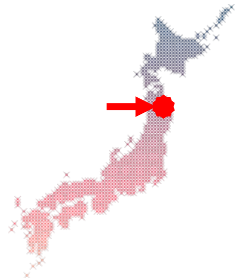
HPG System for Magnet and SRF Systems

	QST: JT-60SA SC-M	RIKEN: RILAC SRF-C	QST-IFMI: RIPac SRF-C	SLAC/FNAL: LCLS-II SRF-C
Mag－Vessel SRF-Cavity	ASME, BPVC Sect. VIII, Div.1	Ref. Regulation	ASME, BPVC Sect. VIII, Div.1	ASME BPC 31.1 （確認中）
Cryo-Piping	ASME BPC 31.1	Ref. Regulation	ASME BPC 31.1	ASME BPC 31.1
Refrigerator	Ref. Regulation	Ref. Regulation	Ref. Regulation	tbc
全システム （完成検査）	Ref. Reguration	Ref. Regulation	Ref. Regulation	tbc

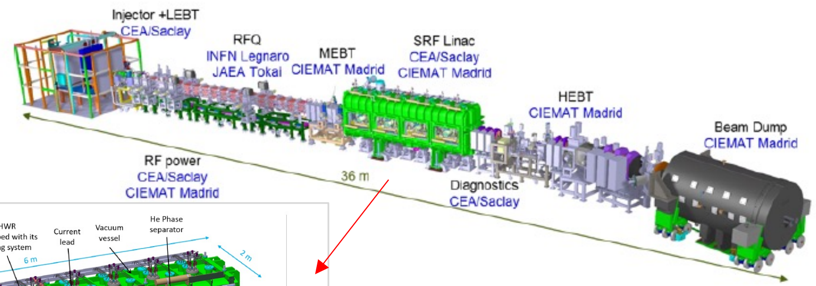
A. Kasugai「Teion-Kogaku」54-4 (2019) p.283

Example of Manufacture in EU and Assemble in Japan(2) （in progress）: QST-IFMIF/EVEDA-LIPac, SRF Cavity and Cryomodule

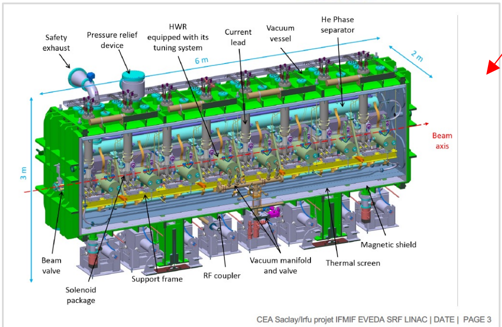
- Component manufacture in Europe & transported to Japan.
- Part of ITER Broader Approach (IETER-BA)



- RS Ordinance accepted by → Aomori Local Government
- Technical detail evaluation before staring manufacture; assisted by KHK)：



- SRF cavities manufacture by（Zanon（Italy））
  - Supervised by CEA (EU, Framce)，
  - Pressure Tested by Zanon in cooperation with a professional inspector,
- Assembly work on site at（IFMIF, Japan）
  - Completion, Final Test is to be carried out in near future.



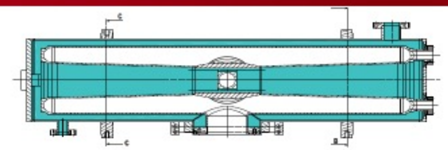
Pressure Test/Licensing for the IFMIF SRF Cavity

cea

CAVITY LICENSING

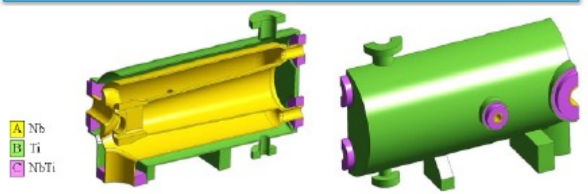
IFMIF LIPAc

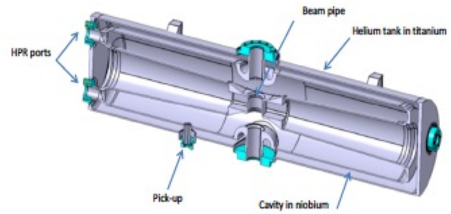
Cavities are considered « Pressure Vessel » as per ASME BPVC Section VIII Div.1. (LHe in the cavities)



Materials: Nb, NbTi and Ti
Nb and NbTi are not listed in ASME BPVC

Complex geometry





- Necessity to perform several analytical calculations + numerical simulations: stress analysis with finite element method, calculation of stresses in welded flanges…
- Tests samples for Nb, NbTi and Ti to determine tensile properties and Charpy impact energy at 4.45K.
- Application form submitted to KHK (High Pressure Gas Safety authority in Japan) for the cavities prior to Prefecture approval. This application form was officially approved in March 2016 (licensing procedure started in Dec. 2013).

CEA Saclay/Irfu projet IFMIF EVEDA SRF LINAC | 06/07/2016 | PAGE 5

Baselines：
- ASME BPVC Sec. VIII Div.1
  - for ＞6-inch dia.,
- ASME B 31.3
  - for < 6-inch dia.

A. Riquelme, TTC Meeting, Saclay

HPGS for IFMIF SRF Cavity & Cryomodule

Following ASME BPVC Sec. VIII Div 1, and BPCC B31.3

Baseline/Guidelines：
- ＞ 6 inch dia.: ASME BPVC Sec. VIII Div.1
- ＜ 6 inch dia.: ASME B 31.3

cea | **LICENSING STRATEGY** | IFMIF LIPAc

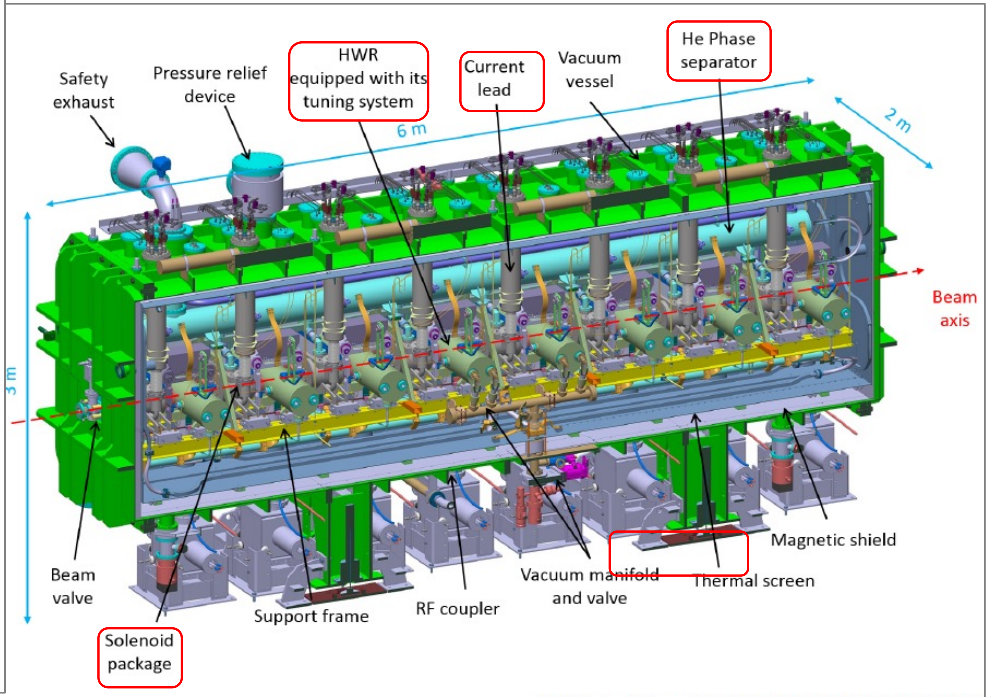
- Cryogenic fluid inside the IFMIF cryomodule ➔ Must comply with the Japanese regulation: **High Pressure Gas Safety Law (HPGSL)**.
- Strategy negotiated with the Japanese authorities : design, fabrication and tests of all the cryomodule components according to **ASME BPVC** or **B31.3.**
- All licensed components are subject to Aomori Prefecture approval before installation of the cryomodule in Rokkasho (application form presented by QST).

Component	Licensing procedure	Code
Cavities	YES – Pressure vessel	ASME BPVC Section VIII Div.1
Phase Separator	YES – Pressure vessel	
Solenoid vessels (CIEMAT)	YES – Pressure vessel	
Current leads assembly (CIEMAT)	YES – Pressure piping	ASME B 31.3
Cryo-piping, thermal shield piping	YES – Pressure piping	
Vacuum vessel /thermal shield	NO – ΔP < 0,1 MPa	x

Pressure vessels as per ASME BPVC Sec. VIII Div.1 §U-1 Internal diameter > 6 in. (152 mm)

Piping as per ASME B 31.3 Internal diameter < 6 in.

CEA Saclay/Irfu projet IFMIF EVEDA SRF LINAC | 06/07/2016 | PAGE 4



コメント（山本）：ASME-BPVC Section VIII Div1 は、一般則、冷凍則の共通な技術基盤（と思う）。

IFMIF SRF Cavity & Cryomodule

HPGS Pressure Test Guideline based on ASME BPVC

APPLICABLE TESTS

- Welding qualification according to ASME BPVC Section IX or ASME B31.3 (WPS, PQR, PTC…)

- **PRESSURE TESTS:** All components falling within the scope of ASME shall be pressure and leak tested (in accordance with ASME and HPGSL requirements).

→ Hydrostatic test: **1.5** (ASME: min. 1,3) times of the maximum allowable working pressure (MAWP). $P_{Htest} = 1{,}5 \times 0{,}15 = 0{,}225\ MPa$

→ Pneumatic test: **1.25** (ASME: min. 1,1) times of MAWP if there is a reason to avoid water contamination. In Pneumatic test, all welding should be inspected by DPT unless it is justified to avoid liquid contamination (ex: cavities). $P_{Ptest} = 1{,}25 \times 0{,}15 = 0{,}187\ MPa$

→ Pressure vessel Hydrostatic test or Pneumatic test with *third party* inspector.

→ Pressure vessel leak tightness test with an *in-shop* inspector.

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cea APPLICABLE TESTS IFMIF LIPAc

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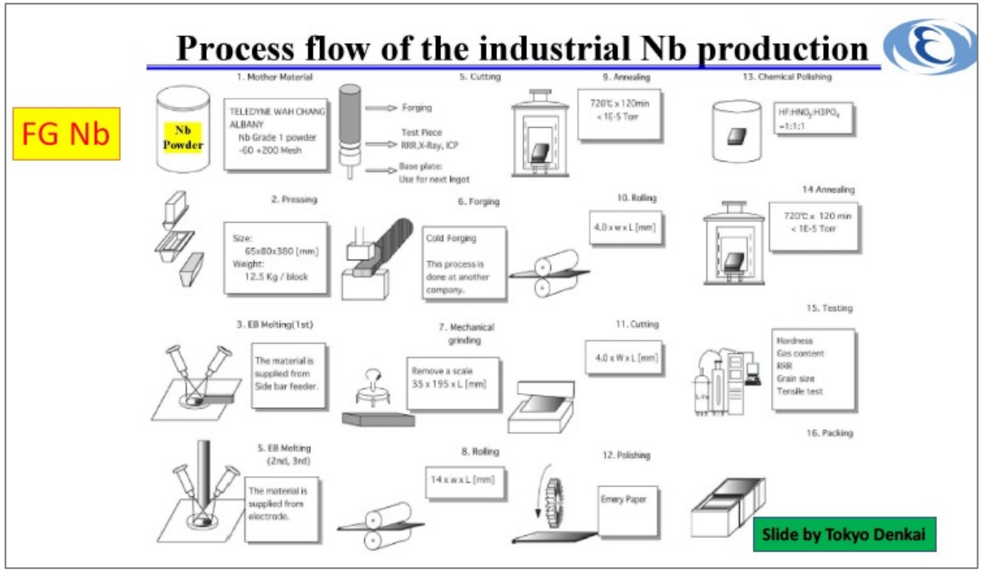
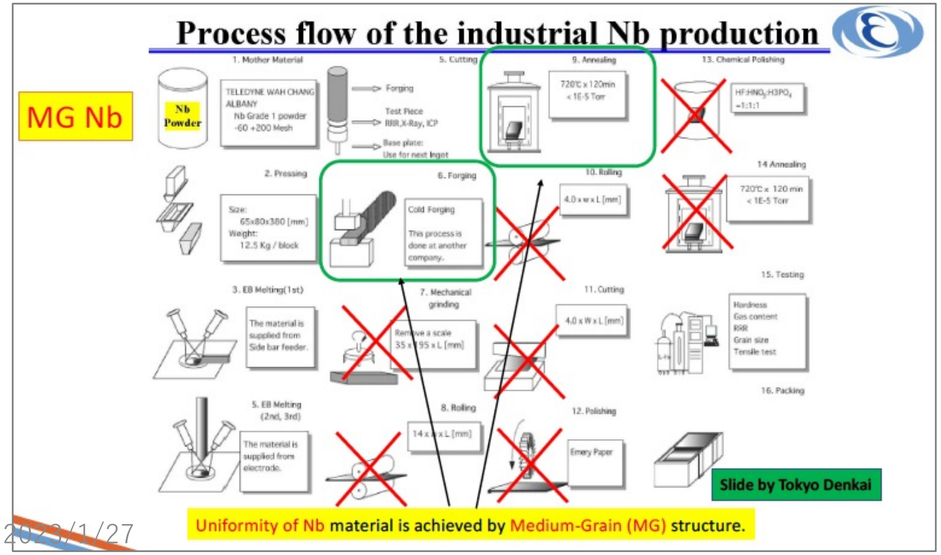
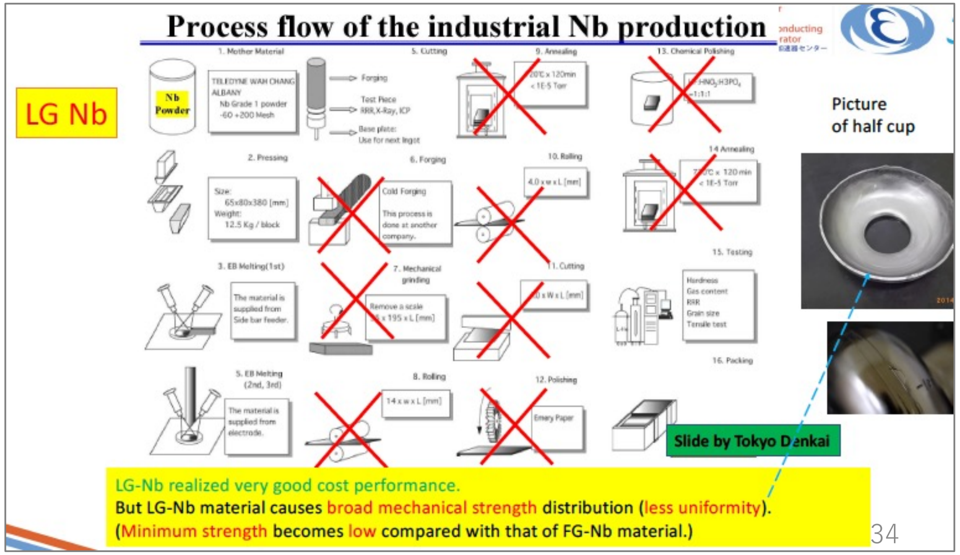
ATI® Medium Grain Nb Mechanical Properties

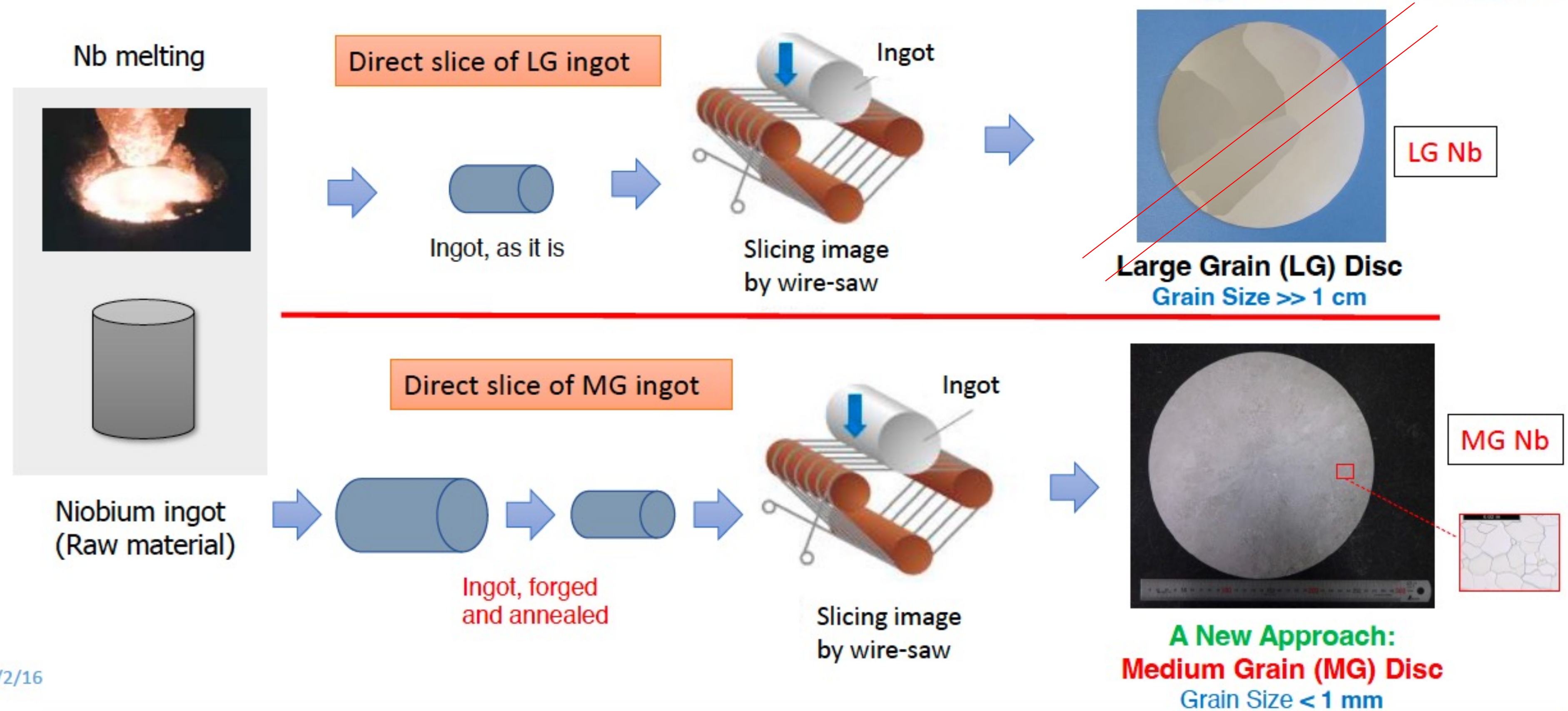
Ashish KUMAR, Ph.D
iCASA, Accelerator Laboratory,
High Energy Accelerator Research Organization (KEK)


Process flow of the industrial Nb production
FG Nb
1. Mother Material
Nb Powder
TELEDYNE WAH CHANG ALBANY
Nb Grade 1 powder
-60 +200 Mesh
5. Cutting
Forging
Test Piece
RRR,X-Ray, ICP
Base plate:
Use for next Ingot
9. Annealing
720℃ x 120min
< 1E-5 Torr
13. Chemical Polishing
HF:HNO3:H3PO4
=1:1:1
2. Pressing
Size:
65x80x380 [mm]
Weight:
12.5 Kg / block
6. Forging
Cold Forging
This process is done at another company.
10. Rolling
4.0 x w x L [mm]
14 Annealing
720℃ x 120 min
< 1E-5 Torr
3. EB Melting(1st)
The material is supplied from Side bar feeder.
7. Mechanical grinding
Remove a scale
35 x 195 x L [mm]
11. Cutting
4.0 x W x L [mm]
15. Testing
Hardness
Gas content
RRR
Grain size
Tensile test
16. Packing
5. EB Melting
(2nd, 3rd)
The material is supplied from electrode.
8. Rolling
14 x w x L [mm]
12. Polishing
Emery Paper
Slide by Tokyo Denkai


Process flow of the industrial Nb production
MG Nb
Slide by Tokyo Denkai
Uniformity of Nb material is achieved by Medium-Grain (MG) structure.


Process flow of the industrial Nb production
LG Nb
Picture
of half cup
Slide by Tokyo Denkai
LG-Nb realized very good cost performance.
But LG-Nb material causes broad mechanical strength distribution (less uniformity).
(Minimum strength becomes low compared with that of FG-Nb material.)

Manufacturing of LG & MG Nb



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* 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.**

7

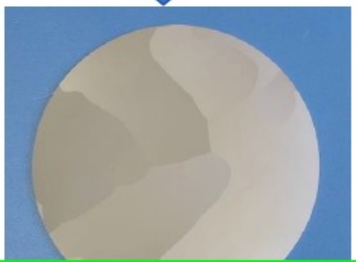
Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz Nb SRF Cavity

Conventional Material

FG Nb

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



R & D Material

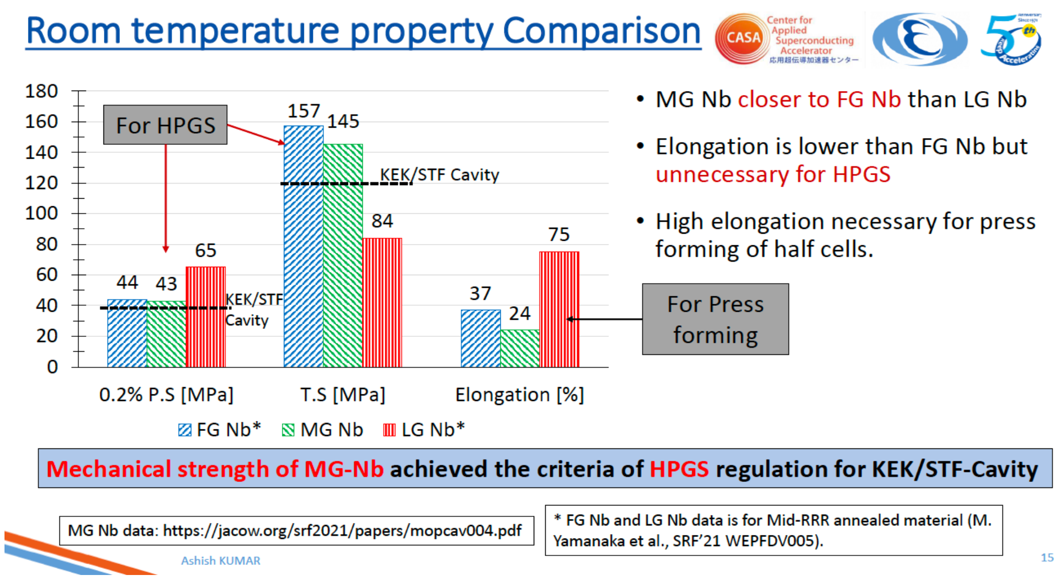
LG Nb

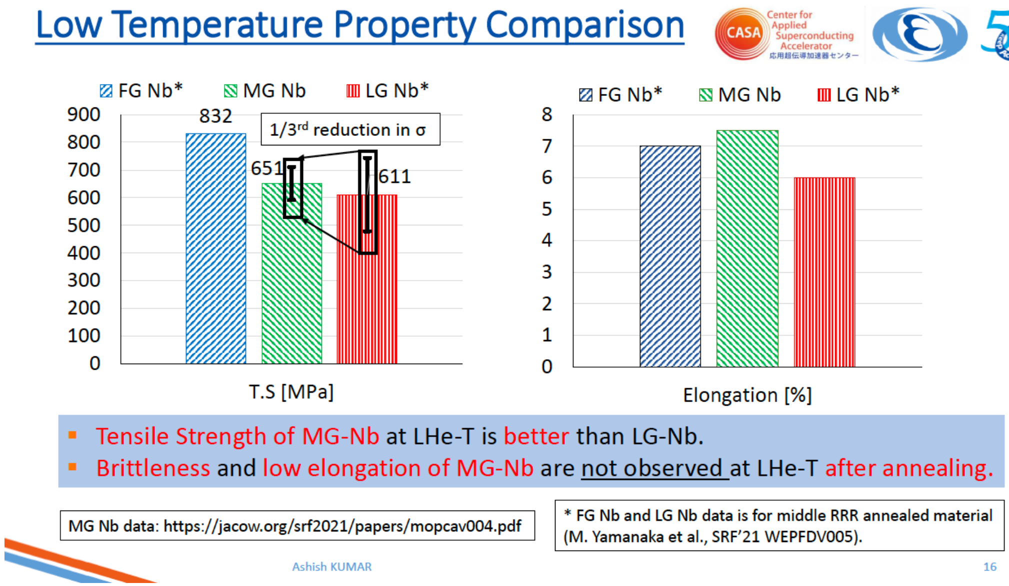
- Grain size > 1 cm.
- Anisotropic mechanical properties.
- Issue with KHK clearance
- Low Cost.

New Material

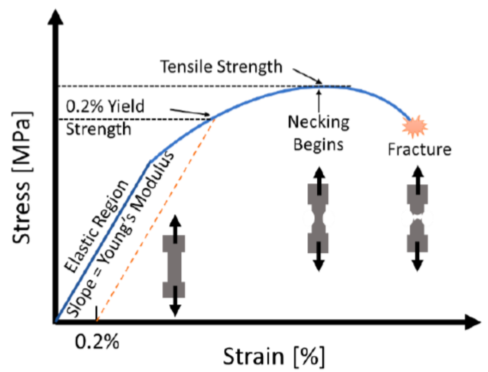
ATI MG Nb

- Grain size - 200-300 µm, occasional 1-2 mm grains
- New material with no data.
- Isotropic properties ✓
- Viable for SRF cavity ✓
- Cost reduction w.r.t FG Nb





ATI MG Nb Specimens



Temperature [K]	Sample Processing	Young's Modulus [GPa]	0.2% Proof Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
300	Annealed	$88.7^{\pm9*}$	$39^{\pm2}$	$123^{\pm5}$	$25.3^{\pm3}$
300	ASR	$89.7^{\pm6}$	$43^{\pm4}$	$145^{\pm7}$	$23.9^{\pm4}$
4.2	Annealed	$114.0^{\pm11}$	$283^{\pm34}$	$651^{\pm60}$	$7.5^{\pm2}$
4.2	ASR	$115.4^{\pm14}$	$284^{\pm22}$	$351^{\pm28}$	$1.8^{\pm1}$

* Error is standard deviation.

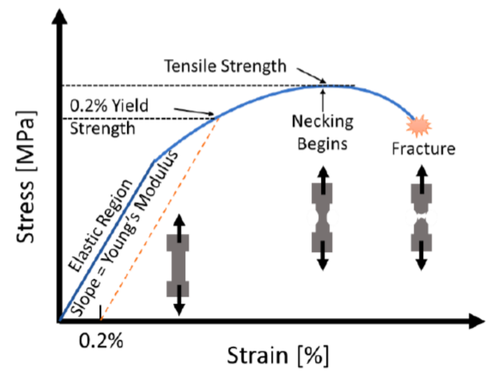
Similarities in Technical Basis to be understood

in comparisons of HPG-RS (Japan), ASME (US), and PED (EU)

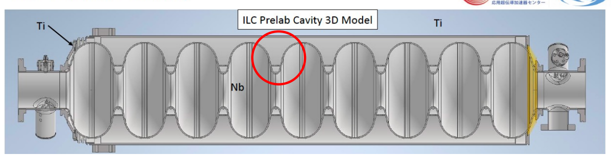
AY's personal understanding/questions

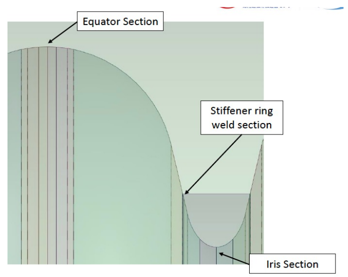
	Refrigeration Safety Japan	ASME US	PED EU
Material	SUS/Cu: specified Nb: not specified	SUS/Cu: specified Nb: not specified	SUS/Cu: specified Nb: not specified
Mechanical stress design – σ-allowed	≤ ¼ σ-tensile @ RT ≤ ¼ σ-tensile @ T-use ≤ 2/3 σ-0.2% @ RT ≤ 2/3 σ-0.2 % @ T-use	To be filled	To be filled
Non-standard	FE analysis, in particular for buckling	To be fille	illed
Fabrication process - **Structure** - **Welding**	Sample tests required	To be fil	To be filled
Pressure Test - **Hydr. Test** - **Pne. Test**	P(h)-test : 1.3~1.5 x WP (p)P-test : 1.1~1.25 x WP	To be filled	To be filled

Similar !



ILC Prelab Cavity





Common criteria need to be established

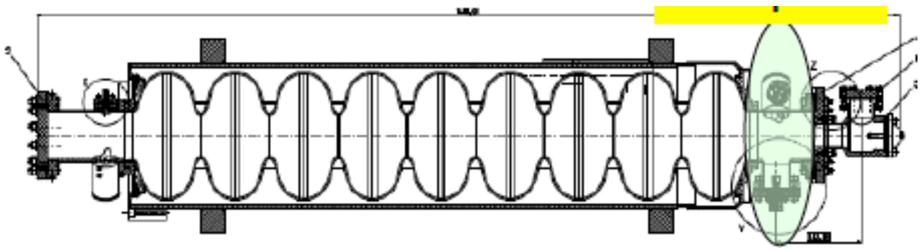
Courtesy: A. Kumar

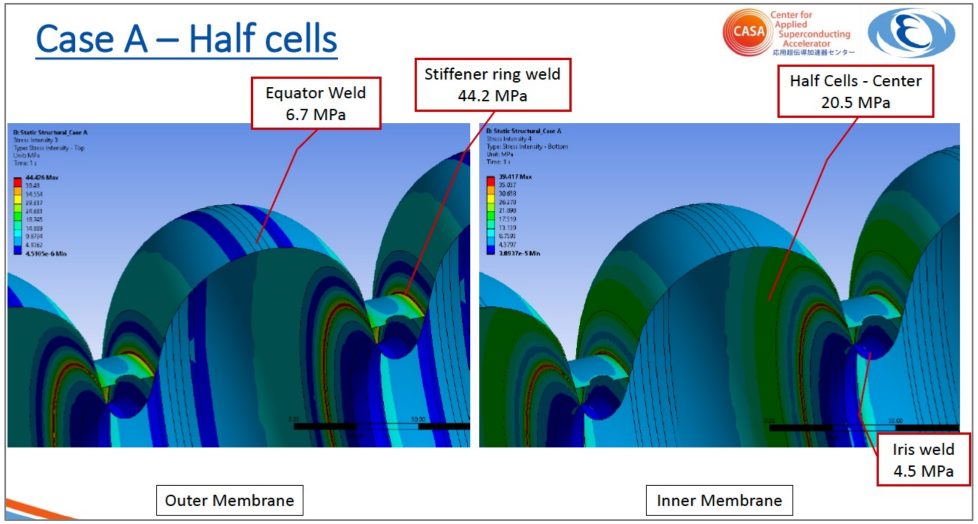
Peak Stress evaluation with allowable mechanical stress

Mechanical stress design ● **s-allowed**	≤ ¼ s-tensile @ RT ≤ ¼ s-tensile @ T-use ≤ 2/3 s-0.2% @ RT ≤ 2/3 s-0.2 % @ T-use

	Allowable Stress (Sm)		
Temperature	Pure Niobium	Titanium (Gr 2)	NbTi55
293 K	22.6	85	128.6
1.8 K	225	255	303.3

$$S_m = \text{lesser of } S_y/1.5 \text{ or } S_u/4$$





Performance of LG Nb and MG Nb Cavities

Credits:

LG Nb cavity results by Hayato ARAKI

MG Nb cavity performance results by Takeshi DOHMAE

Overview of Cavities and their Performance

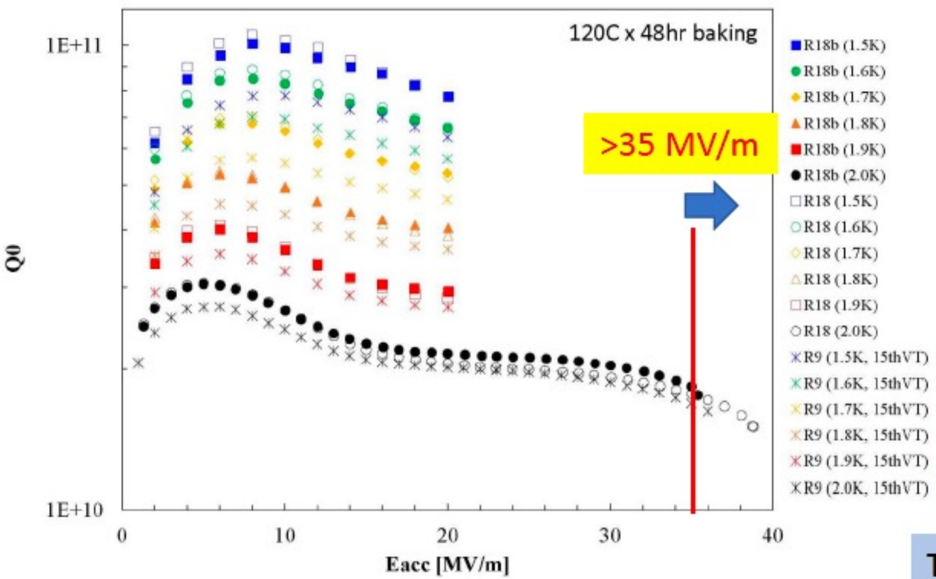
Nb Materials	Cavities	Cavities	Vertical Test Results	ILC Specification
LG Nb (Mid-RRR, High-Ta)		Two 9-Cell	$E_{acc} < 35$ MV/m	✕
LG Nb (High-RRR, Low-Ta)		Two 3-Cell	$E_{acc} > 35$ MV/m	✓
LG Nb (High-RRR, High-Ta)		Two 3-Cell (two 9-Cell under fabrication)	$E_{acc} > 35$ MV/m	✓
MG Nb (High-RRR, Low-Ta)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

MG Nb Material (High RRR, Low Ta)

Results of MG single-cell cavities.
R18, R18b (vs. R9 / FG single-cell cavity).

R18 vs R18b vs R9

R9 data by Ito-san



- R18, R18b were fabricated using MG discs
- Inner surface of R18 was mechanically polished during fabrication (R18b was not)
- VT of R18: 38.8 MV/m with $Q_0=1.5\times10^{10}$
- VT of R18b: 35.4MV/m with $Q_0=1.76\times10^{10}$

Two MG-Nb single-cell cavities have reached > 35 MV/m

2022/2/16

R18 Results Cited From: T. Dohmae et al., SRF' 21 MOPCAV012

R18b cavity results by Takeshi DOHMAE

Conclusions

- ATI MG Nb's mechanical properties does clear the mechanical strength criteria required for high pressure 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 but with a third of reduction in standard deviation of its Tensile strength.
- 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.

A Reference: A. Kumar et al., presented at SRF Conference in 2021.