OHO 高エネルギー加速器セミナー OHO’21

CASA Center for Applied Superconducting Accelerator
応用超伝導加速器センター

1.3-GHz Superconducting Radio Frequency Cavity Materials and their Evaluation

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2021/09/09

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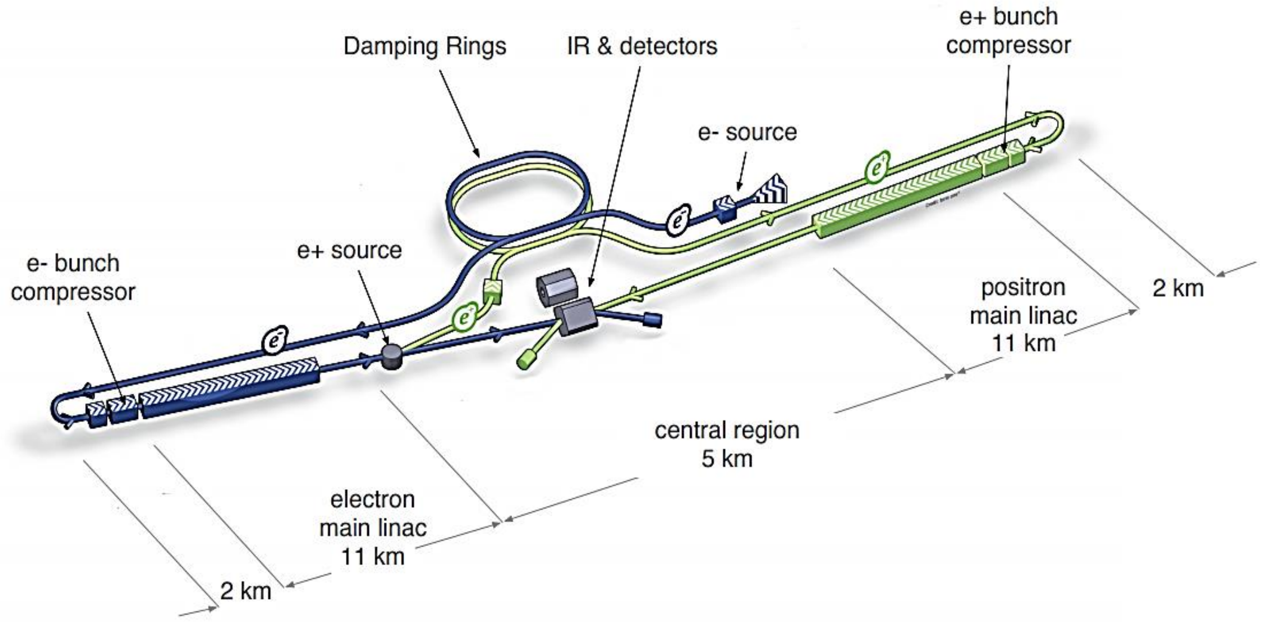
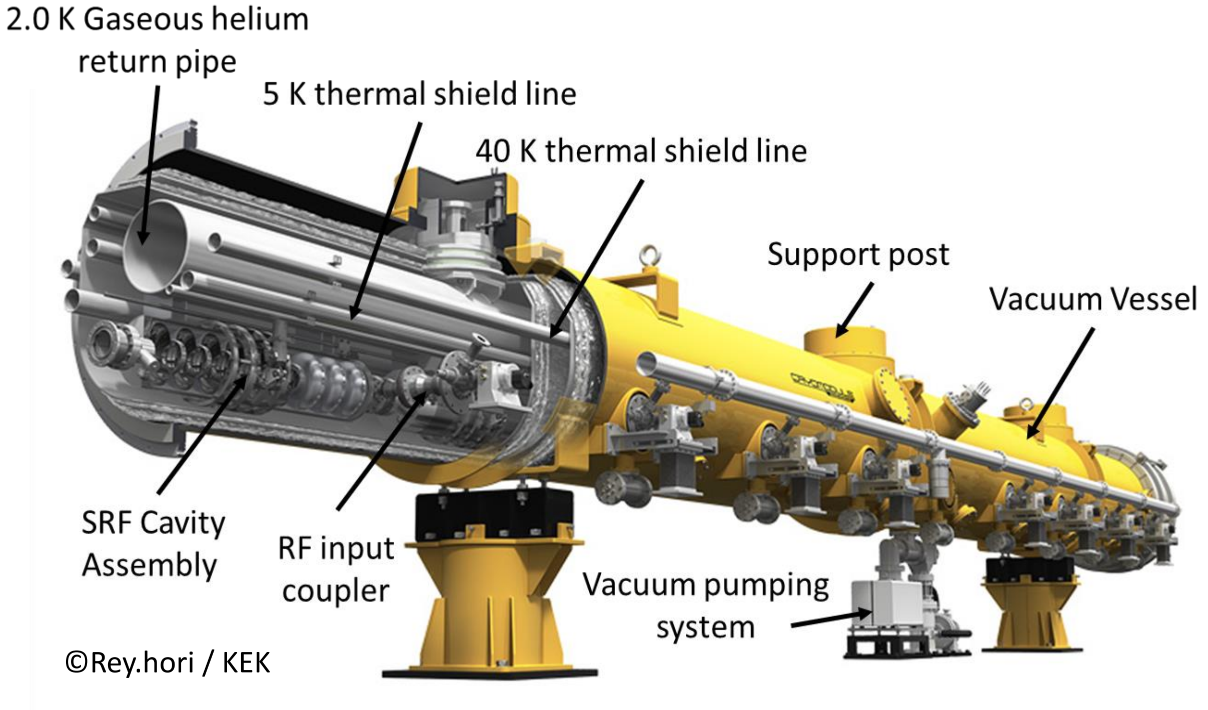
International Linear Collider

International Linear Collider





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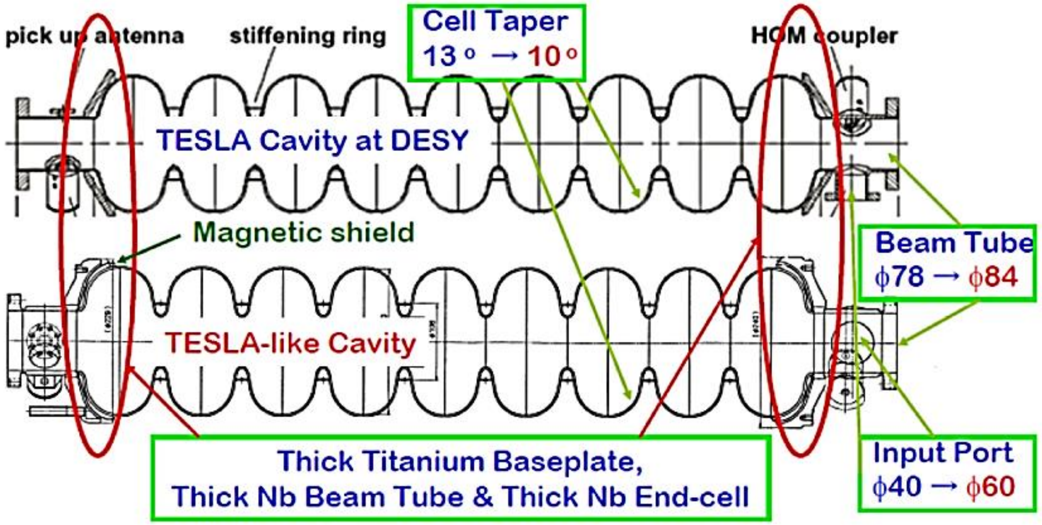
- International Linear Collider is an electron-positron collider accelerator.
- 1.3 GHz SRF Cavities accelerates the electrons and positrons to near speed of light.
- 7800 1.3 GHz SRF cavities in 850 cryomodules to attain centre of mass energy of 250 GeV.

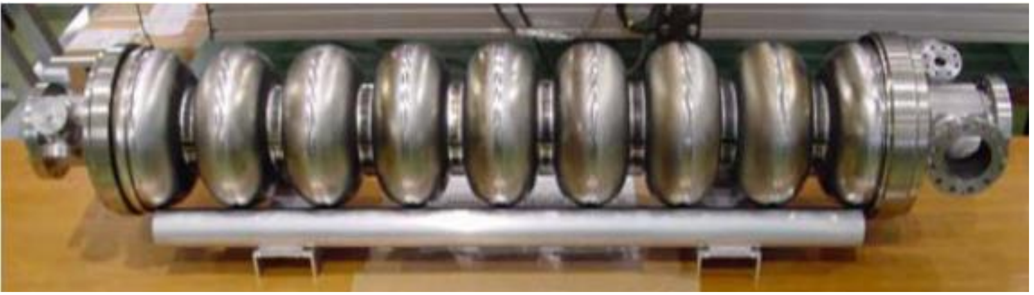
1.3 GHz SRF Cavity

1.3 GHz SRF Cavities

Tesla Cavity

- 9-cell standing wave structure
- Almost 1 m in length
- Lowest TM mode resonates at 1300 MHz.
- Employed in Eu-XFEL (DESY), LCLS-II (SLAC).

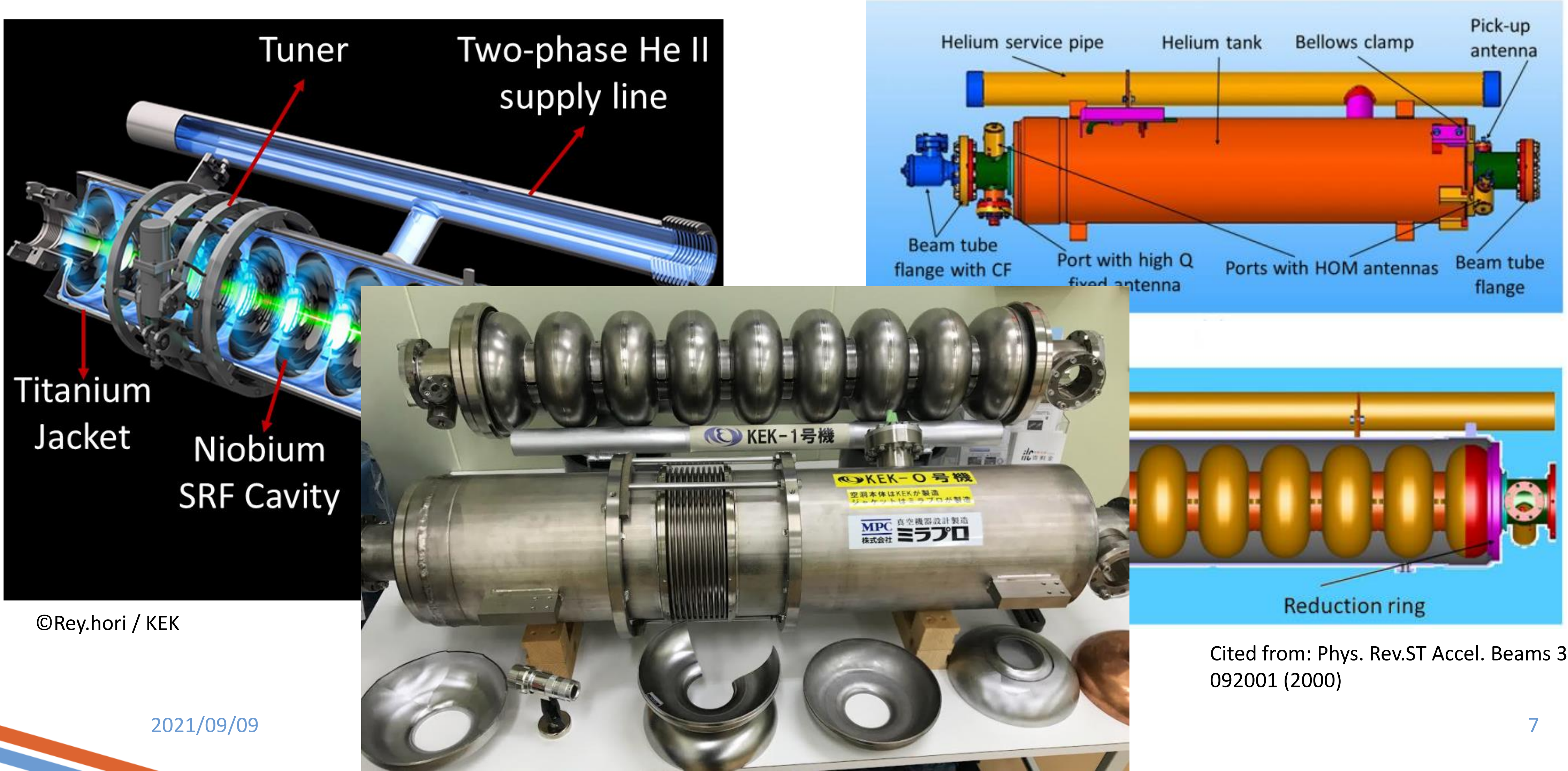




Tesla-like Cavity

- 9-cell standing wave structure
- Optimized for reduction in H_{pk} / E_{acc}.
- Thicker end plates.
- Employed in STF2 (KEK)

SRF Cavity Assembly



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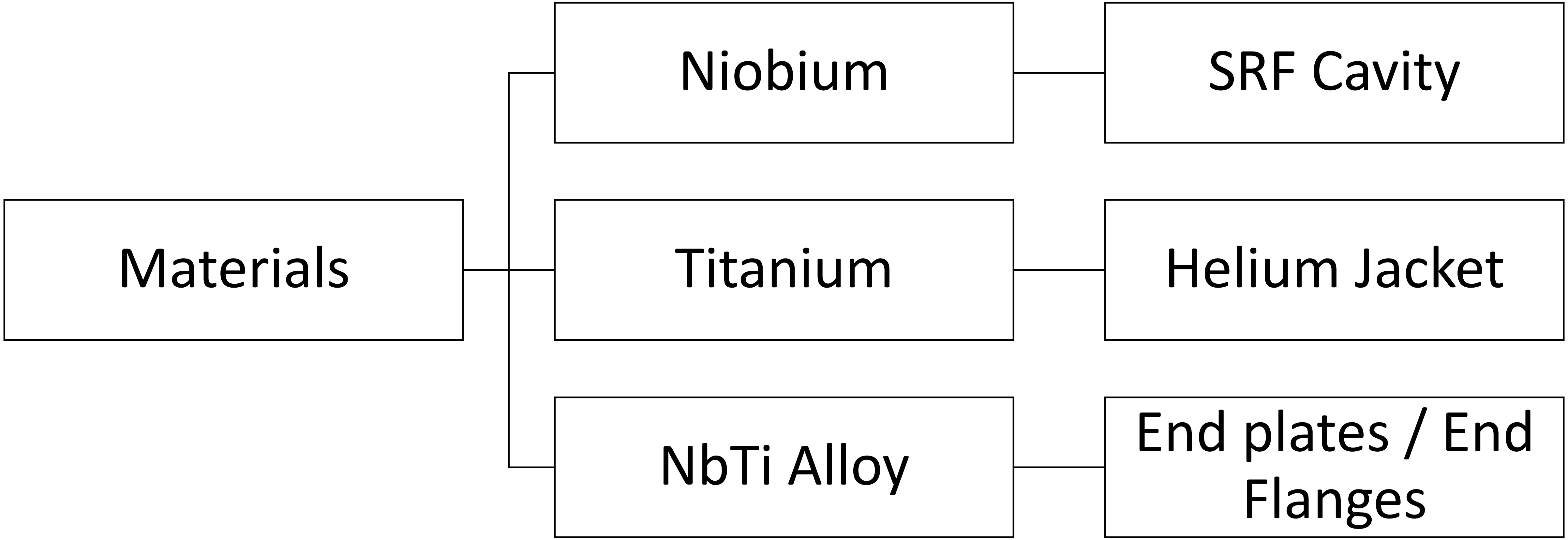
Cited from: Phys. Rev.ST Accel. Beams 3, 092001 (2000)

Materials for SRF Cavity Assembly

Materials for SRF Cavity Assembly



Materials

Niobium

SRF Cavity

Titanium

Helium Jacket

NbTi Alloy

End plates / End Flanges

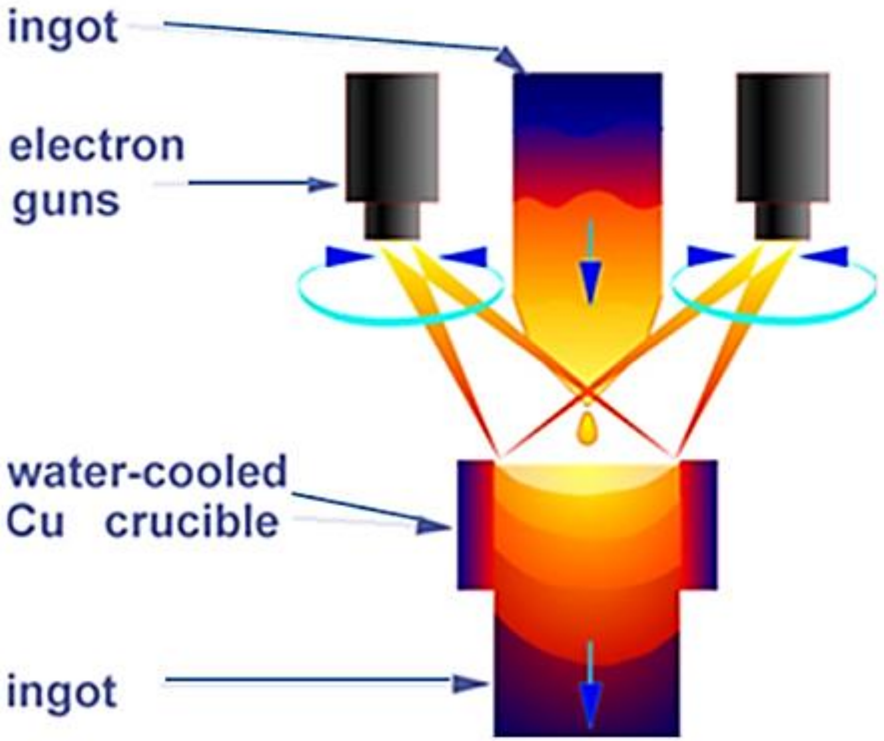
Niobium

- Nb has a body-centred cubic (bcc) crystal structure and a melting point of 2,468 °C.
- Extracted from mines mostly in Brazil.
- It is choice of material for SRF cavity.
- It becomes superconducting at 9.2 K.
- 33^{rd} most abundant material on earth.
- Largest mines are in Brazil.

CBMM Brazil, Araxa Mine

Melting and Purification of Nb

- Melting and purification of Nb by electron beam furnace.
- Melted in vacuum of < 3E-1 Pa for the first melt and < 1E-3 Pa for last melt to obtain high purity Nb.
- Molten globules drop into water cooled copper crucible to form an ingot.
- Gases and impurities with lower melting temperatures than Nb evaporates.
- Most of the impurities are present on the skin of the ingot and is machined away for a purer ingot.



Cited from: arXiv:1501.07142 [physics.acc-ph]

Melting and Purification of Nb

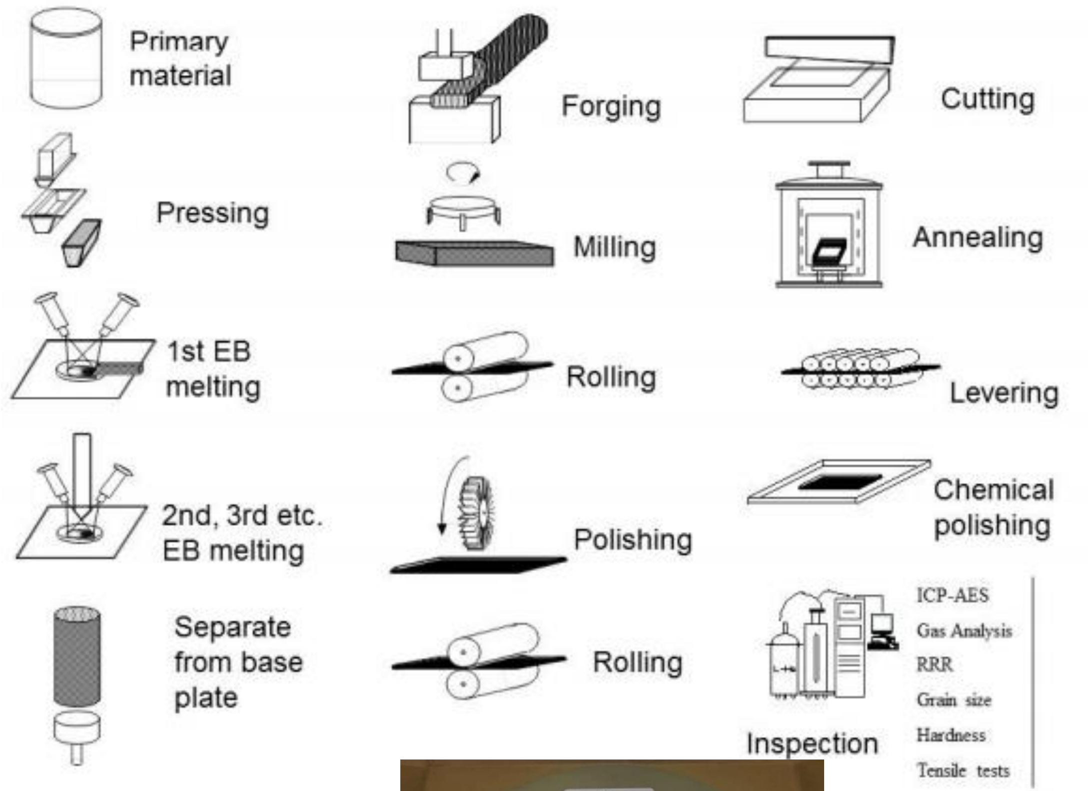
- Several companies can produce high purity refractory metals in larger quantities.
- ATI Wah Chang (USA), Cabot (USA), W.C. Heraeus (Germany), Tokyo Denkai (Japan), Ningxia (China), CBMM (Brazil), H.C. Starck (Germany, USA).
- Leybold furnace with 500 kW nominal power melts the Niobium at 40 – 50 kg/hr (CBMM).
- Another 1.8 MW nominal power melts Nb at 90 – 120 kg/hr and pressures < 1E-3 mbar (CBMM).


EBM Furnace

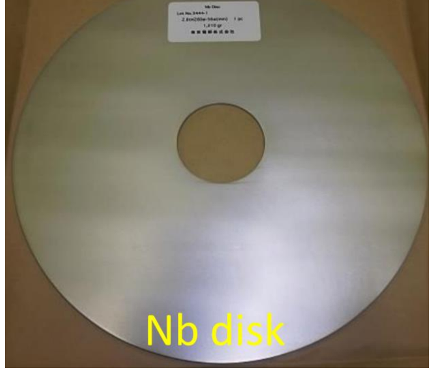

Nb Ingot

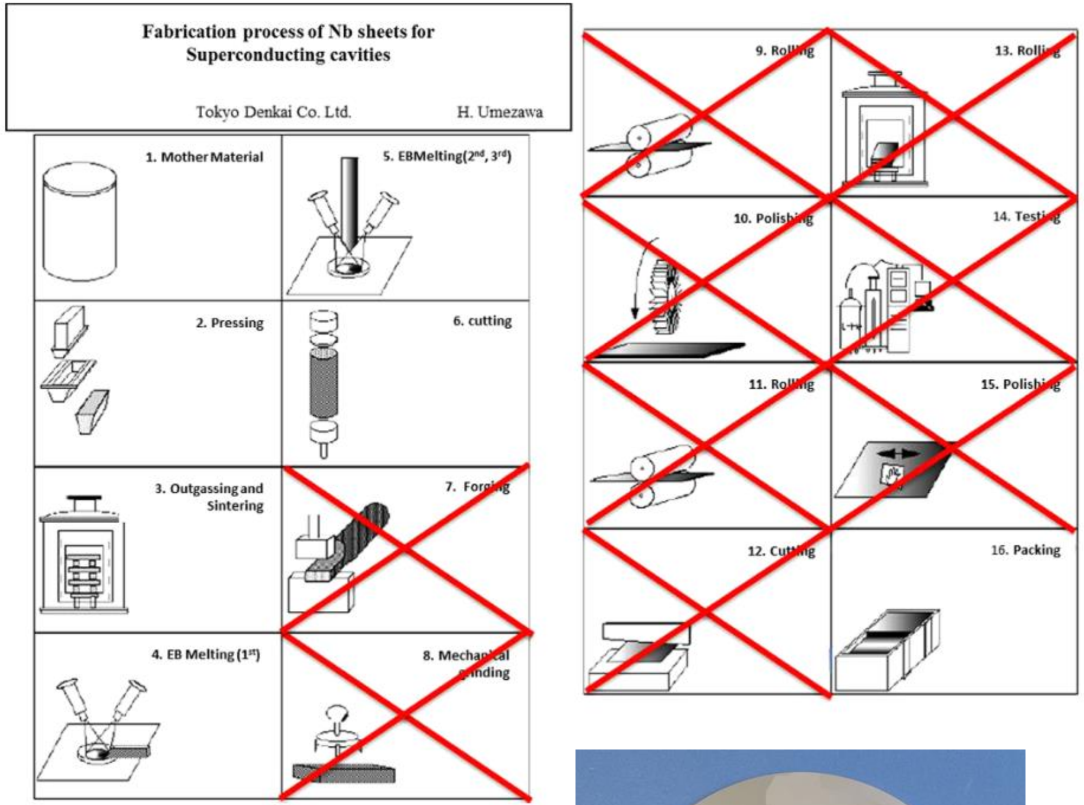
Cited from: AIP Conference Proceedings 927, 191 (2007)

Nb Disk Manufacturing



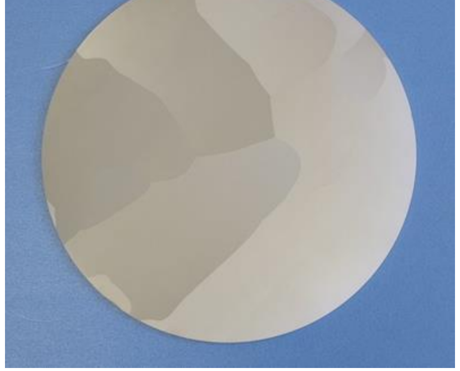
FG Nb



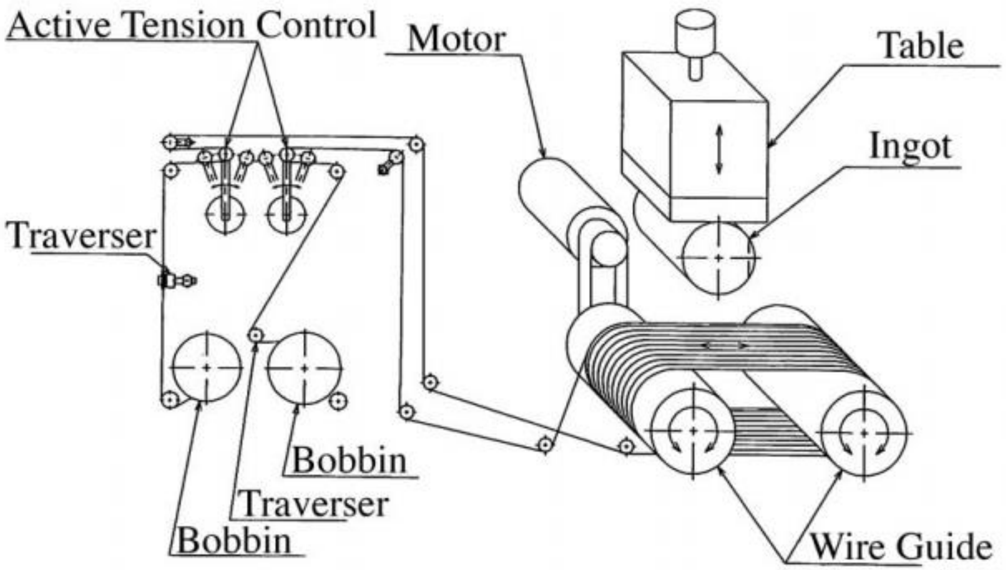


LG Nb

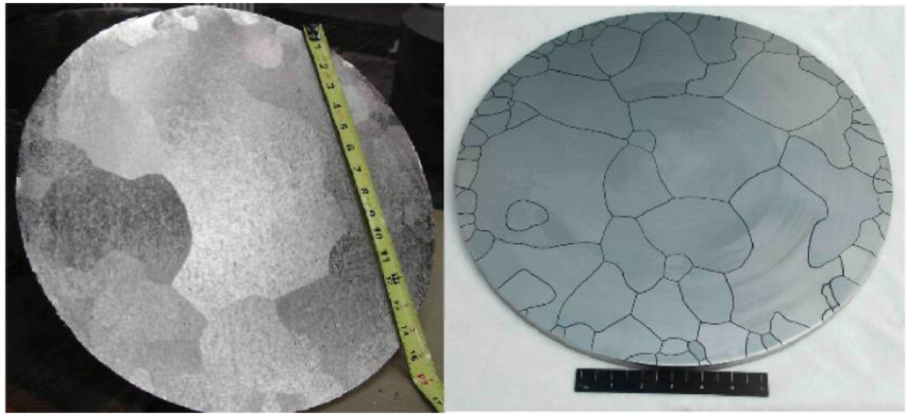
Cited from: Nuclear Instruments and Methods in Physics Research A 774 (2015) 133–150



Direct Slicing of LG Nb



Cited from: AIP Conference Proceedings 1352, 79 (2011)



Cited from: AIP Conference Proceedings 927, 191 (2007)

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.

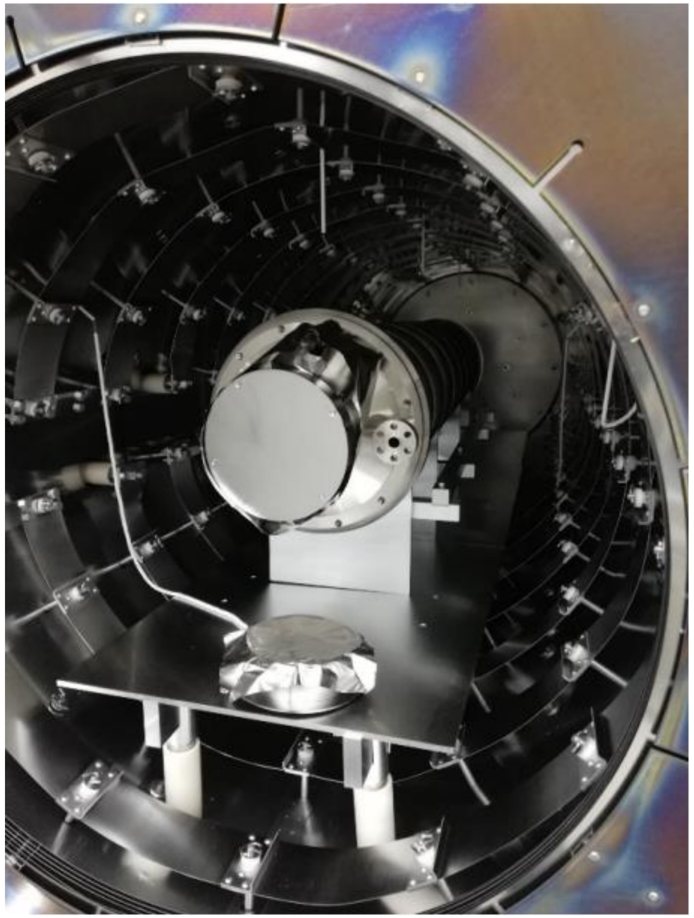
R & D Material

LG Nb

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

Hydrogen Degassing

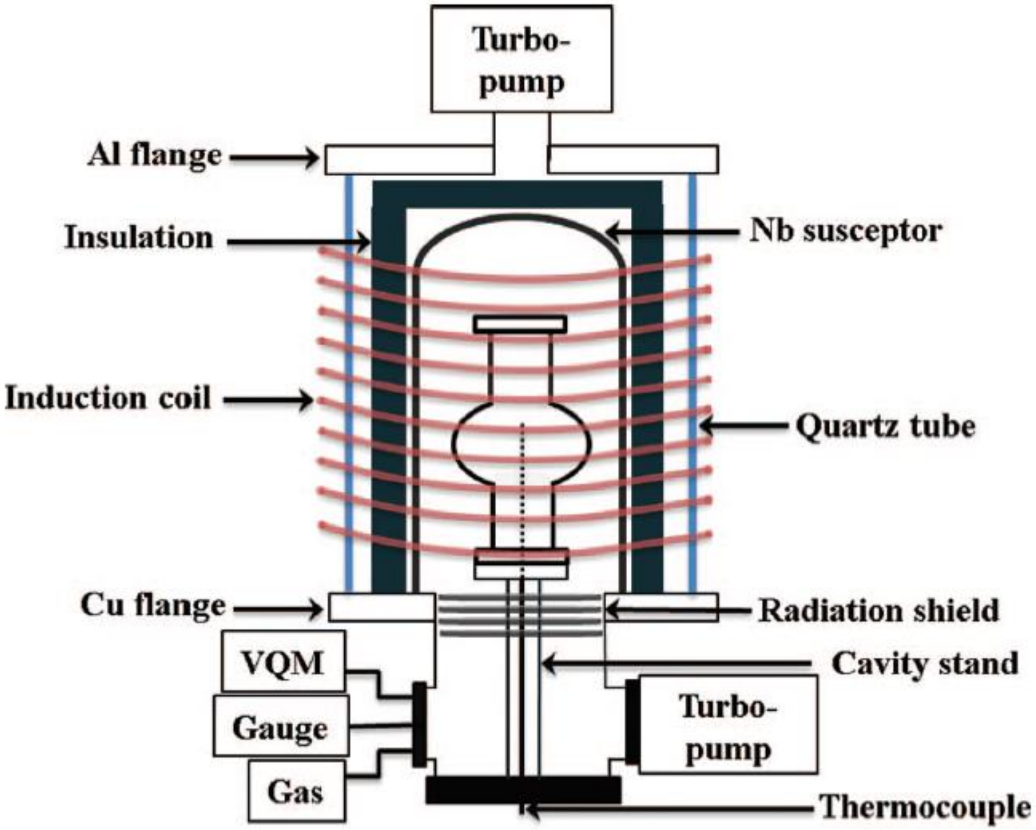
- Hydrogen degassing is necessary to avoid Q-disease.
- Cavities are heat treated at temperatures > 500 °C under vacuum conditions < 10^{-3} Pa).
- Molybdenum or tungsten resistive heating elements provides radiation heating.
- Ultra-high vacuum inside the furnace is created with cryo-pumps.
- Current standard for SRF cavity is 800 °C for 2-3 hours.

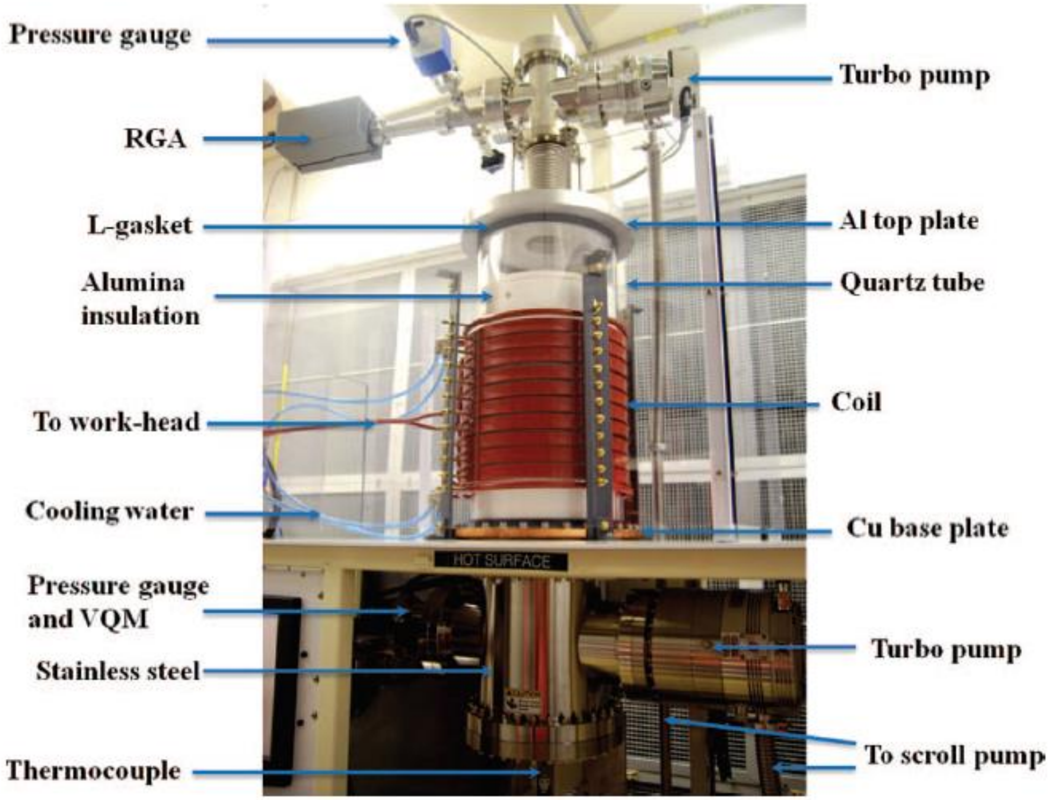


Ultra-high vacuum furnace at KEK

Induction Furnace at Jlab, USA

- Hot zone is made of Niobium and the cavity is treated by black-body radiation.
- Cu induction coil instills eddy current in the Nb to produce heat.

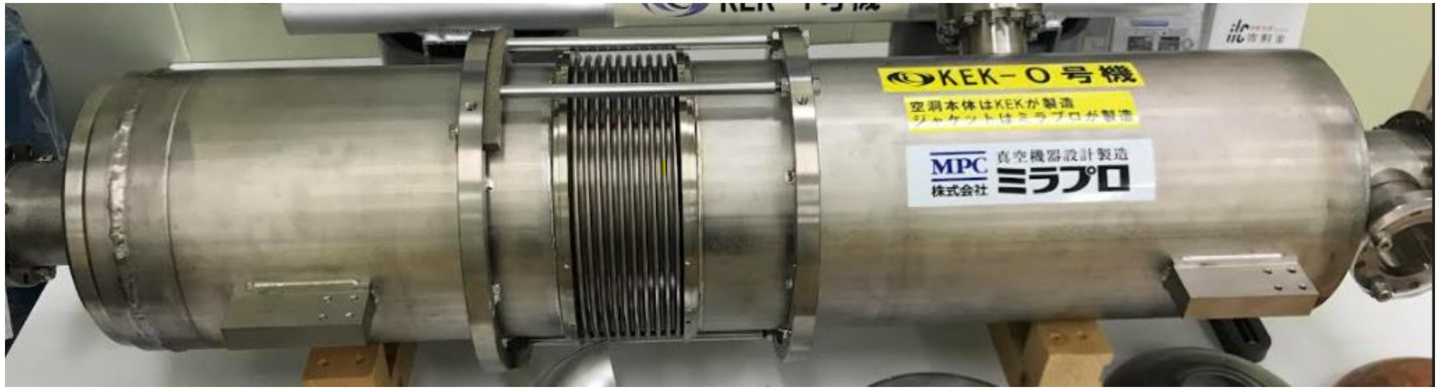




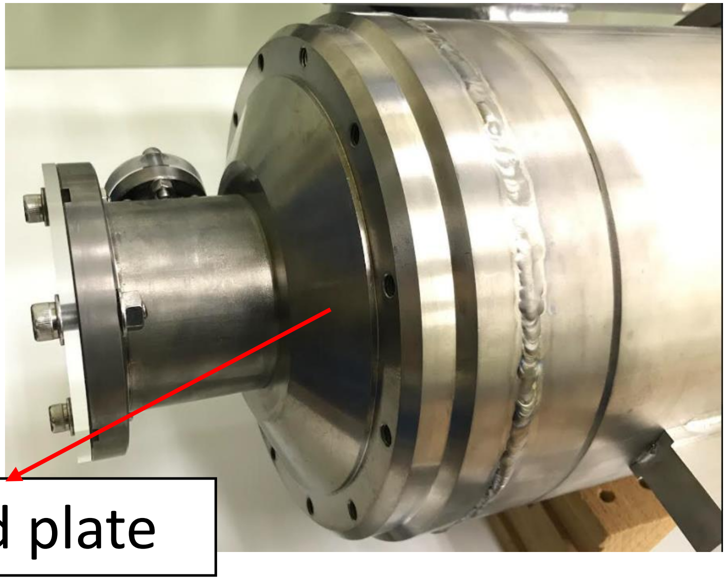
Cited from: Review of Scientific Instruments 83, 065105 (2012)

Titanium

- Material of choice for the helium jacket of the SRF cavity.
- Lower coefficient of thermal expansion and similar to Nb.
- Retains strength and ductility at cryogenic temperatures.
- Sufficient mechanical strength for the helium jacket.
- Commercially available pure Ti can be used, JIS class 1 and class 2.



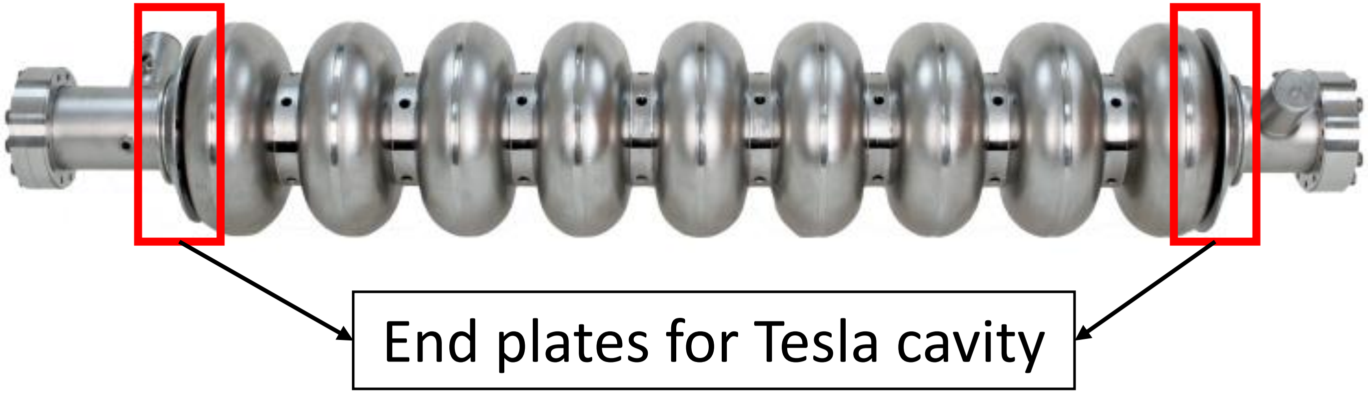
Ti Helium Jacket/Tank

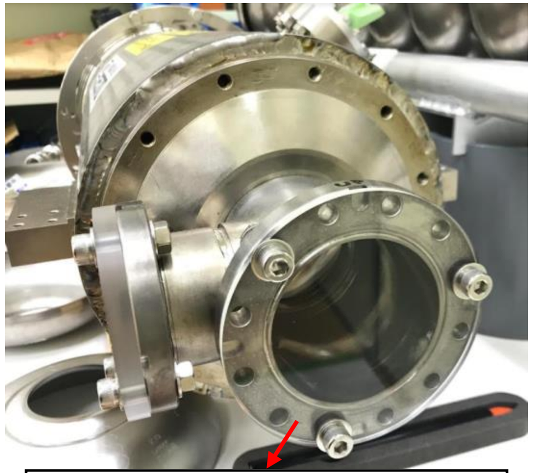


Ti end plate

Niobium-Titanium Alloy

- It is an alloy of Nb and Ti and mostly used as a type II superconductor for superconducting magnets.
- Tesla cavity assembly employs NbTi for conical discs (end plates) of the end-group.
- NbTi's mechanical properties are on par to Ti at high annealing temperatures.
- For Tesla-like cavity assembly, instead of NbTi pure Ti is used for end plates.


End plates for Tesla cavity


End flange

Pressure Vessel Compliance

1.3 GHz 9-Cell SRF Cavity Assembly

Niobium SRF Cavity with its Titanium jacket is considered as a pressure vessel

↓

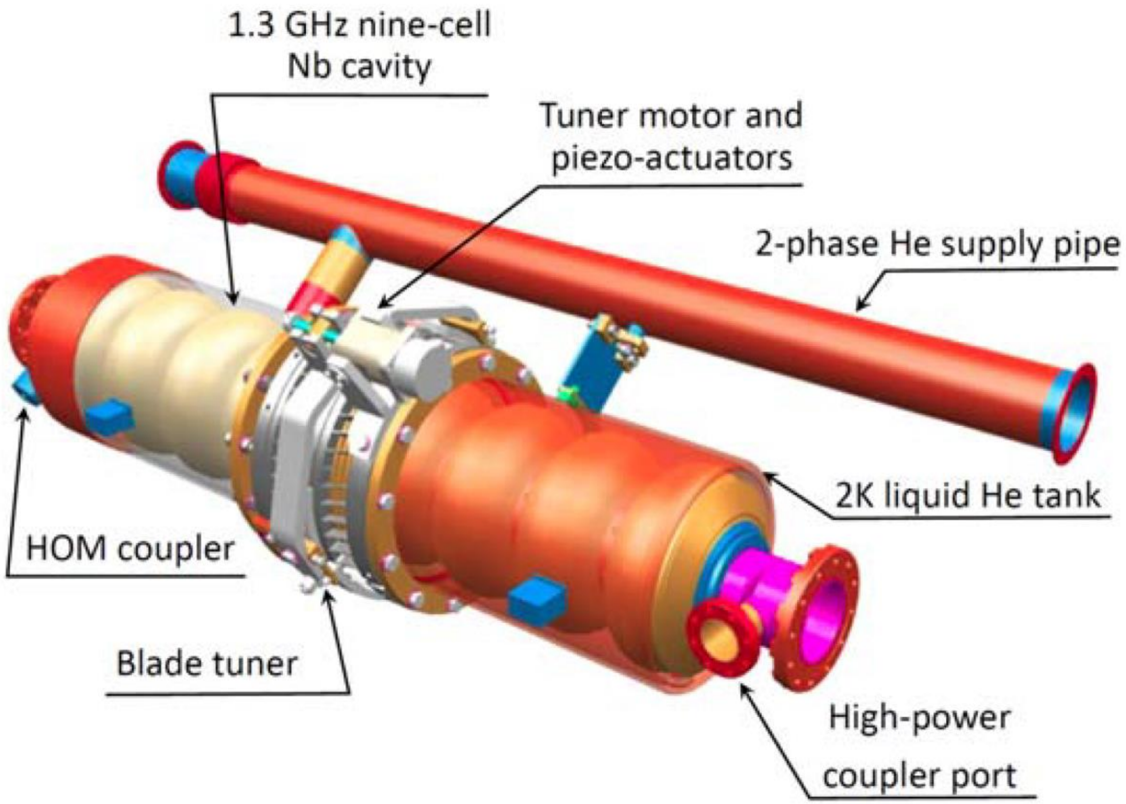
Design must be cleared by high-pressure gas safety authorities

↓

Determine maximum allowable stress and buckling pressure using ANSYS

↓

Nb and NbTi not listed as a material for high pressure vessel design



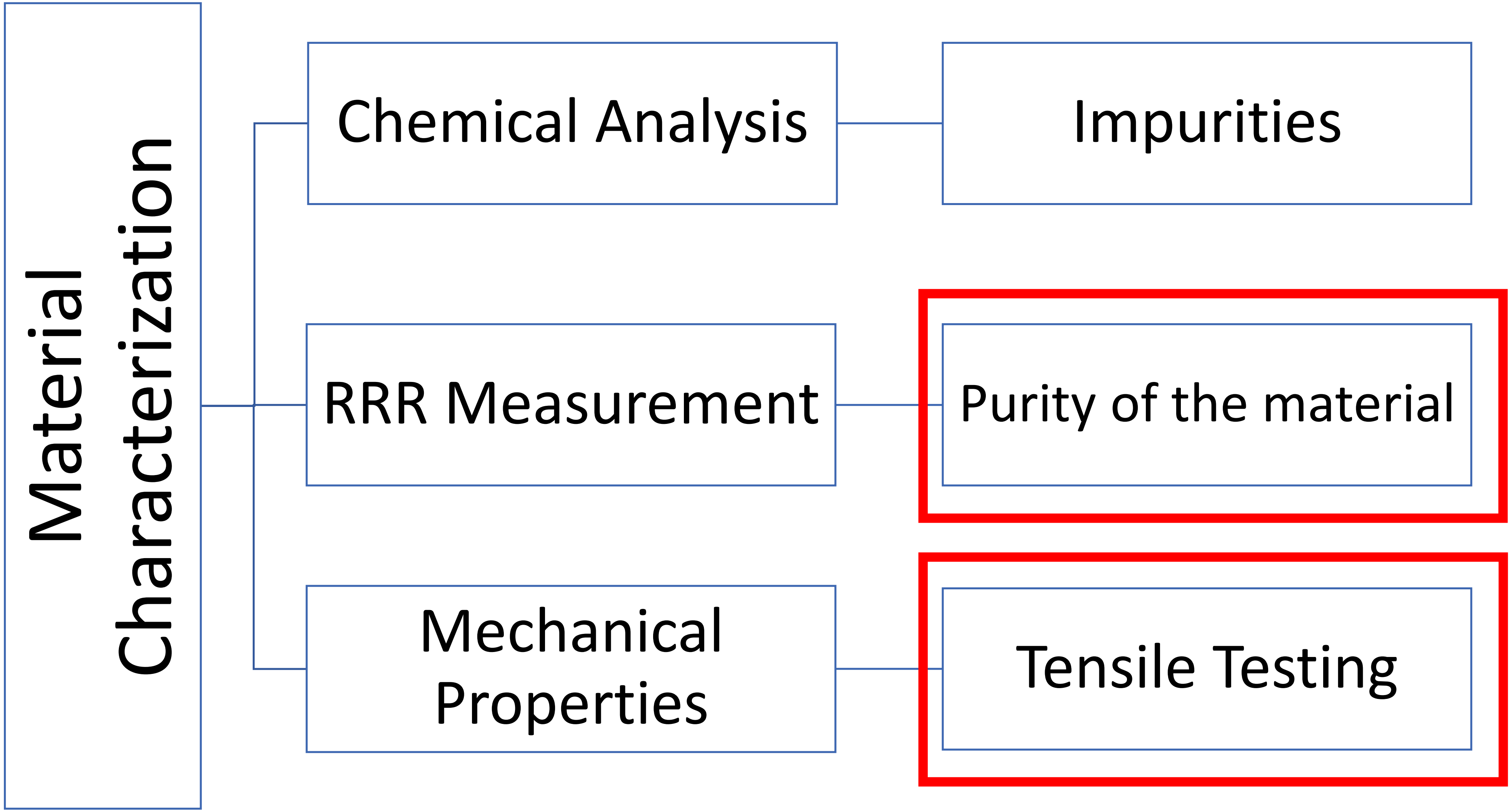
Cited from: The International Linear Collider: A Global Project, arXiv:1903.01629 [hep-ex]

Steps Involved in Preparing Documentation

- Description of the SRF cavity assembly.
- Mechanical properties of the materials at room and in liquid helium temperatures.
- Mechanical properties of welded joints like Nb-Nb, Nb-Ti, Ti-Ti welds etc.
- Stress and buckling analysis of the cavity assembly using CAE software at maximum allowable working pressure (0.2 MPa) and tuner displacement.
- Cavity fabrication information.
- Pressure test and examination reports.
- Documentation to summarize above items to be submitted to the high-pressure gas safety authority.

Methodology for Material Characterization

Material characterization



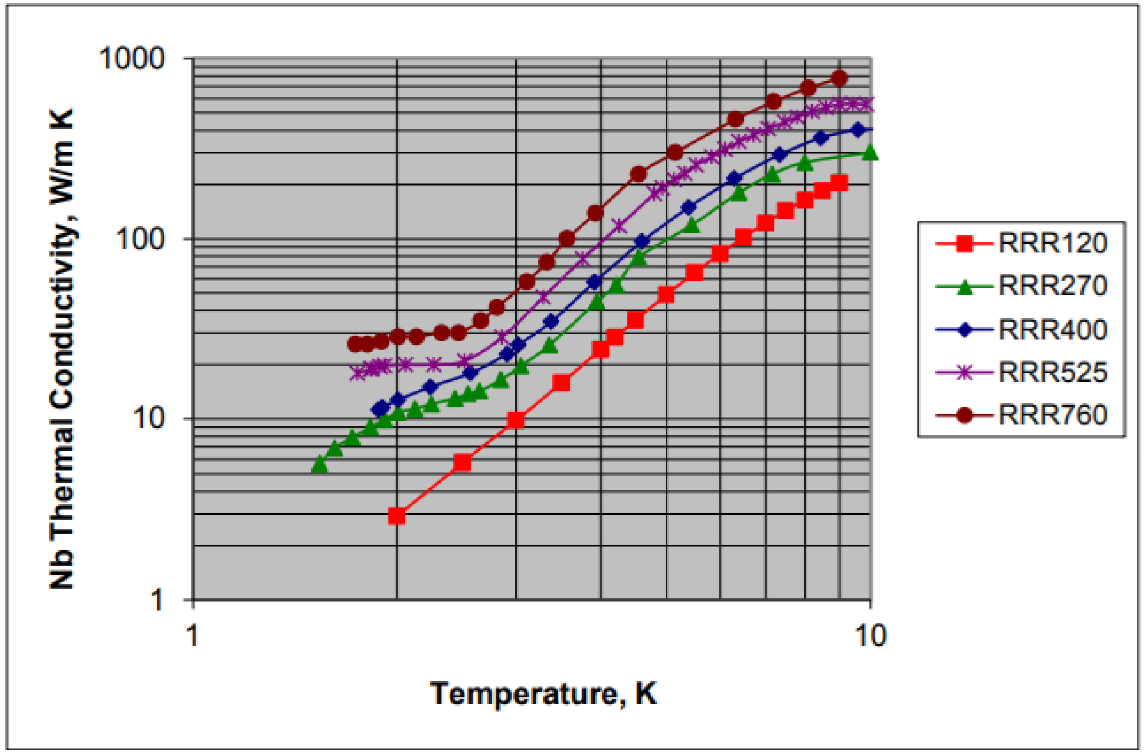
Residual Resistivity Ratio (RRR)

- Indicates the level of purity of a material.
- Purer the material higher the thermal conductivity.
- For SRF cavities high thermal conductive wall (at least 10 W/m-K at 2.0 K) necessary to guide dissipated RF power to He II.

$$\text{RRR for Nb} = \frac{\rho(293\ \text{K})}{\rho(9.3\ \text{K})}$$

$$\text{RRR (normal conductors)} = \frac{\rho(293\ \text{K})}{\rho(4.2\ \text{K})}$$

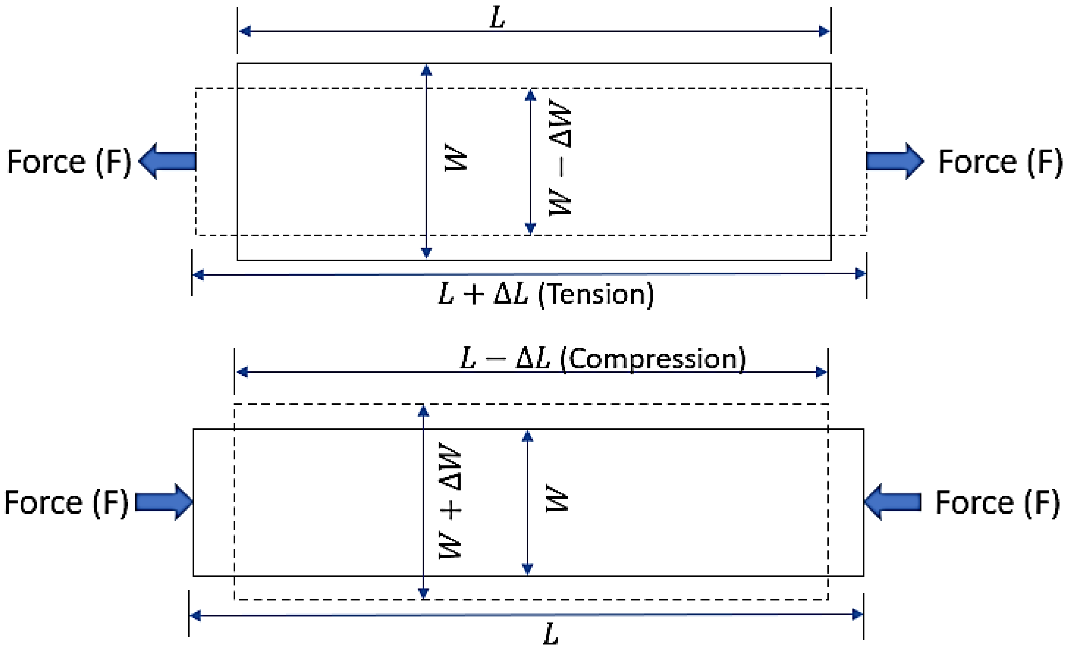
- Nb classified as: low (<100), medium (<300) and **high RRR (>300)**.

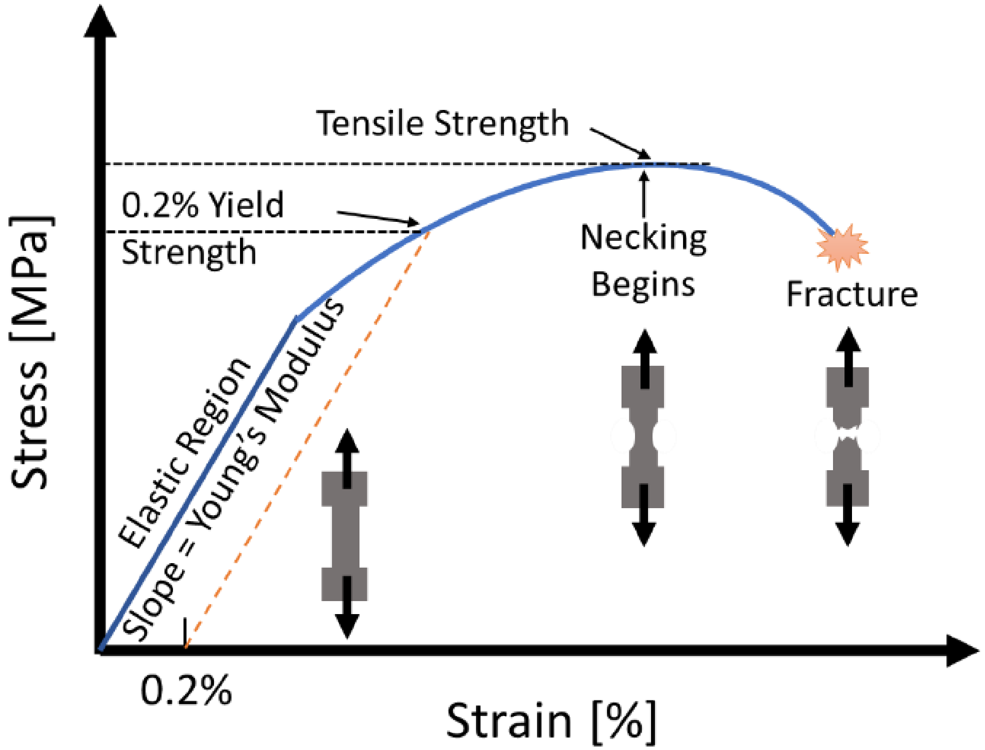


Cited from: arXiv:1501.07142 [physics.acc-ph]

Tensile Testing

- Material is subjected to uni-axial tension until failure.
- Engineering stress (F/L*W) versus engineering strain (ΔL/L) is determined.





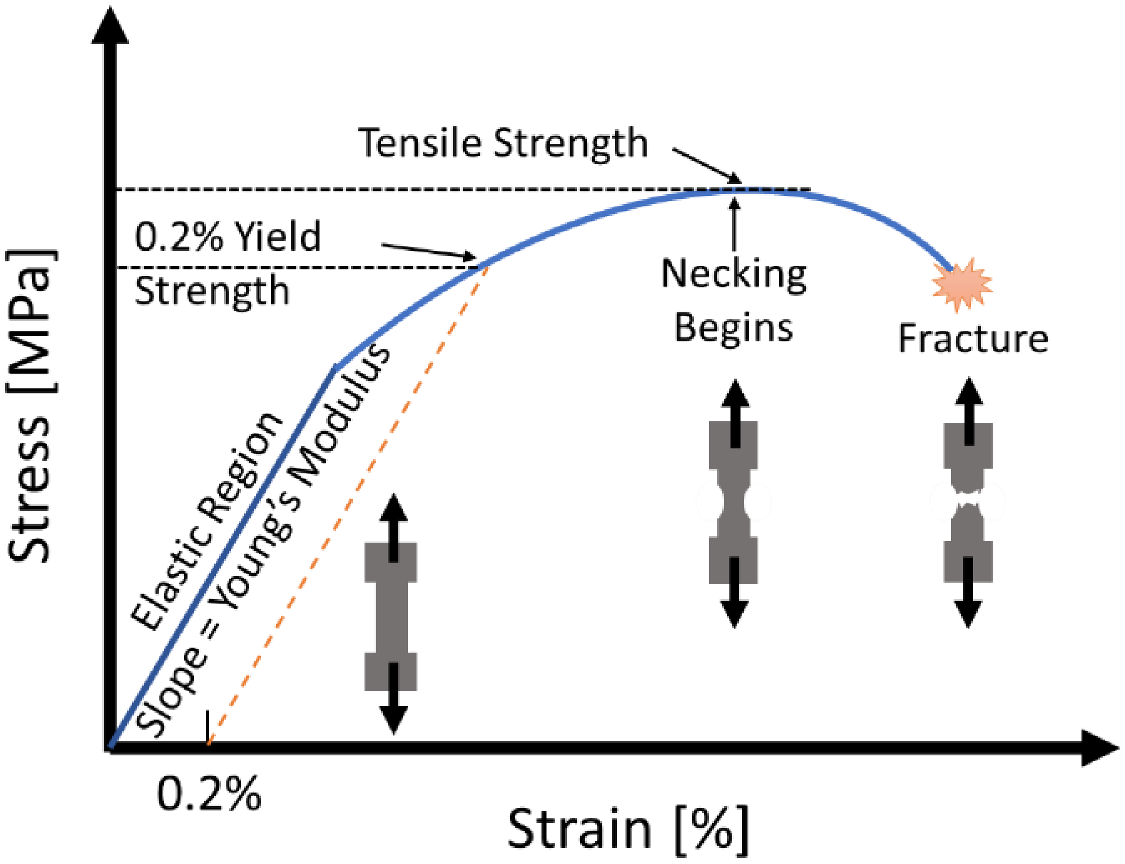
Tensile Testing

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

$$E = \frac{\text{Stress}}{\text{Strain}}\ (in\ Elastic\ Region)$$

- 0.2% Yield Strength (0.2% Y.S) – Stress indicating the limit of elastic behavior

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



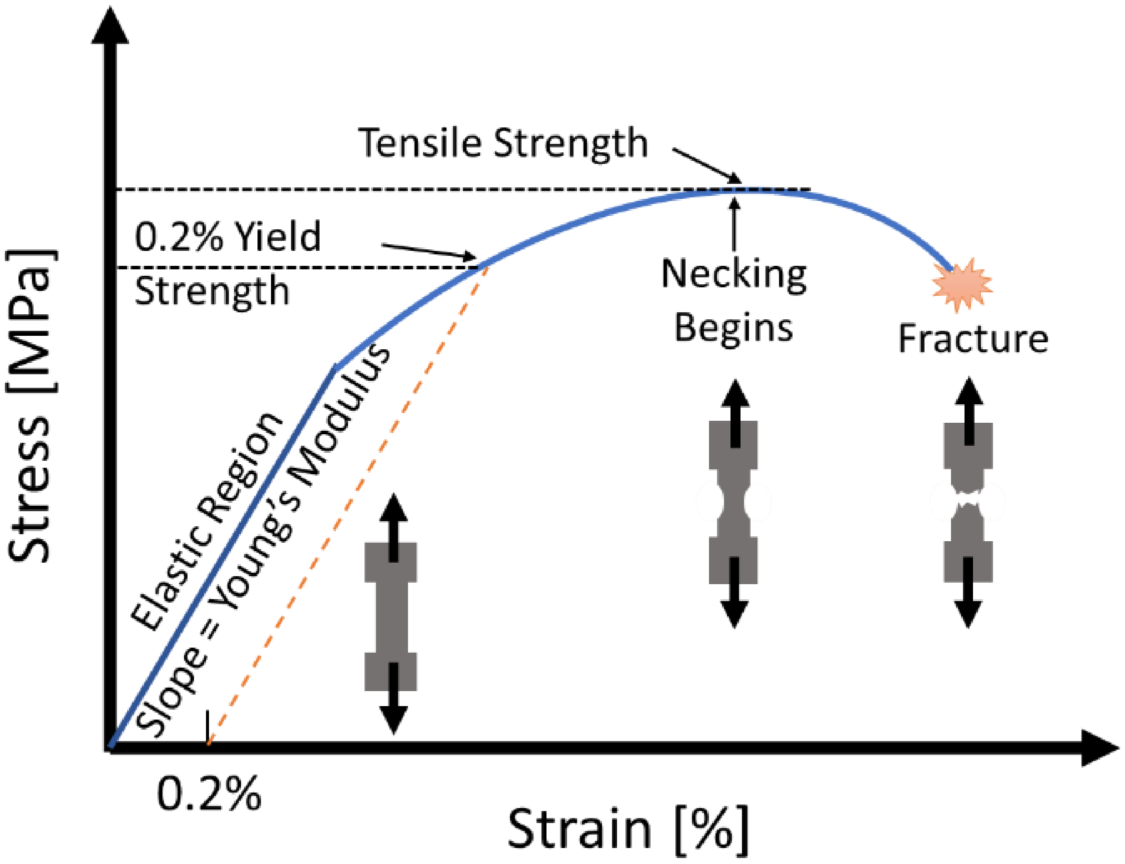
Tensile Testing

- Poisson's Ratio (ν) – absolute value of the ratio of longitudinal strain to the transverse strain

$$\nu = \left|\frac{\text{Longitudinal strain}}{\text{Transverse strain}}\right| = \left|\frac{\Delta L/L}{-\Delta W/W}\right|$$

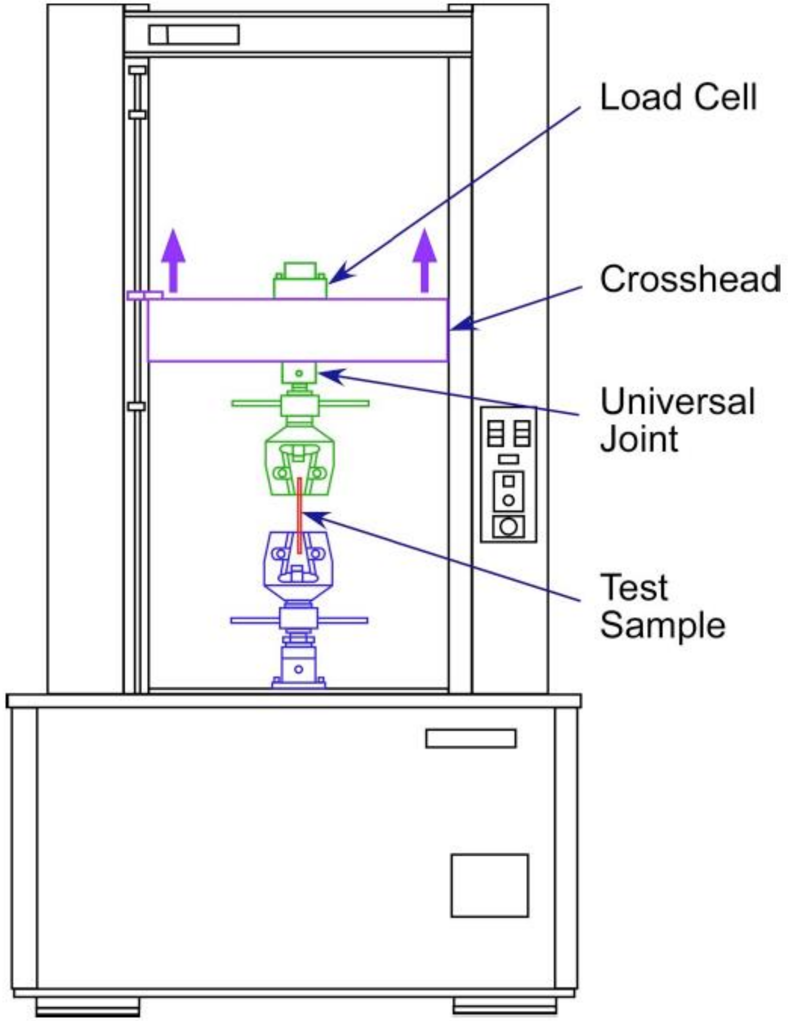
- Elongation – Measure of ductility of a material

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



Tensile Testing Machine

- At KEK, Shimadzu’s® Autograph AG-5000C tensile test machine is utilized.
- Room and cryogenic temperature tests (with cryostat) can be performed.
- Stroke length of approximately 1.5 m.
- Rated for ± 50 KN of force.

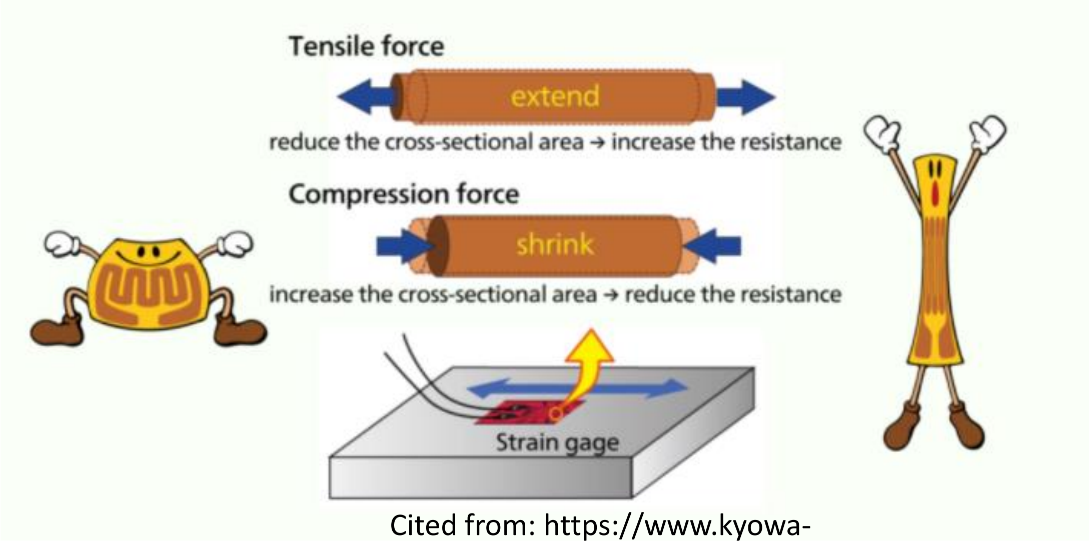


Strain Gages

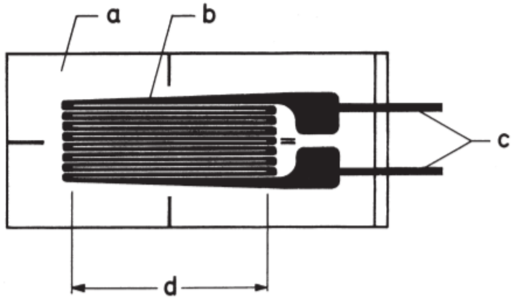
- Its resistance varies w.r.t applied force.
- Metal’s electrical resistance changes when it deforms.
- It transforms the strain applied into proportional change in the resistance.
- 120 Ω Strain gages are most widely used.

$$\frac{\Delta \mathrm{R}}{\mathrm{R}_0} = k\frac{\Delta \mathrm{L}}{\mathrm{L}} = k.\varepsilon$$

k is the gage factor



Cited from: https://www.kyowa-ei.com/eng/technical/strainbasic_course/index.html



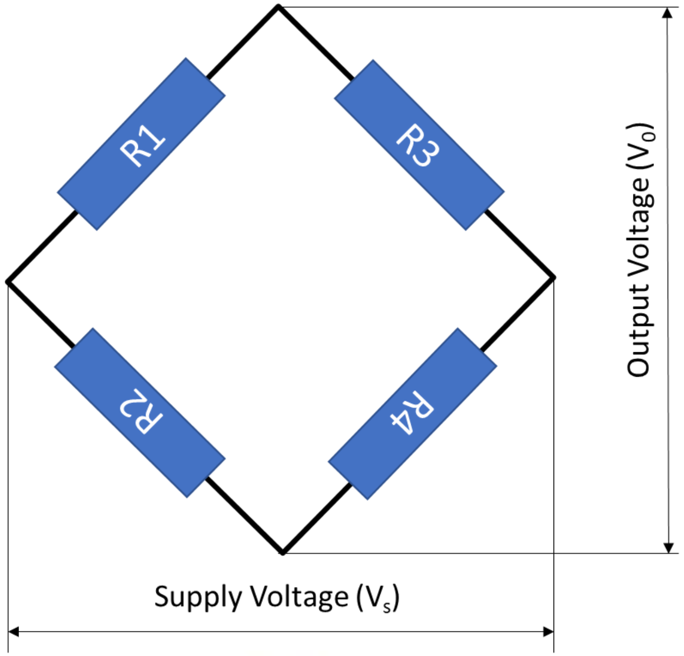
a	carrier material
b	measuring grid
c	connections
d	effective grid length

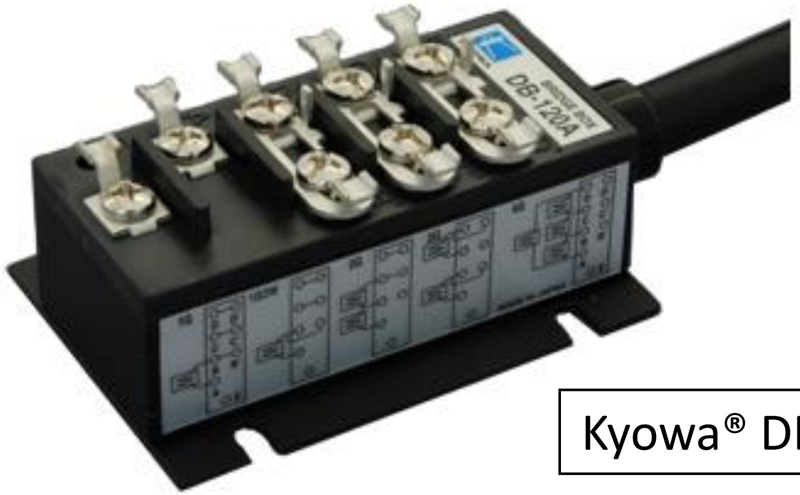
Cited from: Karl F. Hoffman, An Introduction to measurements using strain gages, Hottinger Baldwin Messtechnik GbbH, Darmstadt

Extensometer

- Measures average strain in the gage section.
- Clip-on type doesn’t need independent mounting device.
- Uses a pair of knife edges pressed on the specimen to define the gage length.
- At gage length the circuit is balanced, and material under tension produce output voltage.
- Can measure strains upto 100% and is available for wide range of gage length (10 – 200 mm).

Wheat stone Bridge and Bridgebox

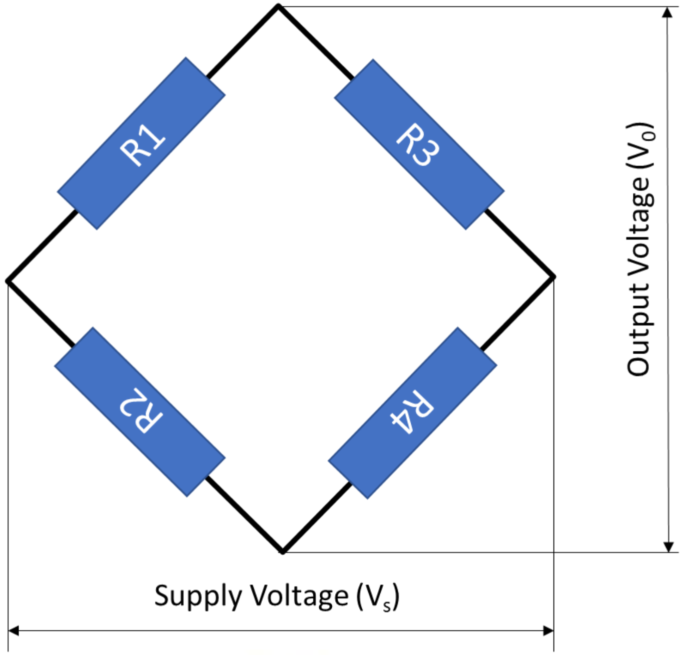




Kyowa® DB-120A Bridgebox

- Measures unknown resistance compared to known resistance values.
- Allows measurements down to milli-ohms.
- 4 resistors in series-parallel connection.
- 2 diagonally opposite terminal to supply excitation voltage and other two to measure output voltage.
- Output in mV / V.

Wheat stone Bridge and Bridgebox



Ratio of output to supply voltage →

$$\frac{V_o}{V_s} = \frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4}$$

Balanced Wheatstone bridge condition →

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

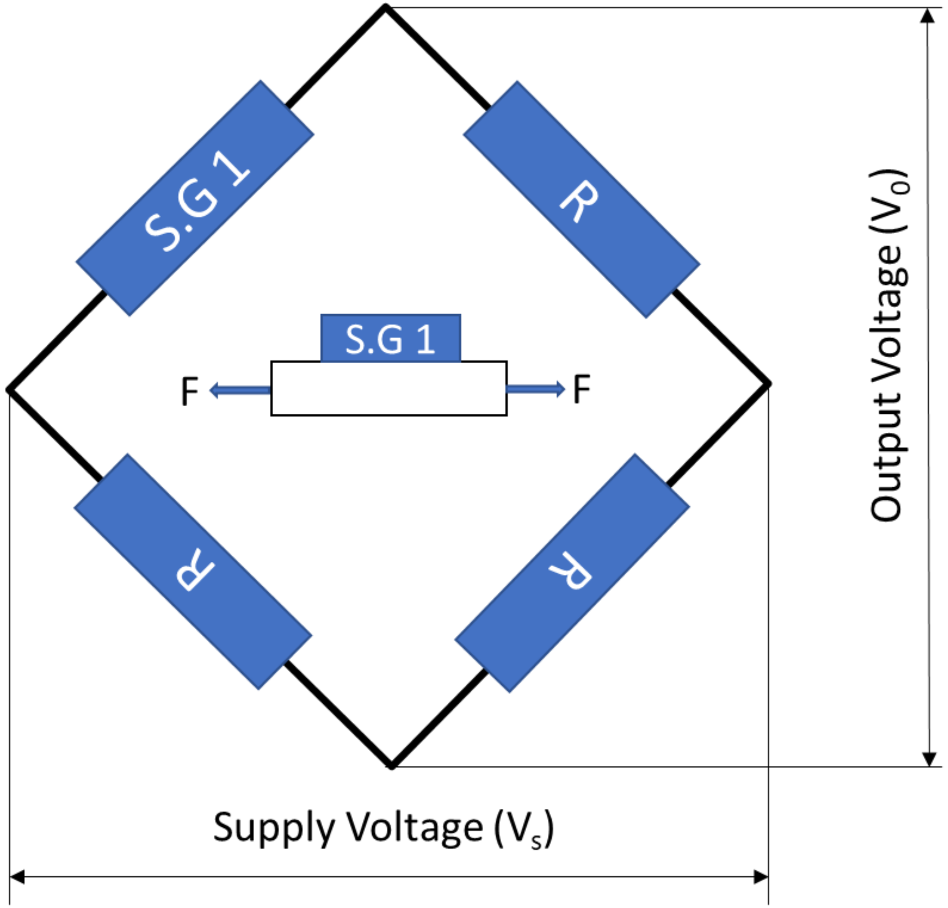
$$\frac{\Delta R}{R_0} = k\frac{\Delta L}{L} = k.\varepsilon$$

↑ Strain Gage

→

$$\frac{V_o}{V_s} = \frac{k}{4}[\varepsilon_1 - \varepsilon_2 + \varepsilon_4 - \varepsilon_3]$$

Configurations of Strain Measurement



Quarter bridge

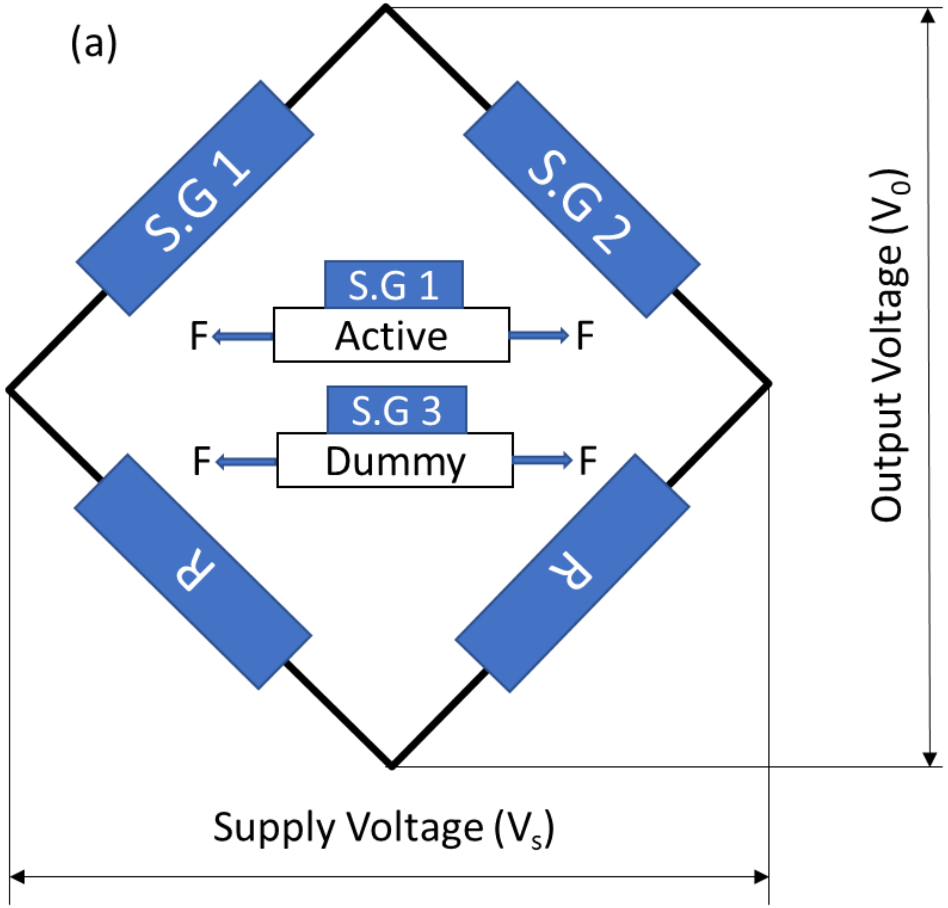
↓

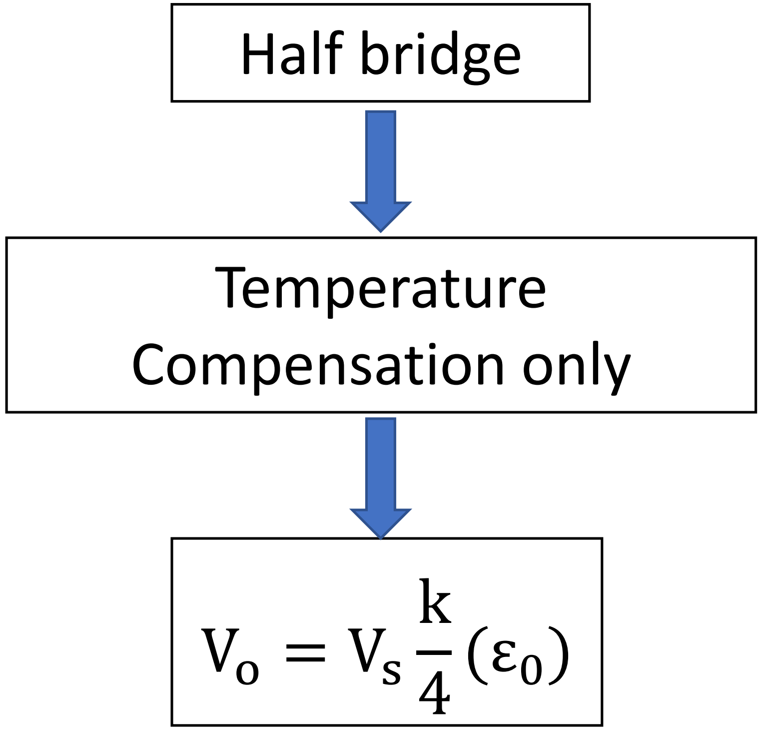
No bending strain cancellation or temperature compensation

↓

$$V_o = V_s \frac{k}{4}(\varepsilon_0)$$

Half Bridge Configuration

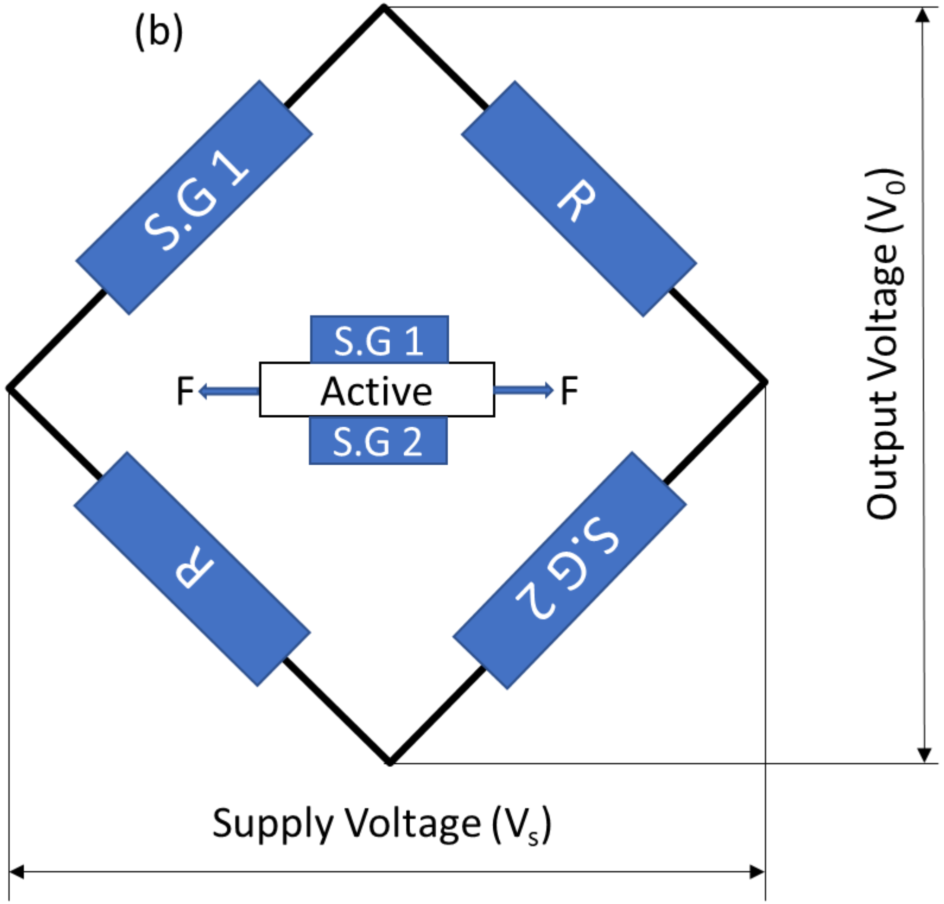


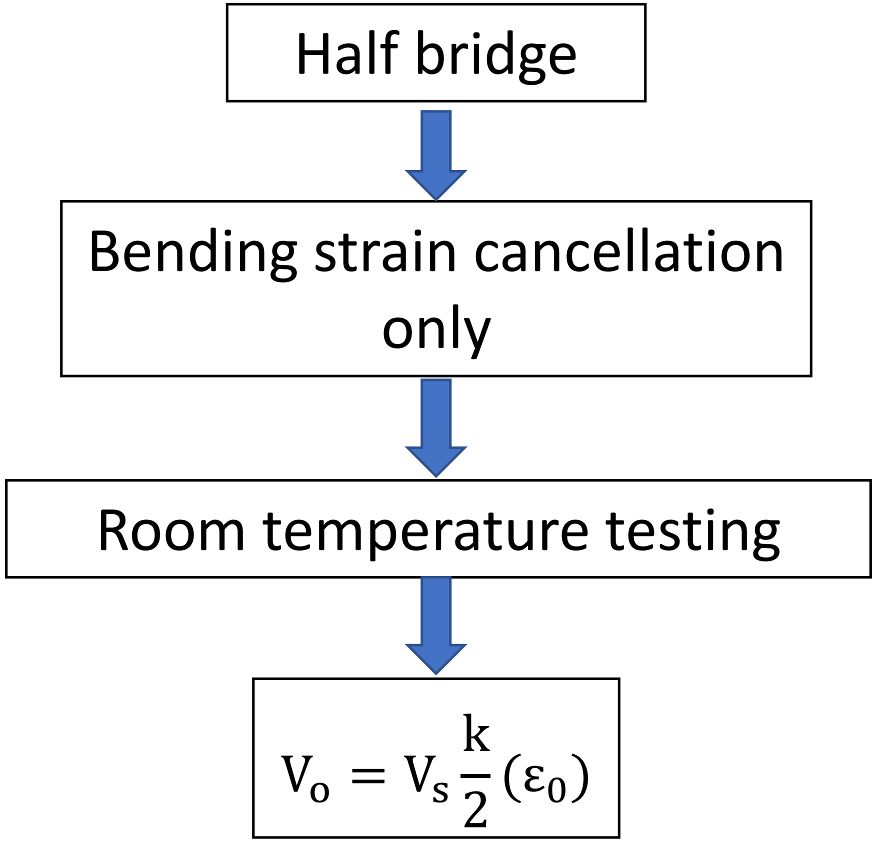

Half bridge

Temperature Compensation only

$$V_o = V_s \frac{k}{4} (\varepsilon_0)$$

Half Bridge Configuration





Half bridge

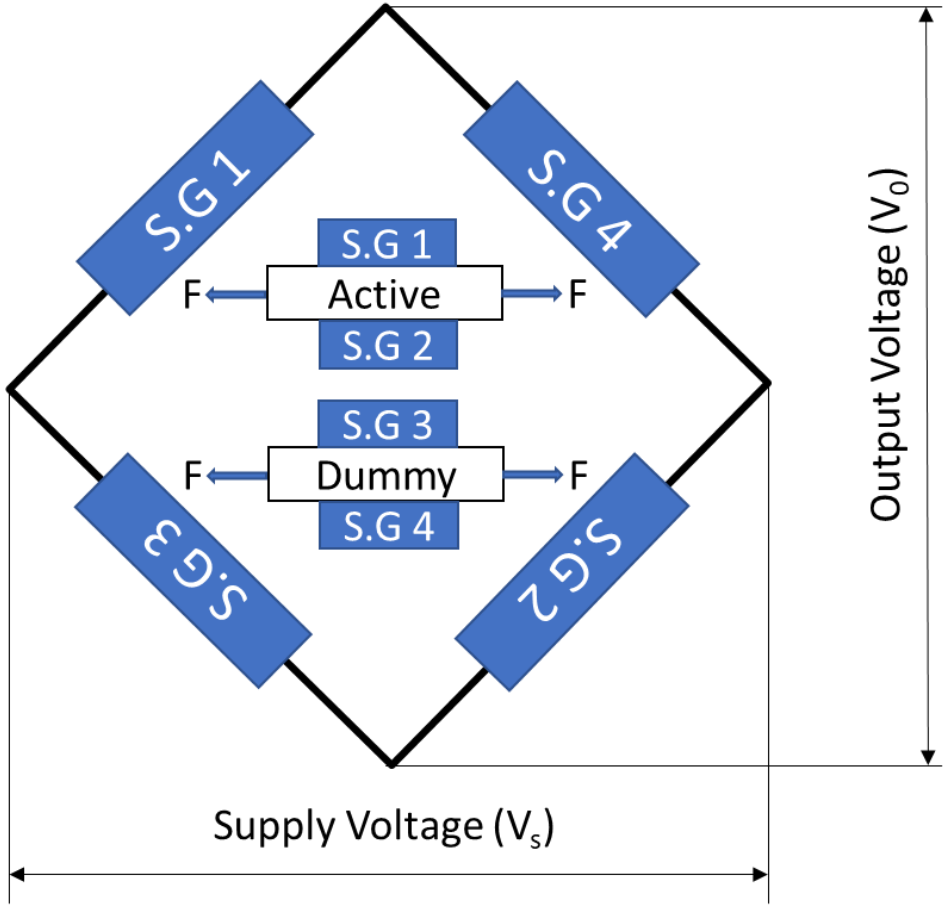
Bending strain cancellation only

Room temperature testing

$$V_o = V_s \frac{k}{2}(\varepsilon_0)$$

*Output voltage is doubled

Full Bridge Configuration



Full bridge

Bending strain cancellation & temperature compensation

Cryogenic temperature testing

$$V_o = V_s \frac{k}{2} (\varepsilon_0)$$

*Output voltage is doubled

Strain Amplifier

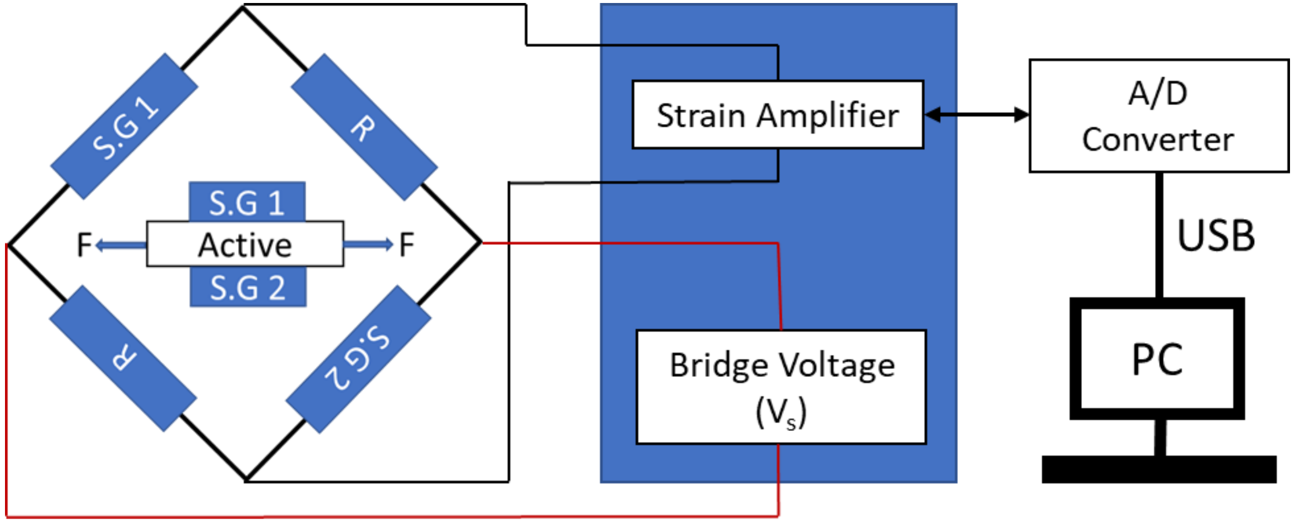
- Output voltage from a Wheatstone bridge circuit is small.
- Electrical amplification for measurement and recording.
- Kyowa® strain amplifiers are used to supply bridge voltage and amplification of the bridge output voltage.
- Bridge excitation voltage of 2 V and 0.5 V.
- Maximum output voltage of 10 V with maximum strain of 9999 micro-strains, i.e 1% strain.
- Internal gain can be set from 200x to 2000x.

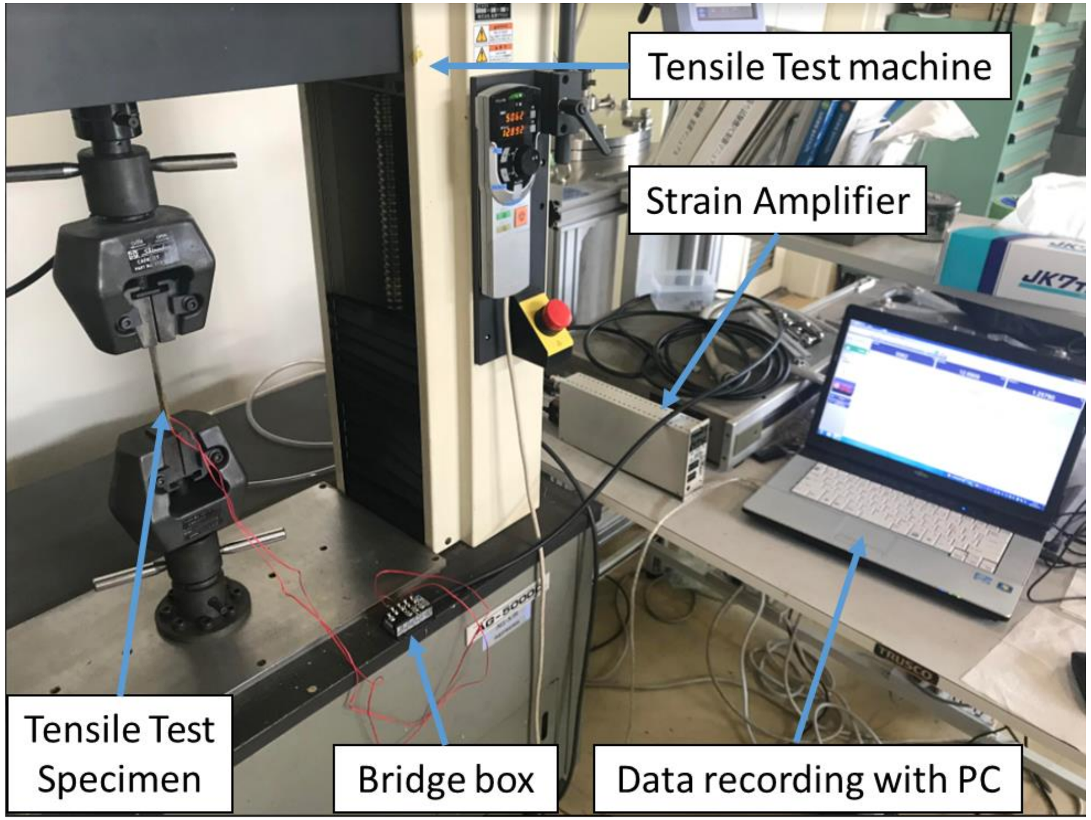
Mechanical Properties

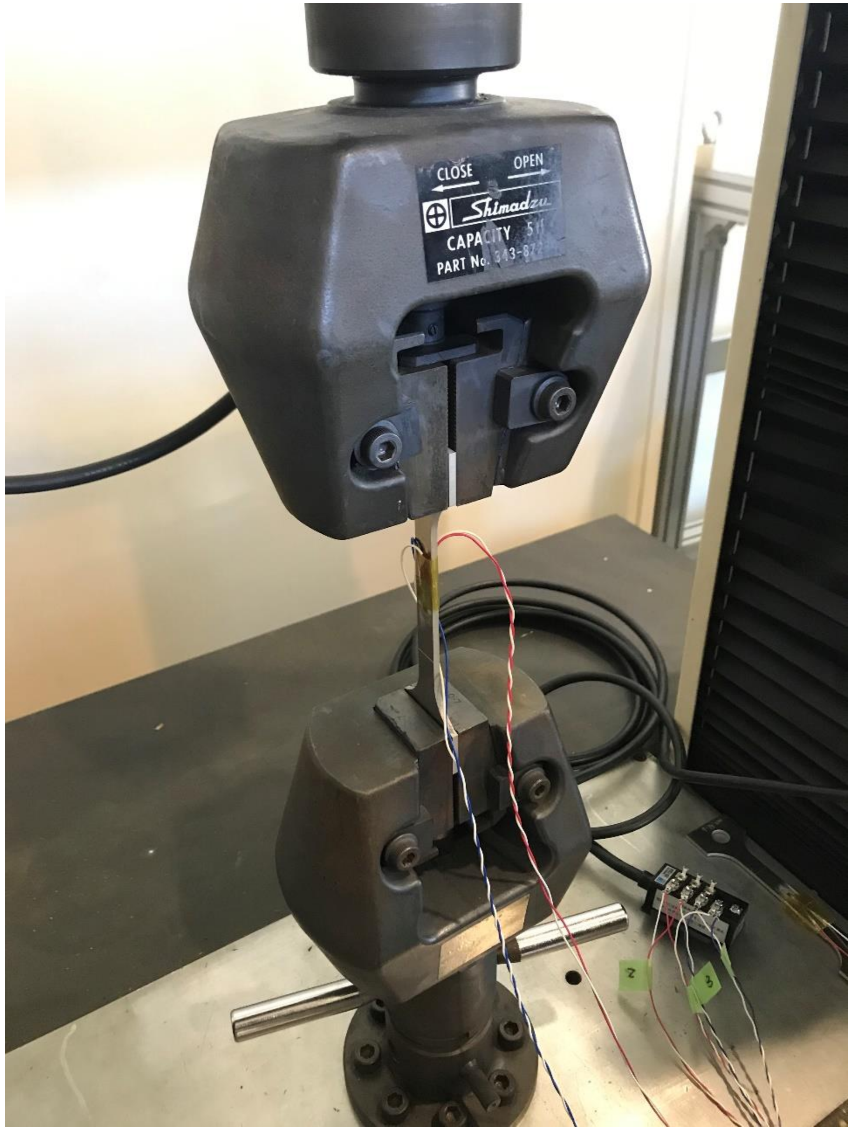
Why Mechanical Characterization?

- Cavity is fabricated at room temperature conditions and operated in LHe.
- Materials should have requisite strength to handle the procedures involved in cavity fabrication, such as press forming, trimming, welding etc.
- Materials should be able to handle stress generated due to large temperature variation.
- SRF cavity assembly must be able to withstand conditions set by high-pressure gas safety authorities for pressure vessels.
- Materials for cavity assembly such Nb, Ti and NbTi are known to be weakest at room temperature conditions.

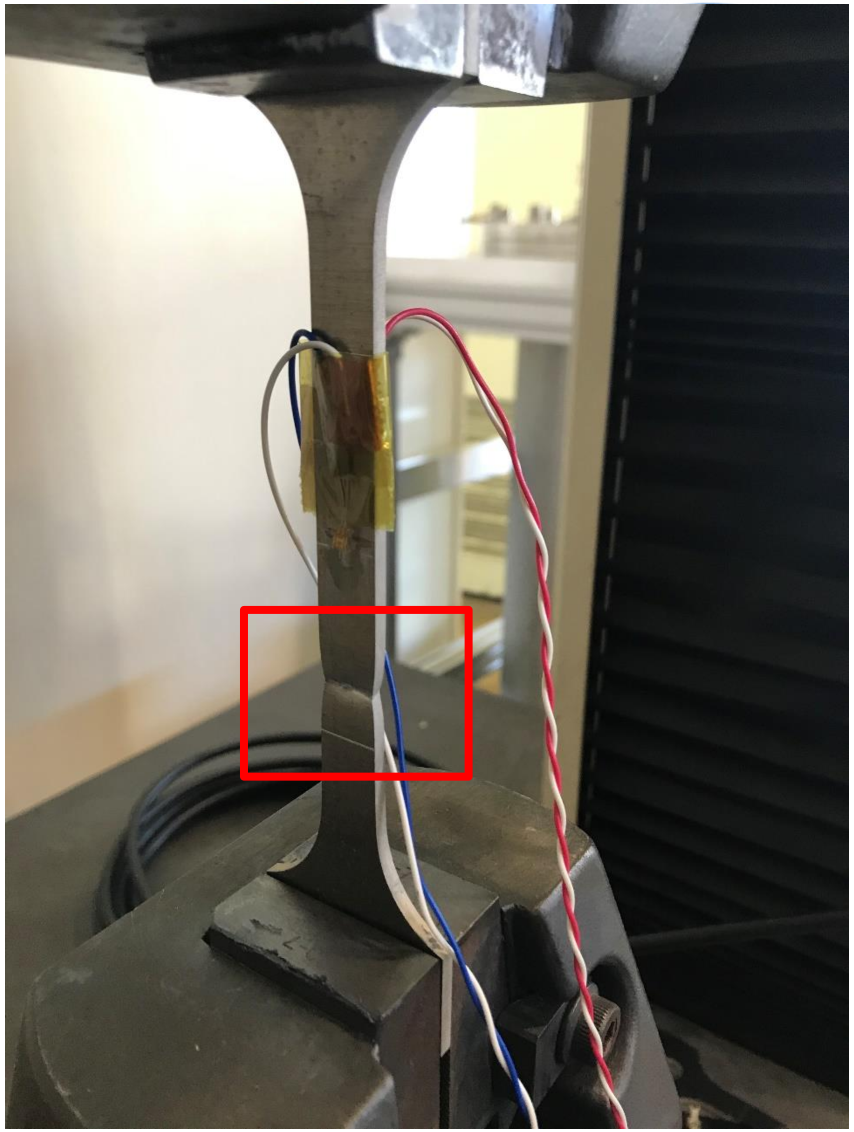
Room Temperature Tensile Tests







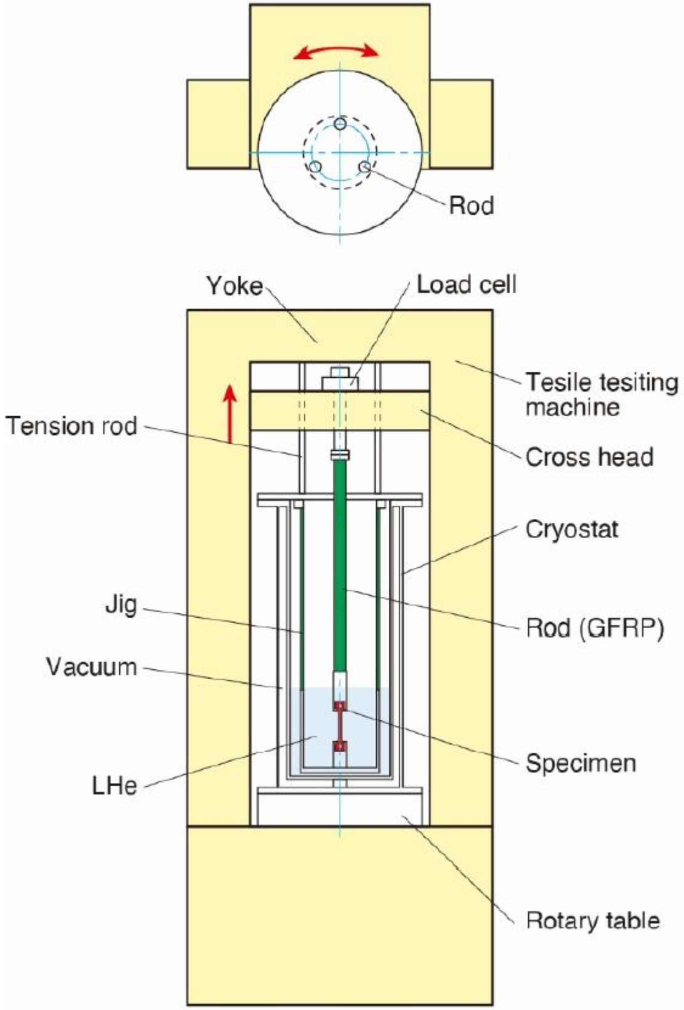
Sample in the jig of tensile test machine



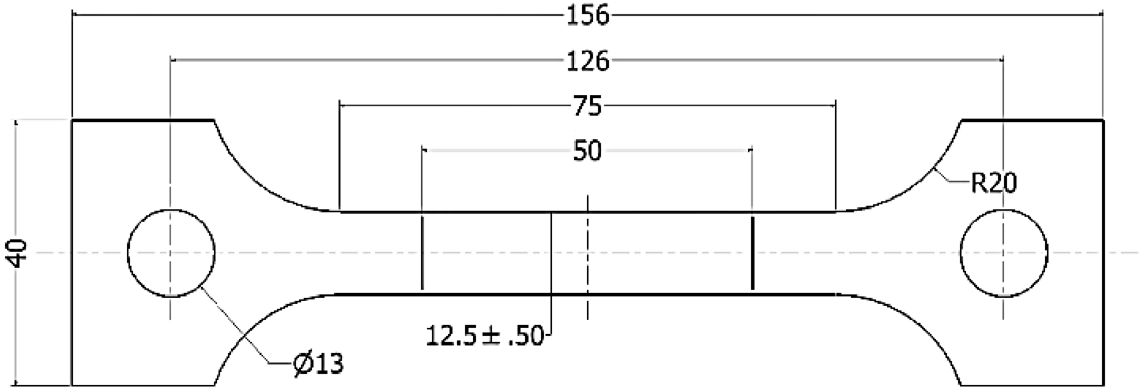
Necking of Aluminum sample

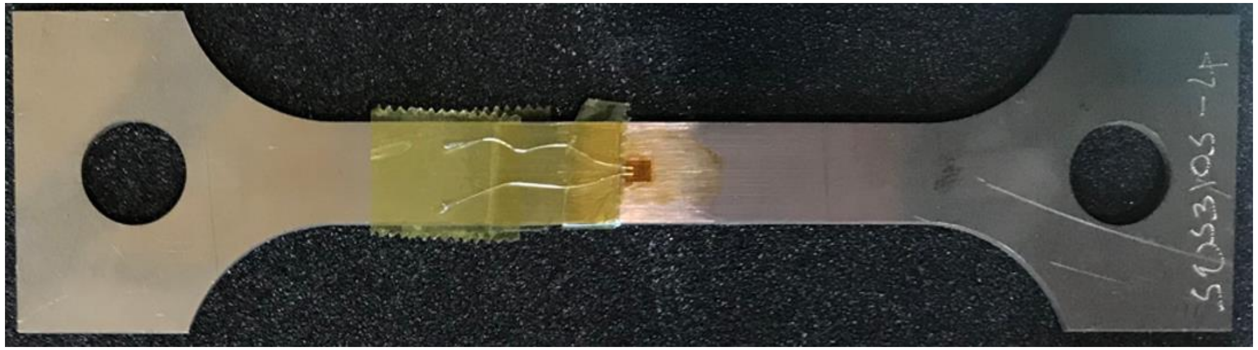
Low Temperature Tensile Testing

- SRF cavity assembly operational temperature is 2.0 K.
- Mechanical properties of metals changes drastically from 300 K to 2.0 K.
- A custom-built cryostat at KEK to dip tensile test specimens in liquid helium.
- Three specimens can be tested in one cooldown cycle.

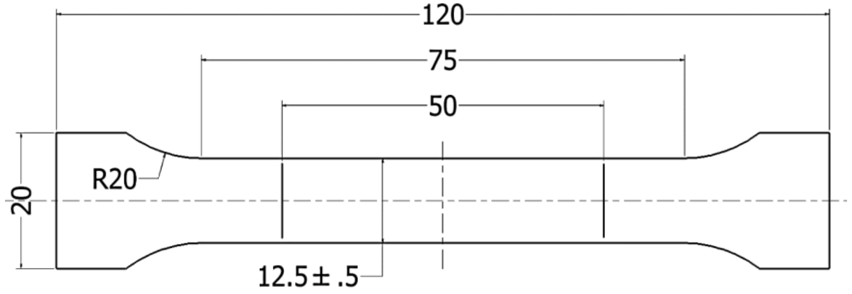


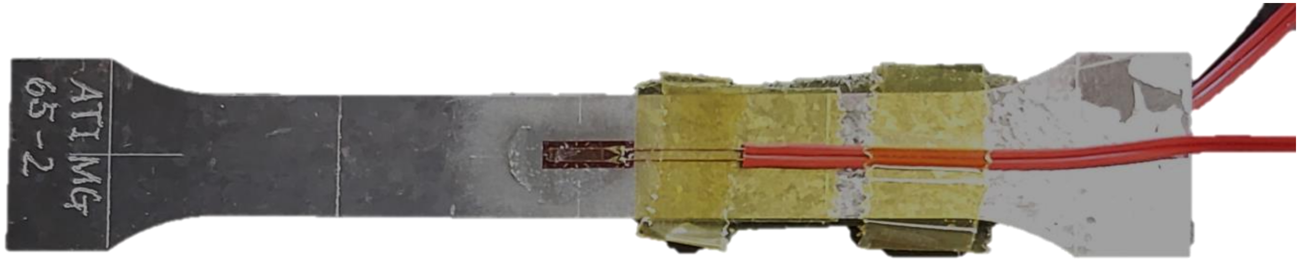
Specimen for Tensile Testing





Cryogenic temperature tensile testing specimen



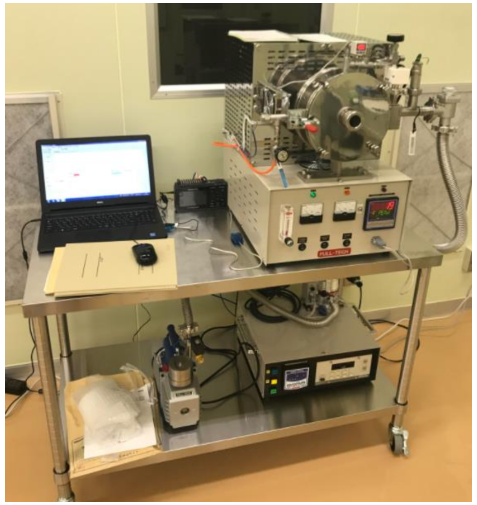


Room temperature tensile testing specimen

Preparation of Tensile Test Specimen

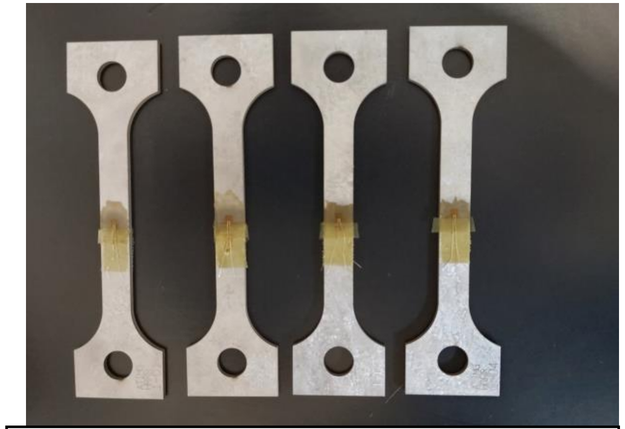

Wire EDM Cut


Chemical Polishing


Annealing


Strain Gage Bonding


Oven for bonding

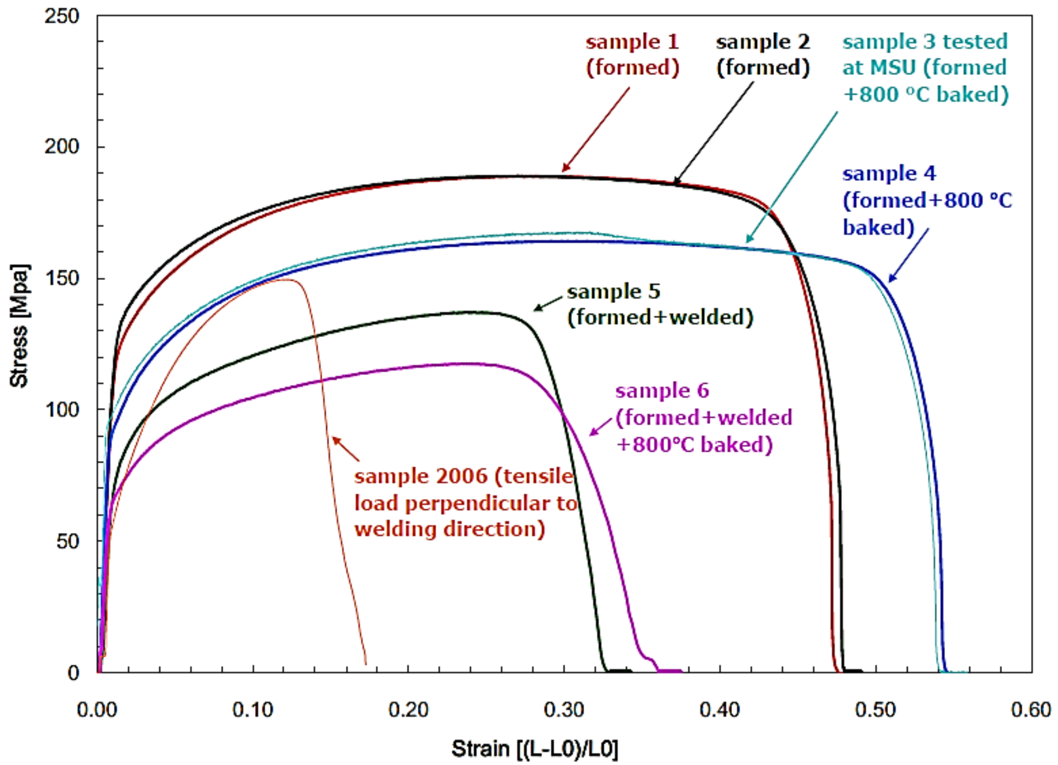

Tensile test specimen

Niobium Mechanical Properties

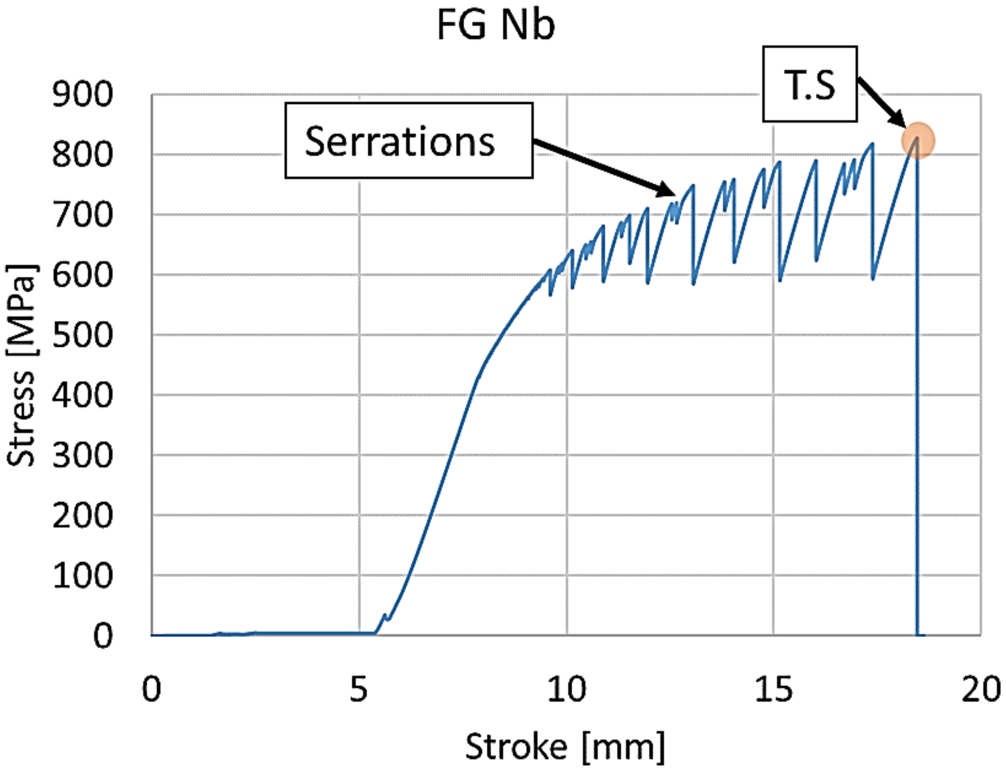
- Mostly properties of FG Nb will be presented.
- FG Nb is a standard material that is considered while designing the SRF cavity.
- Data presented here is for the annealed specimens.
- Employed for Eu-XFEL (DESY), LCLS-II (SLAC) and STF-2 (KEK).
- LG Nb is mainly a research material and currently not used for large scale accelerators.
- LG Nb properties have been studied in details at KEK but the data is still under publication.

Stress-strain curve for FG Nb

- Isotropic mechanical properties (independent of location of tensile test specimen).
- However, properties do deteriorates with annealing.



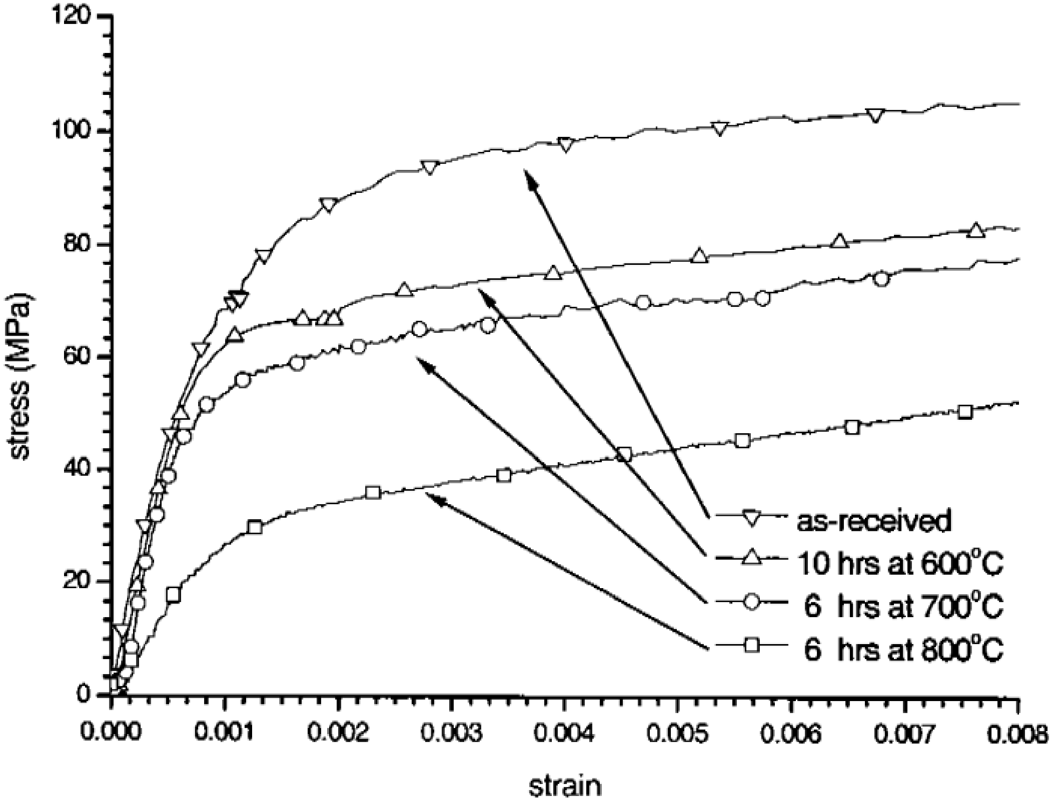
At Room Temperature



In Liquid Helium (4.21 K)

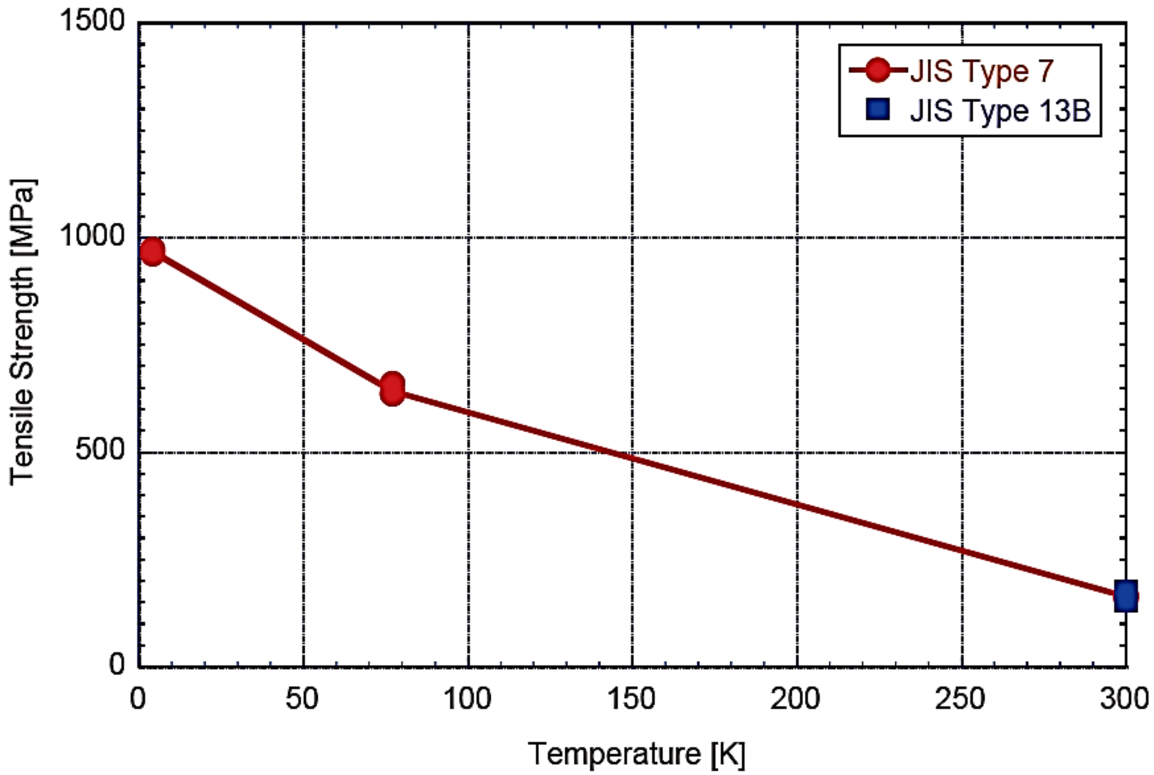
Effect of Annealing on Nb

- Material properties deteriorates with annealing at higher temperatures.
- Least deterioration at 600 °C without any loss in hydrogen degassing performance.
- However, 800 °C is considered as an ideal temperature due to better flux expulsion.
- Annealing relieves residual stresses and helps in recrystallization too.

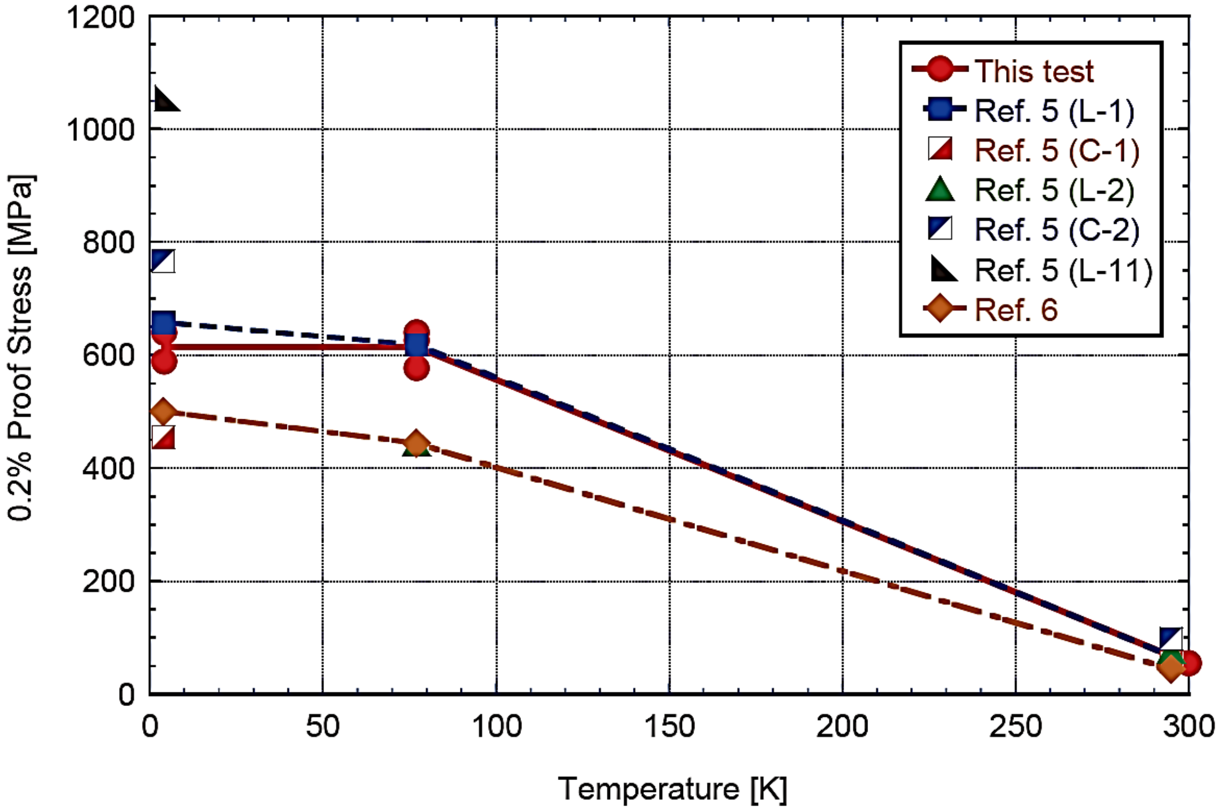


Cited from: AIP Conference Proceedings 671, 227 (2003)

Mechanical Properties of FG Nb



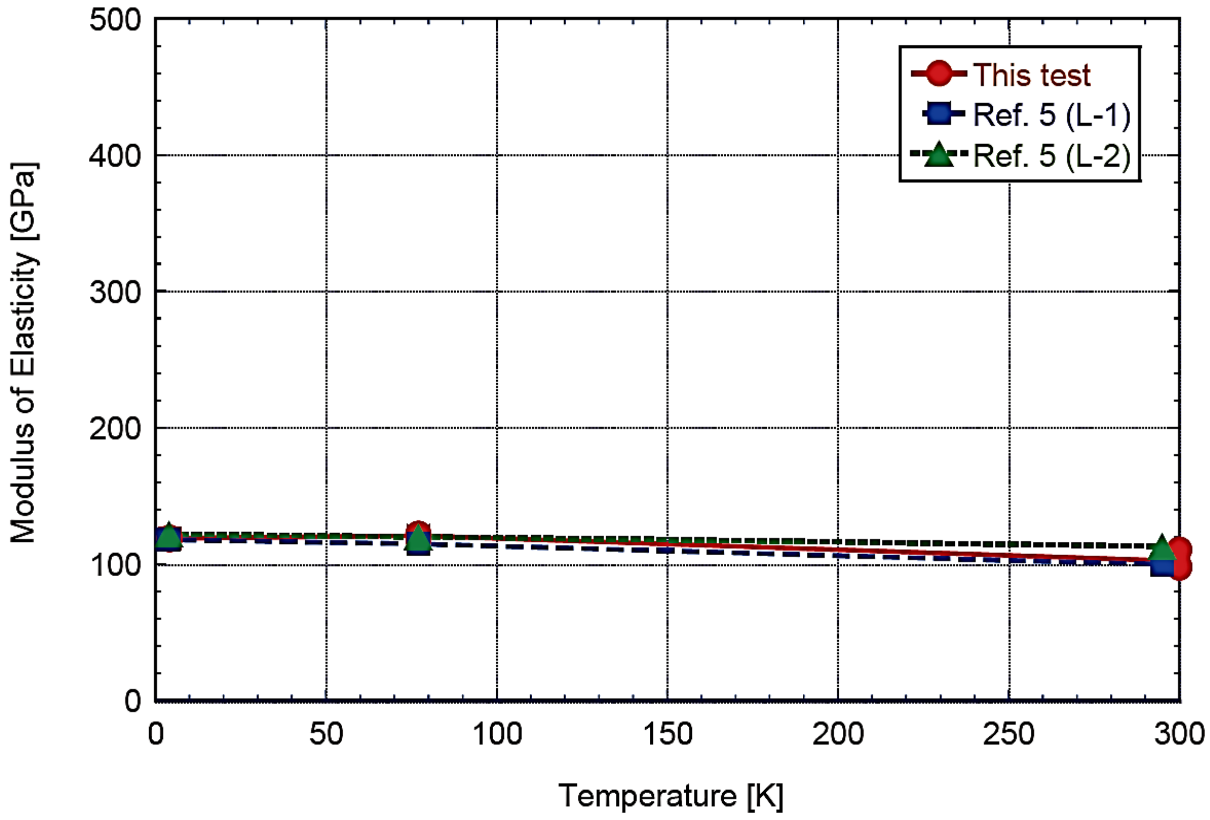
Tensile Strength w.r.t temperature



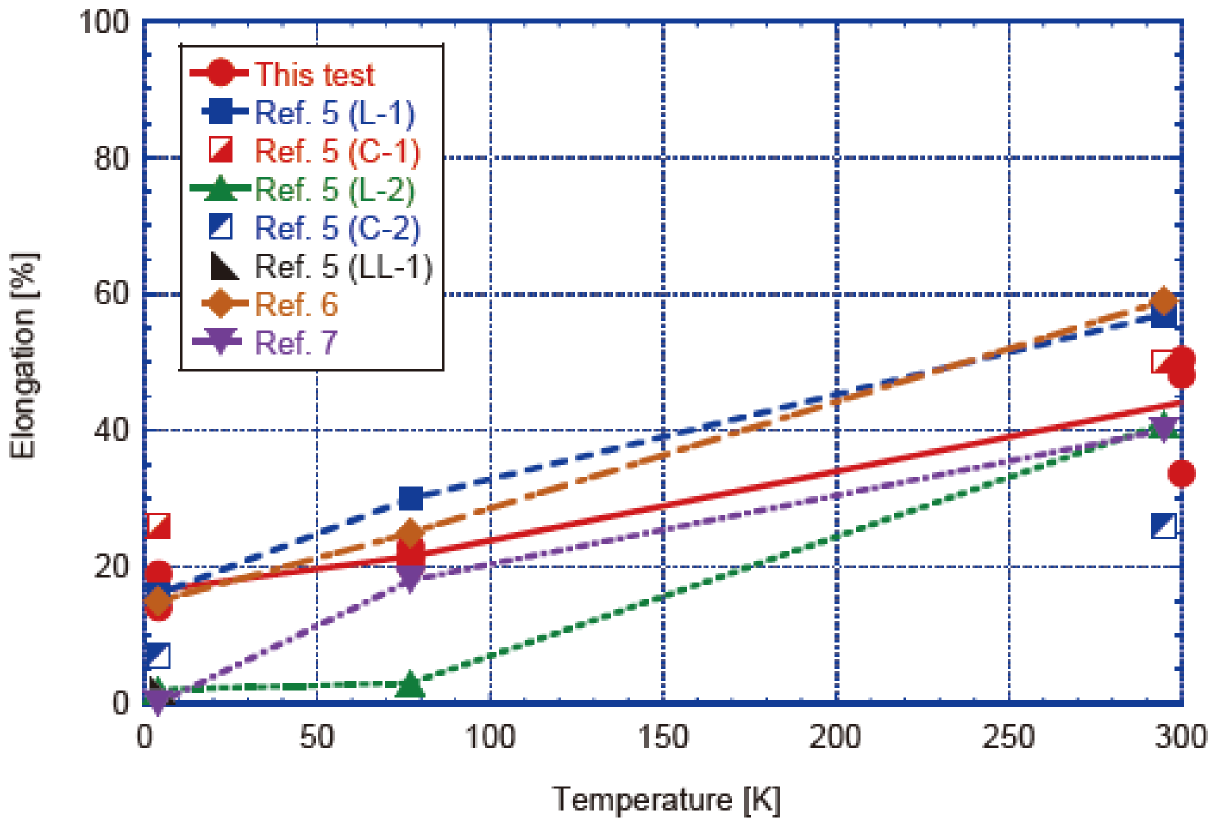
Yield strength w.r.t temperature

Cited from: H. Nakai et al., “Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules”, Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

Mechanical Properties of FG Nb



Young’s modulus w.r.t temperature

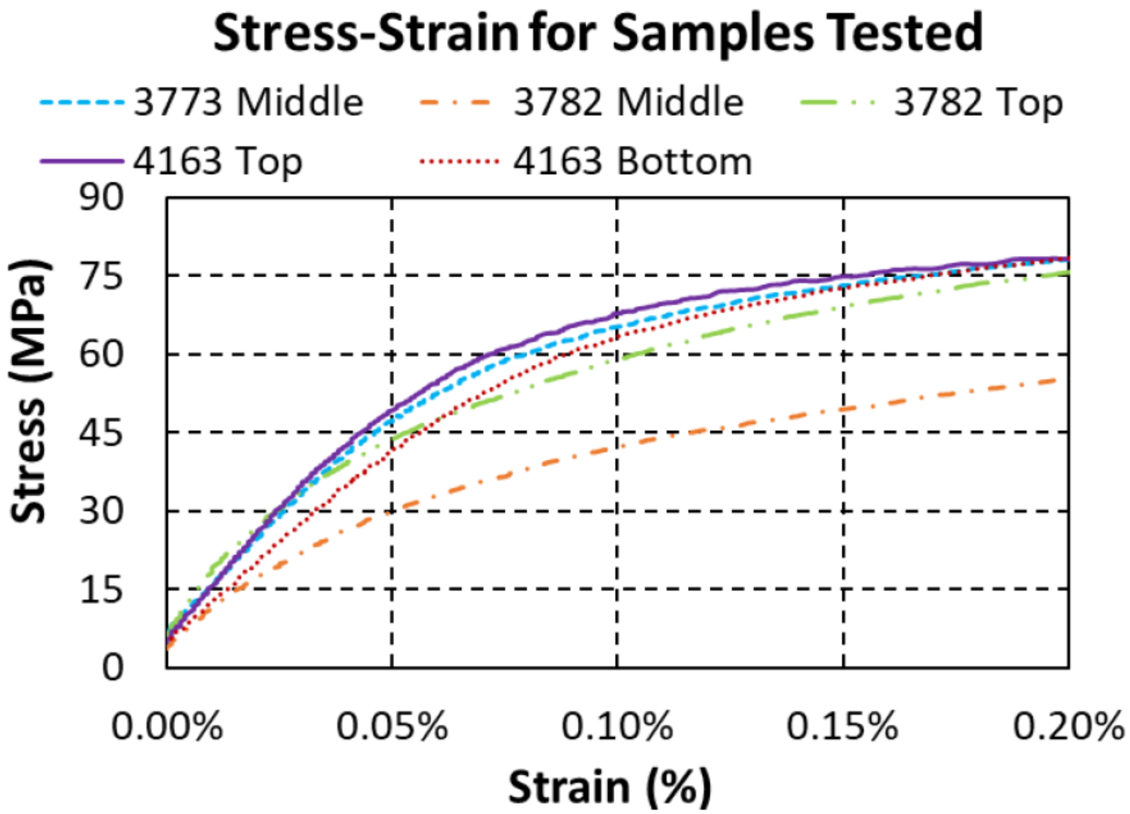


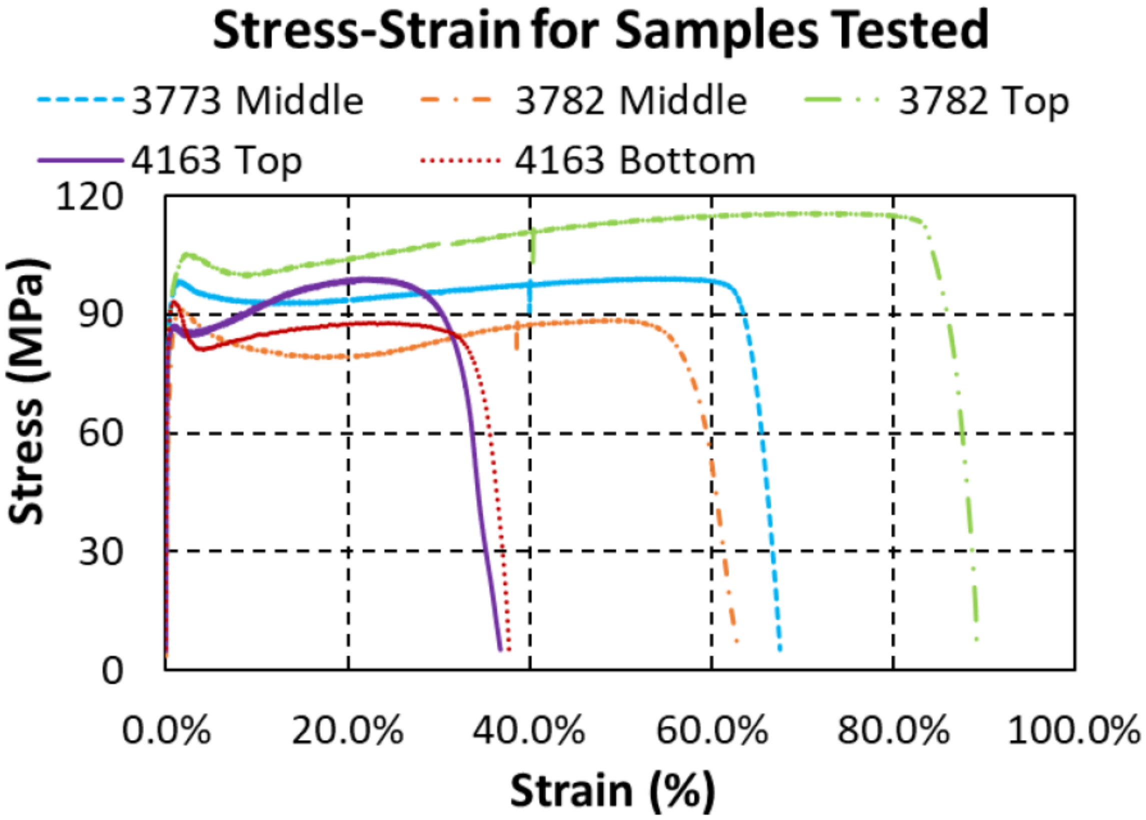
Elongation w.r.t temperature

Cited from: H. Nakai et al., “Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules”, Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

LG Nb Mechanical Properties

- Anisotropic mechanical properties for LG Nb due to grain orientation.
- T.S can be as low as 66 MPa to as high as 124 MPa.

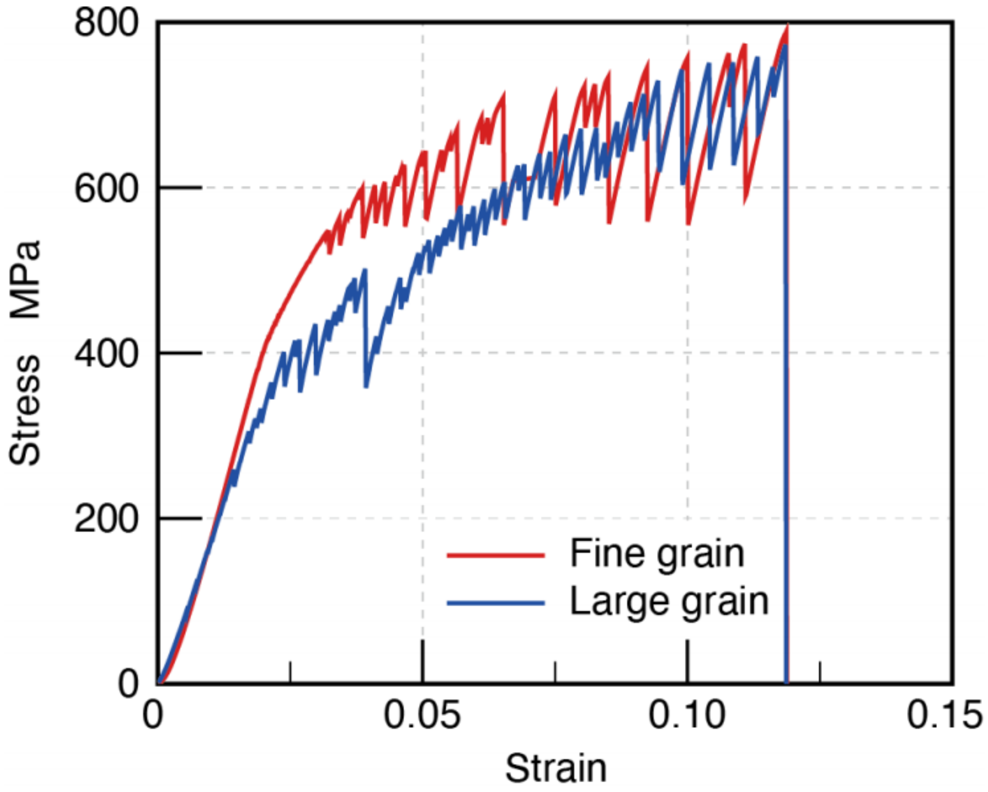


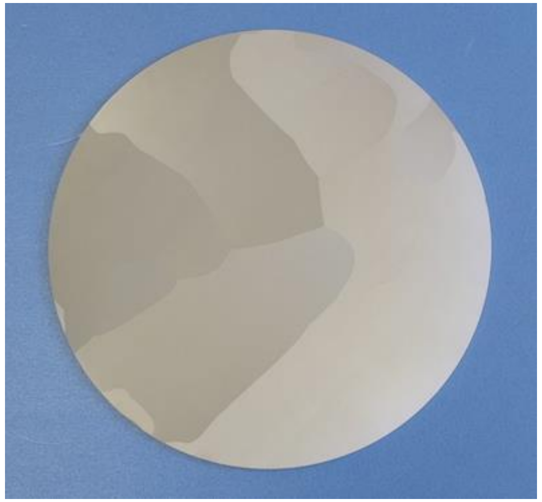


Cited from: IOP Conf. Ser.: Mater. Sci. Eng. 756 012002

LG Nb Mechanical Properties

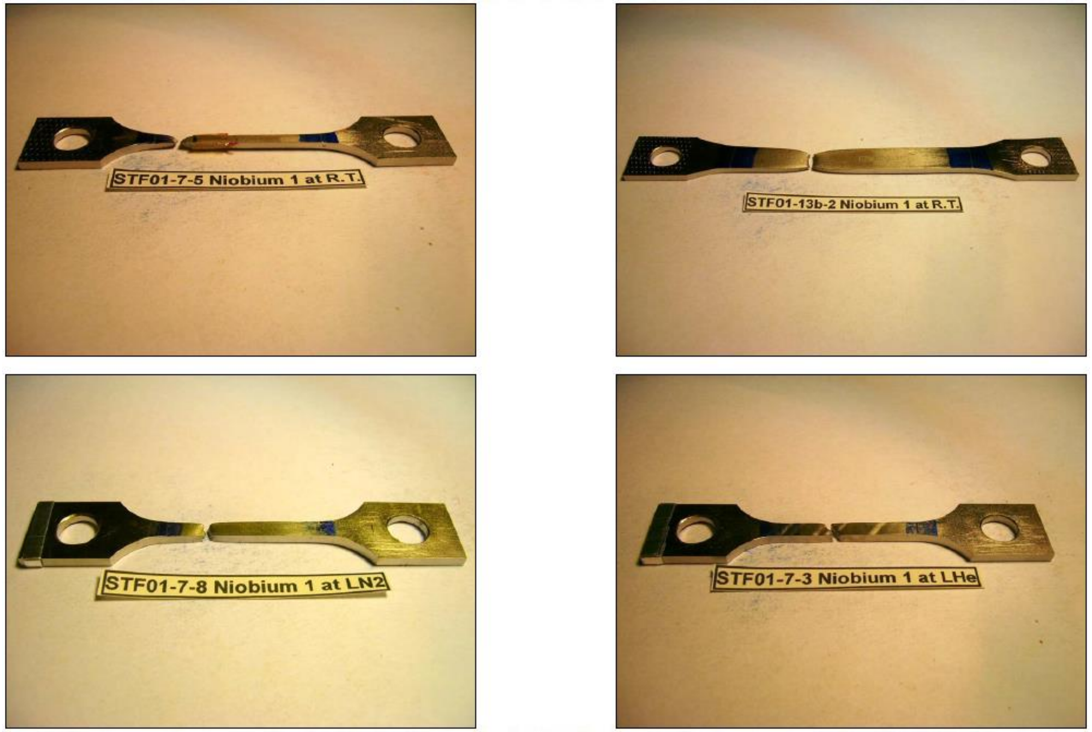
- Large variation in low temperature mechanical properties for LG Nb due to grain orientation.
- T.S can be as low as 400 MPa to as high as 800 MPa.
- 0.2% Y.S is difficult to determine due to serrations in that operational region.



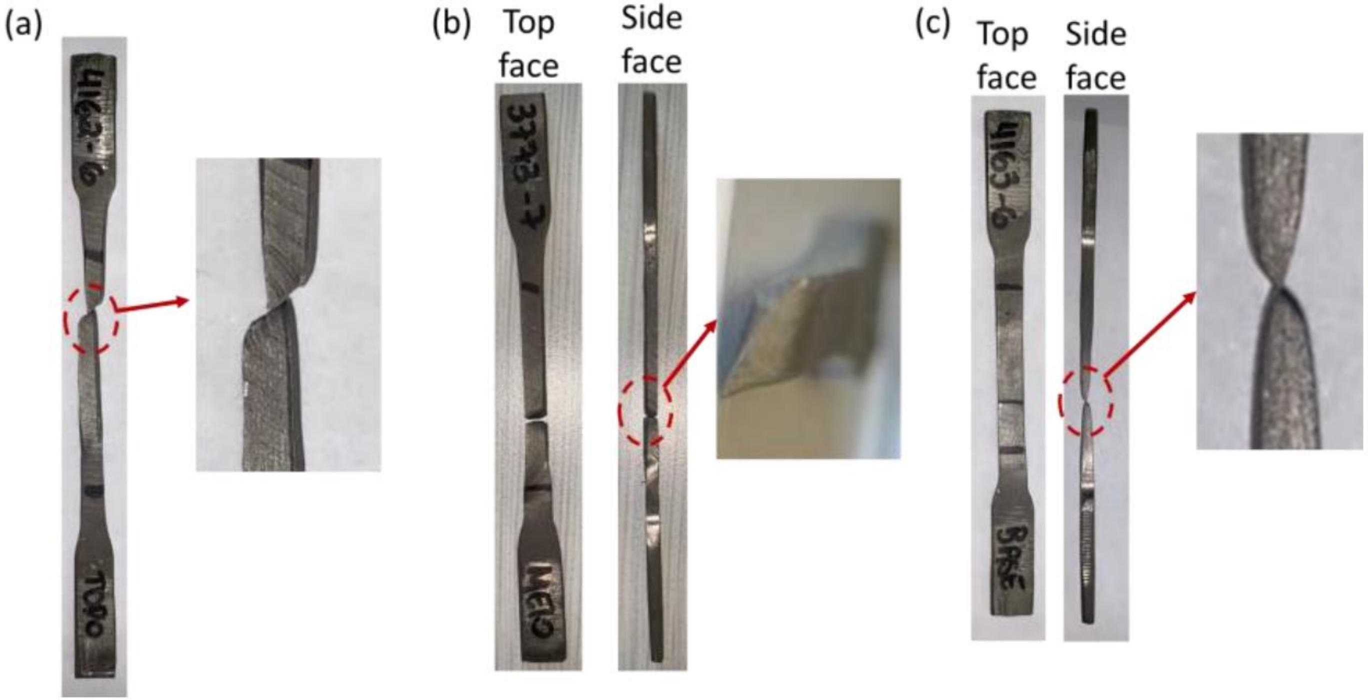


Examples of some tested specimens

Cited from: IOP Conf. Ser.: Mater. Sci. Eng. 756 012002

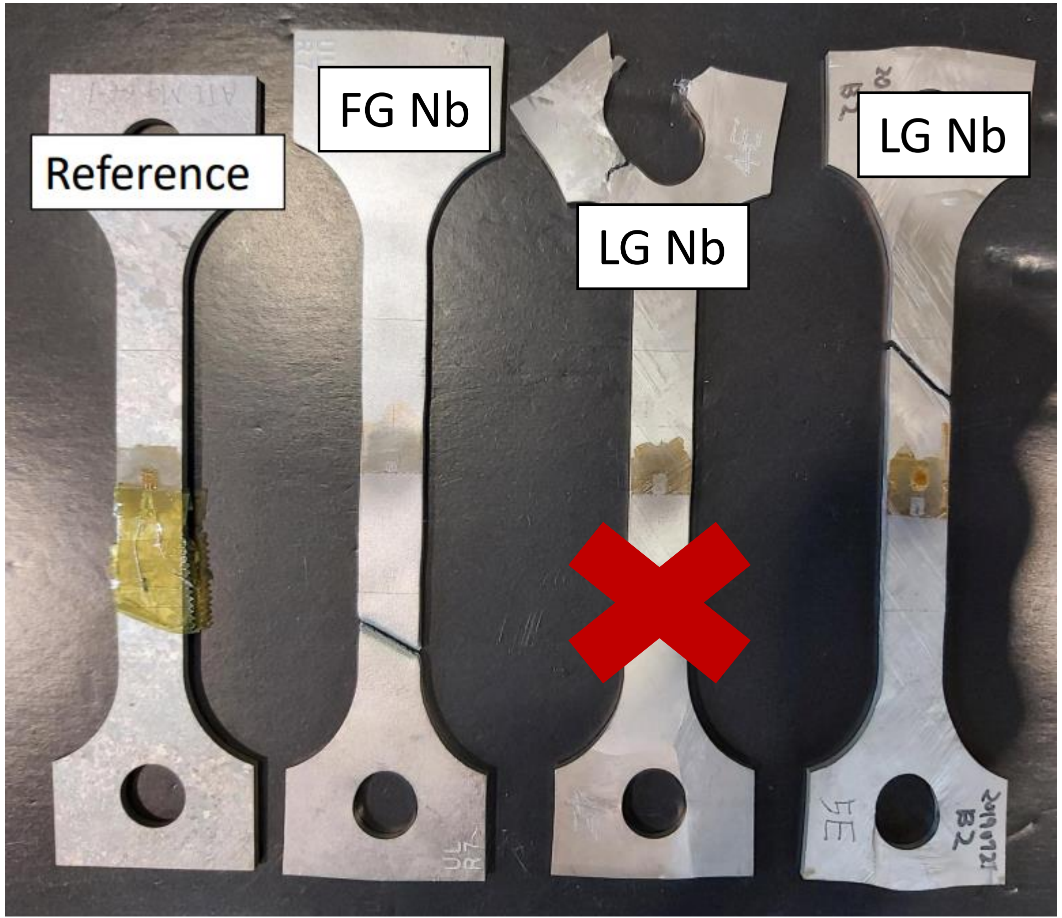


FG Nb tensile tested specimens at KEK by Nakai et al.



Room temperature LG Nb tensile tested specimens by Zhao et al.

Examples of some tested specimens



Low temperature tensile tested specimens (by me)

Nb Mechanical Properties w.r.t SRF Cavity Strength Requirement

Material	Y.S [MPa]	T.S [MPa]	Elongation [%]
FG Nb	~50	~150	~40
LG Nb	66-124	84-136	> 30
Tesla-like	> 39	> 120	> 30
Eu-XFEL	> 50	> 140	> 30

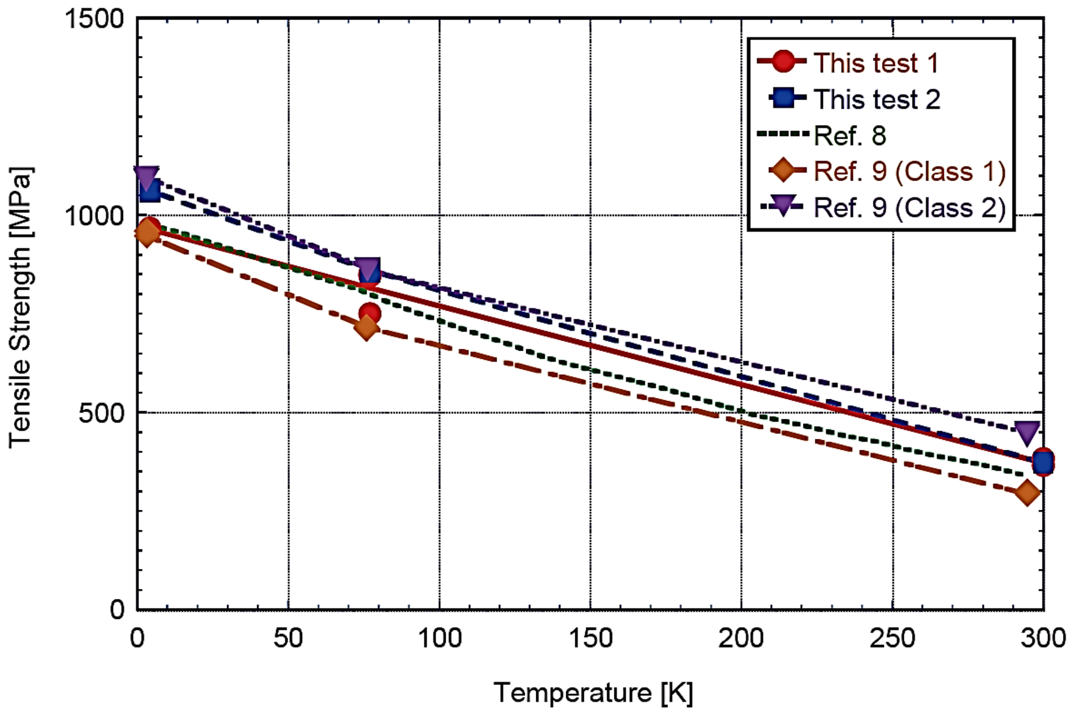
For high-pressure gas safety regulation

Only necessary for formability of SRF cavity half cells

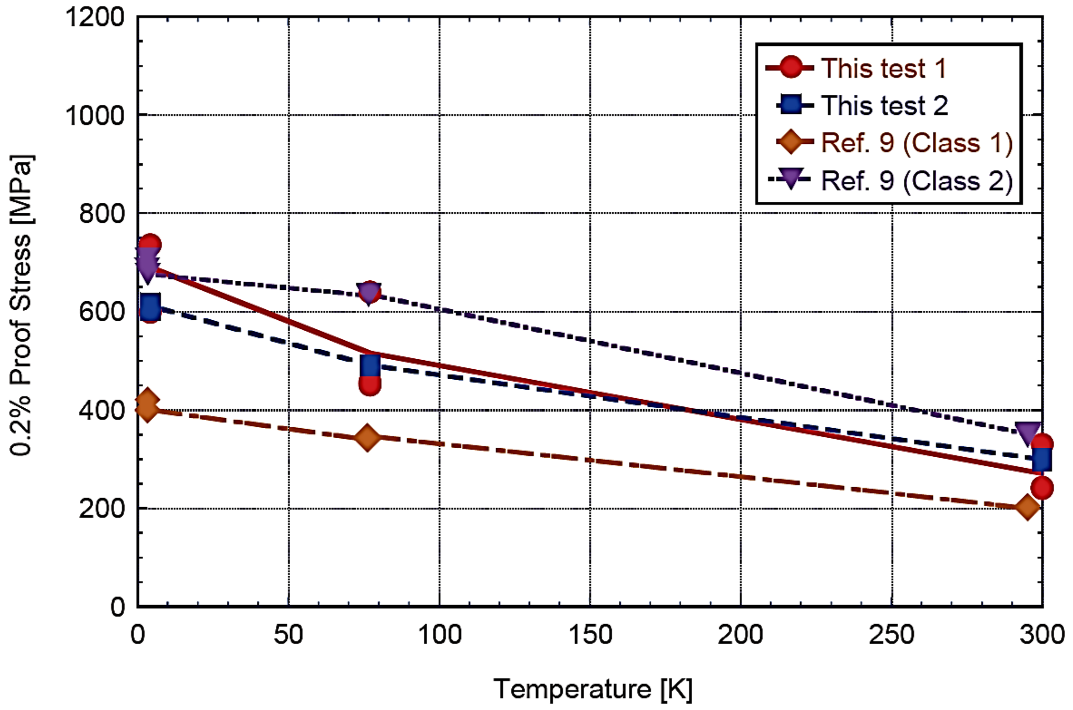
Material	Y.S [MPa]	T.S [MPa]	Elongation [%]
FG Nb	~500	800 - 900	~7
LG Nb	-	400 - 800	~6
Tesla-like		> 300	

Titanium Mechanical Properties

- Sufficient mechanical properties for pressure vessel design.



Tensile Strength w.r.t temperature

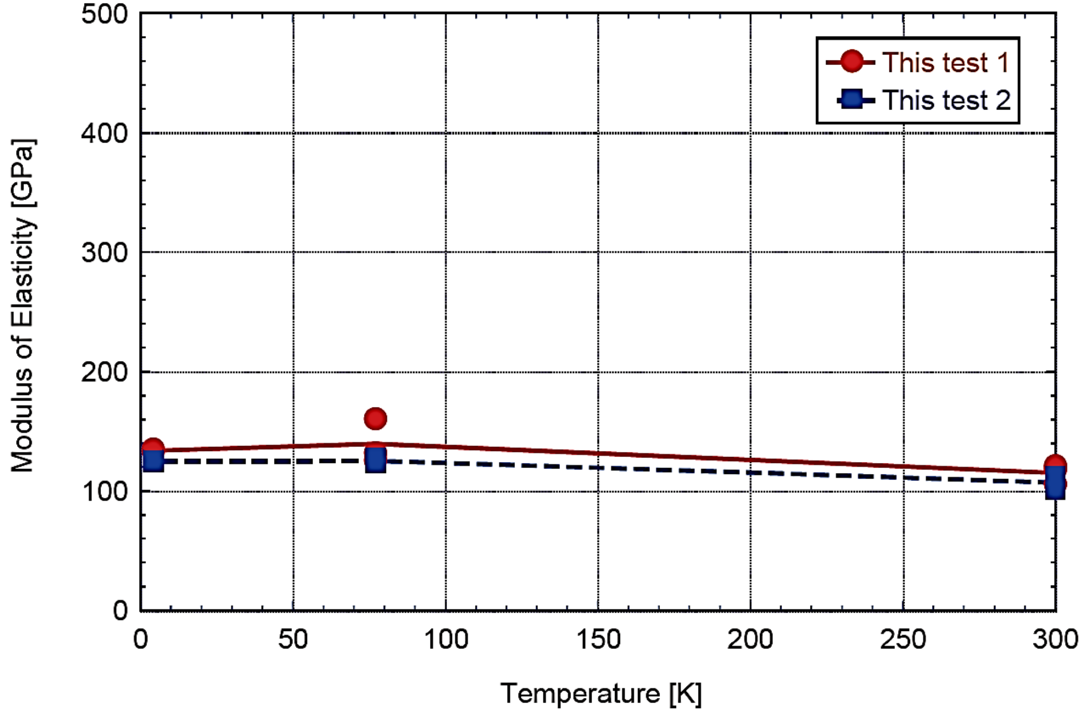


Yield strength w.r.t temperature

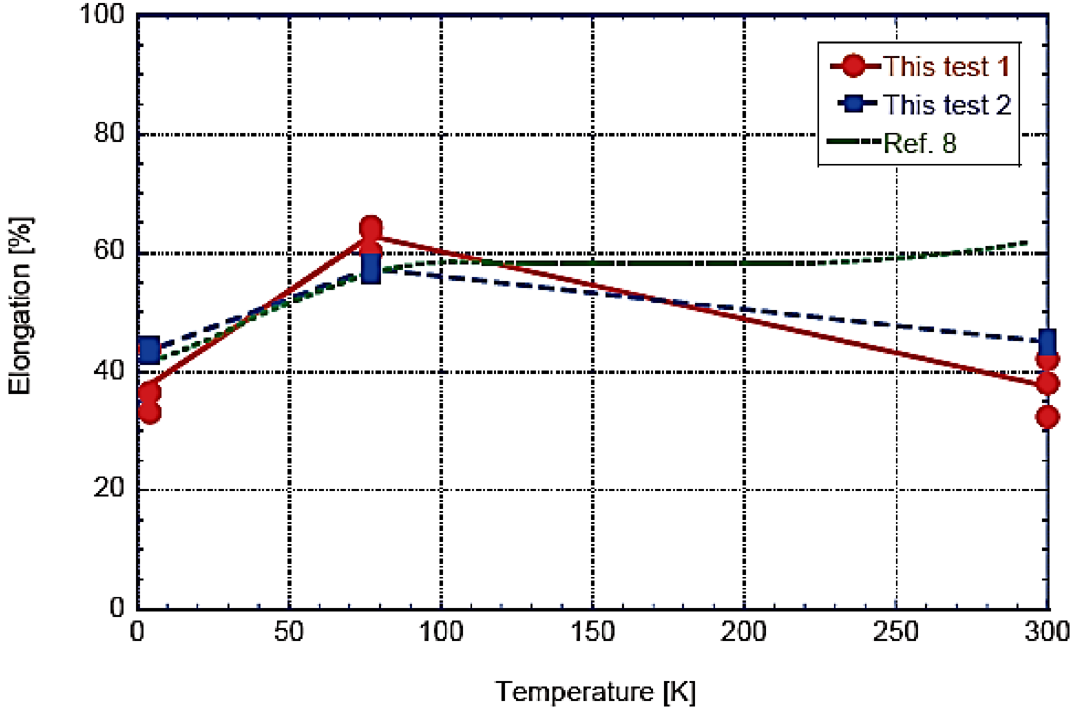
Cited from: H. Nakai et al., “Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules”, Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

Titanium Mechanical Properties

- Young’s modulus and elongation is maintained in operational range.



Young’s modulus w.r.t temperature

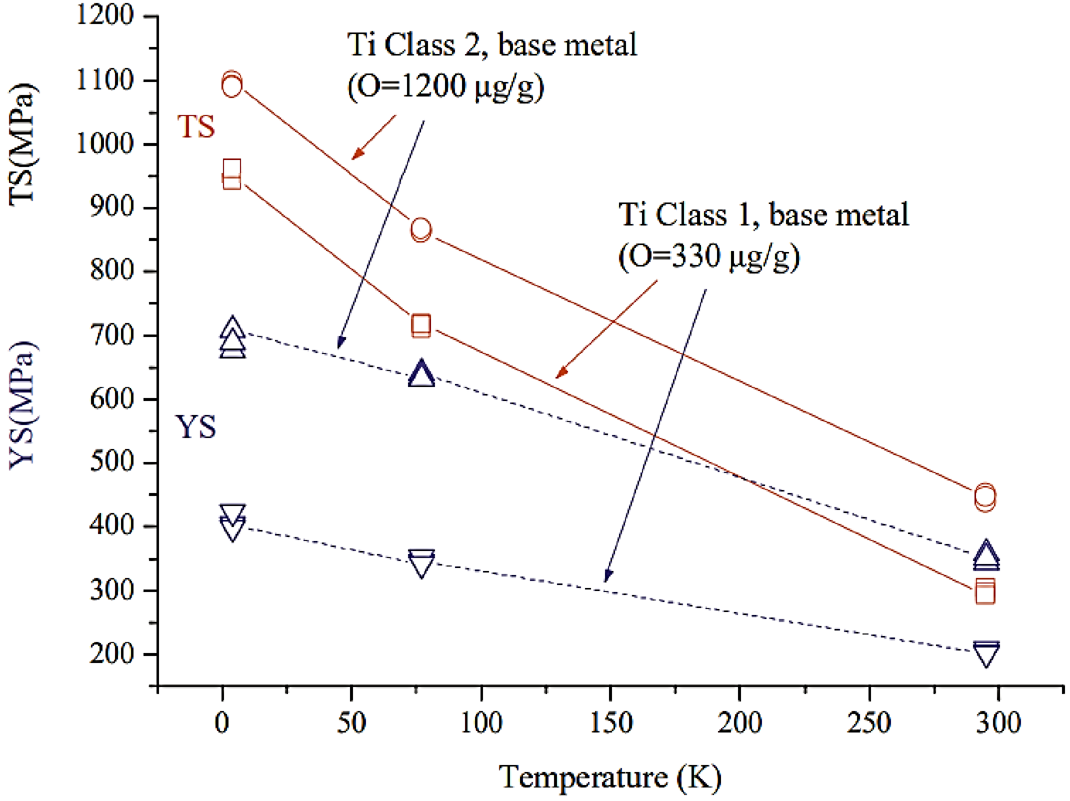


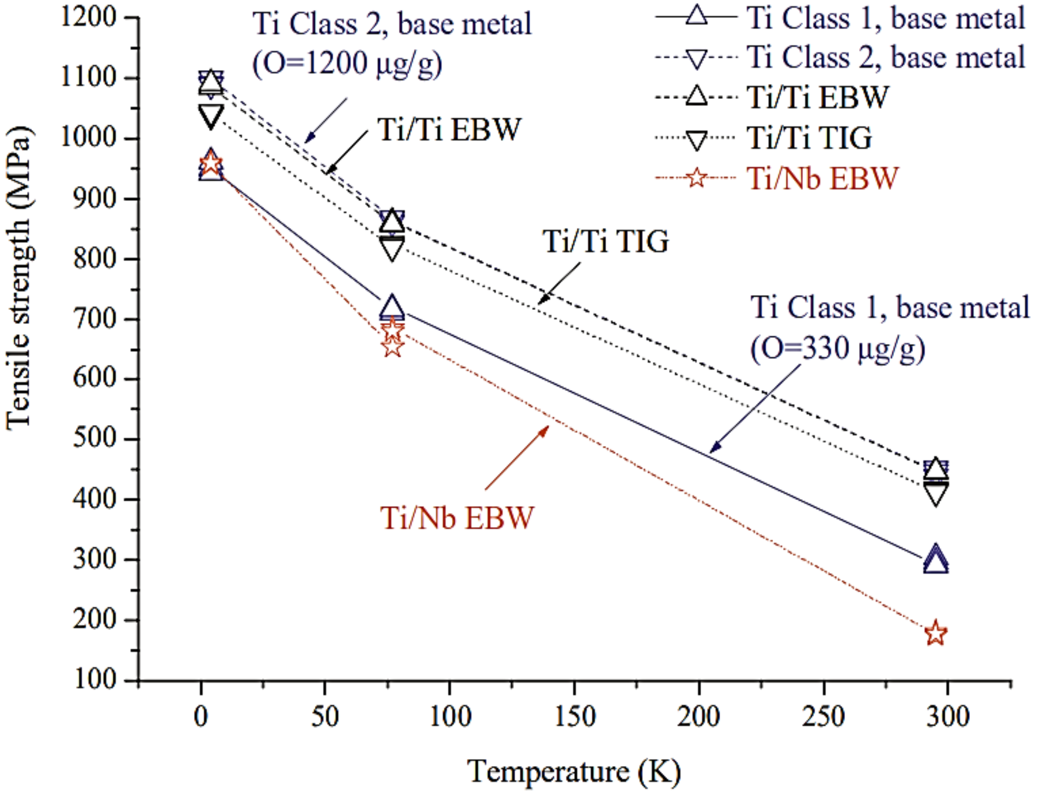
Elongation w.r.t temperature

Cited from: H. Nakai et al., “Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules”, Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

Ti Welded Joints Mechanical Strength

- Ti-Ti weld has similar properties to pure Ti.
- Ti-Nb EBW weld has sufficient strength for SRF cavity assembly.

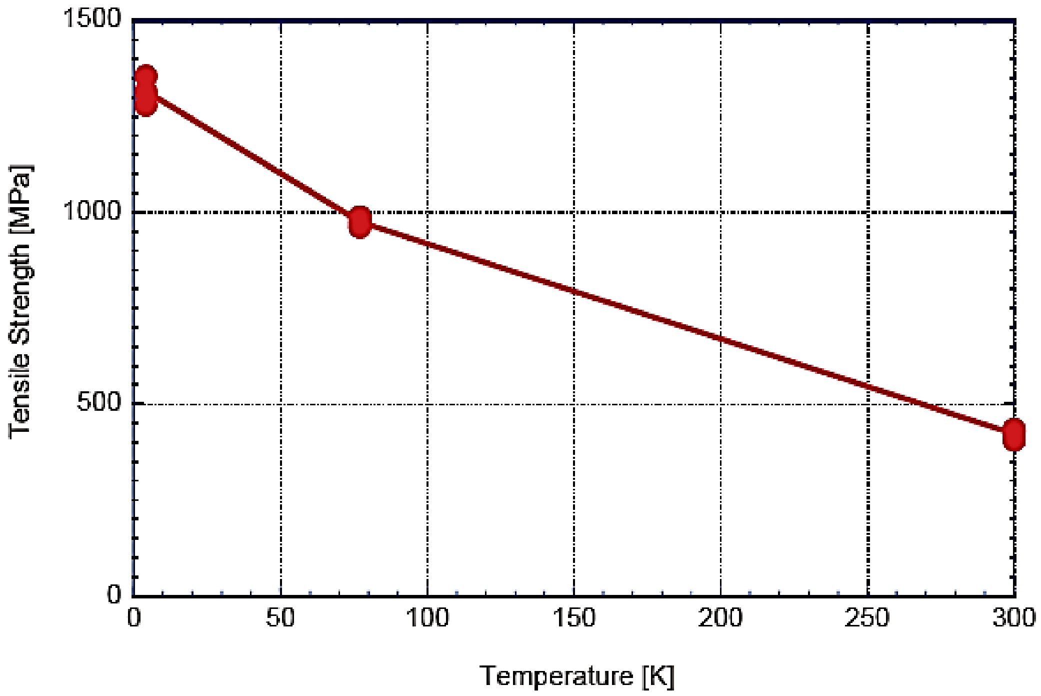




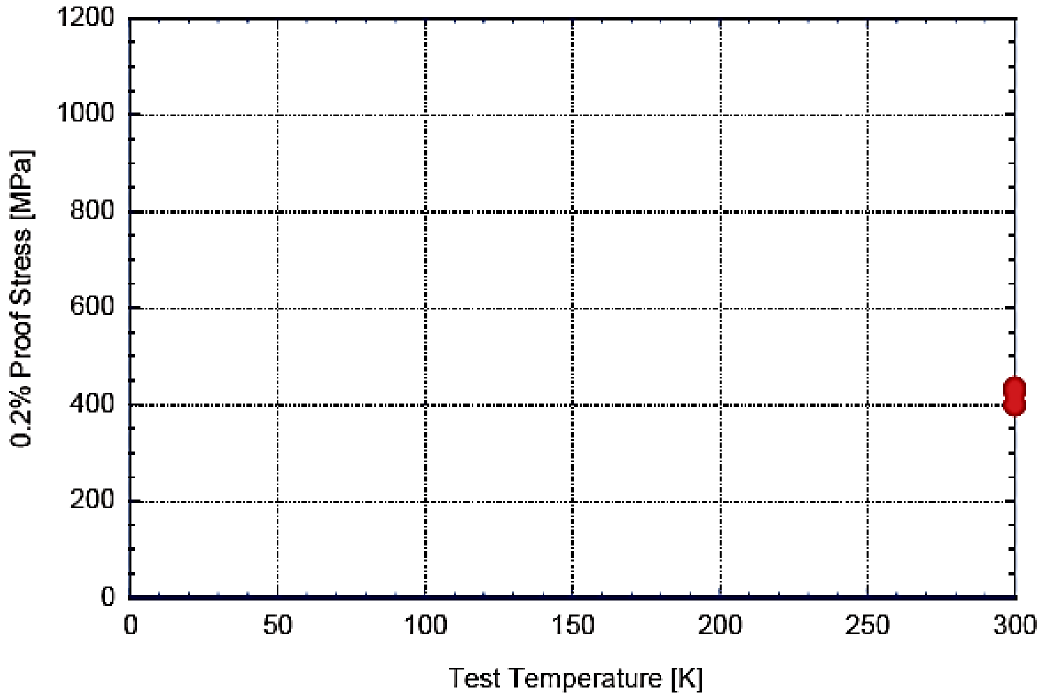
Cited from: K. Mukugi et al., “Low temperature mechanical properties of Titanium and weld joints (Ti/Ti, Ti/Nb) for helium vessels”, in Proc. The 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

NbTi Alloy Mechanical Strength

- Sufficient mechanical properties for pressure vessel design.



Tensile Strength w.r.t temperature

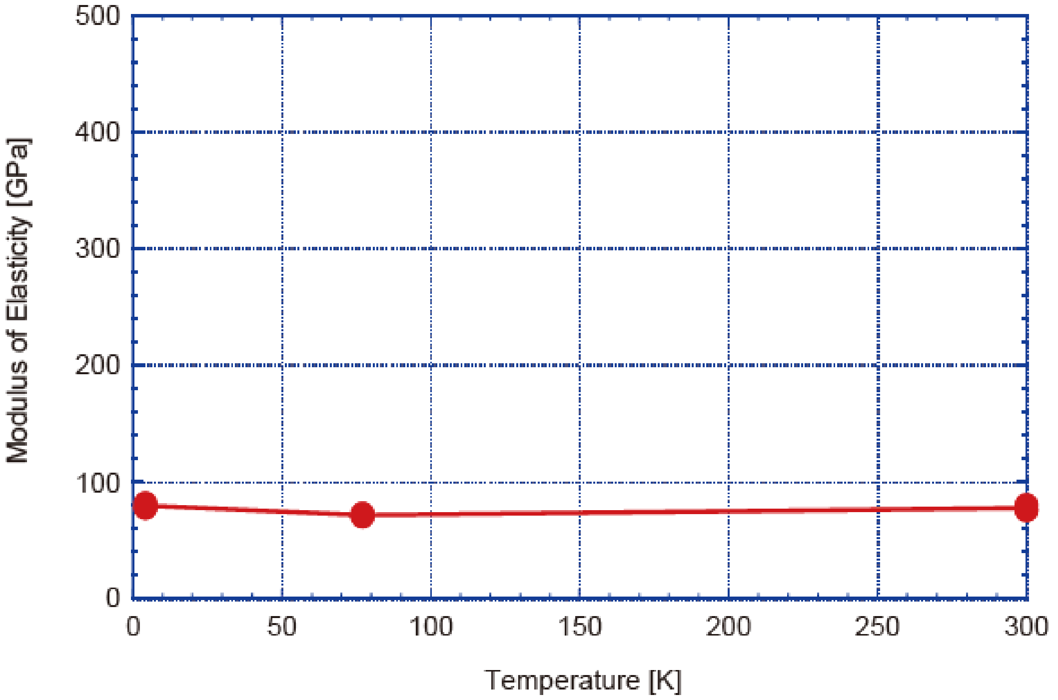


Yield strength w.r.t temperature

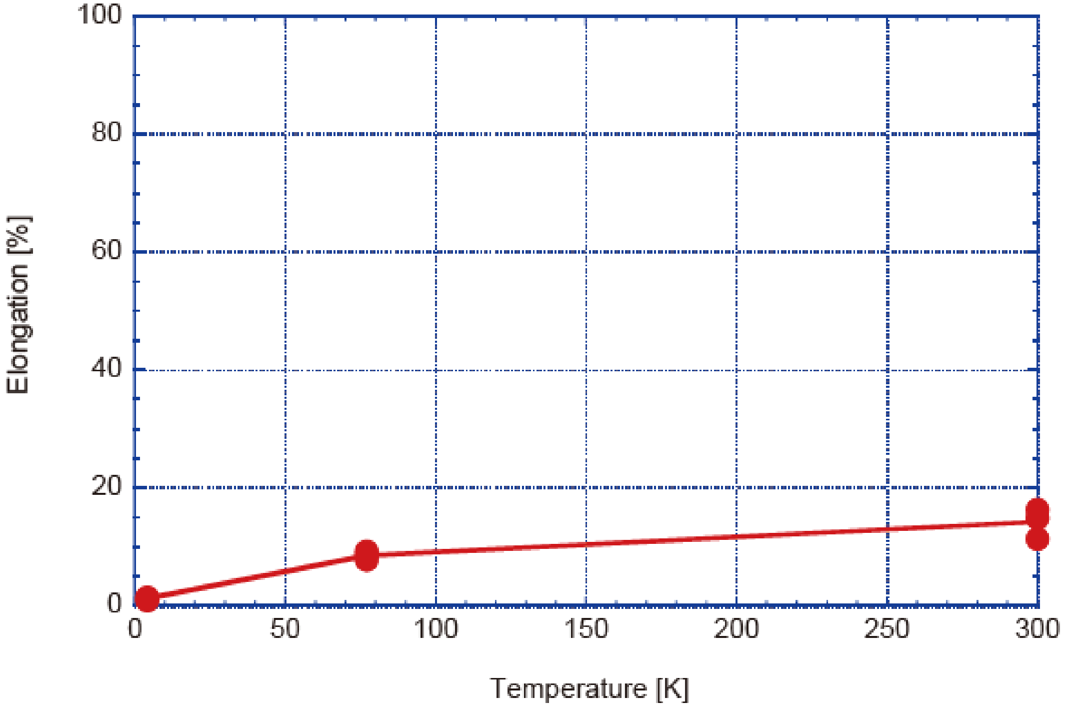
Cited from: H. Nakai et al., “Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules”, Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

NbTi Alloy Mechanical Strength

- Young's modulus is constant and elongation is reduced in operational range.



Young's modulus w.r.t temperature



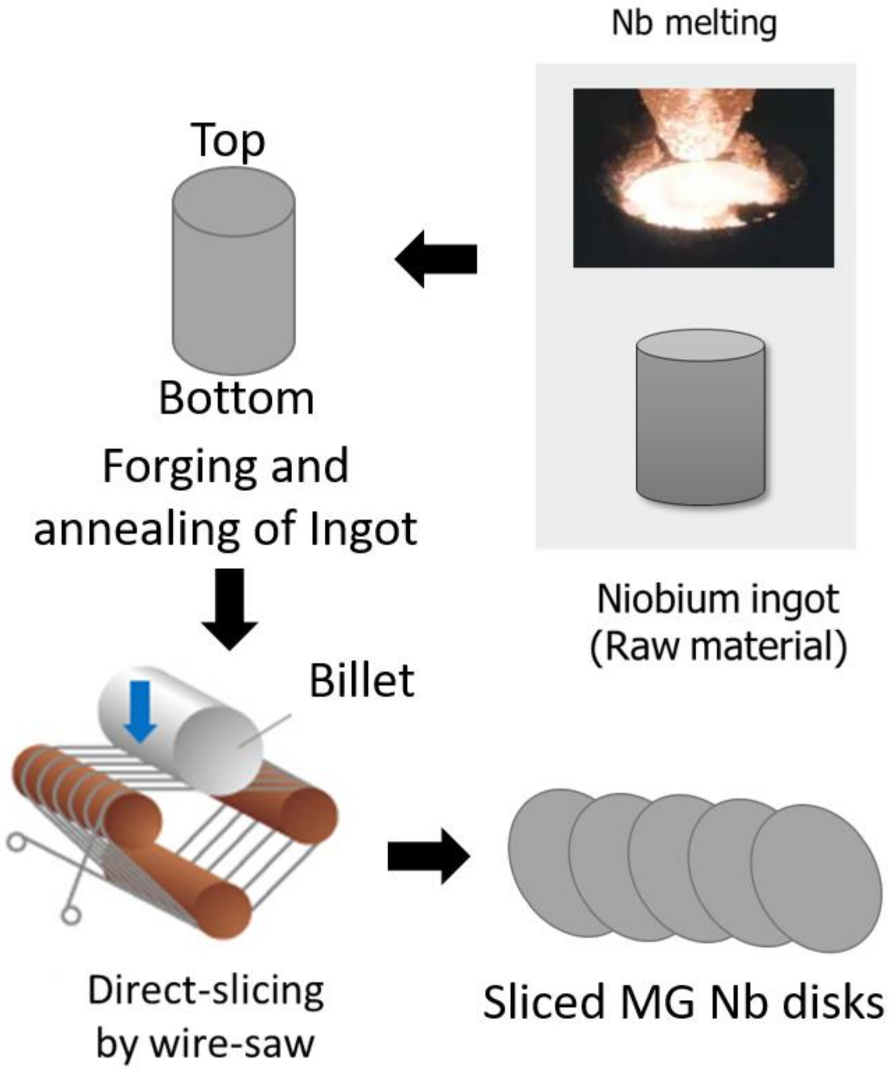
Elongation w.r.t temperature

Cited from: H. Nakai et al., "Tensile test of materials at low temperatures for ILC Superconducting RF cavities and cryomodules", Teion Kogaku (J. Cryo. Super. Soc. Japan) Vol. 48 No. 8 (2013)

Recent Developments in Niobium Material Technology

Medium Grain Niobium

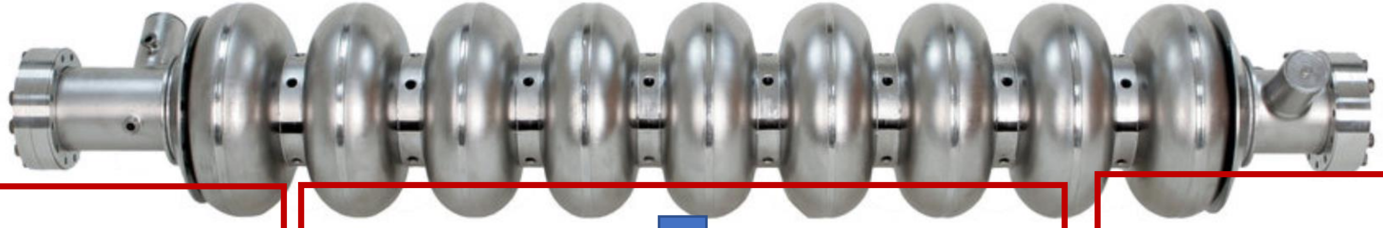
- New material manufactured by ATI (USA).
- It has an average grain size of 200-300 microns, with occasional 1-2 mm grains.
- It is expected to have similar properties as FG Nb.
- Cost effective material as it can be directly sliced after forging.
- Mechanical property characterization is being conducted at KEK.



Cited from: A. Kumar et al., MOPCAV004, SRF 21

Niobium for 9-Cell 1.3 GHz SRF Cavity

9-Cell 1.3 GHz
Nb SRF Cavity



Cited from: A. Kumar et al., MOPCAV004, SRF 21

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

Thank you for your attention!