Hands-on Training

(SRF Cavity)

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at Korea University, Korea
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Hands-on Training (SRF Cavity)

0. Introduction: Surface resistance

1. RRR (Residual Resistivity Ratio) measurement of Niobium, Copper and Aluminum samples (Resistivity by DC measurement)

2. Resonant Frequency and Quality Factor of Niobium and Copper Cavities at RT (Resistivity by RF measurement)

Surface Resistance

Comparison of surface resistance (R_s) between an NC cavity and an SC cavity

- **NC cavity:**
  - Conductivity/Resistivity $$\sigma = \frac{1}{\rho}$$
  - DC resistance $$R = \rho \frac{L}{S}$$
  - Skin depth $$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$ $\mu = 4\pi \times 10^{-7}$
  - RF surface resistance $$R_S = \sqrt{\frac{\omega \mu}{2 \sigma}} = \frac{1}{\sigma \delta}$$

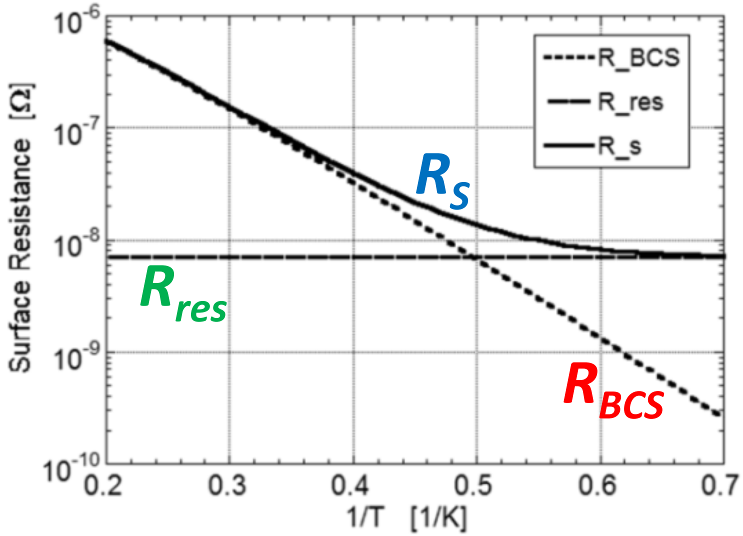
Surface Resistance

- **SC cavity:**

The surface resistance (***R_s***) of an SC cavity is expressed by the sum of a temperature-dependent term (**BCS resistance, *R_{BCS}***) and a temperature-independent term (**Residual surface resistance, *R_{res}***), as follows:

$$R_S = R_{BCS\,(T)} + R_{res}$$

$$R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B \cdot T}\right)$$



R_{BCS} : BCS resistance
R_{res} : Residual surface resistance
k_B : Boltzmann constant
Δ : Gap energy of Cooper pair

Temperature dependence of surface resistance:

$R_S = R_{BCS}(T) + R_{res}$

Surface Resistance

Normal-conducting Cavity ;

- *Surface resistance;* R_S $[\Omega]$

$$R_S = \sqrt{\frac{\omega\,\mu}{2\,\sigma}} = \frac{1}{\sigma\,\delta} \quad [\Omega]$$

f = 1.3 GHz, G = 270 Ω

Cu (20ºC) ; $\sigma = 0.58 \times 10^8$ [1/Ω m]

$R_S = 9.4$ mΩ, ($\delta = 1.8$ μm)

$Q = G / R_S = 2.9 \times 10^4$

Superconducting Cavity ;

- *Surface resistance;* R_S $[\Omega]$

$$R_S = R_{BCS\,(T)} + R_{res}$$

$$R_{BCS} = A\,\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B \cdot T}\right)$$

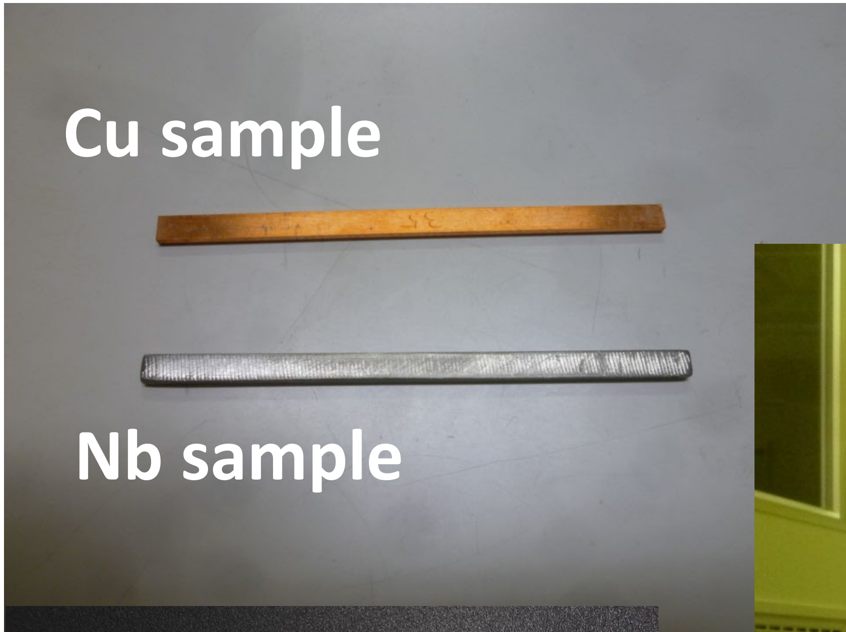
f = 1.3 GHz, G = 270 Ω

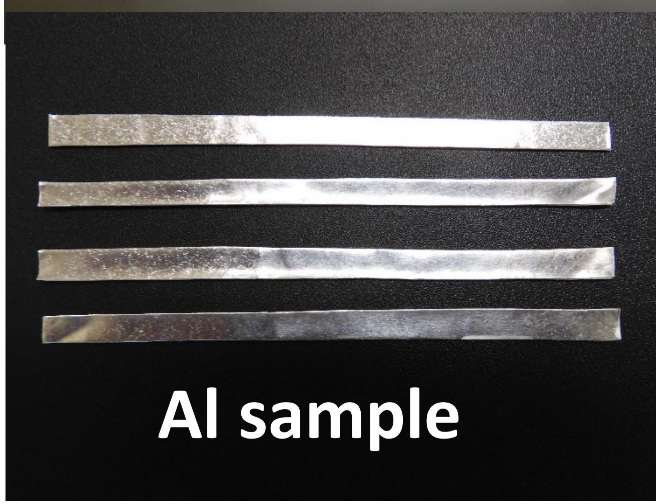
$R_S = 17$ nΩ, ($\lambda_0 = 44$ nm)

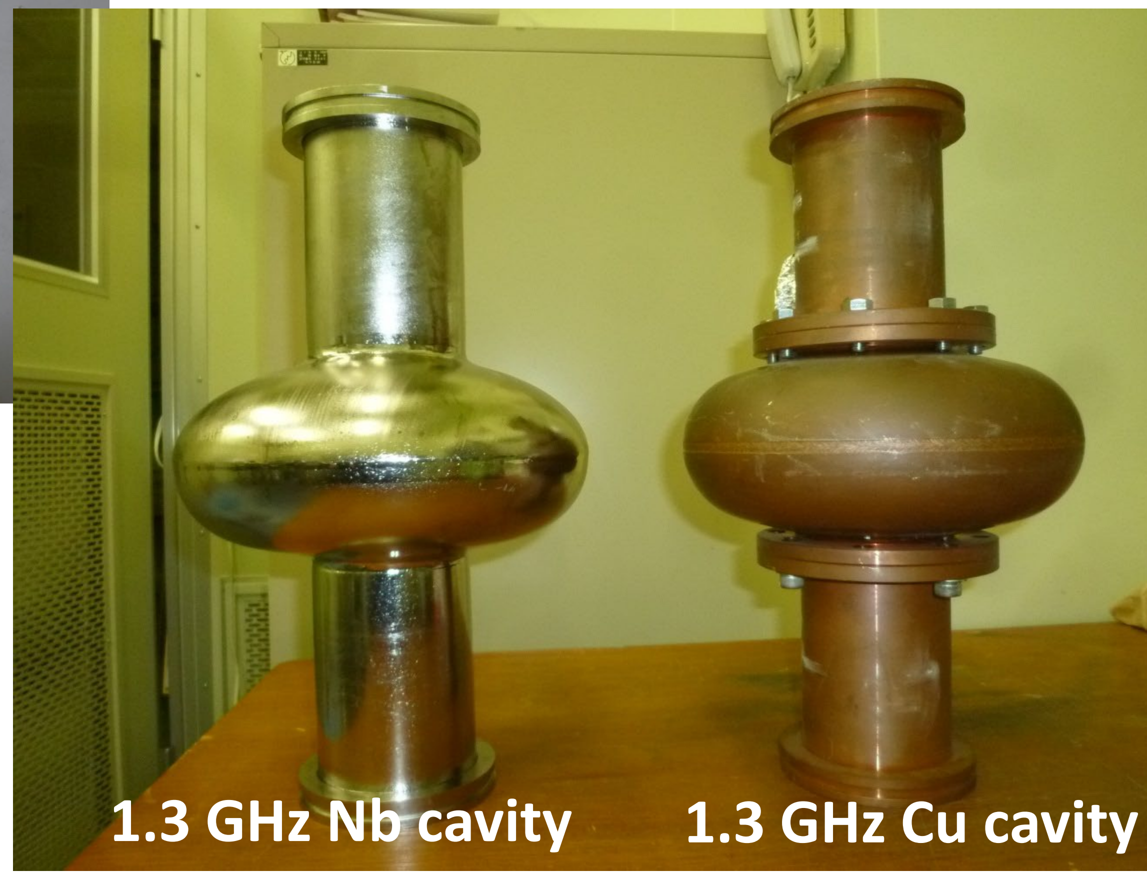
$Q = G / R_S = 1.6 \times 10^{10}$

R_{BCS} : *BCS resistance*
R_{res} : *Residual surface resistance*
k_B : *Boltzmann constant*
Δ : *Gap energy of Cooper pair*

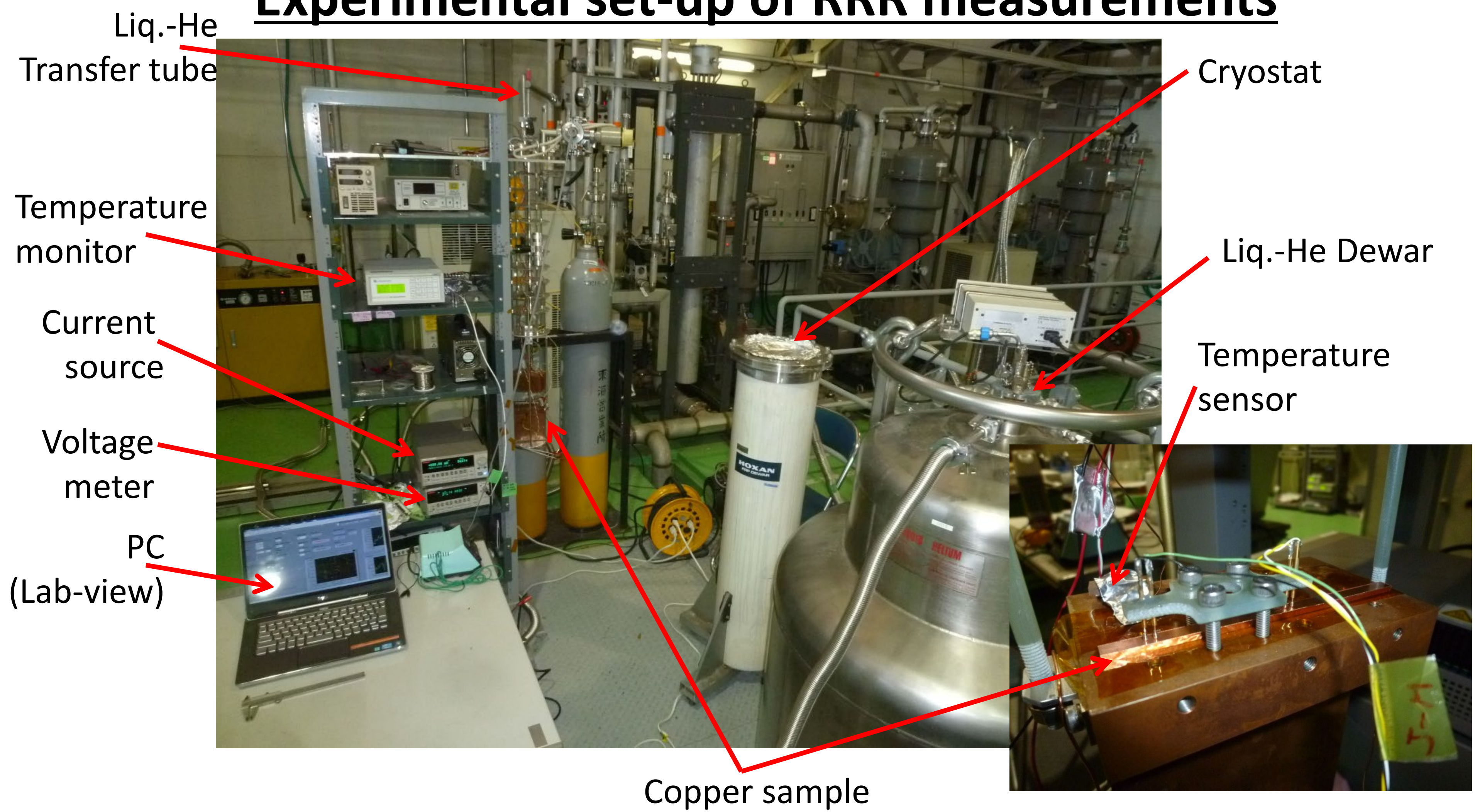
Superconducting RF (SRF) Cavity







Experimental set-up of RRR measurements



Material properties of Nb and Cu

Ohm's law : $V = I \cdot R$

Wiedemann-Franz's law :

$$\frac{\rho}{W\,T} = \frac{\kappa}{\sigma\,T} \equiv L$$

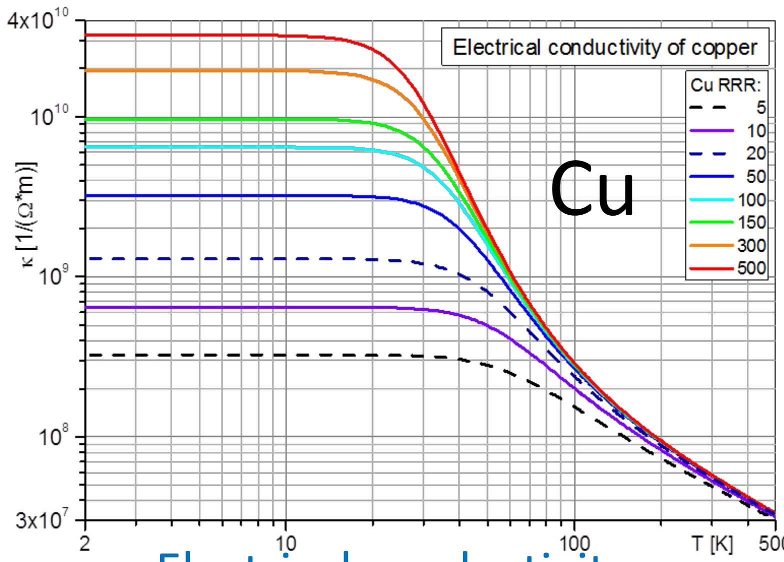
$$\kappa \propto \sigma = \frac{1}{\rho}$$

L : Lorenz constant = 2.45x10^{-8} WΩ/K^2
W : Thermal resistivity
κ : Thermal conductivity
ρ : Electrical resistivity
σ : Electrical conductivity
T : Temperature
α : constant = 6.8x10^{-8}
β : constant = 0.53

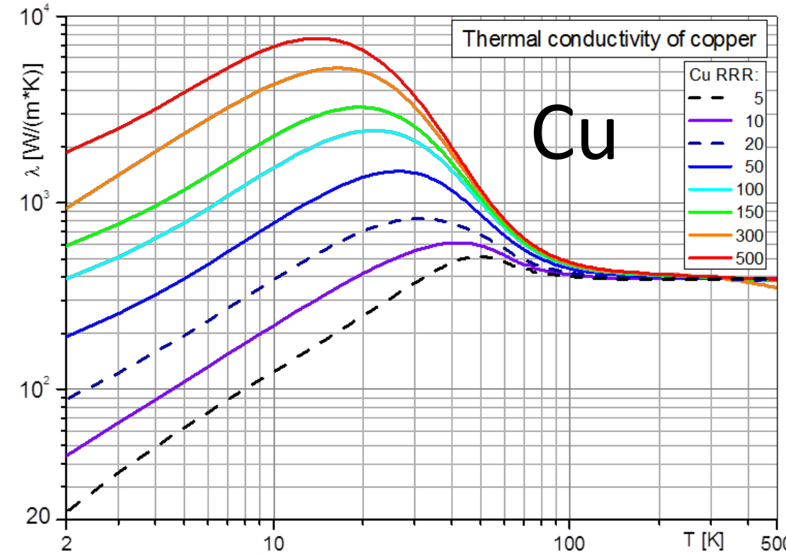
Copper at low temperature (LT): $$\kappa = \frac{1}{\alpha T^{2.4} + \beta / (RRR \cdot T)}$$

Residual Resistance Ratio: $$RRR = \frac{\rho(300\mathrm{K})}{\rho(\mathrm{LT})}$$

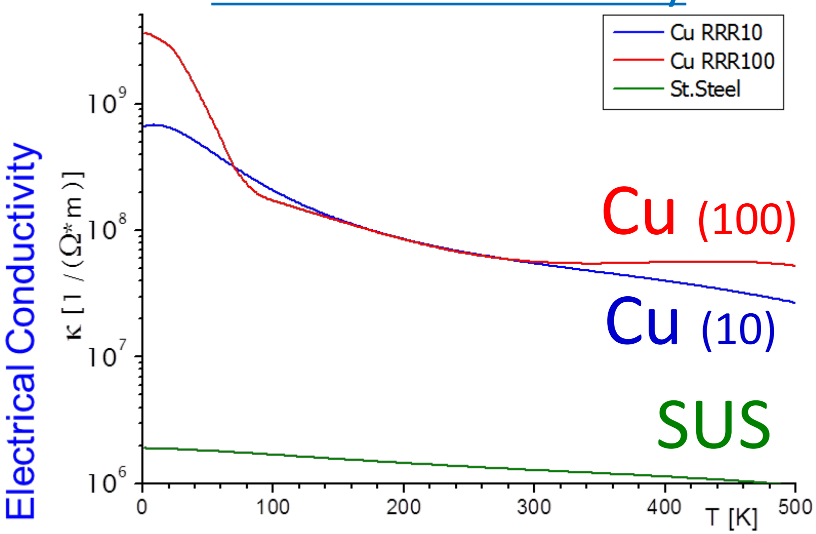
Material properties of Copper

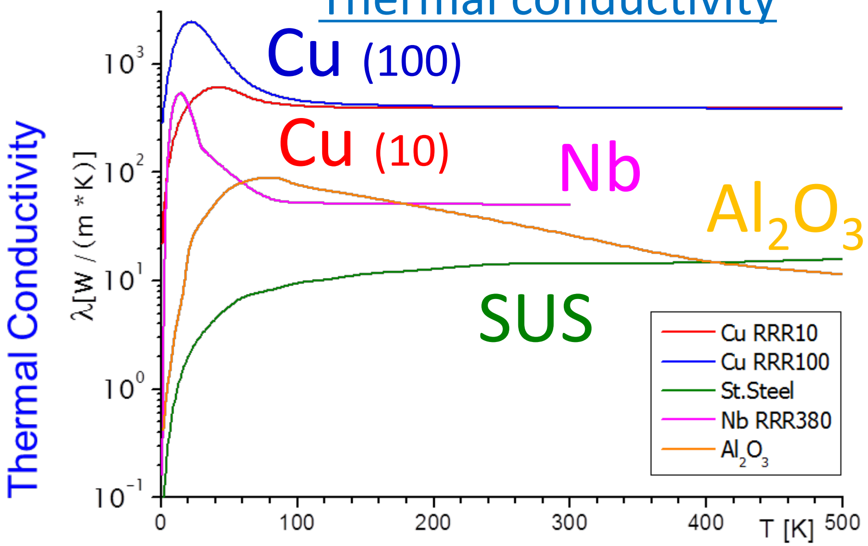


Electrical conductivity



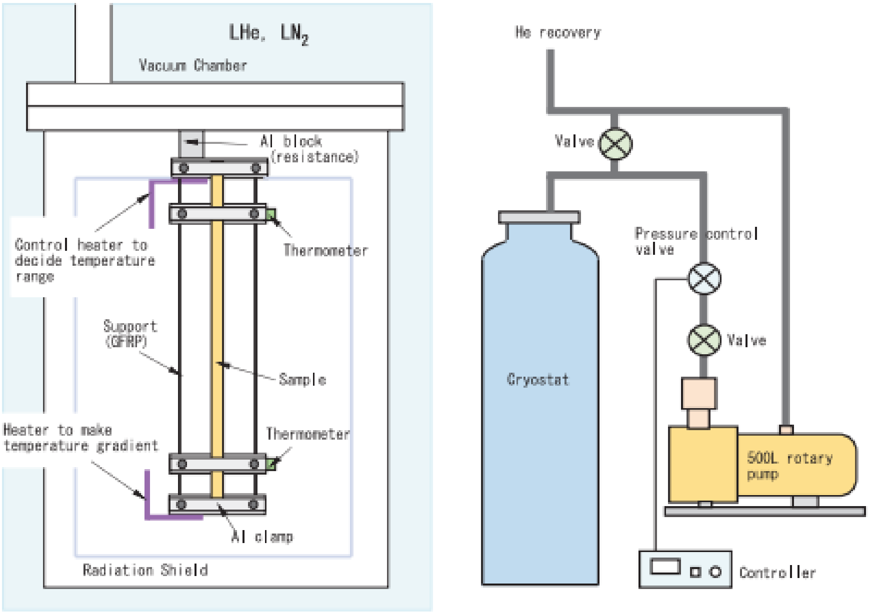
Thermal conductivity





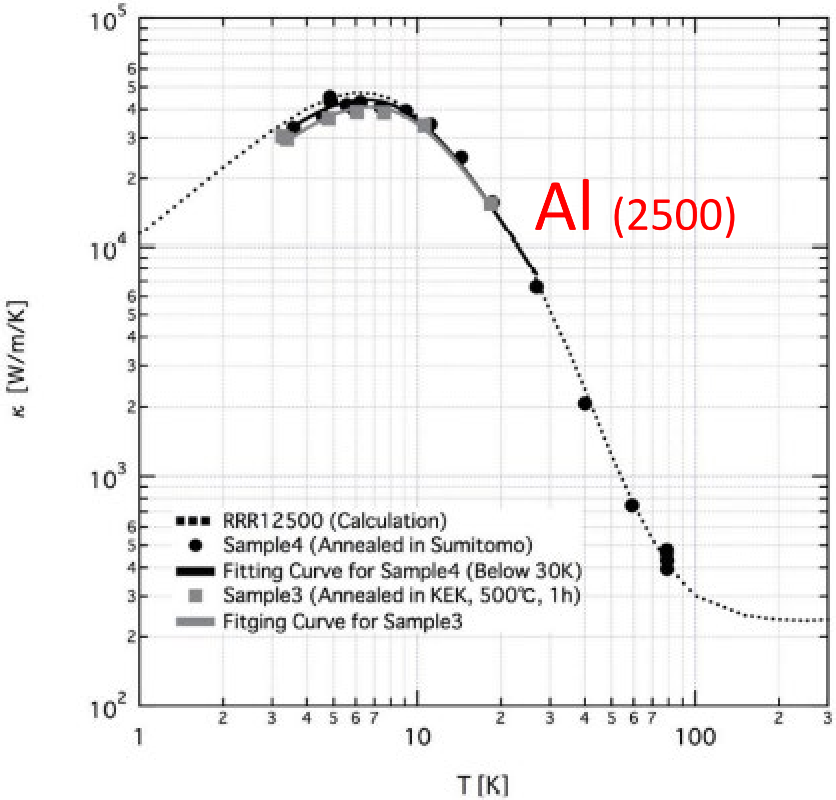
Material properties of Aluminum

	6N Al	5N Al
RRR (as growth)	2,700	1,200
RRR (annealed)	9,000-13,000 (12,000)	2,600



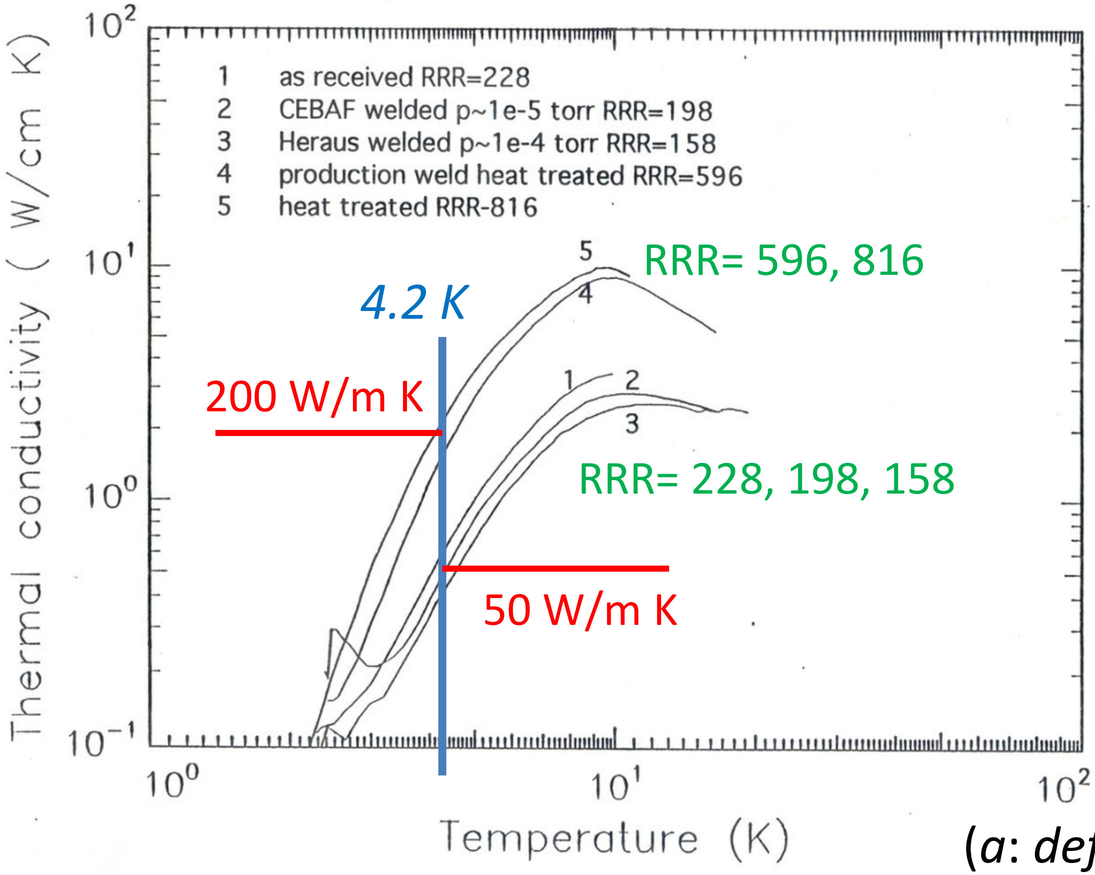
Experimental set-up for thermal conductivity

Thermal conductivity of high purity Aluminum



Material properties of Niobium

Thermal conductivity of Nb; (κ)



RRR : Residual Resistance Ratio

$$RRR = \frac{\rho(300\mathrm{K})}{\rho(9.2\mathrm{K})}$$

κ : Thermal Conductivity of Nb

$$\kappa_{(4.2K)} \approx RRR/4 \quad [W/m \cdot K]$$

H_{quench} : Quench field

$$H_{quech} = \sqrt{\frac{4\,\kappa\,(T_c - T_{He})}{a\,R_{defect}}}$$

(a: defect size, R_{defect}: resistance of defect)

High purity → High thermal conductivity → Increase of quench field

Material properties of Niobium

Material certification of Nb: (Mill sheet)

No. 28378

Surveyor 御立会者 殿

Date 日付 平成25年3月4日

TOKYO DENKAI CO., LTD. 東京電解株式会社

Material 材質	Article 品名	Specification No. 仕様書番号	Lot No.	Size 寸法 mm	Quantity 数量 pcs or gr
Nb	Disc		4378	2.8t×258φ−56φ	58 pcs

Mechanical property

Mechanical properties 機械的特性		T.S 引張強さ N/mm^2	Y.S 耐力 N/mm^2	Elongation 伸び %	Hardness かたさ Hv
Spec 規格	min	120	39	35	---
	max				
Test Results 試験結果	Longitudinal	162	47	56	50.8
	Transverse	171	51	54	

Chemical Composition

Lot No.	Element 成分 Chemical Composition (in Wt%) 化学成分	Ta	W	Ti	Fe	Si	Mo	Ni	Zr	Nb
	Spec 規格 min									---
	Spec 規格 max	0.15	0.02	0.005	0.005	0.005	0.005	0.005	0.01	
4378	Test Results 試験結果	0.0115	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	balance

Ta W

Element 成分 Chemical Composition (in Wt%) 化学成分	O	N	H	C
Spec 規格 min				
Spec 規格 max	0.015	0.01	0.002	0.01
Test Results 試験結果	<0.001	<0.001	<0.0005	<0.001

O N H C

$$\frac{1}{RRR} = \frac{O}{5800} + \frac{N}{2273} + \frac{H}{16322} + \frac{C}{8911} + \frac{Ta}{604690} + \frac{1}{1249}$$

Remarks 備考
Starting Ingot Lot No. NC−1830
RRR Value of Sheet: 298
Grain size ASTM #6

Purity, Thermal property

RRR = 298

Inspection Section Manager

Engineer

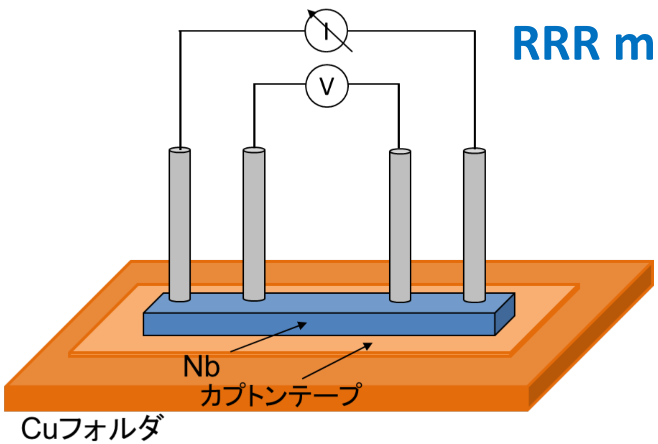
ULTRA HIGH PURITY RARE METAL TOKYO DENKAI

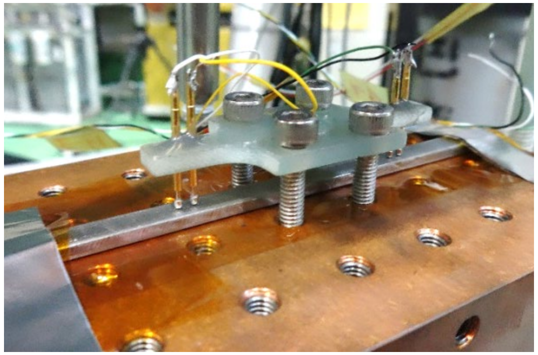
T.S.=Tensile Strength Y.S.=Yield Strength E.V.=Erichsen Value

[by H. Umezawa (Tokyo Denkai)]

Material properties of Niobium

RRR measurement system





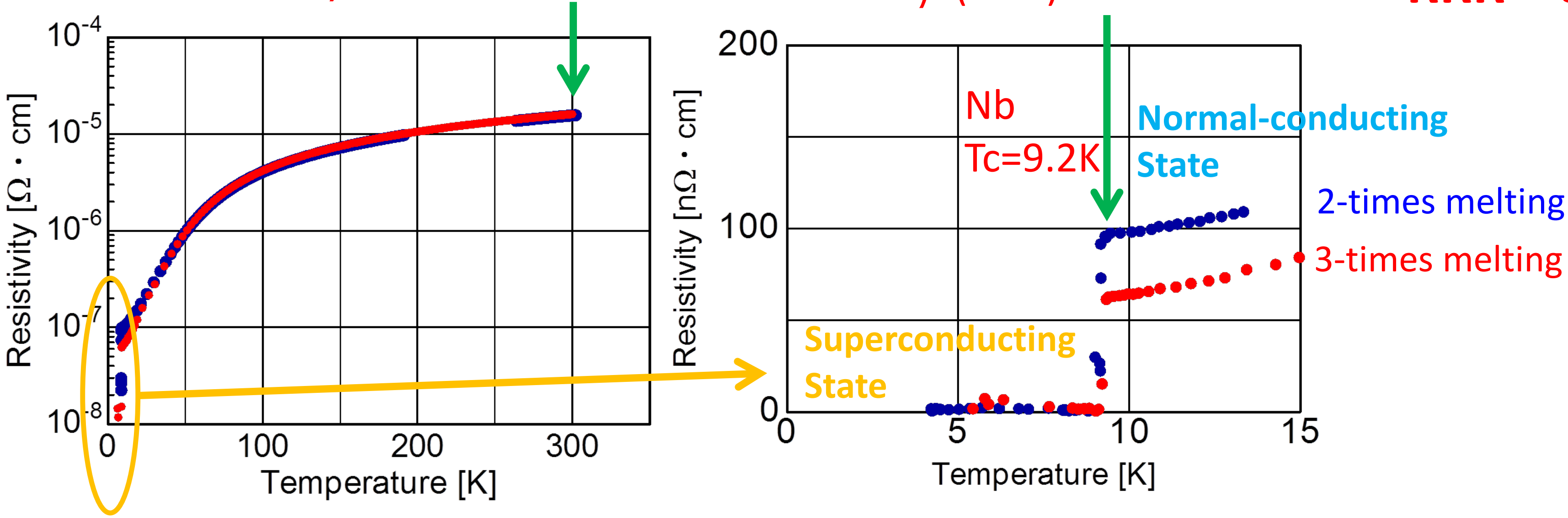
Residual Resistance Ratio

$$RRR = \frac{\rho(300\mathrm{K})}{\rho(9.2\mathrm{K})}$$

ρ (300K) = 2x10^{-5} Ω cm
ρ (300K) = 2x10^{-5} Ω cm

ρ (9.2K) = 1x10^{-7} Ω cm
ρ (9.2K) = 6x10^{-8} Ω cm

RRR = 200
RRR = 330

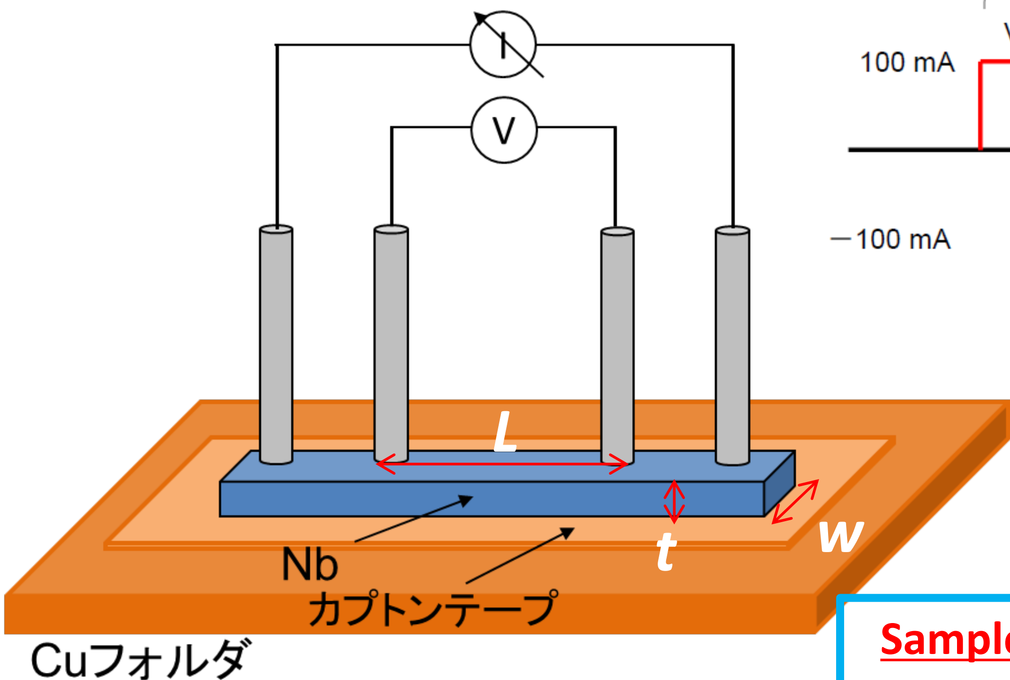


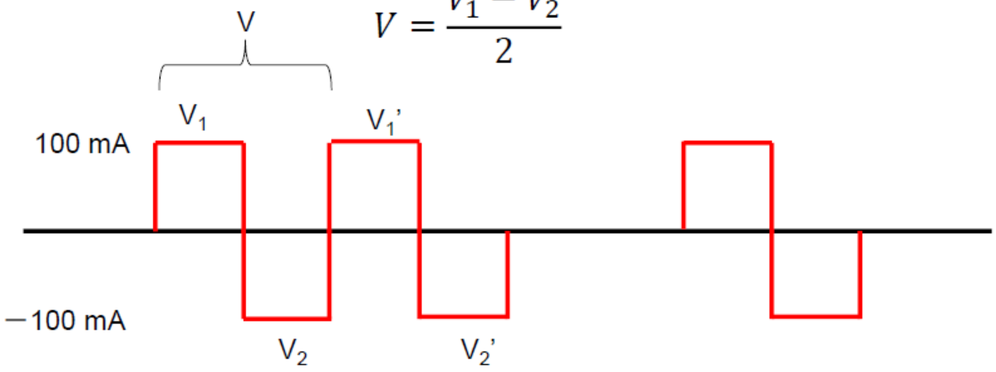
Material properties of Niobium

Constant Current:
+100 mA / -100 mA

Averaging: 10 times

$$V = \frac{V_1 - V_2}{2}$$



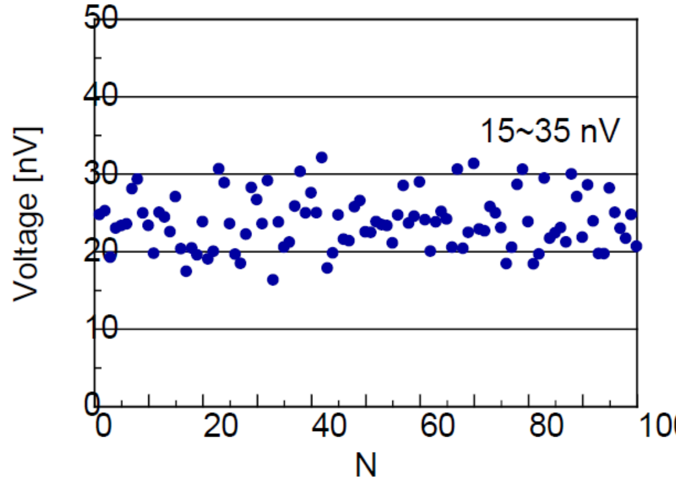


Sample size

L = m

w = m

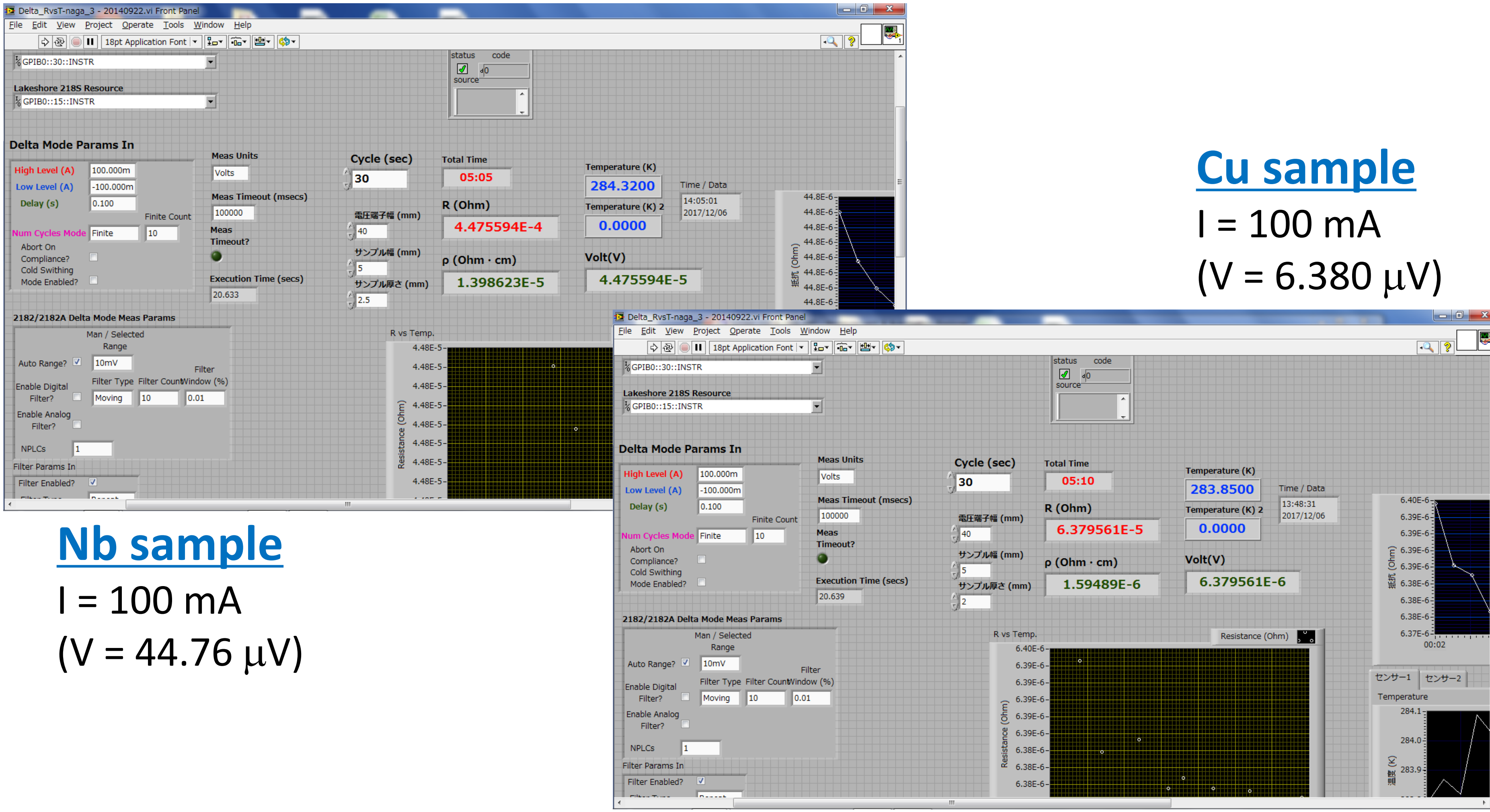
t = m



Background noise level

Examples

Examples of experimental results of RRR measurements



Cu sample

I = 100 mA

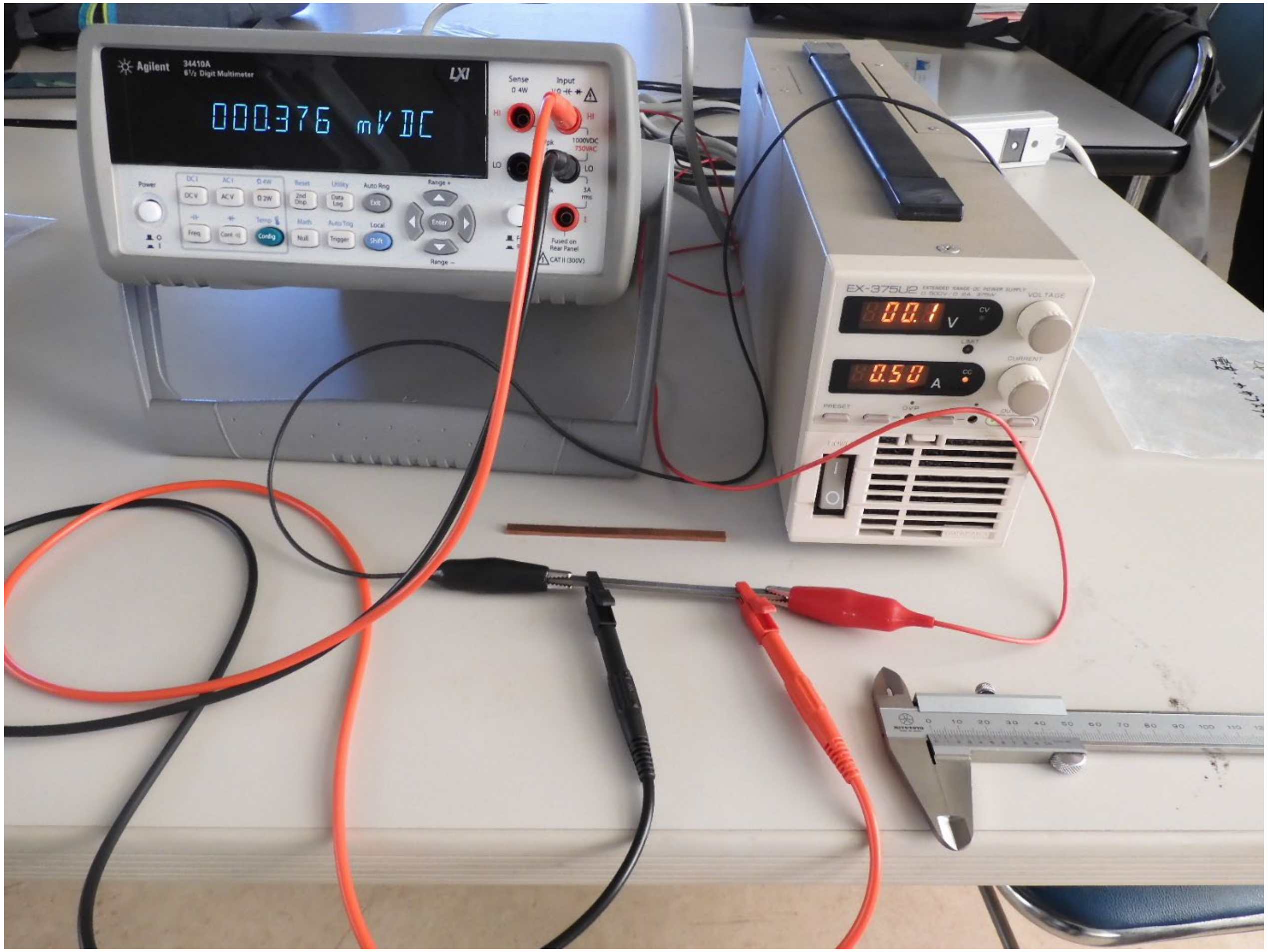
(V = 6.380 μV)

Nb sample

I = 100 mA

(V = 44.76 μV)

Experimental set-up: DC measurement



Measuring instruments : current source x 2
digital volt-meter x 2, vernier caliper x 2

Exercise (1)

Please measure and calculate following parameters at RT;

Cu sample at RT

I = A
V = V
R = Ω

L = m
W = m
t = m
S = m^2

ρ = Ω m

Frequency = 1300 MHz
Rs = Ω

G = 270 Ω
Q =

Nb sample at RT

I = A
V = V
R = Ω

L = m
W = m
t = m
S = m^2

ρ = Ω m

Frequency = 1300 MHz
Rs = Ω

G = 270 Ω
Q =

Al sample at RT

I = A
V = V
R = Ω

L = m
W = m
t = m
S = m^2

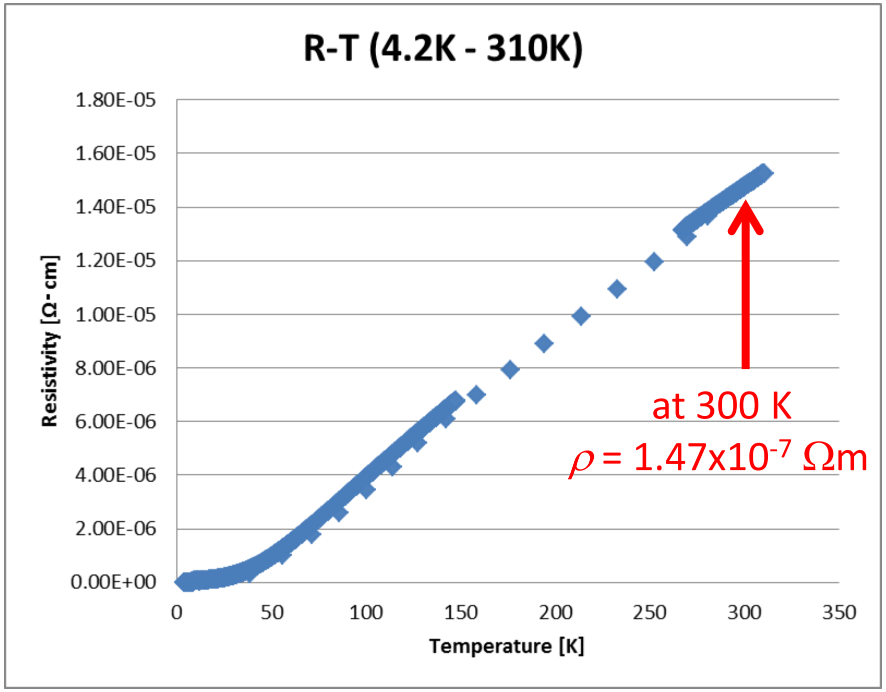
ρ = Ω m

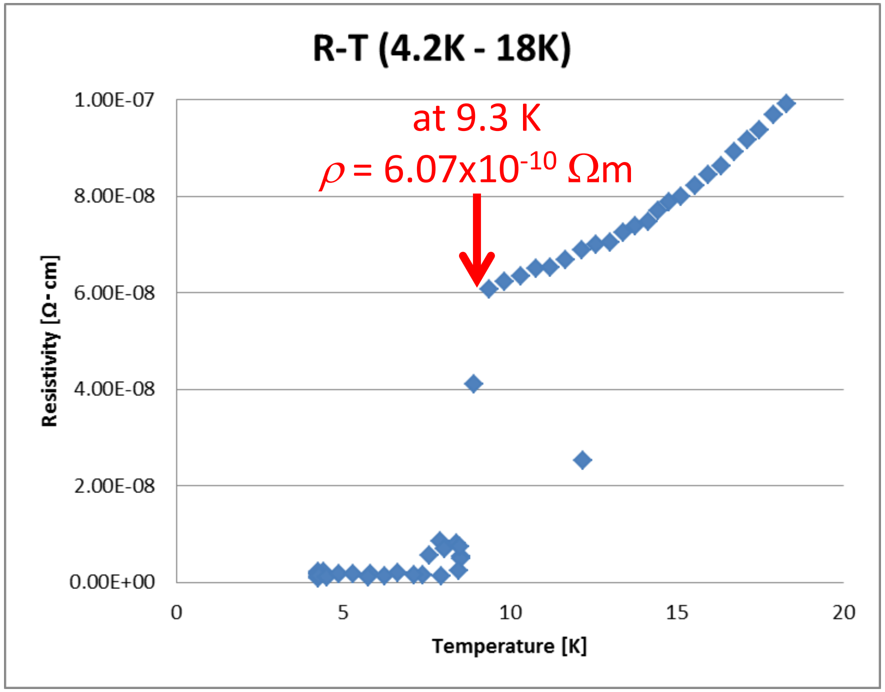
Frequency = 1300 MHz
Rs = Ω

G = 270 Ω
Q =

Exercise (2)

Please calculate the RRR value of Nb sample from the results of following temperature dependence of the resistivity;

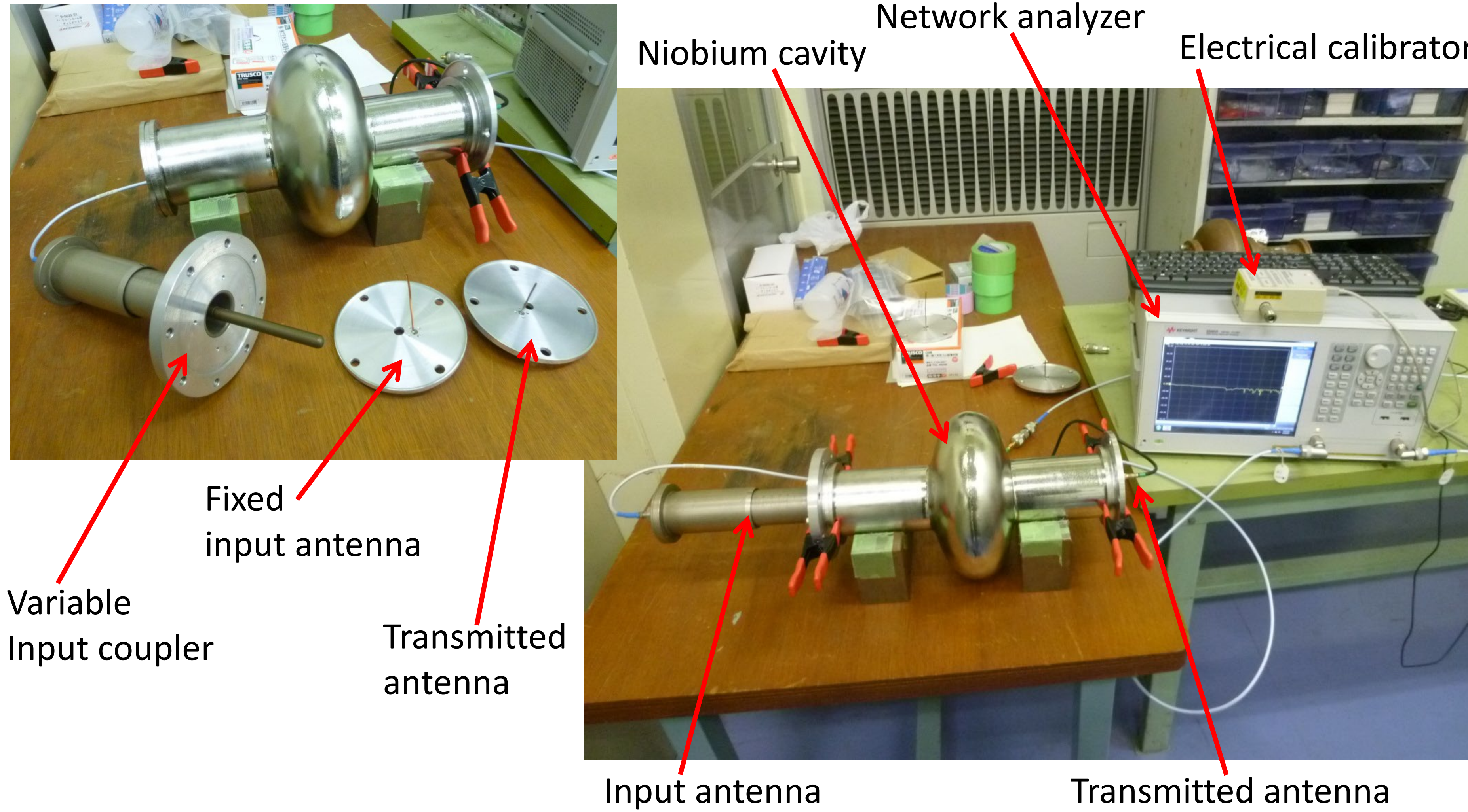




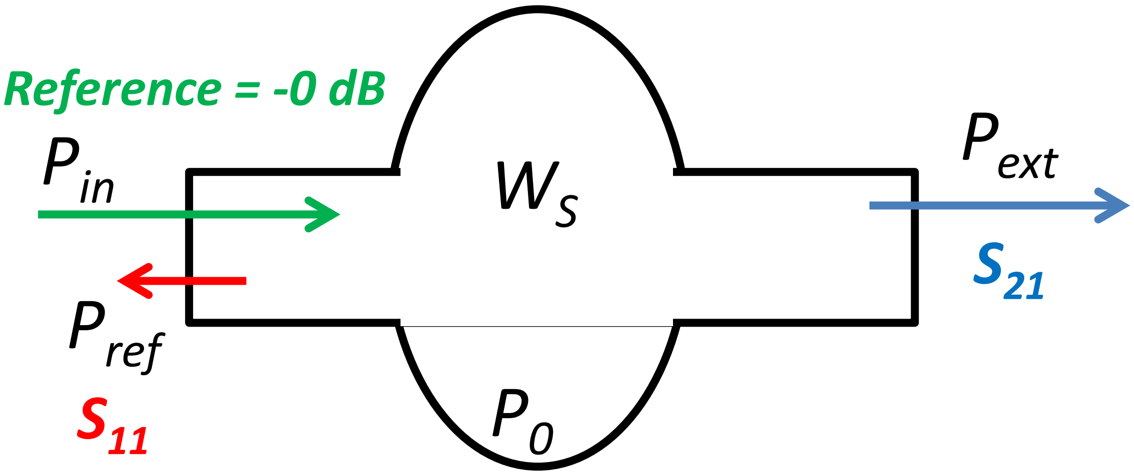
RRR = _____

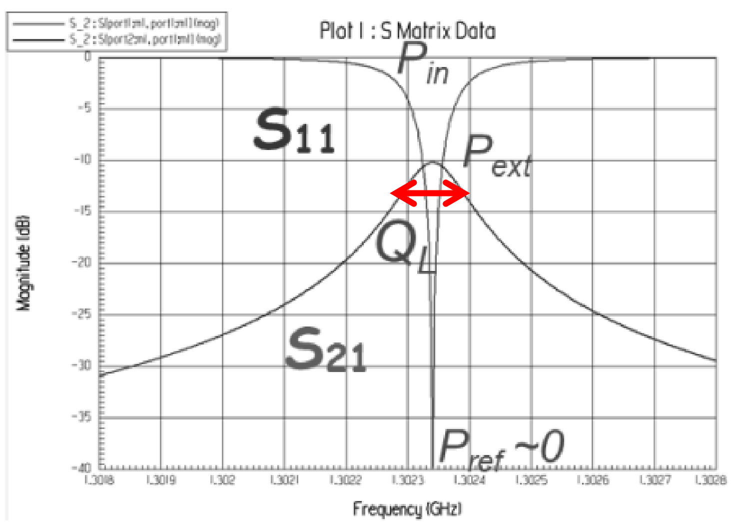
RF measurement of NC cavity

Experimental set-up of RF measurements



RF measurement of NC cavity





T

- Cavity stored energy

$$W_S = \frac{\mu_0}{2}\int^V \left|\vec{H}\right|^2 dV = \frac{\varepsilon_0}{2}\int^V \left|\vec{E}\right|^2 dV$$

- Cavity RF loss

$$P_o = P_{in} - P_{ref} - P_{ext}$$

- Loaded Q Q_L

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{in}} + \frac{1}{Q_{ext}}$$

- Coupling constant (over/under coupling)

$$\beta^* = \frac{1 \pm \sqrt{P_{ref}/P_{in}}}{1 \mp \sqrt{P_{ref}/P_{in}}}$$

$$P_{ref} = 10^{\frac{S_{11}}{10}} \cdot P_{in}\ [W]$$

- Q_L is measured by bandwidth of -3dB.

RF measurement of NC cavity

- Input coupling $$\beta_{in} = \beta^* \cdot (1 + \beta_{ext})$$
- Monitor coupling $$\beta_{ext} = P_{ext} / P_o$$
- Unloaded Q of cavity $$Q_o = Q_L \cdot (1 + \beta_{in} + \beta_{ext})$$
- External Q (calibration) $$Q_{ext} = P_o \cdot Q_o / P_{ext}$$
- Accelerating gradient $$E_{acc} = \frac{\sqrt{R/Q}}{L_{cavity}} \sqrt{P_0 \, Q_0} = Z \sqrt{P_{ext} \, Q_{ext}}$$

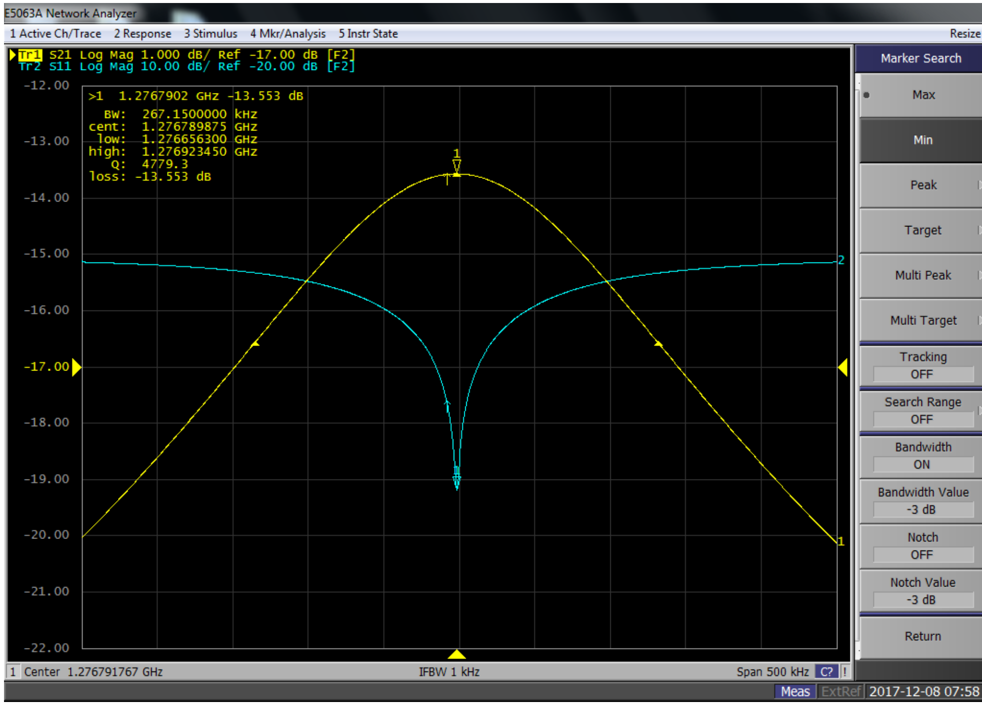
- **Geometrical factor *G* [W]:**

$$G = \omega_0 \mu_0 \frac{\int^V \left| \vec{H} \right|^2 dV}{\int^A \left| \vec{H} \right|^2 dA}$$

- **Quality factor Q_0:**

$$Q_0 = \frac{\omega_0 W_S}{P_d} = \frac{G}{R_S}$$

Examples of experimental results of RF measurements



Cu cavity

Frequency = 1295.1 MHz

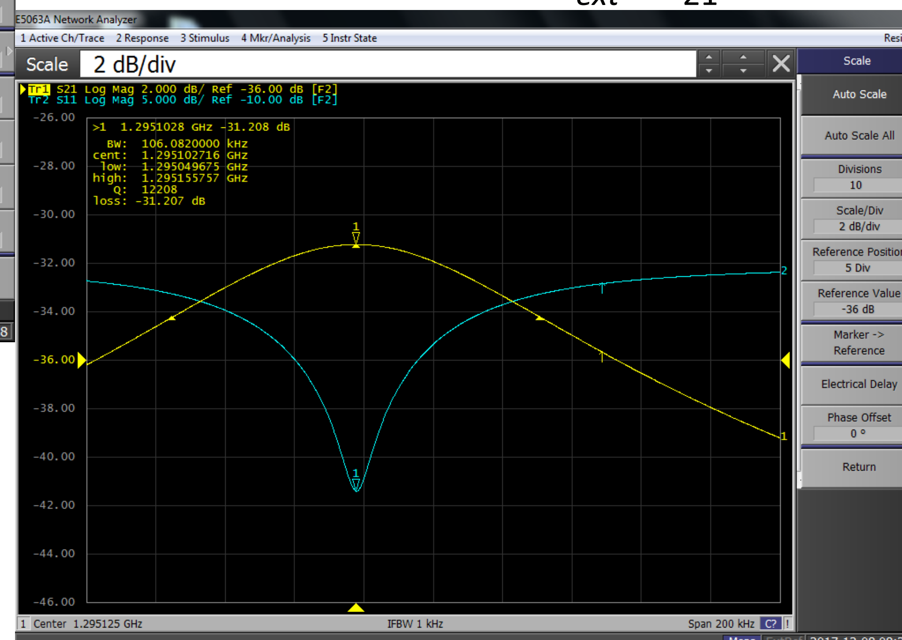
Loaded Q = 12209.

Fixed input coupling

P_{in} : - 0 dB

P_{ref} : S_{11} = dB

P_{ext} : S_{21} = dB



Nb cavity

Frequency = 1276.8 MHz

Loaded Q = 4779.

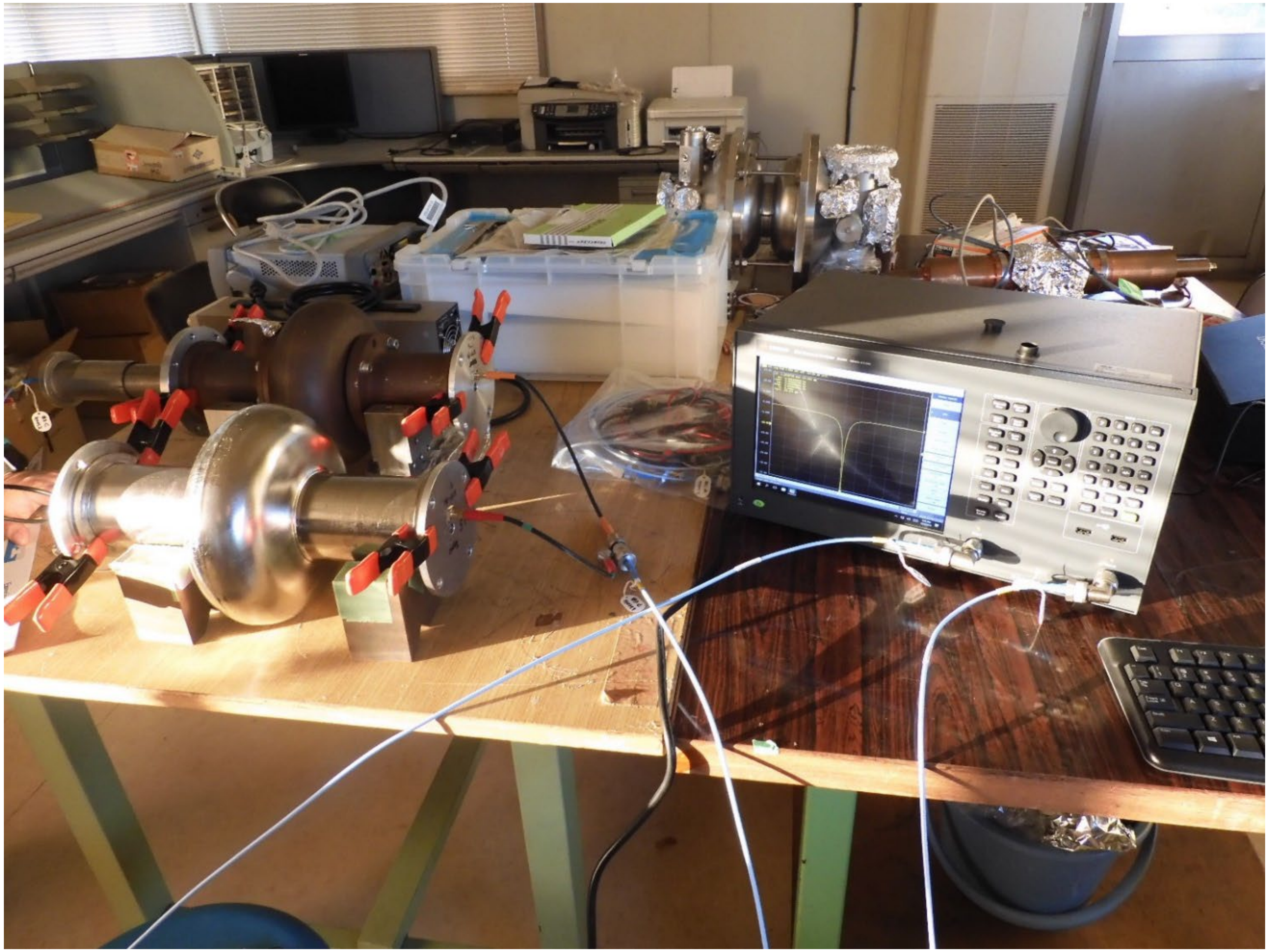
Variable input coupling

P_{in} : - 0 dB

P_{ref} : S_{11} = dB

P_{ext} : S_{21} = dB

Experimental set-up: RF measurement



Measuring instruments : network analyzer x 2
electrical calibrator x 2

Exercise (3)

Please measure and calculate following parameters;

Cu cavity

Frequency = MHz

Loaded Q_L =

P_{ref} : S_{11} = dB

P_{ext} : S_{21} = dB

Q_0 =

Q_{in} =

Q_{ext} =

β_{in} =

Z = 91. P_{in} = 1.0 W

E_{acc} = V/m

G = 270 Ω

R_S = Ω

ρ = Ω m

Nb cavity

Frequency = MHz

Loaded Q_L =

P_{ref} : S_{11} = dB

P_{ext} : S_{21} = dB

Q_0 =

Q_{in} =

Q_{ext} =

β_{in} =

Z = 91. P_{in} = 1.0 W

E_{acc} = V/m

G = 270 Ω

R_S = Ω

ρ = Ω m

$$P_{ref} = 10^{\frac{S_{11}}{10}} \cdot P_{in} \; [W]$$

$$P_{ext} = 10^{\frac{S_{21}}{10}} \cdot P_{in} \; [W]$$

Exercise (4)

Please compare following parameters measured by DC and RF;

Frequency = 1300 MHz
G = 270 Ω

Copper

DC:

Q_0 =
R_S = Ω
ρ = Ω m

RF:

Q_0 =
R_S = Ω
ρ = Ω m

Niobium

DC:

Q_0 =
R_S = Ω
ρ = Ω m

RF:

Q_0 =
R_S = Ω
ρ = Ω m

Superconducting RF (SRF) Cavity

Thank you for your efforts.

Superconducting RF (SRF) Cavity