



Hands-on Training (SC Cavity)

Eiji KAKO (KEK, Japan)

Asian School on
Superconductivity and Cryogenics for Accelerators
at KEK, Japan
2017, Dec. 11-16





Superconducting RF (SRF) Cavity

School Time Table (as of Nov. 13, 2017)

Time	Dec. 10, 2017 Sunday	Dec. 11, 2017 Monday	Dec. 12, 2017 Tuesday	Dec. 13, 2017 Wednesday	Dec. 14, 2017 Thursday	Dec. 15, 2017 Friday	Dec. 16, 2017 Saturday	Dec. 17, 2017 Sunday	Dec. 18, 2017 Monday
- 8:30	Breakfast								
8:30 - 8:40 (10 min.)	Arrival Day	Welcome	Information / Announcement					Excursion	Departure Day
8:40 - 10:10 (90 min.)		Introduction 1 (SC & Cryogenics)	SC Magnet (Theory 1)	SC Magnet (Eng. 2)	SC Cavity (Theory 2)	Special Talk 2 (SC Cavity)	Cryogenics (Eng. 1)		
10:10 - 10:30 (20 min.)		Group Photo	Coffee Break						
10:30 - 12:00 (90 min.)		Introduction 2 (Accelerator 1)	SC Magnet (Theory 2)	Special Talk 1 (SC Magnet)	SC Cavity (Eng. 1)	Cryogenics (Theory 1)	Cryogenics (Eng. 2)		
12:00 - 13:10 (70 min.)		Lunch							
13:10 - 14:40 (90 min.)		Introduction 3 (Accelerator 2)	SC Magnet (Eng. 1)	SC Cavity (Theory 1)	SC Cavity (Eng. 2)	Cryogenics (Theory 2)	Special Talk 3 (SC & Cryogenics)		
14:40 - 15:00 (20 min.)		Coffee Break							
15:00 - 16:00 (60 min.)		Training A Introduction	Training A	Training B Introduction	Training B	Training C Introduction	Training C		
16:00 - 18:30 (150 min.)		Training A		Training B		Training C			
18:30 -		Welcome Party	Dinner				Banquet		



Group B

Training Course

Dec. 11, 12 Superconducting Cavity

Dec. 13, 14 Cryogenics

Dec. 15, 16 Superconducting Magnet

ID #	Name	Institution
B01	LI Dongbing	Institute of High Energy Physics
B02	ZHANG Xiangzhen	Institute of High Energy Physics
B03	CHEN Shu	Peking University
B04	LI Chunlong	Institute of Modern Physics
B05	LIU Lubei	Institute of Modern Physics
B06	MULEY Parag	Indian Institute of Technology Bombay
B07	SONI Vijay Kumar	Inter-University Accelerator Centre
B08	SETH Sudeshna	Variable Energy Cyclotron Centre
B09	DANG Jeong-jeung	Korea Atomic Energy Research Institute
B10	QADRI Muhammad Waqee ur Rehman	Govt. Post Graduate College, Gojra
B11	CHUANG Ping-shun	National Synchrotron Radiation Research Center
B12	YANG Chin-kang	National Synchrotron Radiation Research Center
B13	KWANKASEM Apichai	Synchrotron Light Research Institute

Nb

Cu





Superconducting RF (SRF) Cavity

Group A

Training Course

Dec. 11, 12 Superconducting Magnet

Dec. 13, 14 Superconducting Cavity

Dec. 15, 16 Cryogenics

ID #	Name	Institution
A01	ZHENG Hongjuan	Institute of High Energy Physics
A02	CHEN Meng	Peking University
A03	HU Chuanfei	Institute of Modern Physics
A04	JIANG Tiancai	Institute of Modern Physics
A05	LIU Shichang	Shanghai Institute of Applied Physics
A06	RAJAN Sankaran Sundar	Bhabha Atomic Research Centre
A07	SUMAN Navneet Kumar	Inter-University Accelerator Centre
A08	NIGAM Nitin	Raja Ramanna Centre for Advanced Technology
A09	LEE Seung-hyun	Korea Atomic Energy Research Institute
A10	YOON Jun-young	Korea University
A11	JAN Jyh-chyuan	National Synchrotron Radiation Research Center
A12	CHU Yun-liang	National Synchrotron Radiation Research Center
A13	SOOKSRIMUANG Visitchai	Synchrotron Light Research Institute

Nb

Cu





Superconducting RF (SRF) Cavity

Group C

Training Course

Dec. 11, 12 Cryogenics

Dec. 13, 14 Superconducting Magnet

Dec. 15, 16 Superconducting Cavity

ID #	Name	Institution
C01	TUNNINGLEY Thomas	Australian National University
C02	GONG Dianjun	Institute of High Energy Physics
C03	CHENG Wei	Peking University
C04	HAN Yanning	Institute of Modern Physics
C05	DING Yi	Shanghai Institute of Applied Physics
C06	KUMAR Mukesh	Inter University Accelerator Centre
C07	JINDAL Tejinder	PEC University of Technology Chandigarh
C08	GHOSH Sundeep	Variable Energy Cyclotron Centre
C09	LIM Eun-hun	Korea University
C10	KOPYLOV Stepan	Budker Institute of Nuclear Physics
C11	CHANG Shian-wen	National Synchrotron Radiation Research Center
C12	SUNWONG Prapaiwan	Synchrotron Light Research Institute
C13	WANISON Ramnarong	SOKENDAI

Nb

Cu





Hands-on Training (SC Cavity)

0. Introduction: Surface resistance
1. RRR (Residual Resistivity Ratio) measurement of Niobium and Copper samples (Resistivity by DC measurement)
2. Resonant Frequency and Quality Factor of Niobium and Copper Cavities (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

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$

- 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:

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

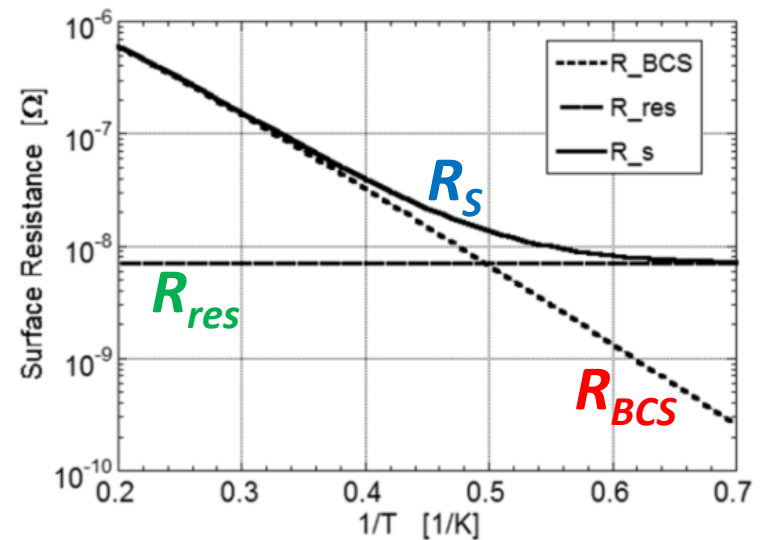
$$R_{BCS} = A \frac{\omega^2}{T} \exp\left(-\frac{\Delta}{k_B \cdot T}\right)$$

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 [Ω]

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

$$f = 1.3 \text{ GHz}, \quad G = 270 \Omega$$

$$\text{Cu (20}^\circ\text{C)} ; \quad \sigma = 0.58 \times 10^8 \text{ [1/}\Omega\text{m]}$$

$$R_S = 9.4 \text{ m}\Omega, \quad (\delta = 1.8 \mu\text{m})$$

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

Superconducting Cavity ;

- Surface resistance; R_S [Ω]

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

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

$$f = 1.3 \text{ GHz}, \quad G = 270 \Omega$$

$$R_S = 17 \text{ n}\Omega, \quad (\lambda_0 = 44 \text{ nm})$$

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

R_{BCS} : BCS resistance

R_{res} : Residual surface resistance

k_B : Boltzmann constant

Δ : Gap energy of Cooper pair

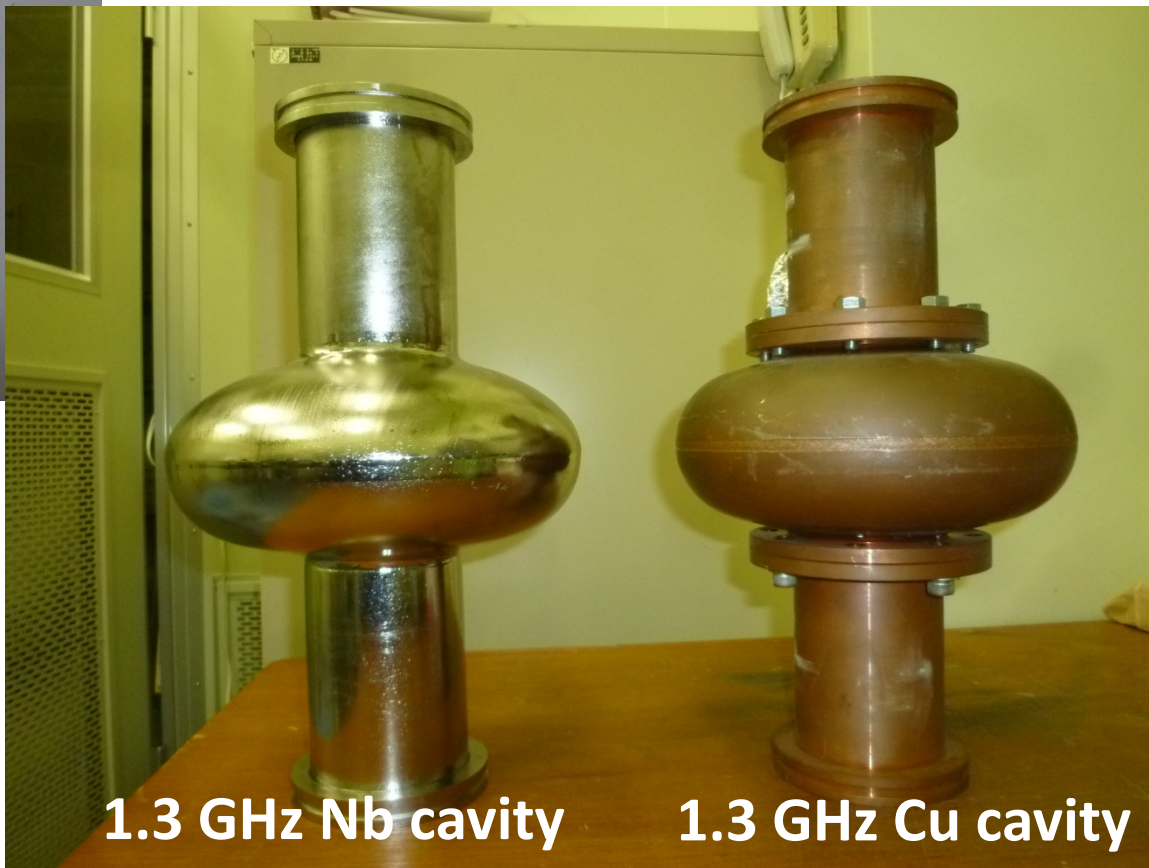


Superconducting RF (SRF) Cavity

Cu sample



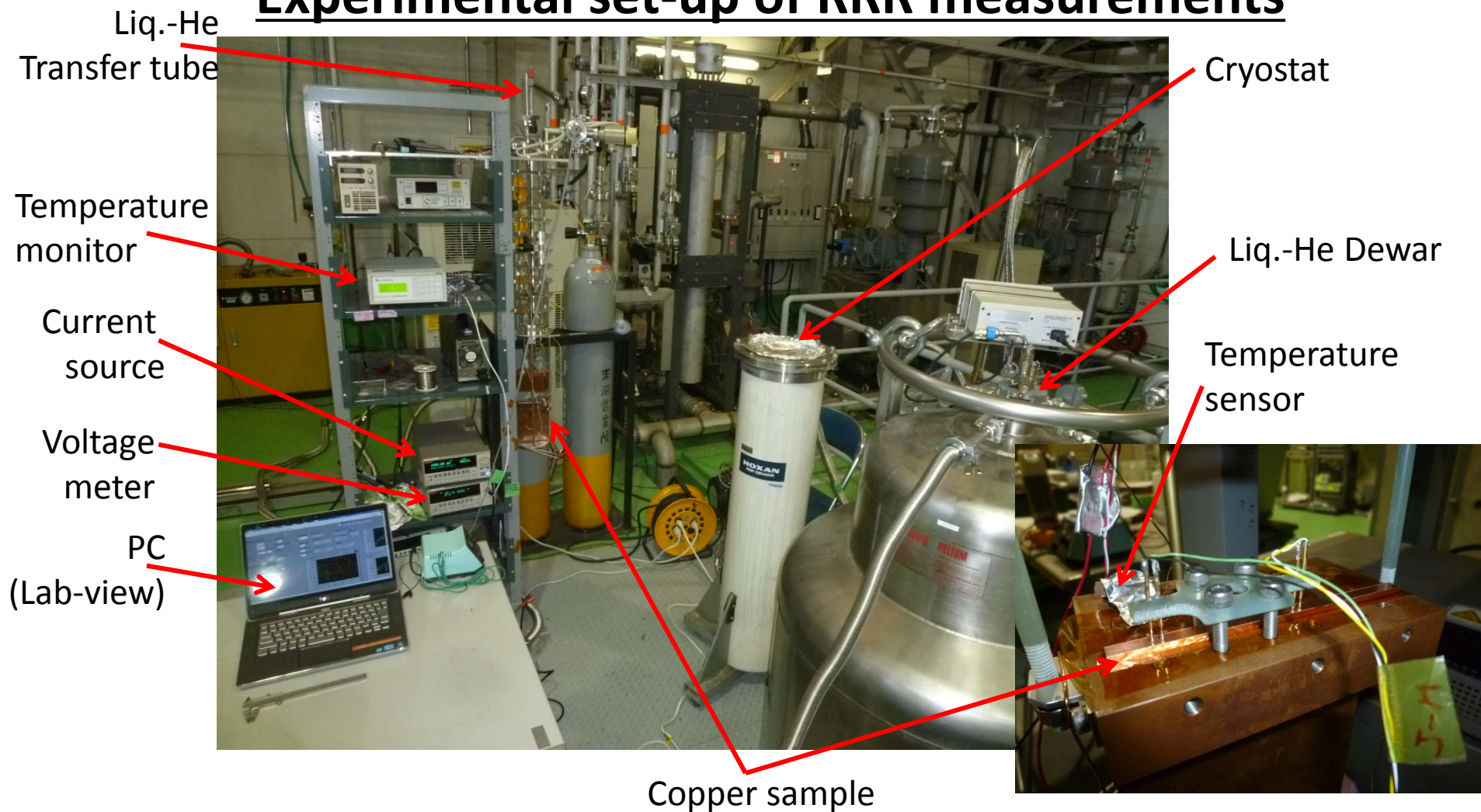
Nb sample



1.3 GHz Nb cavity

1.3 GHz Cu cavity

Experimental set-up of RRR measurements





Material properties of Nb and Cu

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

Wiedemann-Franz's law :

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

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

L : Lorenz constant = $2.45 \times 10^{-8} \text{ W}\Omega/\text{K}^2$

W : Thermal resistivity

κ : Thermal conductivity

ρ : Electrical resistivity

σ : Electrical conductivity

T : Temperature

α : constant = 6.8×10^{-8}

β : constant = 0.53

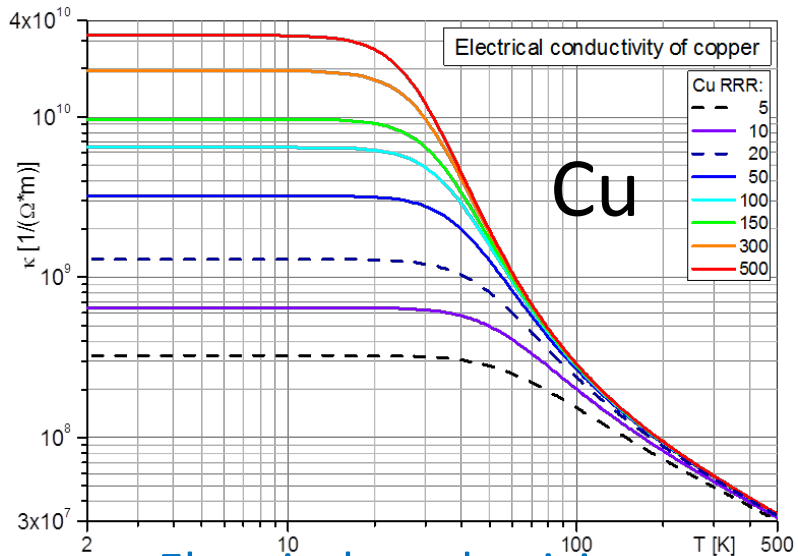
Copper at low temperature (LT): $\kappa = \frac{1}{\alpha T^{2.4} + \beta / (RRR \cdot T)}$

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

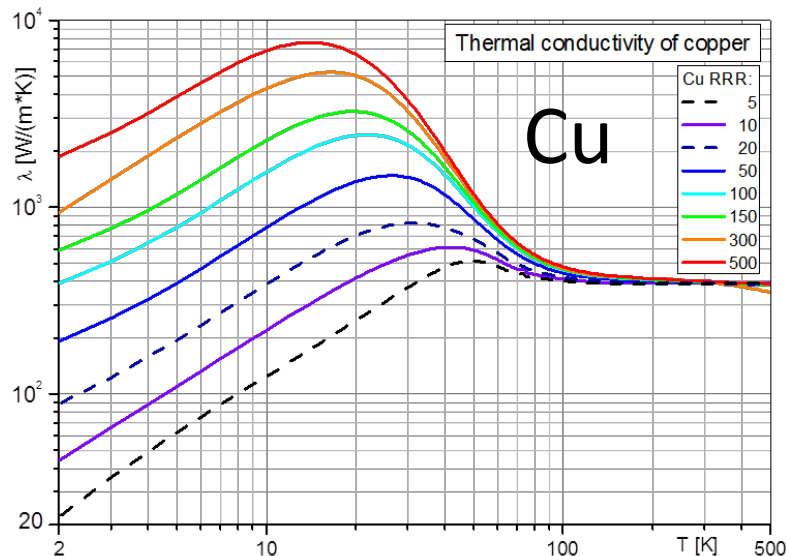




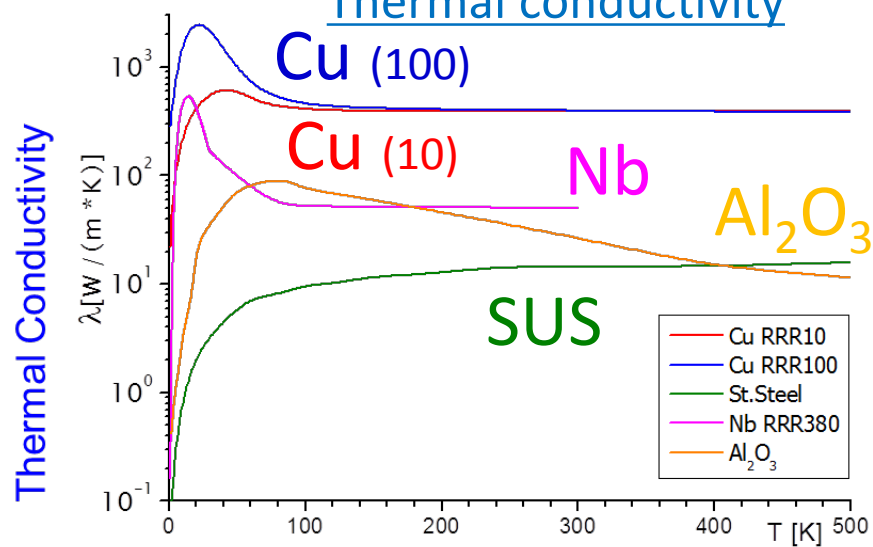
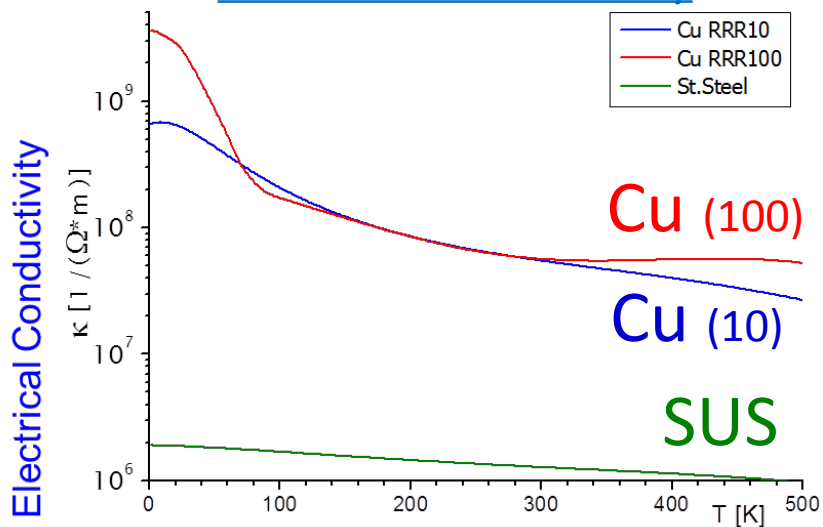
Material properties of Nb and Cu



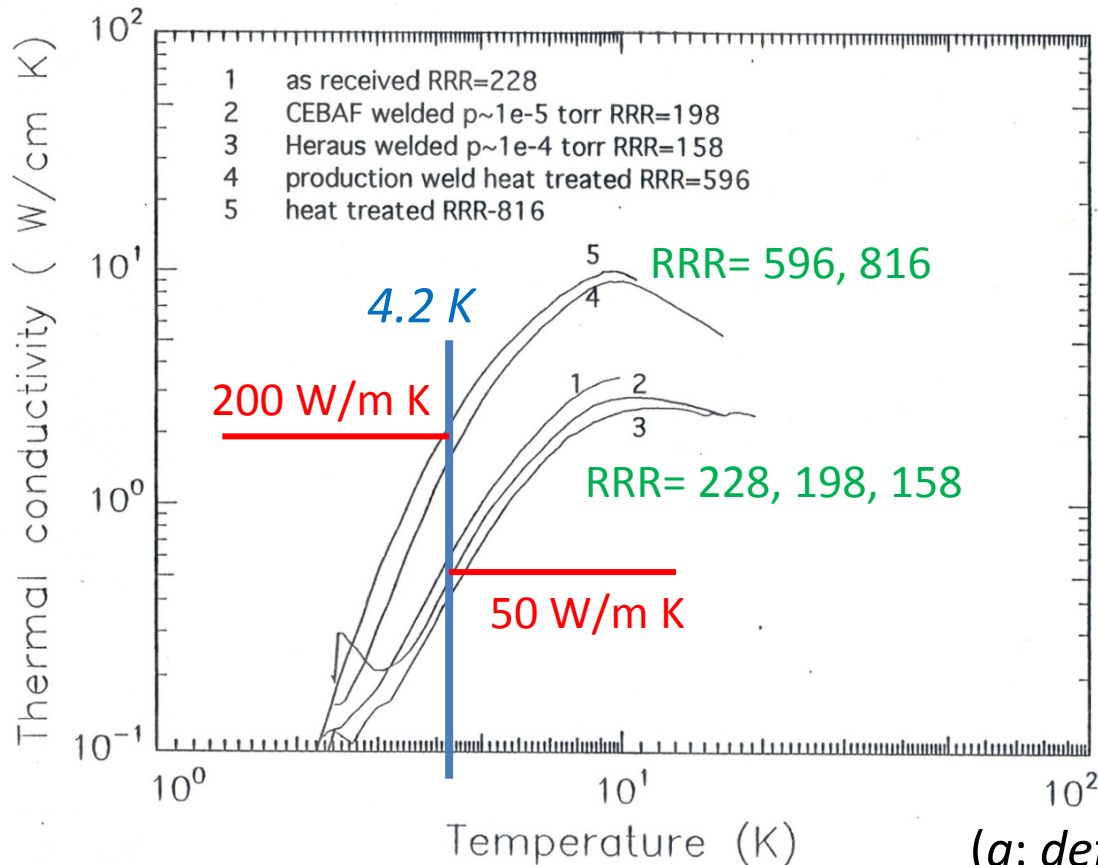
Electrical conductivity



Thermal conductivity



Thermal conductivity of Nb; (κ)



RRR : Residual Resistance Ratio

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

κ : Thermal Conductivity of Nb

$$\kappa_{(4.2K)} \approx RRR / 4$$

$$[W / m \cdot K]$$

H_{quench} : Quench field

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

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

High purity \rightarrow High thermal conductivity \rightarrow Increase of quench field



Material certification of Nb: (Mill sheet)

No. 28378

Surveyor 御立会者		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 Nb	Article 品名 Disc	Quantity 数量 pcs or gr	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					
Specification No. 仕様書番号	Lot No.	Size 寸法 mm	Spec 規格	min max	min max	min max	min max	min max	min max	min max	
	4378	2.8t×258φ-56φ	58 pcs	120	39	35	---				
			Test Results 試験結果	162	47	56	50.8				
			Longitudinal 試験結果	171	51	54	---				
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 max	0.15	0.02	0.005	0.005	0.005	0.005	0.01	---	
4378	Test Results 試験結果		0.0115 Ta	<0.001 W	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	balance
Lot No.	Element 成分	Chemical Composition (in Wt%) 化学成分									
		O	N	H	C						
	Spec 規格	min max	0.015	0.01	0.002	0.01					
4378	Test Results 試験結果		<0.001 O	<0.001 N	<0.0005 H	<0.001 C					
Remarks 備考		Starting Ingot Lot No. NC-1830 RRR Value of Sheet: 298 Grain size ASTM #6									
		Purity, Thermal property RRR = 298									
		T.S.=Tensile Strength Y.S.=Yield Strength E.V.=Ericksen Value									
		Inspection Section Manage TOKYO DENKAI Engine									
		[by H. Umezawa (Tokyo Denkai)]									

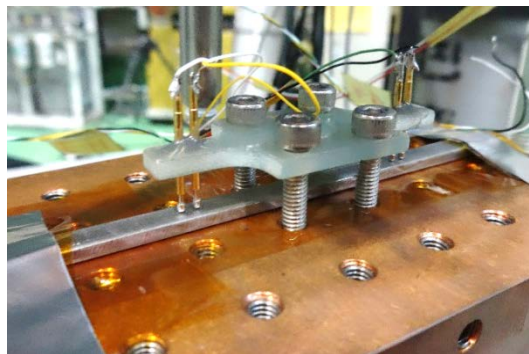
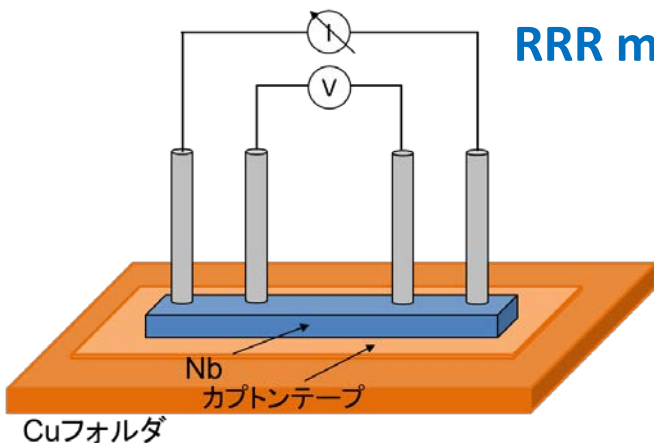
Mechanical property

Chemical Composition

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

Material properties of Niobium

RRR measurement system



Residual Resistance Ratio

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

$$\rho(300\text{K}) = 2 \times 10^{-5} \Omega \cdot \text{cm}$$

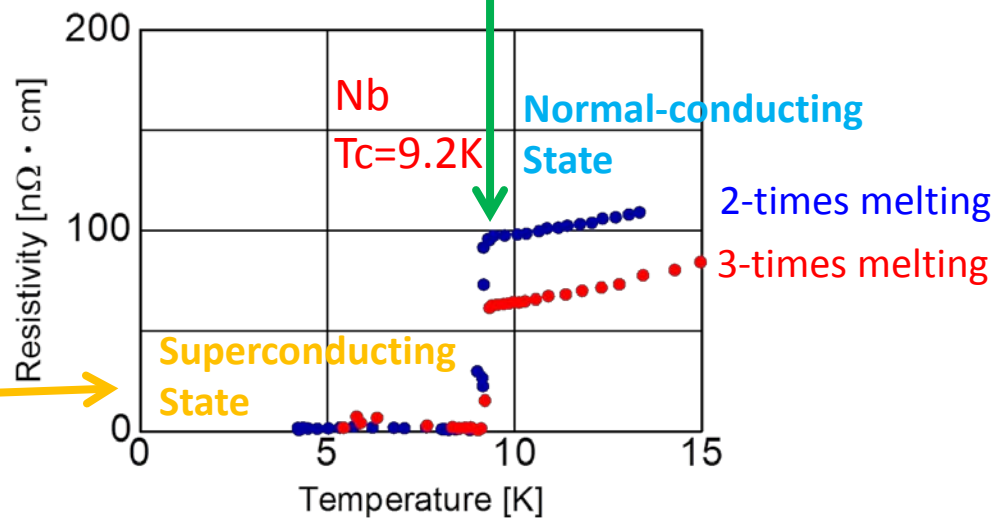
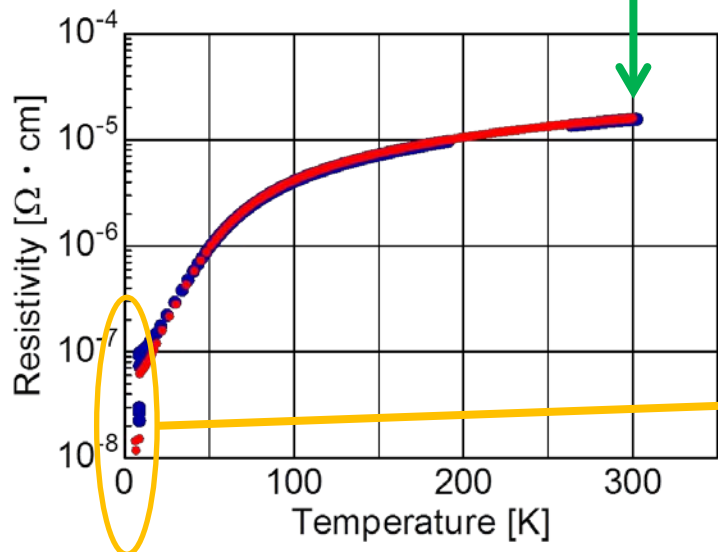
$$\rho(300\text{K}) = 2 \times 10^{-5} \Omega \cdot \text{cm}$$

$$\rho(9.2\text{K}) = 1 \times 10^{-7} \Omega \cdot \text{cm}$$

$$\rho(9.2\text{K}) = 6 \times 10^{-8} \Omega \cdot \text{cm}$$

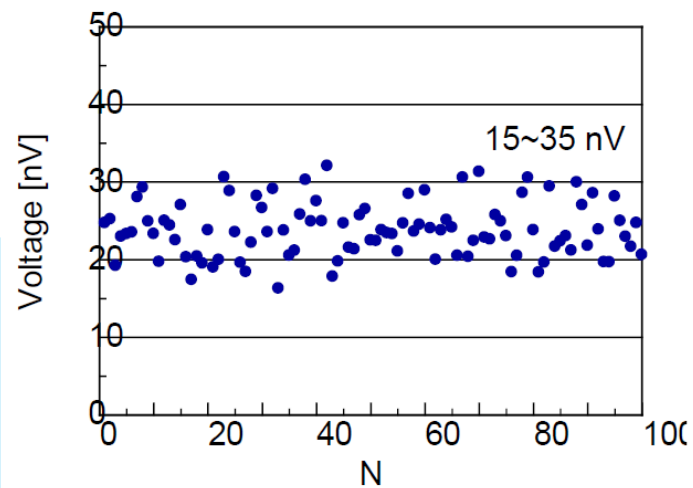
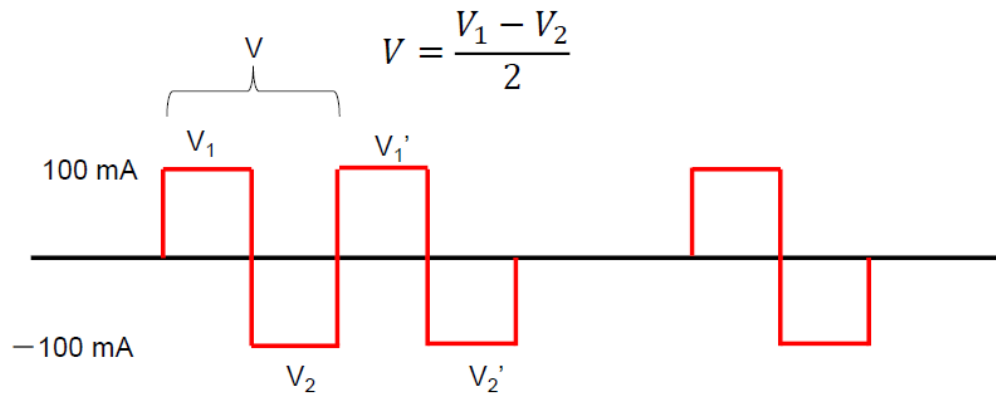
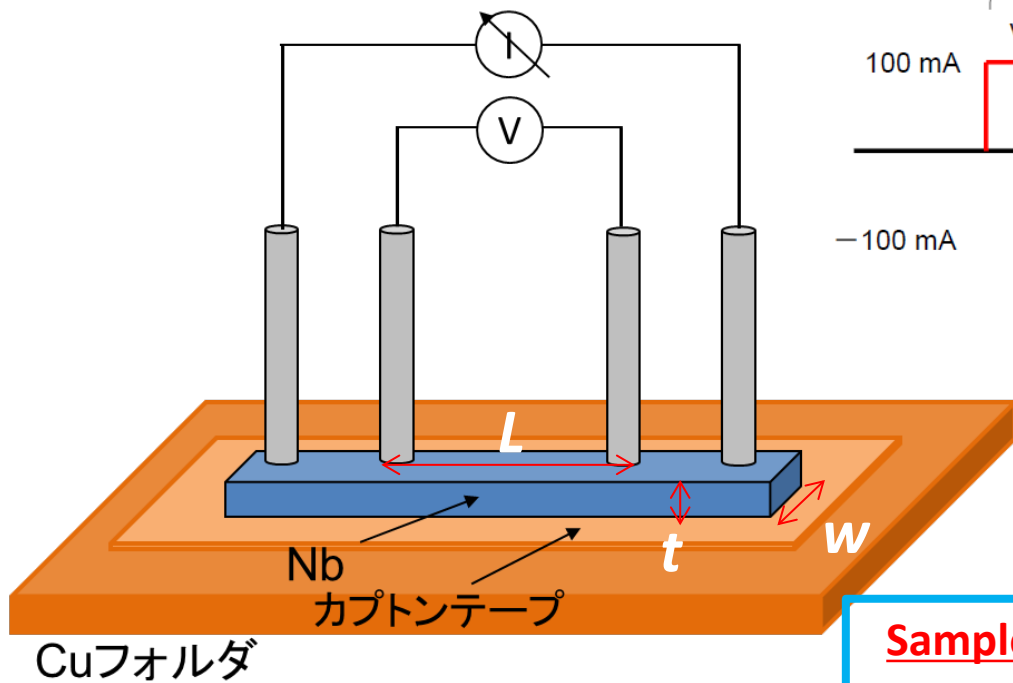
$$RRR = 200$$

$$RRR = 330$$



Constant Current:
+100 mA / -100 mA

Averaging: 10 times



Sample size

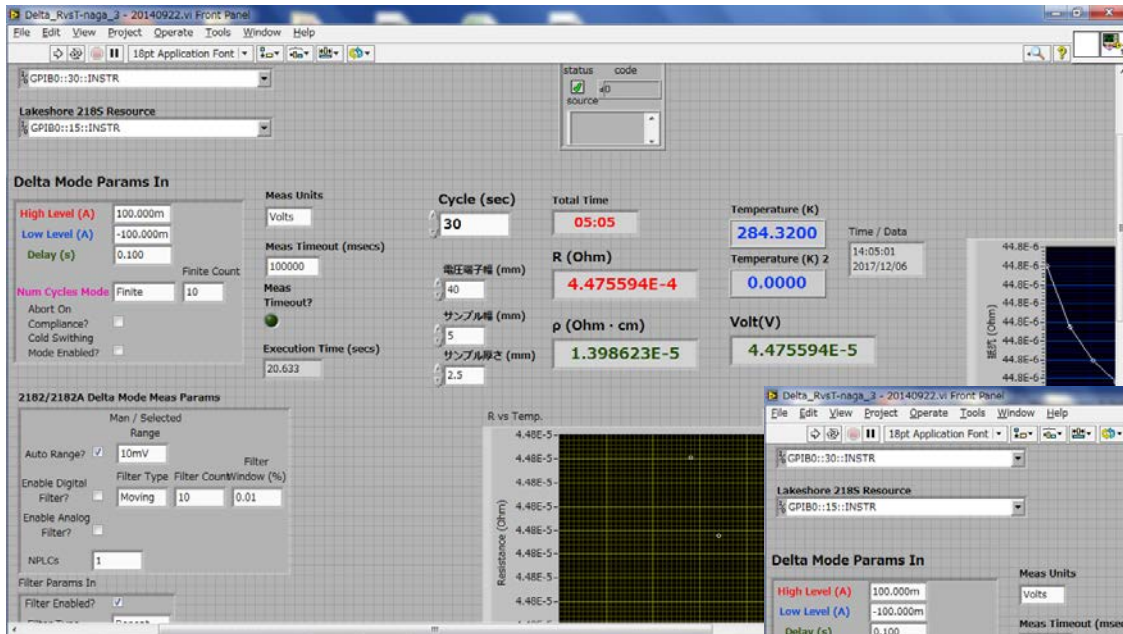
L = m

w = m

t = m

Background noise level

Examples of experimental results of RRR measurements



Nb sample

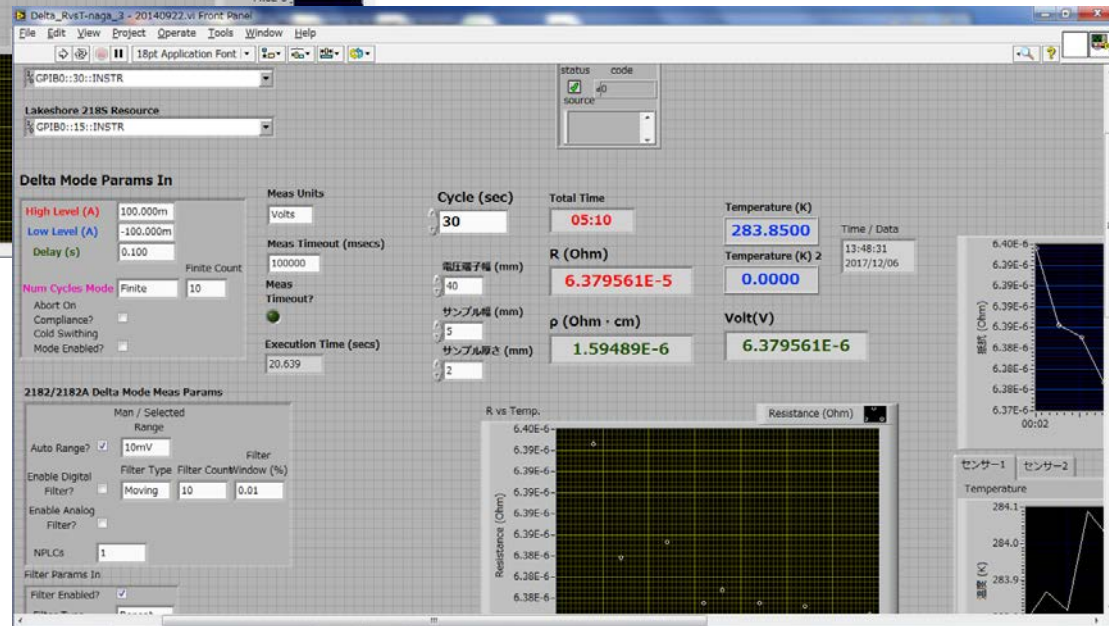
$I = 100 \text{ mA}$

$(V = 44.76 \mu\text{V})$

Cu sample

$I = 100 \text{ mA}$

$(V = 6.380 \mu\text{V})$





Exercise (1)

Please measure and calculate following parameters;

Cu sample at RT

$$I = \quad A$$

$$V = \quad V$$

$$R = \quad \Omega$$

$$L = \quad m$$

$$W = \quad m$$

$$t = \quad m$$

$$S = \quad m^2$$

$$\rho = \quad \Omega m$$

$$\text{Frequency} = 1300 \text{ MHz}$$

$$R_s = \quad \Omega$$

$$G = 270 \quad \Omega$$

$$Q =$$

Nb sample at RT

$$I = \quad A$$

$$V = \quad V$$

$$R = \quad \Omega$$

$$L = \quad m$$

$$W = \quad m$$

$$t = \quad m$$

$$S = \quad m^2$$

$$\rho = \quad \Omega m$$

$$\text{Frequency} = 1300 \text{ MHz}$$

$$R_s = \quad \Omega$$

$$G = 270 \quad \Omega$$

$$Q =$$

Nb sample at 9.2K

$$I = \quad A$$

$$V = \quad V$$

$$R = \quad \Omega$$

$$L = \quad m$$

$$W = \quad m$$

$$t = \quad m$$

$$S = \quad m^2$$

$$\rho = \quad \Omega m$$

$$\text{Frequency} = 1300 \text{ MHz}$$

$$R_s = \quad \Omega$$

$$G = 270 \quad \Omega$$

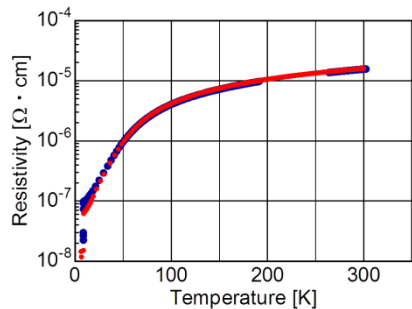
$$Q =$$



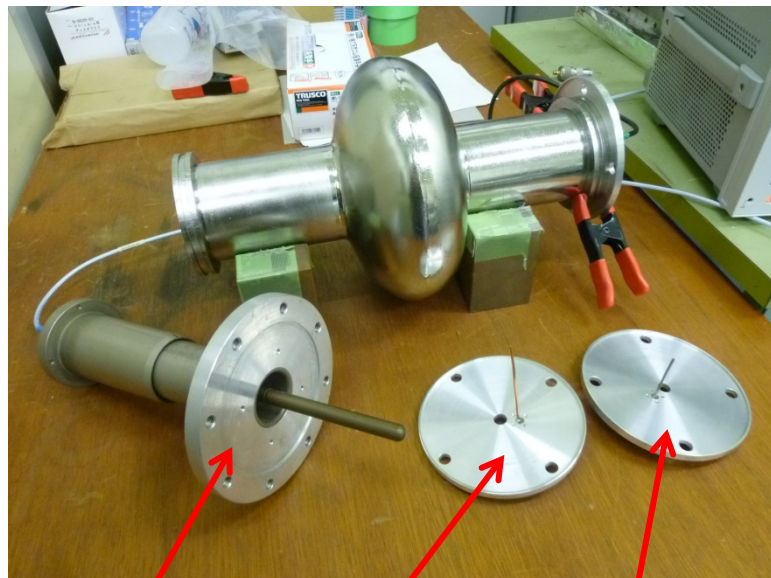


Exercise (2)

Please calculate the RRR value of Nb sample and make a figure of temperature dependence of the resistivity.



Experimental set-up of RF measurements



Fixed
input antenna

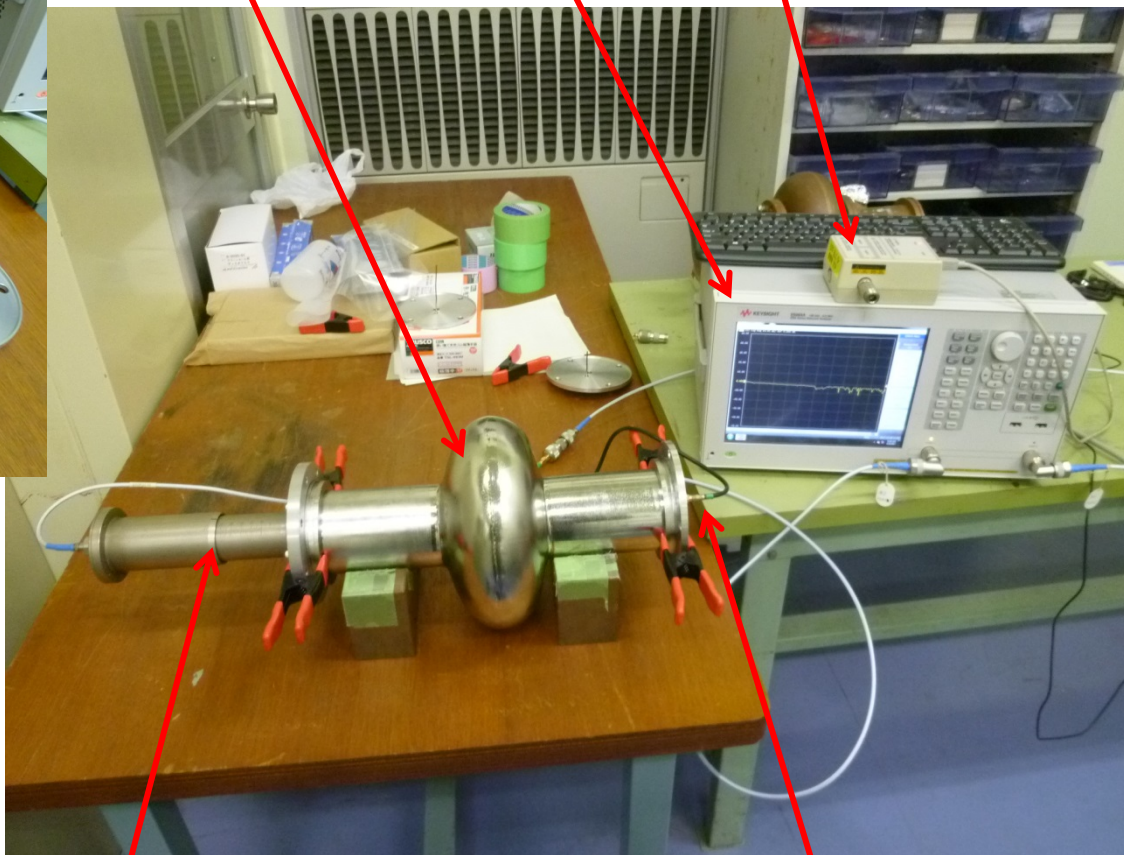
Variable
Input coupler

Transmitted
antenna

Niobium cavity

Network analyzer

Electrical calibrator



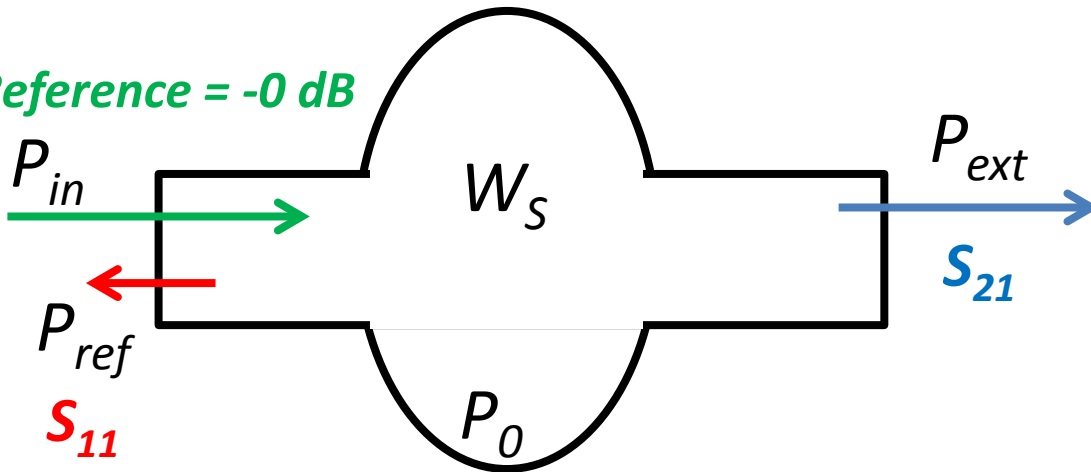
Input antenna

Transmitted antenna



RF measurement of NC cavity

Reference = -0 dB



- Cavity stored energy

$$W_s = \frac{\mu_0}{2} \int_V |\vec{H}|^2 dV = \frac{\epsilon_0}{2} \int_V |\vec{E}|^2 dV$$

- Cavity RF loss

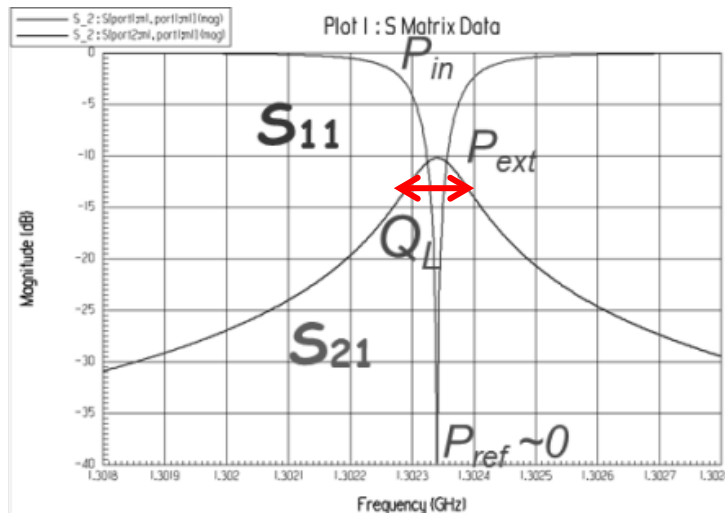
$$P_o = P_{in} - P_{ref} - P_{ext}$$

- Loaded Q

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

- Coupling constant (over/under coupling)

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



- Q_L is measured by bandwidth of -3dB.

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



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 $E_{acc} = \frac{\sqrt{R/Q}}{L_{cavity}} \sqrt{P_o Q_o} = Z \sqrt{P_{ext} Q_{ext}}$

- **Geometrical factor G [W]:**
$$G = \omega_0 \mu_0 \frac{\int_V |\vec{H}|^2 dV}{\int_A |\vec{H}|^2 dA}$$

- **Quality factor Q_o :**
$$Q_o = \frac{\omega_0 W_S}{P_d} = \frac{G}{R_S}$$





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

$Q_0 =$

$Q_{in} =$

$Q_{ext} =$

$\beta_{in} =$

$Z = 91. \quad P_{in} = 1.0 \text{ W}$

$E_{acc} =$ V/m

$G = 270 \Omega$

$R_s =$ Ω

$\rho =$ $\Omega \text{ m}$

Nb cavity

Frequency = MHz

Loaded $Q_L =$

$P_{ref} : S_{11} =$ dB

$P_{ext} : S_{21} =$ dB

$Q_0 =$

$Q_{in} =$

$Q_{ext} =$

$\beta_{in} =$

$Z = 91. \quad P_{in} = 1.0 \text{ W}$

$E_{acc} =$ V/m

$G = 270 \Omega$

$R_s =$ Ω

$\rho =$ $\Omega \text{ m}$

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

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





Exercise (4)

Please compare following parameters measured by DC and RF;

Frequency = 1300 MHz

$G = 270 \Omega$

Copper

DC:

$Q_0 =$

$R_S = \Omega$

$\rho = \Omega \text{ m}$

RF:

$Q_0 =$

$R_S = \Omega$

$\rho = \Omega \text{ m}$

Niobium

DC:

$Q_0 =$

$R_S = \Omega$

$\rho = \Omega \text{ m}$

RF:

$Q_0 =$

$R_S = \Omega$

$\rho = \Omega \text{ m}$





Superconducting RF (SRF) Cavity

Thank you for your efforts.





Superconducting RF (SRF) Cavity

