Thermal transmittance and Kapitza-resistance measurements of Nb_3Sn

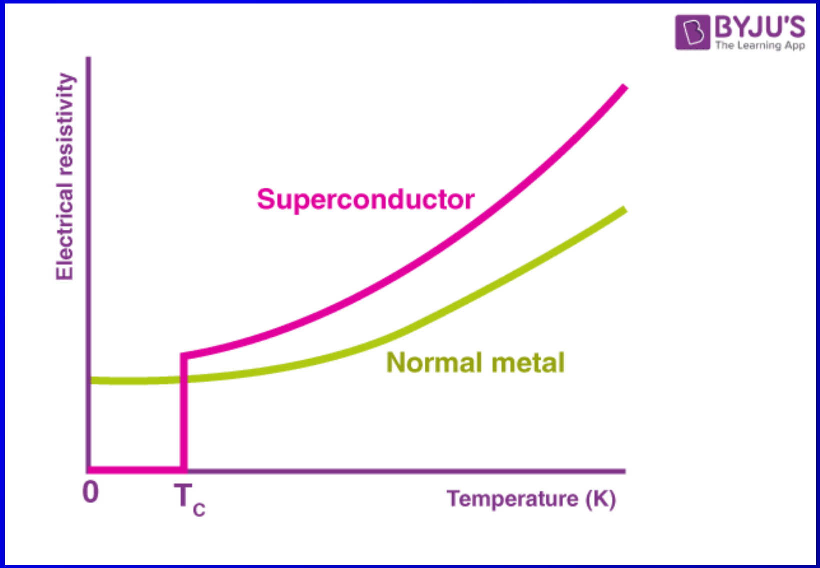
After different treatments

Lasse Koch - on behalf
of the SRF R&D team

Motivation: Why?

Better heat transmittance:

- Heat build up because of cavity inaccuracies
- Cavity needs $T < T_c$
- Heat goes through cavity into helium bath



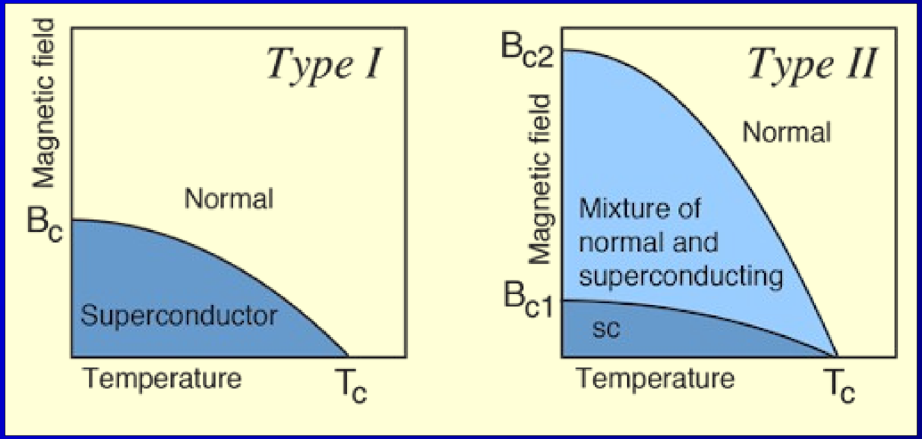
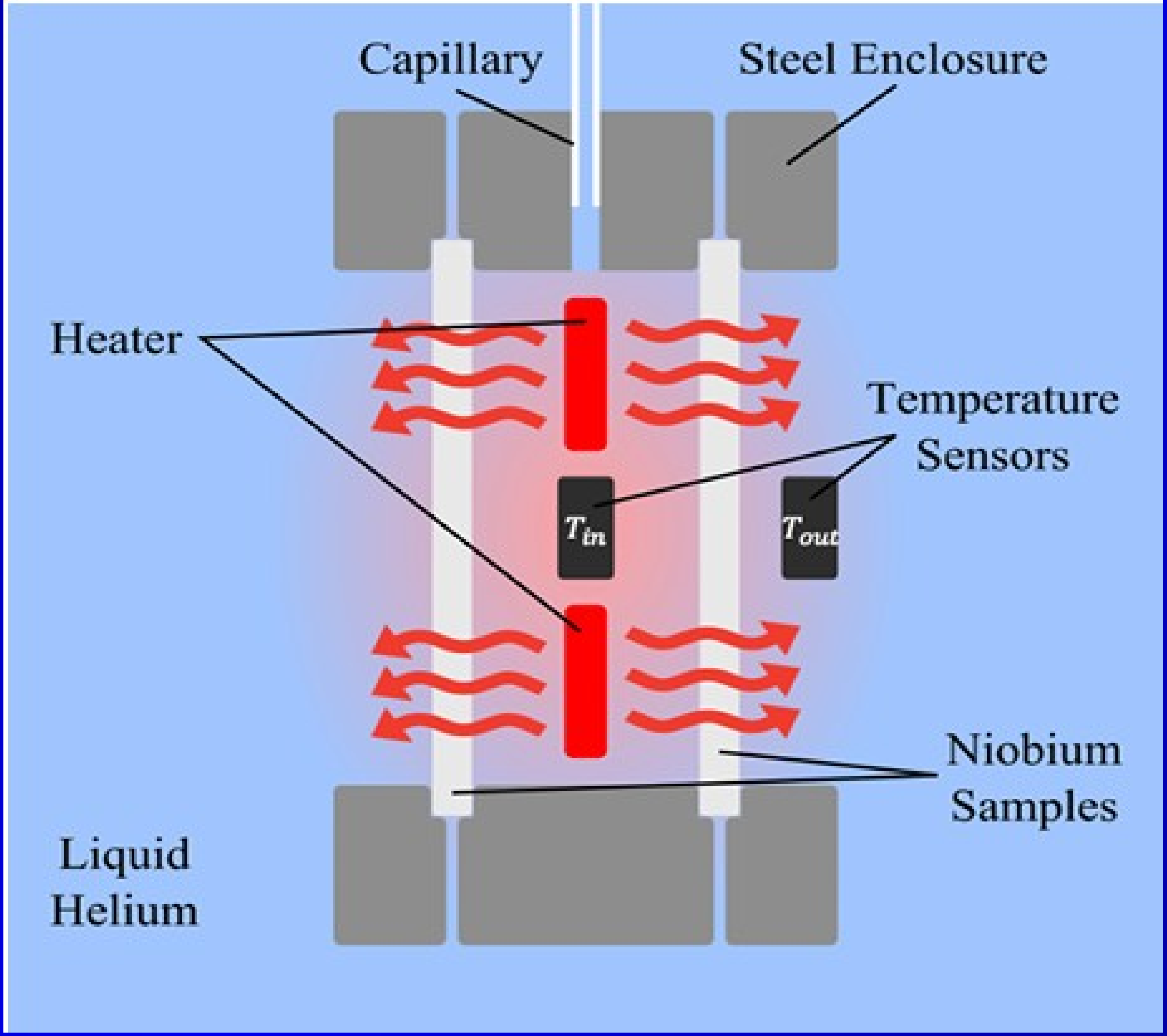


Image Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scbc.html
https://byjus.com/physics/superconductor/

Source: Physik IV UNI Hamburg

NTCI-Device



Measurements are taken below 2K

Source:

Thermal insulance

$$R_{ges} = \sum_{i,j} R_i + R_{i,j}$$

$$R_{i,j} = \frac{\Delta T_{i,j}}{q}$$

$$R_i = \frac{d_i}{\lambda_i}$$

R_{ges} is the total thermal transmittance resistance

$R_{i,j}$ is the resistance between layers (interface resistance)

R_i is the resistance for a material

$\Delta T_{i,j}$ is the temperature difference between layers

q is heat flux

d is thickness

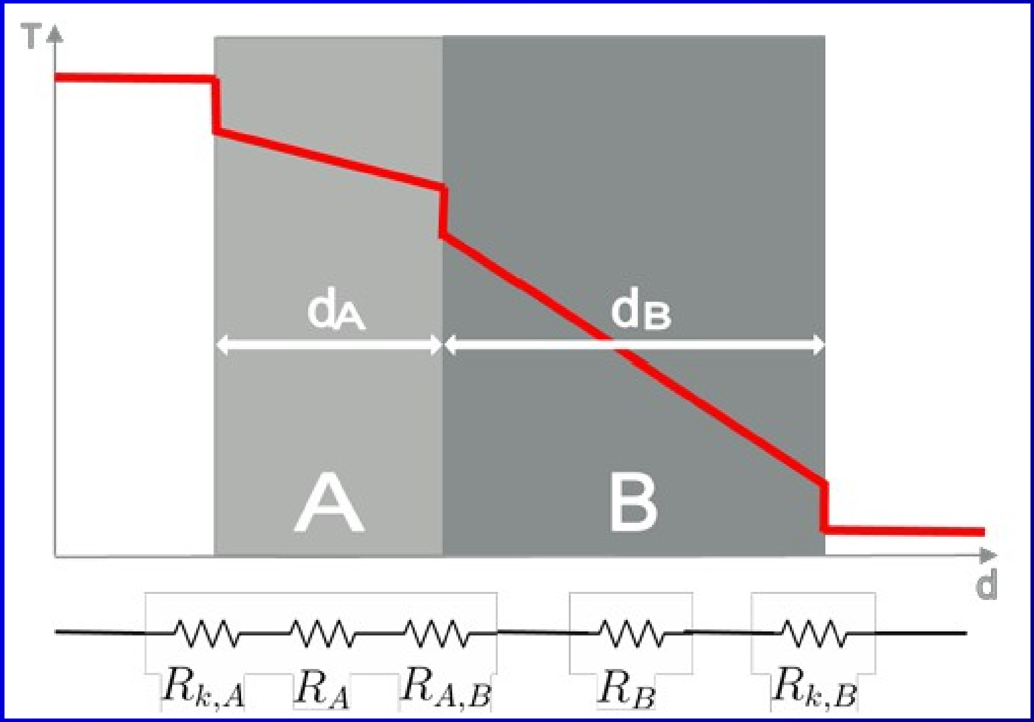
λ is thermal transmittance

Source:

Thermal insulance

- Heat propagates through electrons and phonons
- Phonons can’t easily couple between materials

$$R_{ges} = \sum_{i,j} R_i + R_{i,j}$$



Source: L. King Wärmeleitmessungen von beschichtetem und wärmebehandeltem Niob Bachelor Thesis University Hamburg 2024

Thermal transmittance

K is thermal transmittance

K_0 is thermal transmittance without leaks

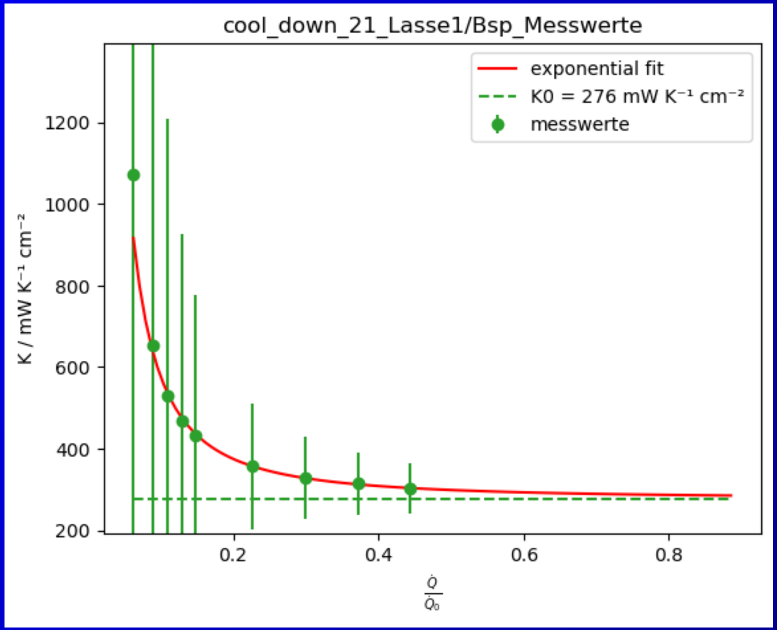
$\dot{Q}_0$ is norm const.

$\dot{Q}$ is heat flux

n, a are fit parameters

$$K(\dot{Q}) = K_0 + a\left(\frac{\dot{Q}}{\dot{Q}_0}\right)^{-n}$$

$$\dot{Q}_0 = \left(\frac{0.01K_0}{a}\right)^{-\frac{1}{n}}$$



the plot with fit is only meant as a example

Source:

Thermal transmittance

K is thermal transmittance (total)

$\dot{\mathbf{q}}$ is heat flux density

$\lambda(T)$ is heat transmittance

T is temperature

d is thickness

R_k is interface resistance

R is resistance

I Is Current

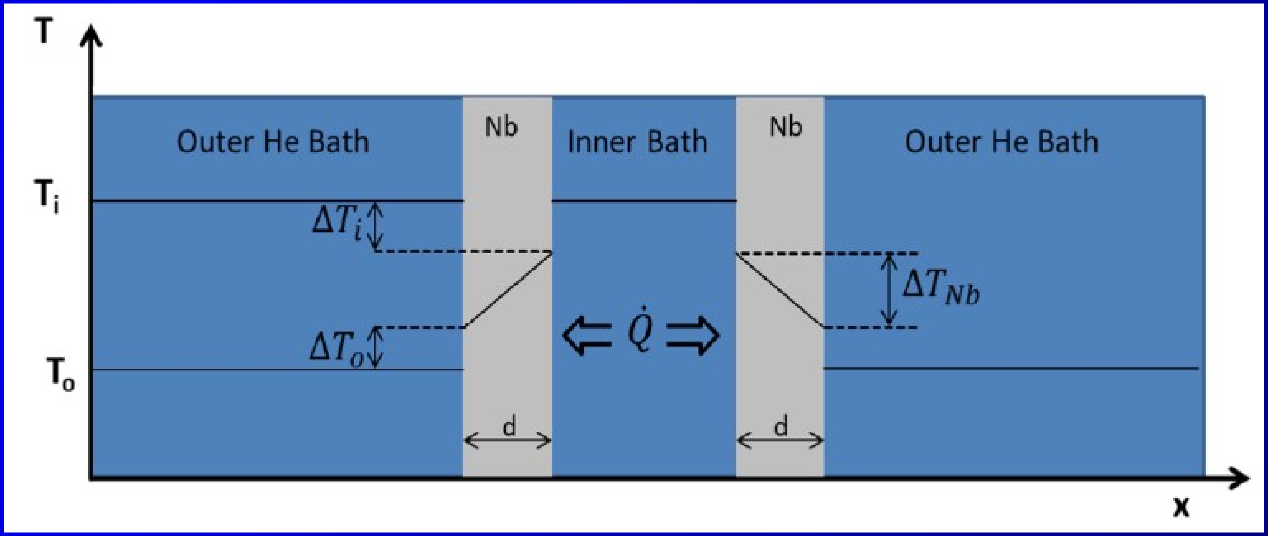
U Is Voltage

P Is Power

$$\dot{\vec{q}} = \lambda(T) \cdot \vec{\nabla} T$$

$$K = \left(\frac{d}{\lambda} + R_k \right)^{-1} = \frac{1}{R}$$

$$I \cdot U = P = \dot{Q}$$



Nb_3Sn: Basics

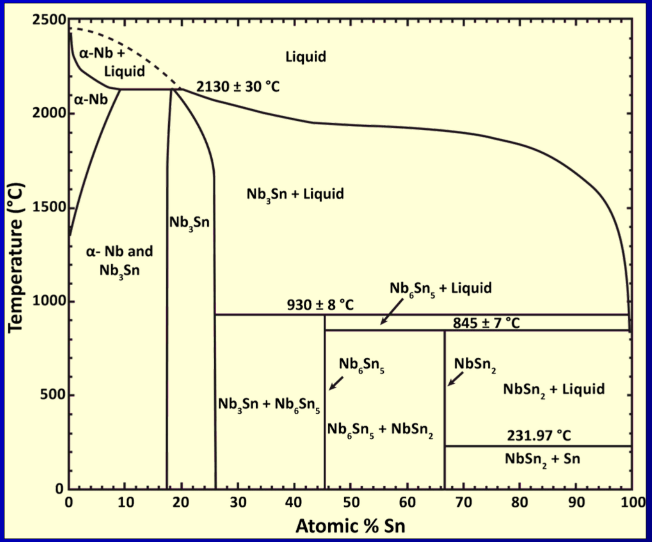
- 3 Niobium per 1 tin
- $T_{c,\,Nb3Sn} = 18.3\,K$

Table 1. Material parameters of Nb and Nb_3Sn.

Property	Nb	Nb_3Sn
T_c [K]	9.25 [3]	18 [1]
κ(0K)	1.4 [3]	34 [1]
ξ_0 [nm]	39 [4]	5.7(0.6) [5]
λ_L [nm]	27(3) [6]	65[7]–89[8]
$\mu_0 H_{c1}$(0K) [mT]	174 [3]	38 [1]
$\mu_0 H_c$(0K) [mT]	199 [3]	520 [1]
$\mu_0 H_{sh}$(0K) [mT]	240 [2]	440 [2]

Problems:

- Exact mixing Not possible
  - ➔ Low B_c
- Complicated Phase diagram



https://en.wikipedia.org/wiki/Niobium%E2%80%93tin

Source: https://indico.cern.ch/event/1376902/contributions/6111651/attachments/2928871/5142450/2%20-%20Fonnesu_ThinFilms_Paris2024.pdf
https://iopscience.iop.org/article/10.1088/1361-6668/ab119e/pdf (Table 1)

Coating

Nb_3Sn & CuBL:

- Good thermal conductivity
- Brittle
- Cu has low melting point
- Nb_3Sn (200nm), Nb (30µm)

(Not representative of our coating)

https://leadrp.net/de/blog/powder-coating-a-commonly-used-surface-finish-process-overview/

Source: https://indico.cern.ch/event/1376902/contributions/6111651/attachments/2928871/5142450/2%20-%20Fonnesu_ThinFilms_Paris2024.pdf

Baseline

Buffered Chemical Polishing (BCP)

- 130µm removed
- Exothermal reaction cooled to ~10°C
- Hydrogen enters the material

Outgassing annealing

- 3h at 800°C
- 10^{-6} mbar

Mid-T

- Medium Temp. ca. 300°C
- 3h

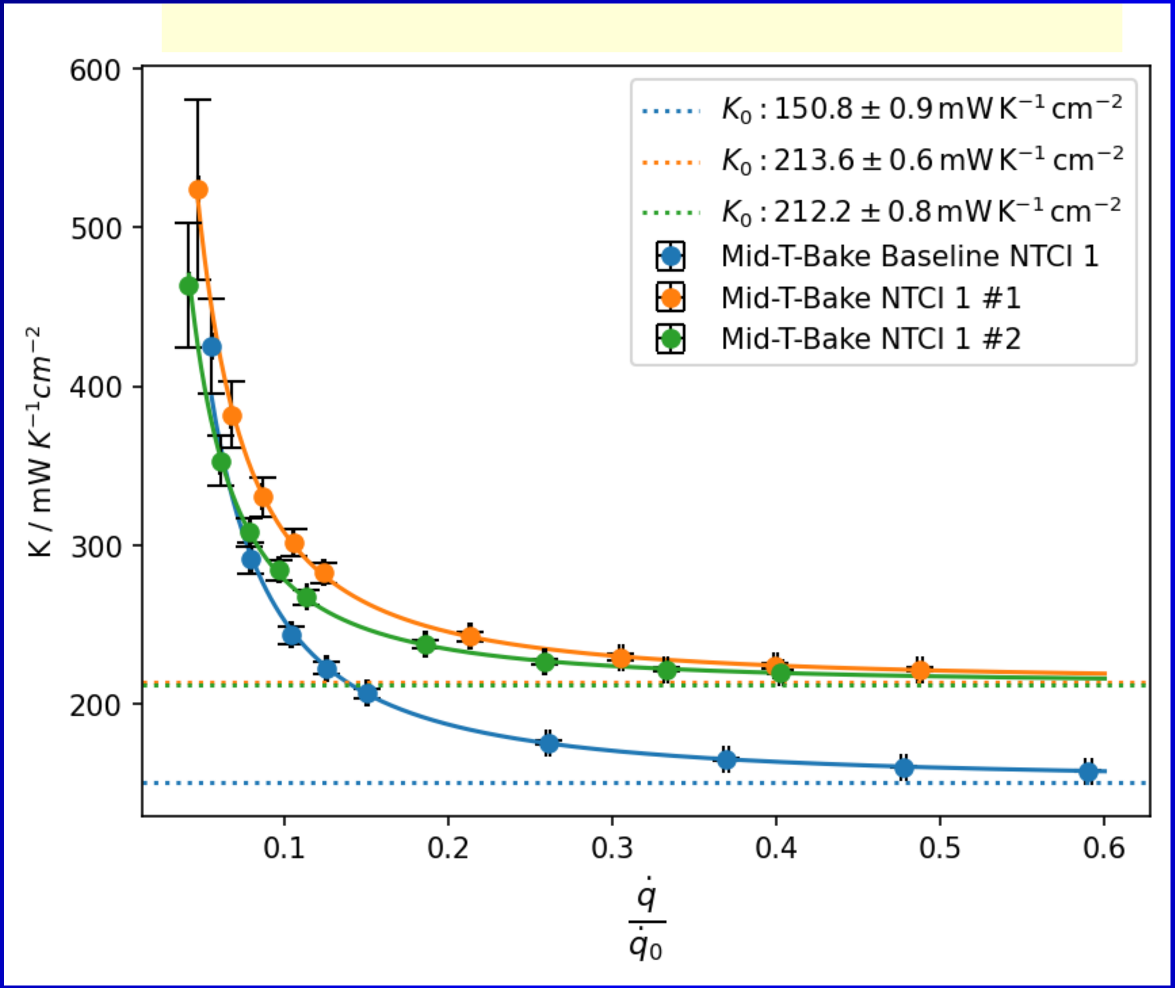
Effects:

- Oxygen diffuses into Nb
- Lower RRR value

https://www.kitchenaid.com/pinch-of-help/major-appliances/how-to-maximize-oven-space.html

Source:

K_0 for Sample pair 17



Before Mid-T: (baseline)

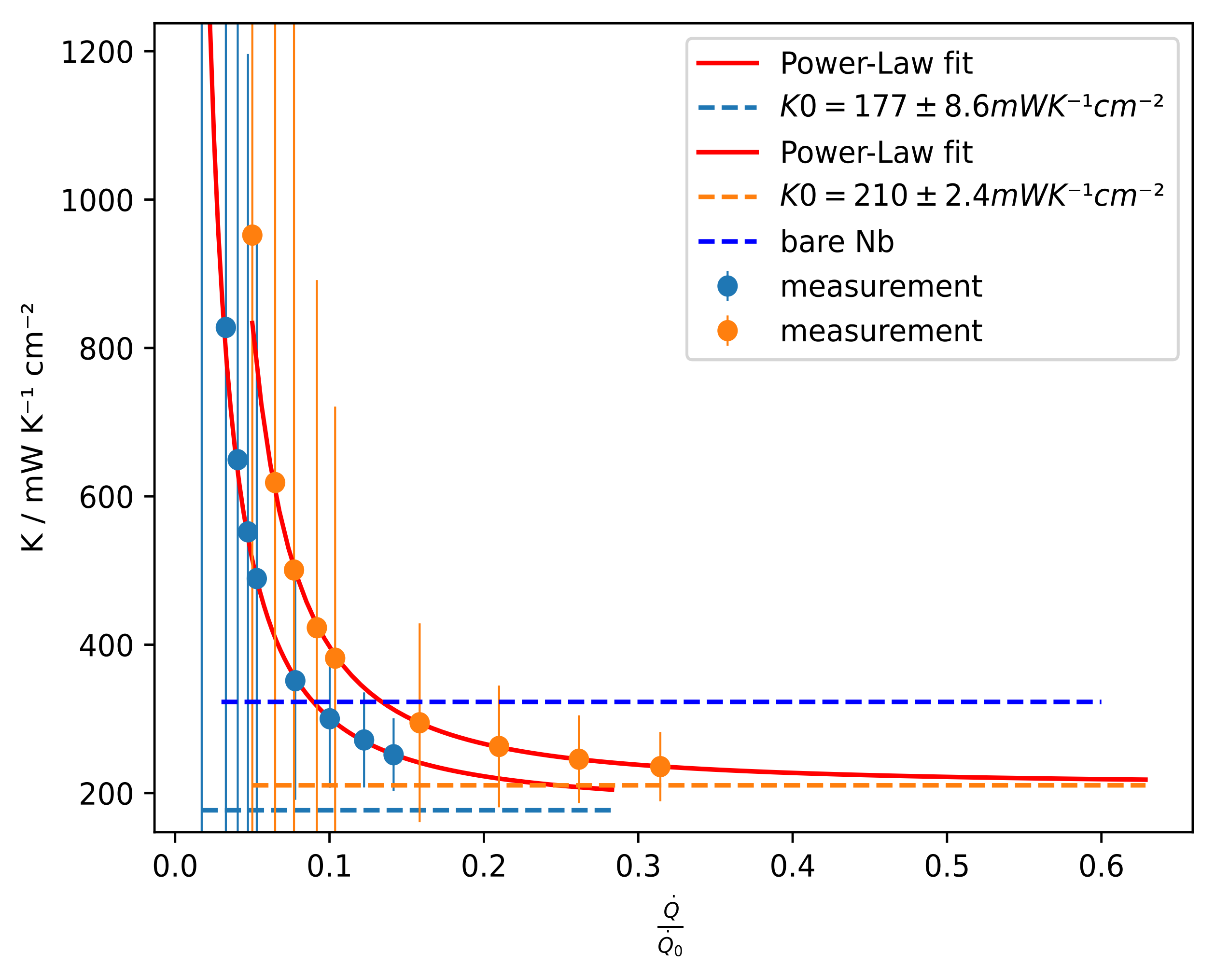
- Thermal transmittance:
  $$K_0 = 150.8 \pm 0.9\,\frac{mW}{Kcm^2}$$
- NTCl 1

After Mid-T:

- Thermal transmittance:
  $$K_0 = 213.6 \pm 0.6\,\frac{mW}{Kcm^2}$$
- NTCl 1

Source: L. King Wärmeleitmessungen von beschichtetem und wärmebehandeltem Niob Bachelor Thesis University Hamburg 2024

K_0 for Sample pair 1



Before Mid-T:

- Thermal transmittance: $K_0 = 210 \pm 8.6 \quad \frac{mW}{K cm^2}$
- NTCI 1

After Mid-T:

- Thermal transmittance: $K_0 = 177 \pm 2.4 \quad \frac{mW}{K cm^2}$
- NTCI 2

Source:

K_0 for Sample pair 1

NTCI's:

- NTCI 2 > NTCI 1
- The difference in K_0 is bigger then it seems

BCP:

- There was a thermal runaway
- Big dents in the Nb
- Not comparable to other samples

After Mid-T:

- Thermal transmittance:

$K_0 = 177 \pm 8.6 \ \frac{mW}{K\,cm^2}$

- NTCI 2

Before Mid-T: (baseline)

- Thermal transmittance:

$K_0 = 210 \pm 2.4 \ \frac{mW}{K\,cm^2}$

- NTCI 1

Source:

Comparing data:

Sample pair 1

Before Mid-T:

- Thermal transmittance:

$K_0 = 210 \pm 2.4 \ \frac{mW}{Kcm^2}$

- NTCI 1

$\vee$

After Mid-T:

- Thermal transmittance:

$K_0 = 177 \pm 8.6 \ \frac{mW}{Kcm^2}$

- NTCI 2

Sample pair 17

Before Mid-T:

- Thermal transmittance:

$K_0 = 150 \pm 0.9 \ \frac{mW}{Kcm^2}$

- NTCI 1

$\wedge$

After Mid-T:

- Thermal transmittance:

$K_0 = 213 \pm 0.6 \ \frac{mW}{Kcm^2}$

- NTCI 1

Source:

Reason for K_0 changes

Higher roughness:

$$\lambda = \frac{h \cdot c_L(P)}{3.83 k_B T}$$

- Lower interface resistance
- 'trapped' phonons create new resonance at λ

Heat coefficient: $\lambda = \frac{RRR}{4}$ (rule of thumb)

- Low RRR $\rightarrow$ Low K_0

The rule of thumb might not always work

Source: Ramiere, Aymeric, Sebastian Volz, and Jay Amrit. "Thermal resistance at a solid/superfluid helium interface." Nature materials15.5 (2016): 512-516.

Future Measurements

NTCI 3 Commissioning

- Sample pair 1 with NTCI 1
- Nb_3Sn (1µm) on Cu w & w/o NbBL (30µm) (w. INFN)
- Nb_3Sn (200nm) on bulk Nb (w. TUDA)
- 2K, 1.8K and 1.5K Measurement for one sample pair

https://de.dreamstime.com/illustration/checkliste.html

Source:

Helpfull Sources

- L. King Wärmeleitmessungen von beschichtetem und wärmebehandeltem Niob Bachelor Thesis University Hamburg 2024
- Wenskat et al. Thermal transmittance measurements of niobium at cryogenic temperatures, Physica C - submitted
- A. Lorf Einfluss von High-T_c -Beschichtungen auf die Wärmeleitfähigkeit von Niob Bachelor Thesis University Hamburg 2024
- Evidence for thermal boundary resistance effects on superconducting radiofrequency cavity performances

Source:

Extra

e impuritie scatt. | e phonon scatt. | lattice phonon scatt. | lattice grain boundary

$$\lambda(T) = R(y)\left[\frac{\rho_{295K}}{L \cdot RRR \cdot T} + aT^2\right]^{-1} + \left[\frac{1}{D(y)T^2} + \frac{1}{BI \cdot T^3}\right]$$

$$R(y) = \frac{2F_1(-y) + 2yln(1+e^{-y}) + \frac{y^2}{1+e^y}}{2F_1(0)}$$

$$\frac{1}{K} = \left(\frac{d}{\lambda} + R_n\right)$$

Different T measurements to guess the T dependence of $\lambda(T)$

Extra $dot\, Q_0$

$$K_{old}(\dot{Q}_0) = K_0 + a\left(\dot{Q}_0\right)^{-n} = 1.01K_0$$

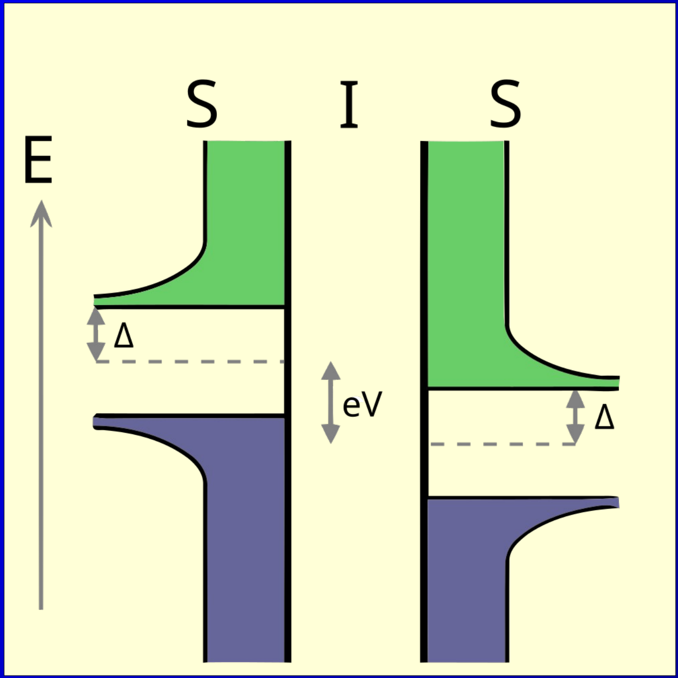
$$\dot{Q}_0 = \left(\frac{0.01K_0}{a}\right)^{-\frac{1}{n}}$$

We have to make Q without unit because of Q^(-1/n)

Source:

SIS

- Superconductor Insulator Superconductor
- Each film is thinner then λ_L
- T_c is higher then niobium
- PEALD (Plasma Enhanced Atomic Layer Deposition)



https://en.wikipedia.org/wiki/Superconducting_tunnel_junction

Title

- aa

Source: