7th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

Thermal Boundary Resistance problems for SRF cavities

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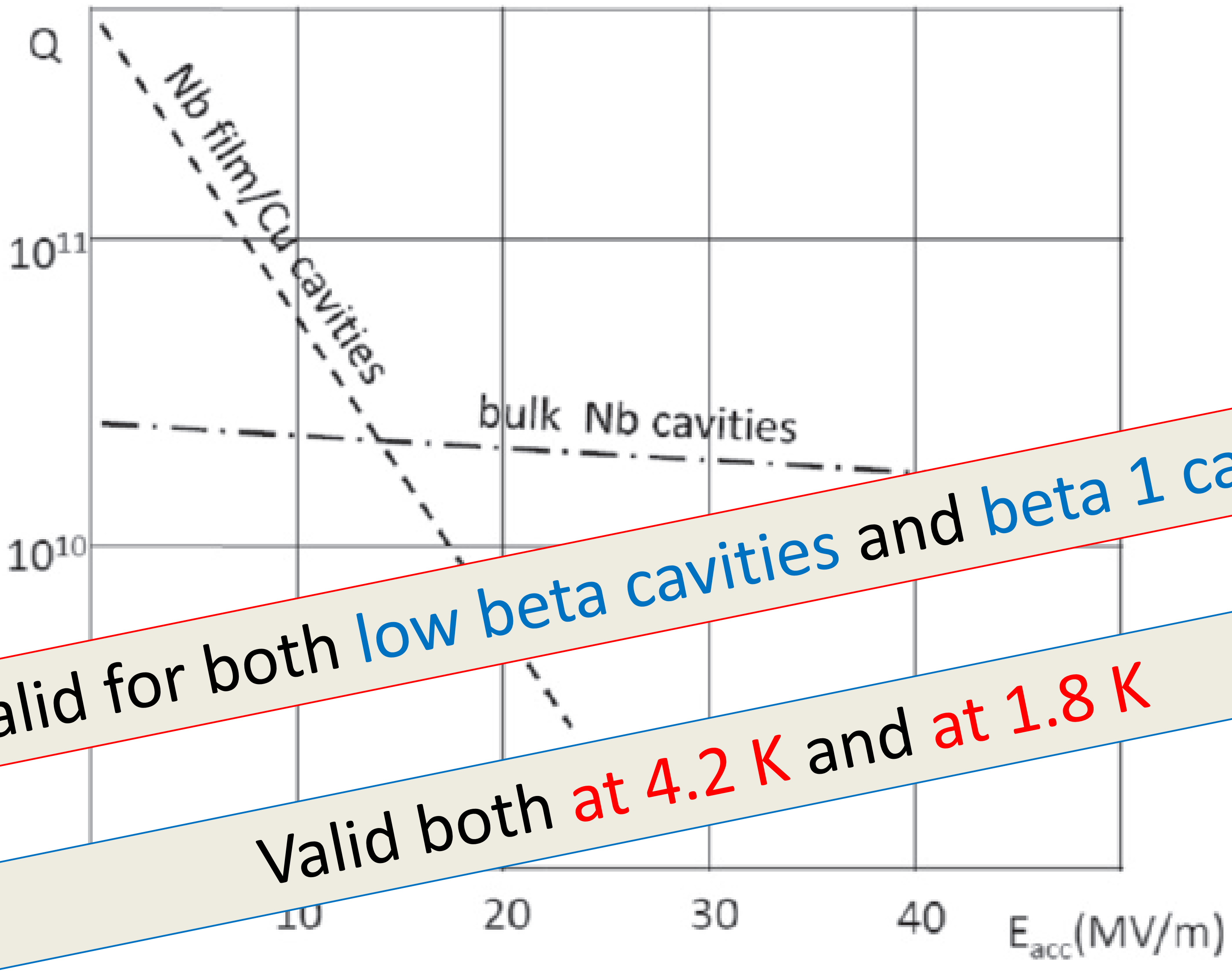
Jefferson Lab
EXPLORING THE NATURE OF MATTER

July 27-29, 2016

The main limitation

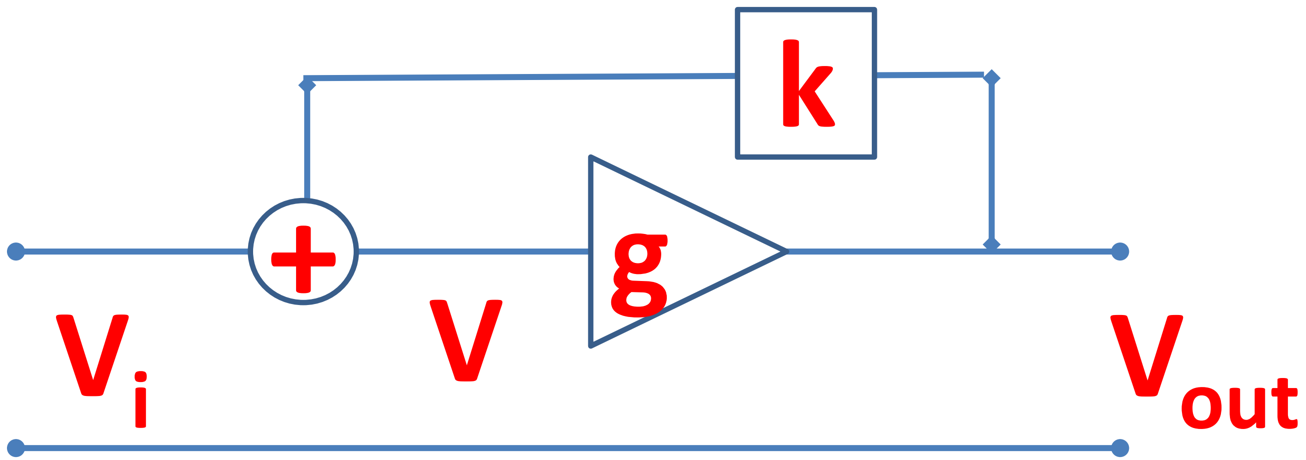


Valid for both low beta cavities and beta 1 cavities

Valid both at 4.2 K and at 1.8 K

Thermal Feedback Model

(Ernst Haebel – CERN 2003)



$$V_{out} = \frac{g\,V_i}{1 - g\,k}$$

Thermal Feedback Model

$$P_{diss} \propto R_S(T)\, U$$

$$U \propto E_{acc}{}^2$$

$$R_S(T) = R_S(T_0) + \left(\frac{\partial R_S}{\partial T}\right)\Big|_{T_0} \Delta T$$

$$R_S(T) = R_S(T_0) + \left(\frac{\partial R_S}{\partial T}\right)\Big|_{T_0} R_{th} P_{diss}$$

Thermal Feedback Model

$$R_S(T) = R_S(T_0) + \left(\frac{\partial R_S}{\partial T}\right)\Bigg|_{T_0} R_{th} P_{diss}$$

$$P_{diss} \propto R_S(T)\, U$$

$$P_{diss} = \left\{ R_S(T_0) + \left(\frac{\partial R_S}{\partial T}\right)\Bigg|_{T_0} R_{th} P_{diss} \right\} \mathrm{U}$$

Thermal Feedback Model

$$P_{diss} = \left\{ R_S(T_0) + \left(\frac{\partial R_S}{\partial T}\right)\Big|_{T_0} R_{th} P_{diss} \right\} \mathrm{U}$$

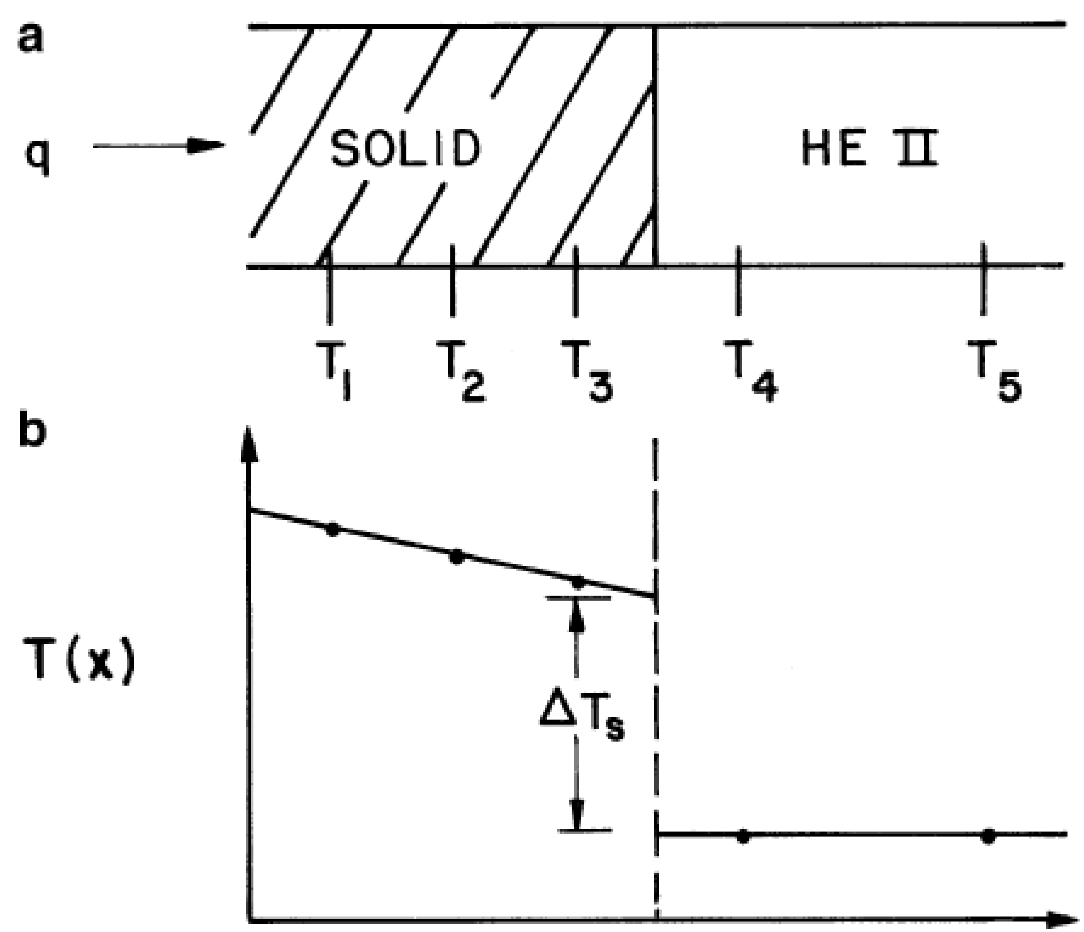
$$Q_0 \propto \frac{U}{P_{diss}} = \frac{\Gamma}{R_{S0}} - \gamma \frac{R_{th}}{R_{S0}} \left(\frac{\partial R_S}{\partial T}\right) \mathrm{U}$$

$$Q_0 = \frac{\Gamma}{R_{S0}} - G \frac{R_{th}}{R_{S0}} \left(\frac{\partial R_S}{\partial T}\right) E_{acc}{}^2$$

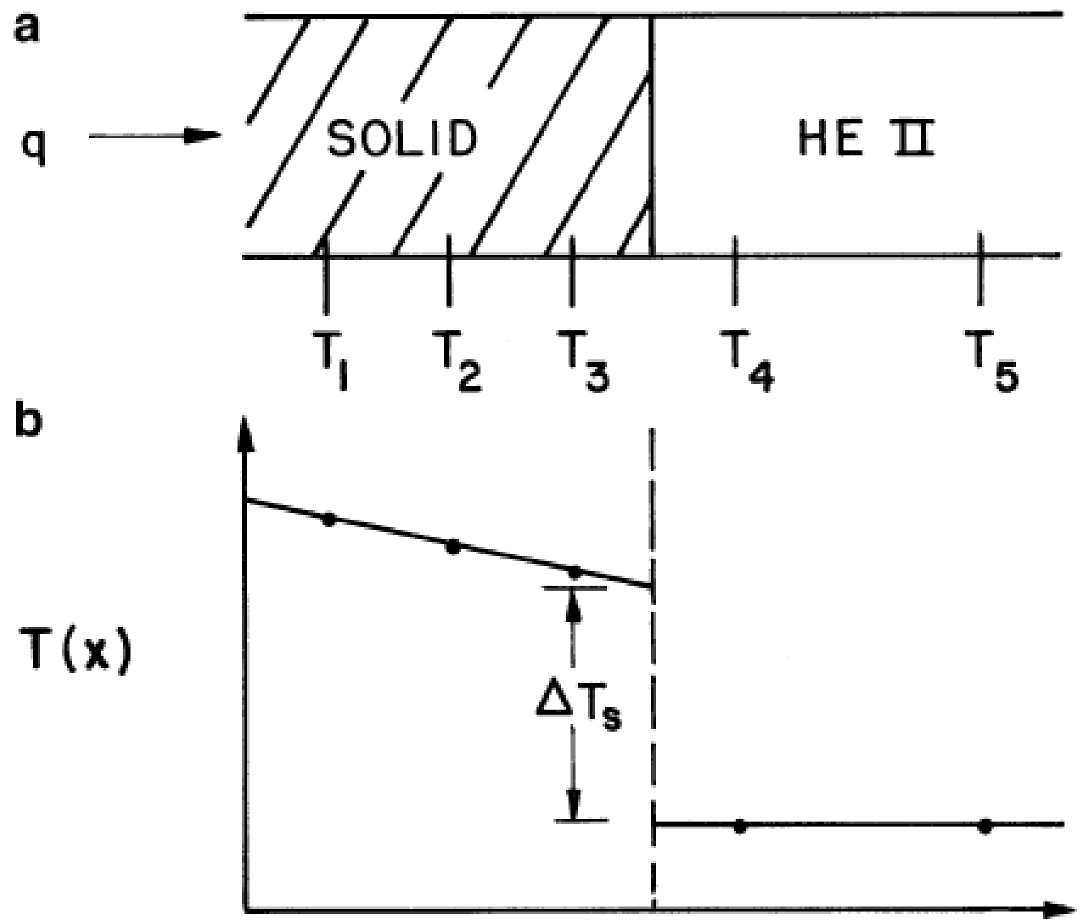
$$Q_0 = \frac{\Gamma}{R_{S0}} - G\,\frac{R_{th}}{R_{S0}}\left(\frac{\partial R_S}{\partial T}\right)E_{acc}{}^2$$

A Q-slope is intrinsic to any cavity supposed a $\mathbf{R_{th}}$ however small

Thermal boundary conductance at the interface between solid and liquid-He was first studied by Kapitza in 1941

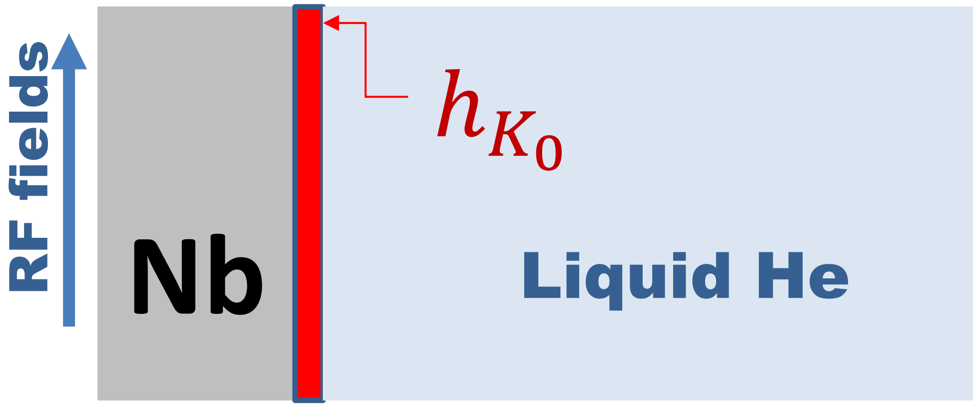


A method to measure R_{th} is described below



The temperature at various points within the solid and He are measured as they vary with applied heat flux q

Kapitza conductance



$$h_{K_0} = \lim_{\Delta T_s \to 0} \frac{q}{\Delta T_s}$$

This quantity has a strong T^n temperature dependence with n varying betwen 2 and 4

Phonon Radiation Limit

A body “above 0 K” contains thermal energy, which in the case of insulators is in the form of a phonon spectrum, while for conductors it may be due partially to the electrons.

Phonon Radiation Limit

In Debye theory, the internal energy may be written as a temperature-dependent quantity,

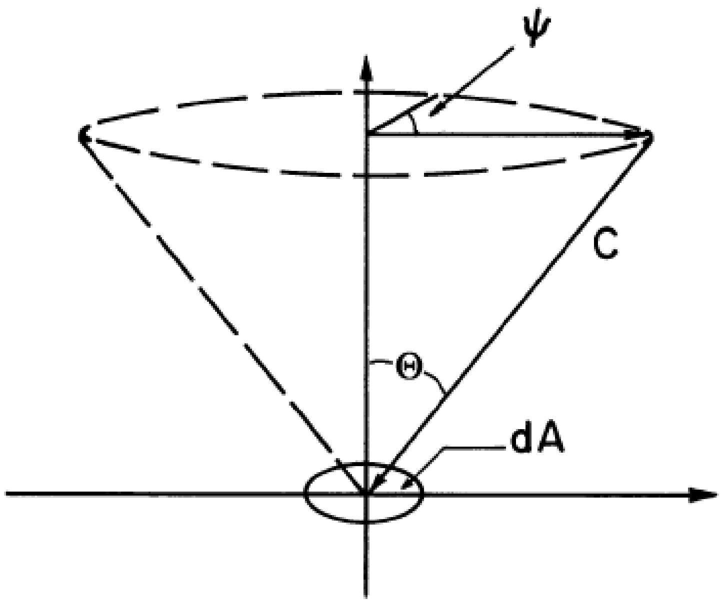
$$E_{Ph} = a\, T^4$$

where $a = \frac{3}{5}\pi^4 (N/V)\, k_B / \Theta_D^3$

and $T \ll \Theta_D$, the Debye temperature

Phonon Radiation Limit

$$q = \frac{1}{4\pi}\int_0^{2\pi} cE_{\text{ph}} \sin\theta \cos\theta d\theta = \frac{1}{4} cE_{\text{ph}}$$



$$E_{Ph} = a\ T^4$$

$$q = \sigma T^4$$

Phonon Radiation Limit

The net heat flux through the interface is a difference between the radiant energy incident on the high-temperature side, $q(T + \Delta T)$, minus that incident from the low-temperature side, $q(T)$

$$q_{net} = q(T + \Delta T) - q(T)$$

$$q_{net} = q(T+\Delta T) - q(T)$$

$$q = \sigma T^4$$

$$q_{net} = \sigma (T+\Delta T)^4 - \sigma (T)^4$$

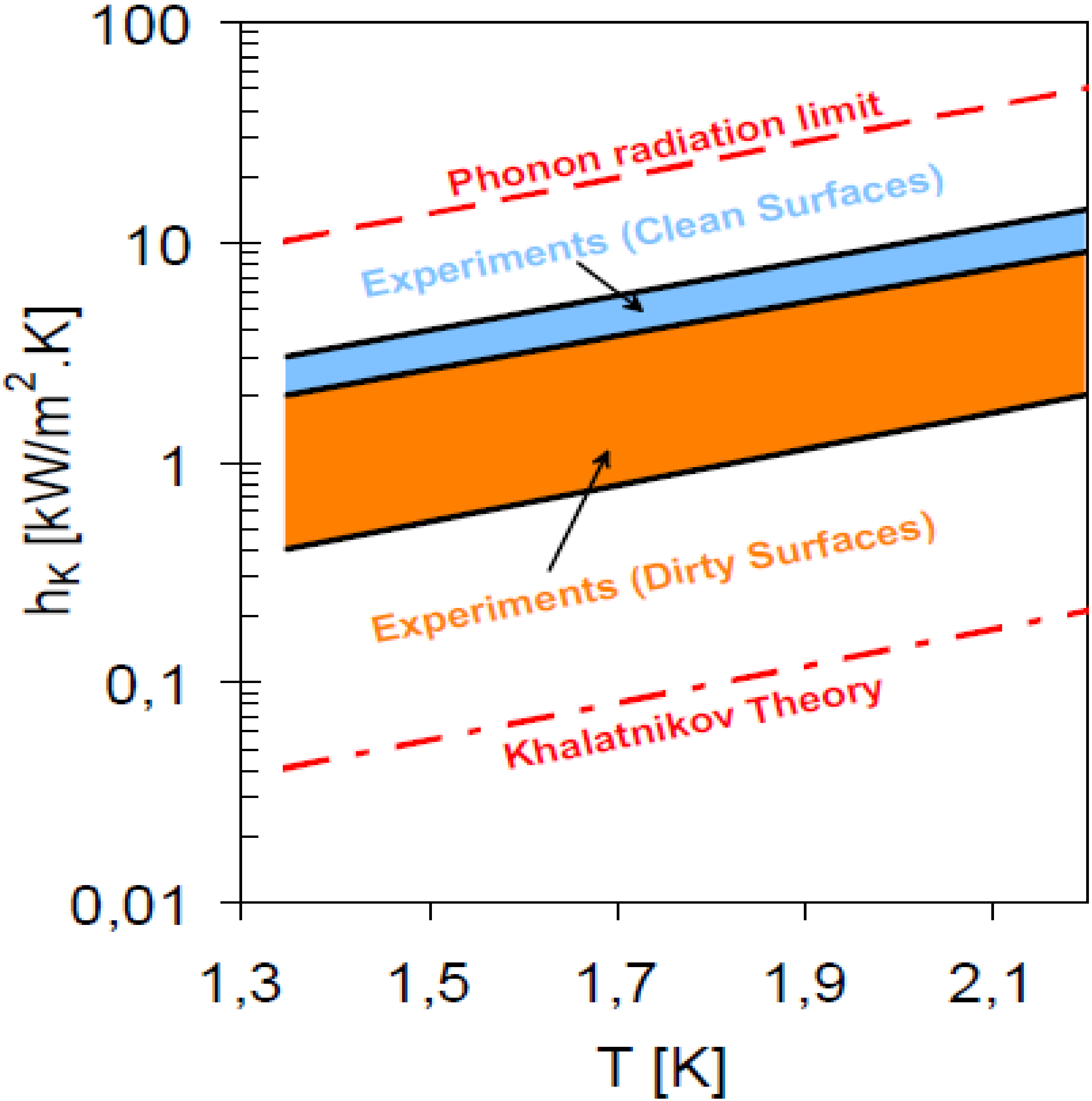
$$q_{net} = 4\sigma T^3 \Delta T \left[1 + \frac{3}{2}\frac{\Delta T}{T} + \left(\frac{\Delta T}{T}\right)^2 + \frac{1}{4}\left(\frac{\Delta T}{T}\right)^3 \right]$$

$$h^{ph}{}_k = 4\,\sigma\,T^3$$

$$h^{ph}{}_{k} = 4\,\sigma\,T^{3}$$

$$R^{ph}{}_{k} \propto\ T^{-3}$$

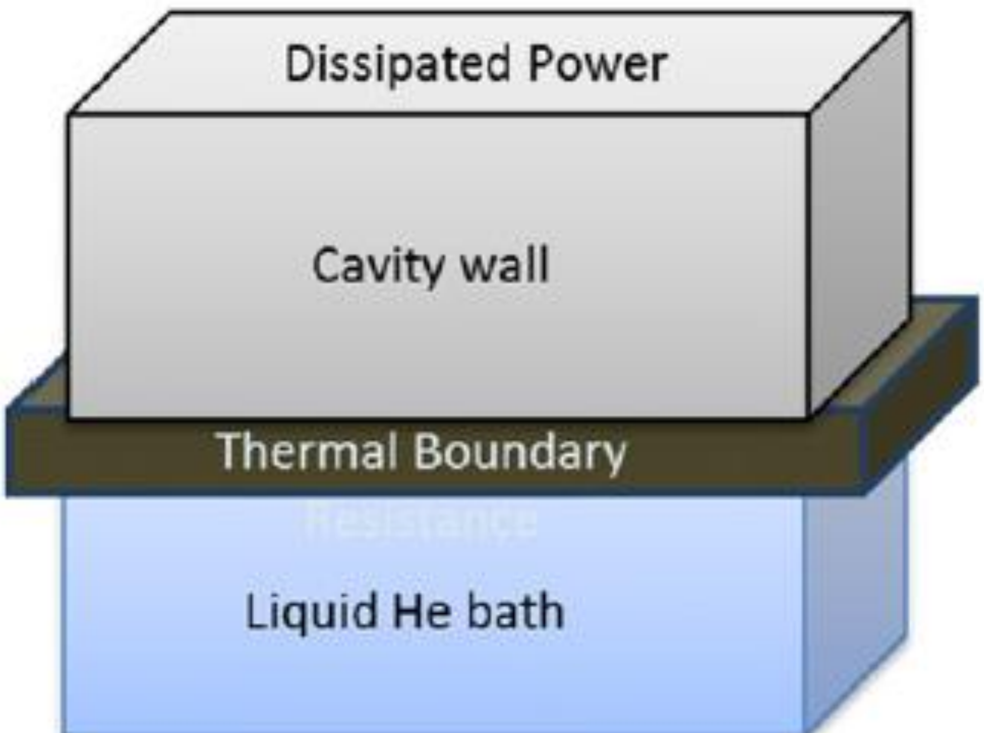
The lower the temperature is, the more important becomes Kapitza resistance!

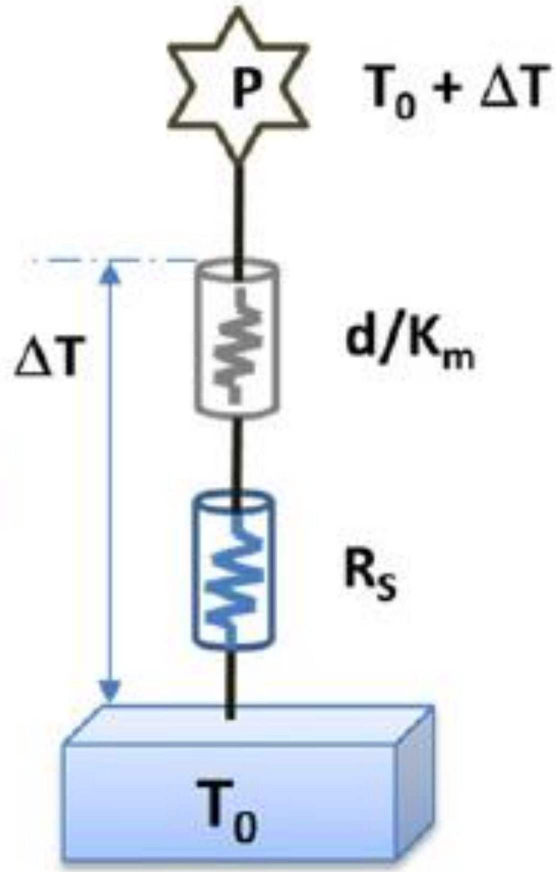


100
10
1
0,1
0,01
1,3
1,5
1,7
1,9
2,1
T [K]
h_K [kW/m^2.K]
Phonon radiation limit
Experiments (Clean Surfaces)
Experiments (Dirty Surfaces)
Khalatnikov Theory

The relevance of **thermal effects** on the cavities has been **widely discussed** in the literature

$$\Delta T \propto R_{th} P_{diss}$$

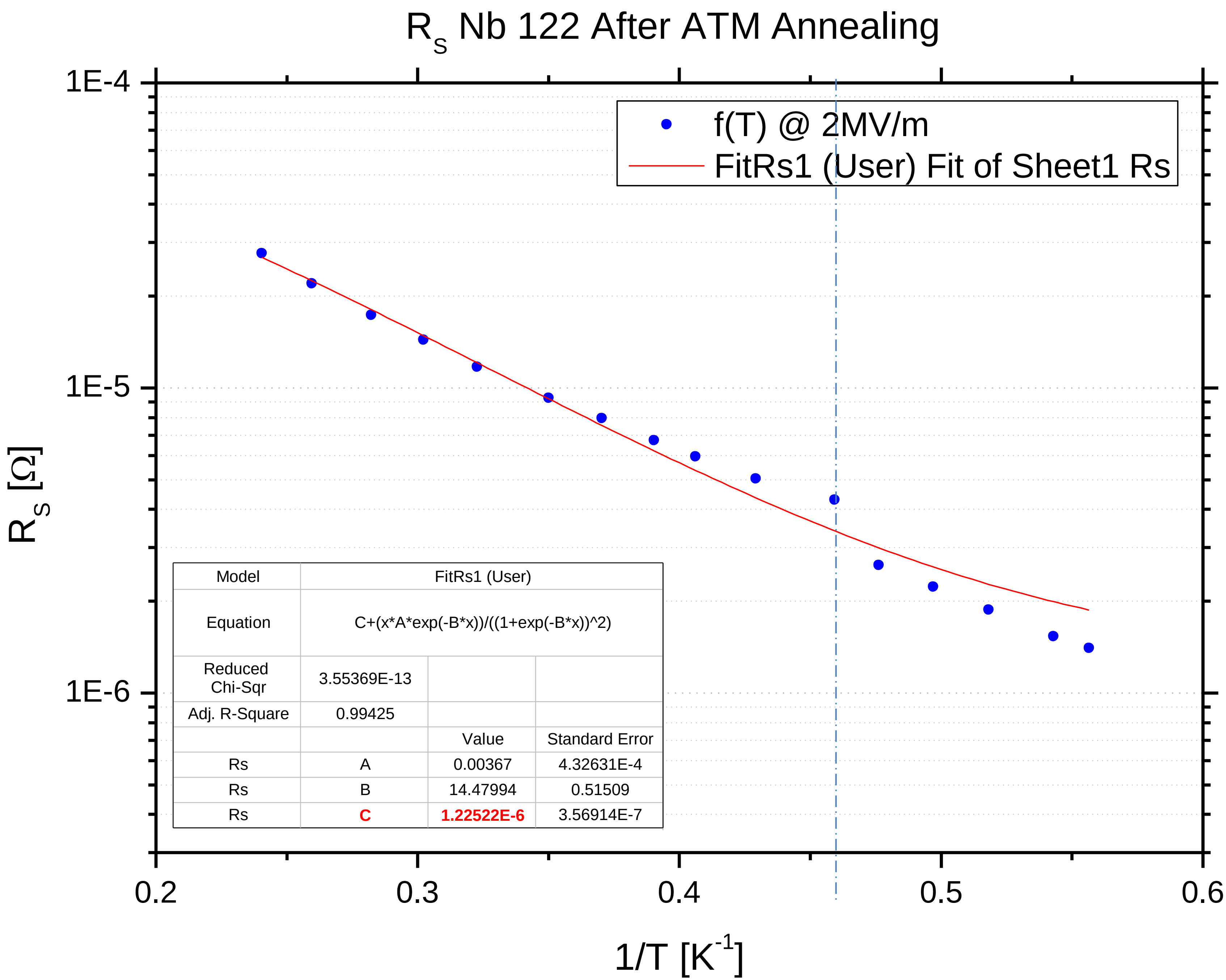




A plethora of papers* state that, beside fundamental interactions, thermal effects are important

* Among the others for instance:
  - Bauer P et al 2006 Physica C ,C441 51
  - Edwards H, Cooper C A, Ge M, Gonin I V, Harms E R and Khabiboulline T N S 2009 Comparison of buffered chemical polished and electropolished 3.9 GHz cavities TUPPO063 Proc. of SRF2009 ed J Knobloch (Berlin, Germany)

Nevertheless never an action was taken in order to control the status of the cavity external surface


R_S Nb 122 After ATM Annealing
1E-4
1E-5
1E-6
R_S [Ω]
0.2
0.3
0.4
0.5
0.6
1/T [K^-1]
f(T) @ 2MV/m
FitRs1 (User) Fit of Sheet1 Rs
Model
FitRs1 (User)
Equation
C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)
Reduced Chi-Sqr
3.55369E-13
Adj. R-Square
0.99425
Value
Standard Error
Rs
A
0.00367
4.32631E-4
Rs
B
14.47994
0.51509
Rs
C
1.22522E-6
3.56914E-7

EFFECT OF LOW TEMPERATURE BAKING ON NIOBIUM CAVITIES *

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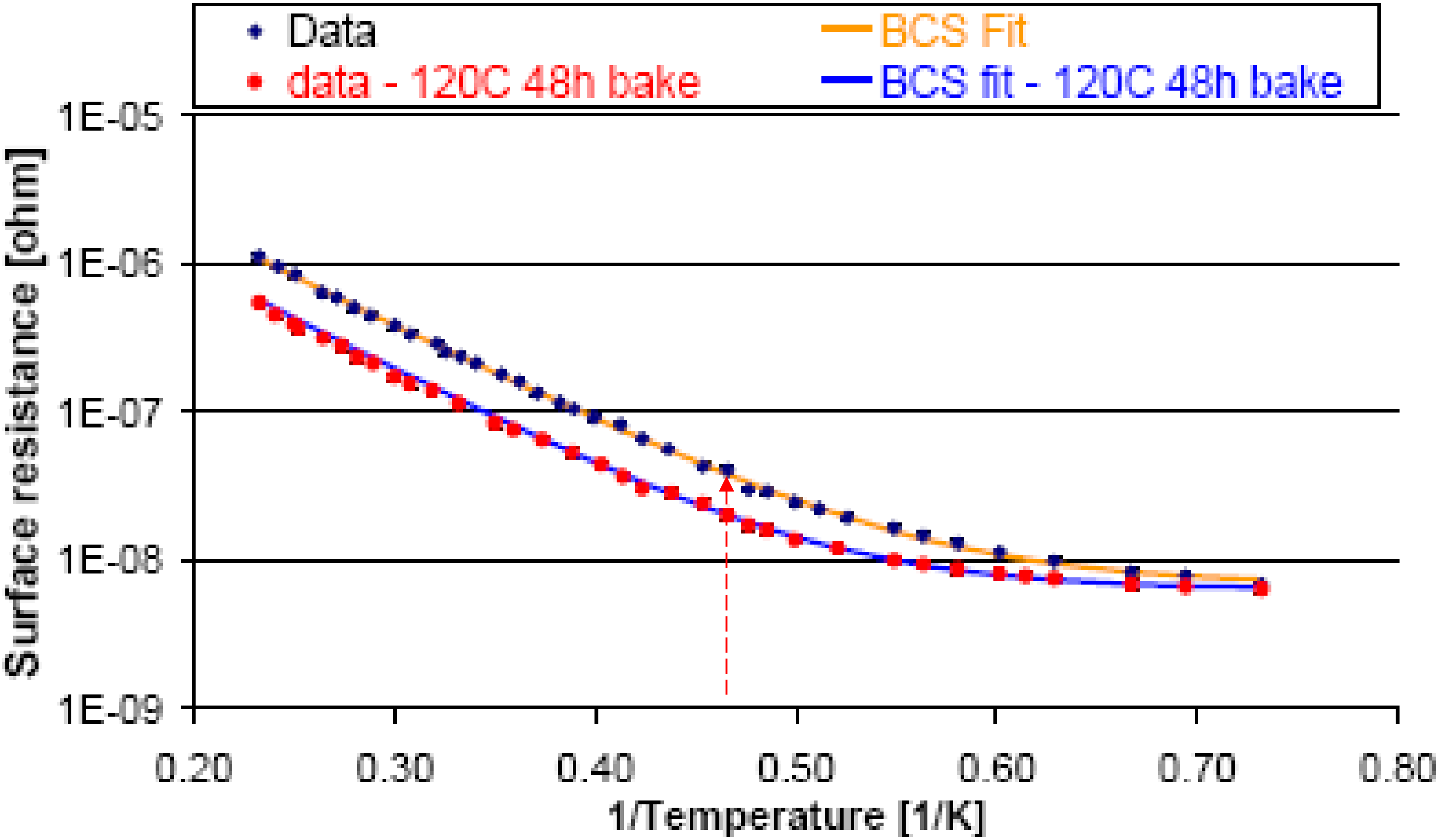

Figure 15: Surface resistance vs. 1/temperature before and after 120°C, 48h baking.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
16, 042001 (2013)

Effect of high temperature heat treatments on the quality factor of a large-grain superconducting radio-frequency niobium cavity

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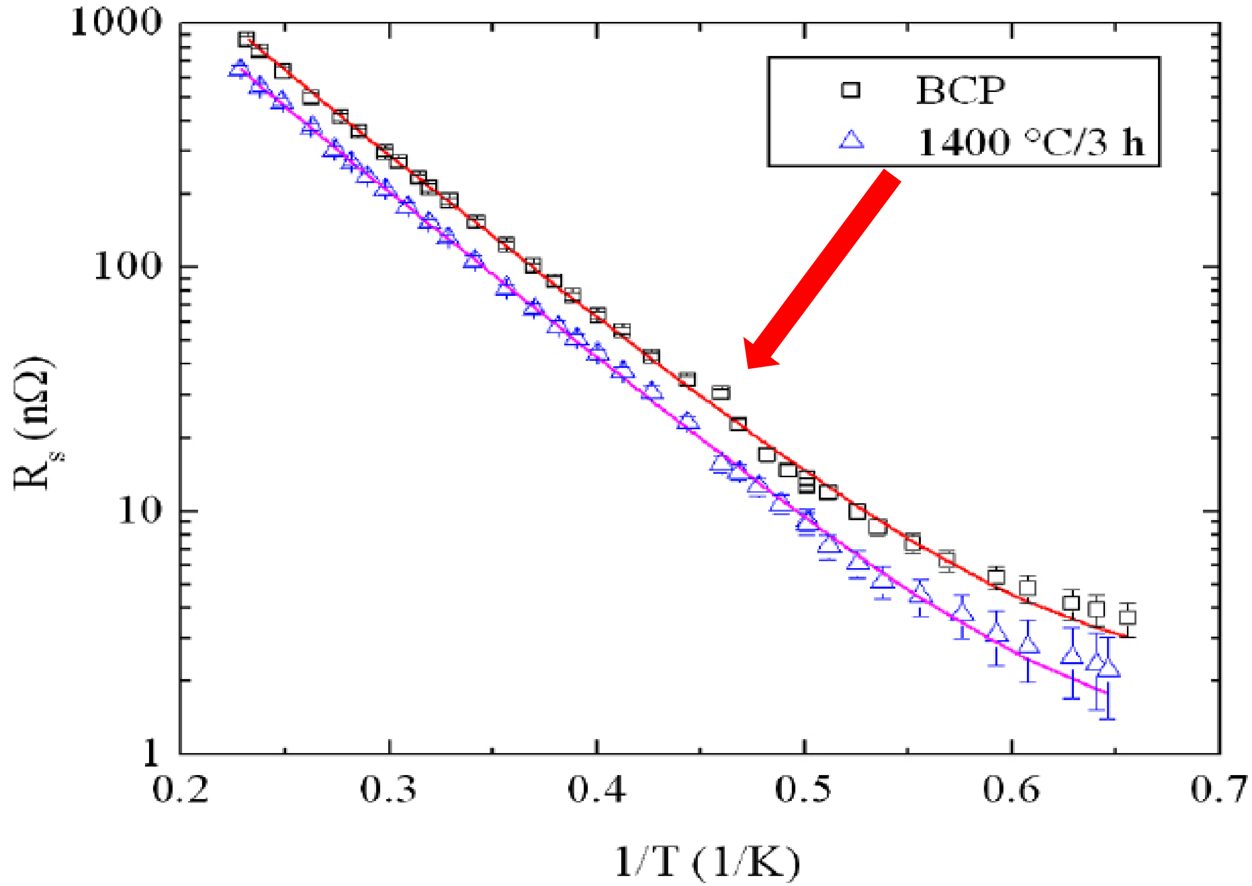
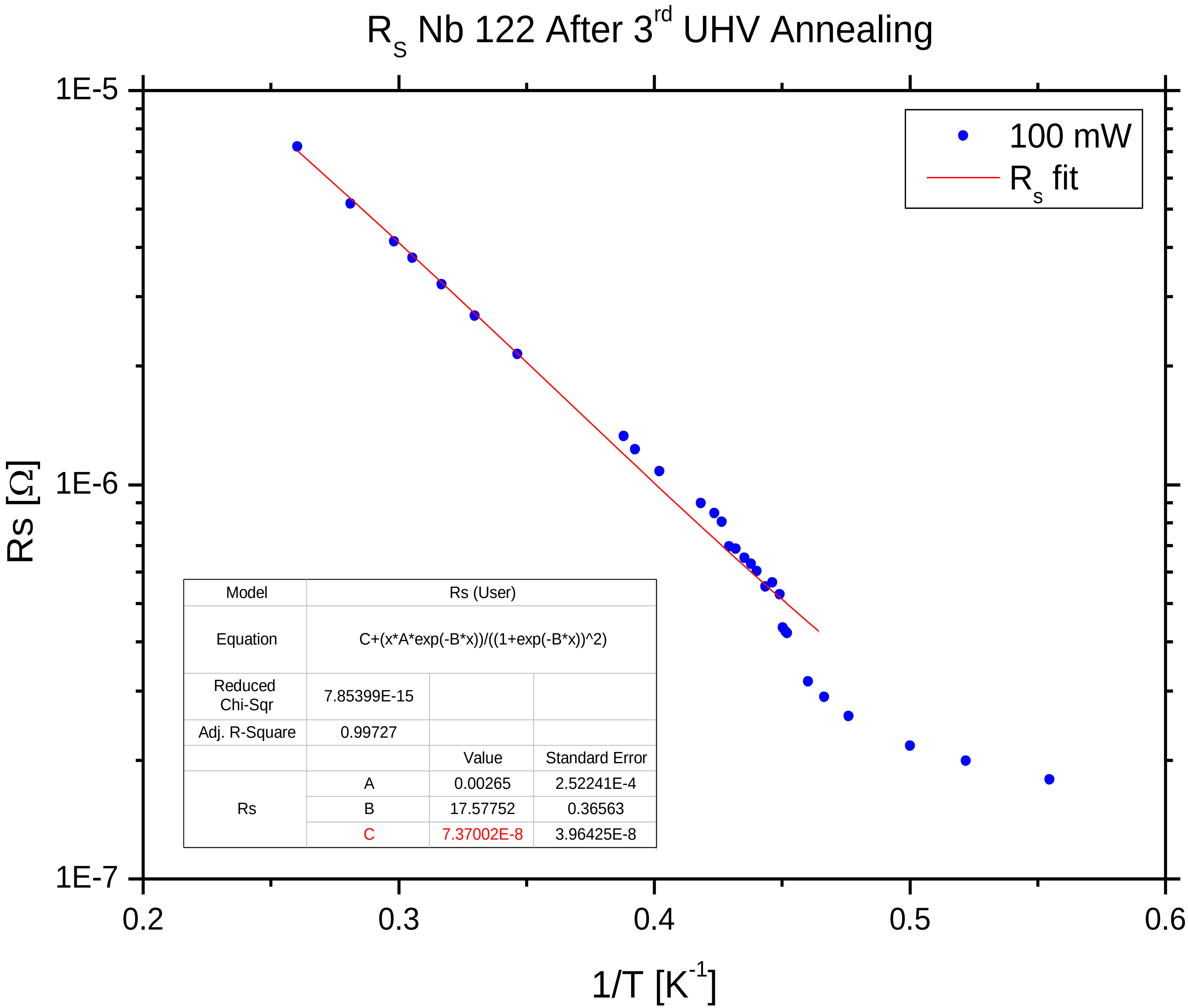
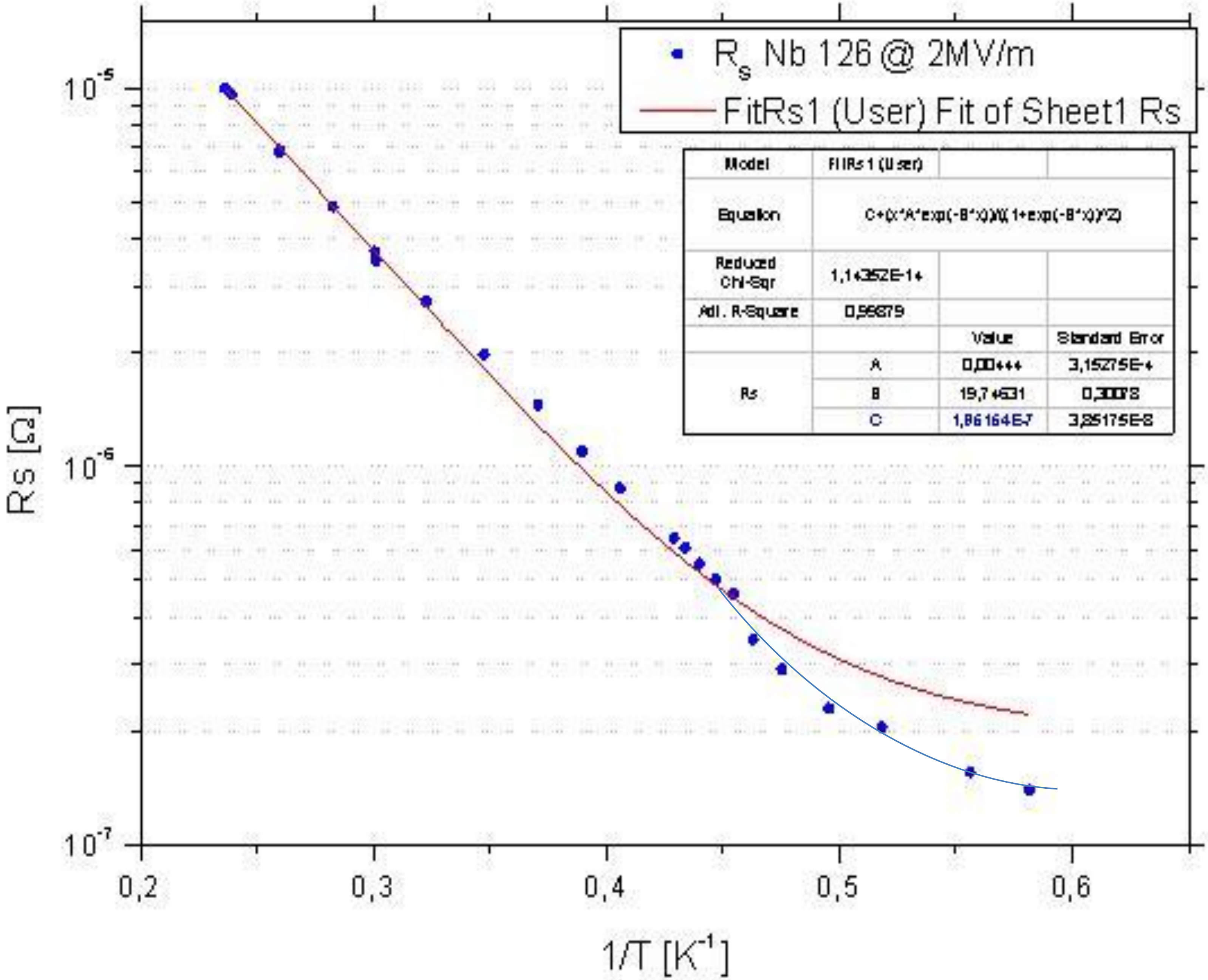


FIG. 9. R_s vs $1/T$ measured after BCP and after HT at 1400°C. Solid lines are least-square fits with $R_s(T) = R_{BCS}(T) + R_{res}$. The values of the fit parameters are $\Delta/kT_c = 1.87 \pm 0.02$, $\ell = (303 \pm 85)$ nm, $R_{res} = (2.0 \pm 0.3)$ nΩ after BCP and $\Delta/kT_c = 1.90 \pm 0.01$, $\ell = (76 \pm 17)$ nm, $R_{res} = (1.0 \pm 0.2)$ nΩ after HT at 1400°C.

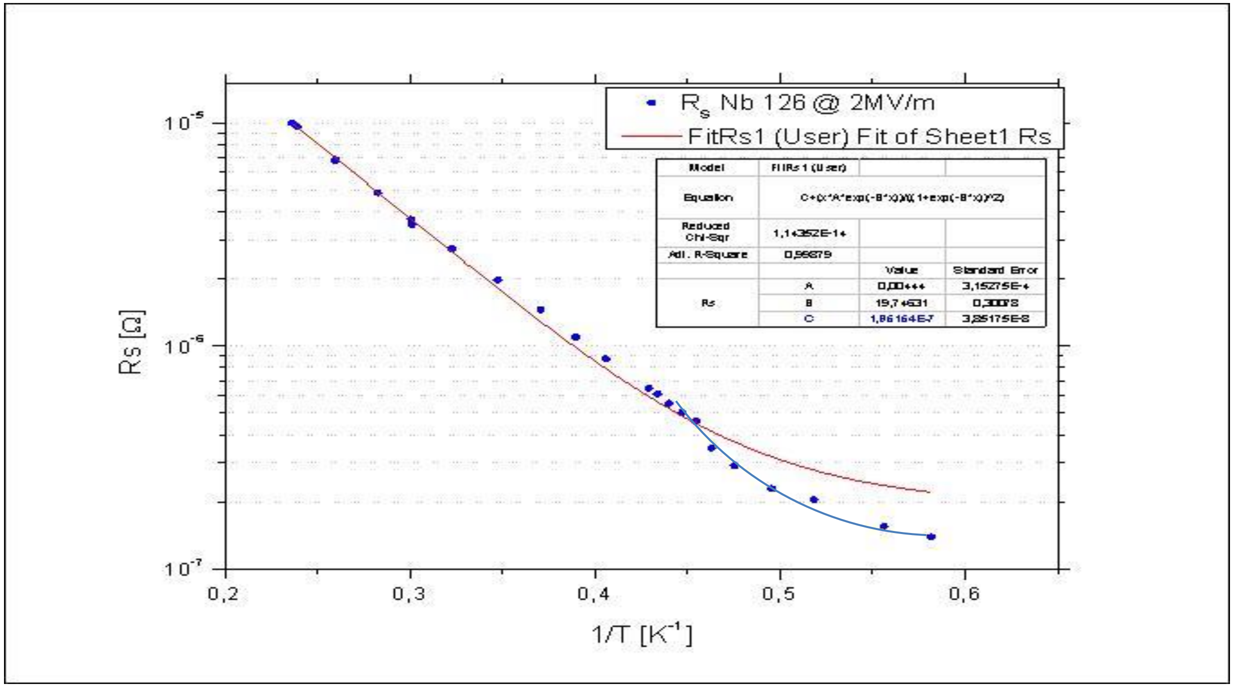


Model	Rs (User)		
Equation	C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)		
Reduced Chi-Sqr	7.85399E-15		
Adj. R-Square	0.99727		
		Value	Standard Error
Rs	A	0.00265	2.52241E-4
	B	17.57752	0.36563
	C	7.37002E-8	3.96425E-8

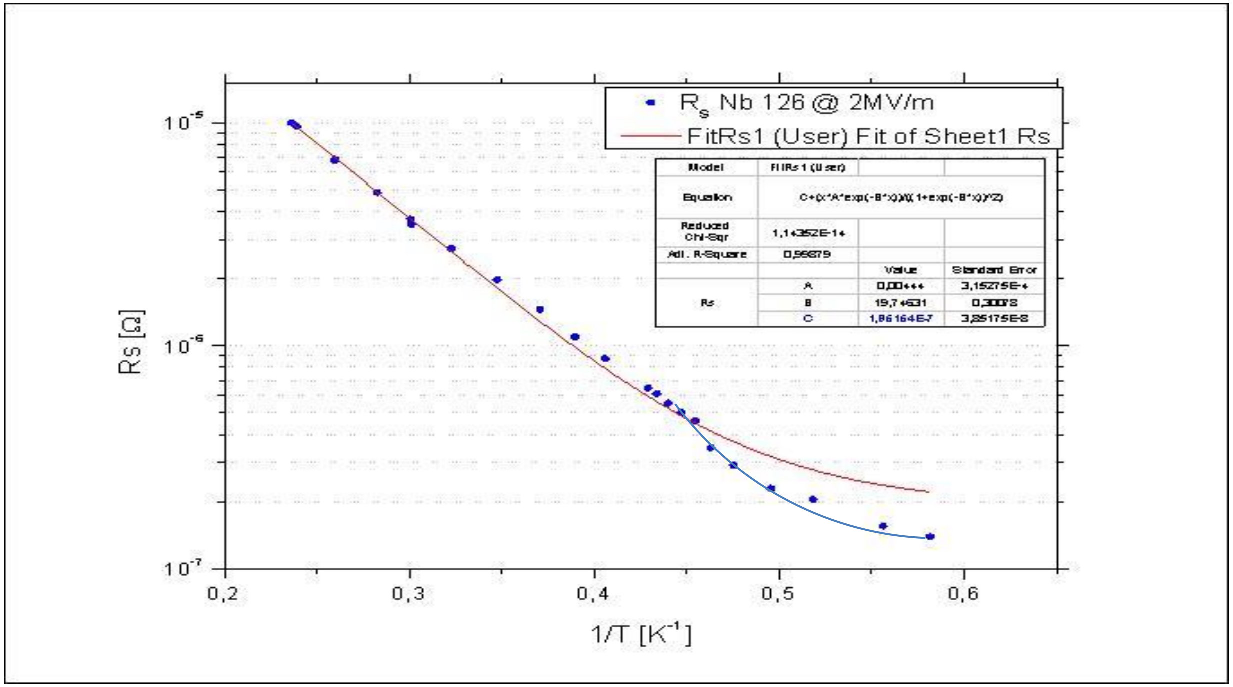


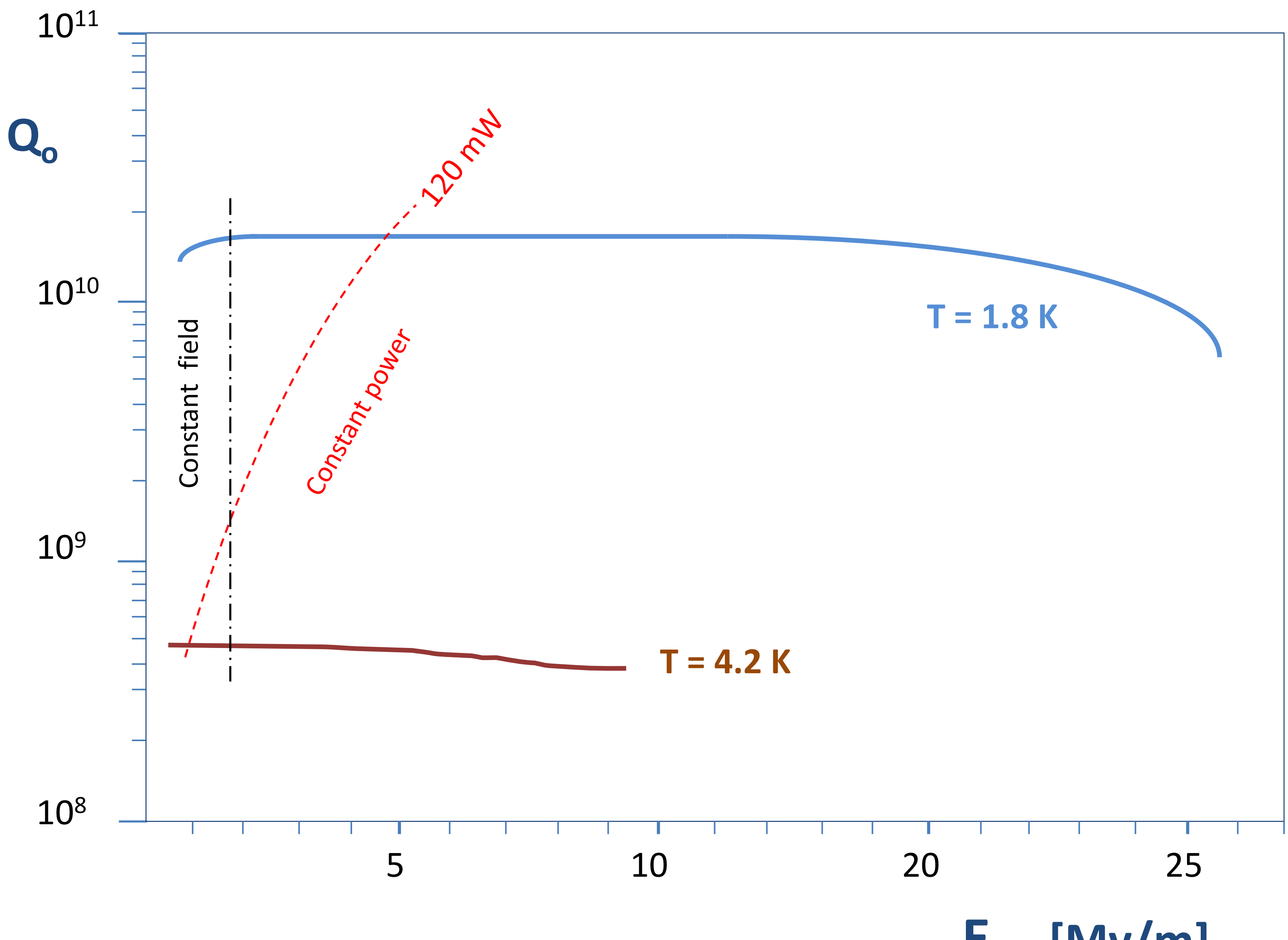
Rs Nb 126 @ 2MV/m
FitRs1 (User) Fit of Sheet1 Rs
Model
FitRs1 (User)
Equation
C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)
Reduced Chi-Sqr
1,14352E-14
Adj. R-Square
0,99879
Value
Standard Error
Rs
A
0,00444
3,15275E-4
B
19,74631
0,30078
C
1,86164E-7
3,25175E-8
Rs [Ω]
1/T [K⁻¹]
0,2
0,3
0,4
0,5
0,6
10⁻⁵
10⁻⁶
10⁻⁷

If we cooled the cavity in ^{3}He instead then in ^{4}He, should we wait a different R_{RES}?

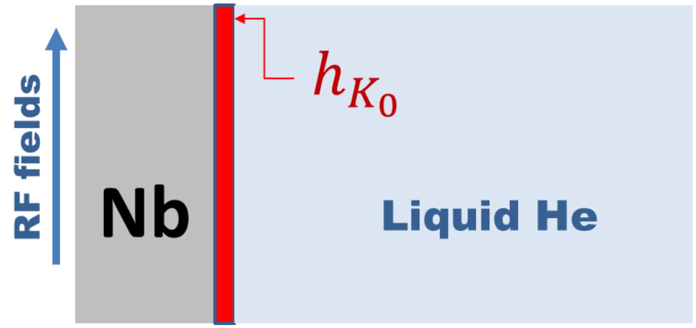


in other words, R_{RES} depends on Liquid He instead than on Nb material?



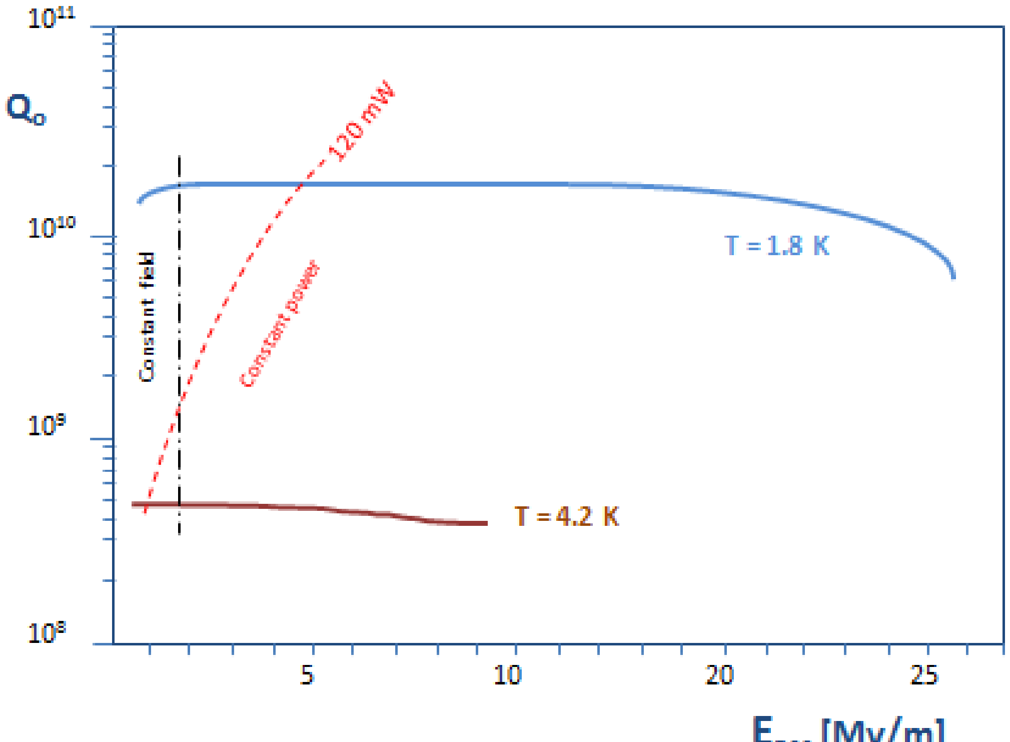


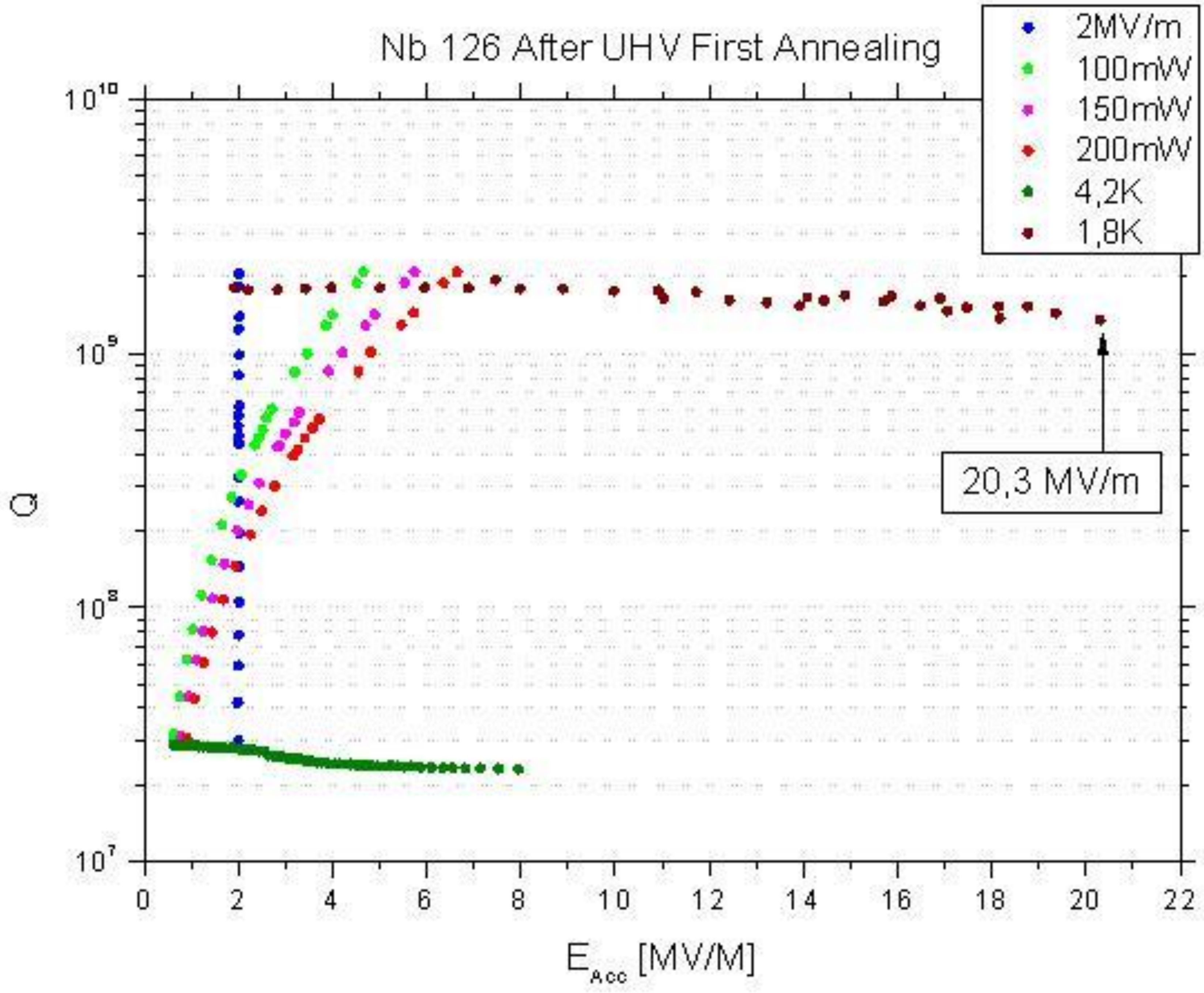
10^{11}
10^{10}
10^{9}
10^{8}
Q_o
120 mW
Constant power
Constant field
T = 1.8 K
T = 4.2 K
5
10
20
25
E_{acc} [Mv/m]

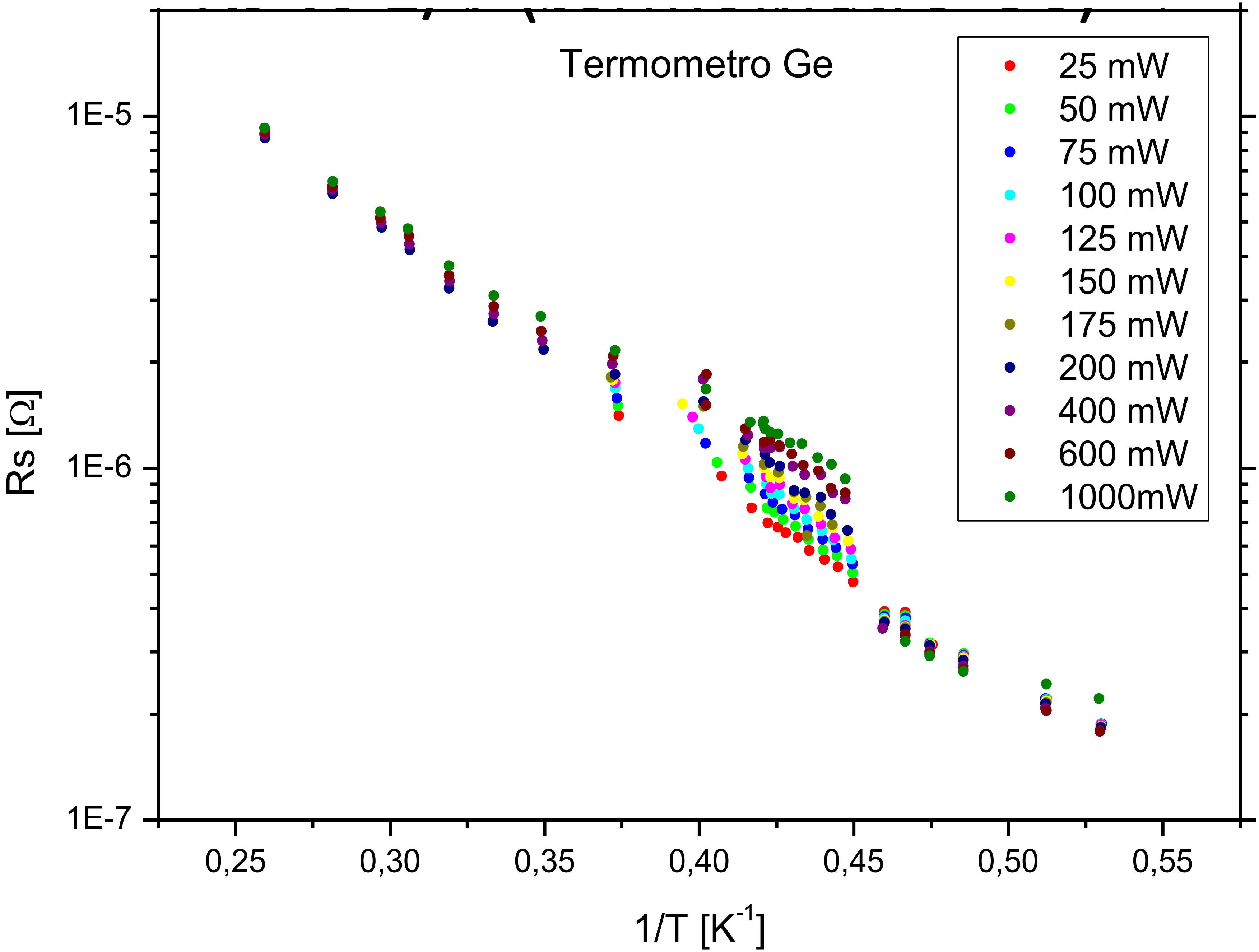


Constant E_{acc} means that both T and W are changing

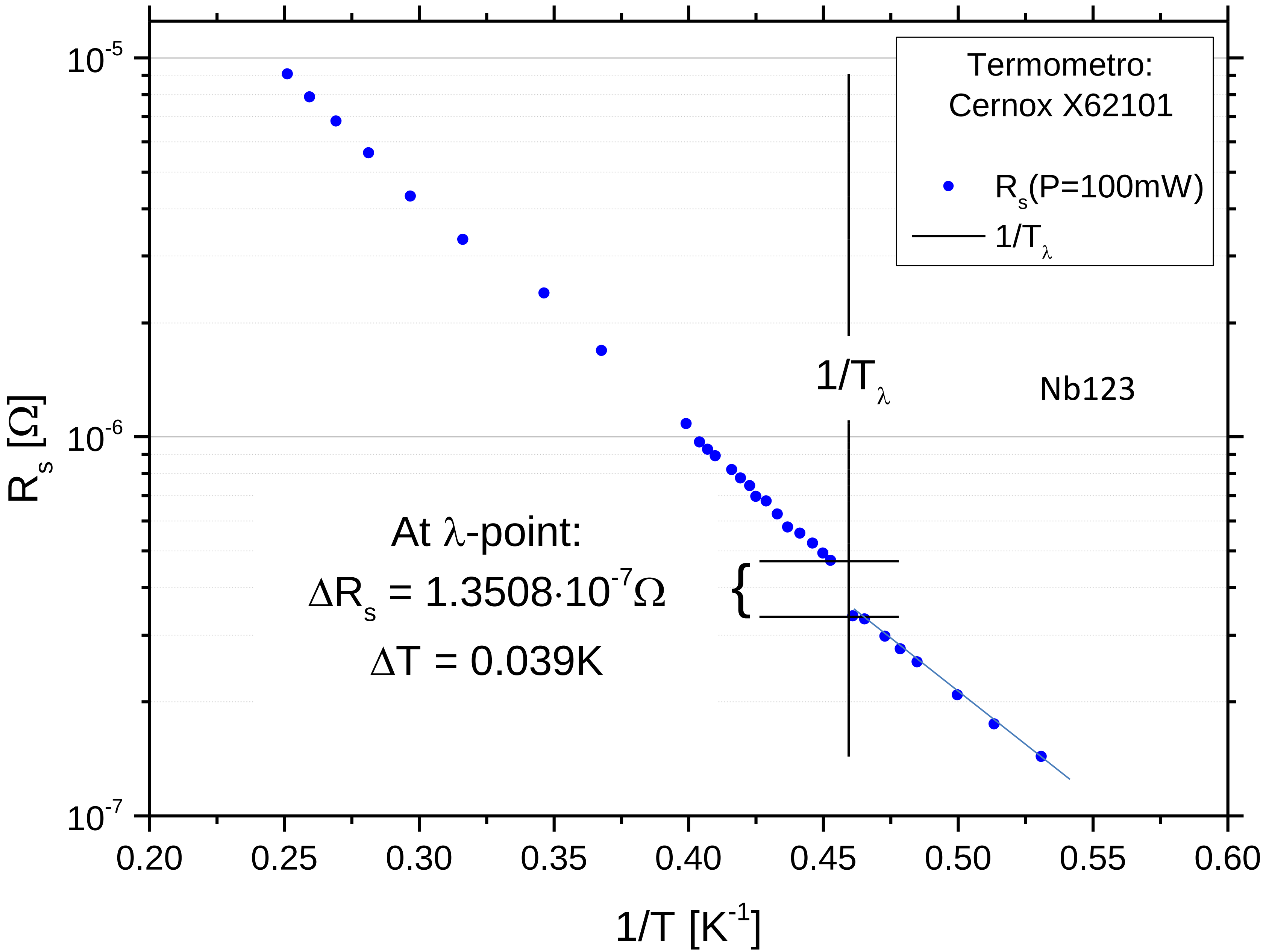
Constant W means that, apart E_{acc} only T is changing




Nb 126 After UHV First Annealing
2MV/m
100mW
150mW
200mW
4,2K
1,8K
20,3 MV/m
Q
10^{10}
10^{9}
10^{8}
10^{7}
0
2
4
6
8
10
12
14
16
18
20
22
E_{Acc} [MV/M]


Termometro Ge
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW
Rs [Ω]
1E-5
1E-6
1E-7
1/T [K^-1]
0,25
0,30
0,35
0,40
0,45
0,50
0,55

Rs vs 1/T [P=100mW]



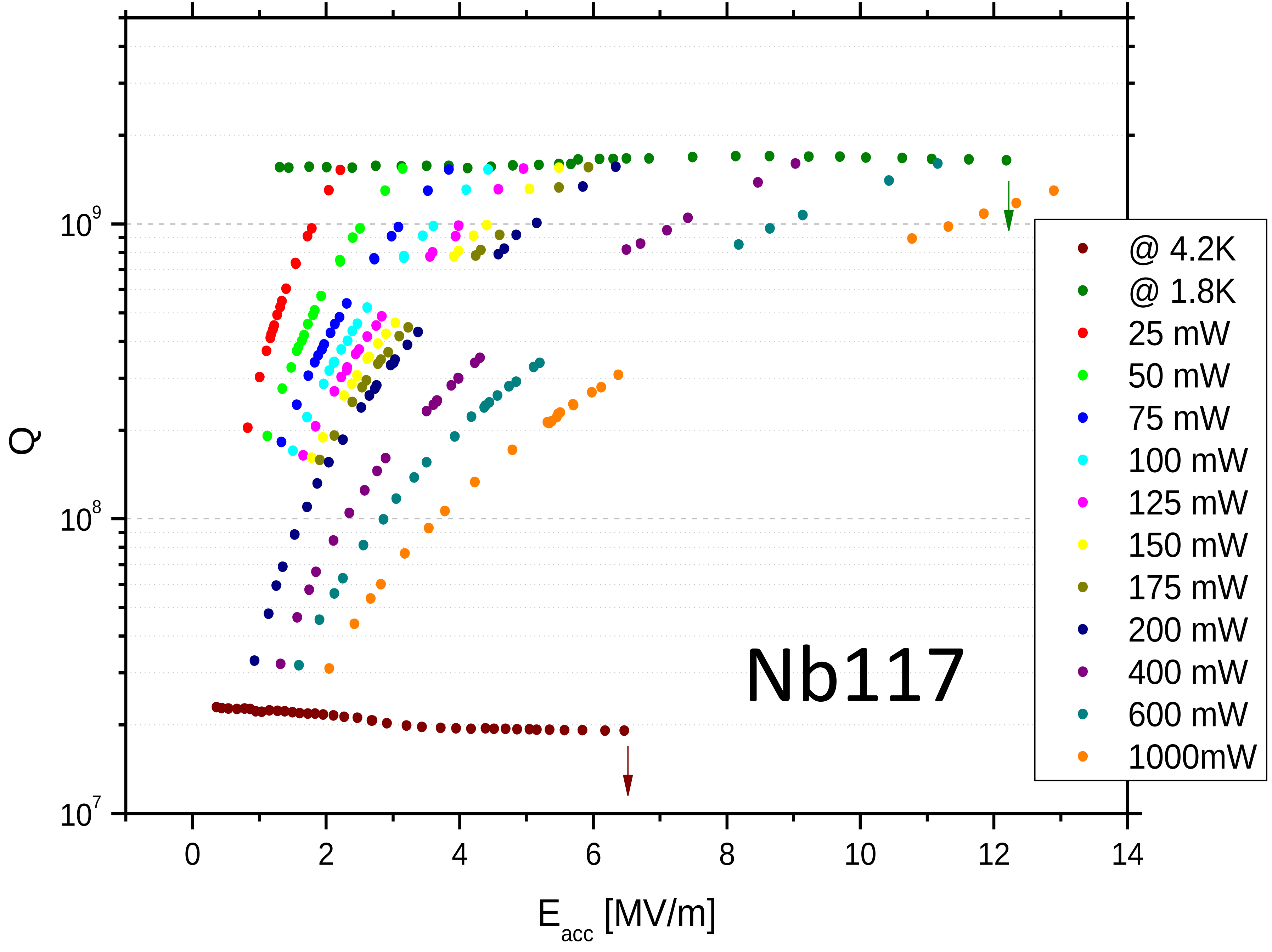
So, whenever we neglect the jump at T_λ, we extract a false value of the strong coupling factor S !!!

$$R_{BCS}(T_0) = \frac{A\omega^2}{T_0} \exp\left[-\frac{sT_C}{2T_0}\right]$$

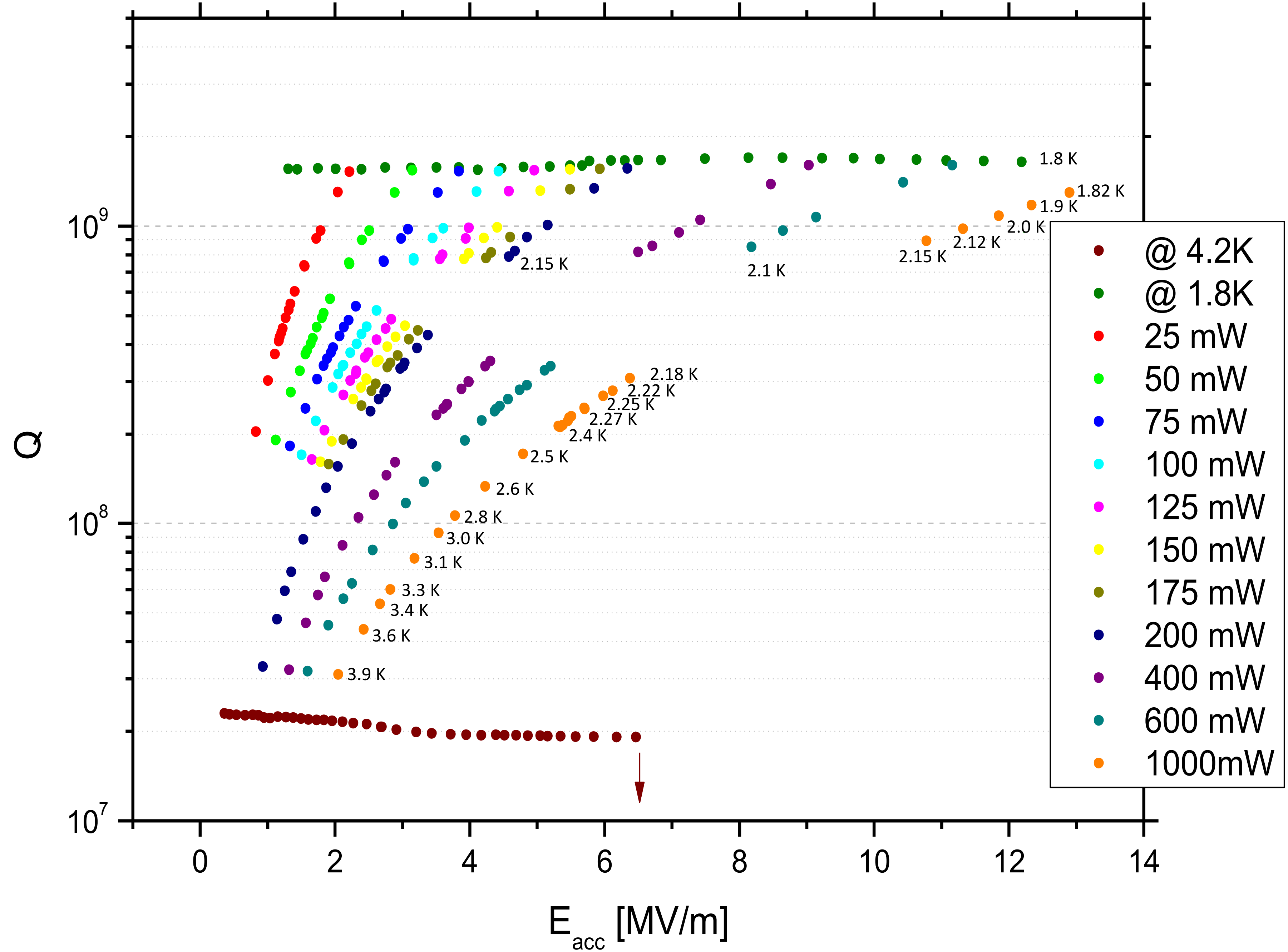
$$R_{BCS}(T_0 + \Delta T) \approx \frac{A\omega^2}{T_0} \exp\left[-\frac{sT_C}{2(T_0 + \Delta T)}\right]$$

$$R_{BCS}(T_0 + \Delta T) \approx \frac{A\omega^2}{T_0} \exp\left[-\frac{sT_C}{2T_0}\left(1 - \frac{\Delta T}{T_0}\right)\right]$$

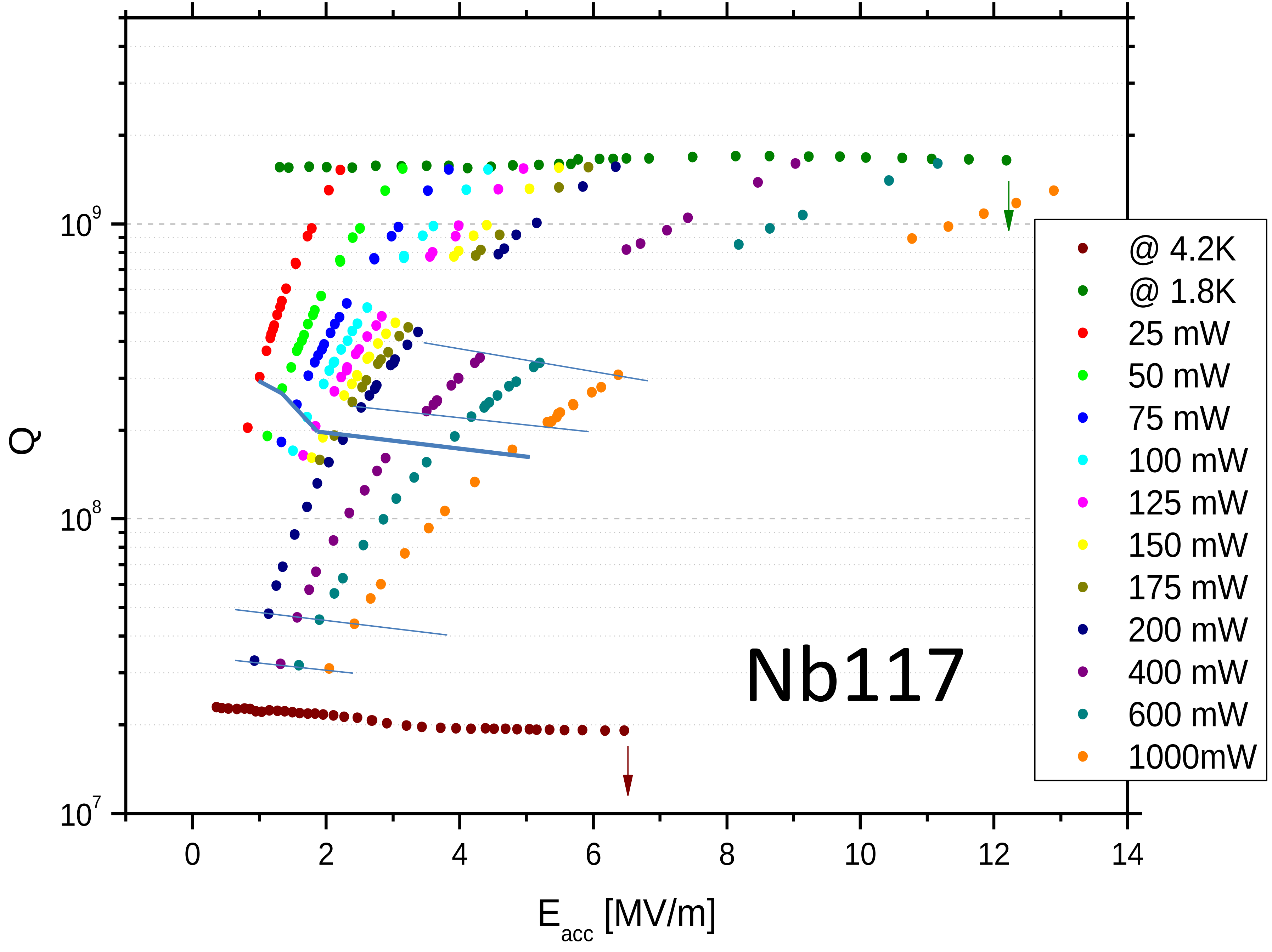
$$s^{meas} = s\left(1 - \frac{\Delta T}{T_0}\right)$$



Q
10^9
10^8
10^7
0
2
4
6
8
10
12
14
E_{acc} [MV/m]
@ 4.2K
@ 1.8K
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW
Nb117



Q
10^9
10^8
10^7
0
2
4
6
8
10
12
14
E_{acc} [MV/m]
1.8 K
1.82 K
1.9 K
2.0 K
2.12 K
2.15 K
2.1 K
2.15 K
2.18 K
2.22 K
2.25 K
2.27 K
2.4 K
2.5 K
2.6 K
2.8 K
3.0 K
3.1 K
3.3 K
3.4 K
3.6 K
3.9 K
@ 4.2K
@ 1.8K
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW



Q
10^9
10^8
10^7
0
2
4
6
8
10
12
14
E_{acc} [MV/m]
@ 4.2K
@ 1.8K
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW
Nb117

Which strange dissipation mechanism makes the Q-factor decreasing linearly with W, but at a certain point it becomes almost constant?

International Cryogenics Monograph Series
Series Editor: Klaus D. Timmerhaus · Carlo Rizzuto

Steven W. Van Sciver

Helium Cryogenics

Second Edition

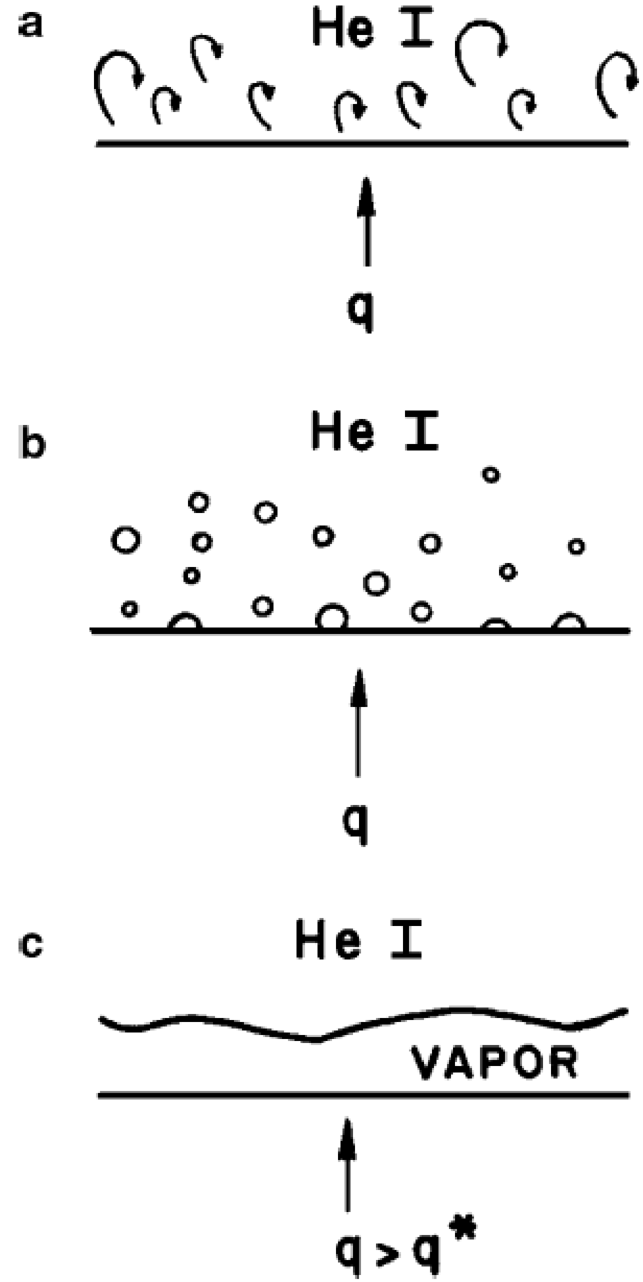
Springer

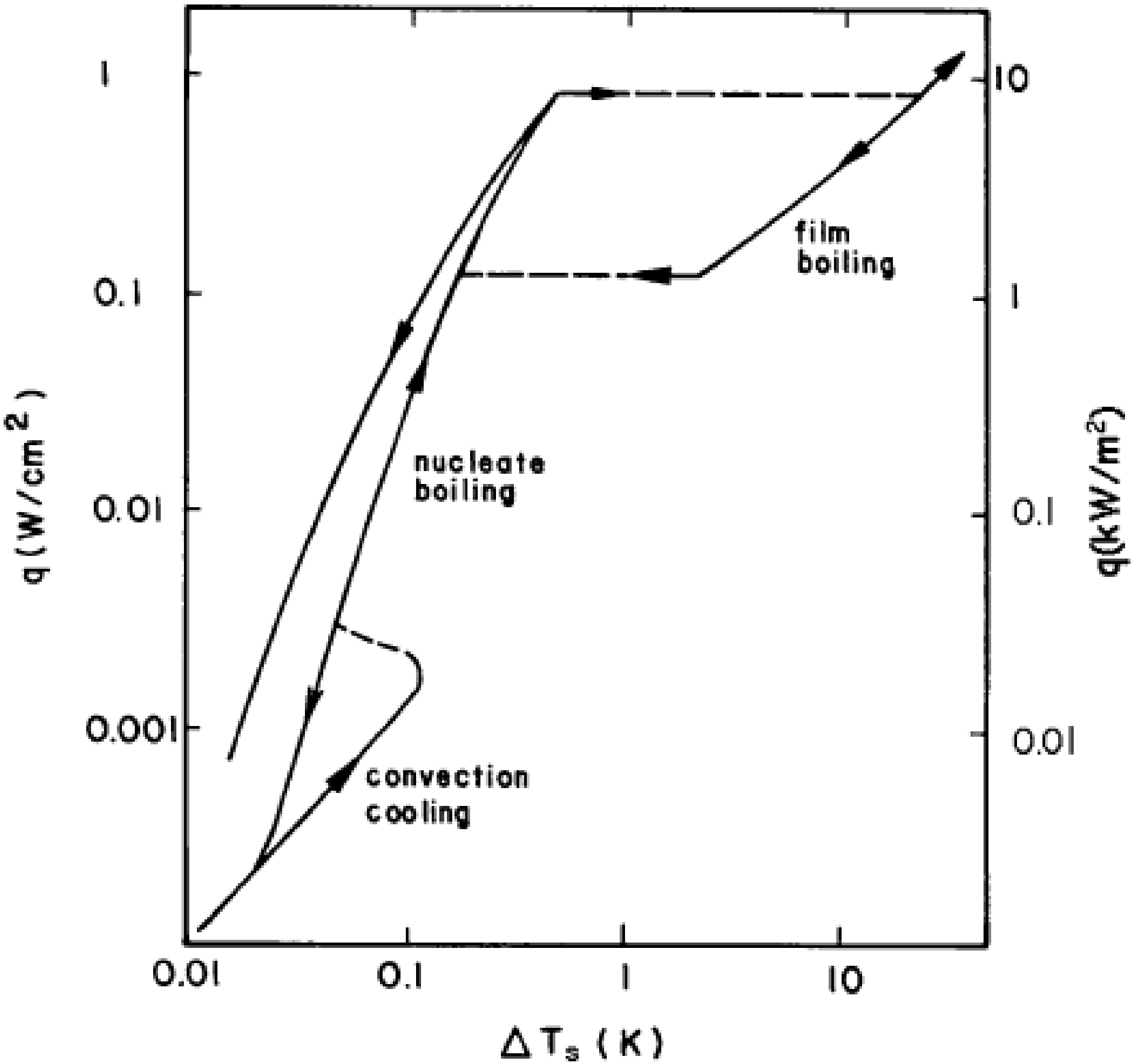
Schemathic representation of regimes of heat transfer:

a) Naural convection

b) Nucleate boiling

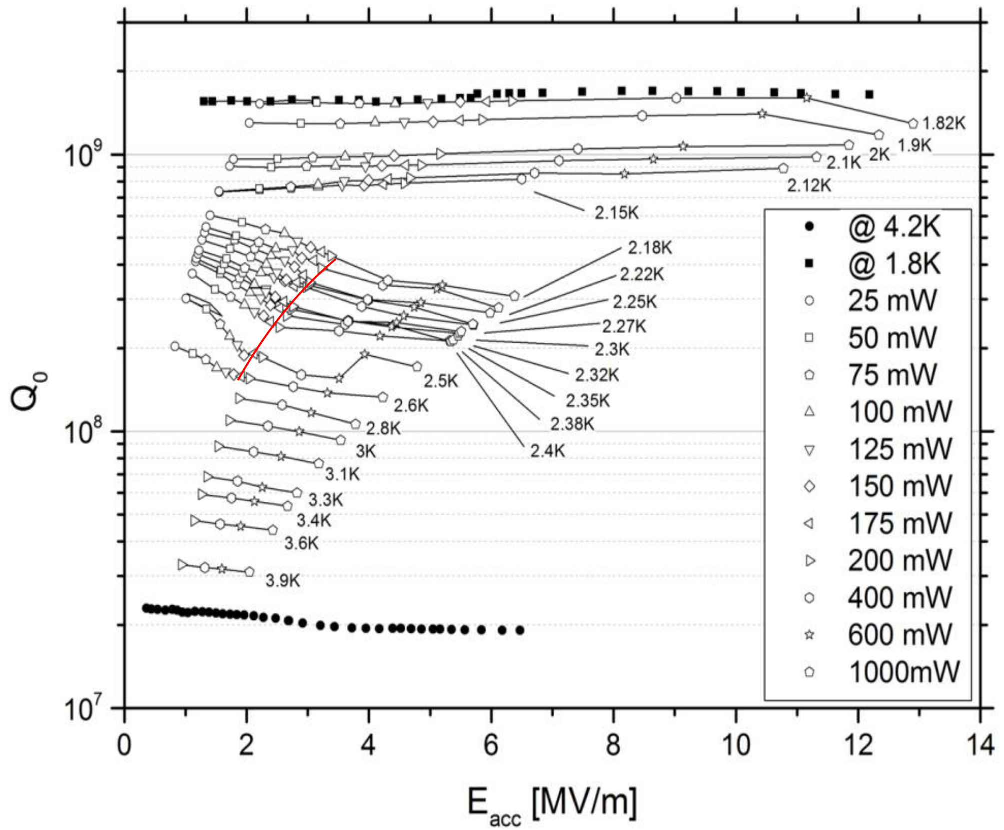
c) Fim boiling





Typical heat transfer for pool boiling liquid

The critical power where the losses change slope do correspond to the **He boiling nucleation**?



Q-SLOPE ANALYSIS OF NIOBIUM SC RF CAVITIES

K.Saito#, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, Japan

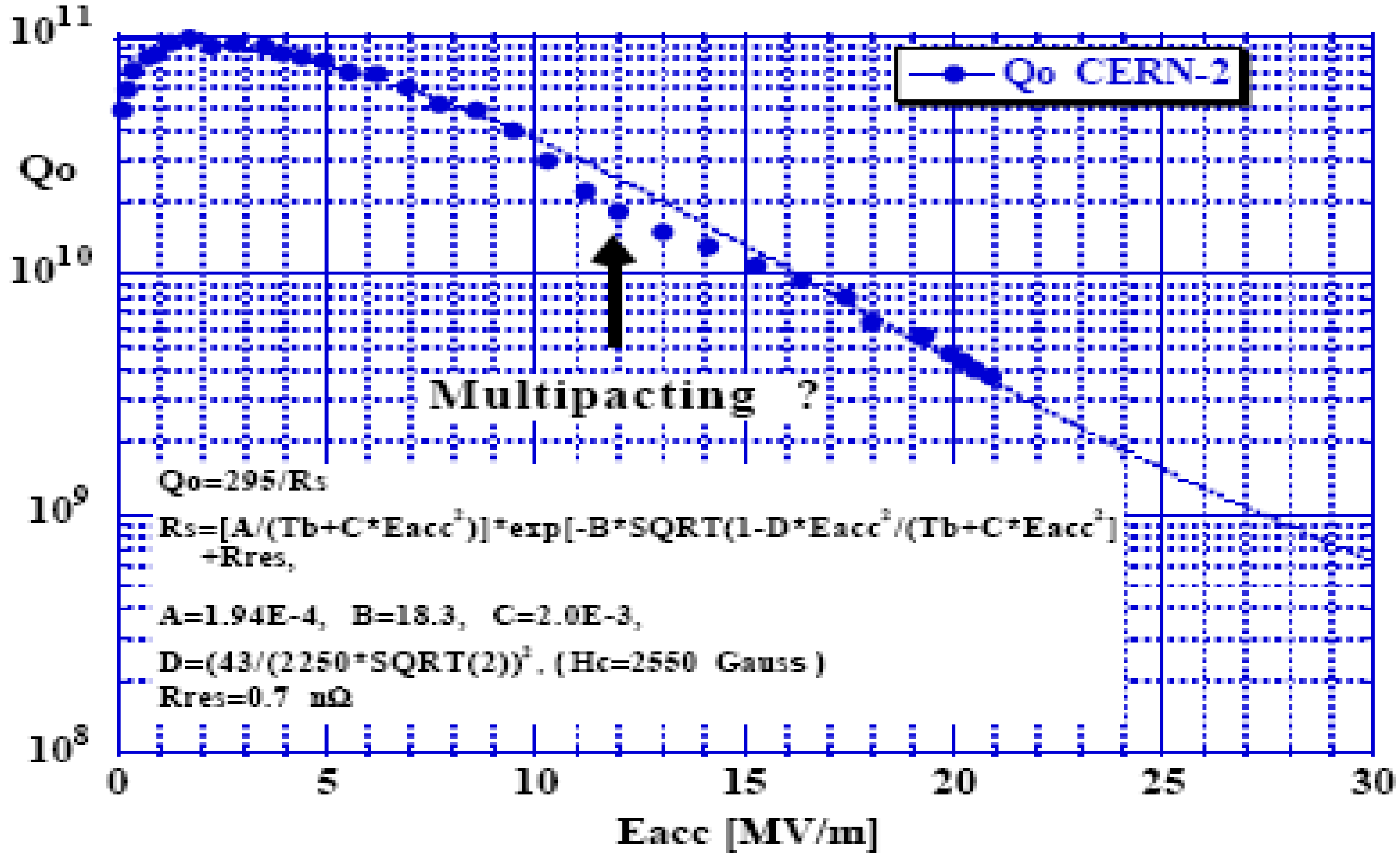
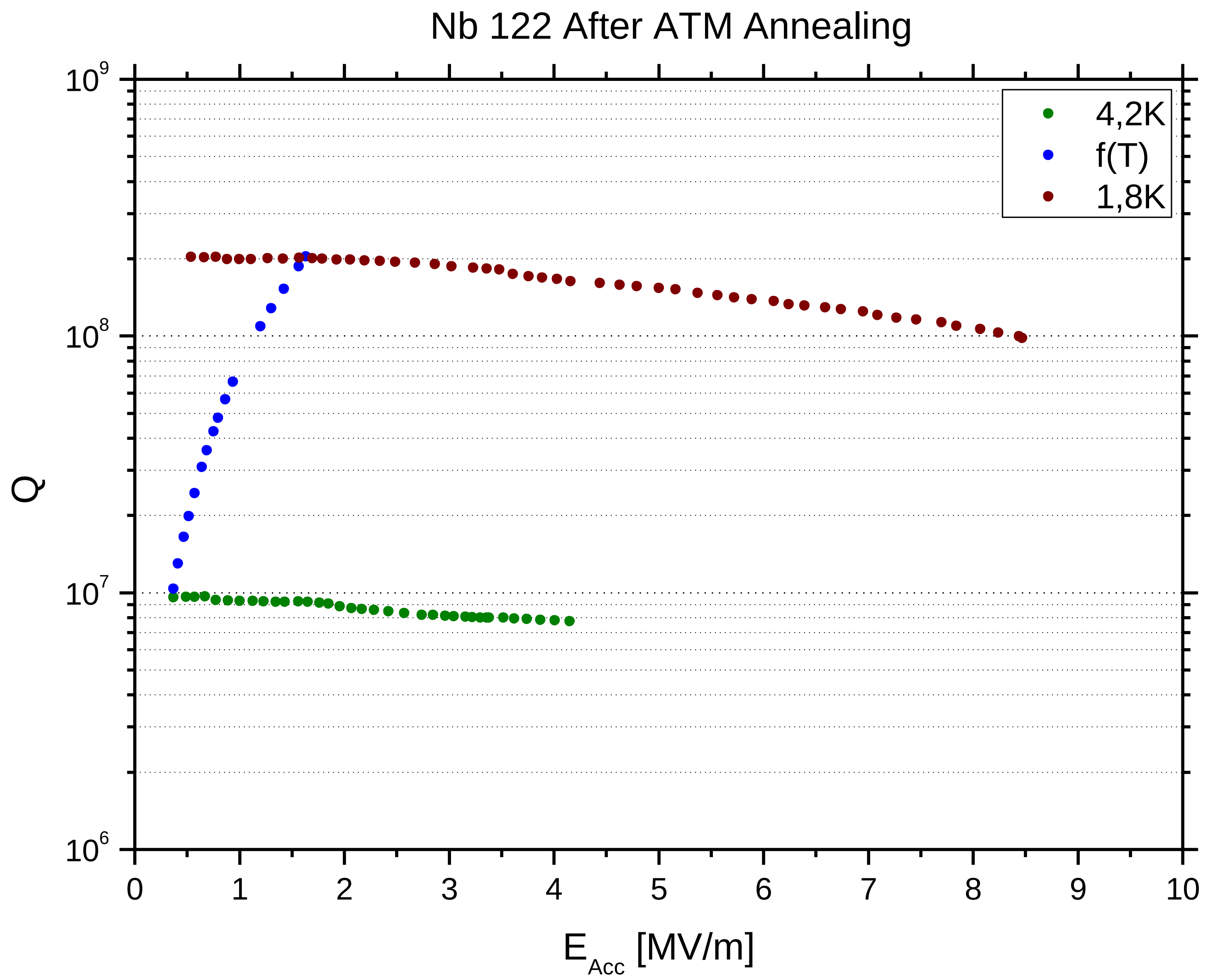


Figure 20: Qo-Eacc excitation curve fitting by the combined model for the 1500MHz niobium film coated cavity at CERN.



Nb 122 After ATM Annealing
Q
10^9
10^8
10^7
10^6
0
1
2
3
4
5
6
7
8
9
10
E_{Acc} [MV/m]
4,2K
f(T)
1,8K

EXPERIMENTAL COMPARISON AT KEK OF HIGH GRADIENT PERFORMANCE OF DIFFERENT SINGLE CELL SUPERCONDUCTING CAVITY DESIGNS

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[a]KEK High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba 305-0801, Japan
[b]DESY Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22603 Hamburg, Germany

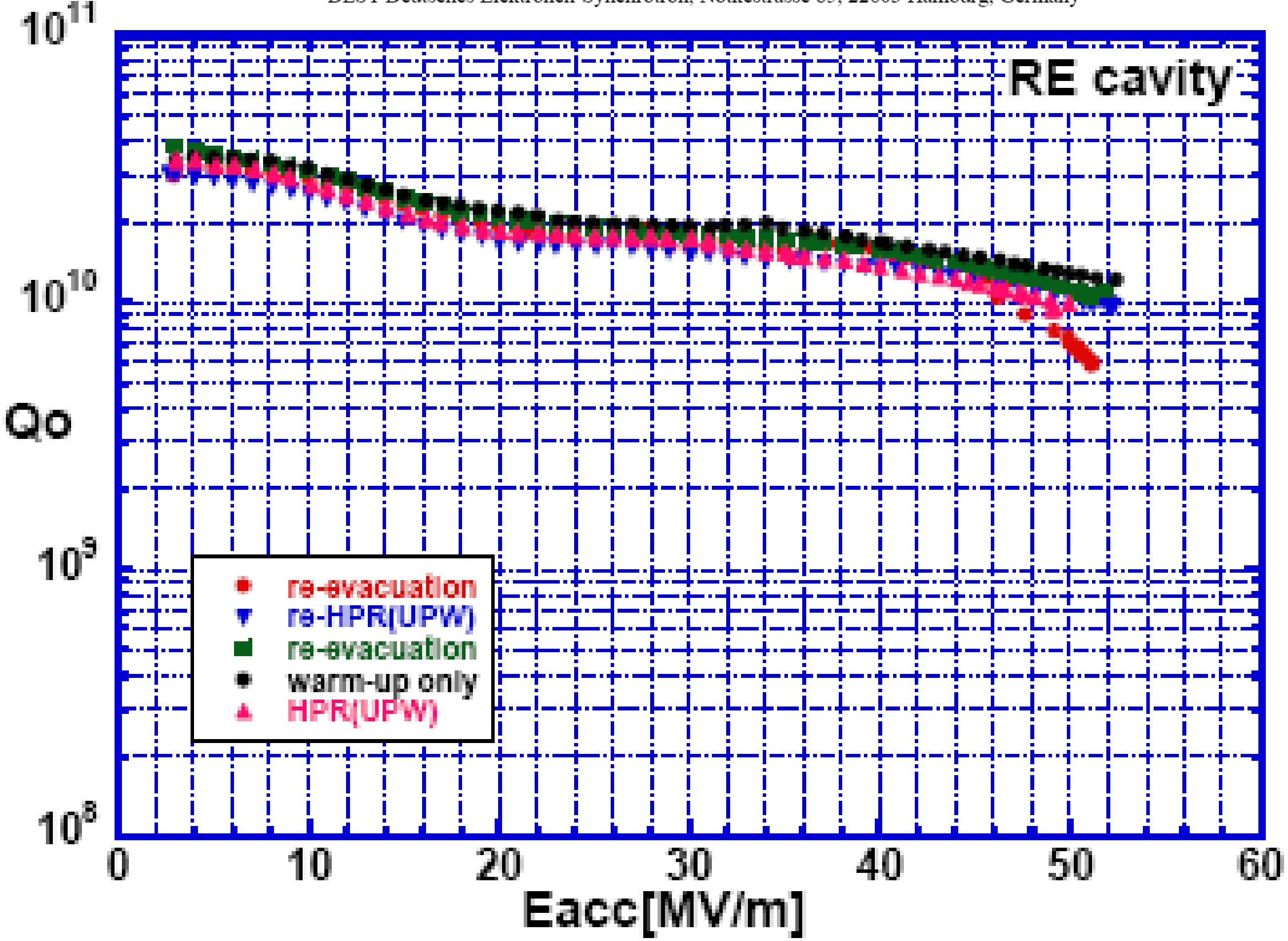
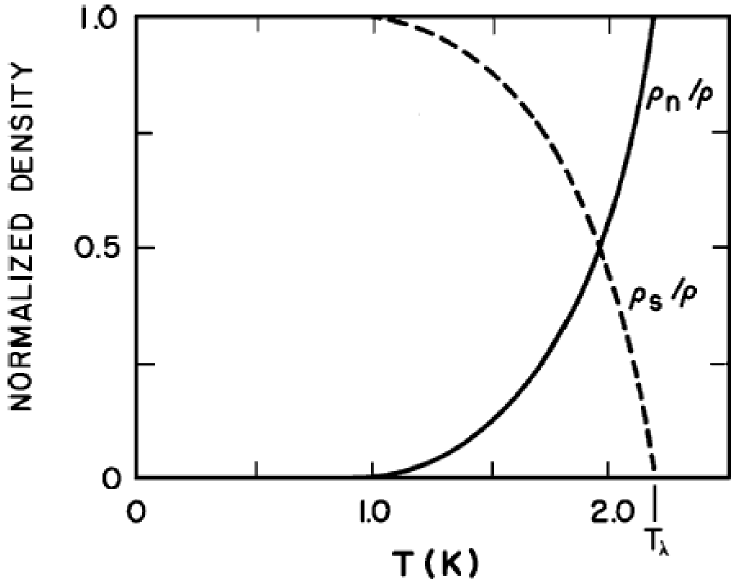


Figure 5: The reproducibility of high gradient.

How is it possible that

He-II will have memory of the boiling nucleation of He-I ?

Actually 1.8 K is very close to T_λ ,



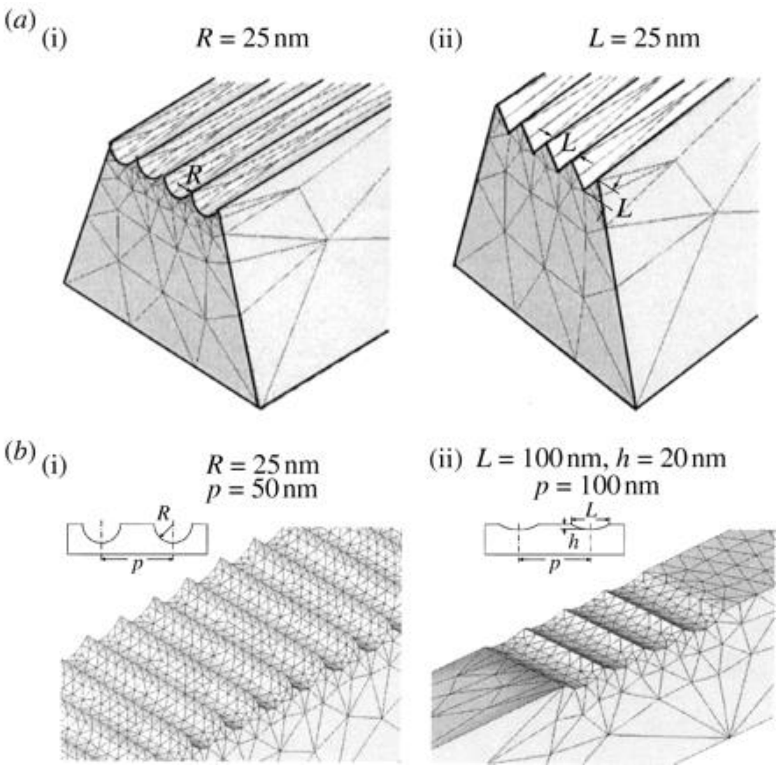
$$\rho = \rho_s + \rho_n$$

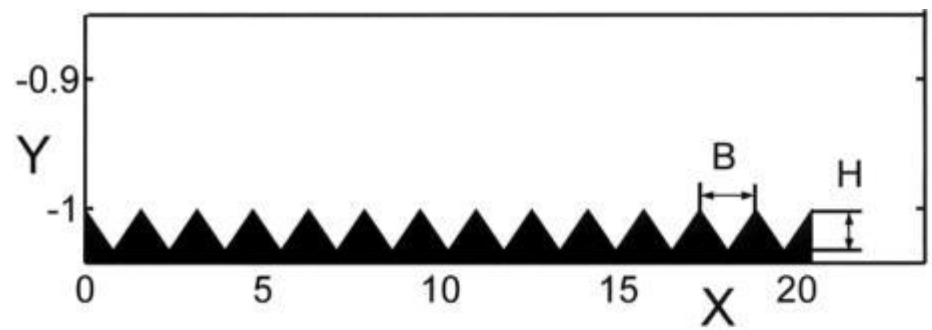
$$\frac{\rho_n}{\rho} = \left(\frac{T}{T_\lambda}\right)^{5.6} \quad \text{for} \quad T \le T_\lambda$$

so at 1.8K ρ_n is ~34% !!

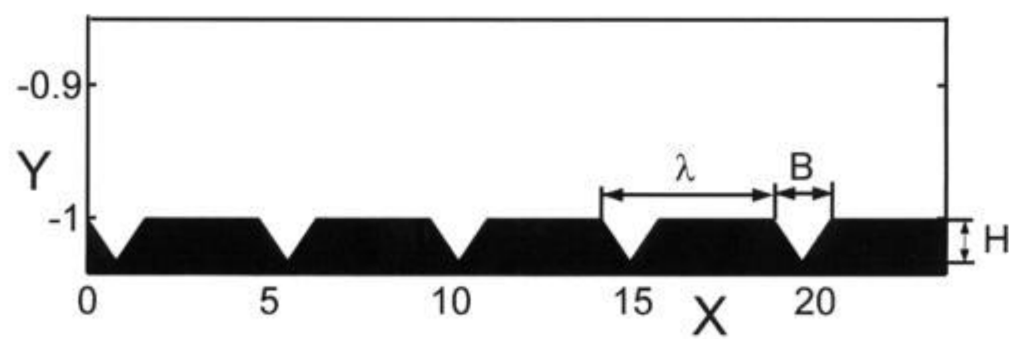
and at 2K ρ_n is ~62% !!

Heat transfer, especially in film and transition boiling regimes, is improved by methods which increase the real surface area by means of groves and fins





A



B

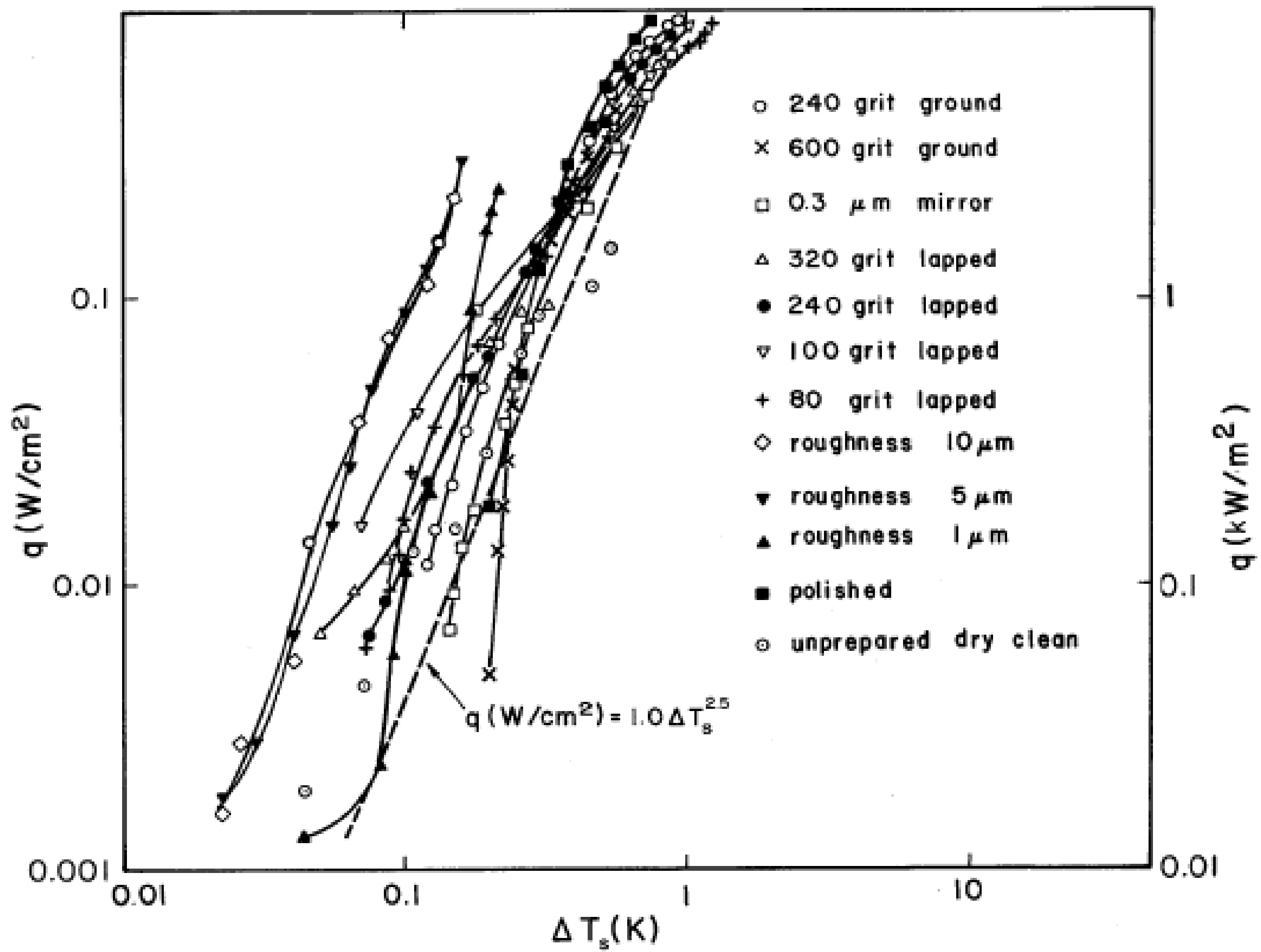


Fig. 5.9 Nucleate boiling heat transfer to He I (Compilation of data and suggested correlation from Schmidt [16])

Van Sciver – Cryogenics

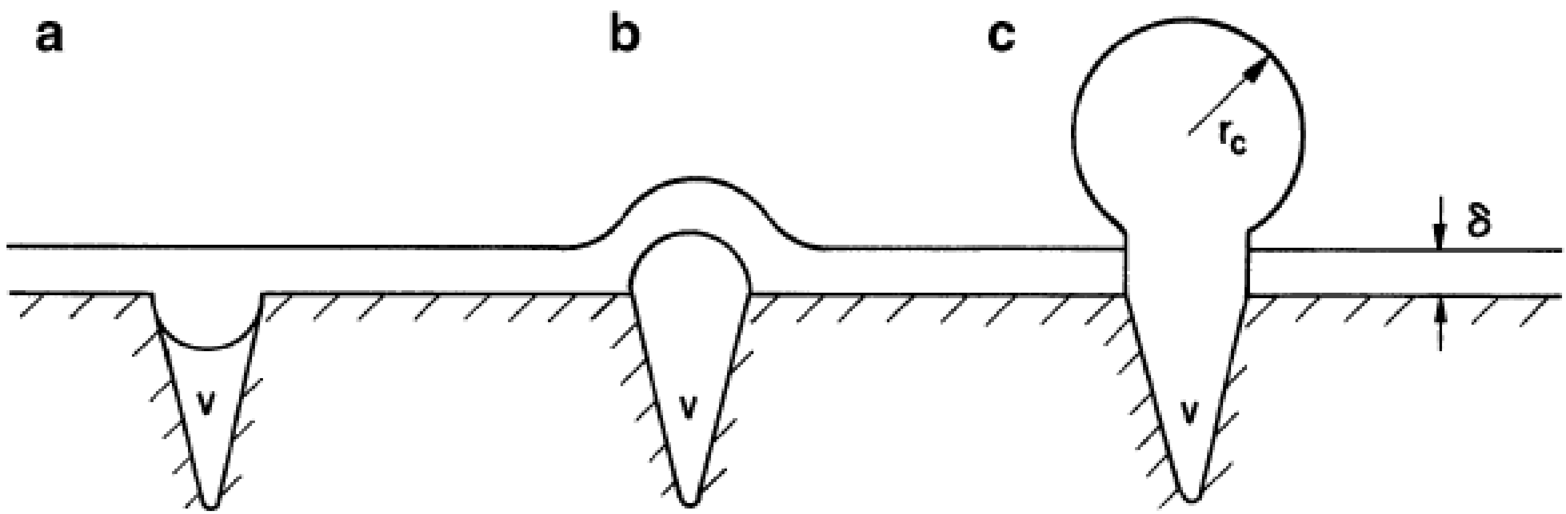


Fig. 5.6 Bubble nucleation on an imperfect surface: (**a**) negative radius of curvature, (**b**) positive radius of curvature, and (**c**) critical radius

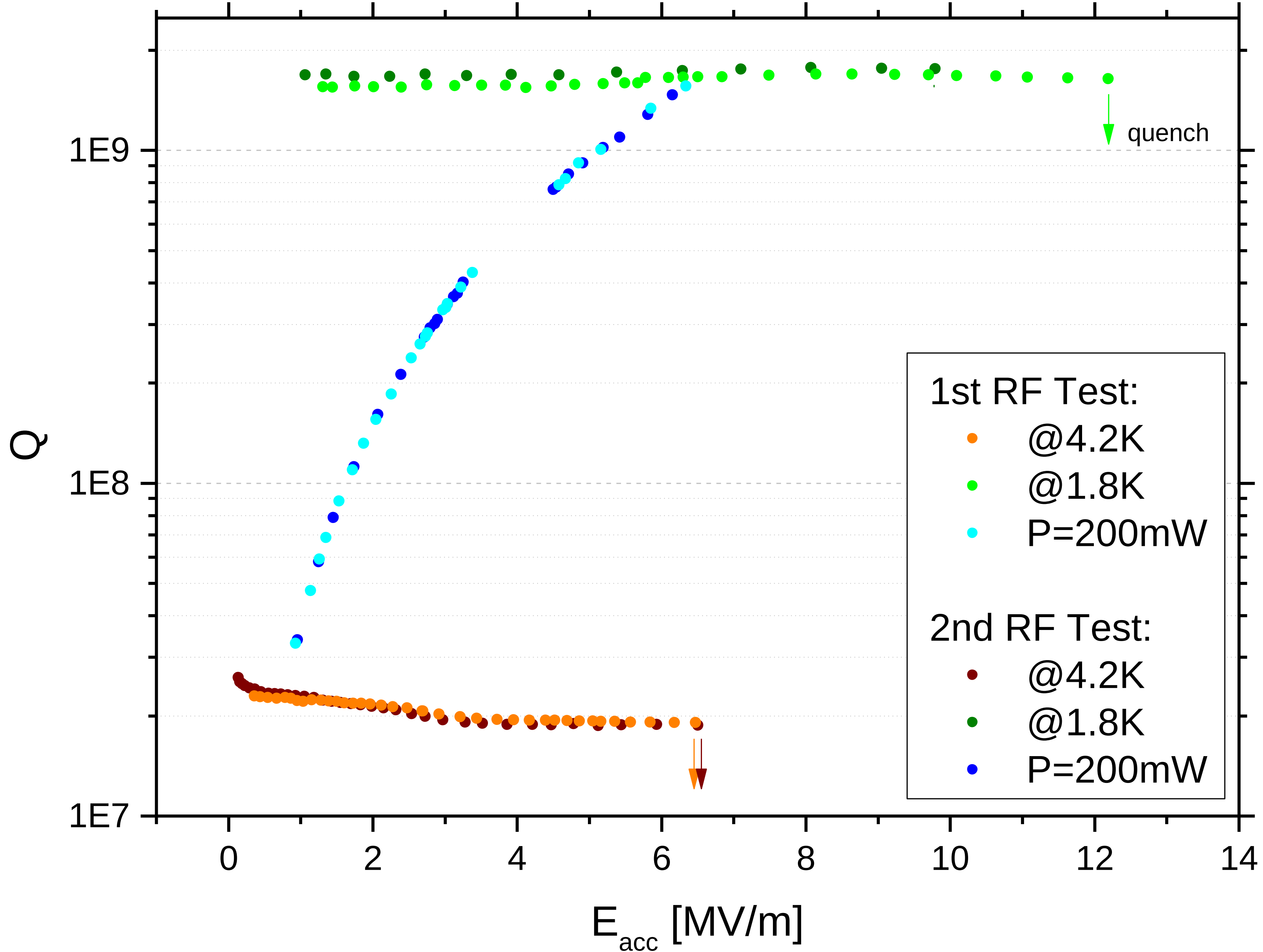
In order to maximize heat transfer,

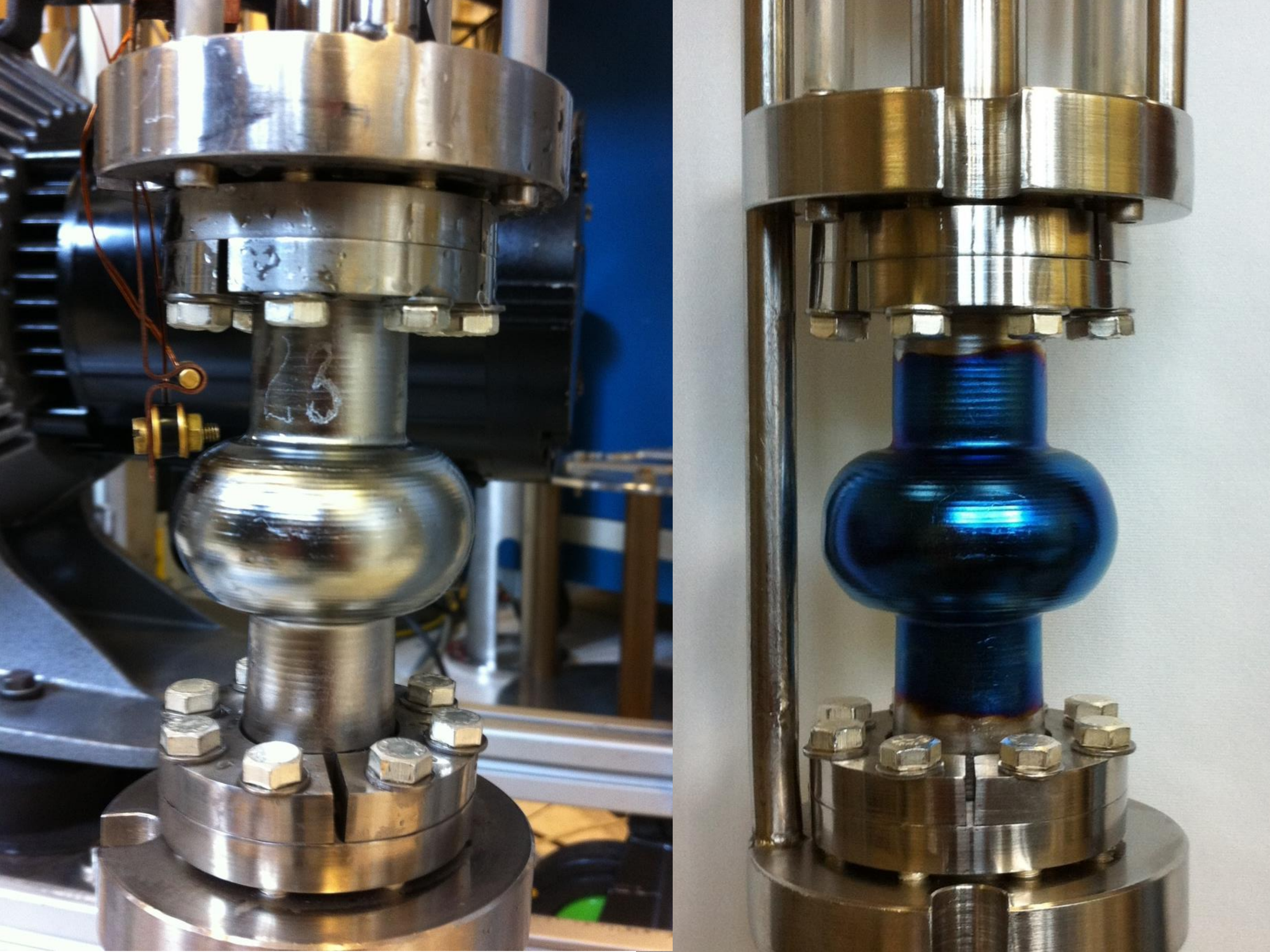
… employ surface structures that facilitate removal of vapor bubbles. Reccomended minimum width of the grooves is 0,3 mm to avoid blanketing the grooves by vapor.

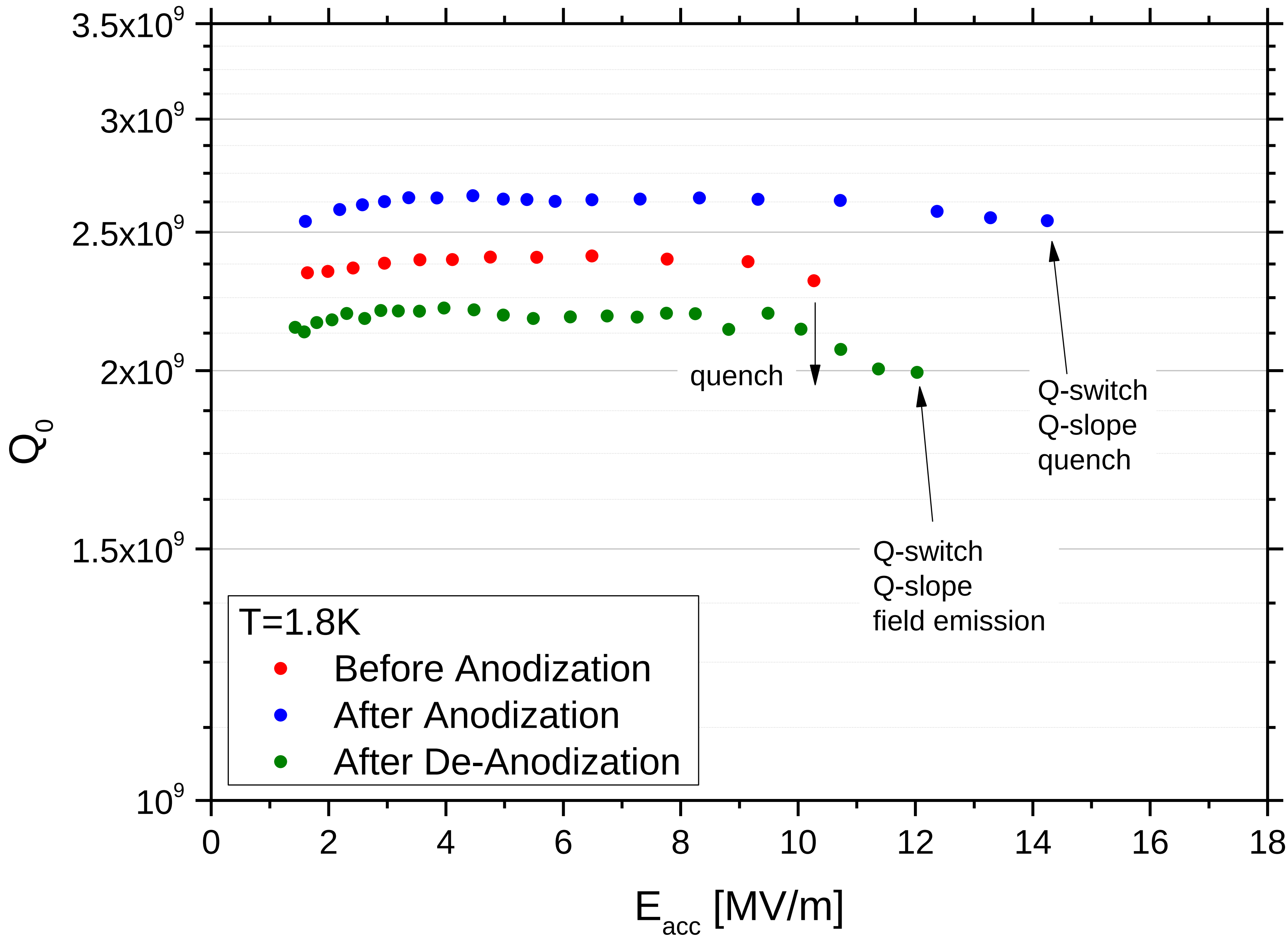
Spinning at LNL

Oxydation of the surface helps to improve transition biling heat transfer

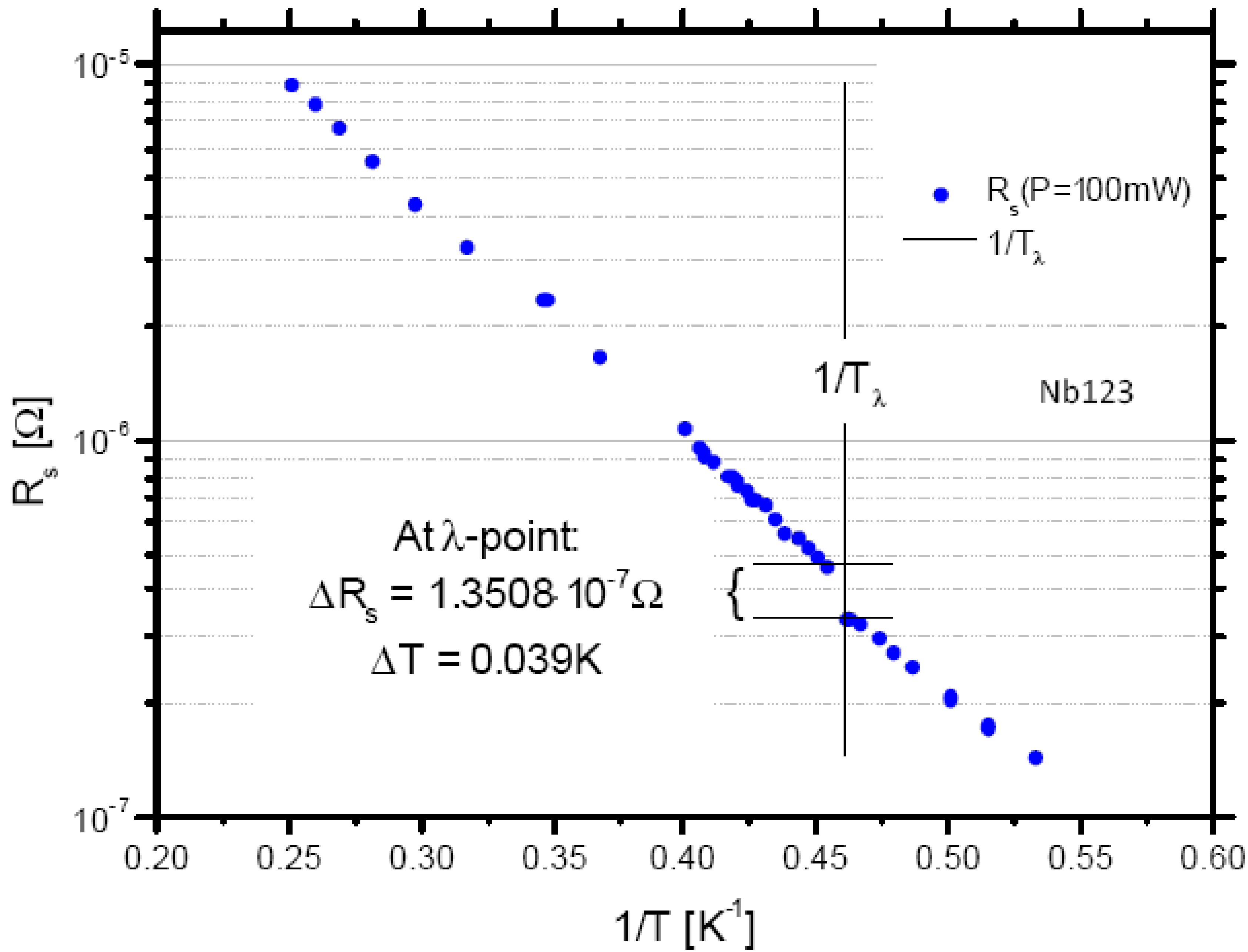
Measured twice







3.5x10^9
3x10^9
2.5x10^9
2x10^9
1.5x10^9
10^9
Q0
0
2
4
6
8
10
12
14
16
18
Eacc [MV/m]
T=1.8K
Before Anodization
After Anodization
After De-Anodization
quench
Q-switch
Q-slope
quench
Q-switch
Q-slope
field emission



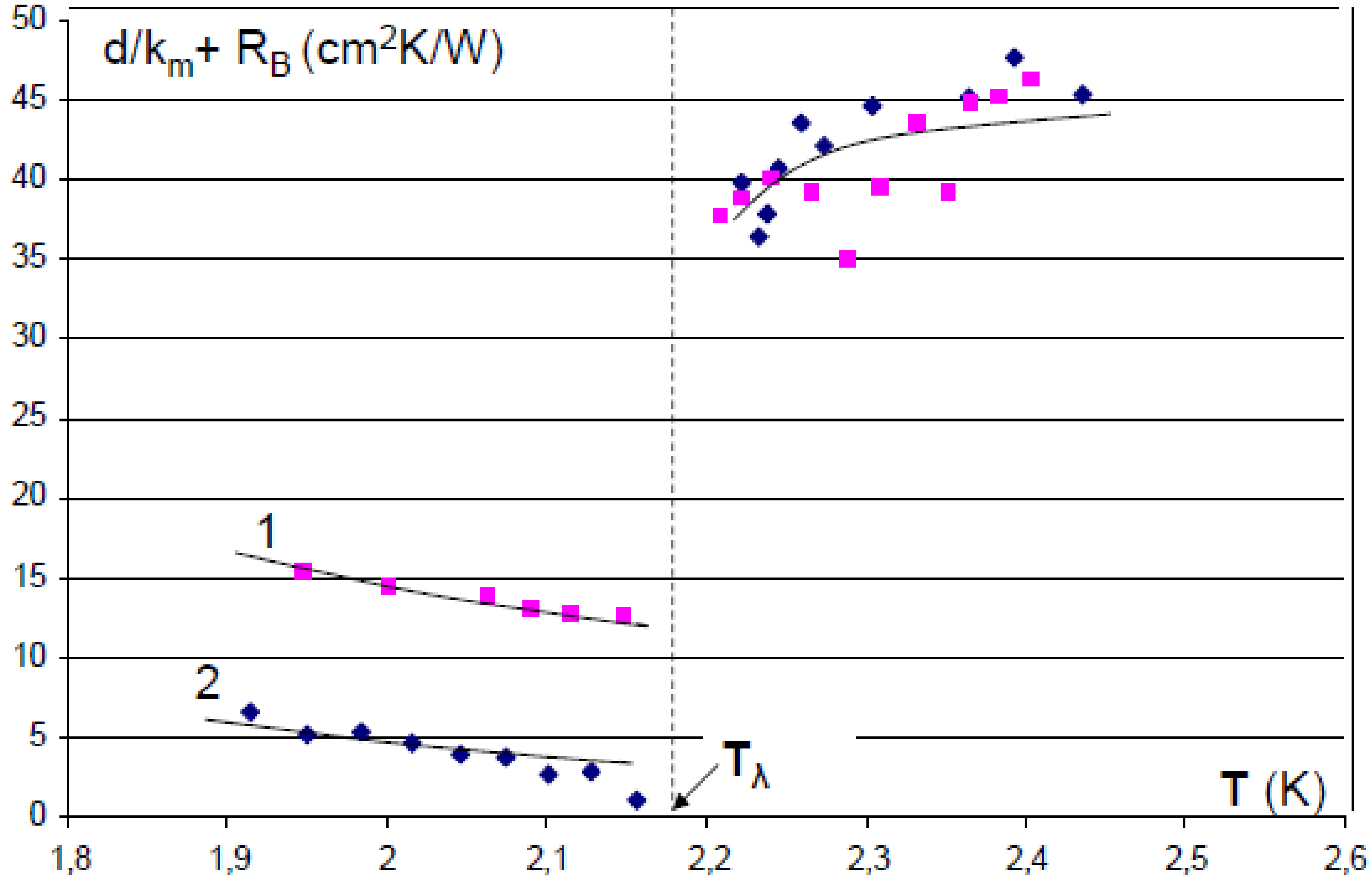
10^{-5}
10^{-6}
10^{-7}
R_s [Ω]
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
1/T [K^{-1}]
R_s(P=100mW)
$1/T_\lambda$
$1/T_\lambda$
Nb123
At λ-point:
$\Delta R_s = 1.3508 \cdot 10^{-7} \Omega$
$\Delta T = 0.039K$

$$R_{BCS}(T) = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta_0}{K_B T}\right)$$

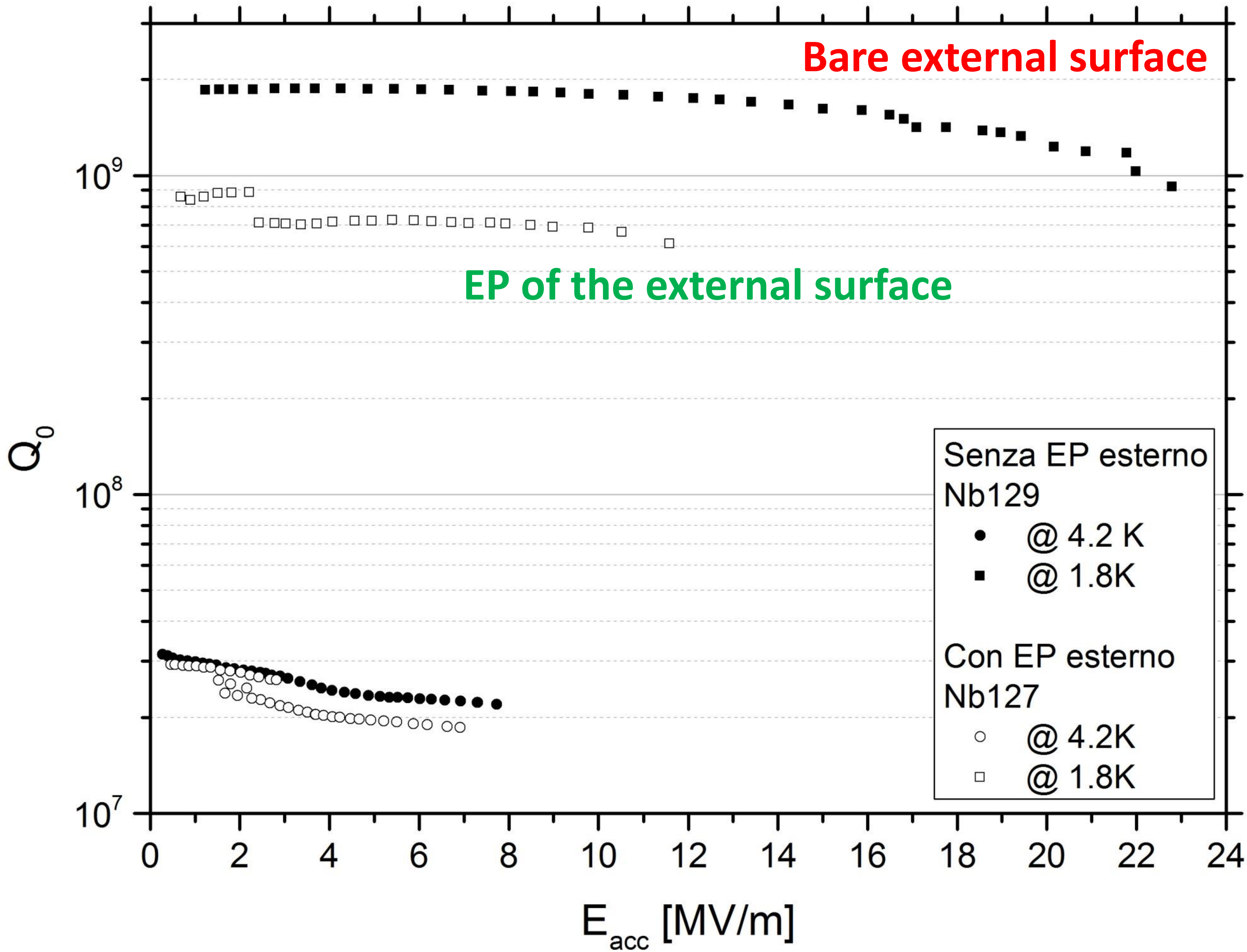
$$R_{BCS}(T_0) = \frac{A\omega^2}{T_0 + \Delta T}\exp\left[-\frac{\Delta_0}{K_B(T_0 + \Delta T)}\right] \cong R_{BCSO}(T_o)\left(1 + \frac{\Delta_o \cdot \Delta T}{K_B T_o^2}\right)$$

$$\Delta T = T - T_0 = \left(\frac{d}{k_m} + R_B\right)P_d$$

$$\frac{d}{k_m} + R_B = \frac{K_B T_0^2}{\Delta_0 P_d}\left[\frac{R_s(T_0) - R_0}{R_{sBCS0}(T_0)} - 1\right]$$



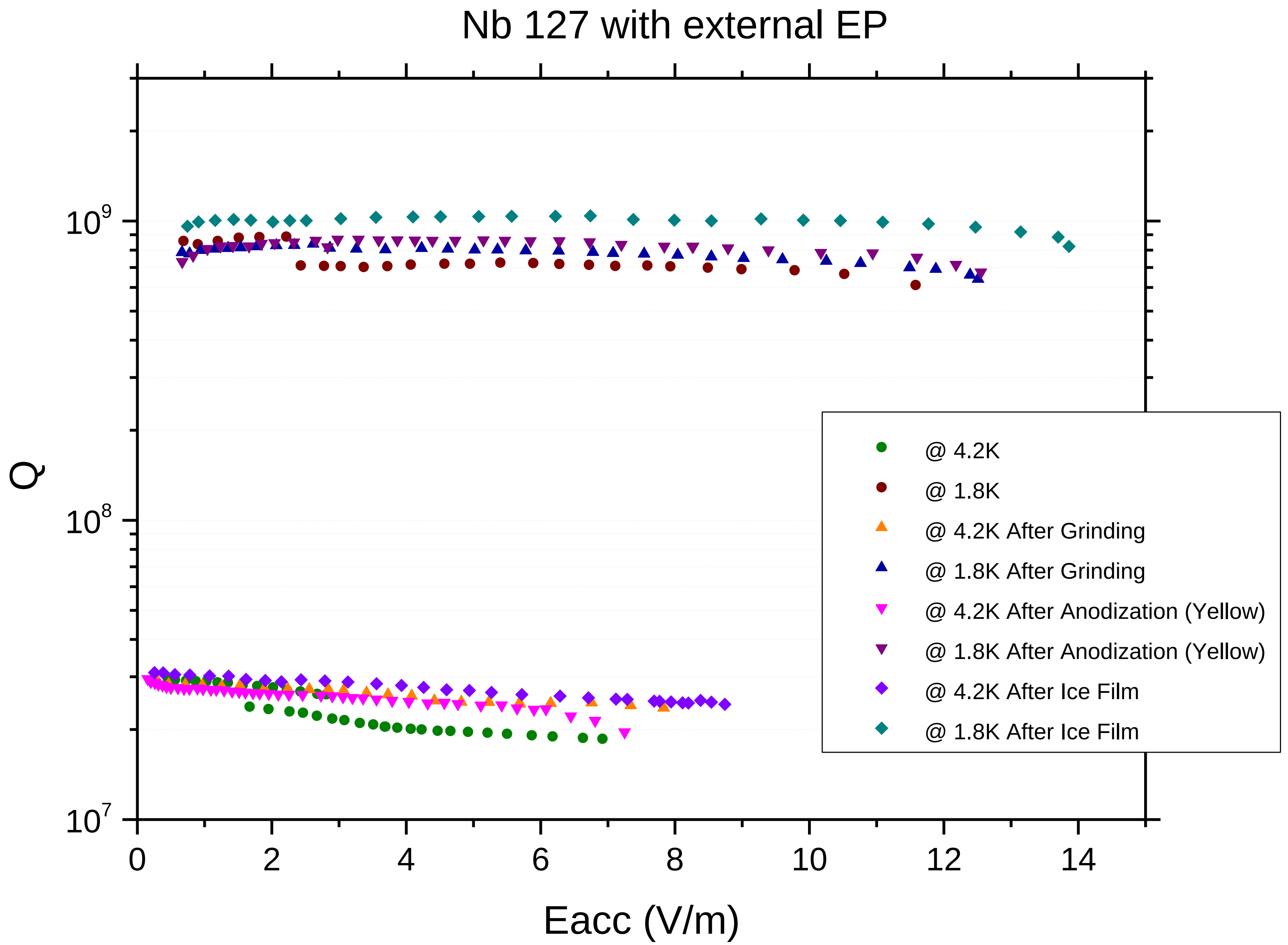
Thermal boundary resistance for a 6GHz Nb cavity: before (1) and after (2) external anodization treatment


Bare external surface
EP of the external surface
Senza EP esterno
Nb129
@ 4.2 K
@ 1.8K
Con EP esterno
Nb127
@ 4.2K
@ 1.8K
Q0
10^9
10^8
10^7
0
2
4
6
8
10
12
14
16
18
20
22
24
Eacc [MV/m]

If we mirror finish the cavity exterior surface, will this behave as a Mirror for thermal phonons

A mirror-like external surface will decrease the nucleation sites for Helium boiling nucleation, promoting then the Liquid He Super-heating

It is well known that water micro-cristallites on the external surface of Nb promote film boiling and then positively affect cavity performances?

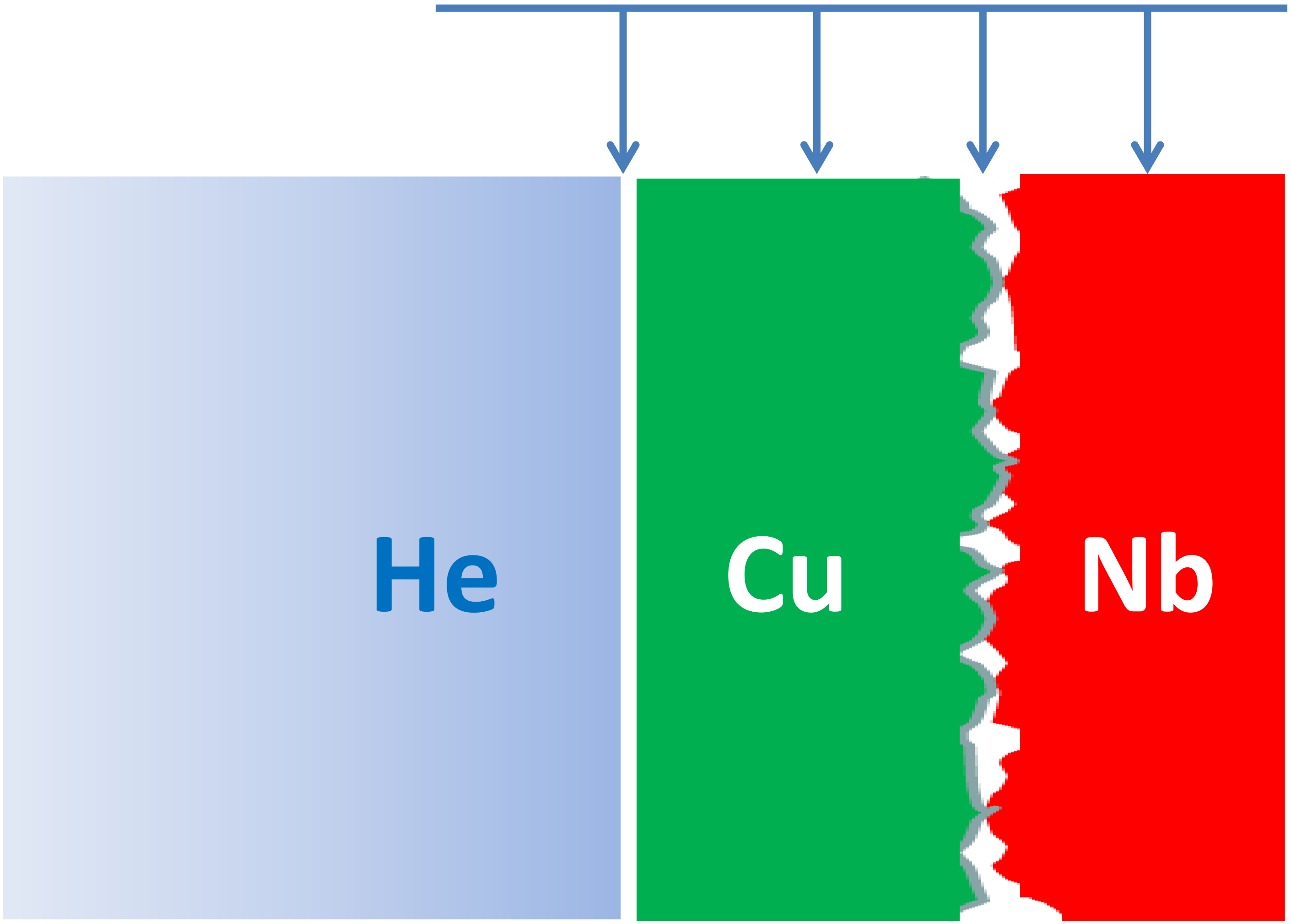

Nb 127 with external EP
Q
Eacc (V/m)
10^9
10^8
10^7
0
2
4
6
8
10
12
14
@ 4.2K
@ 1.8K
@ 4.2K After Grinding
@ 1.8K After Grinding
@ 4.2K After Anodization (Yellow)
@ 1.8K After Anodization (Yellow)
@ 4.2K After Ice Film
@ 1.8K After Ice Film

What do we understand?

... that a deeper understanding

of Cryogenics is mandatory!!!

There are only 4 possible players



3. The Cu-He interface

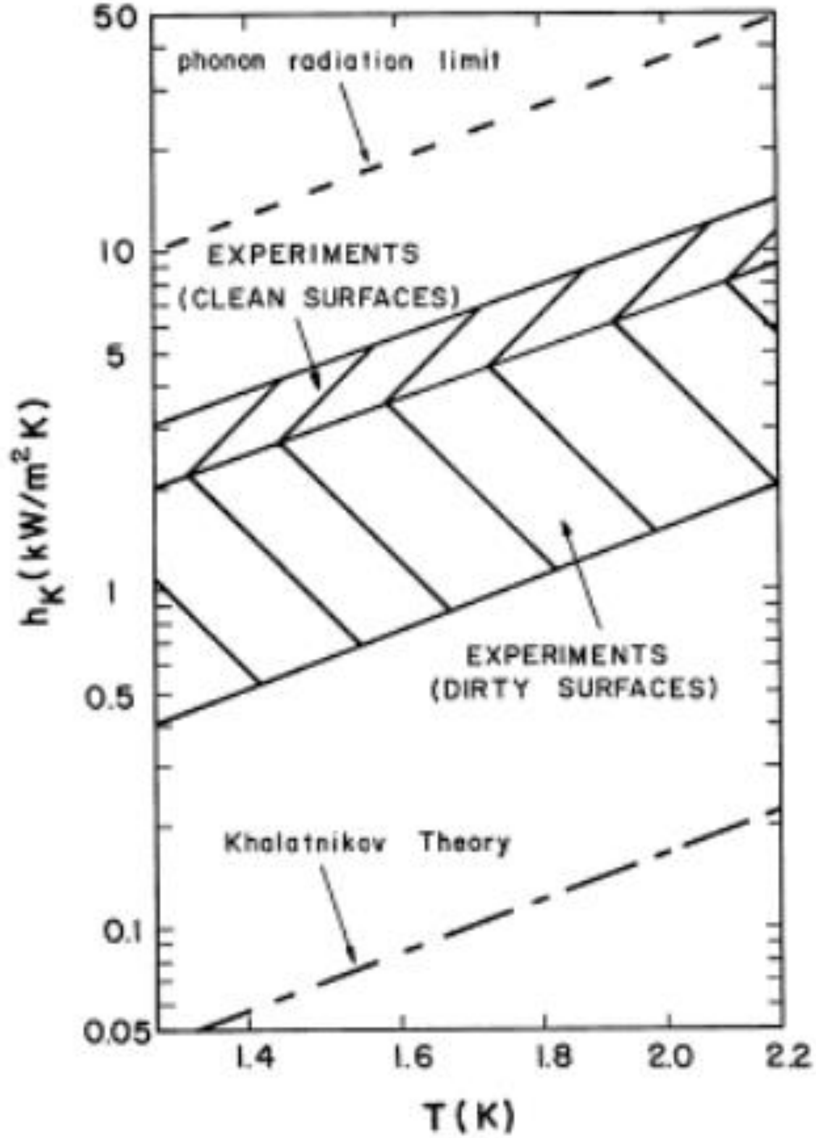


Fig. 7.36 Experimental values for the Kapitza conductance of copper between 1.3 K and T_λ (Compiled by Snyder [54])

3. The Cu-He interface

The Kapitza resistance at the Cu/HeII

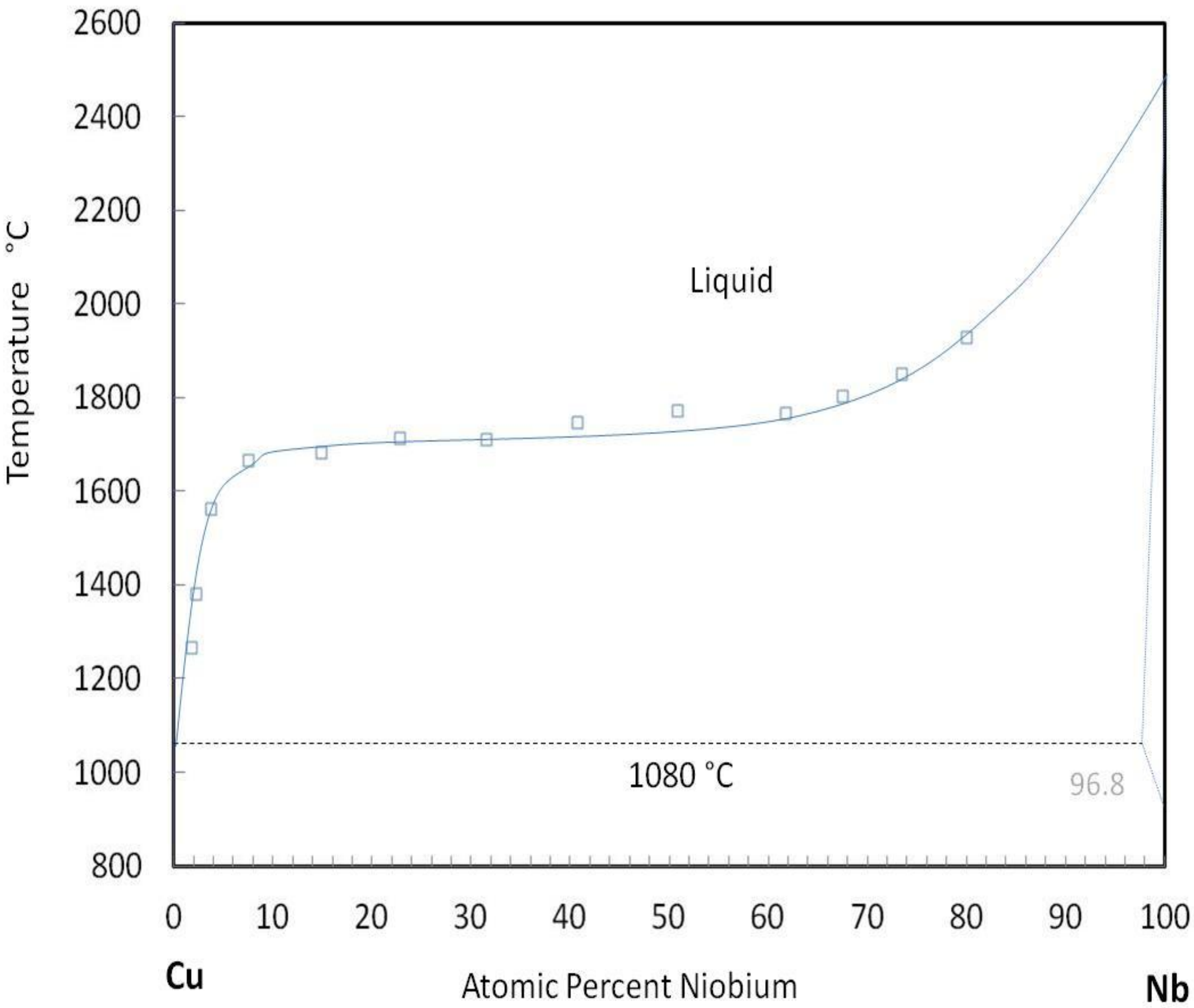
interface, at 1.8K is $R_K = 2\text{-}4\ cm^2K/W$

(in the same range for the Nb/He-II interface)

- N.S Snyder, “Heat transport through helium II : Kapitza conductance”, *Cryogenics, APRIL, 89 (1970)*.
- Van Sciver, S.W., “Helium Cryogenics”, Plenum Press, New York (1986)
- M.M Kado, , Thermal Conductance Measurements on the LHC Helium II Heat Exchanger Pipes, LHC Note 349, CERN-AT-95-34 CR (1995)

The Cu-Nb phase diagram

(after D.J. Chakrabarti and D.E. Laughlin)



The Cu-Nb interface

at CERN, film peeling was even found in some 352 MHz 4-cell cavities when dismounted from LEP several years after of their operation.

The Cu-Nb interface

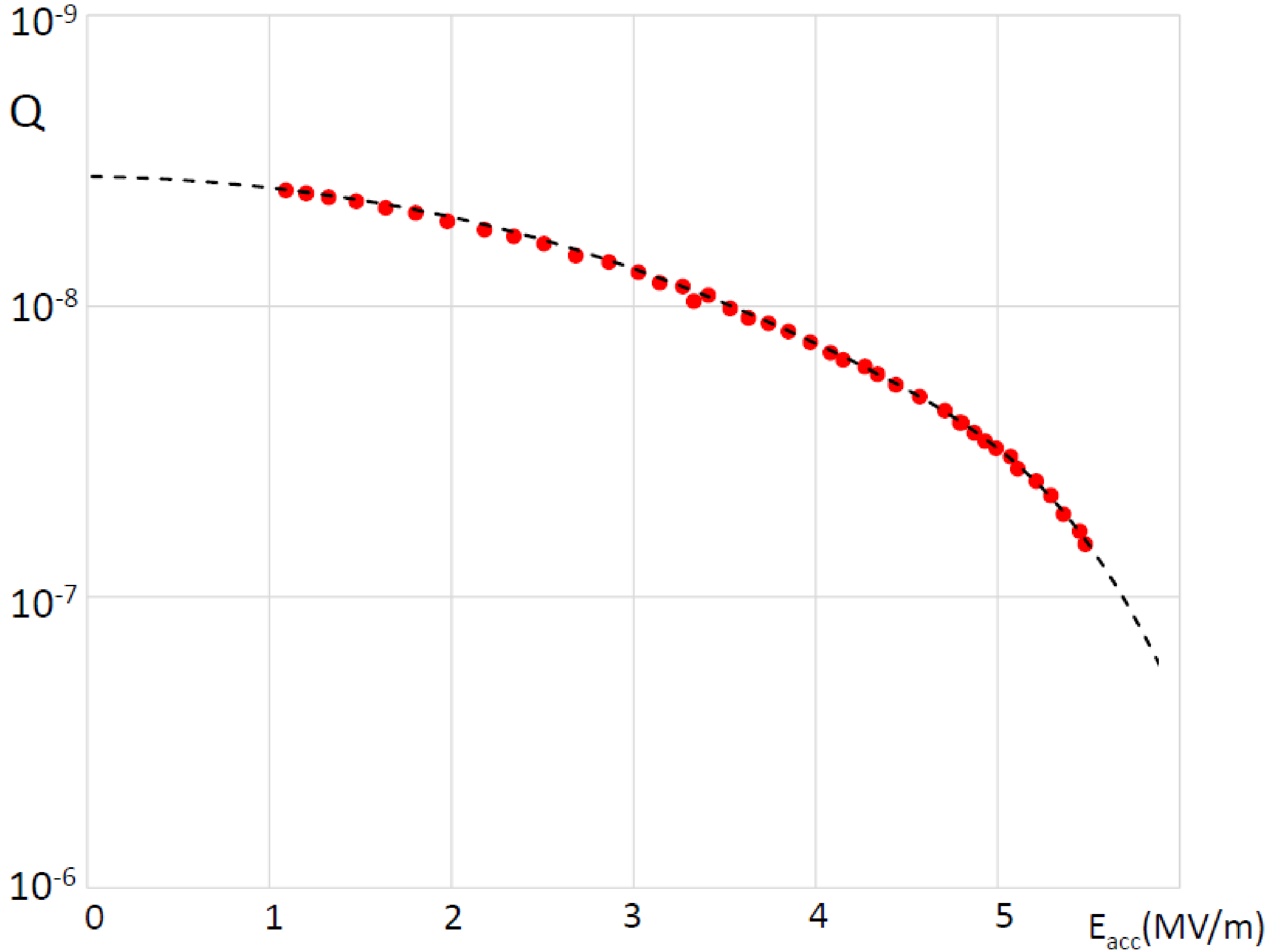
at CERN, film peeling was even found in some 352 MHz 4-cell cavities when dismounted from LEP several years after of their operation.

The Cu-Nb interface

..and even arc coated cavities were not measured because of poor film adhesion

4. The Cu-Nb interface

4. The Cu-Nb interface



A Nb clad Cu 1,3GHz cavity

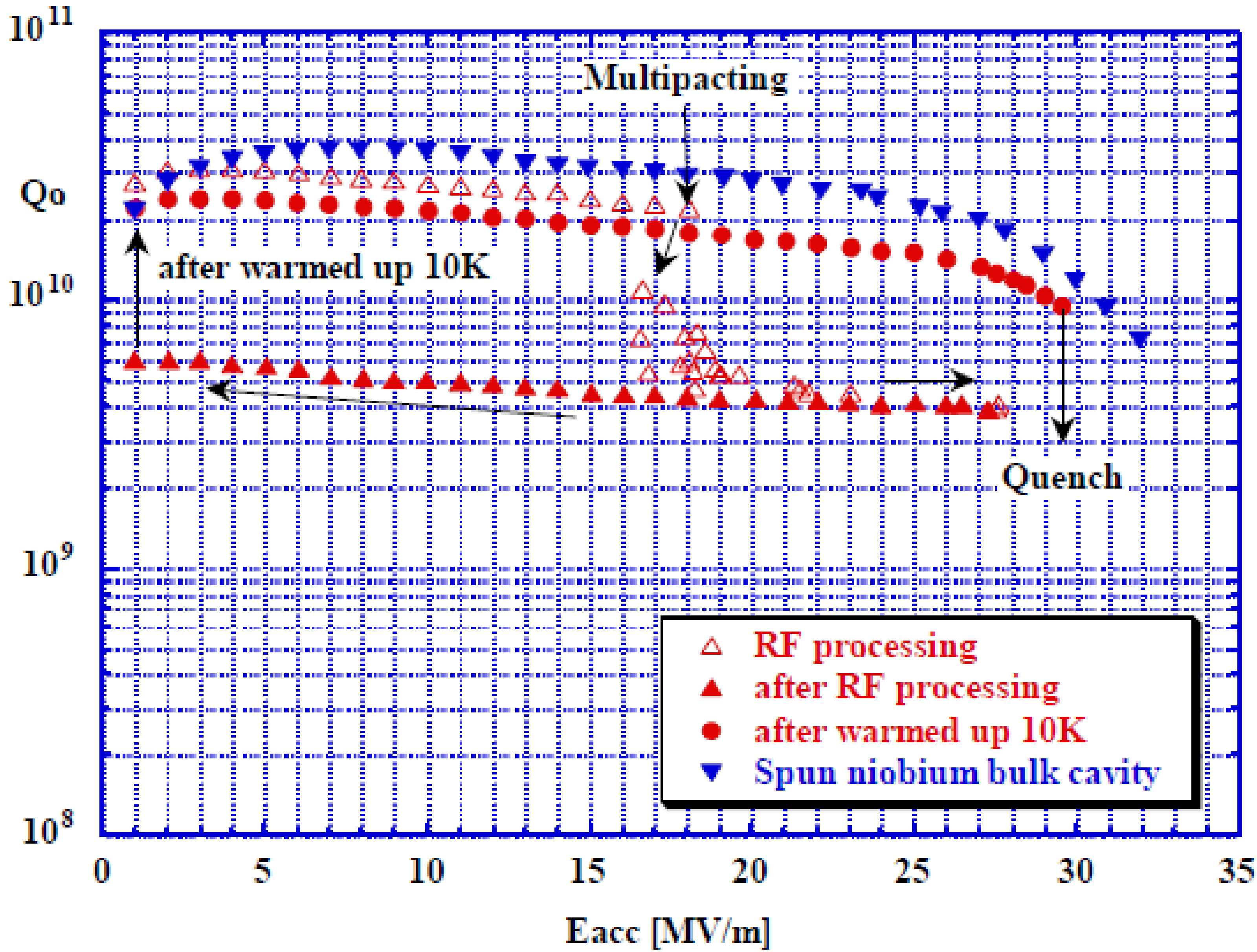


Figure 1: Result of the new Nb/Cu clad spun cavity from RRR = 200 niobium material

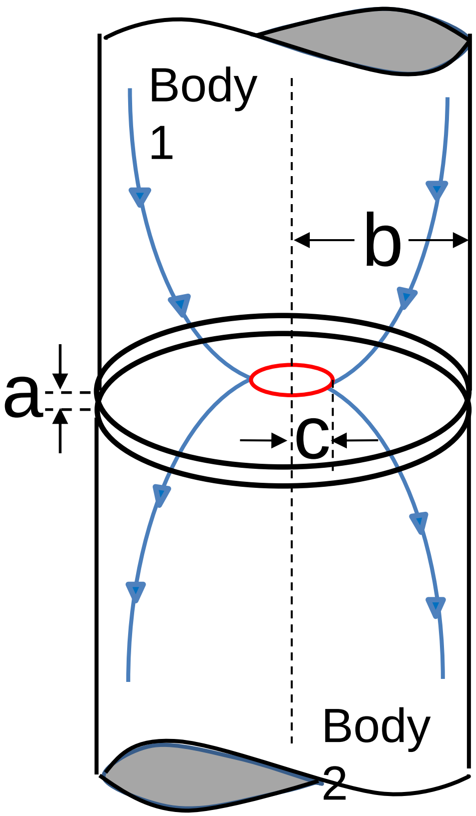
Why Nb clad Cu cavities work,

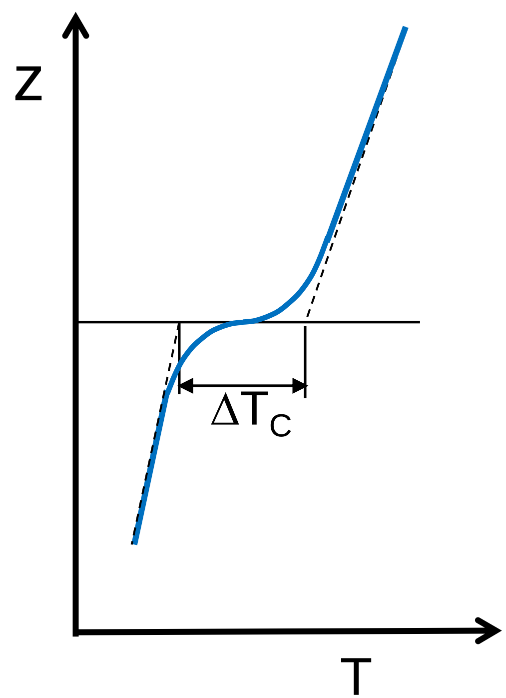
And Nb Sputtered Cu cavities do not?

THERMAL CONTACT CONDUCTANCE

M. G. COOPER*, B. B. MIKIC† and M. M. YOVANOVICH‡

Int. J. Heat Mass Transfer. Vol. 12, pp. 279–300. Pergamon Press 1969. Printed in Great Britain





$$\dot{Q} = h_c \Delta T_c$$

$$h_c = 2k \frac{n c_m}{\psi}$$

Model for the individual flow channel

What it will happen for a non perfect contact between Nb and Cu?

$$\Delta T = R_B P_{RF}$$

$$P_{RF} = \frac{1}{2} R_s(T) H_{RF}^2$$

$$\Delta T = R_B \frac{1}{2} R_s(T) H_{RF}^2$$

$$R_S(T+\Delta T) = \frac{A\omega^2}{T_0+\Delta T}\exp\left[-\frac{\Delta_0}{K_B(T_0+\Delta T)}\right]+R_o$$

(dirty limit and $T \leq T_c/2$)

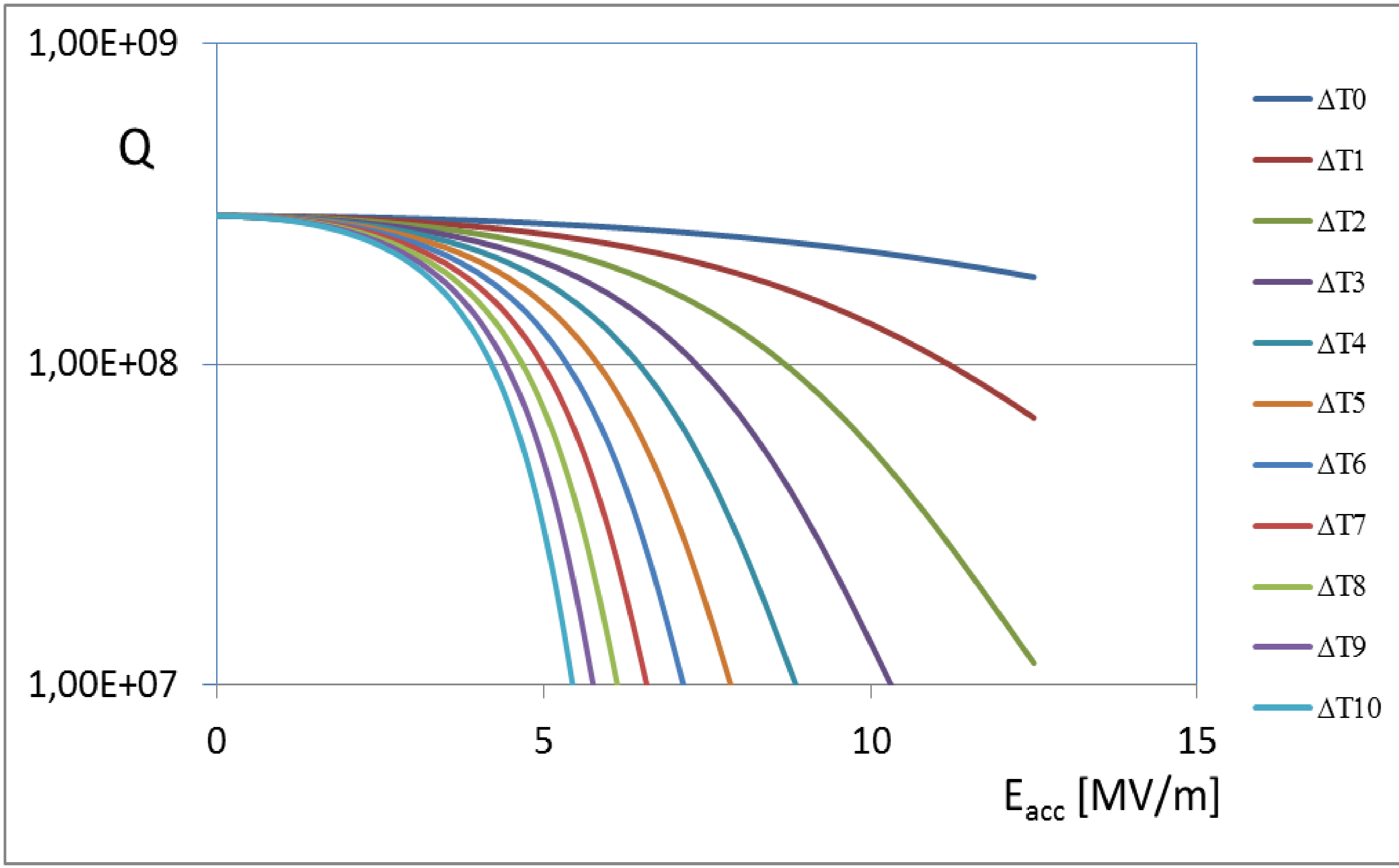
$$\Delta T = R_B \frac{1}{2} R_s(T) H_{RF}^2$$

If the adhesion of Niobium to Copper is not good, the cavity will go in thermal runaway!!!!

$$R_S(T+\Delta T)=\frac{A\omega^2}{T_0+R_B\frac{1}{2}R_s(T)H_{RF}^2}\exp\left[-\frac{\Delta_0}{K_B(T_0+R_B\frac{1}{2}R_s(T)H_{RF}^2)}\right]+R_o$$

increasing the rf field we have an increase in *ΔT* that produces an increase in $R_s(T)$, producing a further increase in *ΔT*, in a kind of "thermal runaway" effect.

$$R_S(T+\Delta T)=\frac{A\omega^2}{T_0+R_B\frac{1}{2}R_s(T)H_{RF}^2}\exp\left[-\frac{\Delta_0}{K_B(T_0+R_B\frac{1}{2}R_s(T)H_{RF}^2)}\right]+R_o$$



Most Probably

$$\overline{R_s(T_o, E_{acc})} = \int_0^{\infty} R_s(T_o, E_{acc}, R_B) f(R_{Nb/Cu}) dR_{Nb/Cu}$$

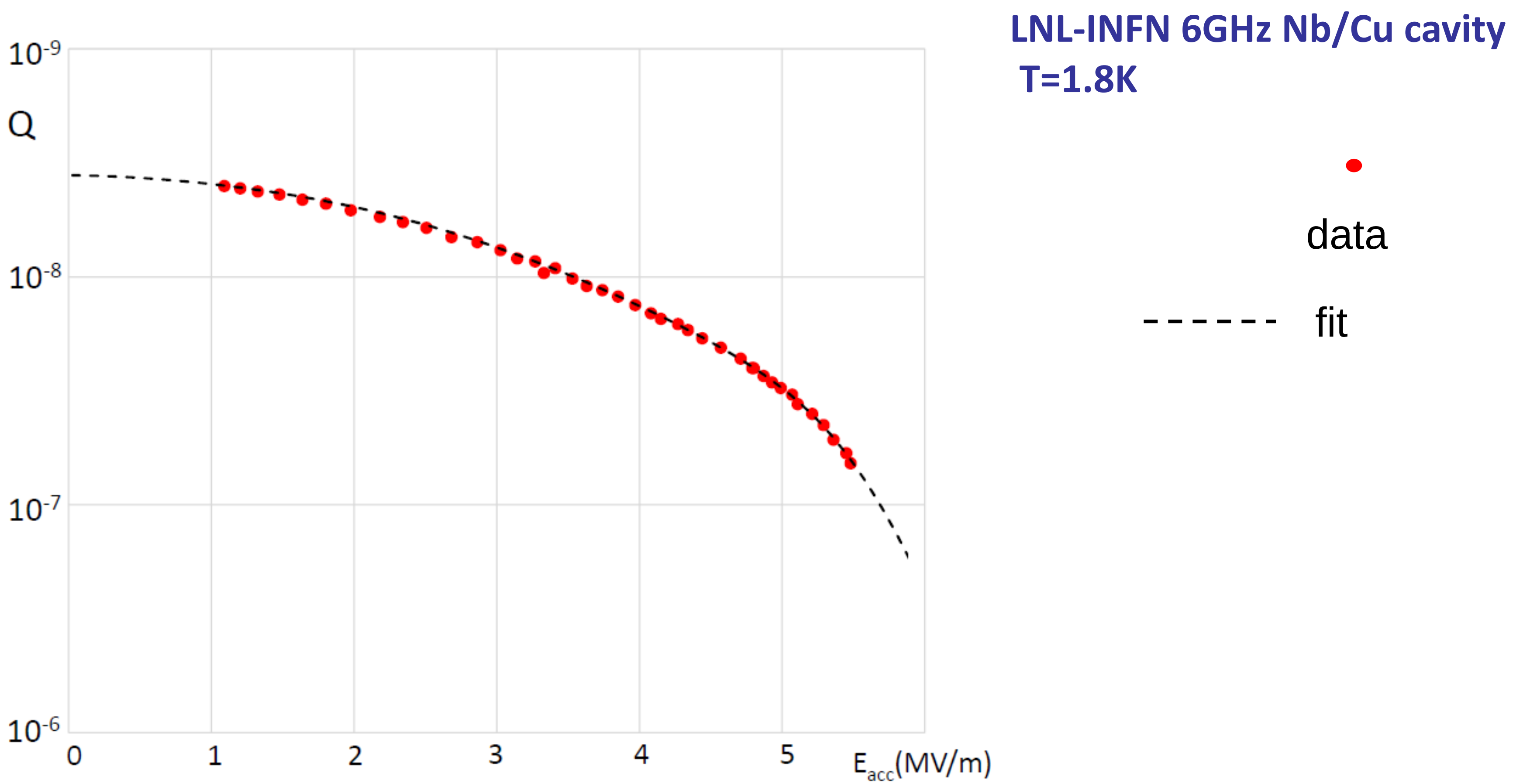
Where $f(R_{Nb/Cu})$ is the statistical distribution function of defects in adhesion

$$\int_0^{\infty} f(R_{Nb/Cu}) dR_{Nb/Cu} = 1$$

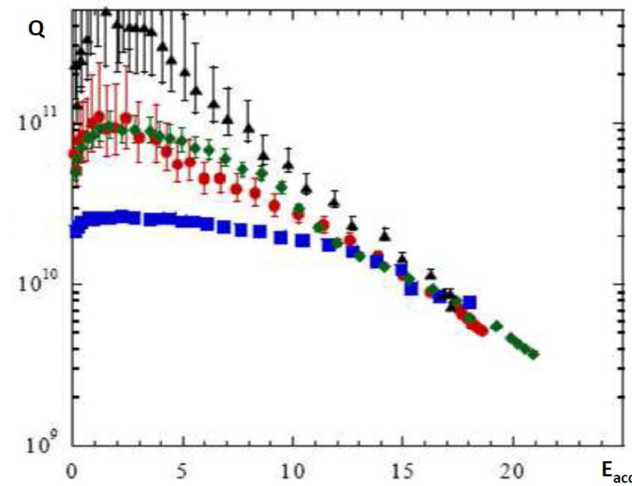
This equation belongs to the class of first type Fredholm integral equations, used for solving inverse problems

$$\overline{R_s(T_o, E_{acc})} = \int_0^\infty R_s(T_o, E_{acc}, R_B) f(R_{Nb/Cu}) dR_{Nb/Cu}$$

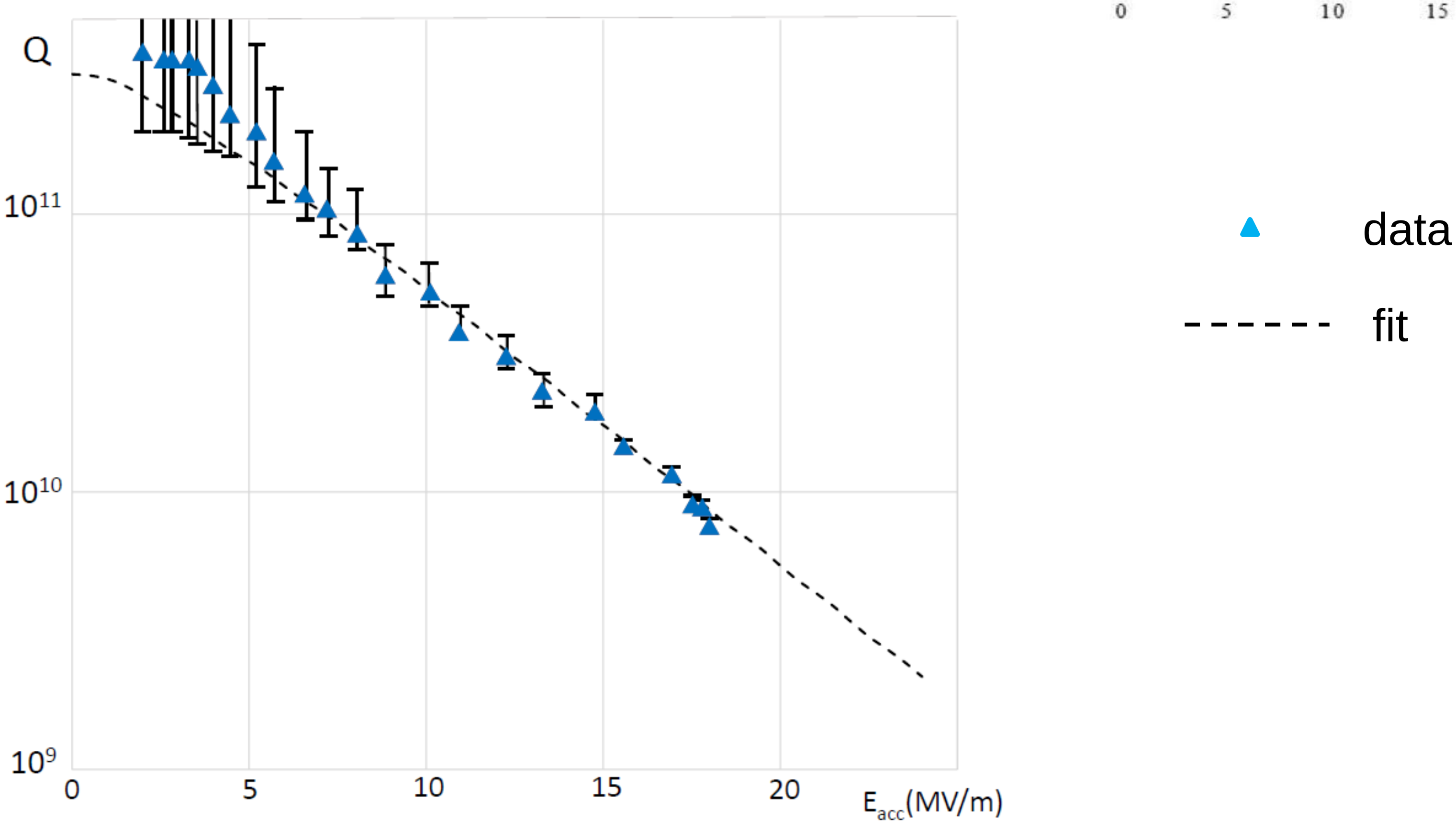
Then solving numerically the integral equation , we can use the solution in order to fit the Q(Eacc) curves and to find the $f(R_{Nb/Cu})$ statistical distribution



2) CERN 1.5GHz Nb/Cu cavity (high quality), T=1.7K



V. Abet-Engels, C. Benvenuti, S. Calatroni, P. Darriulat, M.A.Peck, A.-M. Valente, C.A. Van't Hof, Nuclear Instruments and Methods in Physics Research , p. 1-8, A463 (2001).

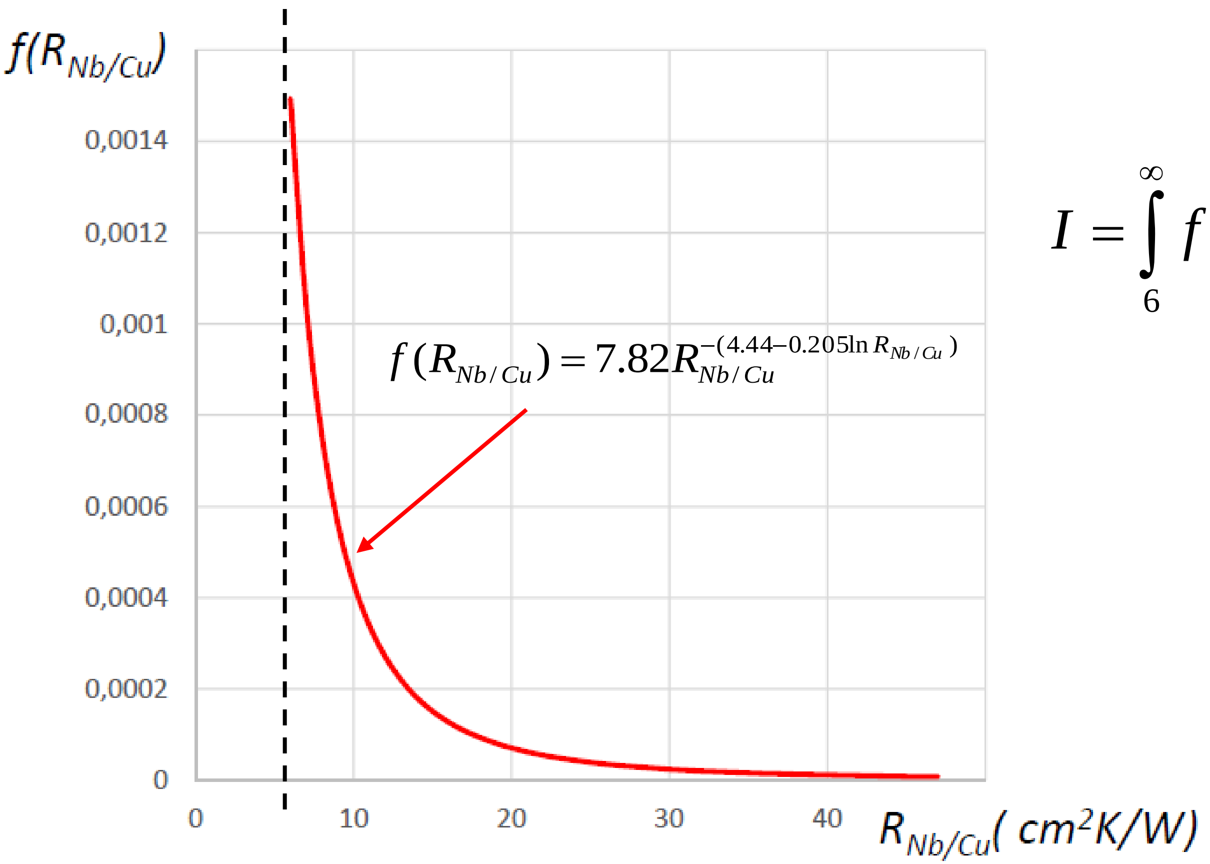


Fitting parameters (from independent measurements)

Tab. I

T_o	$A\omega^2$	Δ_o/K_B	R_0	R_{sn}	$R_{K(Cu/He)}$
1.8K	$6*10^{-3}$ Ω/K	17.5K	0.8μΩ	0.01Ω	3 cm^2K/W

Deduced distribution function $f(R_{Nb/Cu})$

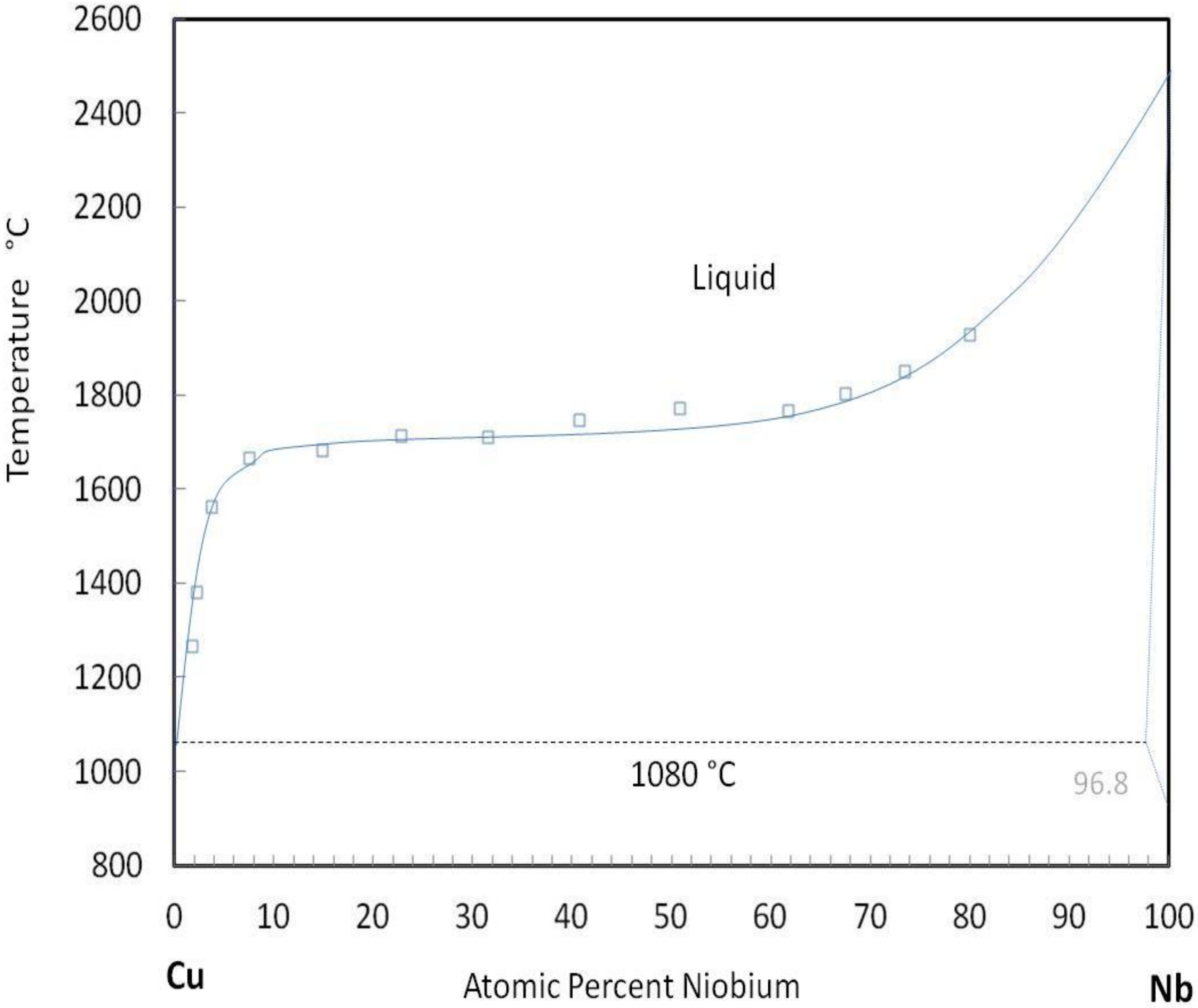


$$I = \int_6^\infty f(R_{Nb/Cu})dR_{Nb/Cu} = 0.005$$

(0.5%)

The Cu-Nb phase diagram

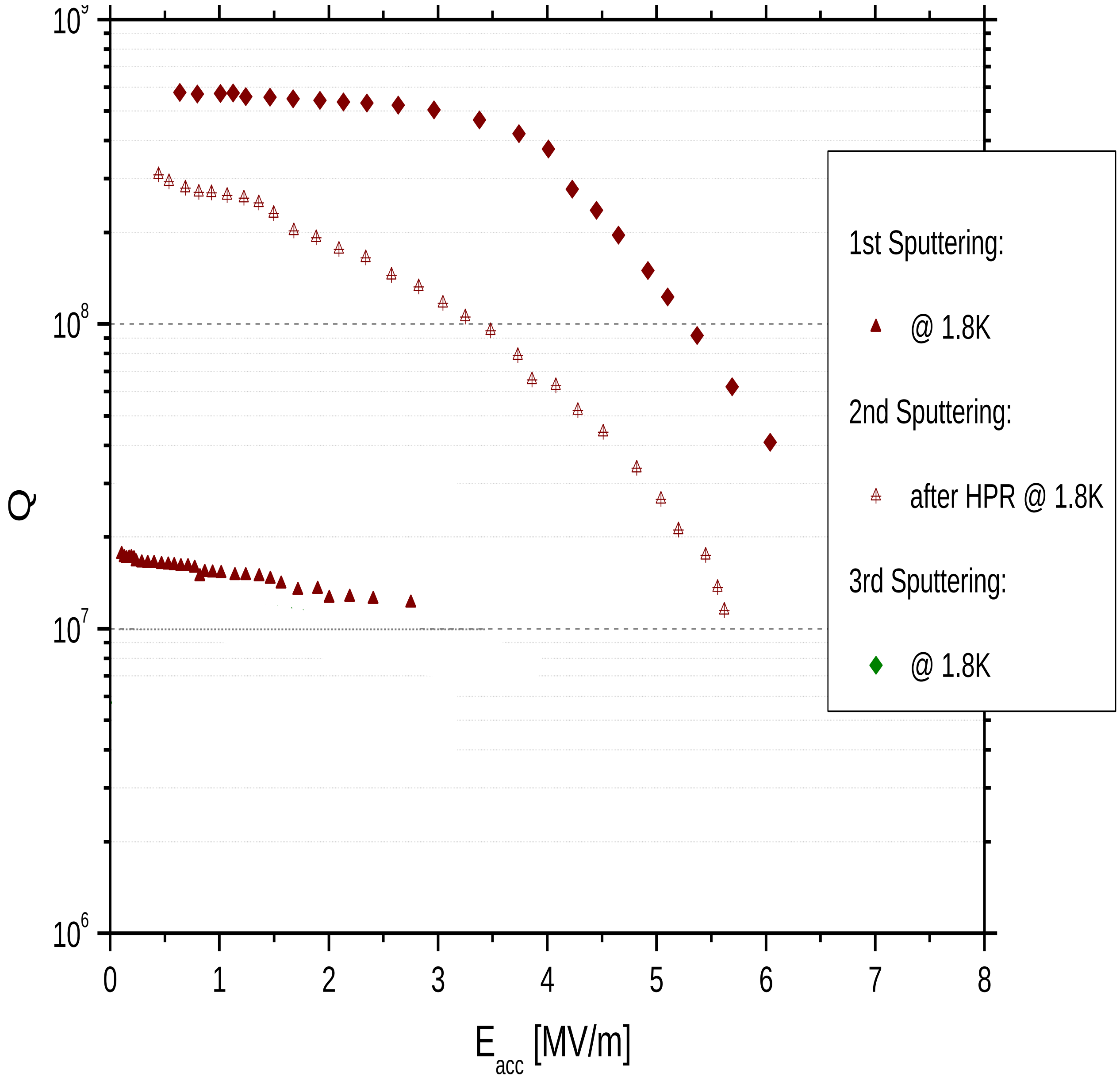
(after D.J. Chakrabarti and D.E. Laughlin)



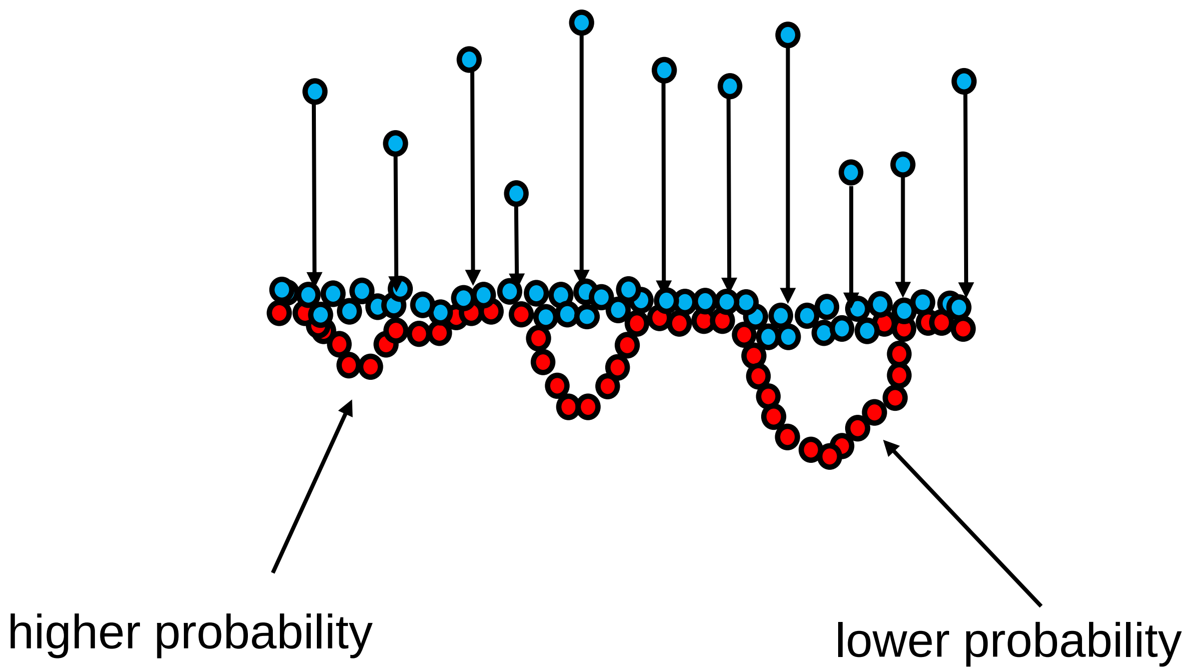
What has high solubility both in Niobium and in Copper?

- Palladium
- Tin
- Alluminum

A palladium underlayer at the Nb /Cu interfce improves performances

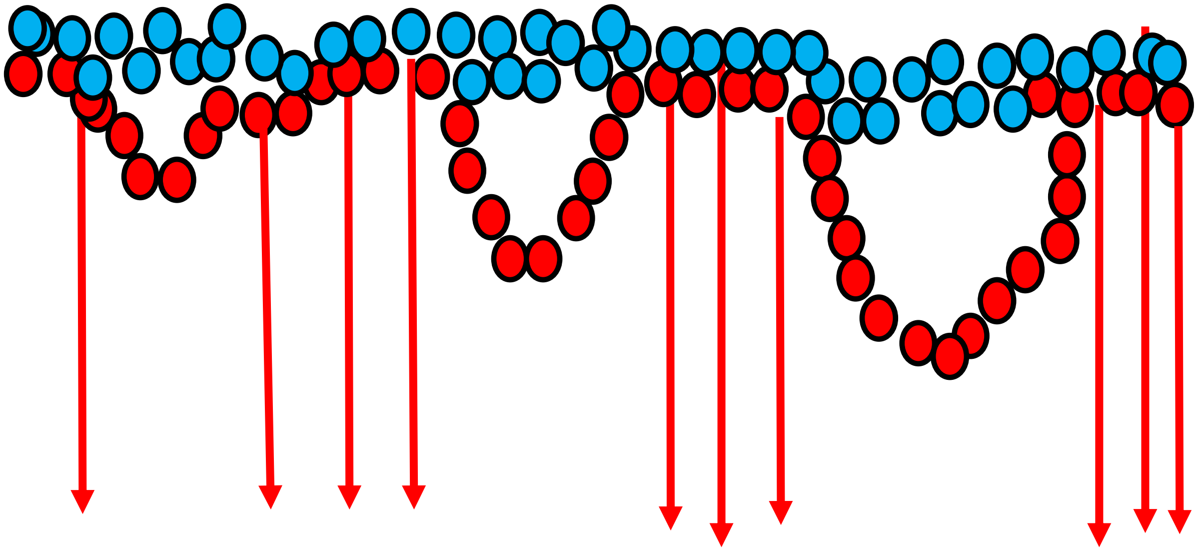


If micro-voids form at the interface they would be log-normally distributed



«Void formation during film growth: A molecular dynamics simulation study»
R.W. Smith and D.J. Srolovitz, J. Appl. Phys., Vol. 79, p. 1448 (1996)

The heat removal from the film to substrated is mediated by the pinholes



Conclusions

If the Nb-Cu interface is not perfect, high values of the **thermal resistance $R_B = R_{Nb/Cu}$ will rise**.

The Nb film areas in loose contact will be gradually driven into the normal state, characterized by a high surface resistance, so that the typically **high Q-slope is due to a progressive "micro-quench" process.**

Two roads of investigation:

Buffer layers and thick films

Conclusions

The two roads of investigation:

Buffer layers and conformal coating of pin holes