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THERMAL BOUNDARY RESISTANCE for SRF cavities

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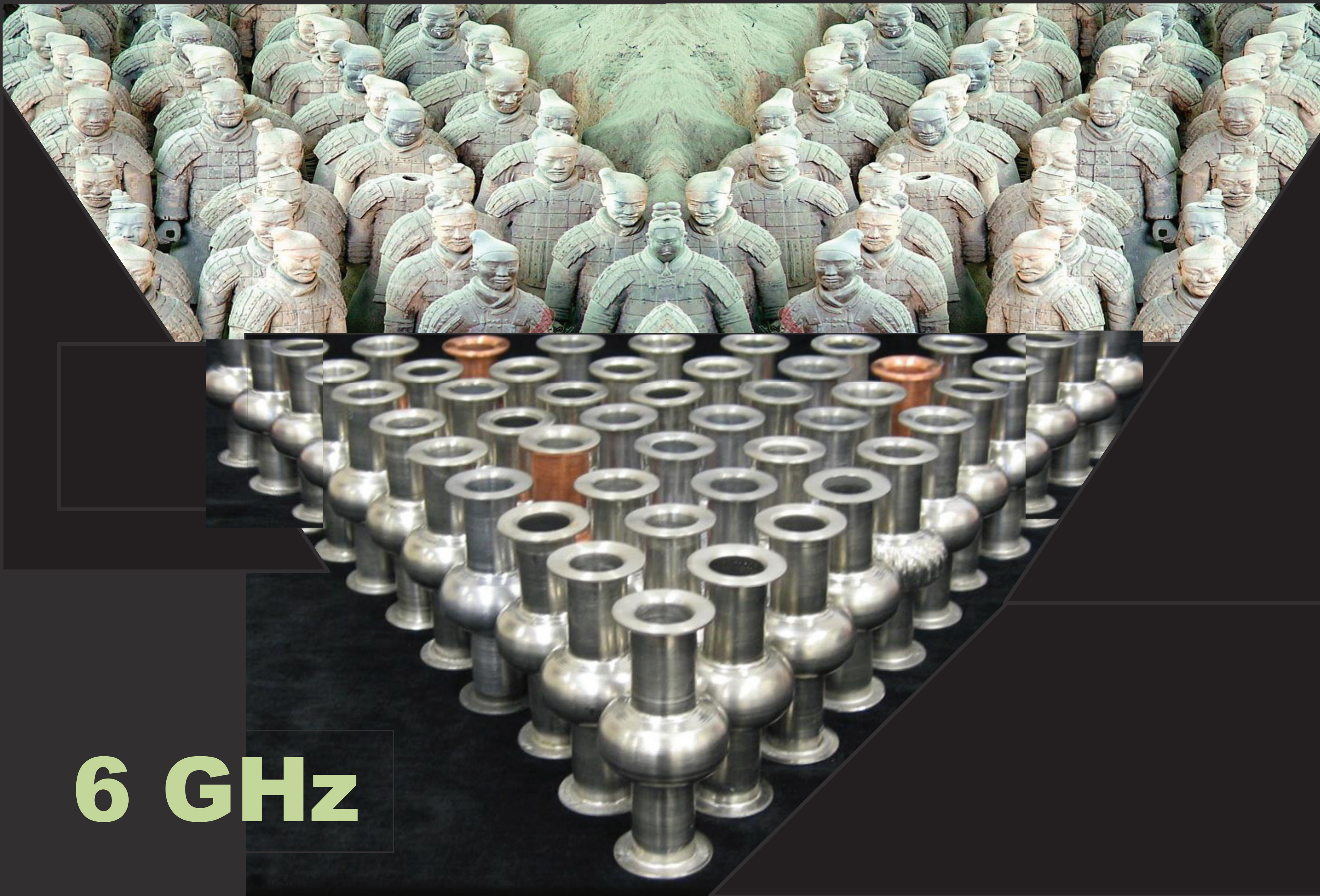
My Talk consists in

20 questions to the

Audience

For the work I am presenting

2 main ingredients needed


6 GHz

In a small, but active, Research Group

6 GHz Cavities

The Ideal Tool For Self-motivation:

Common sentences you can daily hear in the lab:

- «Bye, I go to spin some other 60 cavities!»
- «This week we have tested 12 cavities»
- We just did the EP, I go now to anneal the cavity, tonight we do the rf test
- Is Cavity #148 or cavity #134 that has the highest field?

Second Ingredient:
a Great Team

Question 1:

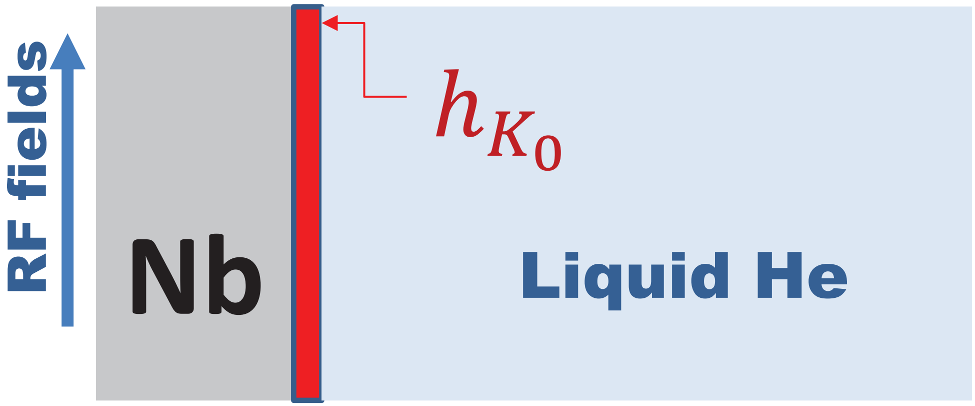
Suppose to have an ideal cavity

(a perfectly omogeneous monocrystal, no trapped flux,)

«R_{RES} = 0 ? »

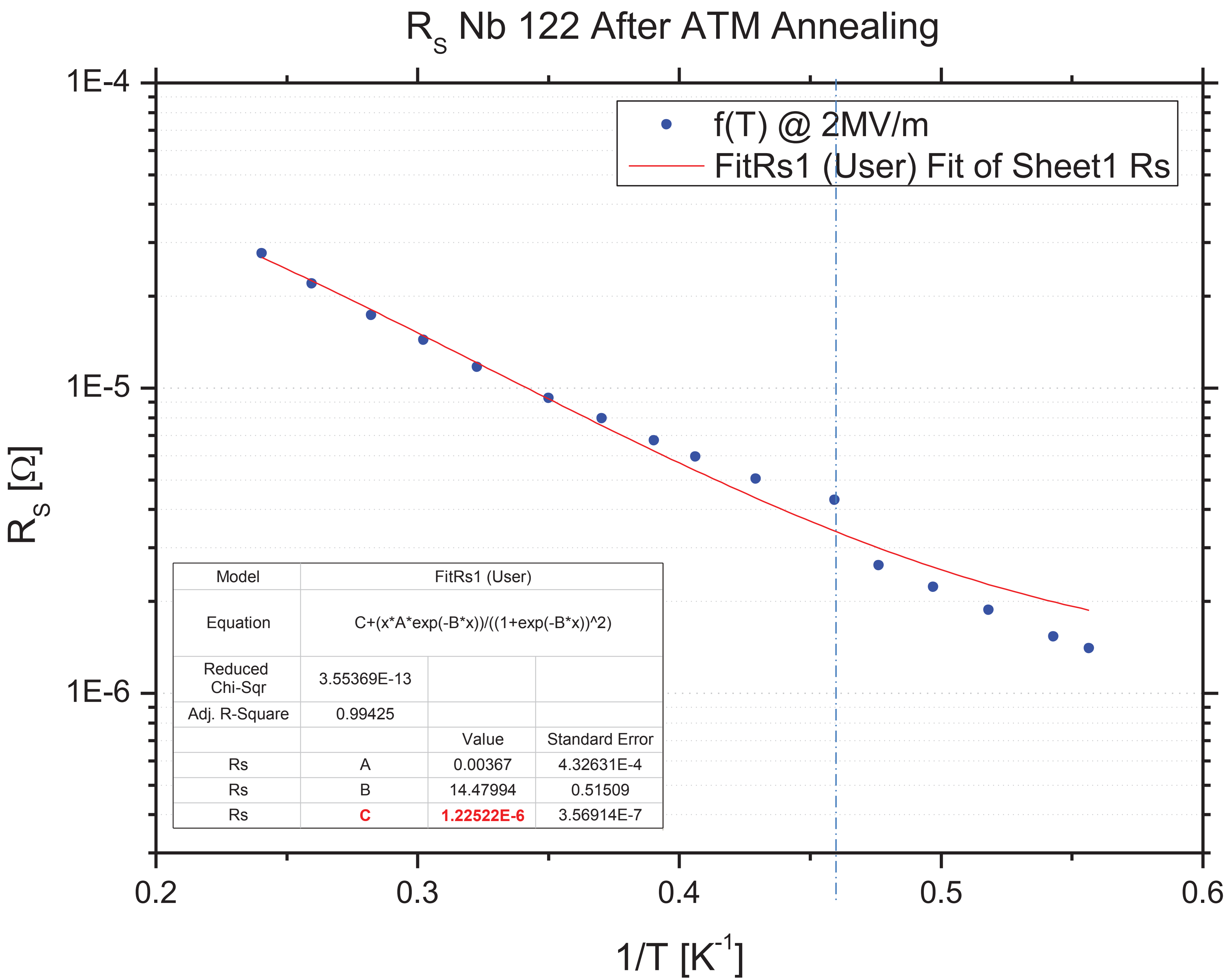
(or will you have still a contribution due to a bad thermal exchange with the Helium bath?

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



RS Nb 122 After ATM Annealing
1E-4
1E-5
1E-6
0.2
0.3
0.4
0.5
0.6
RS [Ω]
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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Jefferson Lab, Newport News, VA 23606
W. A. Lanford
Department of Physics, SUNY Albany, Albany, NY 12222

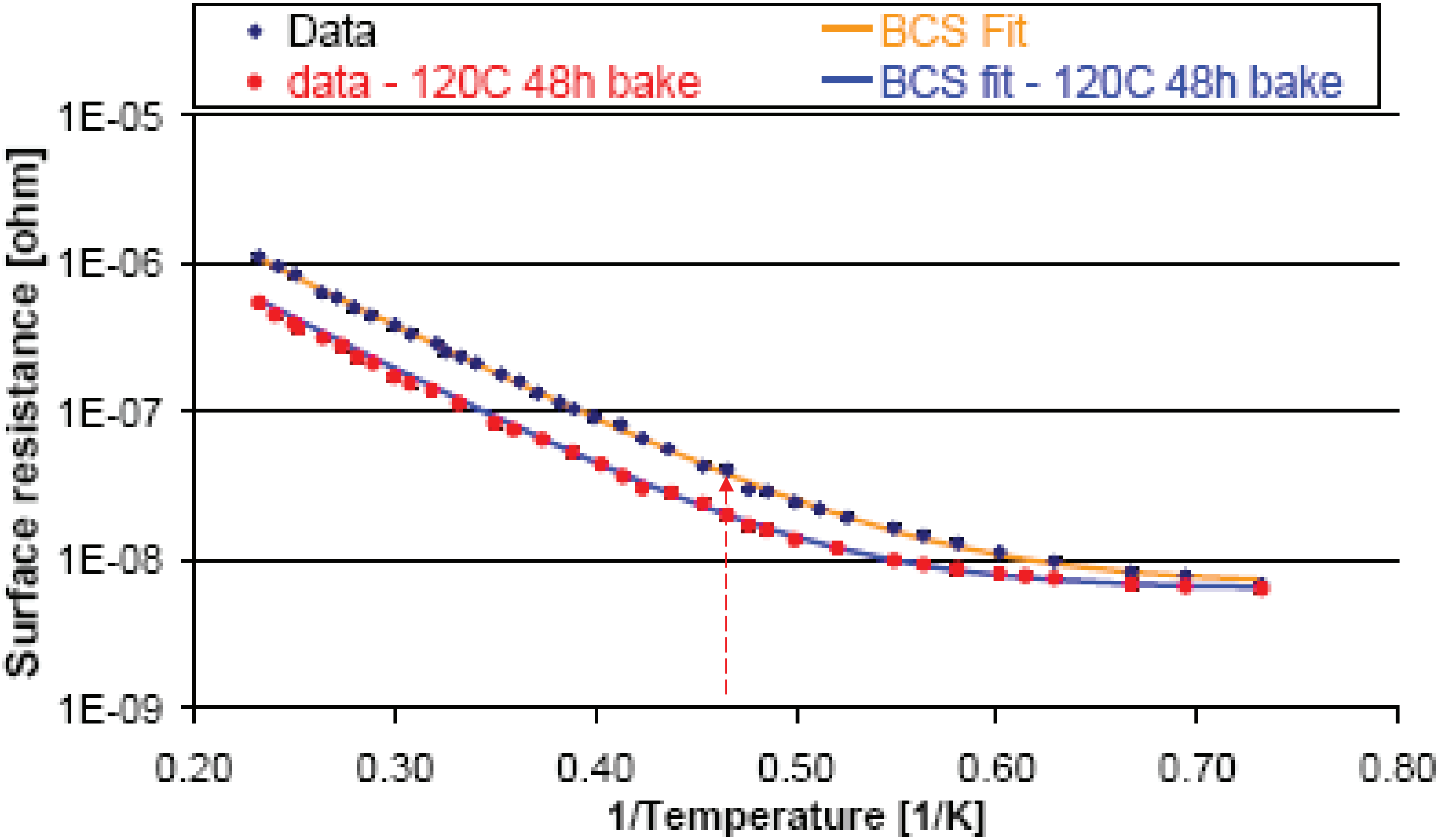


Figure 15: Surface resistance vs. 1/temperature before and after 120°C, 48h baking.

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

P. Dhakal,[1] G. Ciovati,[1] G. R. Myneni,[1,*] K. E. Gray,[2] N. Groll,[2] P. Maheshwari,[3]
D. M. McRae,[4] R. Pike,[5] T. Proslier,[2] F. Stevie,[3] R. P. Walsh,[4] Q. Yang,[6] and J. Zasadzinzki[7]

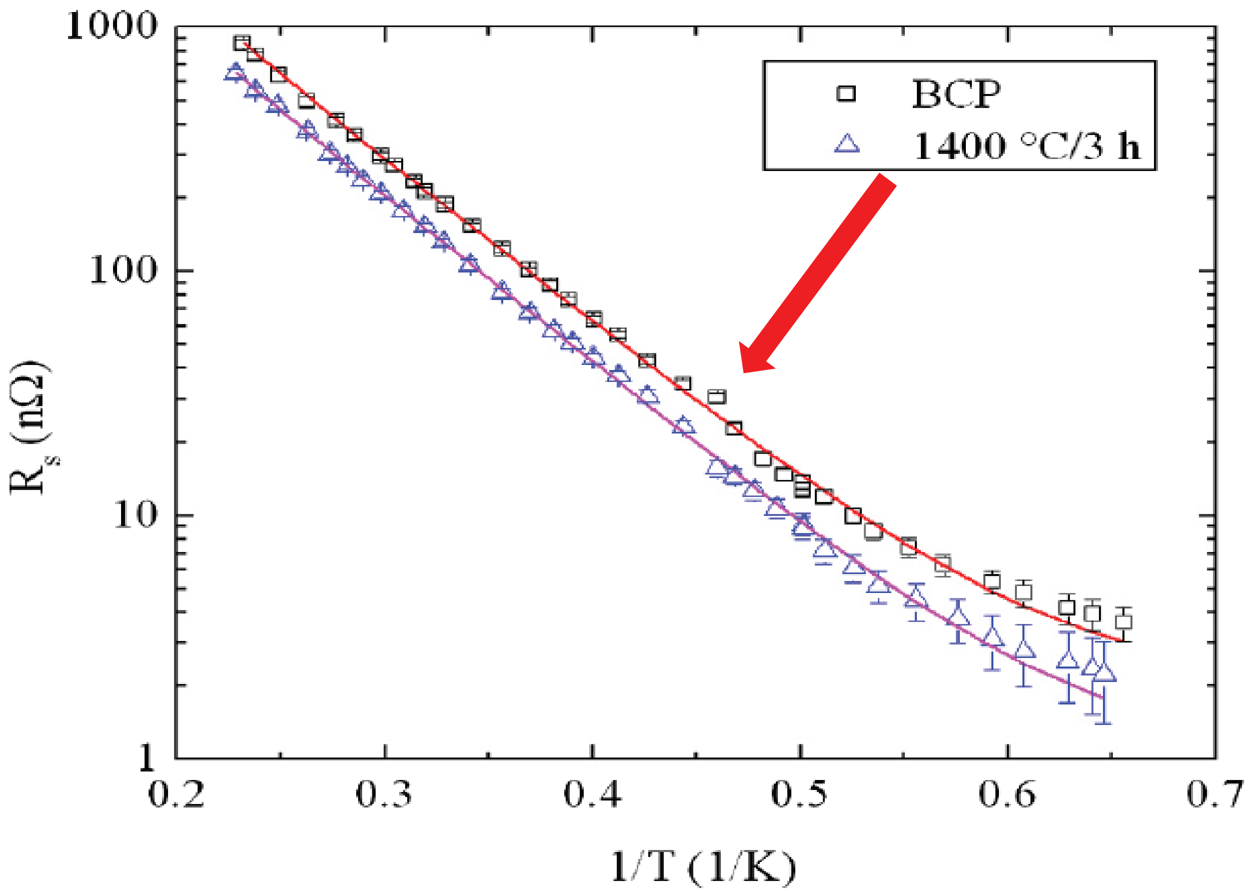
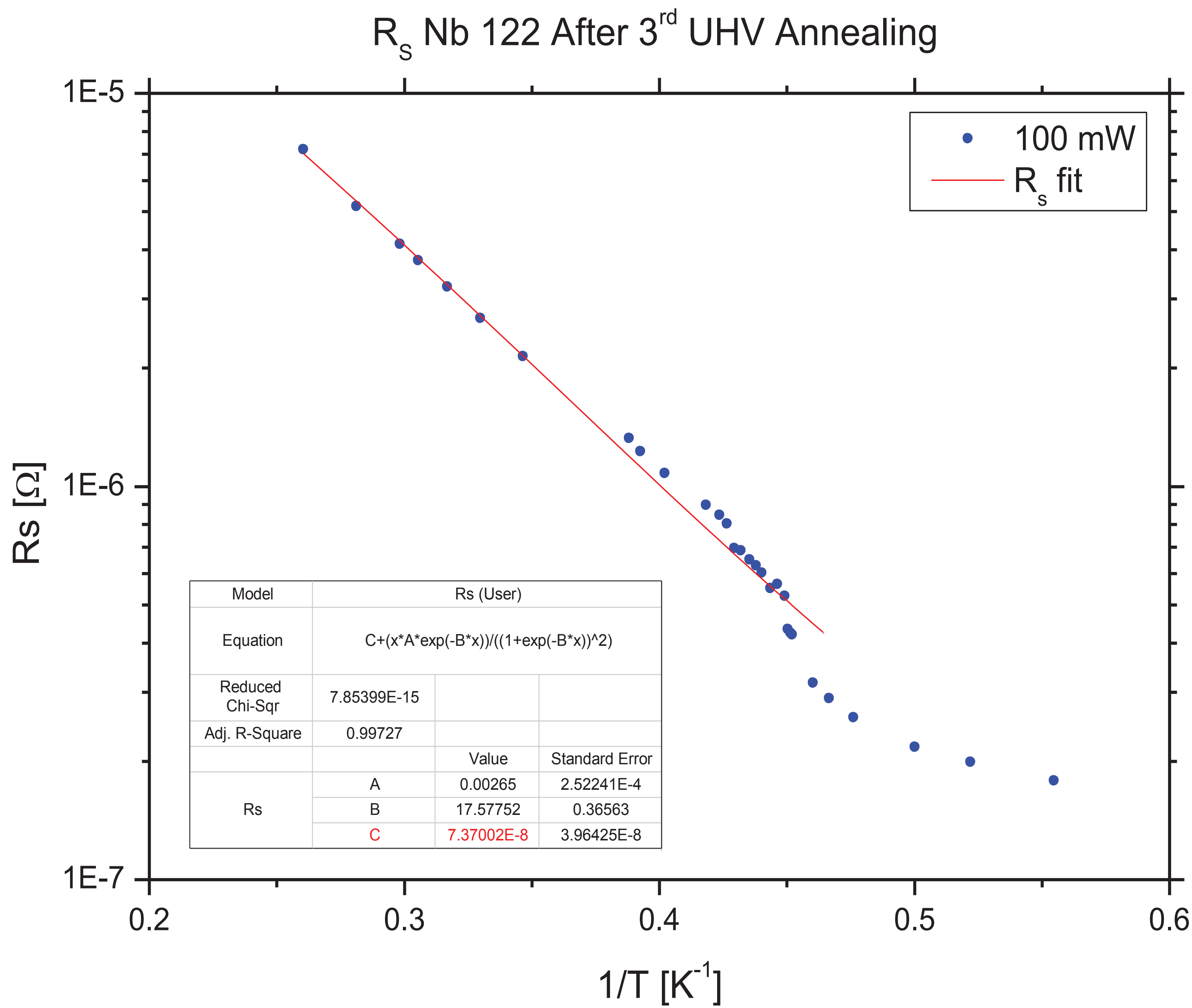
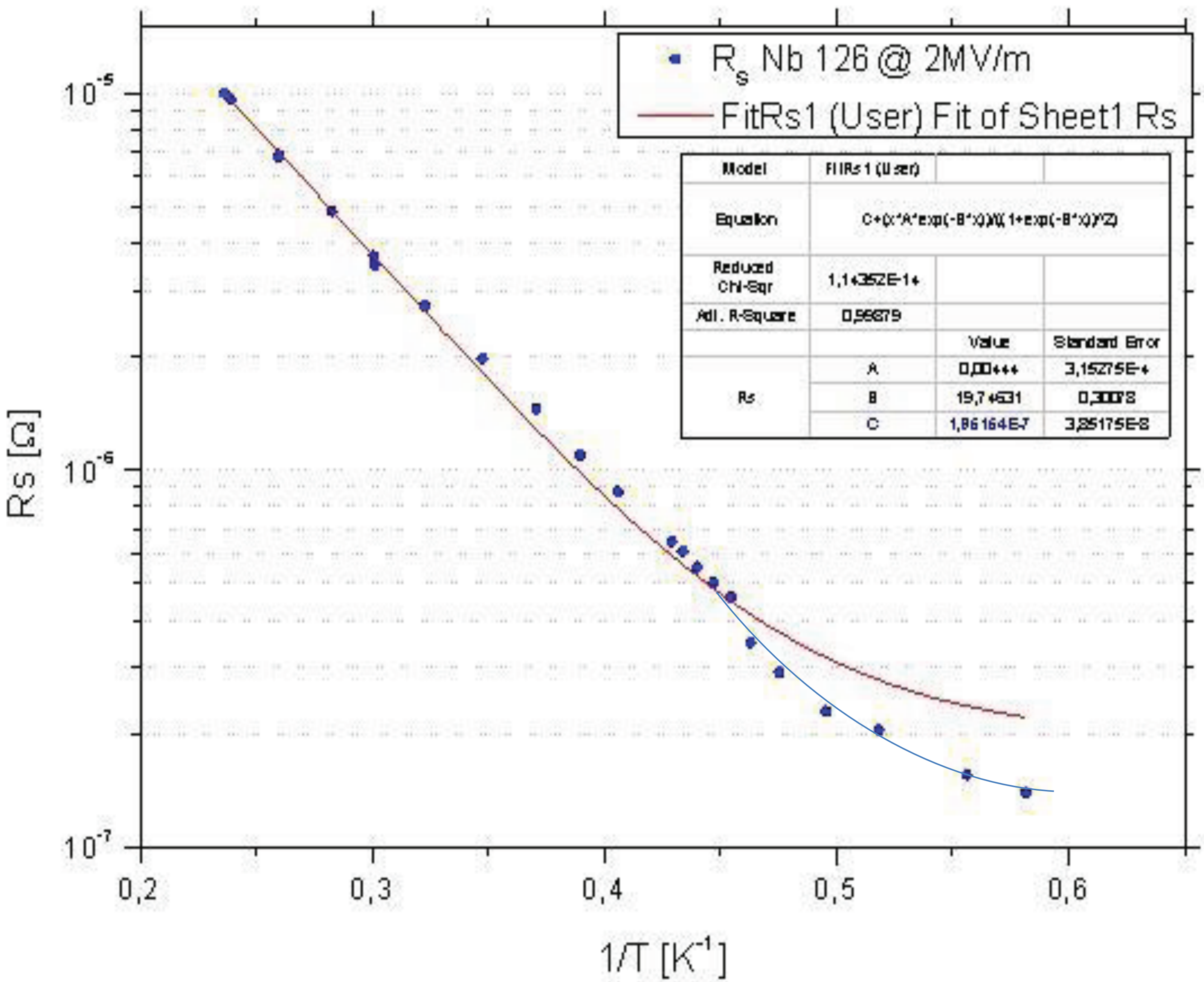


FIG. 9. R_s vs $1/T$ measured after BCP and after HT at 1400°C. Solid lines are least-square fits with $R_s(T) = R_{BCS}(T) + R_{res}$. The values of the fit parameters are $\Delta/kT_c = 1.87 \pm 0.02$, $\ell = (303 \pm 85)$ nm, $R_{res} = (2.0 \pm 0.3)$ nΩ after BCP and $\Delta/kT_c = 1.90 \pm 0.01$,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

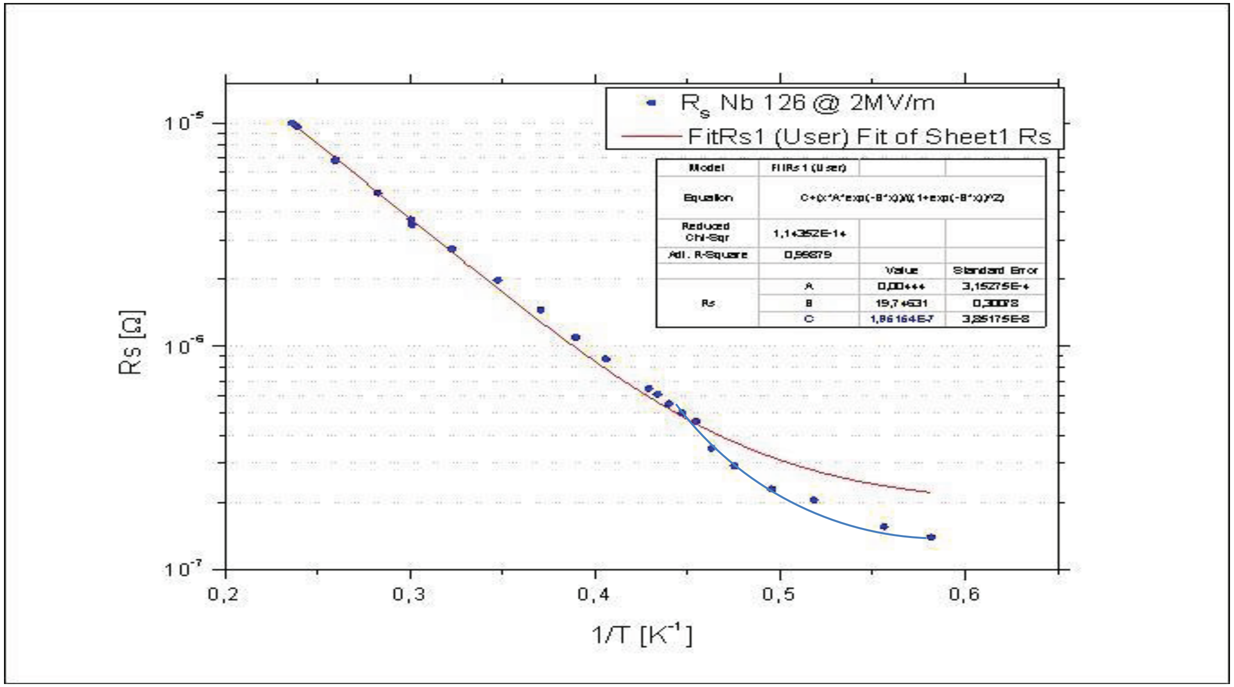


Rs Nb 122 After 3rd UHV Annealing
1E-5
1E-6
1E-7
Rs [Ω]
0.2
0.3
0.4
0.5
0.6
1/T [K-1]
100 mW
Rs fit
Model
Rs (User)
Equation
C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)
Reduced Chi-Sqr
7.85399E-15
Adj. R-Square
0.99727
Value
Standard Error
Rs
A
0.00265
2.52241E-4
B
17.57752
0.36563
C
7.37002E-8
3.96425E-8


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
19,74531
0,30078
C
1,86164E-7
3,85175E-8
Rs [Ω]
1/T [K^-1]
10^-5
10^-6
10^-7
0,2
0,3
0,4
0,5
0,6

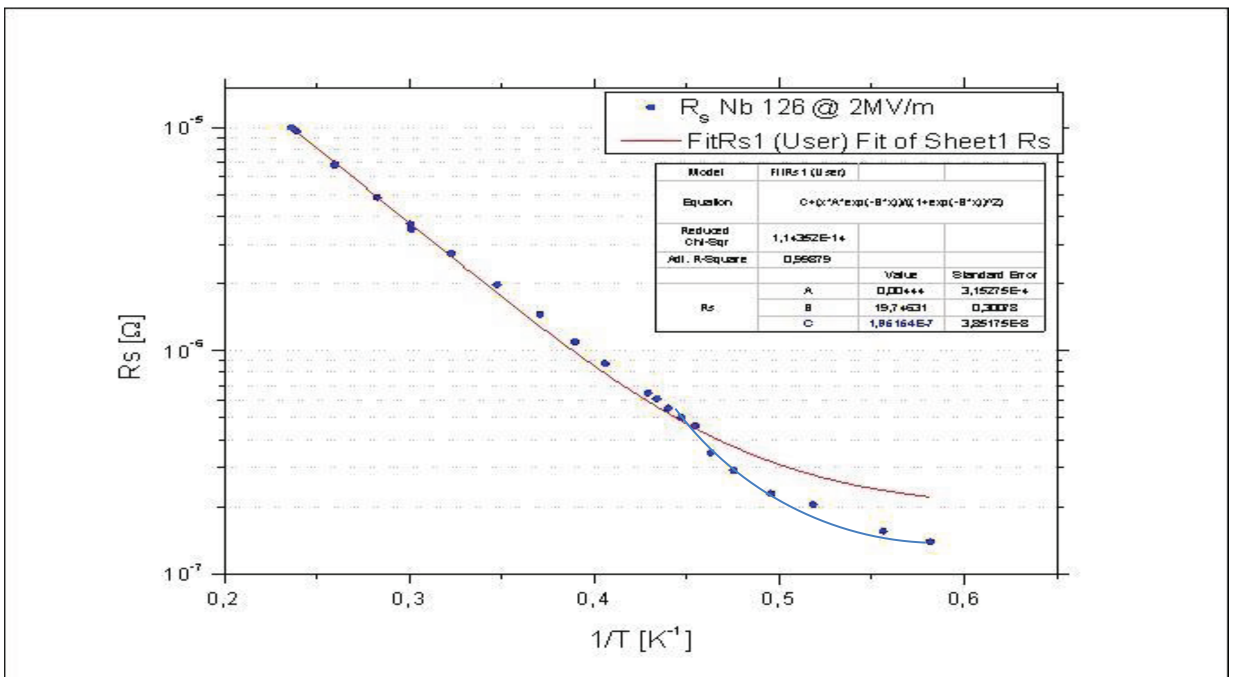
Question 2:

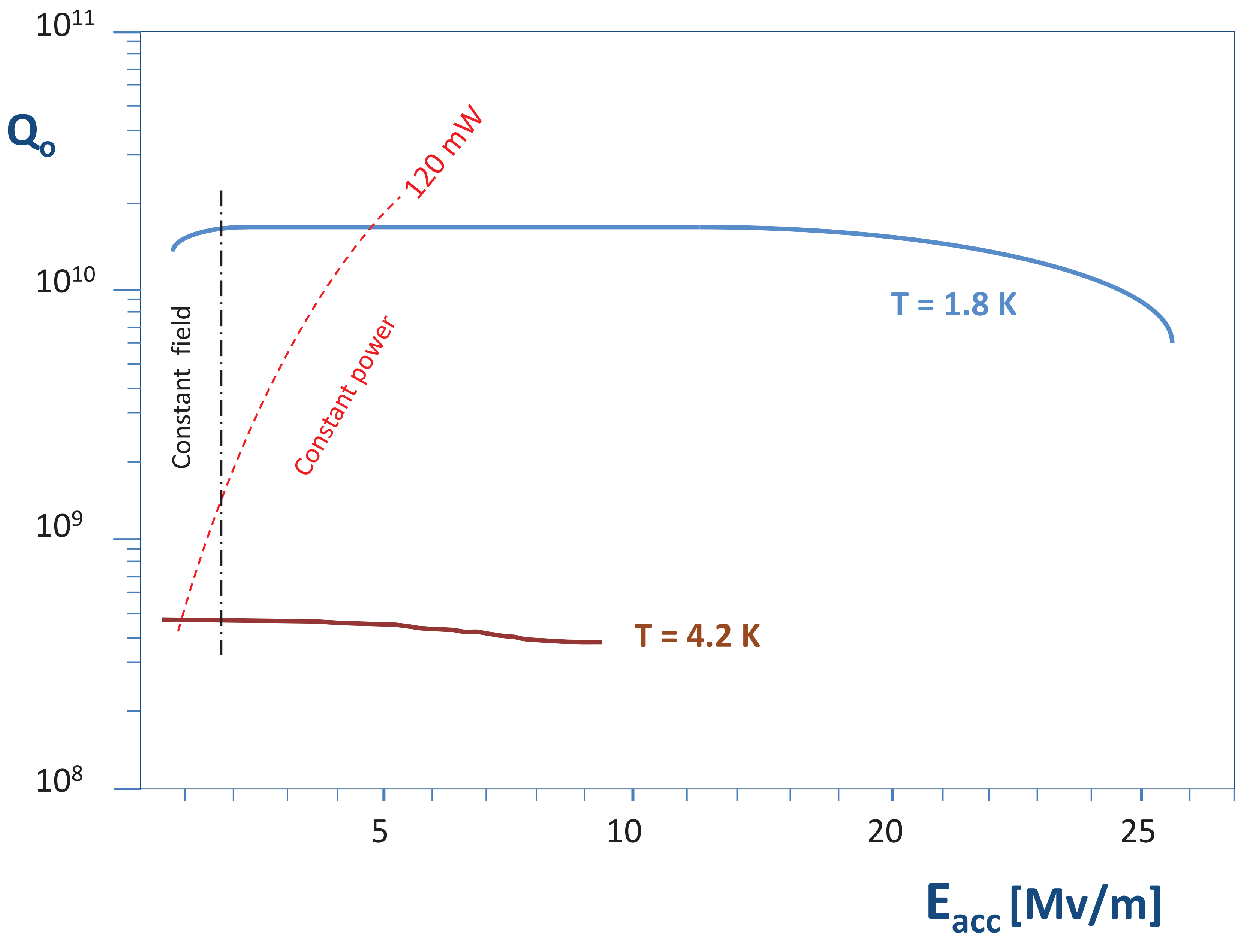
If we cooled the cavity in ^3He instead then in ^4He, should we wait a different R_{RES}?



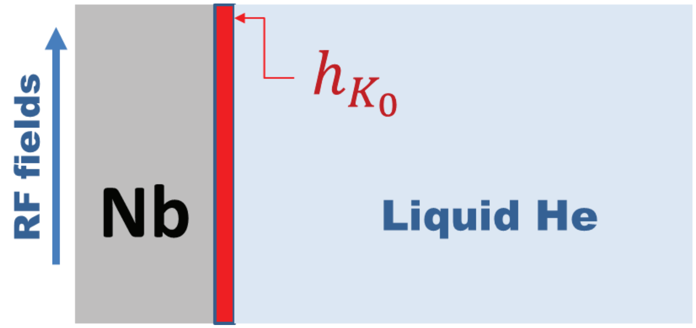
Question 3:

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



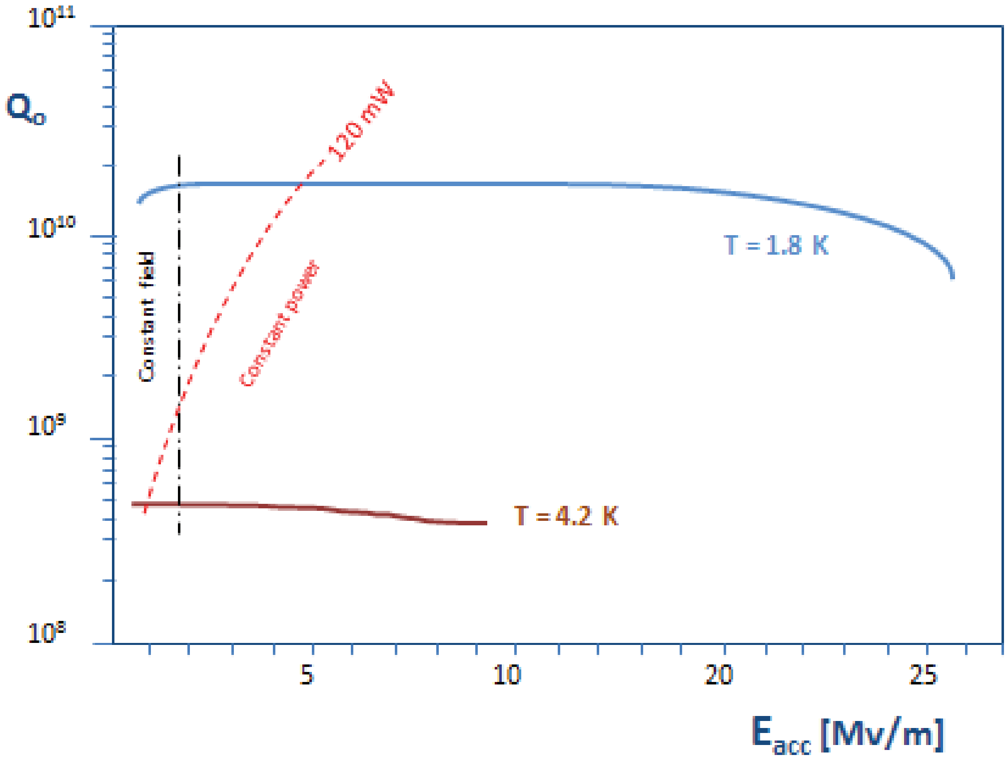


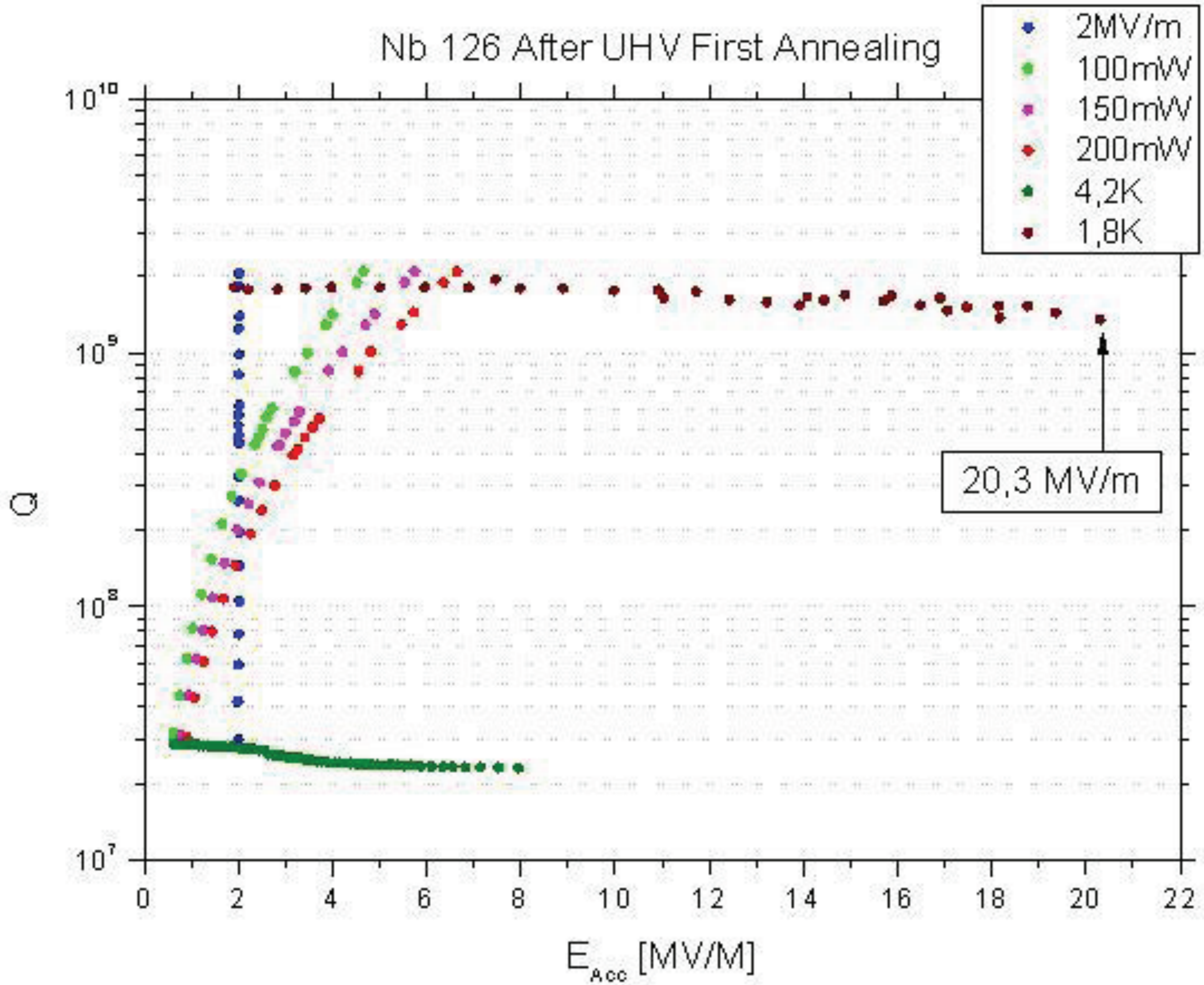
10^{11}
Q_o
120 mW
10^{10}
Constant field
Constant power
T = 1.8 K
10^{9}
T = 4.2 K
10^{8}
5
10
20
25
E_{acc} [Mv/m]

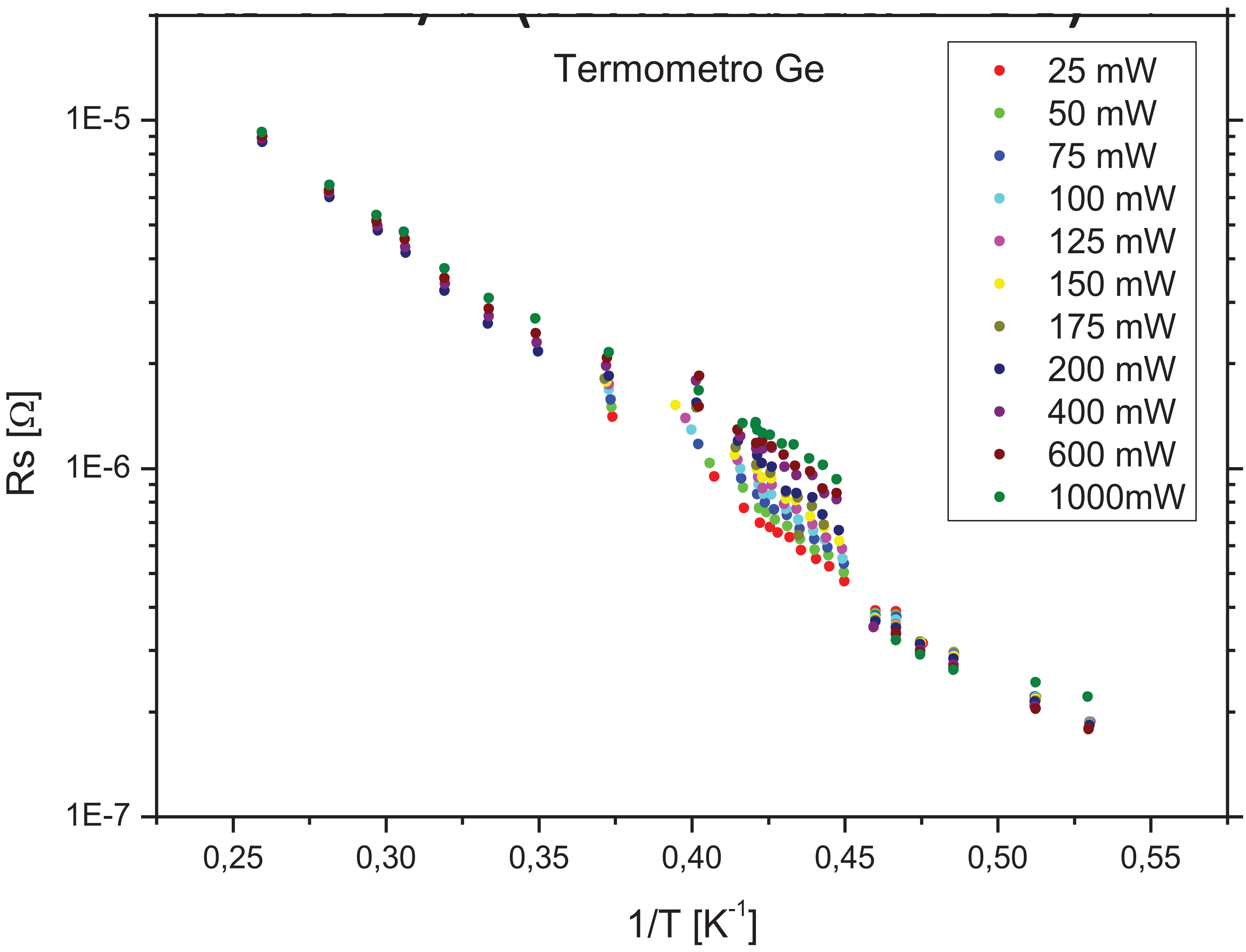


Constant E_{acc} means that both T and W are changing

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



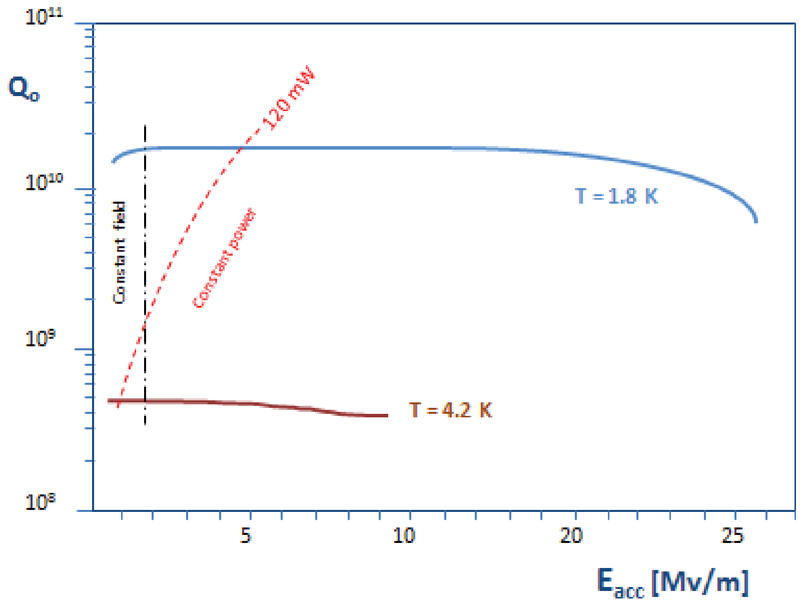

Nb 126 After UHV First Annealing
2MV/m
100mW
150mW
200mW
4,2K
1,8K
20,3 MV/m
Q
10^{10}
10^{9}
10^{8}
10^{7}
0
2
4
6
8
10
12
14
16
18
20
22
E_{Acc} [MV/M]



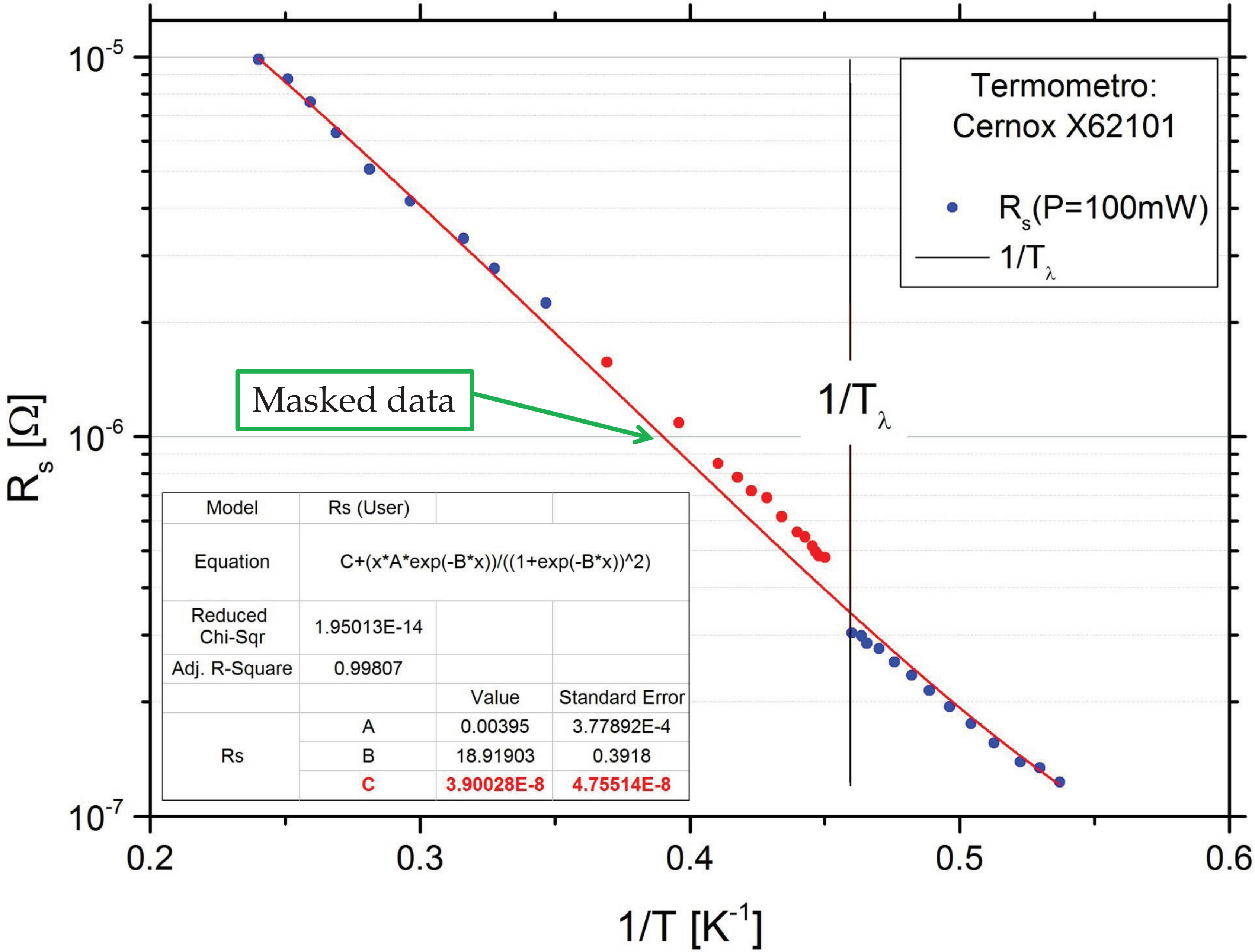
Termometro Ge
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW
1E-5
1E-6
1E-7
Rs [Ω]
0,25
0,30
0,35
0,40
0,45
0,50
0,55
1/T [K-1]

Question 4

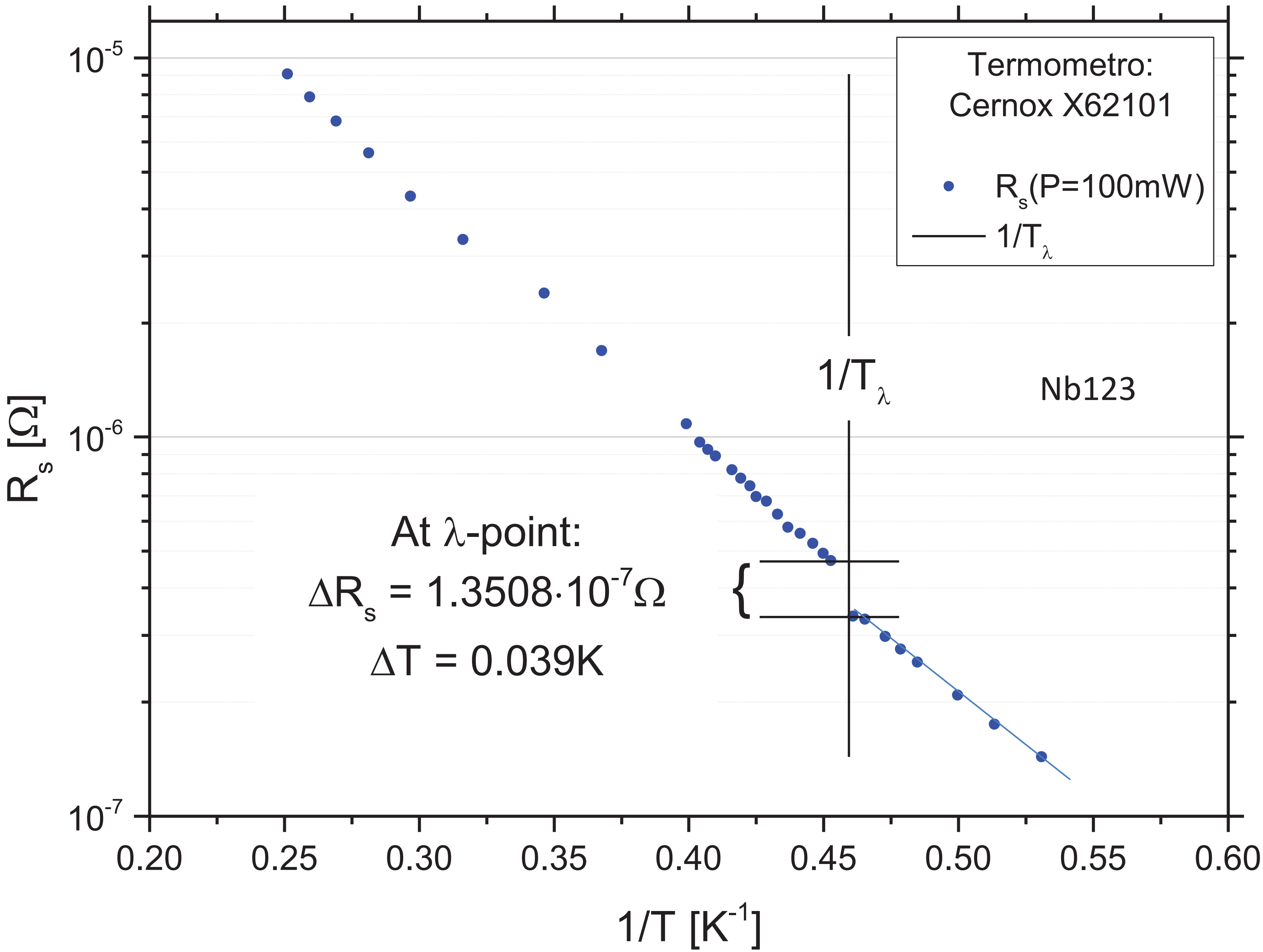
Thermodinamically, shoudn't we prefer the family of $R_s(T)$ at constant W rather than the $R_s(T)$ at constant E_{acc} ?



Expecially then if the curves are mixed


Termometro:
Cernox X62101
Rs(P=100mW)
1/Tλ
Masked data
1/Tλ
Model | Rs (User)
Equation | C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)
Reduced Chi-Sqr | 1.95013E-14
Adj. R-Square | 0.99807
Value | Standard Error
Rs | A | 0.00395 | 3.77892E-4
B | 18.91903 | 0.3918
C | 3.90028E-8 | 4.75514E-8
10-5
10-6
10-7
Rs [Ω]
0.2
0.3
0.4
0.5
0.6
1/T [K-1]

Rs vs 1/T [P=100mW]



Question 5:

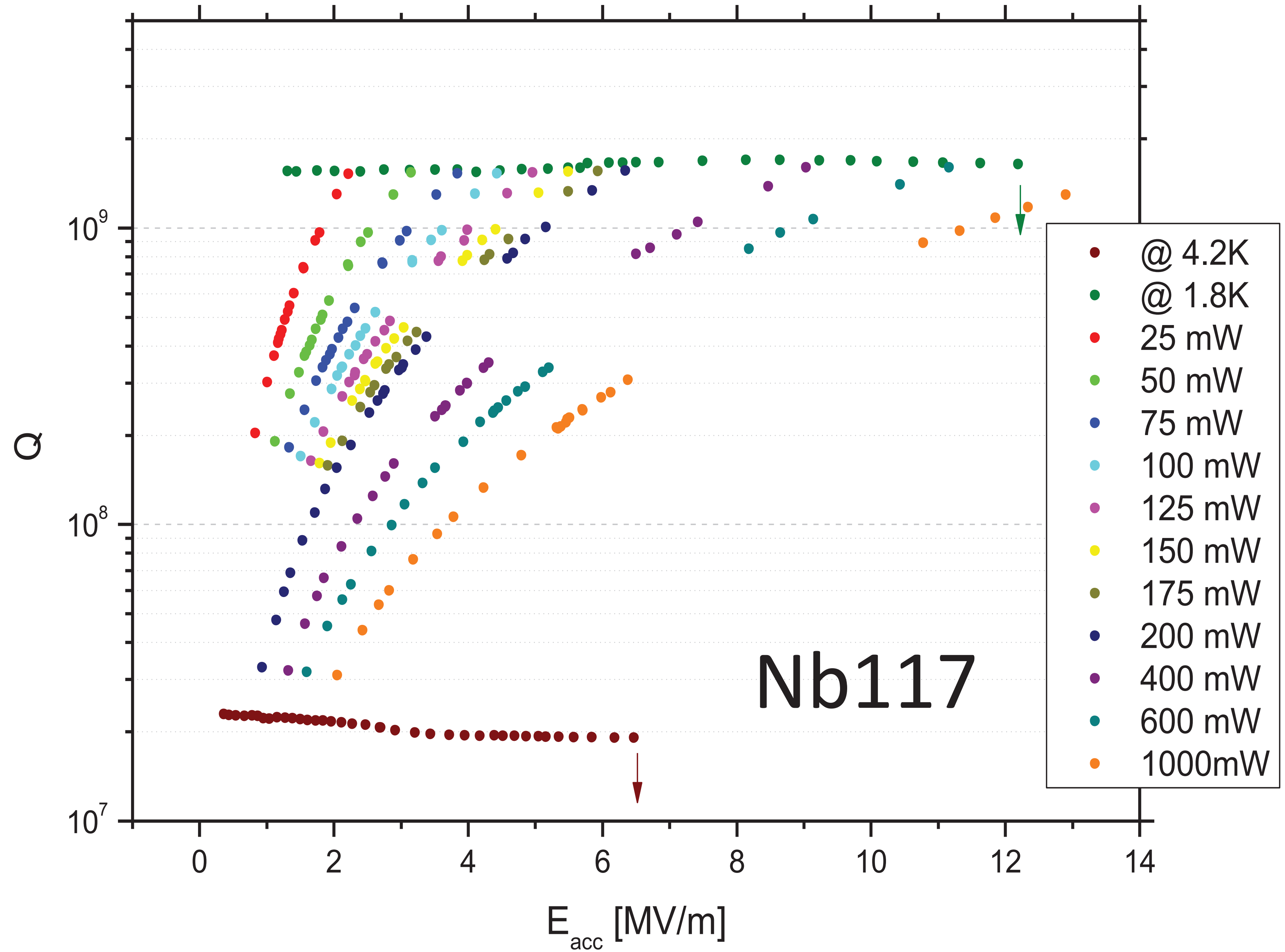
Whenever we neglect the jump at T_λ, don't we extract a false value of the strong coupling factor S?

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

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

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

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



Q
E$_{acc}$ [MV/m]
10^7
10^8
10^9
0
2
4
6
8
10
12
14
Nb117
@ 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

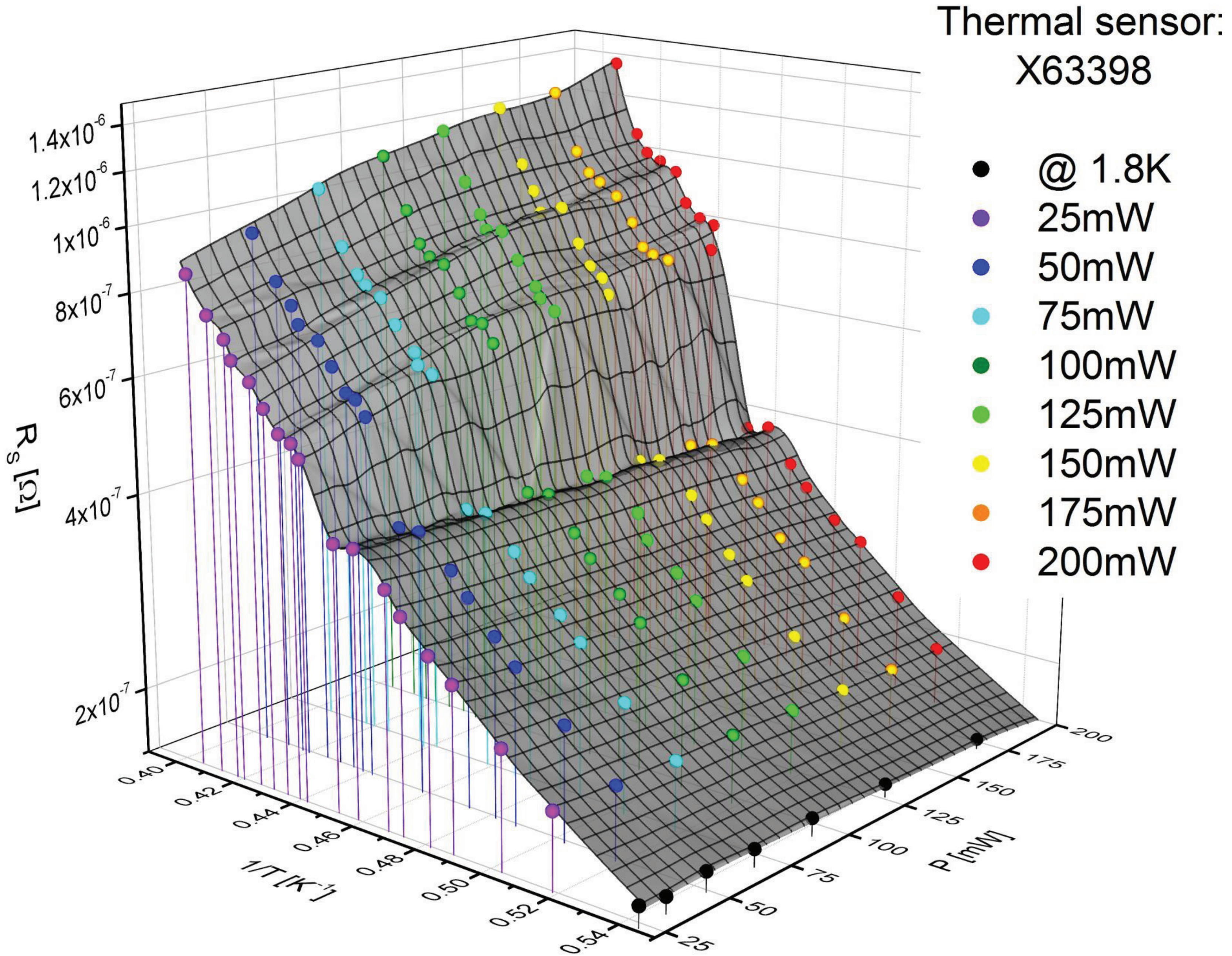
Question 6:

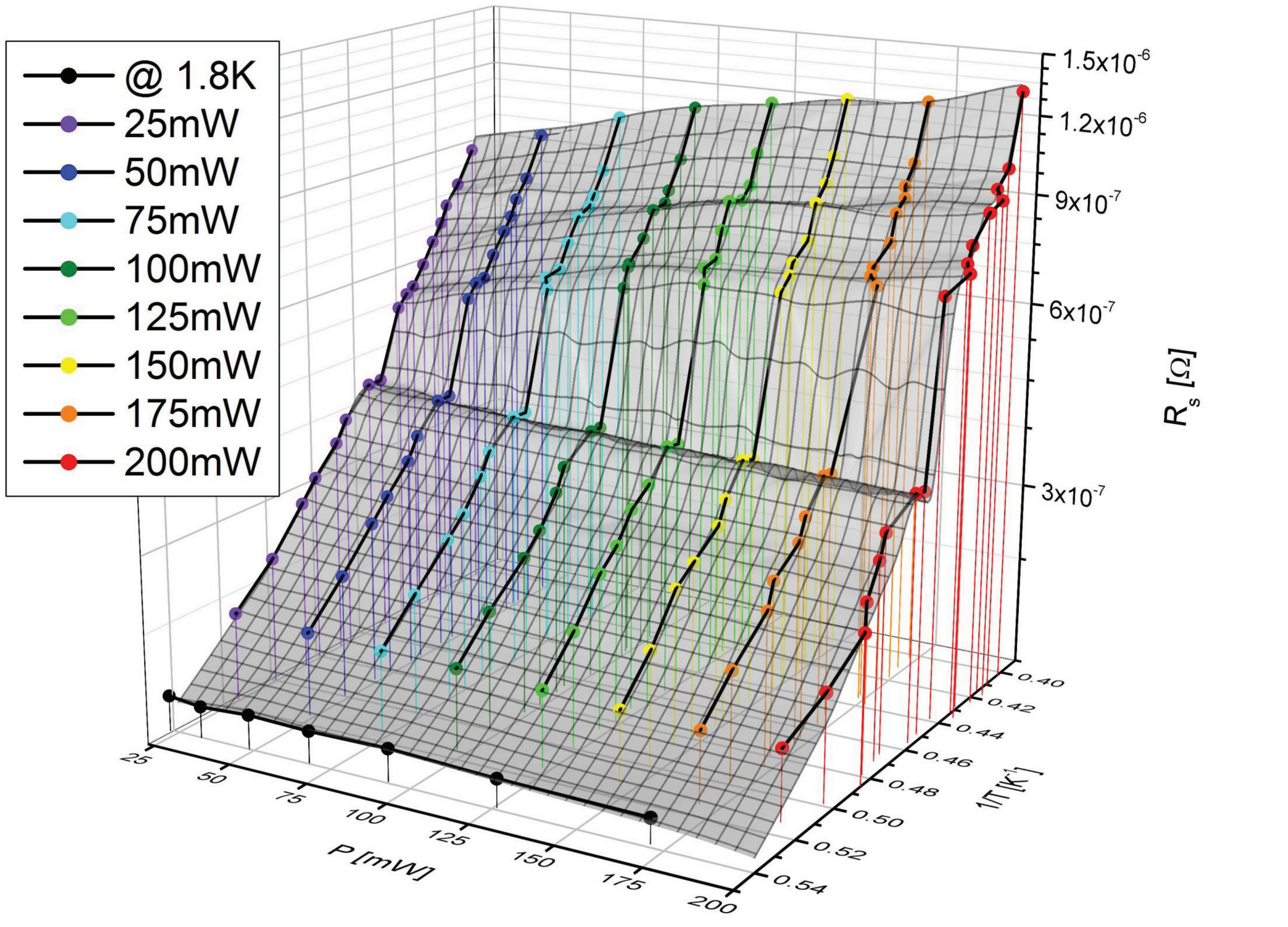
Since $R = R_s (T)$ and $Q = Q (E_{acc})$,

could we

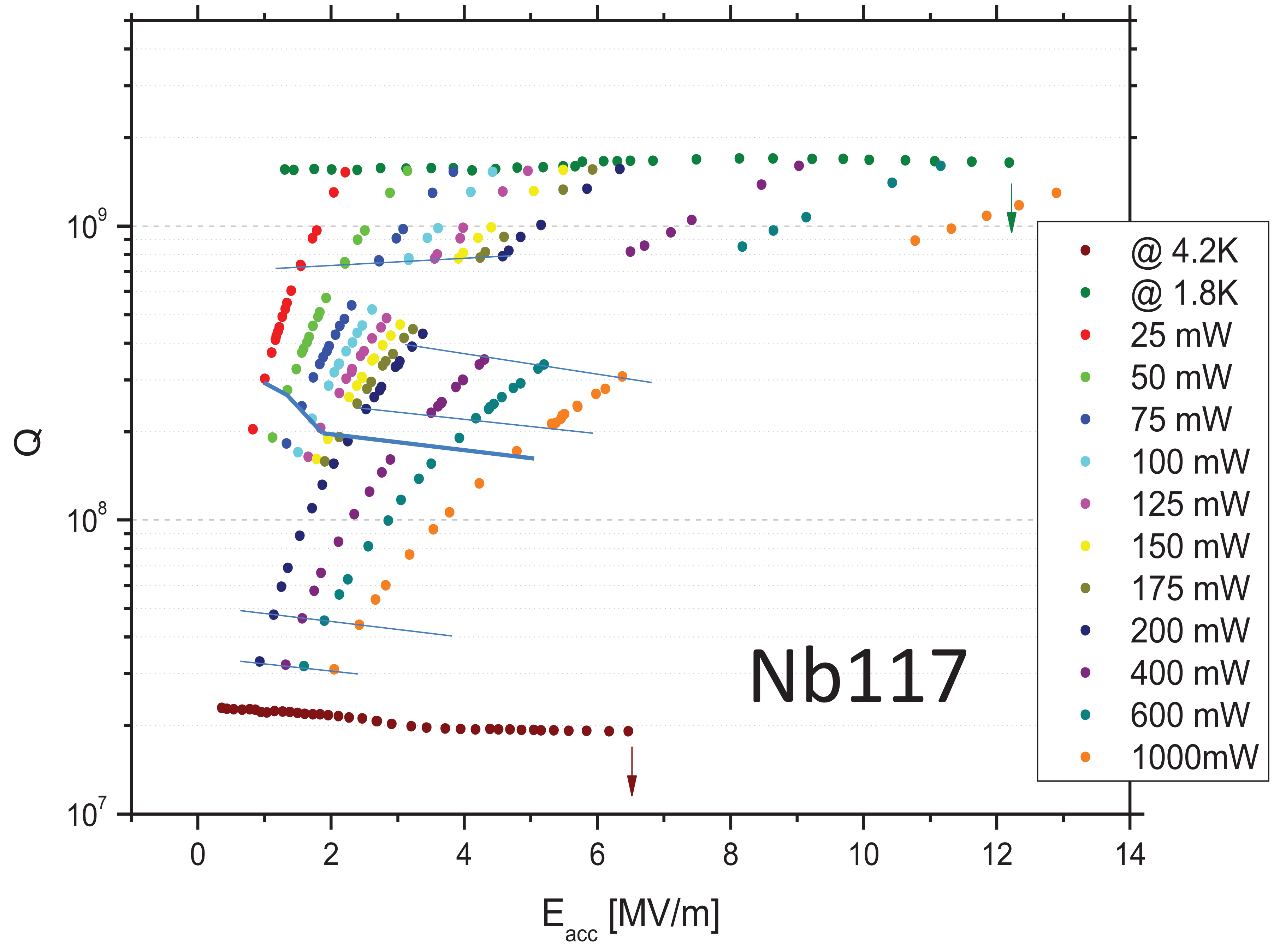
join the 2 curves into 1 graph?

Rs vs 1/T vs P (Cernox X63398)

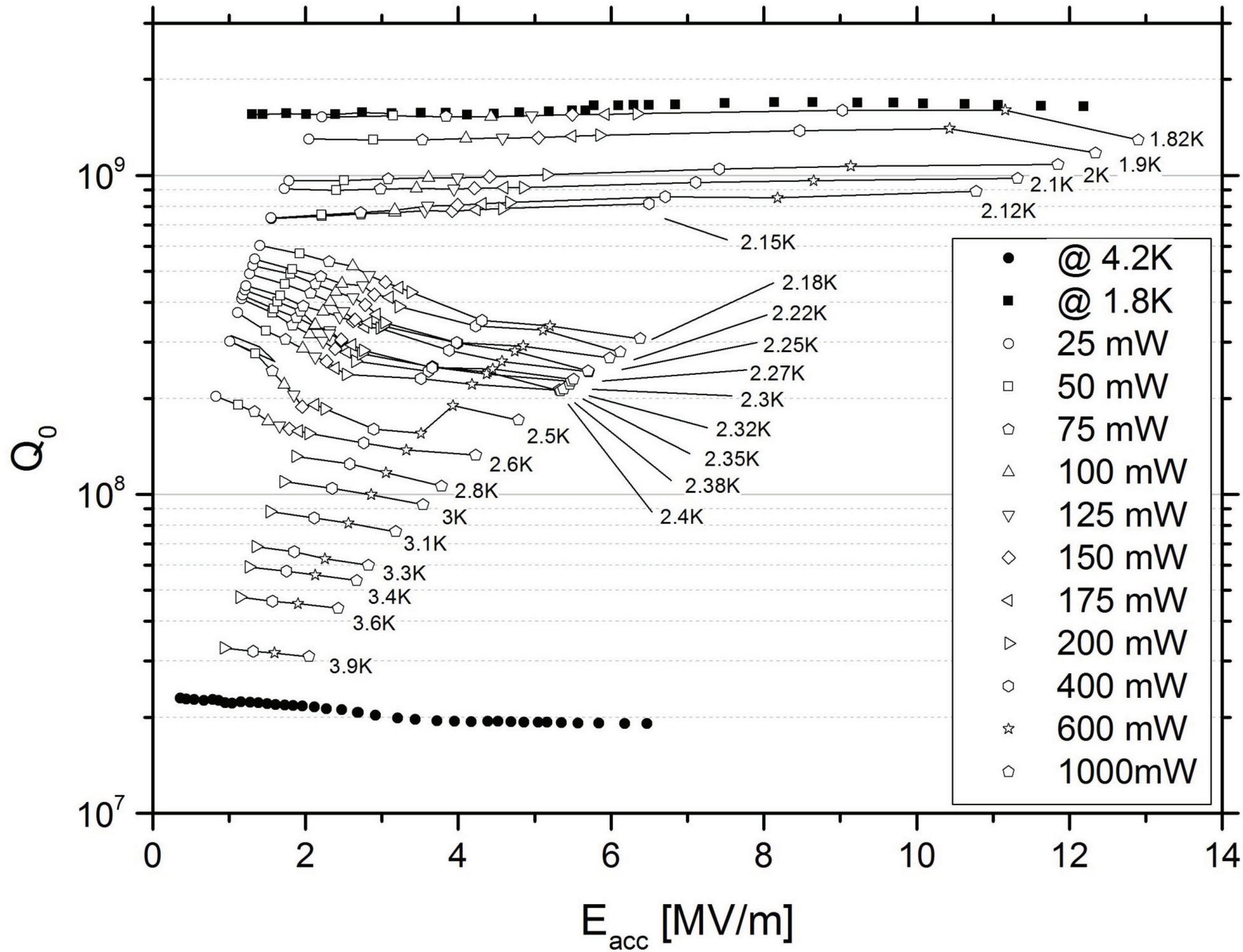




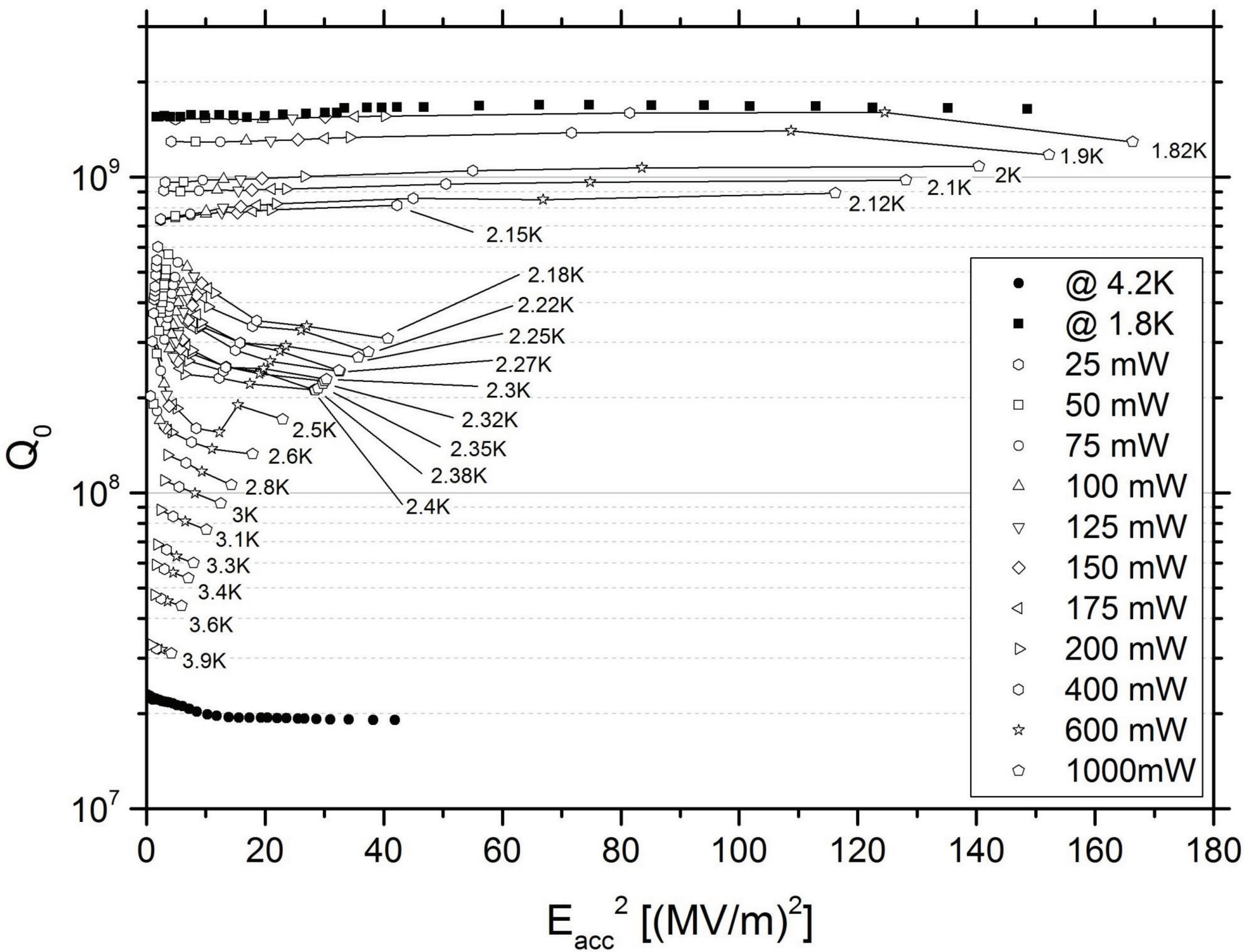
@ 1.8K
25mW
50mW
75mW
100mW
125mW
150mW
175mW
200mW
1.5x10^-6
1.2x10^-6
9x10^-7
6x10^-7
3x10^-7
R_s [Ω]
0.40
0.42
0.44
0.46
0.48
0.50
0.52
0.54
1/T [K^-1]
25
50
75
100
125
150
175
200
P [mW]



Q
E_acc [MV/m]
10^9
10^8
10^7
0
2
4
6
8
10
12
14
@ 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



Q0
Eacc [MV/m]
10^9
10^8
10^7
0
2
4
6
8
10
12
14
1.82K
1.9K
2K
2.1K
2.12K
2.15K
2.18K
2.22K
2.25K
2.27K
2.3K
2.32K
2.35K
2.38K
2.4K
2.5K
2.6K
2.8K
3K
3.1K
3.3K
3.4K
3.6K
3.9K
@ 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



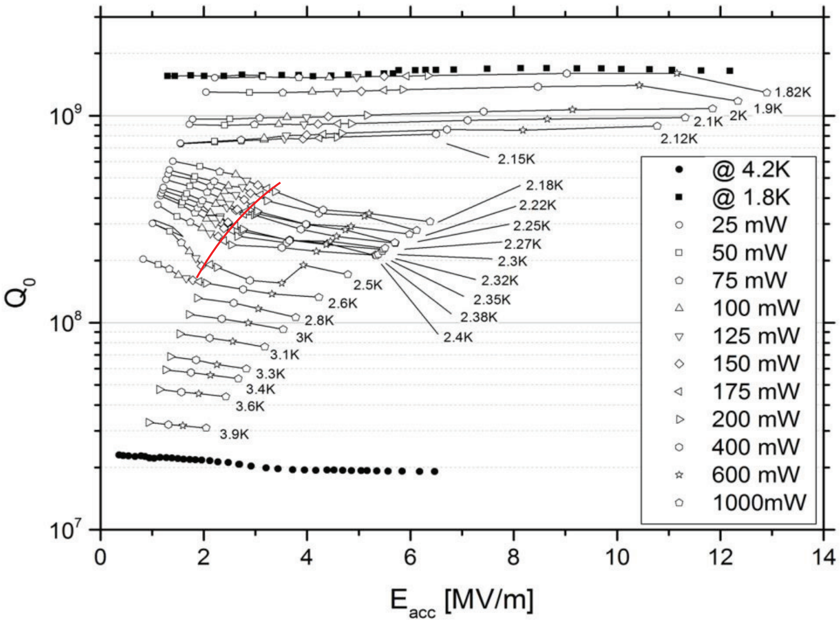
Q0
Eacc2 [(MV/m)2]
1.82K
1.9K
2K
2.1K
2.12K
2.15K
2.18K
2.22K
2.25K
2.27K
2.3K
2.32K
2.35K
2.38K
2.4K
2.5K
2.6K
2.8K
3K
3.1K
3.3K
3.4K
3.6K
3.9K
@ 4.2K
@ 1.8K
25 mW
50 mW
75 mW
100 mW
125 mW
150 mW
175 mW
200 mW
400 mW
600 mW
1000mW

Question 7:

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

Question 8:

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

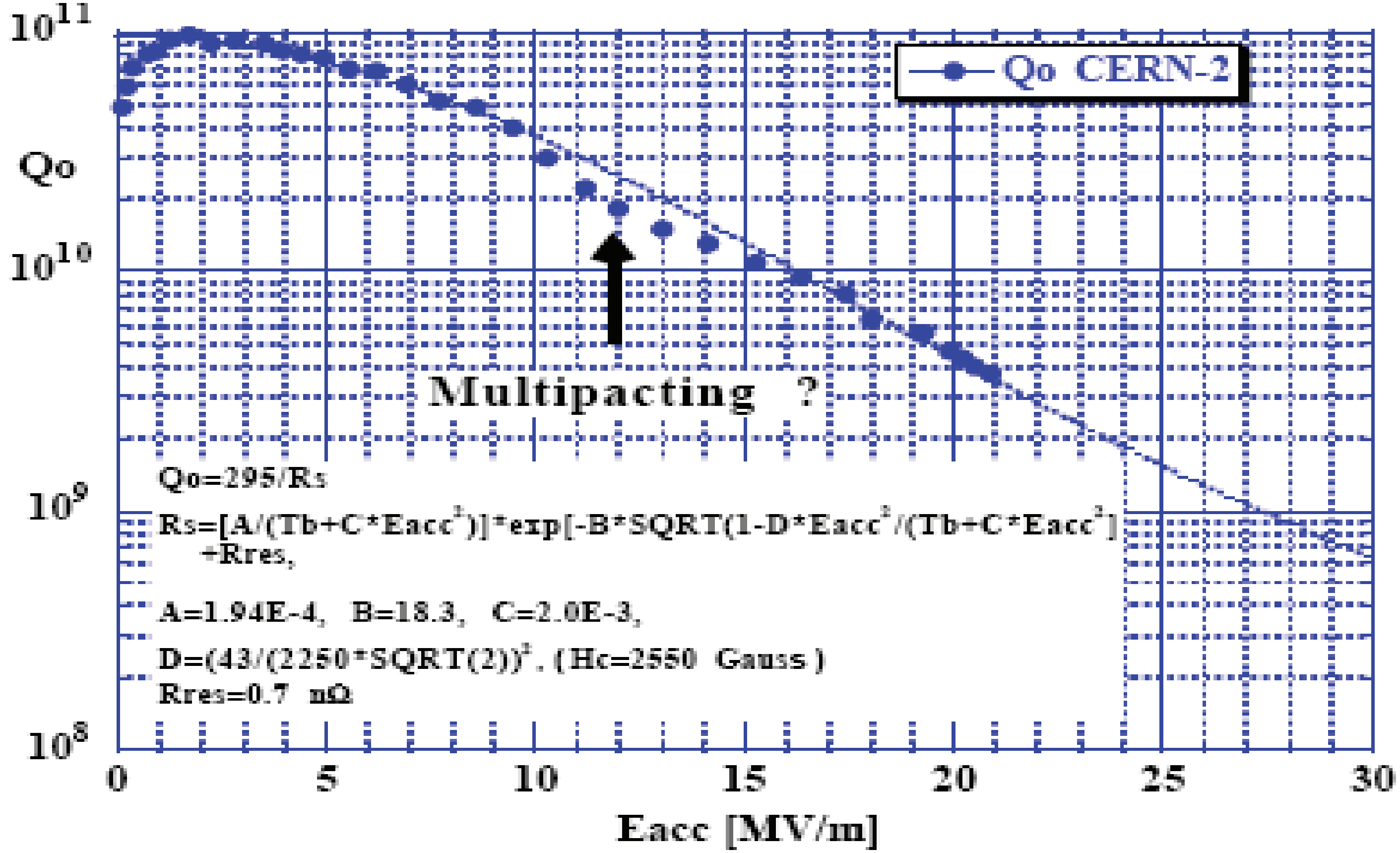
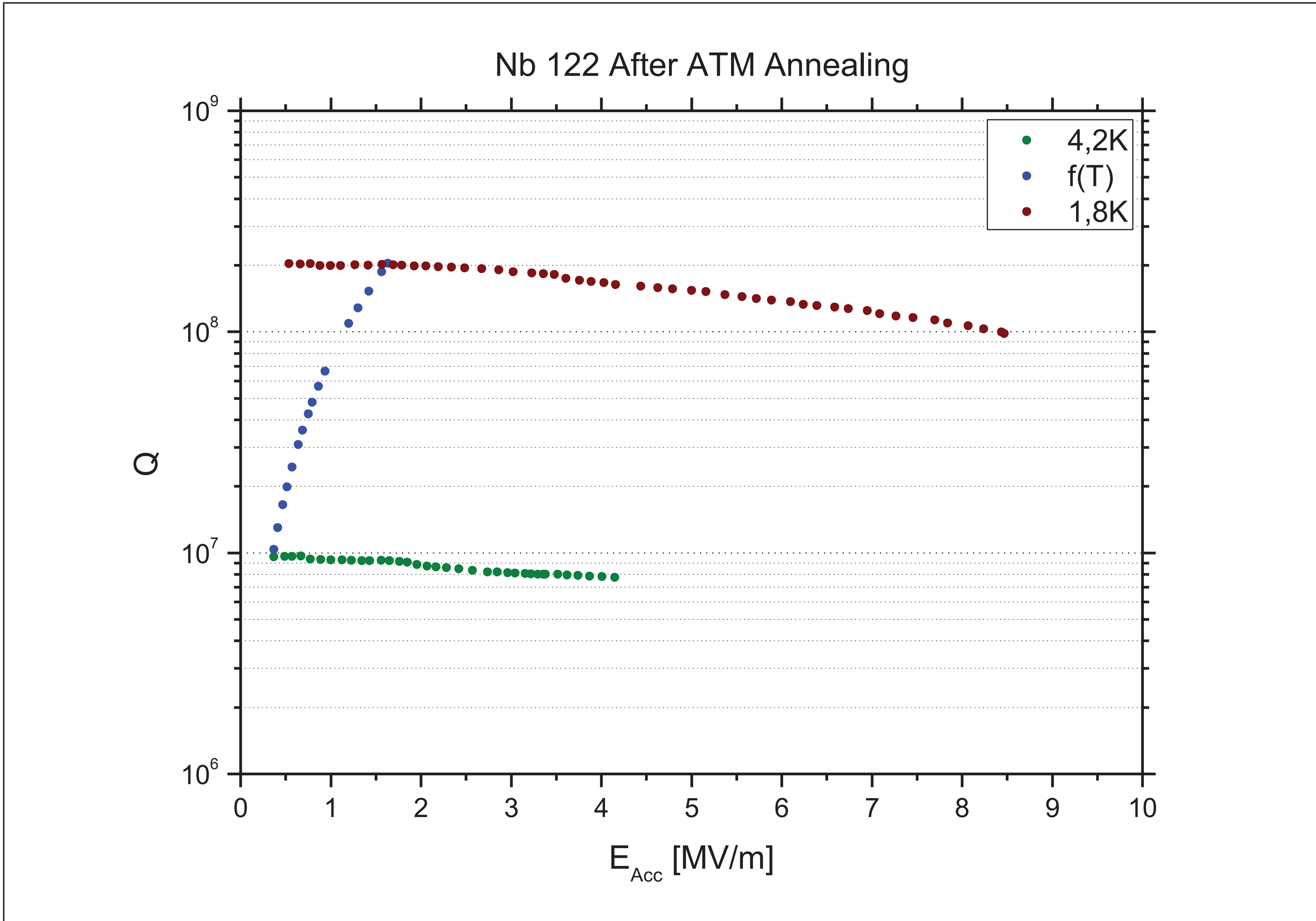


Figure 20: Qo-Eacc excitation curve fitting by the combined model for the 1500MHz niobium film coated cavity at CERN.



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

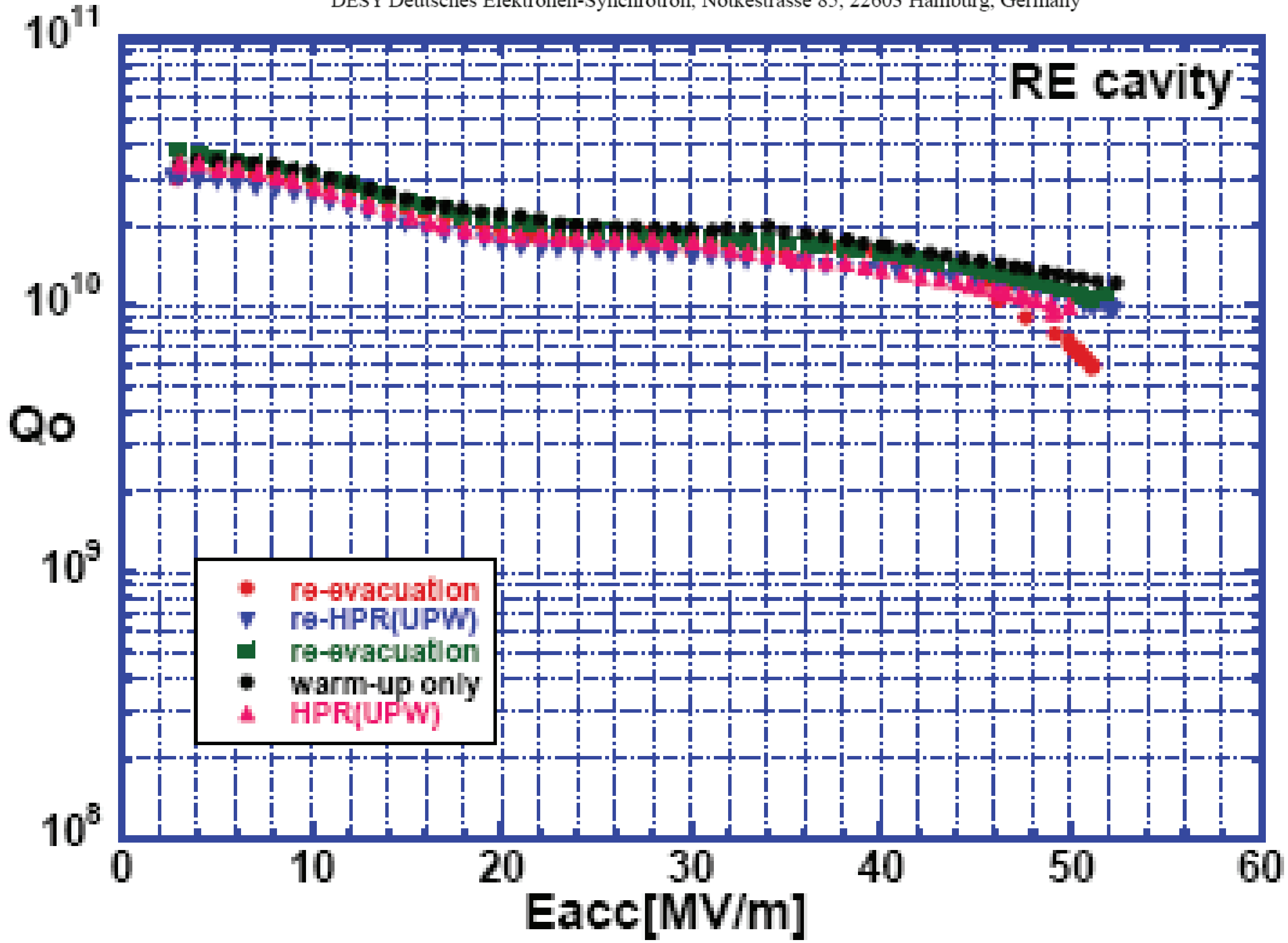


Figure 5: The reproducibility of high gradient.

Question 9:

Is it possible that

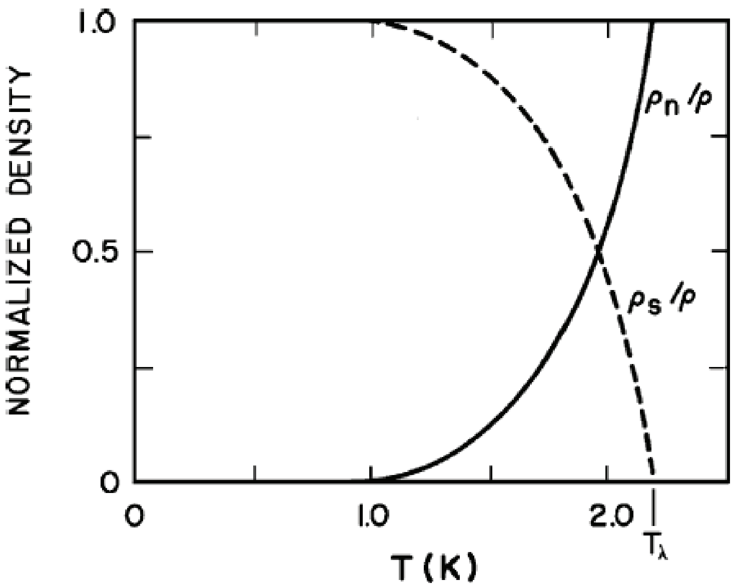
He-II will have memory of the boiling nucleation of He-I ?

QUESTION 10:

Can be the reason that

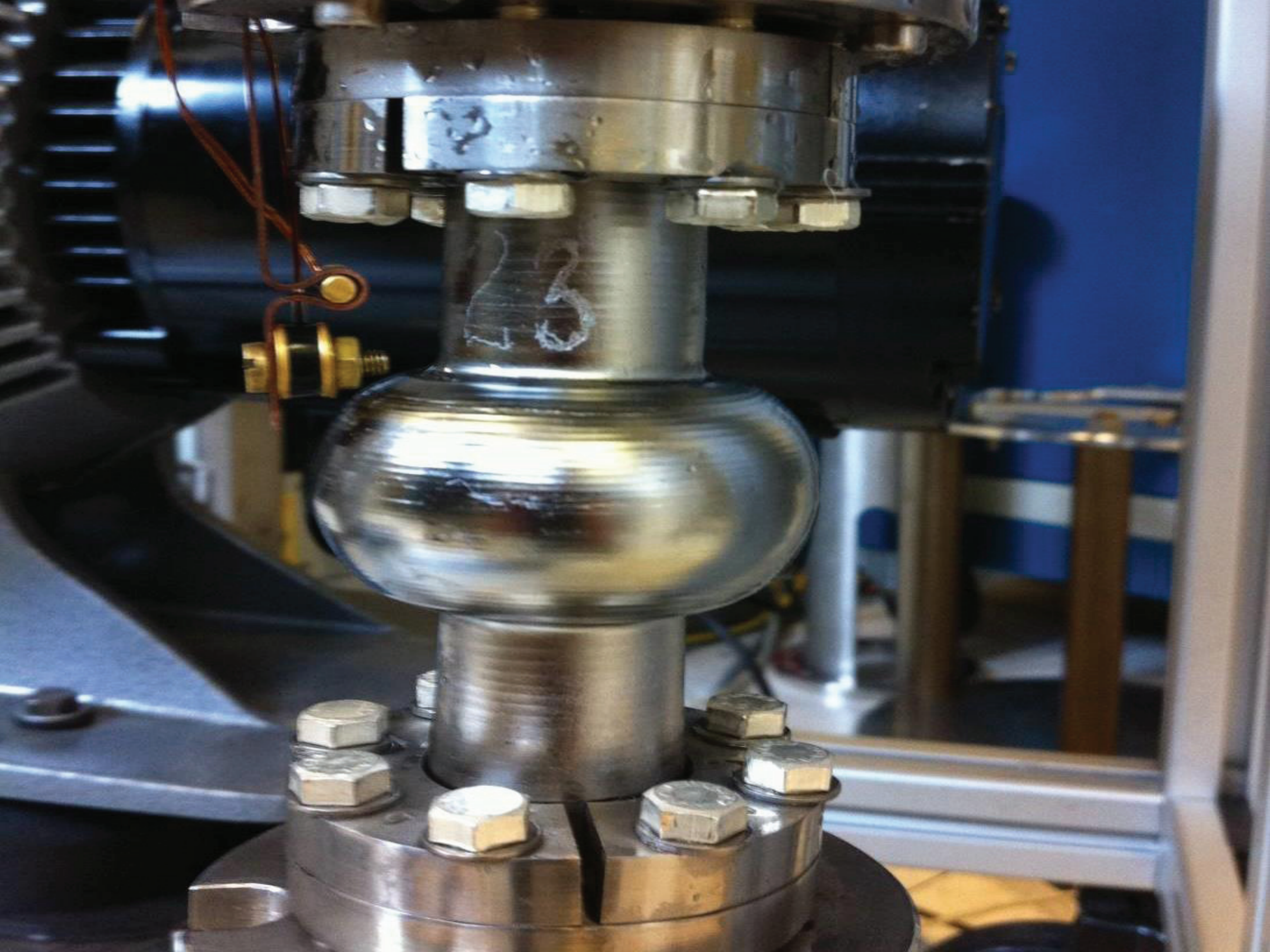
1.8 K is very close to T_λ,

so at 1.8K ρ_n is ~34% ?

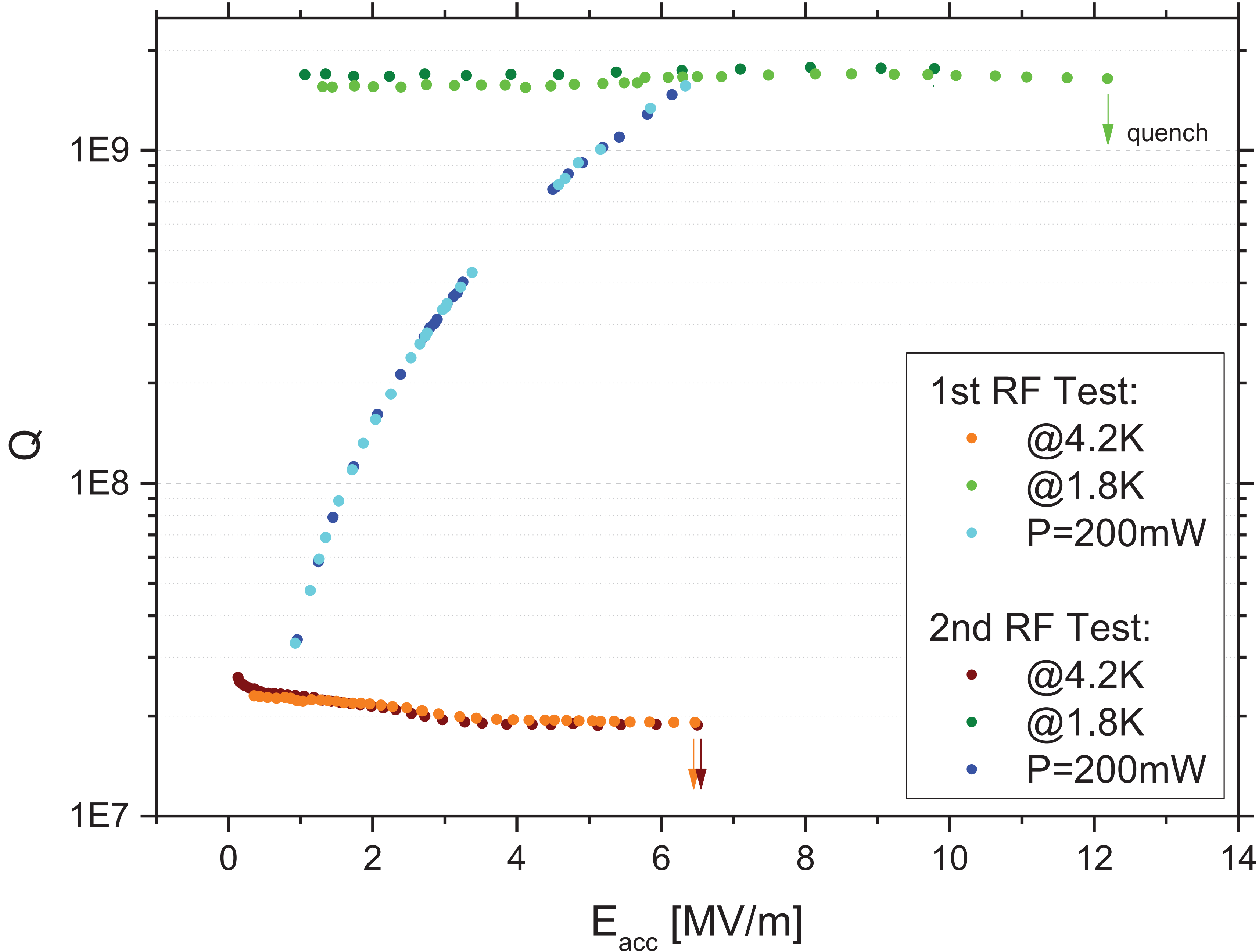


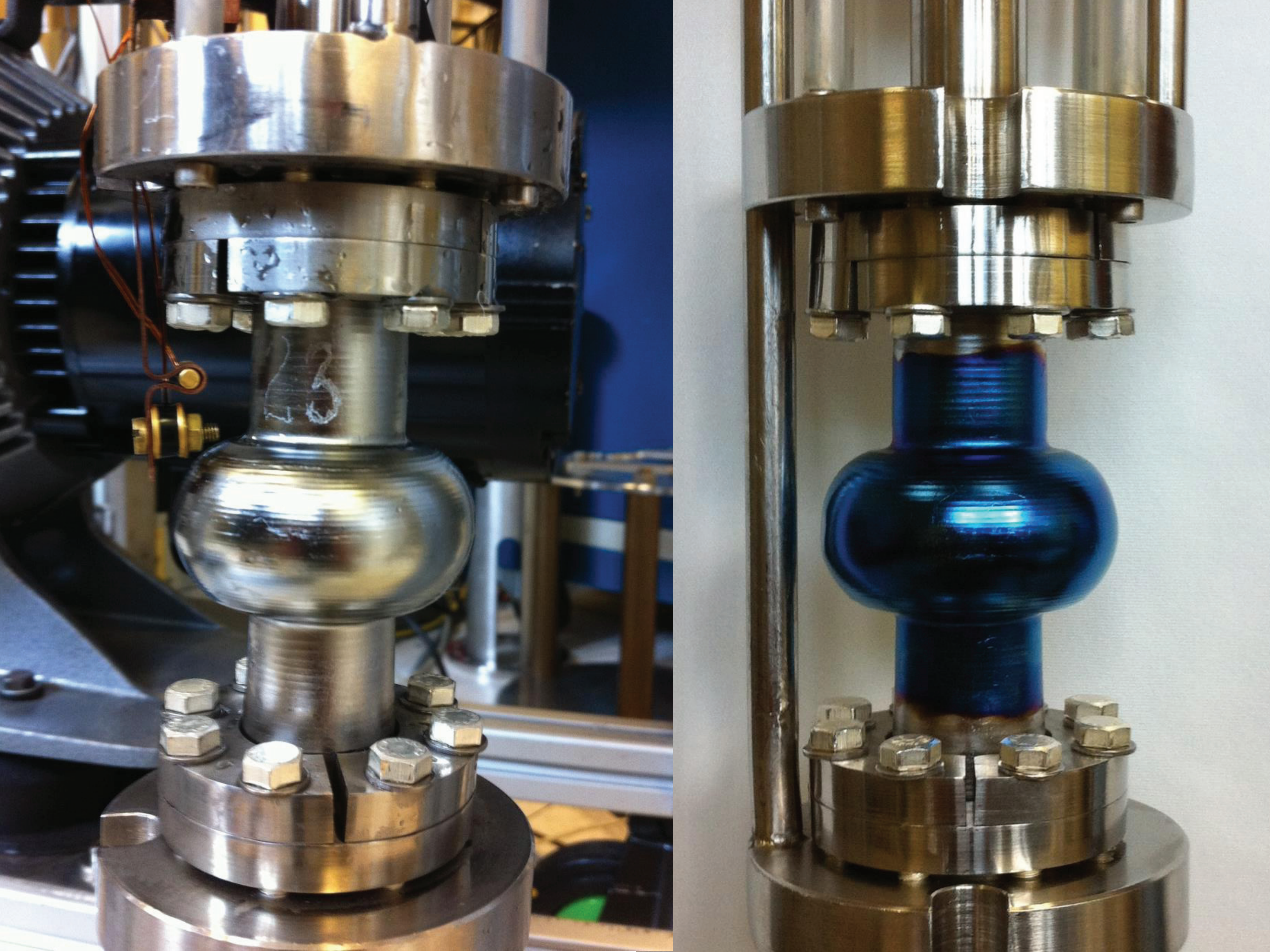
$$\rho = \rho_s + \rho_n$$

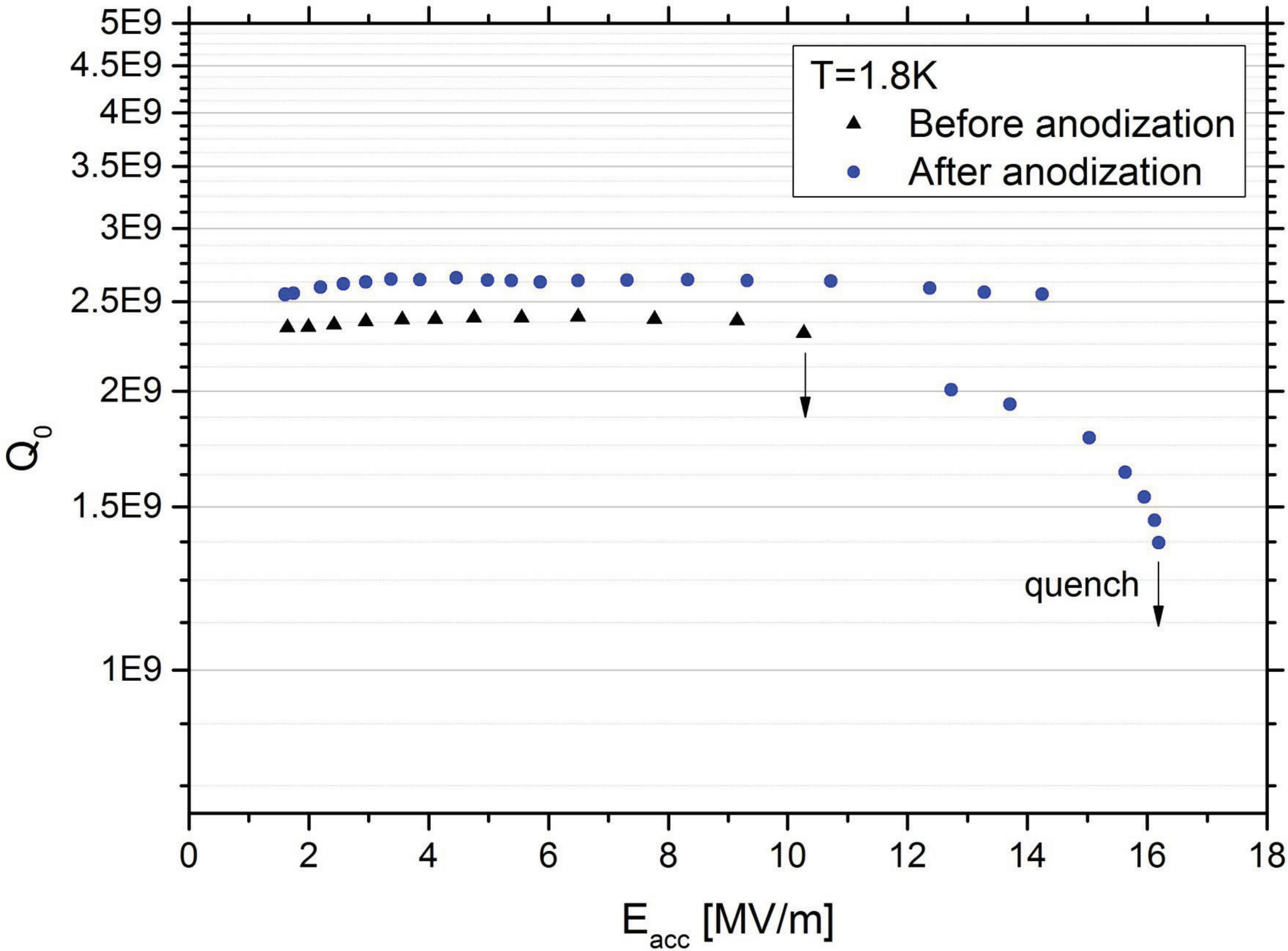
$$\frac{\rho_n}{\rho} = \left(\frac{T}{T_\lambda}\right)^{5.6} \quad \text{for} \quad T \leq T_\lambda$$



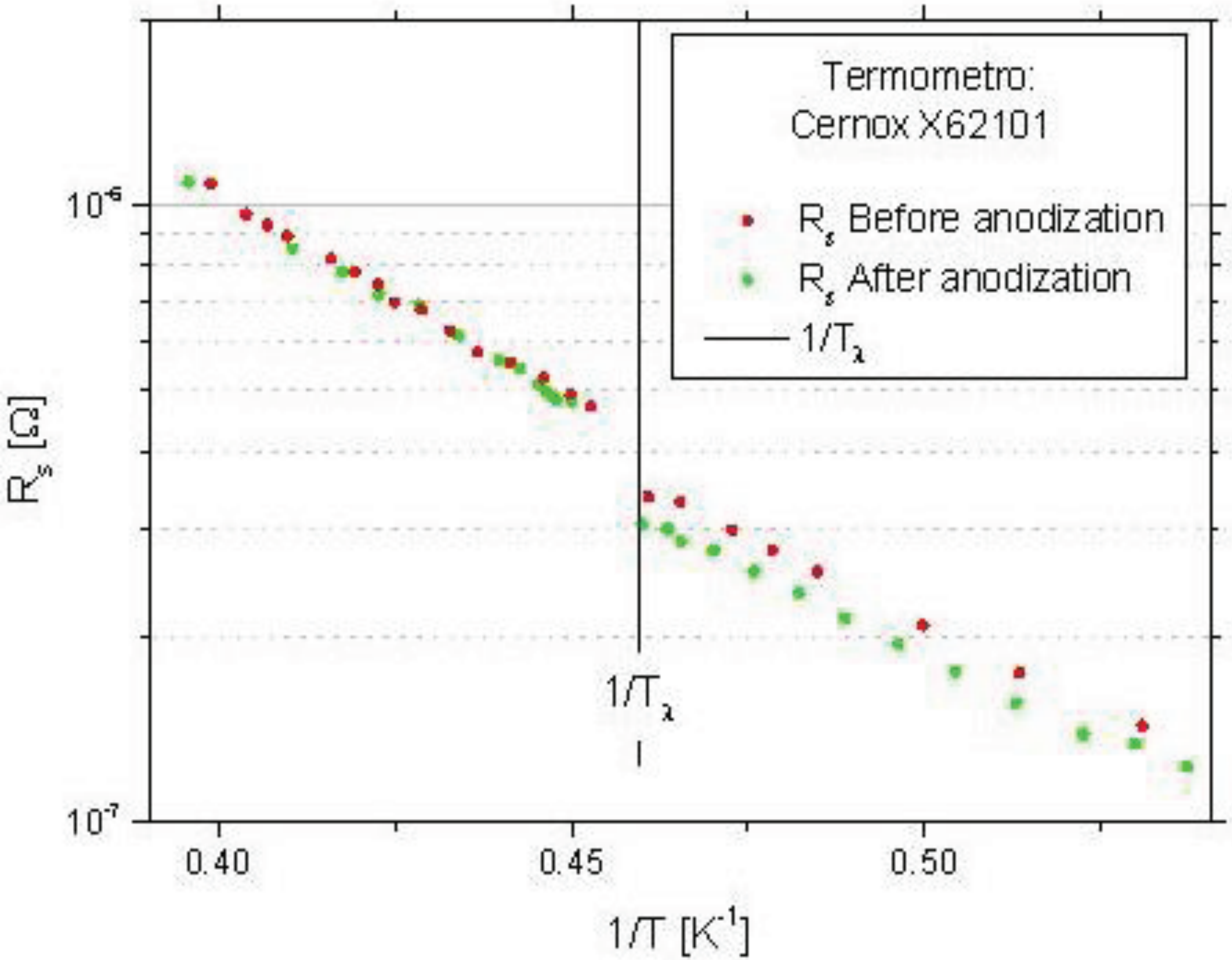
Measured twice



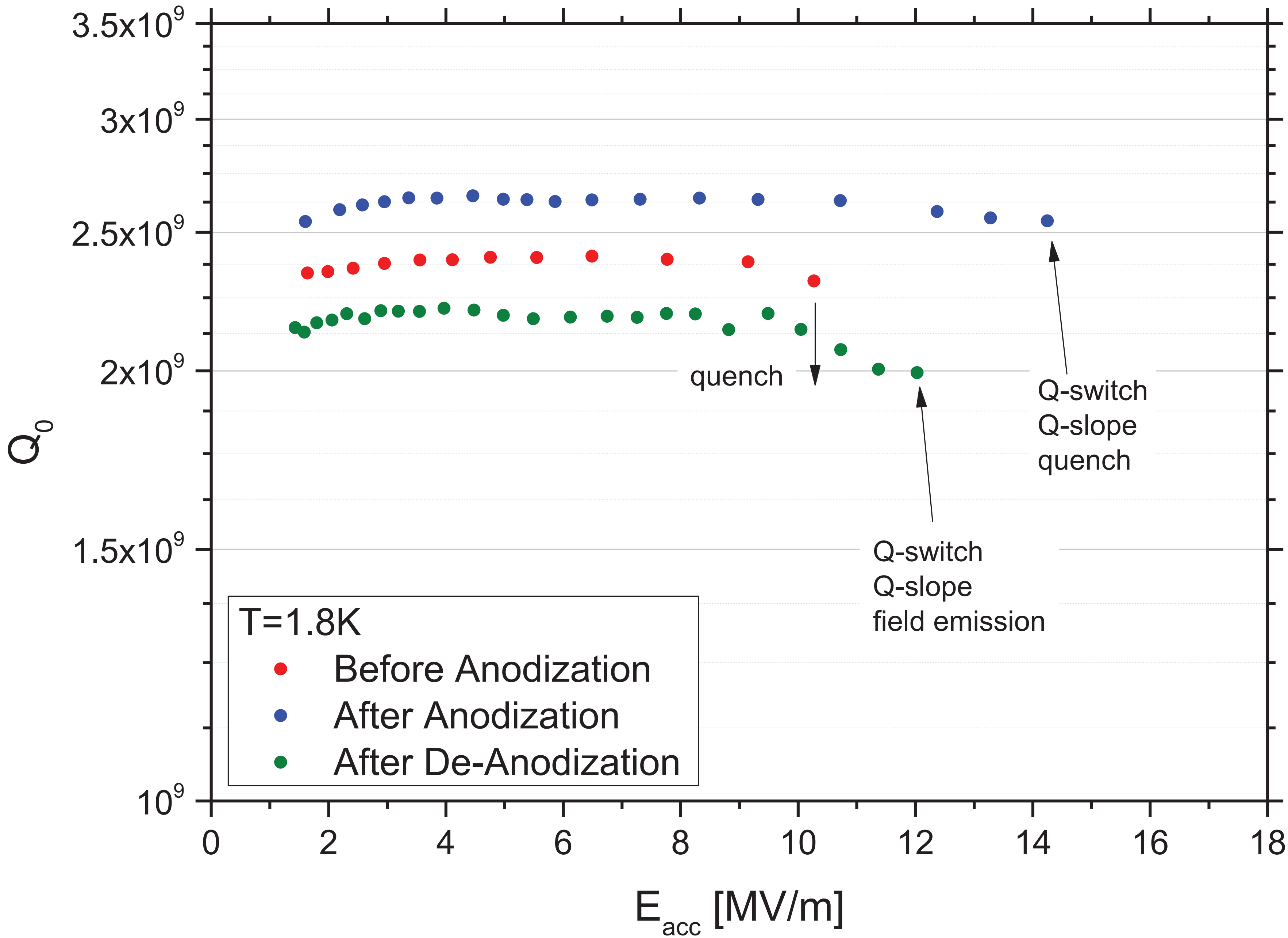




5E9
4.5E9
4E9
3.5E9
3E9
2.5E9
2E9
1.5E9
1E9
Q0
0
2
4
6
8
10
12
14
16
18
Eacc [MV/m]
T=1.8K
Before anodization
After anodization
quench



Termometro:
Cernox X62101
R_s Before anodization
R_s After anodization
$1/T_\lambda$
$1/T_\lambda$
10^{-6}
10^{-7}
0.40
0.45
0.50
R_s [Ω]
1/T [K^{-1}]

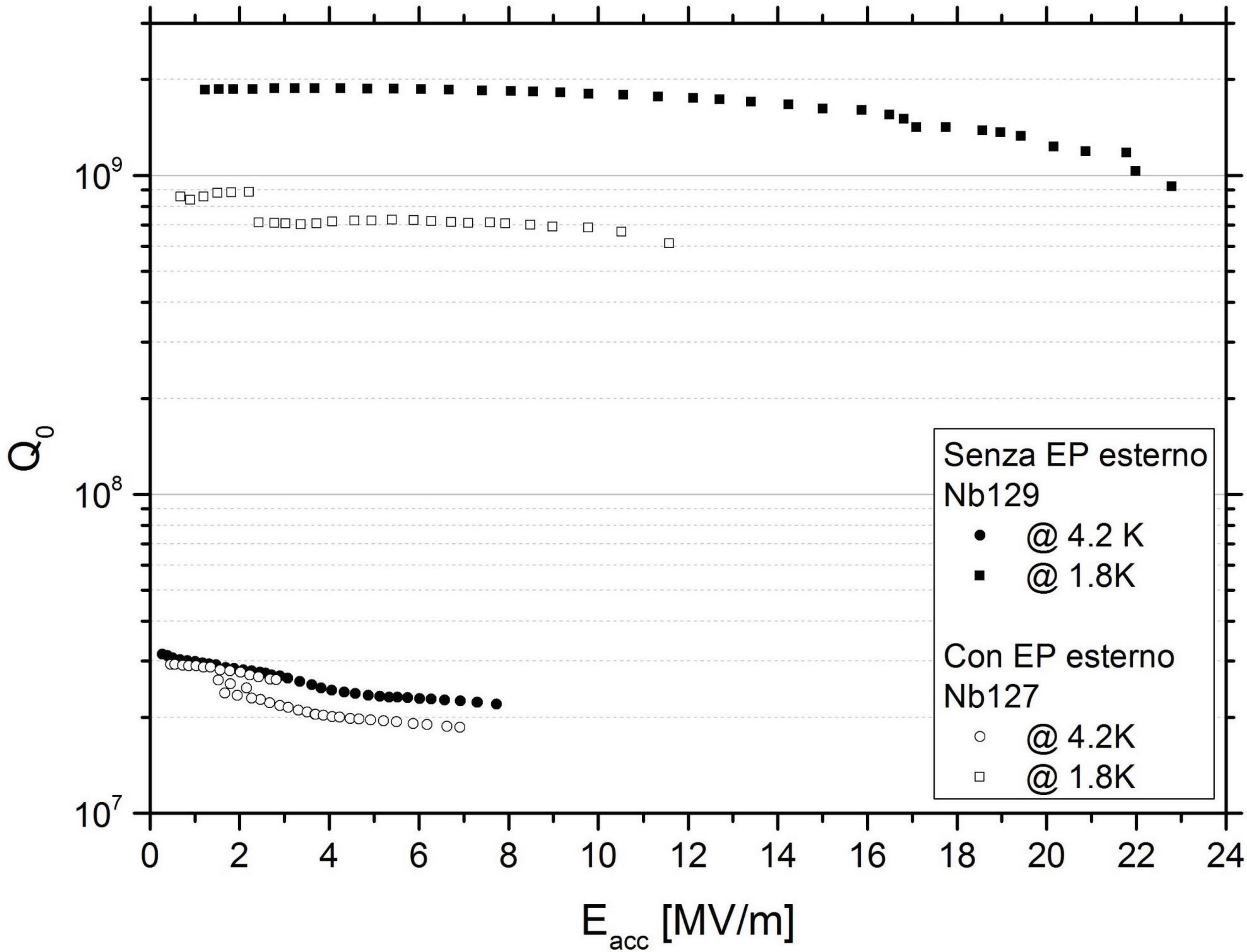


3.5x10^9
3x10^9
2.5x10^9
2x10^9
1.5x10^9
10^9
Q0
0
2
4
6
8
10
12
14
16
18
E acc [MV/m]
quench
Q-switch
Q-slope
quench
Q-switch
Q-slope
field emission
T=1.8K
Before Anodization
After Anodization
After De-Anodization

Question 11:

Why the anodization is responsible of the Q increase?

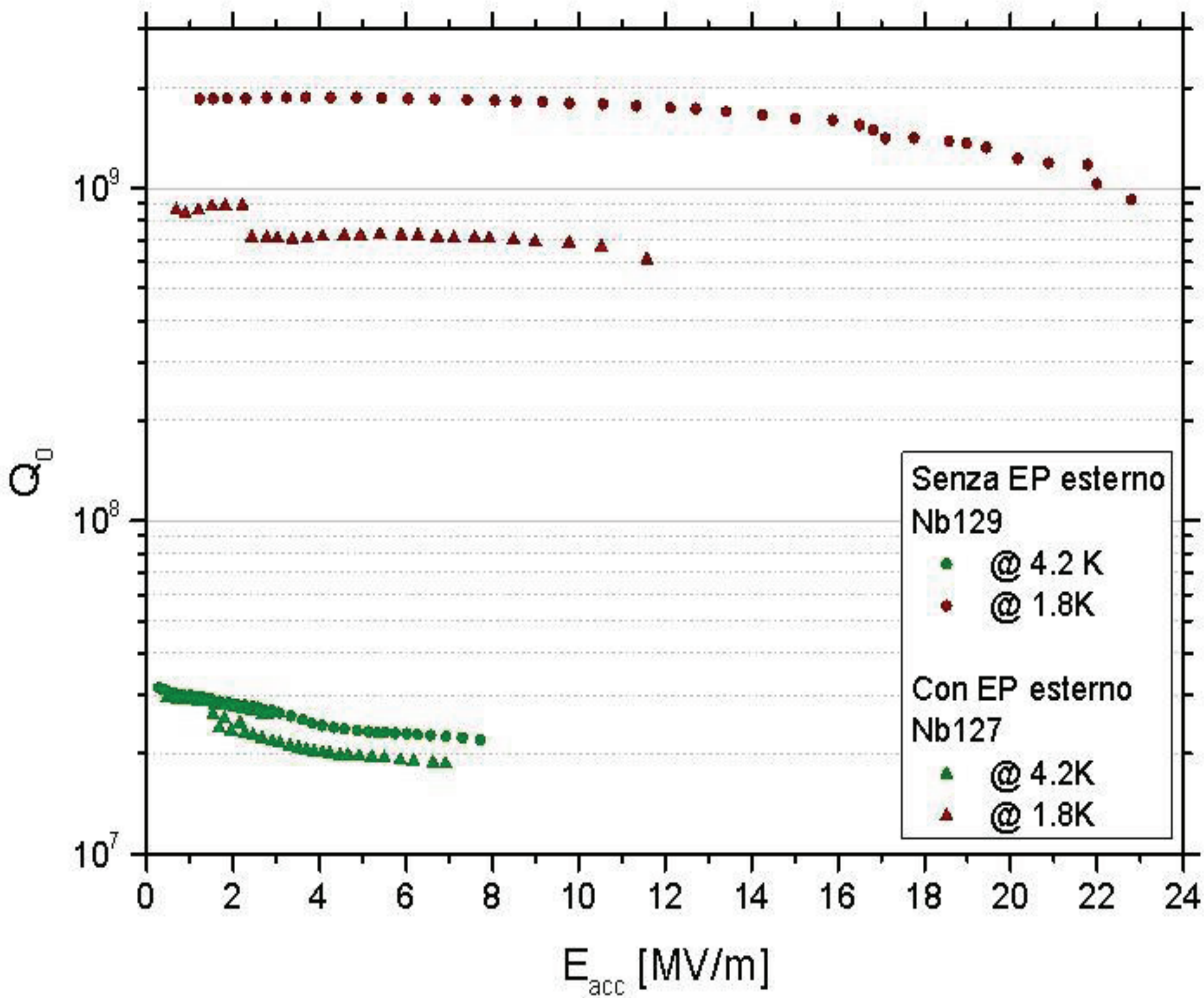
- **because of the lower θ_D ?**
- **because of the boiling nucleation on the external surface ?**
- **because the oxide does not reflect thermal phonons ?**
- **because of both ?**



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

Question 12:

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



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

Question 13:

A mirror-like external surface will decrease the nucleation sites for Helium boiling nucleation,

promoting then

the Liquid He Super-heating

Question 14:

If liquid He Super-heating is detrimental for Q(E_{acc}), Should we worry more about that type of superheating rather than to the Nb H_{Sh}?

Question 15:

If the hypothesis that the external surface of a cavity is important, is the 24 hours 120°C baking effective because it changes the external surface?

Question 16:

If the hypothesis that the external surface of a cavity is important, are the High Q factors got by Anna at FERMILAB due to a change of it?

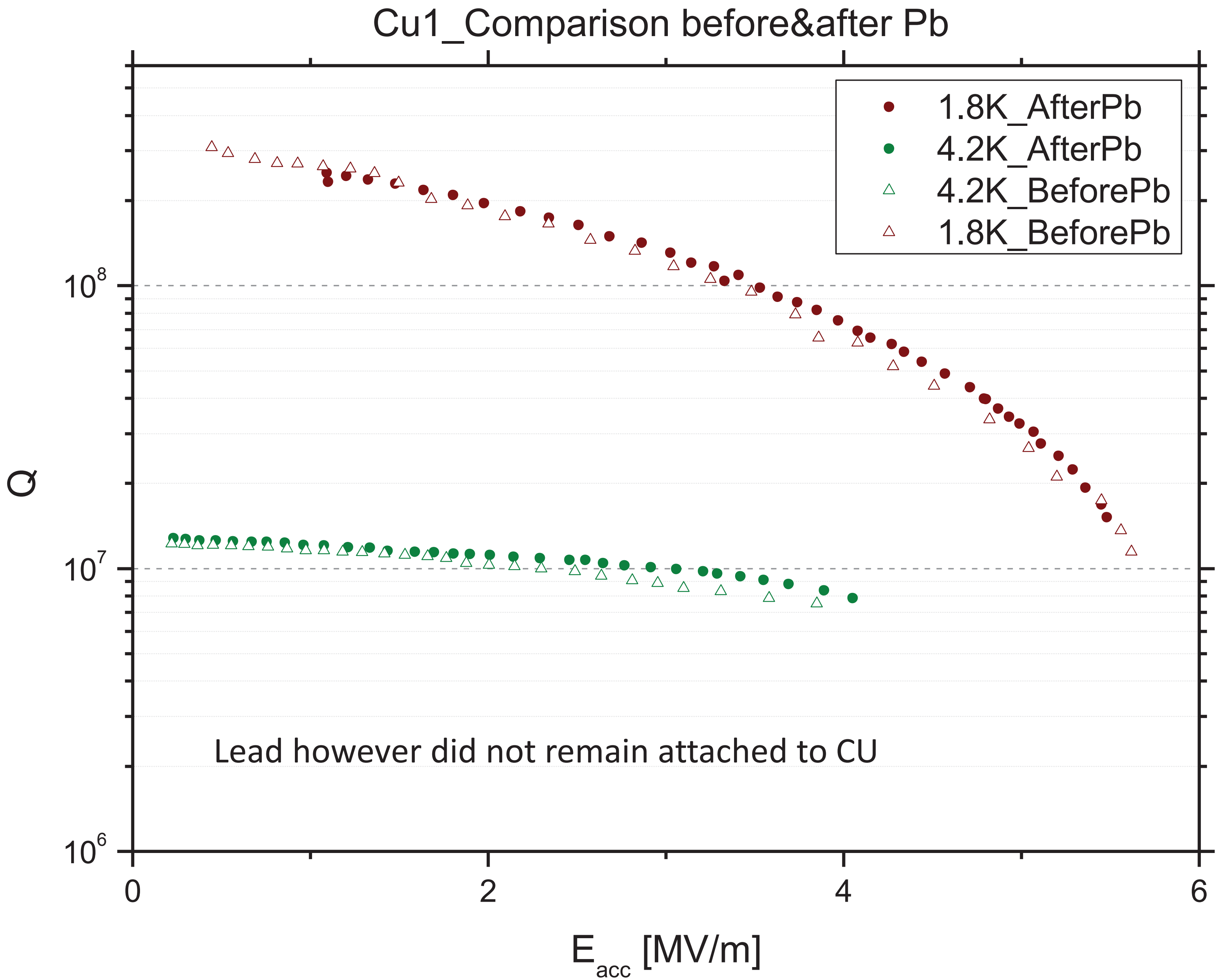
Question 17:

Since the θ_D of the Cu is higher than the one of Nb and in Kapitza it plays as $\left(\frac{T}{\theta_D}\right)^3$, does this contribute to the fact that, at 1.8K, sputtered Nb showsn lower performances?

Outer Lead coating of a sputtered Nb/Cu

BEFORE

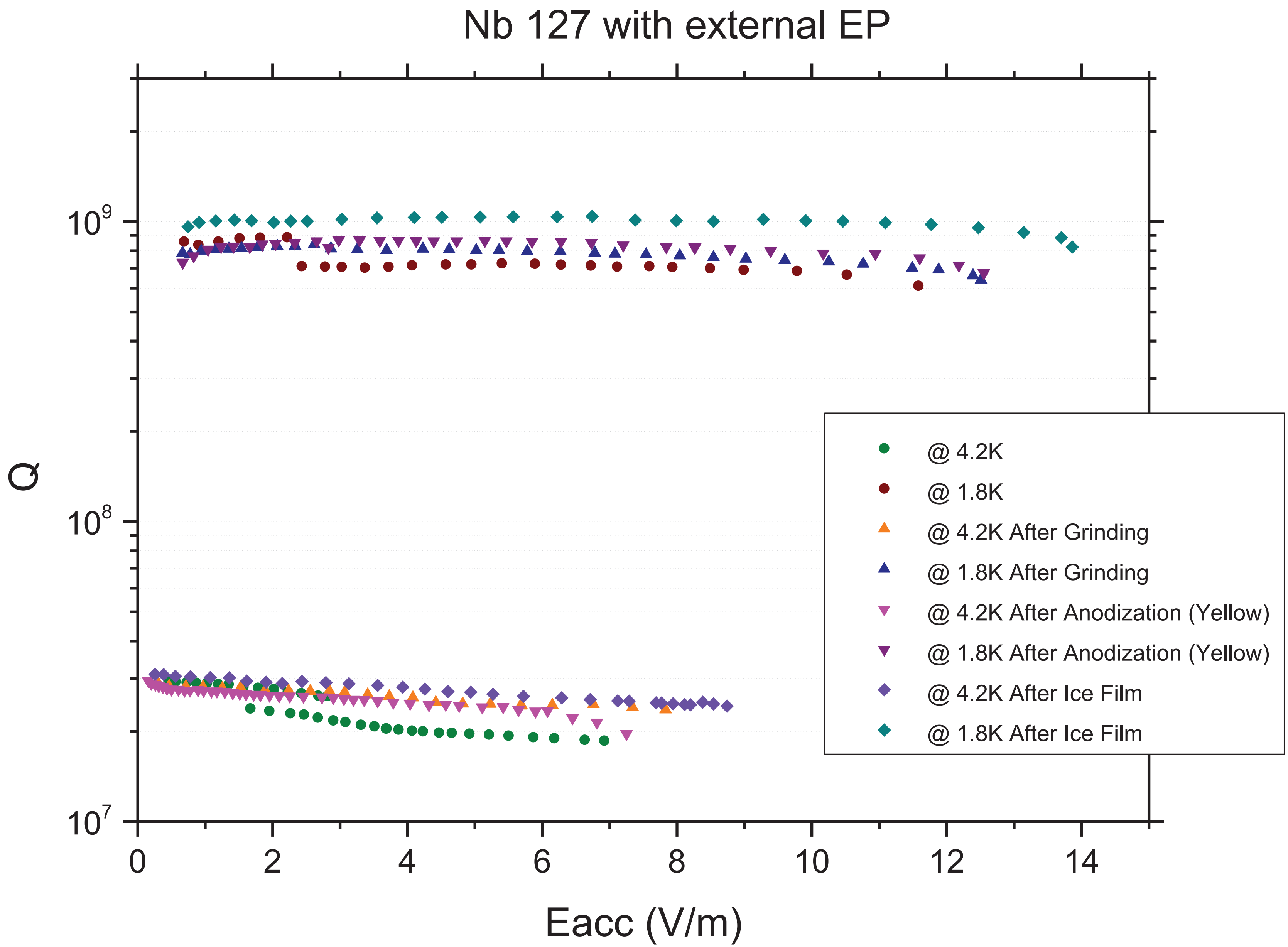
AFTER



Cu1_Comparison before&after Pb
1.8K_AfterPb
4.2K_AfterPb
4.2K_BeforePb
1.8K_BeforePb
Q
10^8
10^7
10^6
0
2
4
6
E_acc [MV/m]
Lead however did not remain attached to CU

Question 18:

Can water micro-cristallites on the external surface of Nb promote film boiling and then positively affect cavity performances?



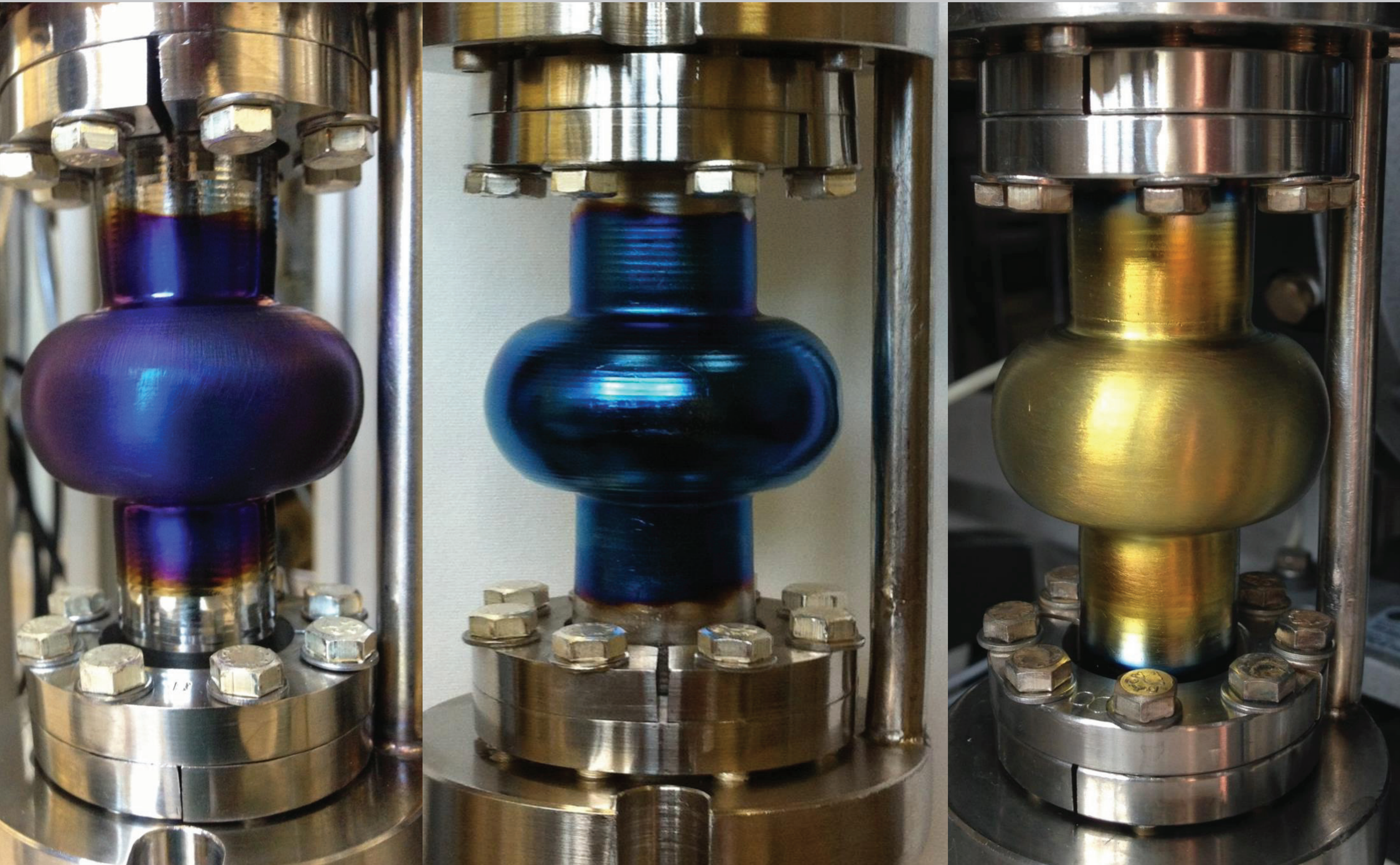
Nb 127 with external EP
Q
Eacc (V/m)
10^9
10^8
10^7
0
2
4
6
8
10
12
14
@ 4.2K
@ 1.8K
@ 4.2K After Grinding
@ 1.8K After Grinding
@ 4.2K After Anodization (Yellow)
@ 1.8K After Anodization (Yellow)
@ 4.2K After Ice Film
@ 1.8K After Ice Film

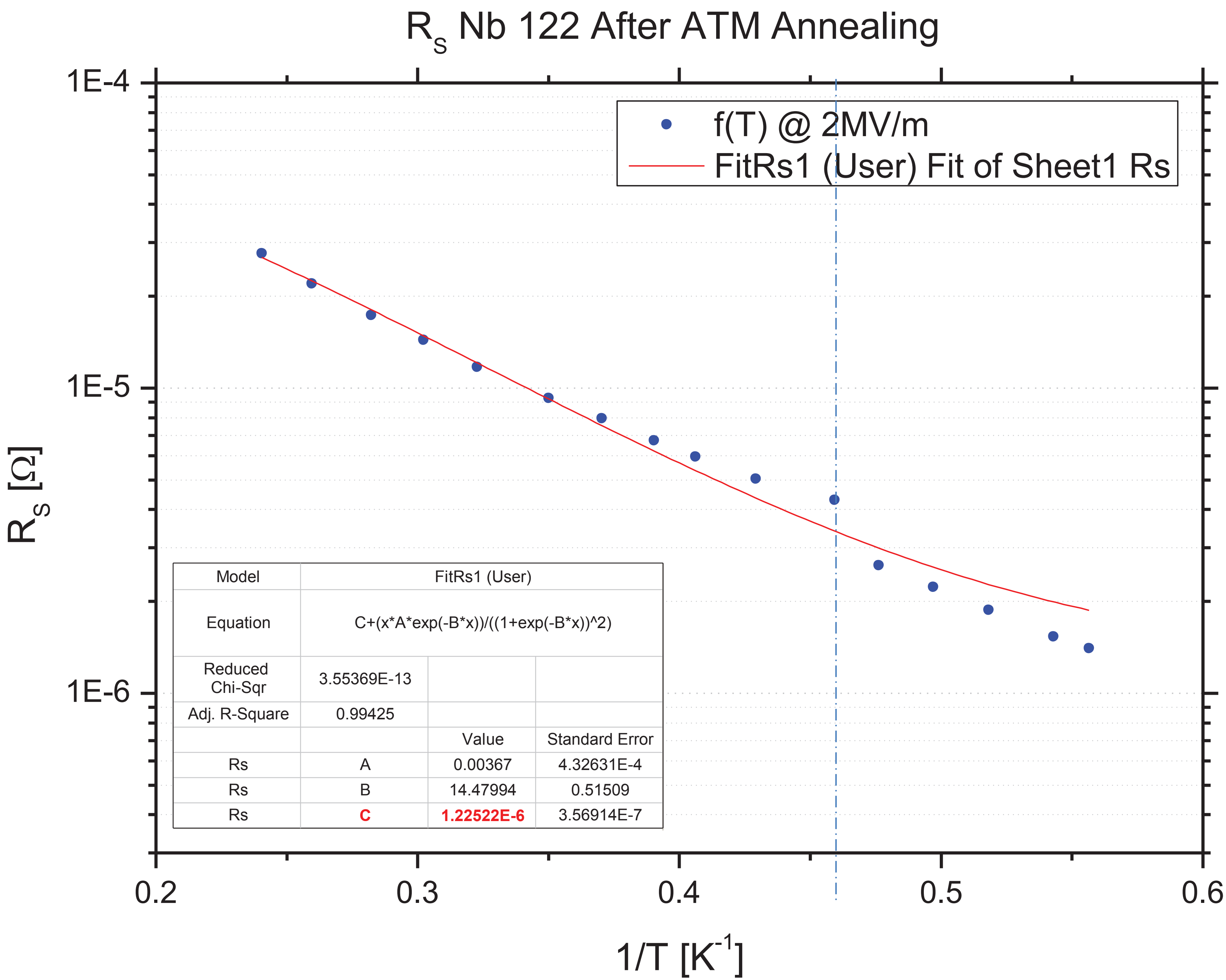
Question 19:

For years we have considered a cavity as an adiabatic system made by the RF fields + Nb, because the He bath has been considered as a stable and infinite reservoir at fixed temperature.

Is it not the time now to consider instead the adiabatic system composed by RF fields + Nb + Liquid Helium ?

Our Summer 2013 fashion collection




R_S Nb 122 After ATM Annealing
f(T) @ 2MV/m
FitRs1 (User) Fit of Sheet1 Rs
1E-4
1E-5
1E-6
0.2
0.3
0.4
0.5
0.6
1/T [K^-1]
R_S [Ω]
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

Question 20:

THE END

(But is it really the end?

Or just the beginning?)