TOWARD QUENCH-FREE PERFORMANCE IN SRF CAVITIES

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&
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6° Workshop on CRAB CAVITIES, CERN, Geneva, Dec 8-10, 2013

Outline of the talk

- **What we actually know about quench**
- **Thin film cavities (almost) never quench**
- **Thinking about the impossible is cost-free**
- **Need to go deeper into Cryogenics**

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- Thinking about the impossible is cost-free
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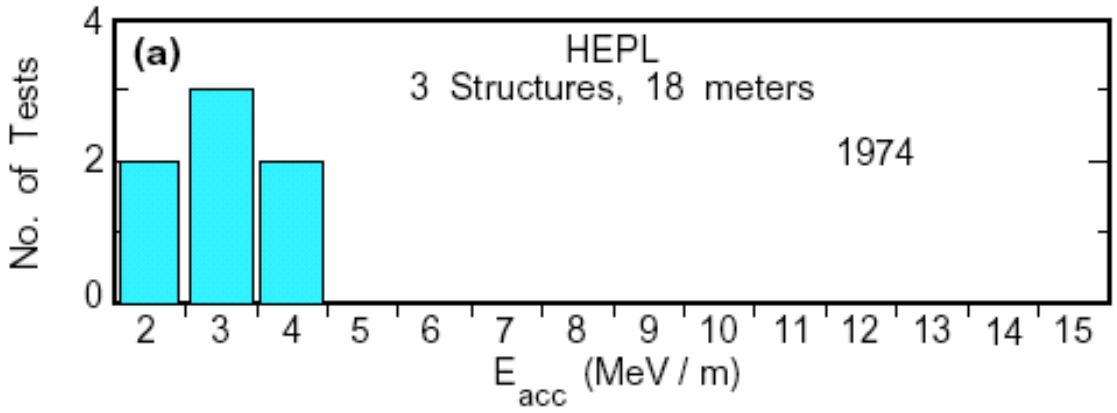
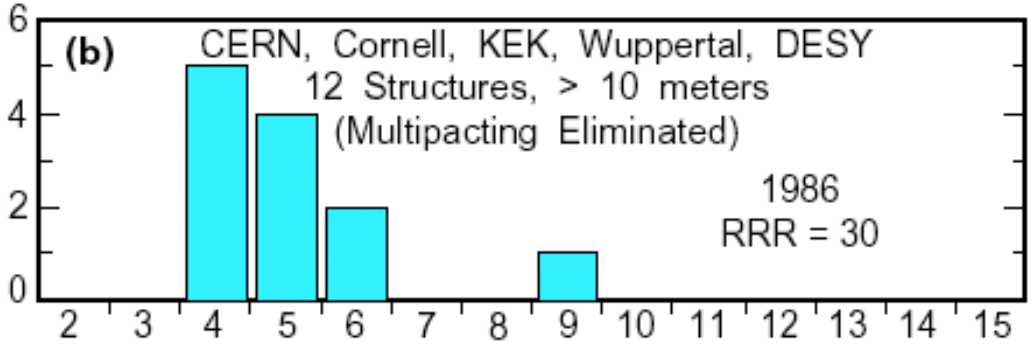
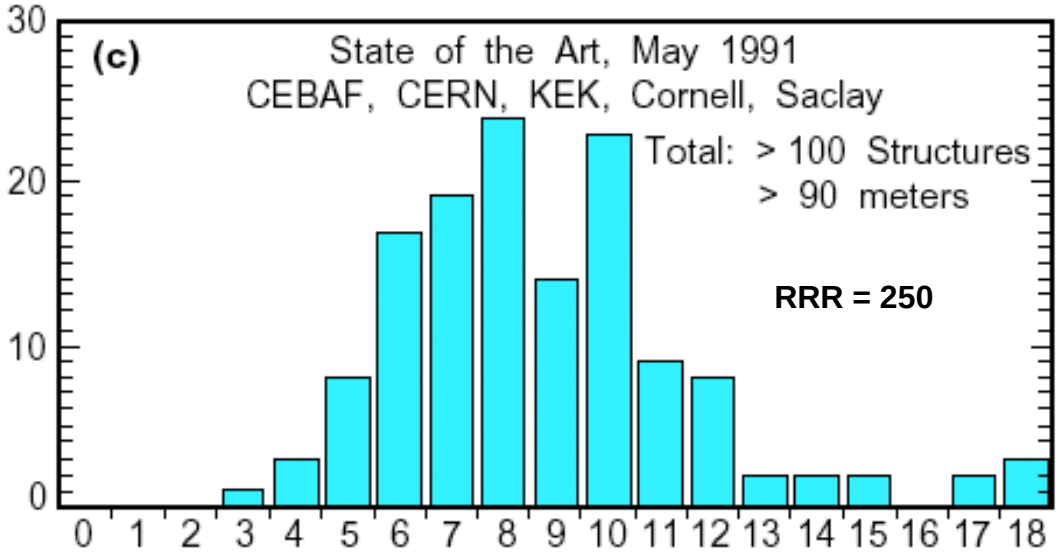


Multipacting

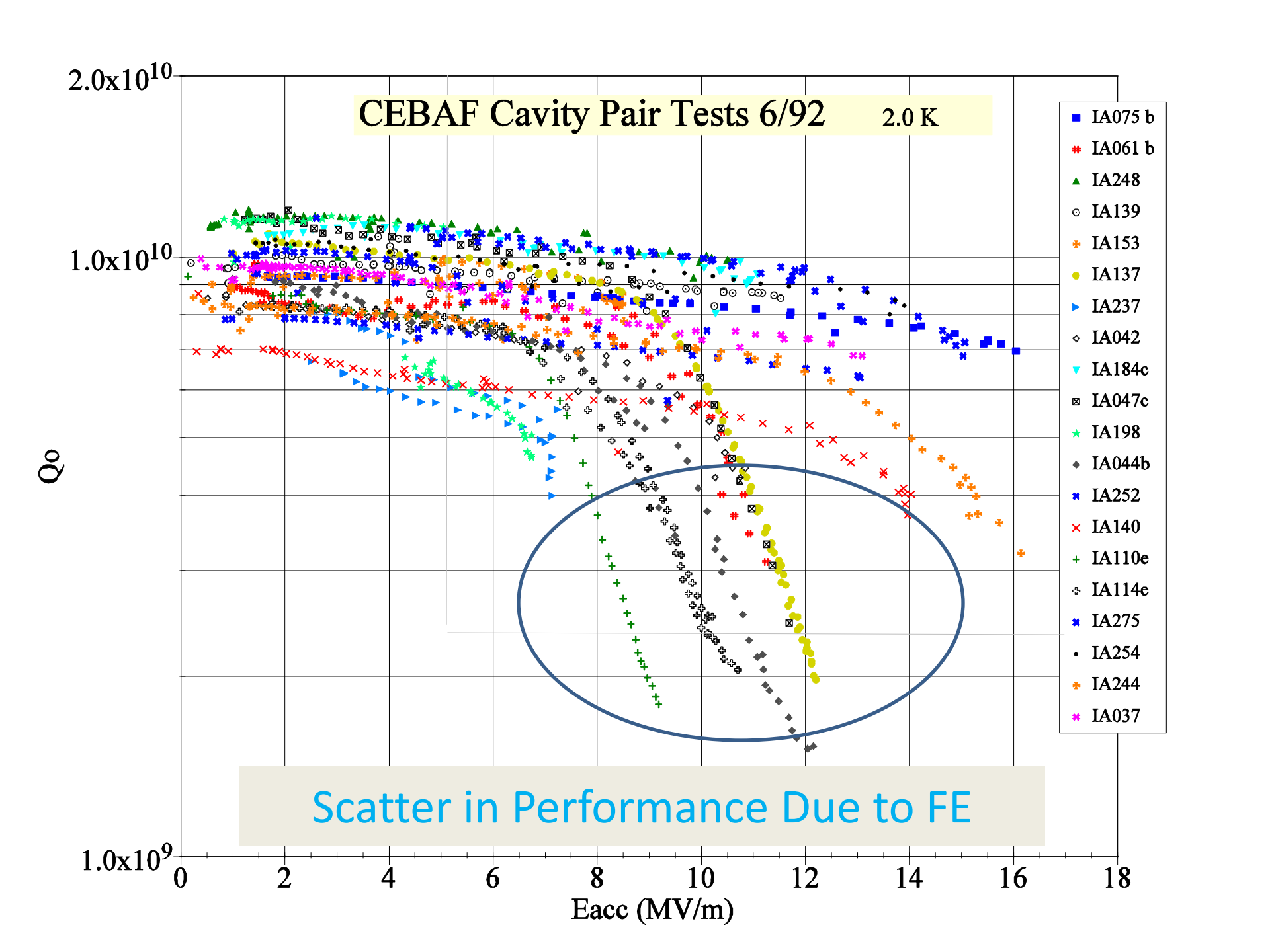


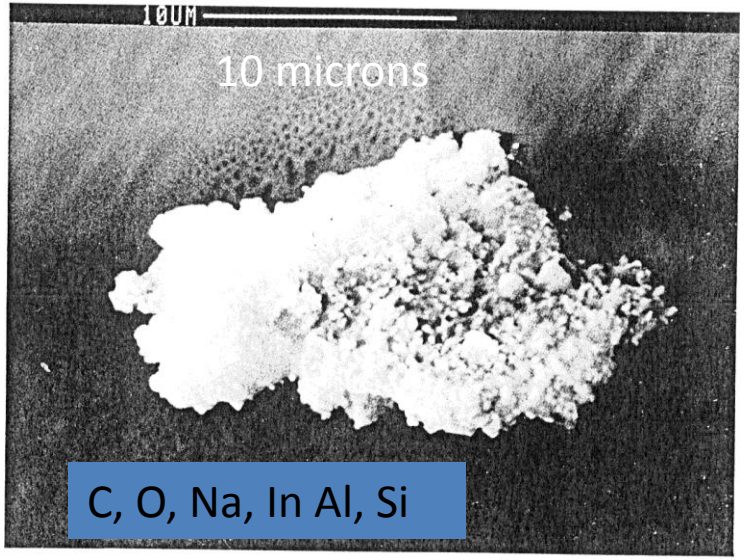
Thermal Breakdown



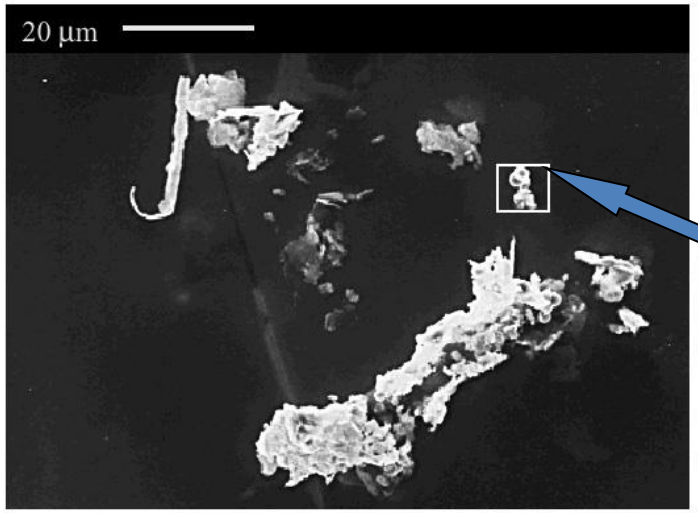
Field Emission

Courtesy H. Padamsee

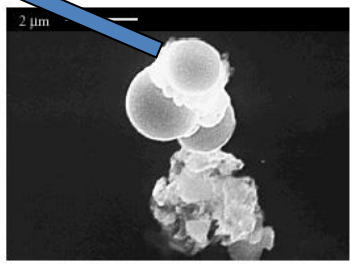

CEBAF Cavity Pair Tests 6/92
2.0 K
2.0x10^10
1.0x10^10
1.0x10^9
Qo
0
2
4
6
8
10
12
14
16
18
Eacc (MV/m)
IA075 b
IA061 b
IA248
IA139
IA153
IA137
IA237
IA042
IA184c
IA047c
IA198
IA044b
IA252
IA140
IA110e
IA114e
IA275
IA254
IA244
IA037
Scatter in Performance Due to FE

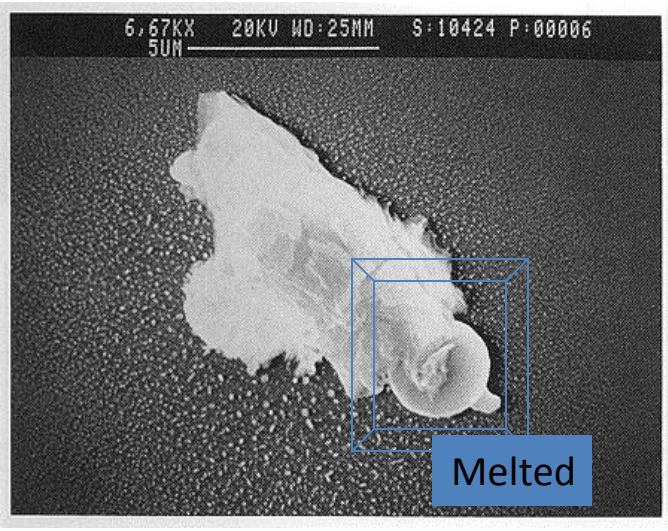


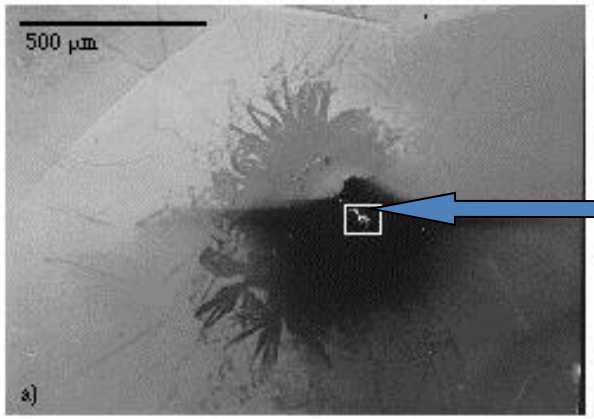
Stainless steel

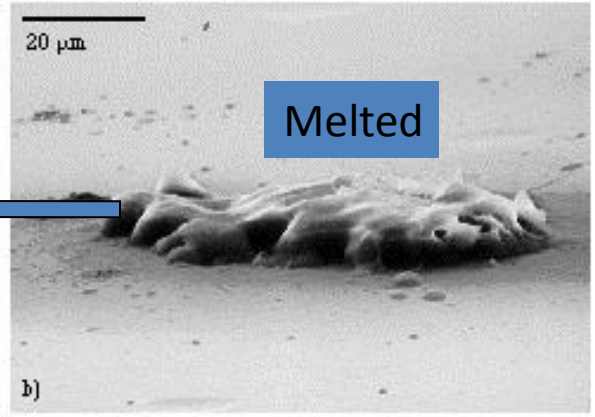


Melted









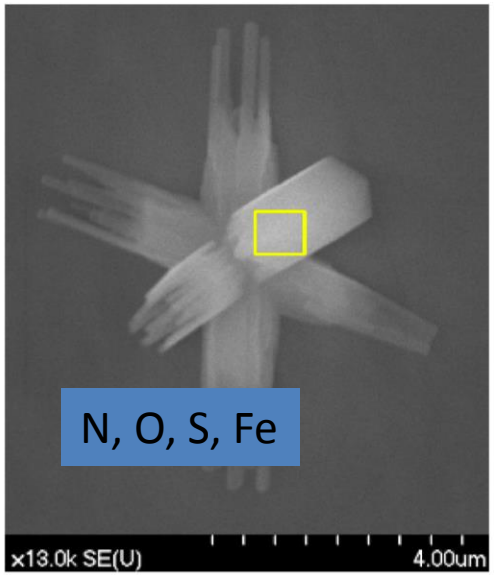
Emitters Found in Niobium SC Cavities

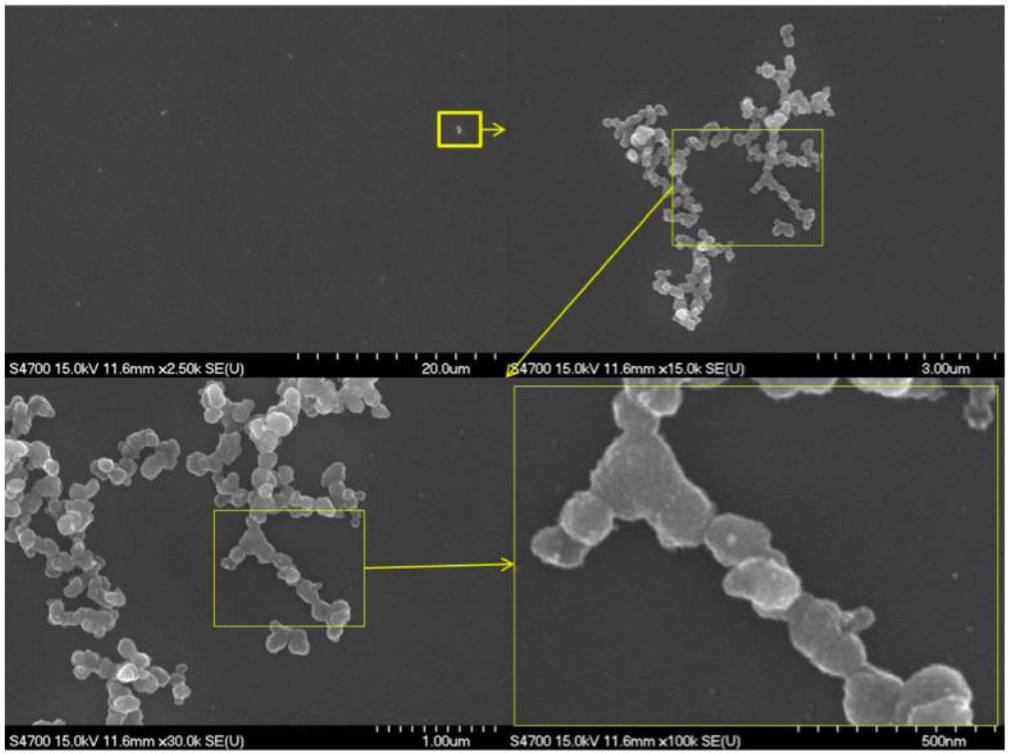
CORNELL UNIVERSITY

Courtey H. Padamsee

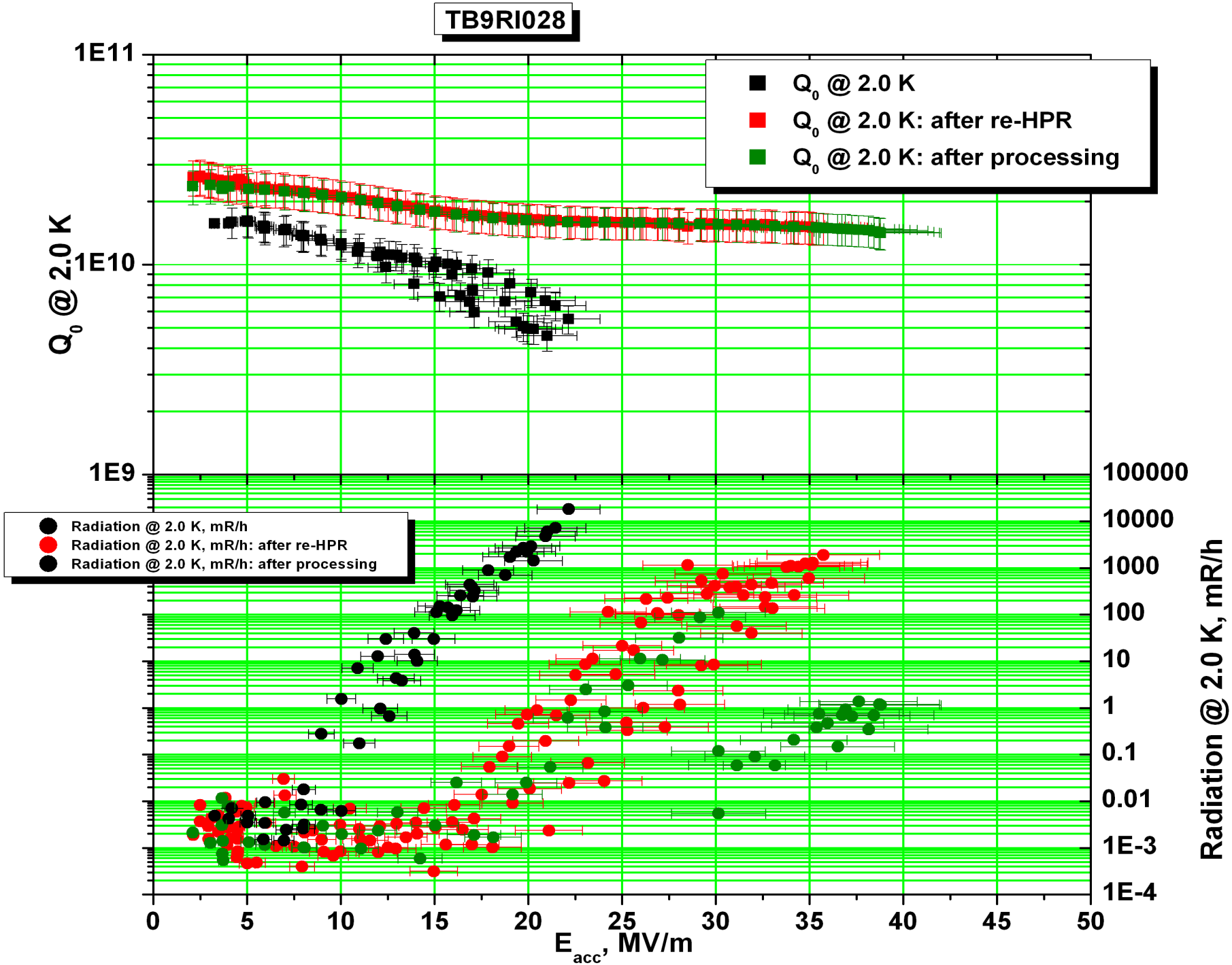
Field Emitters

- Contaminants from surface processing
  - Niobium oxide granules (electropolished surface)
  - Sulfur
    - And other elements



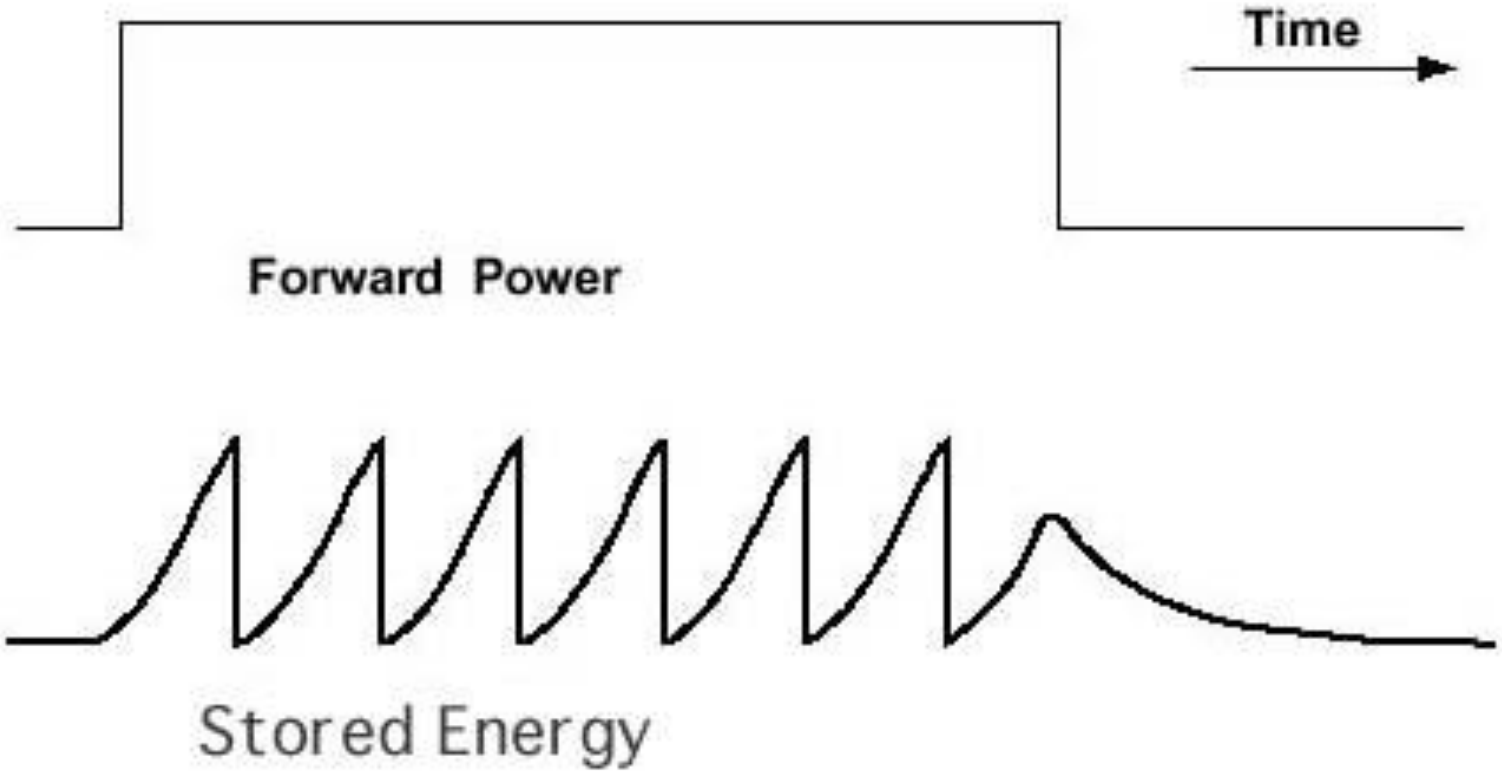


Courtesy X. Zhao


TB9RI028
1E11
1E10
1E9
Q_0 @ 2.0 K
Q_0 @ 2.0 K
Q_0 @ 2.0 K: after re-HPR
Q_0 @ 2.0 K: after processing
Radiation @ 2.0 K, mR/h
Radiation @ 2.0 K, mR/h: after re-HPR
Radiation @ 2.0 K, mR/h: after processing
100000
10000
1000
100
10
1
0.1
0.01
1E-3
1E-4
Radiation @ 2.0 K, mR/h
0
5
10
15
20
25
30
35
40
45
50
E_{acc}, MV/m

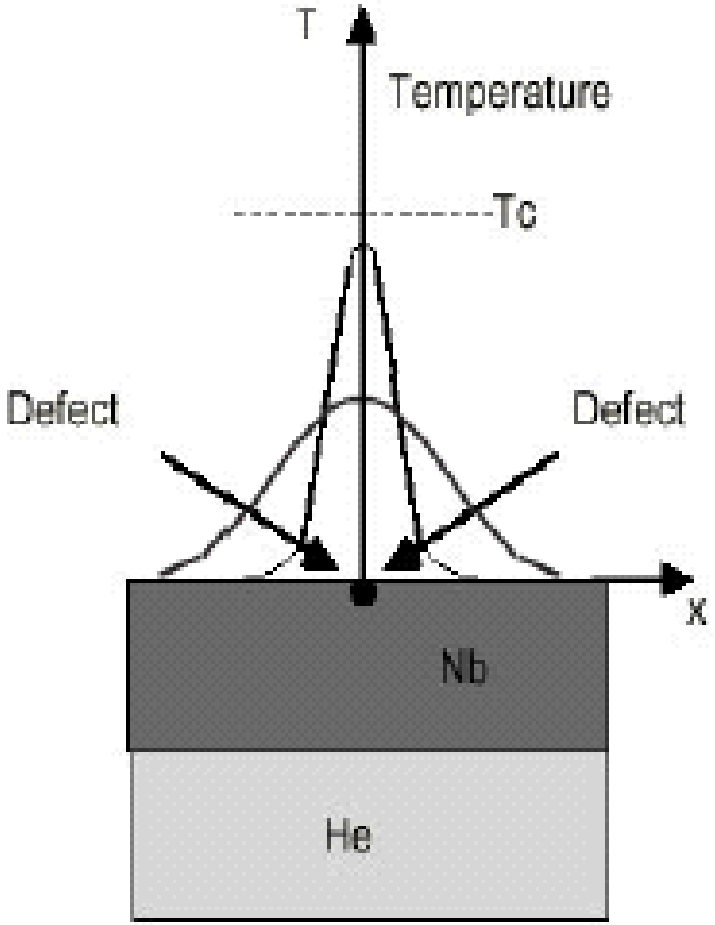
Thermal Breakdown

(Very strong heating observed over extended areas.



Theory of thermal breakdown of NC Defect

A normal conducting spot triggers quench, when it heats the Nb above T_c.



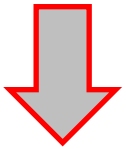
Breakdown field given by (very approximately):

$$H_{tb} = \sqrt{\frac{4K_T (T_c - T_b)}{r_d R_d}}$$

κ_T: Thermal conductivity of Nb
R_d: Defect surface resistance
T_c: Critical temperature of Nb
T_b: Bath temperature

Courtesy H. Padamsee

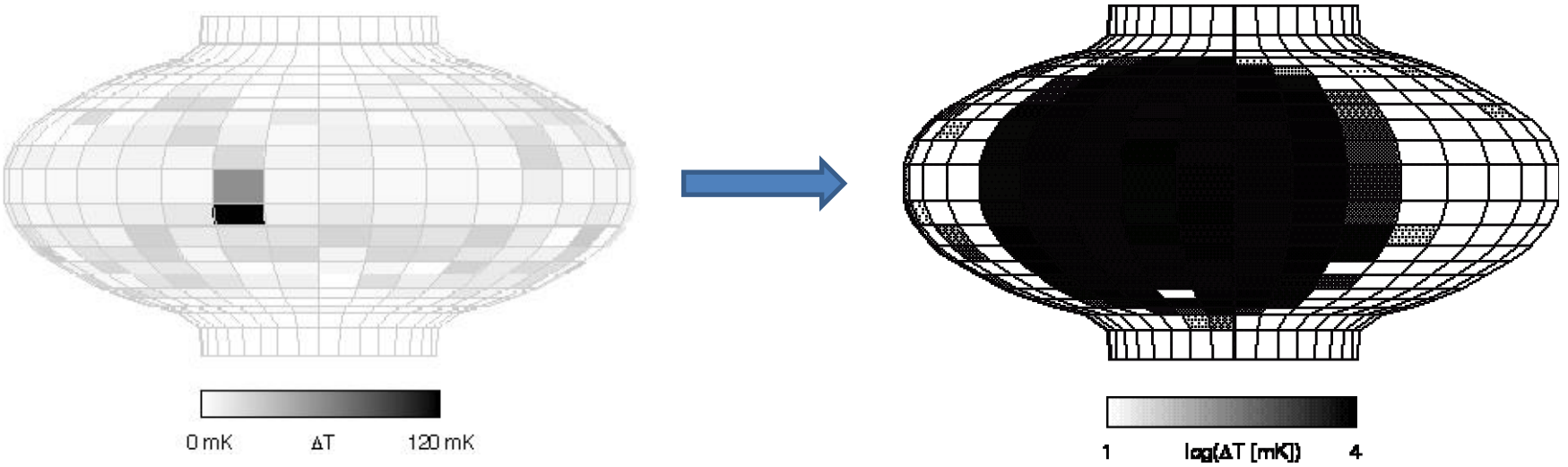
Tolerate unavoidable defects,
but "neutralize" them
by thermally stabilizing them



Improve Bulk Thermal Conductivity
by raising Nb purity

Thermal Breakdown

(Very strong heating observed over extended areas.



Field cannot be increased!

Proceedings of the 1997 Workshop on RF Superconductivity, Abano Terme (Padova), Italy

STUDY OF THERMAL EFFECTS IN SRF CAVITIES

J.Lesrel, S.Bousson, T.Junquera, A.Caruette, M.Fouaidy

I.P.N. (CNRS-IN2P3-Univ.Paris XI) ORSAY

The response time of both thermometer types are much longer than the time needed for the cavity temperature rise (Q_0 drop) during a quench so they are not suited for a reliable study of such transients.

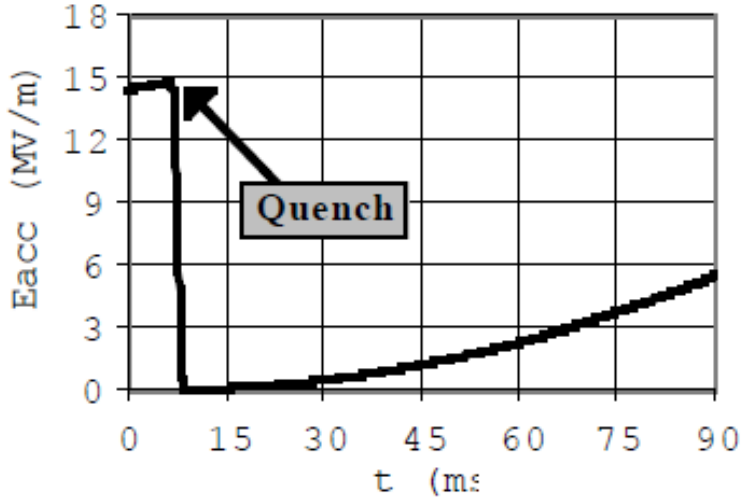


***Fig. 7**: Variation of Eacc during a quench in a 3 Ghz cavity.*

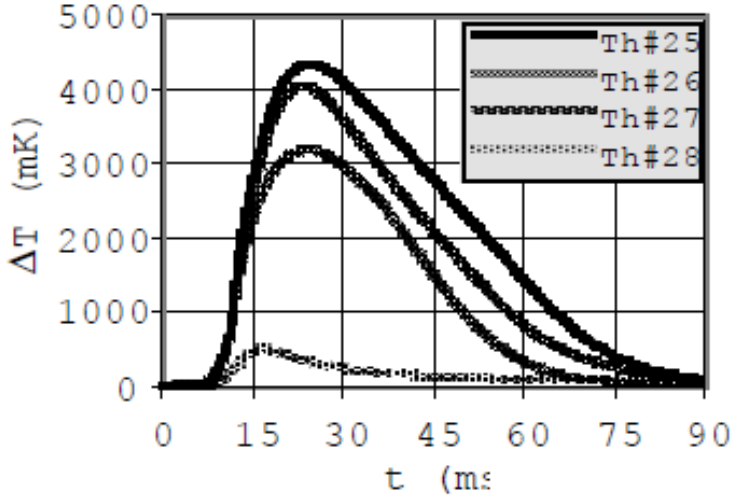


***Fig. 8**: Heatings measured on 4 thermometers during the quench.*

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Without FE, the dissipated power P_{diss} is related to the magnetic field H, the cavity surface S_{cav} and the surface resistance R_s by the relation:

$$P_{diss}(t) = \frac{1}{2} \cdot \iint_{S_{cav}} H^2(t) \cdot R_s \cdot dS$$

During a quench, a normal resistive surface S_N (having a normal surface resistance R_S^N) grows. Then P_{diss} has two contributions: power dissipation in the superconducting area (= S_{cav} - S_N) and in the normal conducting region S_N.

$$P_{diss}(t) = \frac{1}{2} \cdot \iint_{S_{cav}-S_N} H^2(t) \cdot R_s \cdot dS + \frac{1}{2} \cdot \iint_{S_N} H^2(t) \cdot R_S^N \cdot dS \qquad \textbf{(1)}$$

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…. Finally by combining the previous equations, the normal conducting surface is deduced:

$$S_N(t) = \frac{2 \cdot \left(\sqrt{\frac{P_i \cdot \omega}{Q_{ext}}} - \frac{d\sqrt{U(t)}}{dt} \right)}{\omega \cdot \sqrt{U(t)}} - \frac{1}{Q_{ext}} - \frac{R_S \cdot S}{R_S^N}$$

$$\frac{1}{2} \cdot \alpha^2 \cdot \left(\frac{1}{l} \sqrt{\frac{r}{Q}} \right)^2 \cdot R_S^N$$

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I.P.N. (CNRS-IN2P3-Univ.Paris XI) ORSAY

Assuming a circular shape for the expanding normal region $S_N = \pi . R_{NC}^2$, we have an immediatly measurement of the normal conducting surface radius $R_{NC}(t)$ (Fig. 12).

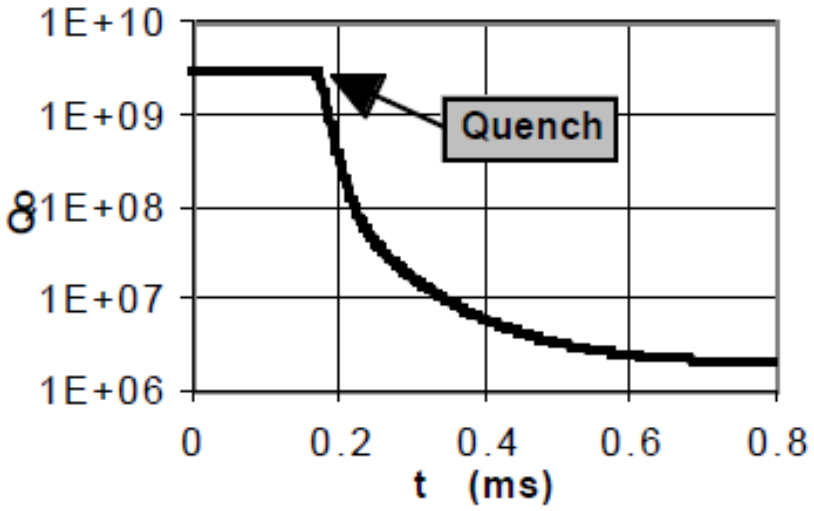

***Fig. 11**: Unloaded quality factor during the cavity quench.*

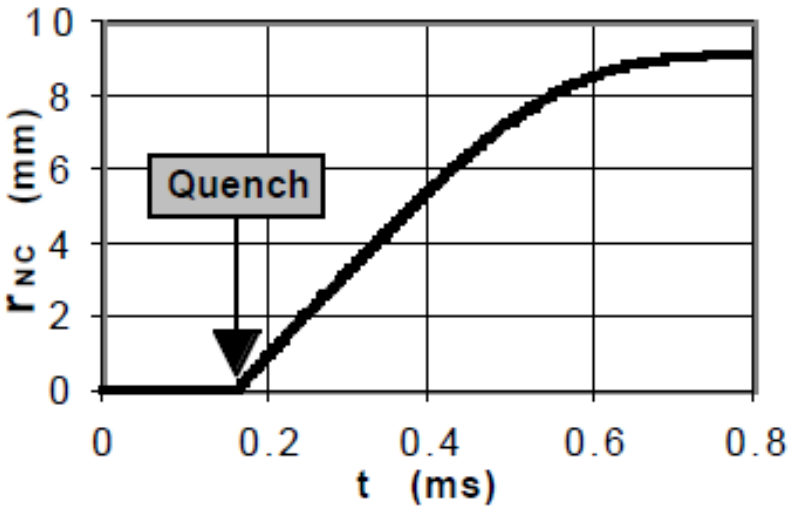

***Fig. 12**: Increase of the radius of the normal conducting area.*

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I.P.N. (CNRS-IN2P3-Univ.Paris XI) ORSAY

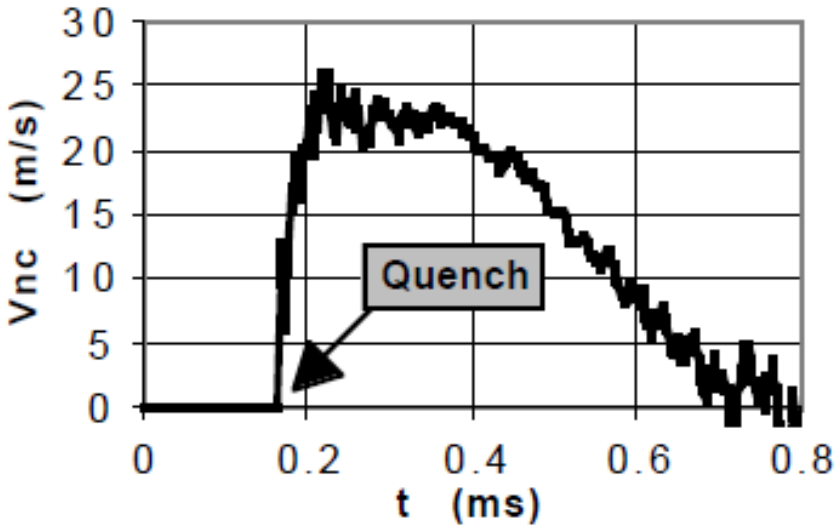

***Fig. 13**: Expansion velocity of the normal conducting area.*

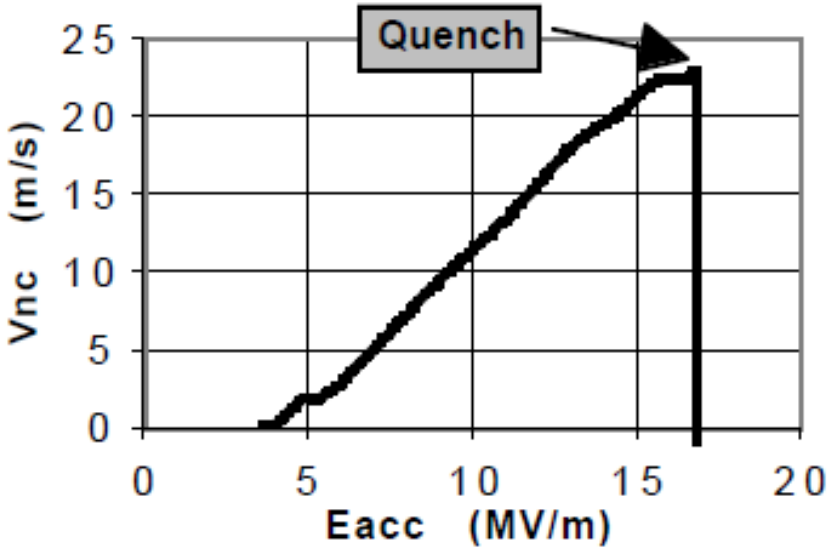

***Fig. 14**: Expansion velocity as a function of the accelerating field.*

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I.P.N. (CNRS-IN2P3-Univ.Paris XI) ORSAY

One important result is that V_{NC} does not depend on the defect radius R_d in the studied range 50 µm-1000 µm.

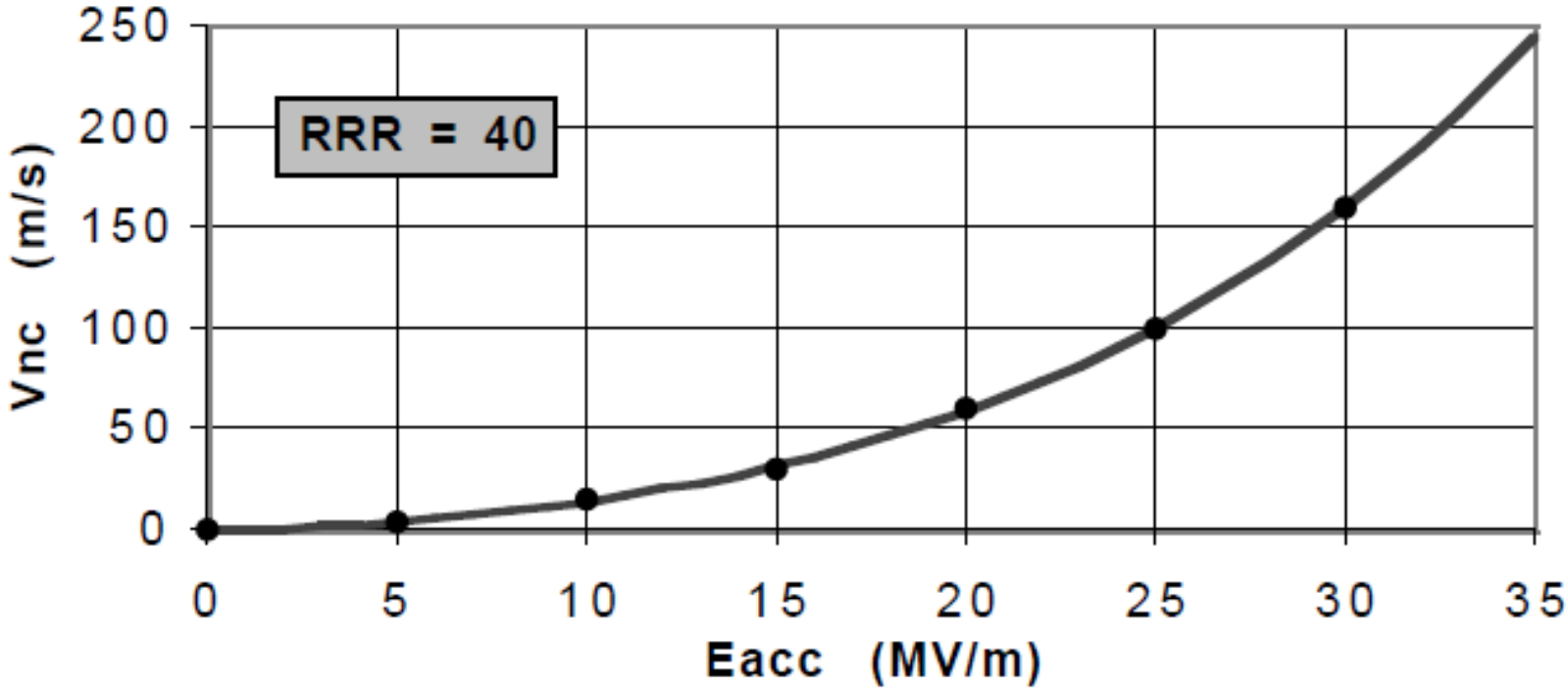


Fig. 15: *Calculated expansion velocity as a function of Eacc.*

Outline of the talk

- What we actually know about quench
- **Thin film cavities (almost) never quench**
- Thinking about the impossible is cost-free
- Need to go deeper into Cryogenics

A REVIEW OF THE NIOBIUM ON COPPER SPUTTERING TECHNOLOGY FOR SUPERCONDUCTING RF CAVITIES

S. Calatroni*, CERN, 1211 Geneva 23, Switzerland

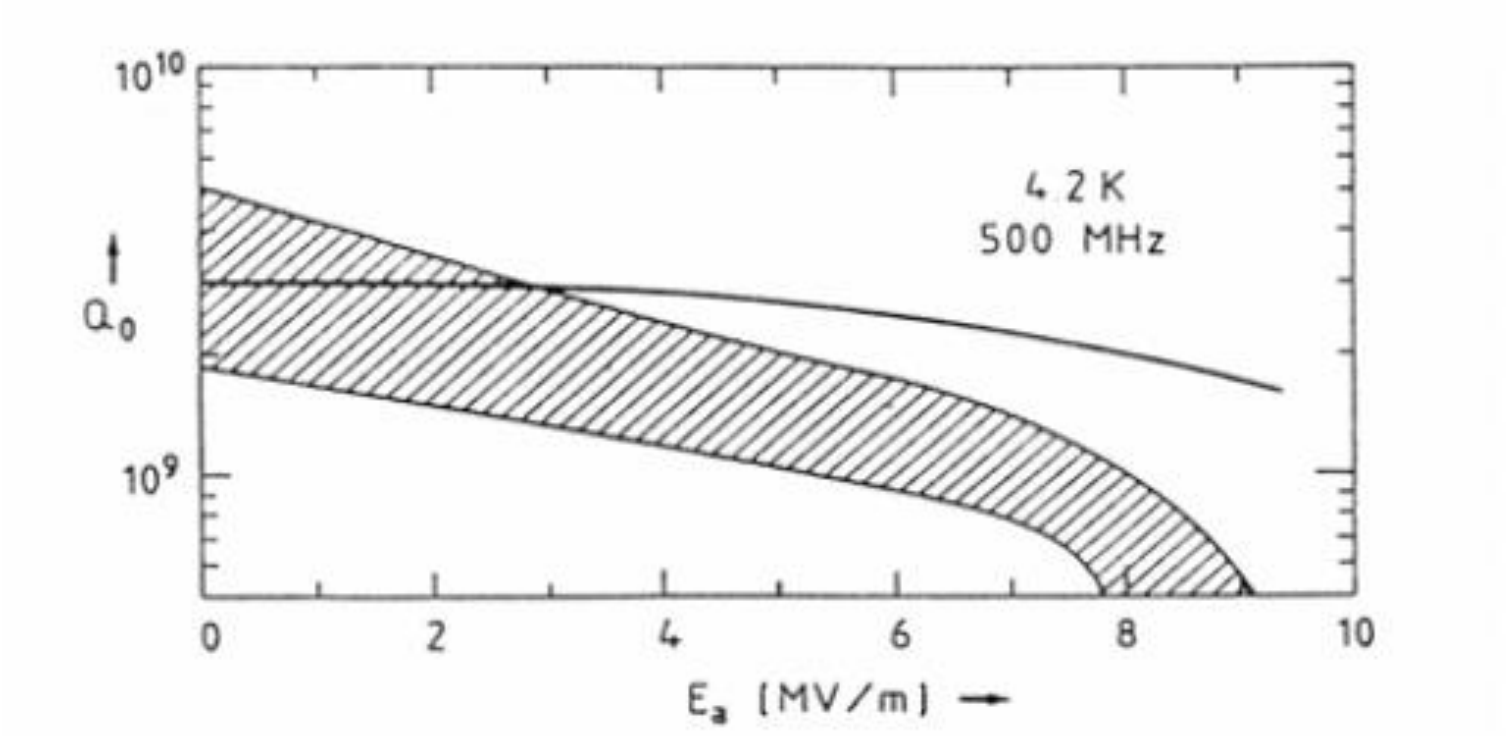


Figure 1: Typical $Q(E_a)$ curves of niobium sheet metal (line) and niobium sputter coated copper cavities (hatched) in the 80's.

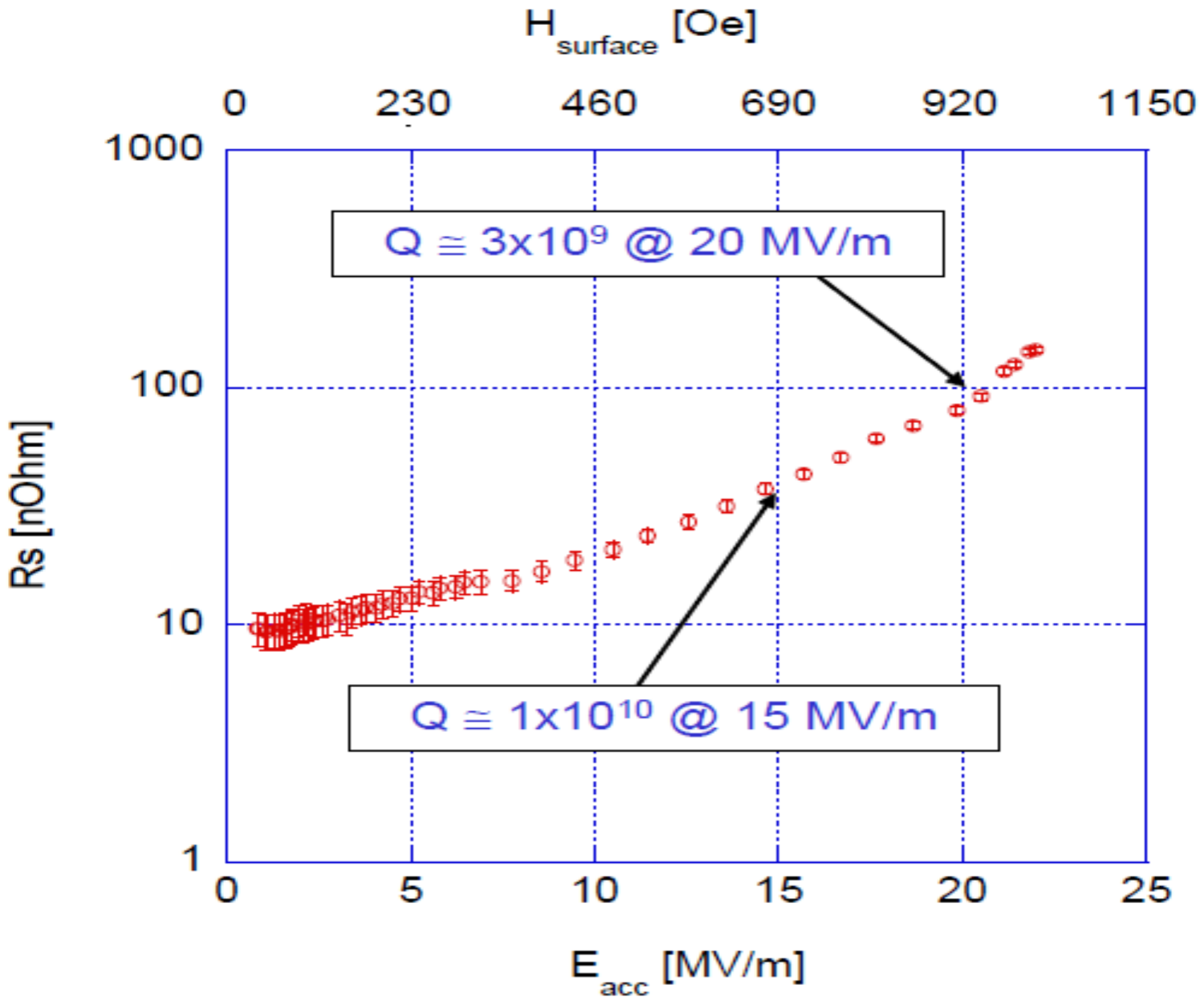
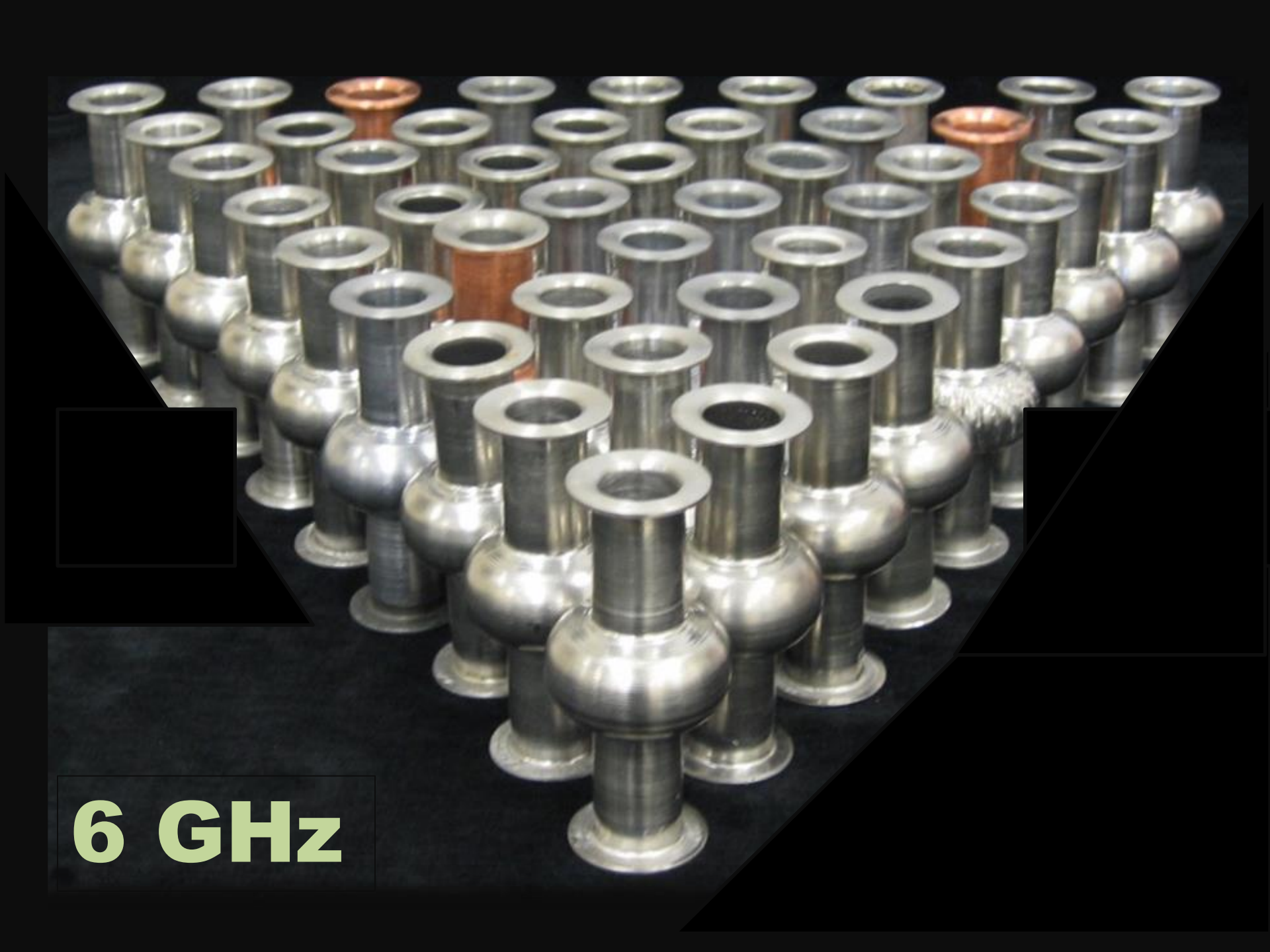


Figure 4: State-of-the art performance of Nb/Cu cavities at 1.7 K and 1500 MHz

on my personal opinion

It is not written on the Bible that «films are worse than the bulk!»


6 GHz

In a small, but active, Research Group

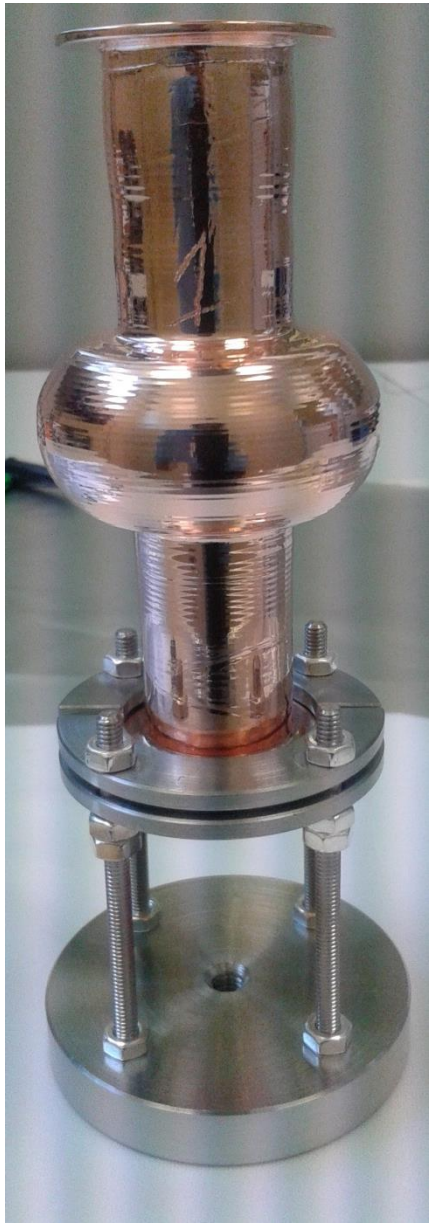
6 GHz Cavities

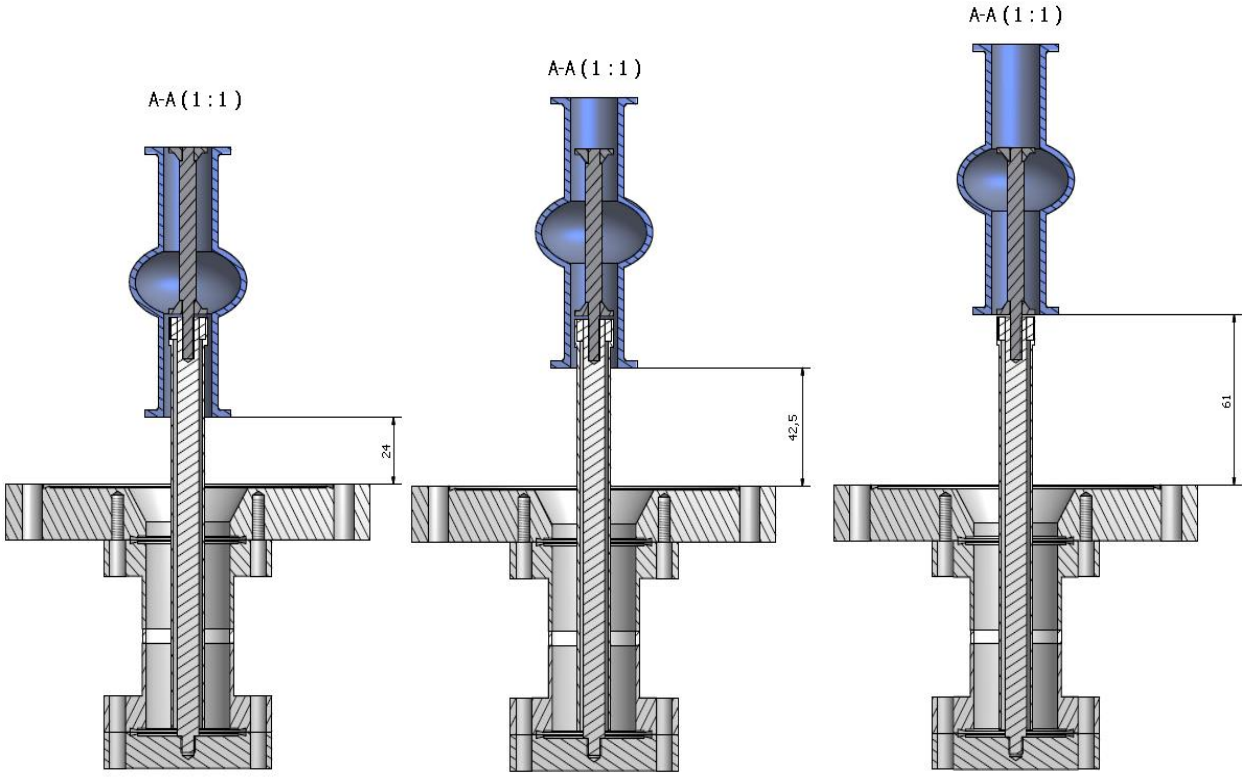
The Ideal Tool For Self-motivation !

Common sentences you can daily hear in our 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!»
- «This year we tested 148 cavities!»

2nd Nb Sputtering - Cu1 6GHz





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Condensed Matter > Materials Science

Niobium-based sputtered thin films for Corrosion Protection of proton-irradiated liquid water targets for [18F] production

H. Skliarova, O. Azzolini, O. Dousset, R.R. Johnson, V. Palmieri

(Submitted on 29 Aug 2013)

Chemically inert Coatings on Havar entrance foils of the targets for [18F] production via proton irradiation of enriched water at pressurized conditions are needed to decrease the amount of ionic contaminants released from Havar. In order to find the most effective protective coatings, the Nb-based coating microstructure and barrier properties have been correlated with deposition parameters as: substrate temperature, applied bias, deposition rate and sputtering gas pressure. Aluminated quartz used as a substrate allowed us to verify the protection efficiency of the desirable coatings as diffusion barriers. Two modeling corrosion tests based on the extreme susceptibility of aluminum to liquid gallium and acid corrosion were applied. Pure Niobium coatings have been found less effective barriers than Niobium-titanium coatings. But Niobium oxide films, according to the corrosion tests performed, showed superior barrier properties. Therefore Multi-layered Niobium-Niobium oxide films have been suggested, since they combine the high thermal conductivity of Niobium with the good barrier properties of Niobium oxide.

Comments: 24 pages, 11 pictures, 6 tables

As far as Nb sputtering is concerned,

The best films for SRF

..... are the worst as diffusion barriers against corrosion protection

Nb films are porous

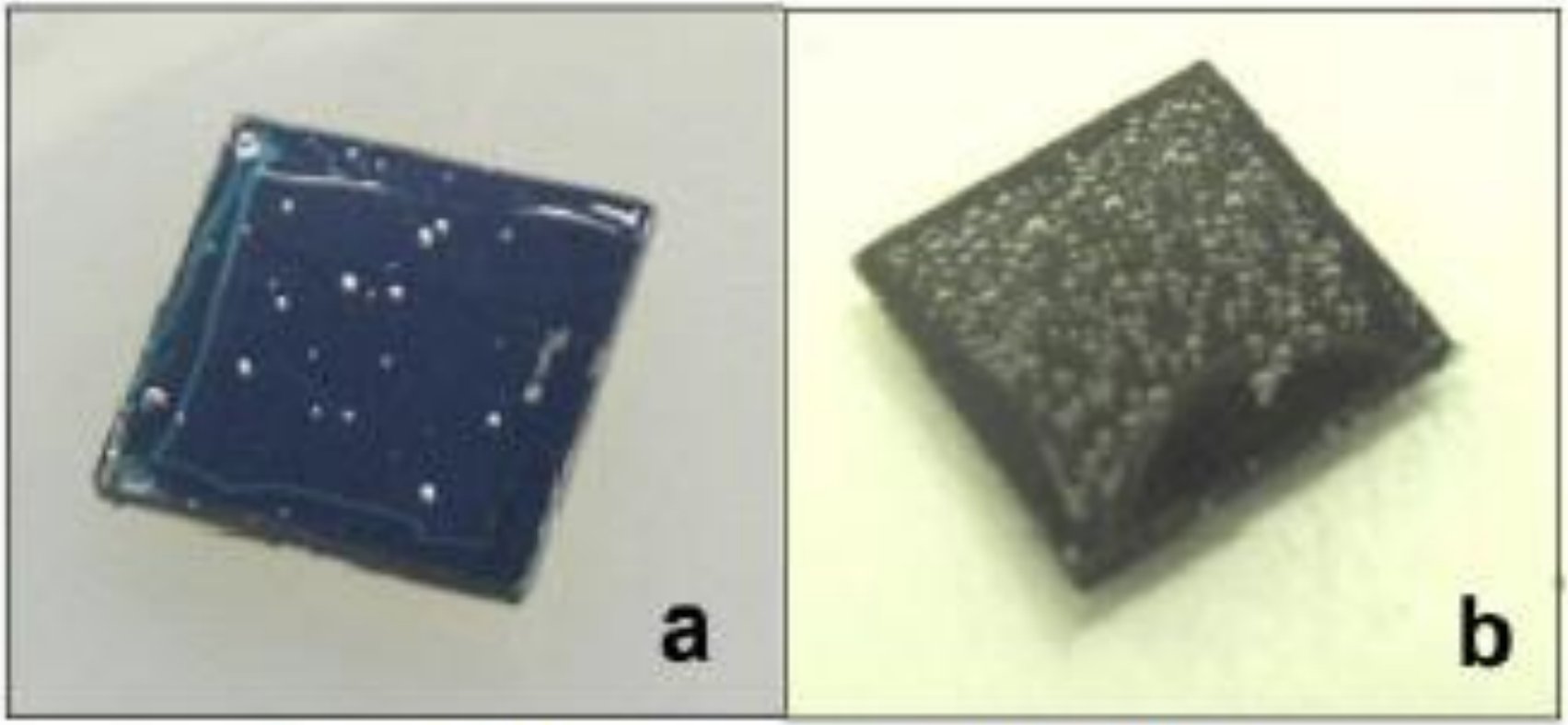


Figure 2 Acid solution resistance: a) high, b) low

Nb sputtered film resistance to Liquid metal Embrittlement

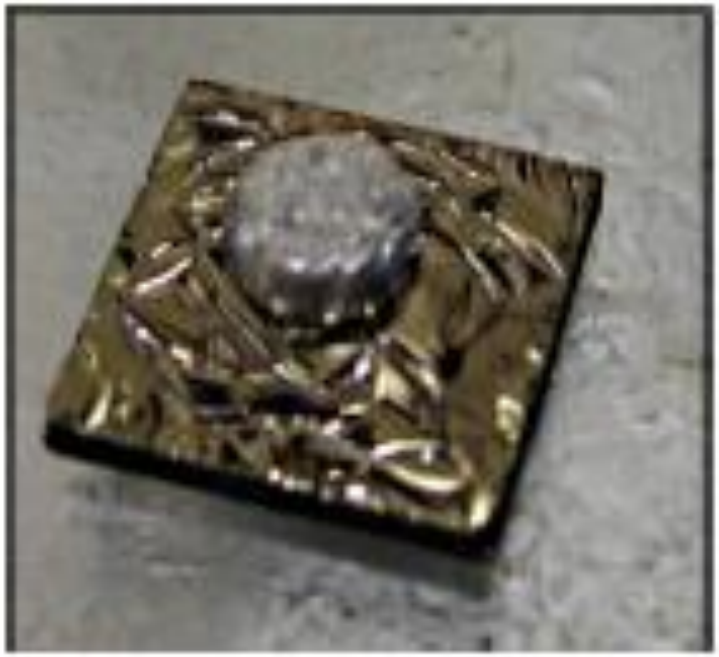


Figure 3 Liquid gallium test: corrosion,

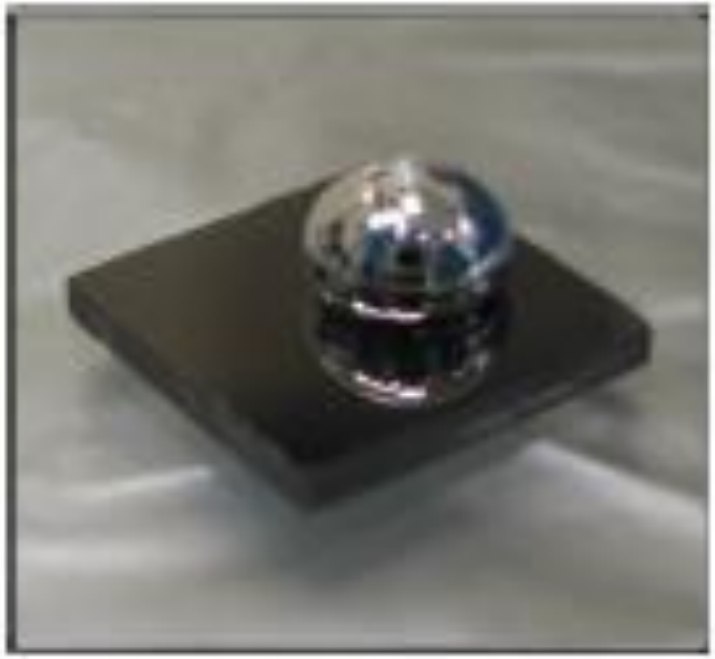


Figure 4 Liquid gallium test: resistance

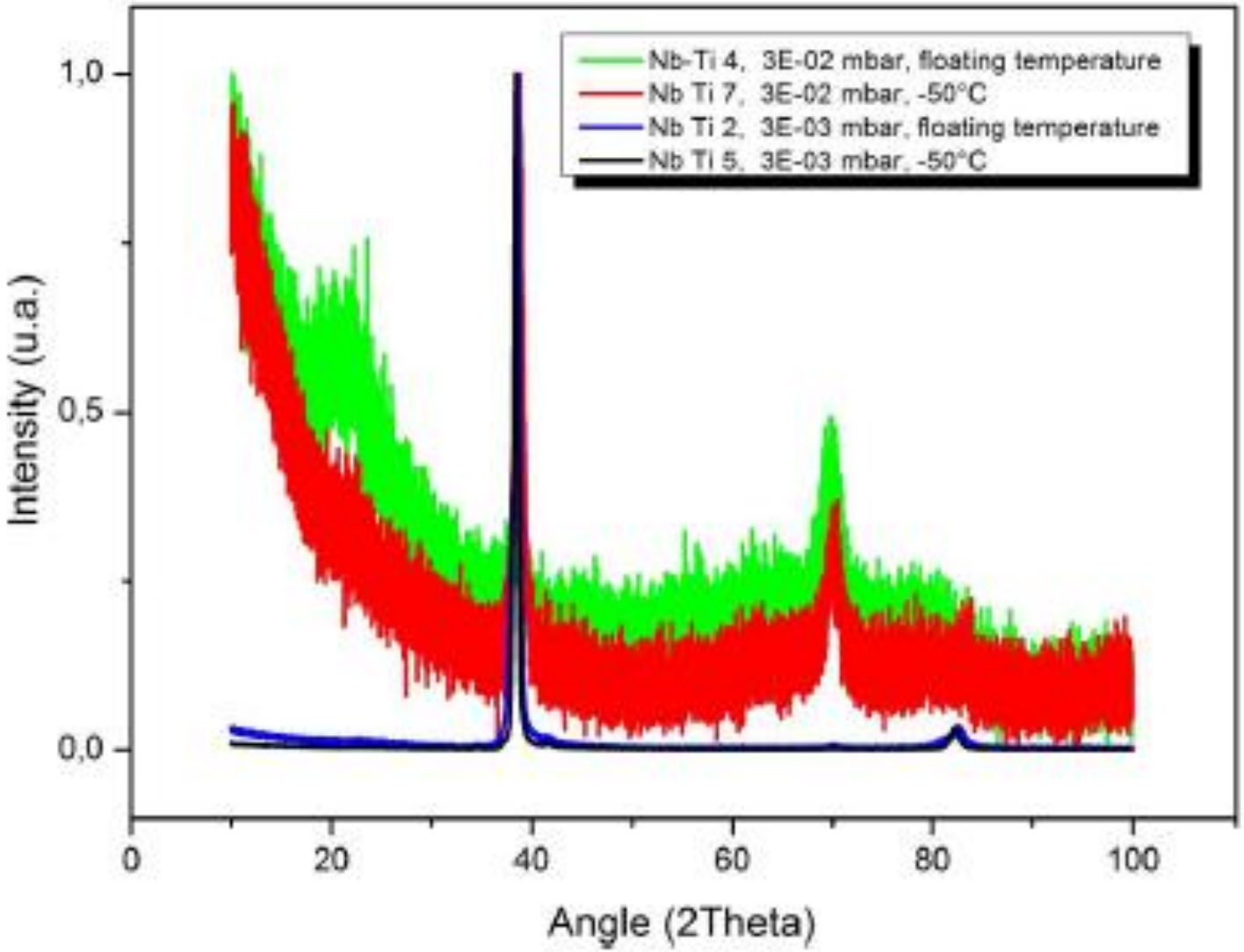
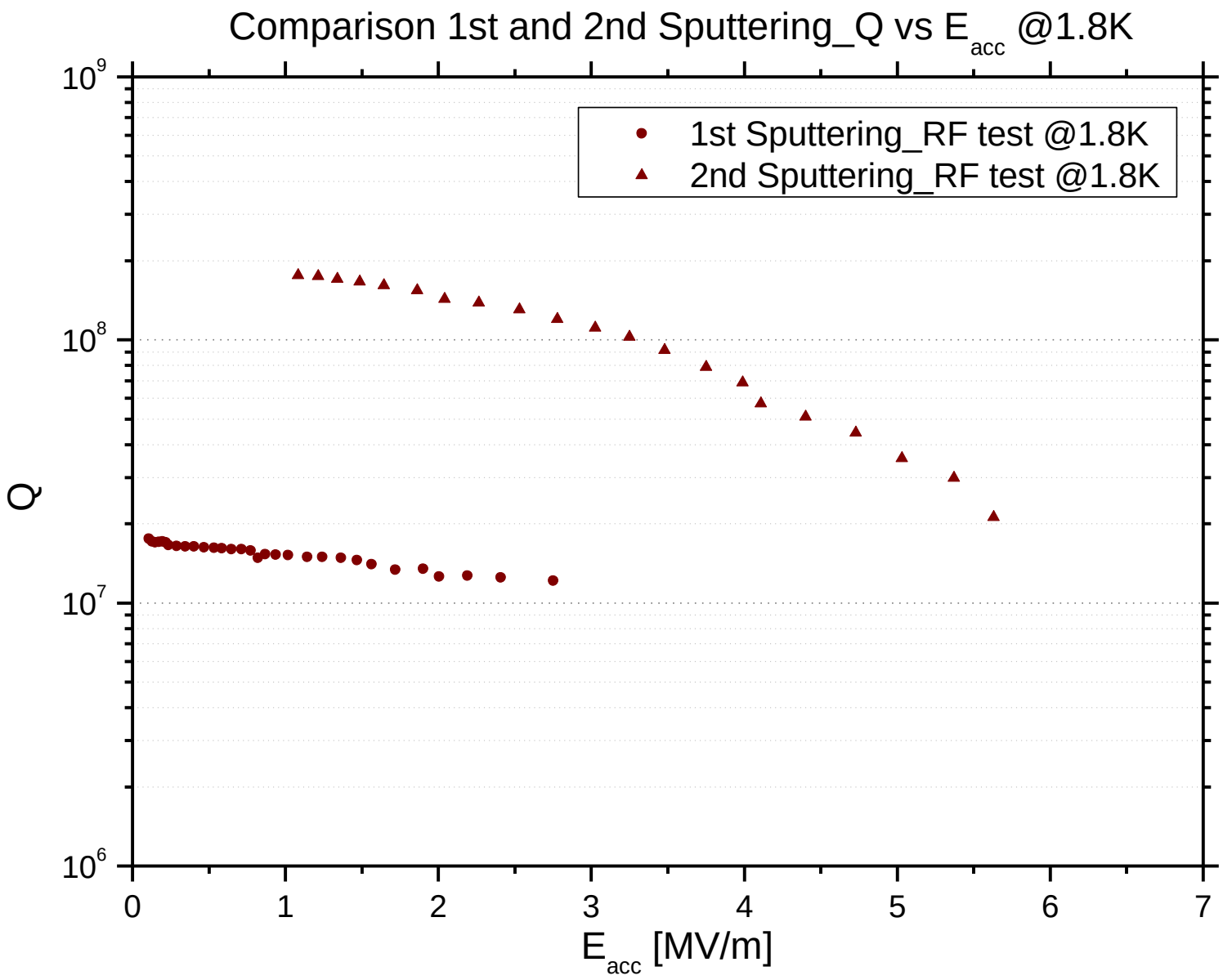
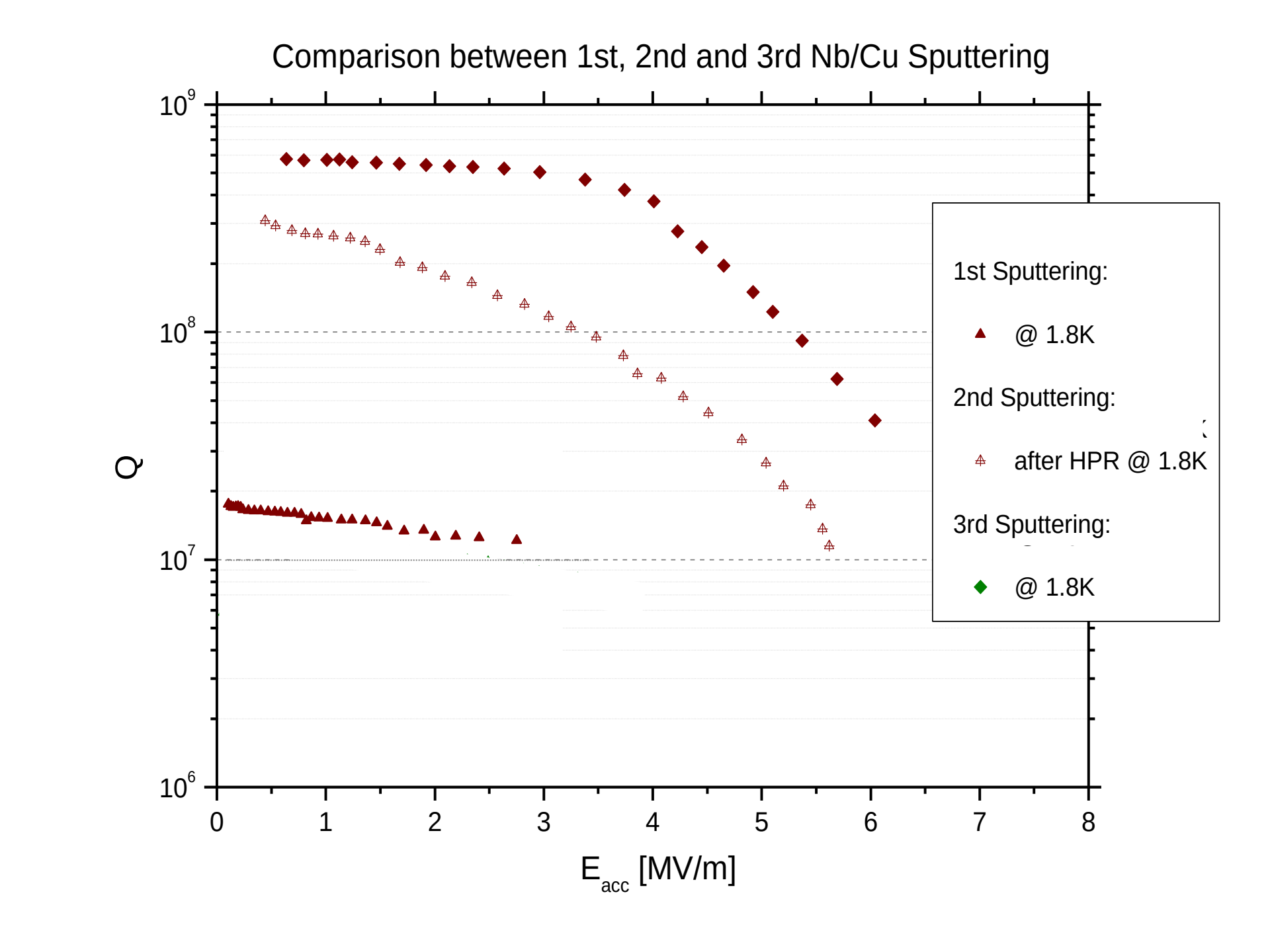


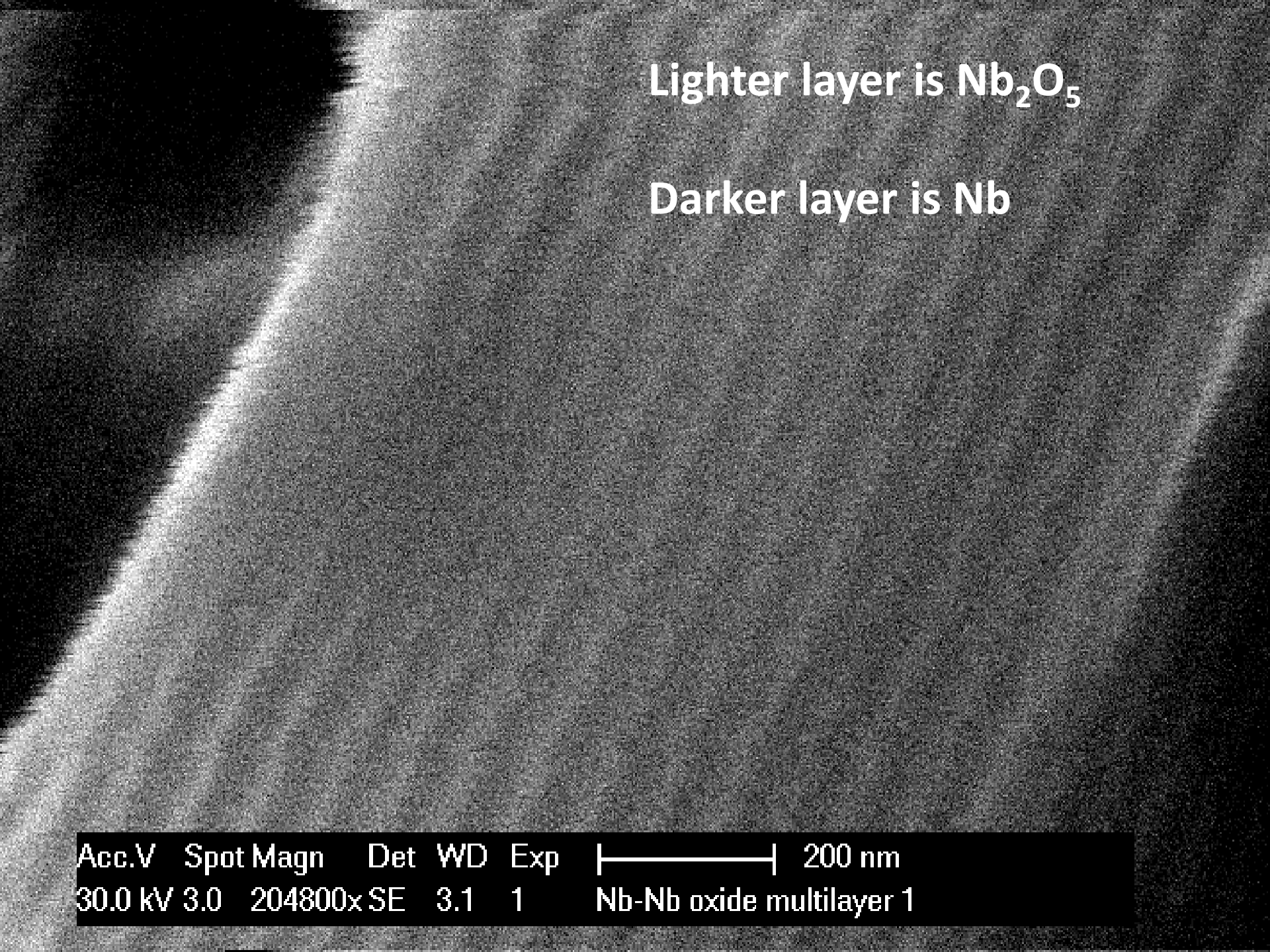
Figure 10 Influence of temperature and pressure on Nb-Ti alloy film deposition

	Nb	Nb-Ti	Nb_2O_5
Low Ar pressure	Crystalline	Crystalline	Amorphous
High Ar Pressure	Crystalline	Amorphous-like	Amorphous
Negative bias	Crystalline	Crystalline	Amorphous
- 50 – 0 °C	Amorphous-like	Depends on Ar pressure	Amorphous

RF test Cu1


Comparison 1st and 2nd Sputtering_Q vs E_acc @1.8K
1st Sputtering_RF test @1.8K
2nd Sputtering_RF test @1.8K
Q
E_acc [MV/m]
10^9
10^8
10^7
10^6
0
1
2
3
4
5
6
7

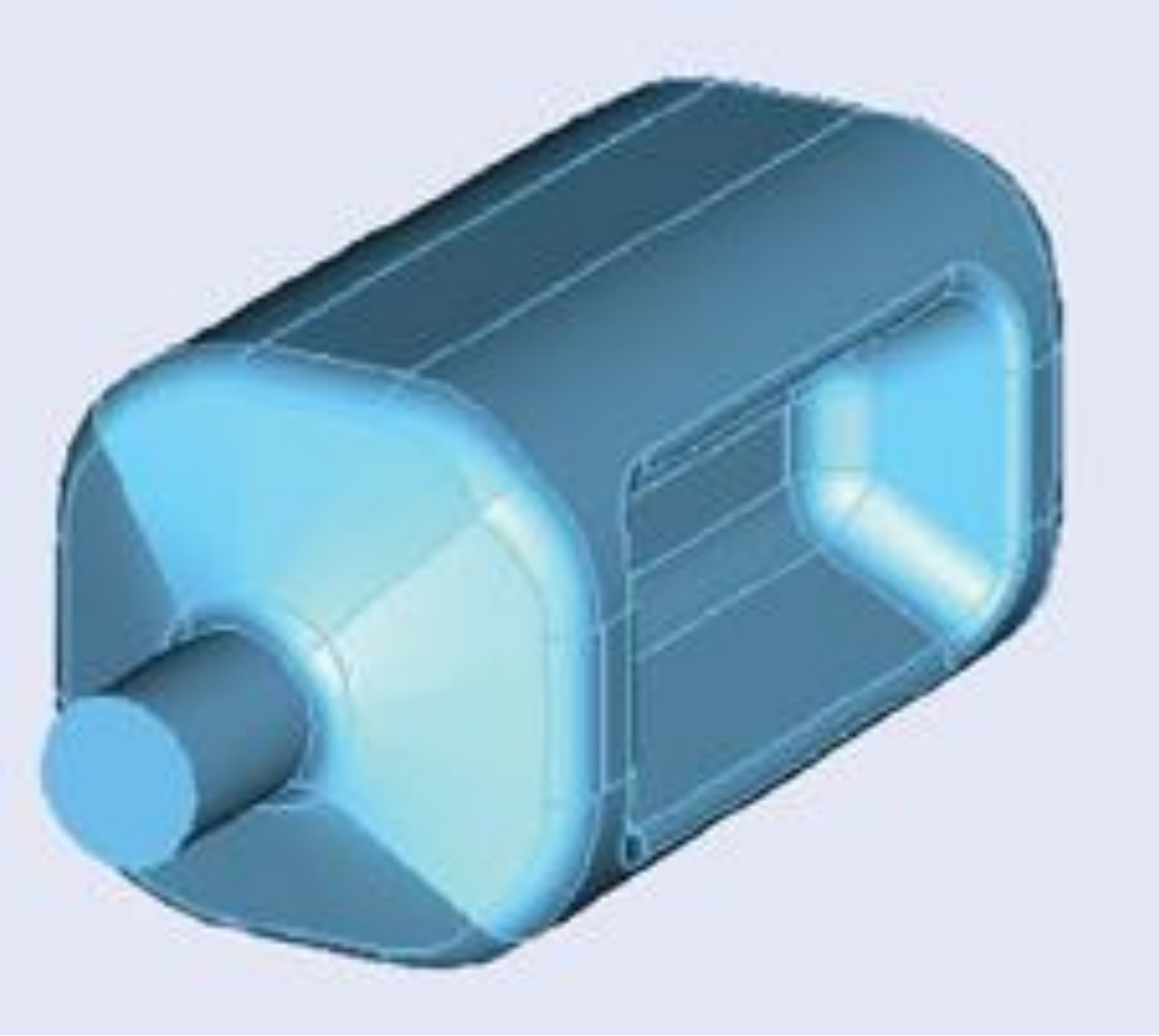

Comparison between 1st, 2nd and 3rd Nb/Cu Sputtering
Q
10^9
10^8
10^7
10^6
0
1
2
3
4
5
6
7
8
E_{acc} [MV/m]
1st Sputtering:
@ 1.8K
2nd Sputtering:
after HPR @ 1.8K
3rd Sputtering:
@ 1.8K


Lighter layer is Nb_2O_5
Darker layer is Nb
Acc.V Spot Magn Det WD Exp 200 nm
30.0 kV 3.0 204800x SE 3.1 1 Nb-Nb oxide multilayer 1

Outline of the talk

- What we actually know about quench
- Thin film cavities (almost) never quench
- **Thinking about the impossible is cost-free**
- Need to go deeper into Cryogenics

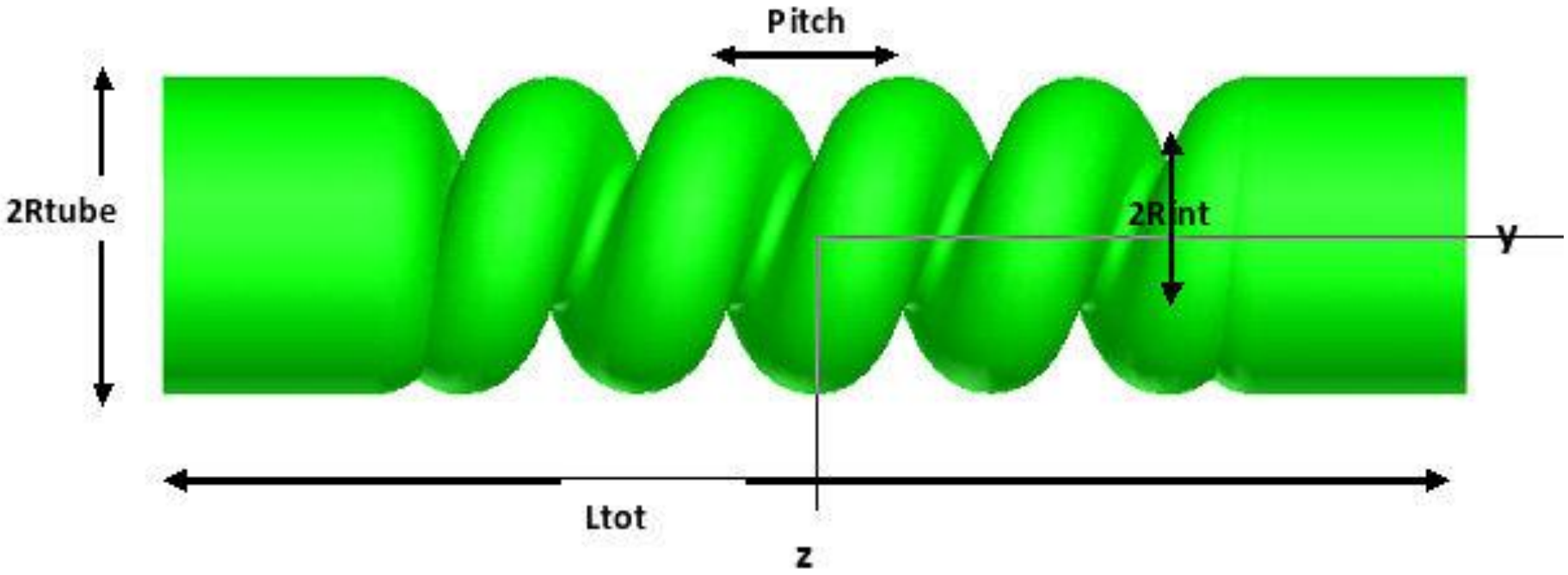
Take the most simple half wave cavity



Crazy Idea n.° 1

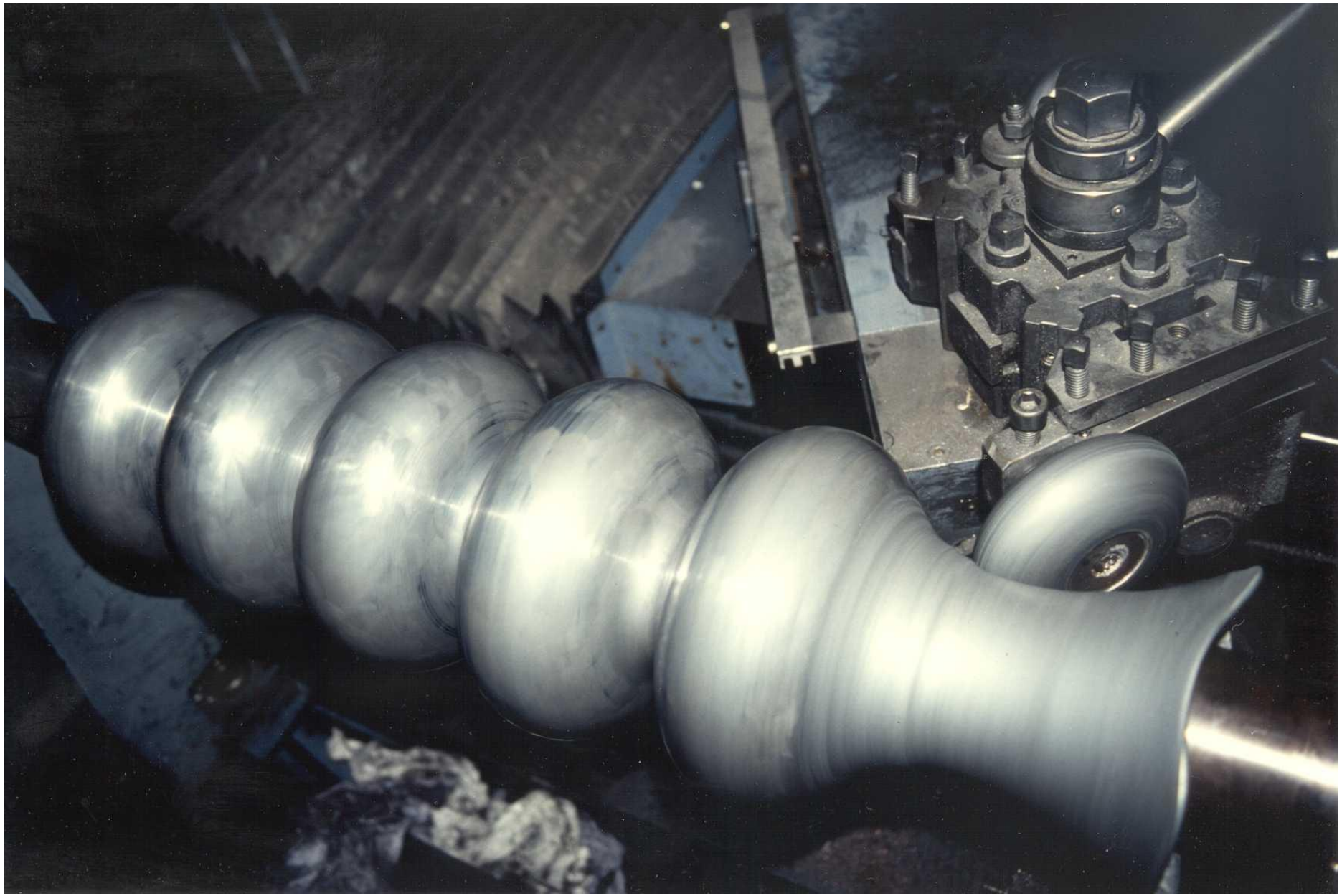
The BCS cavity

(Breaking the Cylindrical Simmetry)

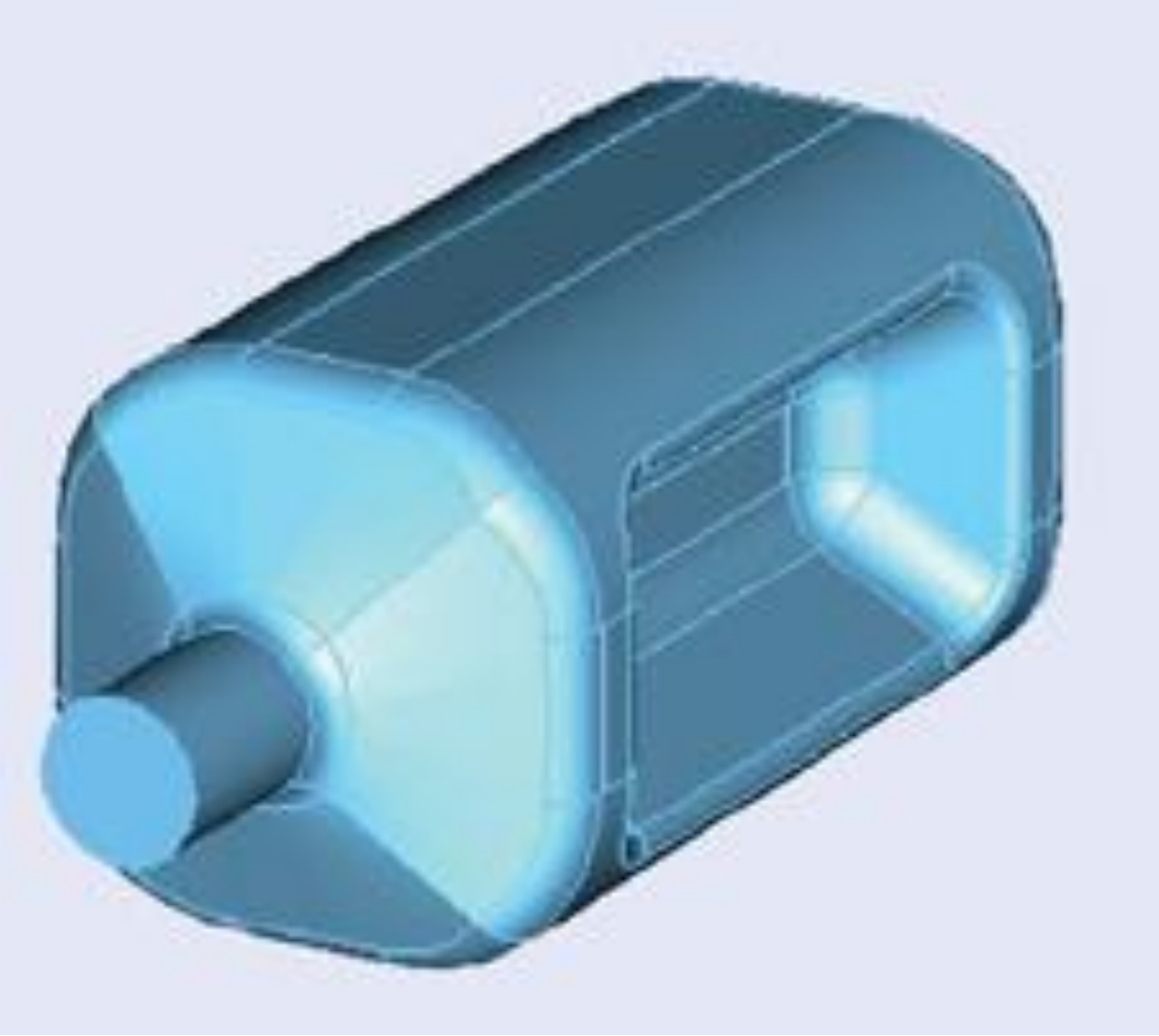


3D printing

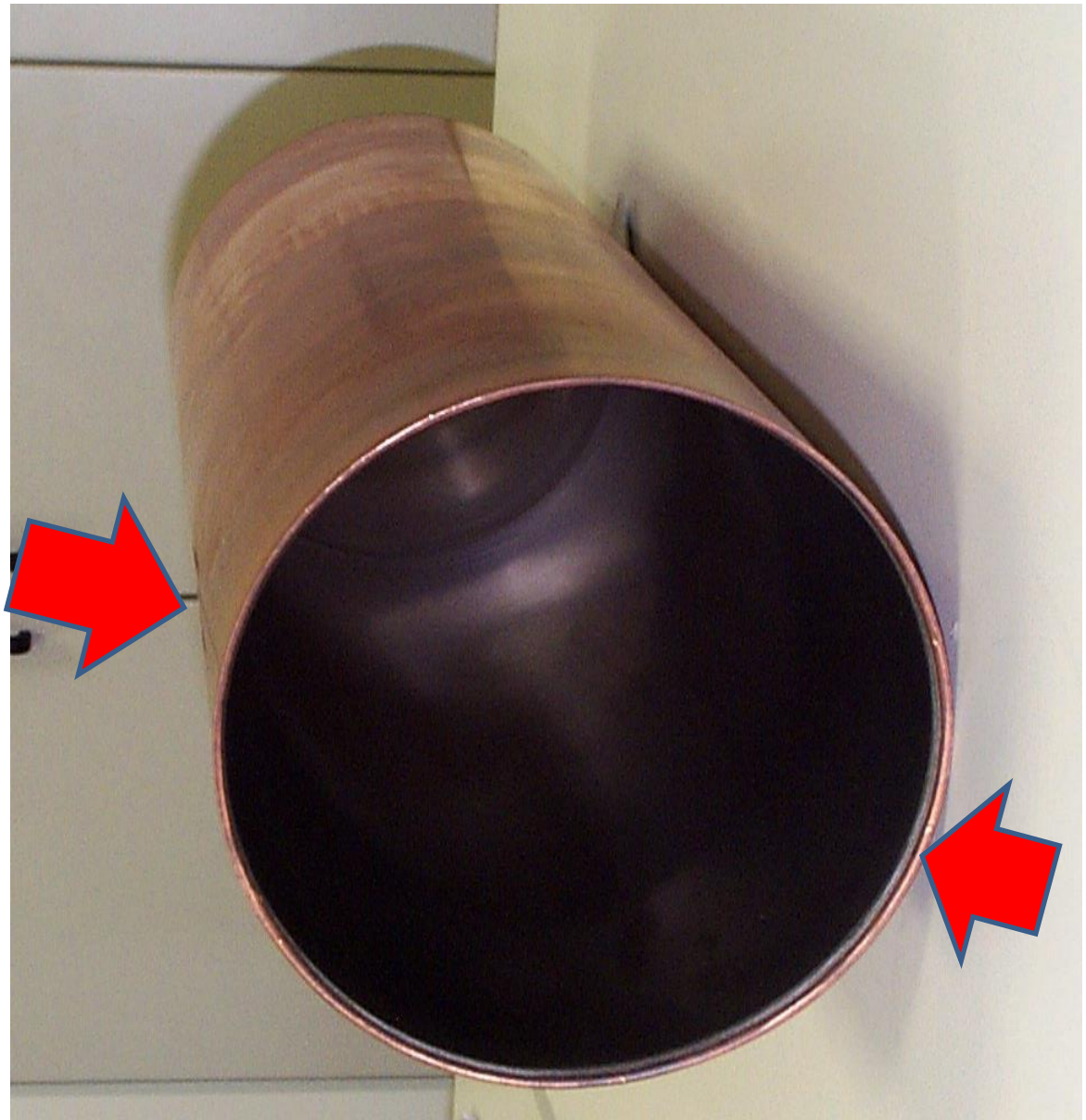
Crazy Idea n.° 2

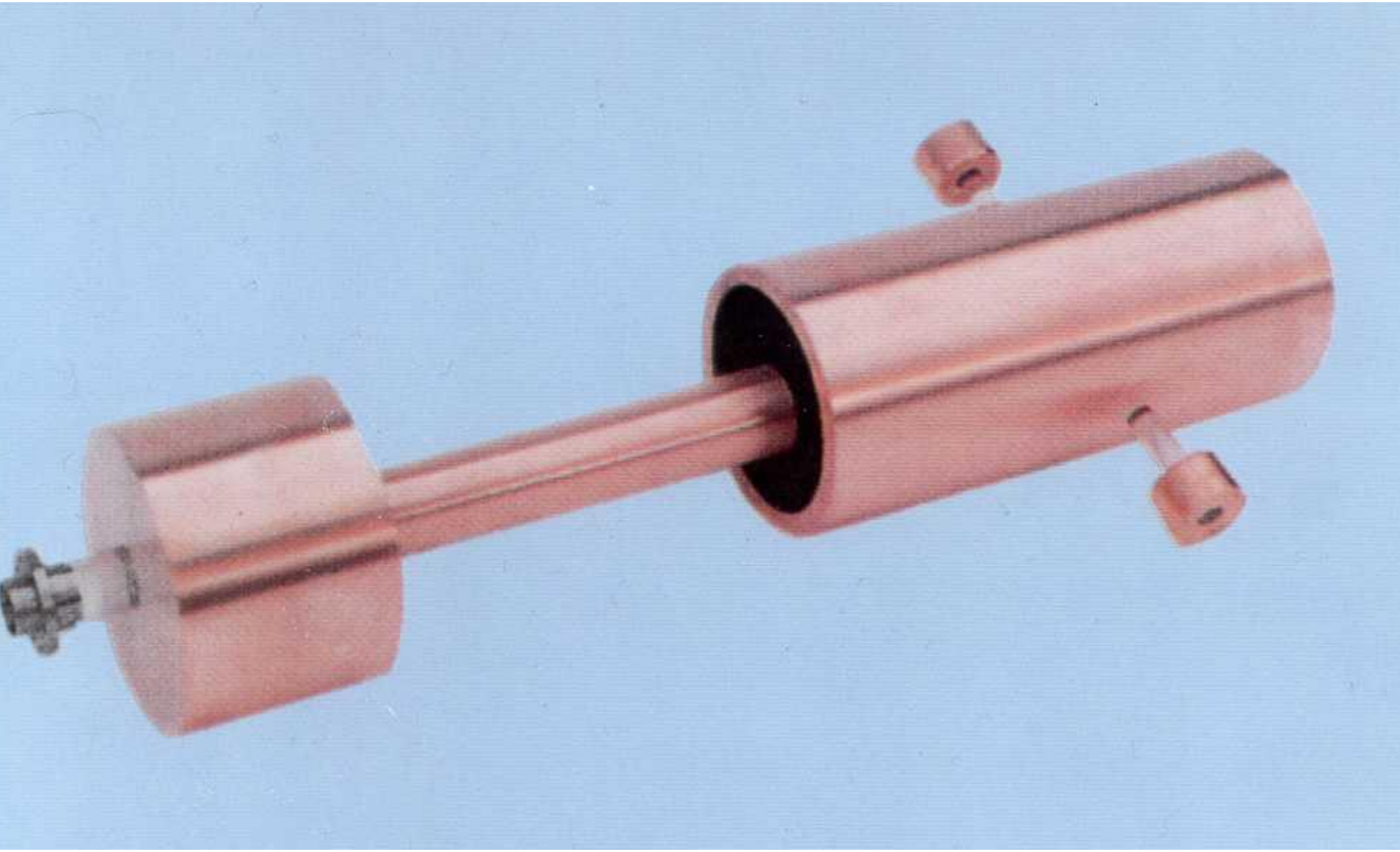


Take the most simple half wave cavity



A totally Seamless Nb Clad Cu Crab cavity is possible



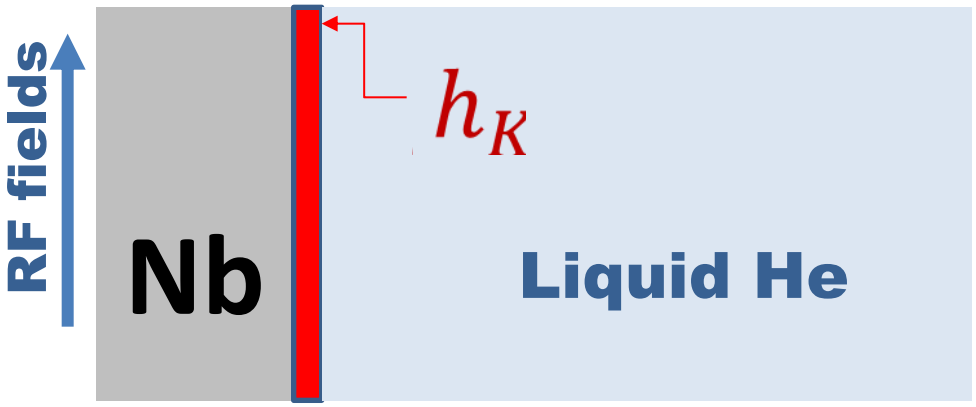


Sputtering Nb onto plates or into tubes and then spinning

Outline of the talk

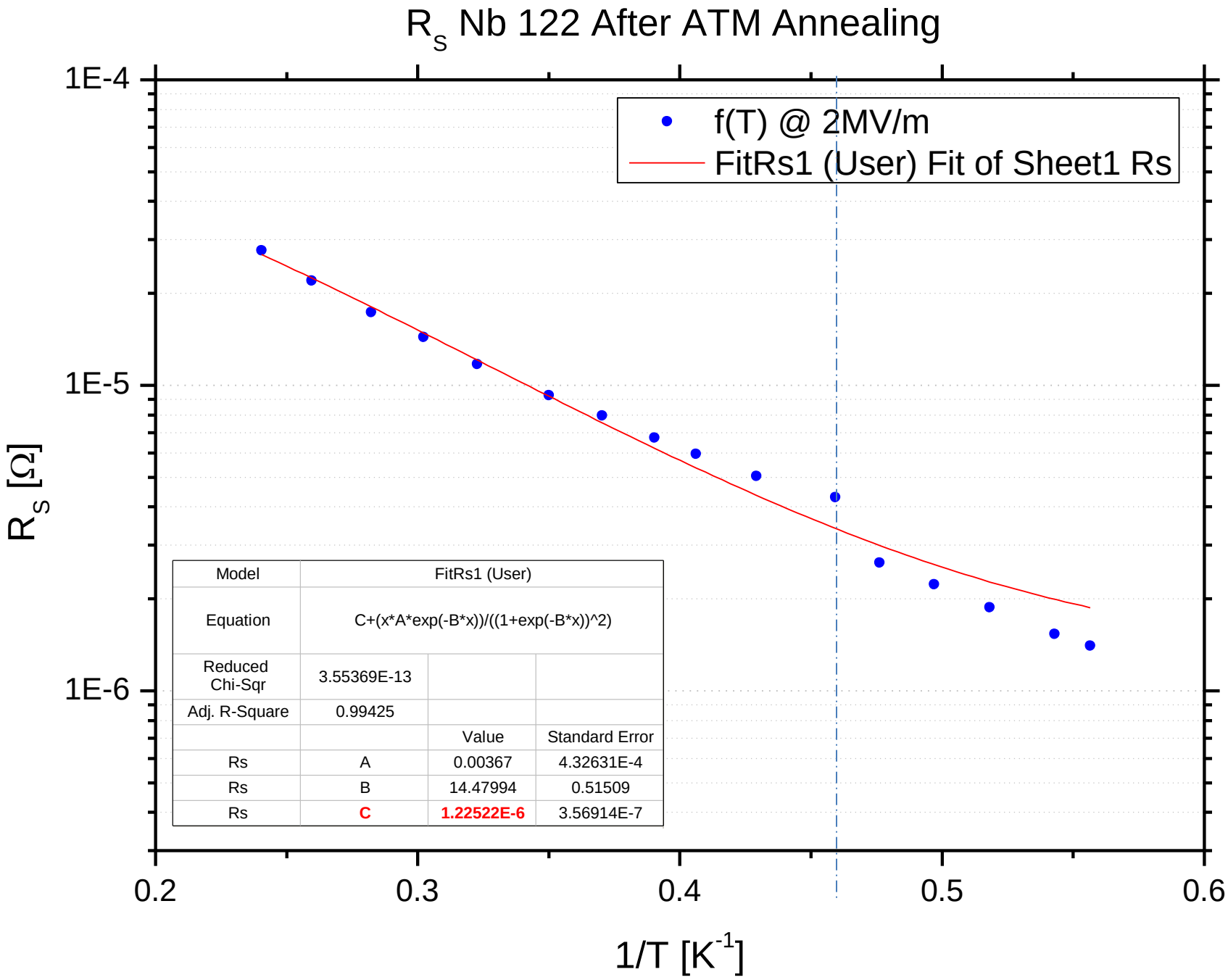
- What we actually know about quench
- Thin film cavities (almost) never quench
- Thinking about the impossible is cost-free
- **Need to go deeper into Cryogenics**

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



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

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]

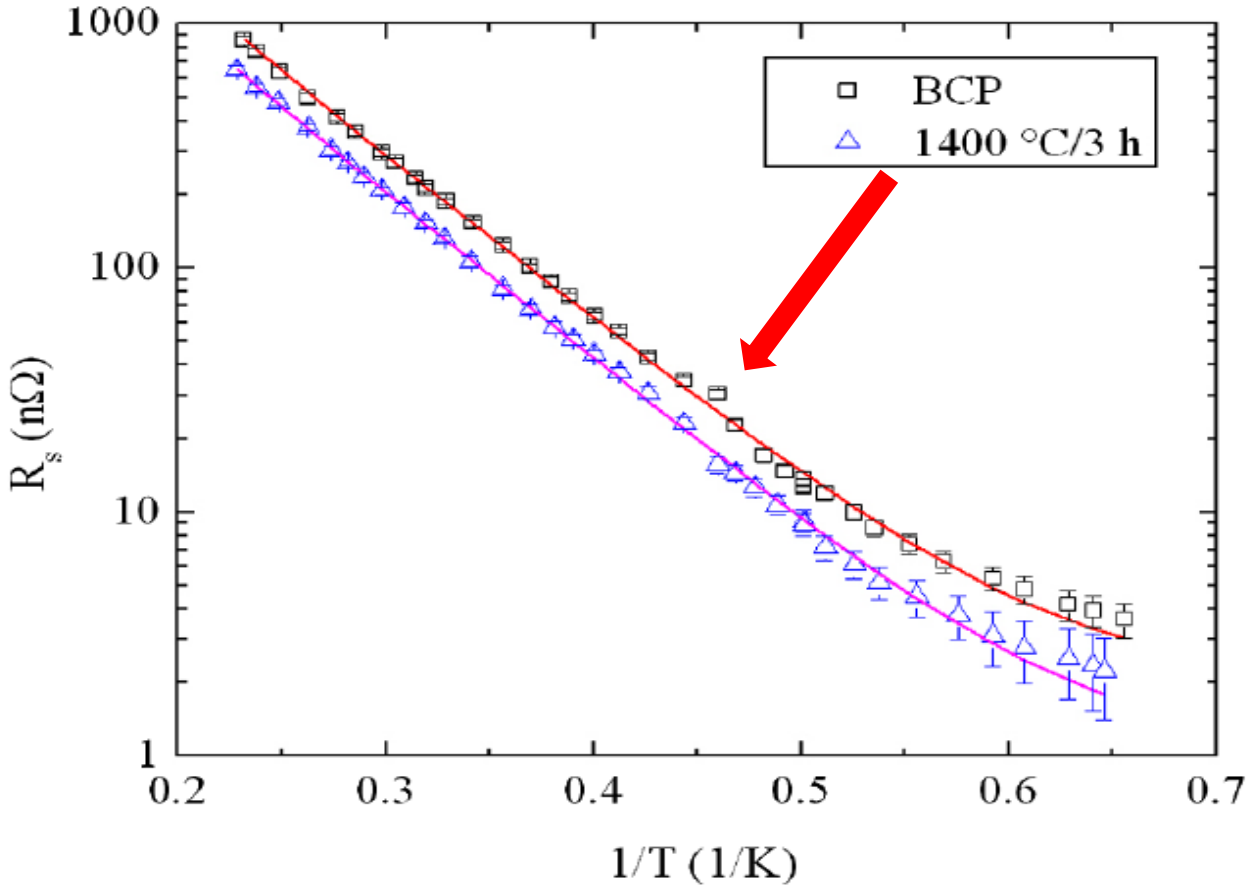
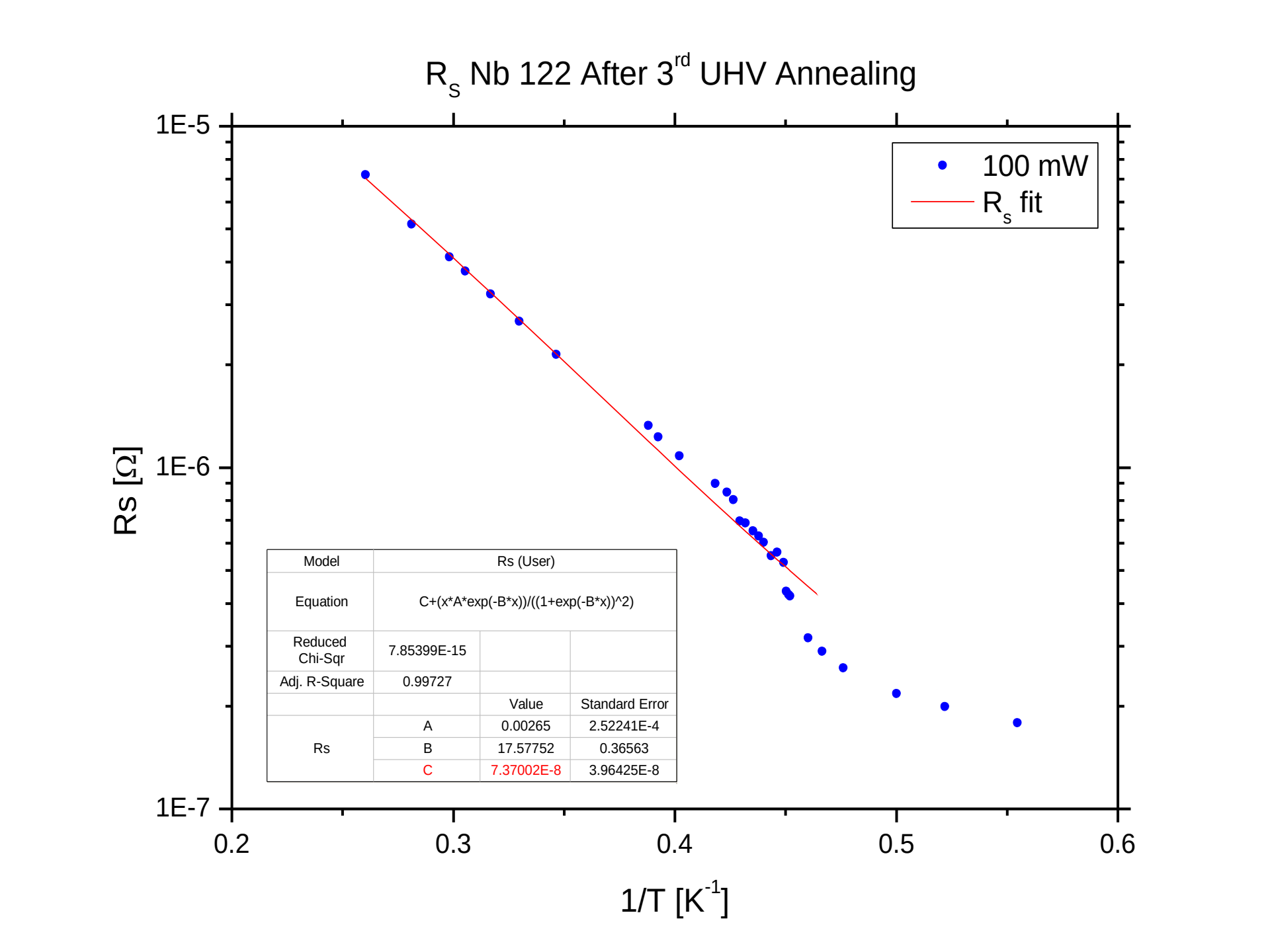
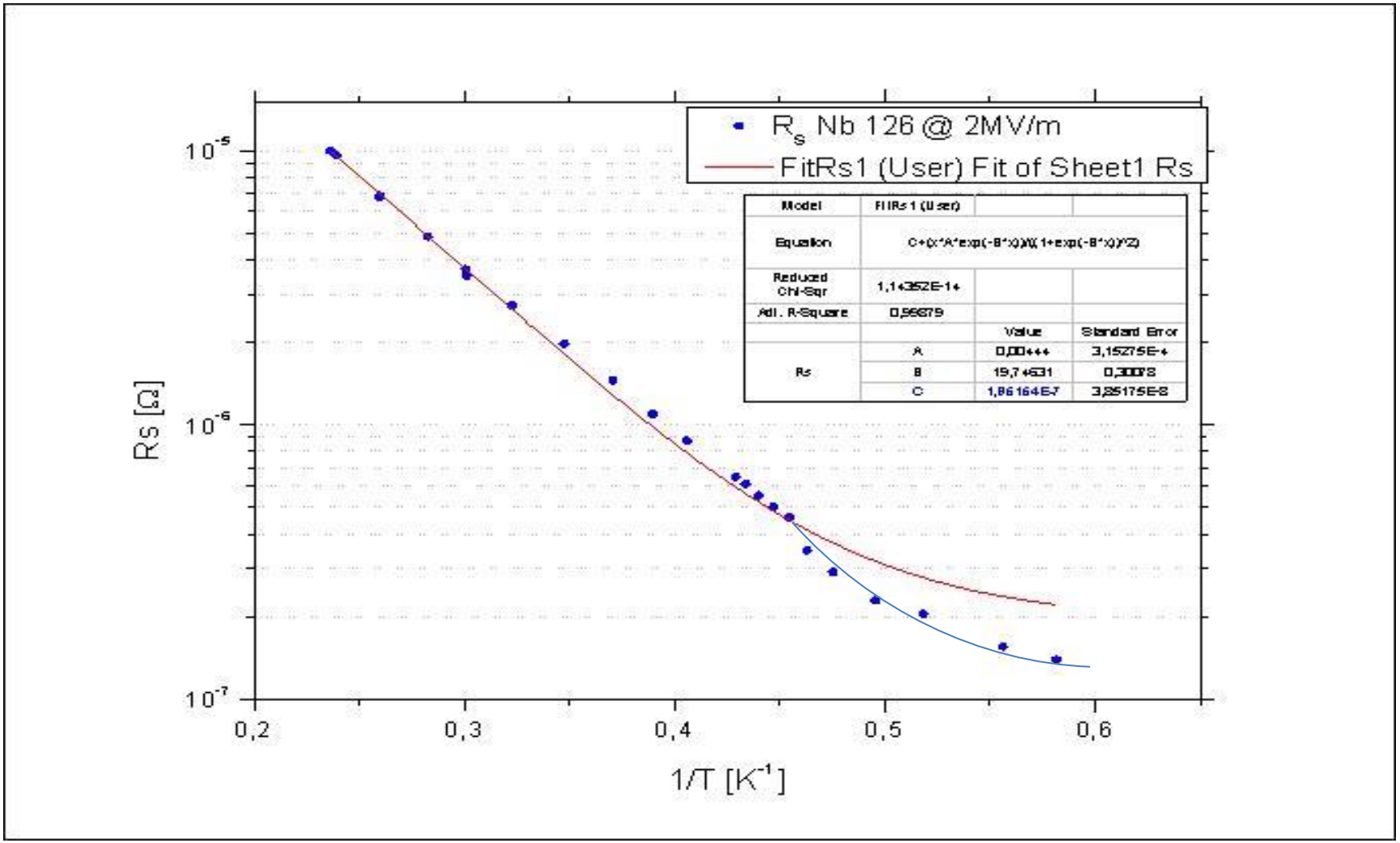


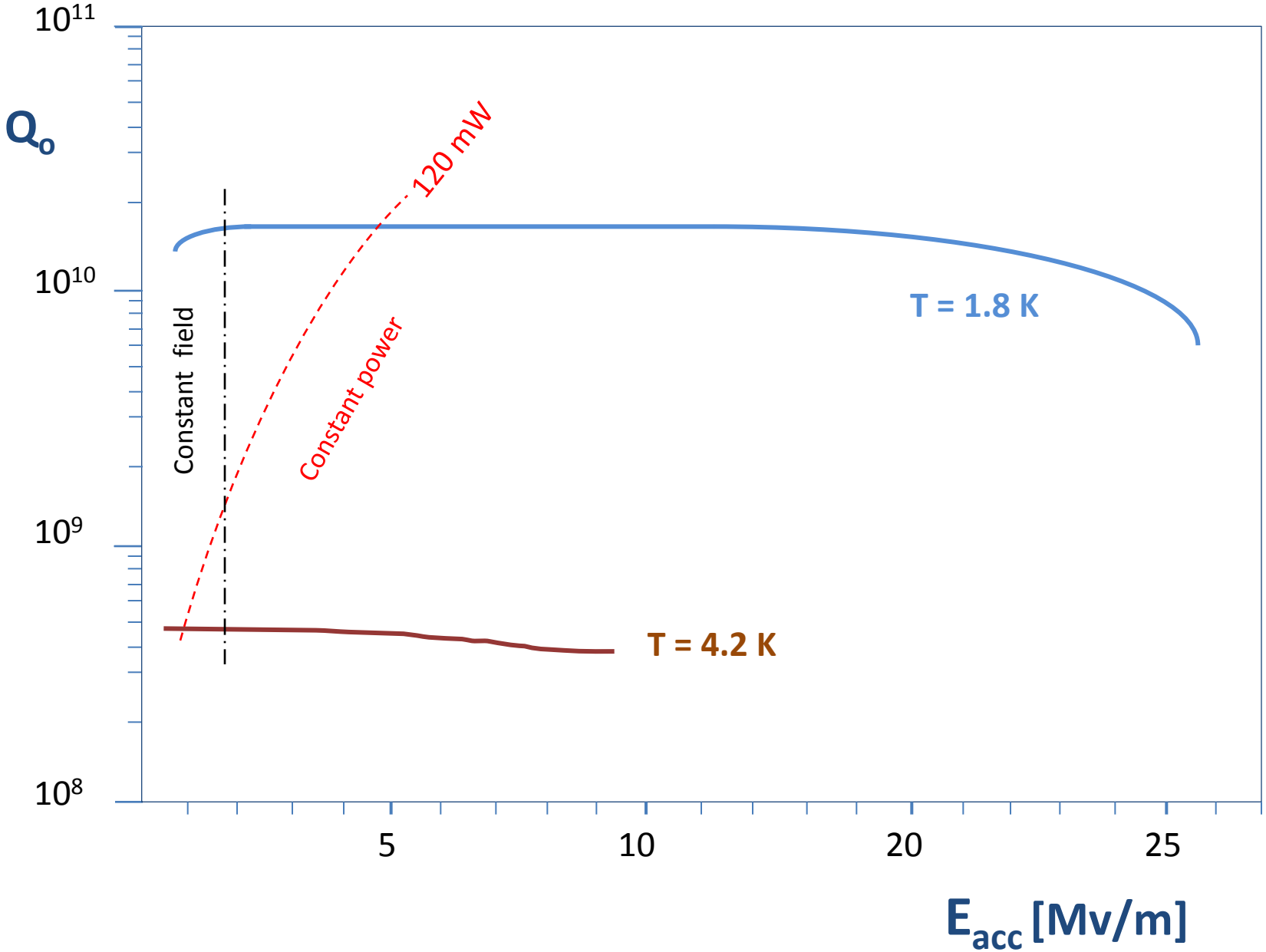
FIG. 9. R_s vs $1/T$ measured after BCP and after HT at 1400°C. Solid lines are least-square fits with $R_s(T) = R_{\mathrm{BCS}}(T) + R_{\mathrm{res}}$. The values of the fit parameters are $\Delta/kT_c = 1.87 \pm 0.02$, $\ell = (303 \pm 85)$ nm, $R_{\mathrm{res}} = (2.0 \pm 0.3)$ nΩ after BCP and $\Delta/kT_c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

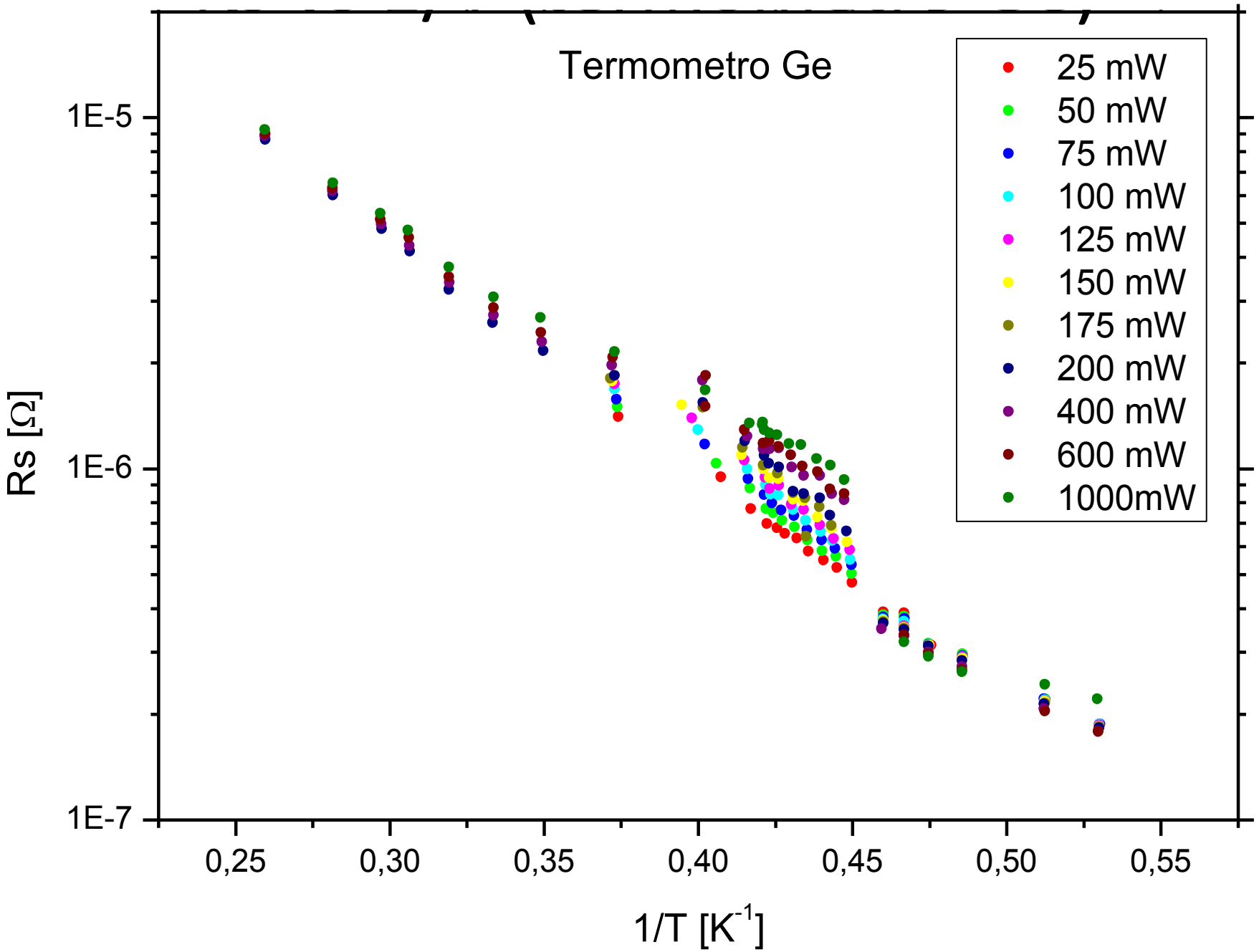

R_S Nb 122 After 3rd UHV Annealing
100 mW
R_s fit
Rs [Ω]
1E-5
1E-6
1E-7
0.2
0.3
0.4
0.5
0.6
1/T [K^-1]
Model
Rs (User)
Equation
C+(x*A*exp(-B*x))/((1+exp(-B*x))^2)
Reduced Chi-Sqr
7.85399E-15
Adj. R-Square
0.99727
Value
Standard Error
Rs
A
0.00265
2.52241E-4
B
17.57752
0.36563
C
7.37002E-8
3.96425E-8

R_{RES} depends on the status of Liq- He

instead than on Nb material?




10^{11}
Q_o
10^{10}
10^{9}
10^{8}
120 mW
Constant power
Constant field
T = 1.8 K
T = 4.2 K
5
10
20
25
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
0,25
0,30
0,35
0,40
0,45
0,50
0,55
1/T [K-1]

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

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

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

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

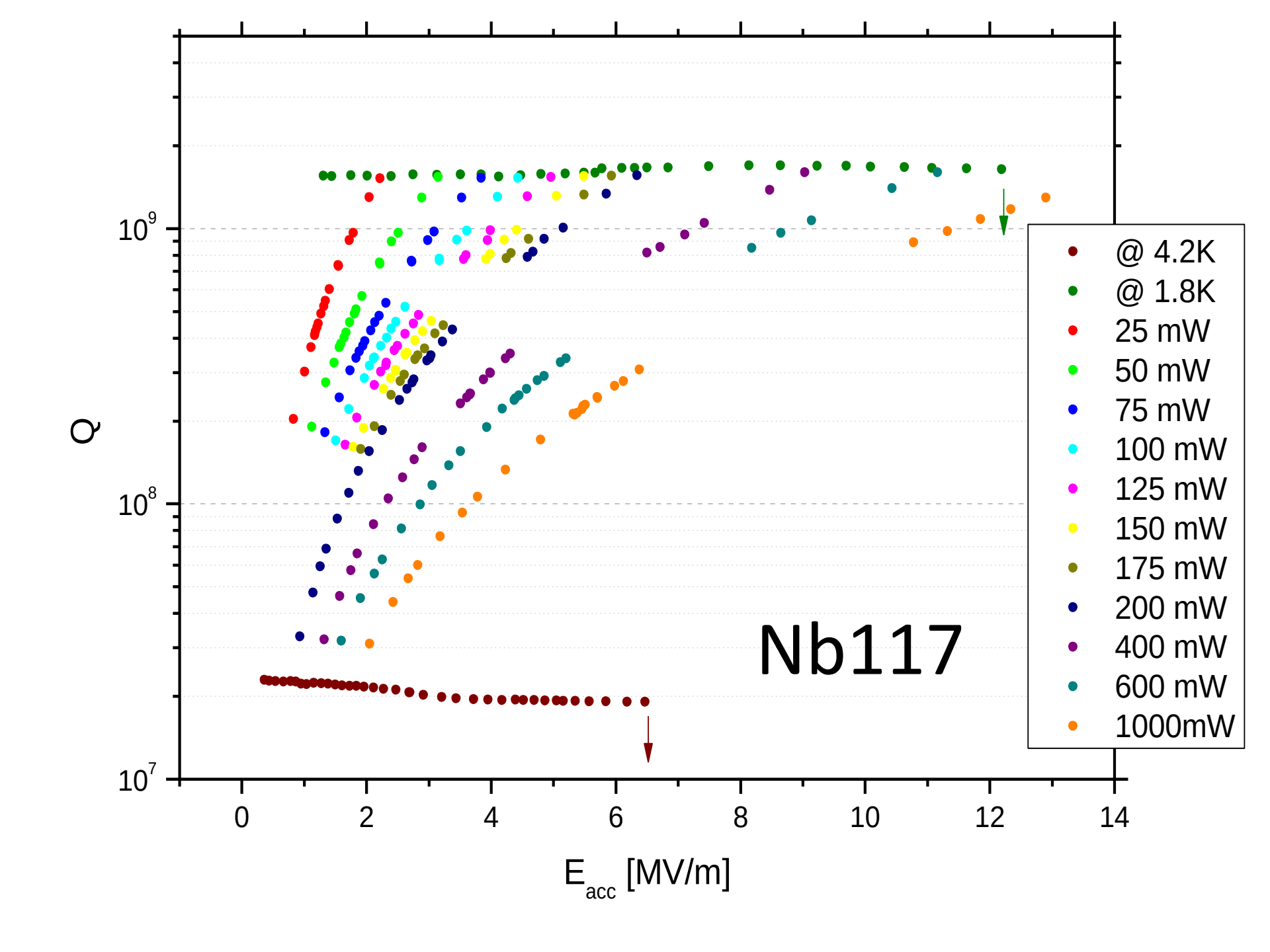
$$R_{BCS}(T_0+\Delta T) \approx \frac{A\omega^2}{T_0}\exp\left[-\frac{sT_C}{2T_0}\right] * \exp\left[-\frac{sT_C}{2}\frac{\Delta T}{{T_0}^2}\right]$$

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

$$R_S(T) \approx R_{BCS}(T) + R_{RES}$$

?????

$$R_S(T_0, W) \approx R_{BCS}(T_0) * \exp\left[-\frac{sT_C}{2} \frac{\Delta T}{T_0^{\,2}} \right] + R_{RES}$$


Q
10^9
10^8
10^7
0
2
4
6
8
10
12
14
E_{acc} [MV/m]
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

the Q-factor decreases linearly with W,

but at a certain point it becomes

almost constant!

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

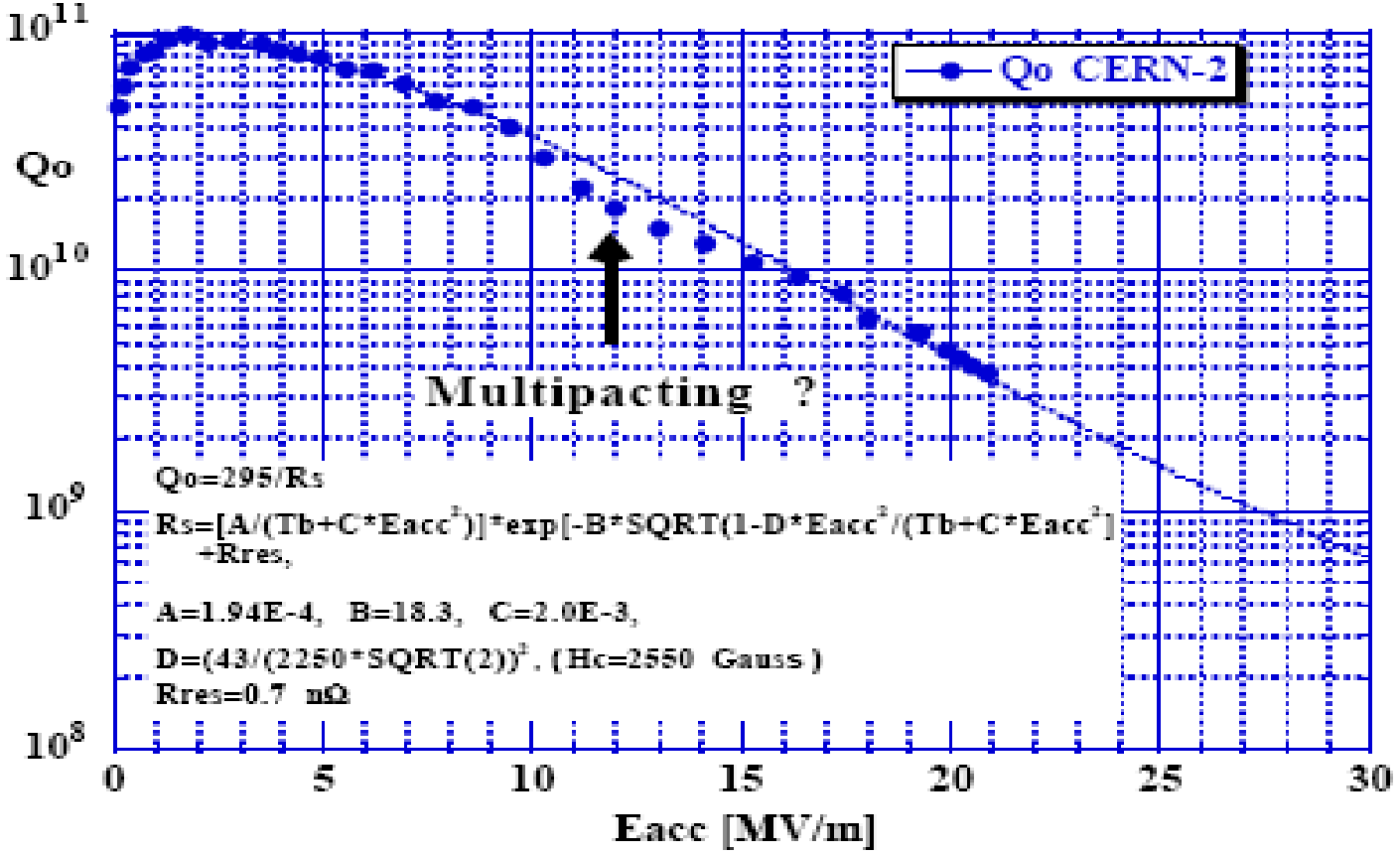


Figure 20: Qo-Eacc excitation curve fitting by the combined model for the 1500MHz niobium film coated cavity at CERN.

Is it possible that

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

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

F. Furuta[#], K. Saito[a], T. Saeki[a], H. Inoue[a], Y. Morozumi[a], T. Higo[a], Y. Higashi[a], H. Matsumoto[a], S. Kazakov[a], H. Yamaoka[a], K. Ueno[a], Y. Kobayashi[a], R. S. Orr[a] and J. Sekutowicz[b]

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

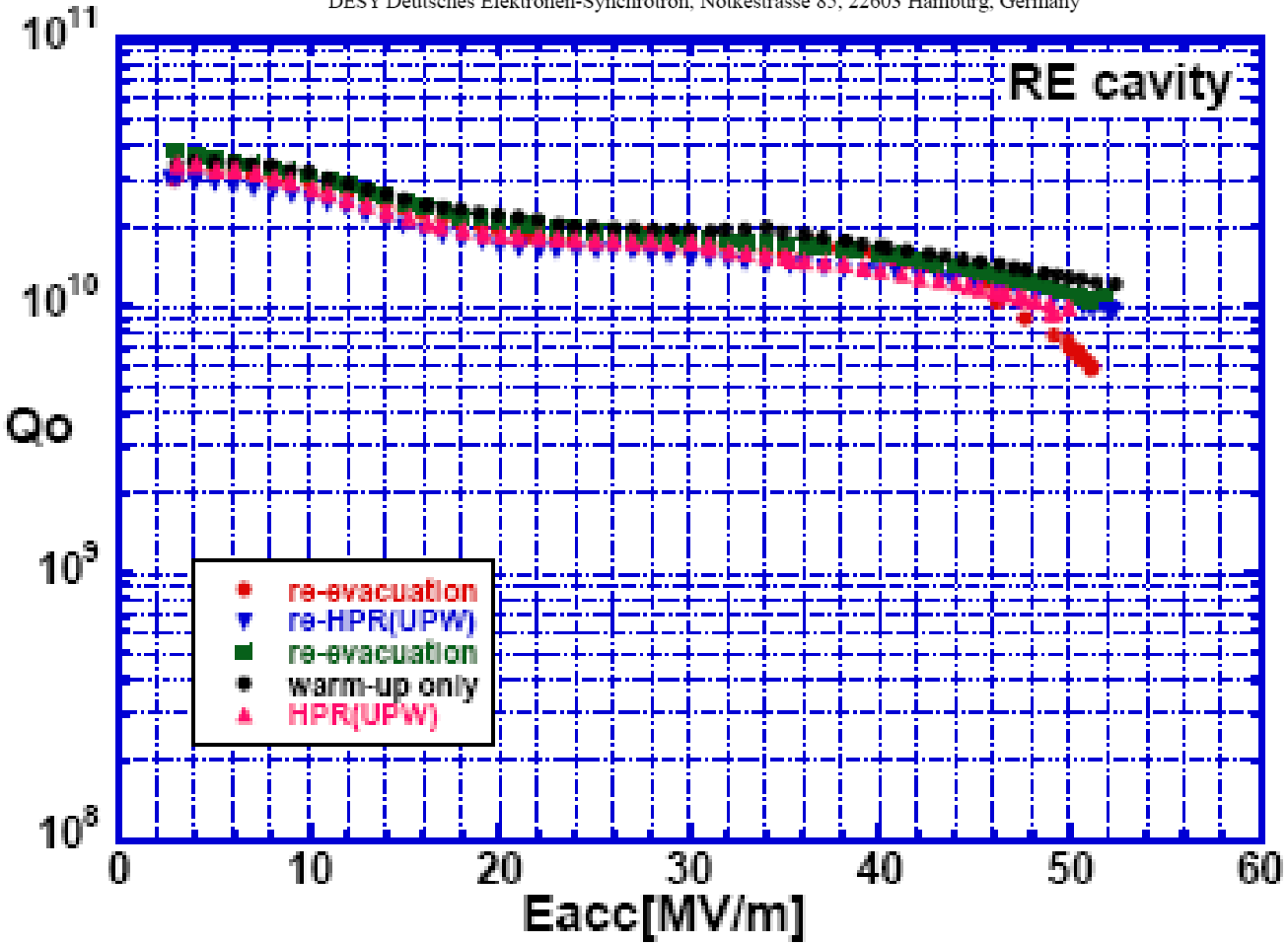
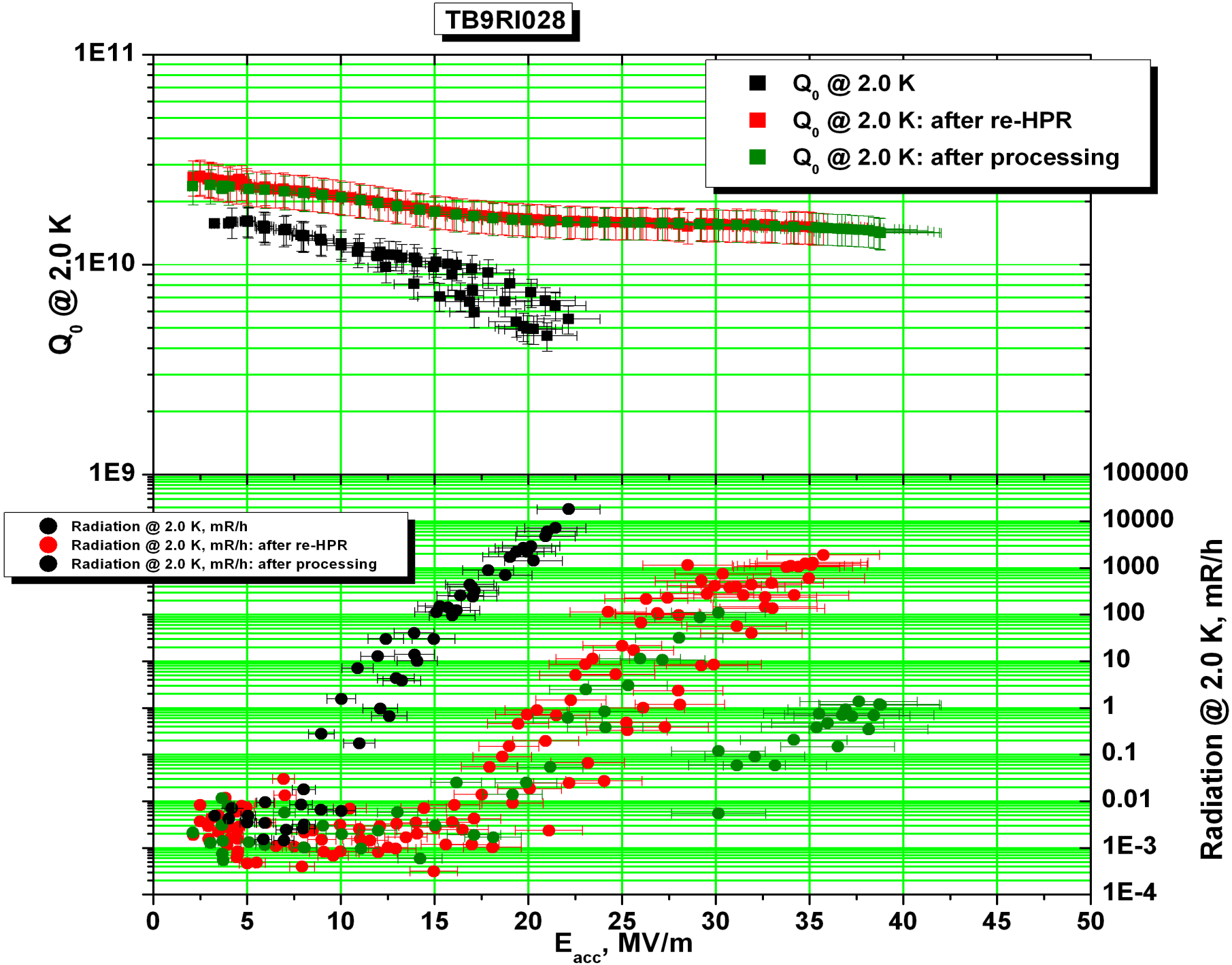
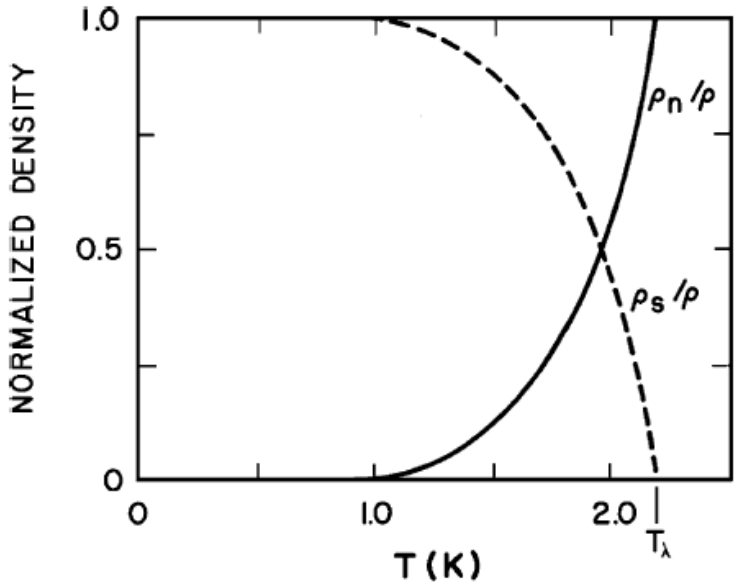


Figure 5: The reproducibility of high gradient.


TB9RI028
1E11
1E10
1E9
Q_0 @ 2.0 K
Q_0 @ 2.0 K
Q_0 @ 2.0 K: after re-HPR
Q_0 @ 2.0 K: after processing
Radiation @ 2.0 K, mR/h
Radiation @ 2.0 K, mR/h: after re-HPR
Radiation @ 2.0 K, mR/h: after processing
100000
10000
1000
100
10
1
0.1
0.01
1E-3
1E-4
Radiation @ 2.0 K, mR/h
0
5
10
15
20
25
30
35
40
45
50
E_{acc}, MV/m

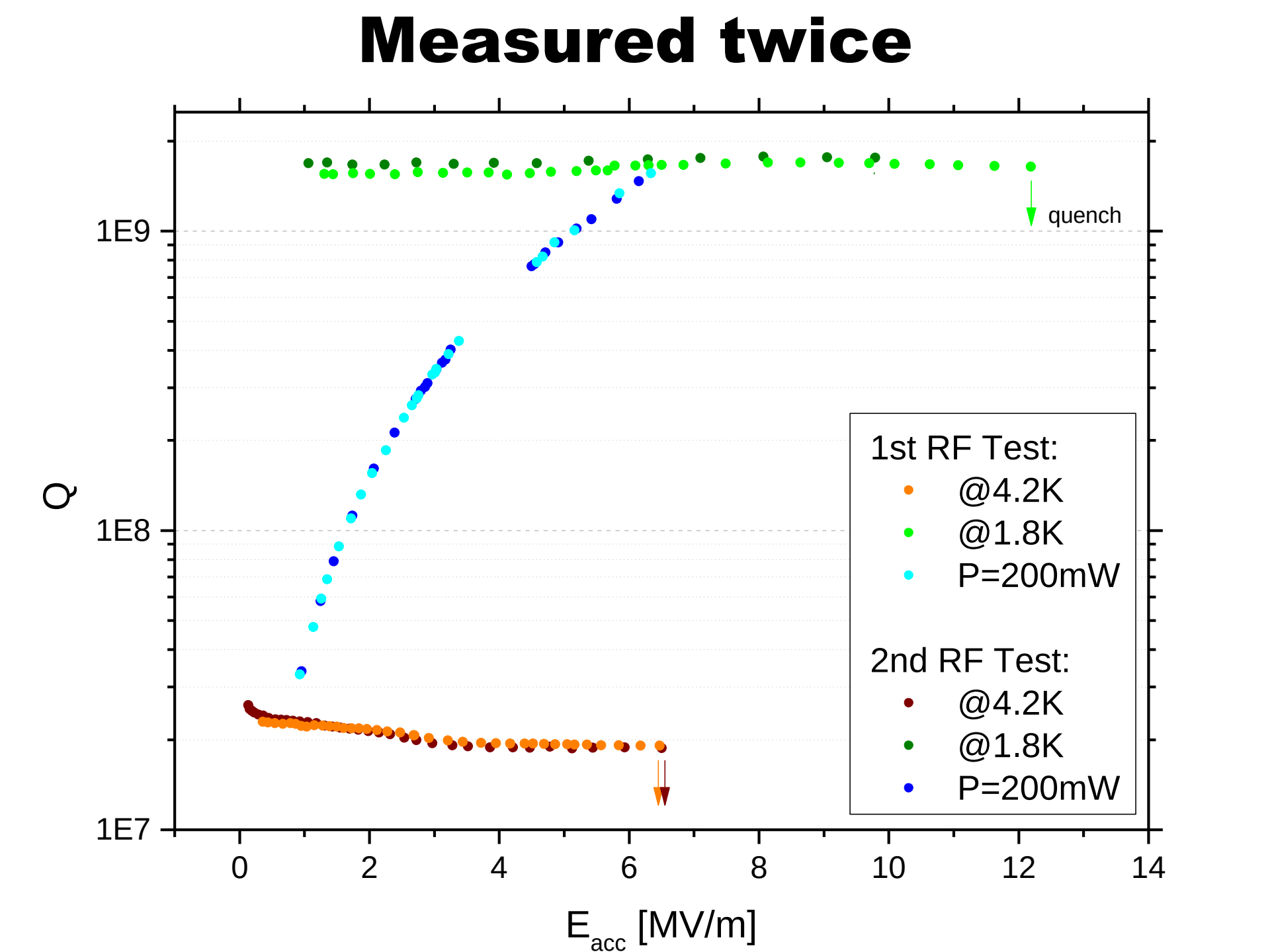
1.8 K is very close to T_λ ,

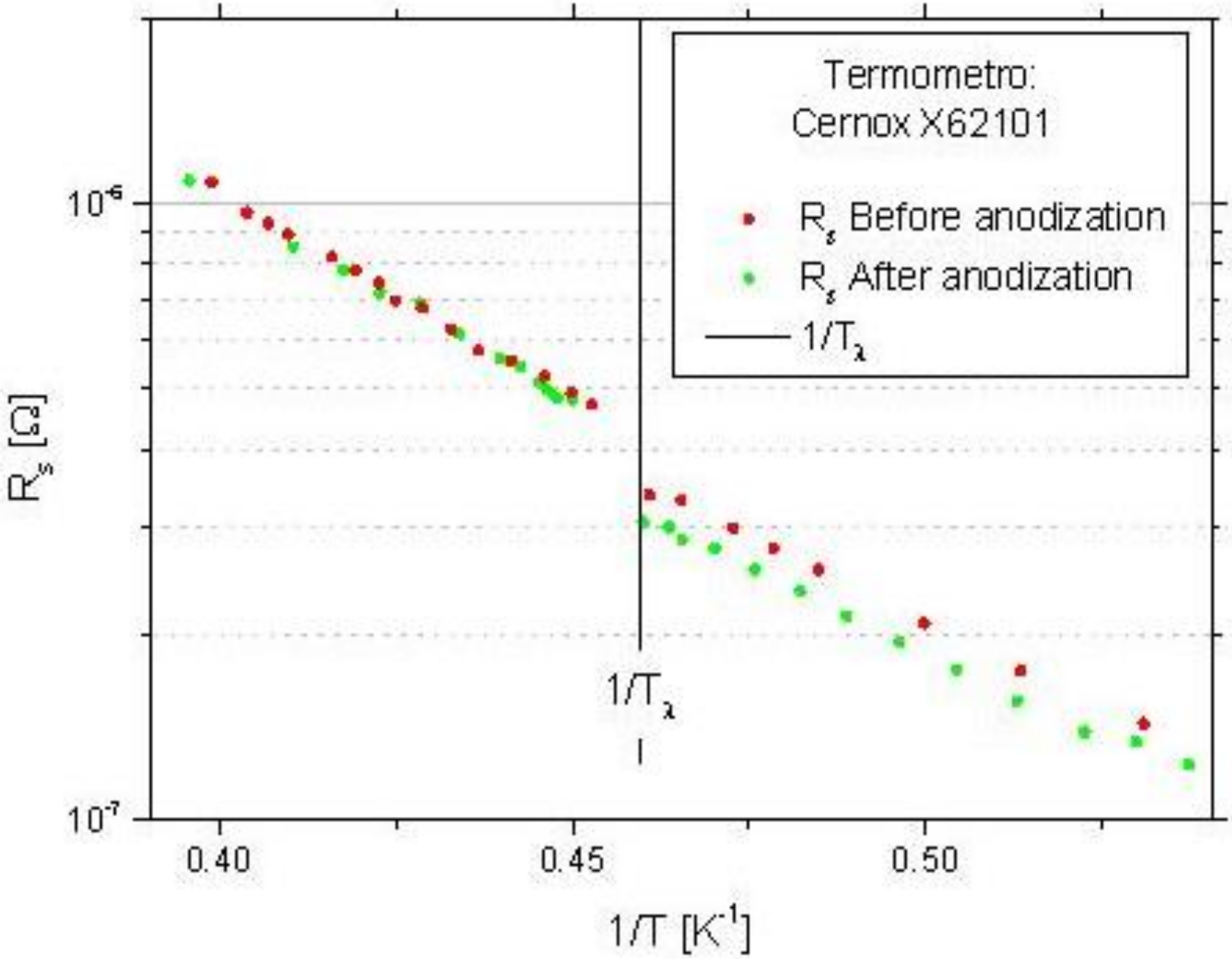
so at 1.8K ρ_n is ~34% !

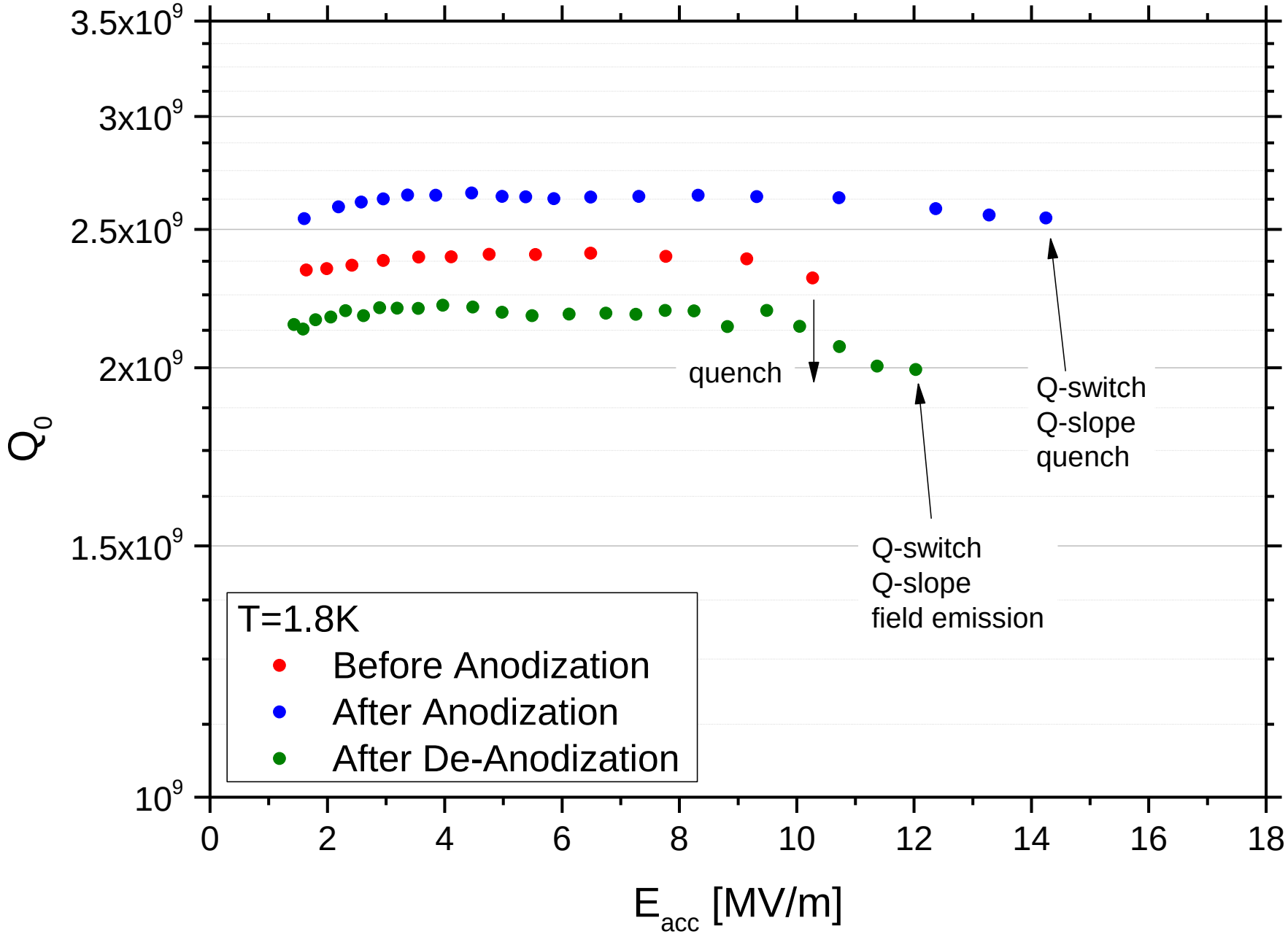


$$\rho = \rho_s + \rho_n$$

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

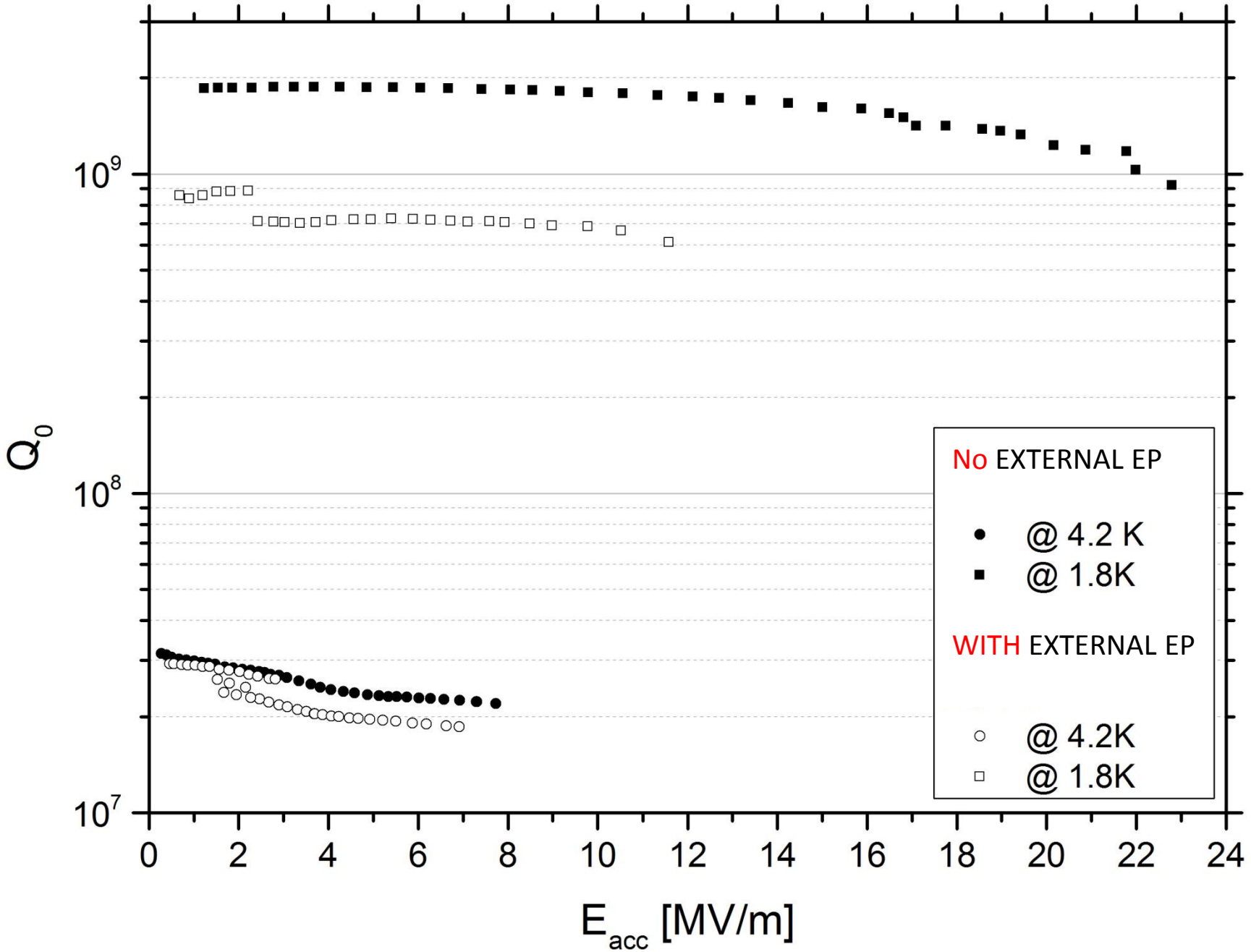

Measured twice
1E9
1E8
1E7
Q
0
2
4
6
8
10
12
14
E_acc [MV/m]
quench
1st RF Test:
@4.2K
@1.8K
P=200mW
2nd RF Test:
@4.2K
@1.8K
P=200mW


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

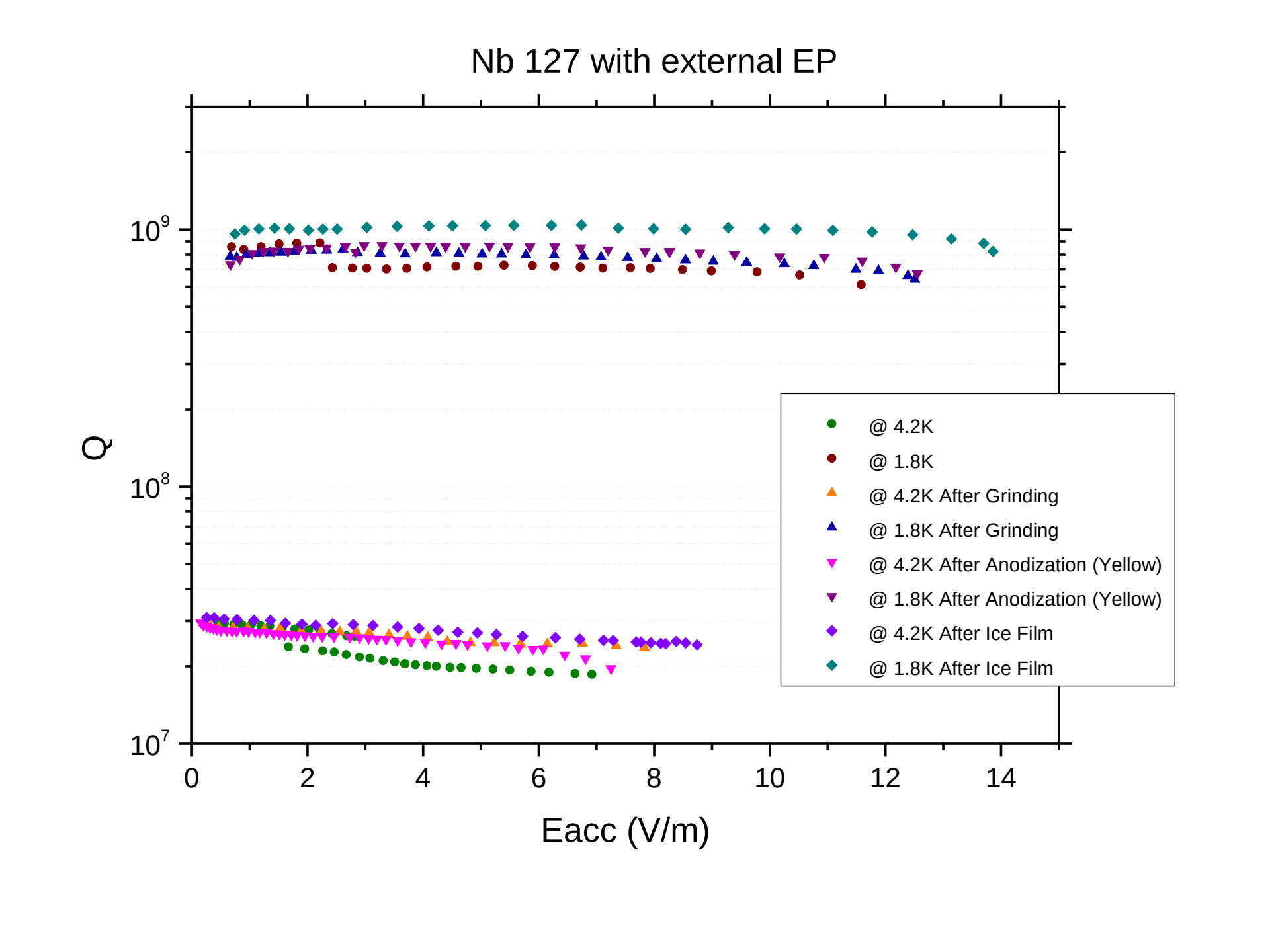
Why the anodization is responsible of the Q increase?

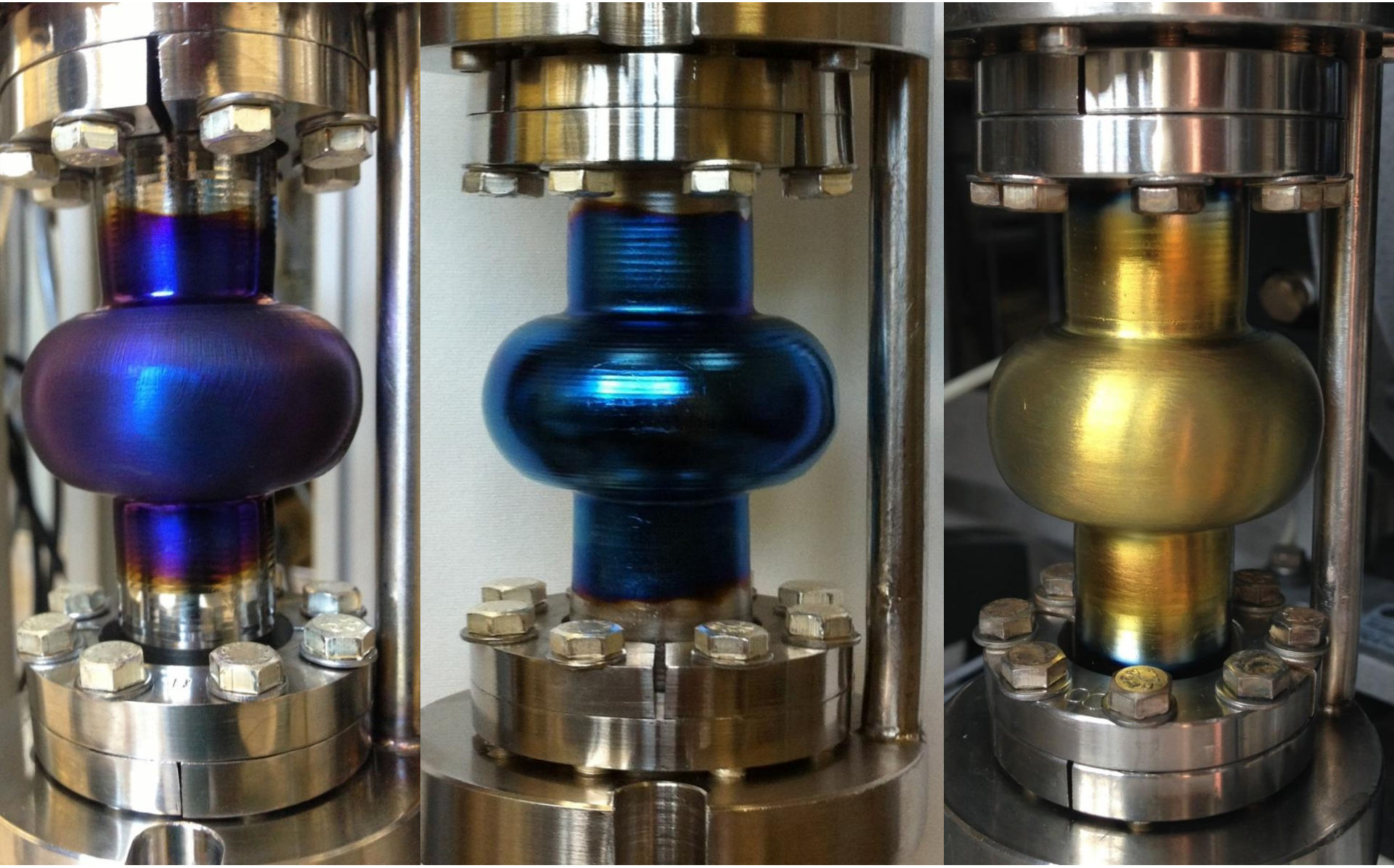
- **because of the lower θ_D ?**
- **because of the boiling nucleation on the external surface ?**
- **because the oxide does not reflect thermal phonons ?**
- **because of both ?**


10^9
10^8
10^7
Q_0
0
2
4
6
8
10
12
14
16
18
20
22
24
E_{acc} [MV/m]
No EXTERNAL EP
@ 4.2 K
@ 1.8K
WITH EXTERNAL EP
@ 4.2K
@ 1.8K

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

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

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 ?