SRF2015

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Thermal Boundary Resistance at the Nb/Cu interrface

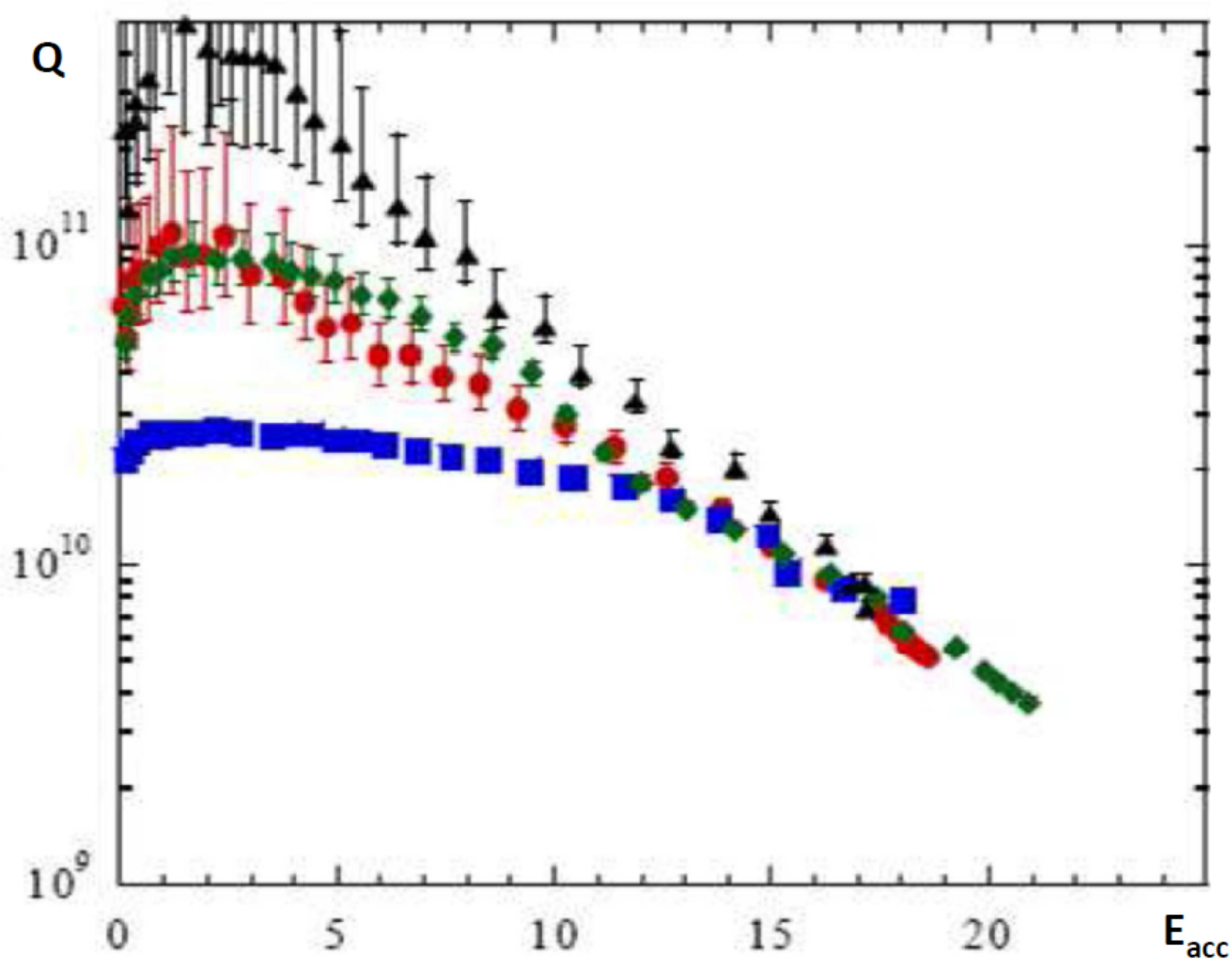
V. Palmieri[£,€], R. Vaglio[$,€]

€ ISTITUTO NAZIONALE DI FISICA NUCLEARE

£ Universita’ di Padova

$ Università di Napoli

Best result ever for Nb Sputtered Cu

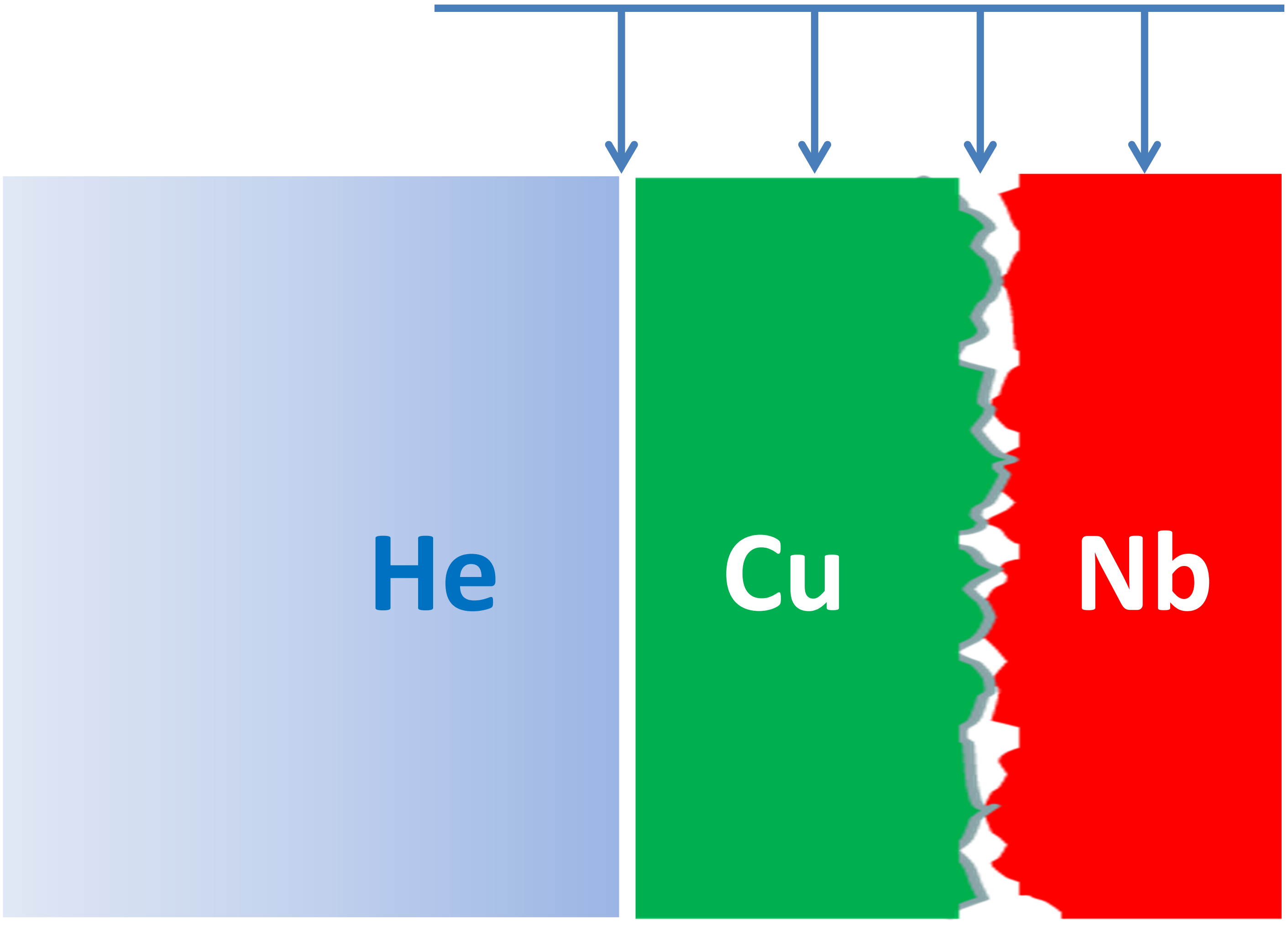


V. Abet-Engels, C. Benvenuti, S. Calatroni, P. Darriulat, M.A.Peck, A.-M. Valente, C.A. Van't Hof, ,NIM in Phys Res., p. 1-8, A463 (2001).

Aim of this talk:

To understand the Physical motivation under the Q-slope for Nb/Cu Cavities

There are only 4 possible players

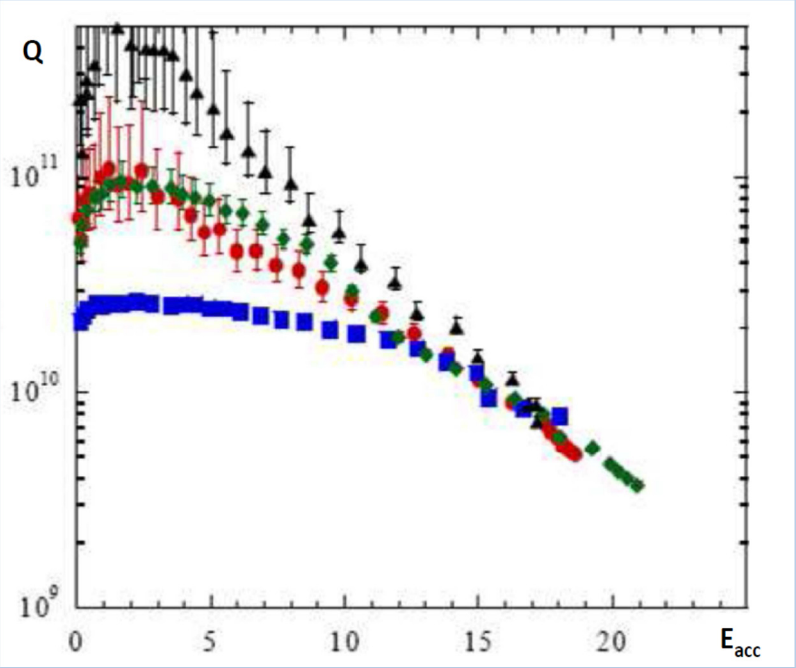


1. The Nb film

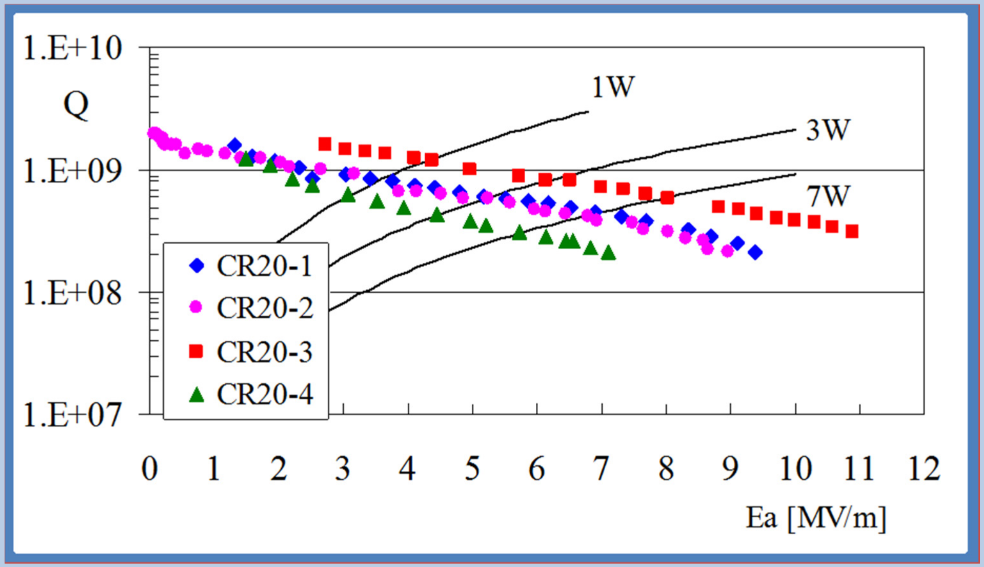
The Q-slope in sputtered cavities is always present, no matter if different sputtering techniques were adopted

1. The Nb film

Elliptical cavities



QWRs



1. The Nb film

All the attempts to improve the film quality did not provide significant benefits

1. The Nb film

At Cern,

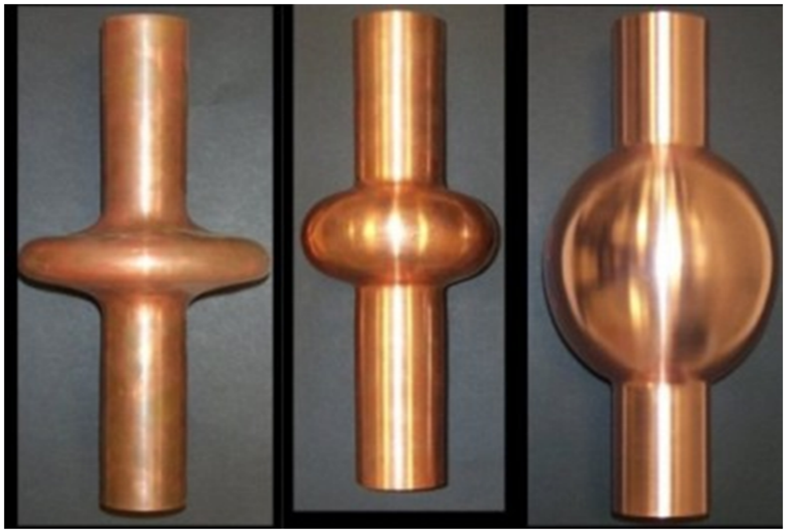
Ne, Ar, Kr, Xe and their mixtures

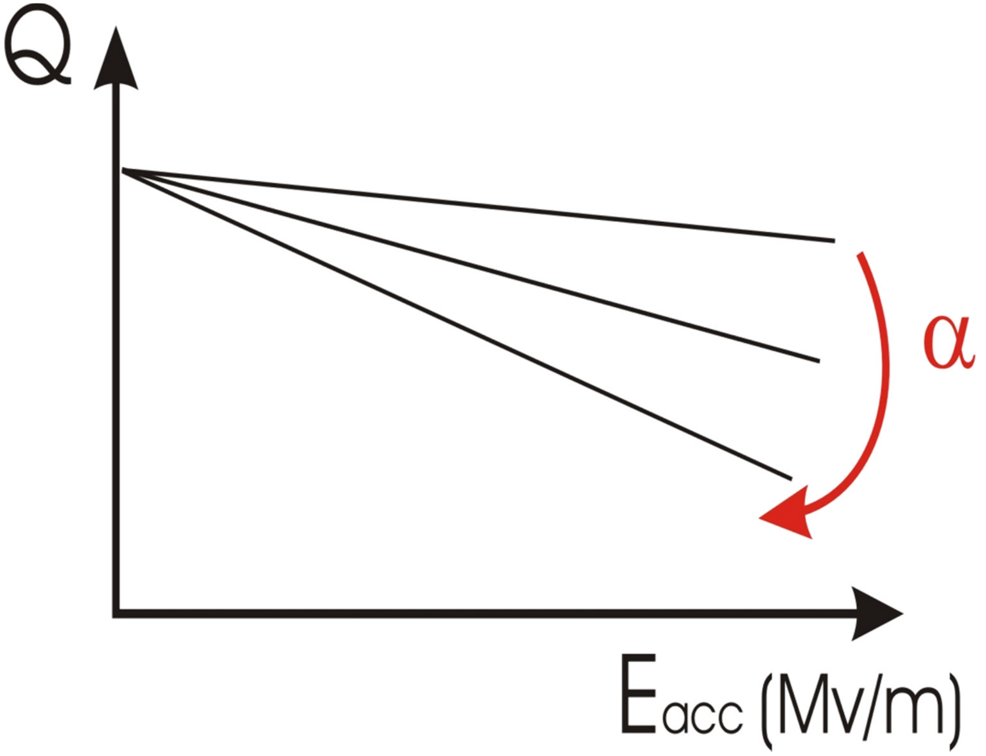
were used as sputtering gases, in order to minimize the effect of gas trapping inside the films

1. The Nb film

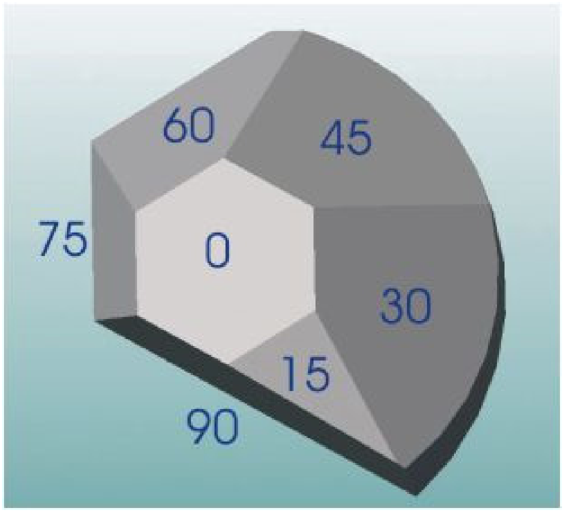
Unfortunately, **No Significant Result!**

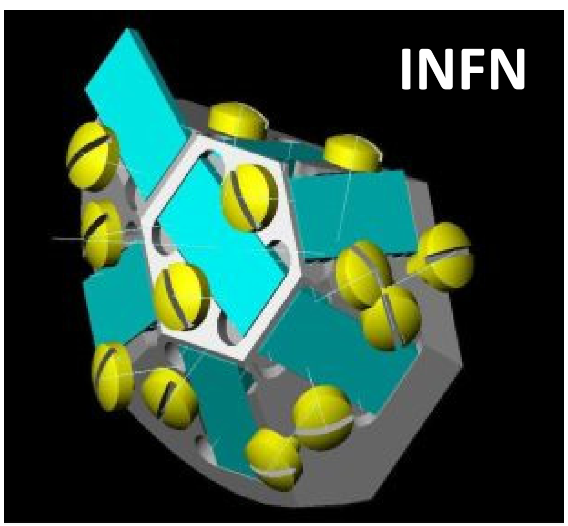
1. The Nb film

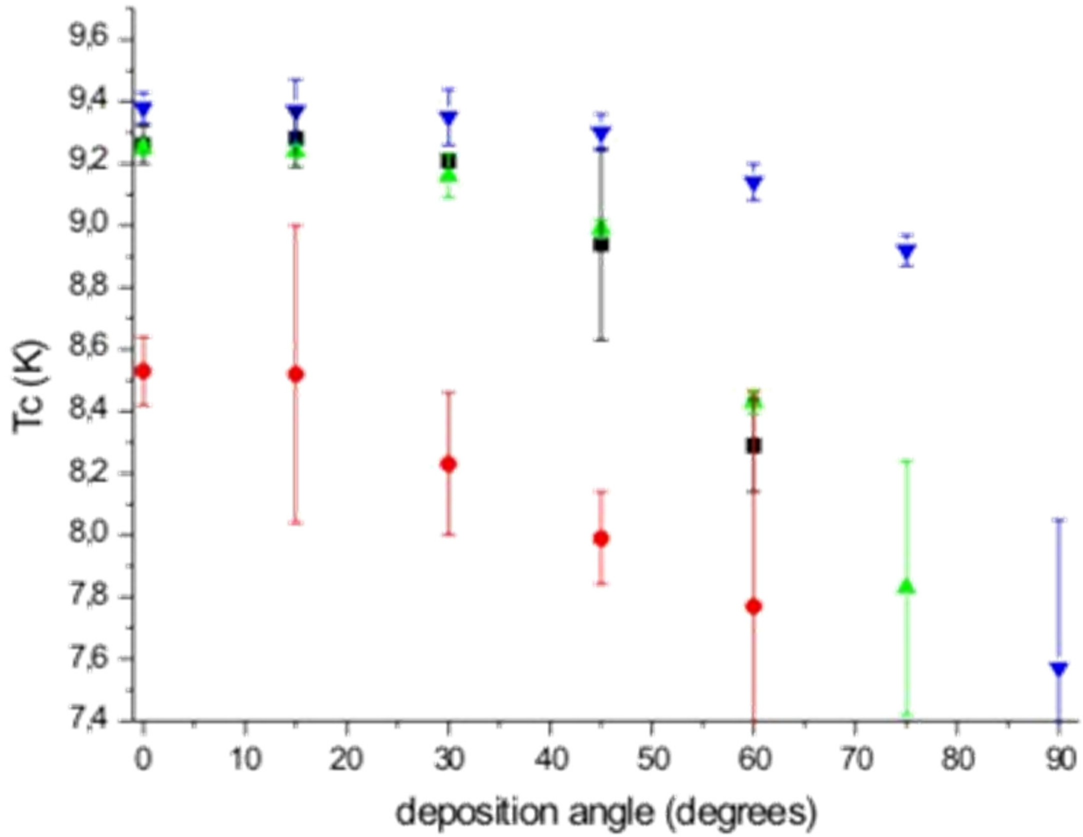




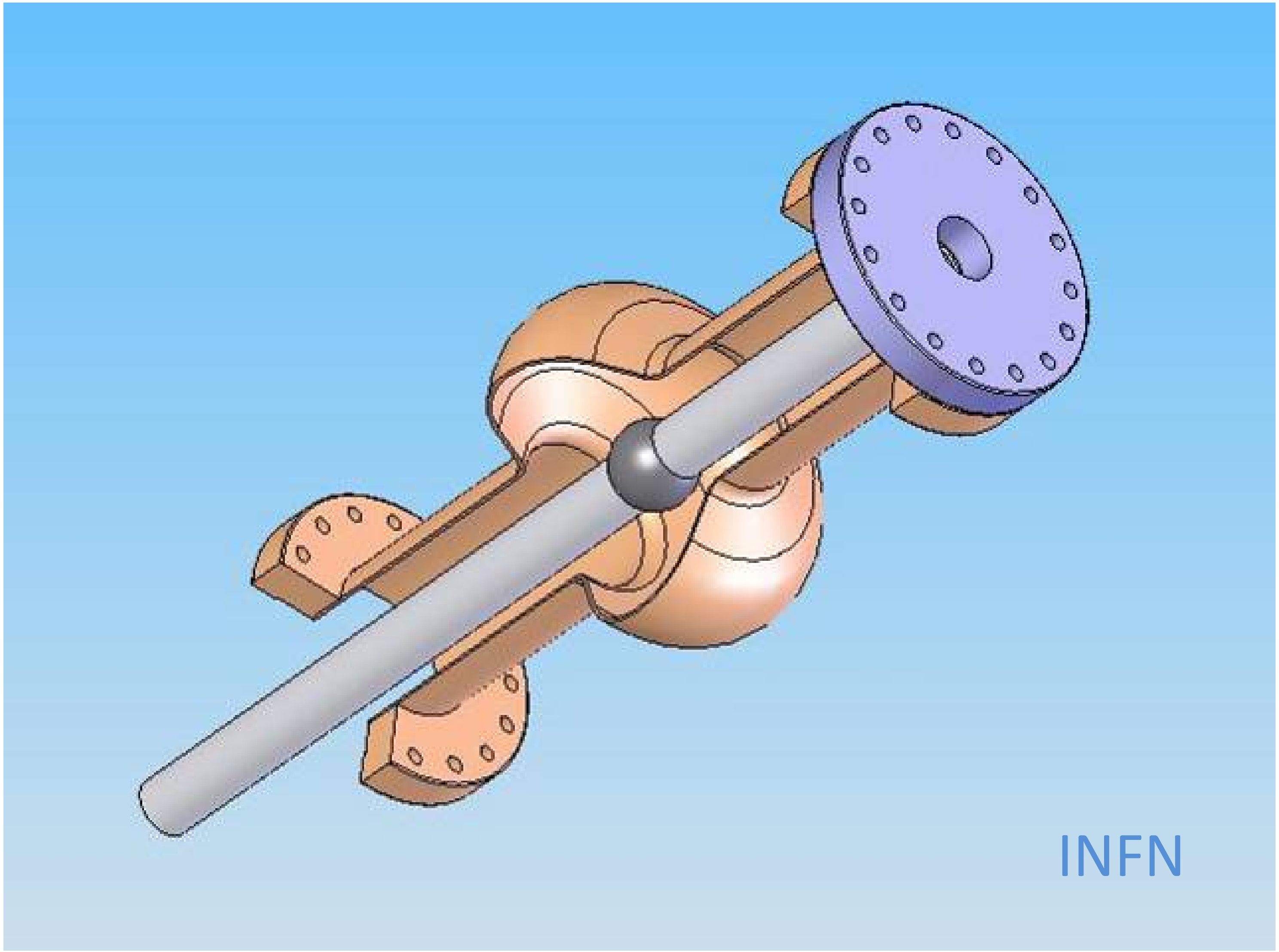
1. The Nb film


60
45
75
0
30
15
90


INFN


9,6
9,4
9,2
9,0
8,8
8,6
8,4
8,2
8,0
7,8
7,6
7,4
Tc (K)
0
10
20
30
40
50
60
70
80
90
deposition angle (degrees)

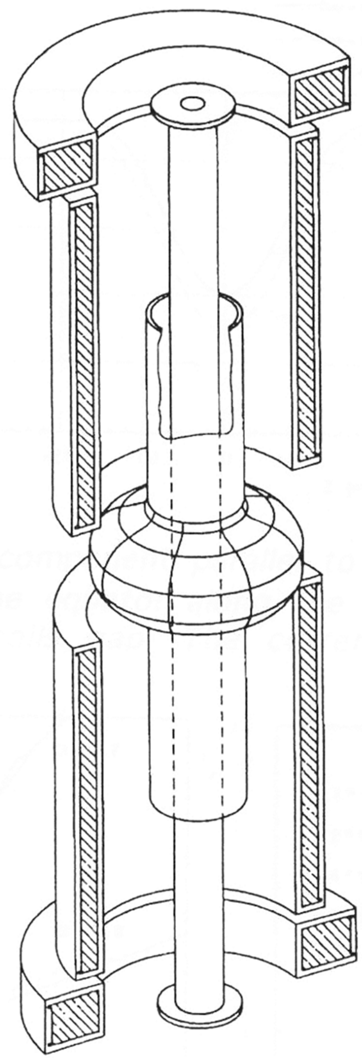
1. The Nb film



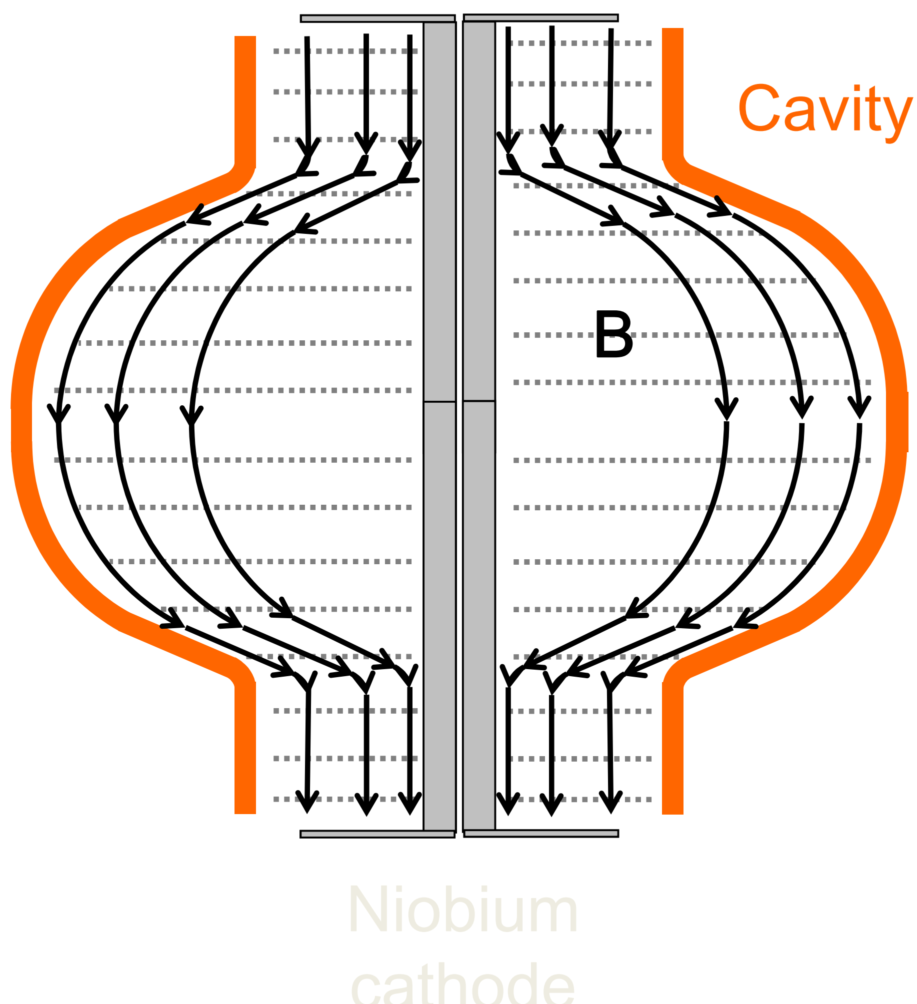
1. The Nb film

Unfortunately, **No Significant Result!**

1. The Niobium Film



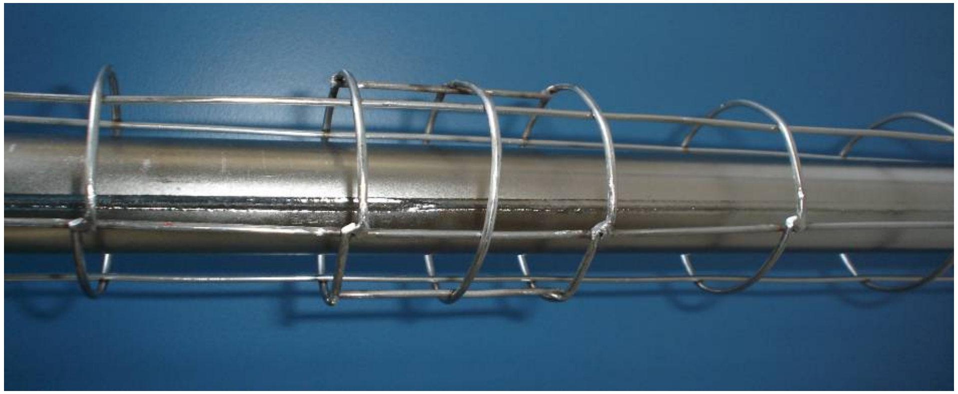
Magnetic field lines follow the cavity shape



1. The Nb film

Unfortunately, **No Significant Result!**

1. The Nb film



1. The Nb film

1. The Nb film

Unfortunately, **No Significant Result!**

1. The Nb film

$$f_i = \frac{(N_i \alpha_i - \beta)}{(N_i \alpha_i - \beta) + \mathbf{R}}$$

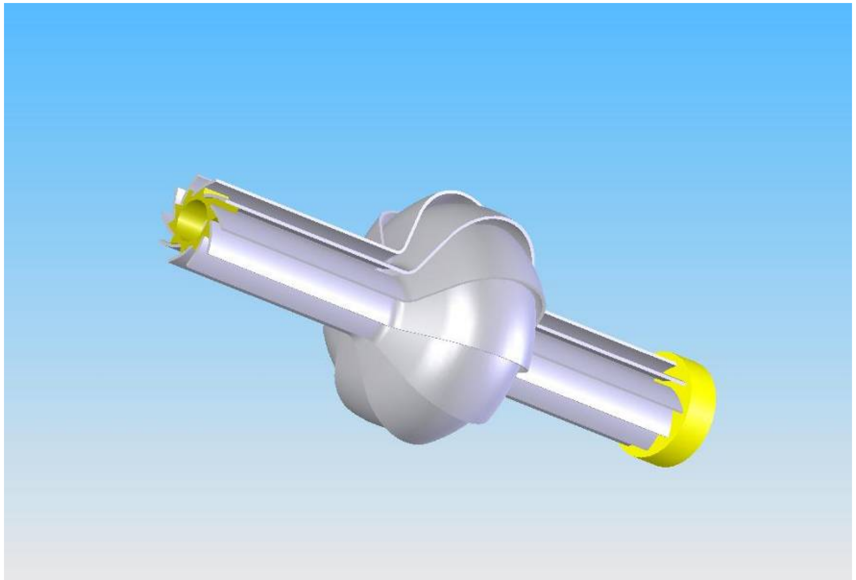
f_i = Fraction of impurities trapped into the film

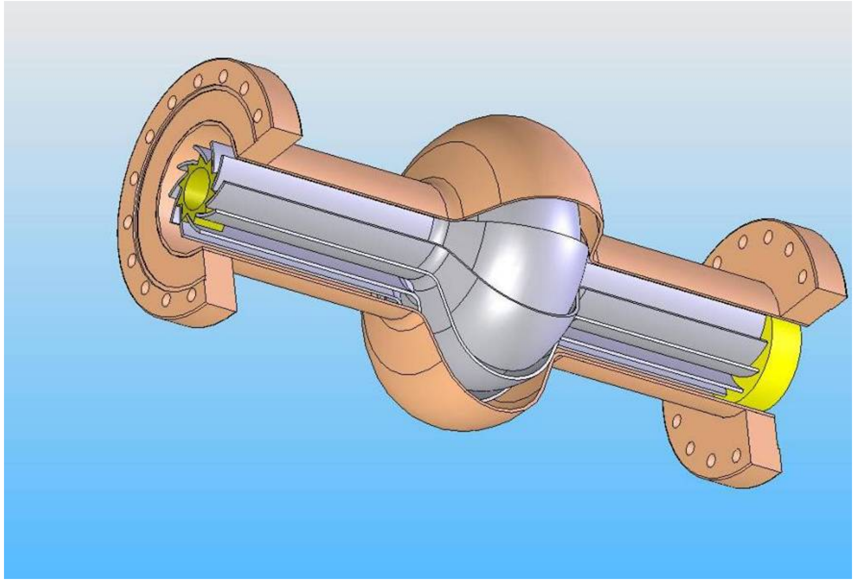
α_i = Impurities sticking coefficient

N_i = Number of atoms impurities arriving on the film surface

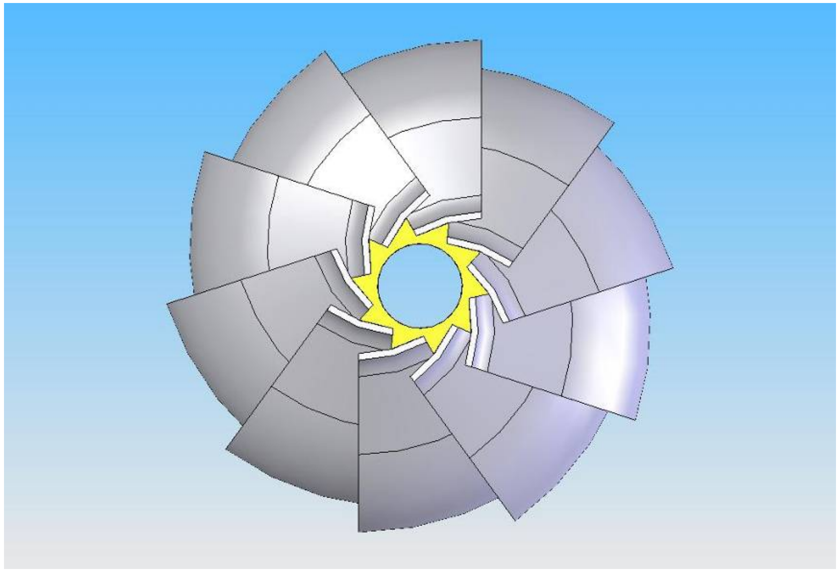
β = **function of the bias current due to impurities ions**

Bias Diode Sputtering: a cavity-shaped Cathode

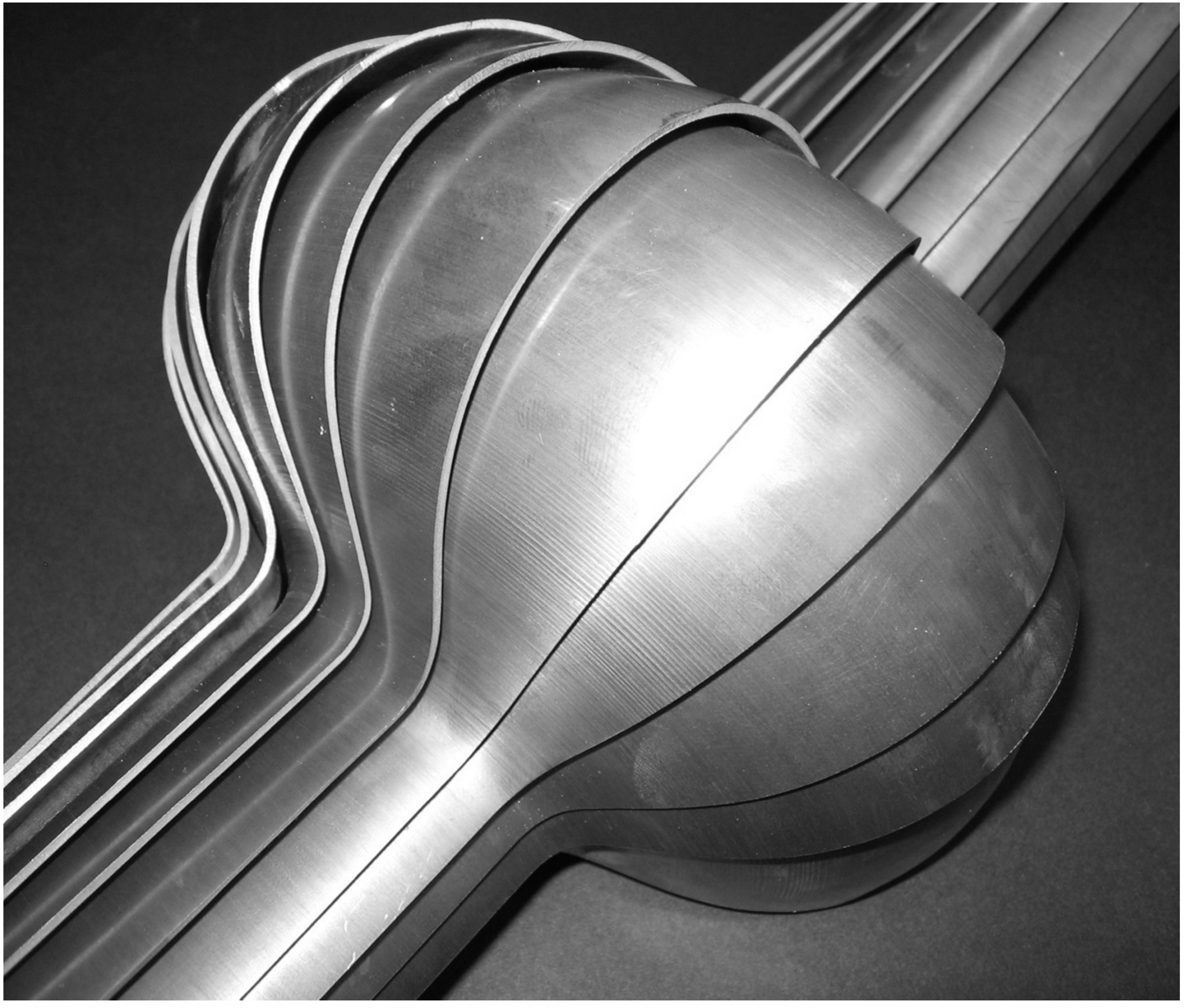




High ratio cathode/substrate area



1. The Nb film



1. The Nb film

Unfortunately, **No Significant Result!**

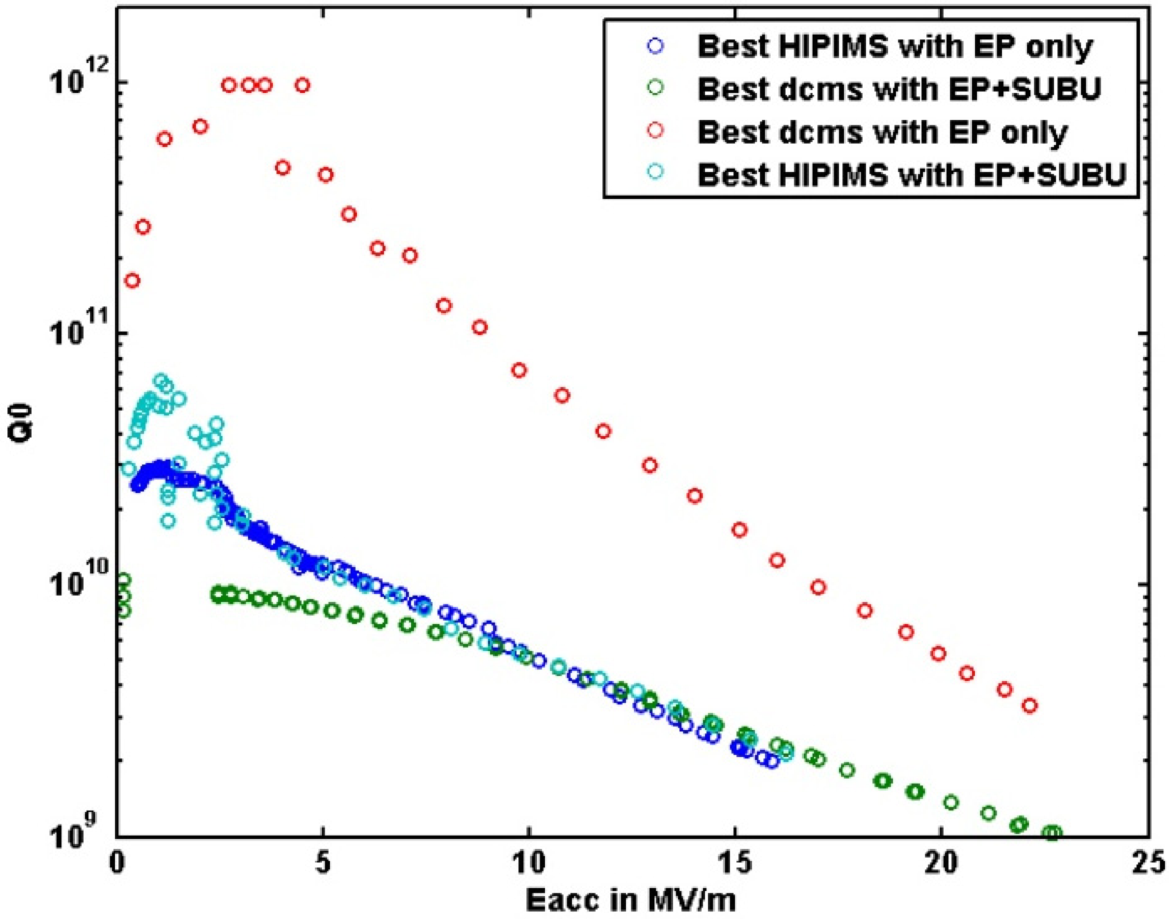
1. The Nb film

About all the Energetic Condensation Deposition techniques,

HIPIMS gave the best results

1. The Nb film

HIPIMS on 1.3 GHz Cavity - Results

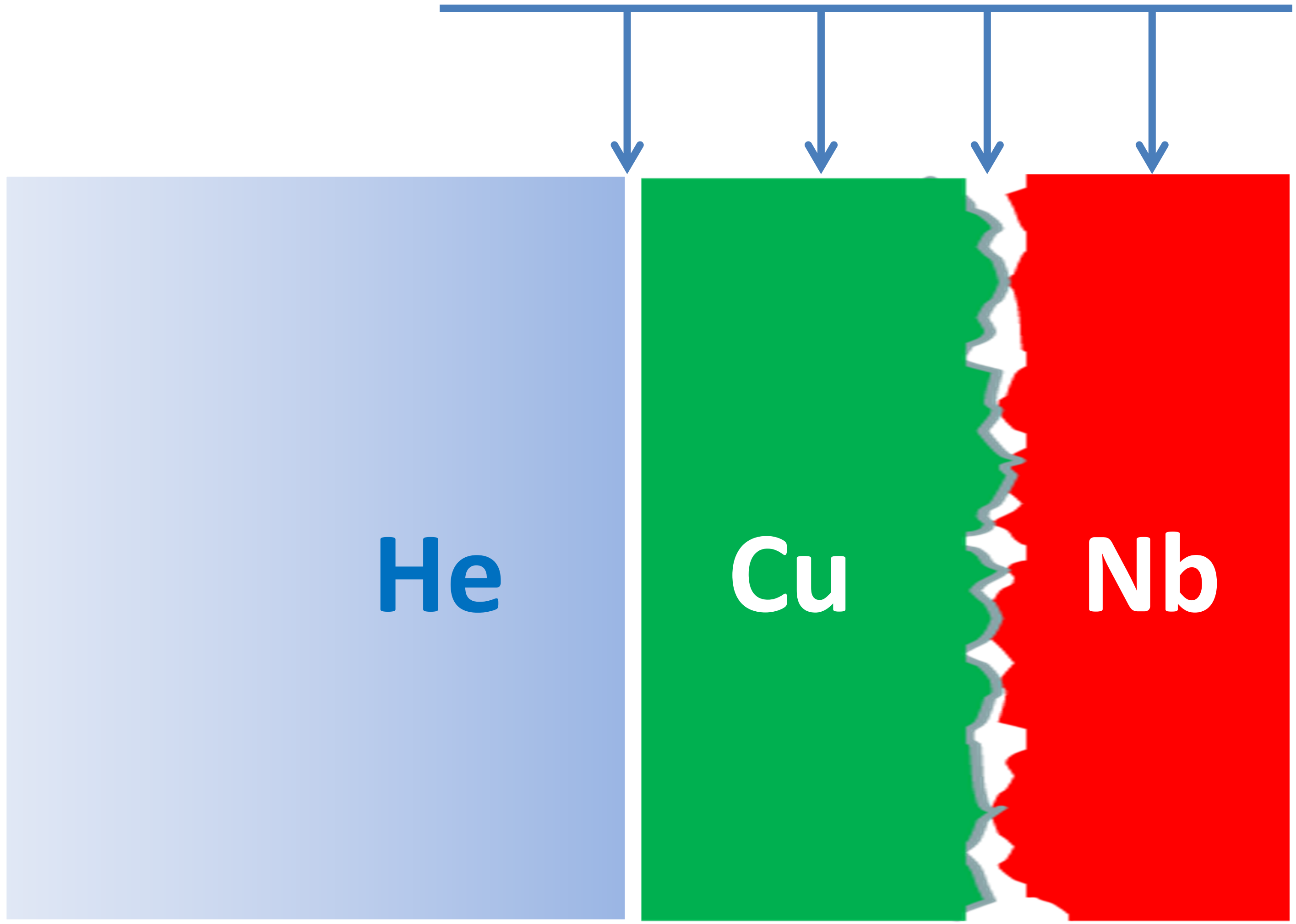


1. The Nb film

Unfortunately, No Significant Result!

(…. up to now!)

There are only 4 possible players



2. The Cu Substrate

Hydrogen or maybe Oxygen could possibly diffuse from the Cu substrate into the film

2. The Cu Substrate

Attempts at CERN to getter Hydrogen,

by depositing a Ti under-layer

between Cu and Nb

C. Benvenuti, S. Calatroni, M. Hakovirta, H. Neupert, M. Prada, A.-M. Valente, "CERN Studies On Niobium-Coated 1.5 Ghz Copper Cavities", Proc of the 10th Workshop on RF Supercond., 2001, Tsukuba, Japan

2. The Cu Substrate

Simply the Nb films behaved in all respects like standard films on Cu

2. The Cu Substrate

In order to prevent Oxygen from Cu diffusing into Nb,

The Copper substrate was sputtered onto a dummy cathode before to deposit niobium

2. The Cu Substrate

Paradoxally, Nb film cavities, an oxidized copper surface works even better than a pure copper surface

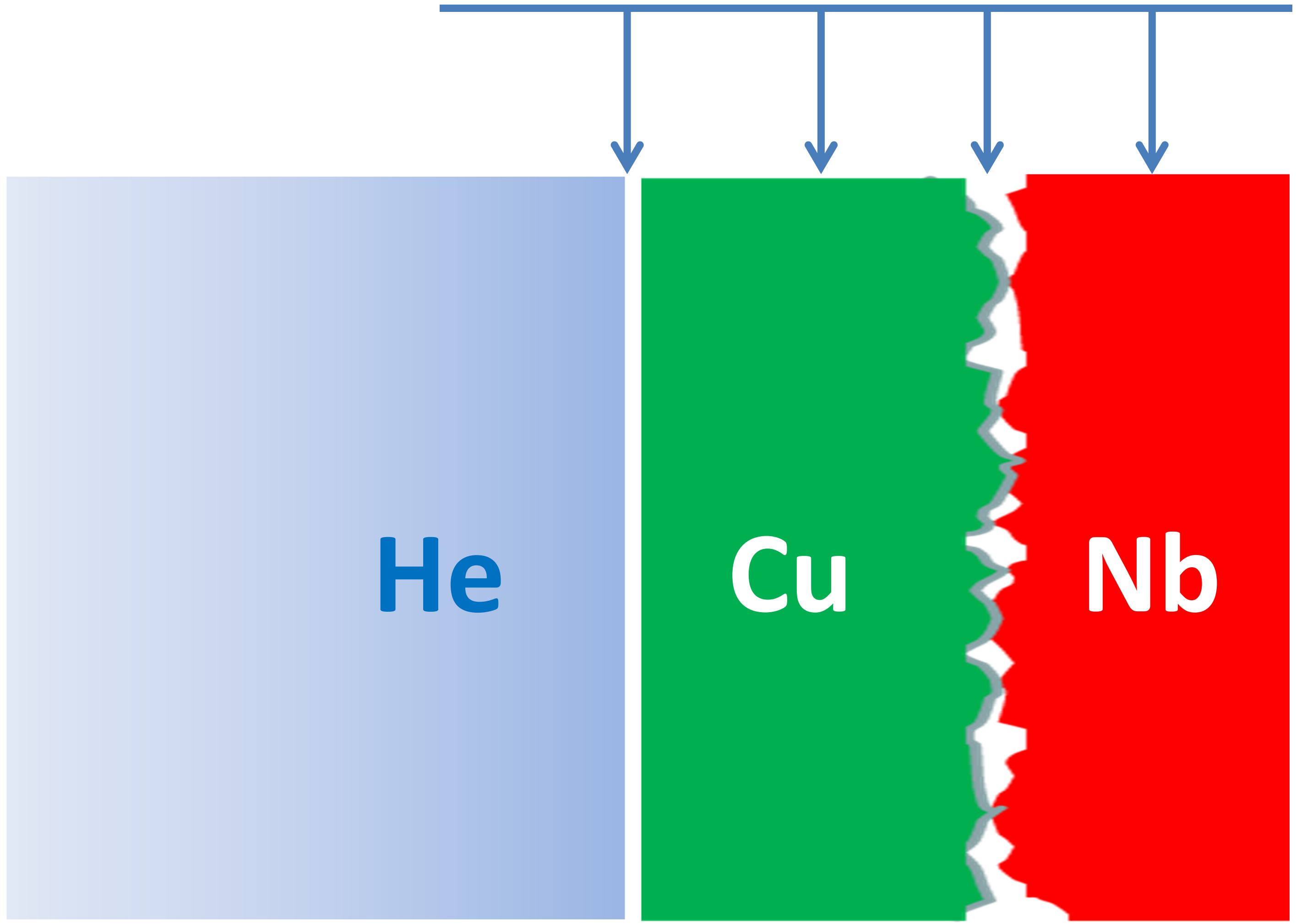
C. Benvenuti, S. Calatroni, P. Darriulat, M.A. Peck, A.-M. Valente, "Fluxon pinning in niobium films", Physica C 351, (2001) p.429-437

2. The Cu Substrate

The Q-drop was consistently larger for

Nb films grown on fully oxide-free copper

There are only 4 possible players



3. The Cu-He interface

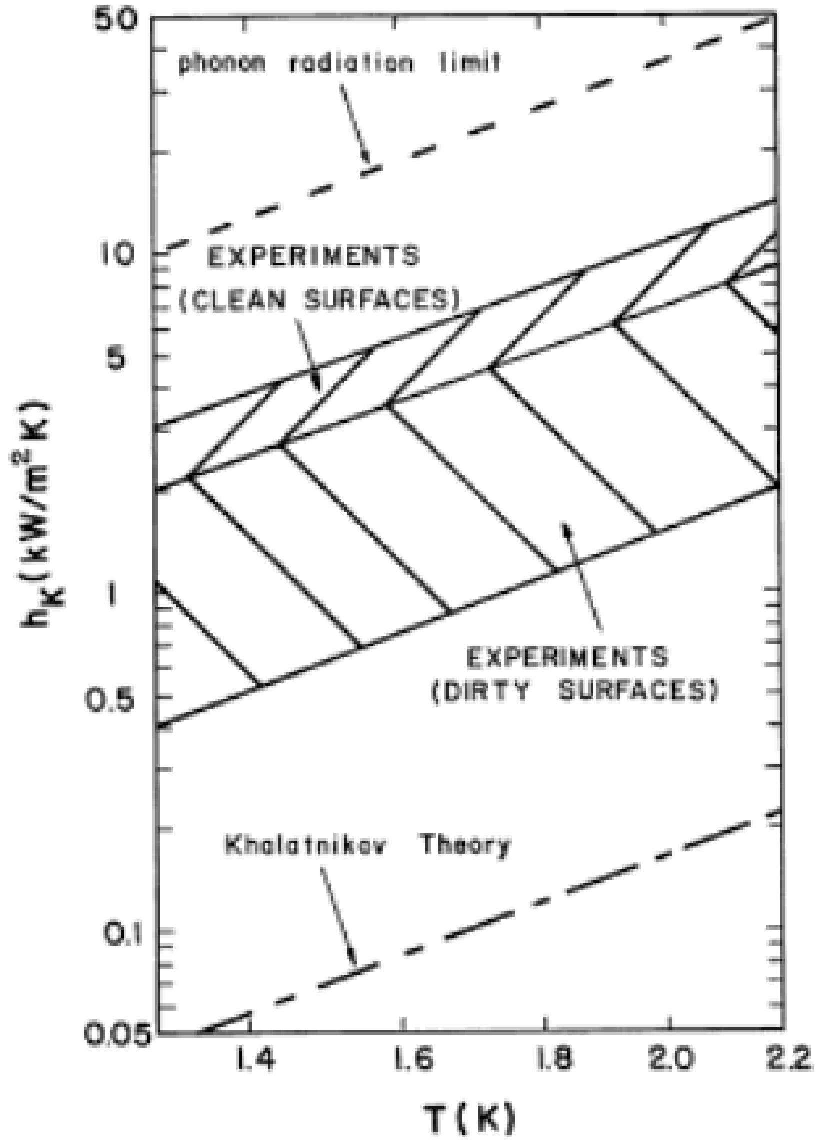


Fig. 7.36 Experimental values for the Kapitza conductance of copper between 1.3 K and T_λ (Compiled by Snyder [54])

3. The Cu-He interface

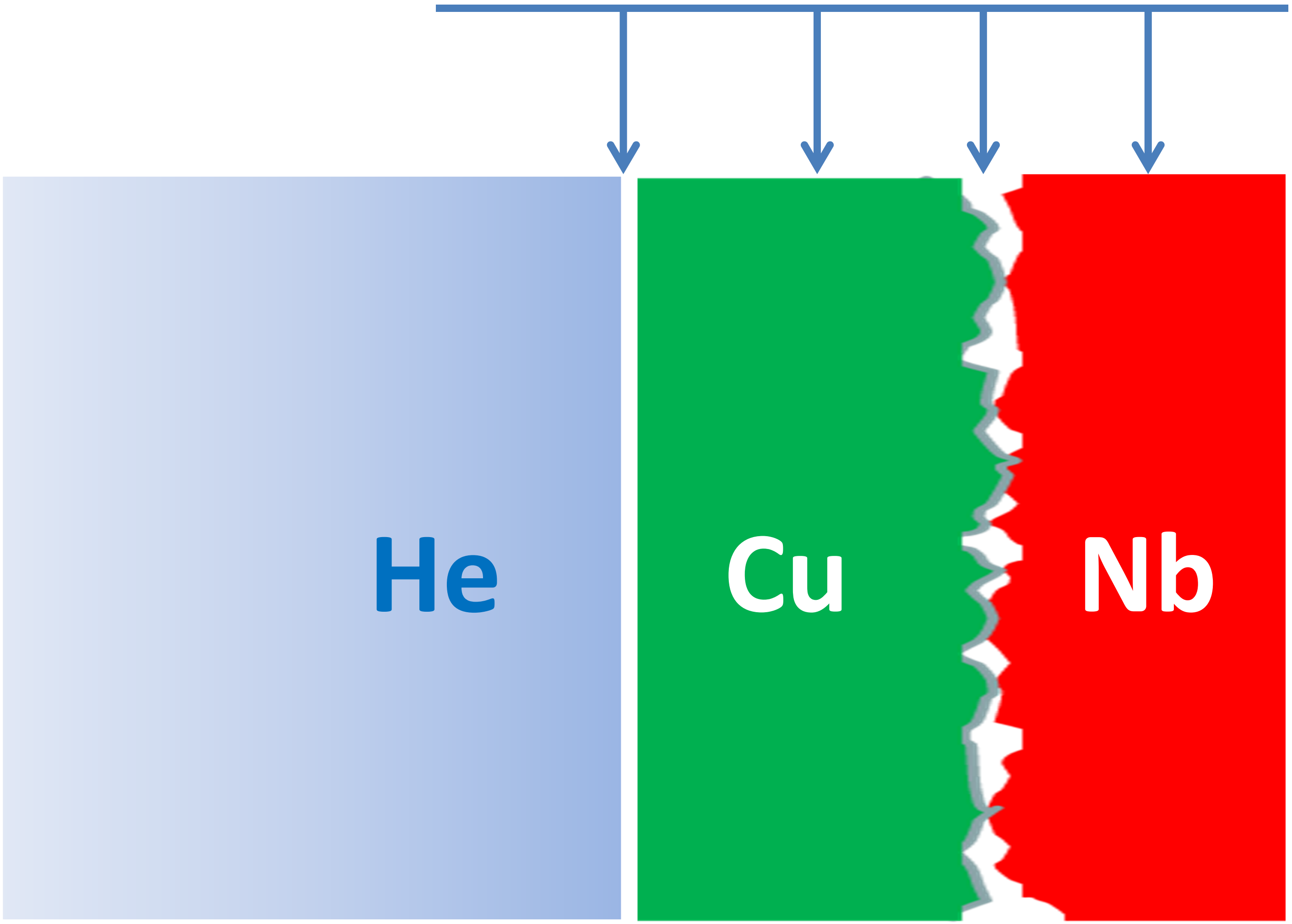
The Kapitza resistance at the Cu/HeII

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)

There are only 4 possible players



4. The Cu-Nb interface

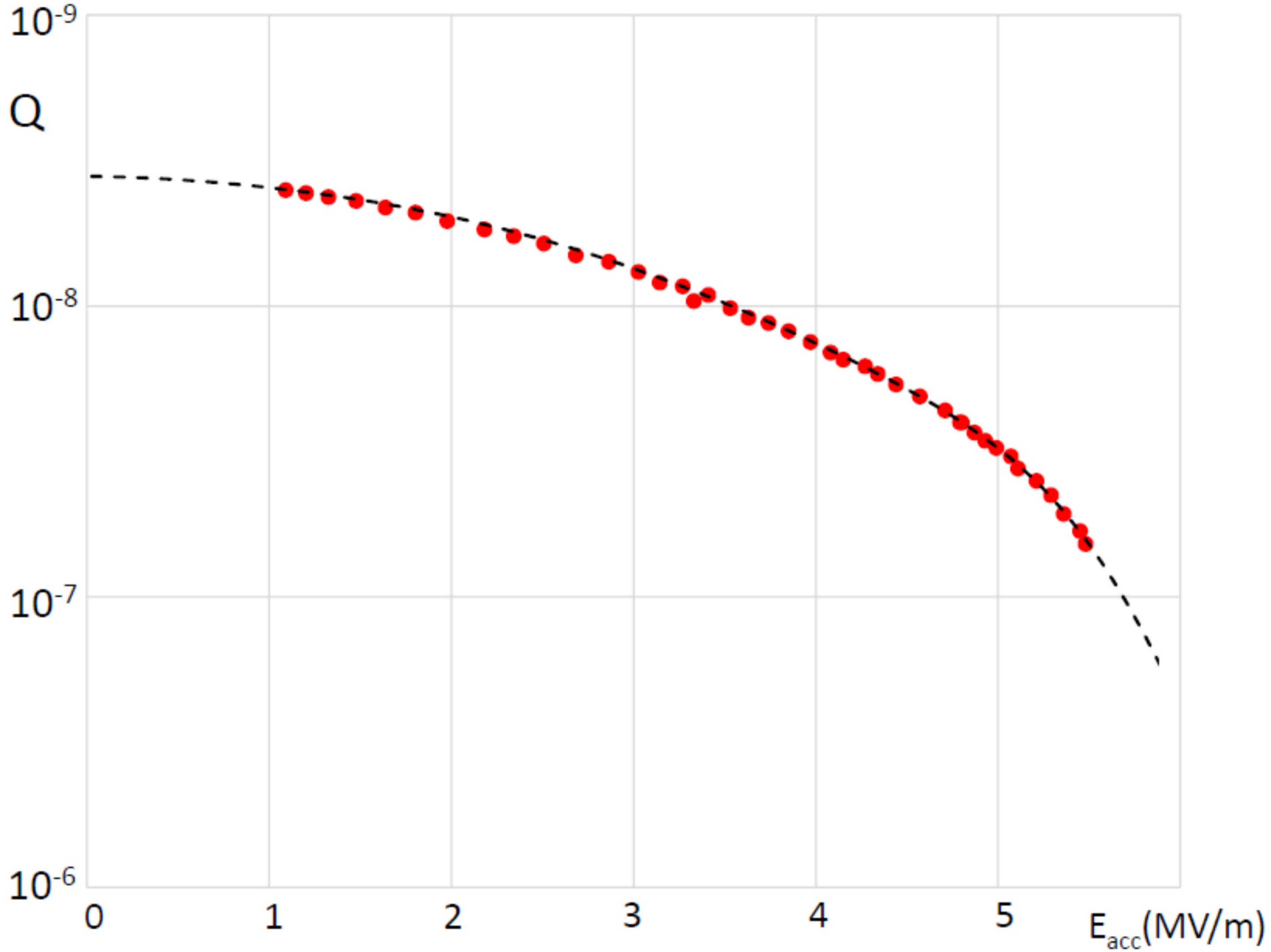
if Nb is in intimate contact with Cu

$$R_{Nb/Cu} = 1/h_k \approx 0.3 cm^2 K/W$$

much smaller than the Cu/He Kapitza value

4. The Cu-Nb interface

4. The Cu-Nb interface



A Nb clad Cu 1,3GHz cavity

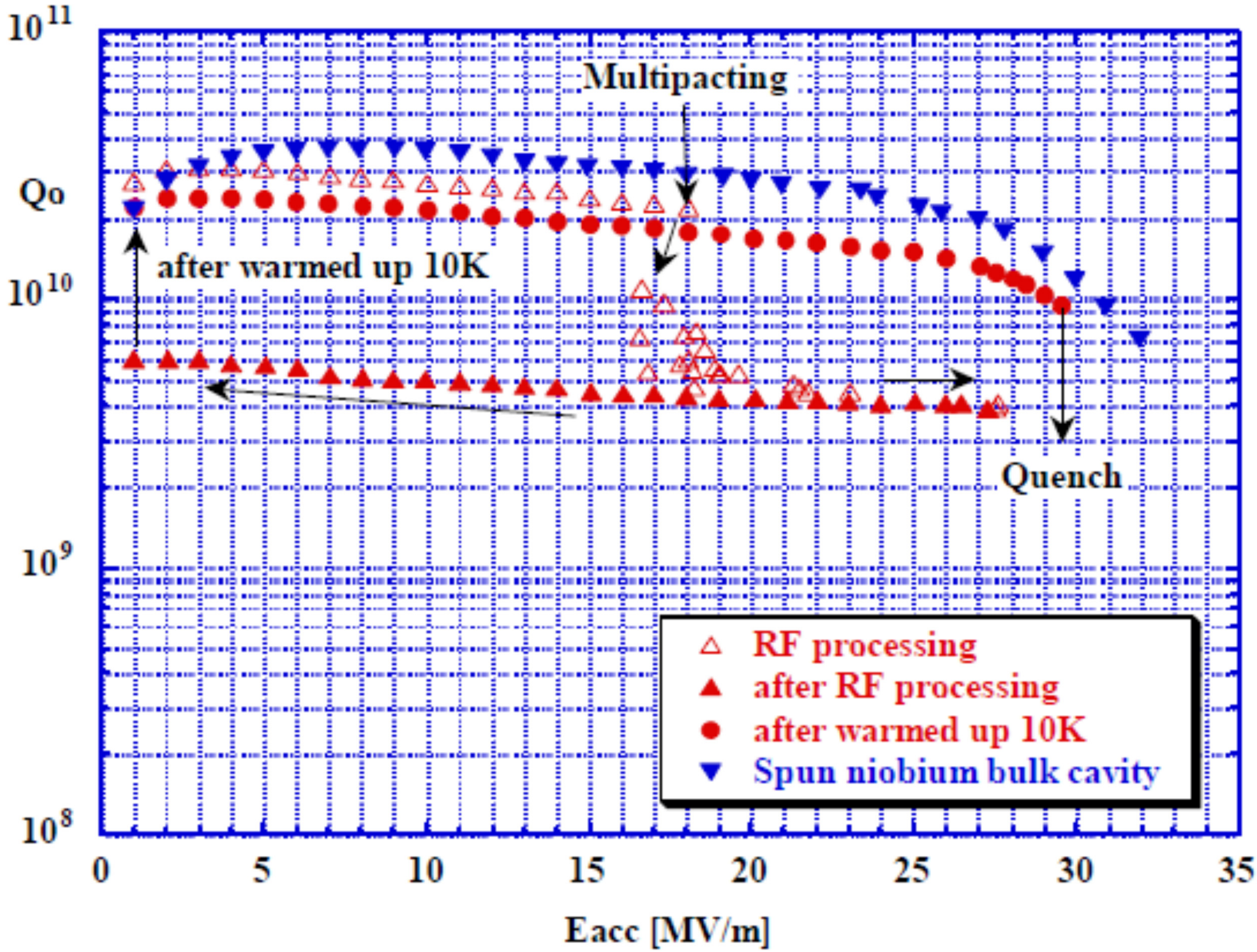


Figure 1: Result of the new Nb/Cu clad spun cavity from RRR = 200 niobium material

Why Nb clad Cu cavities work,

And Nb Sputtered Cu cavities do not?

In what they are different?

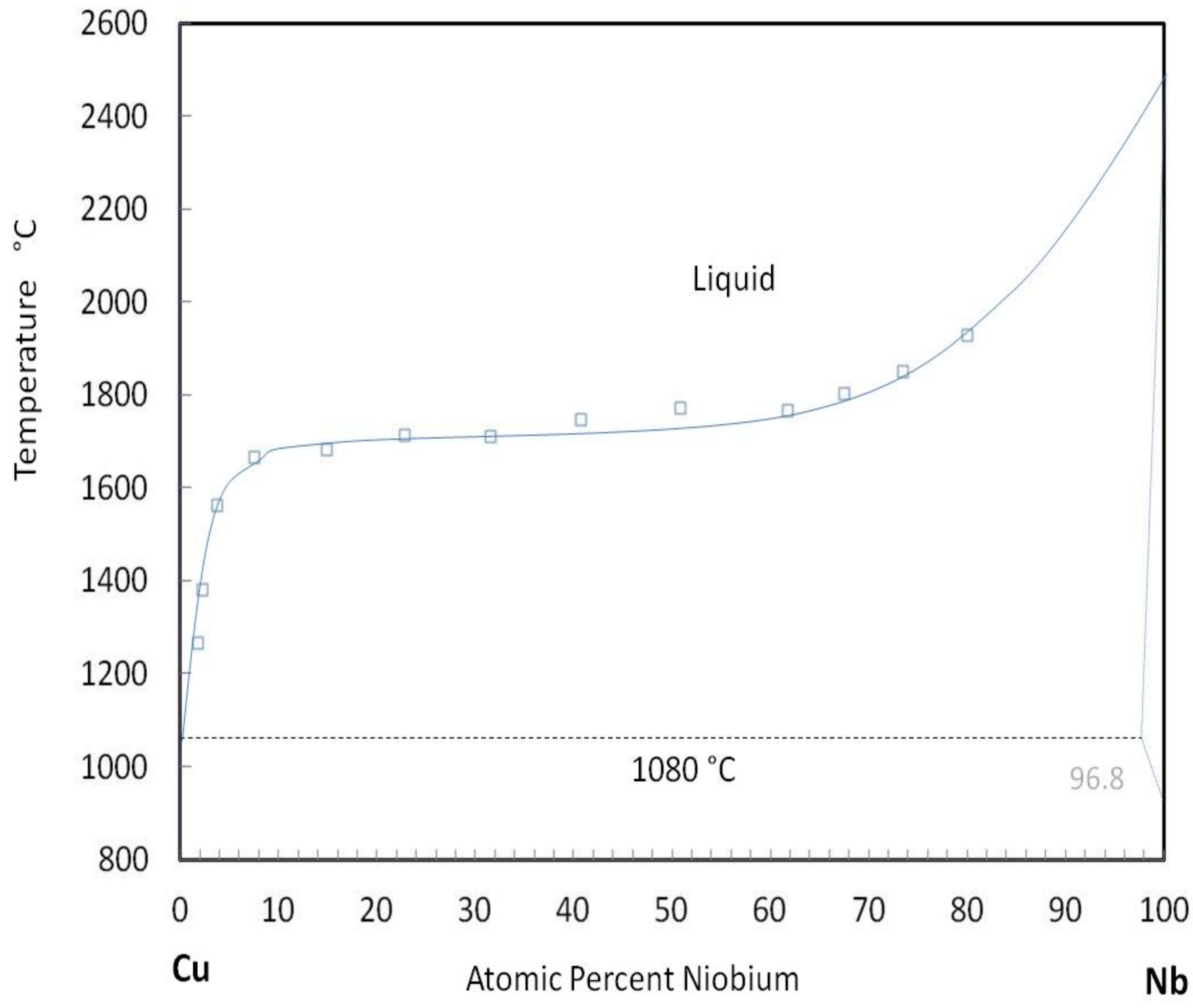
for a **hypotetical film nanoporosity**

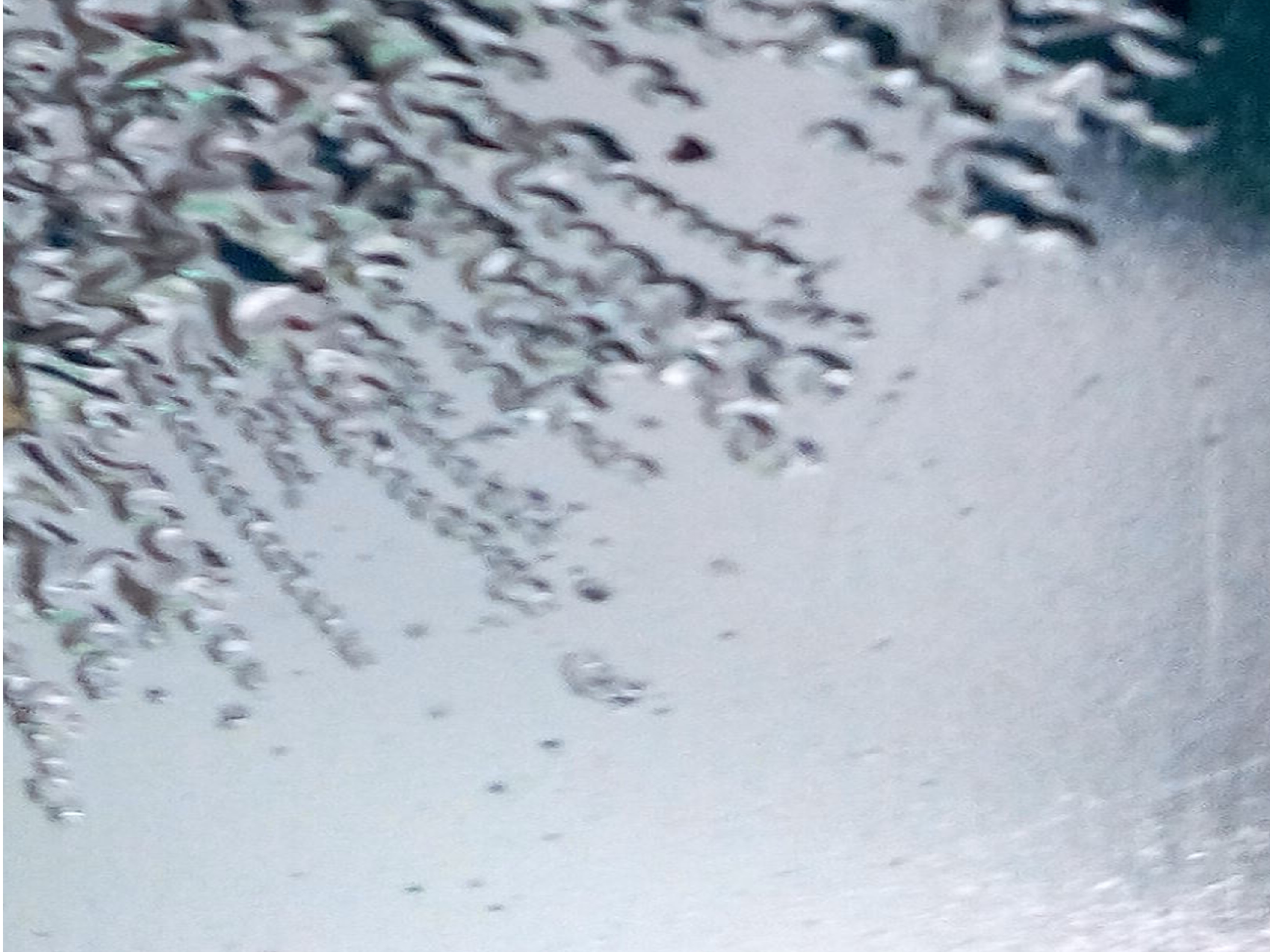
(that would inflence however Q0),

or for a more **diffused interface**?

The Cu-Nb phase diagram

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





4. 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.

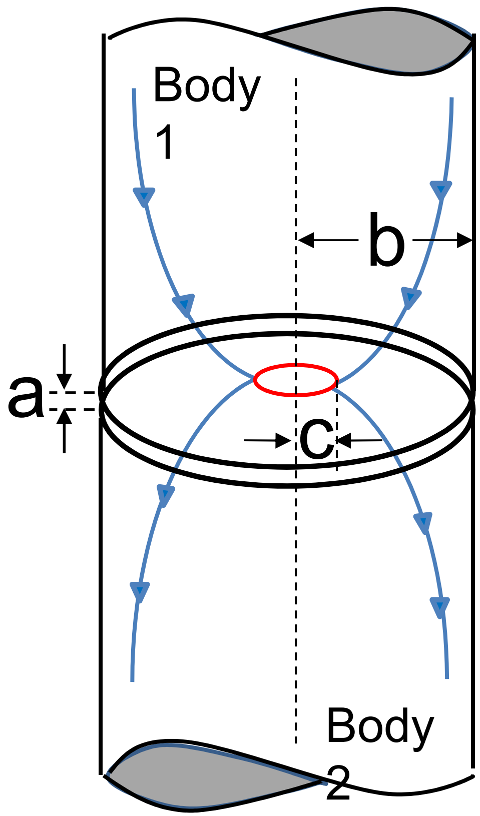
4. The Cu-Nb interface

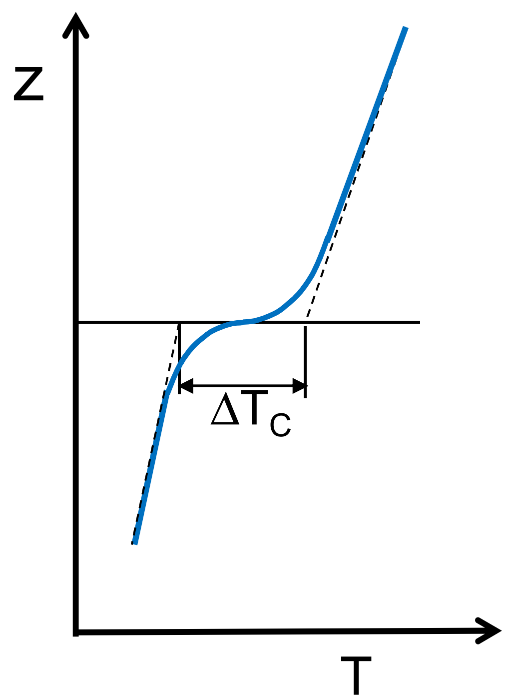
..and even arc coated cavities were not measured because of poor film adhesion

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?

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

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

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

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

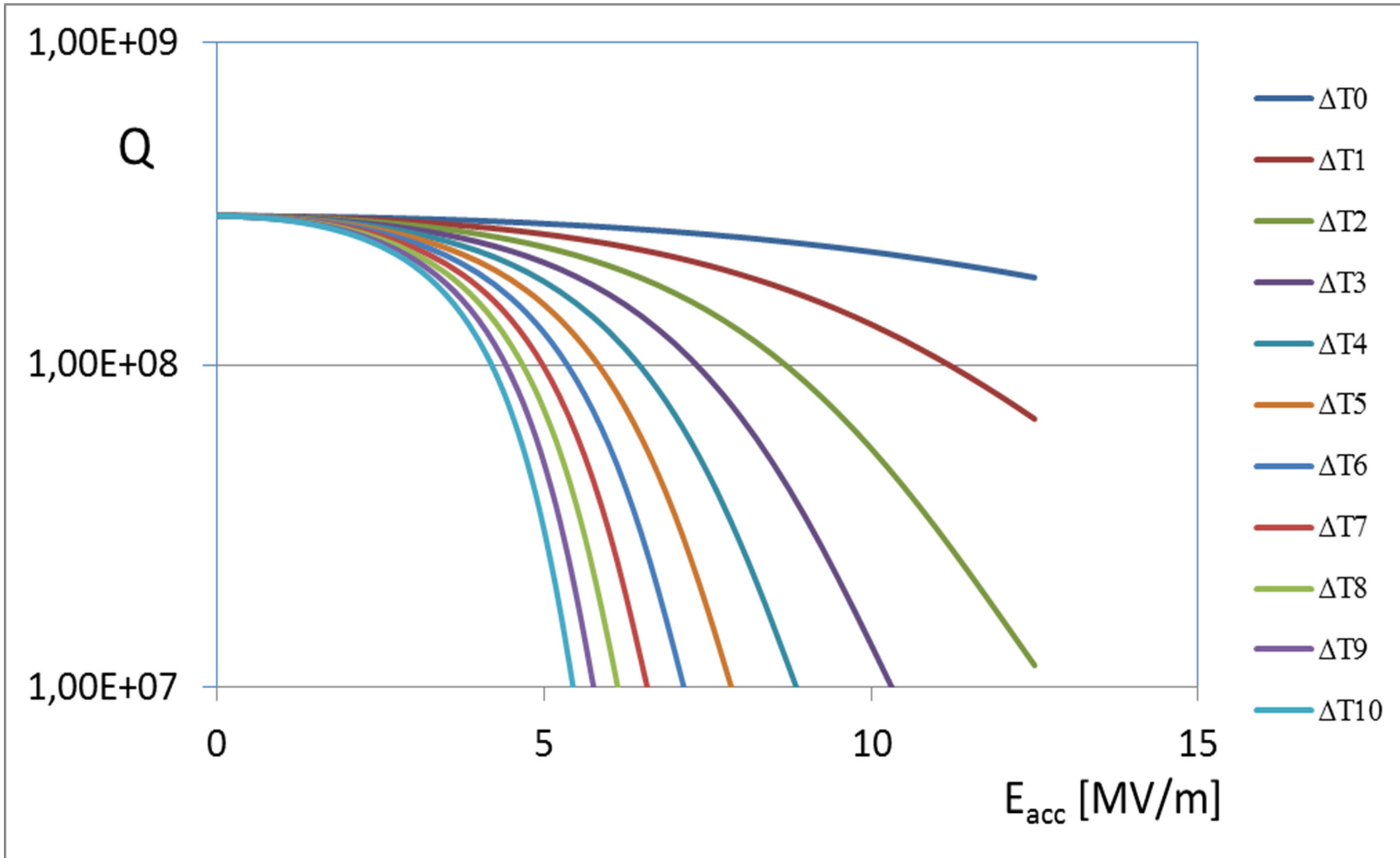
(dirty limit and $T \leq T_c/2$)

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

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

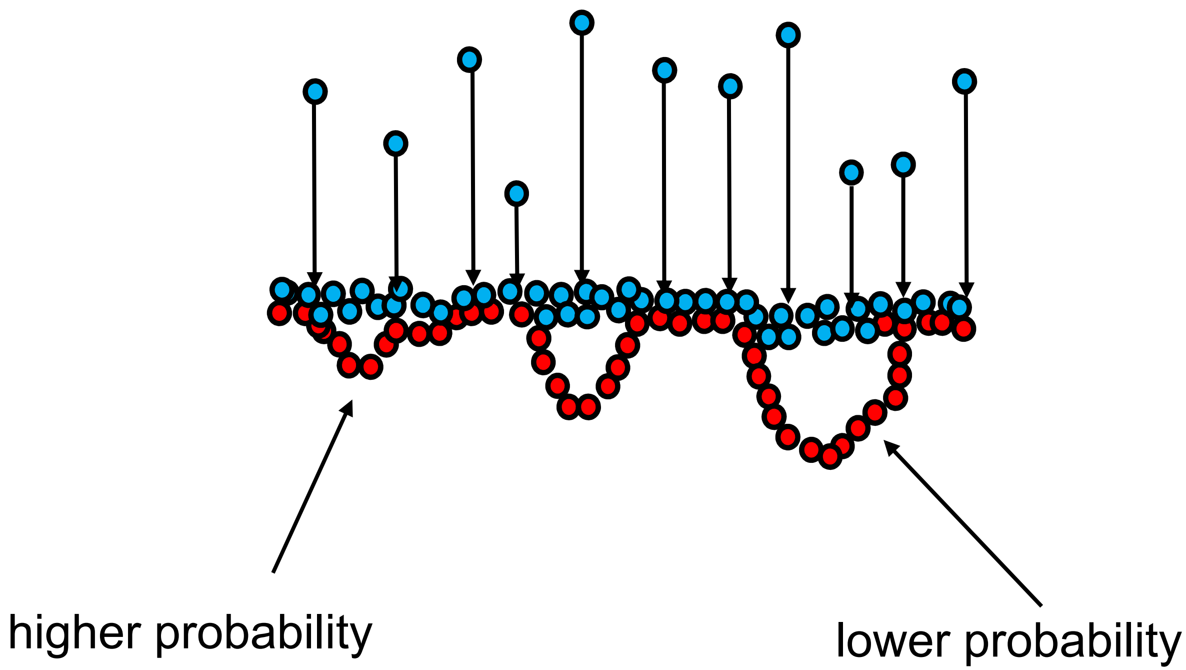
increasing the rf field we have an increase in *ΔT* that produces an increase in $R_s(T)$, producing a further increase in *ΔT*, in a kind of "thermal runaway" effect.

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



If there are weak contact points between Cu and Nb, how probable is they will be all of the same size???

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)

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

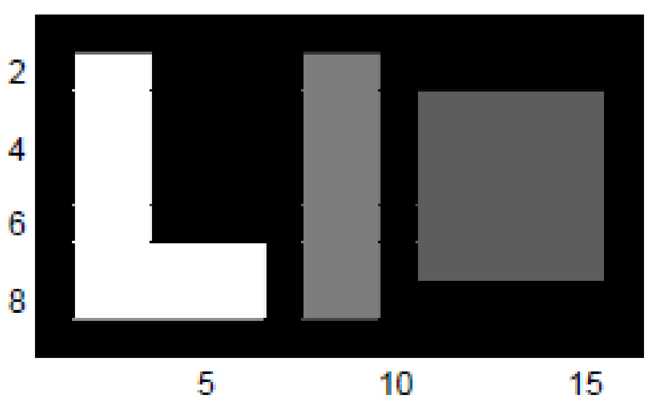
$$\overline{R_s(T_o, E_{acc})} = \int_0^\infty R_s(T_o, E_{acc}, R_B) f(R_{Nb/Cu}) dR_{Nb/Cu}$$

Inverse Problems for Image Processing and deblurring

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

Consider this 9 x 16 array

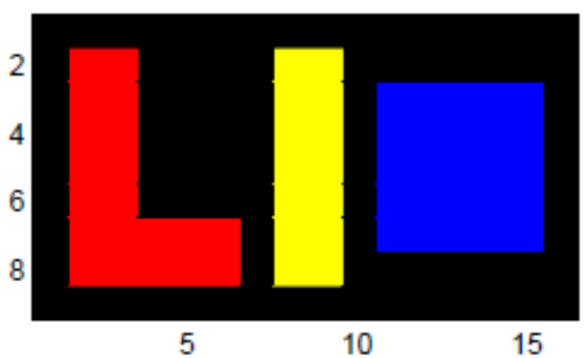
$$\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 8 & 8 & 8 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 8 & 8 & 8 & 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}.$$



8= white,
0 = black,
Intermediate values = different grey

Consider this 9 x 16 array

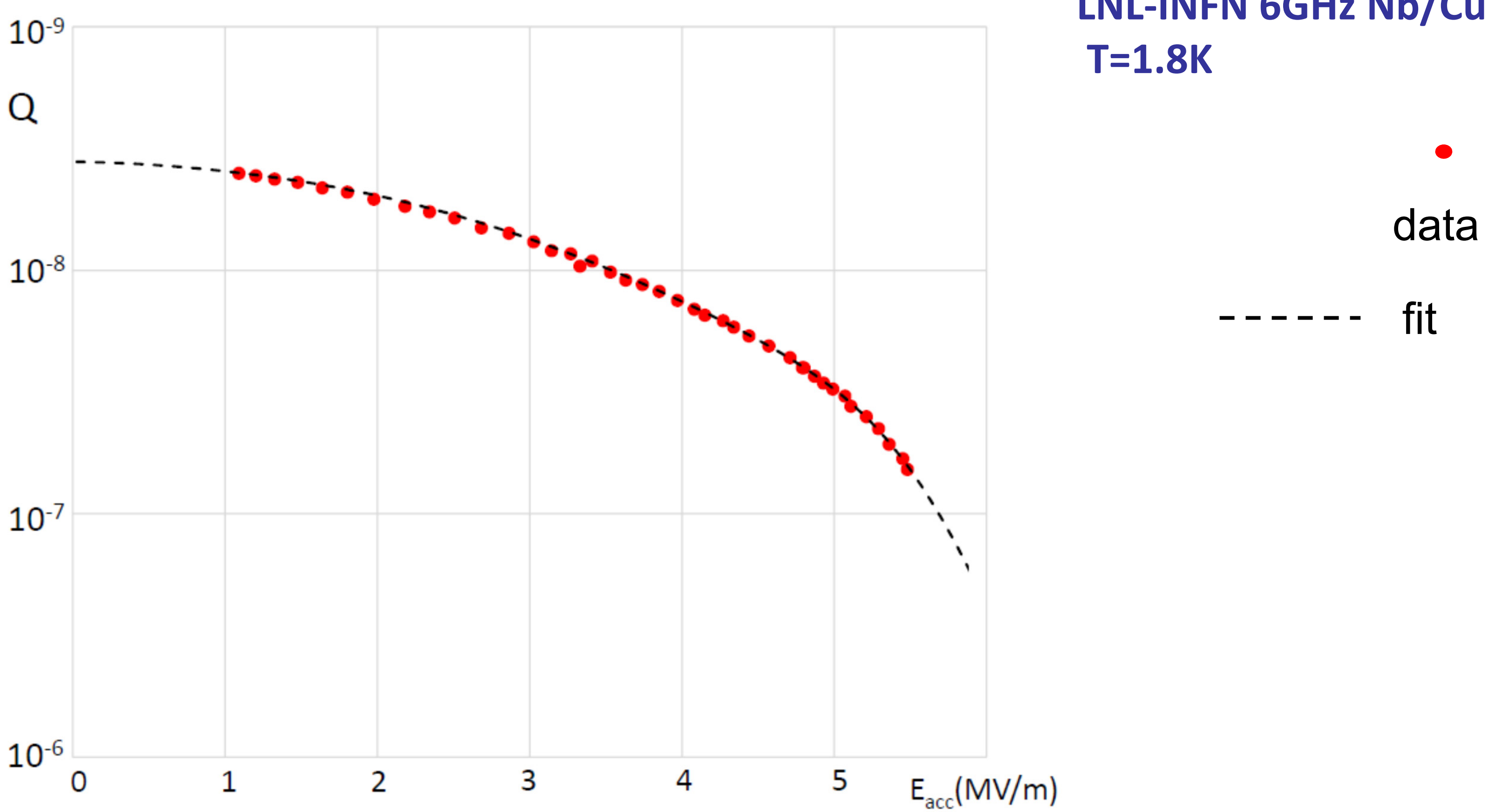
$$
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 8 & 8 & 8 & 0 & 4 & 4 & 0 & 3 & 3 & 3 & 3 & 3 & 0 \\
0 & 8 & 8 & 8 & 8 & 8 & 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}.
$$



the RGB format stores images
As 3 components, which represent their intensities on the red, green, and blue scales. Pure red is represented by *(*1, 0, 0*)* while, the values *(*1, 1, 0*)* represent yellow and *(*0, 0, 1*)* represent blue;

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**

LNL-INFN 6GHz Nb/Cu cavity
T=1.8K

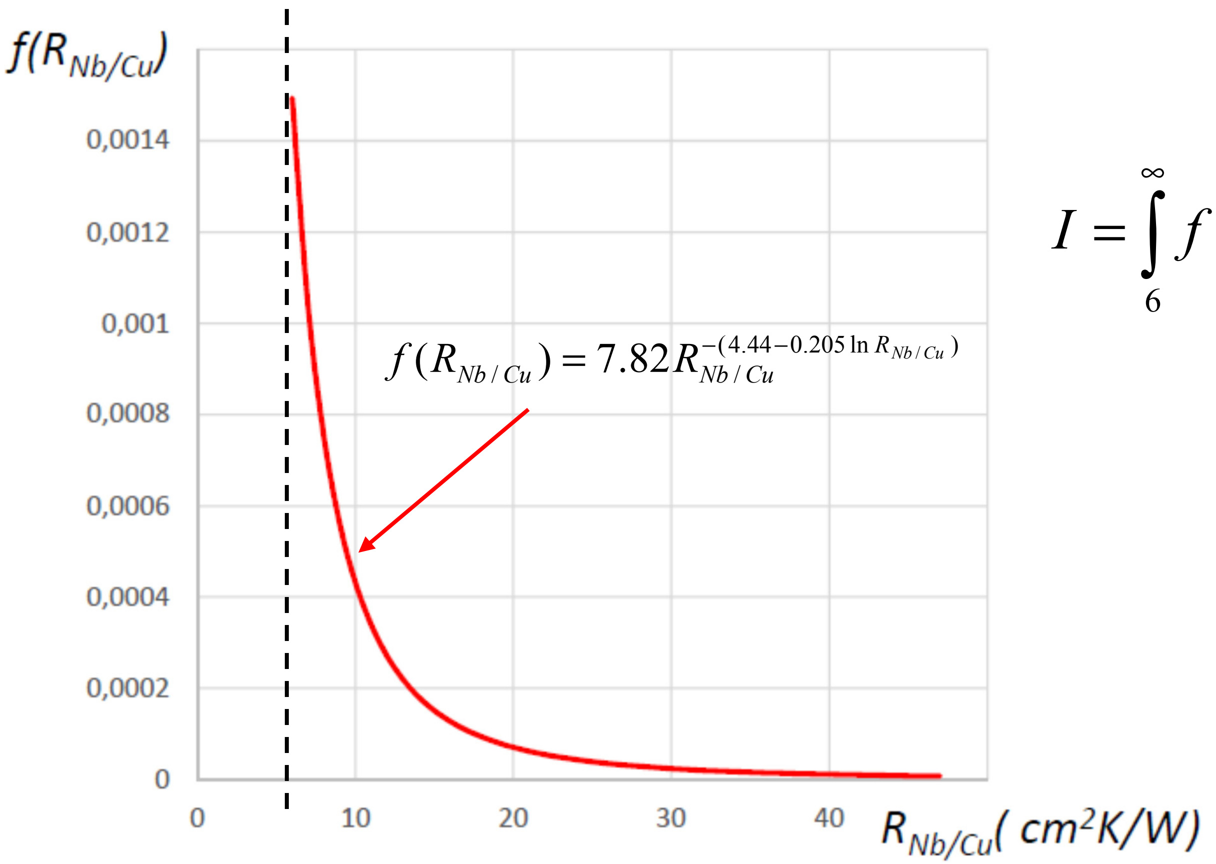


Fitting parameters (from independent measurements)

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 $f(R_{Nb/Cu})$

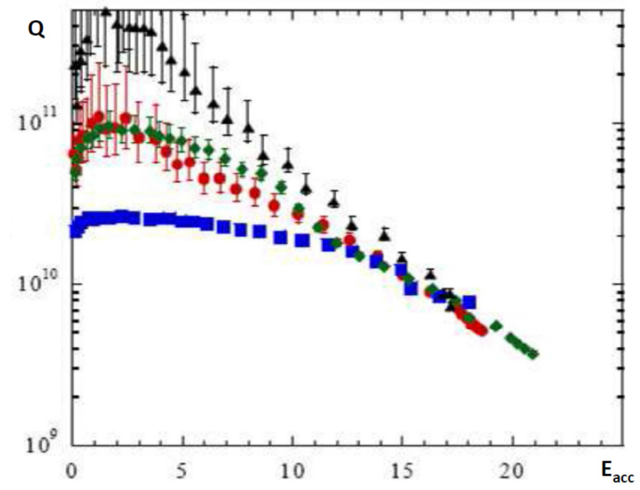


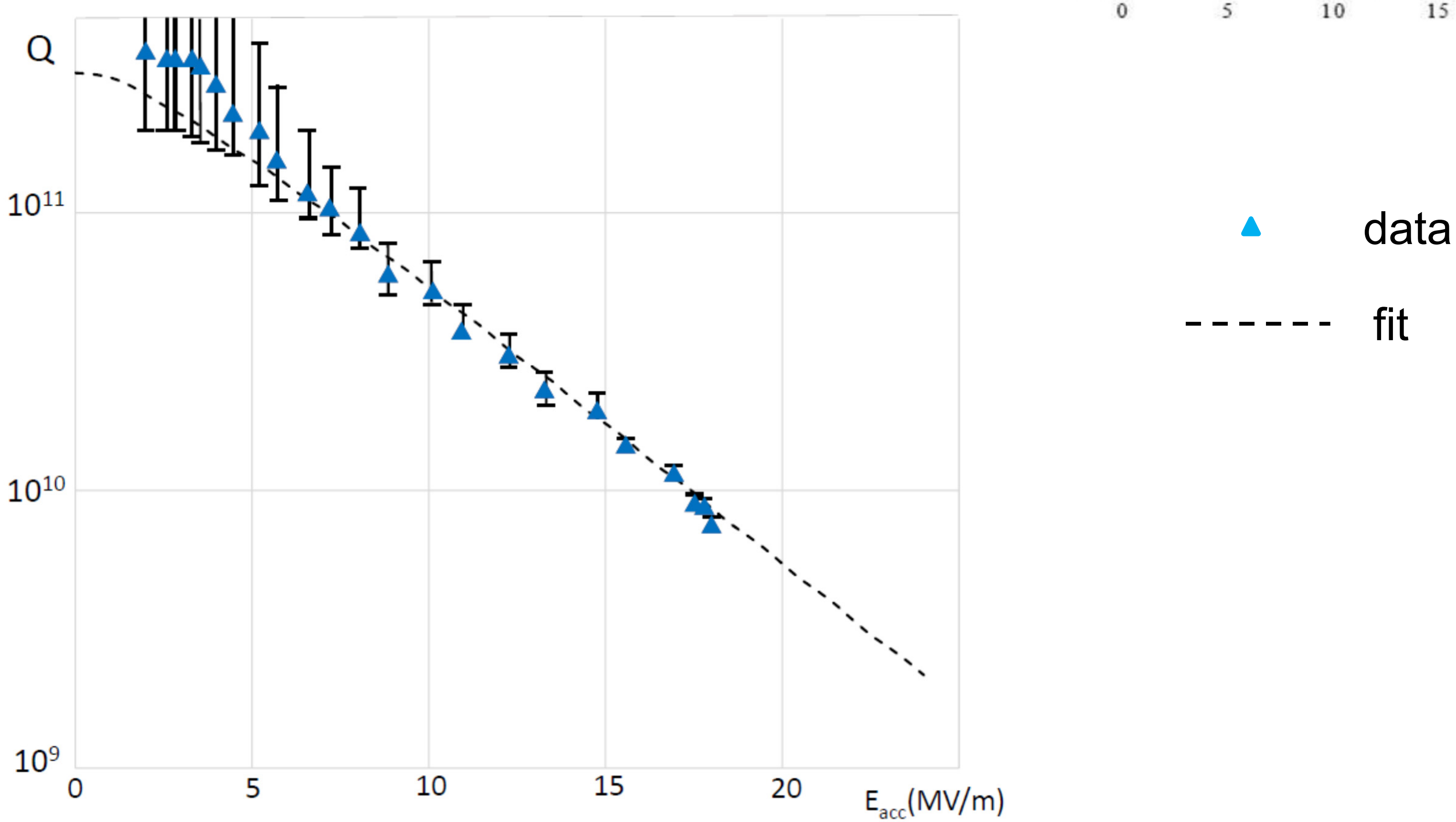
$$I = \int_6^\infty f(R_{Nb/Cu}) dR_{Nb/Cu} = 0.005$$

(0.5%)

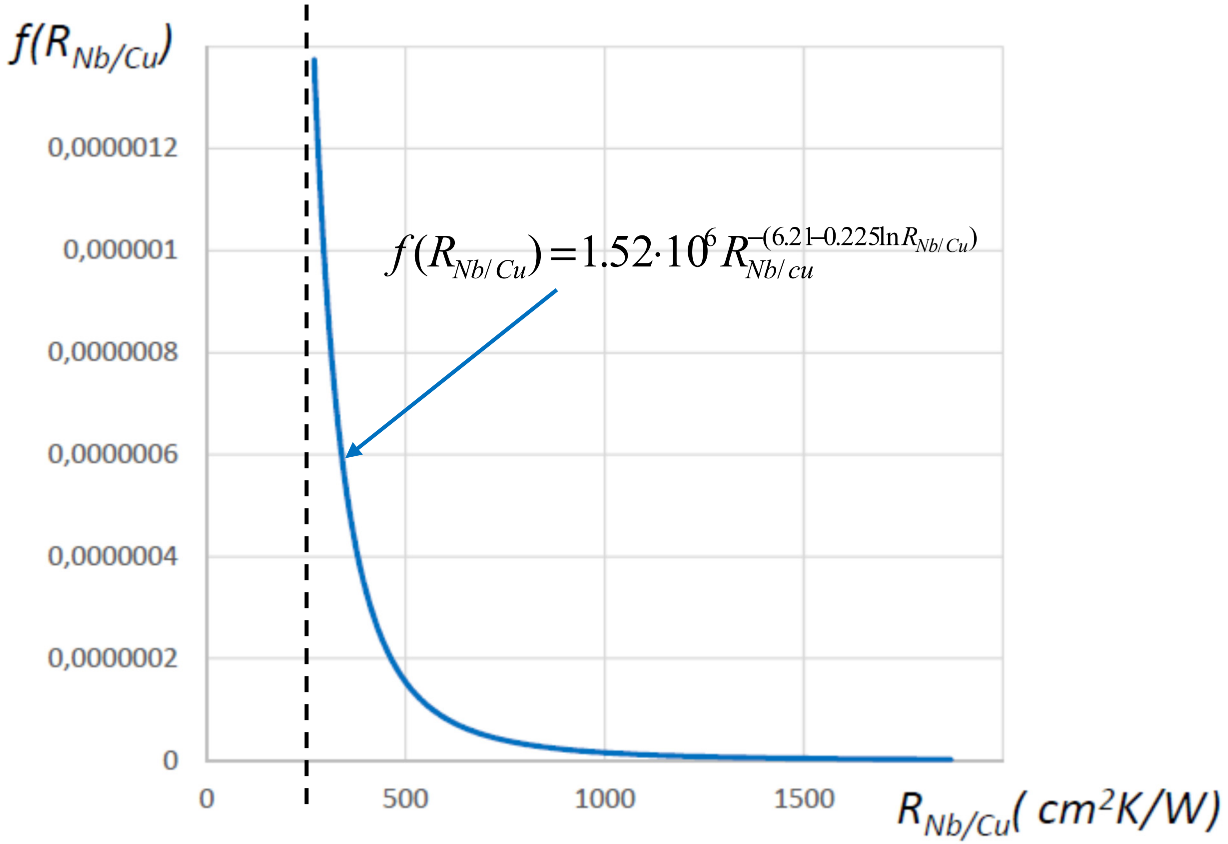
2) CERN 1.5GHz Nb/Cu cavity (high quality), T=1.7K

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).





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



$$I = \int_{250}^{\infty} f(R_{Nb/Cu})\,dR_{Nb/Cu} = 0.0003 \qquad (\,0.03\%\,)$$

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.

Of course these phenomena are typically of the Nb-Cu sputtered cavities and cannot occur in bulk Nb cavity.