Istituto SPIN-CNR

Universita' di Napoli Federico II
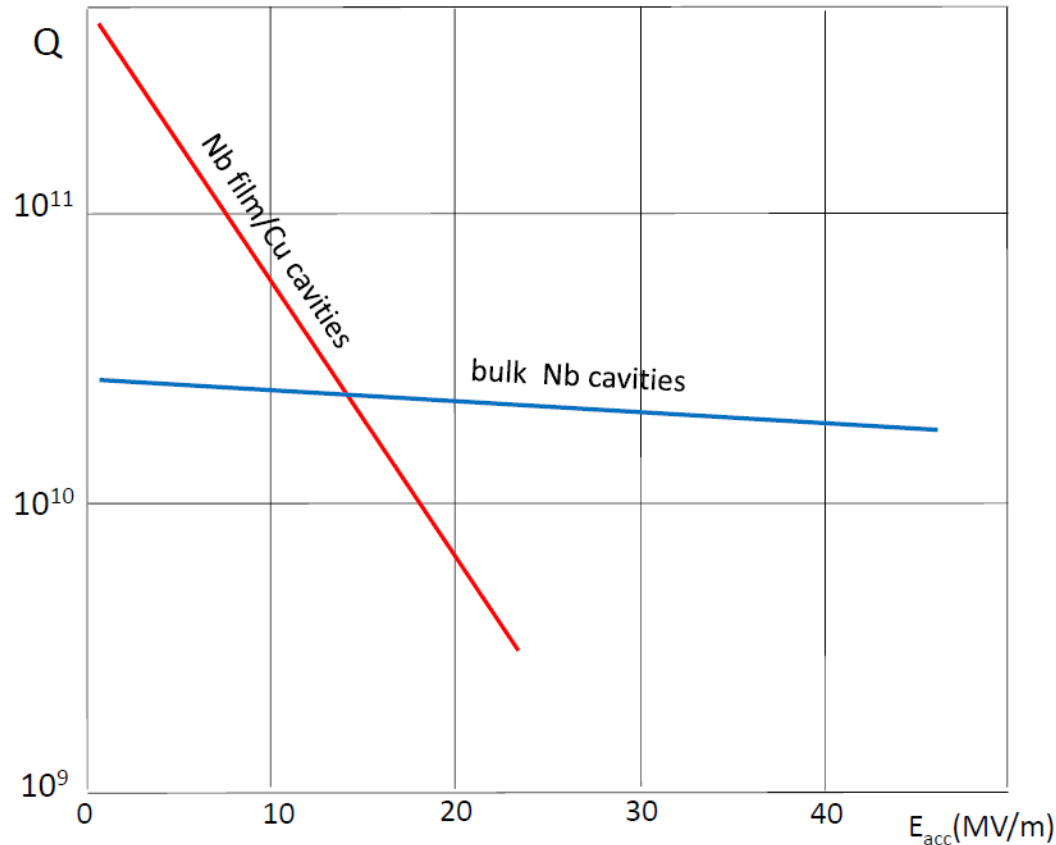
Dipartimento di Fisica

Ruggero Vaglio

Thermal boundary resistance model and defect statistical distribution in Nb/Cu cavities

In collaboration with

Vincenzo Palmieri

SRF 2017, Lanzhou, China

In principle, sputtered thin film Nb/Cu RF superconducting cavities should present many relevant advantages over bulk Nb cavities

Q-factor versus the accelerating field for bulk niobium cavities compared to Nb film sputtered cavities. Typical behavior is schematically reported for 1.3 – 1.5 GHz cavities at low temperatures (1.7-1.8K).

In practice, the large Q-solpe, typically observed in these cavities, limits their use in high field accelerators

Since early nineties researchers tried to understand and fight the Q-slope problem in thin films.

Among others, the following effects were considered :

- hydrogen or oxygen diffusion from the bulk Cu substrate
- grain-boundary losses due to film polycristallinity
- enhanced field dependence of the gap or of the fluxon dissipation

Though all these mechanism can indeed be active, no convincing experimental proof of their relevance has been given and all attempts to fight the problem where not fully successful.

Is there a possible role of thermal effects ?

The relevance of thermal effects in determining the Q-slope in thin film Nb/Cu cavities was excluded because the estimated R_B values are lower for Nb/Cu cavities in respect to bulk Nb (at T ≈ 1.8K) :
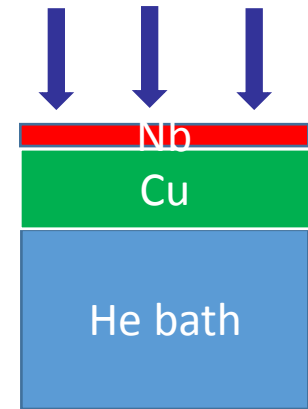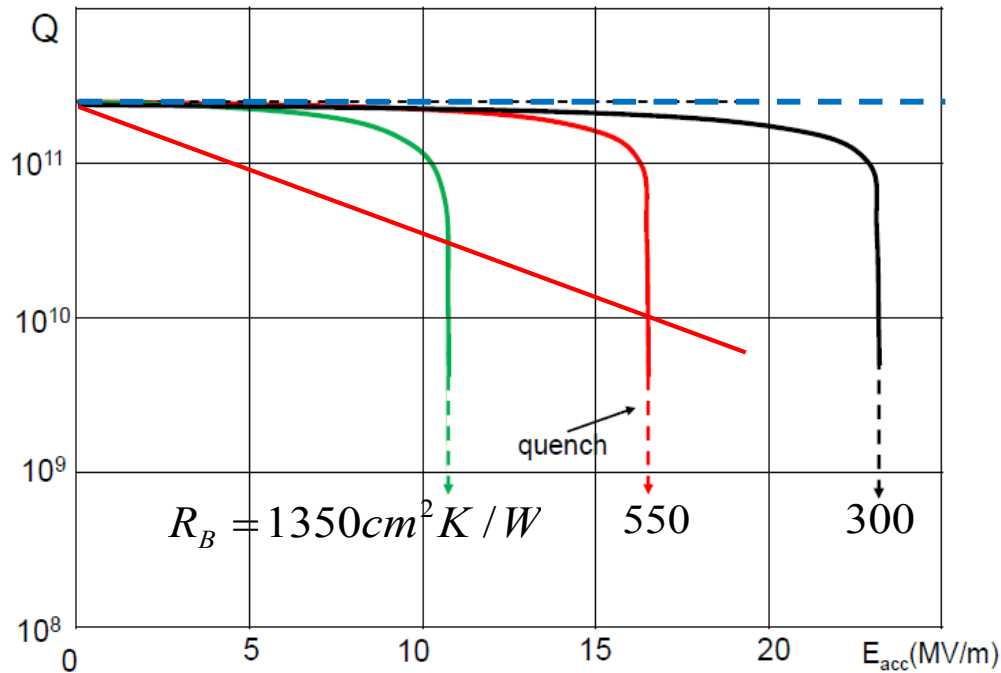

$$R_{Bf} \leq R_{Bb}$$

The thermal feedback model assumes that :

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

$$\Delta T = R_B P_{rf} = \frac{1}{2} R_B R_s(T) H_{rf}^2 = \frac{1}{2} R_B R_s(T)\left(\frac{k}{\mu_o}\right)^2 E_{acc}^2$$

The solution for $R_s = R_s(T_o, E_{acc}, R_B)$ is found by simple iterative methods

Typical calculation results for CERN 1.5GHz Nb/Cu high quality cavity (T_0 =1.7K)

$$E_q = \sqrt{K/R_B} \; ; \quad R_B = 10 cm^2 K / W \Rightarrow E_q > 100 MV / m \; (\text{-- -- -})$$

Benvenuti, Calatroni et al, 10th SRF Workshop, Tsukuba, 2001 : No experimental evidence for significant inner cavity wall temperature increase was found !!

The Thermal Boundary Resistance for two metal sheets in close contact under external pressure, was analyzed (models and experiments) in the seventies:
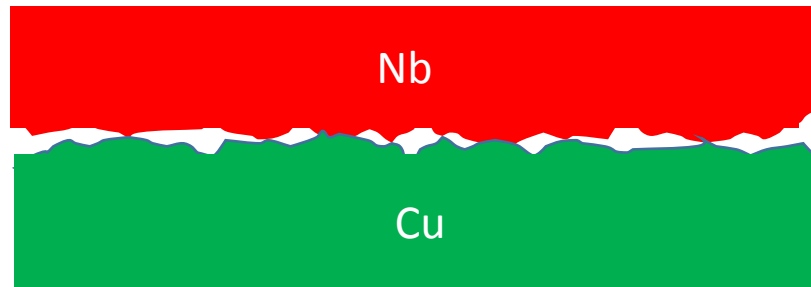
Typically the main contribution to the overall thermal conductivity comes from the interface, due to reduced contact area and distorted thermal flow paths : $R_B = R_{Nb/Cu}$ where $R_{Nb/Cu}$ can assume pretty large values

(For a review see G.Riddone, Report, CERN)

We considered* the possibility that, due to adhesion problems, the Nb/Cu thermal boundary resistance $R_{Nb/Cu}$ could be much higher in respect to standard estimations.

Bad adhesion can be a consequence of :

- absence of intermixing (Nb/Cu is a classical example of non-miscible systems)

- film stress

- Micro-voids at the interphase due to substrate roughness and deposition process

- Included powder particles at the Nb/Cu interphase

Bad adhesion is confirmed by frequently observed cases of film peel-off :
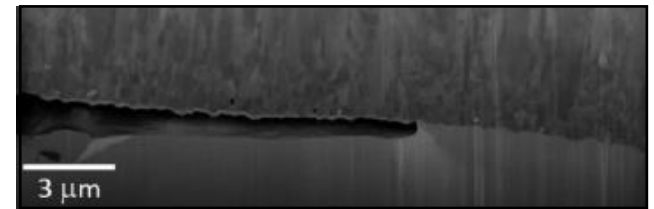

*Palmieri , Vaglio, Superconductor Science and Technology 29 ,015004 (2016)

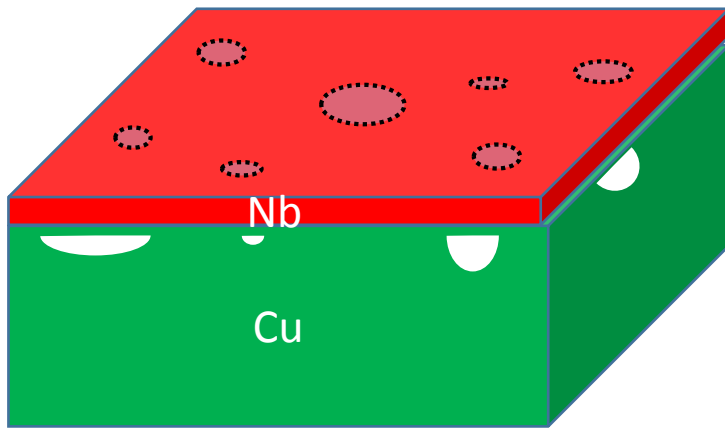# Possible model for a Nb/Cu interface defect :

T_c ⋯⋯⋯⋯⋯⋯⋯⋯

T_{bath}

Nb

Void or powder inclusion

Cu

He bath

CERN

3 µm
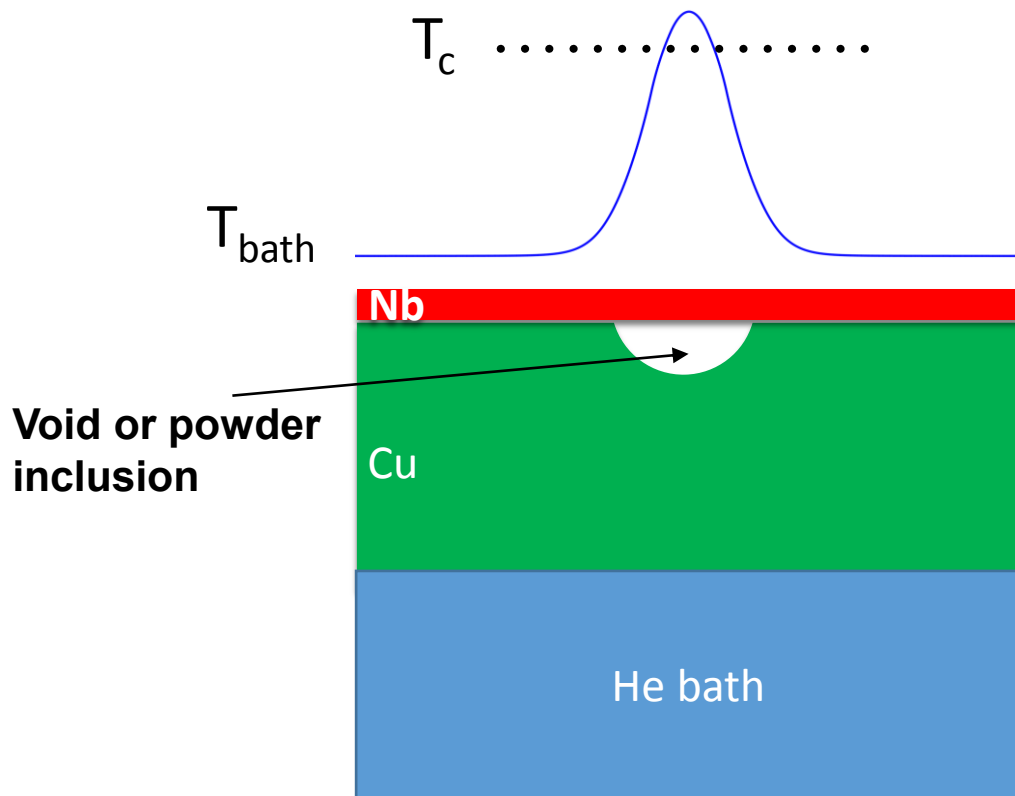
SEM immage Nb/Cu interface

Finte elements calculations performed at CERN on this defect model showed a local thermal increase, that can be well modeld with a local increase of the Thermal Boundary Resistance (TBR) $R_{Nb/Cu}$ (Hernan Poster THPB045)

At the defect the TBR is $R_B = R_{Nb/Cu}$

We call $f(R_{Nb/Cu})$ the distribution function of the values of the TBR over the film surface (f represents the fractional surface area with a given value of the TBR $R_{Nb/Cu}$)
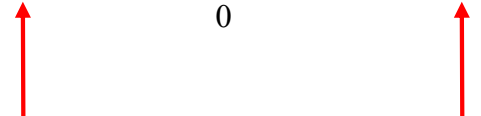
The following relations obviously hold :

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

$$\int_0^\infty R_{Nb/Cu}f(R_{Nb/Cu})dR_{Nb/Cu} = \overline{R_{Nb/Cu}} \quad \text{(} \overline{R_{Nb/Cu}} \text{ represents the average value of the TBR)}$$

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

$$\boxed{Q = \frac{\Gamma}{\overline{R_s(T_o, E_{acc})}}}$$

From the measured **Q** vs **E_{acc}** at a given **T_o** we can deduce the average surface resistance **$R_s(T_o, E_{acc})$** and then obtain the function **$f(R_{Nb/Cu})$** by classical «Inverse Problems» techniques :

$$\overline{R_s(T_o, E_{acc})} = \int\limits_0^\infty R_s(T_o, E_{acc}, R_{Nb/Cu}) f(R_{Nb/Cu}) dR_{Nb/Cu}$$

(from Q measurements)

(calculated by the already introduced iterative method ; above the quench field we assume $R_s = R_n$ where R_n is the normal state **Nb** resistance, assumed to be field-independent)

This equation belongs to the class of first type Fredholm integral equations.

Palmieri , Vaglio, Superconductor Science and Technology 29 ,015004 (2016)

Extracted $f(R_{Nb/Cu})$ for the CERN 1.5GHz Nb/Cu cavity T=1.7K
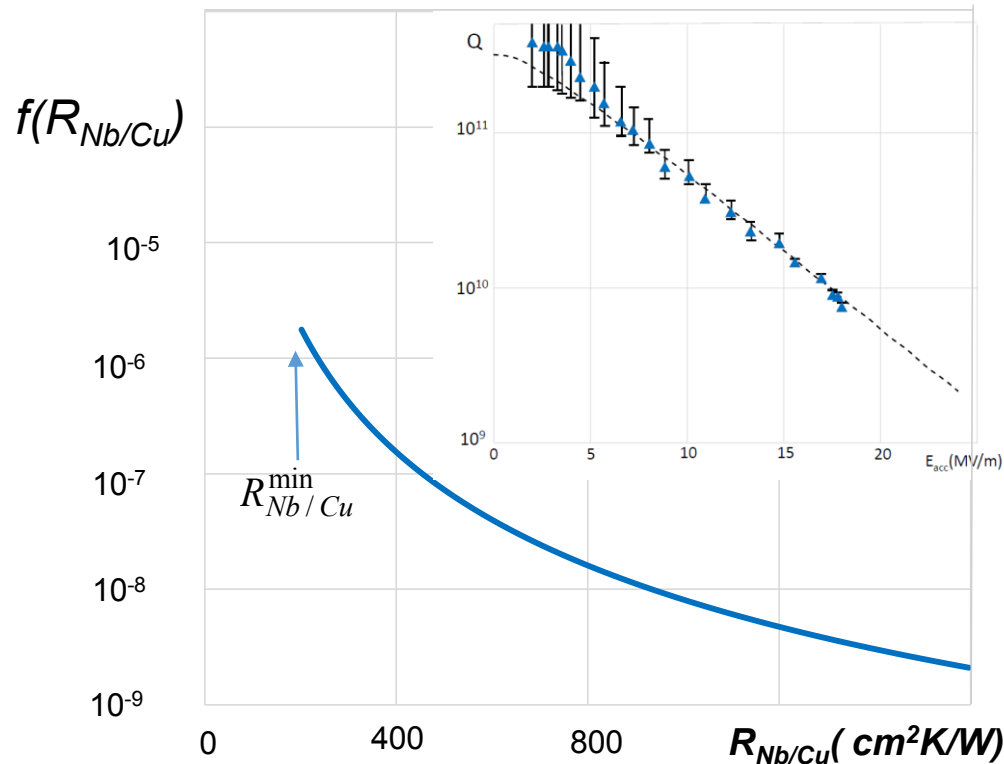
$$f(R_{Nb/Cu}) = \alpha R_{Nb/Cu}^{-\beta}$$

$$I_d = \int_{R_{Nb/Cu}^{min}}^{\infty} f(R_{Nb/Cu}) dR_{Nb/Cu} = 0.0003$$

(I_d fractional area of the detached surface)

$$\overline{R_{Nb/Cu}} \cong 3.5 cm^2 K / W \Rightarrow \Delta T \leq 0.1K$$

$$(\overline{R_{Nb/Cu}} = \int_{R_{Nb/Cu}^{min}}^{\infty} R_{Nb/Cu} f(R_{Nb/Cu}) dR_{Nb/Cu})$$
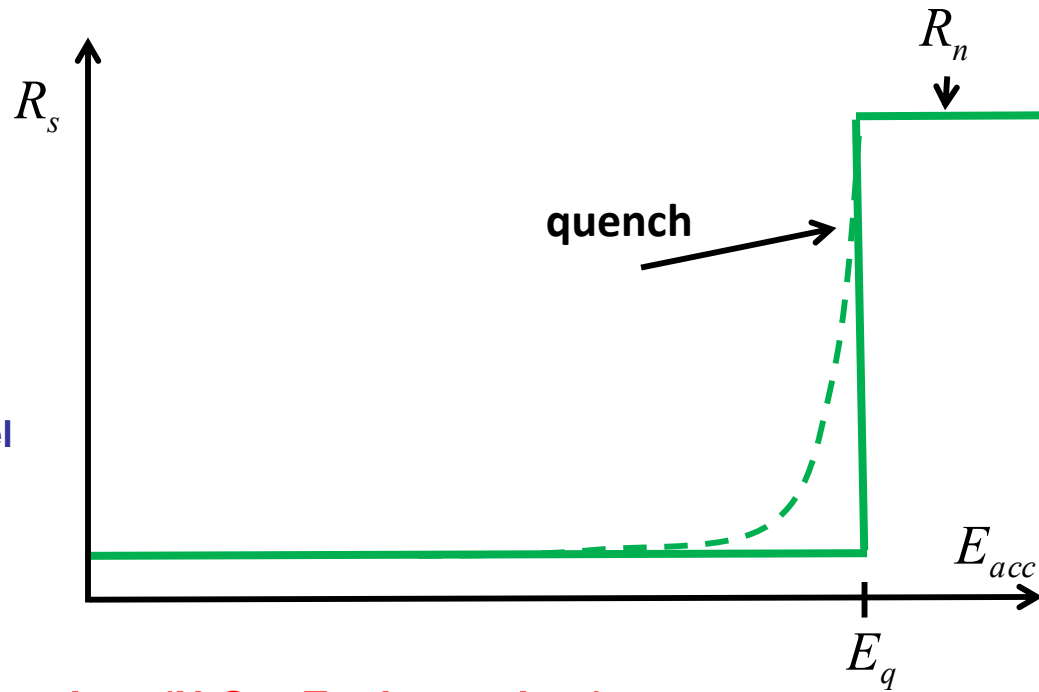

The estimated average value of $R_{Nb/Cu}$ is in any case low, so no average temperature increase of the inner cavity surface is expected, in agreement with experimental results

A power-law (or log-normal) f distribution is compatible with thermal defects due to voids at the interphase due to substrate roughness* or ambient powder size distributions

* R.W. Smith and D.J. Srolovitz, J. Appl. Phys., Vol. 79, p. 1448 (1996)

The inverse problem can be strongly simplified without loosing accuracy , using a step function approximation for $R_s(T_o, E_{acc}, R_{Nb/Cu})$

Results of the simplified procedure (N Q_i – E_{ai} data points) :

$$f_N = \frac{1}{\Delta R_{Nb/Cu,N}} \frac{\overline{R_s(T_o, E_{acc,2})} - \overline{R_s(T_o, E_{acc,1})}}{R_n - R_{so}}$$

$$\overline{R_s(T_o, E_{acc,i})} = \frac{\Gamma}{Q_i}$$

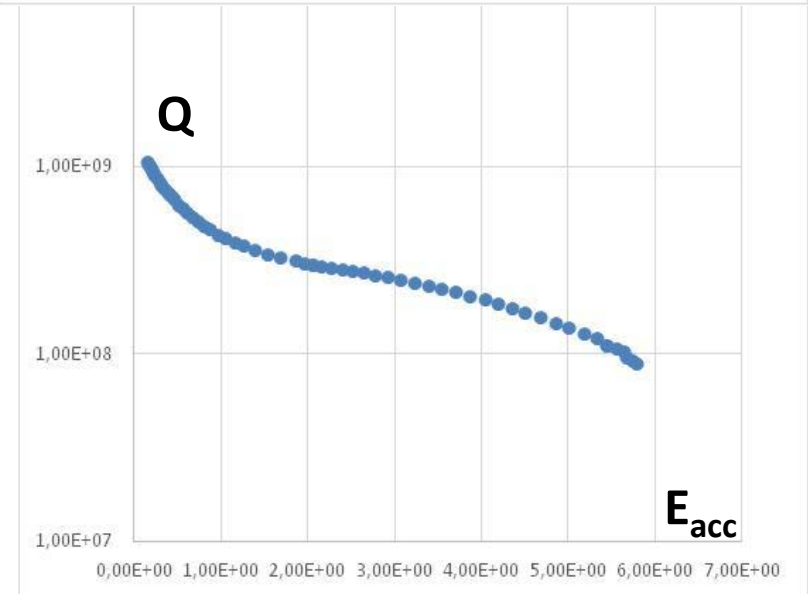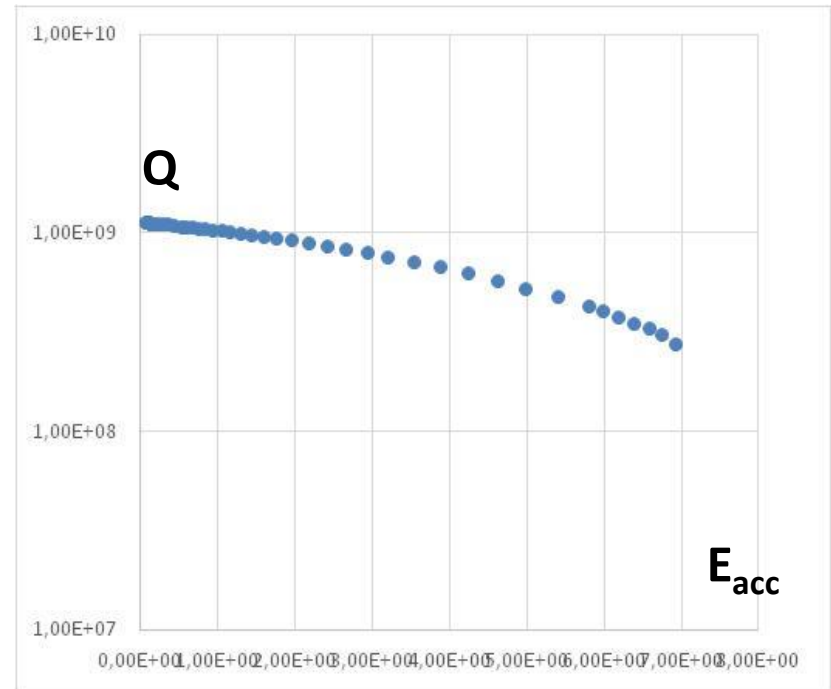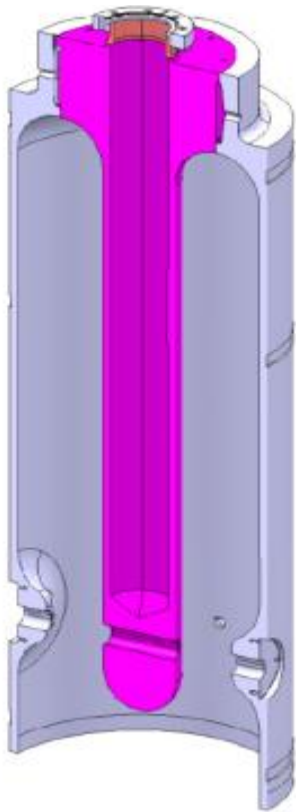..

$$f_2 = \frac{1}{\Delta R_{Nb/Cu,2}} \frac{\overline{R_s(T_o, E_{acc,N})} - \overline{R_s(T_o, E_{acc,(N-1)})}}{R_n - R_{so}}$$

$$f_1 = 1 - \sum_2^N f_i \Delta R_{Nb/Cu,i}$$

$$\Delta R_{Nb/Cu,i} = R_{Nb/Cu,i} - R_{Nb/Cu,(1-i)}, \; with \; R_{Nb/Cu,i} = K / E^2_{acc,(N+1-i)}$$
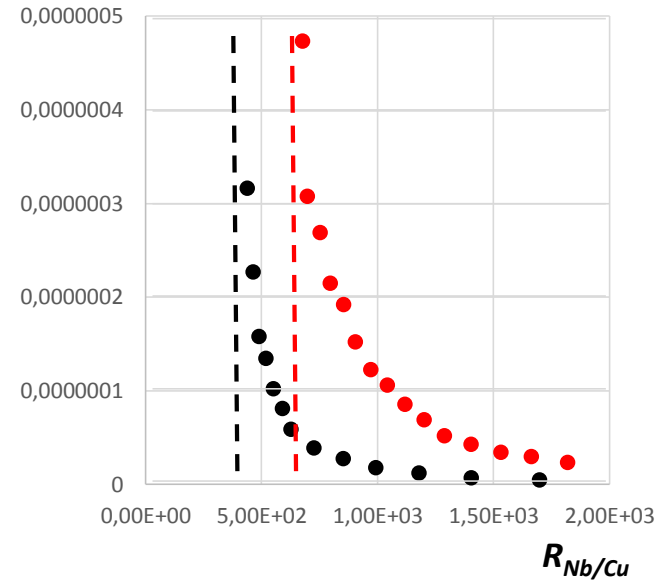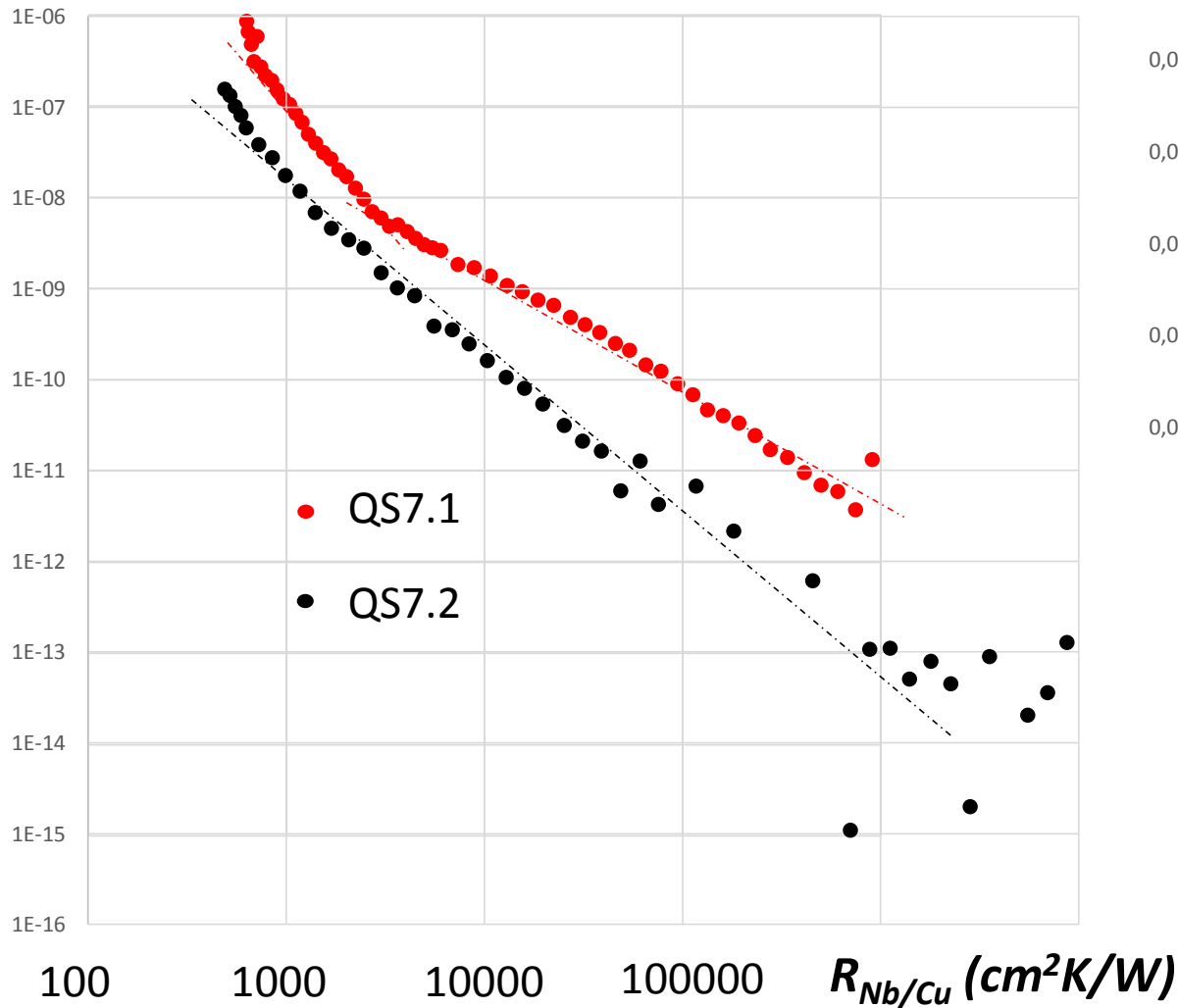
CERN-ISOLDE data*

*Calatroni, Miyazaki, Rosaz, Sublet, Venturini del Solaro, Vaglio, Palmieri.

Phys Rev. AB Vol.19, 092002 (2016)
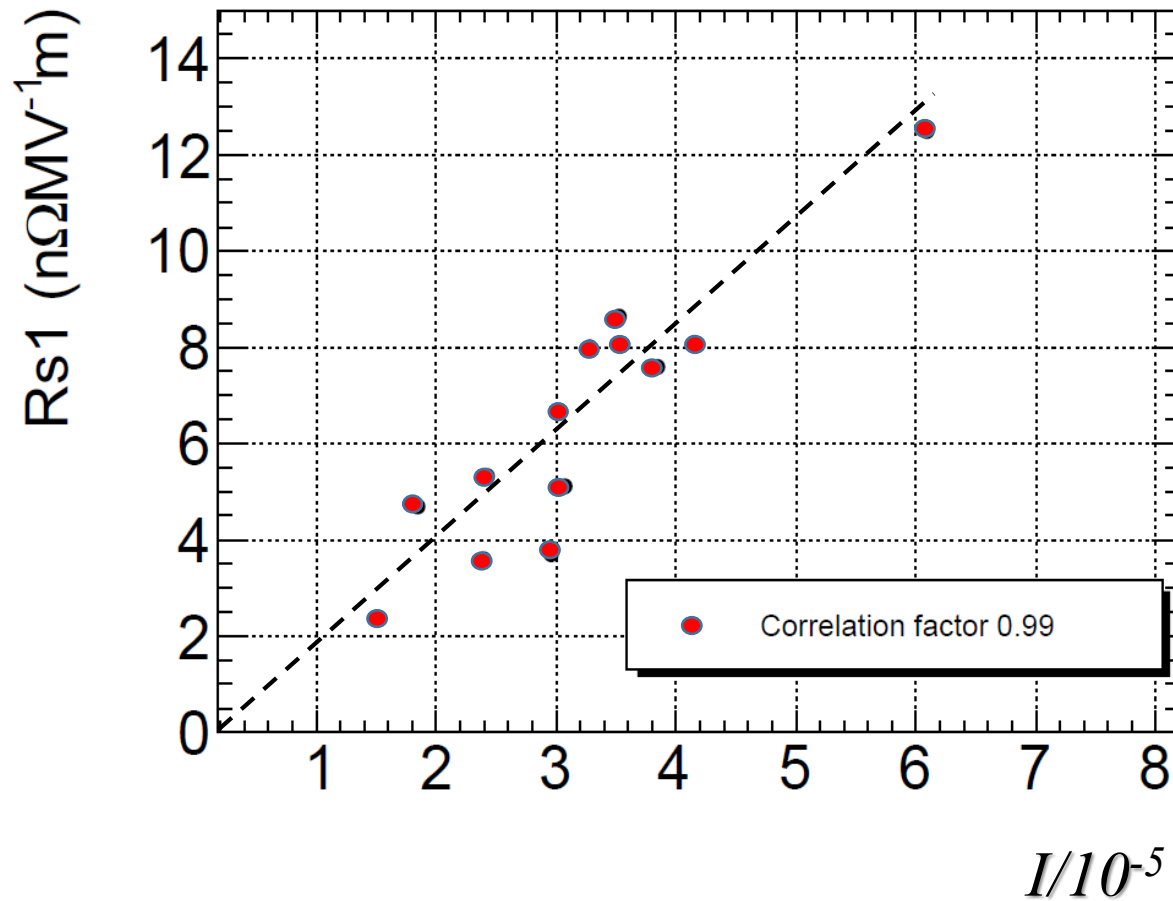
Extracted $f(R_{Nb/Cu})$
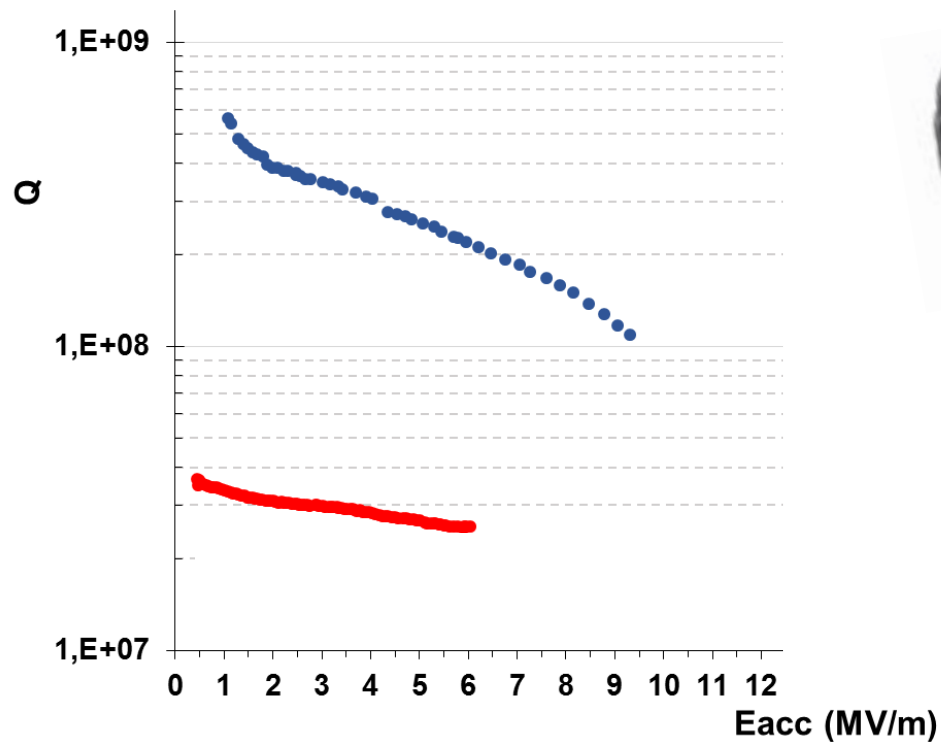
$f(R_{Nb/Cu})$

- QS7.1
- QS7.2

$R_{Nb/Cu}$ (cm^2K/W)

$R_{Nb/Cu}$

$I_d = 0.000063$

$I_d = 0.000230$

CERN-ISOLDE data $\left(R_s(E_{acc}) = R_s^0 + R_s^1 E \right)$
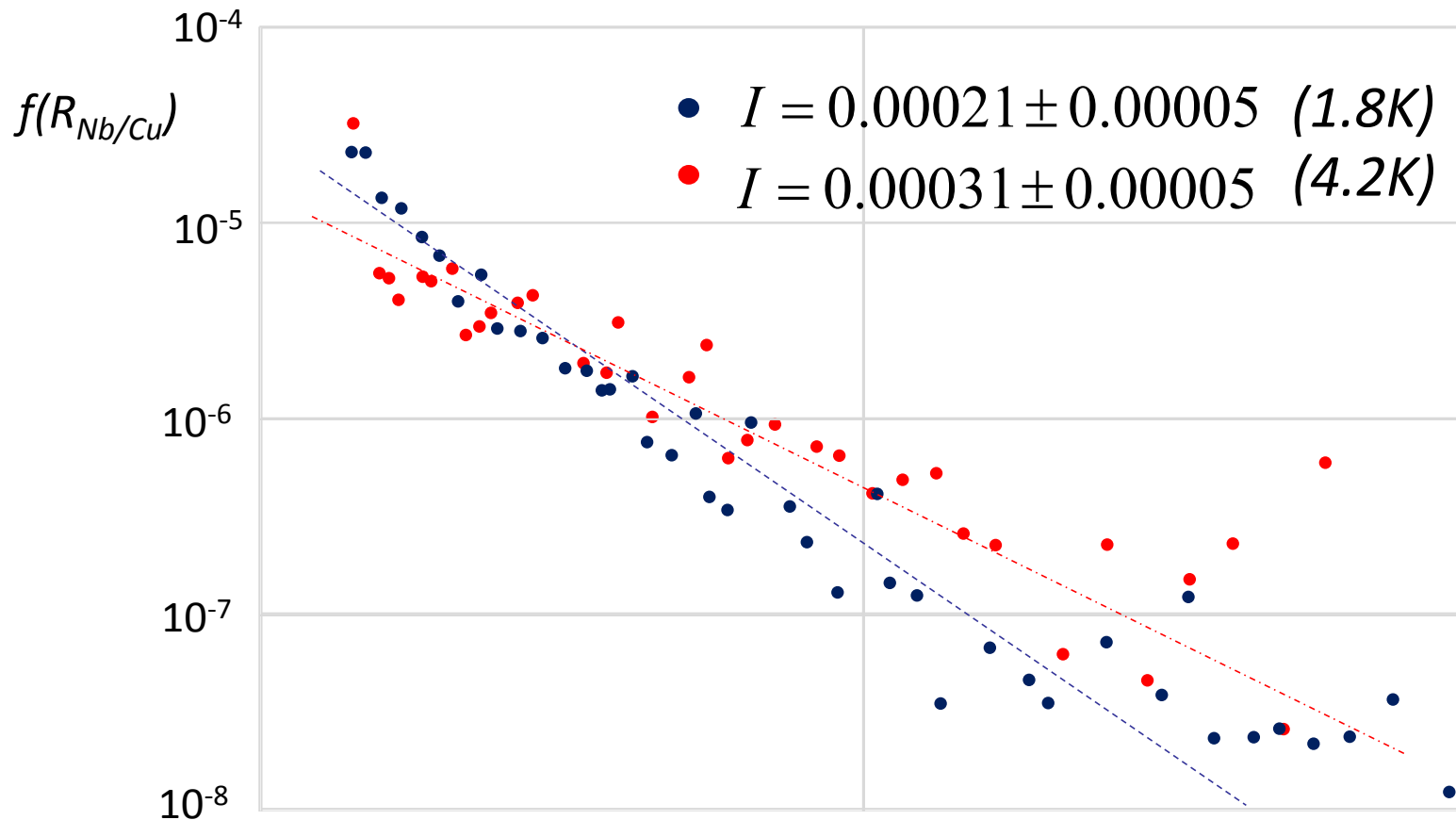

Correlation factor 0.99

LNL 6GHz Palmieri data

1.8K

4.2K

Similar measurements at different temperatures recently performed at CERN on ISOLDE cavities (M.Akira) and using a Test Quadruole Resonator (S.Aull) gave fully analogous results. In the second case it was also proved that the distribution is frequency independent, and that the application of the Same inversion method to Nb bulk cavities gives inconsistent results.

Universita' di Napoli Federico II

Dipartimento di Fisica

Istituto SPIN-CNR

INFN
Istituto Nazionale
di Fisica Nucleare

- **Thermal effects can be relevant in *Nb/Cu* cavities due to enhanched R_B at the interphase due bad film adhesion (voids or powder inclusions).**

- **A simple code has been developed that allows the determination of the statistical distribution of thermal defects from the *Q vs E_{acc}* measurements.**

- **For all the measured cavities (LNL, CERN-ISOLDE-QR) the distribution follows a simple power-law dependence.**

- **The fractional area of the detached surface is always of the order of 10^{-4} - 10^{-5}**

- **The distribution is essentially temperature and frequency independent for thin film cavities, the results appear being fully inconsitent if the «inversion» method is applied to bulk cavities**

- **The validity of the model can be confirmed by independent measurement techniques, or showing that improving the film adhesion sistematically lowers the Q-slope !**

R.Vaglio conclusions : SRF 2017, Lanzhou, China