N-doped surfaces of superconducting niobium cavities as a disordered composite

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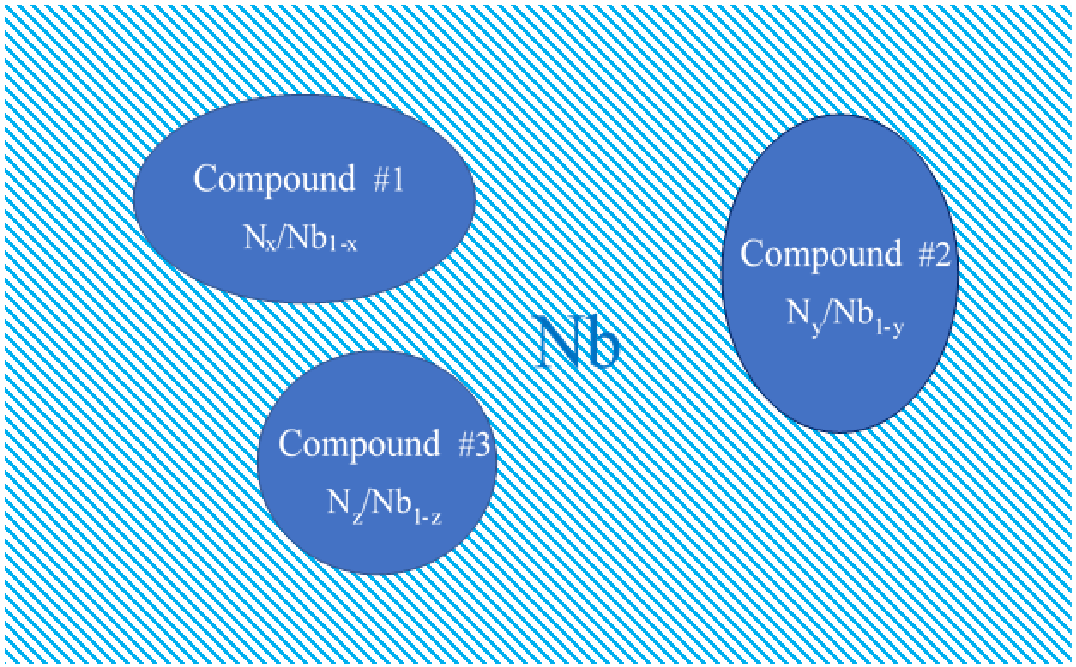
TTC-High Q Working Group 8-Sep-2017 JLAB

1st statement: Nitrogen-rich “compounds” are embedded in “clean” niobium thus forming a “composite”



2nd statement: The lowest critical temperature of the compound is ~ 1.2 K, hence is normal conducting if isolated, but superconducting by proximity of the “clean” niobium.

3rd statement: When the field amplitude B is raised, the compounds gradually become normal conducting above a small threshold field B_c*, far below the critical field B_c of niobium.
The boundary line of normal conductivity is penetrating deeper into the surface (following a logarithmic law).

Consequence: The RF surface resistance R_s can then be described by

$$R_s = R_s^0 \cdot \left[1 - f\left(B\right) + c \cdot f\left(B\right)\right] \qquad (1)$$

c is the ratio of the electrical conductivities of the current across the compound s_m and the conductivity at lowest field s_{Nb}, c = s_m/s_{Nb}.
R_s^0 is the low field surface resistance.

Above B_c* the function **f(B) = ln(B/B_c*)/ln(B_c/B_c*)** (for B_c*<B< B_c and f(B) = 0 else) describes the volume fraction of the compound that has become normal conducting with increasing RF field.

But: This model so far cannot explain the frequency dependence of the slope as observed by M. Martinello et al.

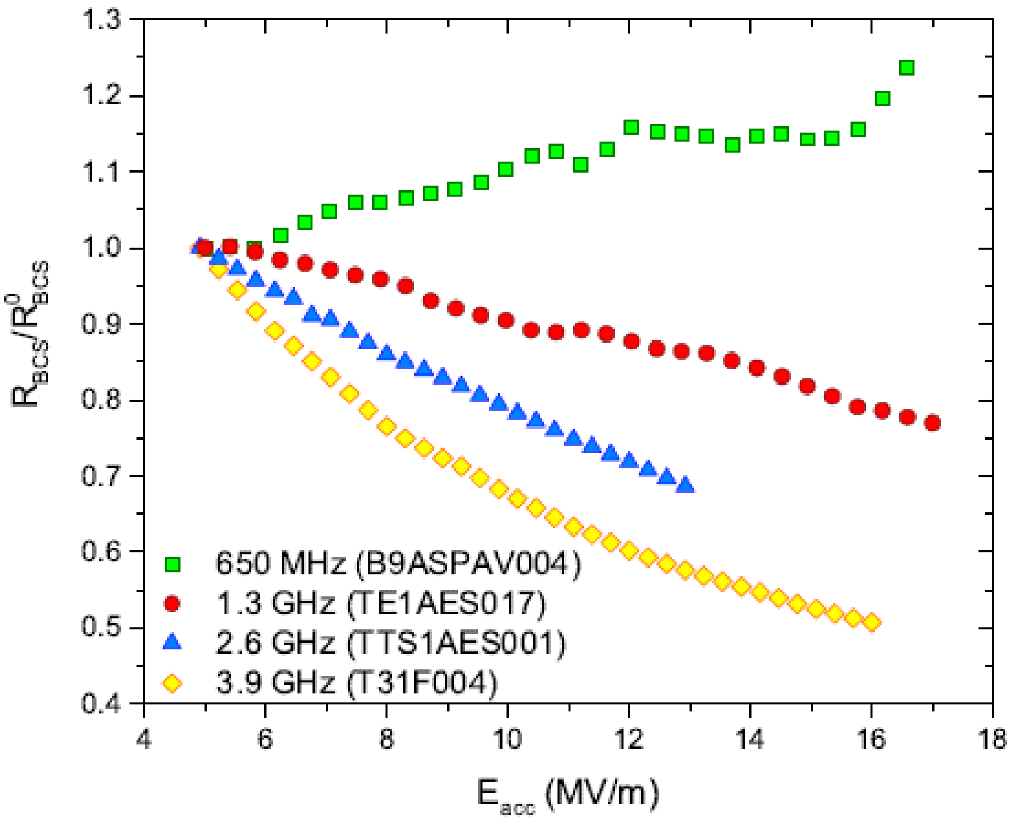


Figure 4: Normalized data R_{BCS}/R^0_{BCS} as a function of the accelerating field for N-doped cavities.

However: Remember the paper of

R. Landauer, The electrical resistance of binary metallic mixtures, Journ. Appl. Phys. **23** (1952) 779

and apply the results for the "compound" as defined previously.

Landauer considered a mixture of two metallic phases of individual conductivities σ_1 and σ_2, with x_1 and x_2 as their respective volume fractions. Then the conductivity σ_m of the infinite uniform medium is

$$4\sigma_m = (3x_1 - 1)\sigma_1 + (3x_2 - 1)\sigma_2 + \sqrt{\left((3x_1 - 1)\sigma_1 + (3x_2 - 1)\sigma_2\right)^2 + 8\sigma_1\sigma_2}$$

Within the compound, the electrical conductivity of the component, when normal conducting, is real, $\sigma_1 = s_1$. That one of the superconducting component is purely imaginary, $\sigma_2 = (\mu_0\lambda^2\omega)^{-1}\cdot i = s_2\cdot i$. This observation introduces the dependence on the frequency $\omega = 2\pi f$ into eq. (1).

Hence, the conductivity σ_m of the compound is complex as well, and its real part s_m describes the RF losses:

$$Re\left(4\sigma_m\right)=4s_m=\left(3x_1-1\right)s_1+\left\{\left[\left(3x_1-1\right)^2 s_1^2-\left(3x_2-1\right)^2 s_2^2\right]^2+\left[2\left(3x_1-1\right)\left(3x_2-1\right)s_1s_2+8s_1s_2\right]^2\right\}^{1/4}\cdot$$

$$\cdot\frac{1}{\sqrt{2}}\sqrt{1+\frac{\left(3x_1-1\right)^2 s_1^2+\left(3x_2-1\right)^2 s_2^2}{\sqrt{\left[2\left(3x_1-1\right)\left(3x_2-1\right)s_1s_2+8s_1s_2\right]^2+\left[\left(3x_1-1\right)^2 s_1^2-\left(3x_2-1\right)^2 s_2^2\right]^2}}}$$

With the numbers as in the Table the final result for R_s/R_s^0 depends on the accelerating field E_{acc} as depicted here:

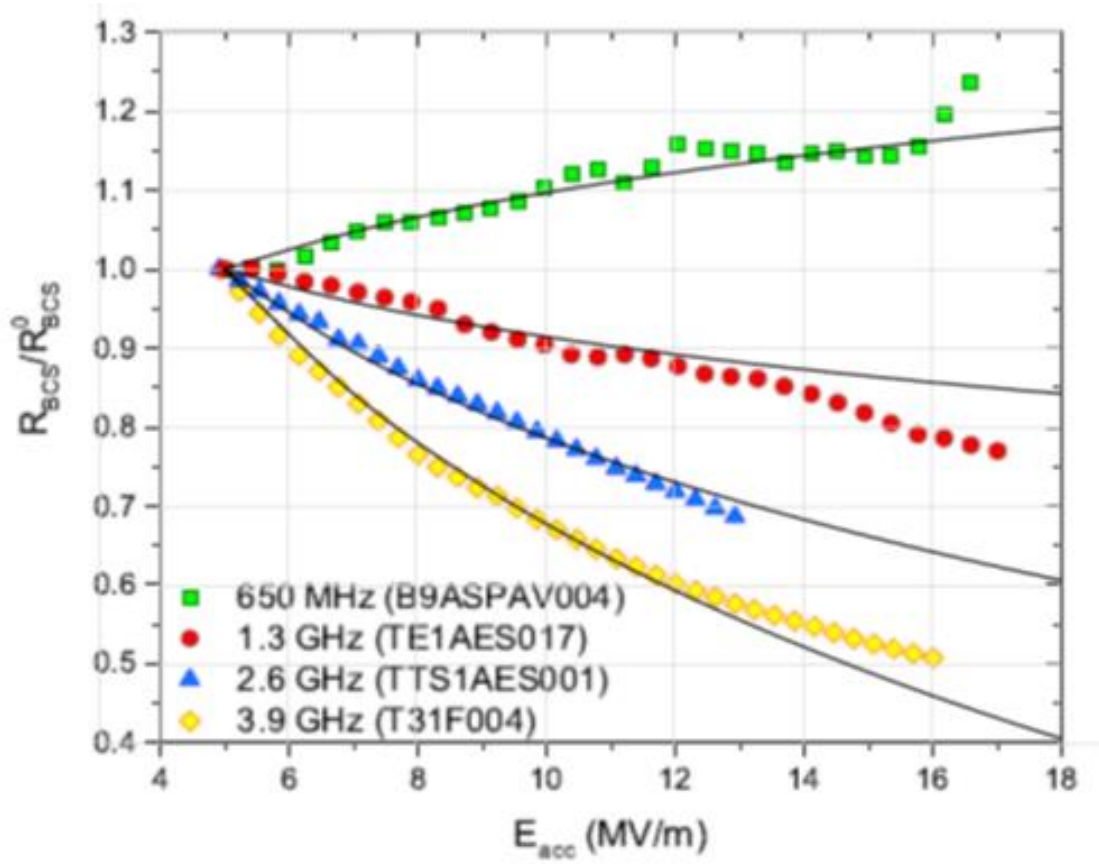


Table: Parameters used in Figure

f [GHz]	λ [nm]	fixed parameters
0.65	60	x_1=0.2
1.3	54	RRR=500
2.6	50	B_c*=20 mT
3.9	66	B_c=120 mT

Figure: The surface resistance R_s is shown as a function of the accelerating field E_{acc}, normalized to the low field surface resistance R_s^0 (adapted from M. Martinello et al., where R_s is called R_{BCS}). Superimposed are the results from this analysis obtained with the parameters as in Table 1 (black lines).

Conclusion:

The model as proposed in arXiv:1407.3220 was challenged with new data.

It was extended by taking into account the complete formula of Landauer describing the electrical conductivity of a binary uniform metallic mixture for the "compound".

When the conductivity in this mixture of the superconducting component of the current through the compound is set imaginary the new data of ref. arXiv:1707.07582v1 are explained in the framework of the model presented.

A look backward

Original model to explain the Q-slope

- WW: On the dependence of the Q-value on the accelerating gradient for superconducting cavities Proc. SRF 2007 Peking University, Beijing TUP16
- WW: TTC LAL Orsay 2009 WG3
- Published here: WW: Field-dependent surface resistance for superconducting niobium accelerating cavities Phys. Rev. ST-AB **14** (2011) 101002

Advent of N-doping

- A. Romanenko and A. Grassellino, Dependence of the microwave surface resistance of superconducting niobium on the magnitude of the RF field, Appl. Phys. Lett. **102** (2013) 252603

→ 1st extension of model

- R. Eichhorn, D. Gonnella, G. Hoffstaetter, M. Liepe, WW, On superconducting niobium accelerating cavities fired under N_2-gas exposure, arXiv:1407.3220 (2014) (first reference to R. Landauer´s paper)

Positive outcome of challenging the model with new data

- WW, R. Eichhorn, Field-dependent surface resistance for superconducting niobium cavities: The case of N-doping, Proceedings of SRF2015, Whistler, BC, Canada, p. 95
- WW, R. Eichhorn, N. Stillin, N-doped niobium accelerating cavities: Analyzing model applicability, Proceedings of LINAC2016, East Lansing, MI, USA, p. 1014

Frequency dependence of slope

- M. Martinello, S. Aderhold, S. K. Chandrasekaran, M. Checchin, A. Grassellino, O. Melnychuk, S. Posen, A. Romanenko, D.A. Sergatskov, Advancement in the understanding of the field and frequency dependent microwave surface resistance of niobium, arXiv:1707.07582v1

→ 2nd extension of model

- WW: N-doped surfaces of superconducting niobium cavities as a disordered composite, arXiv:1708.02841 (2017)
- **based on** R. Landauer, The electrical resistance of binary metallic mixtures, Journ. Appl. Phys. **23** (1952) 779