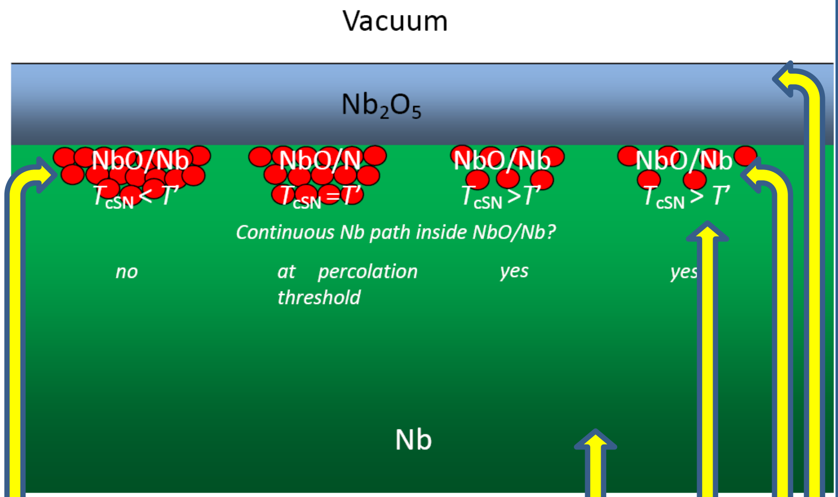
ON THE FIELD DEPENDENT SURFACE RESISTANCE OBSERVED IN SUPERCONDUCTING NIOBIUM CAVITIES

W. Weingarten, CERN, Geneva, Switzerland



Individual contributions to the total surface resistance

the BCS surface resistance

$$R_s = \mu_0^2 \omega^k \sigma_{n0} \lambda^3 \frac{\Delta}{k} ln\left(\frac{\Delta}{\hbar\omega}\right) \frac{e^{-\Delta/k_B T}}{T} \; ; \; k \approx 1.75$$

the non-linear surface resistance

$$R_s^{nl} = \left(R'_{res} + \frac{1}{3}\pi\omega^n \lambda(T)^6 \sigma_{n0} n_d(T) \mu_0^2\right) \cdot \frac{1}{\kappa^2} \left(\frac{\left(\frac{\kappa B}{B_C}\right)^2}{2} + \frac{\left(\frac{\kappa B}{B_C}\right)^4}{3} + + \frac{\left(\frac{\kappa B}{B_C}\right)^6}{4} + \cdots\right)$$

the residual surface resistance

$$n_d(T) = n_{d0} \underbrace{\frac{1}{1 + e^{-(T-T')/w}}}_{\text{Unit step at } T' \text{ with step width } w} \frac{T - T'}{T_c - T'}$$

$$R_{res} = constant$$

the surface resistance describing the low-field Q-increase

$$R_s^{Q-inc} = \frac{2\omega^m L \mu_0^2}{\pi B^2} ; m \approx 1$$

the surface resistance describing dielectric losses

$$R_s^{diel} = \omega^l \varepsilon'' \varepsilon_0 \mu_0^2 (E/B)^2 d ; l \approx 1$$

Reason of study: Understand intrinsic limitations of SRF cavities (Q-slope/Q-drop/low field Q-increase)

Experimental data: The data consist of about 1400 quadruples (R_s, B, f, T) collected from cavity tests of a very broad provenience in temperature T, frequency f, shape, cell number, surface treatment, niobium quality, etc.

Theoretical model: based on the entry of magnetic flux, by the action of the RF magnetic field B, starting at normal conducting "defects" at the surface (nucleation centers) and increasing the normal conducting charge carrier density and consequently the surface resistance.

Specificities of model:

(1) Starting point are normal conducting defects (identical with NbO) of size $2a << \xi, \lambda$ agglomerated in NbO/Nb composite.

(2) These defects are subject to the percolation and proximity effects.

(3) A continuous path of Nb inside NbO/Nb composite exists above a volume ratio of 0.030 (percolation threshold).

- In the Cooper limit of the proximity effect the percolation threshold corresponds to a critical temperature of the defects of $T' = 2.04$ K (percolation temperature);
- If $T > T'$ the defects fragment into its constituents that allow entry of magnetic flux into the circumjacent Nb already for very small $B << B_c$ (Q - slope), with a drastic increase close to B_c (Q - drop);
- If $T < T'$ the defects coalesce into a large normal-conducting defect that does not allows entry of magnetic flux into the circumjacent Nb unless for very large $B \sim B_c$ (Q - drop).

(4) The defects become normal conducting already at low RF magnetic fields $B << B_c$ (low field Q - increase) and give rise to residual surface resistance.

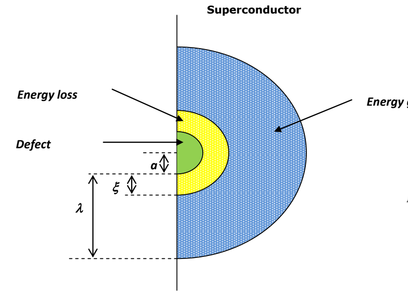
Comparison data vs. model: A fit without free parameters of the large sample of collective cavity data allows the determination of the model-relevant physical parameters, which agree with accepted values.

Fit parameters obtained by χ^2 minimization

Parameter	*Error interval*[*])	*Parameter*	*Error interval*
λ [nm]	(86, 89)	$\Delta/k_B T_c$	(1.68, 1.73)
RRR	(480, 530)	B_c [mT]	(190, 220)
κ	< 0.95	R_{res} [nΩ]	(1.2, 2.0)
R_{res}' [nΩ]	(19, 28)	L [J/m²]	$< 5 \cdot 10^{-12}$
w [K]	< 0.03	T' [K]	(2.01, 2.12)
T_c [K]	(8.8, 10.2)	n_{d0} [m⁻³]	$(0.6, \; 1.1) \cdot 10^{24}$
$\varepsilon'' d$ [m]	$(0.17 \ldots 0.35) \cdot 10^{-12}$	k	(1.740, 1.745)
l	(0.98, 1.01)	m	< 1.1
n	(1.58, 1.60)	[*]) error defined for $\chi^2 < 1300$	

Legend of symbols

Symbol	*Physical parameter*	*Symbol*	*Physical parameter*
λ	penetration depth	$\Delta/k_B T_c$	energy gap of Nb
RRR	residual resistivity ratio	B_c	thermodynamic critical field of Nb
κ	Ginzburg-Landau parameter	R_{res}	residual resistance
R_{res}'	temperature independent term that contributes to Q-drop losses	L	latent heat per square meter
w	width of percolation temperature	T'	percolation temperature
T_c	critical temperature of Nb	n_{d0}	defect density
ε''	dissipation factor in Nb_2O_5	d	thickness of Nb_2O_5
k	exponent of frequency dependent factor (BCS surface resistance)	l	exponent of frequency dependent factor (dielectric losses)
m	exponent of frequency dependent factor (low field Q-increase)	n	exponent of frequency dependent factor (Q-slope/Q-drop)



Small normal defect as condensation nucleus: The superconductor loses energy inside the condensation volume V_c and gains energy inside the magnetic volume V_m

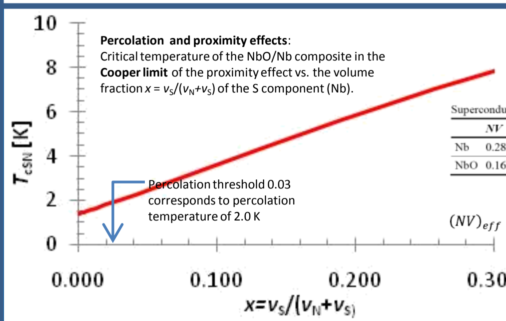
⇒ first entry of magnetic flux at very low B_{c1}^* for $a << \xi, \lambda$

⇒ increase of V_c with RF magnetic field B

⇒ increase of σ_n with B

$$B_{c1}^* = \sqrt{\frac{V_c}{V_m}} B_c \qquad dV_c = \frac{B V_m}{B_c^2 - (\kappa B)^2} dB$$

$$d\sigma_{n0} = \frac{le^2}{m v_F} n_{n0} n_d(T) \frac{2 B V_m}{B_c^2 - (\kappa B)^2} dB$$



Superconducting parameters of Nb and NbO

	NV	Θ_D [K]	T_c [K]	N [cm⁻³]
Nb	0.2835	276	9.25	$5.56 \cdot 10^{22}$
NbO	0.1677	472	1.38	$1.60 \cdot 10^{22}$

$$(NV)_{eff} = \frac{N_N^2 V_N v_N + N_S^2 V_S v_S}{N_N v_N + N_S v_S}$$

$$T_c = 1.14 \Theta_D e^{-\frac{1}{NV}}$$

Results of fit with parameters as above

Typical Q vs. B curves, for an elliptical velocity of light accelerating structure at 704 MHz and 1.5, 2.5, 3.5 and 4.5 K (from above).