DISCUSSION OF POSSIBLE EVIDENCE FOR NON-LINEAR BCS RESISTANCE IN SRF CAVITY DATA TO MODEL COMPARISON

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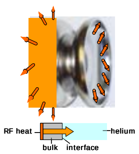
Powerful RF cavities are now being developed for future large-scale particle accelerators from high purity sheet niobium (Nb) superconductor, reaching peak RF surface magnetic fields of up to 180mT. The basic model for Q-slope in SRF cavities is the thermal feedback model (TFBM), the result of the exponential dependence of the Nb BCS surface resistance on temperature and the dependence of the RF power dissipation on the surface resistance. Most important for the validity of the TFBM is what surface resistance contributions (beyond BCS) are included. Here we discuss if the non-linear correction to the BCS resistance as recently proposed by Gurevich could be one of them, comparing TFBM calculations with experimental bulk Nb cavity data from DESY, CEA, J-Lab, Cornell and FNAL.

The Thermal Feedback Model (TFBM)



The steady state heat balance equation (Eq.1) contains conduction and generation terms. The delta-function in the generation term reflects the fact that the RF heating is concentrated in a very thin surface layer. The RF power dissipated per unit area in the cavity depends on the RF magnetic field amplitude H_{RF} and the (temperature dependent) RF surface resistance $R_s(T)$ as given in Eq. 2. The equation assumes that the loss is due to the RF shielding currents only and neglects the contribution by electric surface fields.

$$\frac{\partial}{\partial x}\kappa(T)\frac{\partial T}{\partial x}+P_{diss}(T_m,H_c,..)\delta(x)=0 \quad \left(\frac{W}{m^2}\right)$$

$$P_{diss}=\frac{1}{2}R_s(T_m)H_{RF}^2 \quad \left(\frac{W}{m^2}\right)$$

$$h_{Kap}(T_s,T_0)d(T_s-T_0)=\int_{T_s}^{T_m}\kappa(T')dT' \quad \left(\frac{W}{m}\right)$$

$$\frac{1}{2}R_s(T_m,H_c,..)H_{RF}^2=h_{Kap}(T_s,T_0)(T_s-T_0) \quad \left(\frac{W}{m^2}\right)$$

The solution of Eq. 1 depends on the surface temperatures on both sides of the niobium sheet. The temperature on the RF exposed side, T_m, drives the surface resistance, while the temperature on the helium side, T_s, drives the Kapitza interface conductance. They can be derived exactly from the boundary conditions (Eqs. 3 & 4) for a given H_{RF}, T_0 and R_s (T_m,H_{RF},..). We used a computer program to calculate the exact, numerical solutions of Eqs. (3)&(4). The strong temperature dependence of the BCS resistance is at the core of thermal feedback. The increase of the surface resistance with field is the result of a feedback process during which the surface temperature increases due to RF heating while the RF heating increases with surface temperature. The TFBM is only as good as the surface resistance and thermal parameter models that are put in.

Surface Resistance

$$R_{s,BCS}(T)=A(\omega)\frac{T_c}{T}e^{-\alpha\frac{T_c}{T}} \quad (\Omega)$$

$$R_{s,BCS}(T,H_{RF})=R_{s,BCS}(T,H_{RF}=0)\times ..$$
$$..\times\left[1+C(T,\omega)\left(\frac{H_{RF}}{H_c}\right)^2+...\right] \quad (\Omega)$$

$$C(T,\omega)=\frac{\pi^2}{384}\left[1+\frac{\ln(9)}{3\ln\left(4.1\frac{k_BT\Delta}{(\hbar\omega)^2}\left(\frac{\xi}{\lambda}\right)^2\right)}\right]\left(\frac{\Delta}{k_BT}\right)^2$$

Thermal Properties

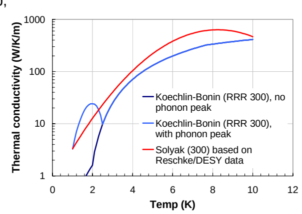
$$\kappa(T)=0.7\,e^{(1.65T-0.1T^2)} \quad \left(\frac{W}{K-m}\right)$$

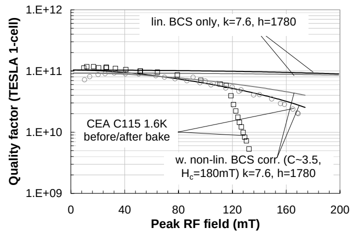
$$h_{Kap}(T,T_0)=200\cdot(T_0^{4.65})\left[1+1.5\left(\frac{T-T_0}{T_0}\right)+....\right.$$
$$\left...+\left(\frac{T-T_0}{T_0}\right)^2+0.25\left(\frac{T-T_0}{T_0}\right)^3\right] \quad \left(\frac{W}{Km^2}\right)$$

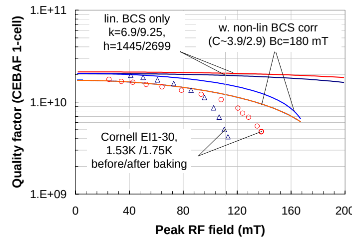
Material Parameters

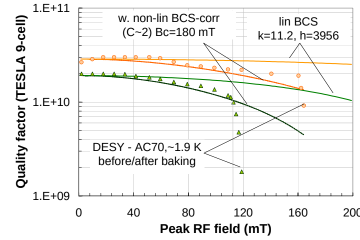
The RF surface resistance of bulk, high purity Nb is usually defined as a sum of BCS resistance ($R_{s,BCS}$), and residual resistance (R_{res}). A phenomenological fit of the linear $R_{s,BCS}$ is given on the left ($\alpha=\Delta/k_BT_c\sim2.0$).
As recently discussed by A. Gurevich the BCS contribution increases at fields approaching the critical field as a result of distortions of the electronic band structure in the superconductor. The first critical field correction term to BCS goes with $C(T,\omega)$, a constant of order unity in Nb at ~ 2 K, that can be calculated from material parameters.

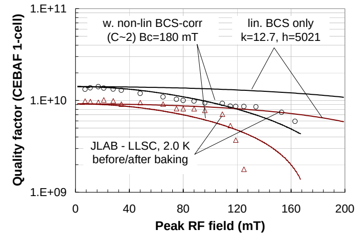
The figure shows different model implementations of the thermal conductivity of polycrystalline, high purity Nb, consistent with experimental data. Instead of using a full-blown model (such as Koechlin and Bonin for instance) we used a simple fit. Note that this fit assumes a "mild" phonon peak. Similarly we used a phenomenological fit for the Kapitza interface conductance, such as proposed by Mittag, for $T-T_0<1.4$ K.









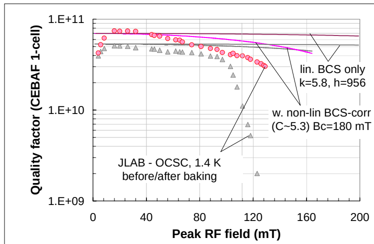


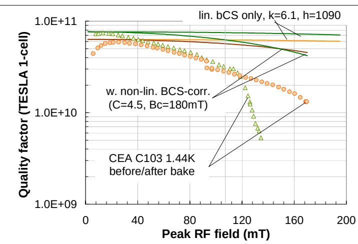
Comparison of TFBM and Cavity Data

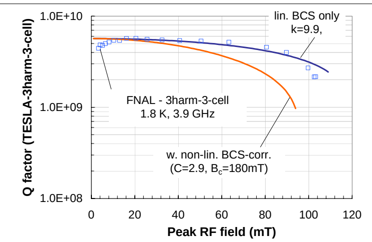
	C-103 CEA	C-115 CEA	D-AC70 DESY	F-3C-1 FNAL	J-LLSC JLAB	J-OCSC JLAB	CU-EI1-30 CORNELL
T_0 (K)	1.44	1.6	2 (1.9)	1.8	2.0	1.4	1.53 (1.75)
G (Ω)	283	283	270	291	282	273	255
d (mm)	2.6	2.6	2.6	2.6	2.6	2.6	2.75
$\kappa(T_0)$?(W/K/m)	6.1	7.6	11.22	9.9	12.7	5.8	6.9 (9.3)
$h_{Kap}(T_0)$ (W/K/m^2)	1090	1780	3956	3080	5021	956	1445 (2699)
R_{res} (nΩ)	3.2 (4.2)	1 (2)	-10 (5.2)	10	17 (9.4)	3.6 (5)	11 (11)
$R_{bcs,lin}(T_0)$ (nΩ)	0.5 (0.3)	1.7 (1.05)	24 (4.3)	40	31 (20)	3.9 (5.1)	5.6 (1)
Δ/k_BT_c	2 (2.05)	1.97 (1.93)	1.53 (1.94)	1.92	2.1 (1.94)	2.09 (2.15)	1.99 (1.99)
A(ω) (10^{-5} Ω)	2.76(2.13)	2.5 (1.2)	0.597(1.058)	14.8	4.4 (1.7)	4.46 (2.38)	3.7 (2.5)
T_c (K) *	9.2	9.2	9.2	9.2	9.2	9.2	9.2
ω/2π (GHz)	1.3	1.3	1.3	3.9	1.5	1.5	1.5
C (T_0,ω)	4.5 (4.5)	3.6 (3.4)	1.5 (2.5)	2.9	2.6 (2.2)	5.2 (5.5)	3.9 (2.9)
μ_0H_c (mT) *	180	180	180	180	180	180	180

TFBM parameters for cavity Q calculation. Linear (Δ/k_BT_c, A(ω)) and non-linear BCS resistance (C(T_0,ω)), thermal conductivity (κ(T_0)) and Kapitza conductance (h_{Kap}). Data out(inside) parentheses are for before(after) the low temperature bake. * assumed values.

The model consists of the exact solution of the TFBM equations, using the linear BCS and residual resistances measured in the cavities at low field and calculated material properties. Calculations were performed with and without the non-linear correction to the BCS resistance. Note that the model implementation here assumes uniform surface properties. The most important criterion the experimental data needed to satisfy for this comparison is that they needed to have as little Q slope as possible, such as to limit as much as possible the surface resistance to the basic residual and BCS components. Most cavities were reduced size prototypes, with the only exception being the DESY AC70 (9-cell TESLA cavity). The Saclay and DESY cavities were electro-polished, the J-Lab, Cornell and FNAL cavities were BCP etched. The J-Lab cavities and the Saclay cavity C115 were also post-purified. The data obtained before and after the low temperature (~120°C, 50 hrs) bake are presented. Essentially all Q measurements were performed in the CW mode. Table 1 summarizes the experimental and model parameters used in the comparison.







The non linear BCS resistance contribution decreases with temperature and increases with frequency. We observed that the CEA C-103 and J-Lab-OCSC cavities, which were tested at lower temperatures than the others (discussed here), show a medium-Q slope that is more pronounced than that which can be predicted even with the addition of the non-linear BCS resistance in the TFBM. Reduced thermal parameters cannot explain this discrepancy. Could that indicate that the increase of non-linear BCS resistance is underestimated? Is it that at very low temperature the resistance is not BCS dominated anymore and some "other" process takes place?
At frequencies beyond 2 GHz, the experimental data are well-described using only linear BCS resistance and residual resistance in the TFBM – see the case of the Fermilab 3rd harmonic cavity, which operates at 3.9 GHz (In this case the TFBM with linear BCS only predicts even the exact quench field!). This discrepancy is surprising since the high frequency regime is BCS resistance dominated! Does this indicate that the non-linear BCS resistance model as formulated here overestimates the non-linear BCS resistance increase at higher frequency? Or is this an indication of a more fundamental flaw of the non-linear BCS model?