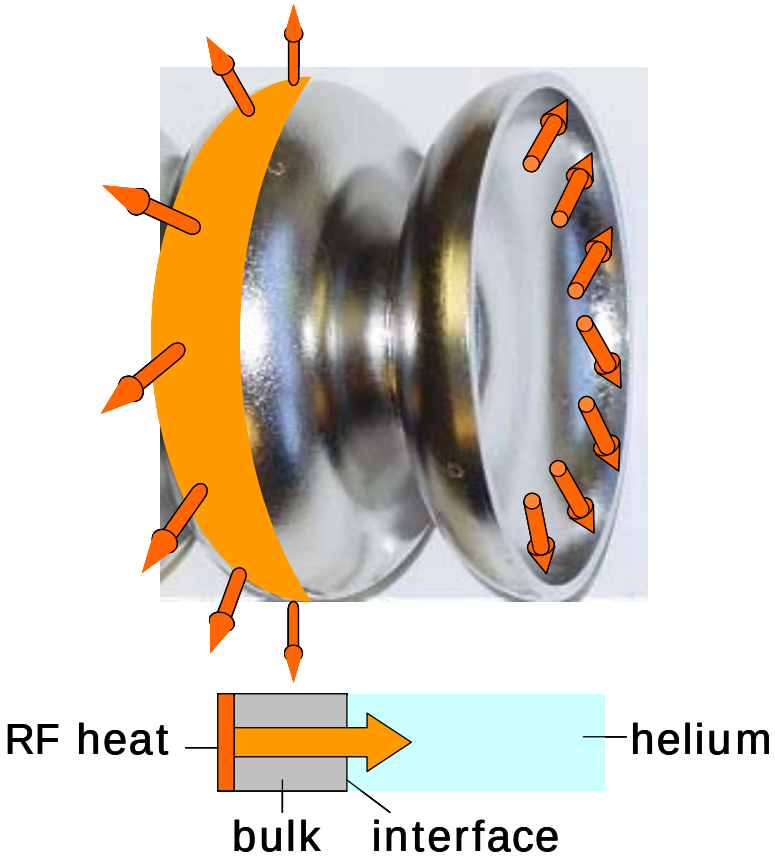
Comparison of thermal feedback models with Q-slope measurements in bulk Nb SRF cavities



P. Bauer,
A. Gurevich,
N. Solyak,
G. Ciovati,
B. Visentin,
L. Lilje

Thermal Feedback

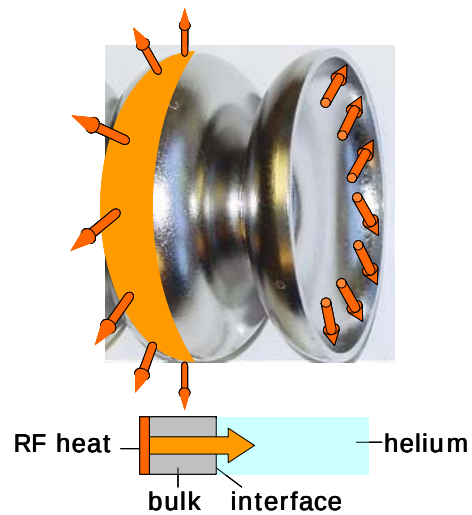
Thermal feed-back: exponential T-dependence of BCS surface resistance: $\rightarrow R_s \rightarrow P_{RF} \rightarrow \Delta T \rightarrow R_s \rightarrow \ldots$

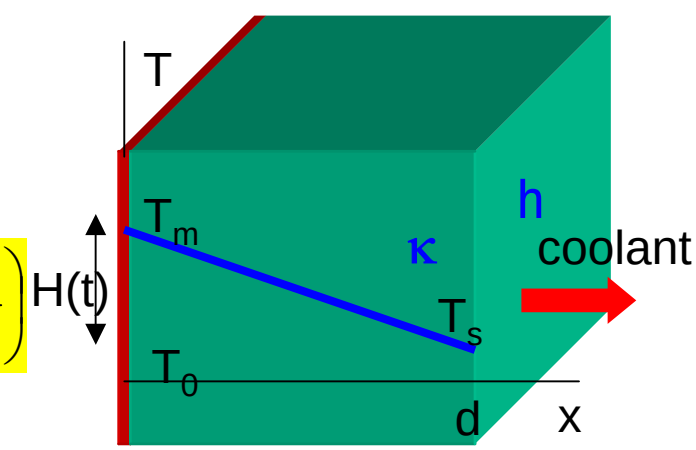
$$P_{RF} = \frac{1}{2} R_s H_{\varpi}^2$$

$$R_s = R_{s,res} + \frac{A(\omega)}{T} e^{-\frac{\Delta}{k_B T}} \left[1 + C \left(\frac{H_\omega}{H_c} \right)^2 \right] + \ldots\ldots + \ldots\ldots$$

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

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



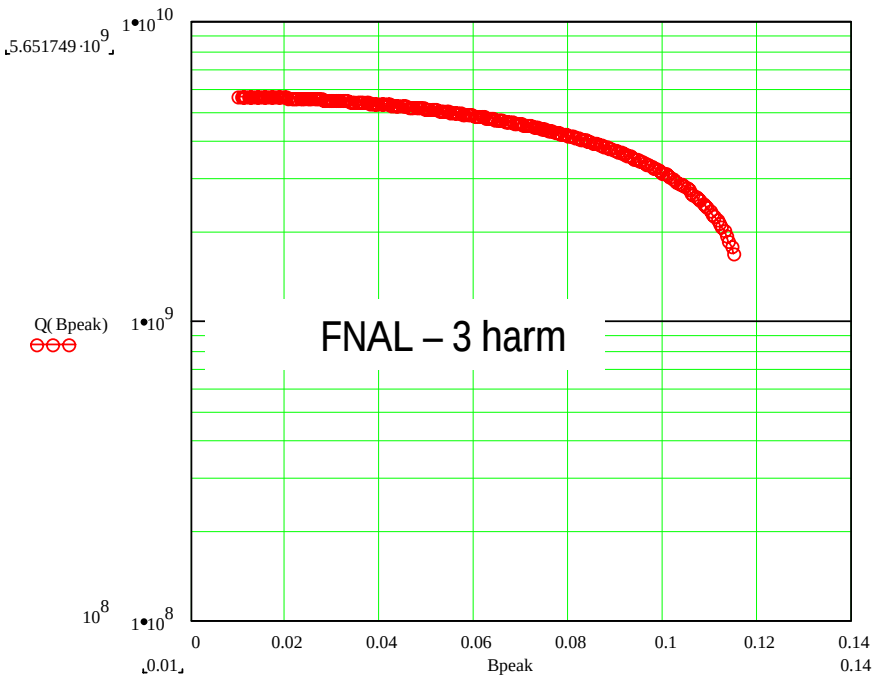


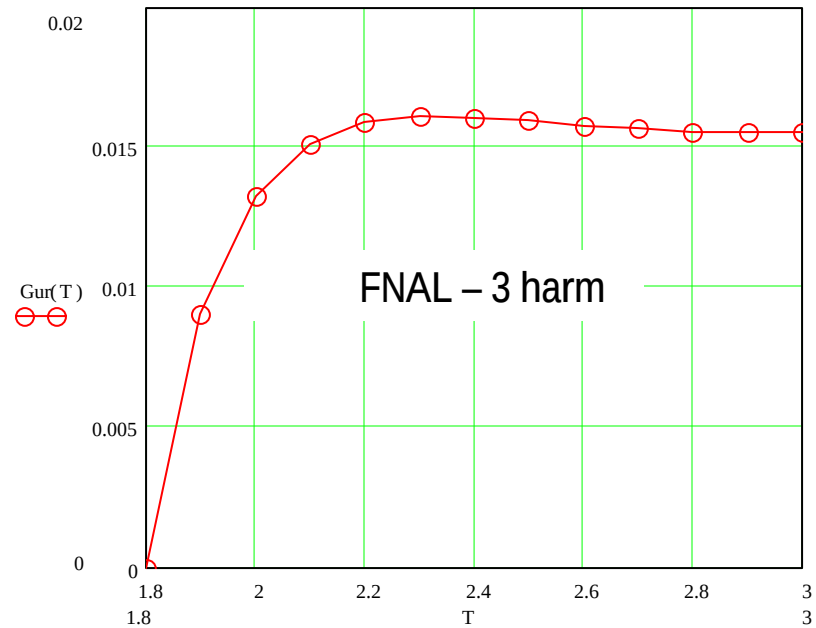
Breakdown RF Field – Linear BCS only

$$H_{RF}^2 = \frac{2(T_m - T_0)T_m}{A(\omega)T_c} e^{\frac{aT_c}{T_m}} \left(\frac{\kappa h_{Kap}}{dh_{Kap} + \kappa} \right) \quad \left(\frac{A^2}{m^2} \right)$$

Thermal runaway occurs at a rather weak overheating. Thermal break-down field depends on T_0 and κ, hd.

$$T_{max} \sim T_0 + T_0^2/(\alpha Tc)$$



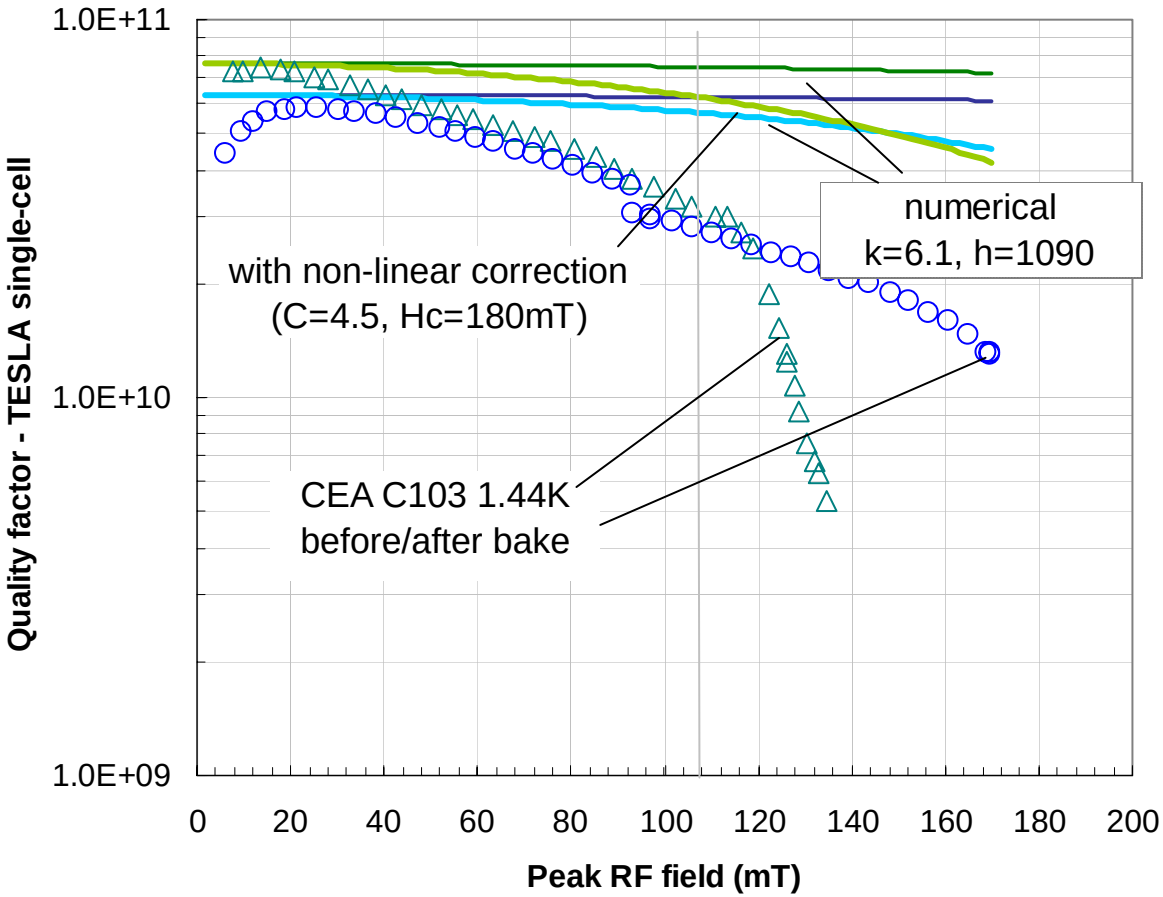


Inserting $\Delta T \sim T_0^2/\Delta$ gives an expression for the Q drop at the thermal quench:

$$Q(H_b) \approx Q(0)/e$$

A. Gurevich

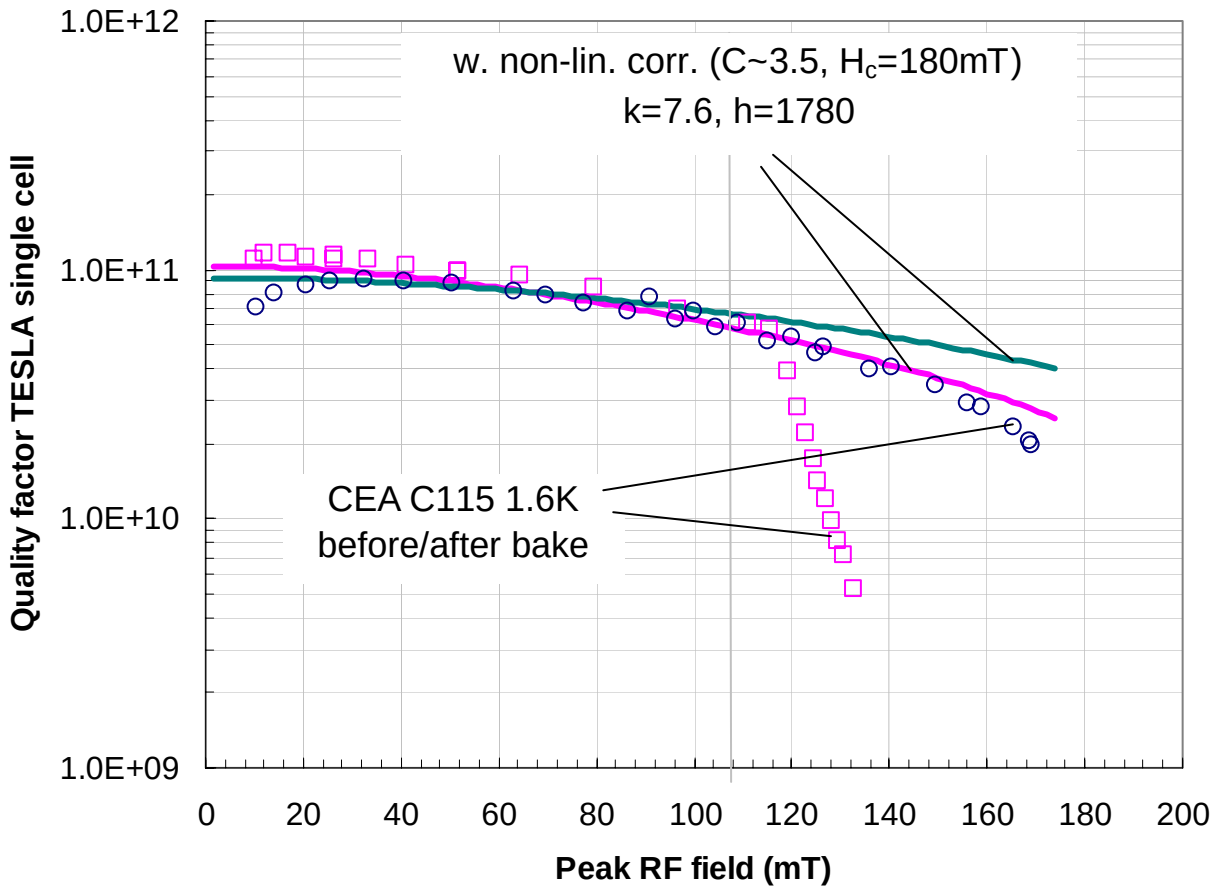
Comparison Model-Data: CEA – C103



Tbath	1.44 K
G	283 Ω
wall	2.6 mm
κ (Tb)	6.1 W/m/K
h_K (Tb)	1090 W/m^2/K
Rres	3.2(4.2) nOhm
Rbcs(Tb)	0.5 (0.5) nOhm
$\Delta/k_B T_c$	2 (2.05)
A(f) $\cdot 10^5$	2.76(2.13) Ω
Tc	9.2 K
f	1.3 GHz
C	4.5 (4.5)
Bc,therm	180 mT

THERMAL MODEL UNDER-ESTIMATES Q SLOPE EVEN WITH NON-LINEAR CORRECTION?

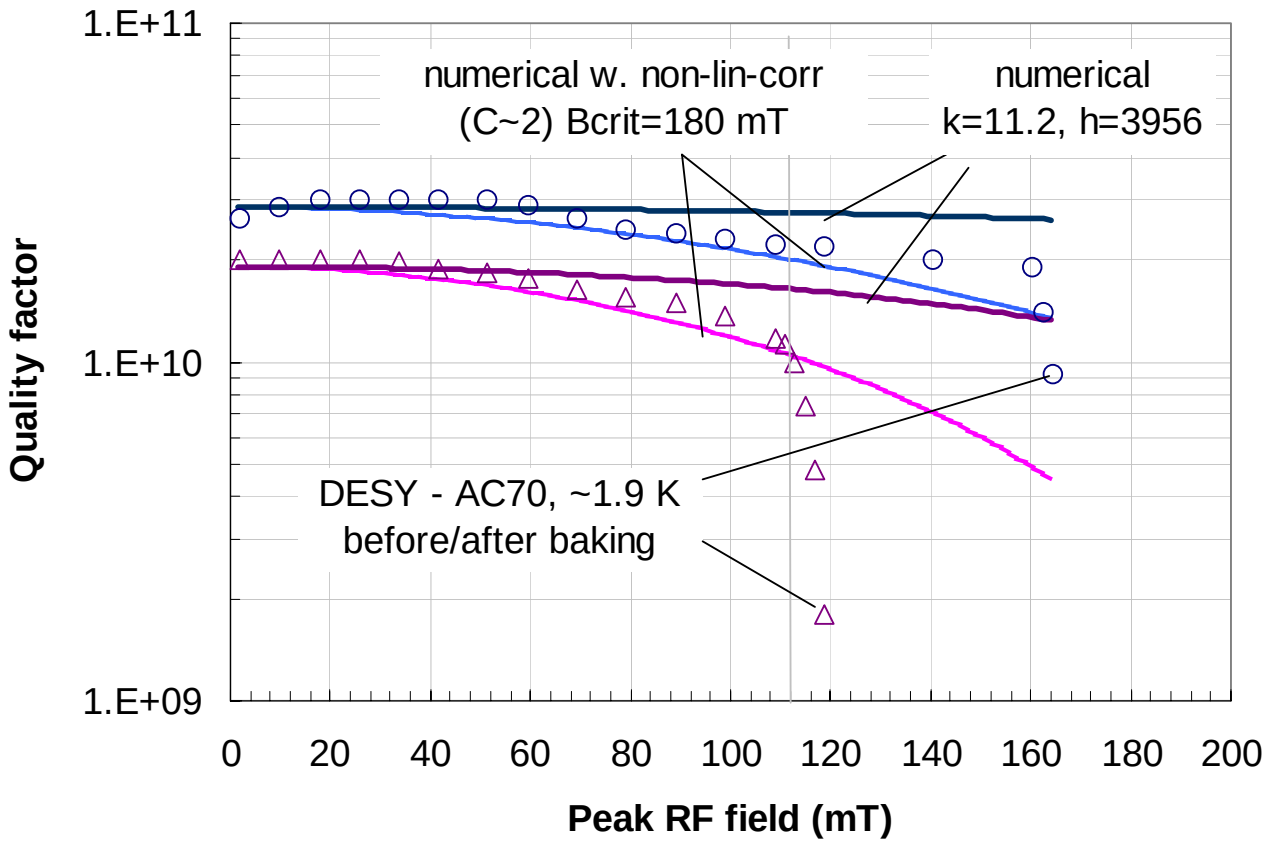
Comparison Model-Data: CEA – C115



Tbath	1.6 K
G	283 Ω
wall	2.6 mm
κ (Tb)	7.6 W/m/K
h_K (Tb)	1780 W/m^2/K
Rres	1(2) nOhm
Rbcs(Tb)	1.7(1.05) nOhm
$\Delta/k_B T_c$	1.97 (1.93)
A(f) 10^5	2.5 (1.2) Ω
Tc	9.2 K
f	1.3 GHz
C	3.6 (3.4)
Bc,therm	180 mT

THERMAL MODEL INCL. NON-LINEAR BCS FITS WELL MEDIUM FIELD SLOPE, BUT UNDER-ESTIMATES ULTIMATE Q SLOPE

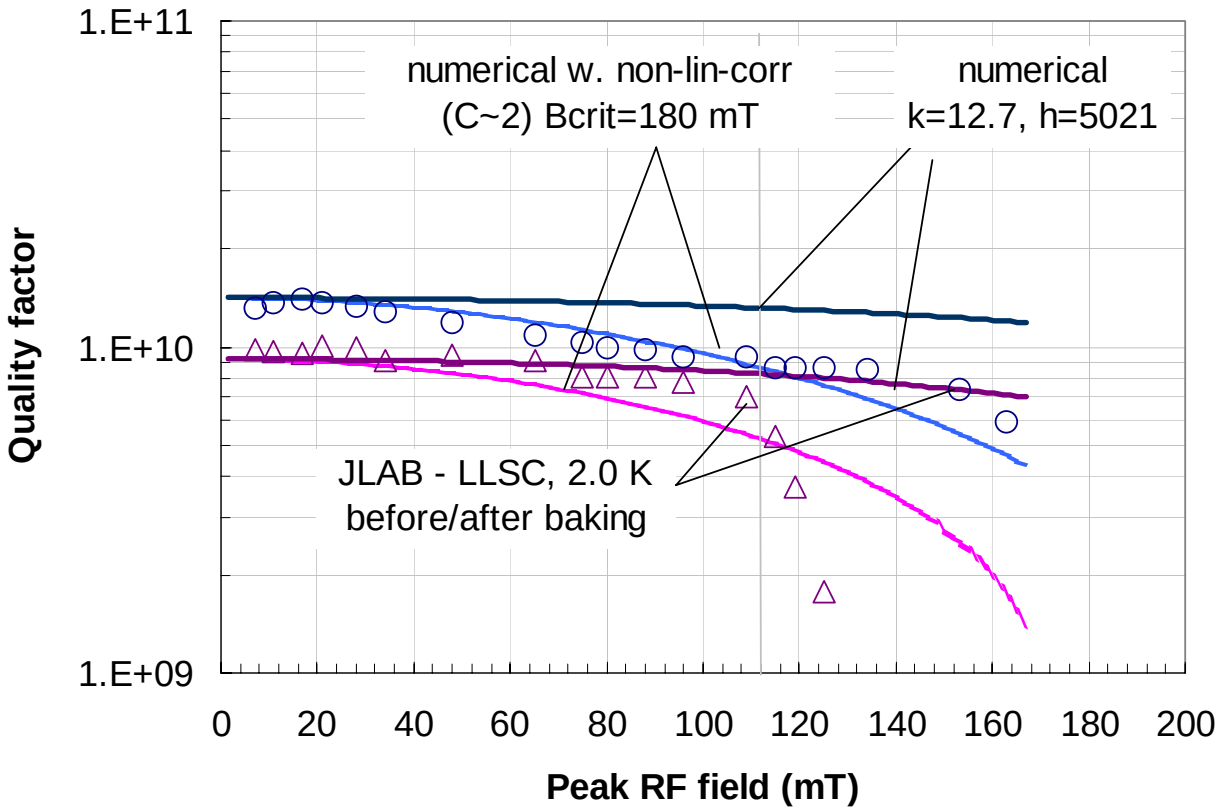
Comparison Model-Data: Best DESY 9-cell cavity



Tbath	2 (1.9) K
G	270 Ω
wall	2.6 mm
κ (Tb)	11.22 W/m/K
h_K (Tb)	3956 W/m²/K
Rres	-10(5.2) nOhm
Rbcs (Tb)	24(4.3) nOhm
$\Delta/k_B T_c$	1.53(1.94)
A(f) $\cdot 10^5$	0.597(1.058) Ω
Tc	9.2 K
f	1.3 GHz
C	1.5 (2.5)
Bc,therm	180 mT

Medium field Q slope is described with non-linear BCS correction BUT Ultimate Q-slope is not well described by models!

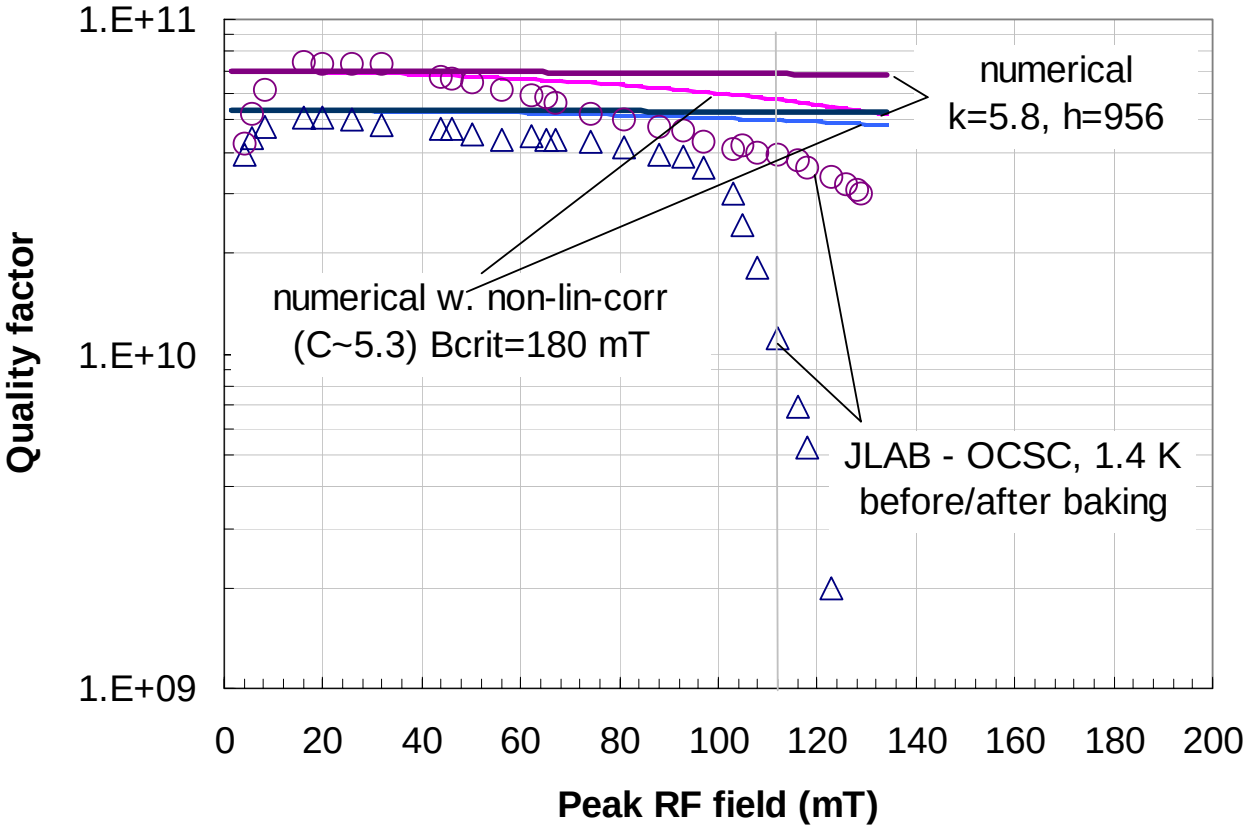
Comparison Model-Data: J-Lab – Low Loss Cavity



Tbath	2.0 K
G	282 Ω
wall	2.6 mm
κ (Tb)	12.7 W/m/K
h_K (Tb)	5021 W/m^2/K
Rres	17(9.4) nOhm
Rbcs (Tb)	31(20) nOhm
$\Delta/k_B T_c$	2.1(1.94)
A(f) $\cdot 10^5$	4.4(1.7) Ω
Tc	9.2 K
f	1.5 GHz
C	2.6 (2.2)
Bc,therm	180 mT

Medium field Q slope is described with non-linear BCS correction BUT Ultimate Q-slope is not well described by models!

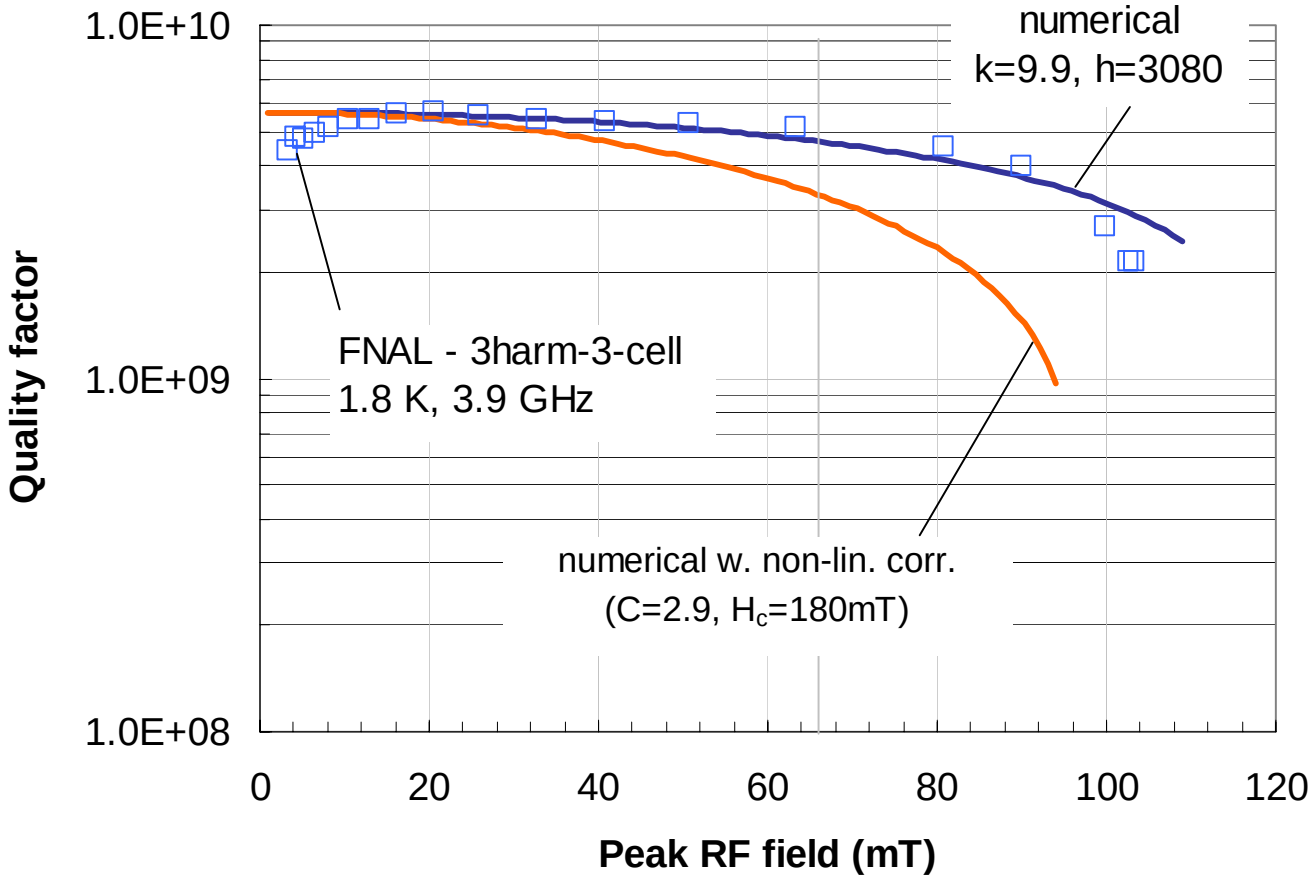
Comparison Model-Data: J-Lab – CEBAF 1-Cell New



Tbath	1.4 K
G	273 Ω
wall	2.6 mm
κ (Tb)	5.8 W/m/K
h_K (Tb)	956 W/m^2/K
Rres	3.6(5) nOhm
Rbcs (Tb)	3.9(5.1) nOhm
$\Delta/k_B T_c$	2.1(2.15)
A(f) $\cdot 10^5$	4.46 (2.38) Ω
Tc	9.2 K
f	1.5 GHz
C	5.2 (5.5)
Bc,therm	180 mT

Neither Medium field nor ULTIMATE Q slope is described, even with non-linear BCS correction!

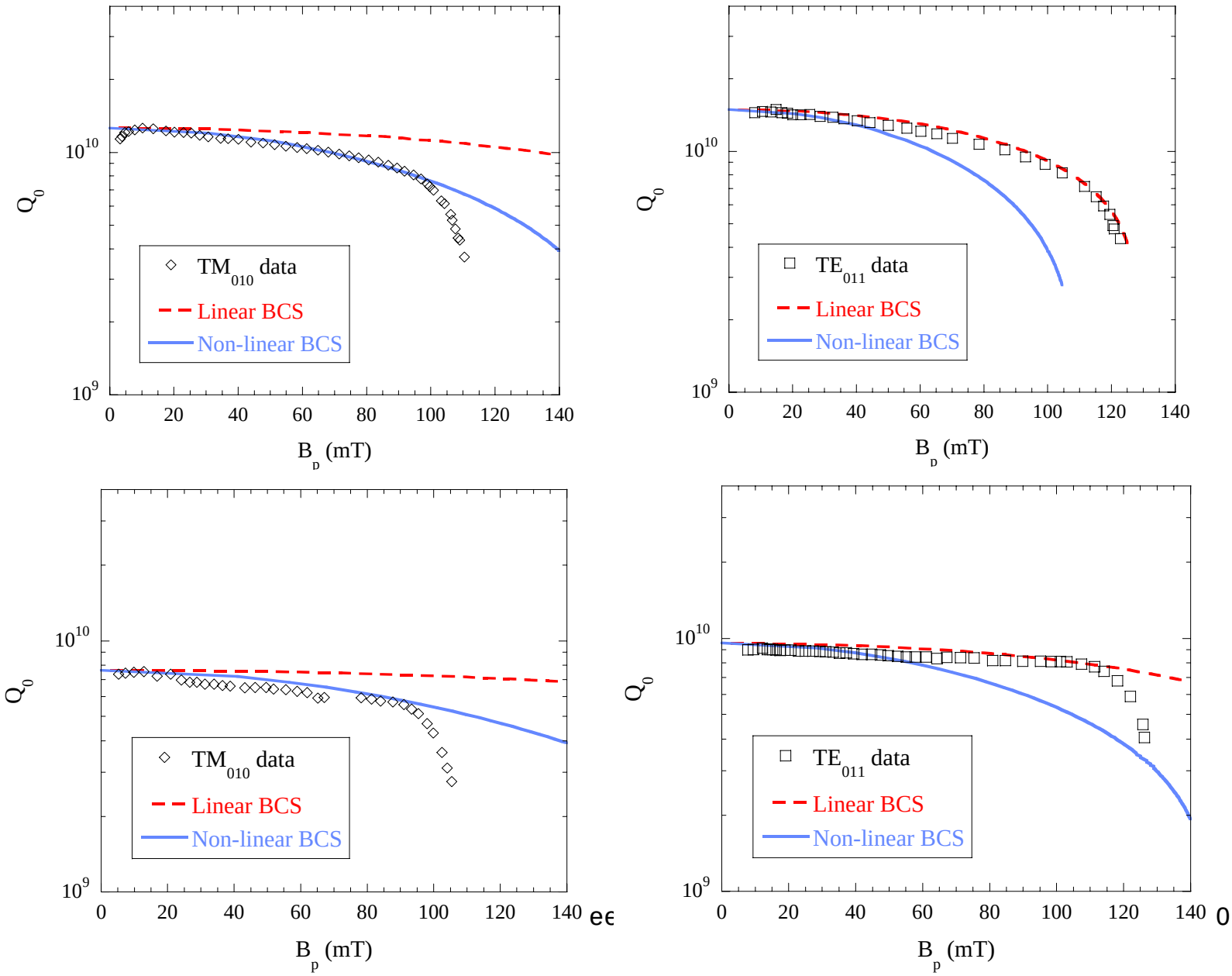
Comparison Model-Data: FNAL 3.9 GHz



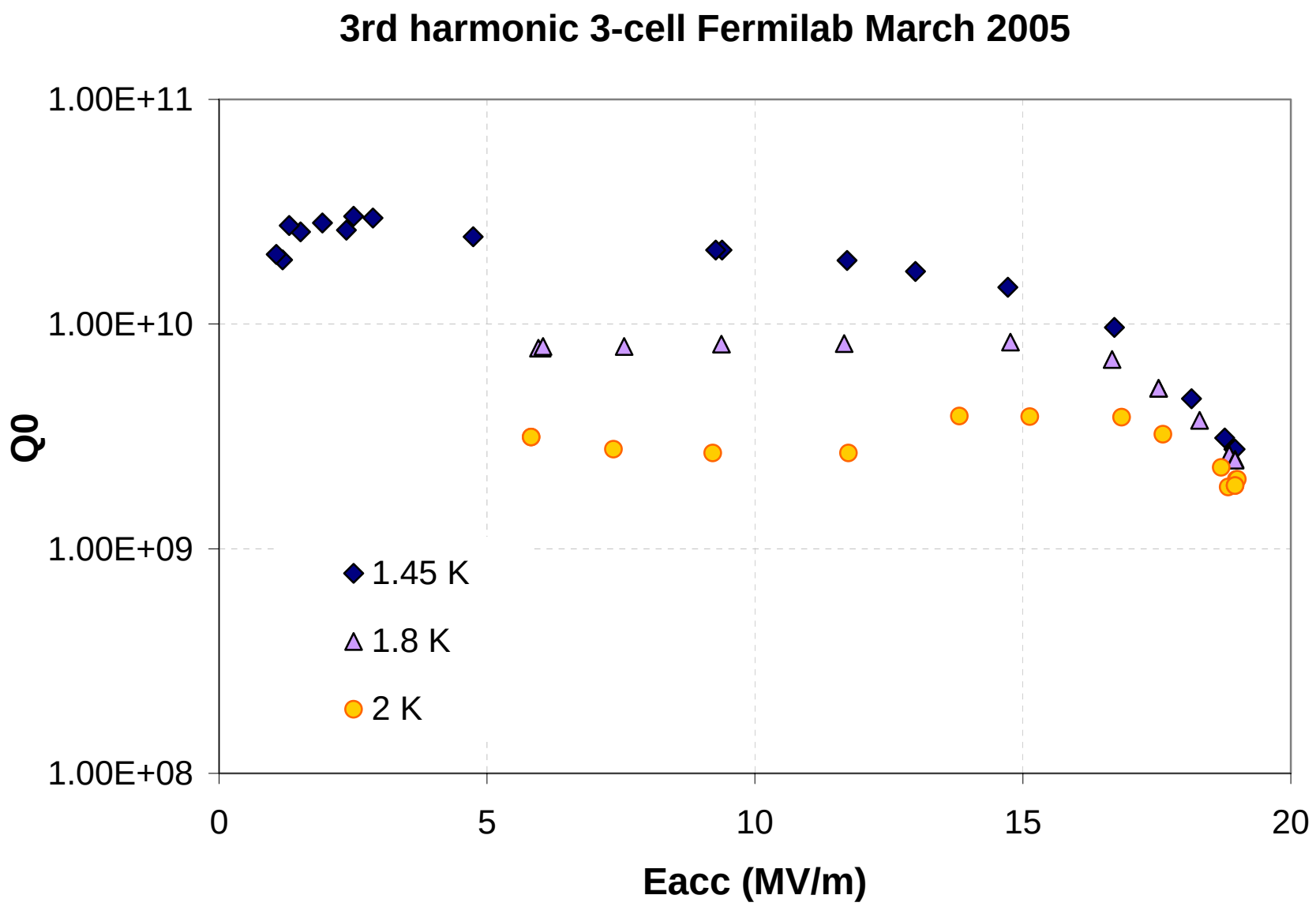
Tbath	1.8 K
G	291 Ω
wall	2.6 mm
κ (Tb)	9.9 W/m/K
h_K (Tb)	3080 W/m^2/K
Rres	10 nOhm
Rbcs (Tb)	40 nOhm
$\Delta/k_B T_c$	1.92
$A(f)\cdot 10^5$	14.8 Ω
Tc	9.2 K
f	3.9 GHz
C	2.9
Bcrit	180 mT

FOR 3.9 GHz CASE LINEAR MODEL APPEARS OK?

G. Ciovati CEBAF 1cell in TM (1.47) and TE (2.82 GHz)



ee 0


3rd harmonic 3-cell Fermilab March 2005
1.00E+11
1.00E+10
1.00E+09
1.00E+08
Q0
0
5
10
15
20
Eacc (MV/m)
1.45 K
1.8 K
2 K

SUMMARY - 1

	C-103	C-115	D-AC70	F-3C-1	J-LLSC	J-OCSC
$_0$ (K)	1.44	1.6	2 (1.9)	1.8	2.0	1.4
(Ω)	283	283	270	291	282	273
(mm)	2.6	2.6	2.6	2.6	2.6	2.6
(T_0) (W/K/m)	6.1	7.6	11.22	9.9	12.7	5.8
$_{ap}(T_0)$ (W/K/m^2)	1090	1780	3956	3080	5021	956
RR *	300	300	300	300	300	300
$_{res}$ (nΩ)	3.2 (4.2)	1 (2)	-10 (5.2)	10	17 (9.4)	3.6 (5)
$_{bcs,lin}(T_0)$ (nΩ)	0.5 (0.3)	1.7 (1.05)	24 (4.3)	40	31 (20)	3.9 (5.1)
$/k_BT_c$	2 (2.05)	1.97 (1.93)	1.53 (1.94)	1.92	2.1 (1.94)	2.09 (2.15)
(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)
$_c$ (K) *	9.2	9.2	9.2	9.2	9.2	9.2
/2π (GHz)	1.3	1.3	1.3	3.9	1.5	1.5
(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)
$_0H_c$ (mT) *	180	180	180	180	180	180

Medium Q	NO	NON-LIN	NON-LIN	LIN	NON-LIN	NO
Ultimate Q	NO	NO	NO	-	NO	NO

SUMMARY - 2

- At 2K THERMAL MODELS wout NON-LINEAR CORRECTION TO RBCS UNDERESTIMATE Q-SLOPE, EVEN FOR BAKED CAVITIES.
- INCLUDING NON-LINEAR CORRECTION OF RBCS DUE TO FIELD IMPROVES THE AGREEMENT.
- THE ULTIMATE Q-SLOPE (before baking) IS DESCRIBED BY NO KNOWN BCS BASED MODEL!
- AT T~1.4 K NOT EVEN THE NON-LINEAR BCS SUFFICES, AT 3.9 GHz LINEAR BCS ONLY FITS DATA?
- THERMAL MODELS APPEAR TO PREDICT REASONABLY WELL QUENCH FIELD IN FNAL 3.9 GHZ CAVITIES (thermally limited)! In 1.3 GHz CAVITIES THE THERMAL QUENCH IS PREDICTED TO BE >300 mT..
- Baking effect cannot be entirely be explained by the change of the linear BCS resistance!

Surface Resistance Review

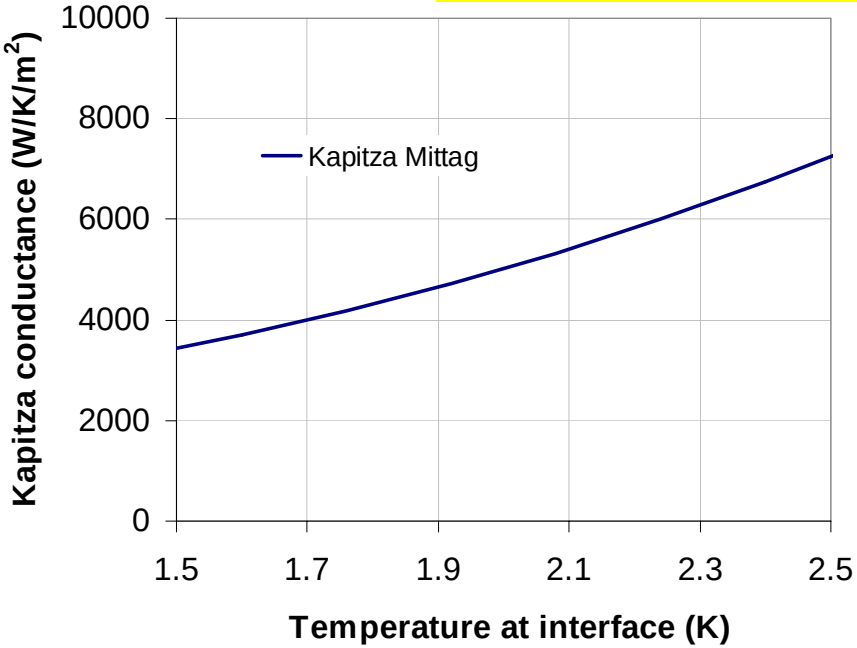
- BCS surface resistance
  - Basic BCS
  - Corrections to BCS due to H_{crit}
  - Interface tunnel exchange
- Residual resistance
  - Dielectric loss in oxide layer
  - Trapped flux (AF)
  - Localized states
- Grain-boundary contribution
  - Field-enhancement at the grain edges
  - Hysteresis loss due to JF in GBs
- ????????????????
  - ???

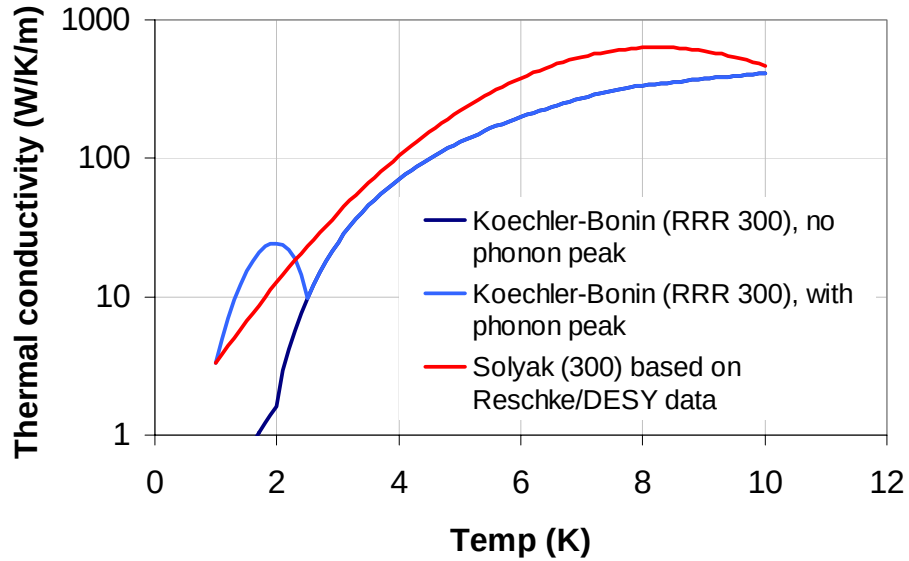
$$R_s \approx \frac{1}{2}\omega^2 \mu_0^2 \lambda_L^2 \sigma_n$$

Material Properties

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

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

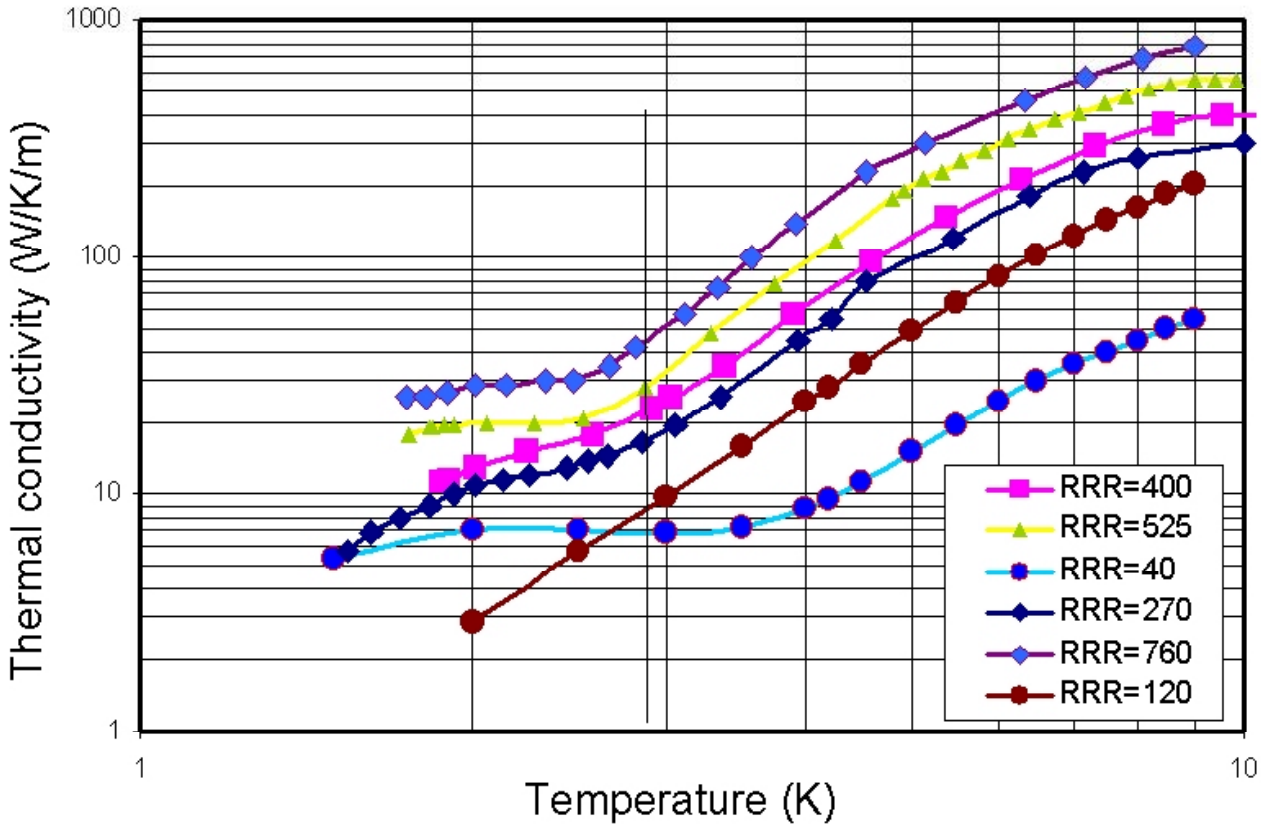




Mittag

Koechler - Bonin

Material Properties



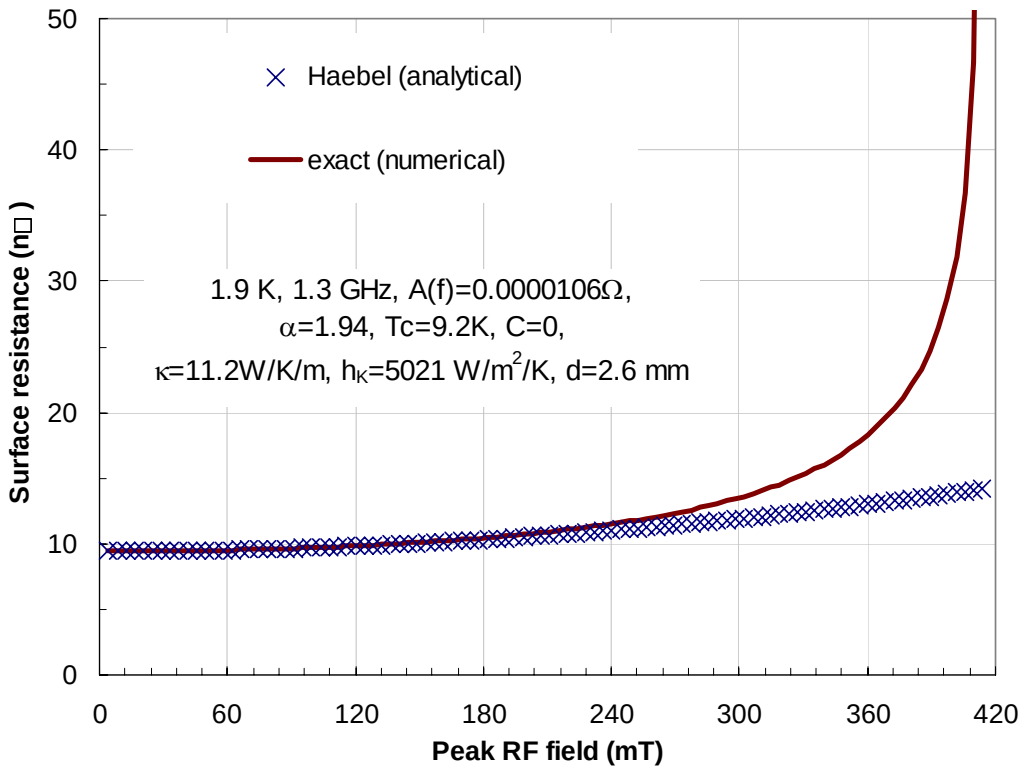
Courtesy of D. Retschke / DESY

Analytical "Haebel" Model

$$R_s(T) \approx R_s(T_0) + \left.\frac{\partial R_s}{\partial T}\right|_{T_0} \Delta T \quad (\Omega)$$

$$\left.\frac{\partial R_s}{\partial T}\right|_{T_0} = \left(R_s(T_0) - R_{s0}\right)\left(\frac{\alpha T_c}{T_0^2} - \frac{1}{T_0}\right)$$

$$R_s(H_{RF}) \approx R_s(T_0)\left[1 + \left(\frac{dh_{Kap}(T_0) + \kappa(T_0)}{2\kappa(T_0)h_{Kap}(T_0)}\right)\left.\frac{\partial R_s(T)}{\partial T}\right|_{T_0} H_{RF}^2\right]$$



First order Taylor expansion of Rs leads to analytical expression for $R_s(H_{RF})$;

Not accurate close to quench!