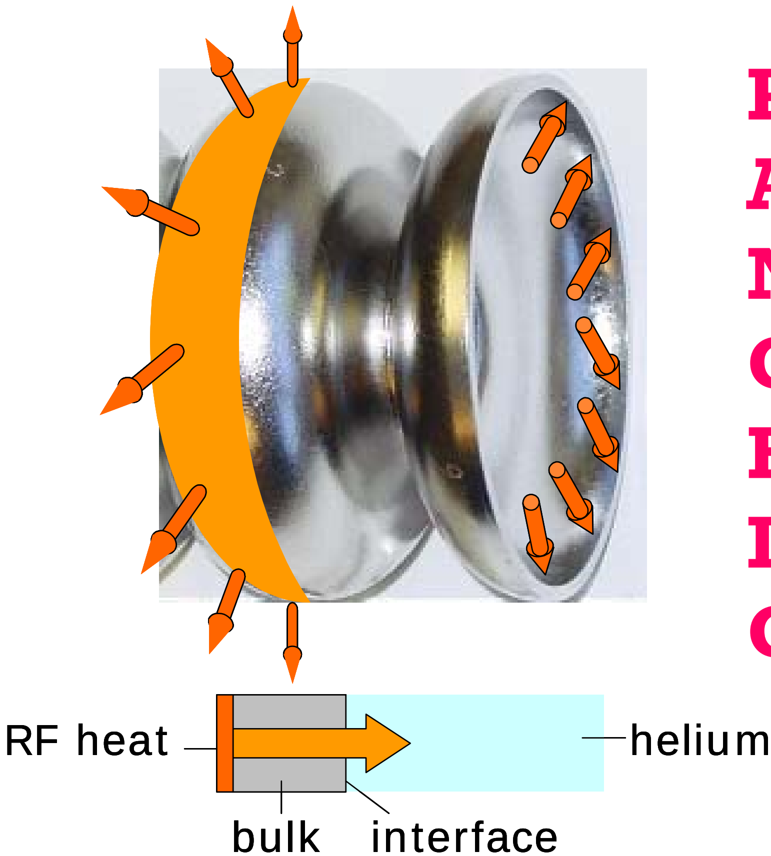
Evidence of Non-Linear BCS Resistance in Multi-Lab Cavity Data to Model Comparison



P. Bauer - FNAL,
A. Gurevich – ASC-UW,
N. Solyak - FNAL,
G. Ciovati - JLab,
B. Visentin - CEA,
L. Lilje - DESY.
G.Eremeev - Cornell

Thermal Feedback

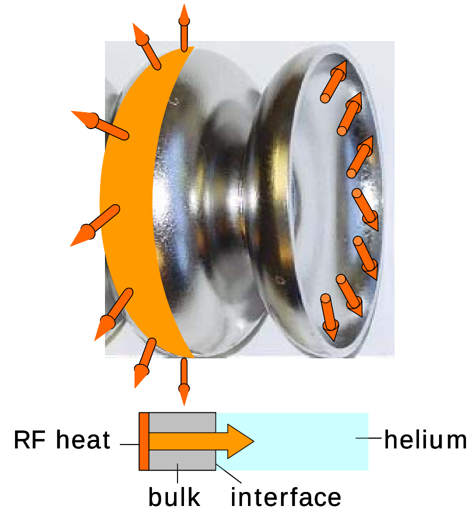
Thermal feed-back: exponential T-dependence of BCS surface resistance: $\rightarrow R_s \rightarrow P_{RF} \rightarrow \Delta T \rightarrow R_s \rightarrow ....$

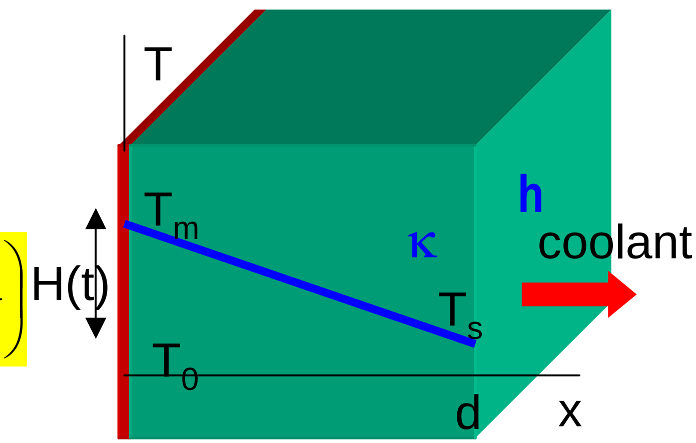
$$P_{RF} = \frac{1}{2} R_s H_\varpi^2$$

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

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

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

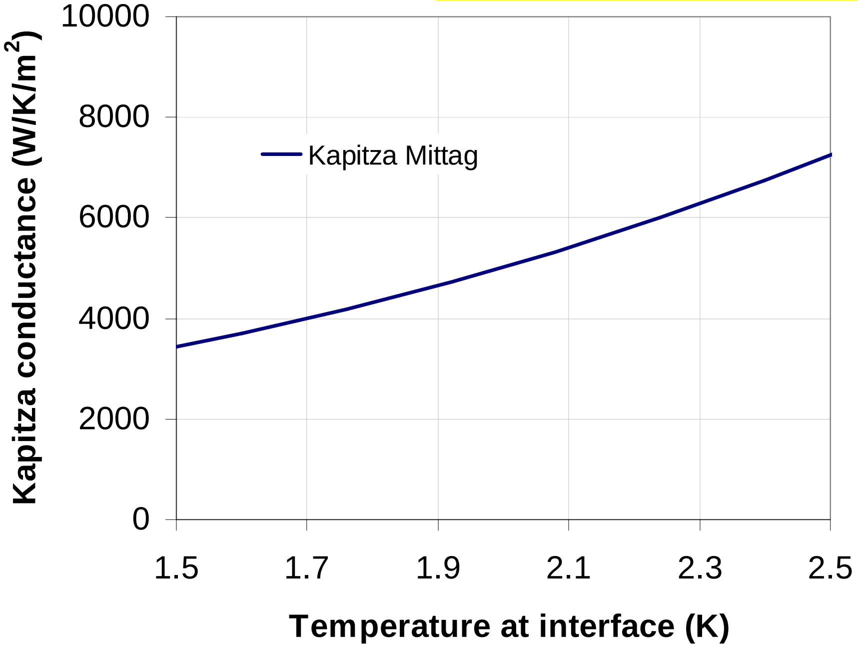




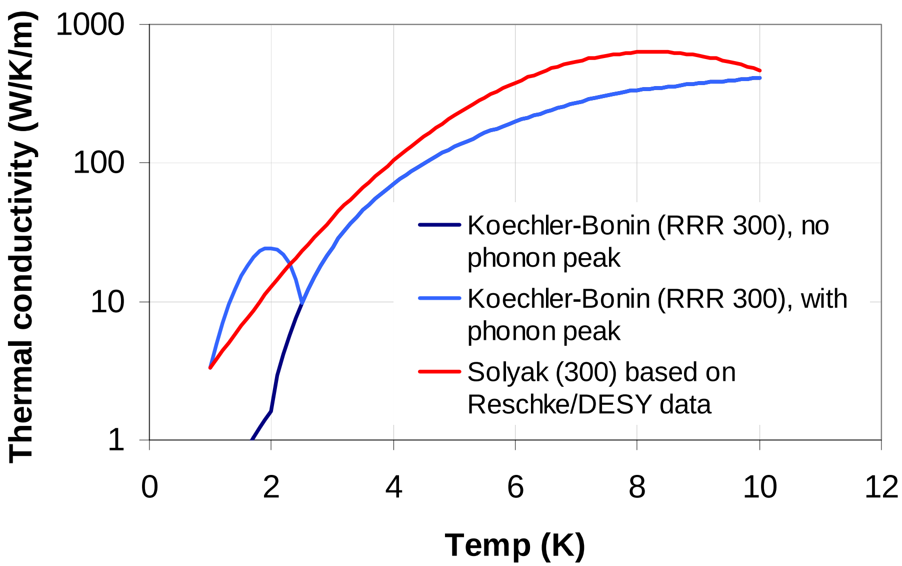
Material Properties

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

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



Mittag

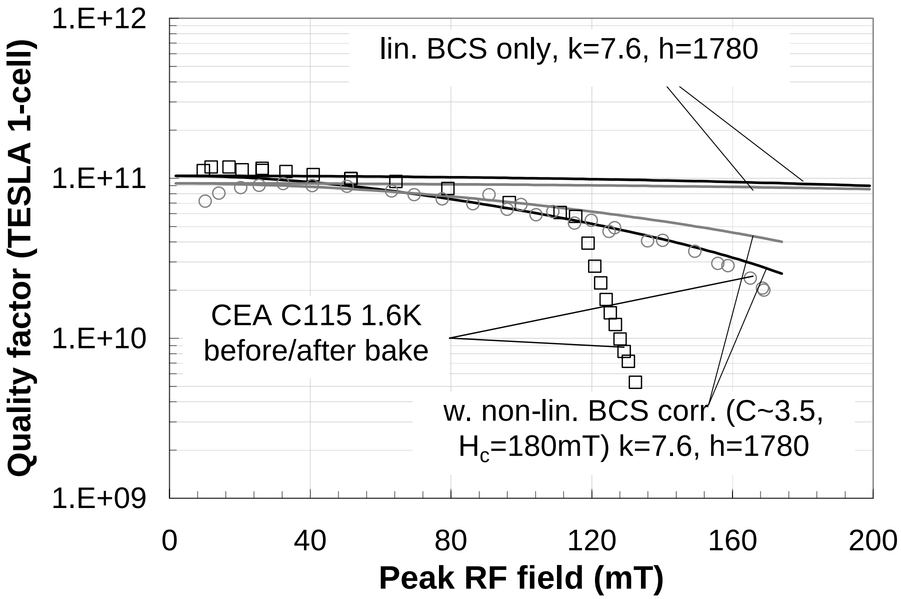


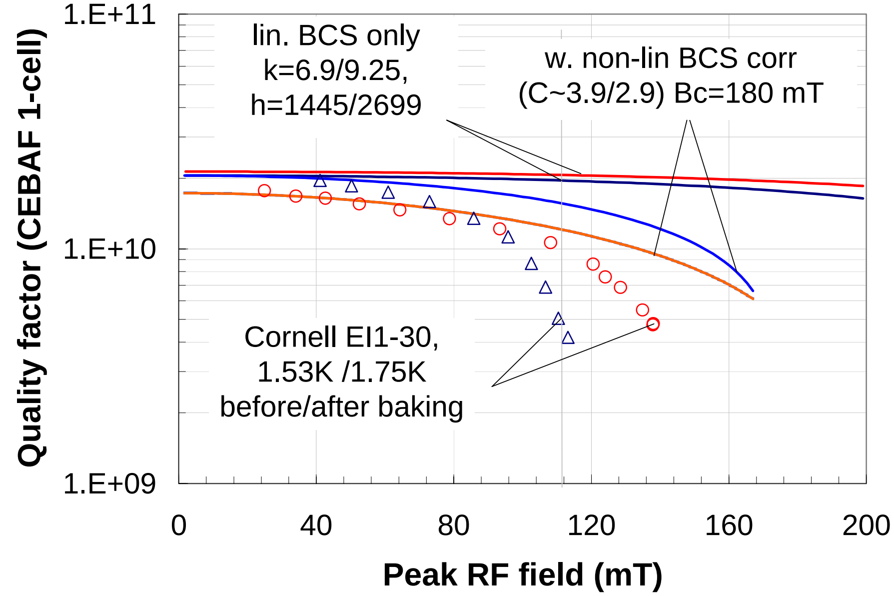
Koechler - Bonin

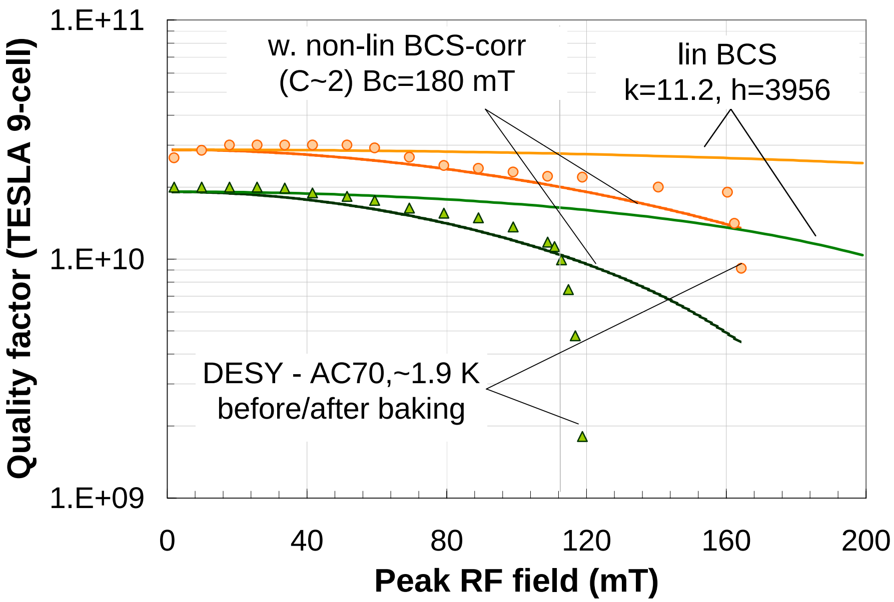
SUMMARY - TABLE

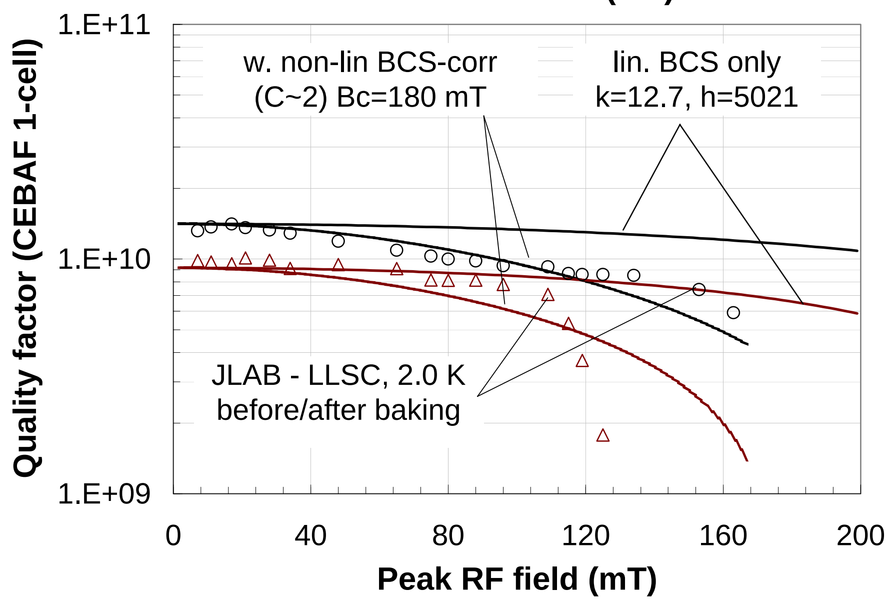
	C-103 CEA	C-115 CEA	D-AC70 DESY	F-3C-1 FNAL	J-LLSC JLAB	J-OCSC JLAB	CU-EI1-30 CORNELL
T_0 (K)	1.44	1.6	2 (1.9)	1.8	2.0	1.4	1.53 (1.75)
G (Ω)	283	283	270	291	282	273	255
d (mm)	2.6	2.6	2.6	2.6	2.6	2.6	2.75
$\kappa(T_0)$? (W/K/m)	6.1	7.6	11.22	9.9	12.7	5.8	6.9 (9.3)
$h_{Kap}(T_0)$ (W/K/m^2)	1090	1780	3956	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)
$A(\omega)$ (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
$\omega/2\pi$ (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

Comparison Model-Data: GRAPHS I

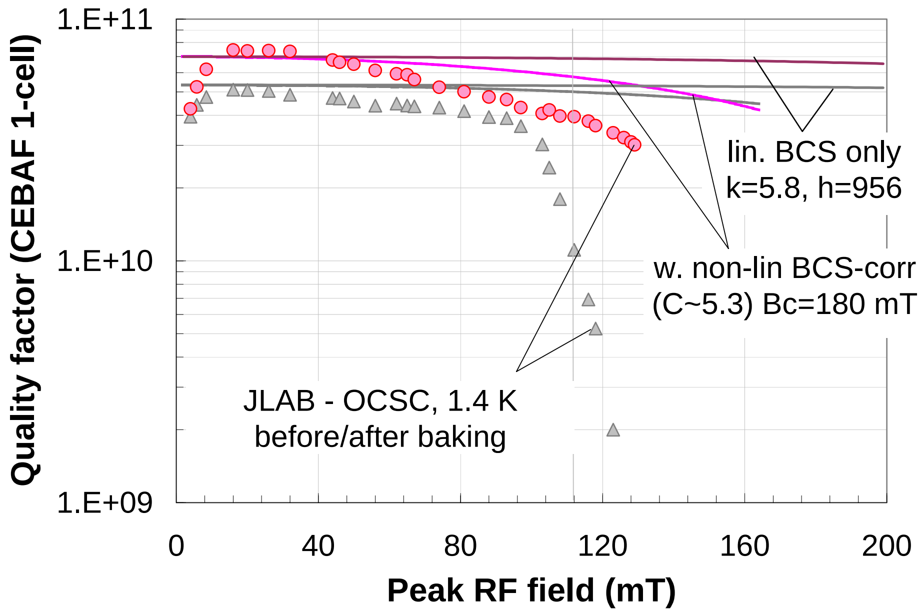


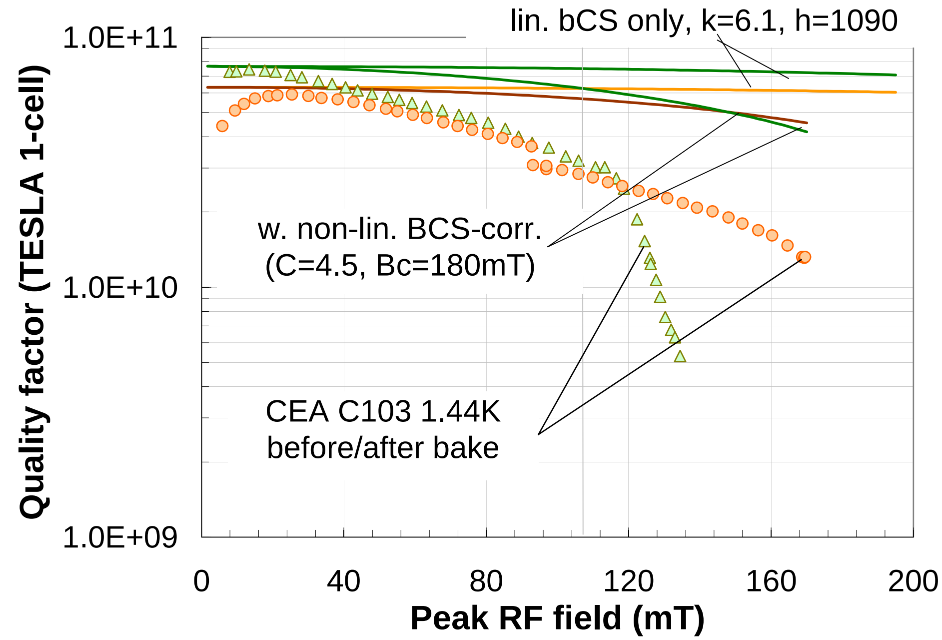


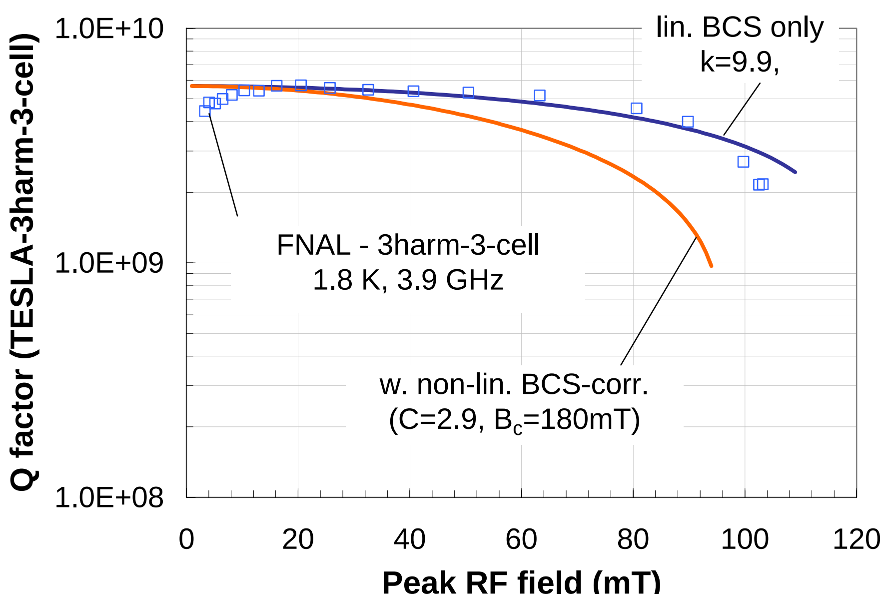




Comparison Model-Data: GRAPHS II







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

C increases with lower T and higher f!

SUMMARY

Assuming

- **A standardized set of thermal material parameters;**
- **Measured low field residual and lin BCS surface resistance contribution;**
- **TFBM in a homogeneous material;**

- **Non-lin BCS surface resistance contribution as recently presented by A. Gurevich can explain medium field Q-Slope;**
- **C is not large enough at lower temps (1.4 K) and too large at higher frequency (f>2 GHz);**
- **Non lin BCS also cannot explain ultimate field Q-drop;**

Surface Resistance Review

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

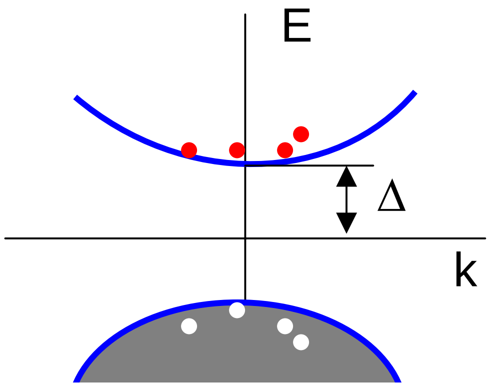
- BCS surface resistance
  - Basic BCS
  - Corrections to BCS due to H_{crit}
  - Interface tunnel exchange
- Residual resistance
  - Dielectric loss in oxide layer
  - Trapped flux (AF)
  - Localized states
- Grain-boundary contribution
  - Field-enhancement at the grain edges
  - Hysteresis loss due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

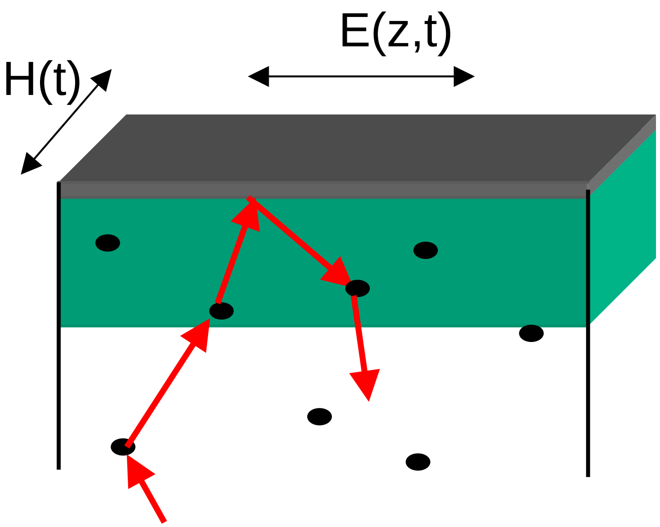
Surface Resistance

$$R_{s,RF} = R_{s,BCS}\left(T_m, H_{DC}, H_{RF}\right) + R_{res}\left(\omega, T, ..\right) + R_{s,FE}\left(H_{RF}, \beta\right) + R_{s,Btrap}\left(H_0\right) + ... \quad (\Omega)$$

- **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

BCS Surface Resistance





A. Gurevich

- **Thermal activation of normal electrons**

  $n_a = n_0(\pi k_B T/2\Delta)^{1/2}\exp(-\Delta/k_B T)$

- **Accelerating electric field**

  $E(z,t) = \mu_0\omega\lambda H_\omega e^{-\lambda|z|}\sin\omega t$

- **Scattering mechanisms and normal state conductivity**: $\sigma_n = e^2 n_0 \ell/p_F$, $p_F = \hbar(3\pi^2 n_0)^{1/3}$

- **Normal skin effect** ($\ell \ll \lambda$): multiple impurity scattering in the λ - belt:

  $R_s \sim (\mu_0^2\omega^2\lambda^3\sigma_n\Delta/(k_B T))\exp(-\Delta/k_B T)$

- **Anomalous skin effect** ($\ell \gg \lambda$): scattering by the gradient of the ac field E(z):

  Effective $\sigma_{eff} \sim e^2 n_0\lambda/p_F$; $\ell \to \lambda$

Linear BCS Surface Resistance for $H_\omega << H_c$

- Solution of the kinetic equation for type-II superconductor for the clean limit and diffusive surface scattering at $\omega^2 << \Delta T$:

$$R_s = \frac{3\mu_0^2\lambda^3\Delta}{2k_B T}\sigma_{eff}\omega^2 e^{-\Delta/(k_B T)}\left[\ln\frac{1.2k_B T\Delta\xi^2}{\hbar^2\omega^2\lambda^2}\right]$$

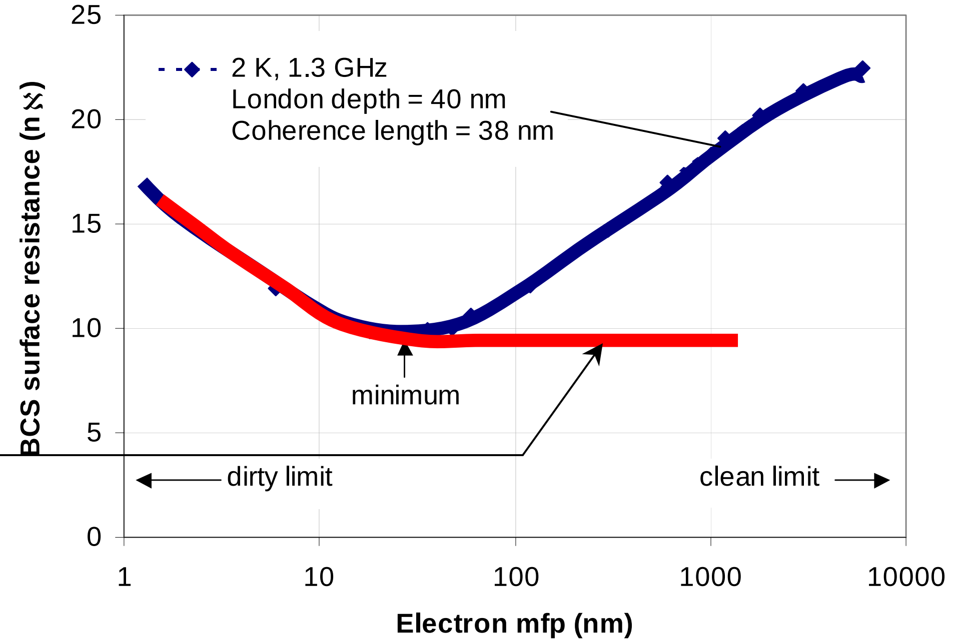
$\Delta/(k_B T_c)$ ~2, T_c~9.2K, ξ~λ~40nm

n_0~$6\cdot10^{28}$ m^{-3}, v_F~ $1.3\cdot10^6$ m/s

- **Effective conductivity** in the **non-local clean limit:**

$$\sigma_{eff} = \frac{n_0 e^2\lambda}{p_F}$$

No dependence of R_s on the normal resistivity and impurity scattering



Nonlinear BCS Surface Resistance

- RF dissipation was calculated for clean limit ($\ell \gg \lambda$) from kinetic equations for a superconductor in a strong rf field superimposed on a dc field;

  $H(t) = H_\omega \cos\omega t + H_0$

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

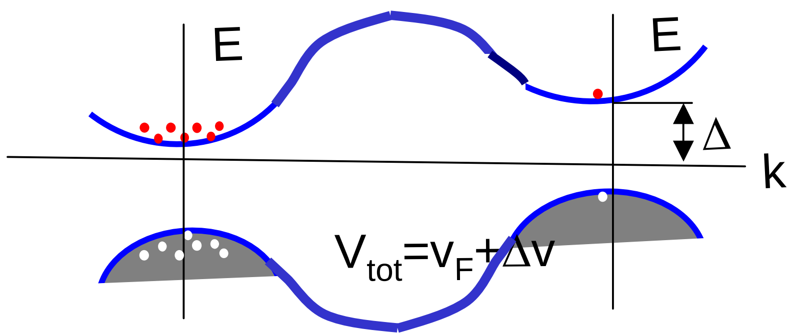
$$C(T,\omega) = \frac{\pi^2}{384}\left[1 + \frac{\ln(9)}{3\ln\left(4.1\frac{k_B T\Delta}{(\hbar\omega)^2}\left(\frac{\xi}{\lambda}\right)^2\right)}\right]\left(\frac{\Delta}{k_B T}\right)^2$$

- Nonlinear correction due to rf pair-breaking increases as the temperature decreases, At low T, the non-linearity becomes important even for comparatively weak rf amplitudes

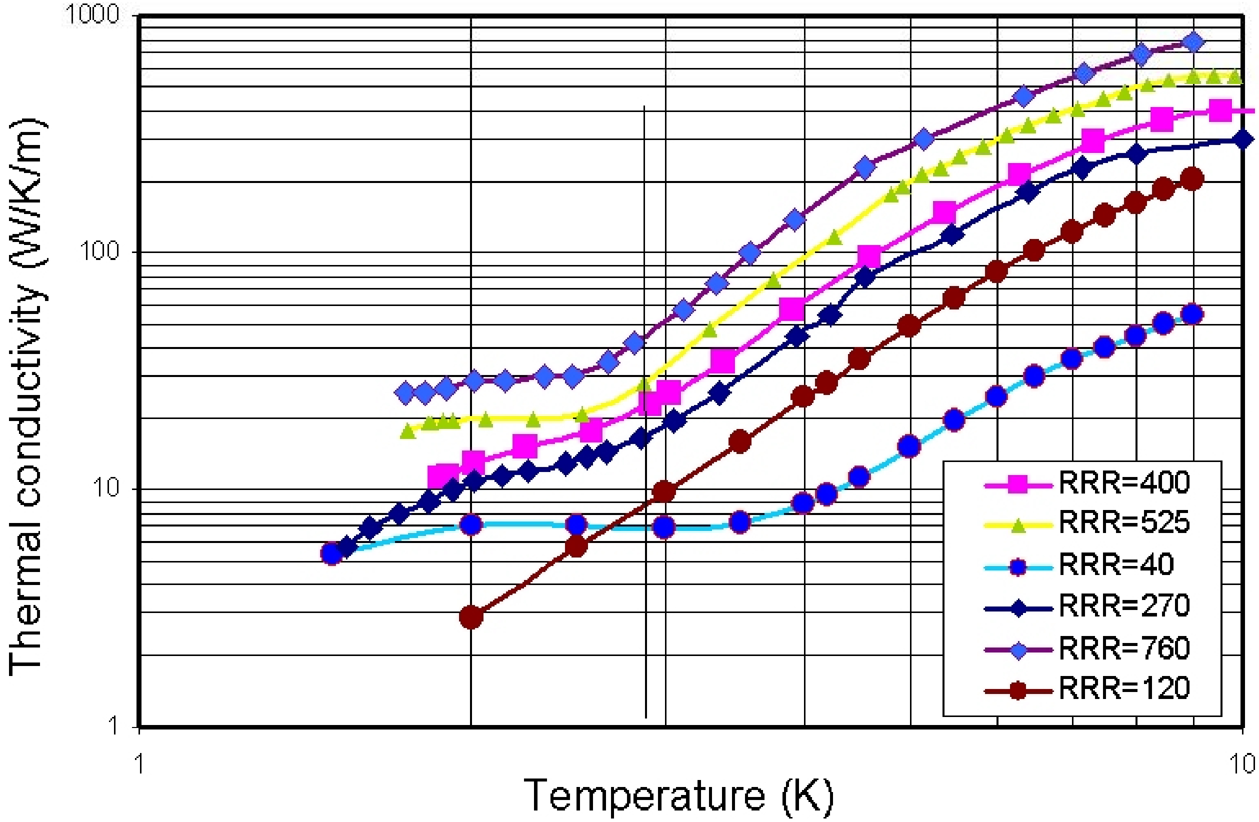
- RF power P depends quadratically on the RF magnetic field;

- Higher order terms $\sim H_\omega^4$ also appear at $H_\omega \sim H_c$;

- Contribution due to the DC magnetic field H_0 is usually counted as "residual";



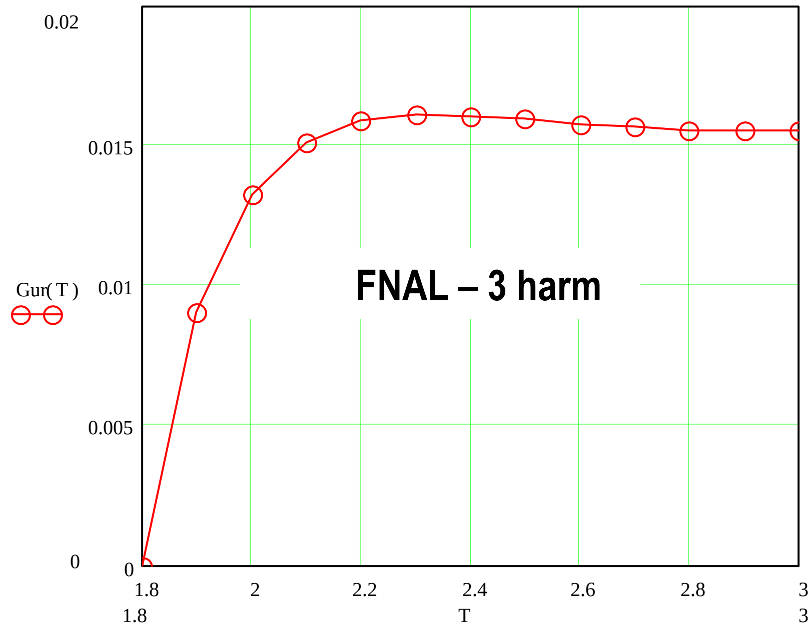
Material Properties



Courtesy of D. Retschke / DESY

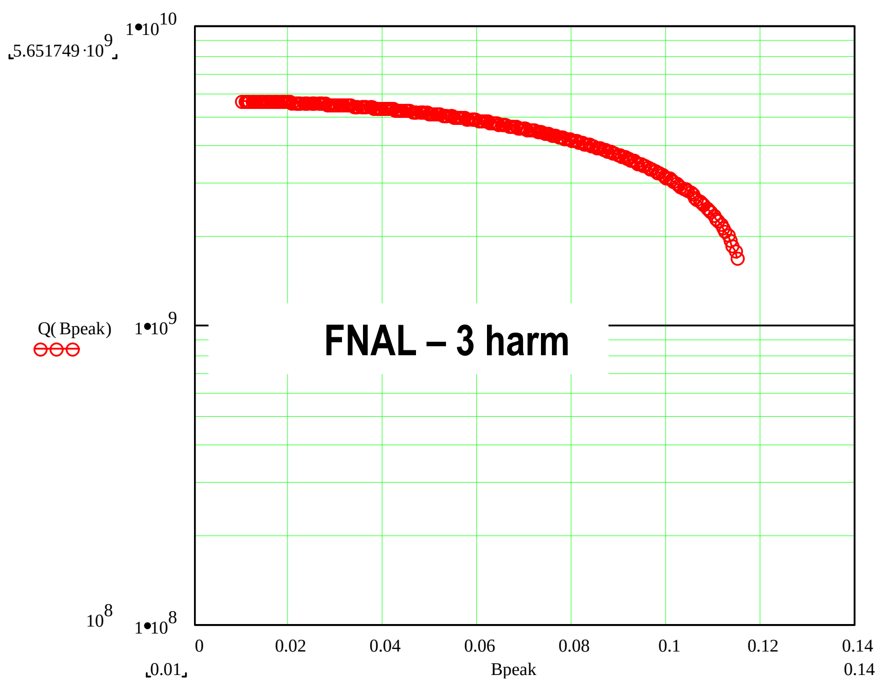
Breakdown RF Field – Linear BCS only

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



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

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

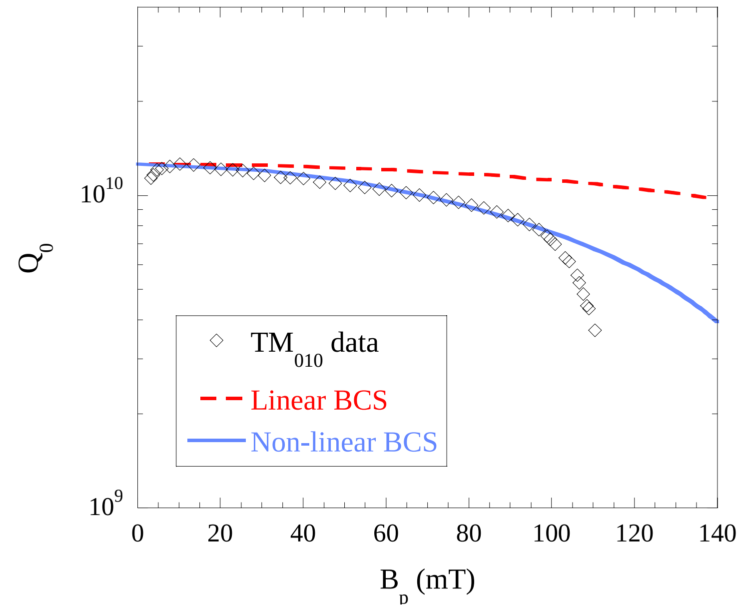


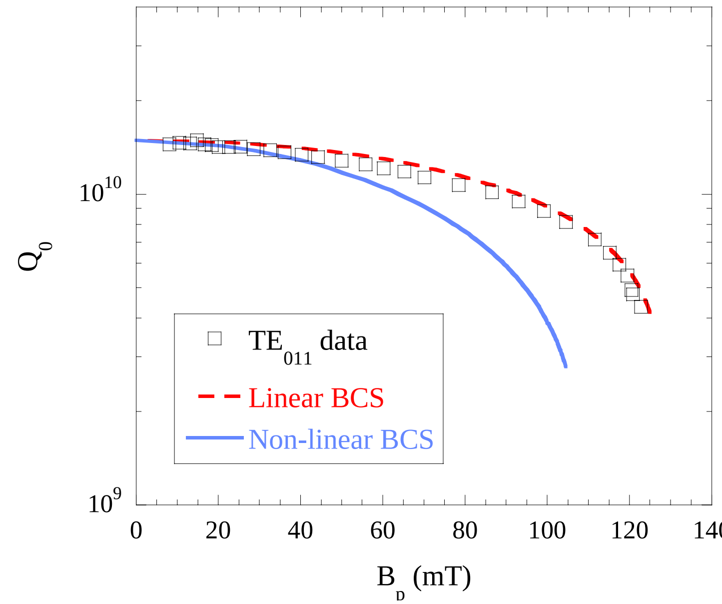
Inserting $\Delta T \sim T_0^2/\Delta$ gives an expression for the Q drop at the thermal quench:

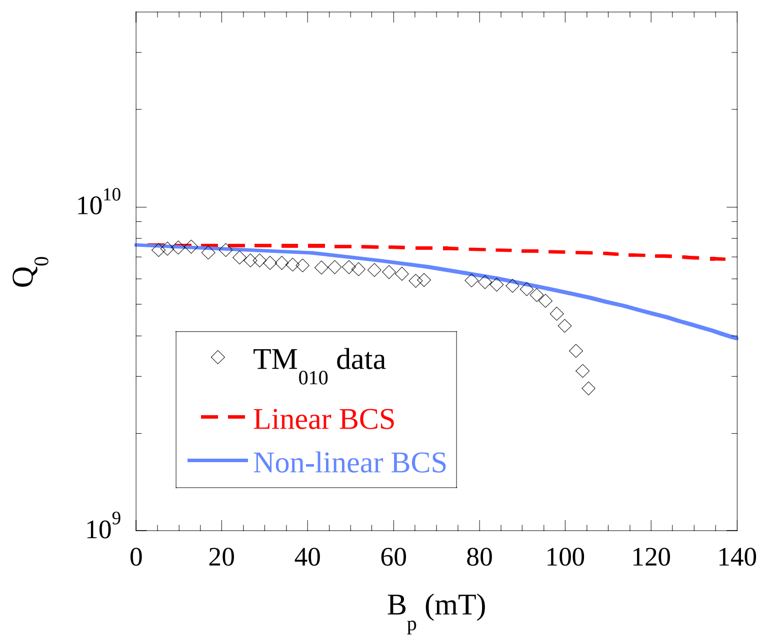
$$Q(H_b) \approx Q(0)/e$$

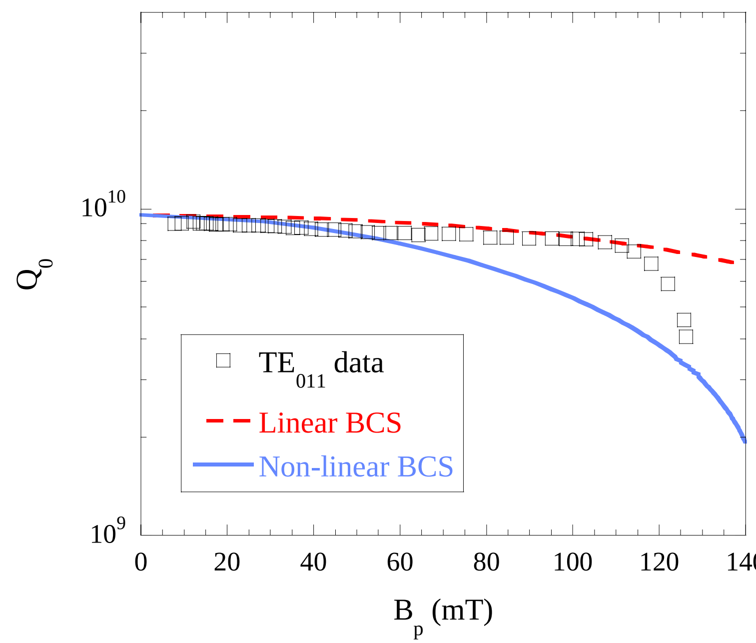
A. Gurevich

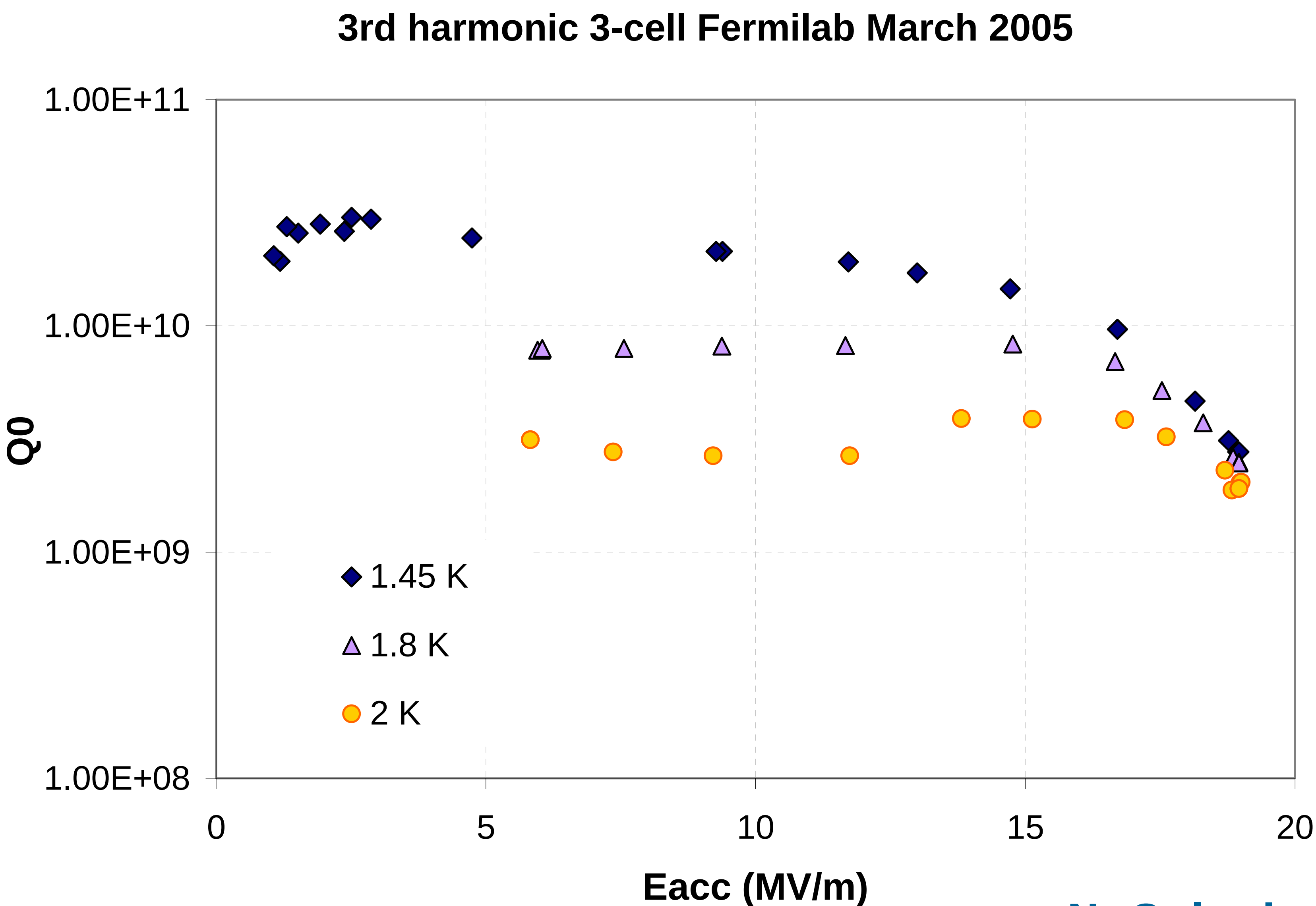
G. Ciovati CEBAF 1cell in TM (1.47) and TE (2.82 GHz)










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

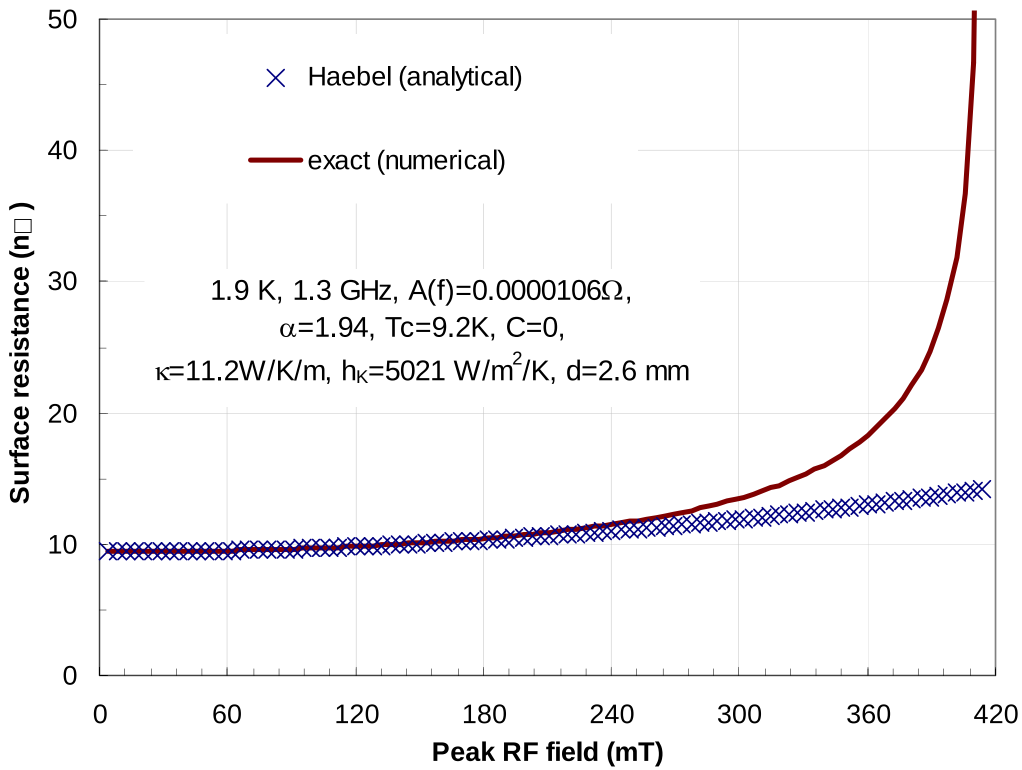
N. Solyak

Analytical "Haebel" Model

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

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

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



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

Not accurate close to quench!