Effect of low temperature baking on niobium cavities

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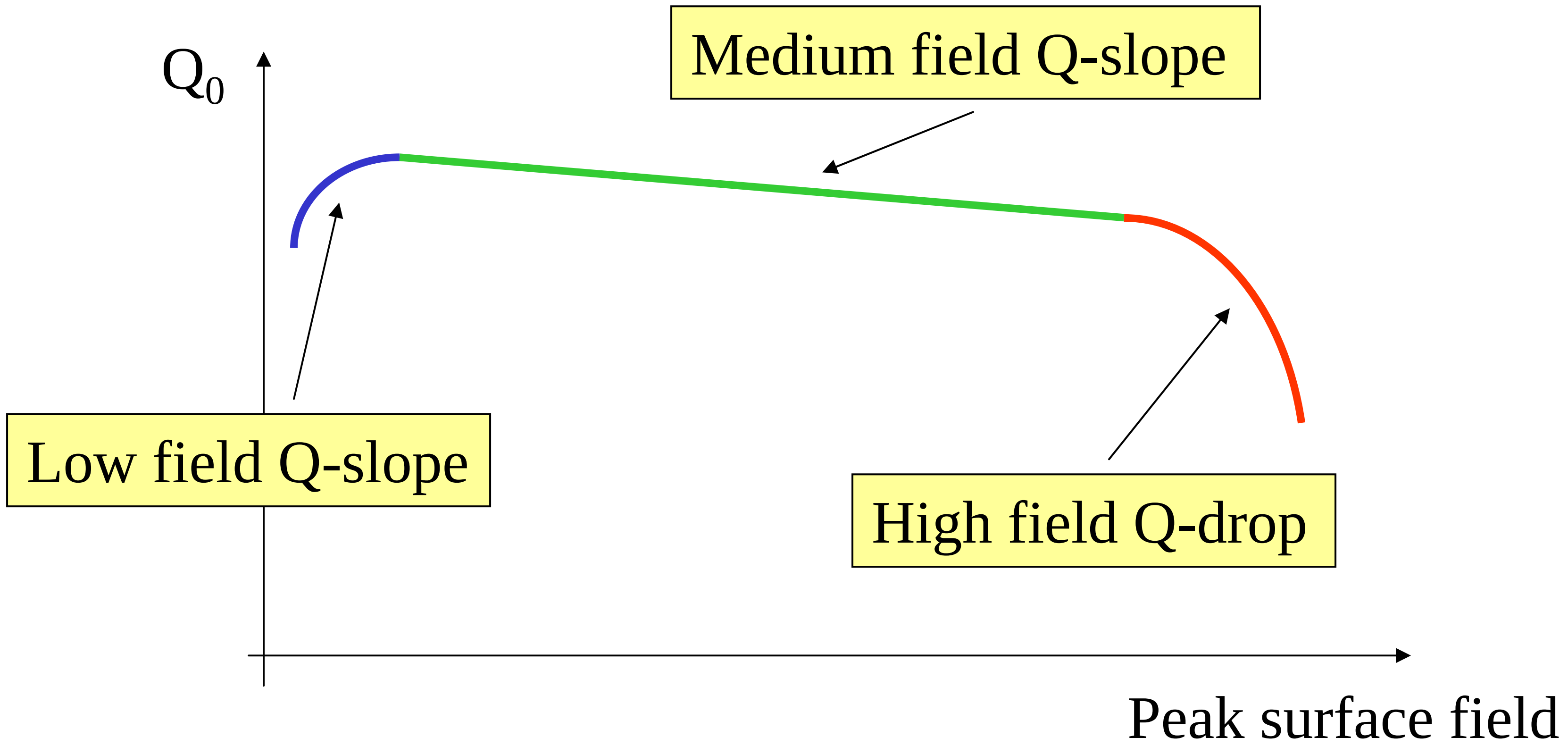
Outline

- Purpose of the study
- Measurement set-up & procedure
- Results
- Models comparison
- Conclusion

Purpose of the study

Excitation curves of bulk Nb cavities show 3 different “anomalous behaviors” in absence of field emission:



- Low temperature baking allows to change the surface composition on a nanometer scale

We studied the variations of the cavity excitation curves and of its basic superconducting parameters after baking at several temperatures for a fixed amount of time

Measurements set-up & procedure

- Measurements on one single cell CEBAF original shape at 1.467 GHz
- Cavity equipped with an input variable coupler and four calibrated Cernox thermometers
- Two Nb samples are prepared with the cavity, one is attached to the test stand.

Cavity preparation and tests for each baking temperature:

a) 20min degreasing, 1min **BCP 1:1:1** with fresh acid (≈ 7 μm removed)

b) ≈1hr HPR, assembly in clean room class 10, evacuation to ≈10^{-8} mbar

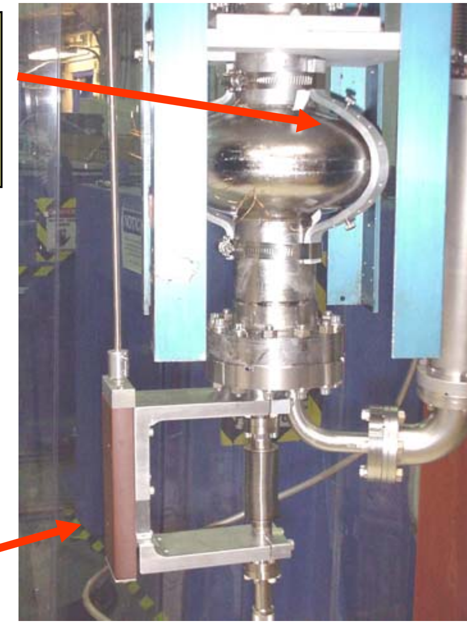
c) Surface resistance measured between 4.2K and 1.37K. Baseline Q_0 vs. field tests at 2.2K, 2K, 1.37K

d) Surface resistance and frequency shift measured between 6K and 280K with a network analyzer

e) Baking for 48hr, temperature controlled within 1°C

f) Points c) and d) repeated

Sample location

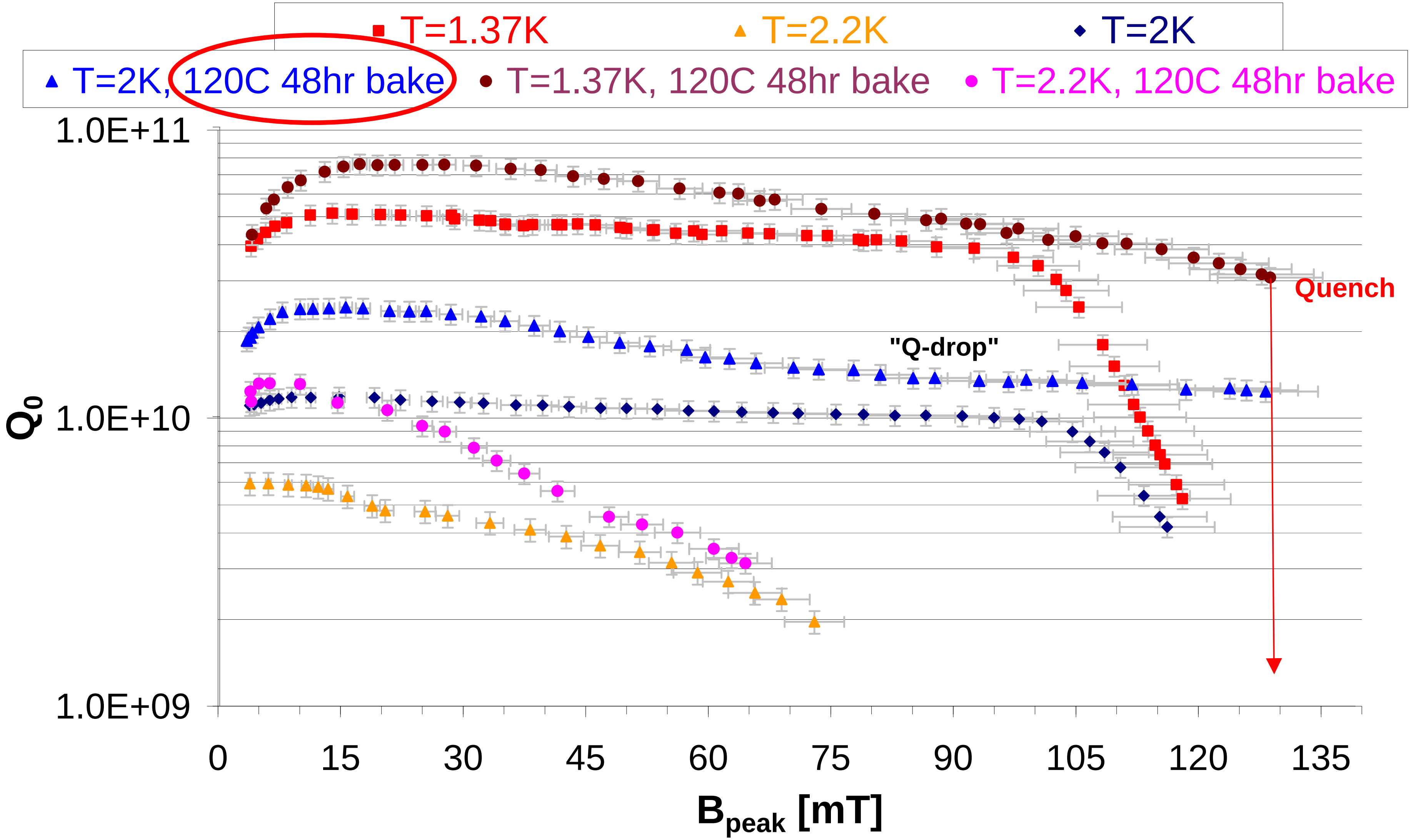


Thermometers frame

Variable coupler

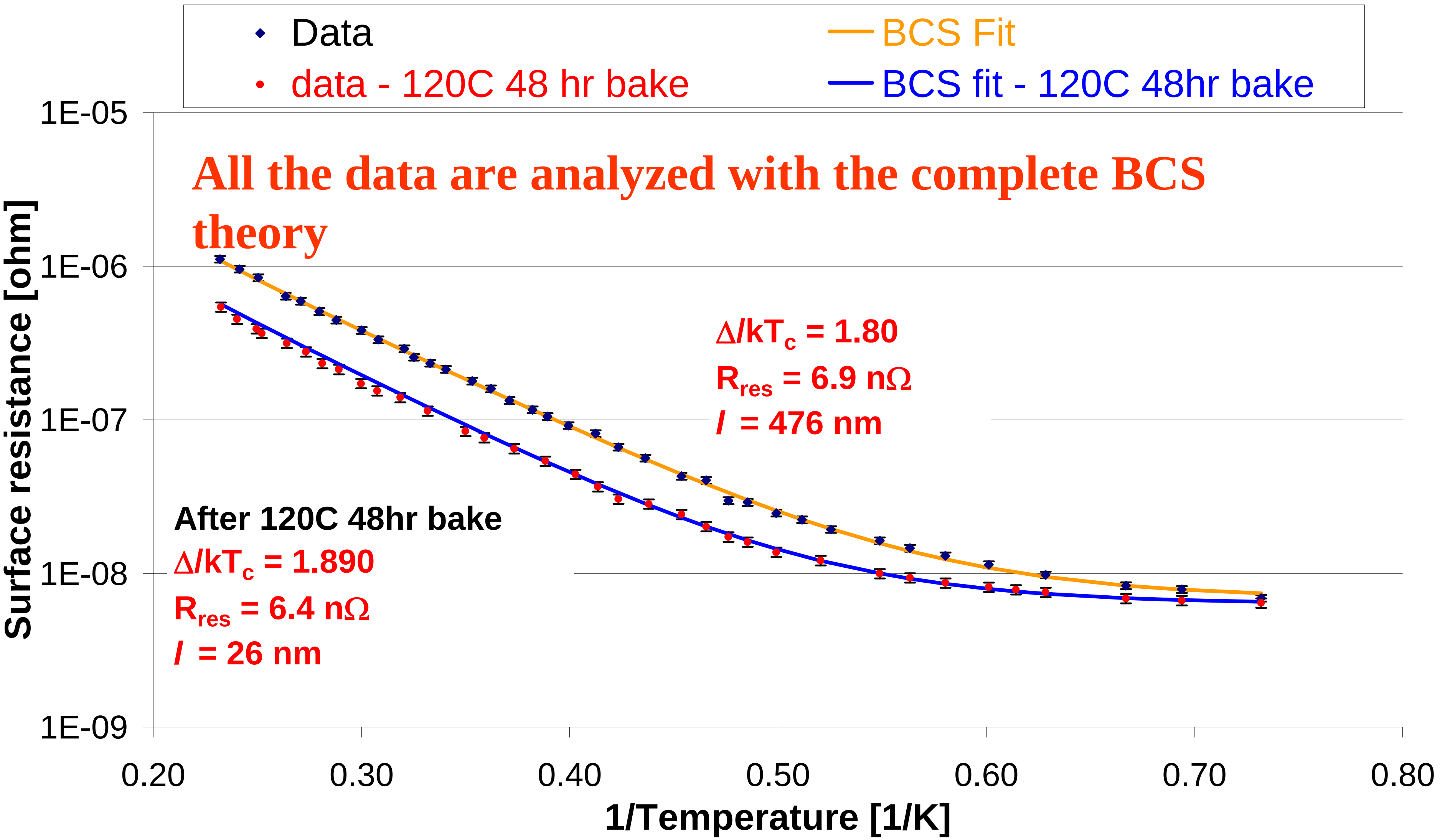
The 2 samples (1 baked, 1 not baked) are measured for their hydrogen content with the Nuclear Reaction Analysis method in SUNY Albany, NY

Results

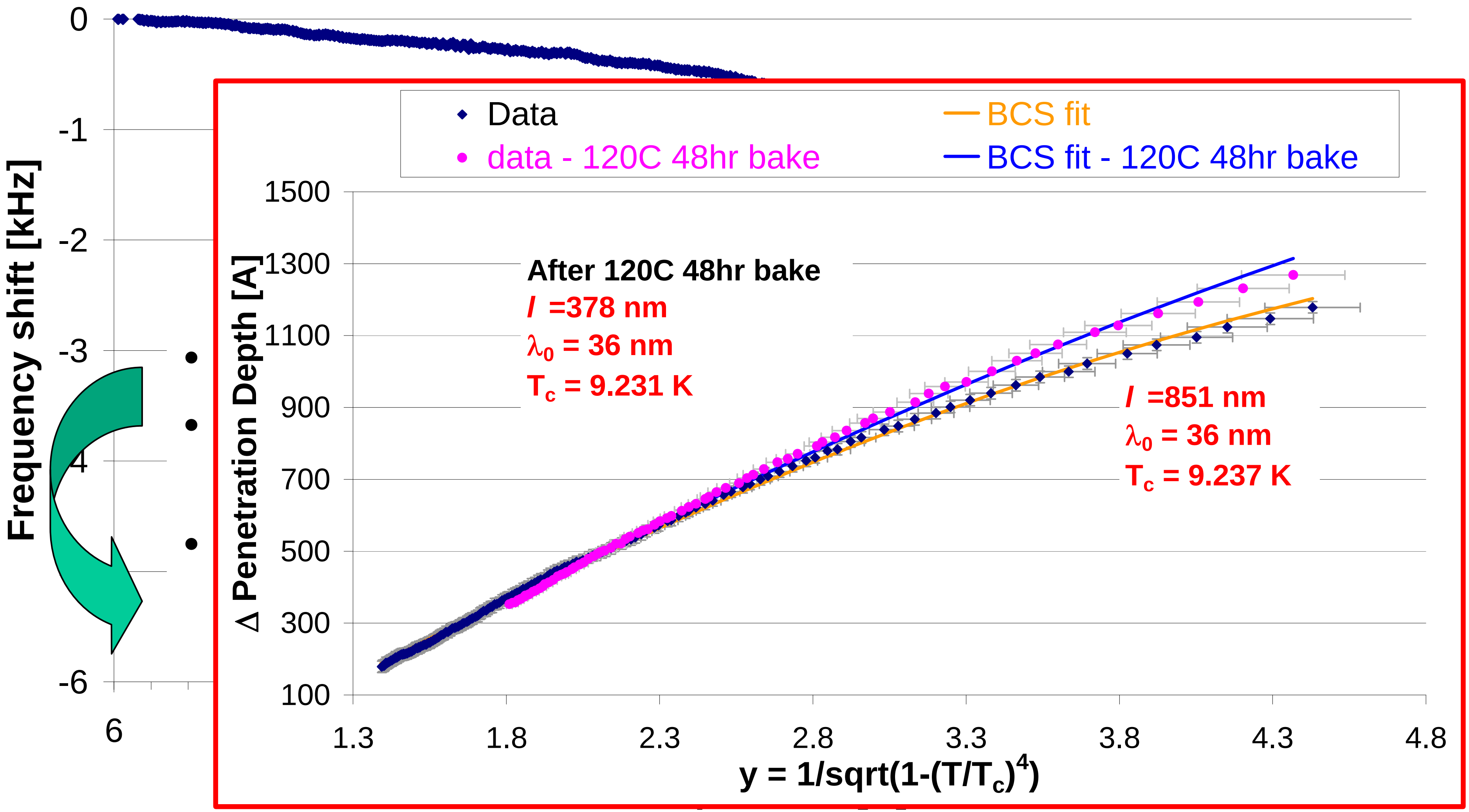


T=1.37K
T=2.2K
T=2K
T=2K, 120C 48hr bake
T=1.37K, 120C 48hr bake
T=2.2K, 120C 48hr bake
1.0E+11
1.0E+10
1.0E+09
Q_0
Quench
"Q-drop"
0
15
30
45
60
75
90
105
120
135
B_{peak} [mT]

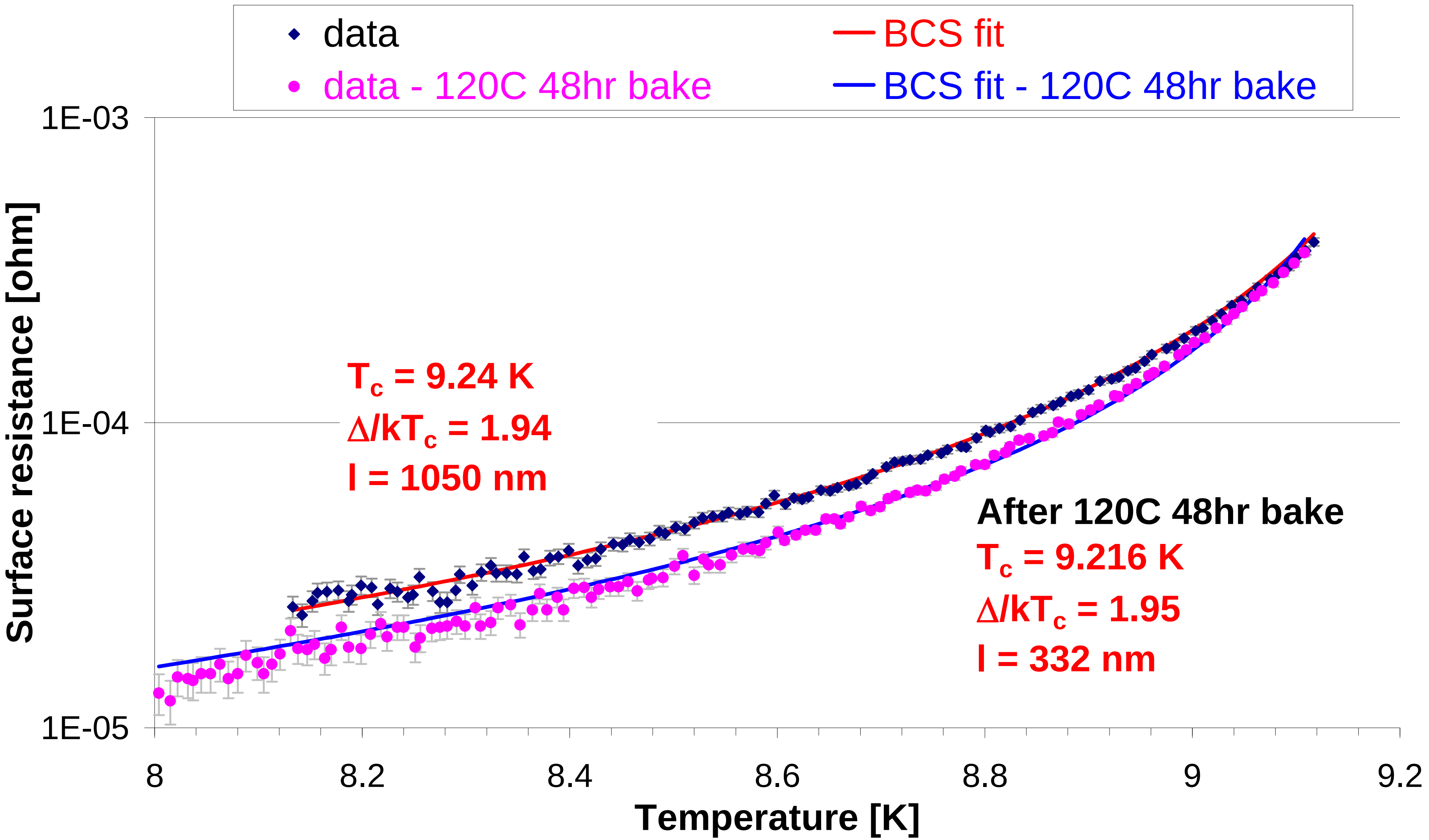
Surface resistance between 4.2K and 1.37K



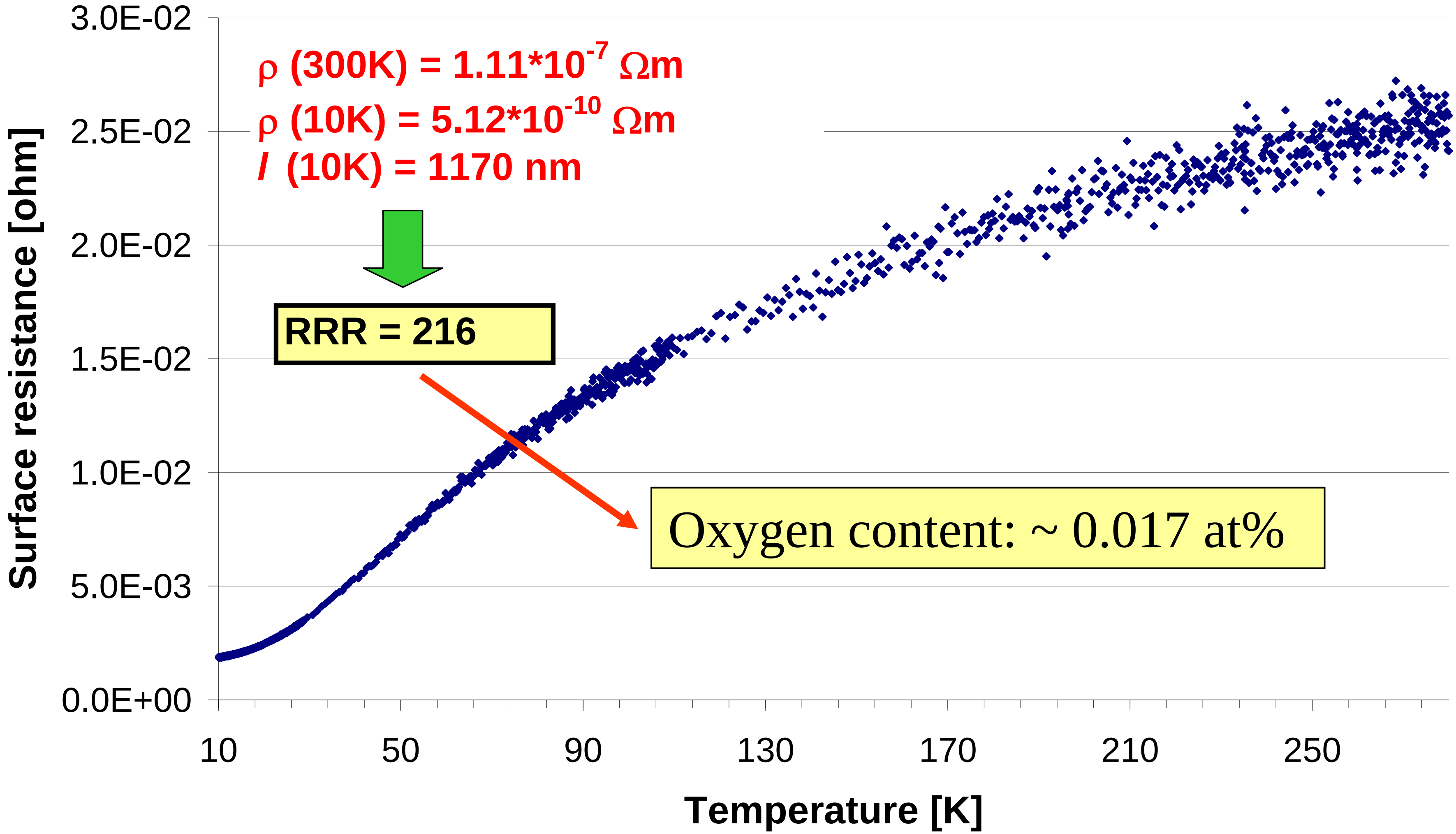
Frequency shift between 6K and 9.5K

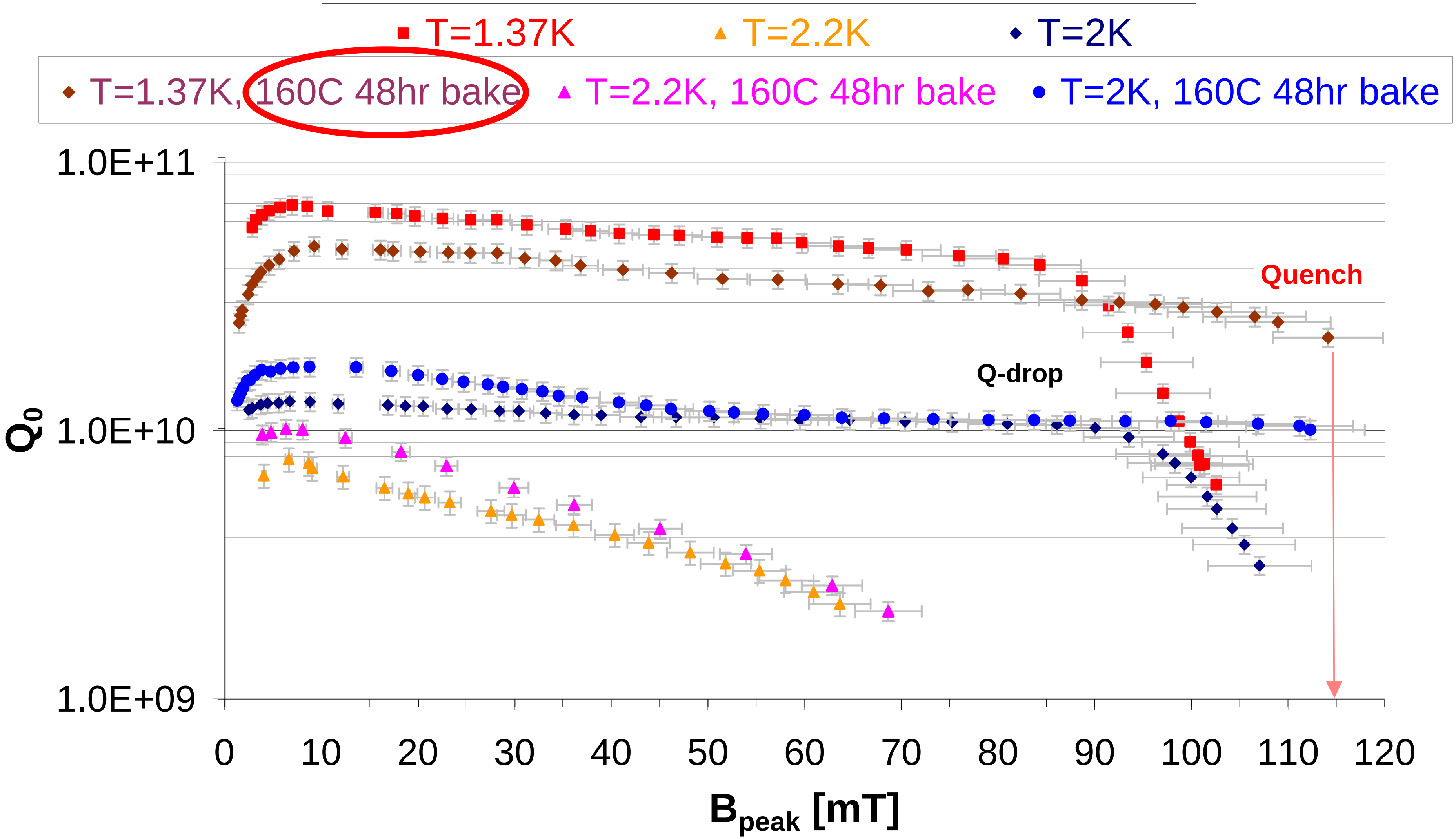


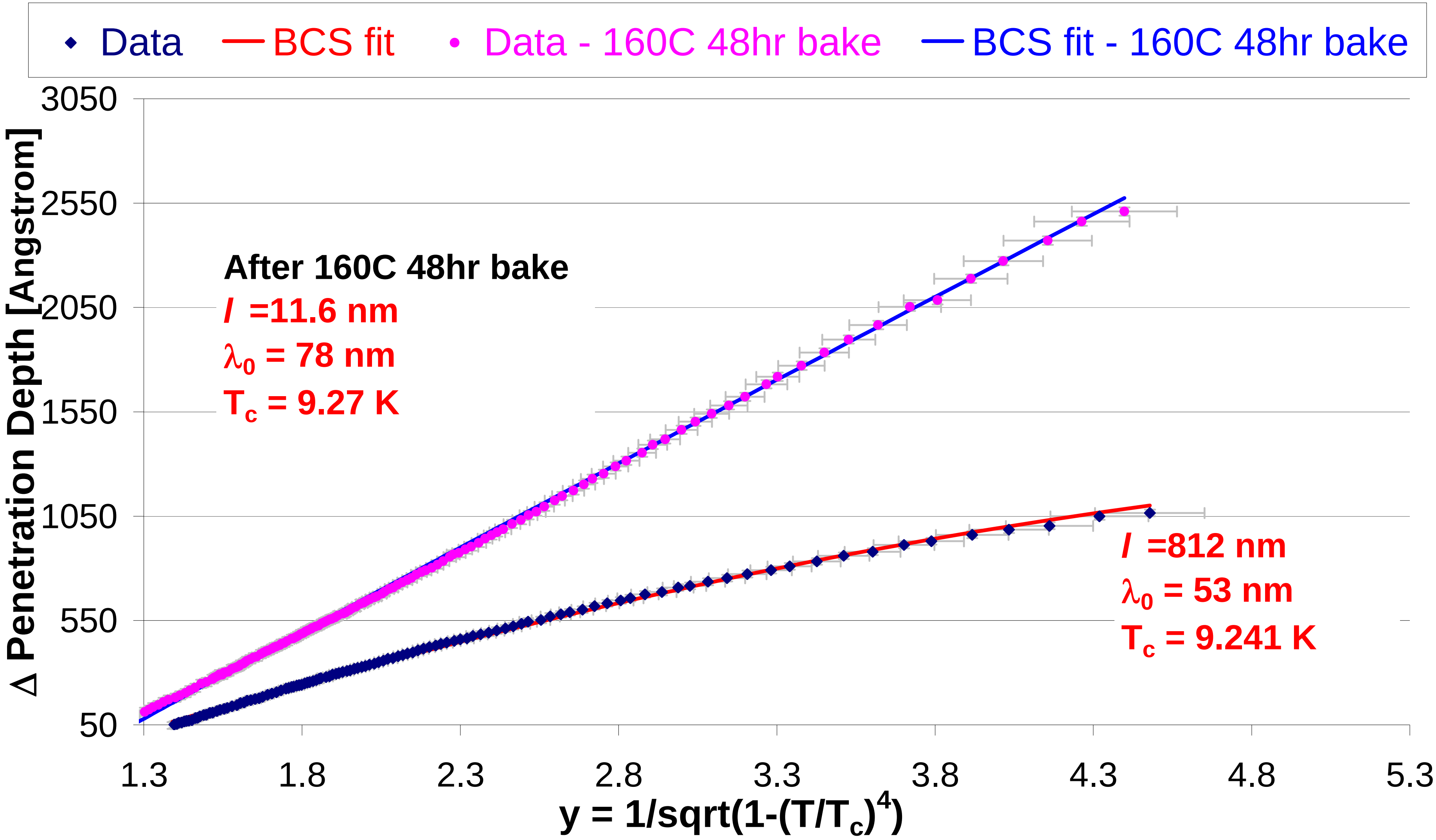
Surface resistance between 6K and 9.5K



Surface resistance between 9.5K and 280K

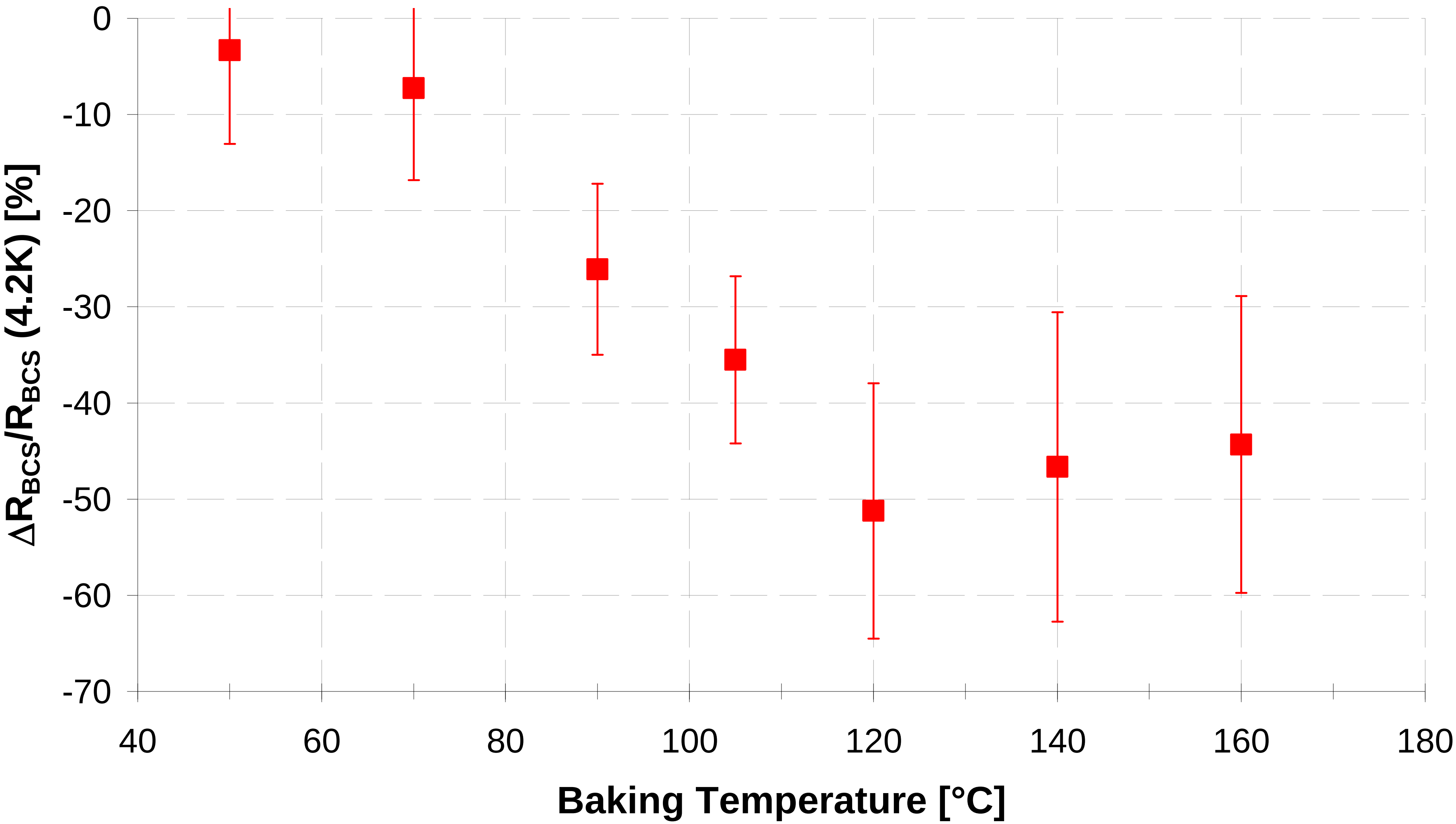



T=1.37K
T=2.2K
T=2K
T=1.37K, 160C 48hr bake
T=2.2K, 160C 48hr bake
T=2K, 160C 48hr bake
1.0E+11
1.0E+10
1.0E+09
Q_0
Quench
Q-drop
0
10
20
30
40
50
60
70
80
90
100
110
120
B_{peak} [mT]

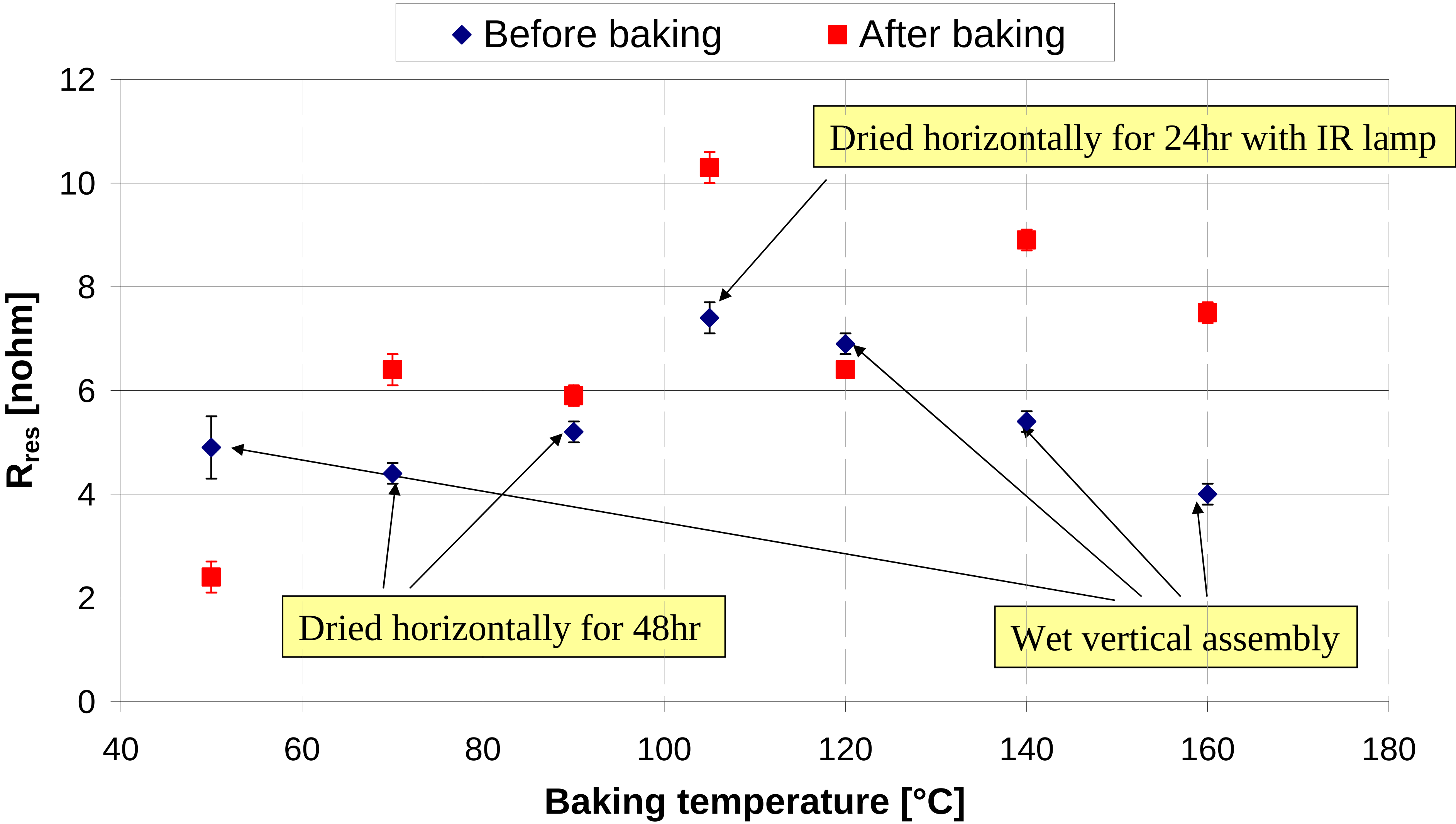


Data
BCS fit
Data - 160C 48hr bake
BCS fit - 160C 48hr bake
After 160C 48hr bake
l =11.6 nm
λ0 = 78 nm
Tc = 9.27 K
l =812 nm
λ0 = 53 nm
Tc = 9.241 K
Δ Penetration Depth [Angstrom]
y = 1/sqrt(1-(T/Tc)4)
3050
2550
2050
1550
1050
550
50
1.3
1.8
2.3
2.8
3.3
3.8
4.3
4.8
5.3

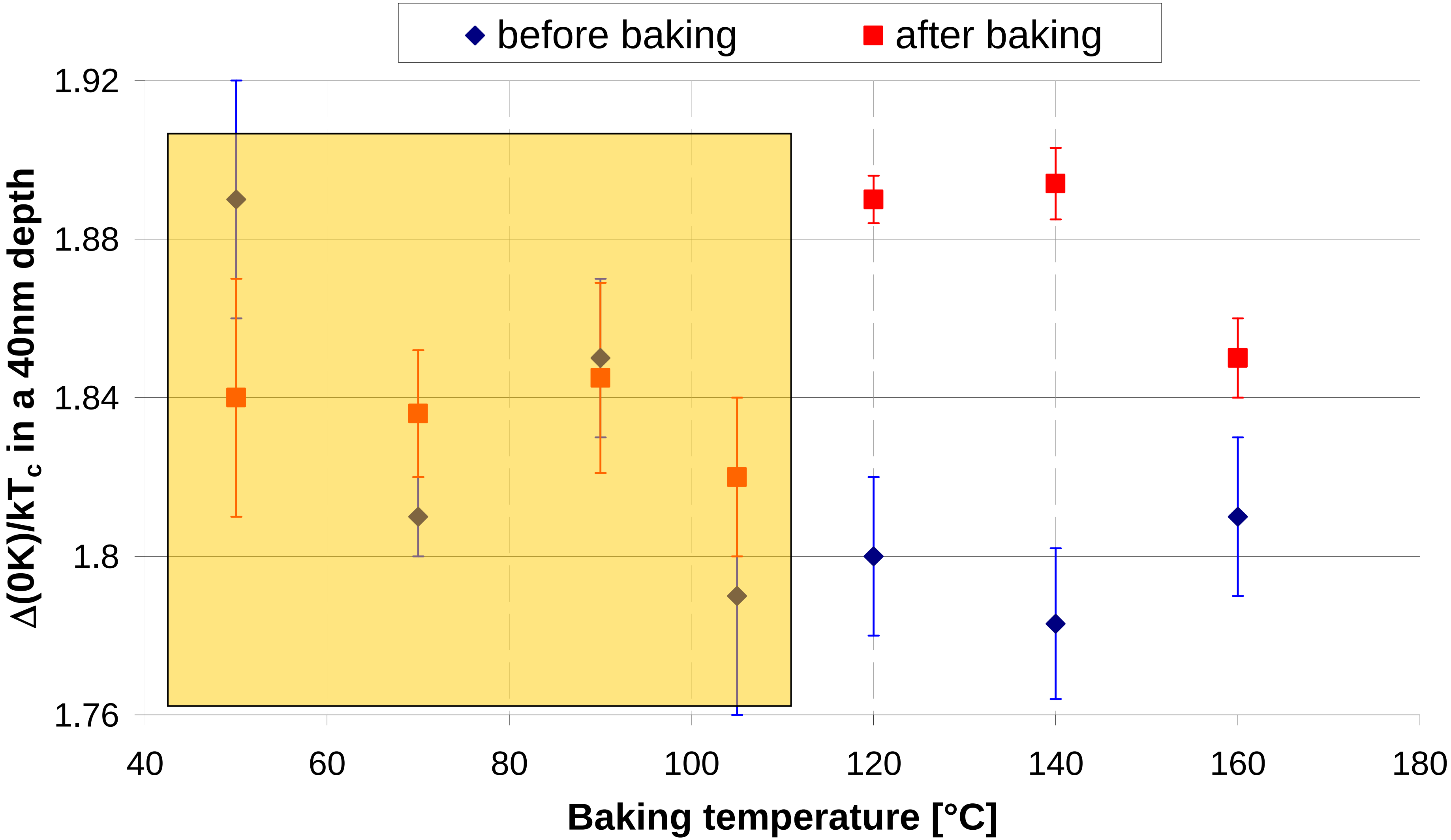
BCS surface resistance variation vs. baking temperature



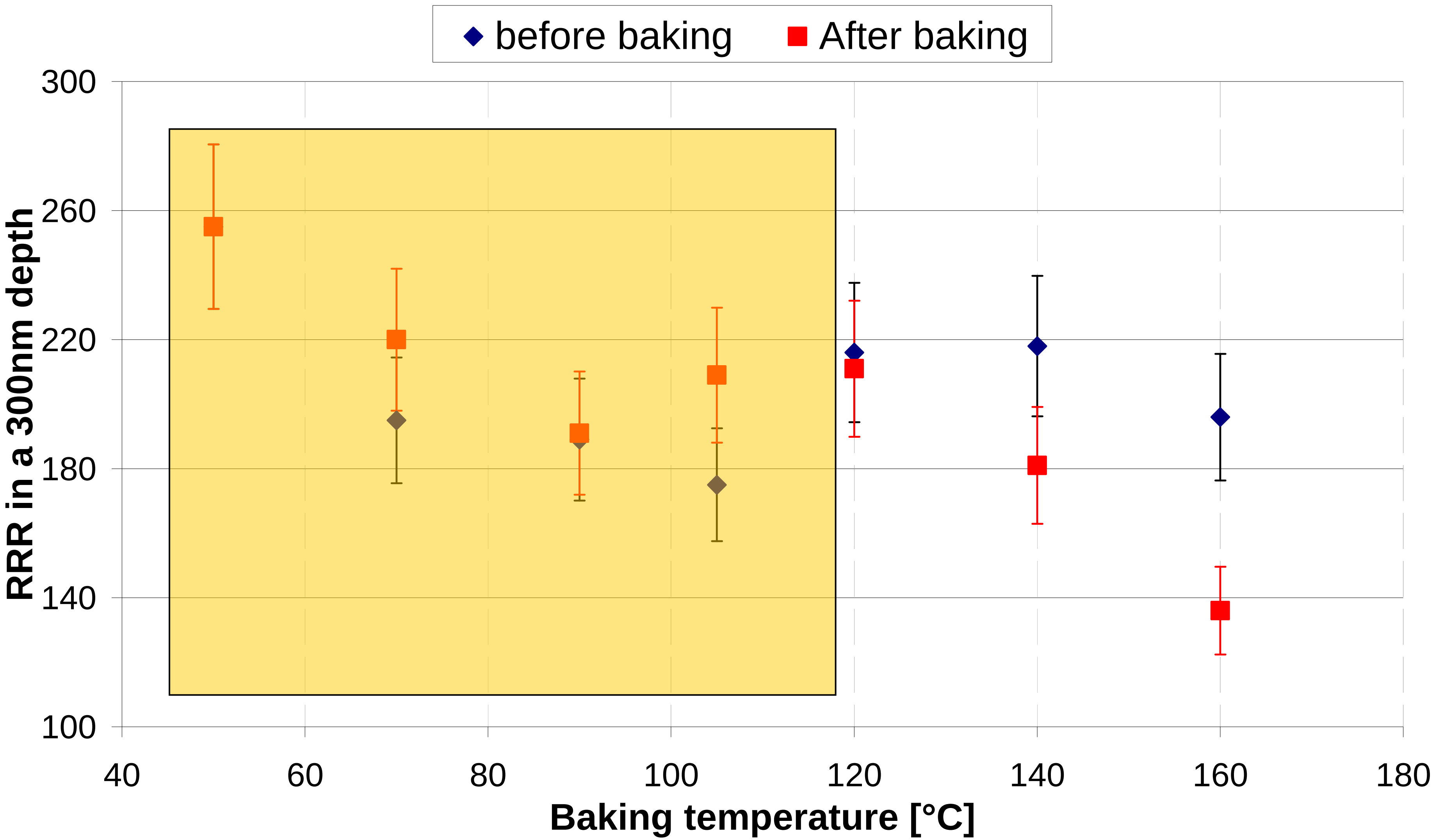
Residual surface resistance vs. baking temperature



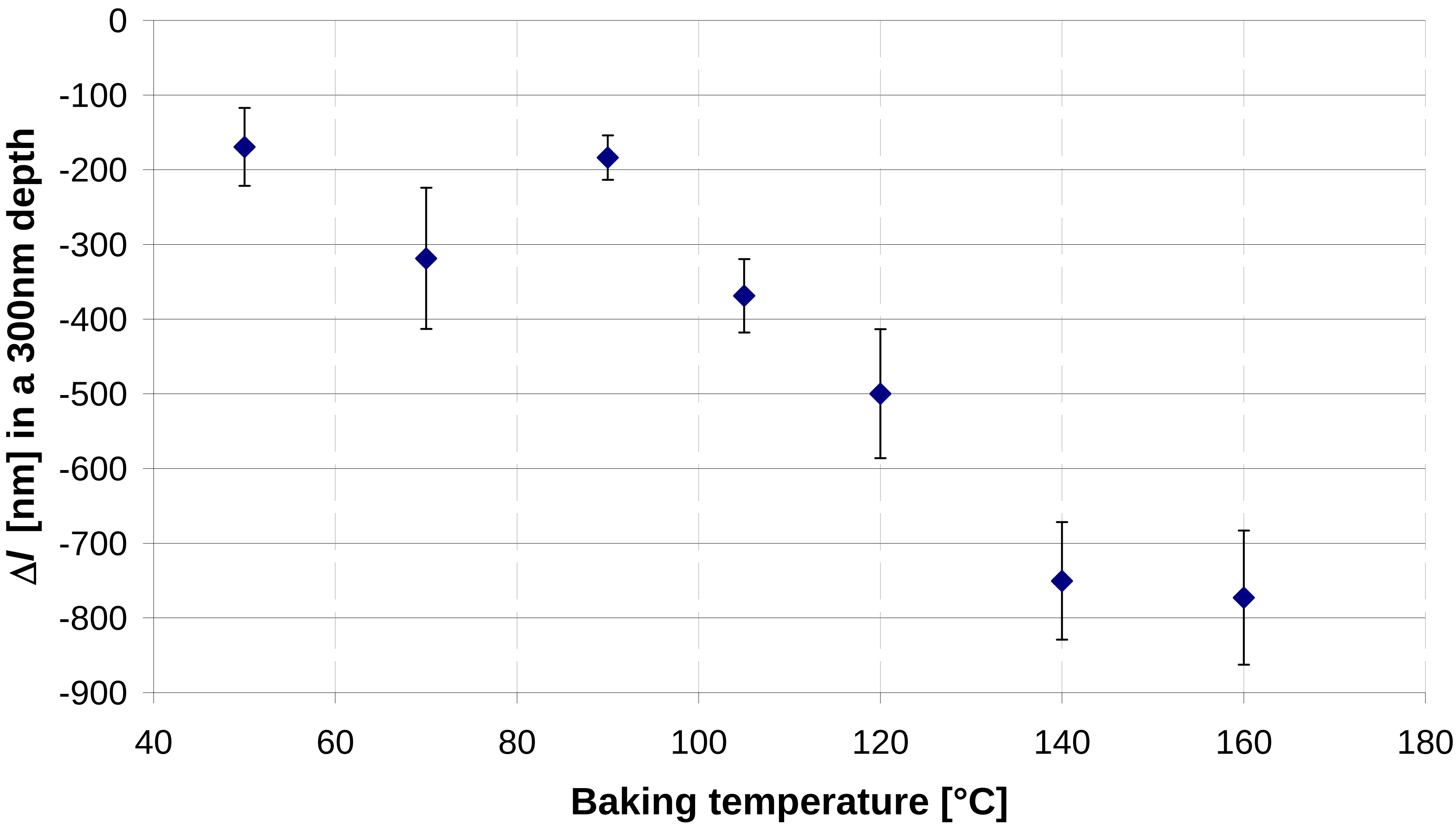
(Energy gap at 0K)/k·T_c vs. baking temperature



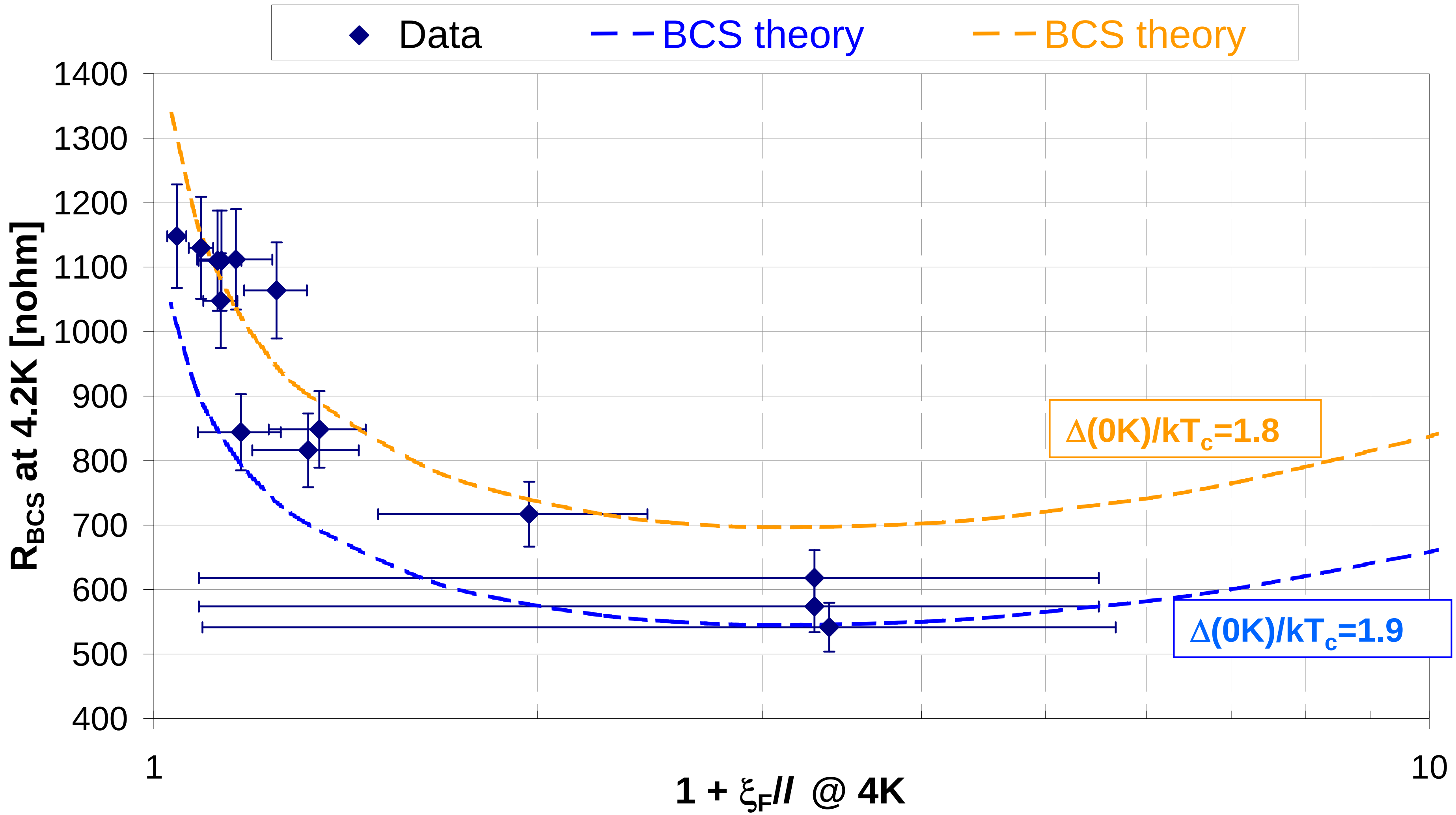
Surface RRR vs. baking temperature



Mean free path variation vs. baking temperature



BCS surface resistance vs. mean free path

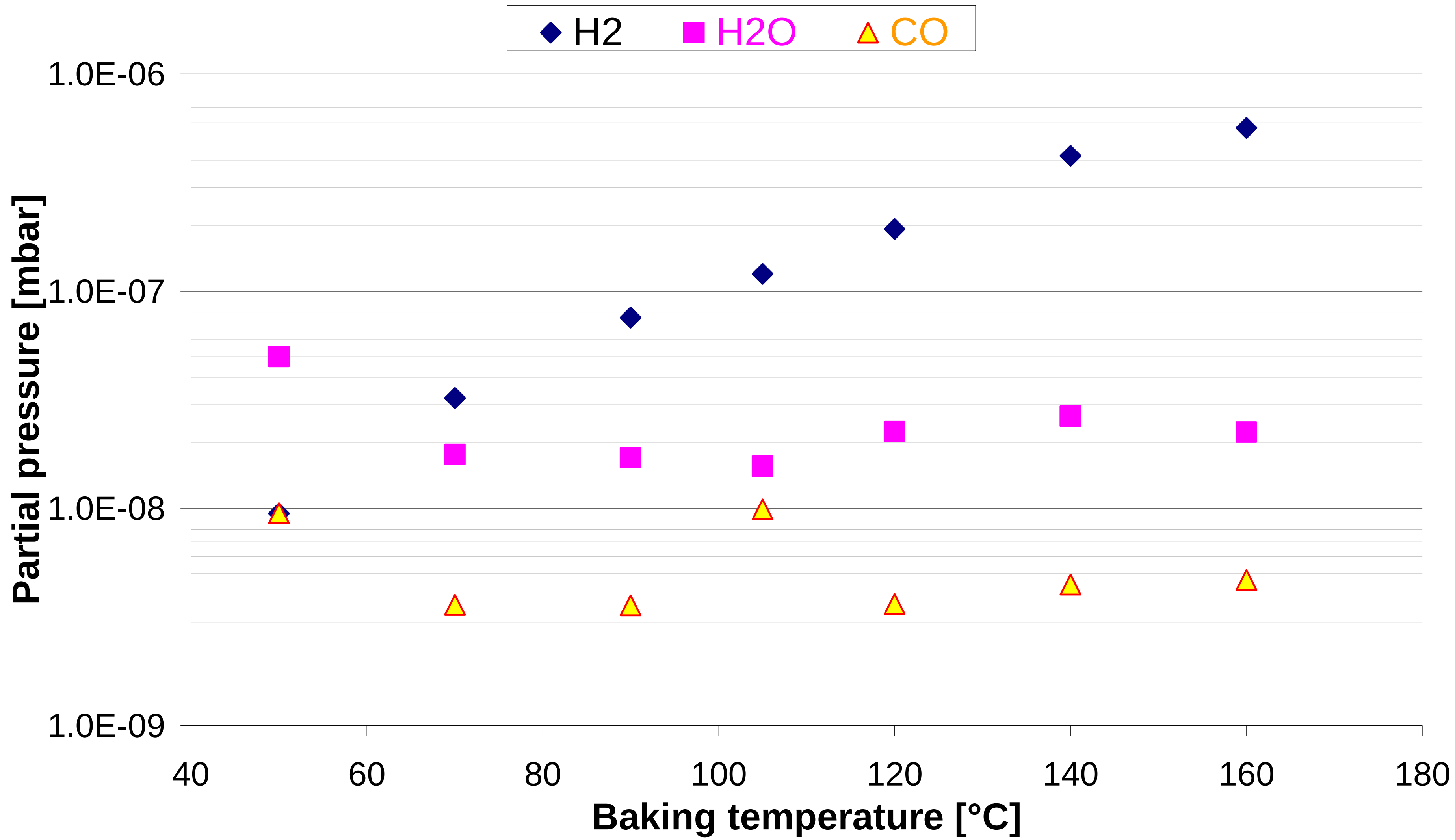


Tendency of superconducting parameters after baking

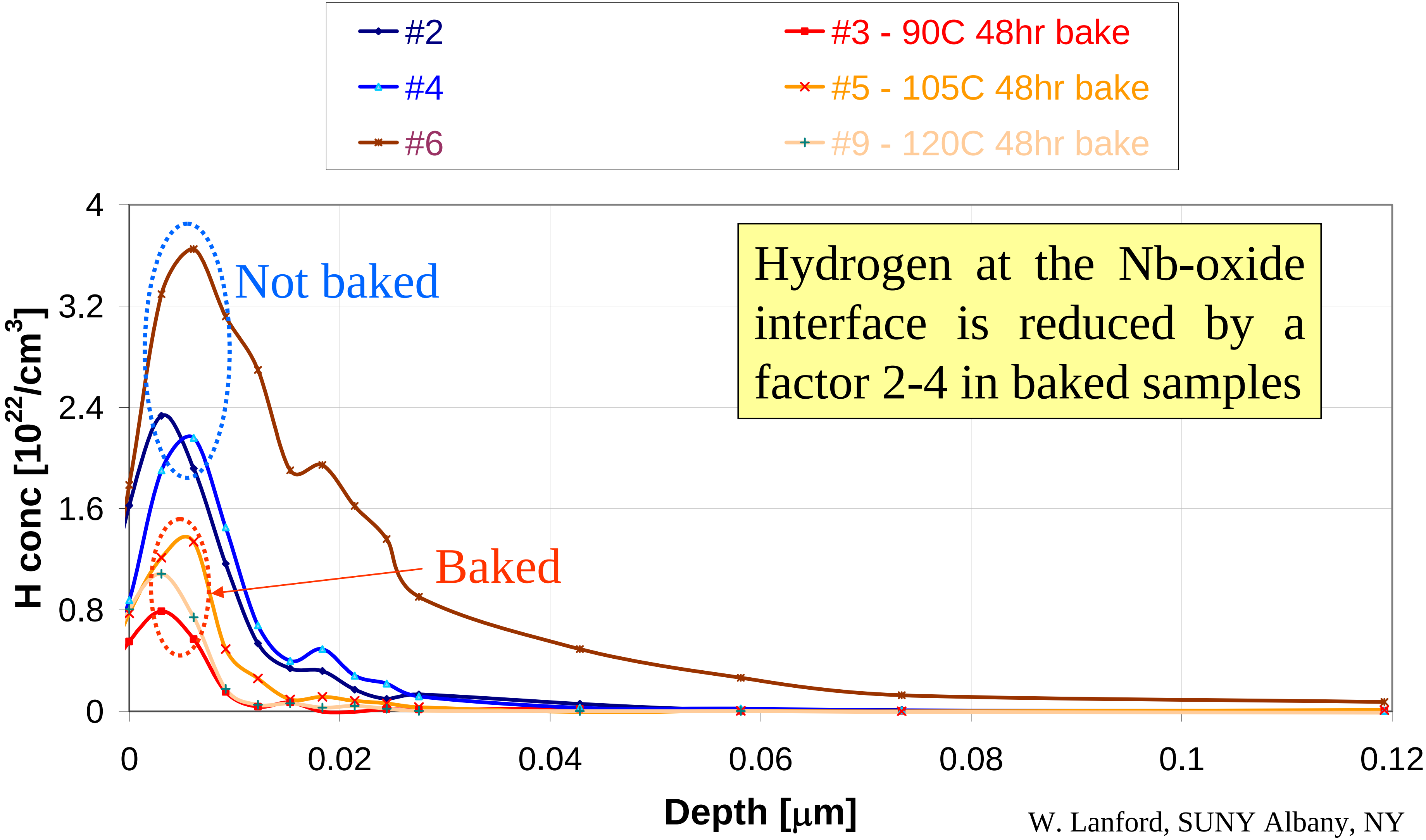
R_{BCS} at 4.2K	↓
R_{res} at B_p=4mT	↑
R_S at 2K, B_p=4mT	↓
Δ(0K)kT_c (40nm depth)	↑
Δ(0K)kT_c (300nm depth)	=

T_c	↓
RRR (300nm depth)	↓
l (40nm depth)	↓
l (300nm depth)	↓
λ(0K)	↑

Main gases partial pressures during baking

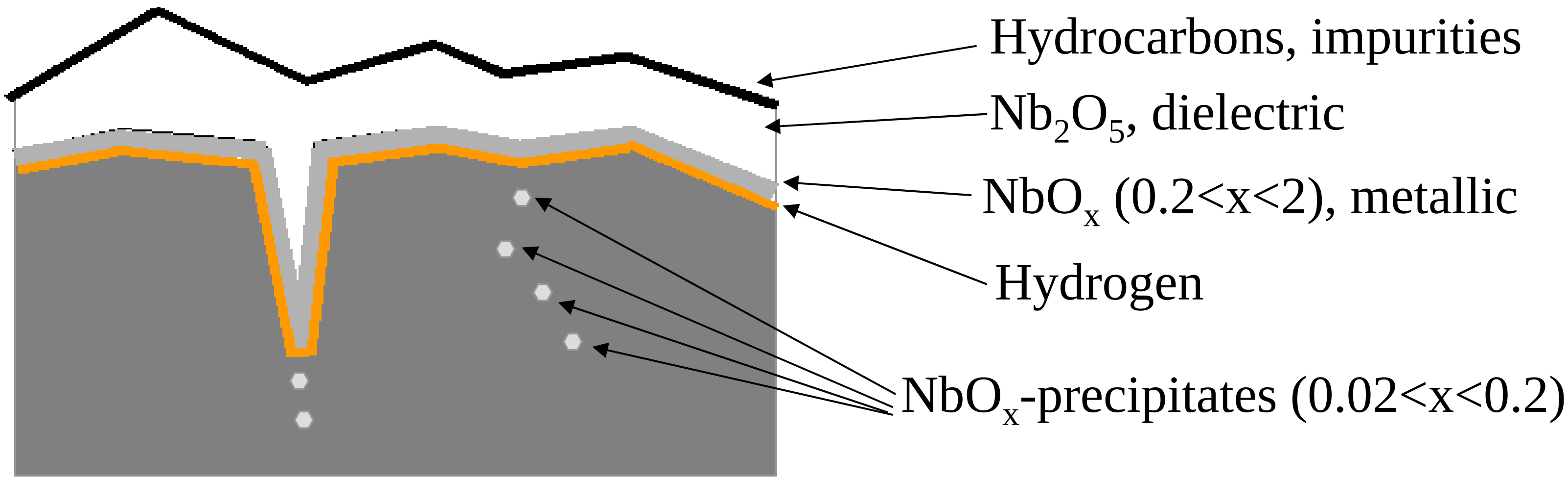


NRA hydrogen depth profiling on Nb samples

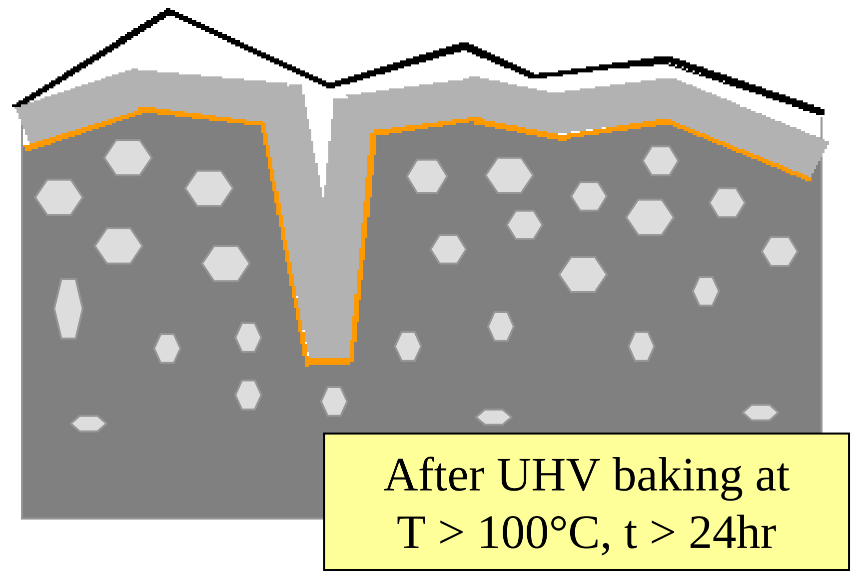


W. Lanford, SUNY Albany, NY

Models comparison



- reduction of mean free path due to oxygen diffusion
- above ≈100°C, the surface oxide layer starts to be depleted and converted to the metallic sub-oxides
- Hydrogen is released from the Nb-oxide interface



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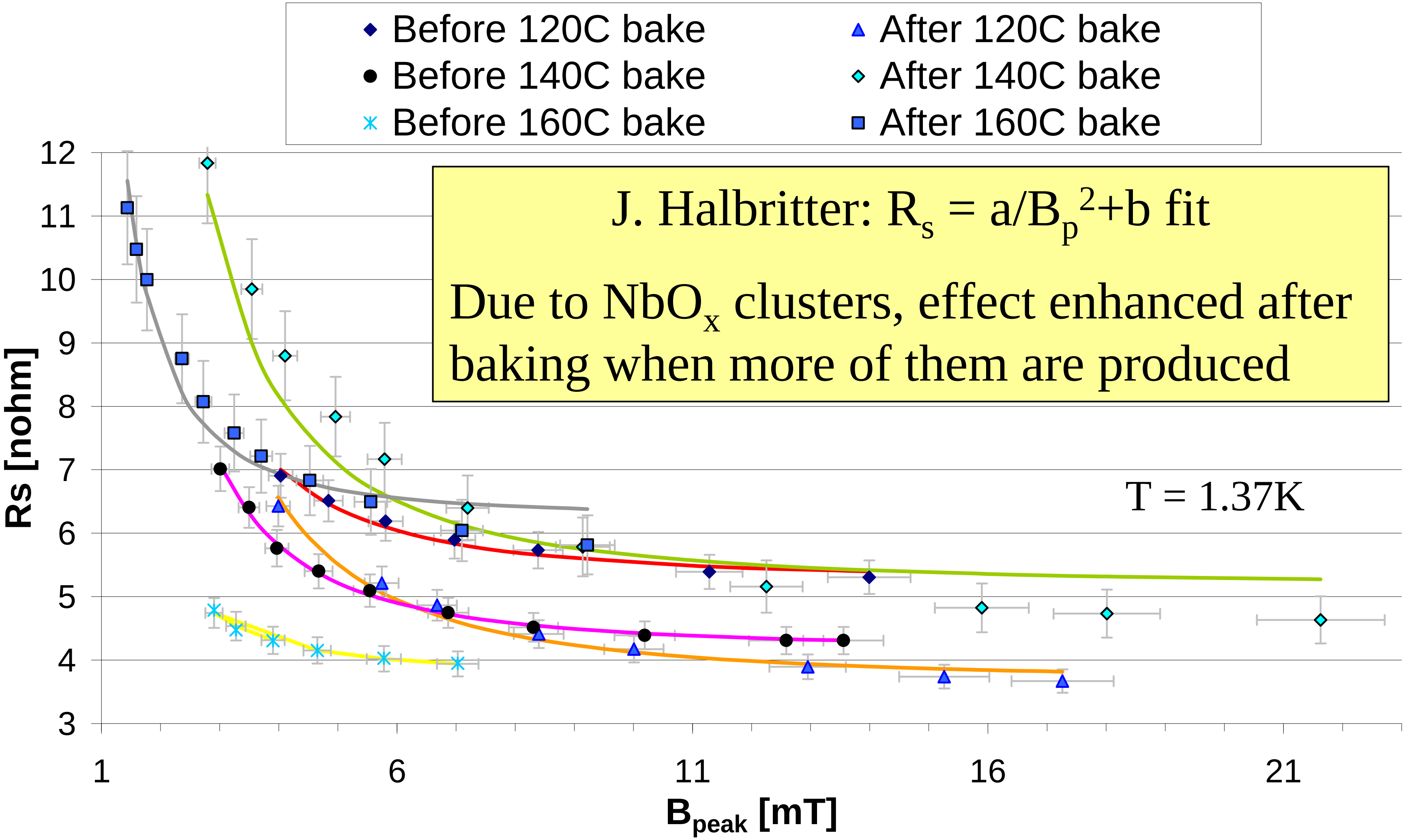
Low field Q-slope



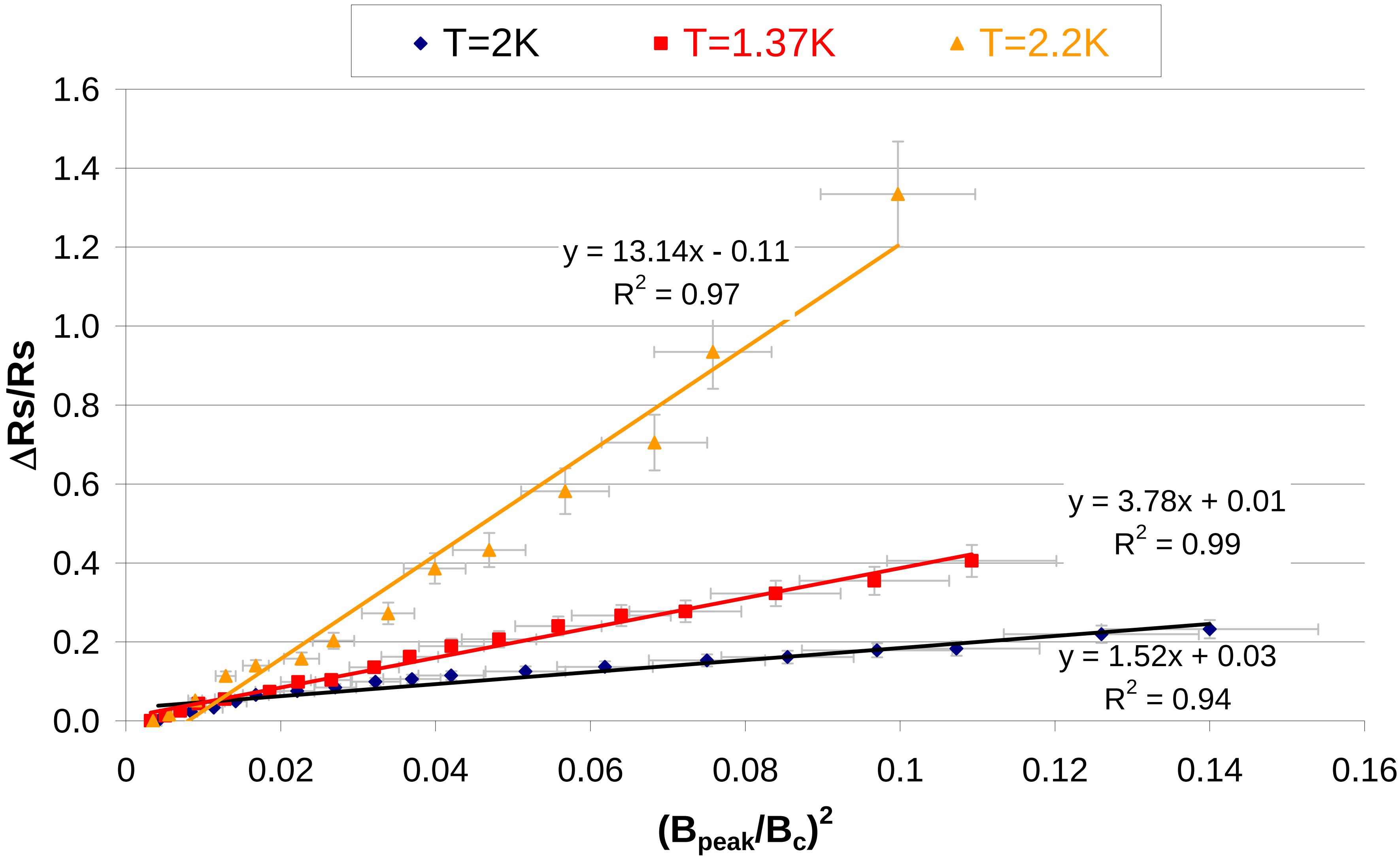
Medium field Q-slope

1. $R_s = R_{s0} \cdot [1+\gamma \cdot (B_{rf}/B_c)^2]$ (From Ginzburg-Landau theory, J. Halbritter)

2. $R_s = a + b \cdot B_{rf}$ (Taylor series in magn. field to 1st order)

3. $R_s = R_{s0}/(1- C \cdot B_{rf}^2)$ (Taylor series in temp. to 1st order, B. Visentin) $C = \gamma/B_c^2$

Model (1) gives the best fits for the data at 1.37K and at 2.2K. The linear dependence (model (2)) is the best fit for the data at 2K



T=2K
T=1.37K
T=2.2K
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ΔRs/Rs
y = 13.14x - 0.11
R2 = 0.97
y = 3.78x + 0.01
R2 = 0.99
y = 1.52x + 0.03
R2 = 0.94
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
(Bpeak/Bc)2

	γ_{meas} Before baking	γ_{meas} After baking
1.37K	1.95	3.46
2K	1.05	2.18
2.2K	14.4	19.8

At T=1.37K, $R_{BCS} \cong 0.4n\Omega$, $R_{res} > 4n\Omega$

$$\mathbf{R_s \cong R_{res} \cong R_{res0} \cdot [1+\gamma_{res} \cdot (B_{rf}/B_c)^2]}$$

- γ and low field surface resistance data before baking allow to estimate thermal conductivity κ and Kapitza resistance R_K at 2K: κ = 6 W/(m·K), $R_K = 1.25 \cdot 10^{-4}$ (m^2·K)/W.
- The 50% increase in γ after baking could be explained by 1 order of magnitude increase in R_K and κ = 1 W/(m·K). Are we missing something?
- T>2.17K, heat transfer limited by He I properties.

High field Q-drop

1) Interface Tunnel Exchange with dielectric oxide layer (J. Halbritter)

$R_S = a + b \cdot \exp(-c/E_{rf})$ Electric field effect

2) T increase at RF surface + Energy gap reduction (K. Saito)

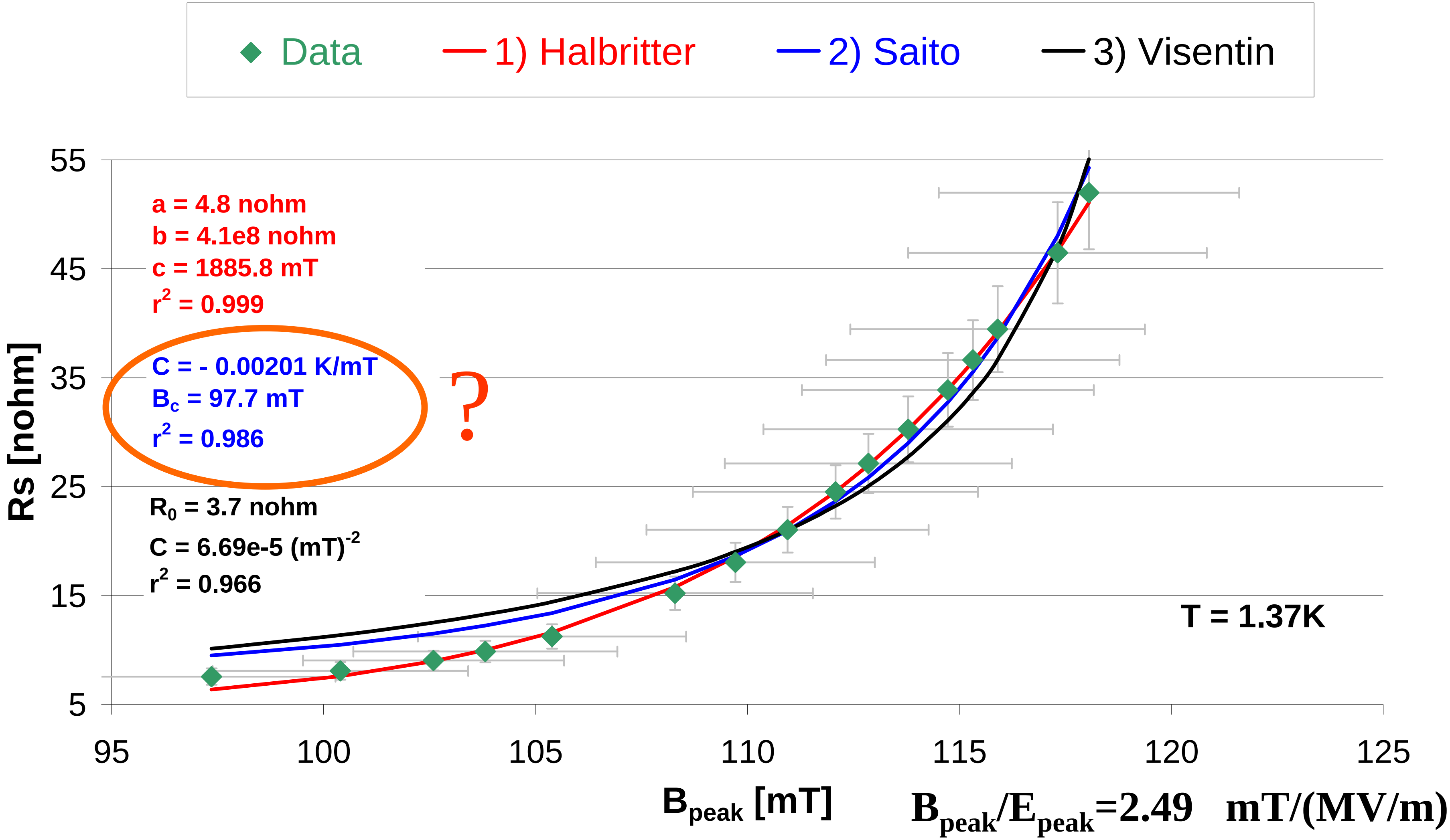
$$R_S = \frac{A}{T + C \cdot B_p} \cdot e^{-\frac{B}{T+C\cdot B_p}\cdot\sqrt{1-\left(\frac{B_p}{\sqrt{2}\cdot B_c}\right)^2}} + R_{res}$$

A, B, R_{res} obtained from R_s vs. T fit

3) Global Heating (B. Visentin)

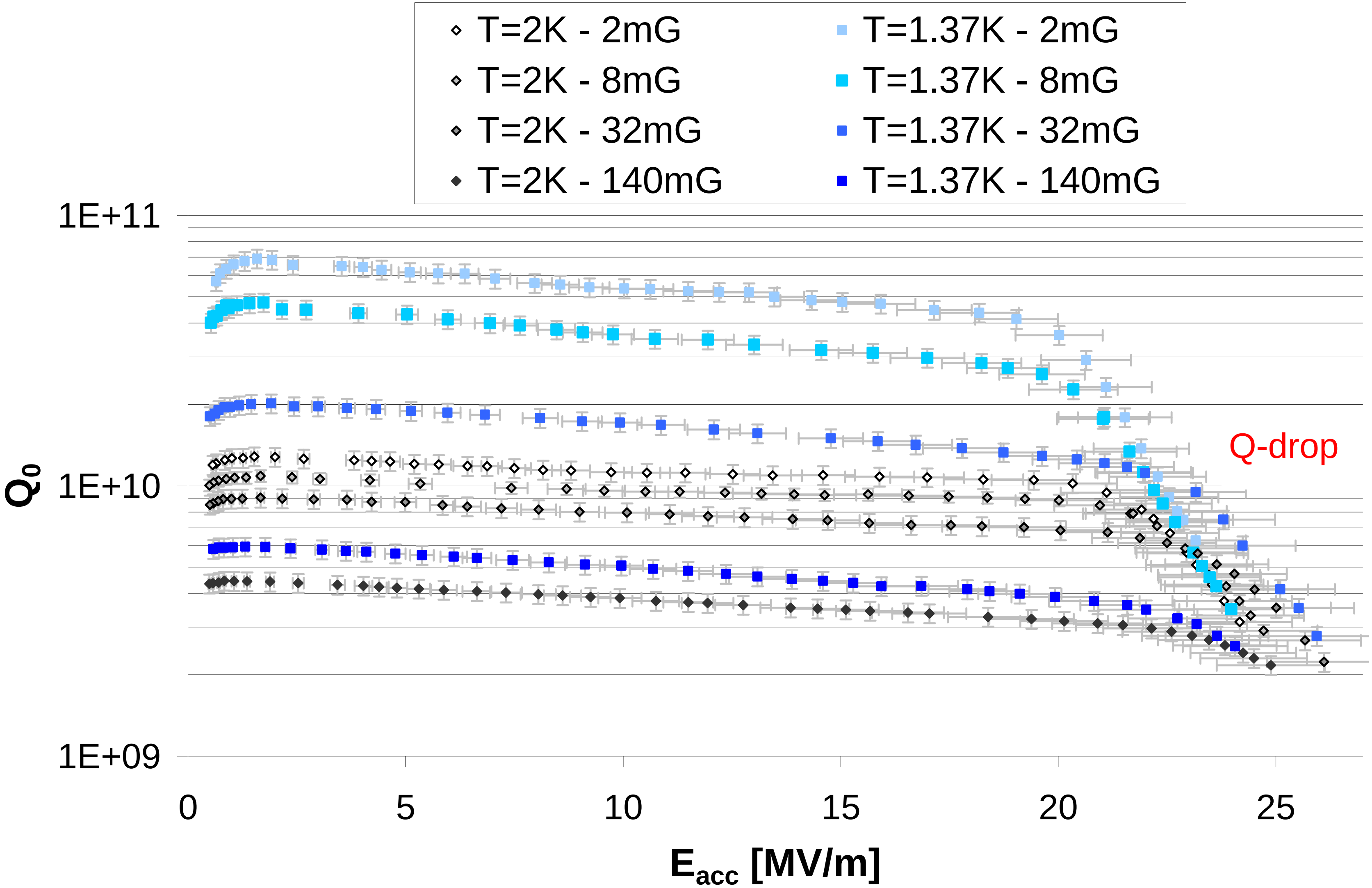
$R_S = R_0/(1 - C \cdot B_p^2)$

Magnetic field effect



Same conclusions on the 2K data and on the 1.37K and 2K data in the test before 160°C baking

Influence of residual DC magnetic field:



Conclusions

• R_{res} has a quadratic dependence from B_{rf} (also seen in Nb thin films)

UHV baking at T>100°C for 48hr:

• improves the Q_0(2K) at low field by as much as 20%

• Mean free path and R_{BCS} are largely reduced

• RF measurements are an excellent tool complementing surface analysis results and giving a good picture of what is happening on the Nb surface

• the influence on the residual resistance and the medium field Q-slope is not clear yet

• the high field Q-drop is eliminated and ITE model best fits the data