Overview on High Field Q-slope (Non-field Emission)

Experiments and Theory

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DESY -MPY-

ANL 2004

- History
- Experimental data
  - Cavity measurements
  - Measurements on samples: BC3, critical currents
- Theories

TESLA

Review on Experiments

- Several people have contributed and helped me in the preparation of this talk: P. Kneisel, D. Reschke, B. Visentin, P Schmüser
- Focus is :
  - mostly on 1.3 GHz niobium bulk elliptical cavities unless otherwise mentioned
  - data not presented by Bernard during SRF2003 (Paper is in the reading list)
- Theories will be looked at only briefly

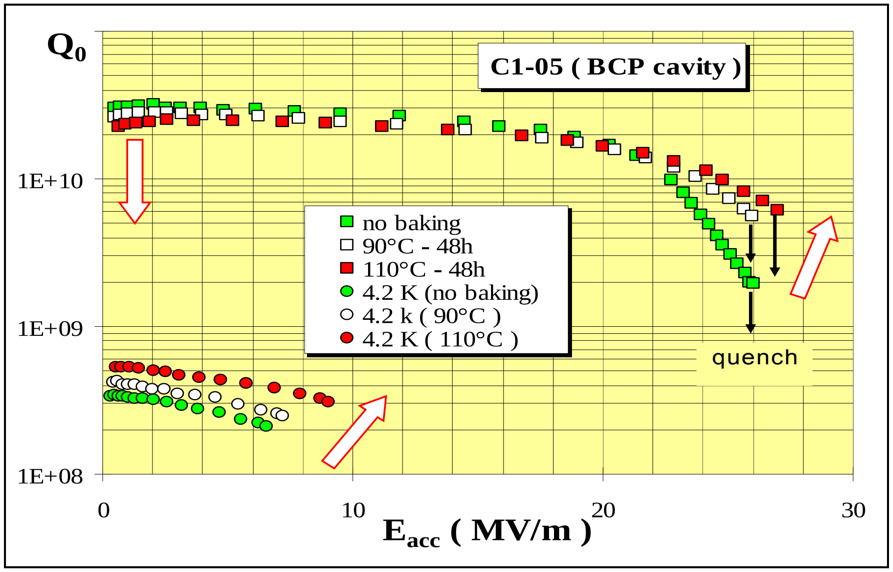
Short History

- 1997 ‘European Headache‘
  - Degradation of the quality factor at fields above 20-25 MV/m without measurable field emission
  - Only for etched cavities???
    - Excellent KEK results on EP
- 1998 B. Visentin at Stockholm
  - Low temperature bake (~110°C) on etchted cavities improves Q at high field
    - ‘In-situ’ bake= Cavity inside is under vacuum
- 1999 EP cavities with Q-slope
  - Measurements on cavities with EP (CERN-CEA-DESY)
  - Low-temperature bake is mandatory for a high field >35 MV/m
  - Reproduced at KEK
    - low temperature bakeout was part of the drying process

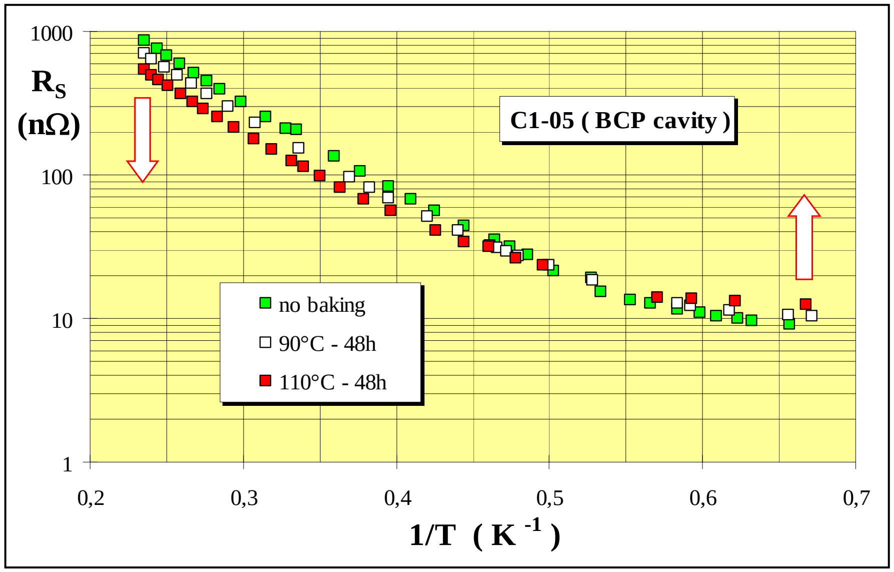
Baking Effect on BCP Cavities ($Q_{slope} - R_{BCS} - R_{res}$)

"in-situ" baking discovered on BCP cavity

slope improvement (90 < T < 120°C) - degradation (T > 150°C)



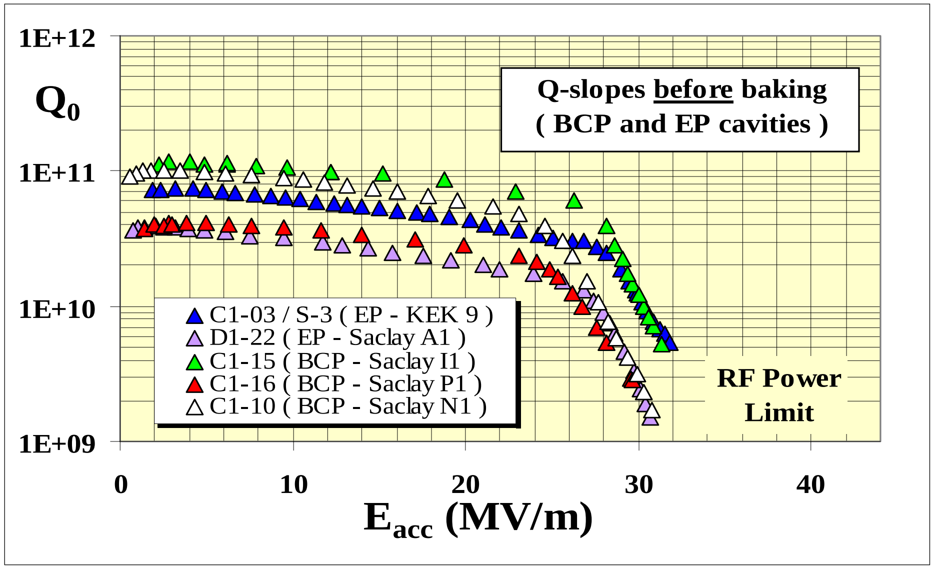
(B. Visentin *et al.* – EPAC '1998 - Stockholm)



Baking Effect on EP Cavities

Same phenomenon on E.P. cavities

before baking: Q-slope identical to BCP



apparent superiority of EP reported before ?

cleaning procedure at KEK

wet cavities (High Power Rinsing)

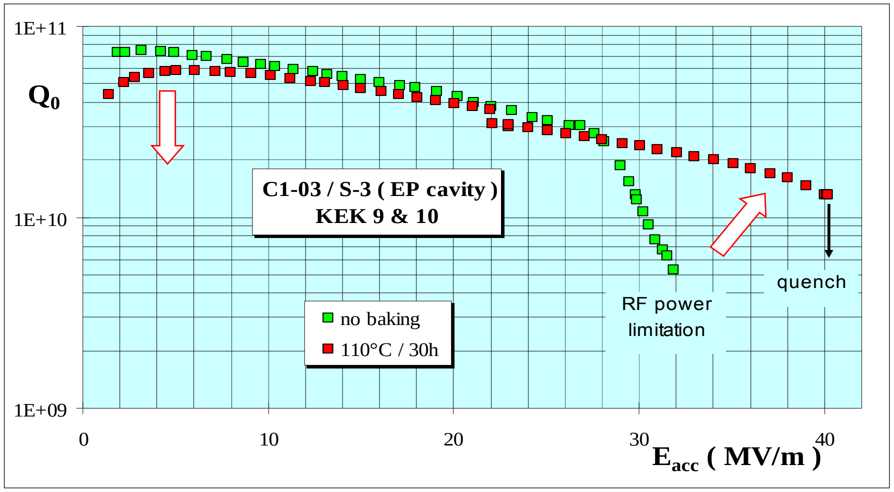
directly pumped out and baked at 85°C/20h

to accelerate pumping speed

SRF ’ 99 Santa Fe

- P. Kneisel. – *TUP 044*
- K. Saïto. – *TUP 031*
- L. Lilje *et al.* – *TUA 001*
- B. Visentin *et al.* – *TUP 015*

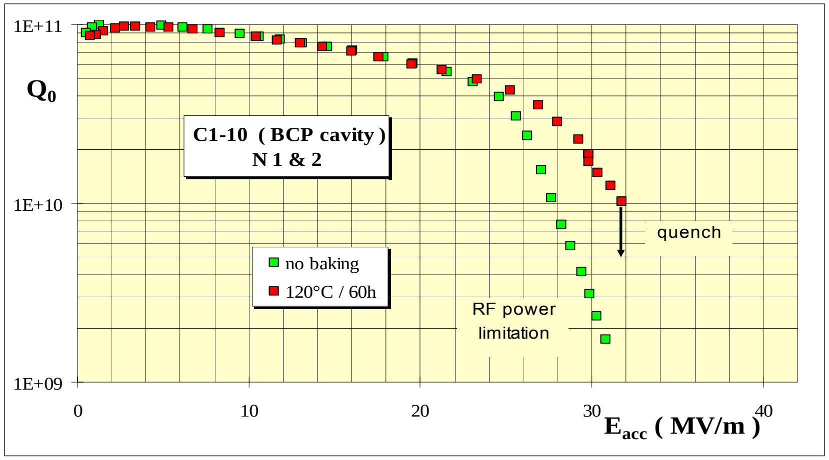
after baking : Q-slope improvement



(*Saclay cavity – EP & tested @ KEK*)

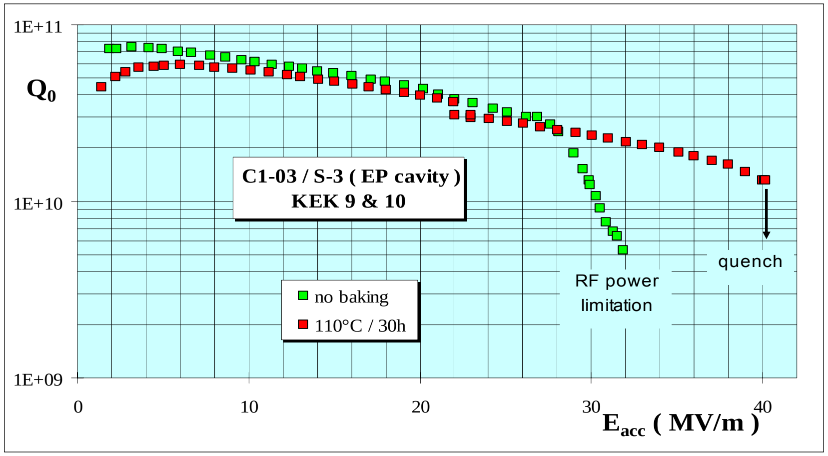
Differences between BCP and EP

- higher efficiency of baking on EP cavities (from 85°C)
- residual slope on BCP cavities even with baking (120°C)

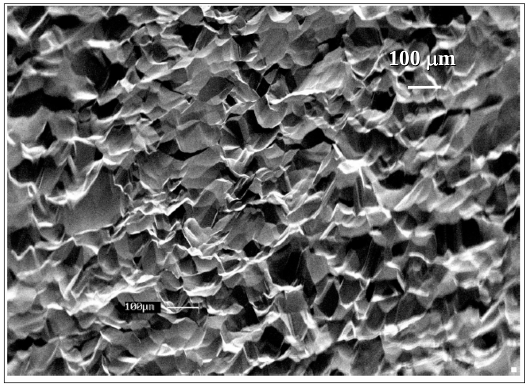


⇦ **BCP**

EP ⇨



- higher quench field for EP cavities (40 MV/m)

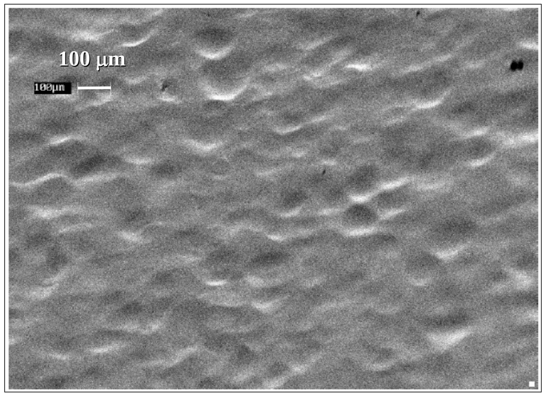


- surface roughness

(R.L. Geng *et al.* - SRF '99 – Santa Fe)

⇦ **BCP** (117 µm) **EP** (90 µm) ⇨

5-9 µm (statistic on step height) 2-5 µm

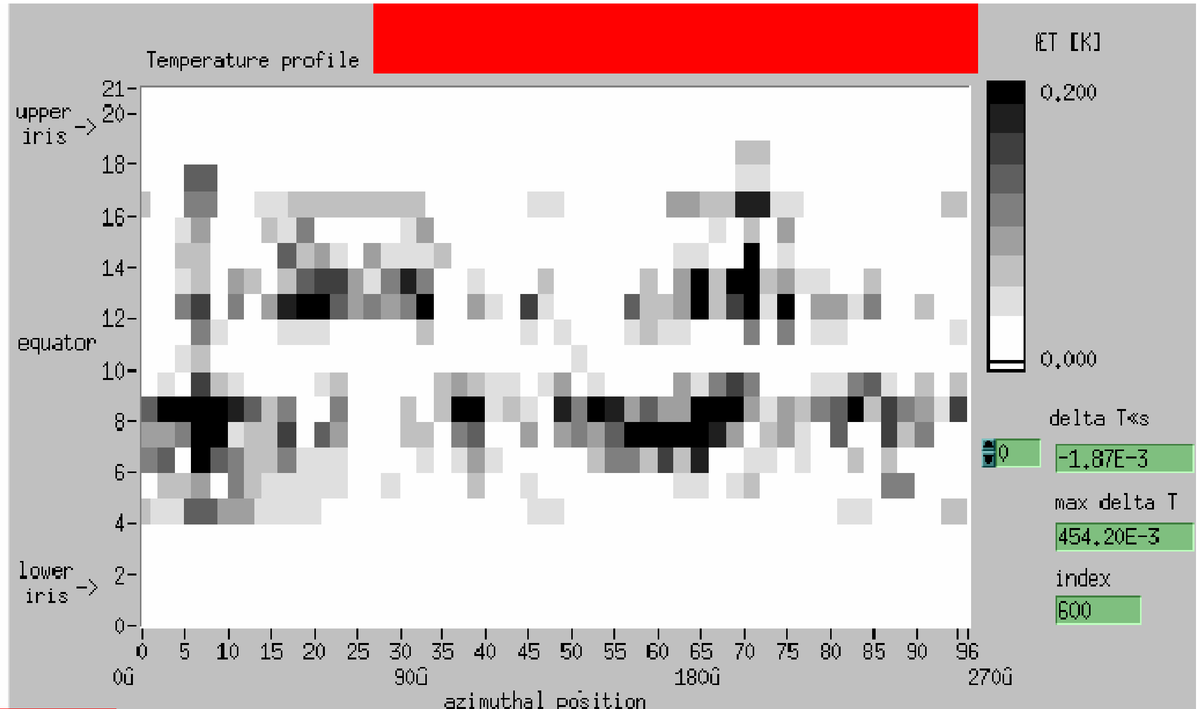


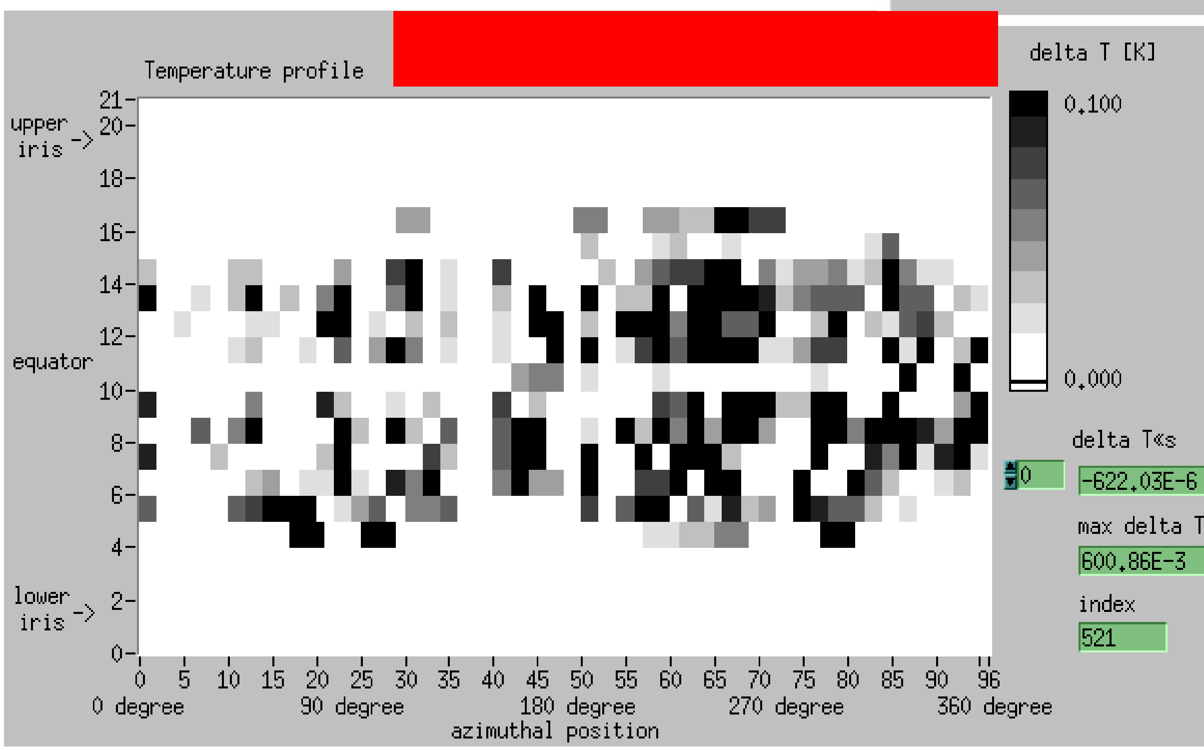
Experimental Data I

- Q(E) curves show a degradation of quality factor at magnetic surface fields of ~100 mT for several surface preparations
  - BCP 1:1:2
  - BCP 1:1:1
  - EP
  - Should the bakeout parameters be different for EP and BCP?
- R_{BCS} reduces by as much a factor of 2
- Residual resistance does not change or increases slightly (a few nOhm)

Temperature Mapping: EP-BCP before bake: You spot the difference!

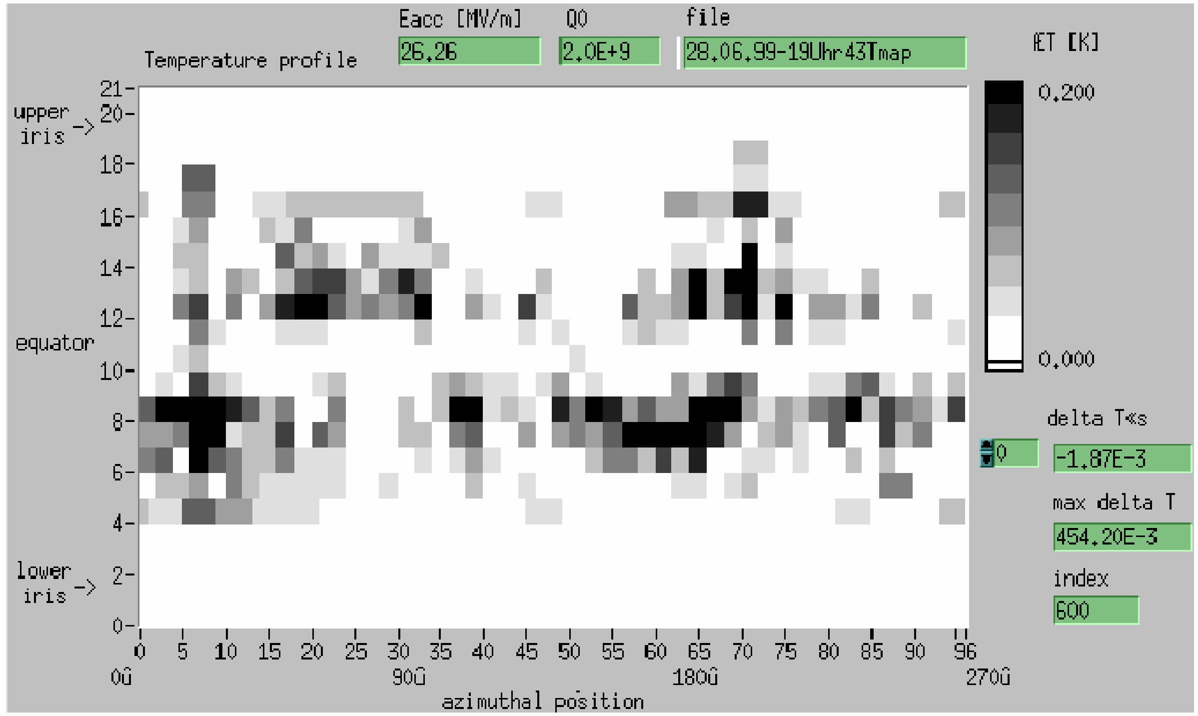
- A beer to the person who tells me which of these T-maps shows the etched cavity
- DESY insiders are excluded!

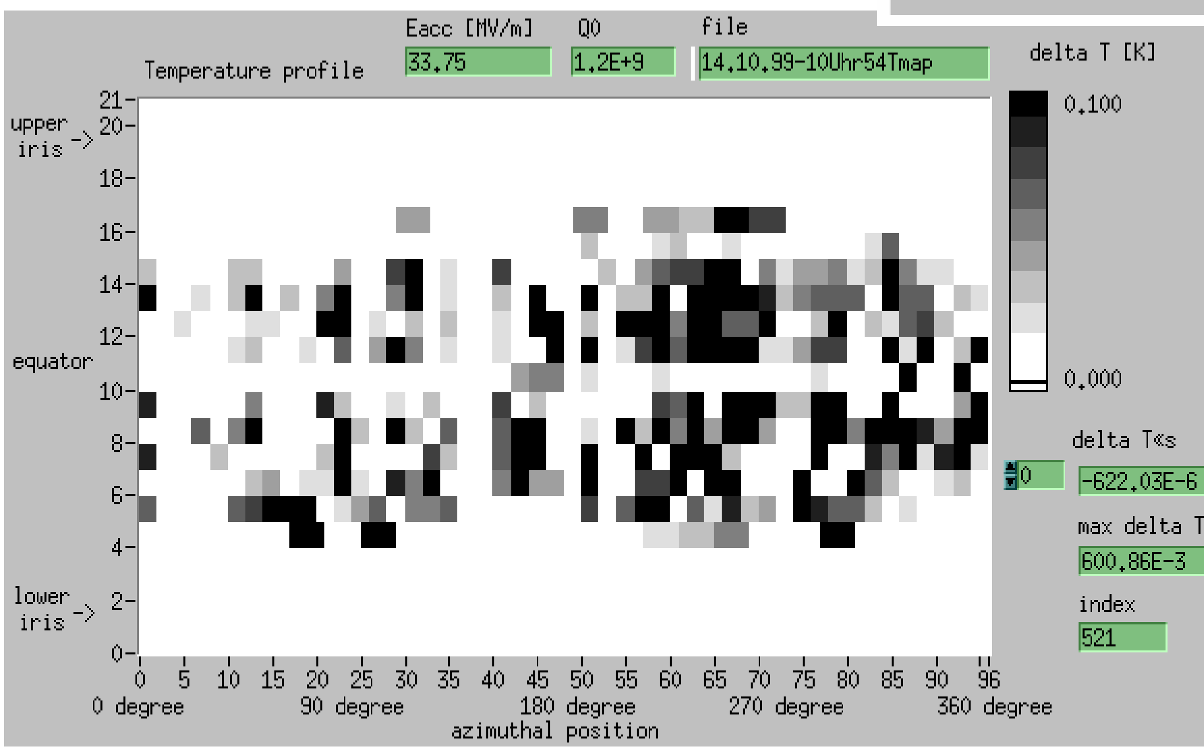




Temperature Mapping: EP-BCP: You spot the difference!

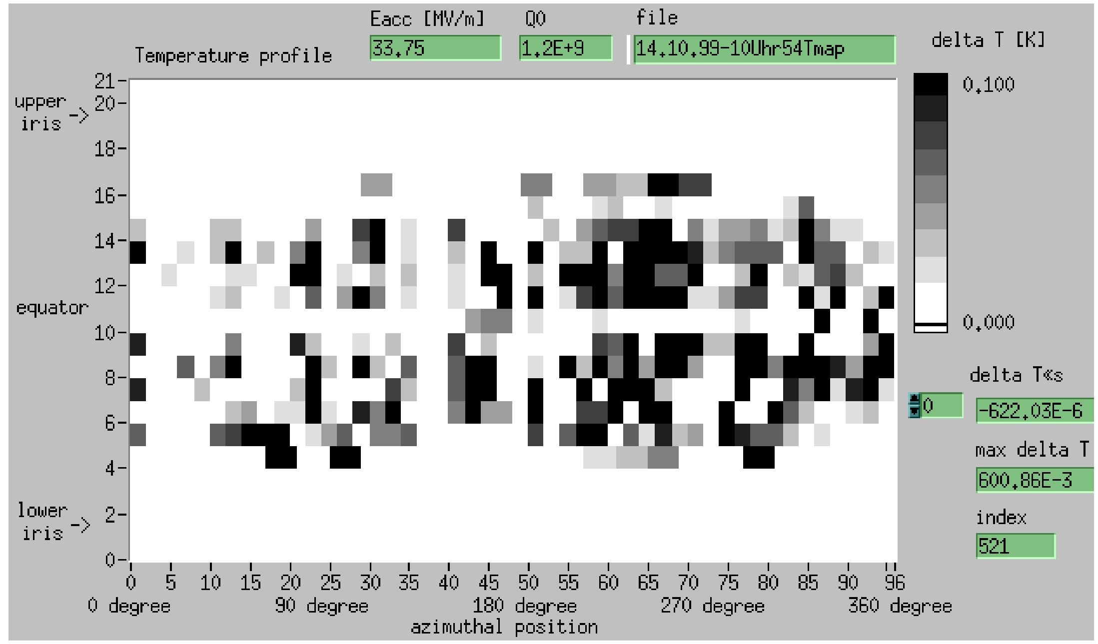
- Top right: BCP
- Lower left: EP
- Marginal difference:
  - Global heating in both cases

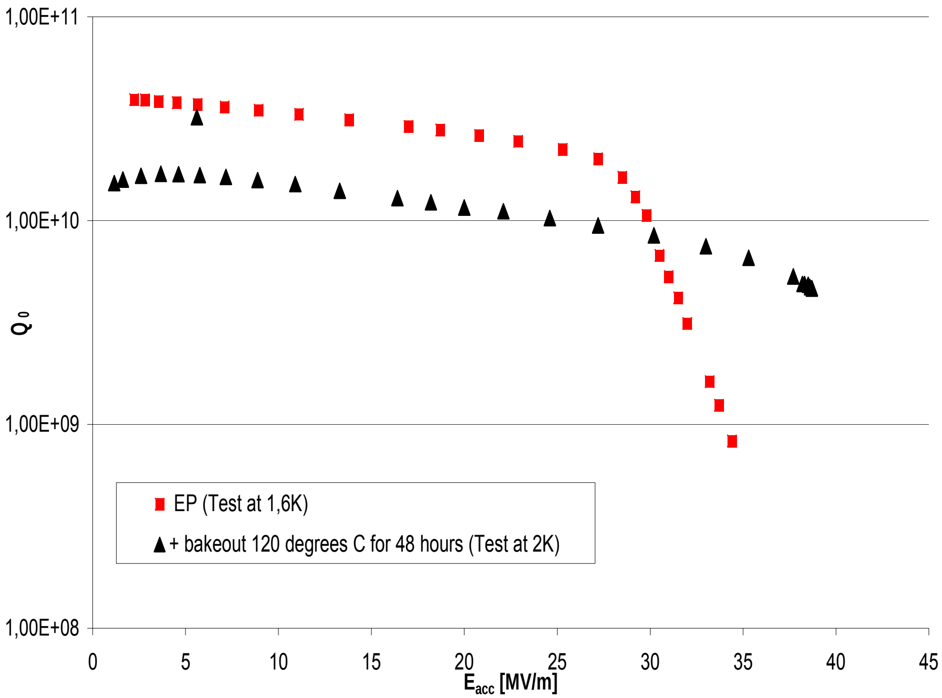


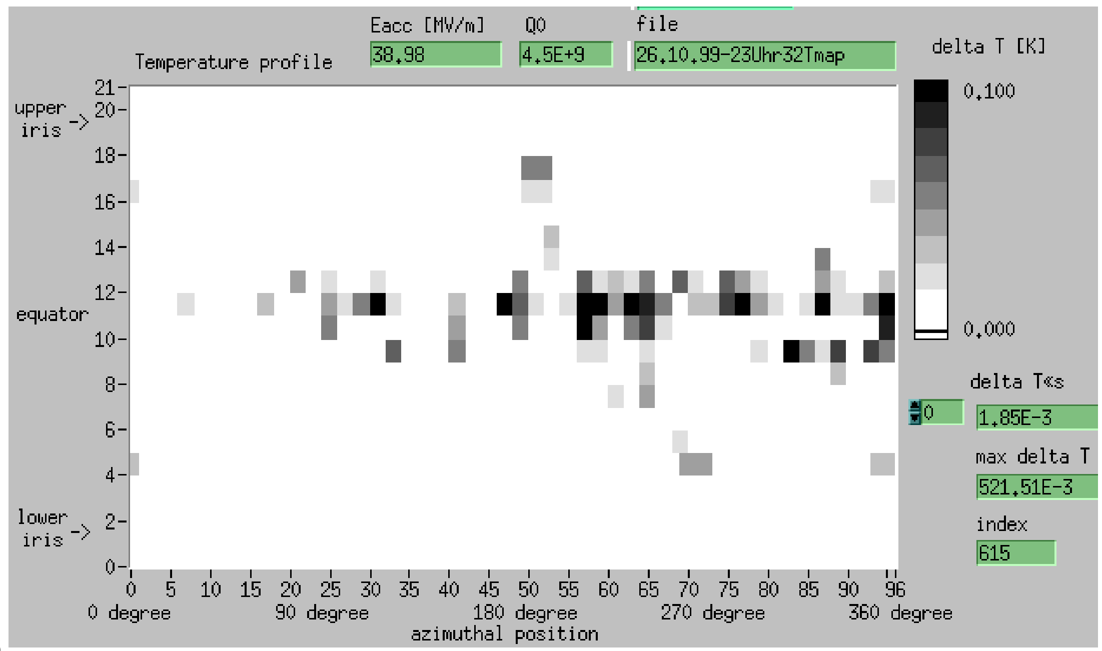


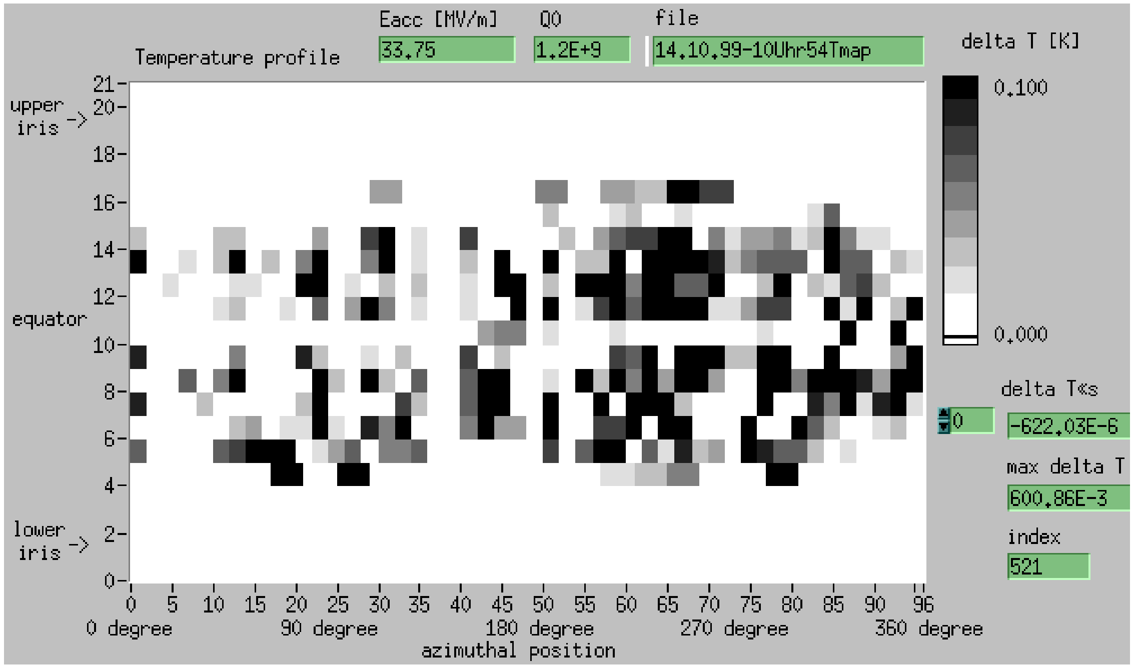
Temperature Mapping

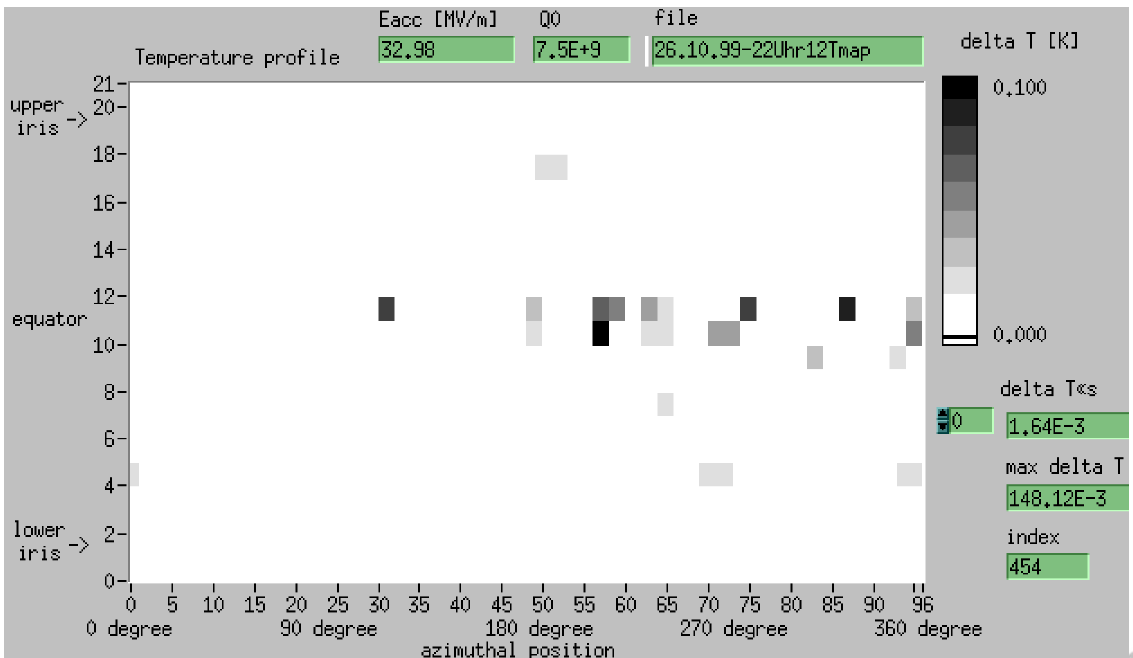
- SRF 1999











Temperature mapping at 33MV/m

... before in-situ bakeout at 120°C

⇒ Large area in the high magnetic field region of the cavity heats up

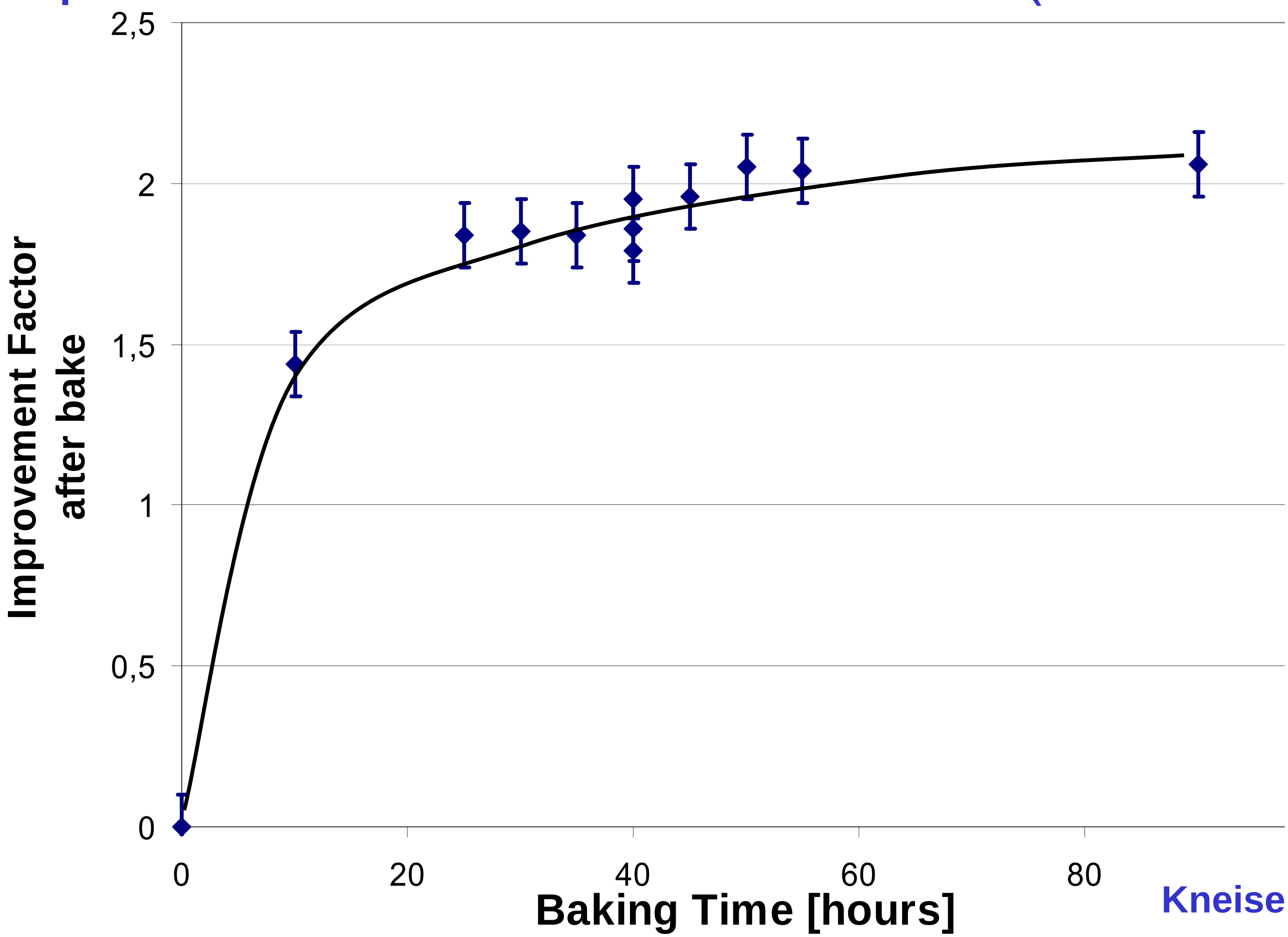
⇒ Global effect

... after in-situ bakeout at 120°C

⇒ Heating of the equator welding

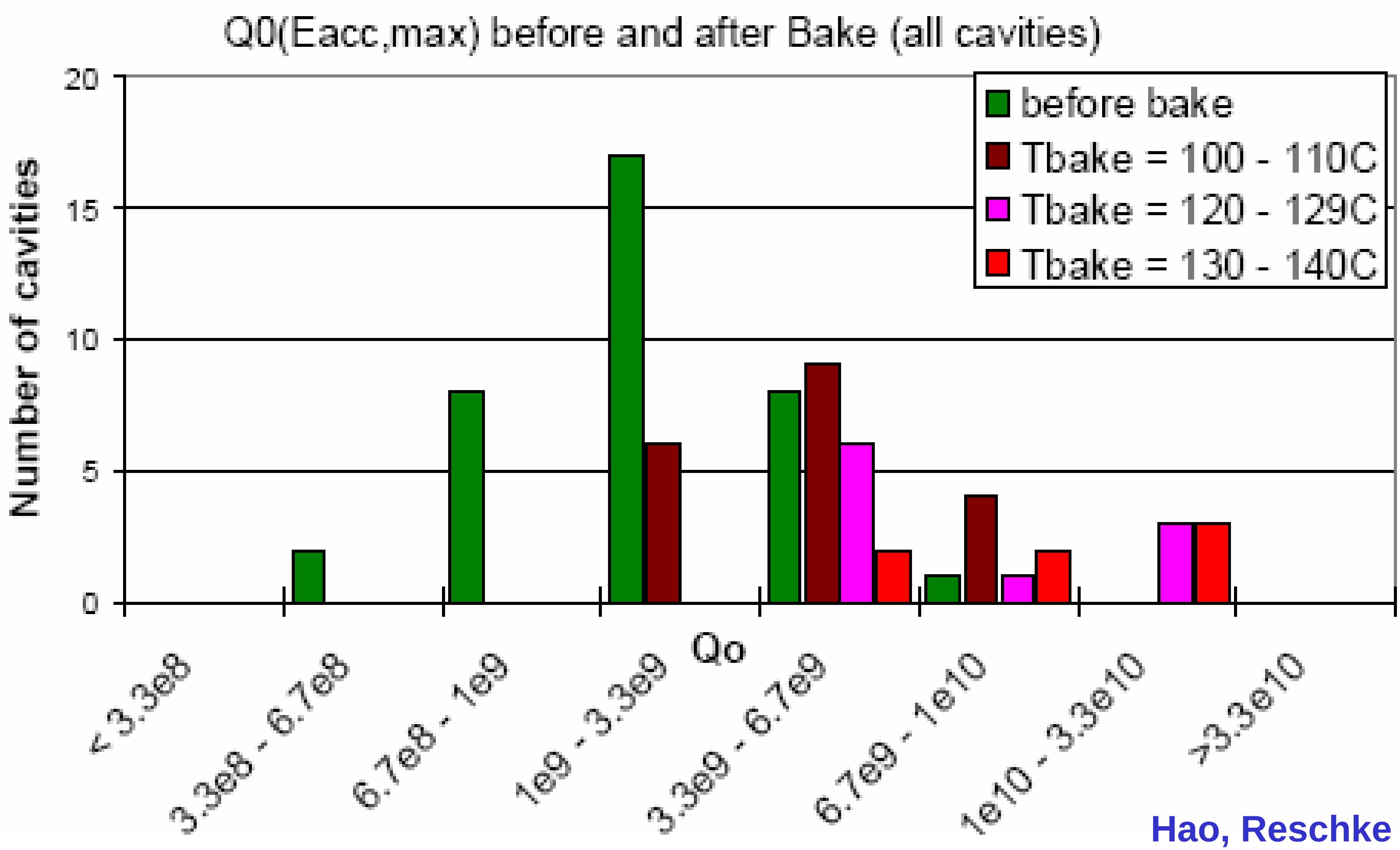
⇒ Change of the surface properties of the niobium

Optimum Duration of the Bakeout (T=140°C)



Kneisel 1999

Bake Temperature



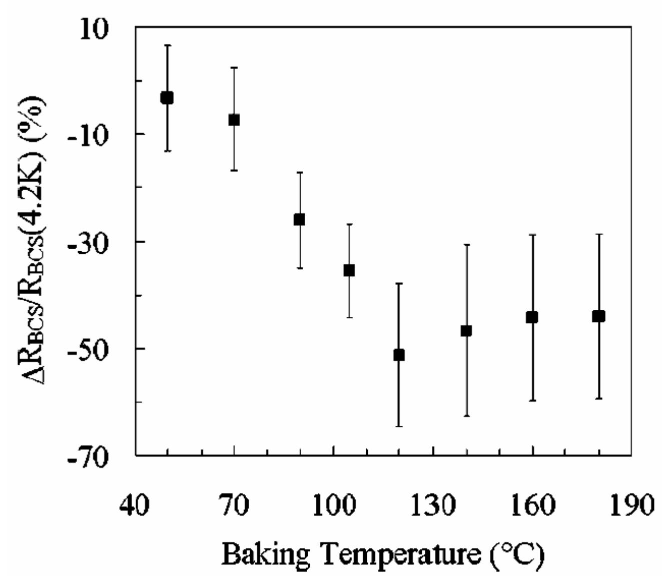
Hao, Reschke 2003

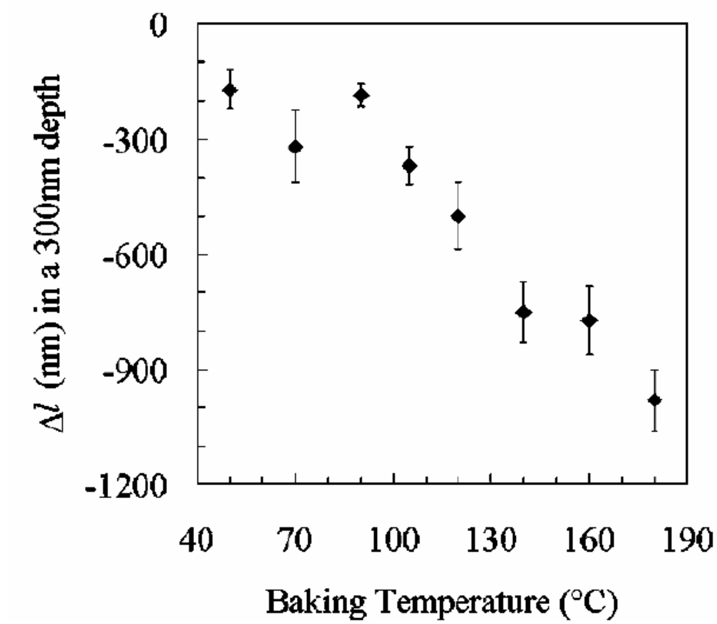
Bake Temperature

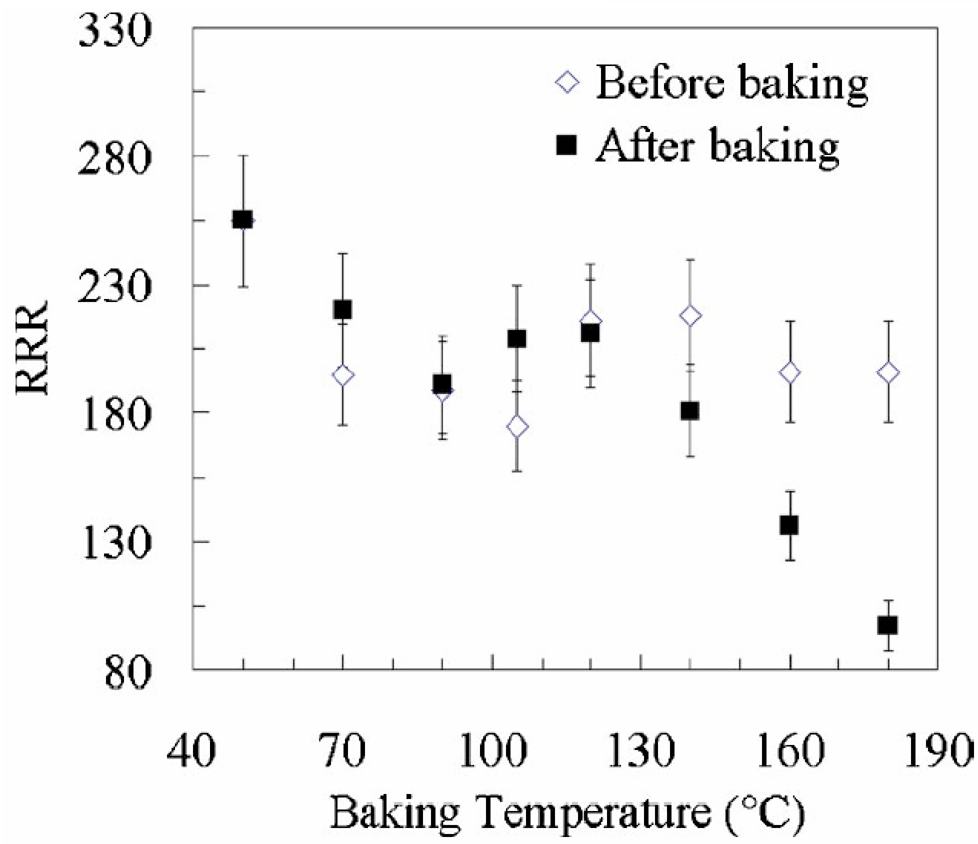
	bake T(°C)	before bake	after bake	Gain	Ratio
Eacc,max (MV/m)	all	31.9	35.6	3.7	
	100-110	31.9	35.9	4.0	
	120-129	32.6	35.8	3.2	
	130-139	30.8	34.4	3.6	
Eacc @Q_0=1× 10^{10} (MV/m)	All	27.0	30.7	3.7	
	100-110	25.9	30.5	4.7	
	120-129	27.9	29.4	1.5	
	130-139	28.2	29.6	1.5	
Q_0(Eacc,max) EP(all cavities) (*10^9)	All	1.9(2.3)	6.7(6.5)		3.5(2.9)
	100-110	2.0(2.2)	5.3(5.1)		2.6(2.3)
	120-129	1.8(2.0)	9.2(7.7)		5.0(3.8)
	130-139	1.5(2.7)	8.0(8.9)		5.4(3.3)

Hao, Reschke 2003

Bake Temperature







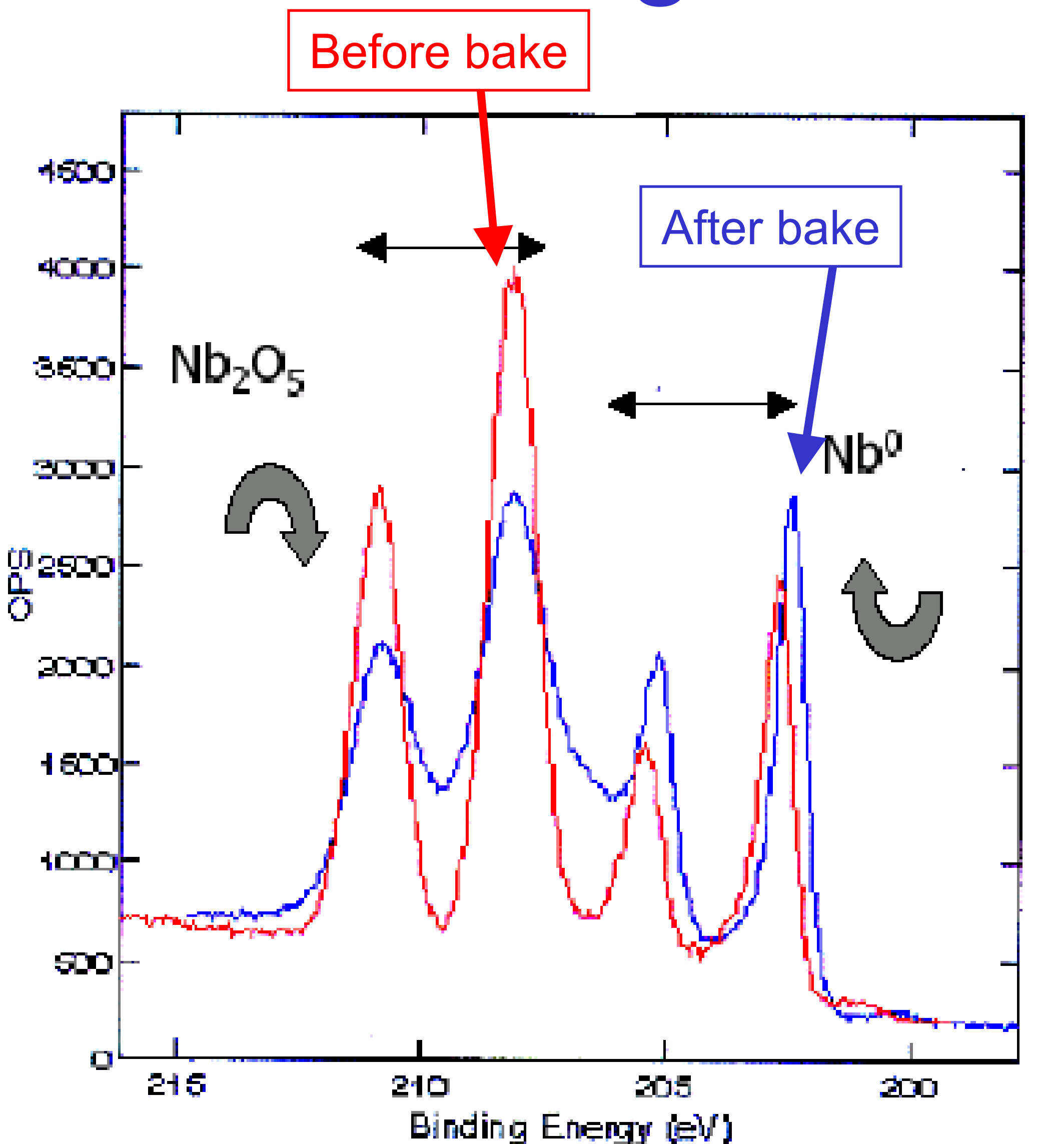
- 1.5 GHz measurements by **G Ciovati et al.** (see reading list)
- R_{BCS} shows a saturation above 120°C
- Reduction of the mean free path
- Surface RRR degrades for T>130°C
  - Within the normalconducting skin depth

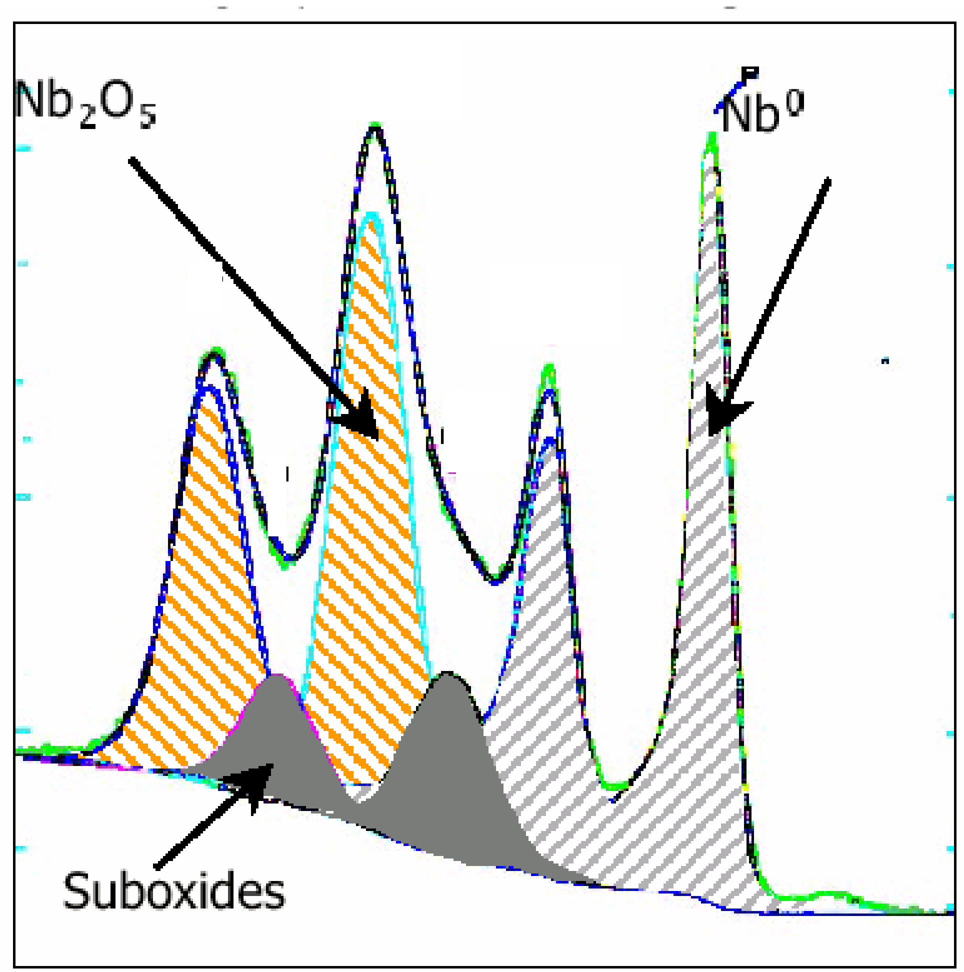
Contamination of the Surface Layer

- These results hint to a contamination of the surface niobium layer relevant for the RF shielding
  - The prime candidate is oxygen…
    - Several XPS measurements show a decomposition of the surface dielectric oxide layer (Nb_2O_5)
    - The suboxides like NbO (and others) seem to be enhanced
  - … but are there other candidates?
- What is depth of the material affected by the bake?

Change of Surface Oxide

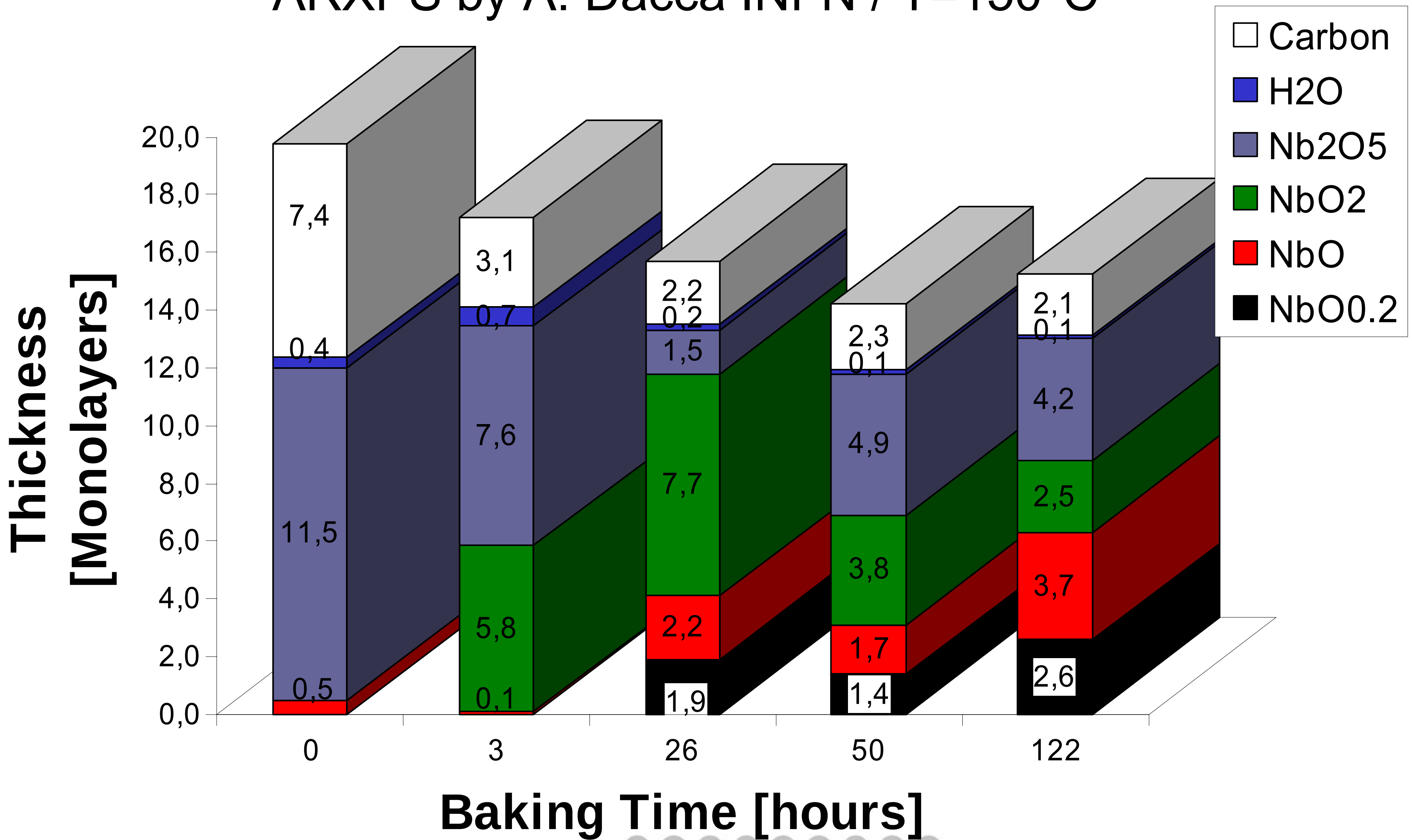
C. Antoine CEA



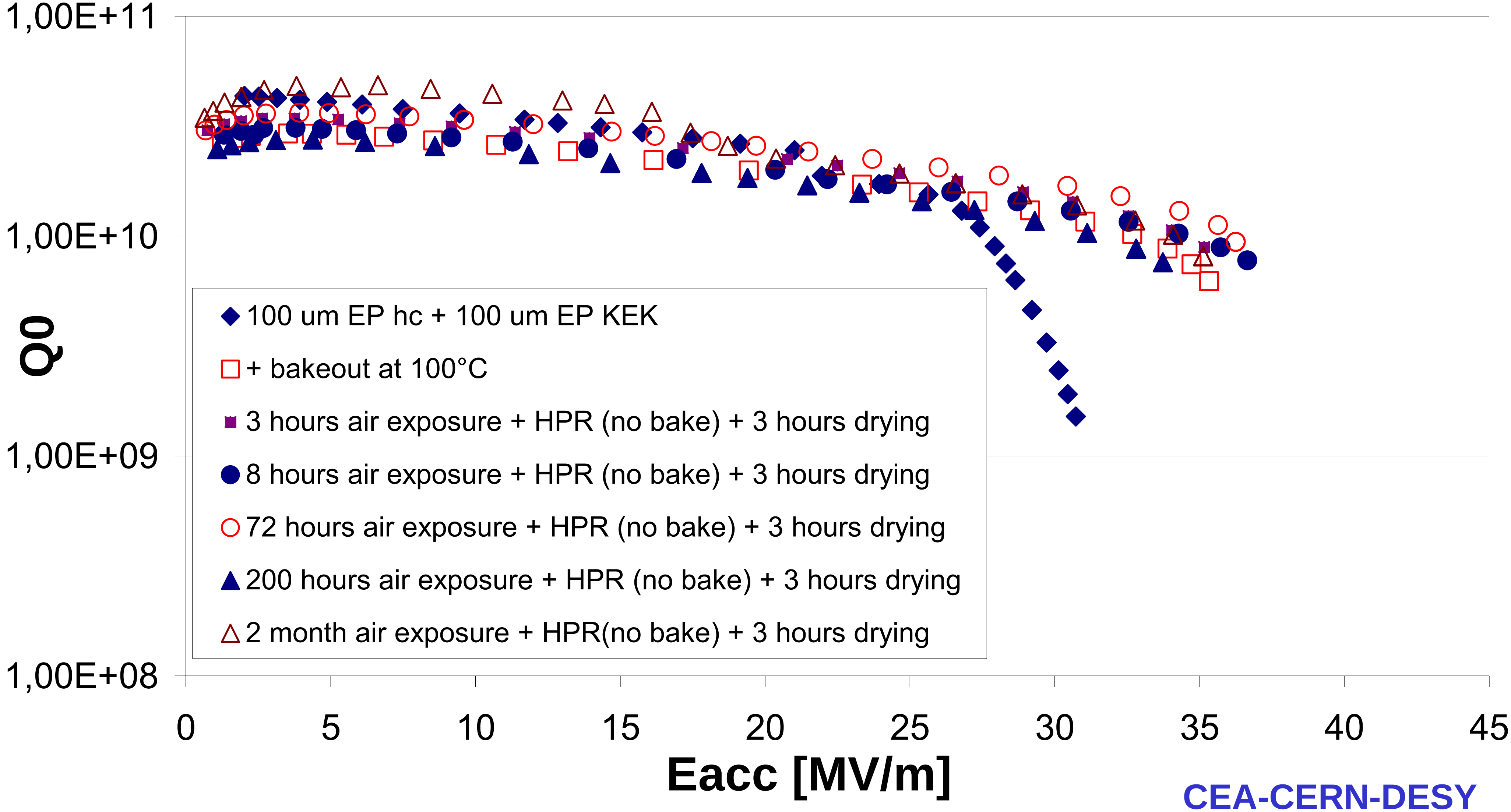


Change of the Oxide Structure

ARXPS by A. Dacca INFN / T=150°C

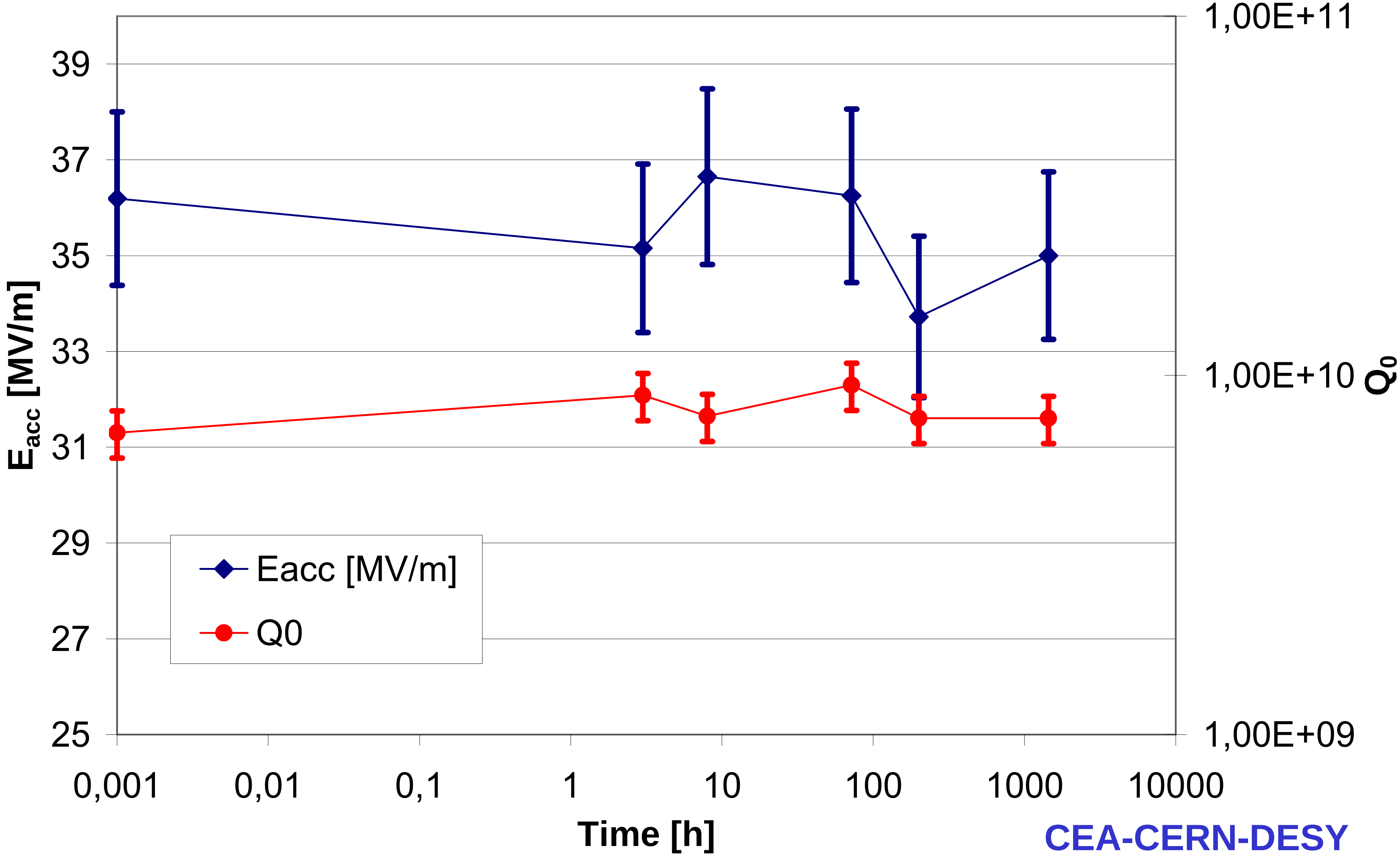


Exposure of a Baked Cavity to Air



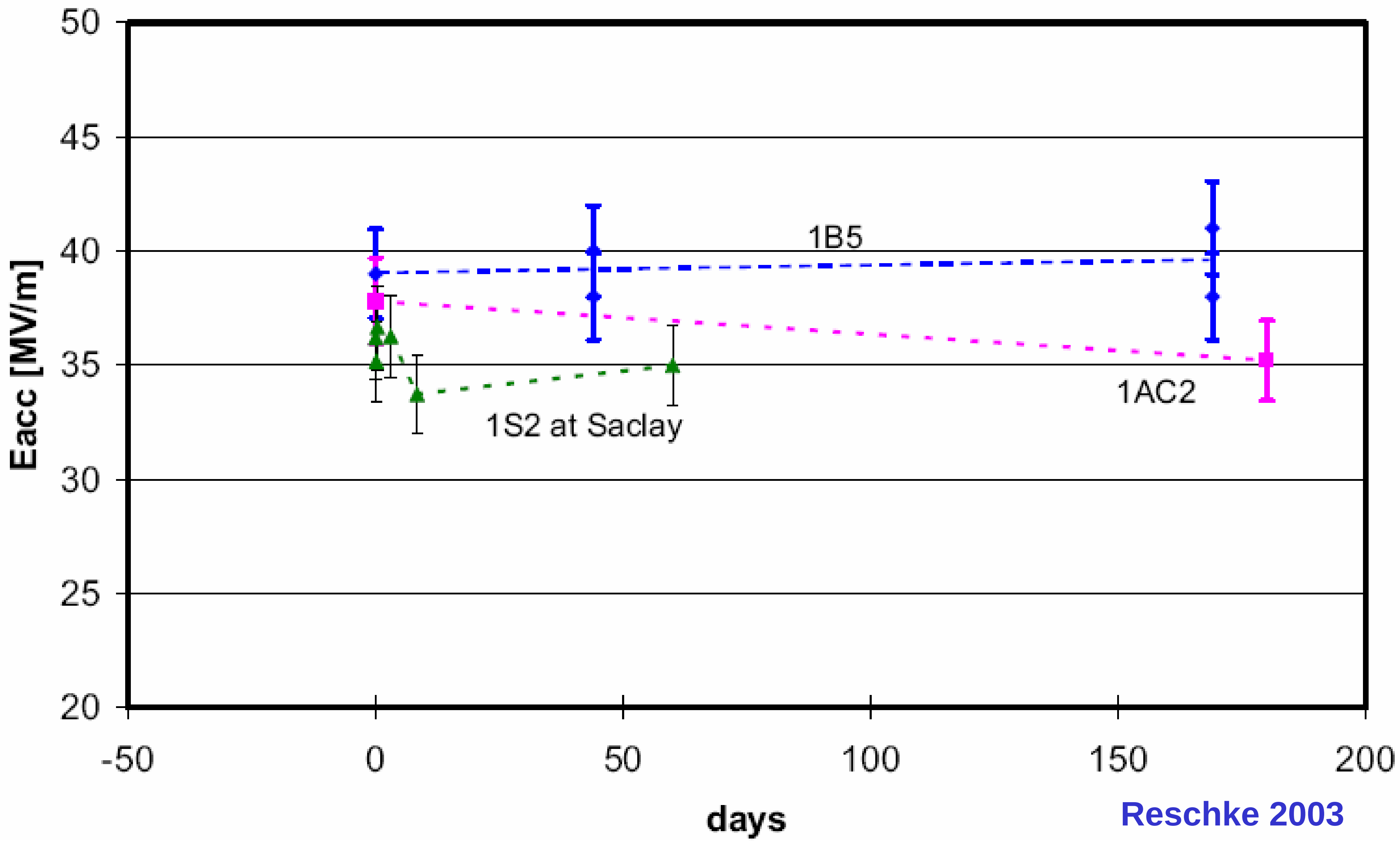
CEA-CERN-DESY

Exposure of a Baked Cavity to Air



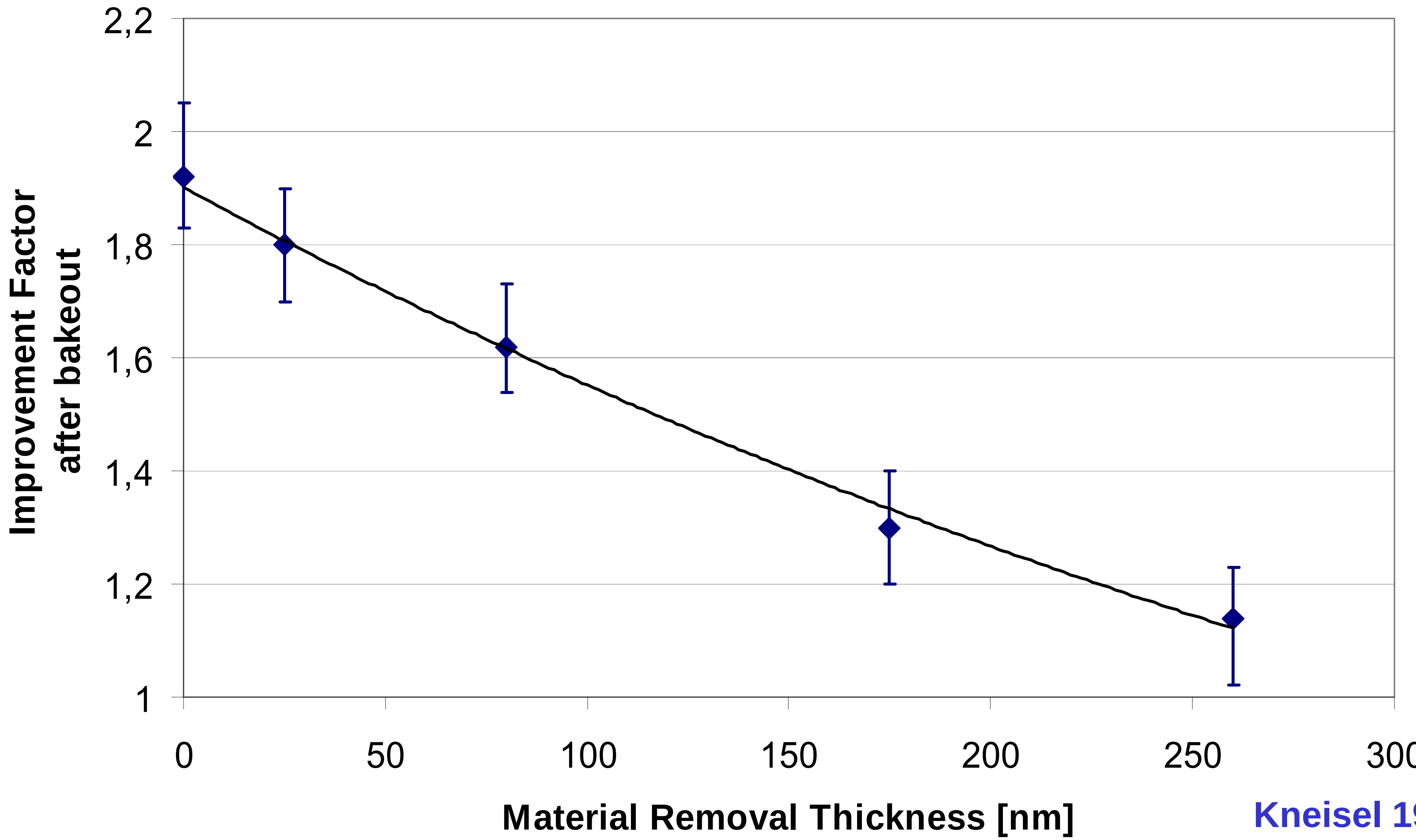
CEA-CERN-DESY

Exposure of a Baked Cavities to Air



Reschke 2003

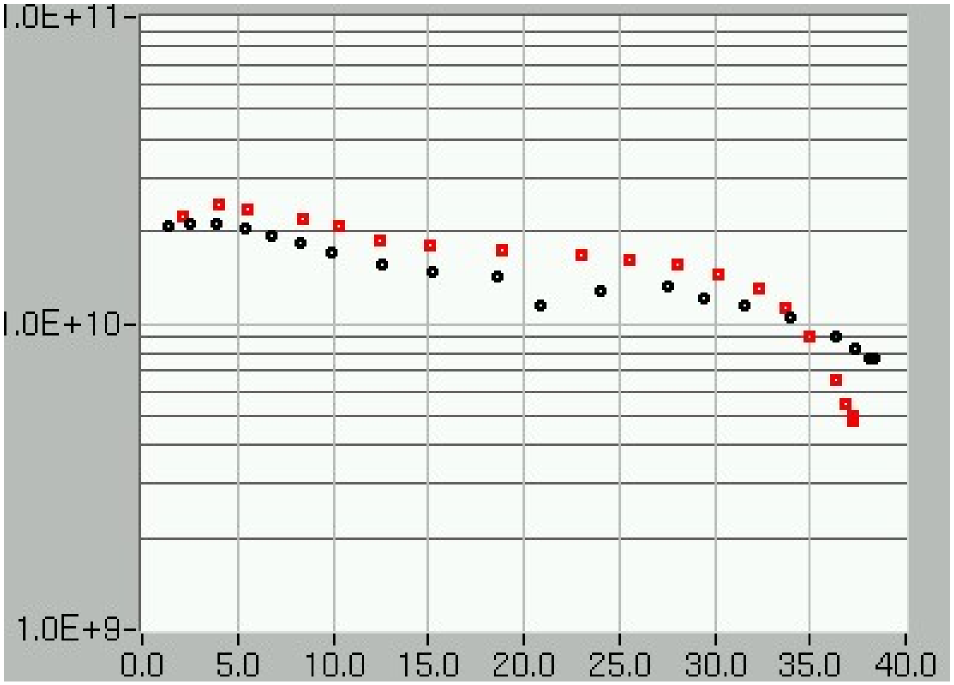
R_{BCS}: Material Depth Affected by the Bake



Kneisel 1999

1B8: oxipolishing (= anod. + HF rinse)

- 30V anodising (≈ 60 nm Nb_2O_5-layer) + HPR + HF-Rinse + HPR
  E_{acc} = 37.3 MV/m @ $Q_0 = 4.8 \cdot 10^9$, limited by BD; no FE



black: after EP + bake + anod + bake + HF rinse

red: + oxipolishing (60 nm)

T = 2K

=> Q-slope without fieldemission present again!

Reschke 2004

Experimental Data II

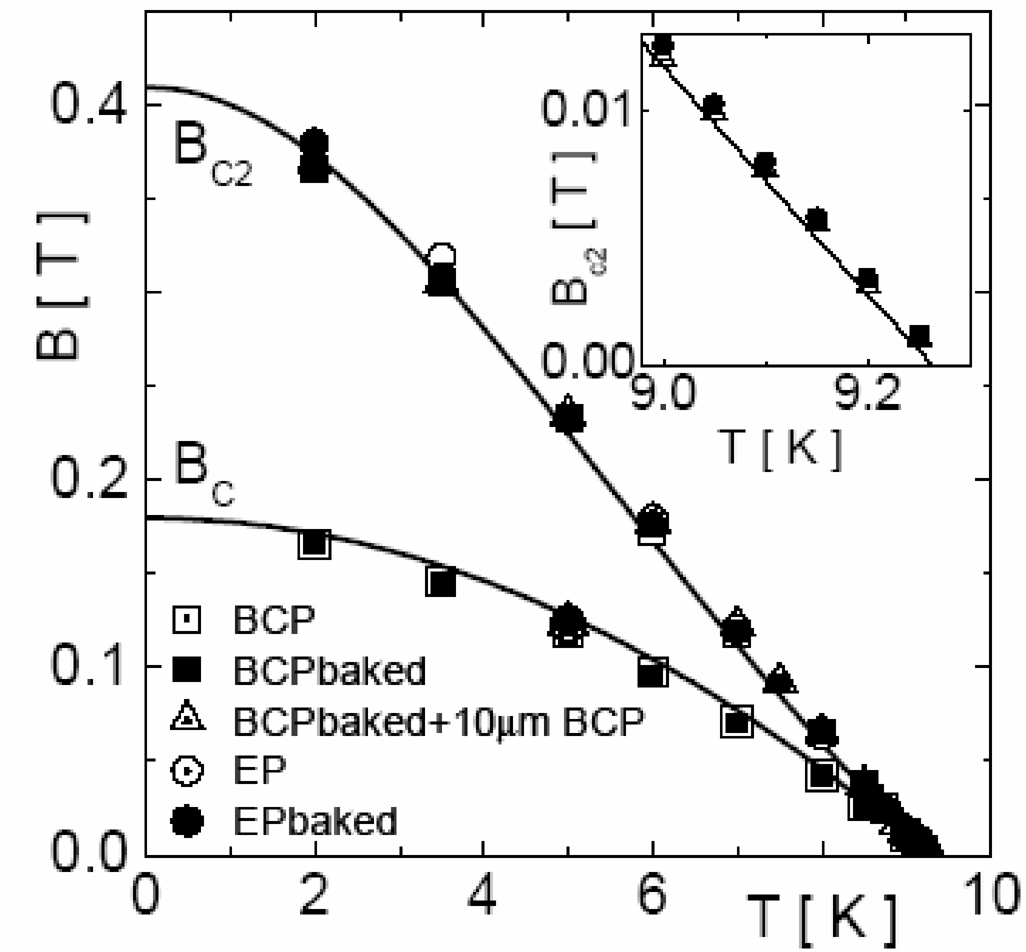
- T-mapping shows heating of a large region (high magnetic field region)
- Temperature for baking
  - Relatively large variety of data available (each lab has a special flavour)
  - Temperatures above 120°C and below 140° C seem favourable
- Surface RRR goes down (G. Ciovati)
- XPS measurements show a change of the chemical surface composition
- Air exposure of the baked surface does not change the cavity performance
- Depth of the bake affected zone
  - 300 nm: R_{BCS} is back to value before bakeout (P. Kneisel)
  - 60 nm: Q-slope re-appears, but not fully back pre-bake state (D. Reschke)

Susceptibility Measurements on Niobium Samples

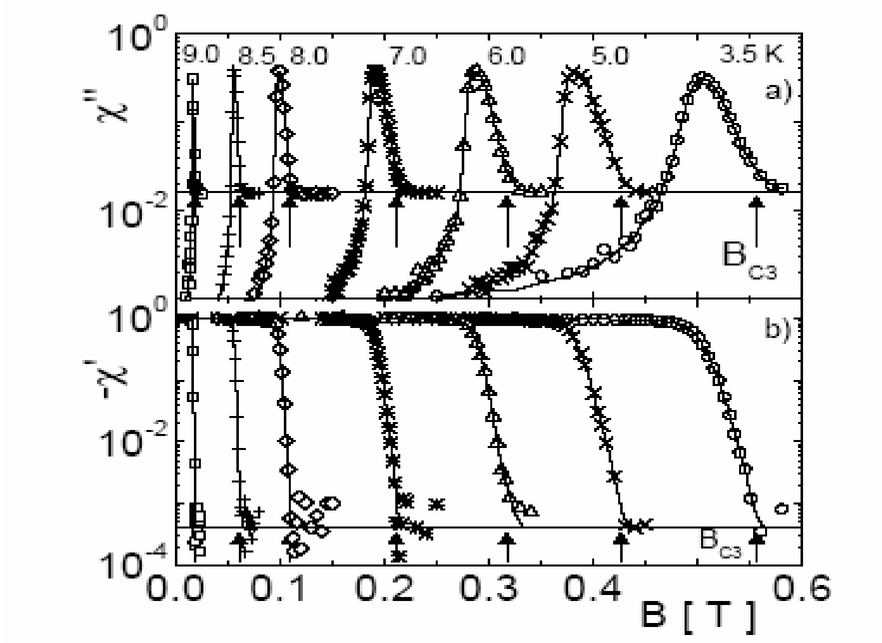
- Bernd Steffen, Sara Casalbuoni et al.
  - Preprint physics/0403045 on xxx.lanl.gov
  - DESY Report 04-027
  - Accepted for publication in NIM A
- Bulk properties
  - B_c, B_{c2}
- Surface properties
  - B_{c3}, critical currents, normal state susceptibility

Susceptibility Measurements: Bulk Properties

- Surface treatment does not change the bulk properties e.g. B_c and B_{c2}
  - EP vs. BCP
  - Baking



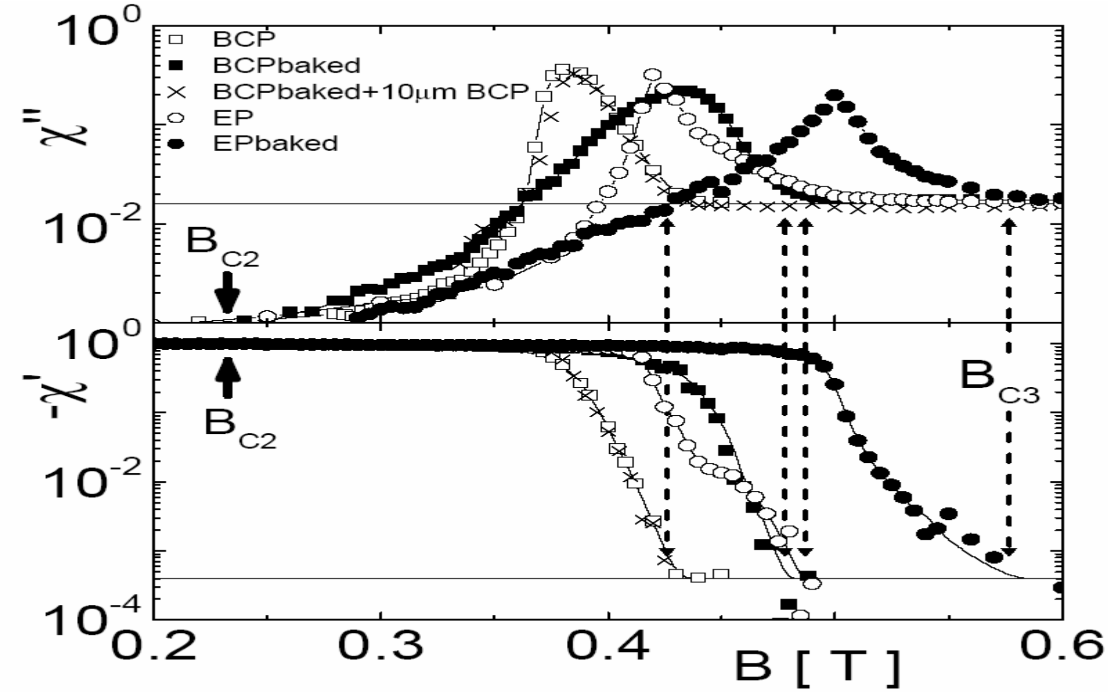
	BCP	EP
T_c [K]	9.263 ± 0.003	
RRR	≈ 300	
surf. roughness on grain [nm]	≈ 1	
steps at grain bound.	1-5 μm	$\lesssim 0.1\mu$m
$B_c(0)$ [mT]	180 ± 5	
$B_{c2}(0)$ [mT]	410 ± 5	
$J_c(0,0)$ [A/mm^2]	240 ± 10	180 ± 10

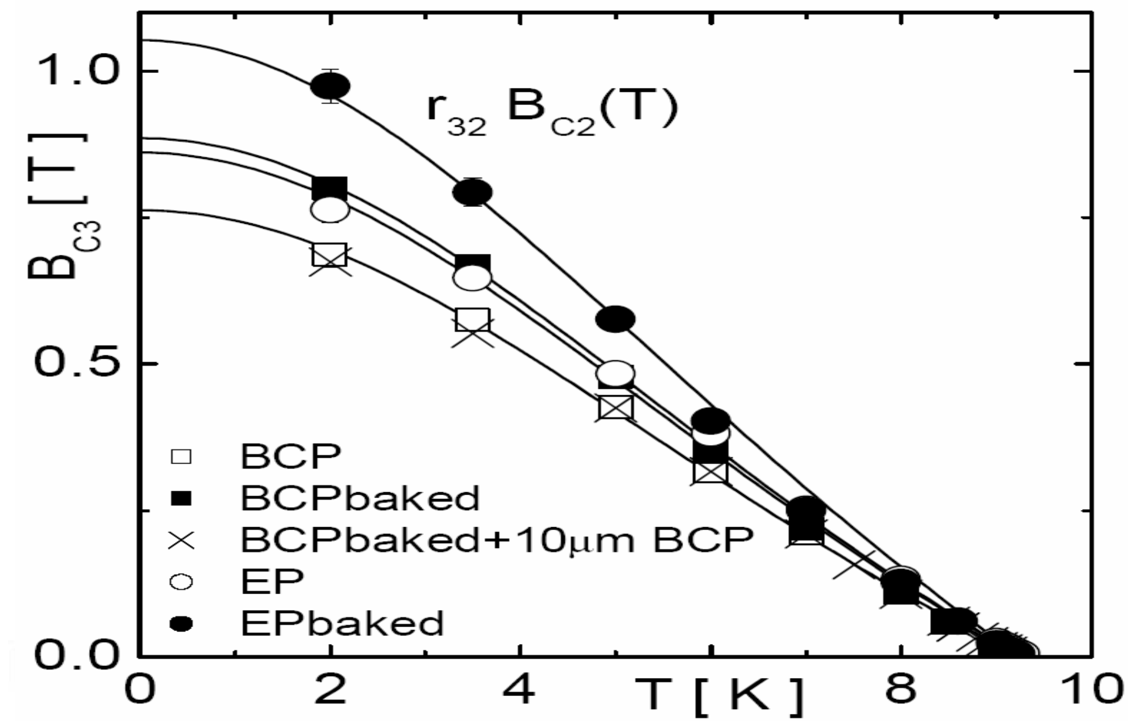


Example: Temperature dependence of B_{c3} for an etched sample

Susceptibility Measurements: B_{c3}

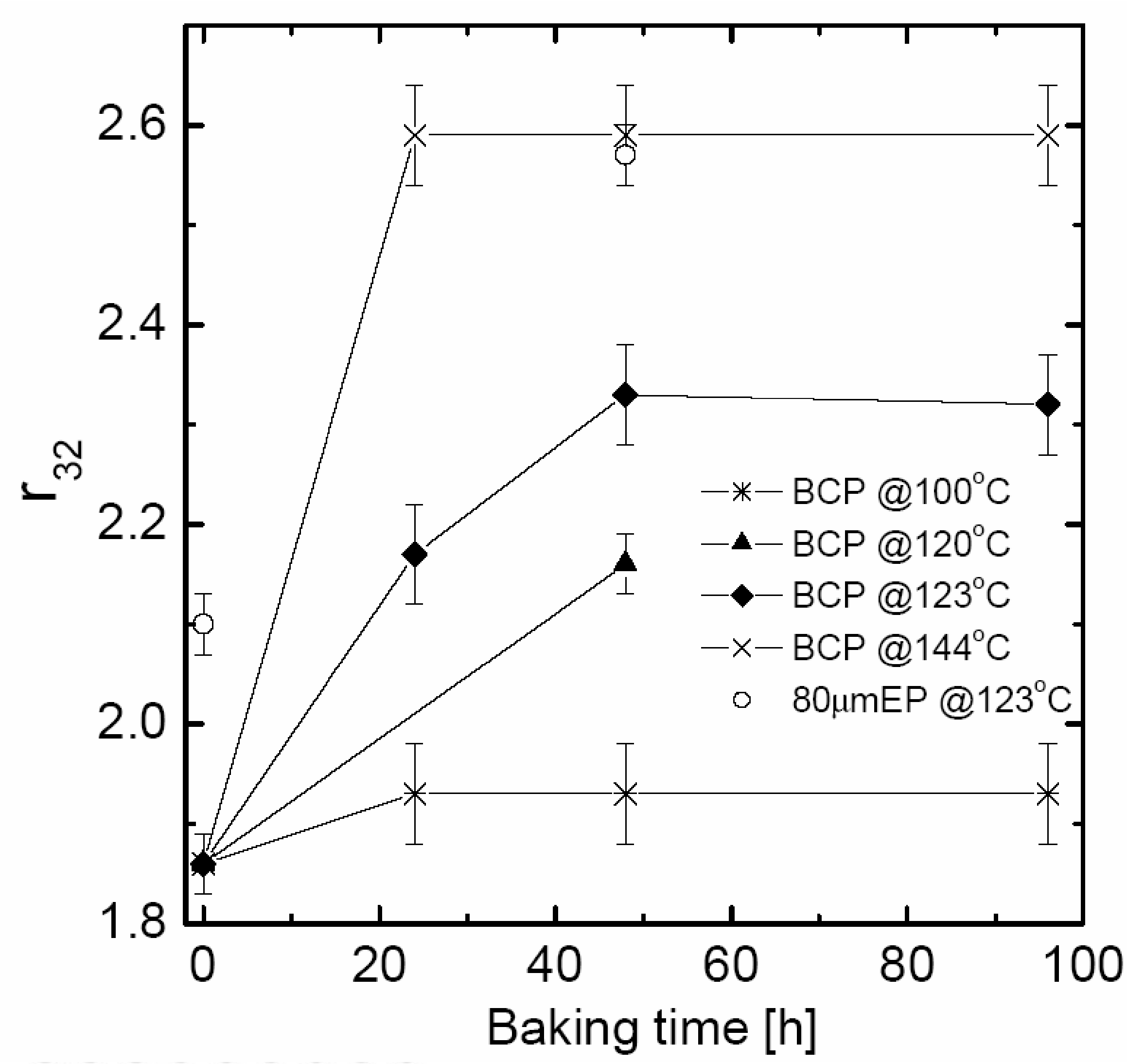
- Surface critical field B_{c3} depends on surface preparation





Ratio of $r_{32}=B_{c3}/B_{c2}$: Bake Temperature and Duration

- r_{32} (Ginzburg-Landau) =1.695
- In these measurements: r_{32} >1.8
- Assume that the surface B_{c2}^{surf} has changed
- Estimation of the impurity content of the surface layer possible

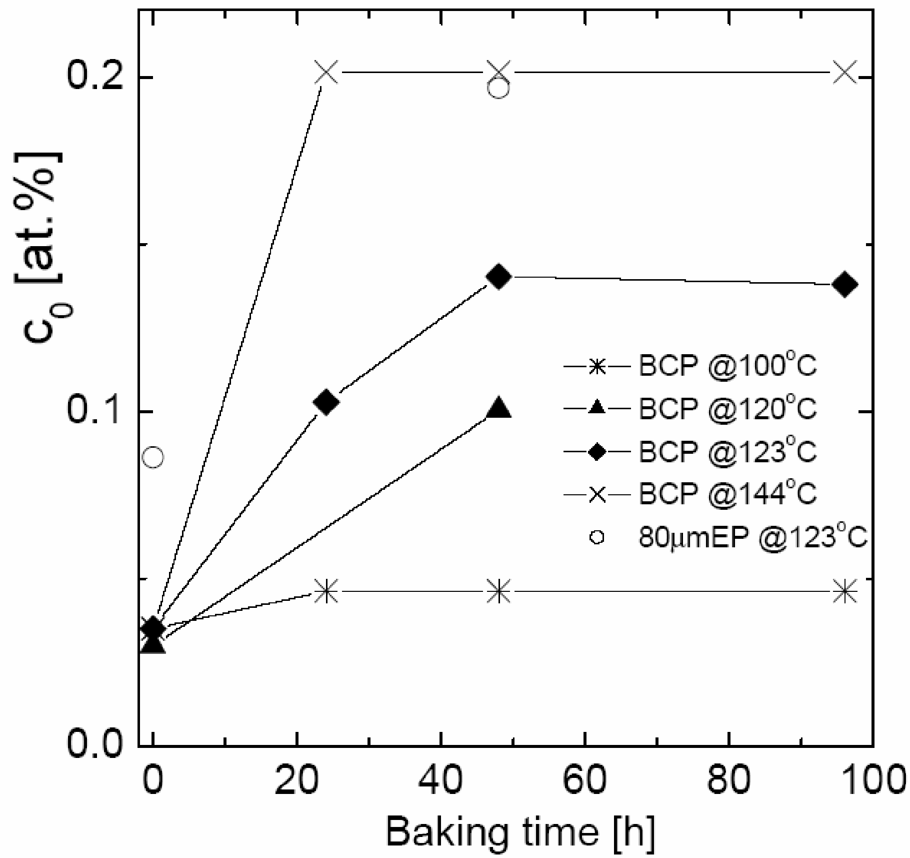


What would be the Oxygen Concentration Inside the Niobium?

- Calculation of the oxygen concentration using a formula found by Koch (1974)

$$r_{GL} = 1.695$$

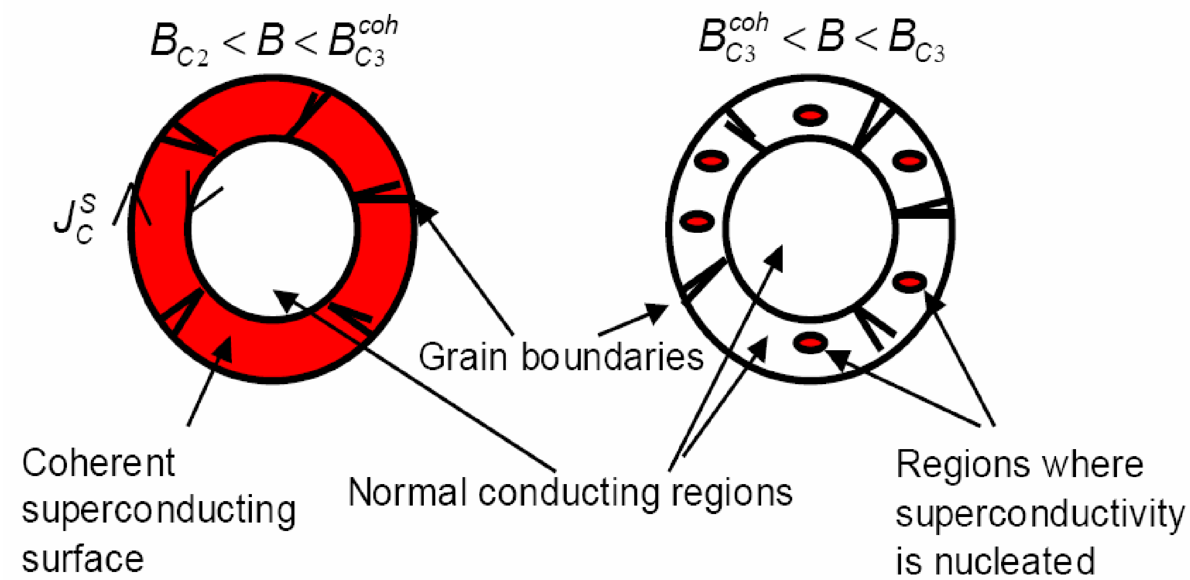
$$B_{c3} = r_{GL}\, B_{c2}^{surf}$$

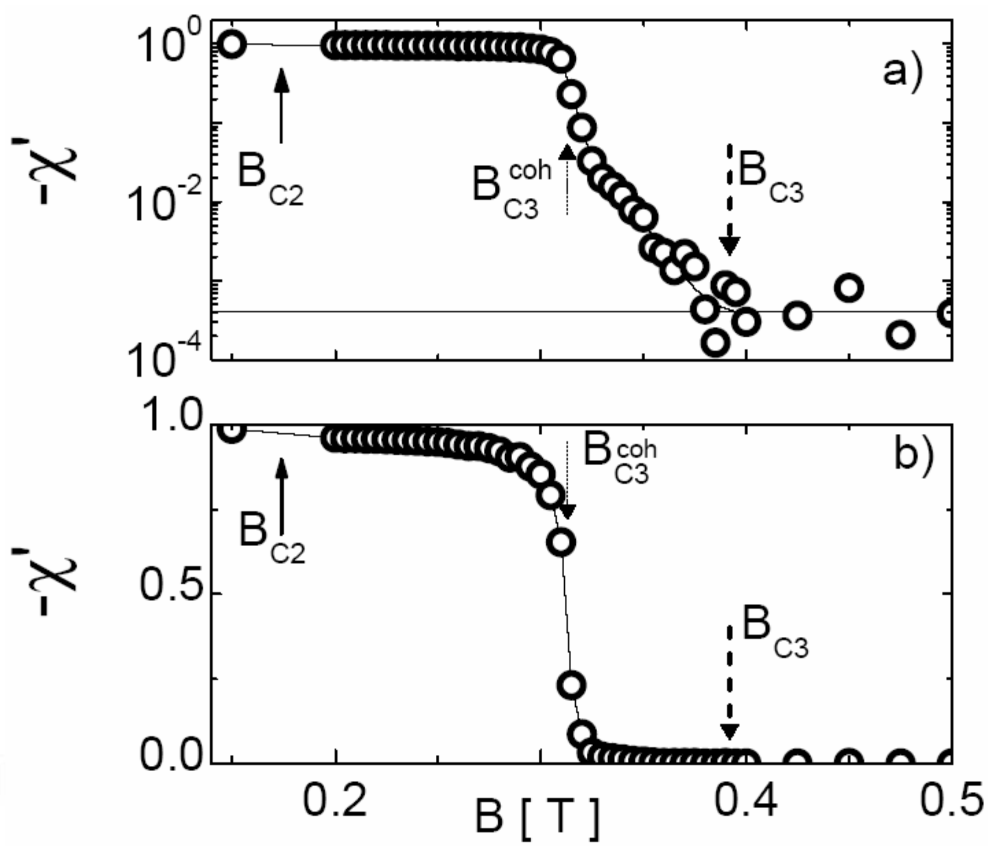


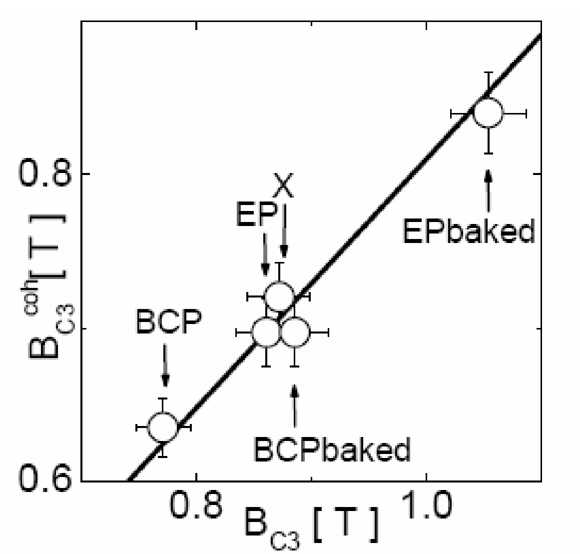
$$c_O\,[at.\,\%] = 1.475 \cdot 10^{-3}(B_{c2}^{surf}\,[\mathrm{mT}] - 276)$$

Critical Surface Fields

- Existence of two critical surface fields
  - At B_{c3} the surface is superconducting only in small superconducting domains
  - At B_{c3}^{coh} a coherent wavefunction exists on the full surface





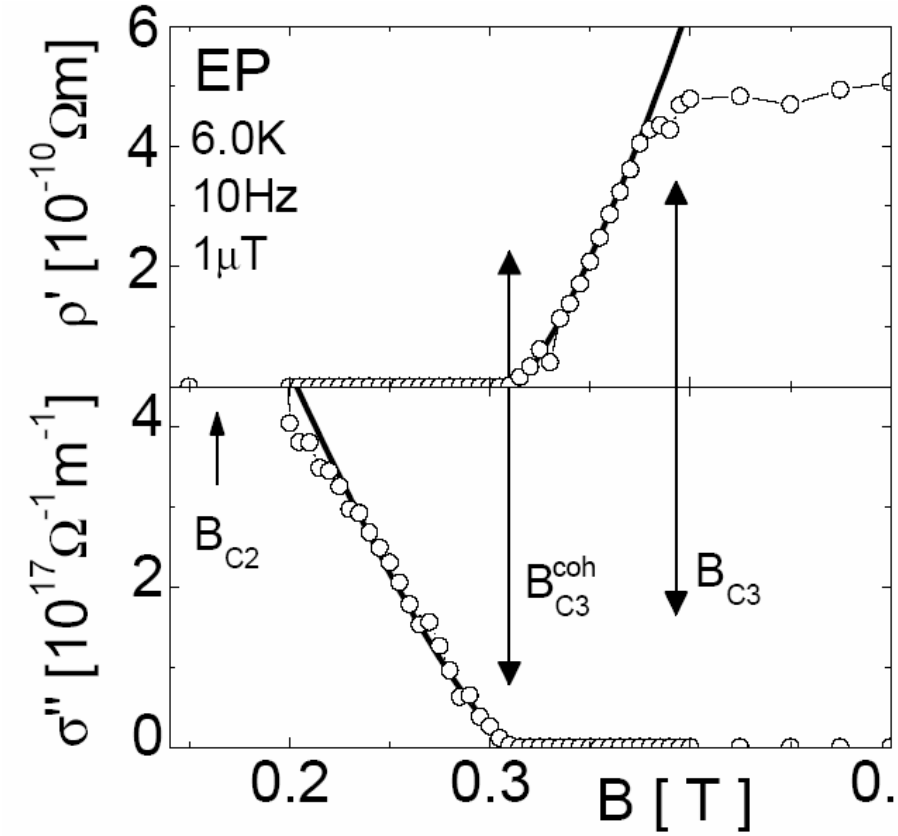


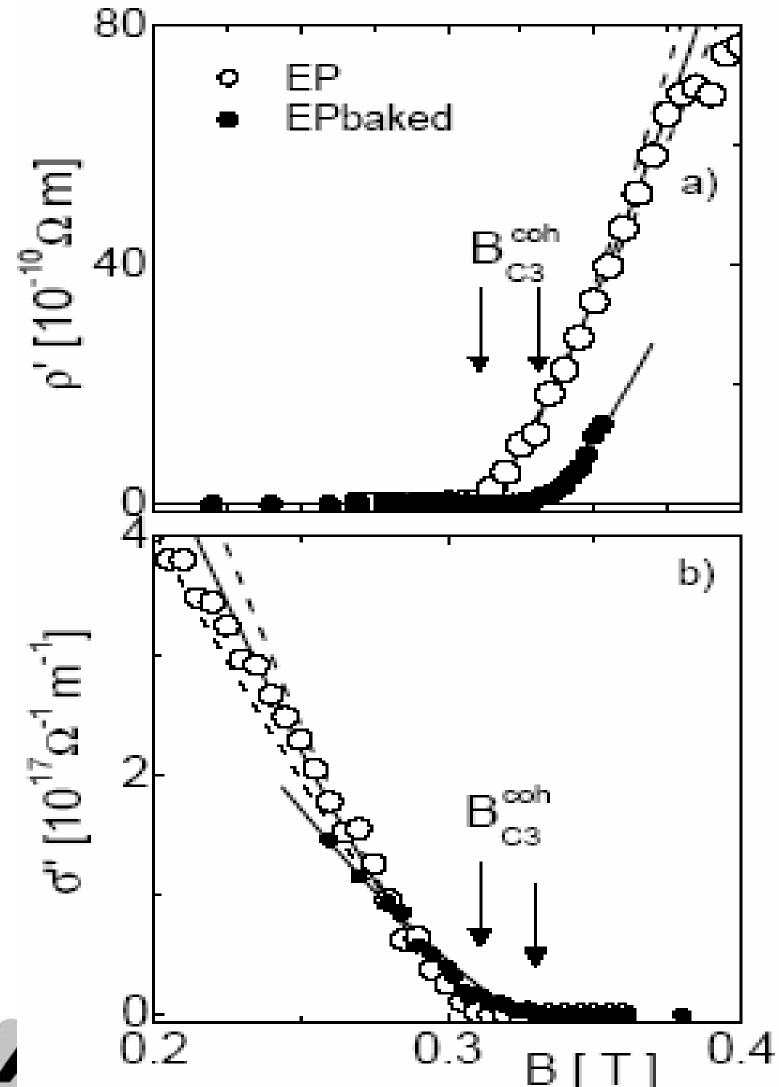
Detailed View of the Transition Region: $B_{c2} < B < B_{c3}$

$$\rho'(B) \propto (B - B_{c3}^{coh})^s \quad \text{for} \quad B_{c3}^{coh} < B < B_{c3}$$

$$\sigma''(B) \propto (B_{c3}^{coh} - B)^t \quad \text{for} \quad B_{c2} < B < B_{c3}^{coh}$$

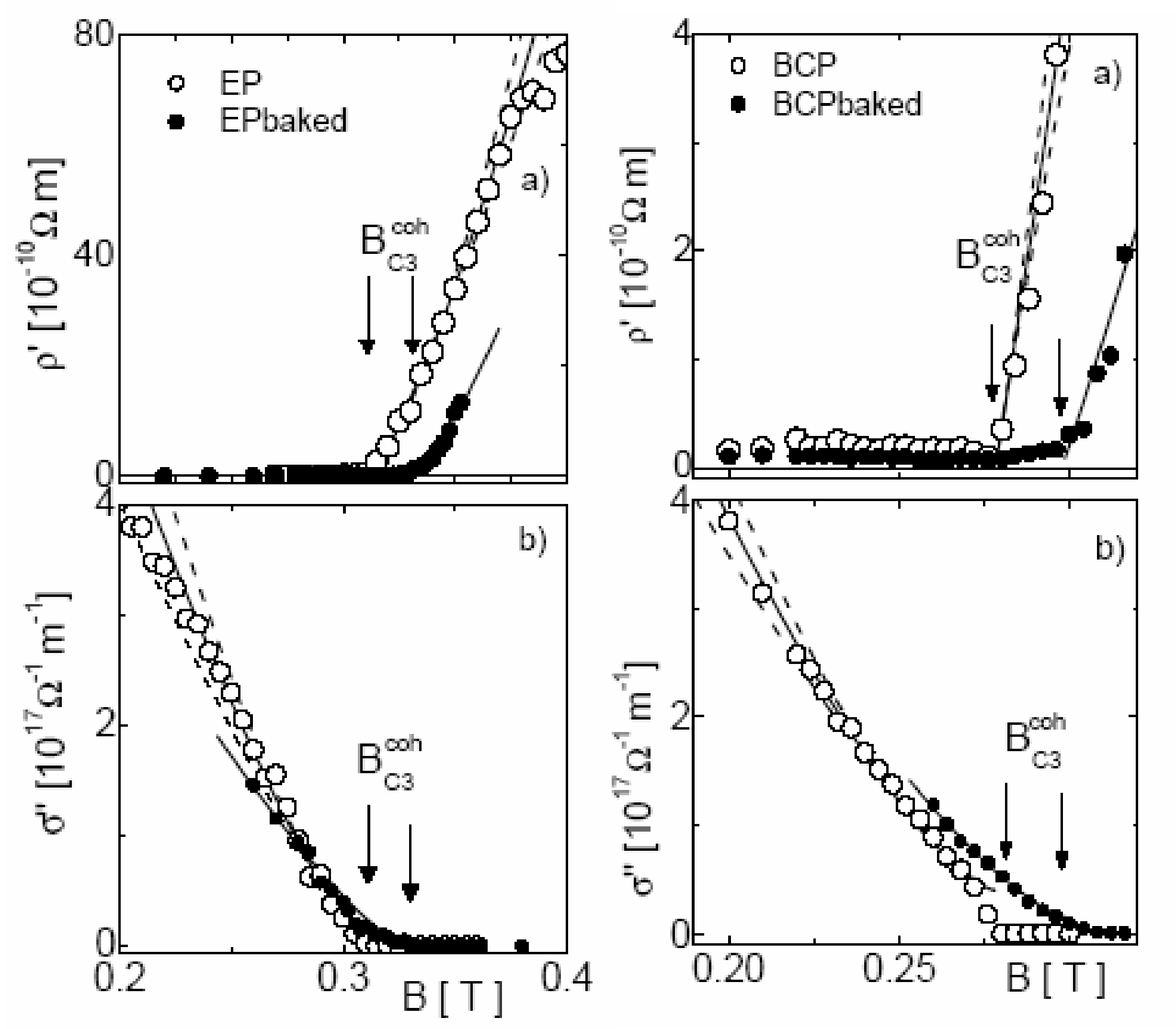
- Power Law Analysis of Resistivity and Conductivity reveals a phase transition
- The effect of baking is seen very clearly





Power Law Analysis: BCP vs. EP

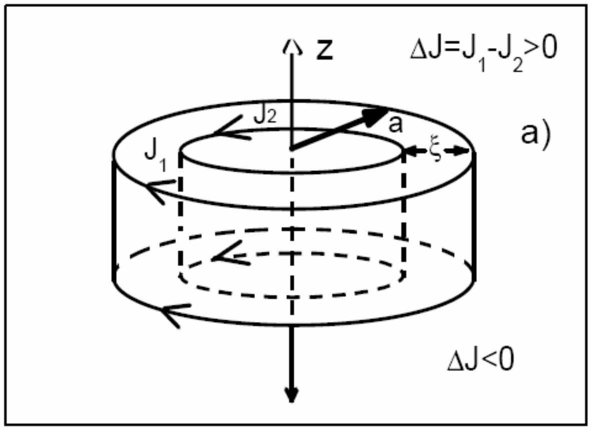
- The critical exponents of the power law fits near B_{c3}^{coh}
  - $s = t = 1.3 \pm 0.1$ for EP
  - $s = 1.05 \pm 0.1$, $t = 1.4 \pm 0.1$ for BCP samples.
- Therefore:
  - the smooth EP surface is able to support planar (two-dimensional) surface currents
  - EP samples feature a coherent surface phase which resembles the Meissner phase in the bulk
  - the rough grain boundaries in a BCP surface enforce more complicated current patterns.
  - In the BCP samples this coherent phase is disturbed by weak links at the grain boundaries.

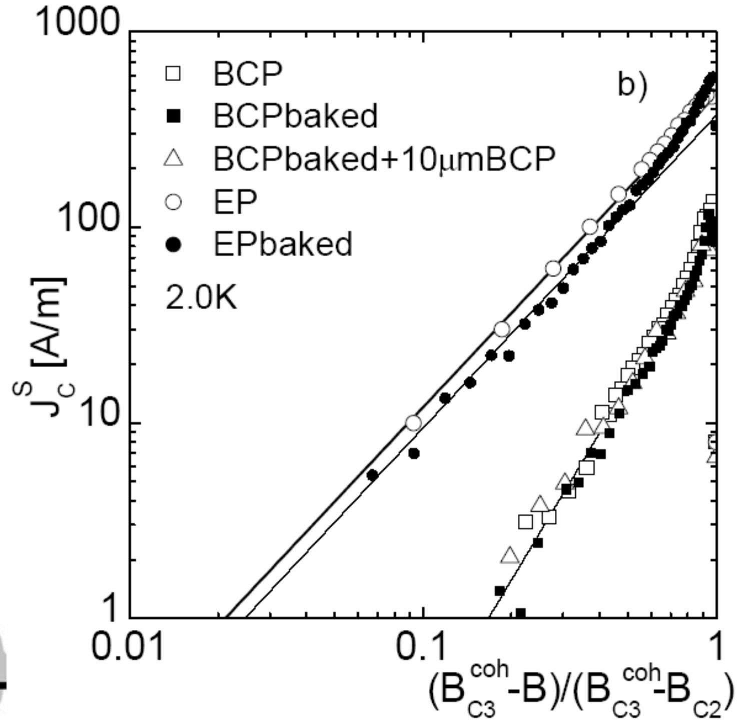


Critical Surface Currents

$$J_c^s(B) \propto \left(1 - \frac{B}{B_{c3}}\right)^v$$

- The surface current is a factor of 6 larger for EP than for BCP
- Power-law analysis
  - **Abrikosov**: v =1.5
  - **EP**: v =1.6 ±0.1
  - **BCP**: v= 2.5 ±0.3
- This indicates that the surface currents for etched surface have to follow more complicated orbits
- lower current density are possibly related to the larger roughness of an etched surface
- Unfortunately the surface currents are about three orders of magnitude too small to sustain an RF magnetic field exceeding B_{C2}

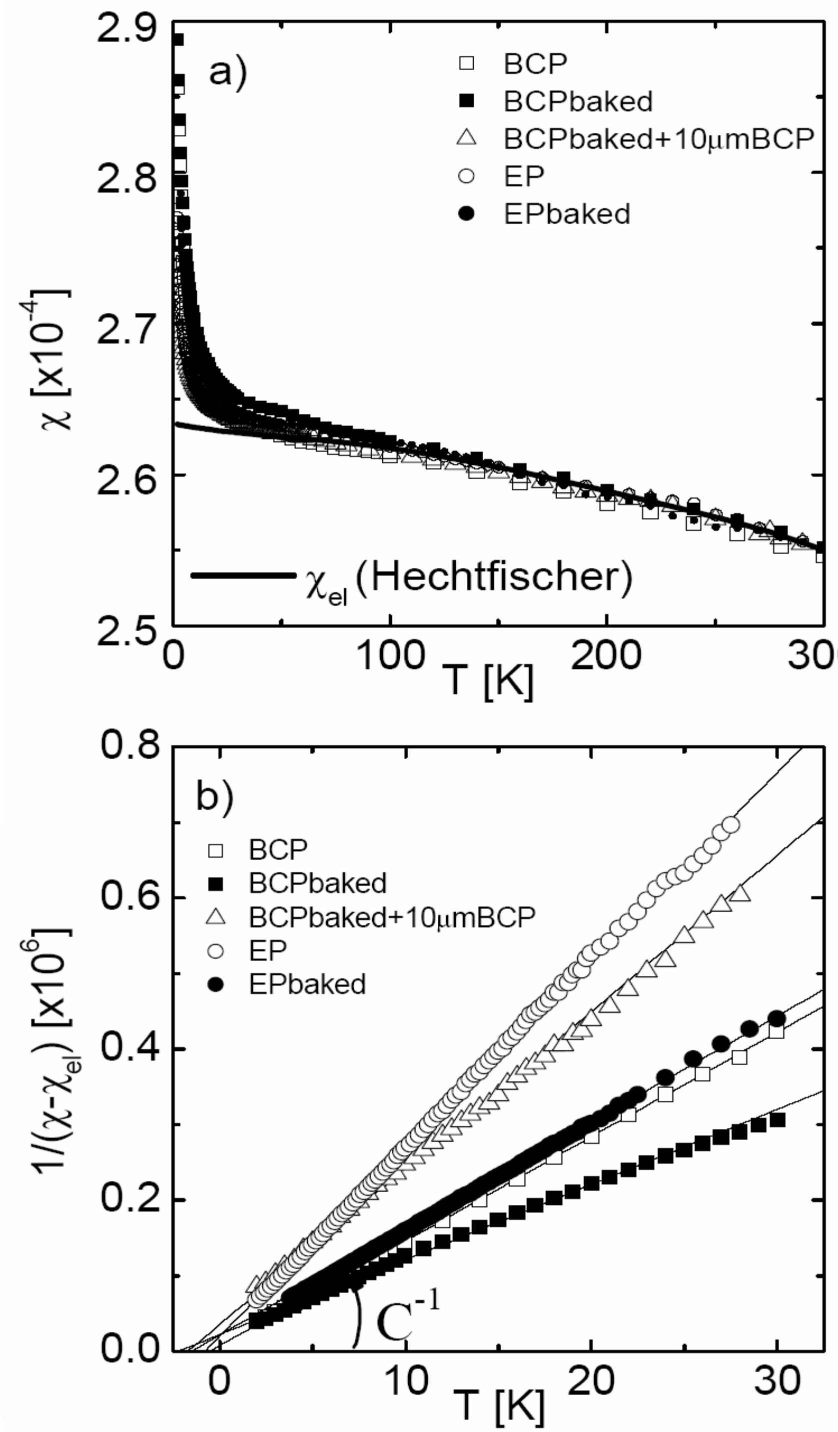




Paramagnetic Susceptibility (Normal state)

- In addition to the usual paramagnetism of the conduction electrons, there are localized paramagnetic impurities
- Curie-Weiss constant is about 100 times larger than expected from oxygen deficiencies in the Nb_2O_5 layer
  - **Evidence for other impurities ???**

Sample	C [μK]	θ [K]
BCP	72.3 ± 0.1	-0.5 ± 0.2
BCP baked	100.6 ± 0.07	-2.2 ± 0.1
EP	40.2 ± 0.3	-0.8 ± 0.2
EP baked	71.0 ± 0.1	-1.5 ± 0.2
BCP baked+10μm BCP	48.3 ± 0.4	-1.7 ± 0.3



Experimental Data III

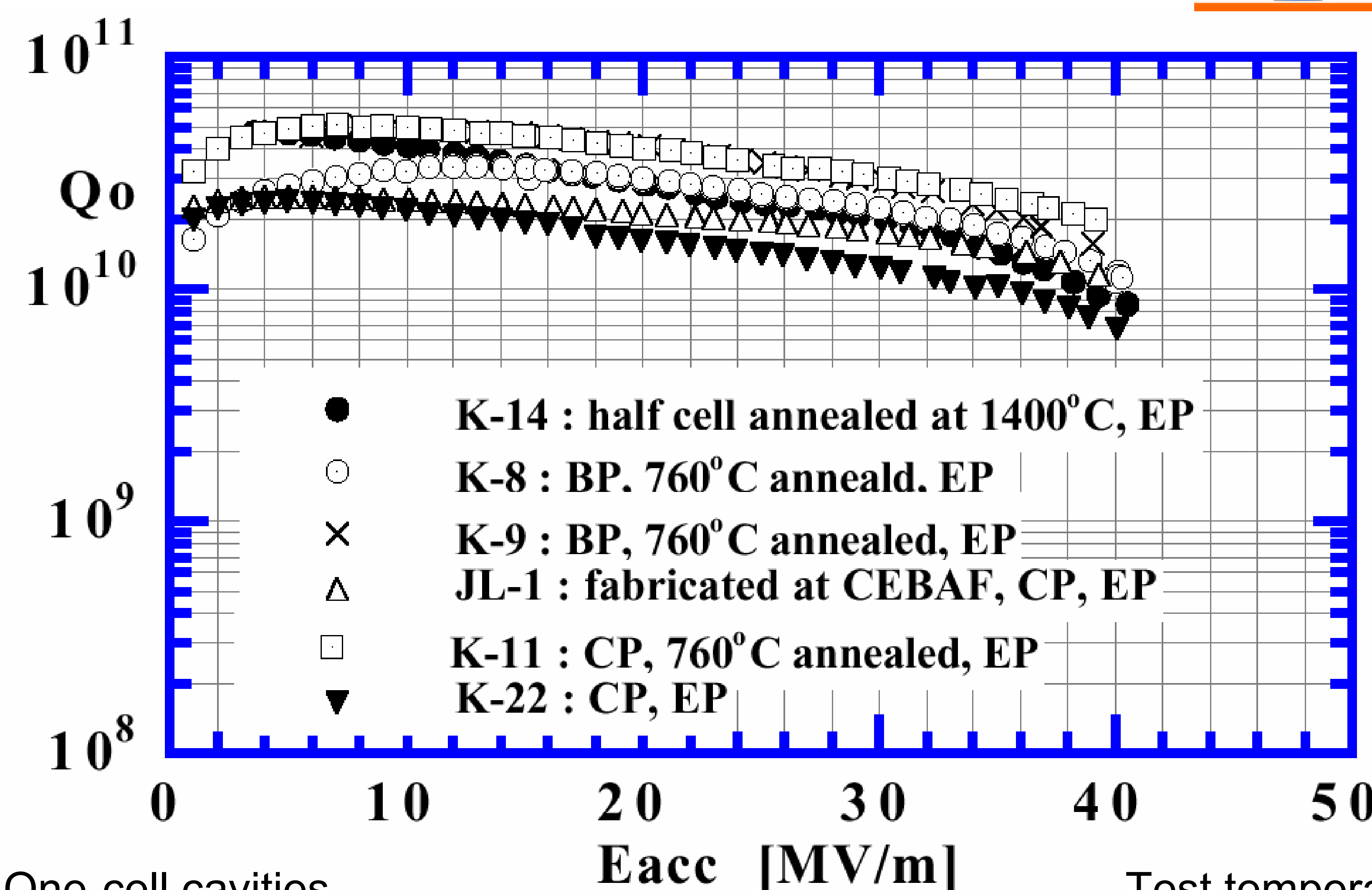
- Sample measurements
  - Bulk properties are not changed
  - Surface properties (B_{c3}, critical current) strongly depend on the surface preparation
  - Critical fields and critical currents
  - Power law analysis of the phase transition hints to the surface topology
    - EP is ‘two-dimensional’, current patterns are more simple
    - BCP has higher dimensionality, more complex current patterns
  - Paramagnetism cannot be explained by oxygen deficiencies alone
- ‘In-situ’ baking is not the only means to change of the slope (B. Visentin et al. – SRF2003 MoP19)
  - Baking under air is effective
  - Plasma discharge
  - ….

Side Remark: EP vs. BCP

- Since the ‘European headache‘ has been cured by EP and baking - thanks to Kenji et al.-….
- … we should now together cure the ‘Japanese Headache‘ discovered yesterday:
  - There exist a few good etched cavities.
  - WHY?
- I do not know the medication, but we can look at the available data.

Electropolished 1,3 GHz Elliptical Niobium Cavities

K. Saito et al. KEK 1998/1999

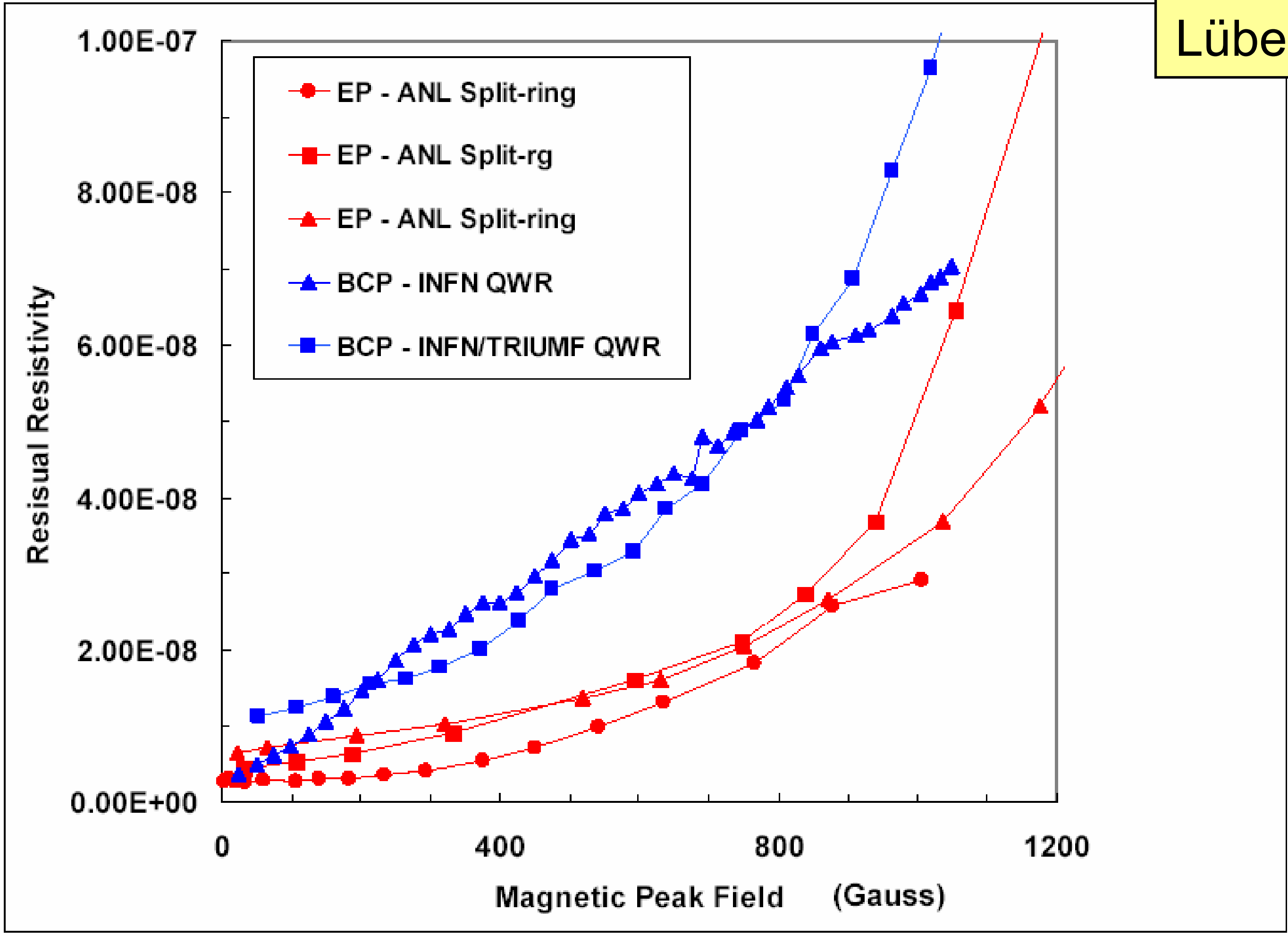


One-cell cavities

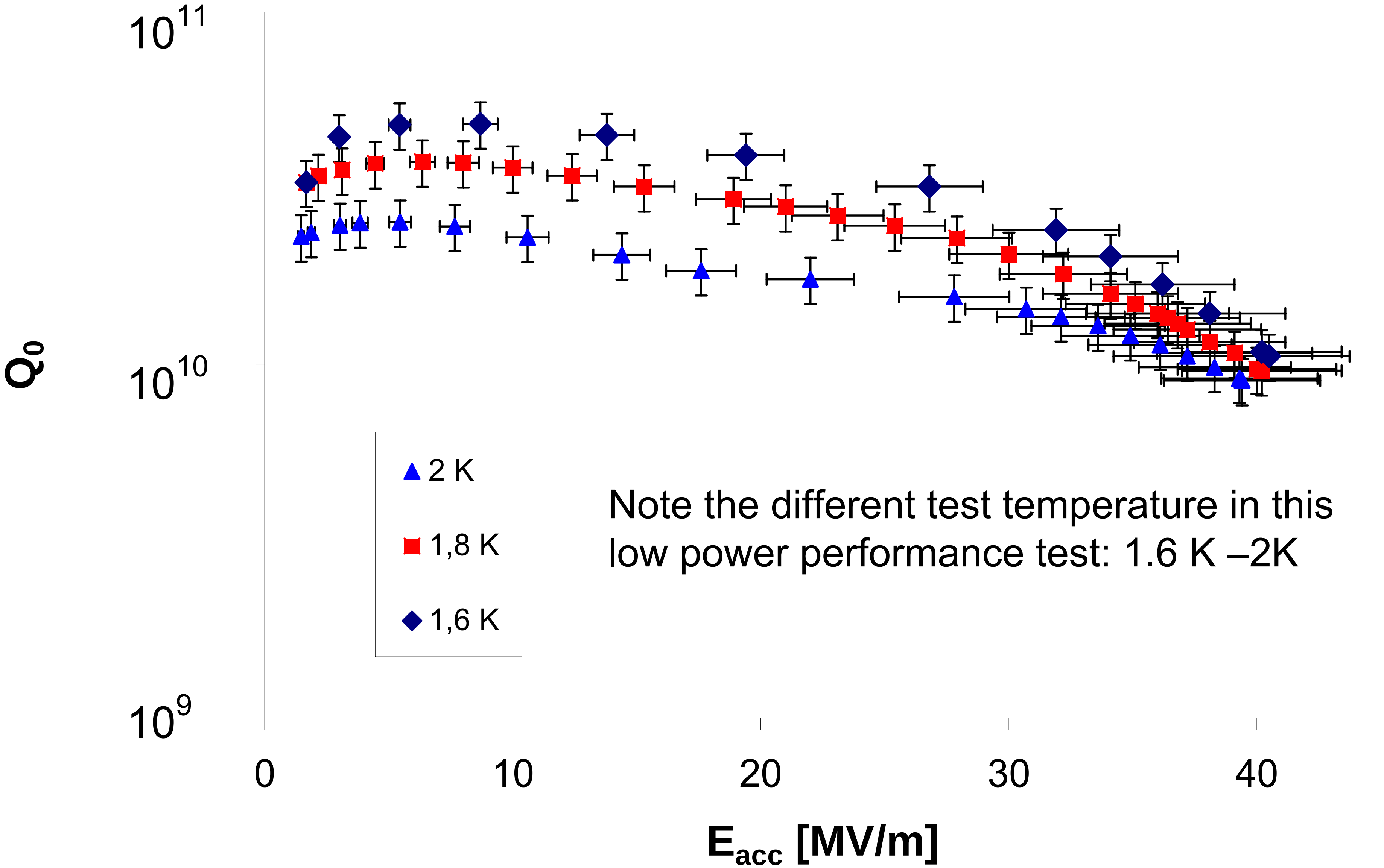
Test temperature: 1.6 K

4.2 K Residual resistivity – 80-100 MHz Quarter-wave structures

Ken Shepherd, SRF 2003, Lübeck



AC70: EP at DESY



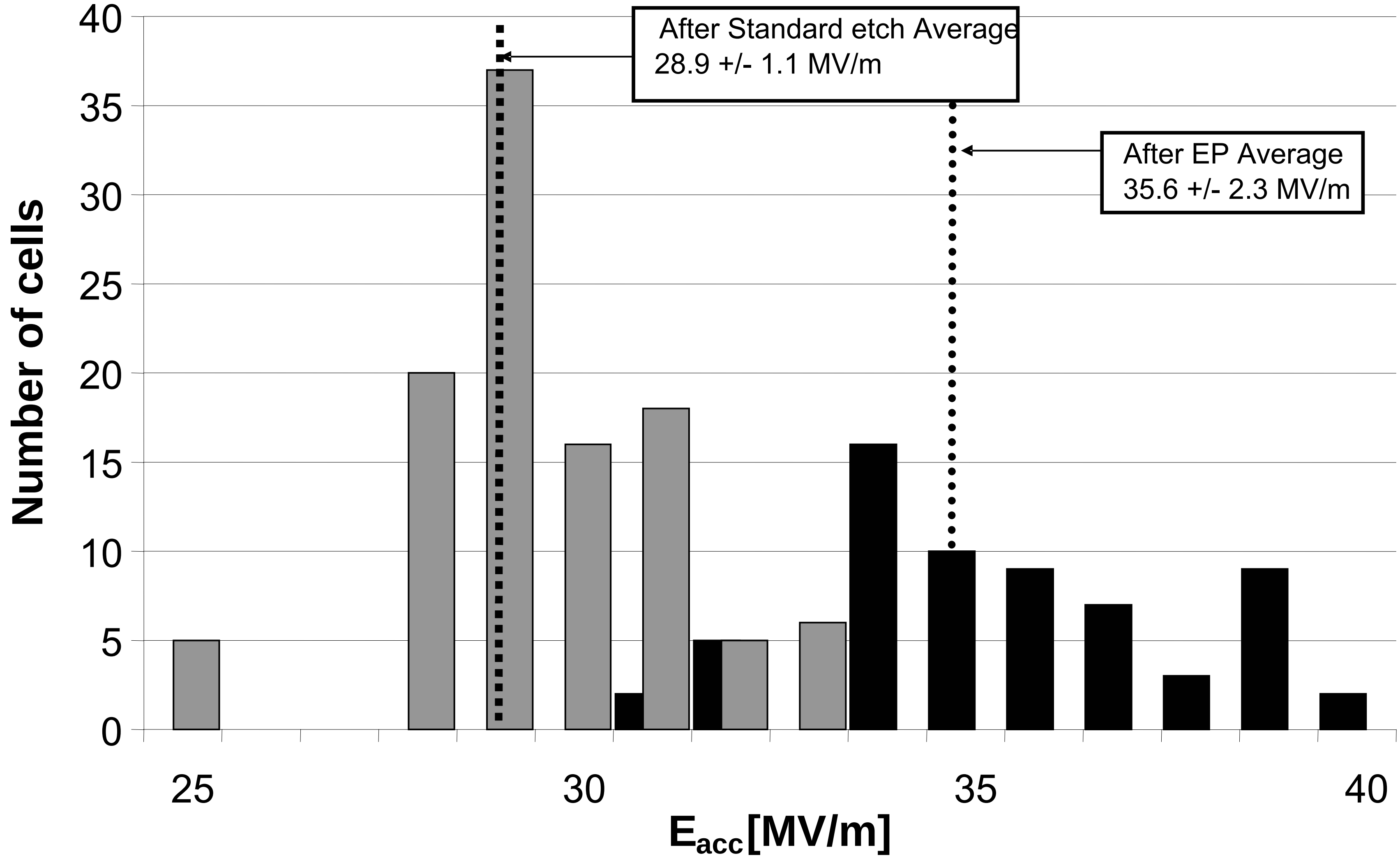
Note the different test temperature in this low power performance test: 1.6 K –2K

1.3 GHz High Gradient Data: EP vs. BCP

Surface treatment	**Type of cavitiy**	**# of cavities at E_{acc}>35MV/m or B_{surf}>140 mT**	**Bake**	**Comment**
BCP 1:1:2	Single-cell	1	Yes	Saclay
	Multi-cell	2	No	DESY Q<5*10^9, High power test only
BCP 1:1:1	Single-cell	4-5	No	Kneisel (1995), 1 NbCu clad
EP	Single-cell	16	Yes	Various: 6 KEK, 7 CERN-CEA-DESY, 3 Seamless (Saito et al.)
	Multi-cell	5	Yes	KEK-DESY cw, 3 of these in High power test

Comparison of EP to Standard Etch

(Results from the KEK-DESY Collaboration)



- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells in cw measurement)

Open Questions on Experiments

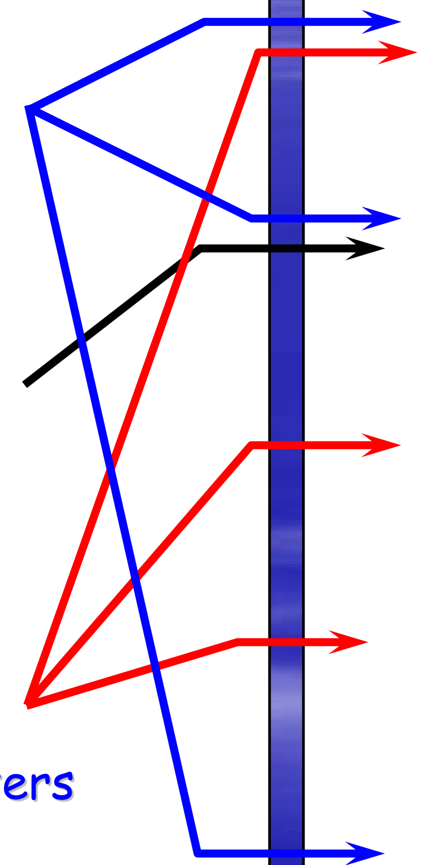
- Likely not complete….
  - Q-Slope/Bake
    - Is there a difference for baking EP or BCP cavities?
      - Is there a difference between BCP 1:1:1 and 1:1:2?
    - Is it really oxygen?
    - Is there information for other frequencies?
    - What more can we learn from samples?
      - Susceptibility
      - Critical currents
      - Surface analysis should profile into a depth of about 100 nm
  - EP has a much higher probability to achieve very high surface fields and higher Q.
    - This also true for low-beta structures!
    - There is the first indication that surface topology might play a role
    - Why?

Theories

- Haven’t changed much since SRF 2003…

Experiments

- Difference (EP/BCP)
  Surface Roughness
  (grain boundaries)
- Modification of
  Interface Oxide / Metal
  (Oxygen Diffusion)
- Change of
  Superconducting Parameters
  (R_{BCS} , B_C …)

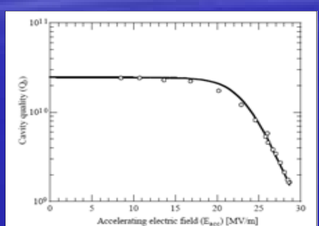


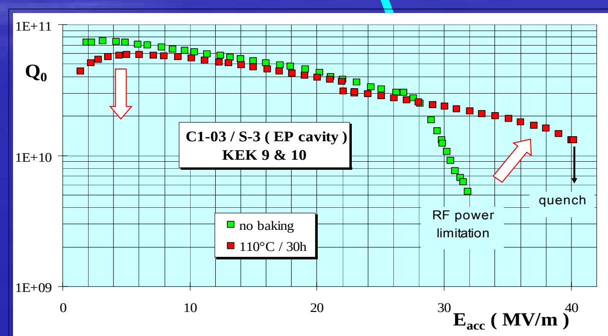
Models

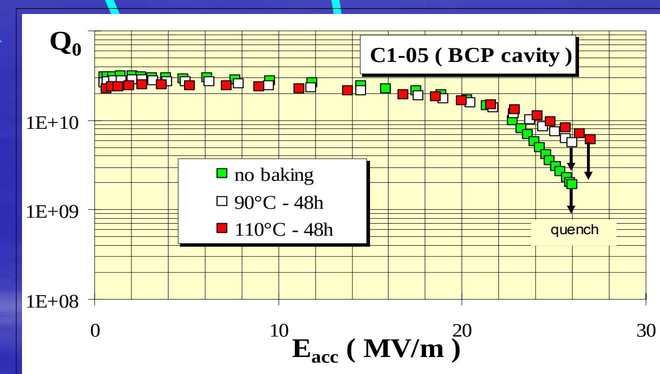
- Magnetic Field Enhancement
- Interface Tunnel Exchange
- Thermal Feedback
- Magnetic Field Dependence of Δ
- Granular Superconductivity

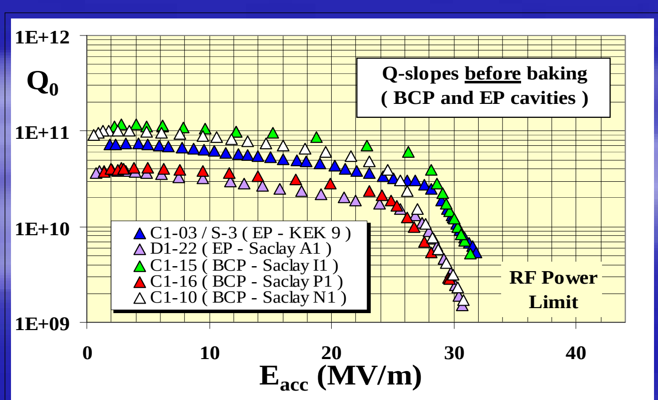
Theoretical Models ⇔ Experiments

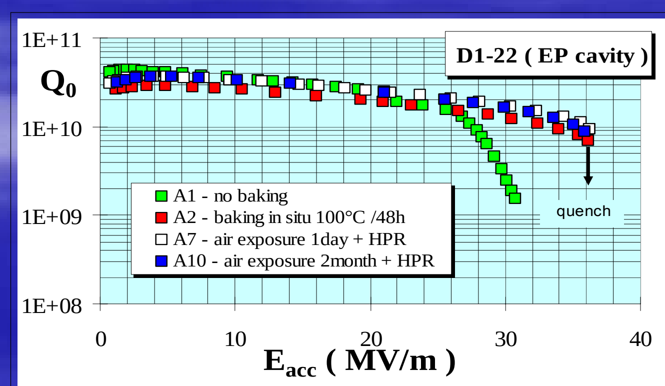
Q-Slope Fit	Slope before baking (EP ≡ BCP)	Slope Improvement after baking	No change after 2 m. air exposure	Slope after baking (EP < BCP)	Exceptional Results (BCP)	Quench (EP > BCP)	BCP Quench unchanged after baking

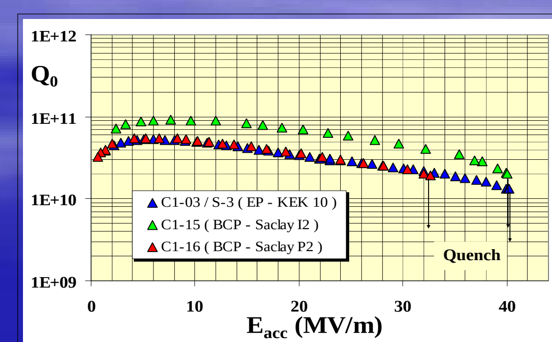






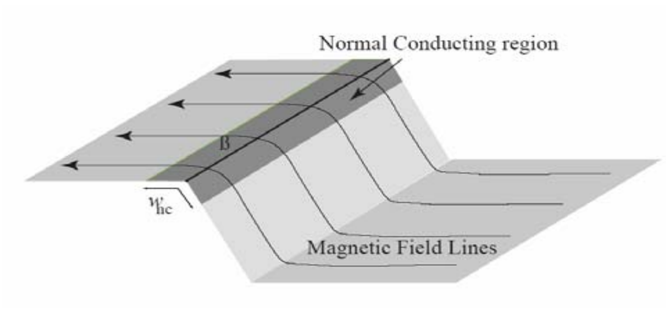






Magnetic Field Enhancement at G.B.

(J. Knobloch - SRF ’99 - Santa Fe)



microstructure on RF surface

(surface roughness - step height 10 μm)

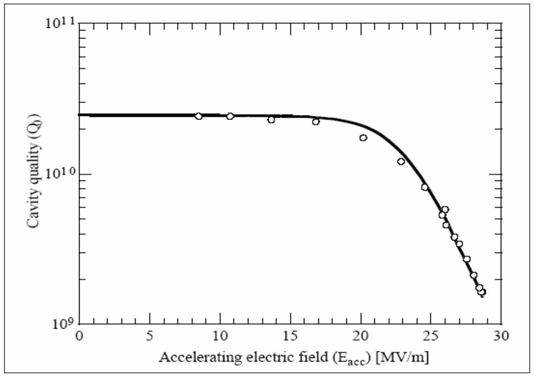
magnetic field enhancement $\beta_m H$

normal conducting region if $\beta_m H > H_C$

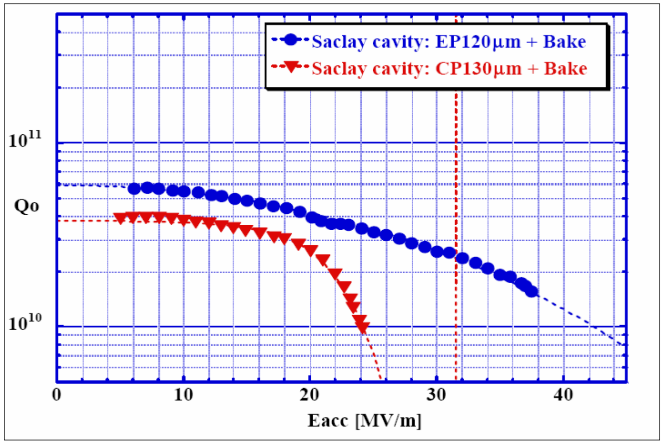
factor $1.6 < \beta_m < 2.5$ (BCP)

Q-slope origin

the most dissipative G.B. ⇨ quench (equator)



electromagnetic code + thermal simulation ⇨ $Q_0(E_{acc})$



(K. Saïto - PAC ’2003 - Portland)

EP : (H_C/β_m = 223 mT) **β_m=1**

BCP : (H_C/β_m = 95 mT) **β_m=2.34**

Comments (H - enhancement)

- Explanations :
  - Q-slope for BCP before baking (good simulation)
  - Q-slope improvement after baking ($H_C \uparrow$)
  - better slope for EP after baking (β_m lower ~ 1)

- Not consistent with :
  - slope before baking for EP cavities

    (same slope with β_m lower and H_C higher than BCP)
  - flat slope (and 40 MV/m) on BCP cavities C1-15 & C1-16
    (roughness : 4 to 8 µm > 2 µm ⇨ high β_m)
  - quench value unchanged for BCP after baking (in spite of $H_C \uparrow$)

Interface Tunnel Exchange

RF field on metallic surface

$$\begin{cases} H^{\parallel} \rightarrow Z^H \rightarrow R^H = R^0\left(1+\gamma^* H^2/H_C^2+\ldots\right) & (\textit{Taylor series}) \\ E^{\perp}\ (\textit{causes electron emission}) \rightarrow Z^E & (\textit{negligible for clean metal}) \end{cases}$$

Dielectric oxide layer on metal → enhancement of Z^E by I.T.E.

(localized states of Nb_2O_{5-y} and density of state of Nb)

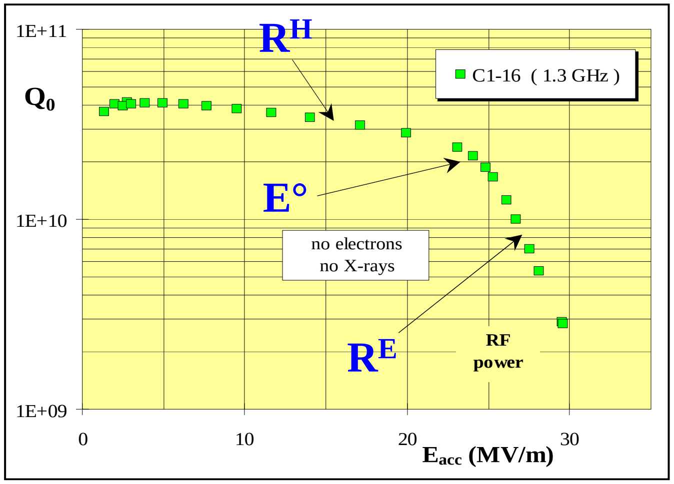
with electron diffusion at NbO_x - Nb_2O_{5-y} interface

$$R^E \propto e^{-\frac{C}{\beta^* E^{\perp}}}$$

starting at E° onset value

β^* : *electric field enhancement factor*

conventionally fitted by: $R^E = R^0\left(E^{\perp}\right)^8$



I.T.E. ≡ quantitative description of Q-slope

ITE reduction by :

- smoothening surface (EP)

  (β* ↓ and E° ↑)

- baking : Nb_2O_{5-y} vanished - better interface

  (reduction of localised states)

(J. Halbritter - SRF '01 – Tsukuba)

(IEEE Trans. on Appl. Supercond. 11, 2001)

Comments (I.T.E.)

- Explanations :
  - Q-slope improvement after baking ($Nb_2O_5 \downarrow$)
  - better slope for EP after baking (smooth surface - lower β^*)

- Not consistent with :
  - similar slopes (before baking) for EP and BCP cavities

    (surface roughness and β^* are different)
  - unaltered slope after a surface re-oxidation ($Nb_2O_5 \uparrow$ - 2 months later)
  - exceptional flat slopes on BCP cavities C1-15 & C1-16
    (in spite of roughness : 4 to 8 µm - higher β^*)

Thermal Feedback

Temperature Dependence of Surface Resistance

(V. Kurakin - EPAC'94 - London)

(E. Haebel - TTF Meeting - 1998)

$$H_S \;\rightarrow\; \Delta T = R_{therm}\,\Delta P_{diss} \propto R_S\, H_S^2/2 \;\rightarrow\; R_S(T) = R_S(T_0) + \frac{\partial R_S}{\partial T}\Delta T$$

$$R_S(T) = \frac{R_S(T_0)}{(1 - C.E_{acc}^2)} \quad \Rightarrow \quad Q_0 = G/R_S = \left(a - b.E_{acc}^2\right)$$

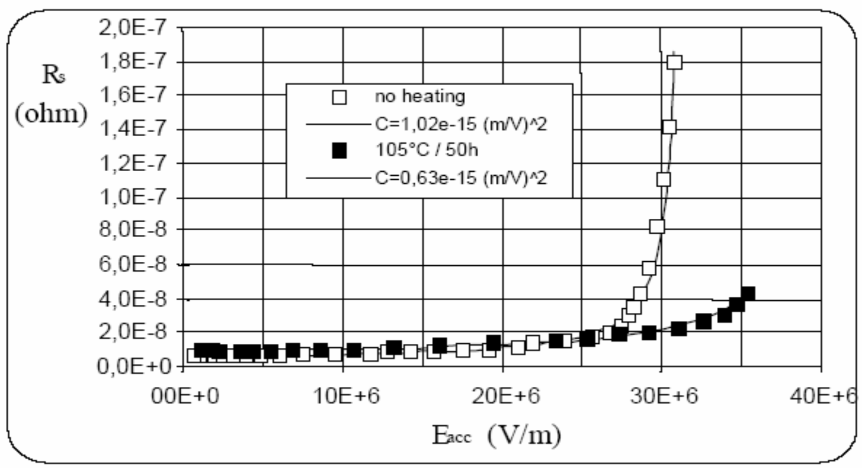
$$R_{BCS} = A(\lambda_L, \xi_F, \ell)\,\frac{\omega^2}{T}\,e^{-\Delta/kT}$$

fit parameter :

$$\begin{cases} C \approx 1.10^{-15}\,(V/m)^{-2} \\ C \approx 2.10^{8}\,\dfrac{\partial R_S}{\partial T} \end{cases}$$

baking effect : $\frac{\partial R_S}{\partial T}(A\downarrow)$

$$C \approx \underbrace{\frac{1}{2}\left(\frac{4.10^{-9}}{\mu_0}\right)^2\left(\frac{e_{Nb}}{\kappa_{Nb}} + \frac{1}{h_K}\right)}_{\approx 2.10^9}\frac{\partial R_S}{\partial T}$$



(B.V. *et al.* SRF'99 - Santa Fe)

Energy Gap Dependence

Exponential variation

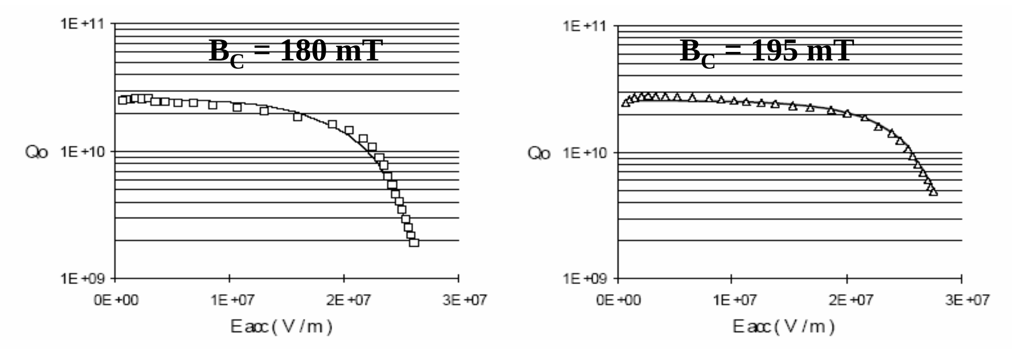
$$R_S = G/Q_0 = R_{res} + A(\lambda_L, \xi_F, \ell)\,\frac{\omega^2}{T}\,e^{-\Delta/kT}$$

magnetic field dependence of Δ ?

$$\Delta(H) = \Delta(0)\left(1 - H^2/H_C^2\right)$$ for $T/T_C < 0.36$

(A. Didenko - EPAC ' 96 - Sitges)

(V. Mathur *et al.* - Phys. Rev. Let. 9, 374 - 1962)



B_C "fit factor"

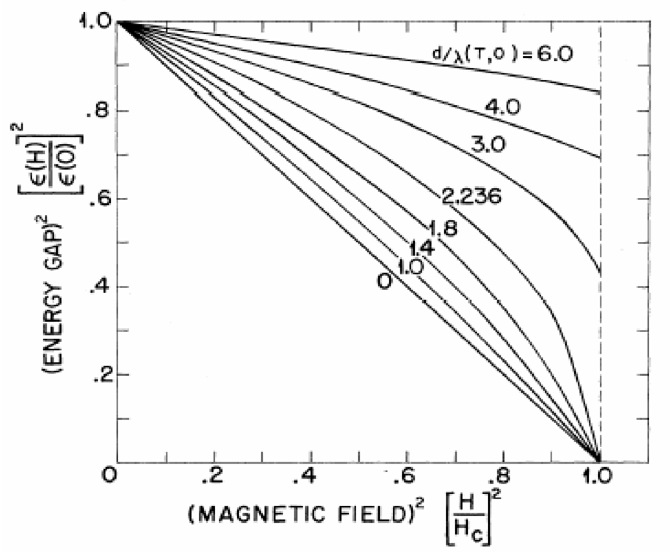
R_{res}, A, $\Delta(0)$ from $R_S(1/T)$ at low field

(B.V. *et al.* - EPAC ' 98 - Stockholm)

only rigorous and experimentally proved

for thin films

(normal state transition 2nd order if $d/\lambda < 5^{1/2}$)



for bulk material (d >>λ)

Δ(H) : few % variation

Granular Superconductivity

Grain Boundaries contribution to surface resistance ?

(polycrystalline nature of Nb) - Grain Boundary ≡ weak link (Josephson junction)

(B. Bonin and H. Safa - Superc. Sci. Tech. 4, 1991)

Theory valid for sputtered thin films

effect negligible for bulk niobium (grains ~ 10 µm) :

exception :

segregation of impurities located at grain boundaries

Difficulties to apprehend the baking as a way to clean G.B.

(low temperature - diffusion O)

Experiment on Grain Boundaries Specific Resistance (H. Safa *et al.* – SRF '99 – Santa Fe)

Similarities EP / BCP

	Q-Slope Fit	Slope before baking (EP ≡ BCP)	Slope Improvement after baking	Slope after baking (EP < BCP)	No change after 2 m. air exposure	Exceptional Results (BCP)	Quench (EP > BCP)	BCP Quench unchanged after baking	Validity
Magnetic Field Enhancement	Y	N (β_m et $H_C \neq$)	Y (H_C ↑)	Y (β_m < ; H_C >)	-	N (high β_m)	Y (β_m < ; H_C >)	N (H_C ↑)	Y
Interface Tunnel Exchange	Y (E^8)	N ($\beta* \neq$)	Y (Nb_2O_{5-y} ↓)	Y (low $\beta*$)	N (Nb_2O_{5-y} ↑)	N (high $\beta*$)	-	-	Y
Thermal Feedback	Y (parab.)	Y	Y (R_{BCS}↓ R_{res}↑)	N	-	N	-	-	N (coeff. C)
Magnetic Field Dependence of Δ	Y (expon.)	N ($H_C \neq$)	Y (H_C ↑)	Y (H_C >)	-	N	-	-	N (thin film)
Segregation of Impurities	-	N (≠ segreg.)	N (only O)	-	-	Y (cleaning)	-	-	Y

Summary on High field Q-slope and Baking

- Experimentally:
  - Baking is effective to cure the Q-degradation at high field
    - Especially EP cavities allow very high gradients
    - Etched cavities usually show breakdowns at lower fields
      - But there are exceptions from this!
      - Is there a difference in BCP 1:1:1 and 1:1:2?
  - Sample measurements show a change of the surface layer
    - Baking effect is clearly observed
    - Clear difference between etched and electropolished samples
    - Indications that the surface topology can play a role
- Theoretically…
  - … we are still looking for the 'experimentum crucis'