Q-Slope at High Gradients

(Niobium Cavities)

Review about Experiments and Explanations

Bernard VISENTIN

CEA - Saclay

Introduction

- *Q degradation at high accelerating fields*
- *Empirical Cure with cavity baking*
- *Problem only push away farther*
- *Understand Q-slope origin*

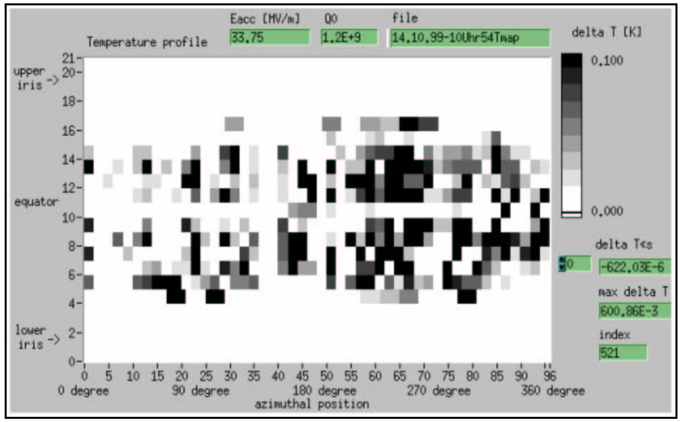
Outline

- Q-Slope : Definition and Features
  - Baking Effect
    - Experimental Observations (Q slope - R_{BCS} - R_{res})
    - Standard Chemistry (BCP) and Electropolishing (EP)
    - Consequences on Nb Surface (diffusion process – oxides – B_C)
  - Theoretical Models
    - Differences between BCP & EP
    - Interface Oxide
    - Superconducting Parameters Change
  - Experiments ⇔ Models
  - Conclusion

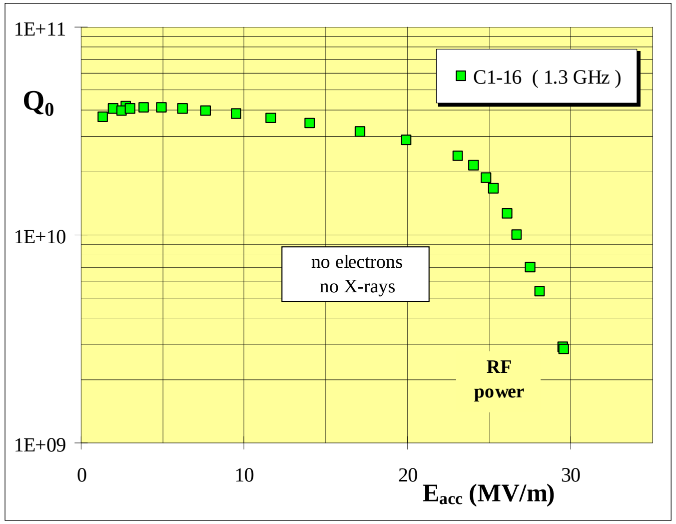
Q-Slope : Definition and Features

quality factor ⇨ strong degradation

- E_{acc} > 20 MV/m TTF cavities (B_p > 85 mT)
- field emission not involved (no e^-, no X rays)
- T map : global heating (B_p max)
- limitation by RF power supply or quench
- seemingly a typical feature of BCP cavities



(L. Lilje *et al.* - SRF '99 - Santa Fe)



(Nb 1-cell cavity)

"European Headache"

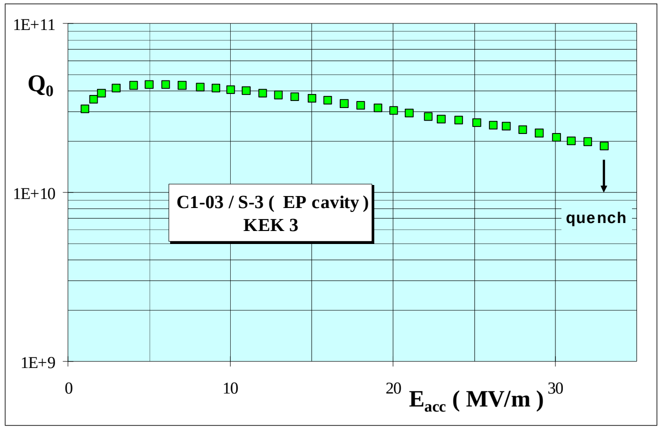
superiority of EP

without Q-slope

K. Saïto *et al.*

SRF '97

(Abano Terme)

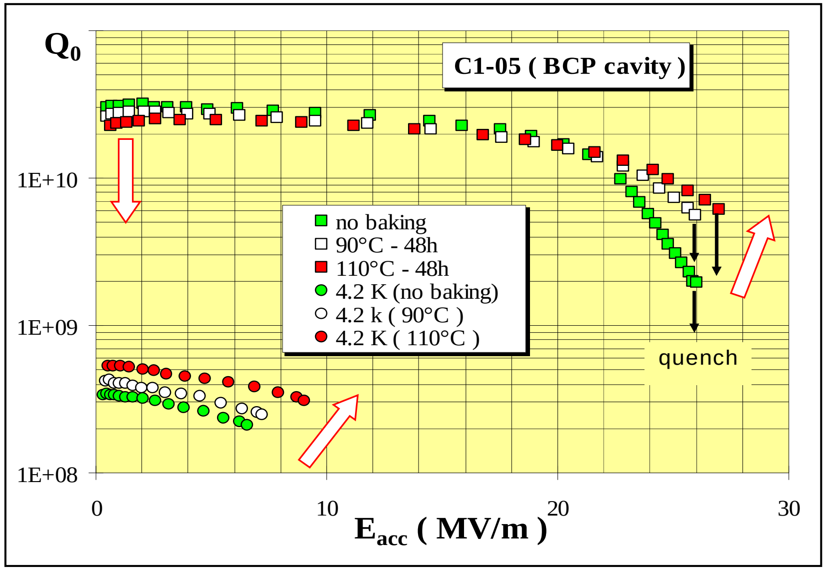


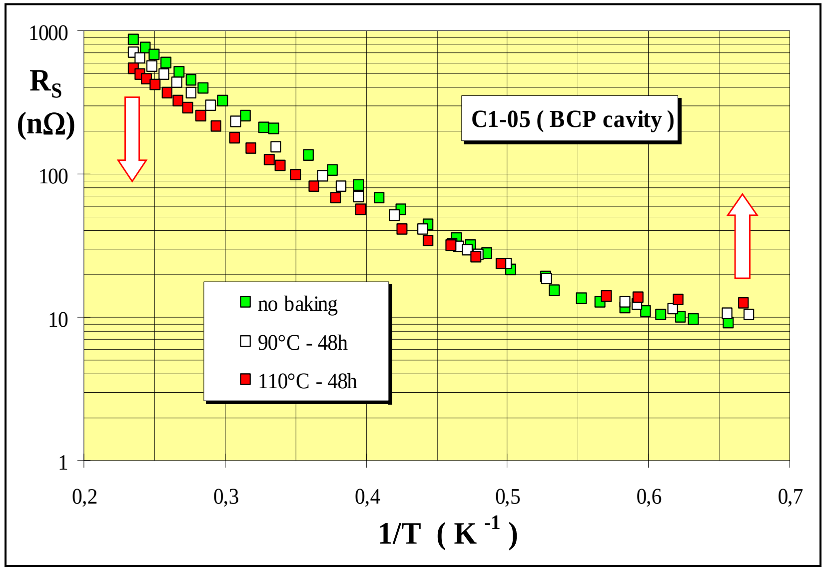
(E. Kako *et al.* - SRF '99 - Santa Fe)

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)



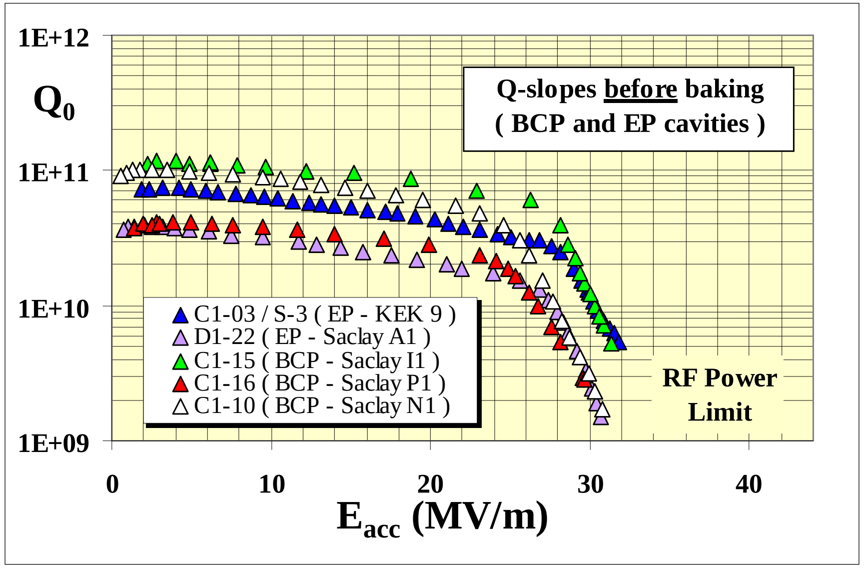


(B. Visentin *et al.* – EPAC '1998 - Stockholm)

Baking Effect on EP Cavities

Same phenomenon on E.P. cavities

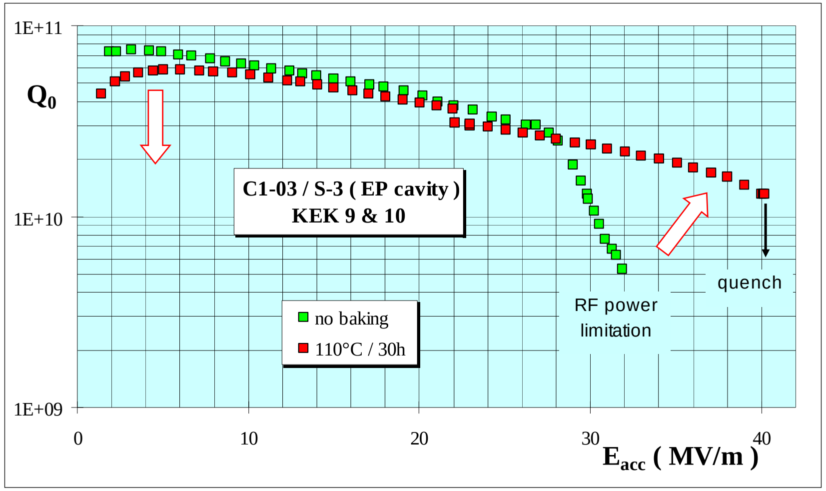
before baking: Q-slope identical to BCP



apparent superiority of EP reported before ?
cleaning procedure at KEK
wet cavities (High Pressure Rinse)
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



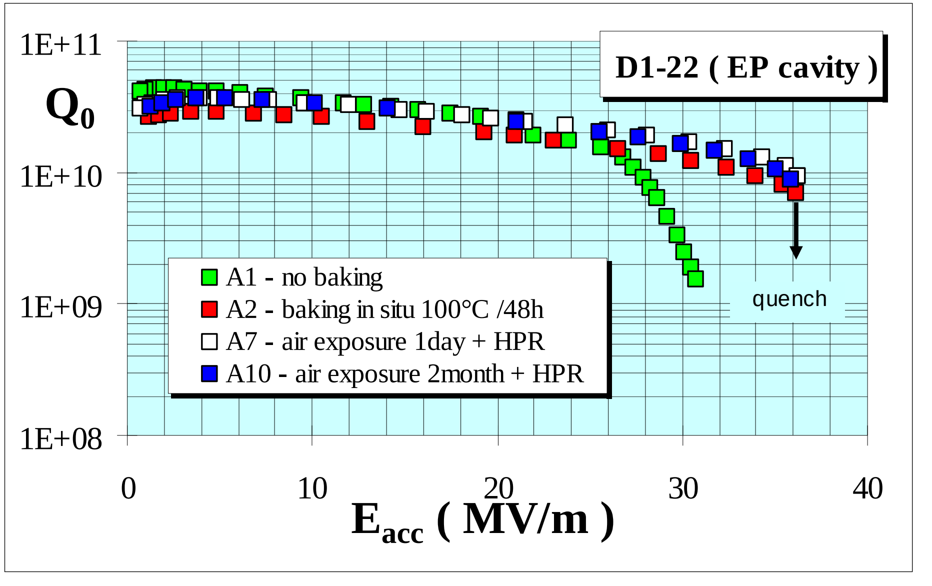
(*Saclay cavity – EP & tested @ KEK*)

Surface Re-Oxidation after Baking ?

Unaltered Q-slope

after Air exposure (3 hours to 2 months) followed by :
High Pressure Water Rinse + Drying (laminar flow – 3 h)
- standard conditioning for RF tests -

- 3 hours (cavity closed)
- 8 hours (cavity closed)
  RF test bench
- 1 day (cavity closed)
- 9 days (cavity open)
  (under laminar-flow : class 10)
  in clean-room
- 2 months (cavity open)
  left on the shelf



Baking at the Atmospheric Pressure ?

BCP + High Pressure Rinse

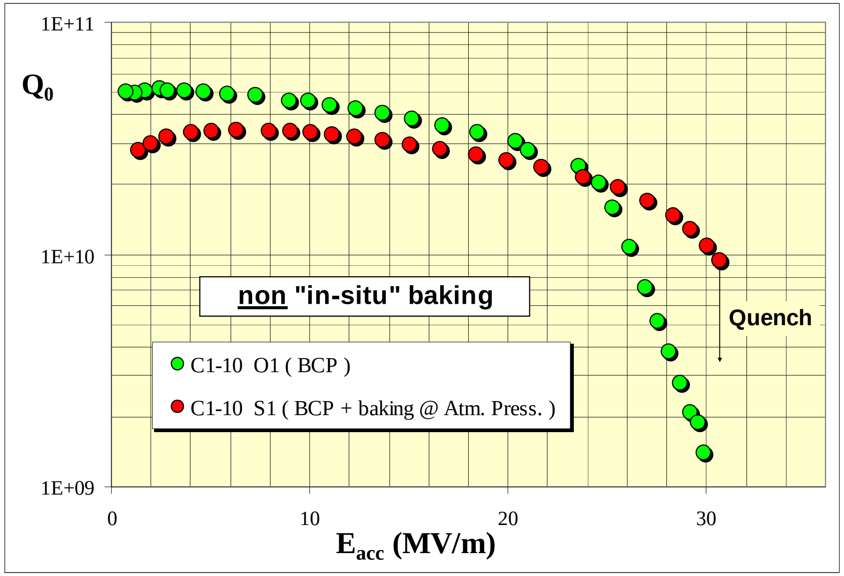
Wet Cavity inside Drying Oven (110°C / 60 h)

@ Air Atmospheric Pressure - no pumping

new H.P.R. for RF test

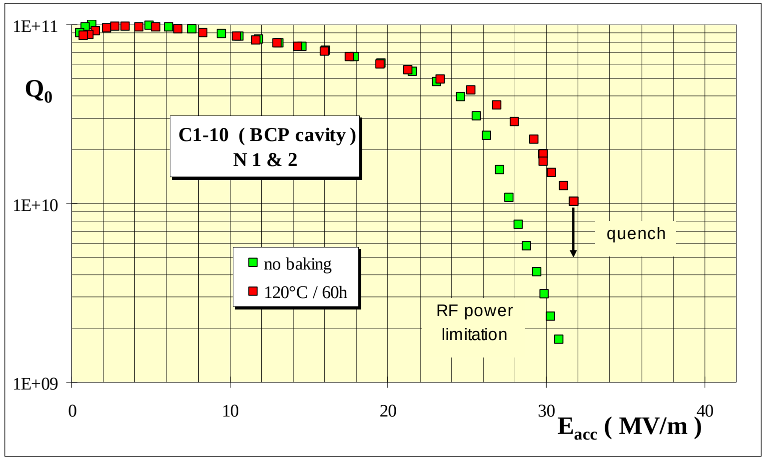
- Cavity (C1-10)
- Q-slope improvement
- Similar to "in-situ baking"

(B. Visentin *et al.* – this workshop)



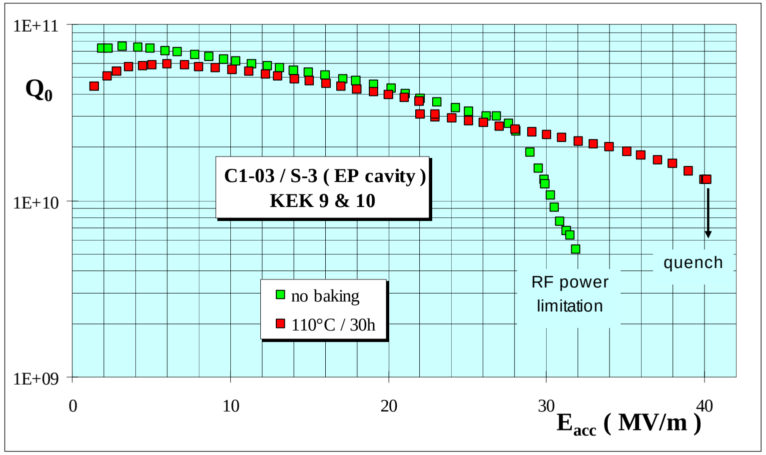
Differences between BCP and EP

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

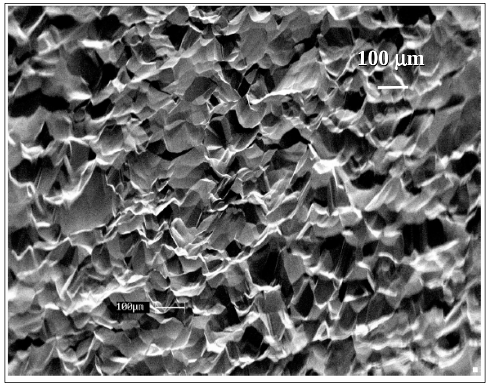


⇦ **BCP**

EP ⇨



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

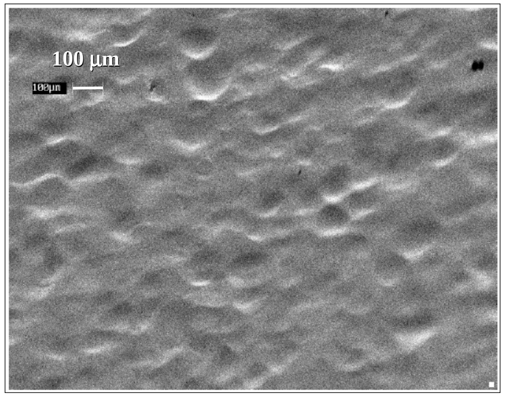


- surface roughness

(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



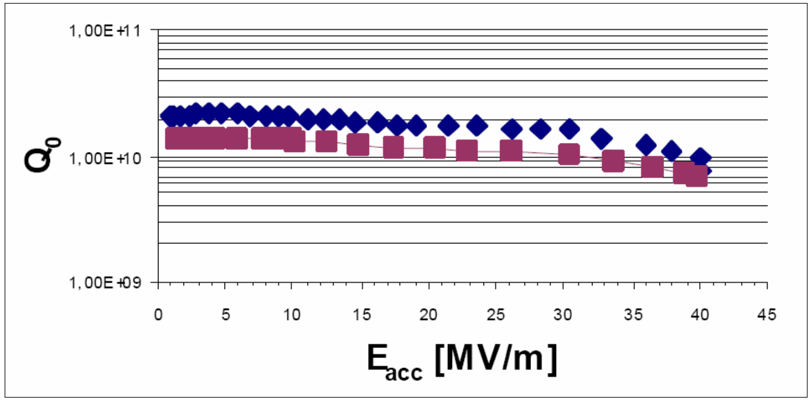
Some Exceptions (?)

Total removal of Q-slope after baking (BCP cavities)

(with or without quench fields at 40 MV/m)

Nb cavity "defect free" : (**BCP** but **no baking** specified)

(P. Kneisel *et al.* – SRF '1995 – Gif/Yvette)

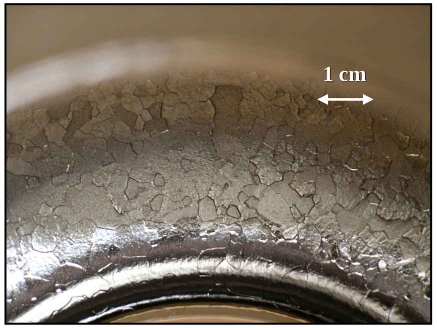


C1-15 (inner surface) ⇨

not very smooth

large grains : 2-3 mm²

high steps : 4 to 8 µm

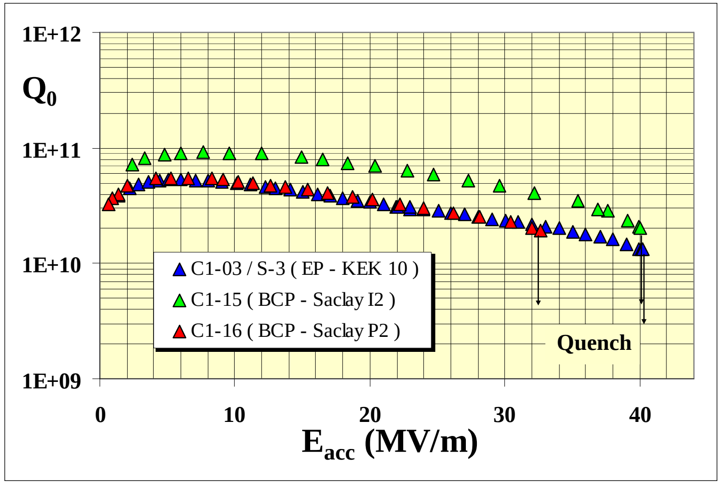


One NbCu clad cavity : 1NC2 (**BCP + 140°C/30h**)

(W. Singer *et al.* – SRF '2001 - Tsukuba)

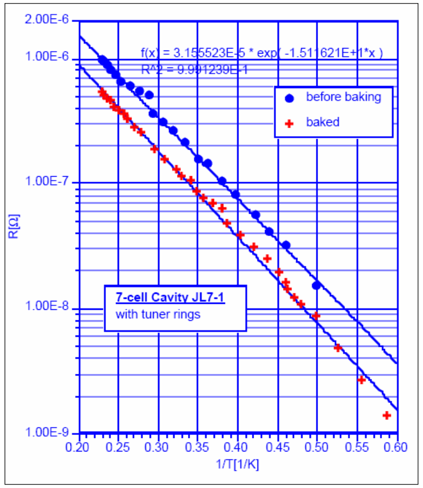
Two Nb cavities : C1-15 & C1-16 (**BCP + 120°C/60h**)

(B. Visentin *et al.* – EPAC'2002 – Paris & this workshop)



Baking Consequences on Nb Surface (1)

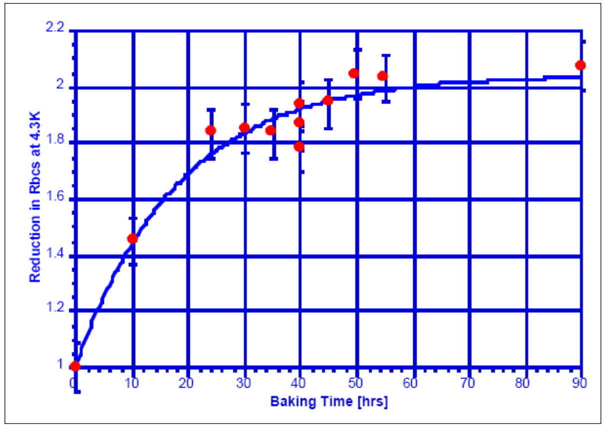
R_{BCS} (T_{bake}) : ⇩



(P. Kneisel - SRF '99 - Santa Fe)

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

R_{BCS} ⇩ (baking time) ⇨ saturation

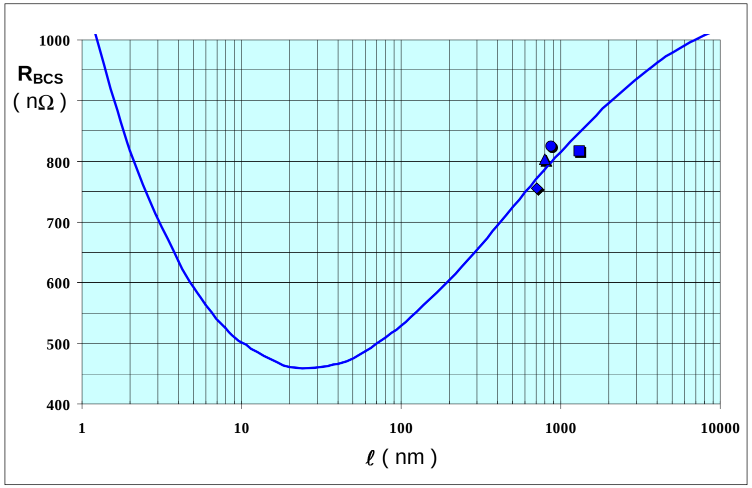


diffusion process

(300 nm)

R_{BCS} @ T = 4.2 K

T_{bake} = 145°C



λ_L = 31 nm

ξ_F = 62 nm

Δ = 1.46 meV

T = 4.2 K

Baking Consequences on Nb Surface (2)

(F. Palmer – IEEE Trans. Mag. - 1987)

Influence of oxide layers on Nb surface resistance

(Nb_2O_5 and NbO)

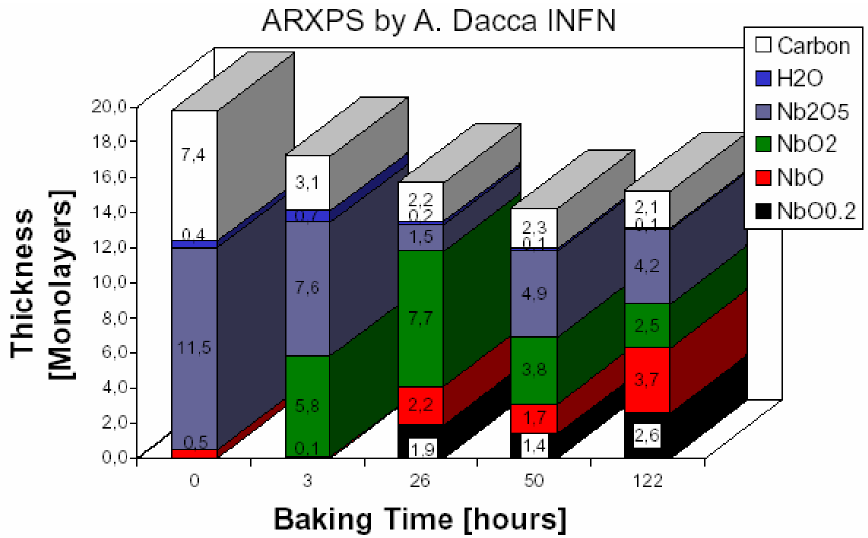
Oxygen can diffuse at low temperature

Change

of the structure oxide

after baking

(Nb_2O_5 ⇩ and NbO - $NbO_{0.2}$ ⇧)



(A. Daccà - sample 4 - T=150°C)

A. Dacca *et al.* - Applied Surf. Science - 1998

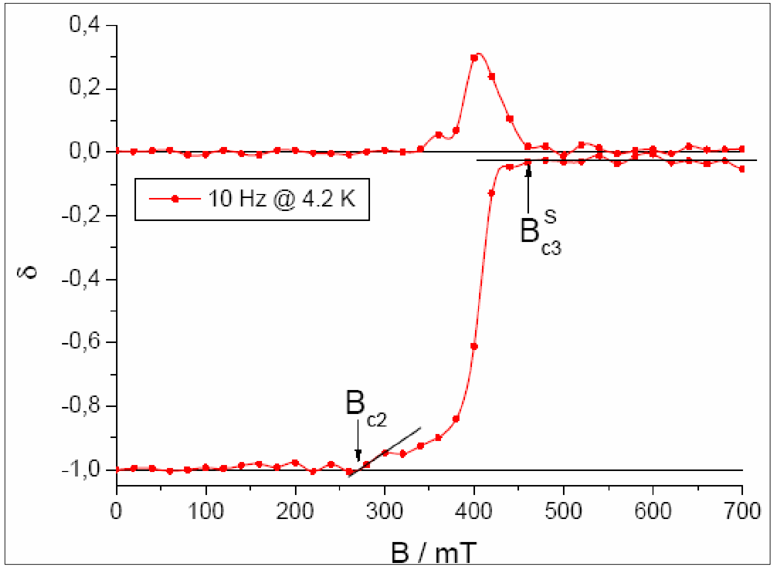
C. Antoine *et al.* - SRF ’99 - Santa Fe

Q. Ma *et al.* - SRF ’01 - Tsukuba

Baking Consequences on Nb Surface (3)

Surface Magnetic Field :

(B. Steffen - TTF Meeting - 2003)



Susceptibility measurements (on sample)

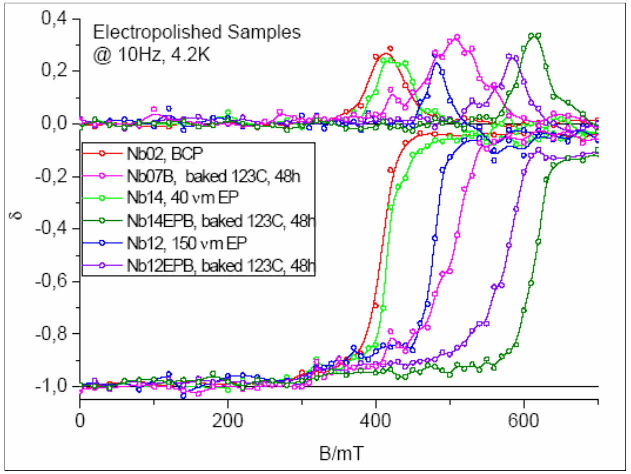
Surface field : $B_{C3}^{surf} = 1.7\ B_{C2}^{bulk}$

larger field for EP compare to BCP

All values are increased by baking

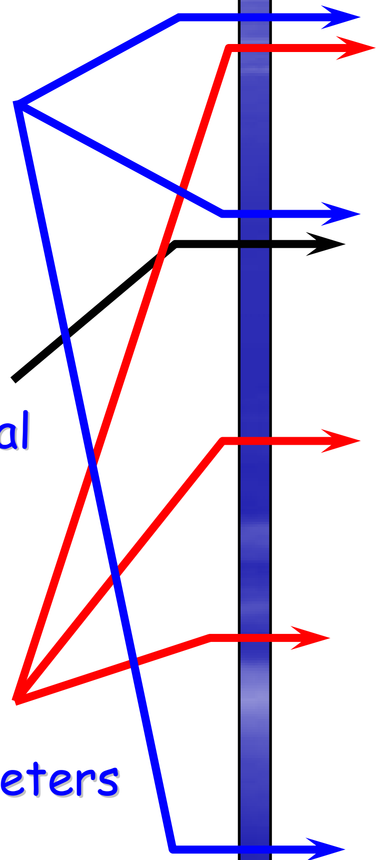
(interpreted by enhancement of impurities : O ?)

	Bc3S/mT	Bc2S/mT
BCP unbaked	464	273
baked 123C, 48h	560	329
baked 144C, 48h	625	368
150µm EP unbaked	520	306
baked 123C, 48h	620	365
40µm EP unbaked	480	282
baked 123C, 48h	660	388



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

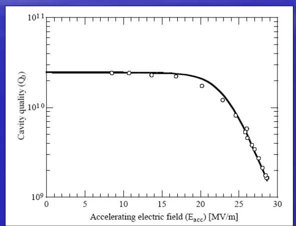
Thermal Feedback

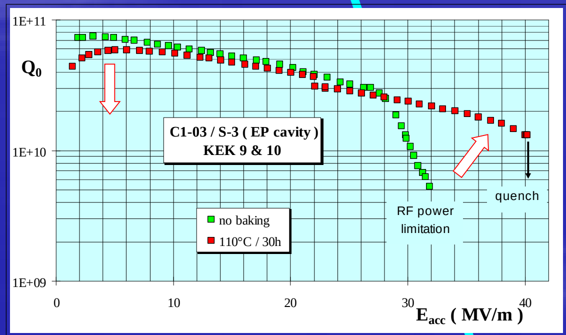
Magnetic Field Dependence of Δ

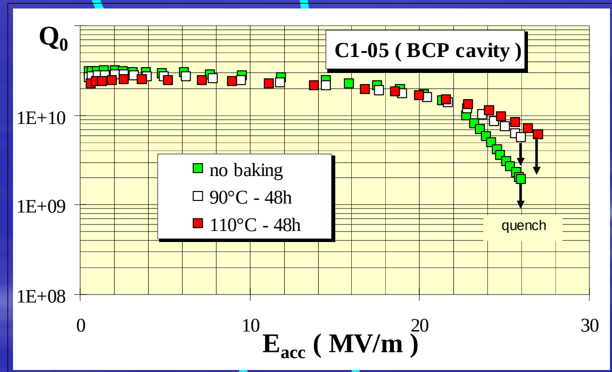
Granular Superconductivity

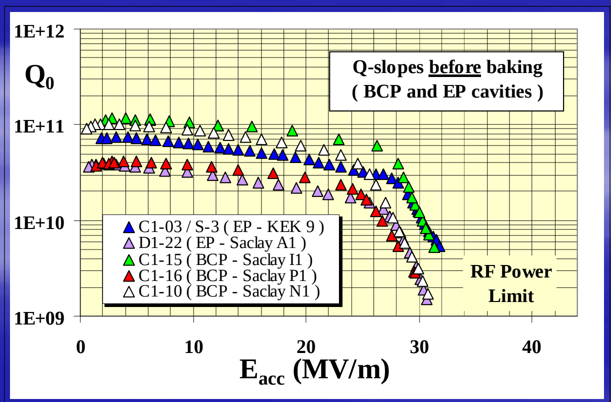
Theoretical Models ⇔ Experiments

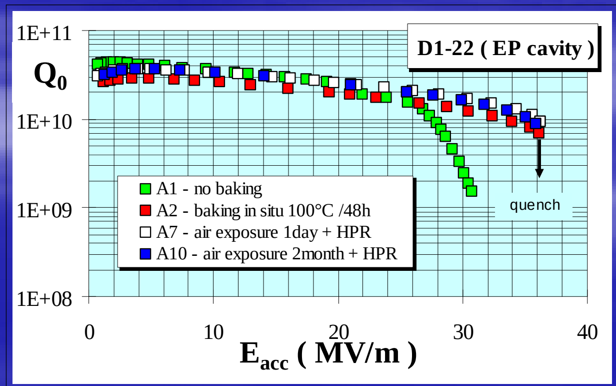
Q-Slope Fit	Slope before baking (EP ≡ BCP)	Slope Improvement after baking	No change after 2 m. air exposure	Slope after baking (EP < BCP)	Exceptional Results (BCP)	Quench (EP > BCP)	BCP Quench unchanged after baking

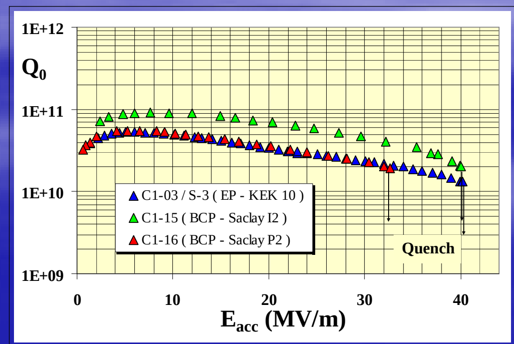






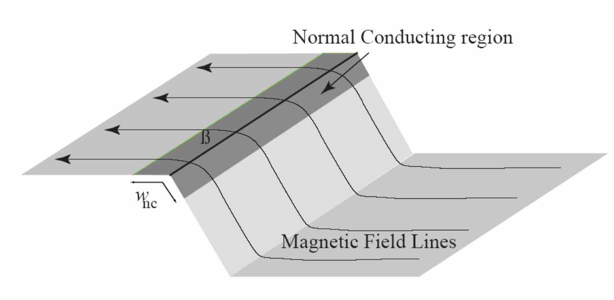






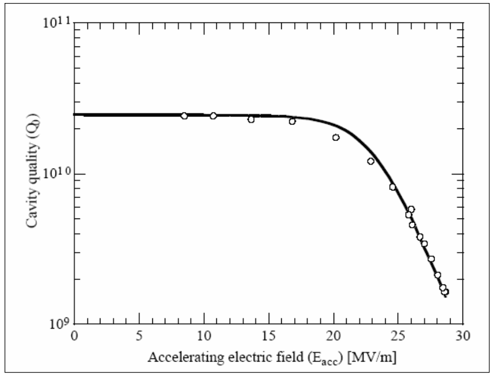
Magnetic Field Enhancement at G.B.

(J. Knobloch - SRF '99 - Santa Fe)



Q-slope origin

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



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

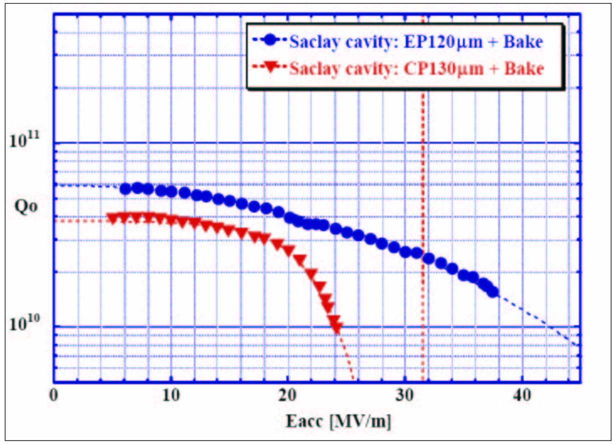
microstructure on RF surface

(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)



(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

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

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)

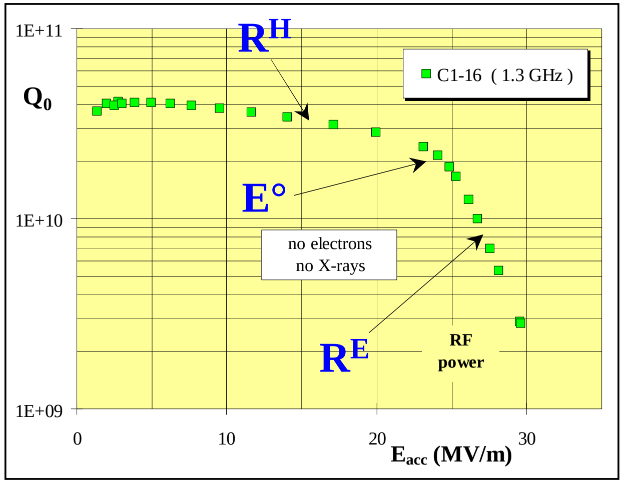
with electron diffusion at NbO_x - Nb_2O_{5-y} interface

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

starting at E° onset value

β^* : *electric field enhancement factor*

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



(J. Halbritter - SRF '01 – Tsukuba)

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

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)

Comments (I.T.E.)

- **Explanations :**
  - Q-slope improvement after baking (Nb_2O_5 ↓)
  - 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 ↑ - 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)

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

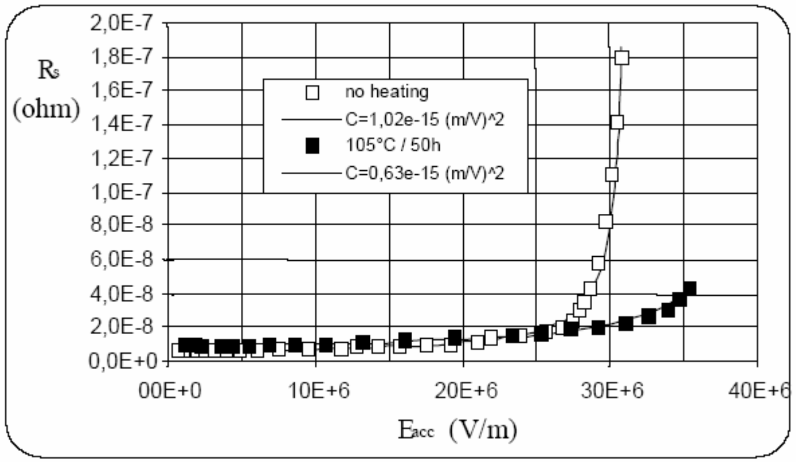
$$R_S(T) = \frac{R_S(T_0)}{(1 - C.E_{acc}^2\ )} \quad \Rightarrow \quad Q_0 = G/R_S = \left(a - b.E_{acc}^2\ \right)$$

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

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 : $\dfrac{\partial R_S}{\partial T}(A \downarrow)$

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



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

Energy Gap Dependence

Exponential variation

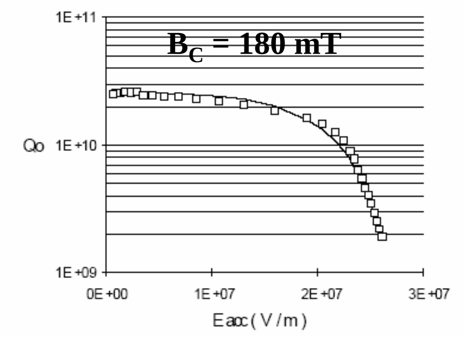
$$R_S = G/Q_0 = R_{res} + A(\lambda_L, \xi_F, \ell)\,\frac{\omega^2}{T}\,e^{-\Delta/kT}$$

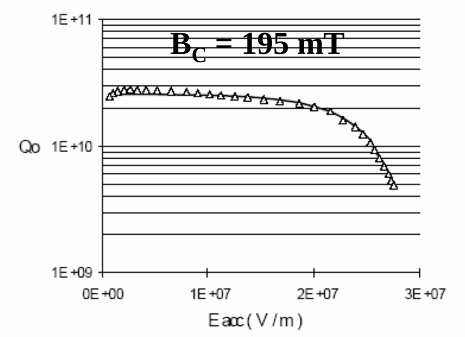
magnetic field dependence of Δ ?

$$\Delta(H) = \Delta(0)\left(1 - H^2/H_C^2\right)$$ 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"

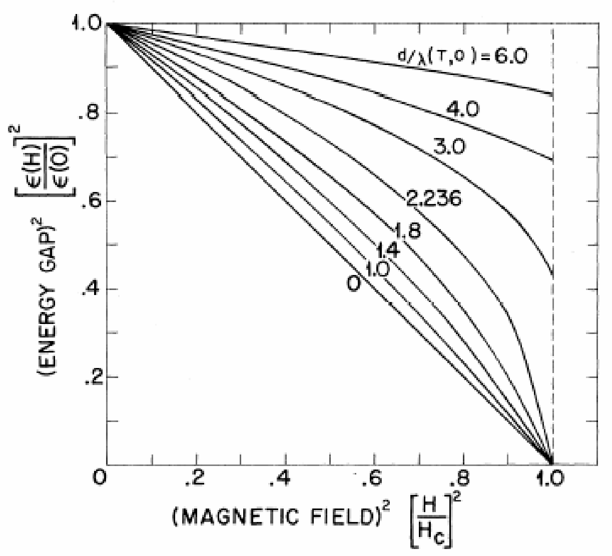
R_{res}, A, $\Delta(0)$ from $R_S(1/T)$ at low field

(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)

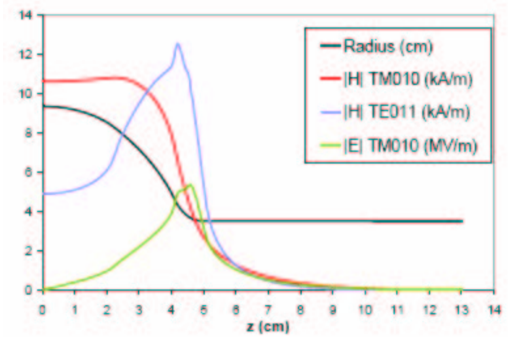
Similarities EP / BCP

	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 ($H_C \uparrow$)	Y ($\beta_m <$; $H_C >$)	-	N (high β_m)	Y ($\beta_m <$; $H_C >$)	N ($H_C \uparrow$)	Y
Interface Tunnel Exchange	Y (E^8)	N ($\beta * \neq$)	Y ($Nb_2O_{5-y} \downarrow$)	Y (low $\beta *$)	N ($Nb_2O_{5-y} \uparrow$)	N (high $\beta *$)	-	-	Y
Thermal Feedback	Y (parab.)	Y	Y ($R_{BCS} \downarrow$ $R_{res} \uparrow$)	N	-	N	-	-	N (coeff. C)
Magnetic Field Dependence of Δ	Y (expon.)	N ($H_C \neq$)	Y ($H_C \uparrow$)	Y ($H_C >$)	-	N	-	-	N (thin film)
Segregation of Impurities	-	N (≠ segreg.)	N (only O)	-	-	Y (cleaning)	-	-	Y

Experimental Program at J.Lab.

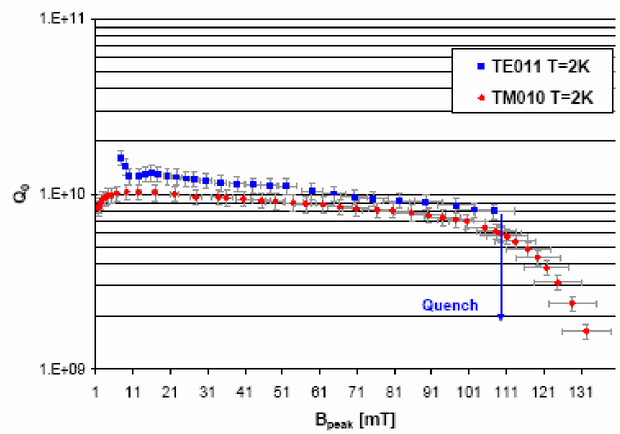
" H enhancement at grain bound. " ⇔ " Interface Tunnel Exchange "

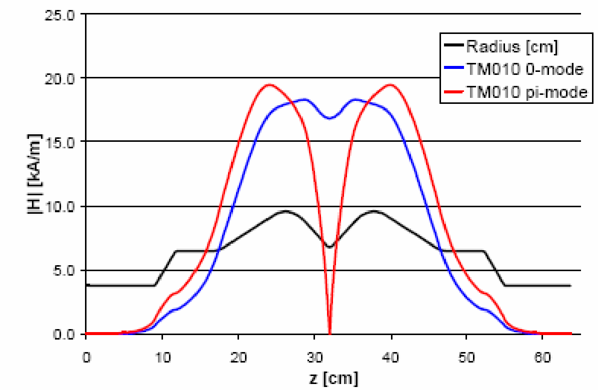
- Single cell cavity (BCP - EP - w/o Baking) excited in modes TM_{010} or TM_{011} : H_S
- Two cell cavity TM_{010} (0-π mode) : scan the surface (E, H)
- Q_0 (B_{peak}) - (BCP - EP - w/o Baking)



- Preliminary results :

(G. Ciovati *et al.* - PAC ' 2003 - Portland)

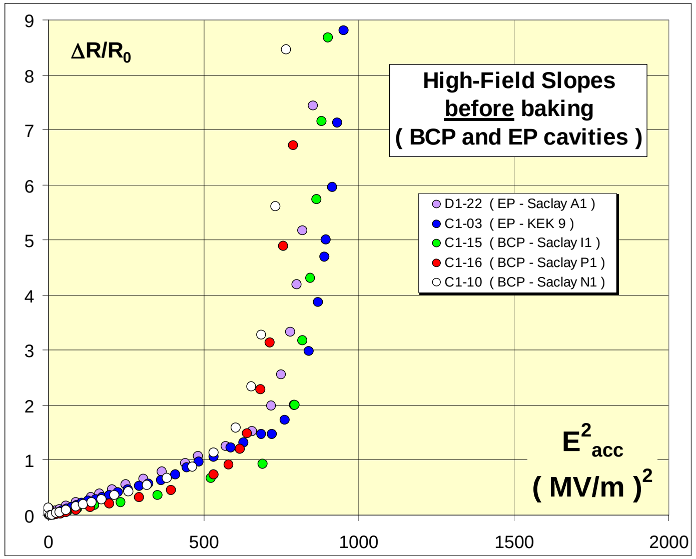


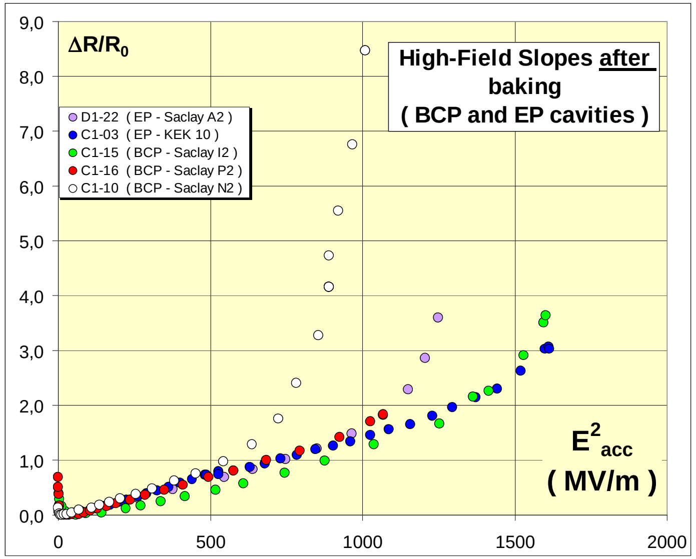


Conclusion

Experiments and Models have to progress in the future
to understand the phenomenon and to cure it

all the more so since
Q-slope is not totally removed by baking (even for EP cavities)





if quench improvement possible (> 40 MV/m) ⇨ Q-slope appearance

Papers at this Workshop

❑ Q-slope

A Review of High-Field Q-Slope Studies at Cornell - H. Padamsee *et al.* (**Mo-P14**)
Why does the Q-slope of a Nb cavity change…? - I.V. Bazarov *et al.* (**Th-P02**)
Q-slope analysis of niobium SC RF cavities - K Saito (**Th-P19**)
Q-Slope : Comparison BCP and EP - Modification by Plasma… - B. Visentin *et al.* (**Mo-P19**)

❑ Baking

A Pleasant Surprise: Mild Baking Gives Large Improvement… - G. Eremeev *et al.* (**Mo-P18**)
Low temperature heat treatment effect on high-field EP cavities - J. Hao *et al.* (**Mo-P16**)
Effect of low temperature baking on niobium cavities - G. Ciovati *et al.* (**We-O14**)

❑ Surface Analysis

In situ XPS investigation of the baking effect … - K Kowalski *et al.* (**Th-P09**)
Near-Surface Composition of Electropolished Niobium … - A.M. Valente *et al.* (**Mo-P15**)
Grain boundary specific resistance and RRR measurements… - S. Berry *et al.* (**Th-P03**)