Review of Frontier Workshop and Q-slope results

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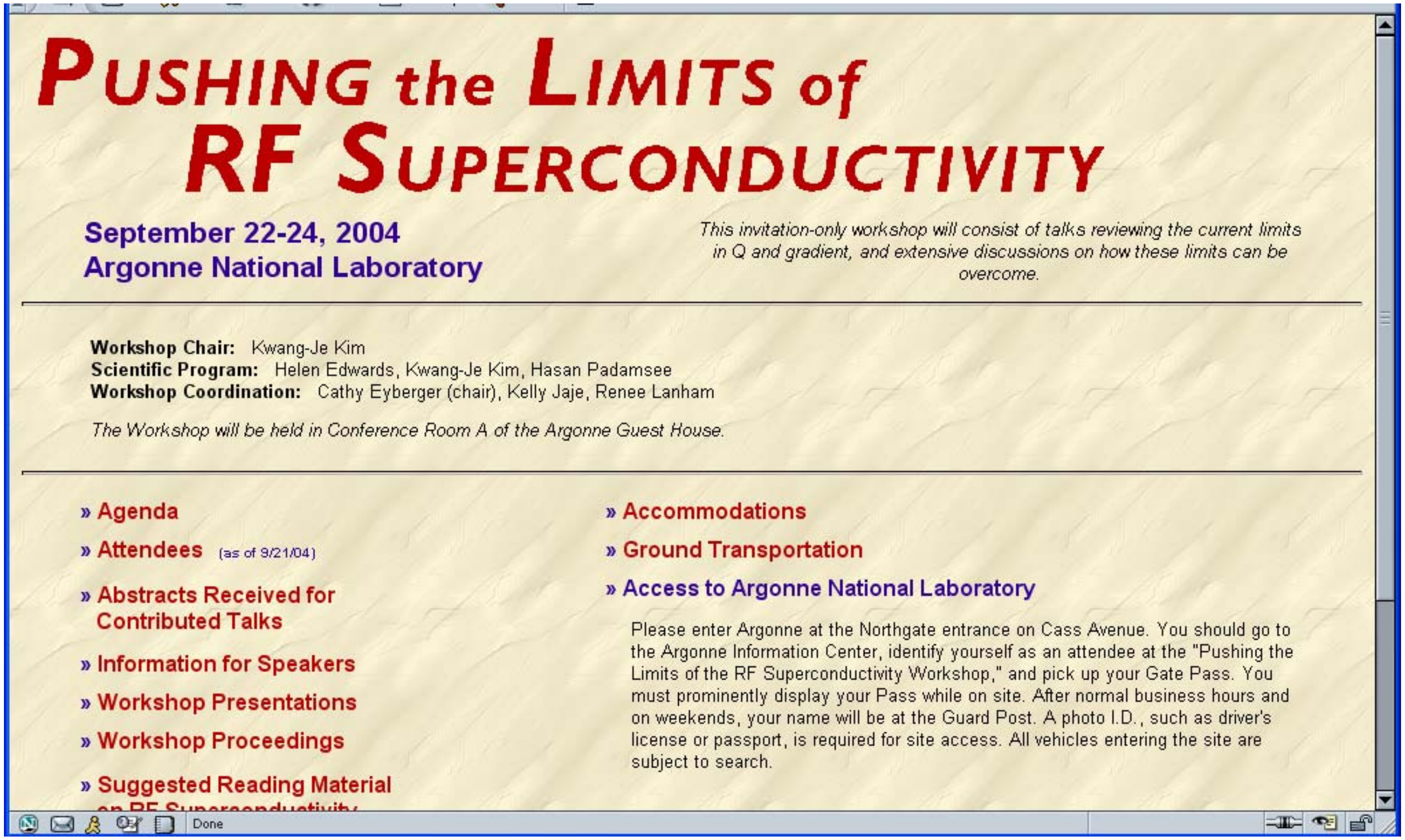
Jefferson Lab

12th SRF Workshop, July 10th-15th 2005, Cornell

Workshop on Pushing the Limits of RF Superconductivity

- September 22-24, 2004
- Hold at Argonne National Laboratory
- 64 participants invited to discuss how to push the limits of RF superconductivity for particle accelerators
- 30 talks divided in three sessions:
  - Ultimate field limits, new materials, new geometries
  - High Q, field emission, Q-slopes
  - Future research paths to ultimate performance

Workshop's website: http://www.aps.anl.gov/conferences/RFSC-Limits/



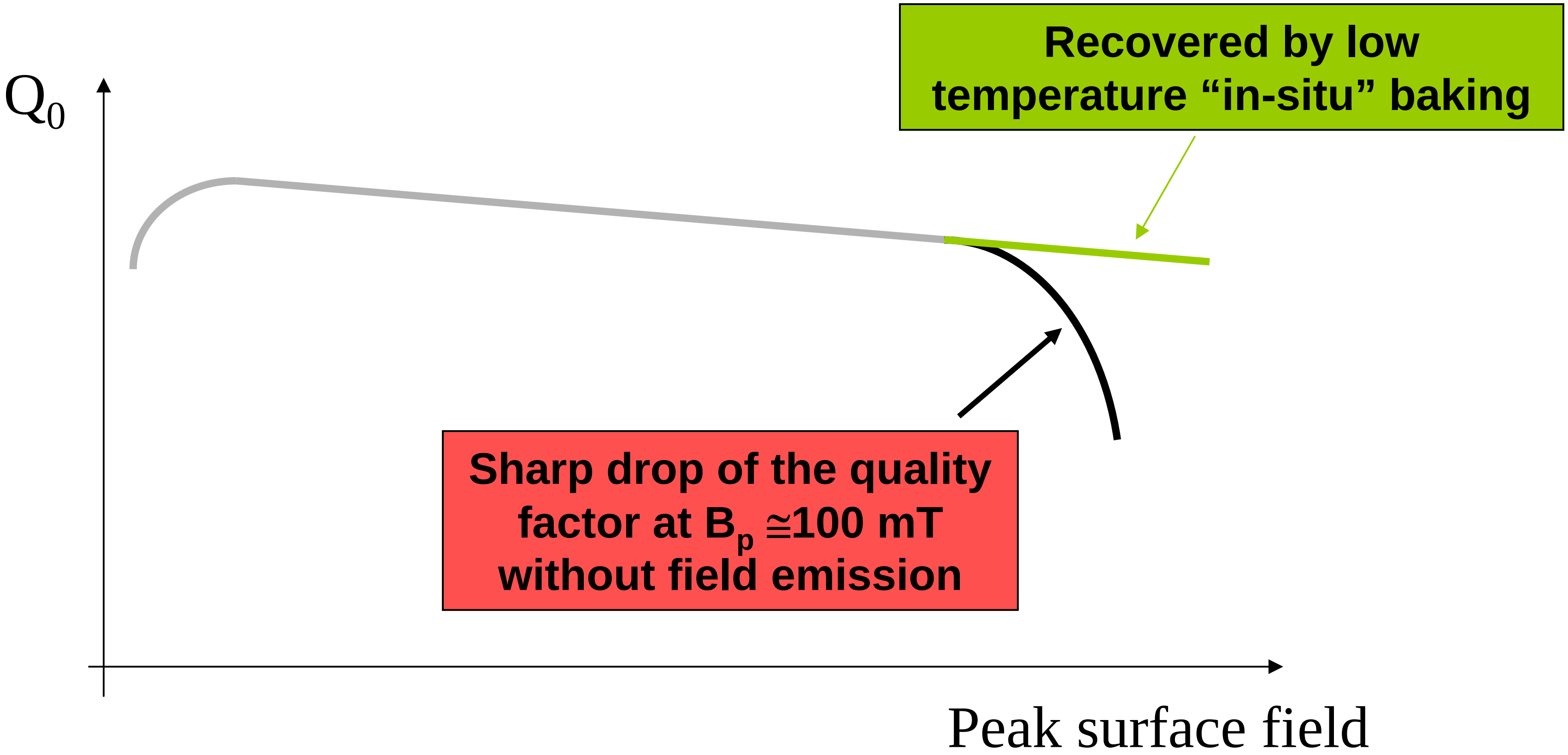
Workshop's presentations available on-line (http://www.aps.anl.gov/conferences/RFSC-Limits/Presentations.html)

Workshop's proceedings published as Argonne Report ANL-05/10, March 2005

Outline

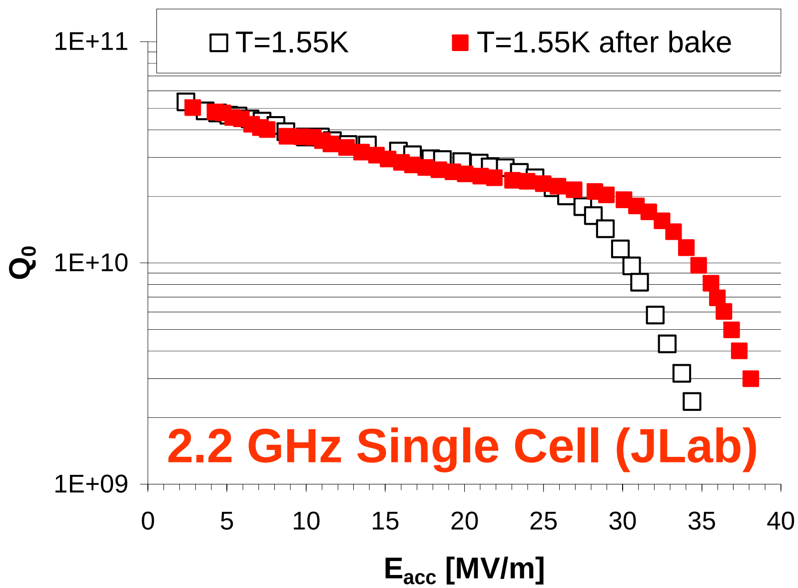
- Overview of knowledge on high field Q-slope (or "Q-drop")
- Improved oxygen diffusion model and possible explanation of Q-drop
- Summary

Q-drop: obstacle before the ultimate limit

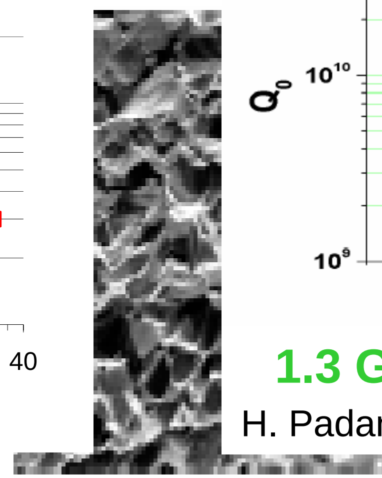


BCP treated cavities (1)

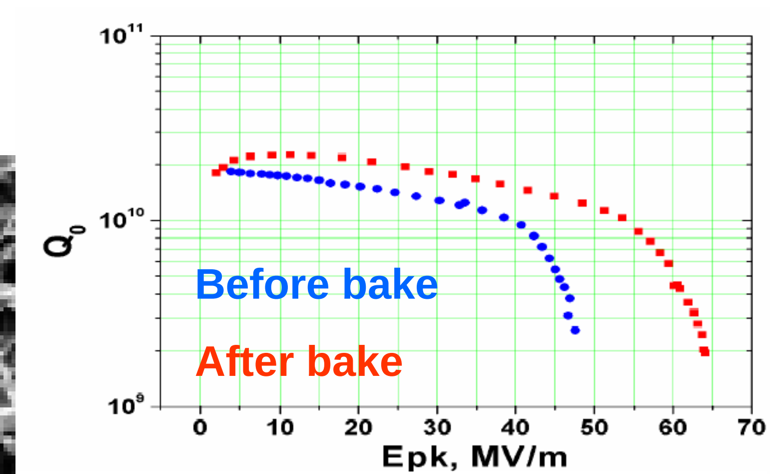
- Fine grain (~ 50μm), rough surface (5-10μm)



P. Kneisel *et al*.-PAC 05-TPPT076



R.L. Geng *et al*.-SRF 99-TUP021



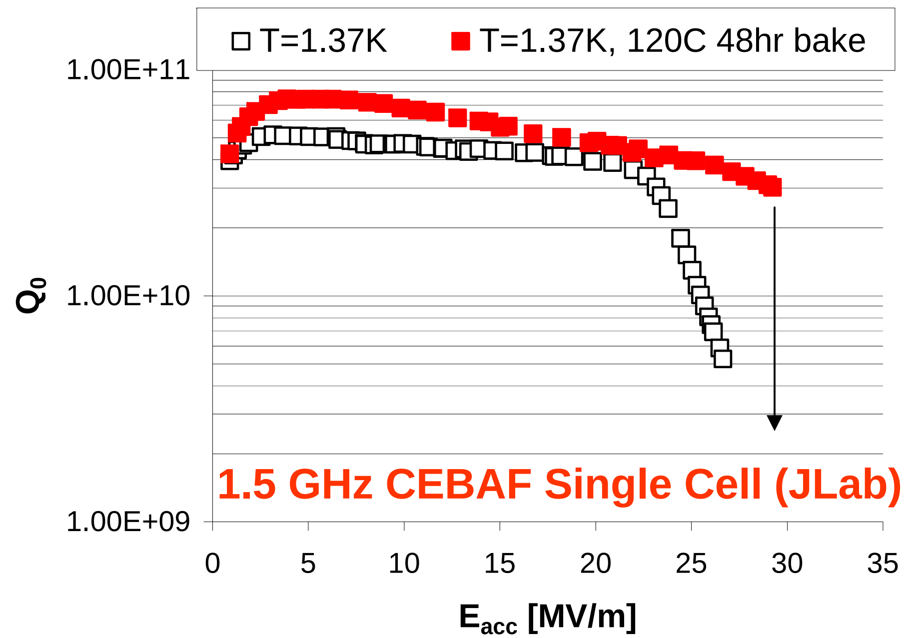
1.3 GHz Single Cell (Cornell)

H. Padamsee *et al*.-Frontier Workshop-p. 291

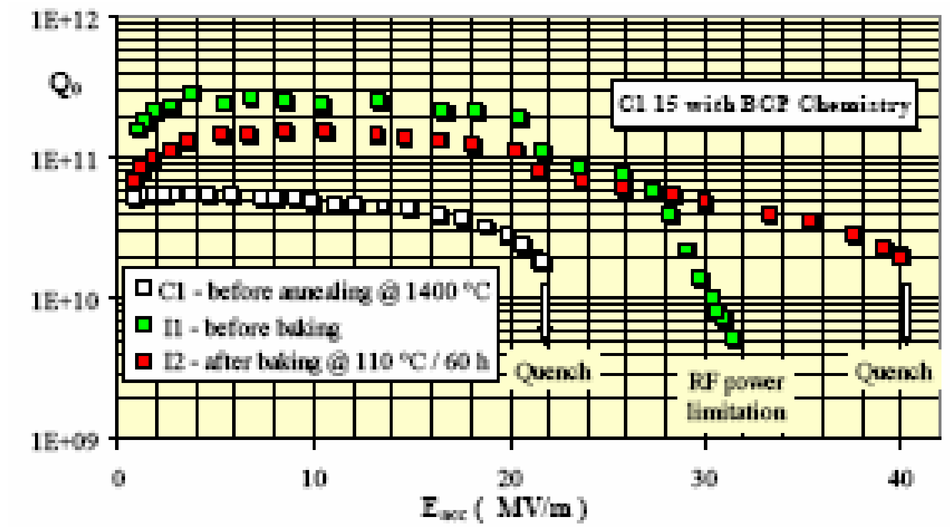
Q-drop STILL PRESENT after baking

BCP treated cavities (2)

- Larger grains (1-5mm) by post-purification, rough surface (5-10μm)



G. Ciovati-*J. Appl. Phys.* 96, p. 1591 (2004)



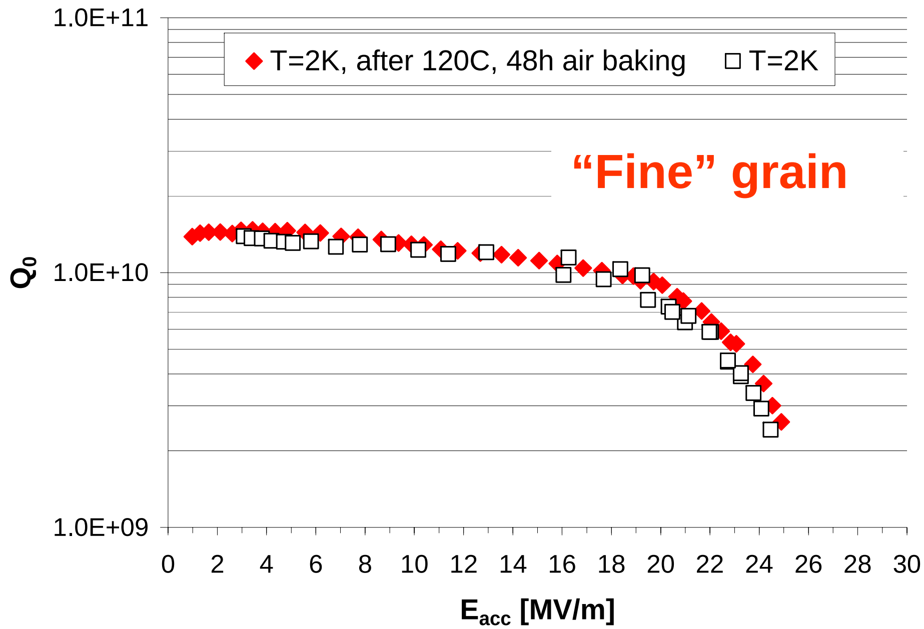
1.3 GHz Single Cell (Saclay)

B. Visentin *et al*.-EPAC 02-THPDO013

Q-drop RECOVERS after baking

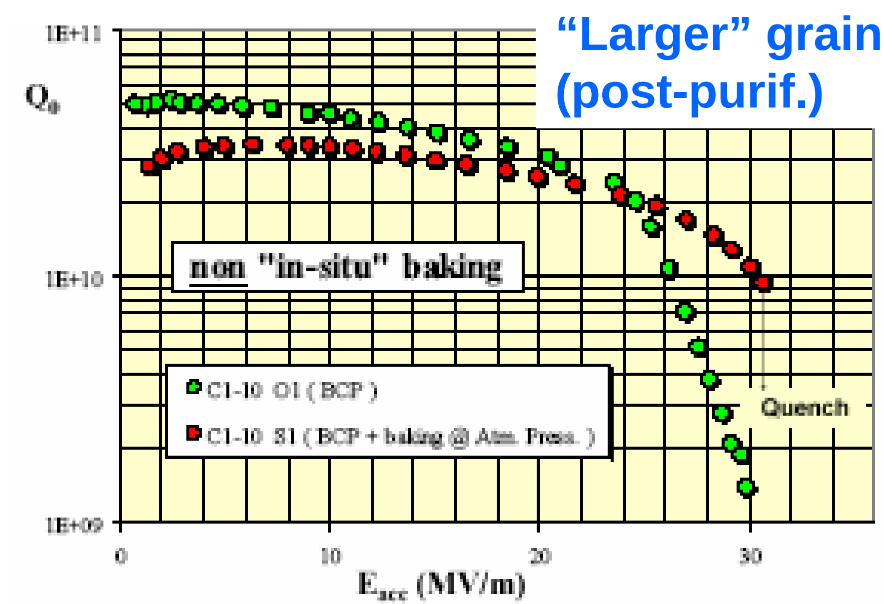
BCP treated cavities (3)

“Air” baking



1.5 GHz CEBAF Single Cell (JLab)

G. Ciovati, unpublished



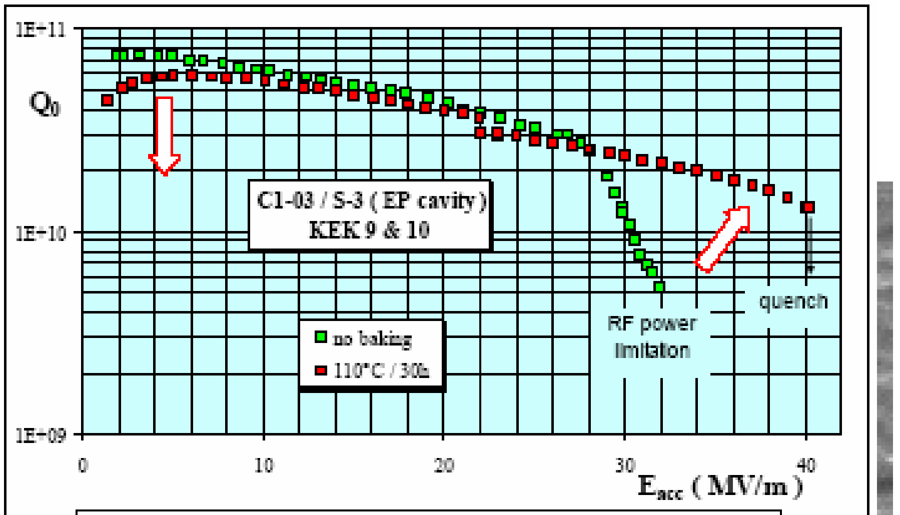
1.3 GHz Single Cell (Saclay)

B. Visentin *et al*.-SRF 03-MOP19

- Reduced Q-drop improvement
- Higher residual resistance

EP treated cavities (1)

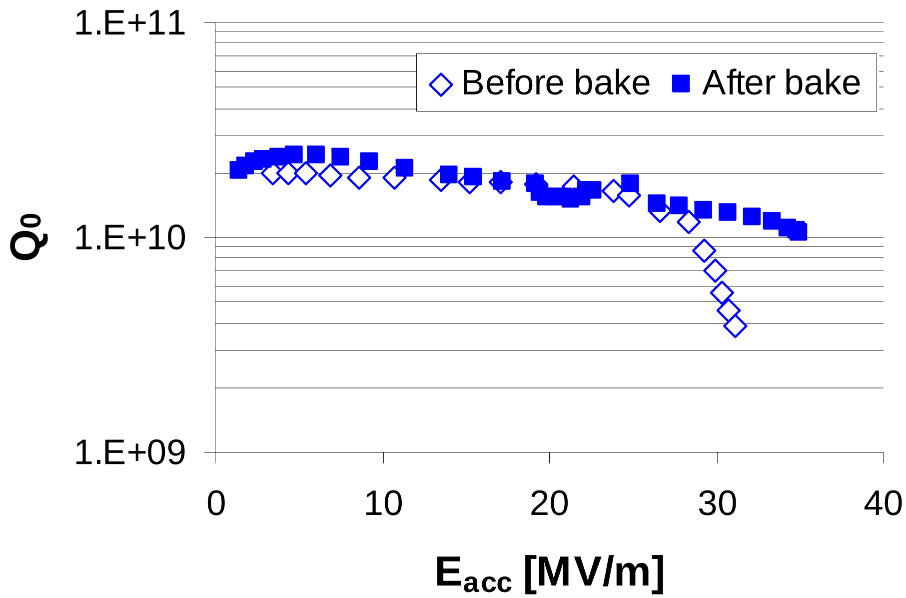
- Fine grain (~ 50μm), smooth surface (2-5μm)



1.3 GHz Single Cell (Saclay)

B. Visentin *et al.*-SRF 03-TUO01

R.L. Geng *et al*.-S



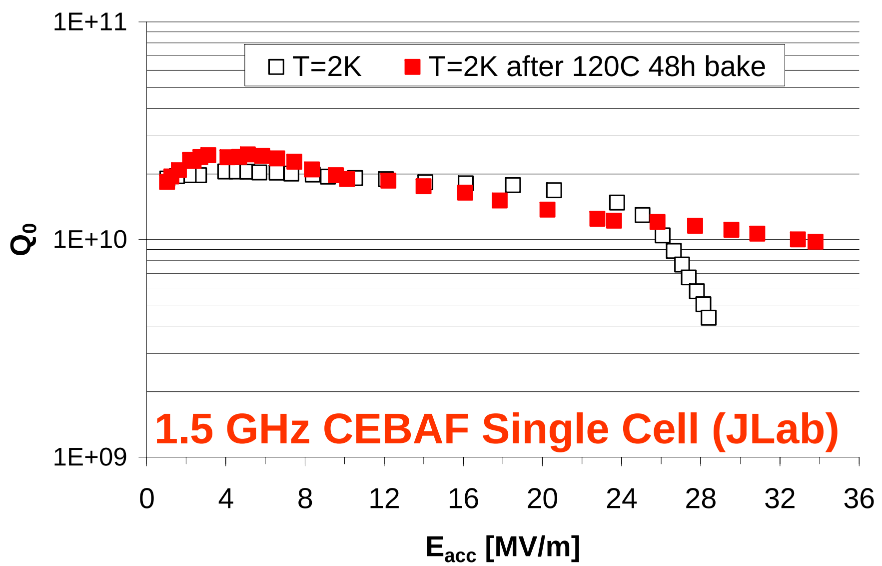
1.3 GHz 9-Cell Cavity AC76 (DESY)

L. Lilje -EPAC 04- WEAOCH03

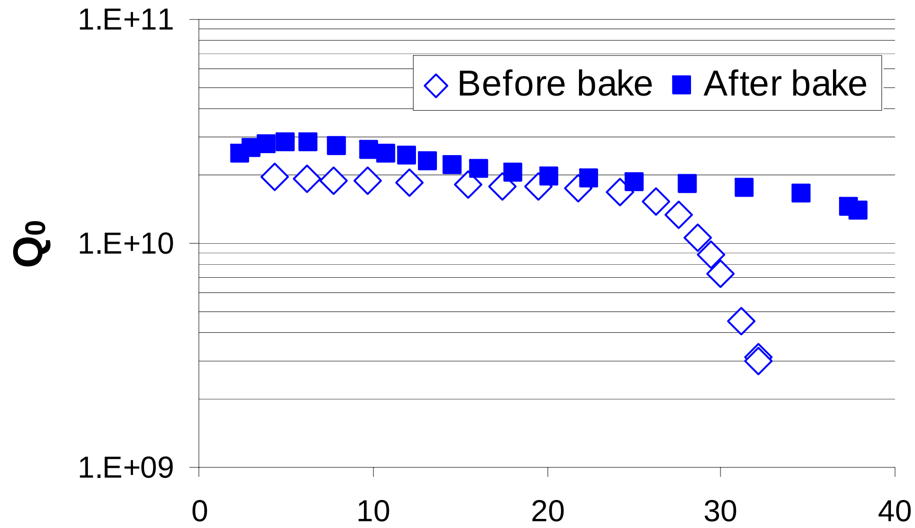
Q-drop RECOVERS after baking

EP treated cavities (2)

- Larger grains (~ 1mm) by post-purification, smooth surface (2-5μm)



G. Ciovati, J. Mammosser, unpublished



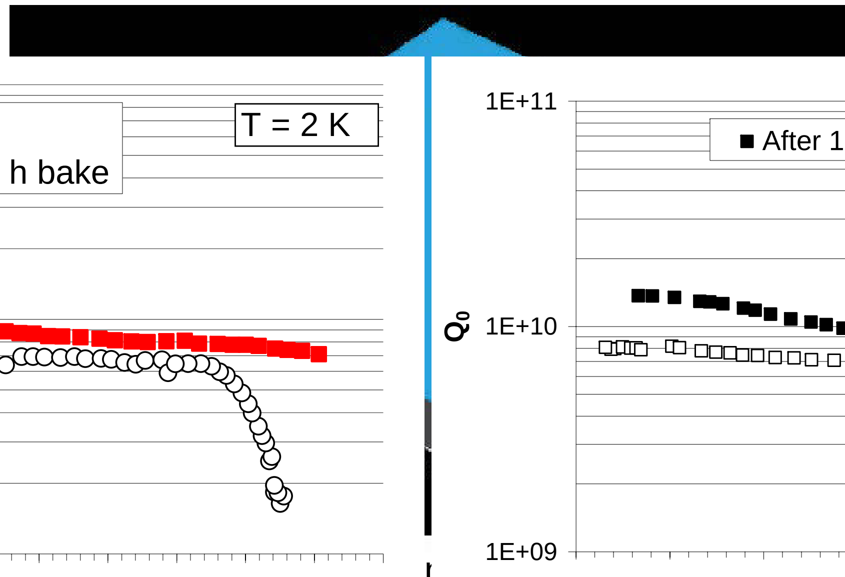
1.3 GHz 9-Cell Cavity AC78 (DESY)

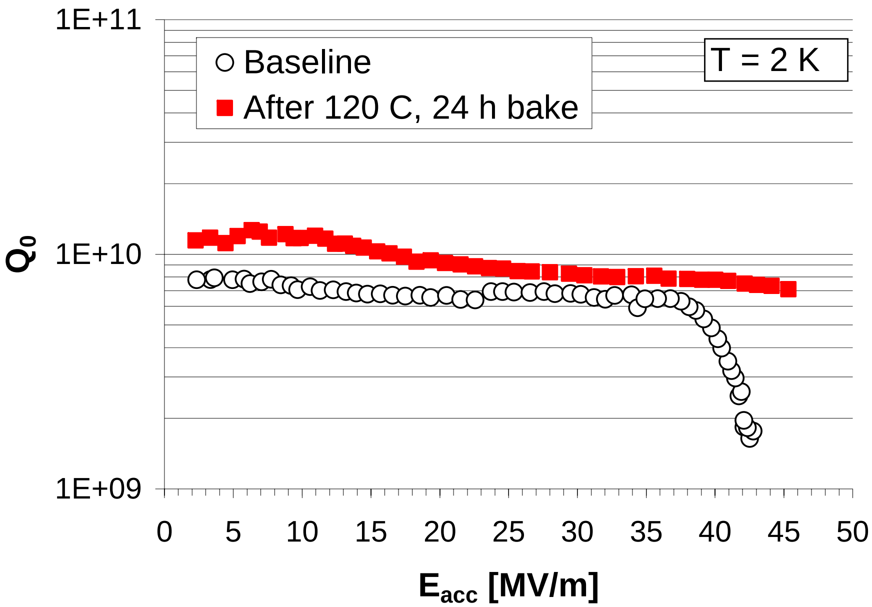
L. Lilje -EPAC 04- WEAOCH03

Q-drop RECOVERS after baking

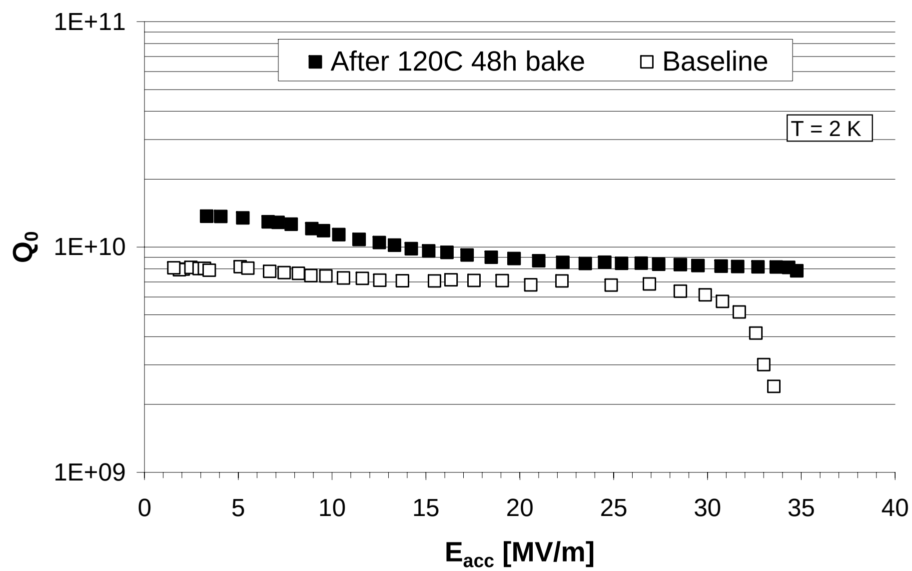
Single grain BCP cavities

- One grain, very smooth surface (<1μm) with BCP





2.3 GHz CEBAF LL Single Cell (JLab)

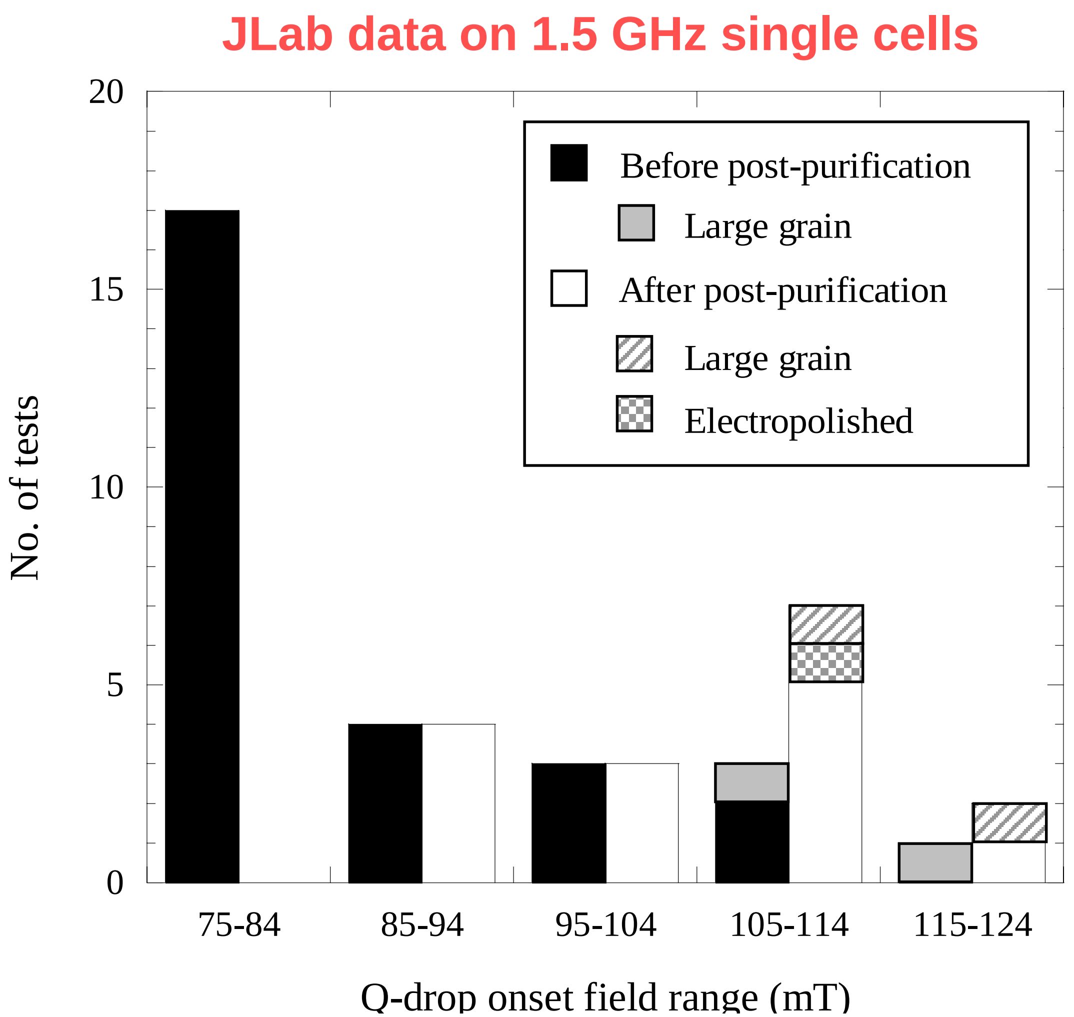


2.2 GHz CEBAF HG Single Cell (JLab)

P. Kneisel *et al*.-PAC 05-TPPT076

Q-drop RECOVERS after baking

Statistic on Q-drop onset field



Conclusions (1)

- Q-drop is common to BCP, EP and Single crystal cavities
- The onset field is ↑ the ↓ the density of grain boundaries is
- The baking effect is different on polycrystalline “fine grain” Nb treated by BCP and EP, but is similar for ↓ density of grain boundaries
- “Air” baking less effective than “UHV” bake

Origin of Q-drop: E- or B-field?

- Interface Tunnel Exchange Model[1]: resonant absorption of energy due to tunneling of normal e^- between metal and oxide in the presence of strong E-field

$$R_S^E = b \cdot [\exp(-c/E_{rf}) - \exp(-c/E_0)]$$

Excellent fit to experimental data

- All other models[2,3,4,5]: Q-drop is a magnetic field effect

[1]J. Halbritter, *IEEE Trans. on Appl. Superc.*, 11 No. 1 (2001) 1864

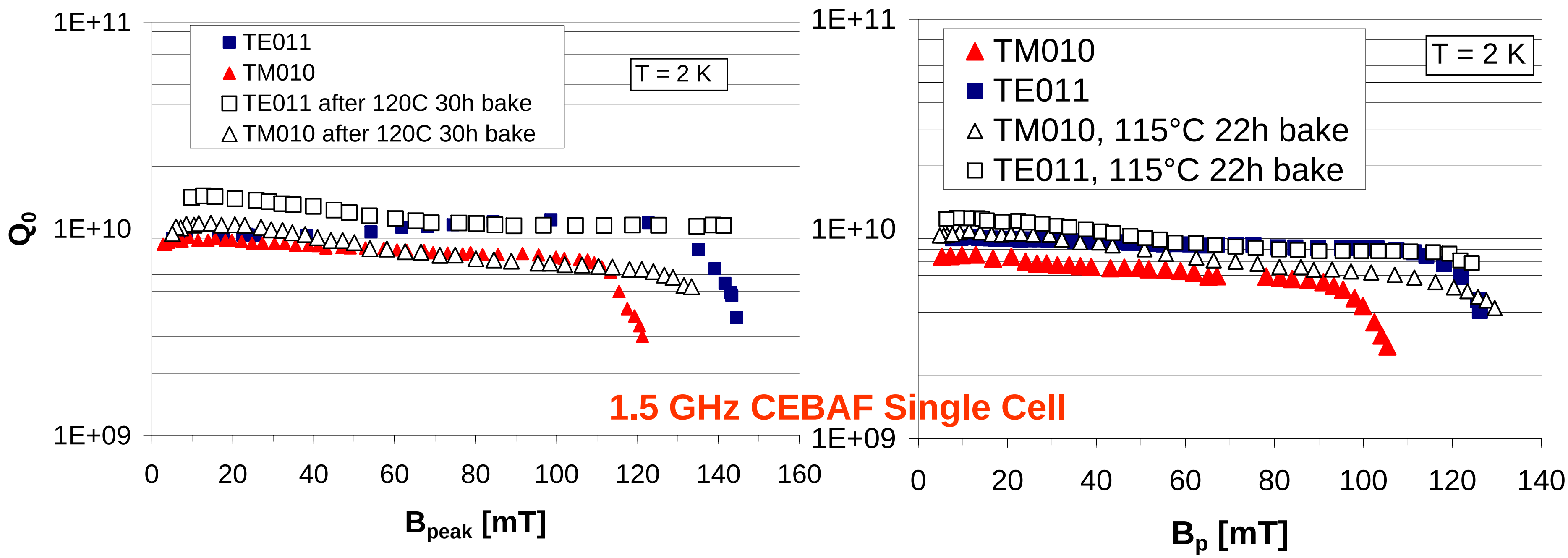
[2]K. Saito, *Proc. 11th SRF Workshop*, Travemuende, Germany (2003), ThP17

[3]A. Gurevich, Argonne Report ANL-05/10, (2005) p. 17

[4]H. Safa, *Proc. 10th SRF Workshop*, Tsukuba, Japan (2001) p. 279

[5]J. Knobloch et al., *Proc. 9th SRF Workshop*, Los Alamos, NM (1999) p. 77

Measurements on TE_{011} mode

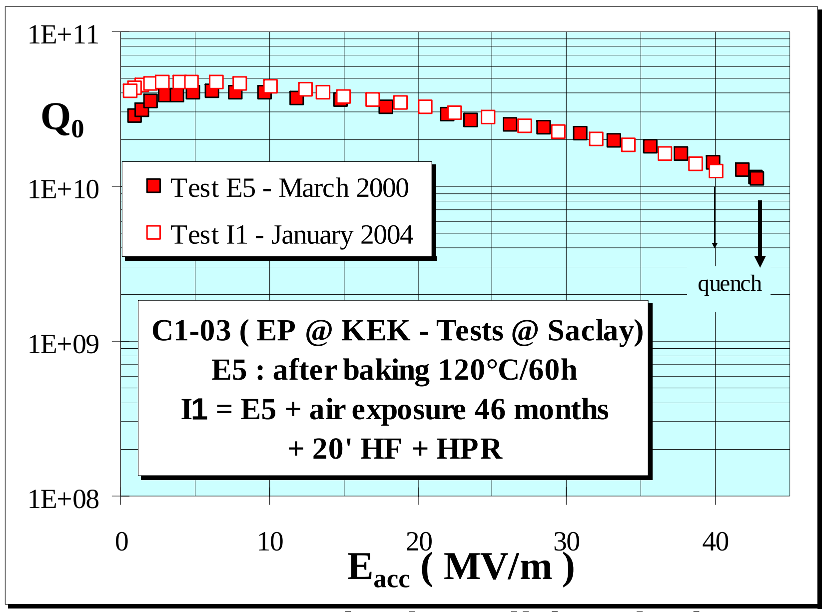


G. Ciovati and P. Kneisel – Frontier Workshop – p. 74

After post-purification, Q-drop appears in TE_{011} mode (zero E-field on surface) with the same field dependence as for TM_{010} mode and recovers after baking

HF treatment

- HF used to remove oxide layer after baking. The surface is being re-oxidized after rinsing and air exposure



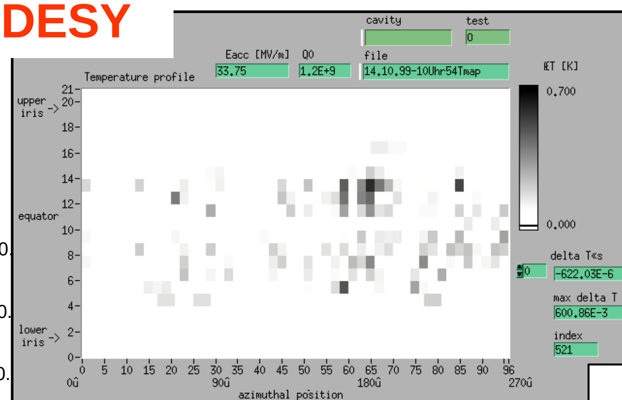
1.3 GHz Single Cell (Saclay)

B. Visentin – Frontier Workshop – p. 94

Q-drop is NOT restored after a new oxide layer is formed

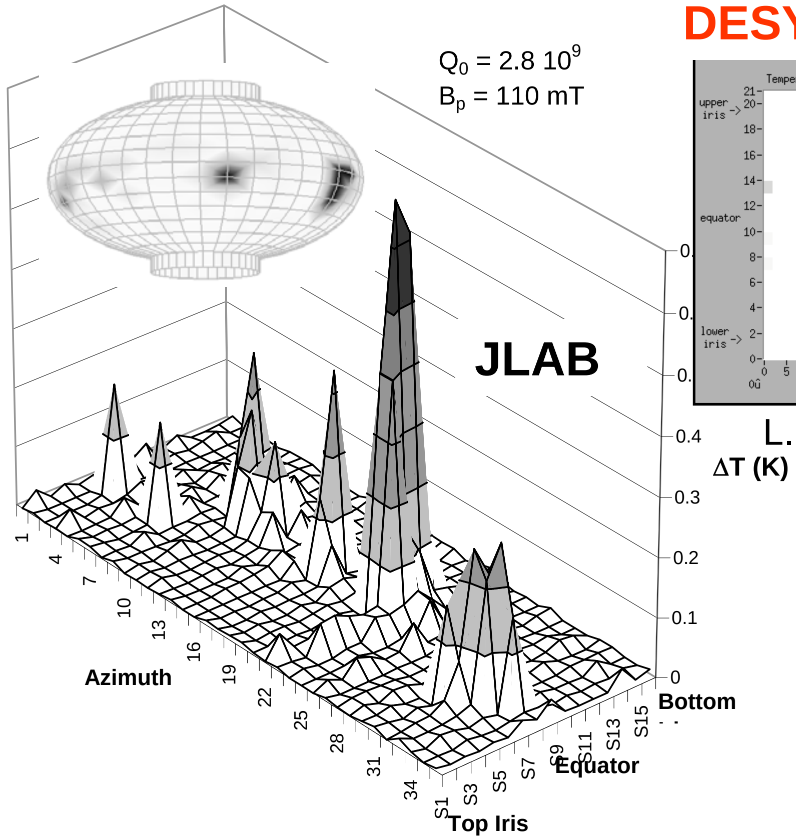
Temperature maps before baking

DESY



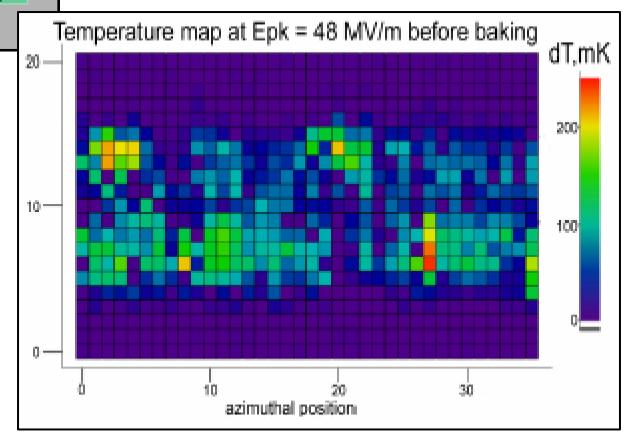
L. Lilje *et al*.-SRF 99-TUA001

JLAB



G. Ciovati-unpublished

CORNELL



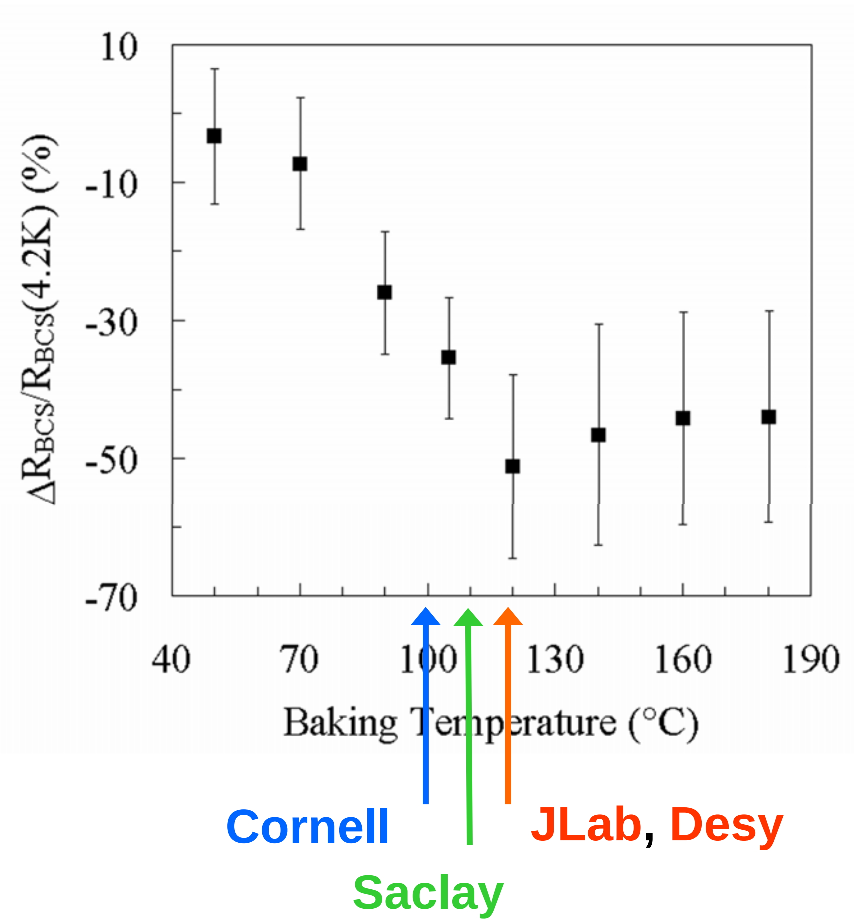
G. Eremeev *et al*.-SRF 03-MoP18

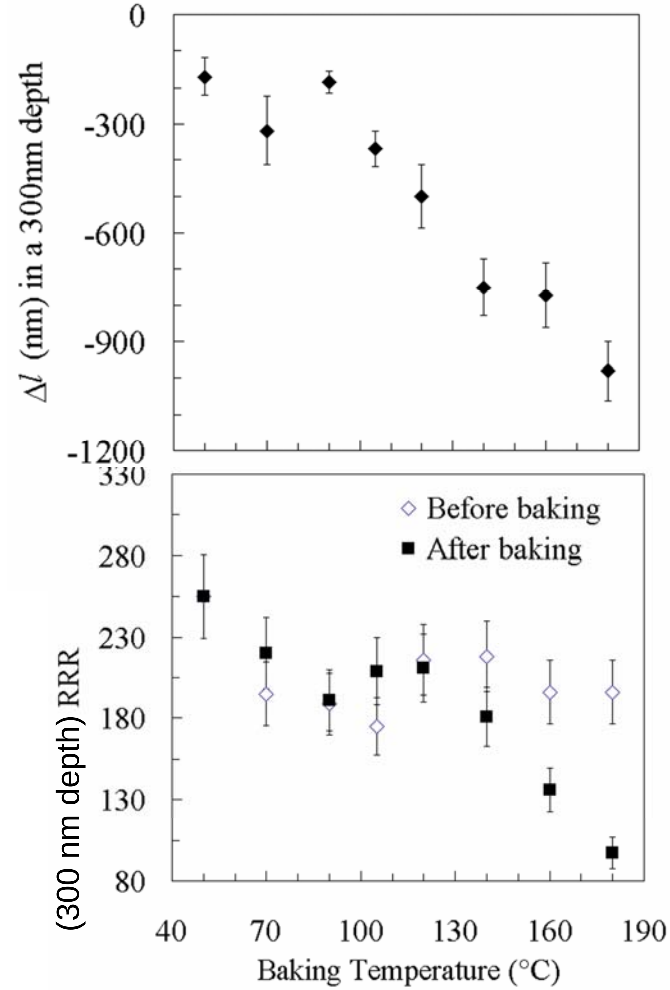
"Patchy" losses develop at the cavity equator (high magnetic field region)

Conclusions (2)

- The Q-drop is due to high magnetic field
- The benefit of baking is maintained after
  - exposure to air for 3 years
  - high pressure water rinsing
  - build-up of new oxide layer

Baking effect on low field R_s





G. Ciovati-*J. Appl. Phys.* 96, p. 1591 (2004)

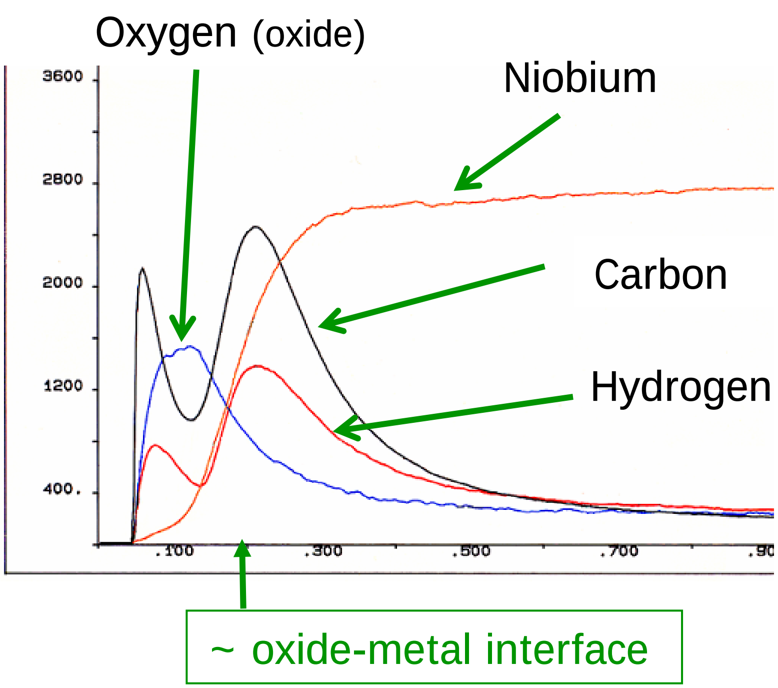
- Decrease of R_{BCS} due to strong ↓ of l and slight ↑ of energy gap
- The physics of the niobium surface changes from CLEAN (l > 200 nm) to DIRTY LIMIT ($l \approx 25$ nm $\cong \xi_0$)

Surface studies on samples

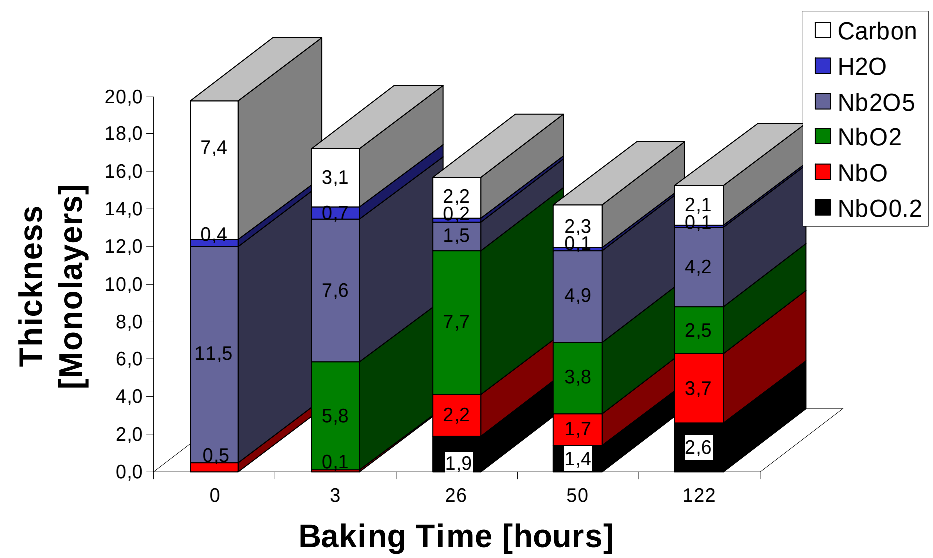
• Natural oxide (Nb_2O_5) decomposes into sub-oxides (NbO, NbO_2), thinner oxide layer

• Segregation of interstitial oxygen near metal-oxide interface, measured conc. up to 10 at.%

• Hydrogen? Very difficult to measure accurately, no clear data yet

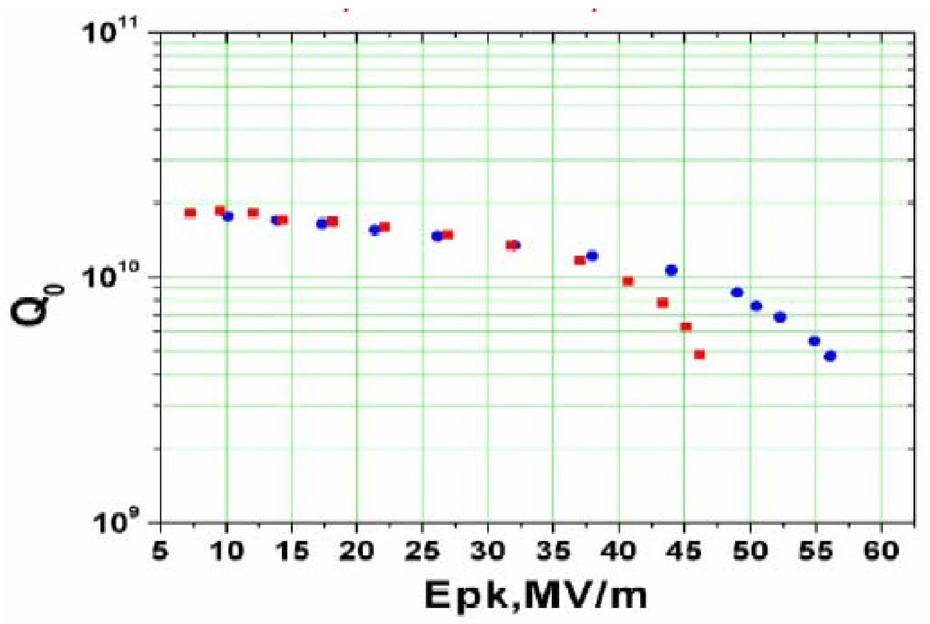


C. Antoine – Frontier Workshop – p. 65

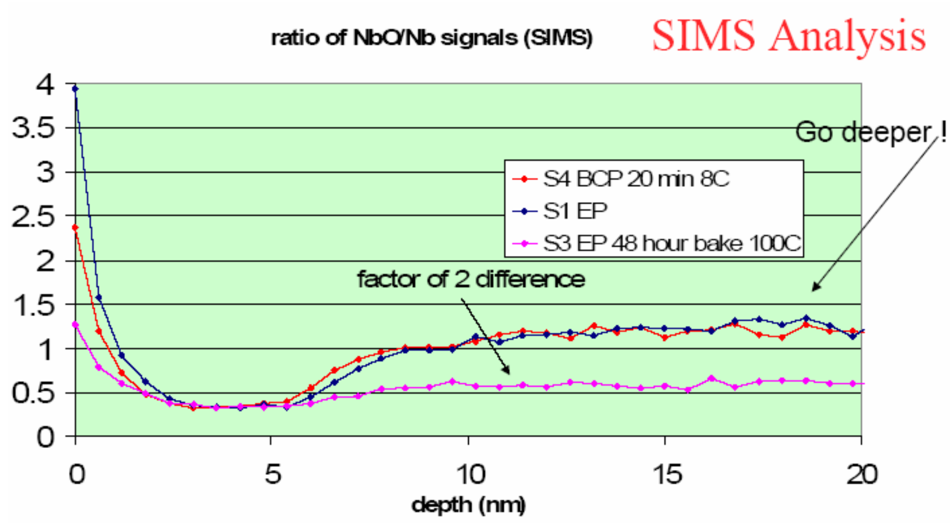


A. Dacca` *et al.,* Appl. Surf. Sci., 126 (1998) p. 219

How deep is the baking benefit?



Red squares – additional 30 V/60 V anodizing
Blue circles – BCP + 100 C baking



H. Padamsee *et al.* – Frontier Workshop – p. 293

Cavity test result: original Q-drop is obtained after ≈ 20 nm thick Nb was converted to oxide

Sample analysis: oxygen concentration in 20 nm depth reduced by baking

Susceptibility meas. on samples

- r_{GL} (Ginzburg-Landau) =1.695
- In these measurements: r_{32} >1.8

Two possible explanations:

- $B_{c2}^{surf} > B_{c2}^{bulk}$

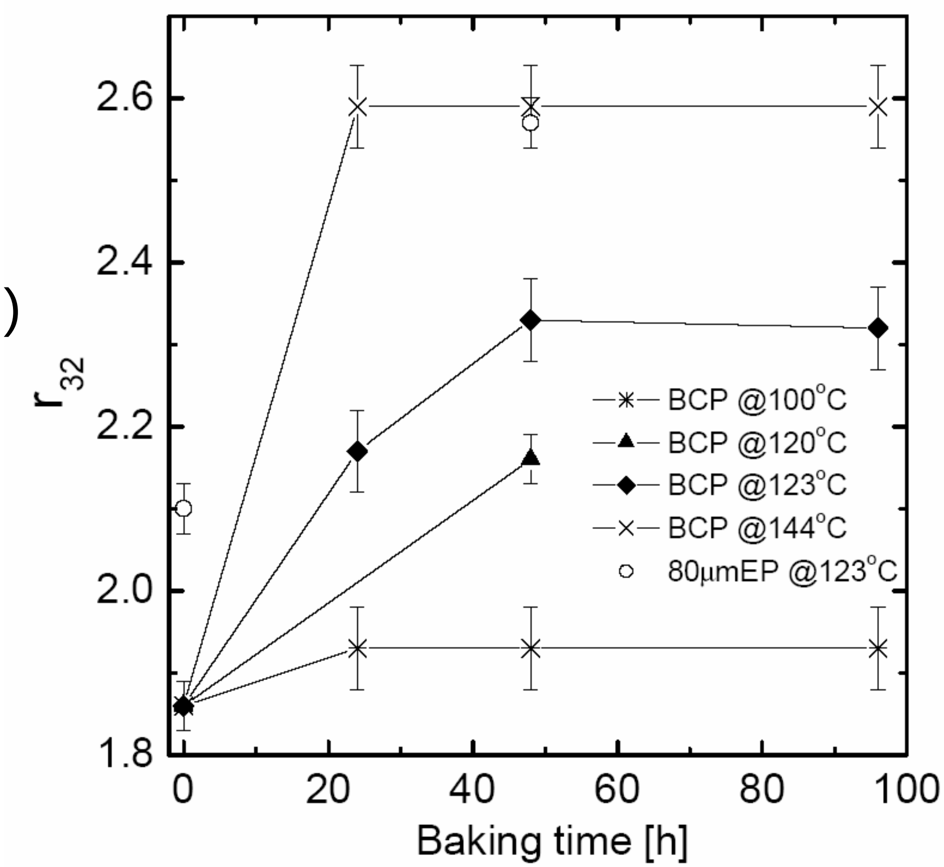
$$B_{c3}=r_{GL}B_{c2}^{surf} \text{ ("naïve" model)}$$

- impurities in a layer $d \leq \xi$

$$r_{32}=1.67[1+(1-\chi_G)\sqrt{1.7\, d/_{x}}]$$

↑ T_{bake}, time: ↑ *d*, ↓ *l*

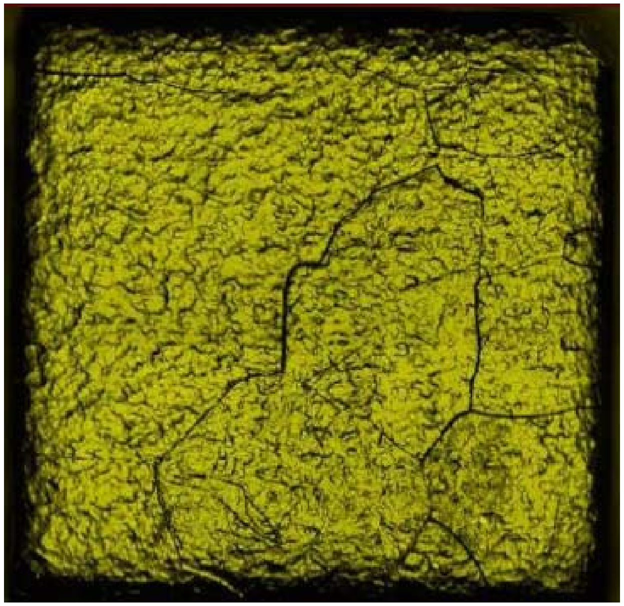
$r_{32}=B_{c3}/B_{c2}$: depends on bake temperature and duration



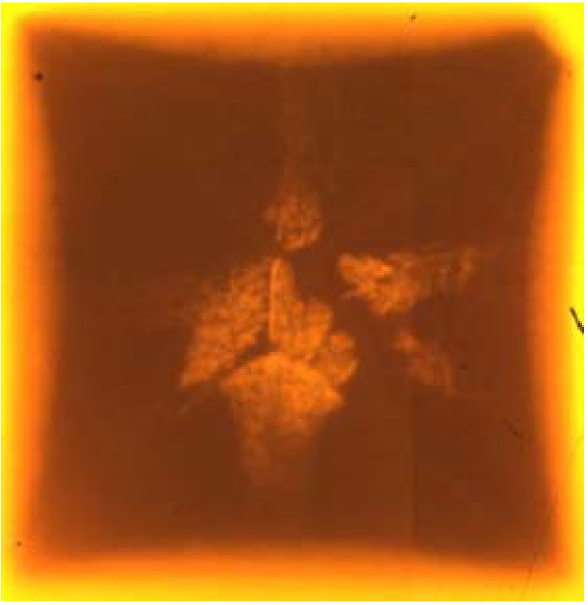
S. Casalbuoni *et al.* – SRF 03 – WEO13

Magneto-optical meas. on samples

- Study flux penetration in Nb samples



Optical image, large grain sample (by post-purif.) BCP treated



MO image at 57 mT, 7 K

Evidence of flux penetration along grain boundaries!

P. J. Lee *et al.* – Frontier Workshop – p. 84

Conclusions (3)

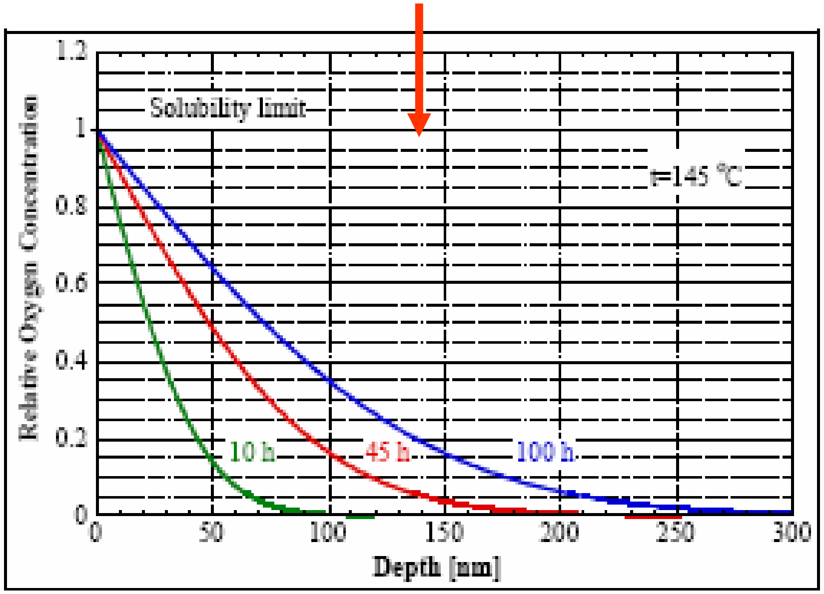
- Impurity diffusion occurs during baking
  - Decrease of mean free path (cavity meas.)
  - Susceptibility measurements (samples)
  - XPS analysis (samples)
- High O concentration near the surface (≈20nm deep) reduced by baking
- Flux penetration may occur at grain boundaries

Is Oxygen the enemy?

Oxygen diffusion models

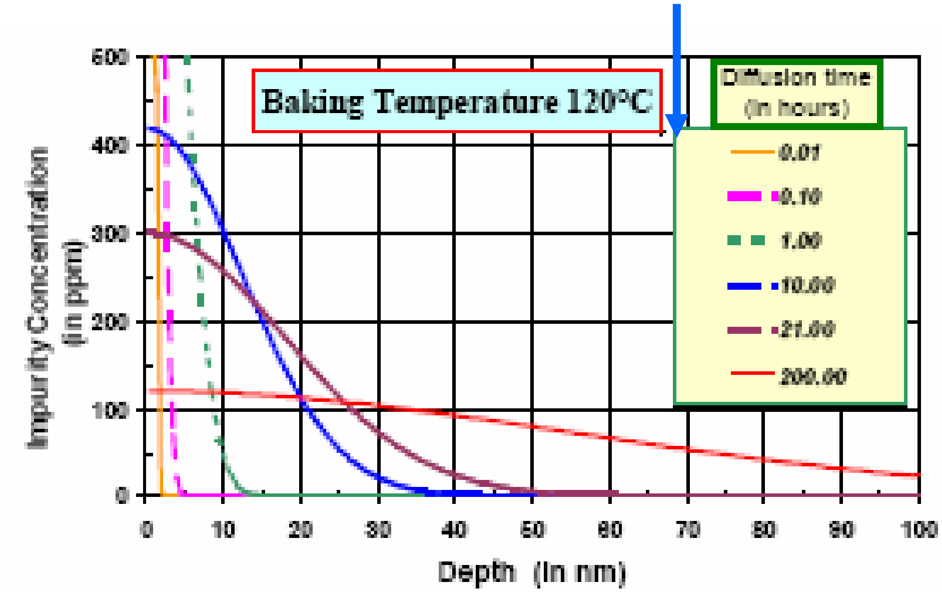
- Solve diffusion equation

Infinite source of oxygen at the surface



S. Calatroni *et al.* – SRF 01 – PR025

Fixed amount of oxygen



H. Safa – SRF 01 – MA008

Improved model

- Contribution from dissociation of oxide layer

$$Nb_2O_5 \xrightarrow{k} NbO \qquad k(T) = Ae^{-E_a/RT}$$

A ≅ 3×10⁹ 1/s E_a ≅ 135 kJ/mol

$$\frac{\partial u(x,t)}{\partial t} = \underbrace{D(T)}_{0.0138e^{-\frac{112kJ/mol}{RT}} cm^2 s} \frac{\partial^2 u(x,t)}{\partial x^2} + \underbrace{q(x,t,T)}_{u_0 k(T) e^{-k(T)t}\delta(x)}$$

Diffusion equation with source at x=0

First order reduction kinetic

Solution:

$$u(x,t) = \frac{u_0}{\sqrt{\pi D(T)}} \int_0^t \frac{k(T)e^{-k(T)s}}{\sqrt{t-s}} e^{-\frac{x^2}{4D(T)(t-s)}}$$

Concentration of oxygen produced by the oxide reduction

u_0 ≅ 1000 at.% nm, obtained from comparison with data

B. R. King *et al.,* Thin Solid Films 192, p. 351 (1990)

Q. Ma and R. Rosenberg – SRF 01 – PR007

- Diffusion of interstitial oxygen existing before baking

$$\frac{\partial v(x,t)}{\partial t} = D(T)\frac{\partial^2 v(x,t)}{\partial x^2} \qquad v(0,0) = v_0$$

Solution:

$$v(x,t) = \frac{v_0}{\sqrt{4\pi D(T)t}} e^{-\frac{x^2}{4D(T)t}}$$

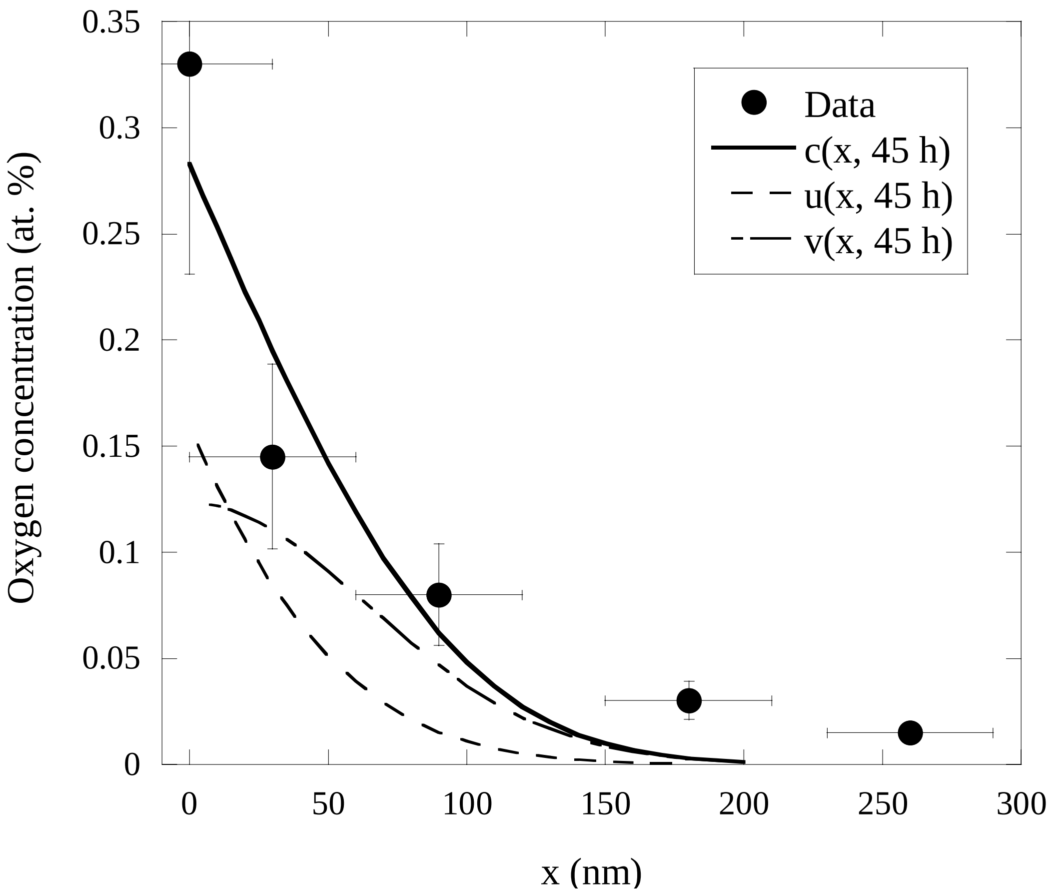
$\cong$ 10 at.% nm

I. Arfaoui *et al.*, J. Appl. Phys. 91, p. 9319 (2002)

General solution:

$$c(x,t) = u(x,t) + v(x,t)$$

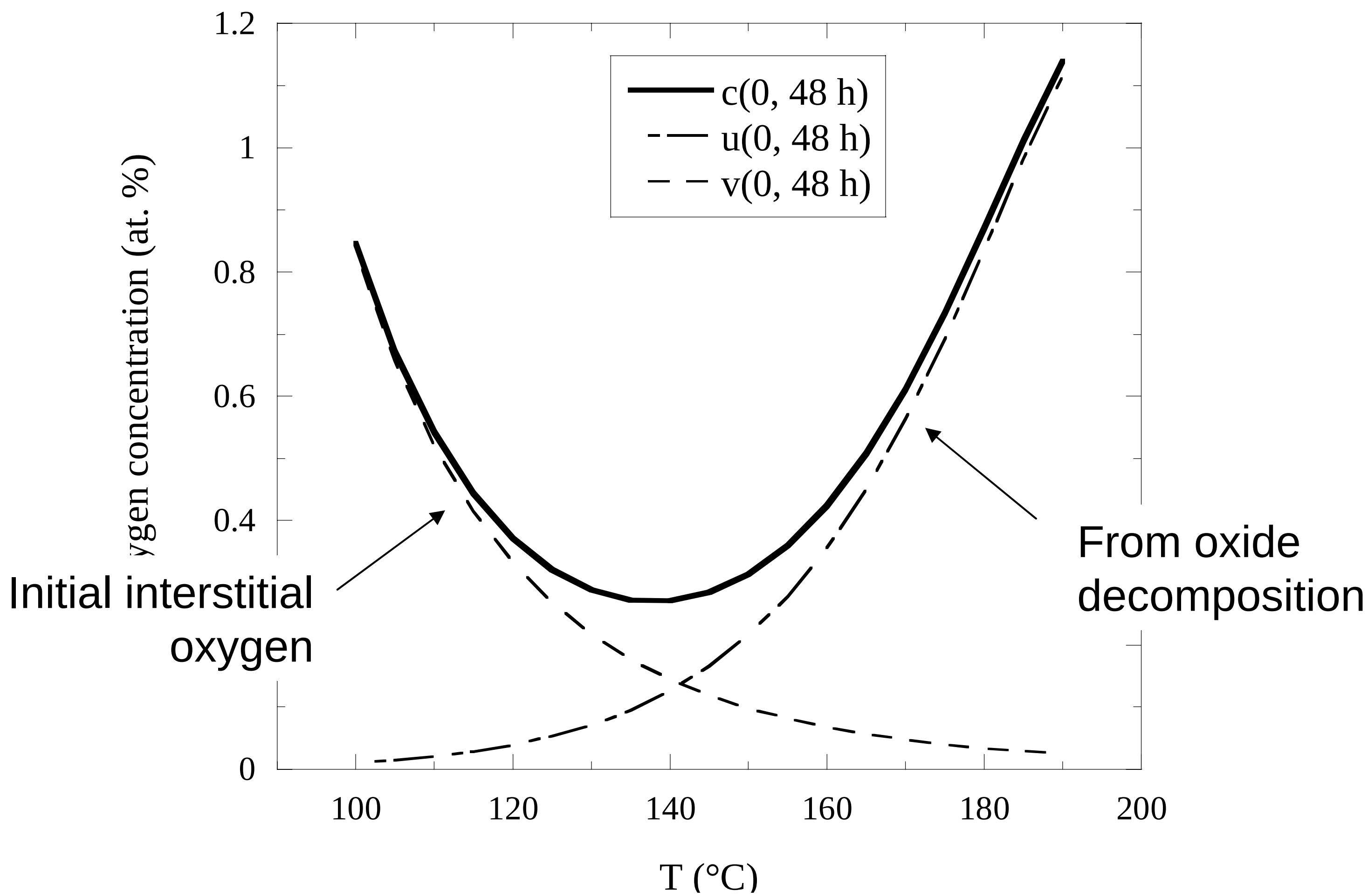
Comparison with data



Comparison with data obtained by successive anodizations on cavity baked at 145°C, 45h

Data are from: P. Kneisel – SRF 99 - p. 328

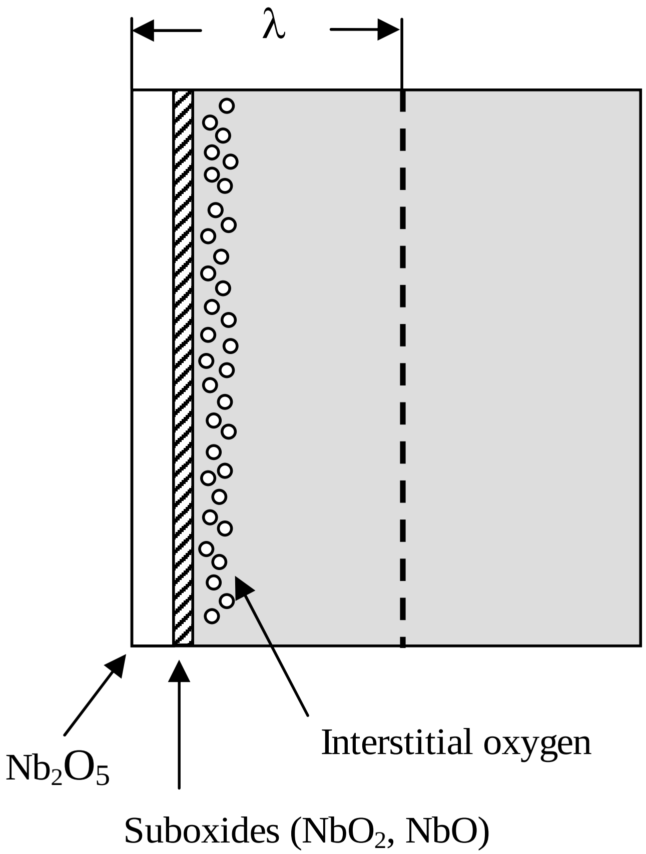
Oxygen concentration at the surface as function of baking temperature



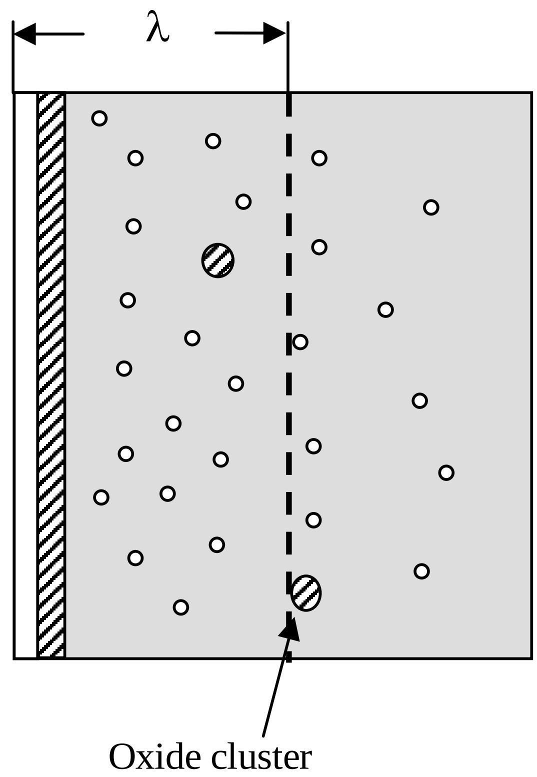
Optimum baking temperature: lowers O conc. near the surface

Schematic of the Nb surface

Before baking



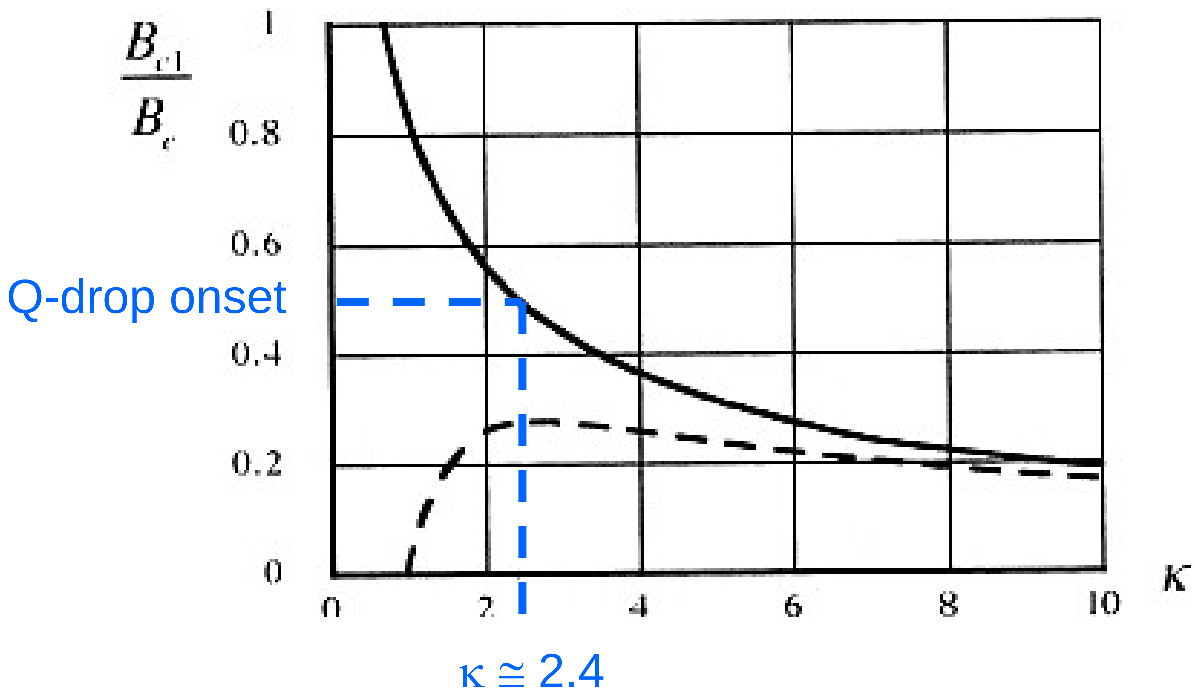
After baking



How is O related to the Q-drop?

Hypothesis

J. R. Waldram, *Superconductivity of metals and cuprates*, IoP, 1996



Interstitial oxygen concentration of ≅ 0.56 at.%[#]

[#] C.C. Koch *et al.*,Phys. Rev. B 9 (1974) p. 888

Flux penetration at reduced B_{c1}

- There exist a surface barrier which prevents vortices from penetrating even above B_{c1}[1]

BUT

the surface barrier can be reduced to zero in non-uniform (rough) surfaces[2]

→ Surface morphology

→ Changes in surface barrier

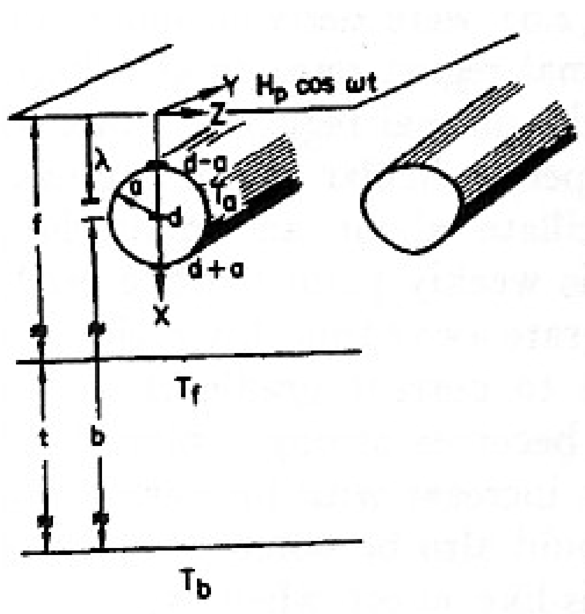
→ Onset of Q-drop (↑ smoother surfaces)

[1]C. Bean and J. D. Livingston, *Phys. Rev. Lett.* 12 p. 14 (1964)

[2]R. D. Blois and W. de Sorbo, *Phys. Rev. Lett.* 12 p. 499 (1964)

Losses due to flux penetration

- Rabinowitz[1] calculated the power loss due to a normal conducting fluxoid in rf field



$R_s(B_p) \propto \exp(D/B_p)$

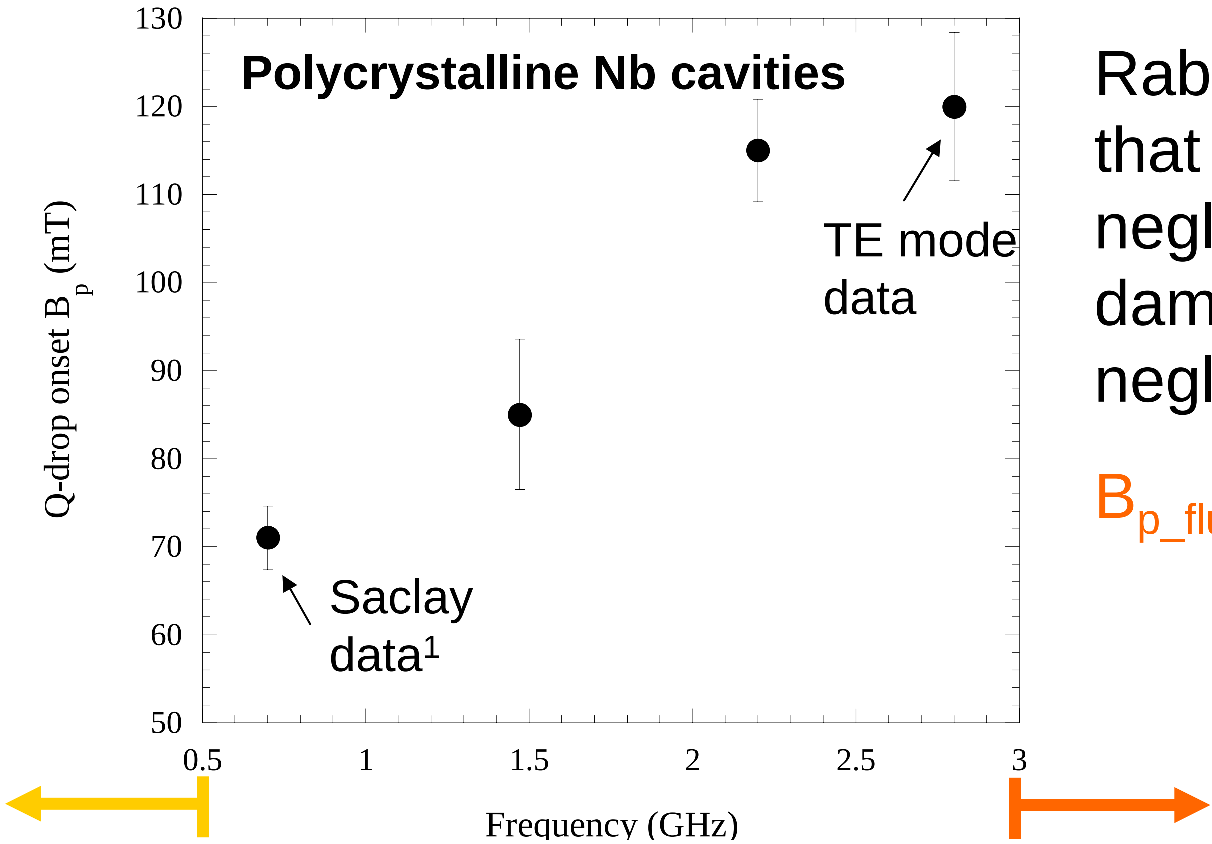
$$D \approx \frac{\Delta}{k_B F}\sqrt{\frac{k_1}{N R a \ln\left[\left(f-d\right)/a\right]}}$$

$D \cong 2.2$ T (with $\rho=\rho_n$)

$D \cong 5 \div 8$ mT from experiments

[1]M. Rabinowitz, *J. Appl. Phys.* 42 p. 88 (1971)

Q-drop onset freq. dependence



Rabinowitz[3] calculated that for the case of negligible viscous damping and negligible pinning

$B_{p\_flux\_penetration} \propto \omega$

No Q-drop found on low-beta, low frequency cavities up to $B_p \approx 100$ mT [2]

↑ R_{BCS}, global heating

[1]B. Visentin – Frontier Workshop – p. 94

[2]M. Kelly *et al.* – Frontier Workshop – p. 278

[3]M. Rabinowitz, *J. Appl. Phys.* 42 p. 88 (1971)

Summary

- The onset field of the Q-drop and the effect of baking seem to depend on the density of grain boundaries
- The Q-drop appears to be driven by magnetic-field
- There is a high oxygen concentration at the oxide/metal interface which seems to be diluted by baking
- An improved oxygen diffusion model can be linked to a change of the onset field for flux penetration to explain the Q-drop and the baking effect

Open issues

- Is there enough experimental evidence to exclude H from playing a role in the Q-drop?
- How can we test the hypothesis of flux penetration during Q-drop?
- Interpretation of experimental data against O hypothesis:
  - Saclay data: Q-drop is not restored after HF rinsing of baked cavity (O conc. near surface restored as before baking)

Acknowledgements

P. Kneisel, G. Myneni, J. Halbritter, J. Delayen,
A. Gurevich, H. Padamsee, C. Antoine

Thank You!