High field Q-slope and the baking effect

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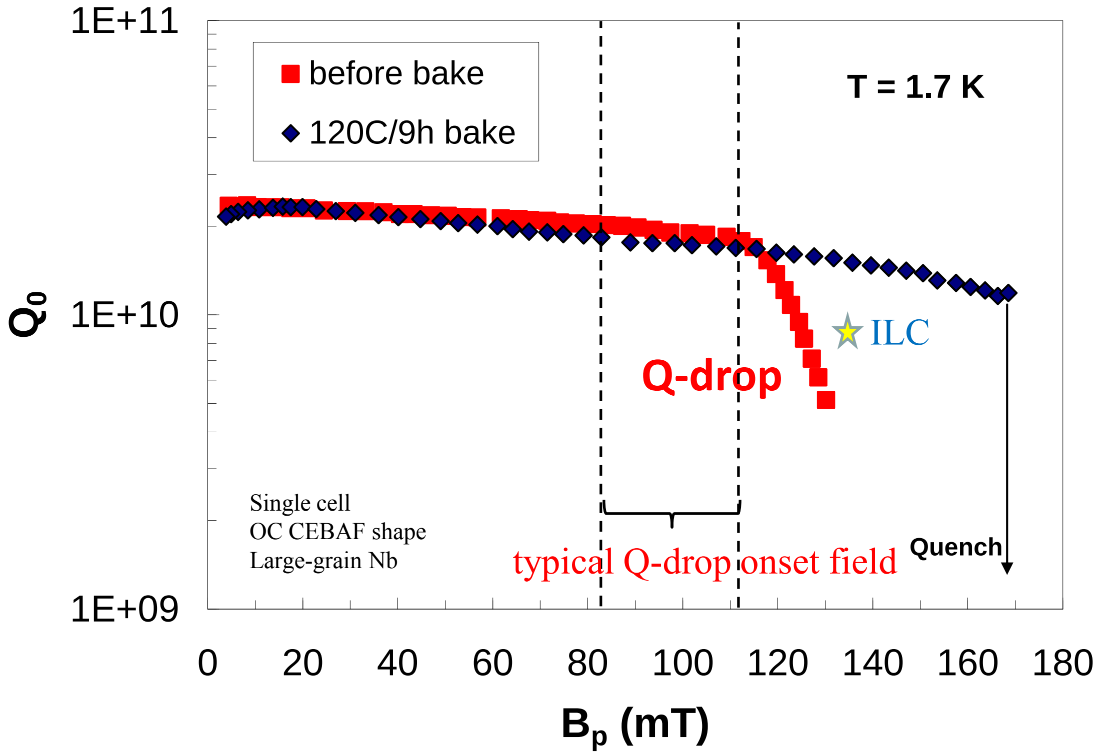
Outline

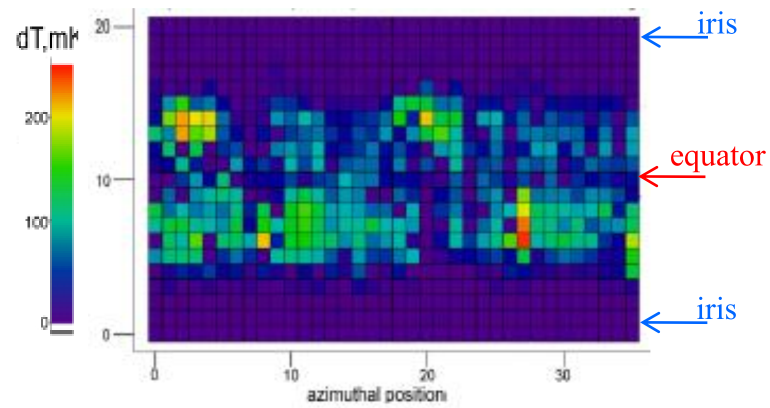
- Q-drop and baking effect: the essential facts
- Models to describe the cavity excitation curves
- "Oxygen pollution" model: new results against it
- Hot-spots due to magnetic vortices
- Recent results on Nb sample measurements
- New results on cavity heat treatments
- Conclusions

Q-drop and baking effect: essential facts

G. Ciovati, P. Kneisel and A. Gurevich, *Phys. Rev. STAB* **10** (2007) 062002



G. Eremeev et al., *SRF'03*, MoP18

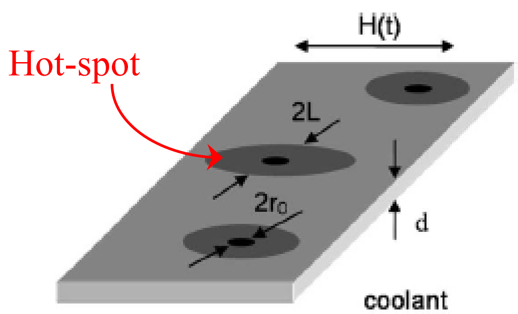


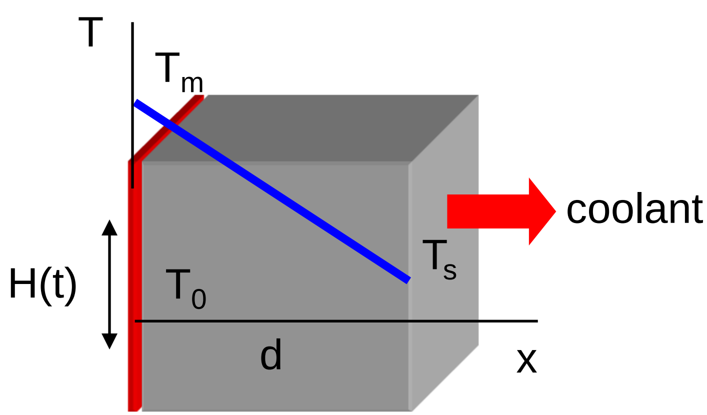
Temperature map during Q-drop

- Q-drop ➡ non-uniform hot-spots due to high surface magnetic field
- Low-temperature (120 °C) baking ➡ reduced intensity of the hot-spots, higher Q maintained at higher field
  - Its effectiveness depends on the material/processing combination

Models to describe the cavity excitation curves

Gurevich model





- The effect of "defects" with reduced superconducting parameters is included in the calculation of the cavity R_s

  → Hot-spots

- This non-linear R_s is used in the heat balance equation

$$u(\theta) = \theta e^{1-\theta}$$

$$\frac{2B_p^2}{B_{b0}^2} = 1 + g + u(\theta) - \sqrt{\left[1 + g + u(\theta)\right]^2 - 4u(\theta)}$$

$$Q_0(B_p) = \frac{Q_0(0)e^{-\theta}}{1 + g\Big/\left[1 - \left(B_p/B_{b0}\right)^2\right]}$$

Fit parameters:

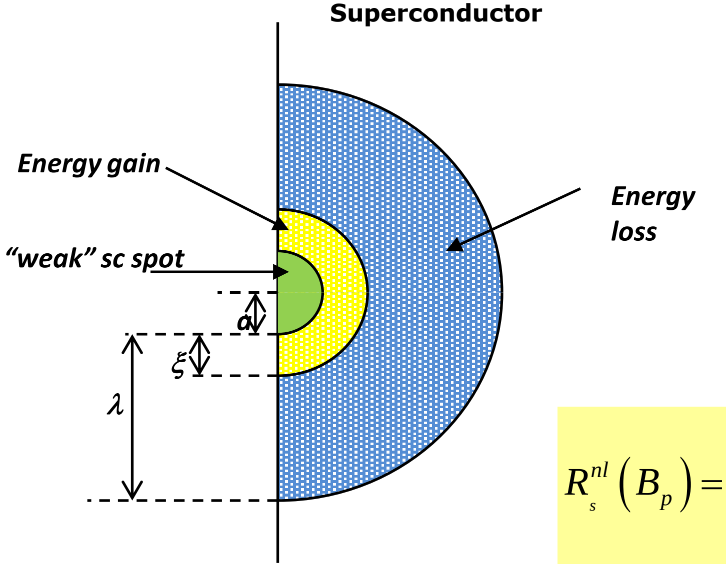
g related to the No. and intensity of hot-spots

$Q_0(0)$ low-field Q_0

B_{b0} quench field

A. Gurevich, *Physica C* **441** (2006) 38

Weingarten model



- n_{s0} defects per unit volume at the Nb surface with lower critical field (B_0) << B_{c1}(Nb)
- The size of the nc region increases with field, above B_0

$$R_s^{nl}(B_p) = \frac{4}{3}\pi\mu_0\lambda^3 f n_{s0}\left\{\left(\frac{B_0}{B_p}\right)^2 + \frac{1}{2}\left(\frac{B_p}{B_c}\right)^2\left[1+\frac{2}{3}\kappa^2\left(\frac{B_p}{B_c}\right)^2\left(1+\frac{3}{4}\kappa^2\left(\frac{B_p}{B_c}\right)^2\cdots\right)\right]\right\}$$

Low-field Q-increase

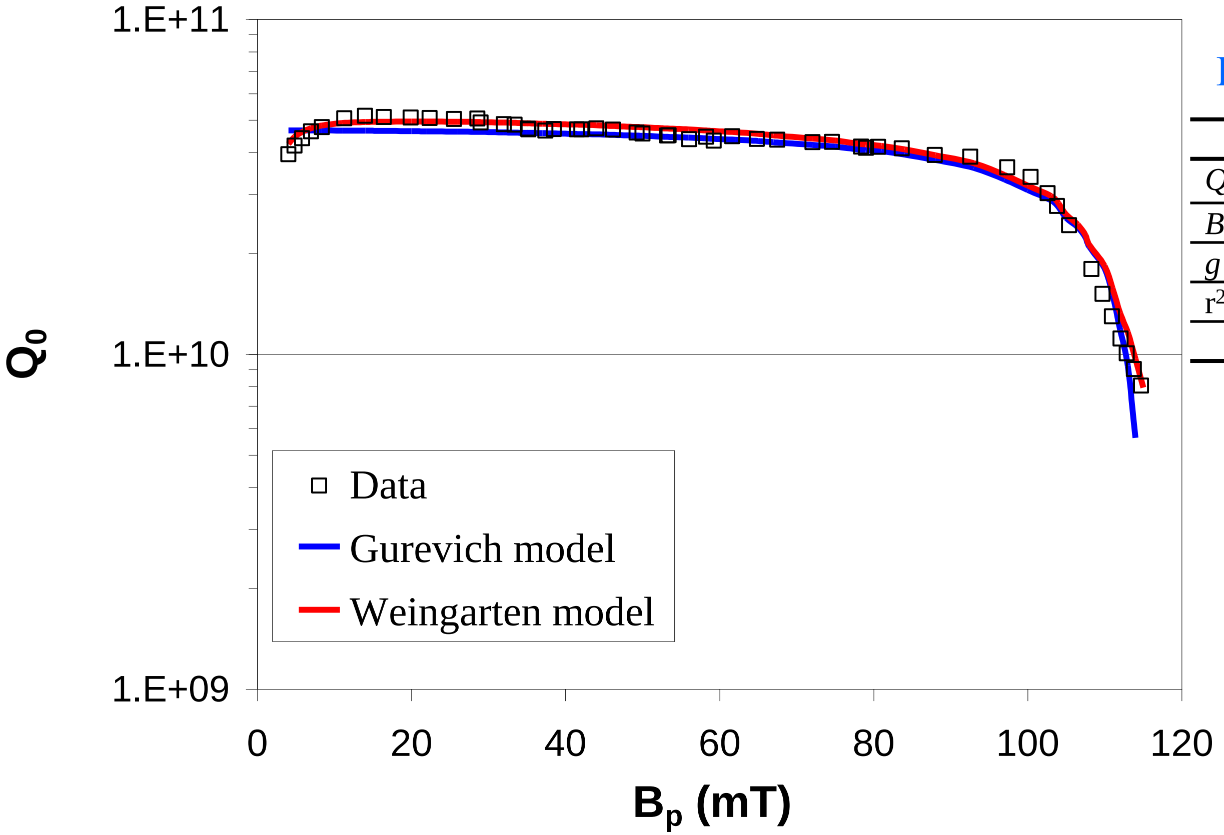
Medium and high-field Q-slopes

Fit parameters: n_{s0}, B_0, R_{res}, κ (Ginzbug-Landau parameter)

Poster TUPPO052

W. Weingarten, *SRF'07*, TuP16

Models comparison with data



Data from: G. Ciovati, *J. Appl. Phys.* **96** (2004) 1591.

Fit parameters values

Gurevich model		Weingarten model	
$Q_0(0)$	5.5×10^{10}	R_{res} (nΩ)	5
B_{b0} (mT)	115	B_0 (mT)	1.5
g	0.18	n_{s0} (1/m^2)	2×10^{10}
r^2	0.960	κ	1.767
		r^2	0.985

Both models give good agreement with experimental data

What are the “defects” invoked by both models?

“Oxygen pollution” model

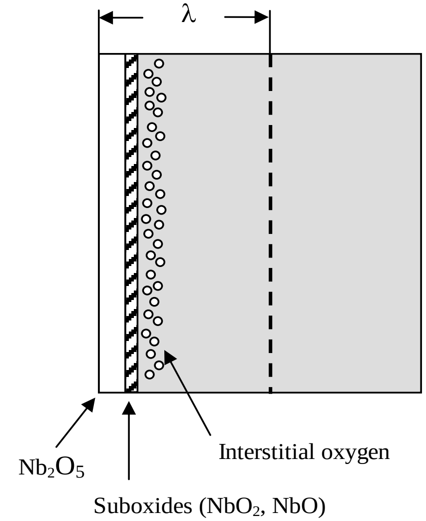
- Surface analysis of Nb samples shows high concentrations of interstitial oxygen (up to ~ 10 at.%) at the Nb/oxide interface
- Interstitial oxygen reduces T_c and the H_{c1}

Magnetic vortices enter the surface at the reduced H_{c1}, their viscous motion dissipating energy

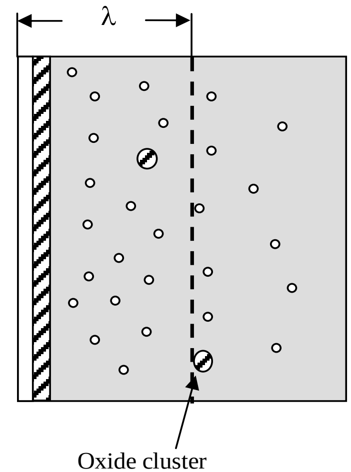
- The calculated O diffusion length at 120°C/48h is ~ 40 nm

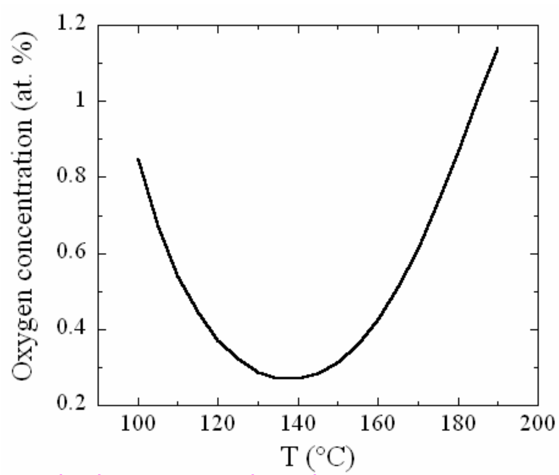
Interstitial oxygen is diluted during the 120°C baking, restoring the H_{c1} value for pure Nb

Before baking



After baking





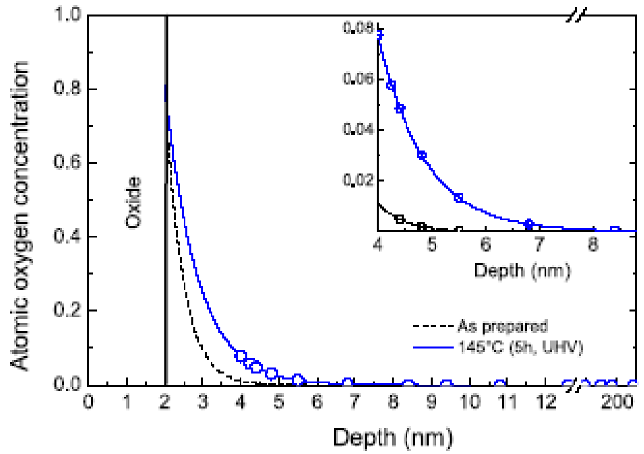
Calculated oxygen concentration at the metal/oxide interface as a function of temperature after 48h baking

G. Ciovati, *Appl. Phys. Lett.* **89** (2006) 022507

Oxygen pollution model: shortcomings

The model cannot explain the following experimental results:

- The Q-drop did not improve after 400°C/2h "in-situ" baking, while O diffuses beyond λ[1]
- The Q-drop was not restored in a baked cavity after additional baking in 1 atm of pure oxygen, while higher O concentration was established at the metal/oxide interface[2]
- Surface analysis of single-crystal Nb samples by X-ray scattering revealed very limited O diffusion after baking at 145°C/5h[3]



[1] G. Eremeev, Ph.D. Dissertation, Cornell University, 2008
[2] G. Ciovati, P. Kneisel and A. Gurevich, *Phys. Rev. STAB* **10** (2007) 062002
[3] M. Delheusy, Ph.D. Dissertation, University of Paris-Sud IX, 2008

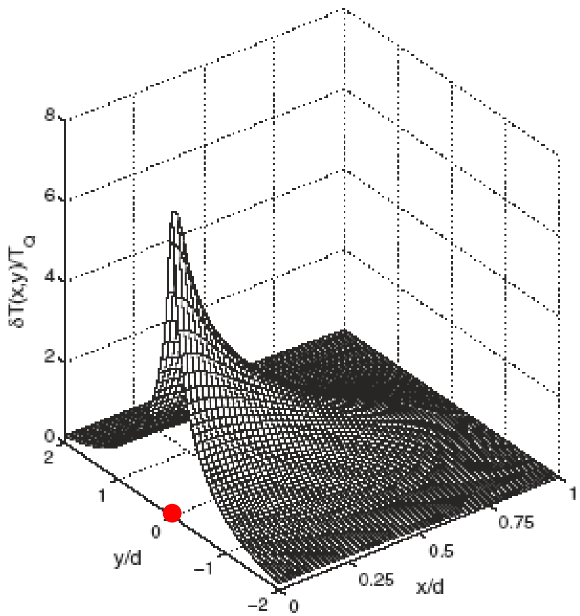
Magnetic vortices as sources of "hot-spots"

Theoretical calculations show that:

- Oscillation of magnetic vortices, pinned near the Nb surface during cool-down across $T_{c,}$ cause localized heating
- Periodic motion of vortices pushed in & out of the Nb surface by strong RF field also cause localized heating

A. Gurevich and G. Ciovati, *Phys. Rev. B* **77** (2008) 104501

High-field losses due to vortices

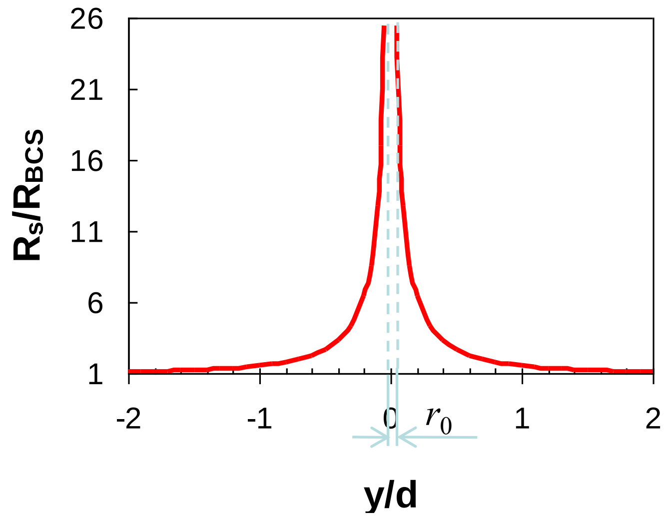


Overheating due to vortex motion

$$R_s(x=0,y) = R_{BCS}(T_0,\omega)\coth^{\sigma}\left(\frac{\pi|y|}{4d}\right) \qquad |y| > r_0$$

d: wall thickness

∝ local dissipated power



The local dissipated power is different in the case of isolated vortices vs. nearly-spaced vortices

Local dissipation due to vortex motion produces a long-range hot-spot

A. Gurevich and G. Ciovati, *Phys. Rev. B* **77** (2008) 104501

Eliminating vortex hotspots by thermal gradients

- Thermal force acting on the vortex: $f_T = -s^*(T)\nabla T, \qquad s^* = -\phi_0 \dfrac{\partial H_{c1}}{\partial T}$

- The condition $f_T > J_c\Phi_o$ gives the critical gradient which can depin vortices:

$$|\nabla T|_c = \frac{J_c}{|\partial H_{c1}/\partial T|} \cong \frac{J_c \mu_0 T_c^2}{2B_{c1}T}$$

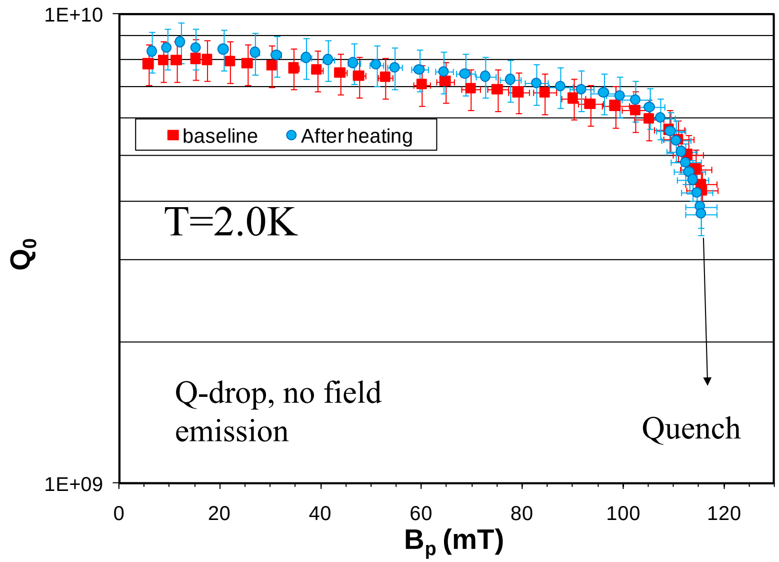
Taking $B_{c1} = 0.17$T, $J_c = 1$kA/cm^2 and T = 2 K for clean Nb yields $|\nabla T|_c \approx 1.5$ K/mm

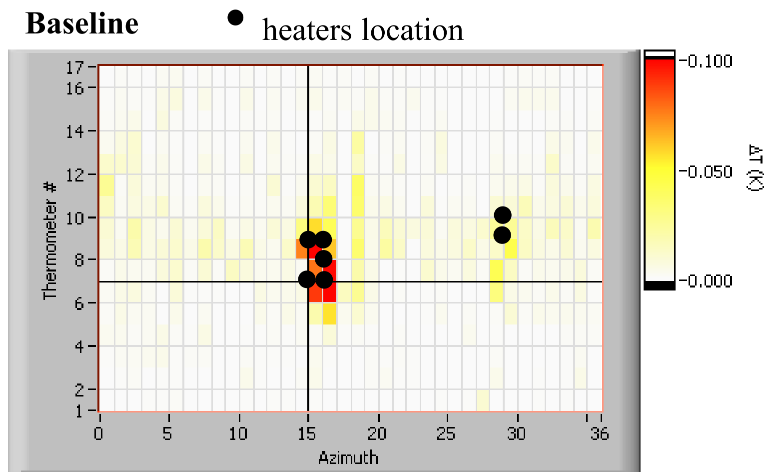
→ Vortices in Nb may be moved by moderate thermal gradients

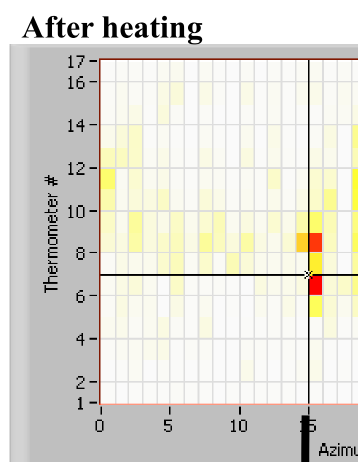
→ Any change of thermal maps after applying local heaters indicate that some of the hot-spots are due to pinned vortices

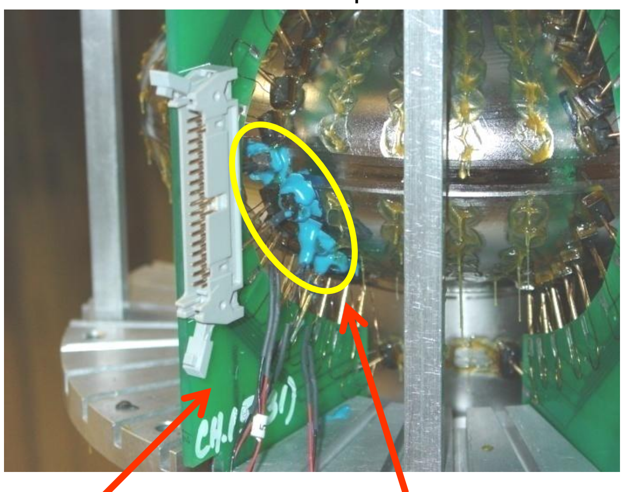
A. Gurevich, talk TU104 at SRF'07 Workshop, http://web5.pku.edu.cn/srf2007/home.html

Experimental results



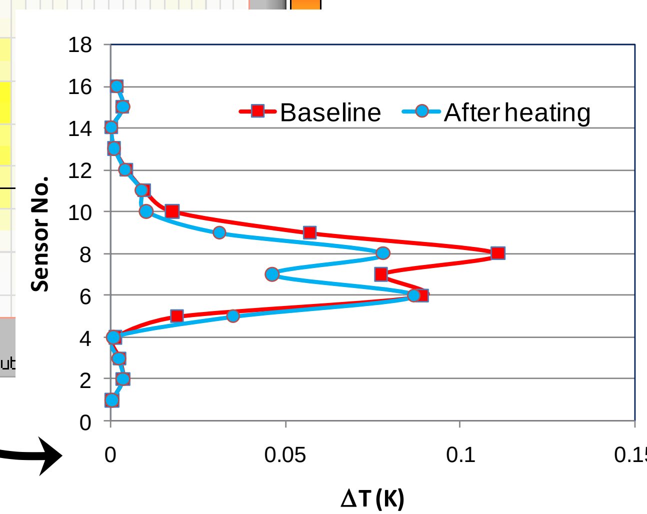






Thermometry board

Heaters providing |∇T|≅0.5 K/mm



G. Ciovati and A. Gurevich, *Phys. Rev.* STAB 11 (2008) 122001

What we learned from the experiments

- Small No. of heaters, small area of the cavity surface is affected
- Heat supplied was marginally sufficient to displace vortices (estimated 1.5 K/mm at 2 K, only applied 0.5 K/mm)

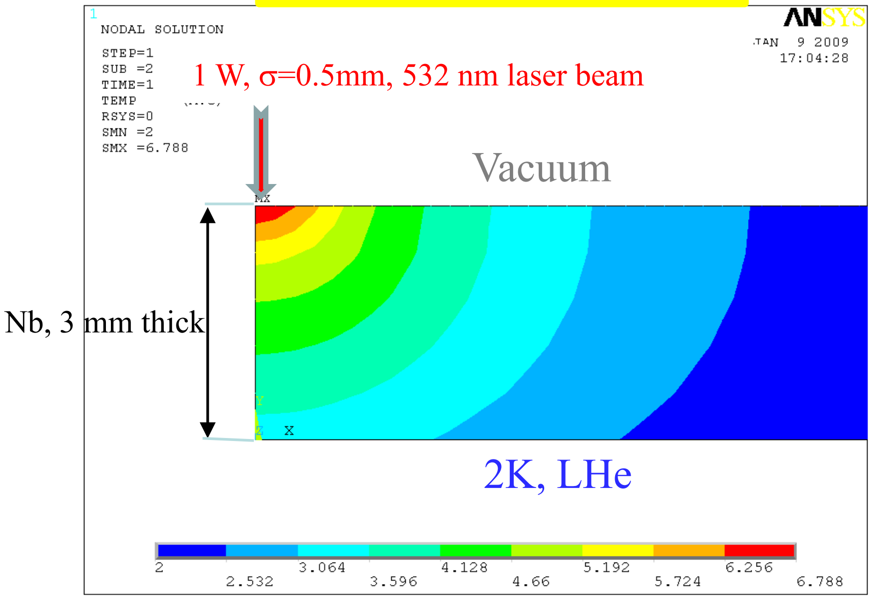
• No drastic change in $Q_0(B_p)$ performance
• Changes in T-maps indicate re-distribution of vortices over larger area

A stronger thermal gradient directed outward could push vortices deeper into the bulk

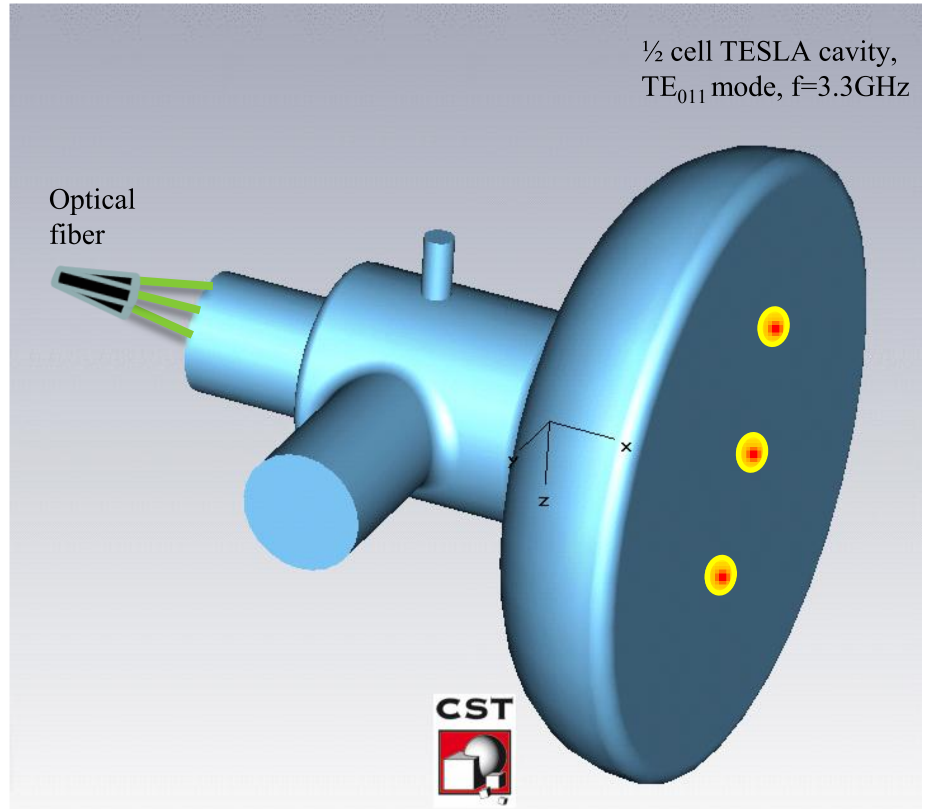
Local laser heating to move pinned vortices

Laser shining on the inner cavity surface → Higher ∇T

→ Push pinned vortices deeper into the bulk



ANSYS Simulation done by G. Cheng



Microwave Studio simulation done by J. Mondal

- Hot-spots will be identified by an array of thermometers on flat plate
- Laser will be scanned over hot-spot locations to push pinned vortices into the bulk
- Laser Scanning Microscopy to identify "lossy" regions with µm-space resolution can be done "in-situ" with the same apparatus

Talk TUOBAU02

- By now, I may have convinced you that a plausible cause of the hot-spots are magnetic vortices…

What impurities or defects in Nb pin vortices or favors their entry into the surface?

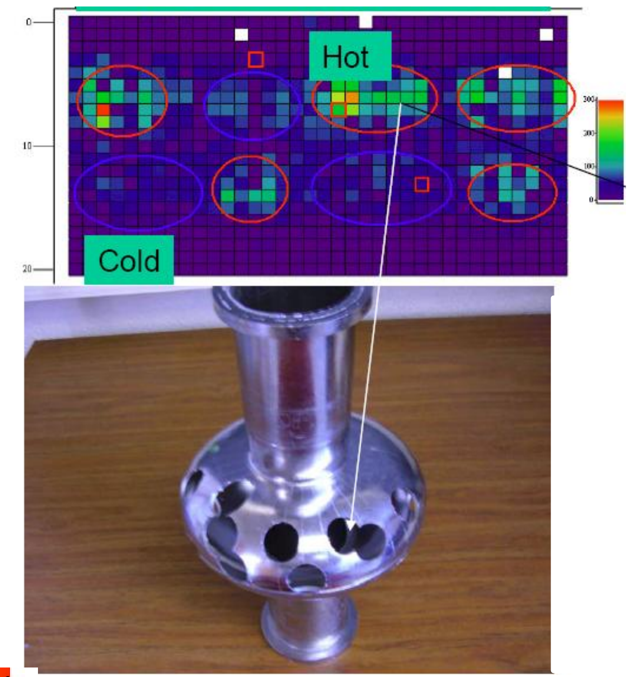
Recent results on Nb sample measurements…

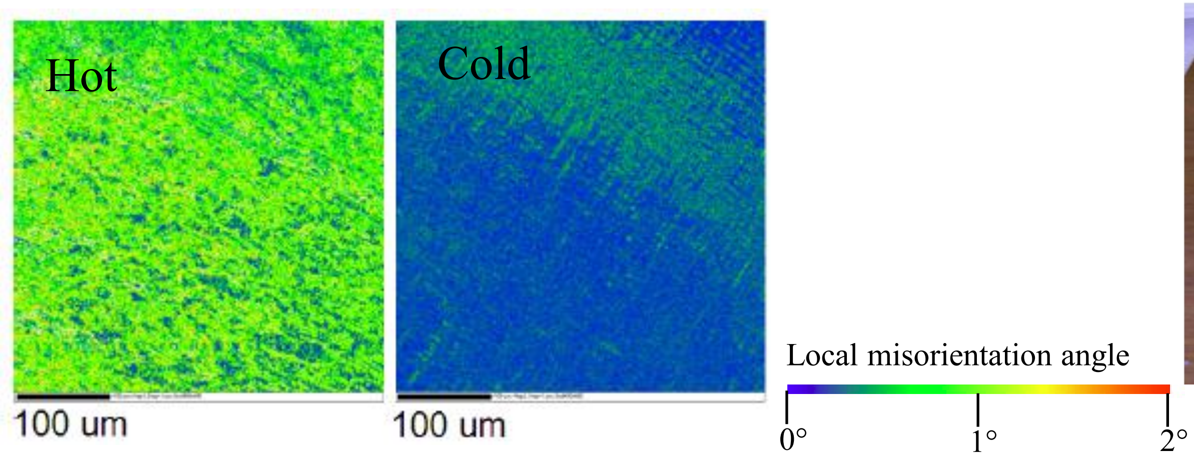
Surface analysis of “hot-spot” samples

Samples from regions of high and low RF losses were cut from single cell cavities and examined with a variety of surface analytical methods.

No differences were found in terms of:

- roughness
- oxide structure
- crystalline orientation



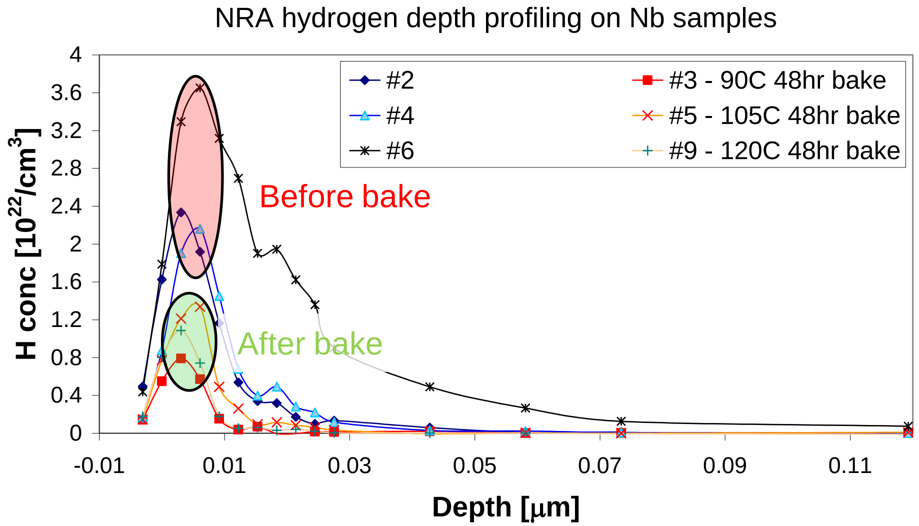


It was found that “hot-spot” samples have a higher density of crystal defects (i.e. vacancies, dislocations) than “cold” samples

More in the next talk…

A. Romanenko, Ph.D. Dissertation, Cornell University, 2009

Possible role of surface Hydrogen



- High concentration of interstitial H has been measured at the metal/oxide interface of Nb samples after BCP treatment and is reduced by the low temperature baking

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

- Thermal desorption studies showed two hydrogen desorption peaks at 130 °C and 198 °C, interpreted as hydrogen desorption from surface and subsurface sites[1]

- Measurements by Positron Annihilation Spectroscopy (PAS) show that the defect density (vacancies) increases with hydrogen concentration in Nb samples[2]

- Hydrogen affects the magnetic behavior of Nb by lowering the magnetic susceptibility for increasing H concentration[3]

[1]A.L. Cabrera and J. Espinosa-Gangas, J. Material Research **17** (2002) 2698.
[2]J. Cizek et al., Phys. Rev. B **69** (2004) 224106.
[3]U. Kobler and J.-M. Welter, J. Less Common Metals **84** (1982) 225.

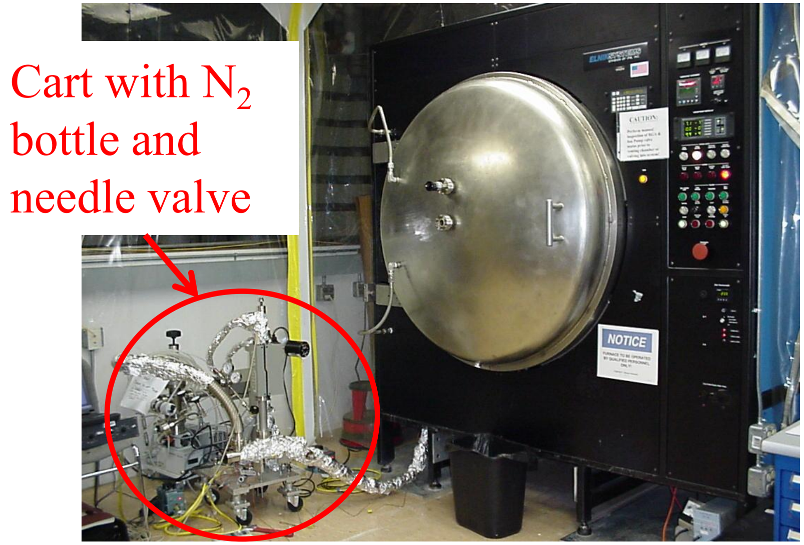
Passivation of the Nb surface

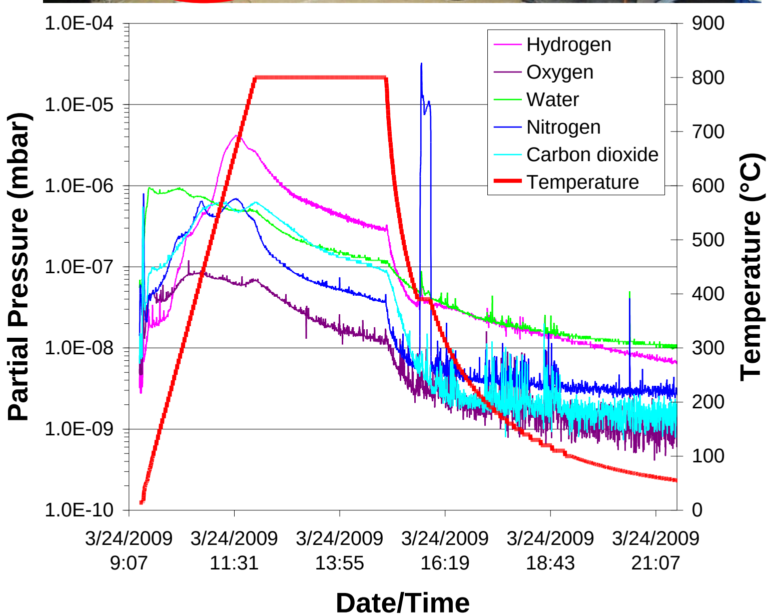
How can we improve the Nb surface to reduce pinning and maintain a high surface barrier to flux penetration?

- Heat-treat the cavity under vacuum at high temperature (≥ 800°C, ~3h) to reduce lattice defects, hydrogen content and oxide layer thickness
- Passivate the Nb surface by growing a thin nitride layer (~10nm thick) at an intermediate temperature (~400°C) to prevent re-absorption of hydrogen and oxygen during cool-down and water rinses
- The low-temperature baking can be easily added to the process
- Do not apply any chemical etching afterwards!

This concept had been discussed already in 1971 (P. B. Wilson, "Theory and suggested experimental procedure for the production of a nitride layer on niobium", SLAC-TN-71-7, (1971)

Heat treatment process





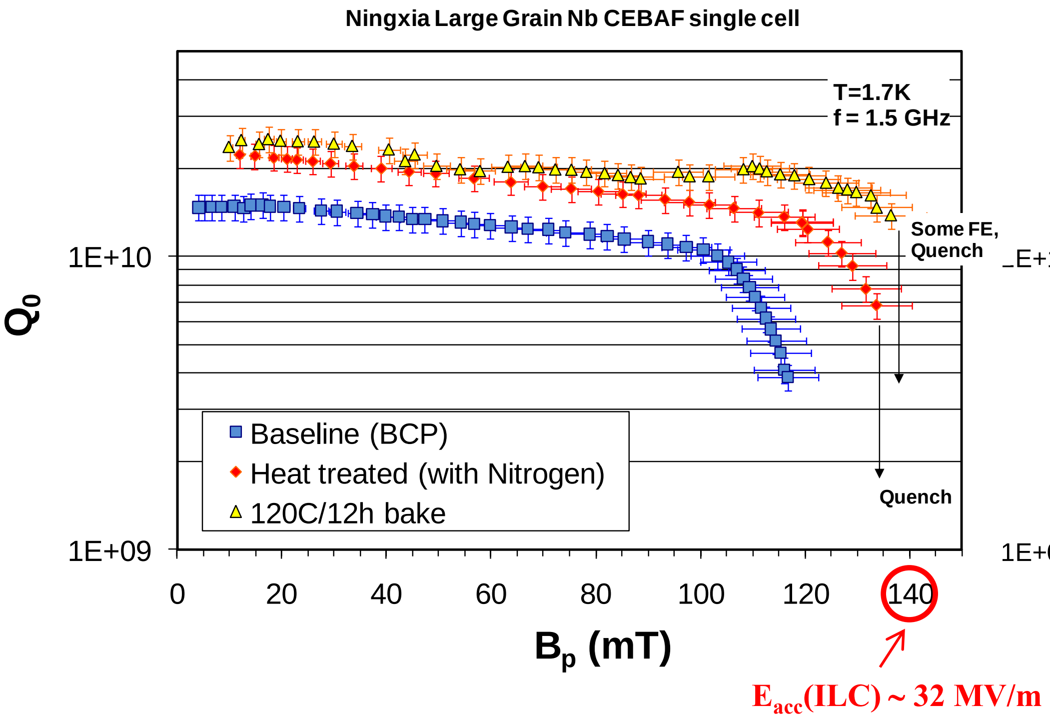
- 800°C/3h, admit N_2 (10^{-5} mbar) at 400°C/20min, cooldown
- Nb samples were treated with the cavities and depth profiling of the impurities was done at NCSU

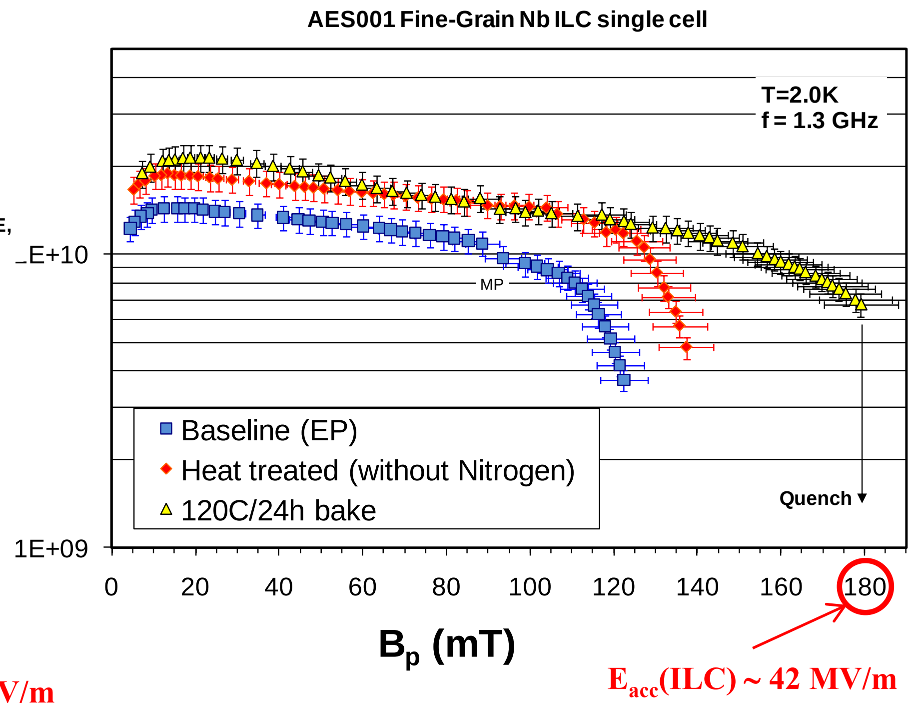
No nitride layer was formed

~ 2 orders of magnitude lower hydrogen content

Poster TUPPO061

Initial results





- Although we were unable to produce the thin nitride layer in the present “production” furnace an improvement of the Q_0 **(~40%)** and $B_{p,onset}$ **(~15%)** was achieved.
- A new “cleaner”, more flexible furnace is currently being developed to fully explore the possible advantages of Nb surface passivation

Conclusions

- Cavity $Q_o(B_p)$ curves are well described by models considering anomalous losses due to defects of "general" nature
- Theoretical calculations and initial experiments suggest that hot-spots are related to magnetic vortices
  - New experiments with local laser heating are planned to confirm this
- Not clear which impurity/defect favors vortex pinning/entry
  - Hydrogen induced vacancy clusters?
  - Cavity surface passivation to reduce surface defects and impurities will be explored with a new furnace

Acknowledgements

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A. Gurevich, *Florida State University*

F. Stevie, *North Carolina State University*

S. Anlage, *University of Maryland*

THANK YOU FOR YOUR ATTENTION