Materials
and
Material R&D in Support of ILC

2nd ILC Workshop
Snowmass August 13 – 27, 2005

Performance Limitations of SC Nb Cavities

- Critical Magnetic Field $H_{crit} \sim 185$ mT

  Reduced Hp/Eacc (LL, RE –shape)

  $E_{acc} \geq 50$ MV/m , but $E_{peak} \geq 110$ MV/m
- Field Emission: Contamination Control

  Clean Processing and Assembly

  Prevention of Re-contamination
- "Q – drop" : remedy is "in-situ" baking

  more effective on "smooth" (EP) surfaces?
- Defects: $H_{RF} < H_{crit}$ (need for QA)
- Residual Resistance(Q-slope): might influence operations Temp.

Material R & D

- R & D in direct support of ILC
  - Standard fine grain niobium(RRR,impurity contents)
  - Large grain/single crystal niobium
  - NbCu clad material, seamless fabrication
- "Basic" R & D aimed at understanding physics
  - Surface physics (oxidation,…)
  - Effect of hydrogen, grain boundaries,flux penetration..
  - Q vs E ("slope", "drop", residual resistance,special devices…,)
  - Critical Magnetic field

R & D in direct support of ILC

Fine Grain Niobium

- Material is best known
- Specifications accepted
- Impurity contents, especially Ta
  Should be re-evaluated
  but only for cost savings
  purposes
- Mechanical properties
  reproducible? Grain size,
  texture, yield strngth..,spring
  back
- QA: eddy current/squid
  scanning
  Is sensitivity suffiecient?
  For 40 MV/m(150 mT) defects
  are < 10 micron
  Scanning after forming (curved
  surface?)
- Heat treatment:
  Hydrogen degassing (600 –
  800C
  Post-purification at >1200C
- Surface treatment:
  BCP sufficient?
  EP necessary?
  Reproducibility of process

Large Grain/single crystal Niobium

- Initial results encouraging
- More statistics needed
- Potential advantages:
  Reduced costs
  Elimination of EP
  Less QA
  Better mech.
  Properties/reproducibility
  Lower Residual resistance
  Phonon peak in λ(T)
- Issues/Goals:
  Single Crystal Technology
  Qualification of vendors
  Cost effective slicing
  Specifications
  Fabrication, e.g EBW, if grain
  boundaries are present

Nb/Cu Clad Material

- Has been demonstrated to
  achieve very high gradients
  and Q's
- Fabrication process of clad
  material has been
  developed, but may need
  further refinement
- Seamless fabrication of
  multi-cell structures
  successful
- Possible cost reduction,
  because of thinner Nb
- Lorentz force detuning can
  be "customized"
- Issues
  Contamination in EB weld
  Cavities still "quench"
  or when in "barrier"
  Reduction of Q-value
  Cooldown sensitive because
  of thermo-currents

Summary Fine Grain Niobium

- Many examples of high performance cavities (single+multi-cell) exist
- Present specifications seem to be adequate unless cost savings can be realized with modifications in impurity contents (e.g Ta)
- Material is readily available
- QA of sheets are carried out only at DESY to eliminate defects in starting material; is sensitivity good enough?

  Scanning of curved surfaces necessary?
- Heat treatments:600C,800C,>1200C?
- Electropolishing + "in situ" baking necessary to achieve high Q-values at gradients $\geq$ 30 MV/m
- Better Micro-structure control might be necessary

  (micro yielding, spring back, reproducible mechanical properties)

This material is the BCD choice

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Large Grain/Single Crystal Niobium[1]

- Since the first ILC workshop we have fabricated and tested 5 single cell cavities (1300 MHz – 1500 MHz) from sliced material (wire EDM and saw cut) from 3 different ingots ("A","B","C"),3 different shapes, CBMM
- We have fabricated and tested 2 single crystal cavities from ingot "A" at 2.3 GHz, CBMM
- We have fabricated two 2.3 GHz cavities with material from a second vendor (WC) with somewhat smaller grains (not yet tested)
- We have fabricated and tested a single cell cavity from large grain niobium from China-Ningxia
- We have fabricated a 7-cell HG –Jlab-Upgrade cavity, which has been tested
- We are in the process of fabricating an ILC LL 7-cell cavity
- We have received a large grain ingot ("D") of dia 10.5" with 800 ppm Ta for fabricating single and multi-cell ILC cavities

Large Grain/Single Crystal Niobium[2]

CBMM

Ingot “D”,800 ppm Ta

Ingot “A”, 800 ppm Ta

Ingot “B”, 800 ppm Ta

Ninxia

Ingot “C”, 1500 ppm Ta

Wah Chang

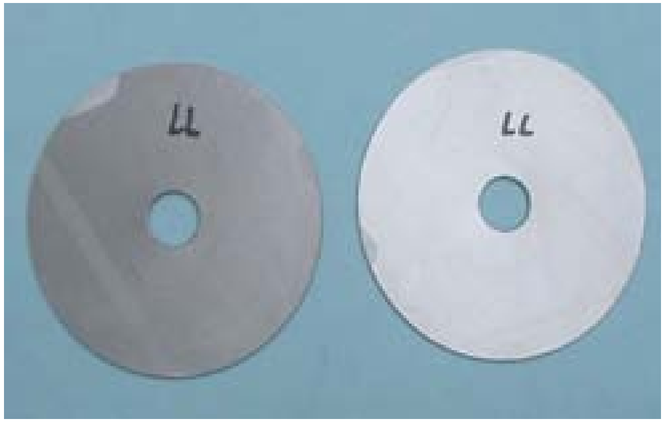
Heraeus

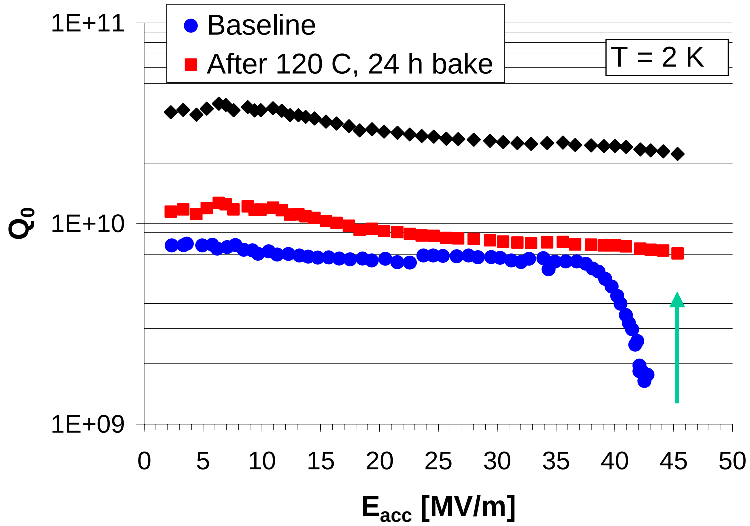
Summary of Large grain/Single Crystal Tests at Jlab

Suppl.	**Ingot**	**RRR/Ta [ppm]**	**Type/ Nc**	**F [GHz]**	**Q [10^{10}] (2K, E_{max})**	**E_{acc} [MV/m]**	**Fabrication**
CBMM	A	280/800	HG / 1	1.5	**1.25**	**34**	*W-EDM*
CBMM	B	280/800	HG /1	1.5	**9.3**	**32**	*W-EDM*
CBMM	C	280/1500	ILC_LL / 1	1.3	**1.4**	**34**	*S-cut / W-EDM*
CBMM	B	280/800	OC / 1	1.5	**0.5**	**25**	*S-cut (80 µm)*
CBMM	B	280/800	HG / 1	1.5	**0.48**	**27.5**	*S-cut, removal test ~ 75 micron removal*
CBMM	A (single)	280/800	HG / 1	2.2	**0.5**	**38** *(185/165 mT)*	*W-EDM*
CBMM	A (single)	280 / 800	ILC_LL/1	2.3	**0.7**	**45**	*W-EDM*
CBMM	A	280/800	HG /7	1.5	**0.85**	**18-19** *(FE, MP, quench?)*	*W-EDM*
CBMM	C	280/1500	ILC_LL /7	1.3			*S-cut / W-EDM In fabrication*
Ninxia		330-360/150	OC / 1	1.5	**0.21**	**33** *(Q-drop still after bake)*	*S-Cut, machined*
Wah Chang	C1/C2	> 300 / < 500	HG/1	2.2		*Not yet tested*	*W-EDM*
Wah Chang	B1/B2	> 300 / < 500	HG/1	2.2		*Not yet tested*	*W-EDM*

Large Grain/Single Crystal Niobium[3]

Nb Discs





LL cavity 2.3GHz

$E_{peak}/E_{acc} = 2.072$

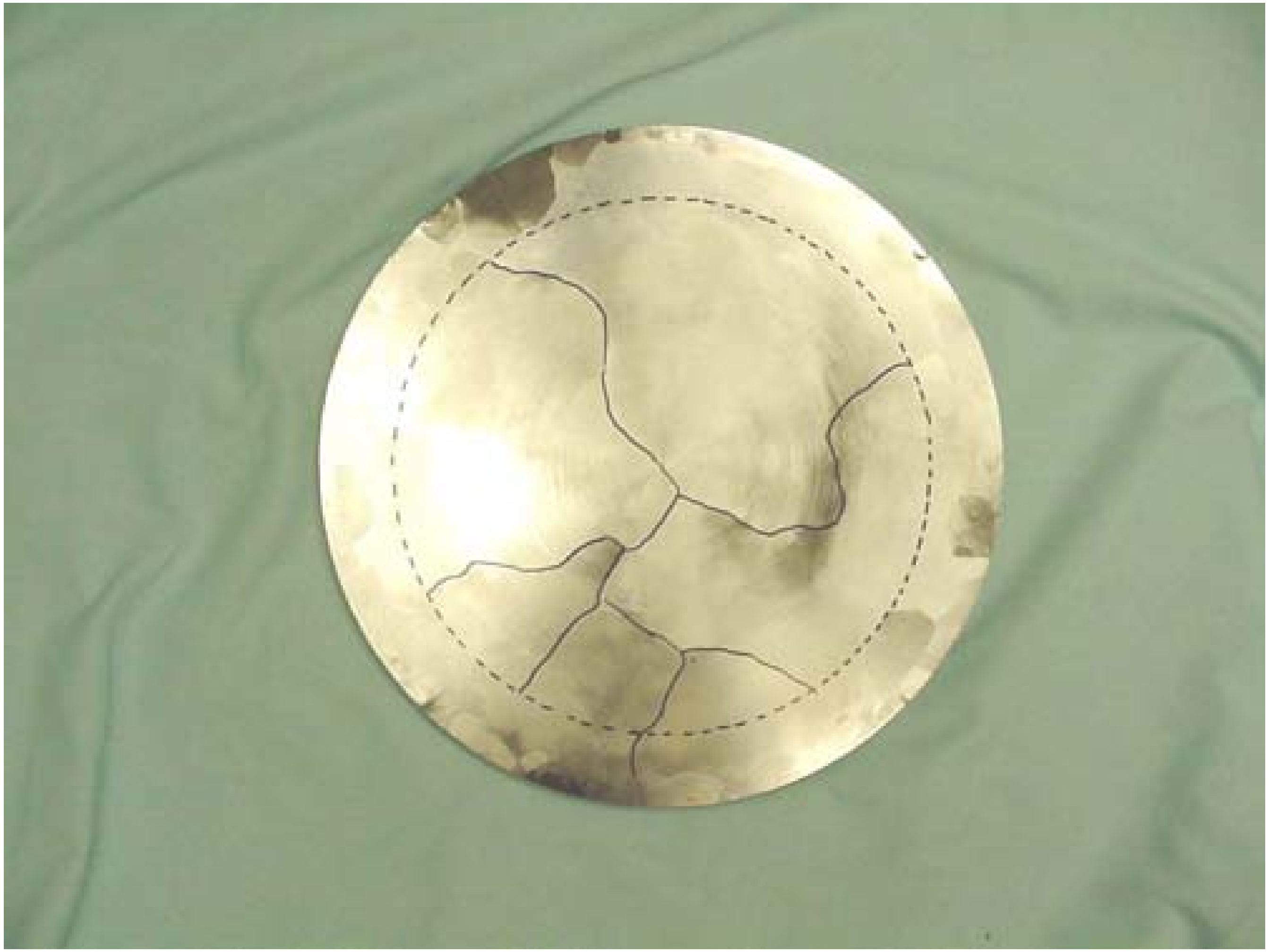
$H_{peak}/E_{acc} = 3.56$ mT/MV/m

Large Grain/Single Crystal Niobium[4]

- Main effort should be verification of positive results on single cell cavities in multi-cell cavities and materials from different vendors
- Jlab has plans for fabricating 2 high gradient 7-cell cavities and 2 TESLA type 9-cell cavities from ingot "D"[CBMM] with Ta contents of 800 ppm; however there are problems with funding and internal priorities for EBW
- DESY [W.Singer] plans to fabricate single cell cavities from Heraeus material
- Wah Chang advertised to offer large grain/single crystal niobium for sale: any takers right now and quick fabrication+testing?
- Ninxia/Beijing University offered large grain niobium

Large Grain/Single Crystal Niobium[5]

Ingot "D", CBMM



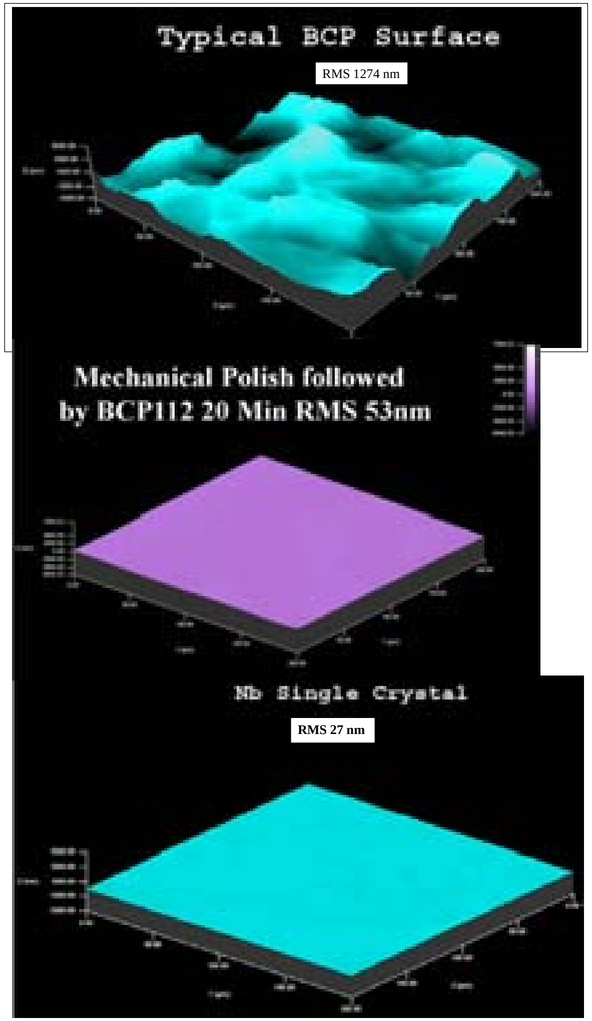
Large Grain/Single Crystal Niobium[6]

Potential Advantages

- Reduced costs
- Comparable performance
- Very smooth surfaces with BCP, no EP necessary
- Possibly elimination of "in situ" baking because of "Q-drop" onset at higher gradients
- Possibly very low residual resistances (high Q's), favoring lower operation temperature (B. Petersen), less "cryo power" and therefore lower operating costs
- Higher thermal stability because of "phonon-peak" in thermal conductivity
- Good or better mechanical performance than fine grain material (e.g. predictable spring back..)
- Less material QA (eddy current/squid scanning

Surface Roughness (1)

BCP provides very smooth surfaces as measured by A.Wu, Jlab



RMS: 1274 nm fine grain bcp

53 nm after ~ 35 micron, single Crys

27 nm after ~ 80 micron,single Crys

251 nm fine grain ep

Large Grain/Single Crystal Niobium[7]

R & D topics/Issues:

- Technology to provide single crystals(prefered option)
- Effective cutting: wire EDM too slow?
- Forming: how uniform, grain slippage
- Welding: do grain boundaries cause problems?
- Is there a chance of vacuum leaks through grain boundaries?
- Surface roughness: appropriate acid agitation during bcp, uniformity of material removal, preferential etching at GB?
- Mechanical properties depending on grain orientation?
- Is oxidation depending on crystal orientation?
- Internal stresses and strains due to deep drawing using neutron diffraction techniques (NIST proposal)

R & D in direct support of ILC

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Nb/Cu clad Material[1]

- Is being pursued at DESY(W.Singer et al) and KEK (K. Saito et al), seamless fabrication
- One topic of the European CARE program (W. Singer)
- So far good performance only demonstrated on single cell cavities, but technology for 3-cell cavities is developed (hydroforming)
- Demonstration on complete multi-cells TESLA-type cavity necessary

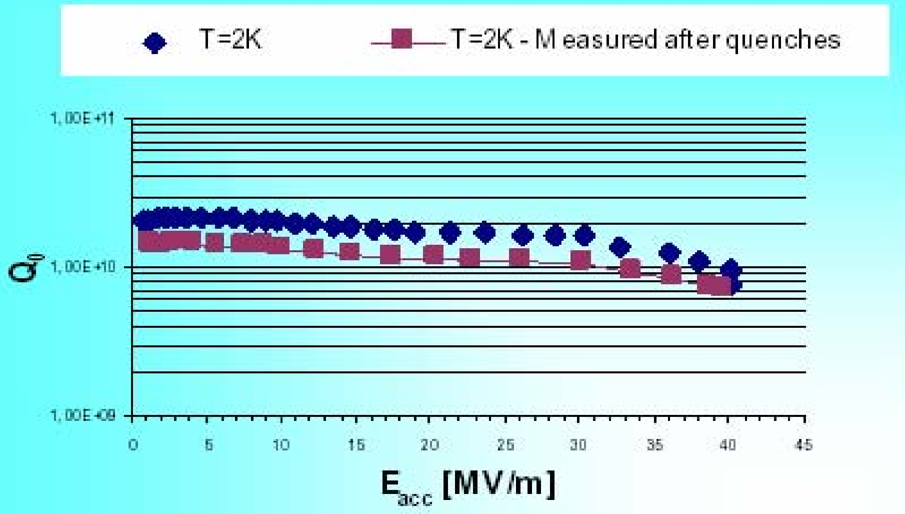
Nb/Cu clad Material[2]

Advantages

- cost effective: allows saving a lot of Nb (ca. 4 mm cavity wall has only ca. 1 mm of Nb and 3 mm Cu). Especially significant for large projects like ILC
- bulk Nb microstructure and properties (the competing sputtering technique does not have such advantages)
- the treatment of the bulk Nb BCP, EP, annealing at 800°C, bake out at 150°C, HPR, HPP can be applied (excluding only post purification at 1400°C).
- high thermal conductivity of Cu helps for thermal stabilization
- stiffening against Lorentz - force detuning and microphonics can be easily done by increasing of the thickness of Cu layer.
- fabrication by seamless technique allows elimination of the critical for the performance welds especially on equator

W. Singer SRF 2005

Nb/Cu clad Material[3]



NbCu single cell cavity 1NC2 produced at DESY by hydroforming from explosively bonded tube. Preparation and HF tests at Jeff. Lab: 180 μm BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR (P. Kneisel).

40 MV/m without EP

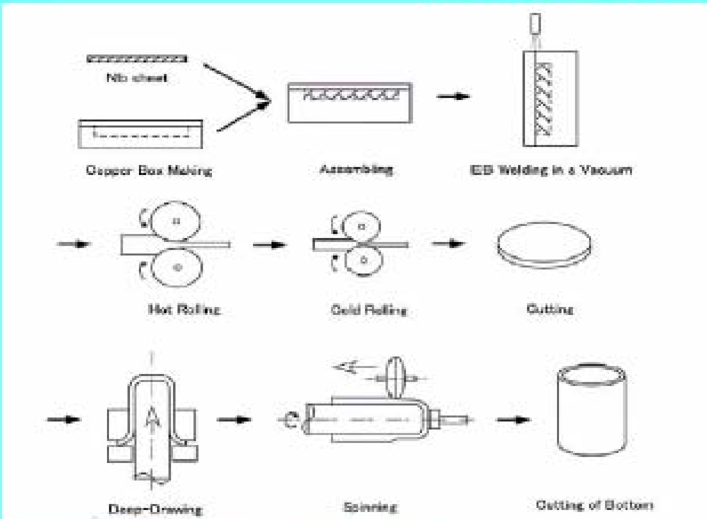
W. Singer SRF 2005

NbCu cavities hydroformed from explosively bonded tubes at DESY.

Difficult to get reproducibly high bonding quality. Hot bonding fabrication procedure of NbCu tubes seems to be more promising

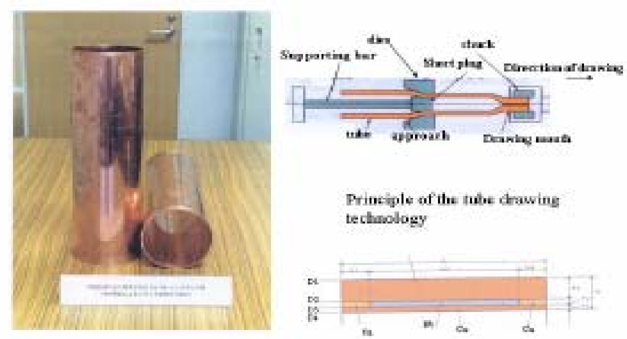
Nb/Cu clad Material[4]

- Hot bonded NbCu tubes



Fabrication principle of sandwiched hot rolled Cu-Nb-Cu tube (KEK and Nippon Steel Co.)

Hot roll bonded Cu-Nb-Cu tube produced at Nippon Steel Co.



Cu-Nb-Cu Sandwiched Tubes (KEK)

Fabrication principle of sandwiched coextruded Cu-Nb-Cu tube (KEK)

W. Singer SRF 2005

Nb/Cu clad Material[5]

Nb/Cu Clad Seamless Tubes and Cutting

Nb/Cu clad Material[6]

Problems

- Possibility of leaky welds because of Cu contamination
- Nb/Cu cavities still quench,resulting in Q-degradations
- Cooldown needs to be very uniform because of thermo – currents
- Cooldown of cryomodules would need modification
- Cracks sometimes appear in iris region during fabrication
- No industrialization efforts yet

Nb/Cu clad Material[7]

Conclusion

On laboratory level the most work is done.

Industrialization of seamless technique is the main remaining task

W. Singer SRF 2005

Nb/Cu clad Material[8]

R&D Topics

- How will the end groups be handled?

  Composite material, solid Nb, sputtered Nb flanged with sc joint?
- How will the He-vessel be handled?End dish to beam pipe?
- Complete cavities with end groups need to be fabricated and tested
- Test in module, cooldown uniformity?
- [Is “pipe-cooling” a possible concept?]
- Can the Lorentz force detuning be reduced? How can one vary the Cu thickness?

Basic R&D:Understanding Physics

- There are 3 main issues, probably interconnected

Critical Field

•Kenji's analysis of experimental data?

• Theoretical evaluation

• DC measurements

• Suszeptibility measurements on samples

• Flux penetration (UW)

• Special vehicles:

e.g. TE_{011} single crystal

TE_{011} coaxial samples

other sample cavities

• Impurities in Nb(squid scanner)

"Q –drop"

• T-mapping to pinpoint "hot spots" (A. Gurevich's model)

• Effect of grain boundaries

• Flux penetration:

"flux gate/squid mapping"

• seamless single crystal

• Impurities/topography of weld

• frequency dependence

of Q-drop onset

Surface/Oxidation

• Nb-Oxide interface for different crystal orientations with SIMS…

•Effect of surface chemistry (TE_{011} ..)

• Residual resistance contributions:

"accustic hot spots" (A. Gurevich, SRF 2005)

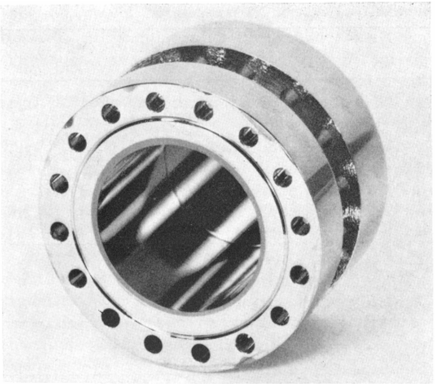
• Grain boundary/weak links: impurities such as e.g. oxygen, hydrogen

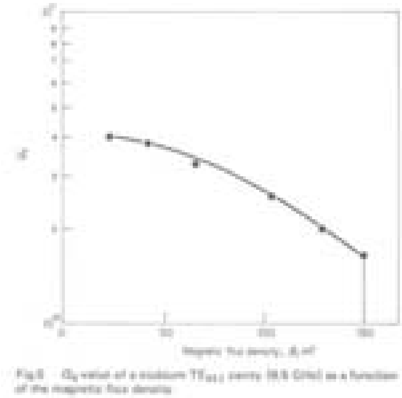
•…..

Critical field

- Analysis of experimental data by K.Saito suggest a limiting field of H ~ 180 mT for high purity defect-free niobium
- Further verification could be done with e.g.
  - TE_{011} cavity, single crystal, seamless (see Siemens cavity),X-band

  H ~ 159 mT(K. Schnitzke et al; Phys. Lett 45A(1973)241)





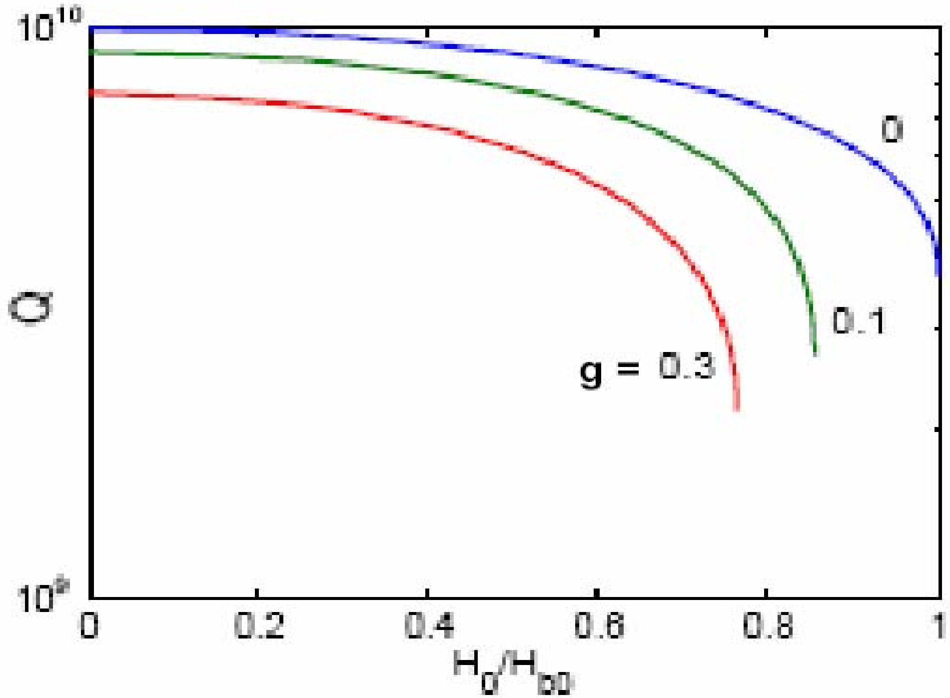
  - Coaxial samples in coaxial TE_{011} cavity
    can also be used for different material and treatments
  - Pulsed rf critical field measurements at 11.4 GHz(I.Campisi)

Q-drop [1]

- Q-drop is common to BCP, EP and Single crystal cavities in high RRR niobium
- The “onset” field increases with increased grain size (reduced # of grain boundaries?)
- The baking effect is different in “fine grain” niobium treated by BCP and EP; it is similar for increased grain size (e.g. after post purification @ T>1250C)
- “Air baking “is less effective than “UHV” baking,but more/newer data available from B.Visentin(SRF 2005)

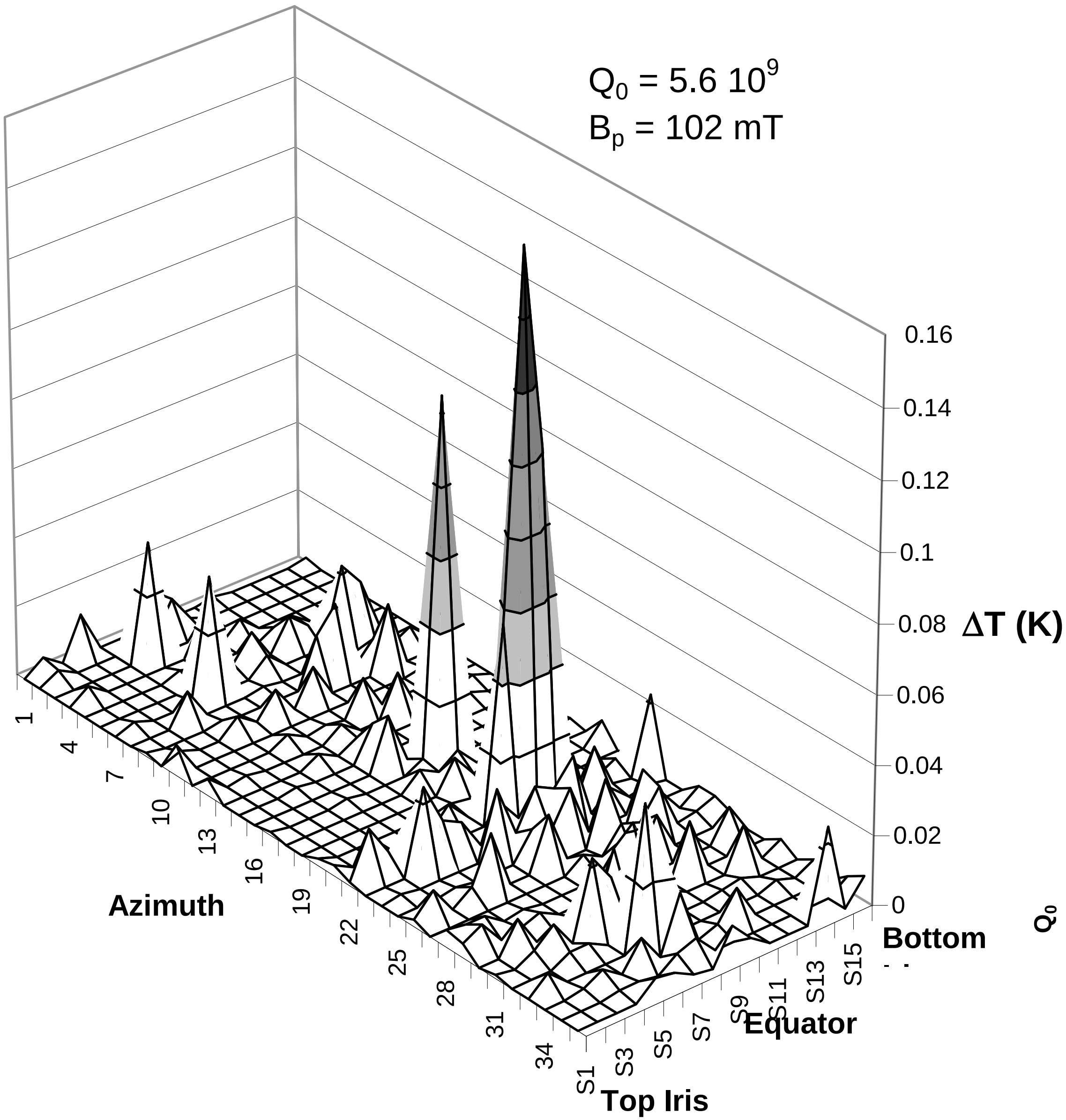
Q – drop[1][A. Gurevich,SRF 2005]

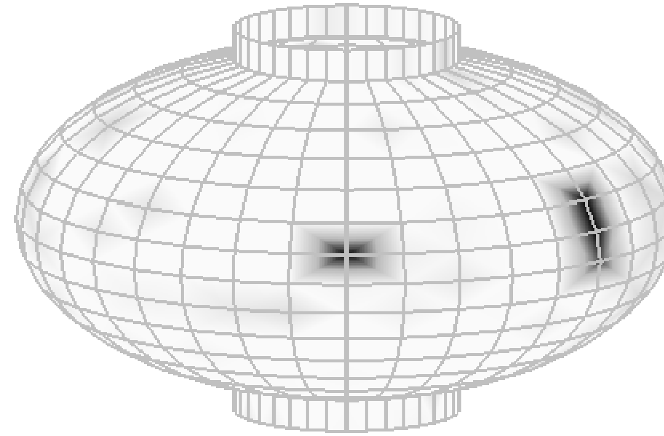
Q(H) for the linear BCS+hotspots ($\Gamma_n = 0$)

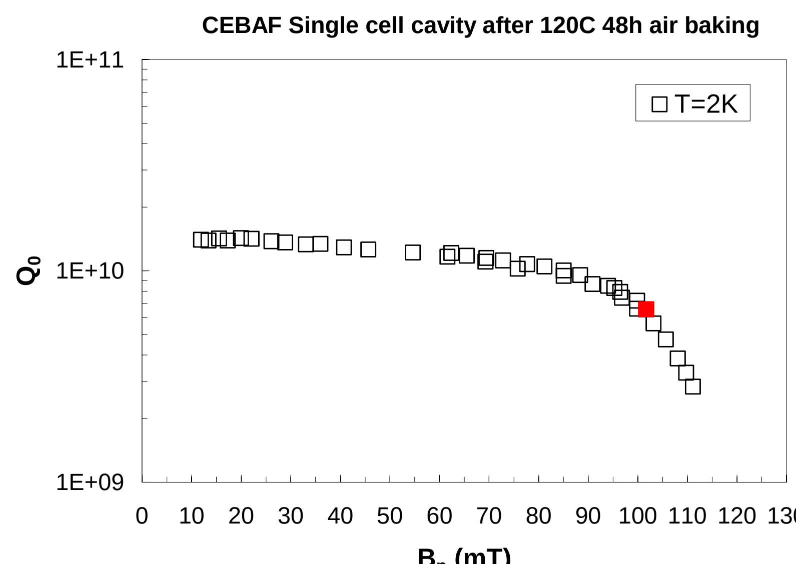


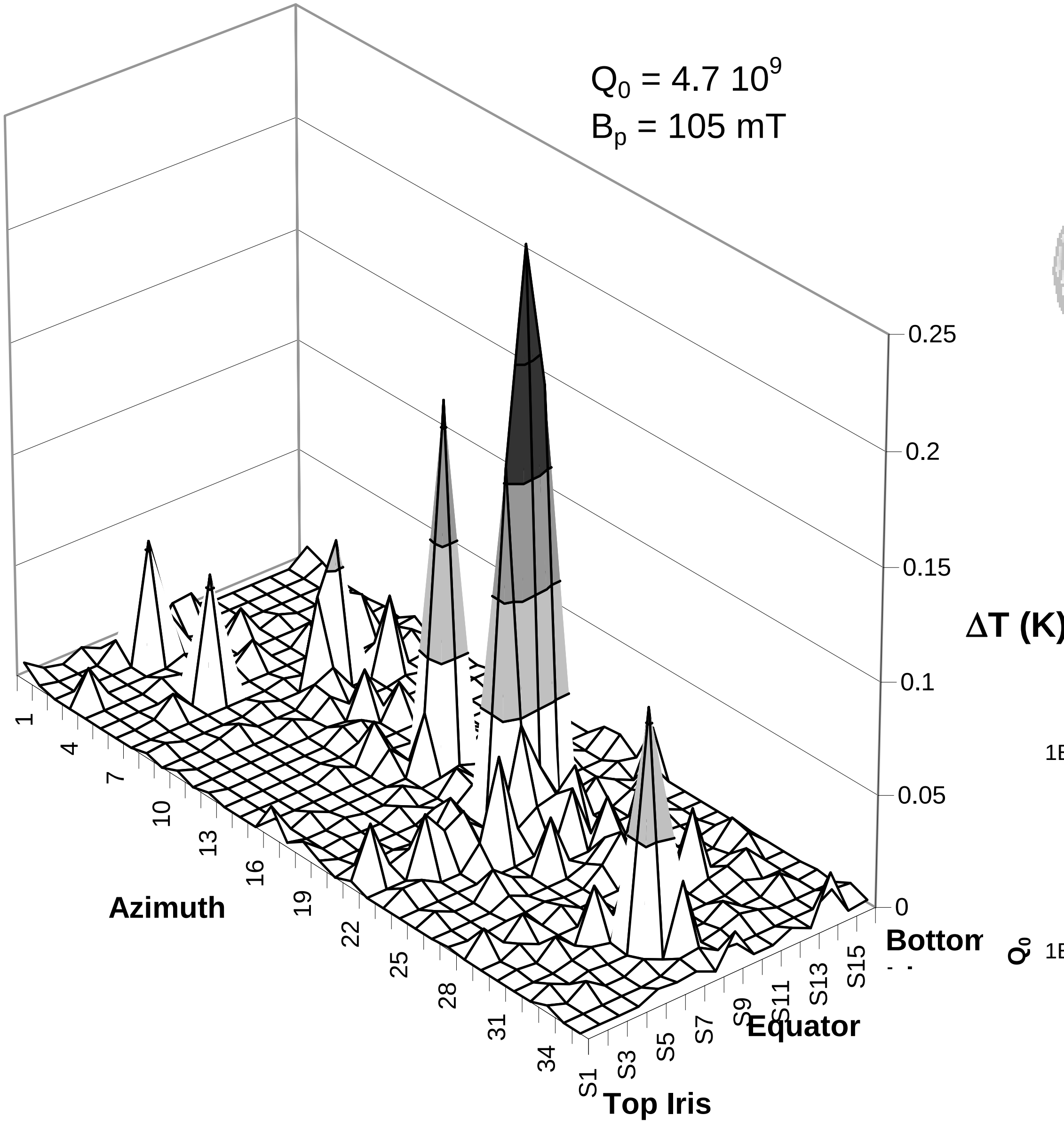
Hotspots reduce the breakdown field: $H_b \cong \left(1 - \frac{\sqrt{g}}{2}\right) H_{b0},$

Hotspots increase the high-field Q slope: $\frac{Q_0}{Q_b} = \frac{(1+\sqrt{g})e}{1+g} > e$


$Q_0 = 5.6\ 10^9$
$B_p = 102$ mT
ΔT (K)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Azimuth
1
4
7
10
13
16
19
22
25
28
31
34
Top Iris
Equator
Bottom
S1
S3
S5
S7
S9
S11
S13
S15




CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
1E+11
1E+10
1E+09
B_p (mT)
0
10
20
30
40
50
60
70
80
90
100
110
120
130



Q_0 = 4.7 10^9
B_p = 105 mT
0.25
0.2
0.15
0.1
0.05
0
ΔT (K)
1
4
7
10
13
16
19
22
25
28
31
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Azimuth
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S5
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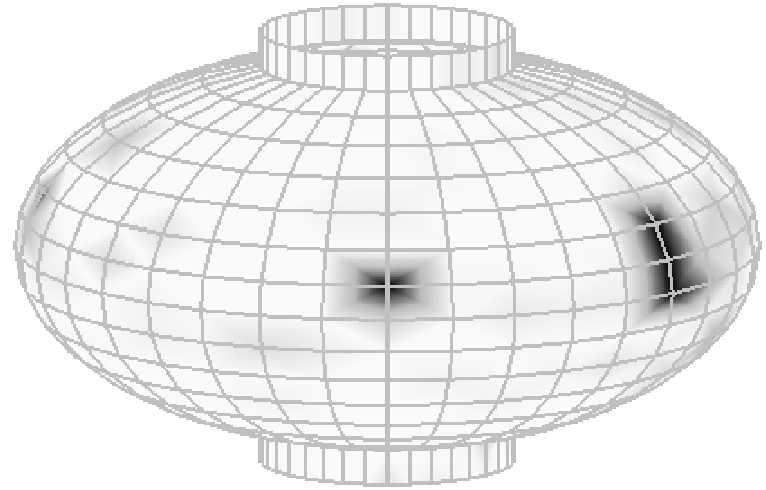

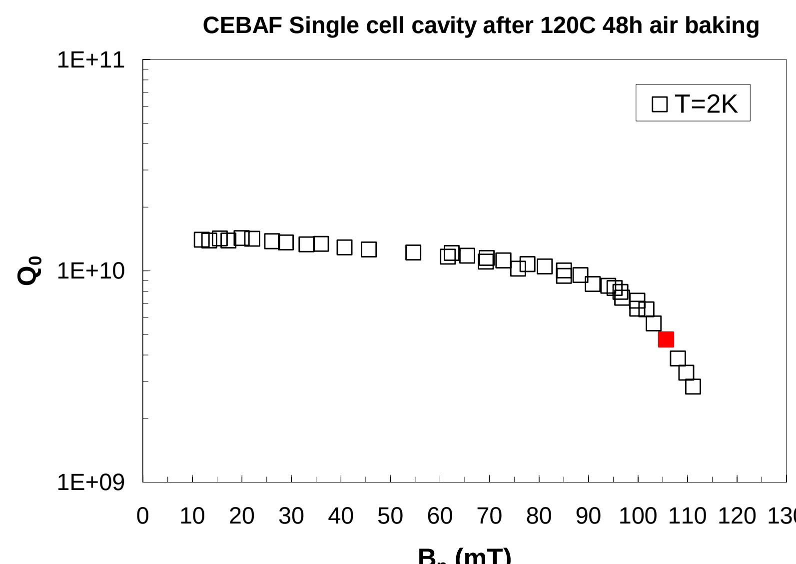

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1E+09
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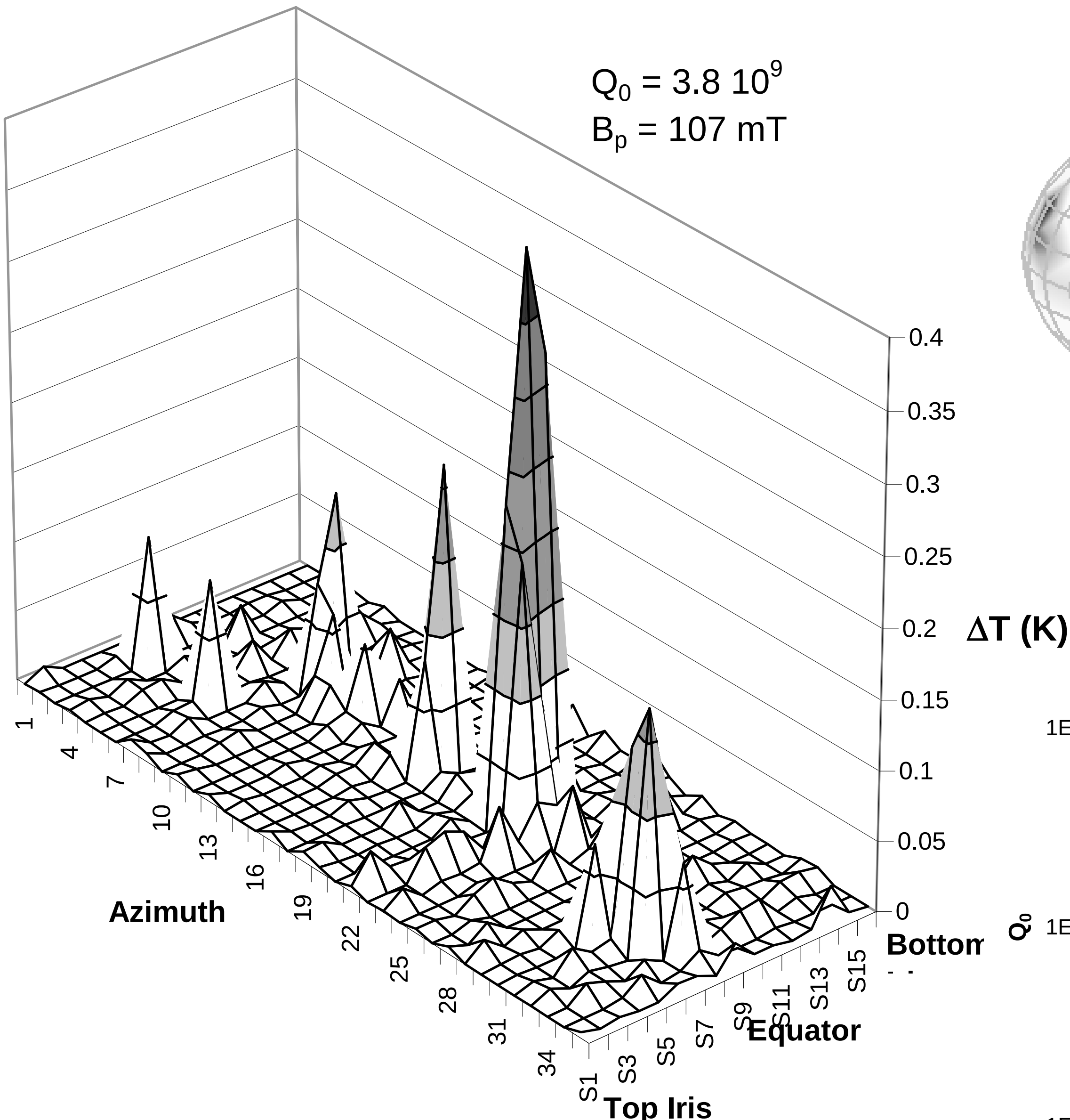
110
120
130
B_p (mT)


Q_0 = 3.8 10^9
B_p = 107 mT
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
ΔT (K)
1
4
7
10
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Azimuth
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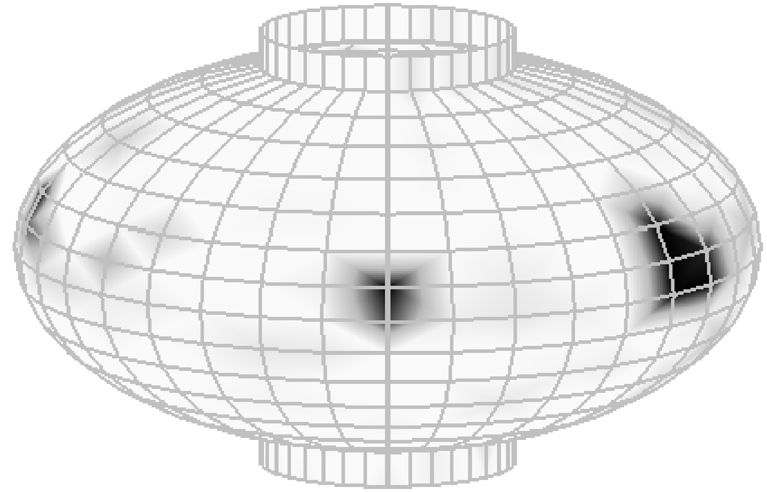

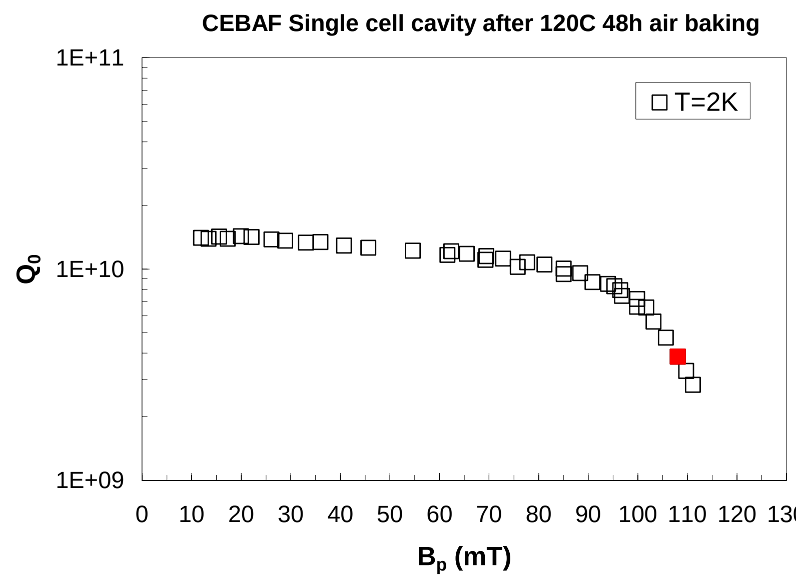
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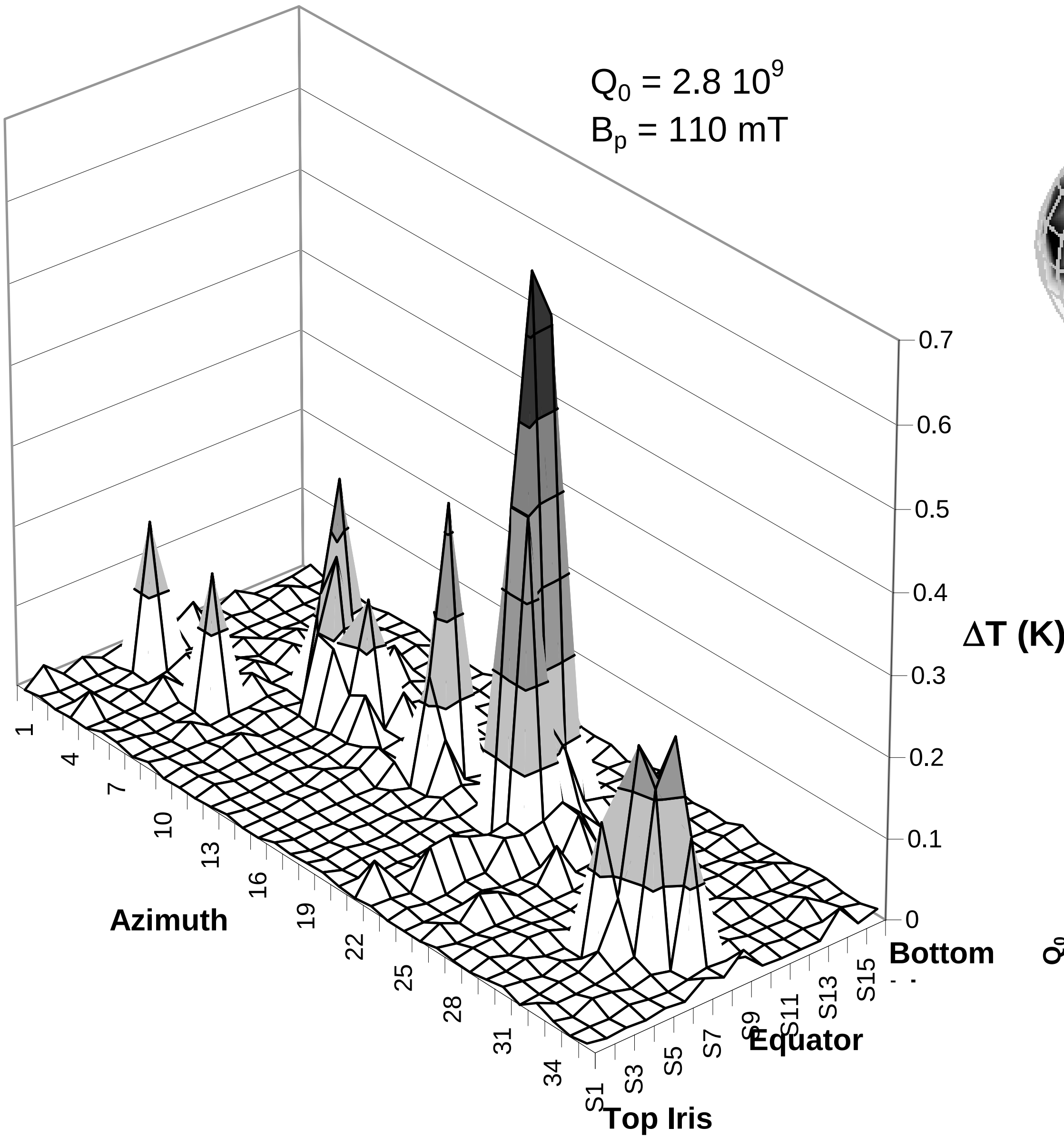
110
120
130
B_p (mT)



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$B_p = 110$ mT
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
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4
7
10
13
16
19
22
25
28
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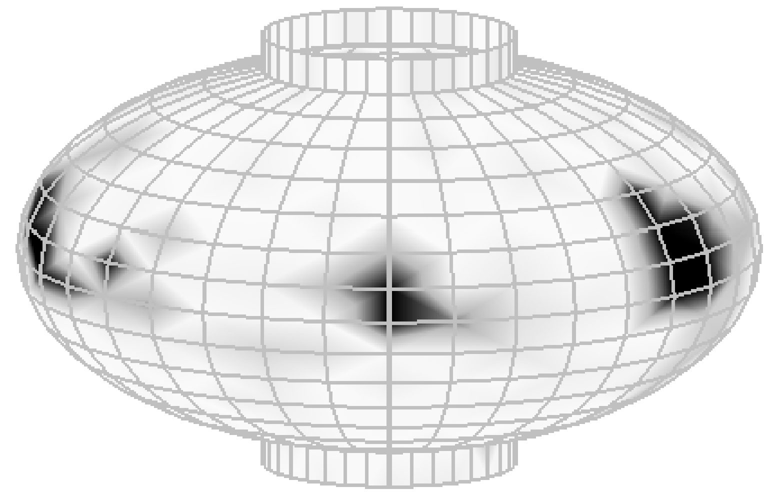
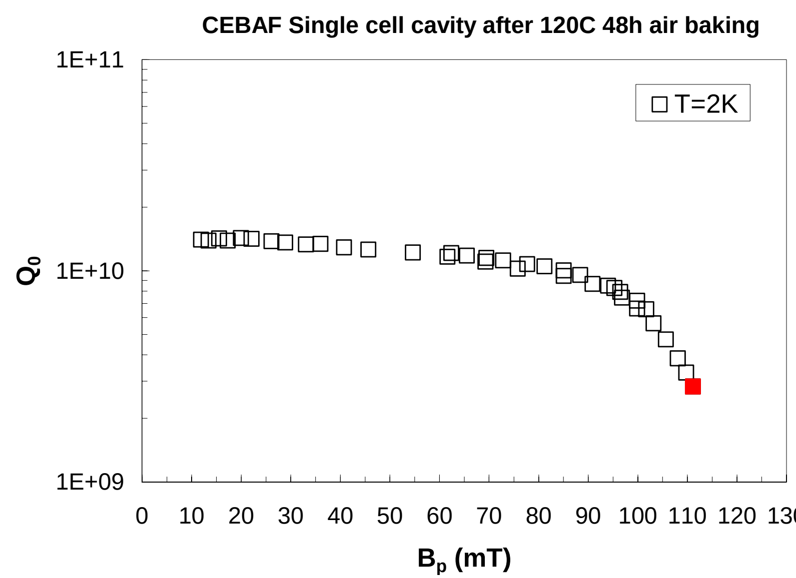
Bottom





CEBAF Single cell cavity after 120C 48h air baking
1E+11
1E+10
1E+09
Q_0
T=2K
0
10
20
30
40
50
60
70
80
90
100
110
120
130
B_p (mT)

Q – drop[3][A. Gurevich,SRF2005]

Conclusions

- Ultimate cavity performance (in the absence of vortex penetration) is limited by nonlinear BCS pairbreaking and heating effects.

- Acoustic resonances and mechanisms of the residual resistance

- Hotspots limit the high-field cavity performance:
  - New mechanism of nonlinearity, which can offset the BCS nonlinearity,
  - Reduce the breakdown field
  - Increase the high-field Q slope

- Mechanisms of hotspot formation
  - Acoustic hotspots
  - Vortex penetration along GBs
  - Nonuniform surface oxide layers

Challenges

- Understanding nonequilibrium superconductivity and impurity surface scattering on nonlinear BCS resistance and rf breakdown
- Dynamics of vortex penetration and dissipation in rf field

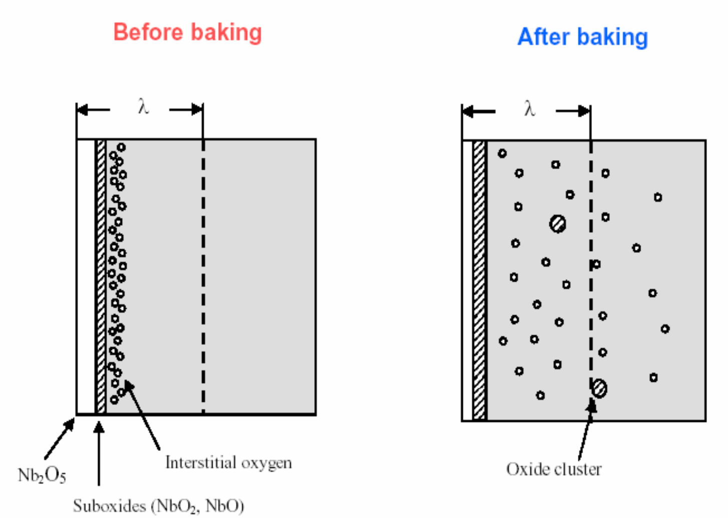
Q – drop[2]

G. Ciovati (SRF 2005):

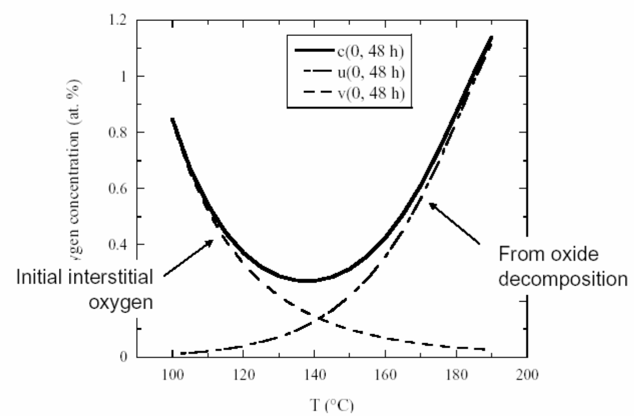
- Improved oxygen diffusion model taking into account the decomposition of the oxide layer
- Oxygen dilution changes κ of material to lower values, ➞ larger onset fields for Q-drop
- Smoother surface provides

  Surface barrier for flux penetration

Schematic of the Nb surface



Oxygen concentration at the surface as function of baking temperature



Optimum baking temperature: lowers O conc. near the surface

Q – drop[4]

- Proof "Hot Spot" Model :Suggestion was made(P.Bauer):
  - T-map "hot spot"
  - Cut cavity apart and analyze with e.g. Atom probe Tomography
  - Since "hot spots" on T-maps are near equator weld, one should investigate weld prior to cavity cutting and look for differences
- Flux penetration at grain boundaries
  - Superimpose a dc magnetic field (dc current through cavity walls) on the rf field – fluxons in penetration depth are moved by dc current and add to resistance (G. Ciovati)
  - Check flux penetration as function of surface conditions
- Frequency dependence of Q-drop onset :
  - No Q-drop observed at 9.5 GHz up to 155 mT (Pfister, Cryogenics, Jan 1976, p.17) in reactor grade Nb (single crystal?)
  - Measure f-dependence with e.g. coaxial cavity

Q – drop[5]

- Oxygen diffusion model
  - Generate a “oxygen-free” niobium surface by “in situ” heat treatment at high temperatures in UHV (e.g. F. Palmer,3rd SRF Workshop)
  - Introduce in a controlled way oxygen into the penetration depth, e.g. ion implantation?

Surface/Oxidation[1]

- The goal is to link features of the metal/oxide interface to performances of cavities
- However, it is known that cavity surfaces are non-uniform (T-maps) and the challenge is to draw conclusions from at most mm^2 size spots investigated by surface analysis to m^2 cavity areas.
- Nevertheless, several areas seem of interest to explore:
  - Oxidation behavior of single crystal niobium of different crystallographic orientation compared to fine grain niobium oxidation
  - Impurities in grain boundaries such as oxygen,carbon, nitrogen..
- Atom Probe Tomography (see D.Seidman, SRF 2005) seems to be a new powerful tool in addition to standard methods such as e.g.SIMS (work in progress FNAL/Northwestern/UW)

Surface/Oxidation[2]

Conclusions and next steps

- Nanochemical, atomic scale analyses of the oxide surface and of the near-surface bulk niobium are being performed
  - "Smooth" transition from surface Nb_2O_5 to Nb_2O (and into the bulk Nb)
  - Ability to detect small number of contaminant atoms in the oxide surface and in the near-surface bulk niobium
  - Levels of oxygen in the near-surface bulk niobium (metal) of 5-10 atomic percent, which is consistent with bulk Nb-O phase diagram

- More analysis to come
  - Interpretation of mass spectra
    - Improved analysis conditions
  - Improved specimen preparation techniques (reliability and repeatability)
    - Focused ion beam (FIB) milling and/or femtosecond laser ablation
  - Many classes of samples

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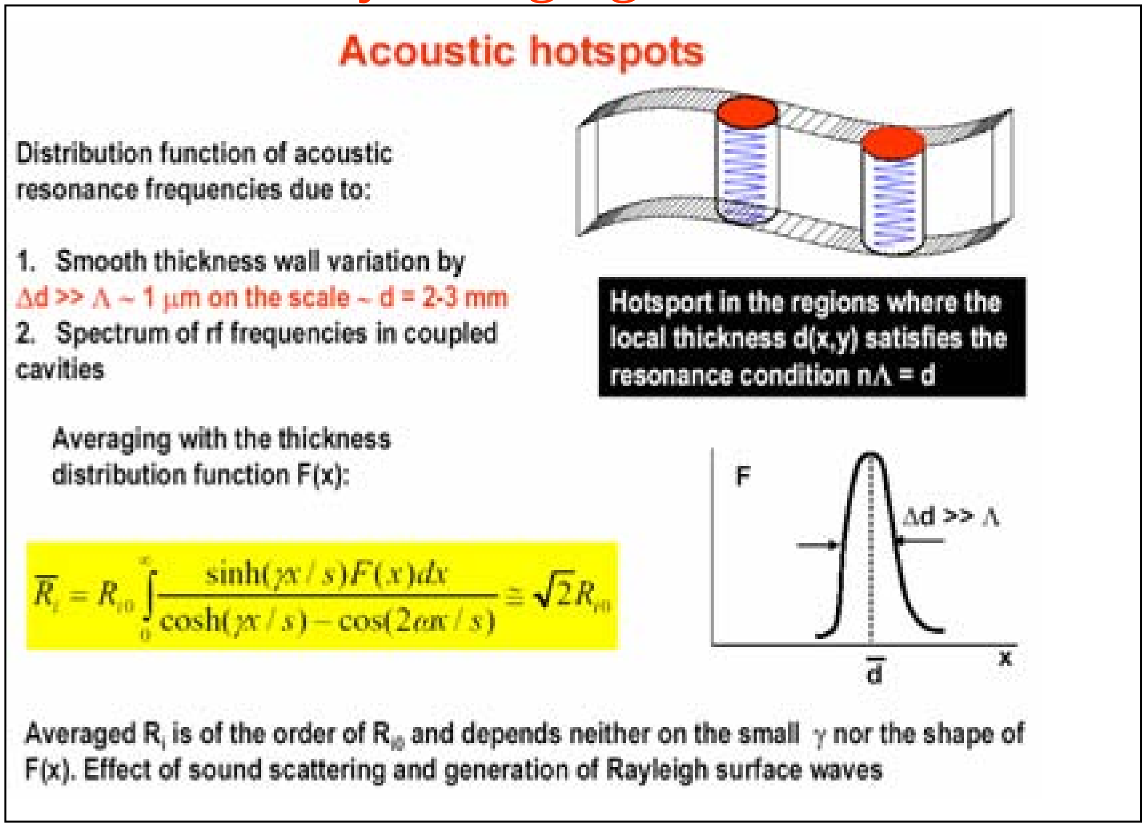
13 July 2005

NUCAPT
Northwestern University Center for Atom-Probe Tomography

Surface/Oxidation[3]

- Residual Resistance contribution from "accustic hot spots" (A. Gurevich, SRF 2005)
- Verification by changing outer surface of the cavity after test



Surface/Oxidation[4]

- Residual resistance: understanding low and medium field Q-slope
- Ongoing studies at Jlab utilizing T-mapping on large grain material with varying grain size, effect of grain boundaries

RF SC Theory

- Calculations to estimate surface resistance contribution due to magnetic vortex penetration in RF fields (possibly Fermilab/University of Wisconsin, A. Gurevich, JLab – G. Ciovati?)
- Estimate surface resistance contribution of weak-links (grain-boundaries, patches with suppressed superconductivity) (possibly Fermilab/University of Wisconsin, A. Gurevich, JLab – G. Ciovati?)
- Linear and Non-linear BCS resistance in the clean and dirty limits (possibly Fermilab/University of Wisconsin, A. Gurevich)