Outline

- Gaps in our knowledge
  - Call out the needs along the way
- Gaps in our capabilities
- A proposal
  - to fill the 2nd gap

Applications on the Horizon

- Light sources…FELs, ERLs
  - Need > 20 MV/m, CW operation, high Q
- High Intensity proton linacs
  - Need > 25 MV/m, pulsed, several % duty factor, high Q to lower dynamic heat load
- Linear collider
  - Need 35 MV/m, pulsed, 1% duty factor
- Common denominator: high gradient, high Q
- Muon acceleration
  - Need > 15 MV/m, low frequency, Nb-Cu

Gaps in Knowledge

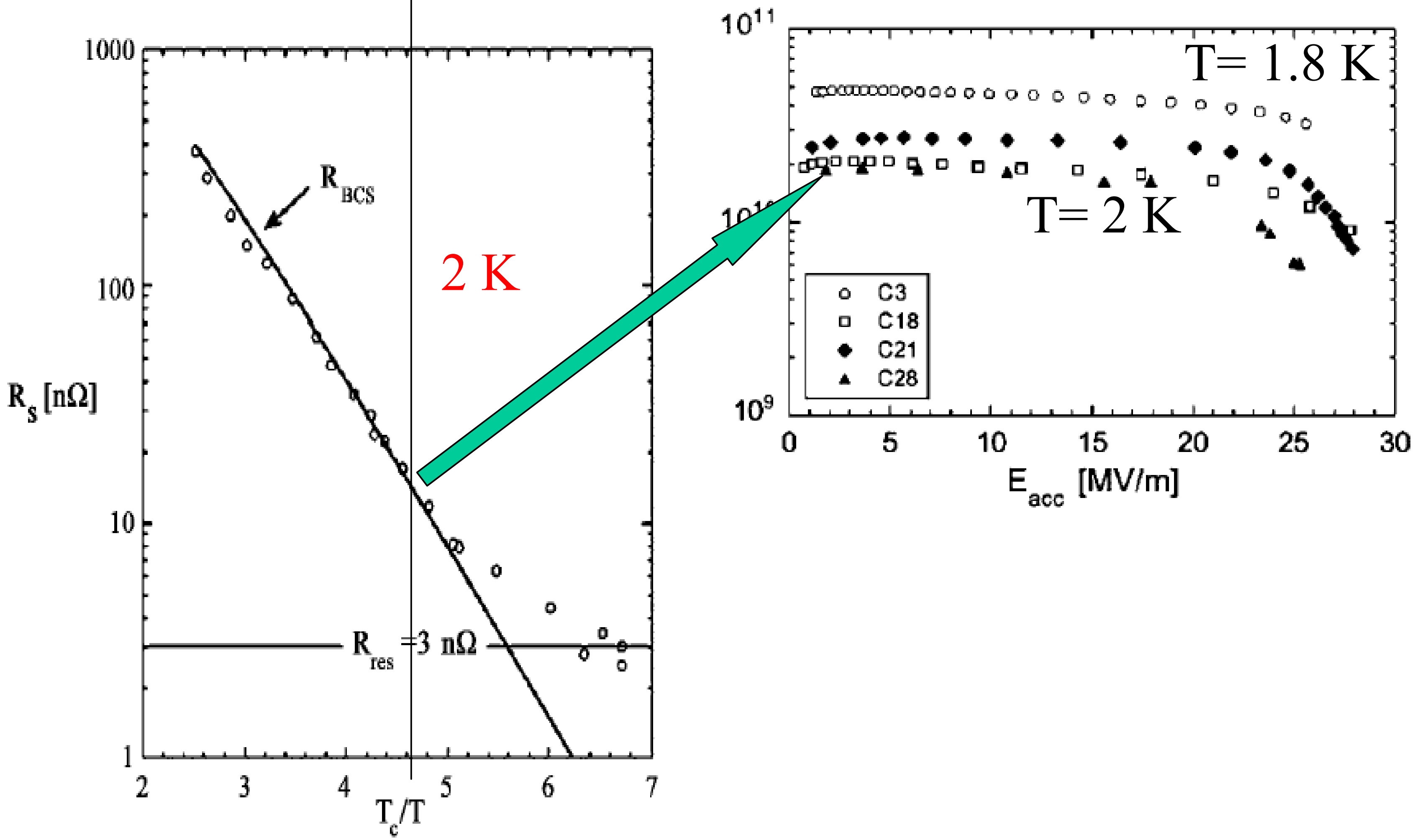
- What do we need to get Q >10^10?
- What is the limiting field for Nb? 50? 40 MV/m?
- What is the cause of high field Q-slope in Nb?
- Why does high-field Q-slope decrease with EP and baking?
- What is the cause of general Q-slope in Nb-Cu?
- Is there any connection between Nb and Nb-Cu Q-slope
- Are there materials with higher capability than Nb?

Q: Important Issue for CW and high DF Eg ERL...

- High Q needed for CW operation at high gradient

- Dynamic heat load dominates
- Eacc = 20 MV/m, Q = 10^{10} => P/L = 40 watt/m
- 5 GeV Linac has 10 kW dynamic heat load at low temperature
- AC power = 7.5 MW….ouch

Future Q Improvements ?



BCS Contribution still important
At 1300 MHz and 2 K

$T = 2$ K, $Q = 2.6 \times 10^{10}$

TESLA $Q = 10^{10}$

Lower Temperature

$T = 1.8$ K, $Q = 6.3 \times 10^{10}$

$T = 1.7$ K, $Q = 1.1 \times 10^{11}$

$T = 1.6$ K, $Q = 1.9 \times 10^{11}$

If achieved, higher gradient
CW usable

One of several needs:
Shield Earth's magnetic field to 1 mOe
$R \approx 1$ nΩ, $Q = 2 \times 10^{11}$

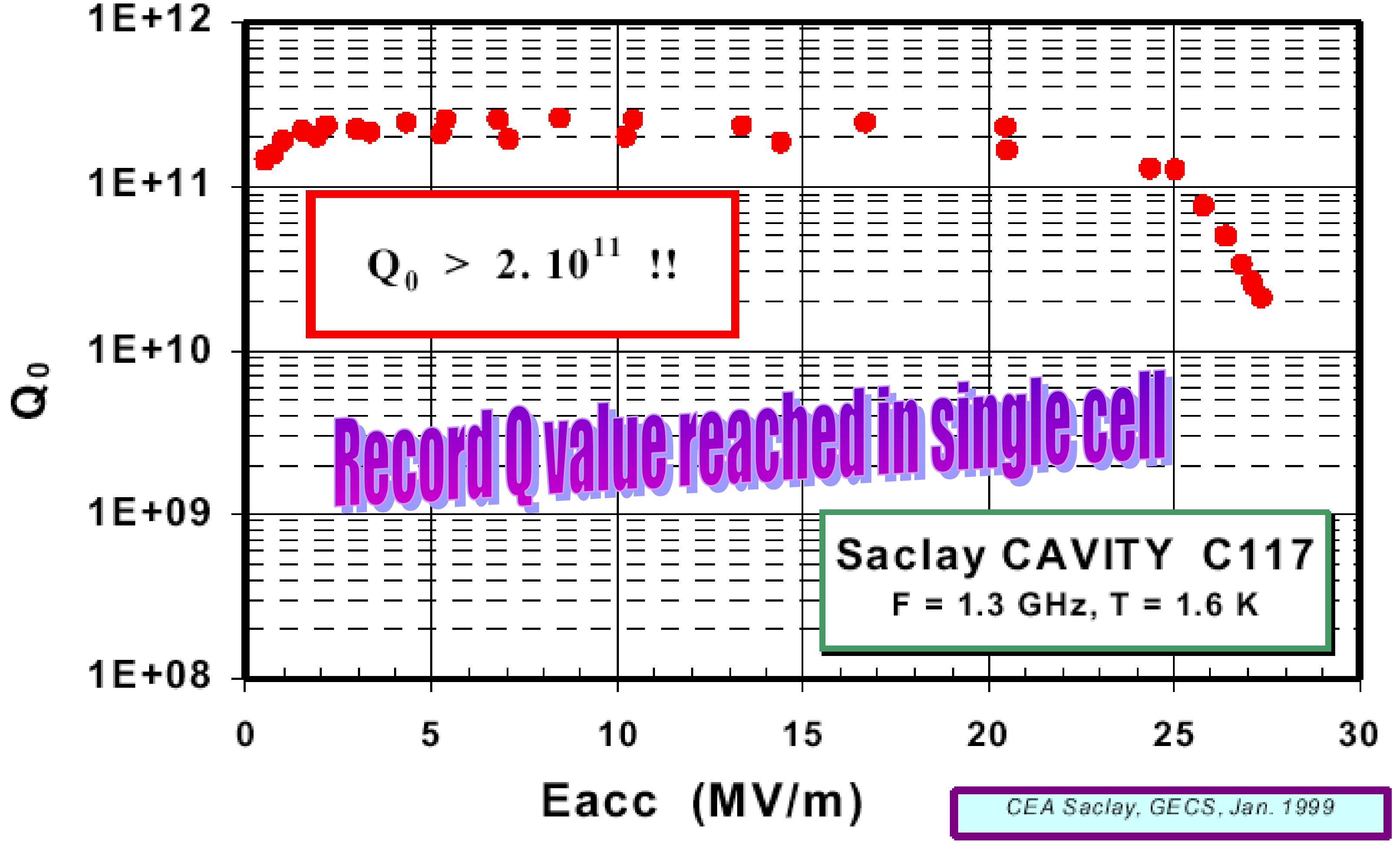
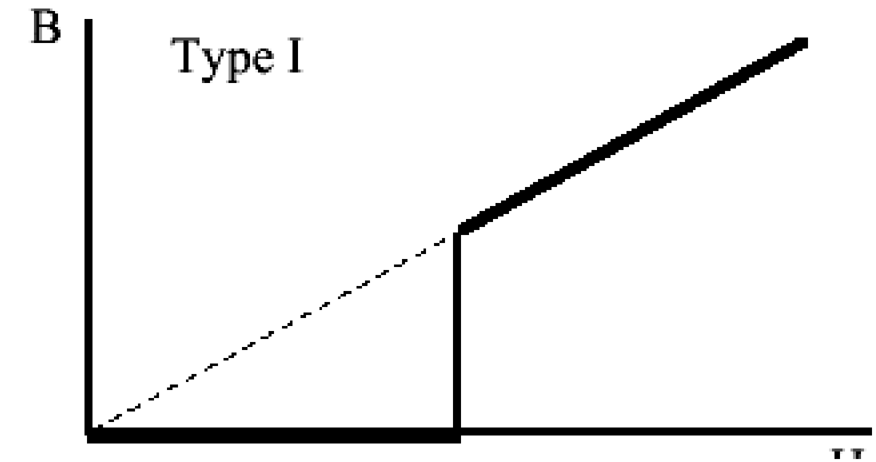
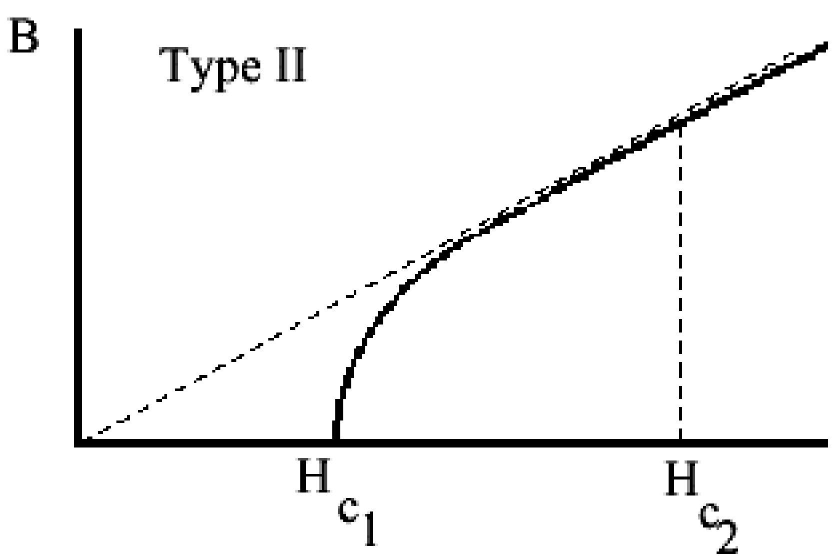
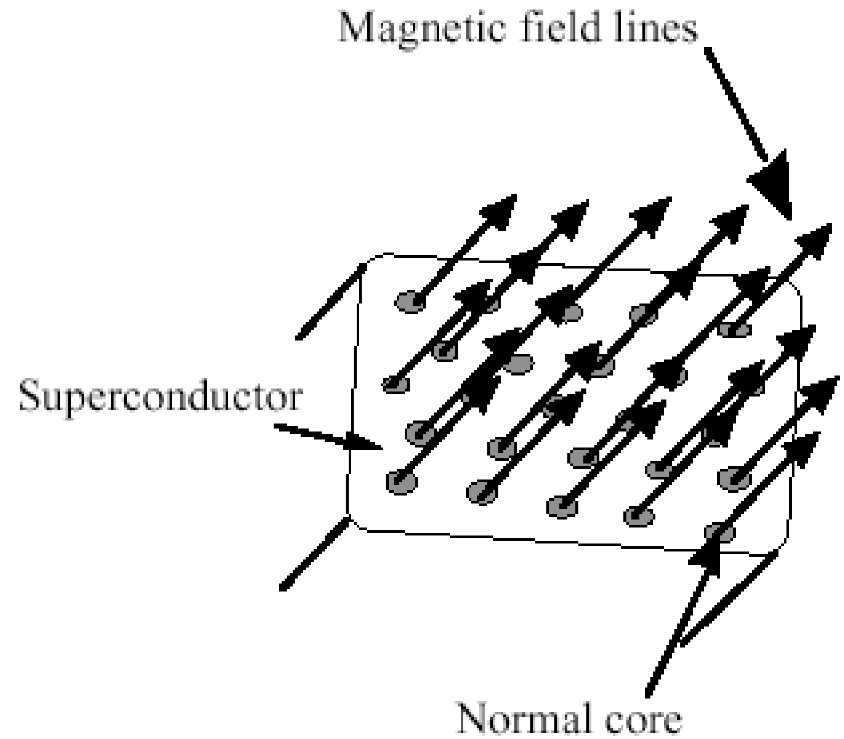


Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}.

RF and
DC
Critical
Magnetic
fields





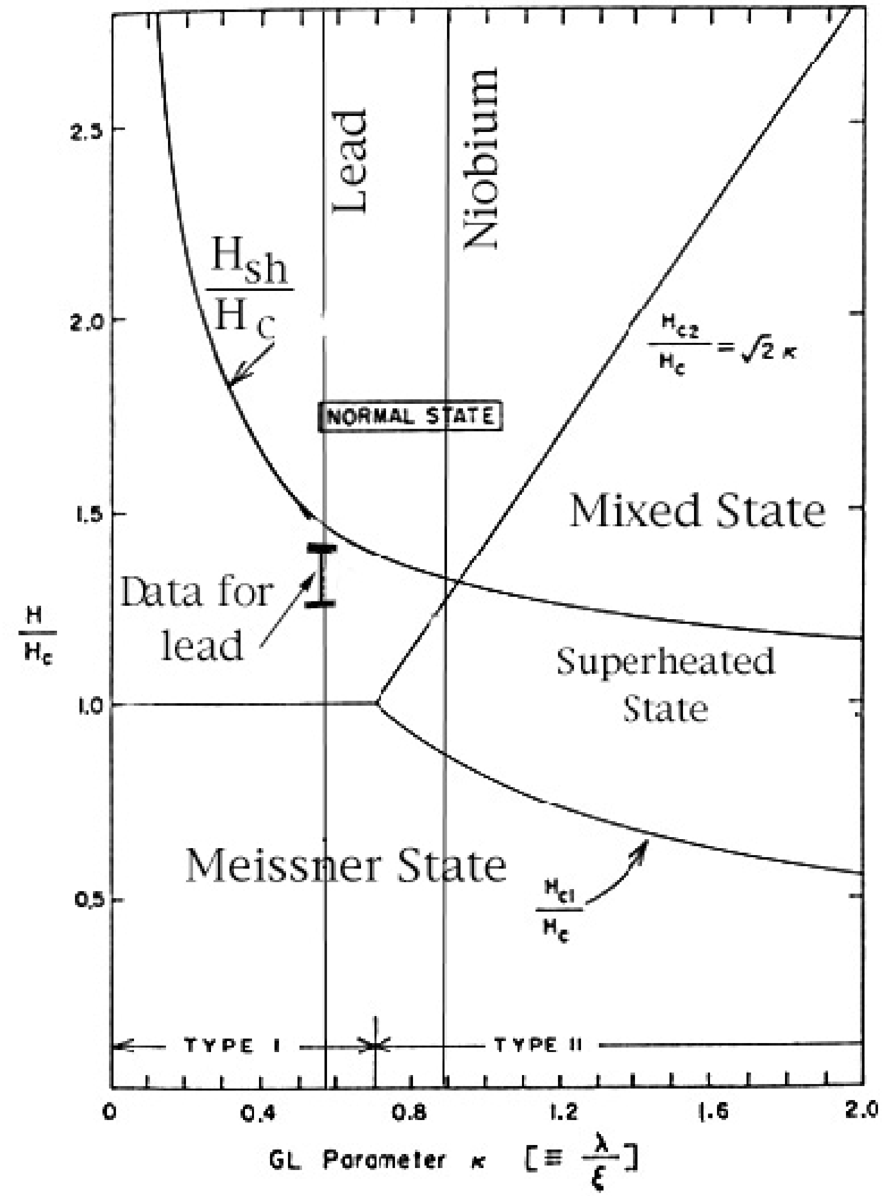


RF Critical Magnetic Field

- Phase transition, flux nucleation requires some time
  - (1 μs?) …Need to measure
- → So $H_{rf} > H_{c1}$
- even $H_{rf} > H_c$ up to the superheating field.

- At T= 0 K
  - Critical RF field, Hsh, for Nb is about 2400 Oe (240 mT).

- For typical $v = c$ cavities this is achieved at an accelerating field of $E_{acc} \approx 50$ MV/m.



2.5
2.0
1.5
1.0
0.5
$\frac{H}{H_c}$
0
0.4
0.8
1.2
1.6
2.0
GL Parameter κ $[\equiv \frac{\lambda}{\xi}]$
Lead
Niobium
$\frac{H_{sh}}{H_C}$
NORMAL STATE
$\frac{H_{c2}}{H_c} = \sqrt{2}\,\kappa$
Mixed State
Data for lead
Superheated State
Meissner State
$\frac{H_{c1}}{H_c}$
TYPE I
TYPE II

Superheating field

$$H_{\rm sh} \approx \frac{0.89}{\sqrt{\kappa_{\rm GL}}} H_{\rm c} \quad \text{for} \quad \kappa \ll 1,$$

$$H_{\rm sh} \approx 1.2 H_{\rm c} \quad \text{for} \quad \kappa \approx 1,$$

$$H_{\rm sh} \approx 0.75 H_{\rm c} \quad \text{for} \quad \kappa \gg 1.$$

$$\lambda_L(T) H_{sh}^2(T) = \xi(T) H_C^2(T)$$

Pulsed measurements of Hsh

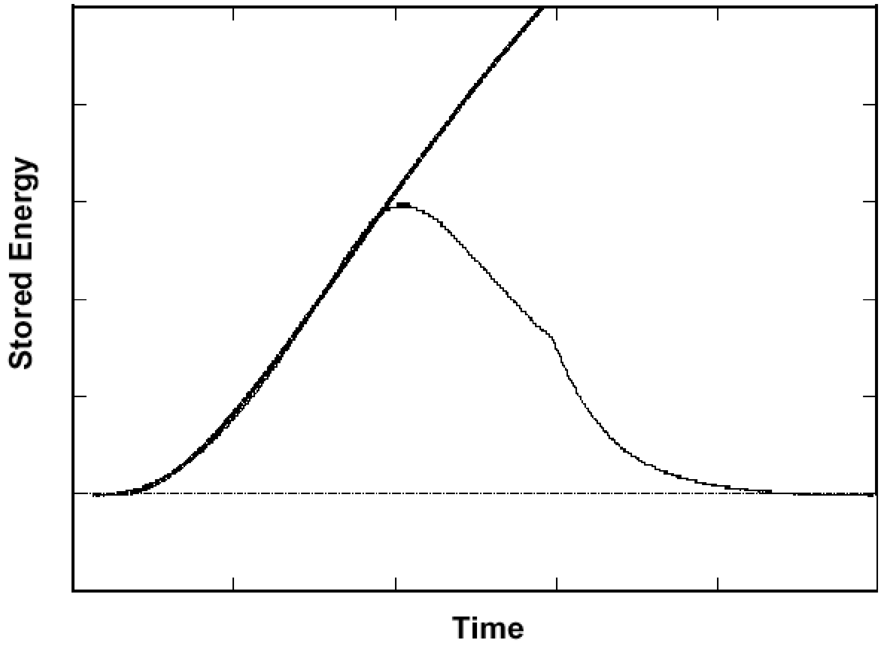
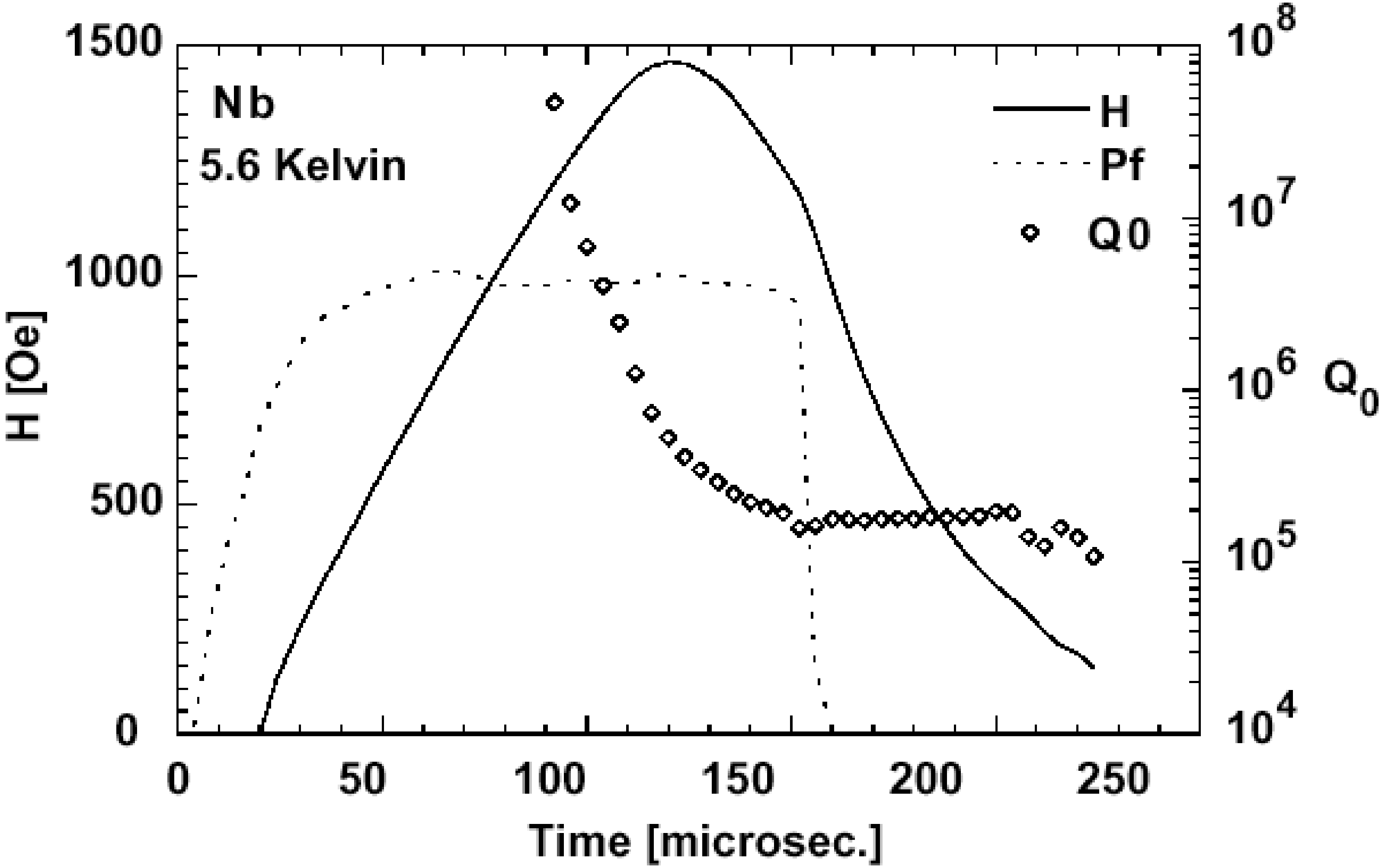


Figure 1: Comparing the behavior of a cavity that quenches with an idealized cavity with no quench. The point where the two diverge is the H_c^{rf}.



Nb
5.6 Kelvin
H
Pf
Q0
H [Oe]
Q_0
Time [microsec.]
0
500
1000
1500
0
50
100
150
200
250
10^4
10^5
10^6
10^7
10^8

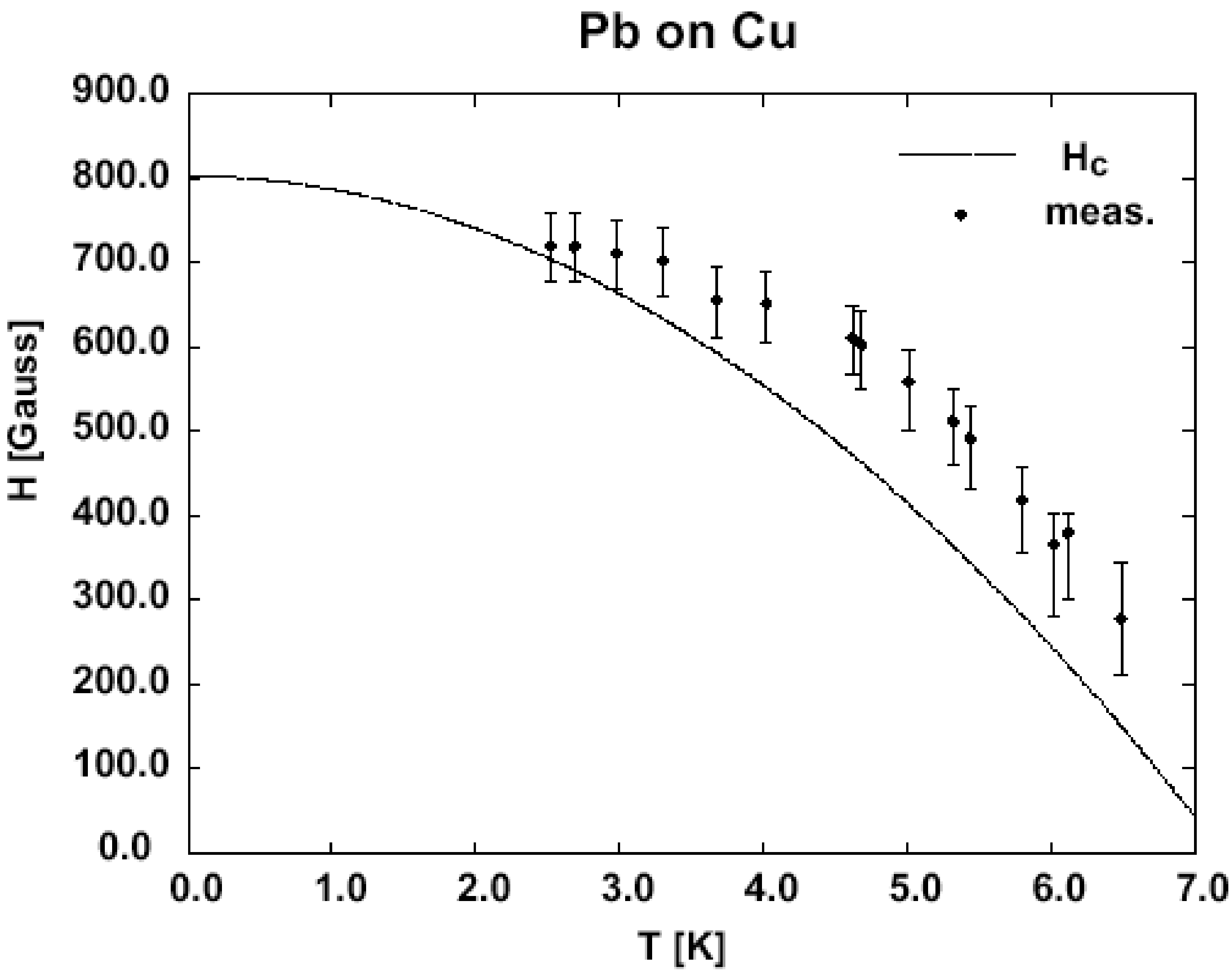
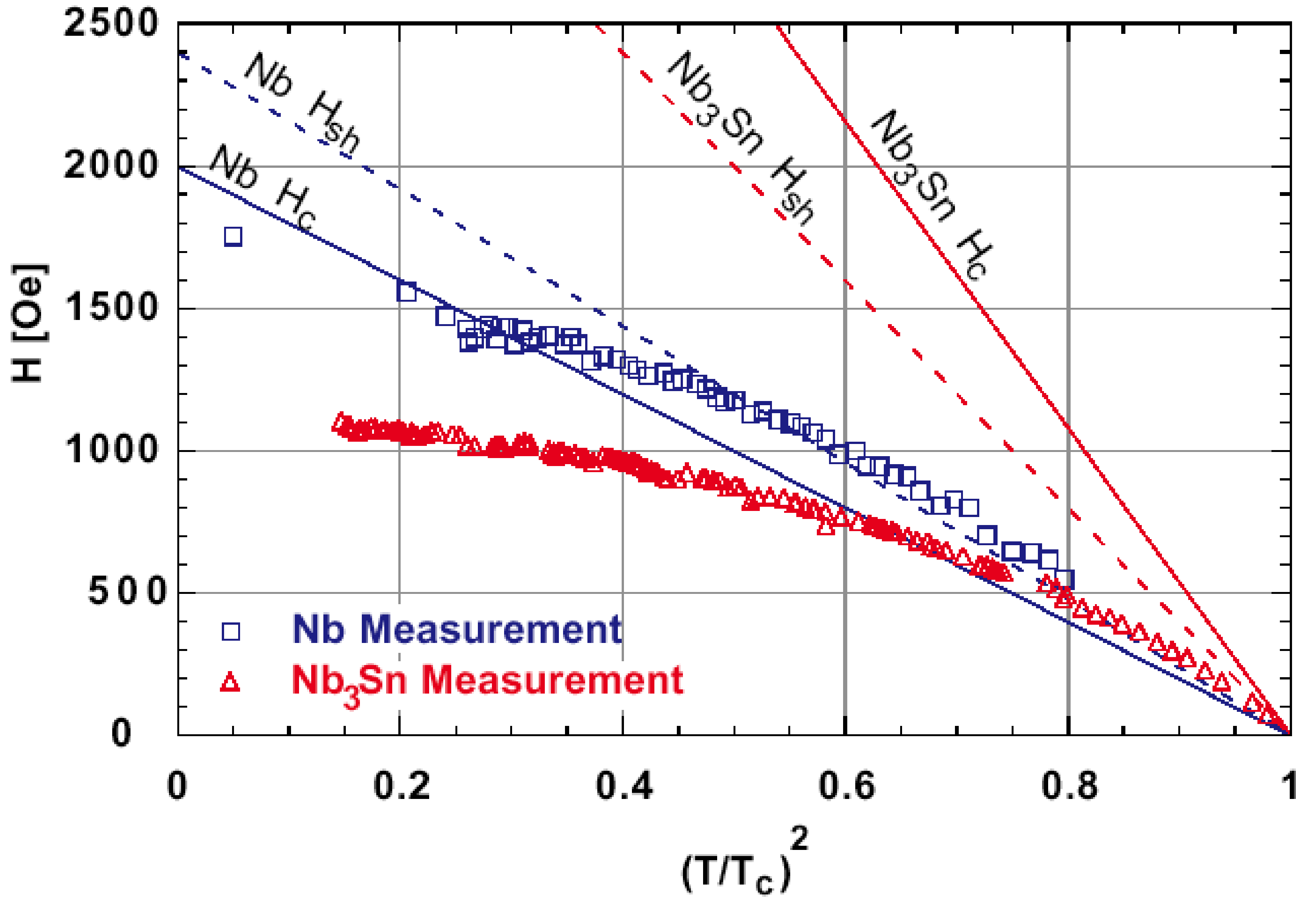
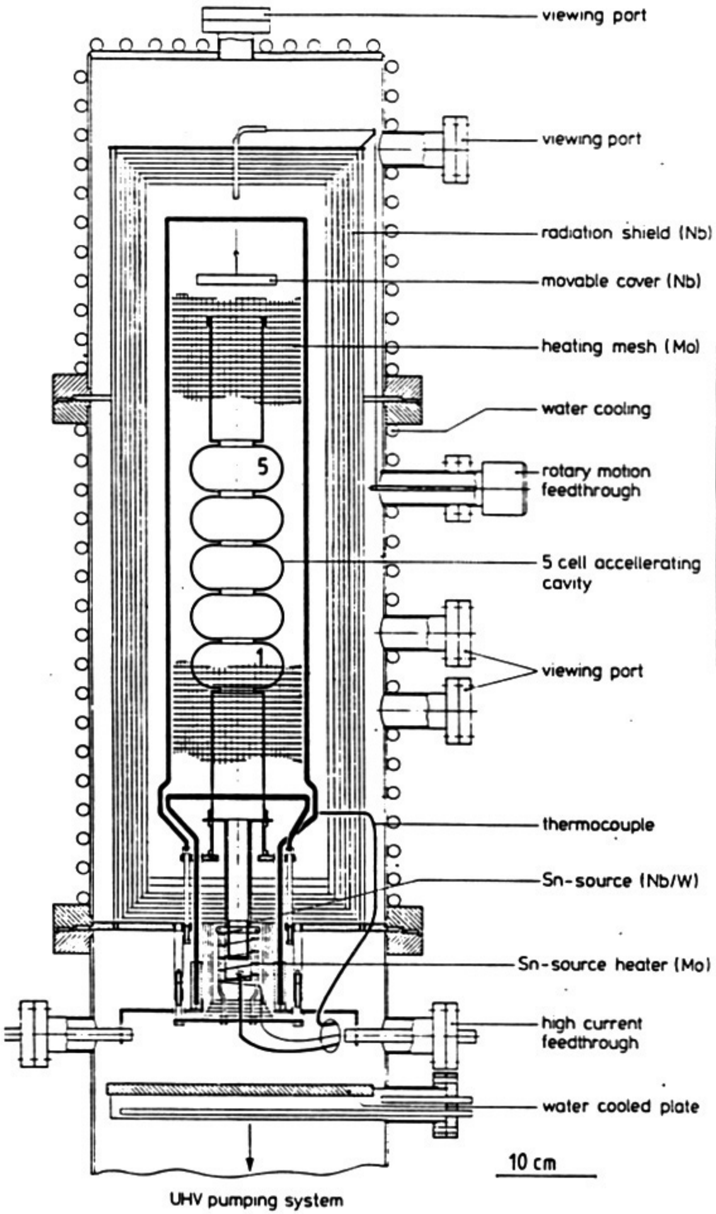


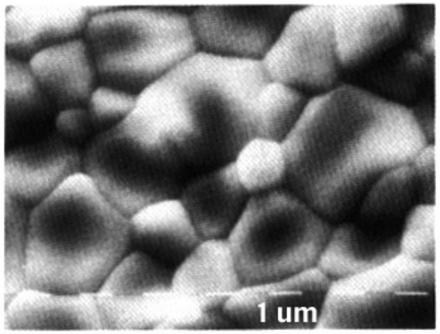
Figure 3: Measuring the H_c^{rf} of lead by pulsing a lead coated copper 1.3 GHz cavity.



2500
2000
1500
1000
500
0
H [Oe]
0
0.2
0.4
0.6
0.8
1
(T/T_c)^2
Nb H_sh
Nb H_c
Nb3Sn H_sh
Nb3Sn H_c
Nb Measurement
Nb3Sn Measurement



Reaction Furnace

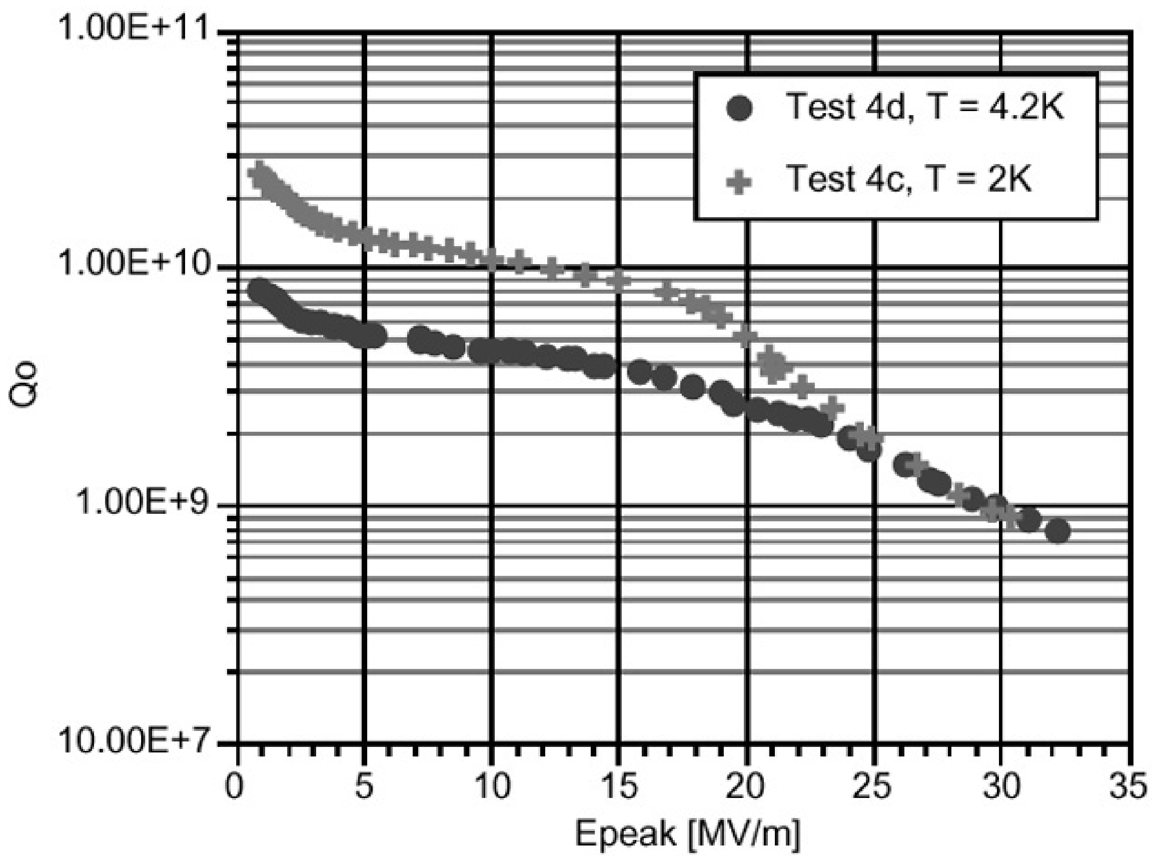


Grain Structure

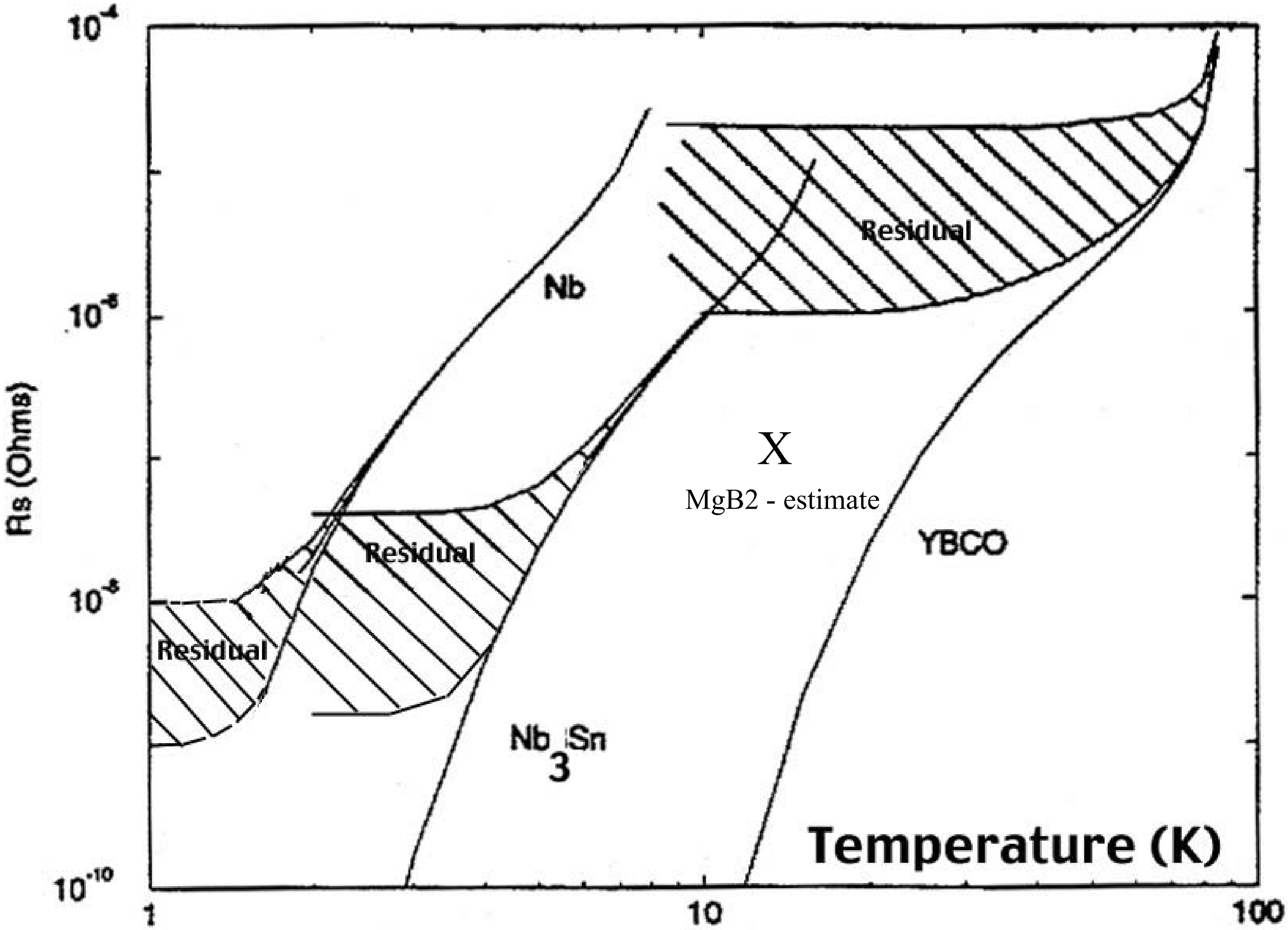
Wuppertal

Nb-3-Sn

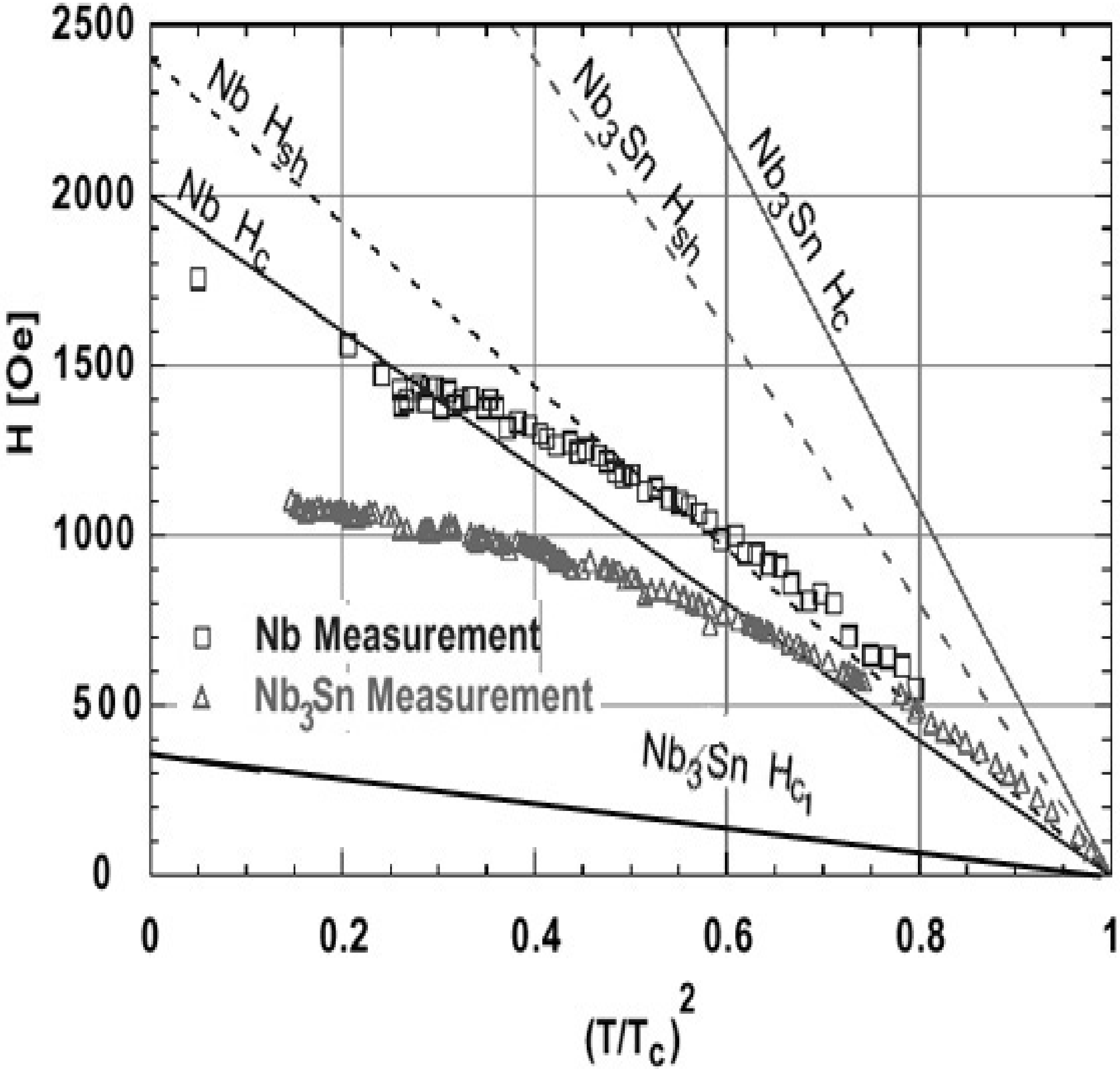
Nb-3-Sn - Best Performance CW
Maybe material was not so good
Need better material



Is there Hope for HTS?
A Comparison of Superconductors @ 1 GHz



Revisit Hsh - Saito



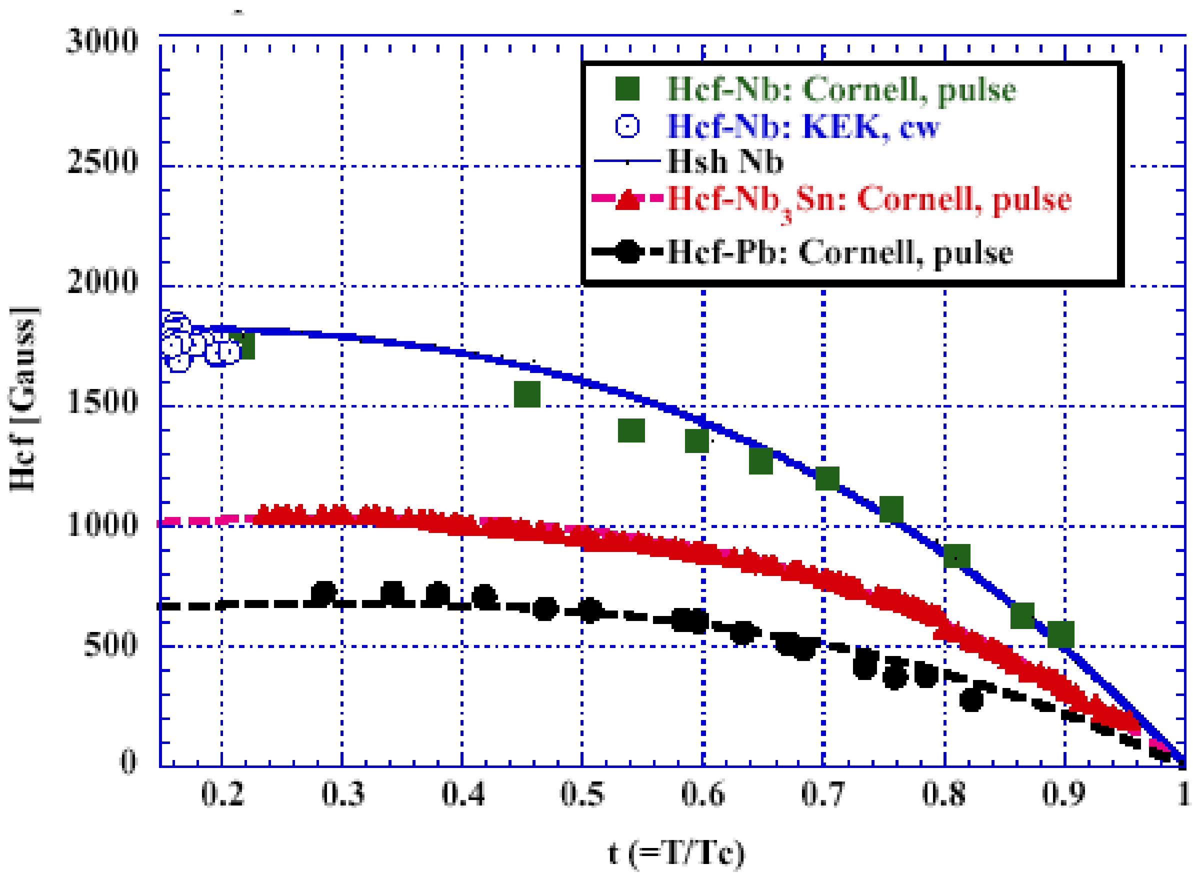


Figure 10: Critical RF fields (Hcf) of sc cavities and Hsh.

$$\lambda_L(T)H_{sh}^2(T) = \xi(T)H_C^2(T)$$

Need to measure Hc, λ and ξ

Ideally measure Hc from specific heat

Difficulties with this method

- Ideally: Measure DC : Hc2
- Determine ξ from Hc2
- Determine Hc from specific heat
- Get λ, -> Hsh
- But Saito derives Hc from Hc1 via
  - DC magnetization…not reliable, flux trapping empirical relation (between Hc1 and Hc)

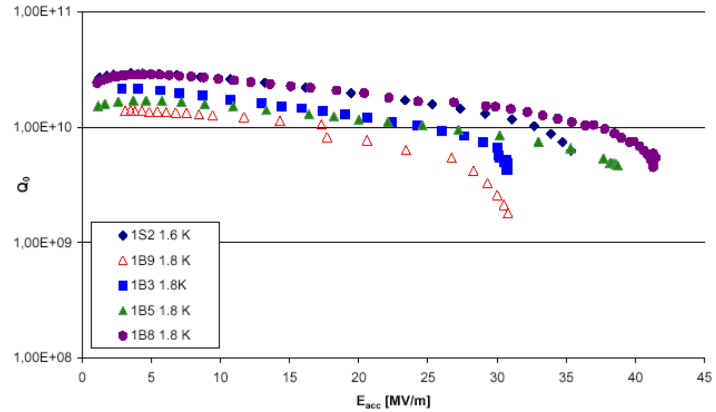
$$Hc2 = \phi_0/(4\pi\xi^2)$$

$$Hc \cdot \xi\lambda_L = \phi_0/(4\pi)$$

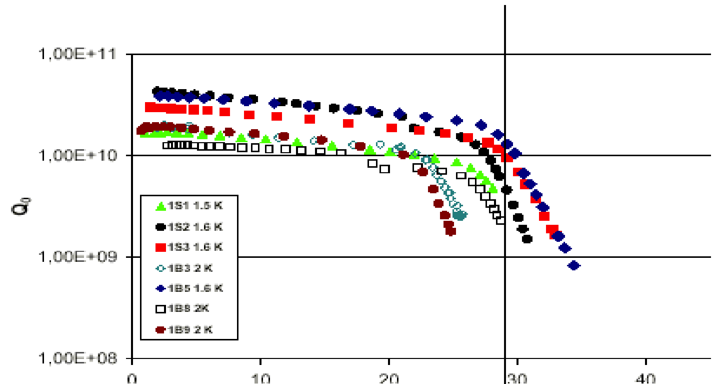
$$\lambda_L(T)H^2_{sh}(T) = \xi(T)H^2_C(T)$$

High Field Q-slope

EP + 100 C

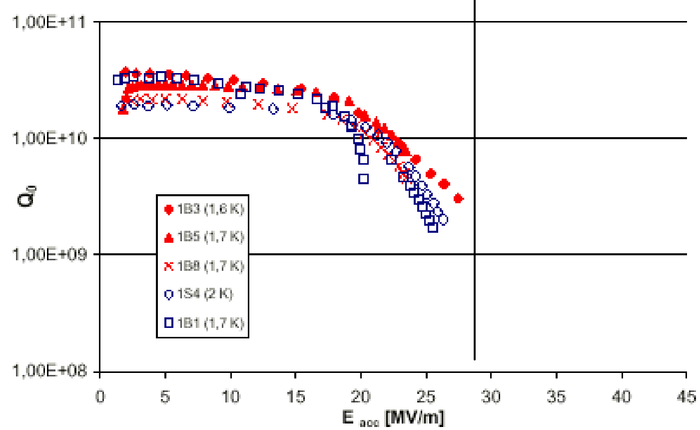


EP cavities show less Q-Slope



CERN/DESY Results

BCP



Saito again: Hc = 2230 Oe !?

niobium cavities with Hp/Eacc=43.8 Gauss/(MV/m) will be written as following [27]:

$$R_S(Eacc) = R_{BCS}(Eacc) + R_{res}$$

$$= \frac{A}{T + C \cdot Eacc} \cdot \exp[-\frac{B}{T + C \cdot Eacc} \cdot \sqrt{1 - \left(\frac{43.8 Eacc}{\sqrt{2} \cdot H_c} \right)^2}] + R_{res} \quad (7).$$

A factor $1/\sqrt{2}$ front of H_C in eq. (7) comes from the AC effective field. A, B and Rres are obtained by the temperature dependence measurement of Rs at low field. $C \cdot Eacc$ term in eq.(7) appears by heat stay effect on the RF surface due to the poor thermal conductivity in sc state. In our case these values are A=1.45E-4, B=18.6. Rres =2~10nΩ, and C = (3~5)E-3. When fixed A, B and Rs to the experimental values, eq.(7) includes two free parameters : C and Hc. Fig.11 shows the fitting results with a cavity performance by EP or CP. Eq.(7) nicely fits both results with reasonable H_C value: Hc=2230 Gauss for EP smooth surface. For the enough electropolished surface, the resultant Hc is the real thermo-dynamic critical magnetic field because no field enhancement

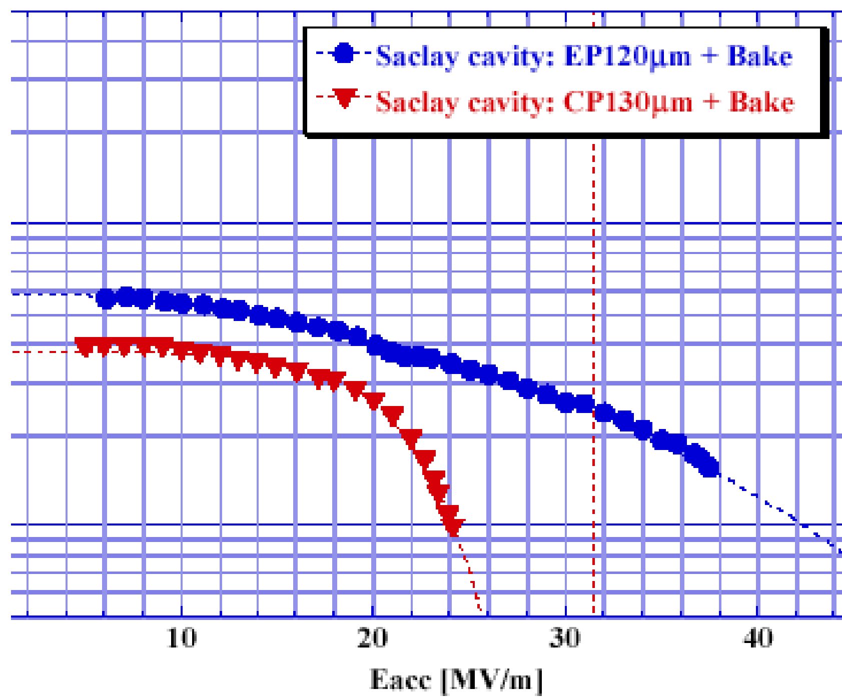
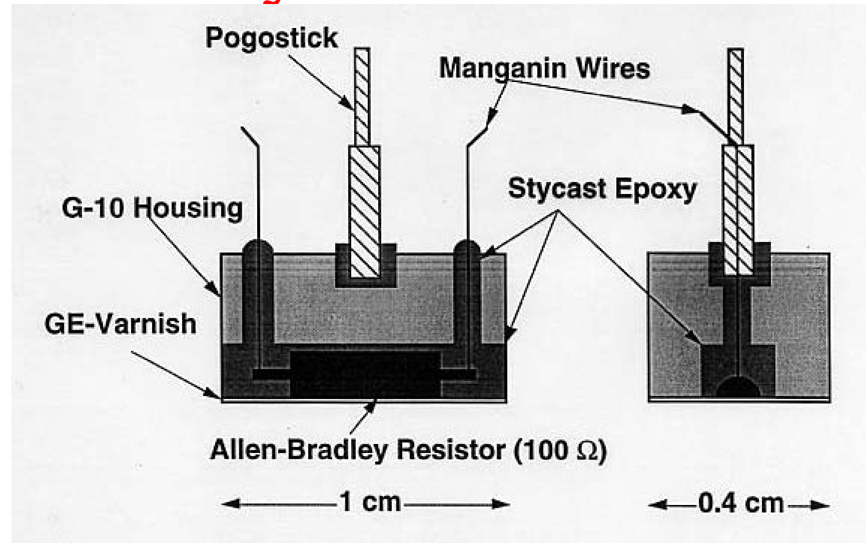
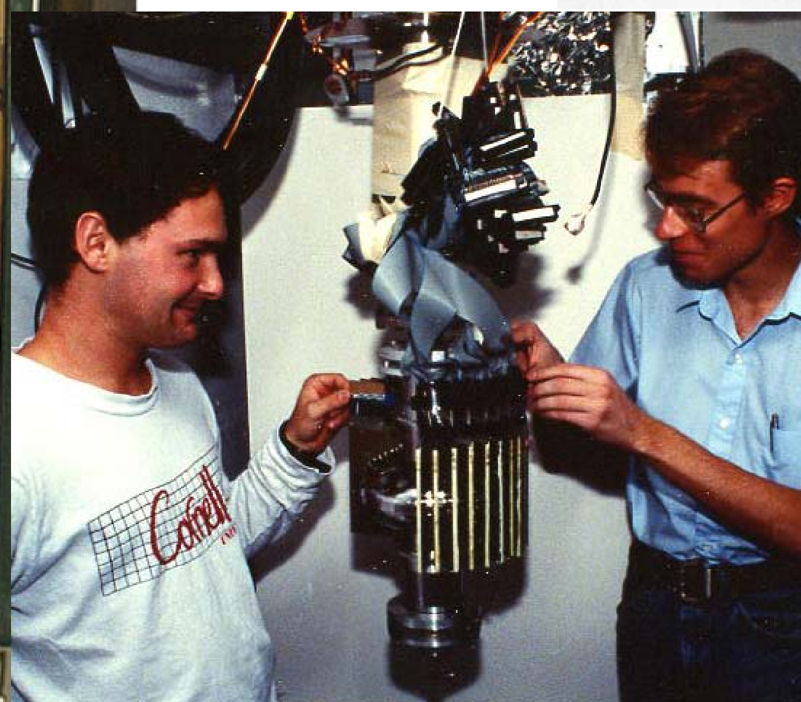
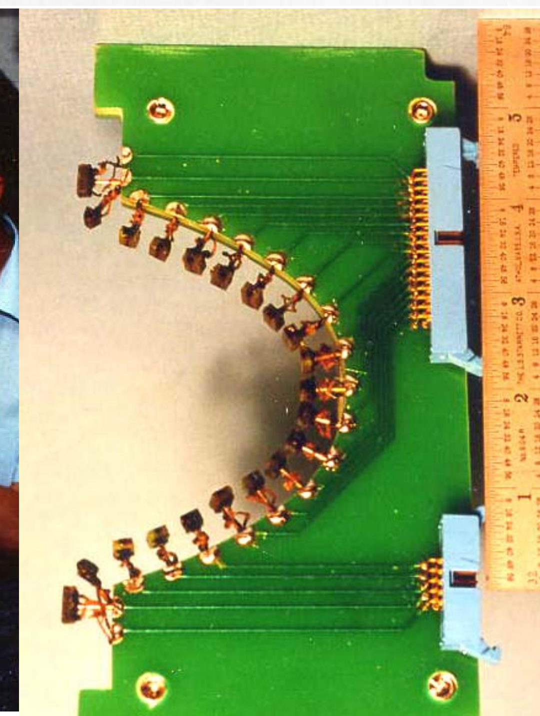


Figure 11: New Q-slope analysis.

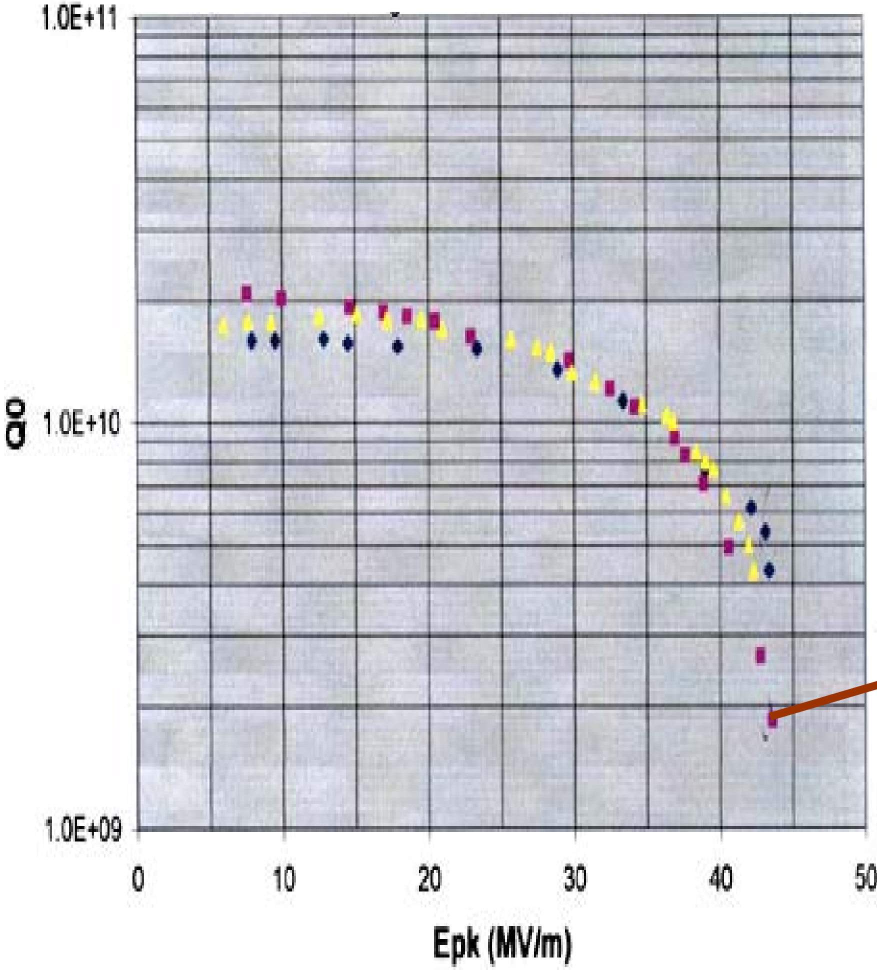
Thermometry

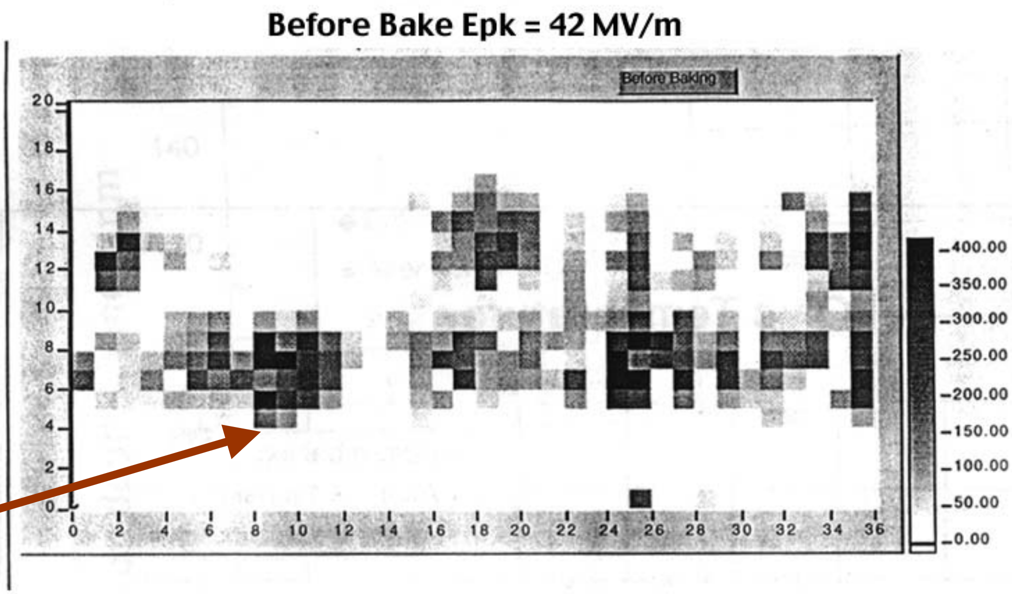






Temperature Map

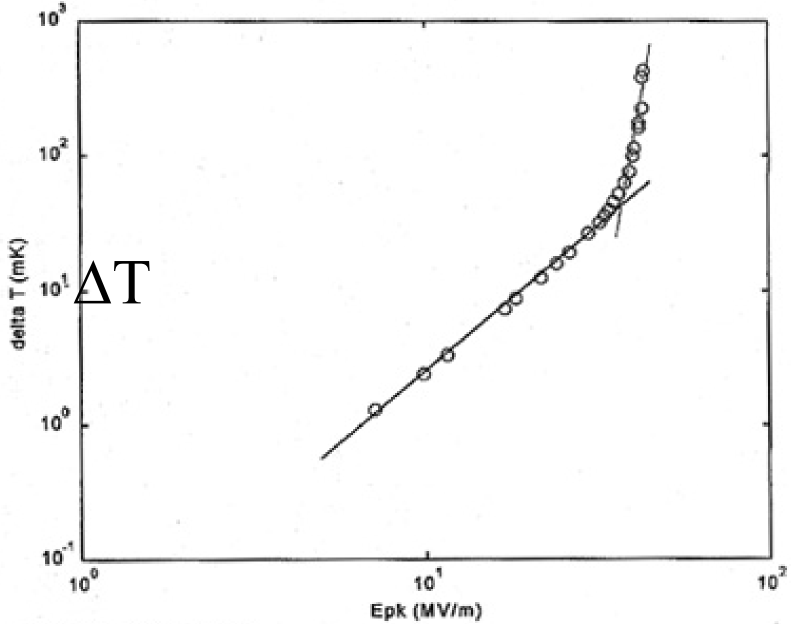




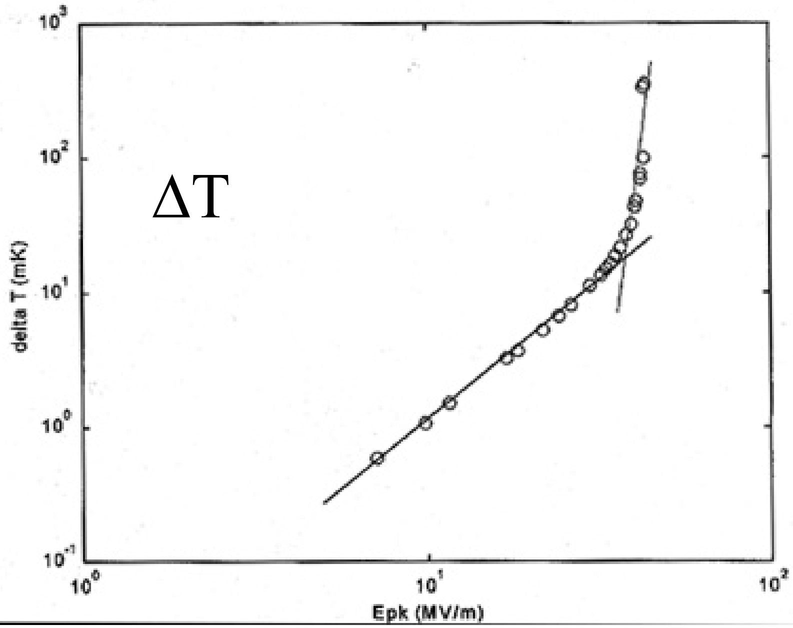
Q-Decline

Thermometry Research on High Field Q-Decline

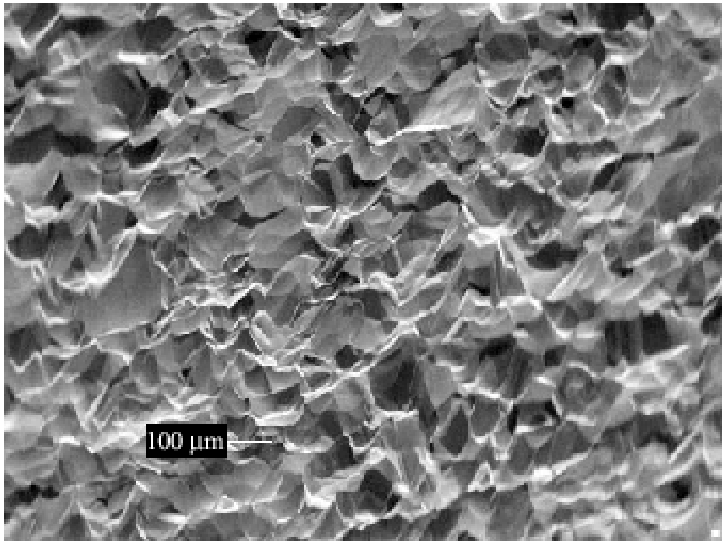
9 26 2.14 14.08

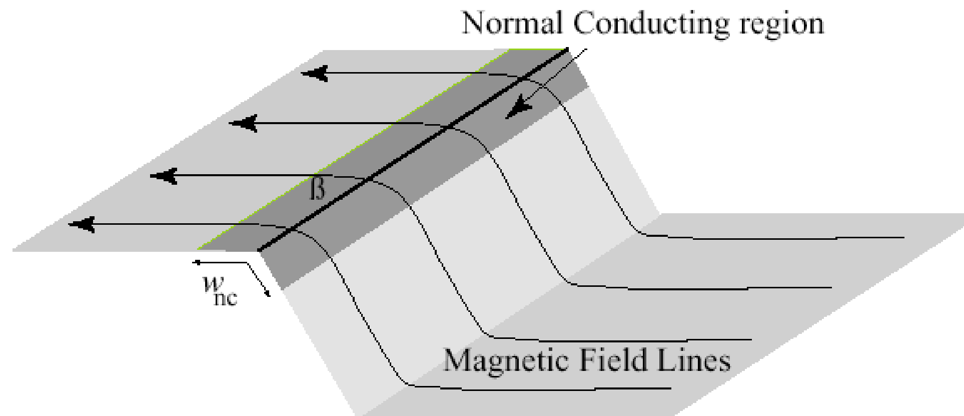


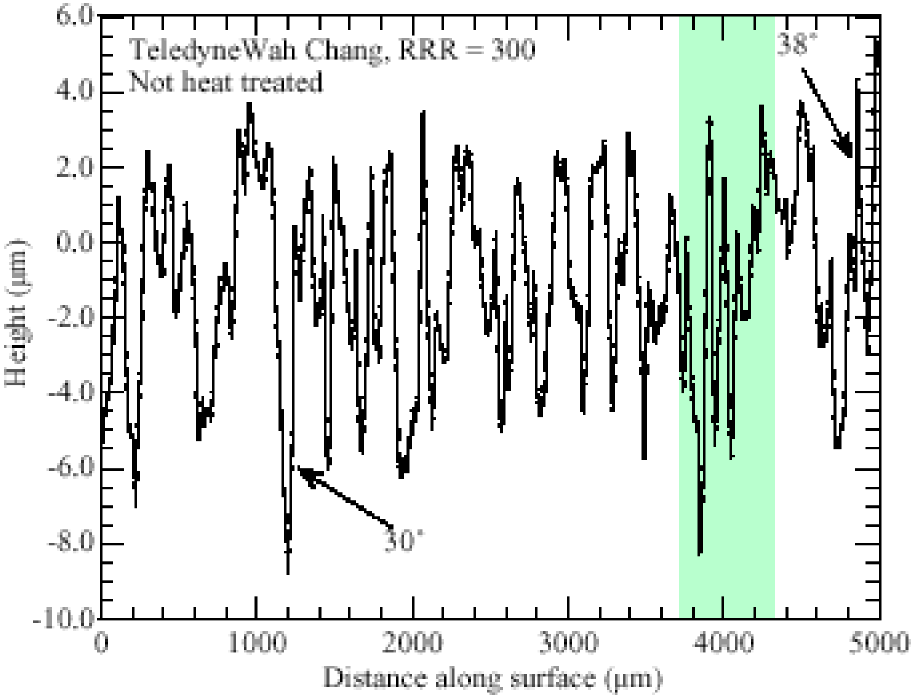
10 26 2.07 18.30



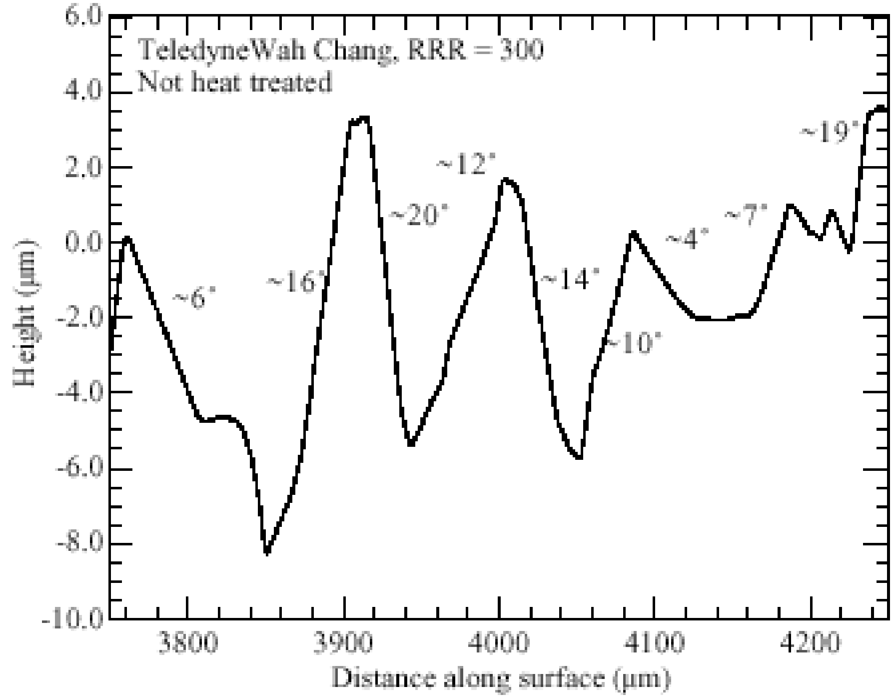
Local Transitions Observed
In temperature maps


100 µm

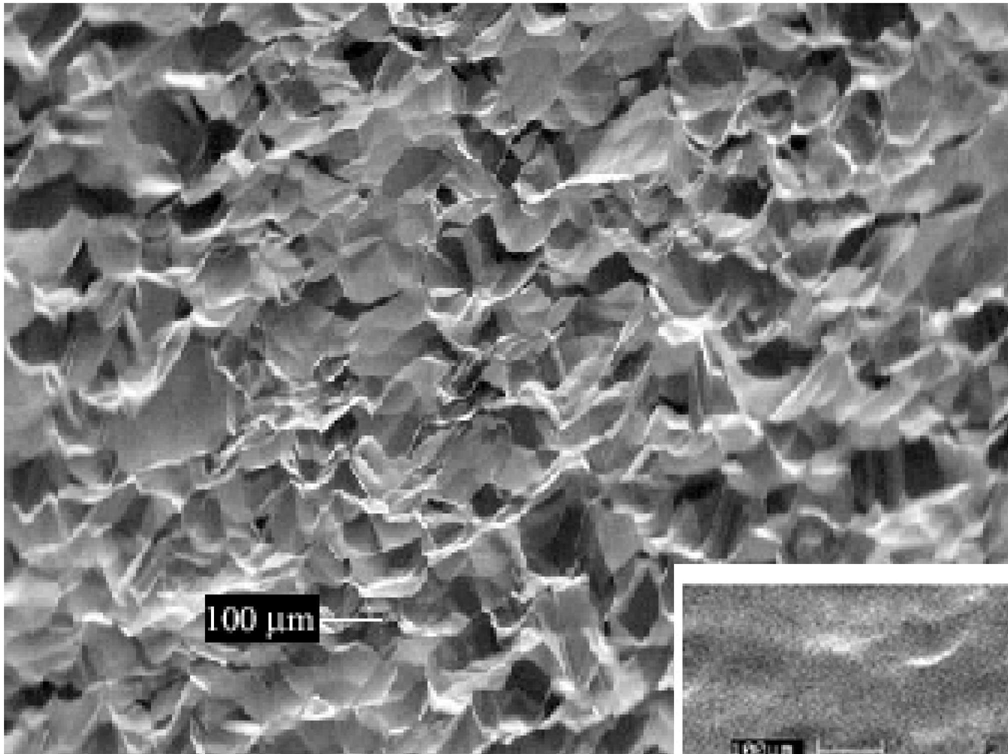

Normal Conducting region
ß
w_{nc}
Magnetic Field Lines


TeledyneWah Chang, RRR = 300
Not heat treated
38°
30°
Height (µm)
Distance along surface (µm)
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
0
1000
2000
3000
4000
5000

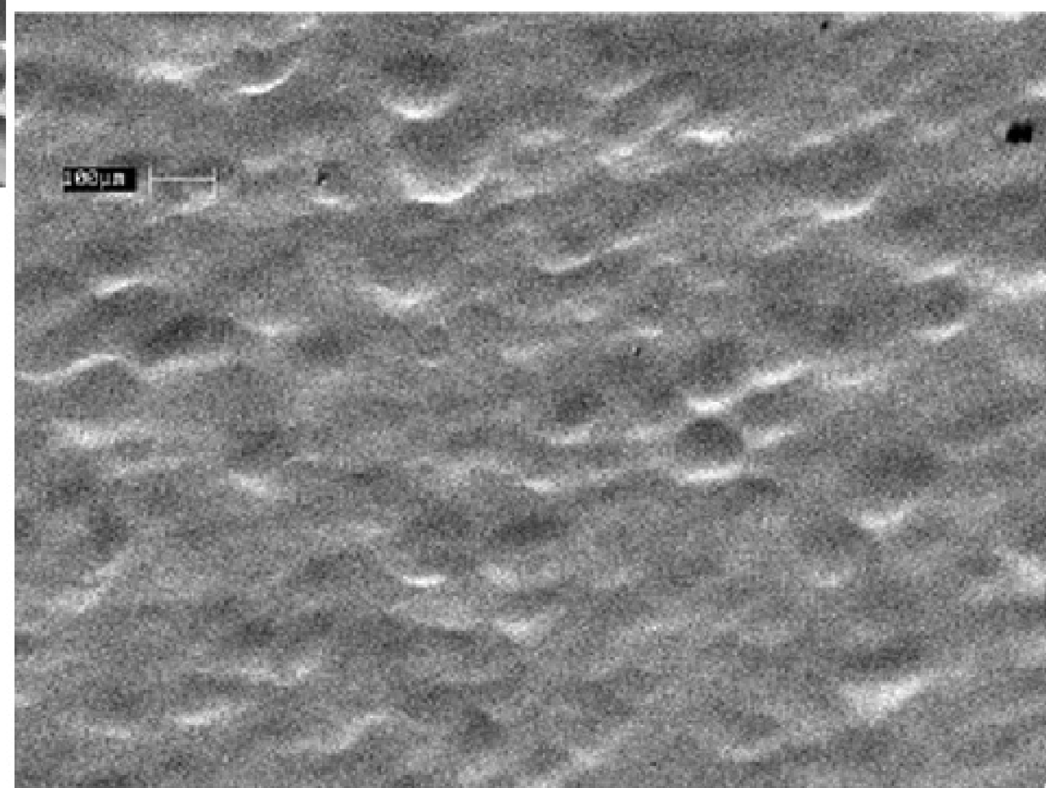
(b)


TeledyneWah Chang, RRR = 300
Not heat treated
~6°
~16°
~20°
~12°
~14°
~10°
~4°
~7°
~19°
Height (µm)
Distance along surface (µm)
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
3800
3900
4000
4100
4200

(c)

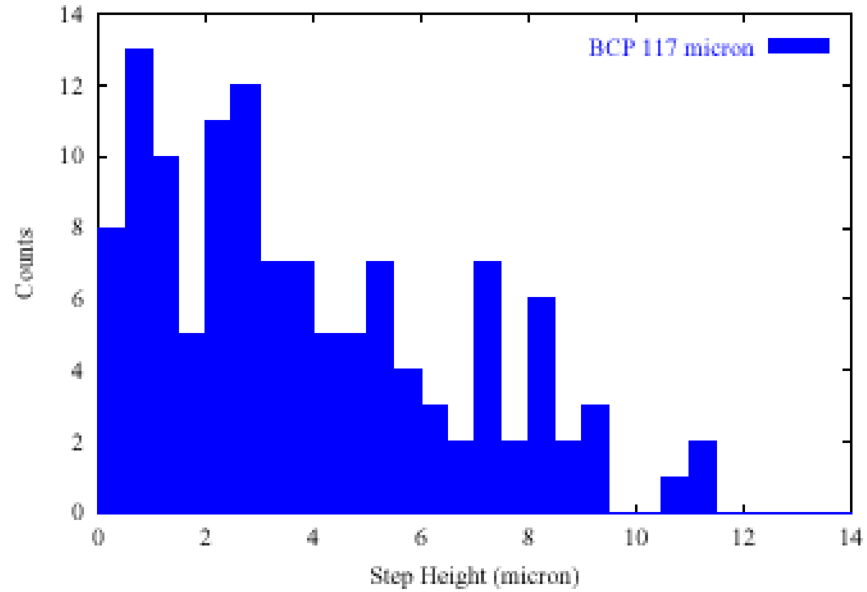


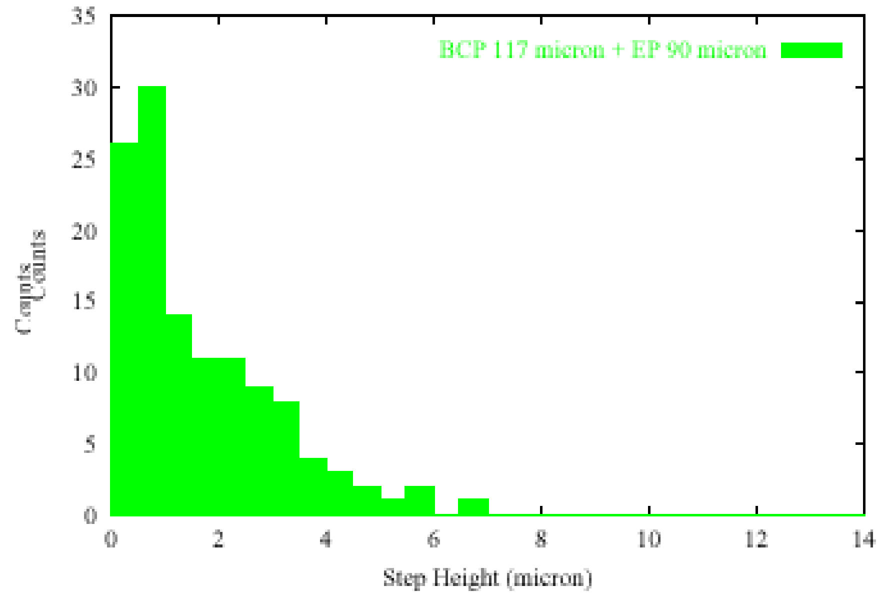
BCP Step =5 µm



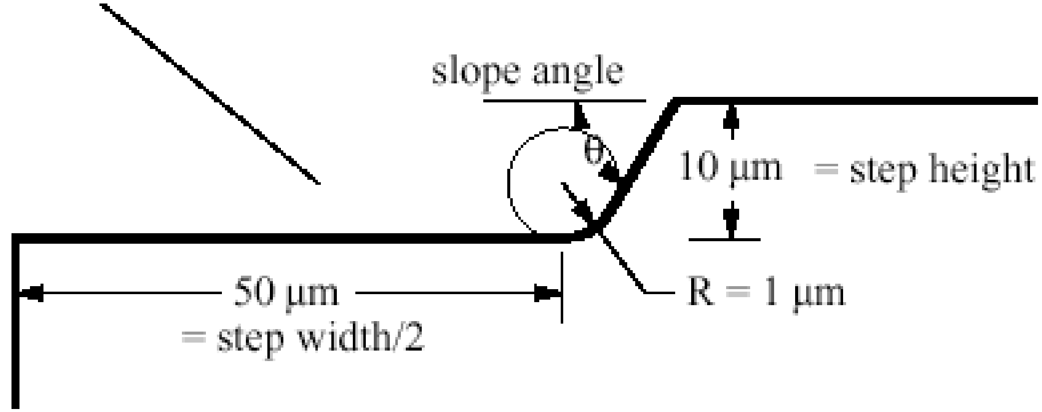
Electropolishing
Reduces Grain
Boundary Steps
Reduces Q-slope

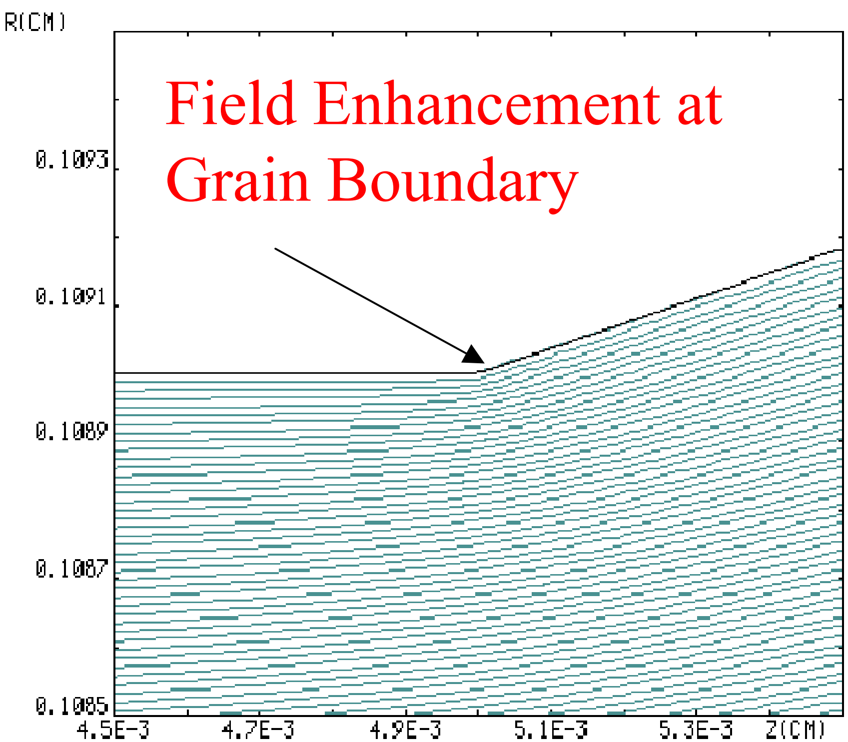
EP
Step = 1 µm

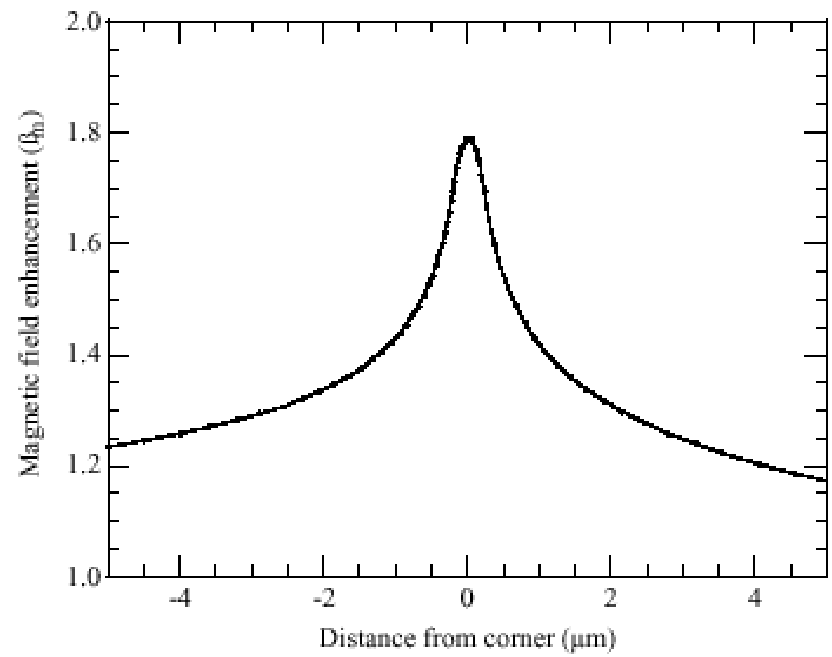

BCP 117 micron
Counts
Step Height (micron)
0
2
4
6
8
10
12
14


BCP 117 micron + EP 90 micron
Counts
Step Height (micron)
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14

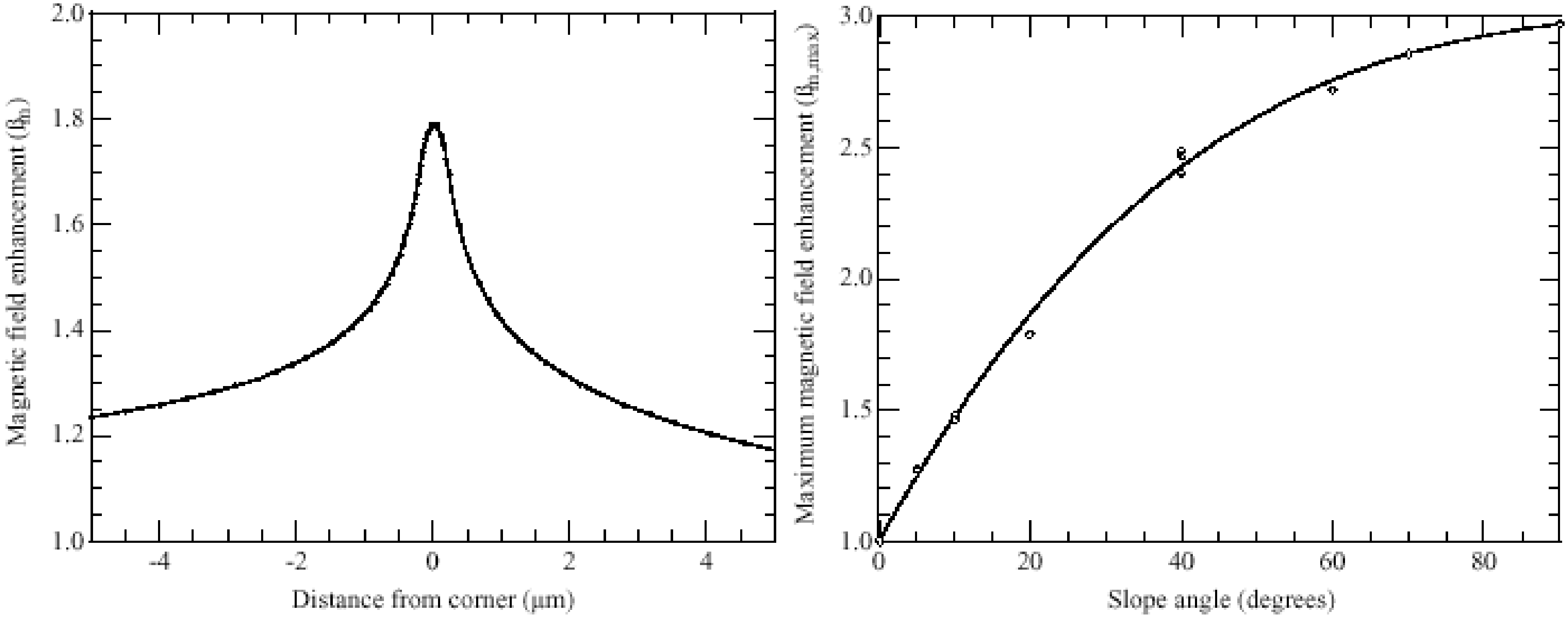
(c)







Knobloch et al

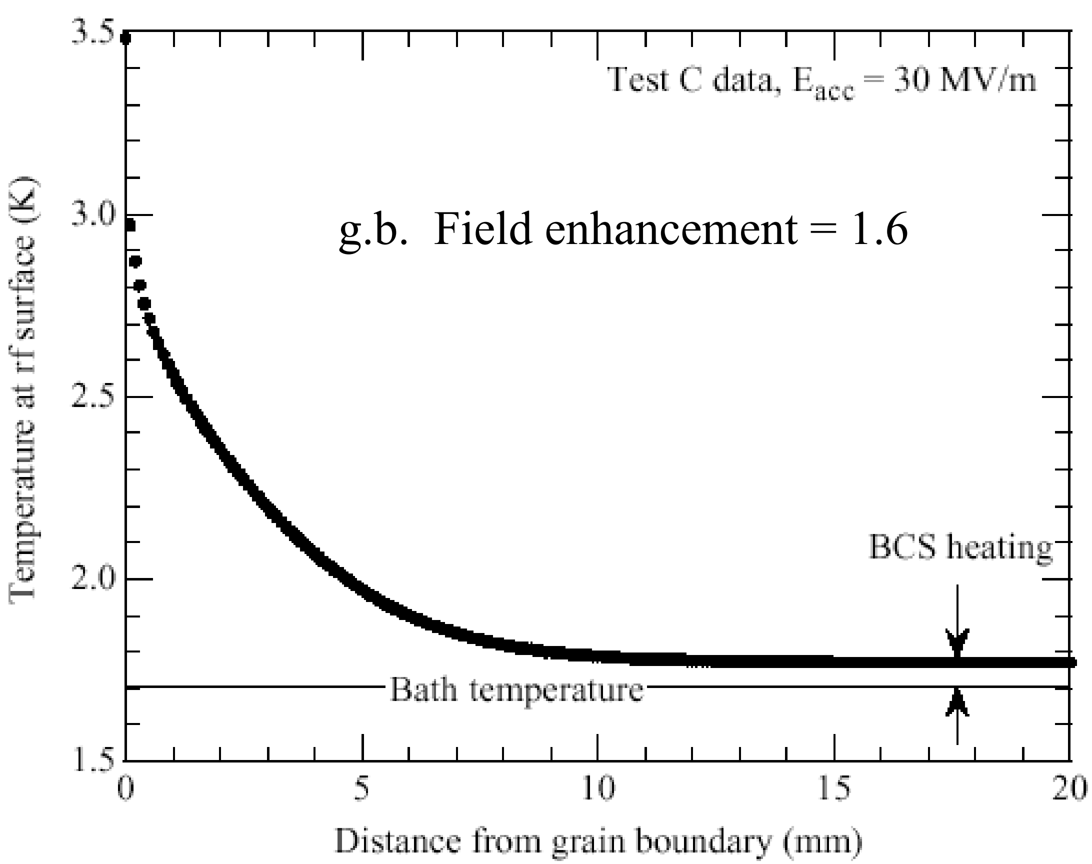


(a) (b)

Figure 11: Magnetic field enhancement due a 100 μm $\times$ 10 μm step. (a) Field enhancement along the rf surface near the corner (slope angle = 20°). (b) Maximum field enhancement versus slope angle.

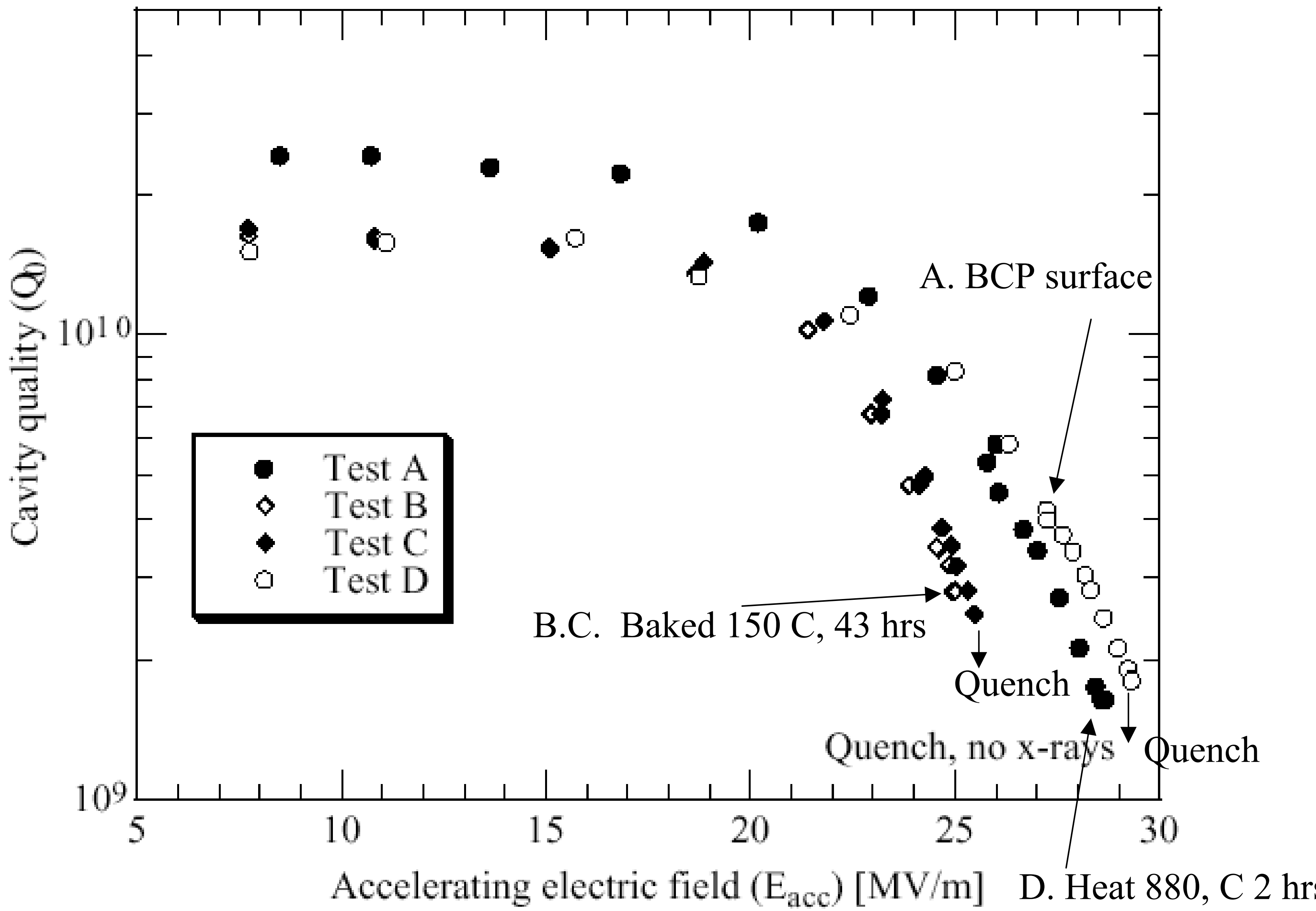
Temperature (K)
1.738
1.932
2.126
2.32
2.513
2.707
2.901
3.095
3.289
3.483
Y
X

(a)



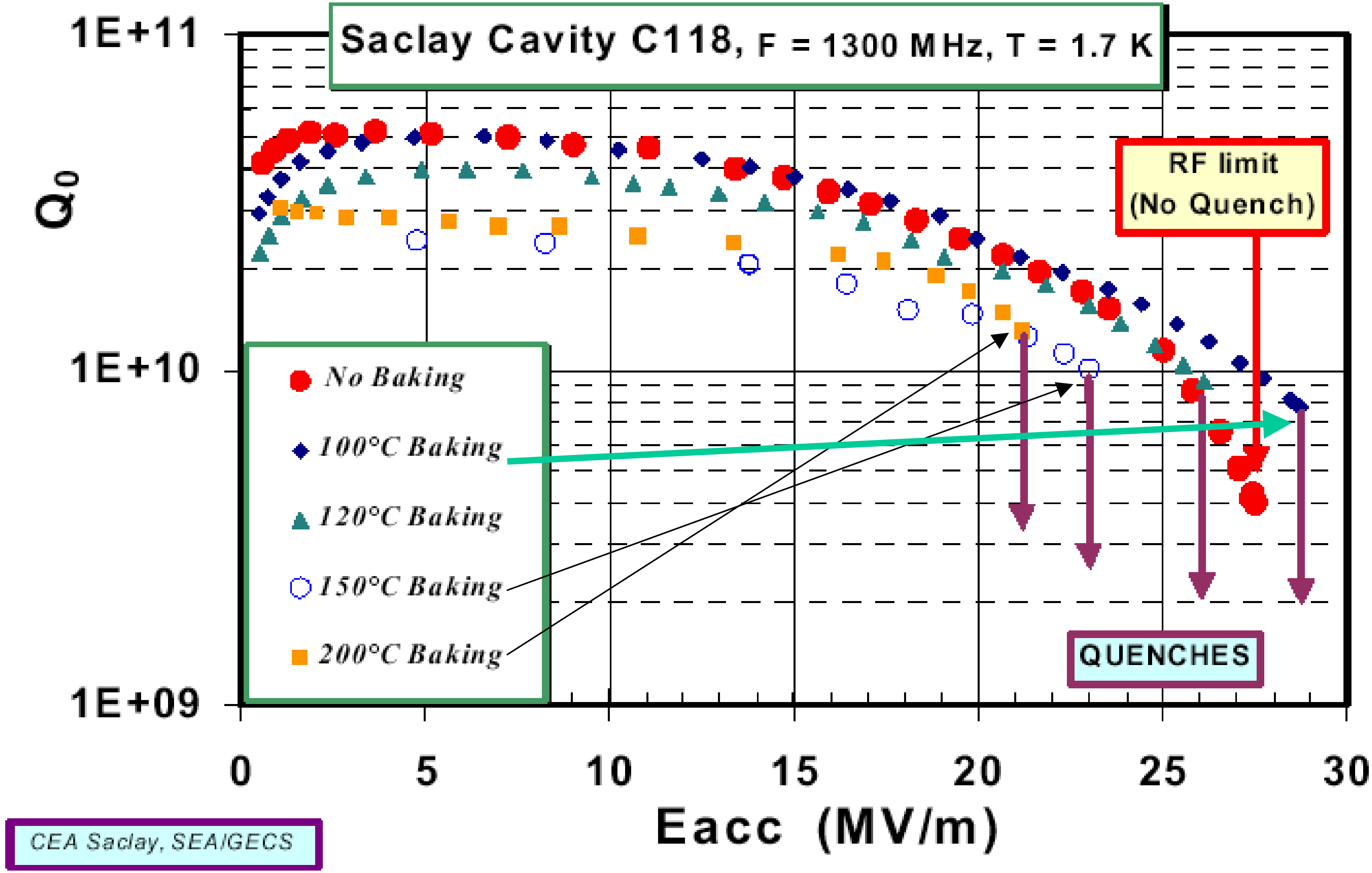
Test C data, E$_{acc}$ = 30 MV/m
g.b. Field enhancement = 1.6
BCS heating
Bath temperature
Temperature at rf surface (K)
Distance from grain boundary (mm)
3.5
3.0
2.5
2.0
1.5
0
5
10
15
20

Influence of Baking at 150 C



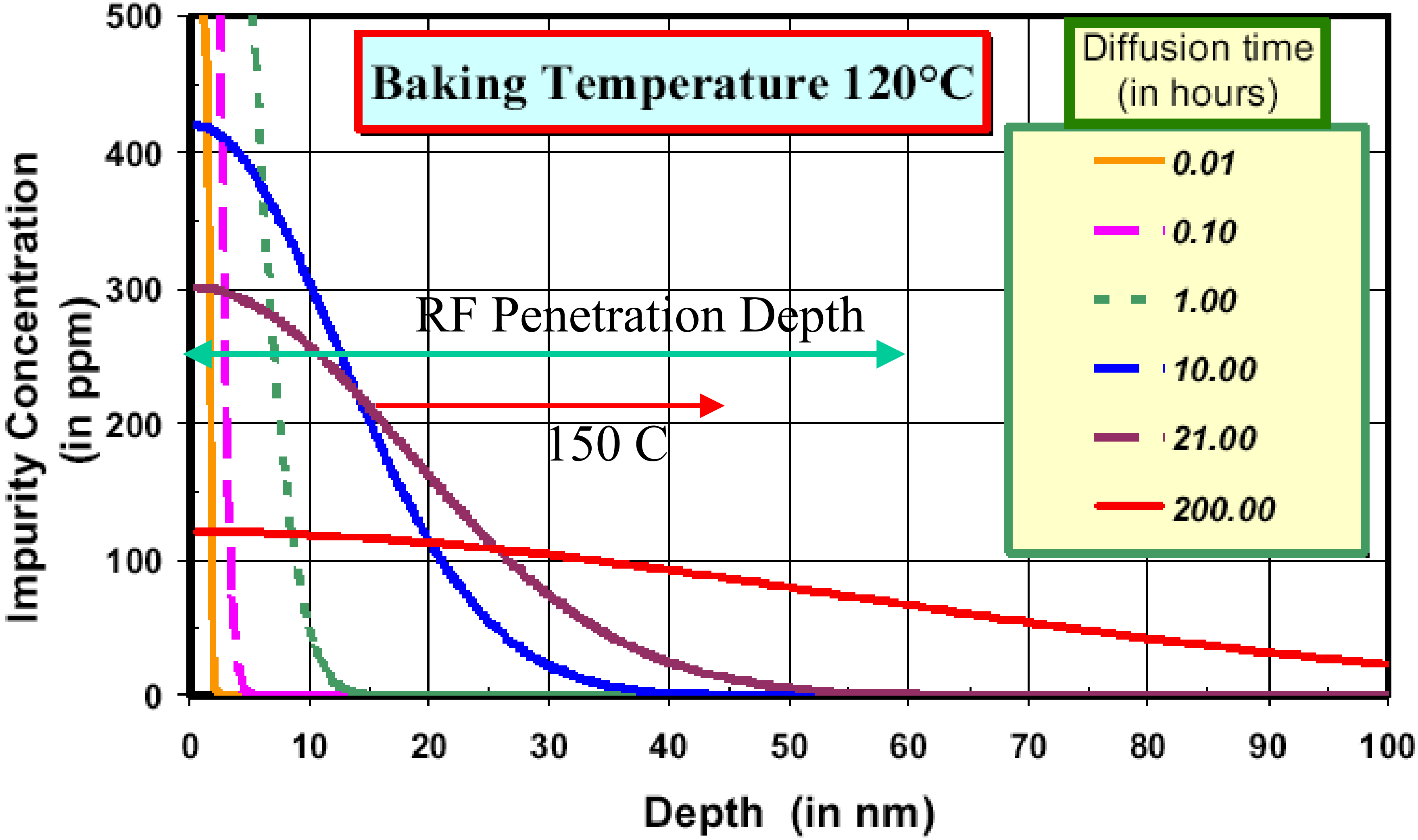
Similar Results Confirmed by Saclay

But there is something new

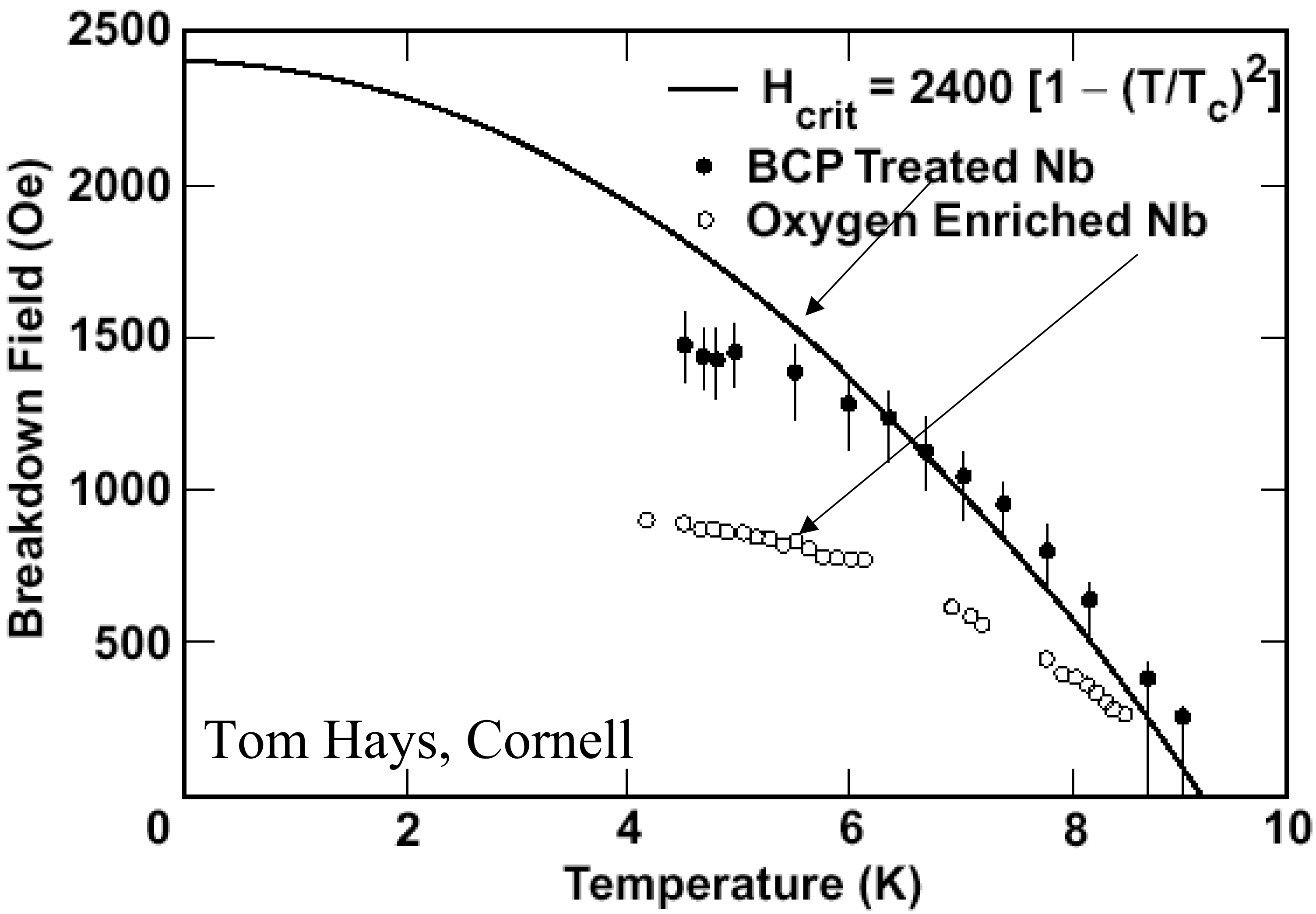


Gentle Baking REDUCES Q slope !!

Need real measurements of oxygen profile

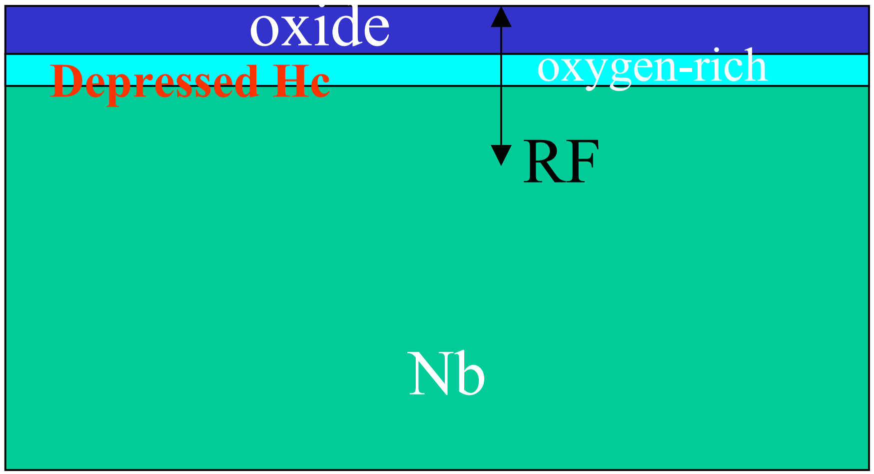


Possible Explanation of Mild Baking Effect:
Independent RF Critical Field Measurements Show That:

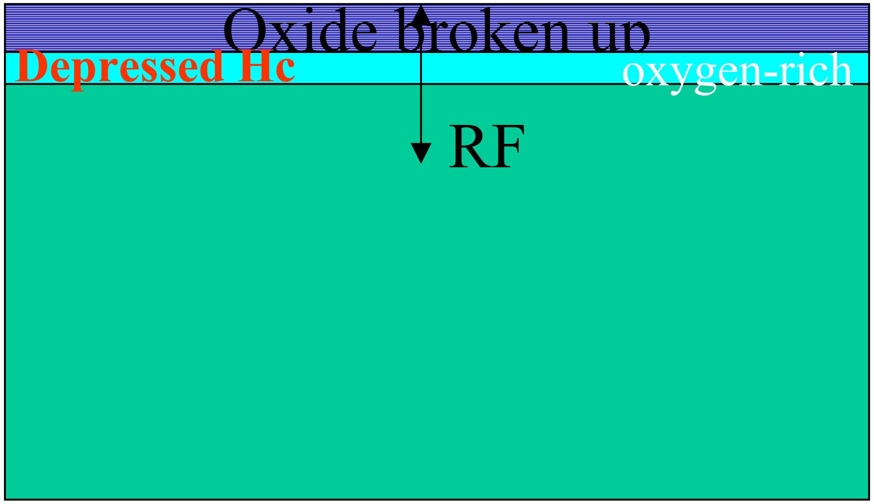


Higher Oxygen Content Means Lower RF Critical Field

Need O profile measurements

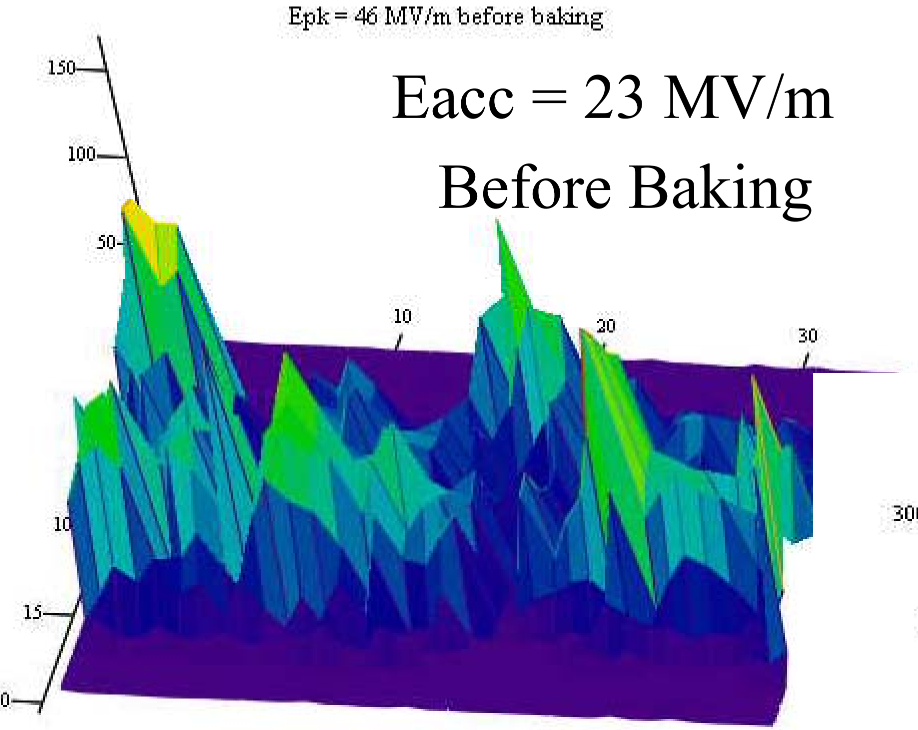


150 C,
48 hours



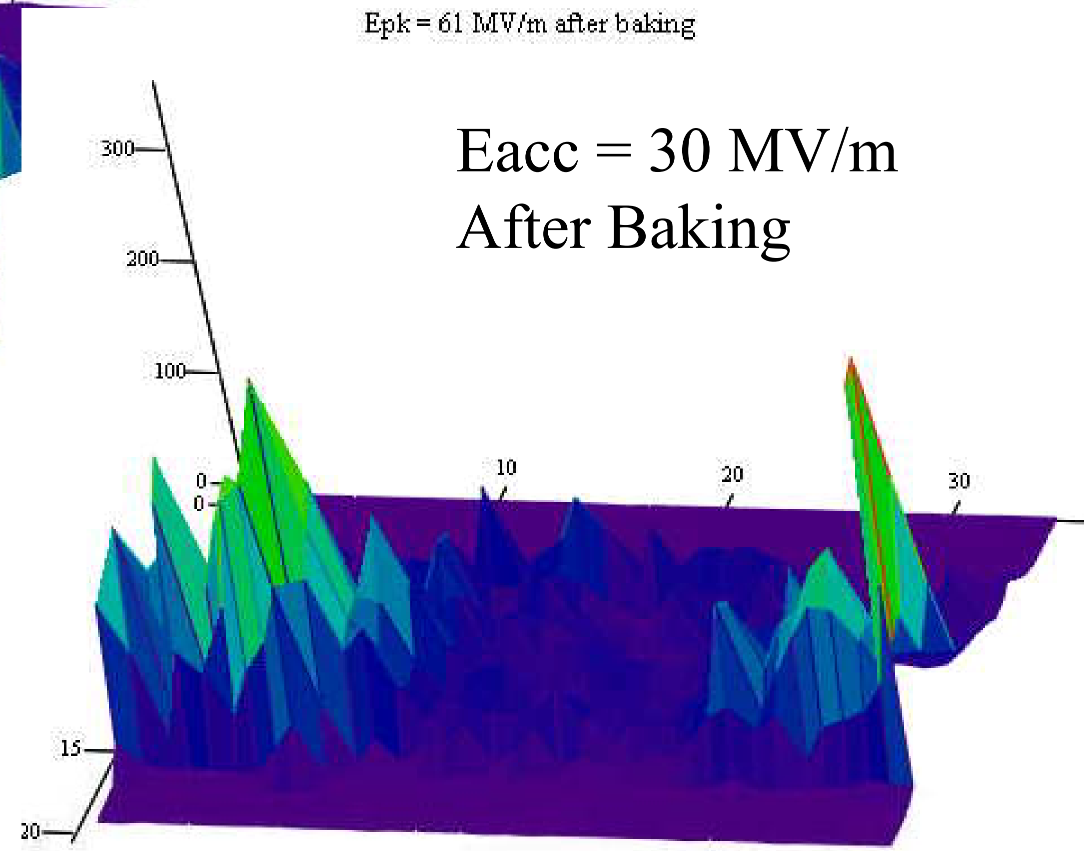
New

Mild Baking Reduces Q-Decline



Eacc = 23 MV/m

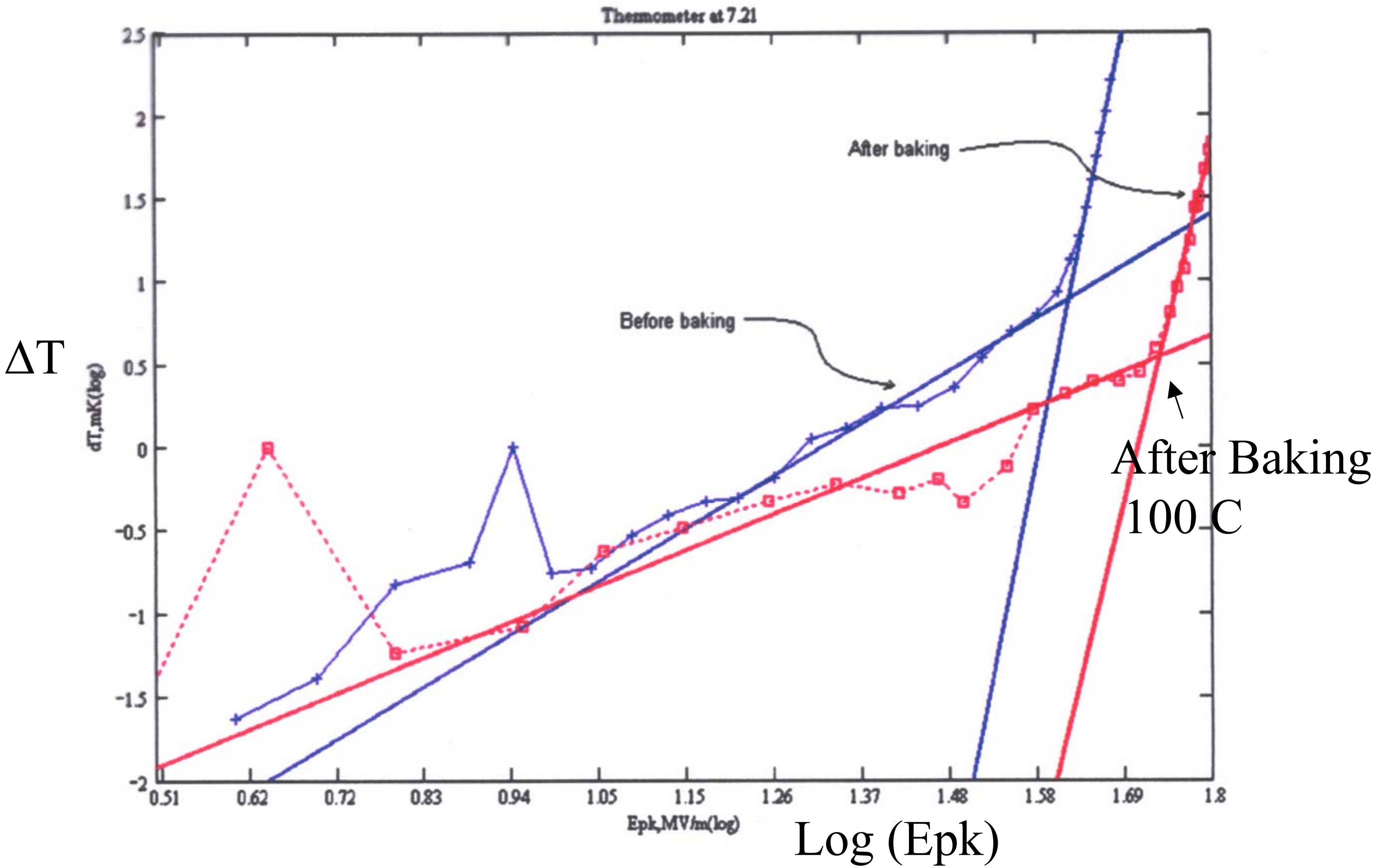
Before Baking



Eacc = 30 MV/m

After Baking

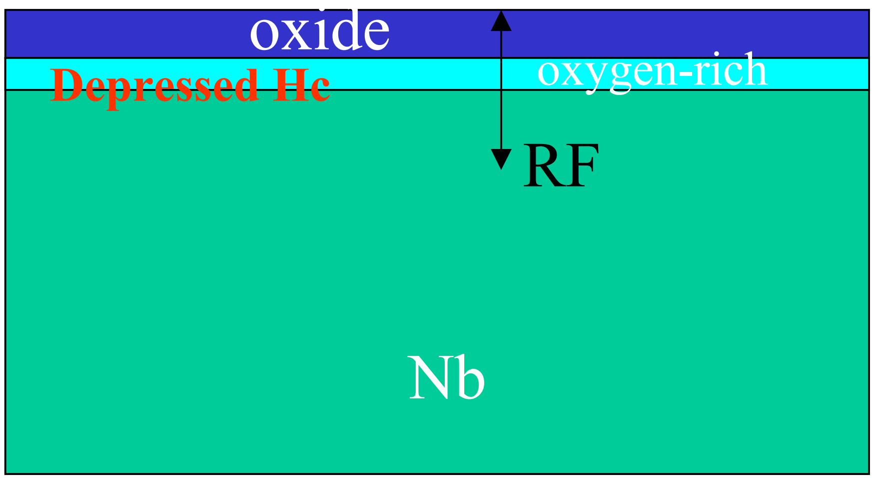
Baking Pushes Transition to Higher Fields

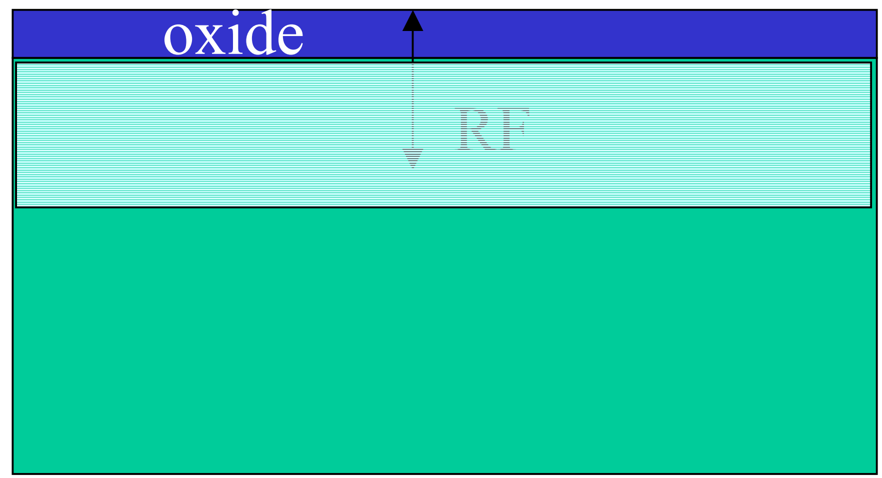


Need O profile measurements

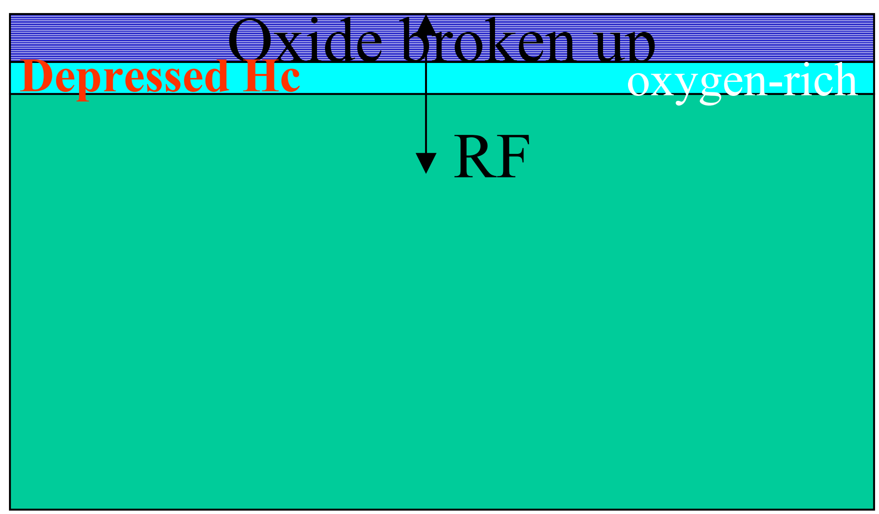
Safa

100 C, 48 hours



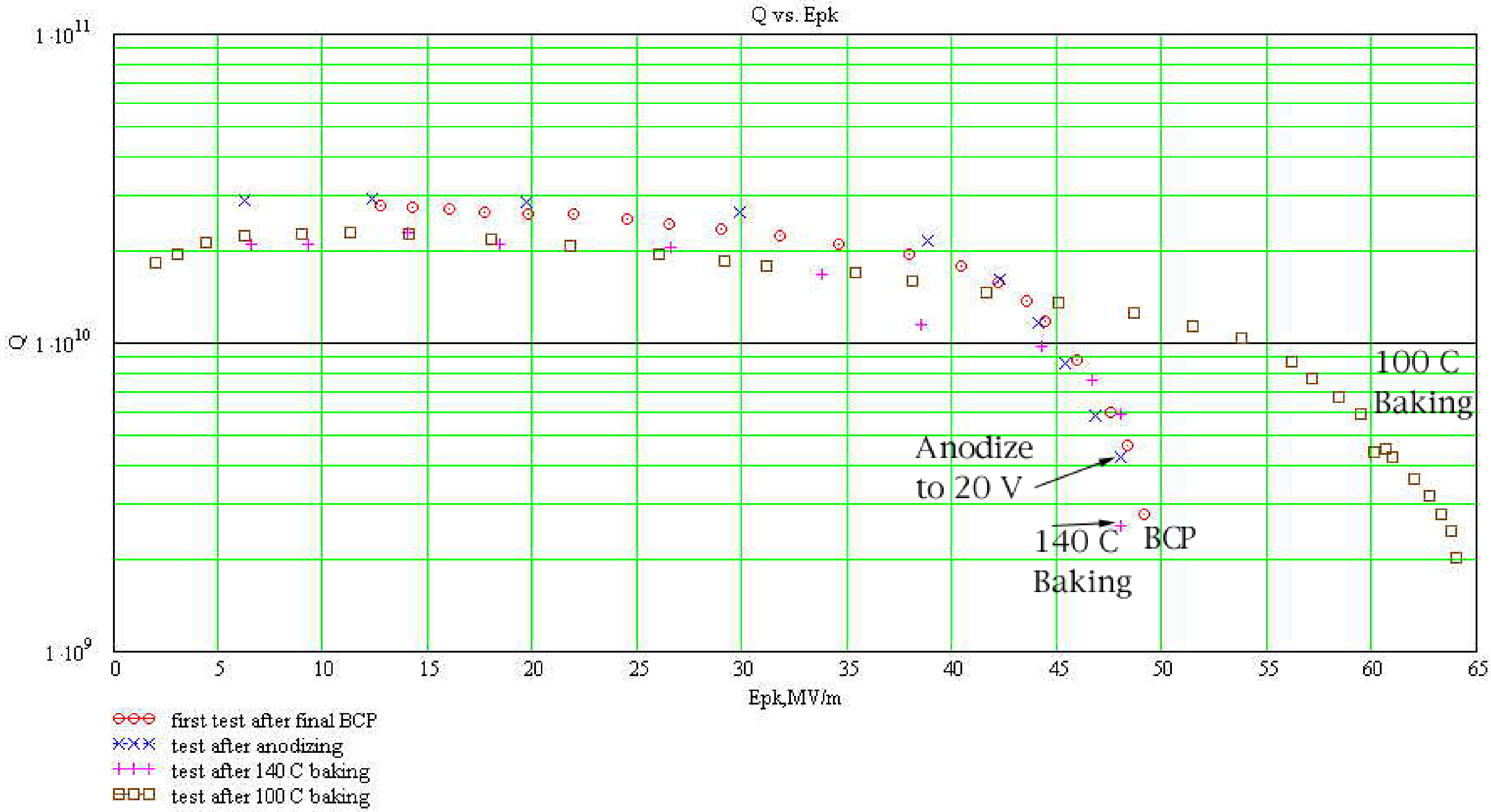


150 C,
48 hours

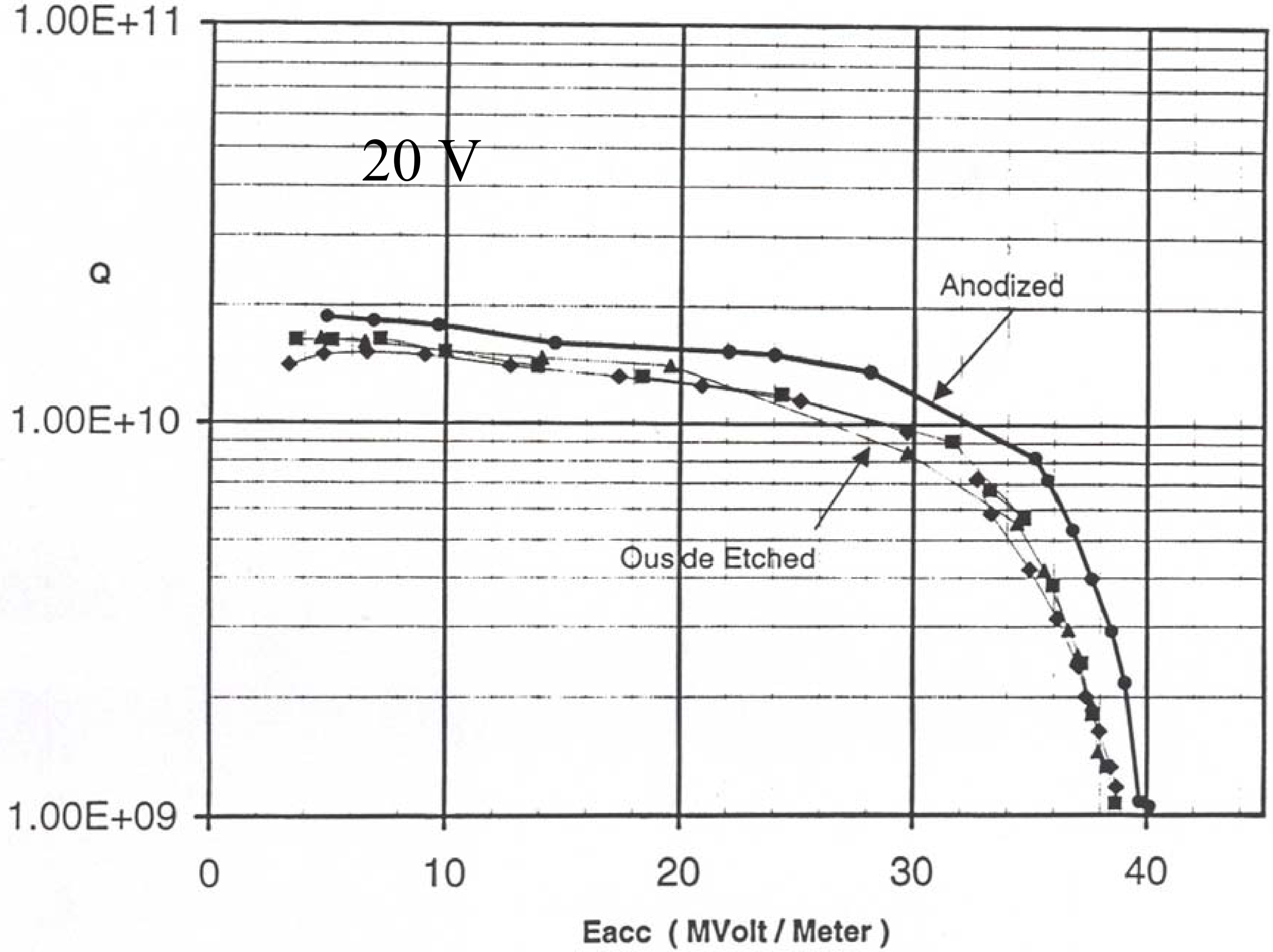


New

Anodizing Does Not Help !



Changing the Growth of Oxide (By Anodizing) Has Small Effects



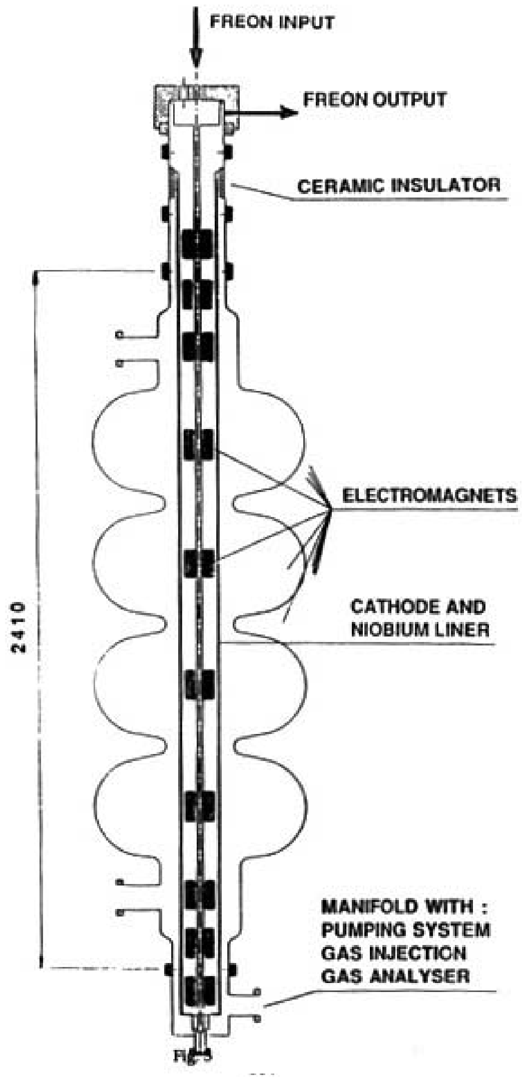
Nb-Cu

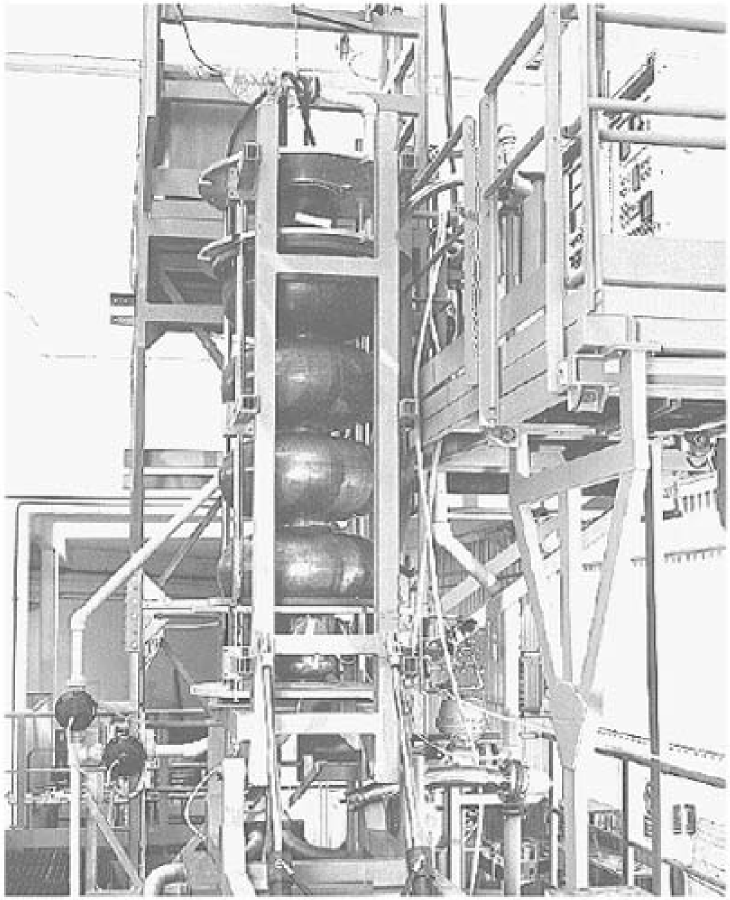
Important issues for
Neutrino Factory…Muon Colliders

General Q-slope Mechanism in Nb_Cu films

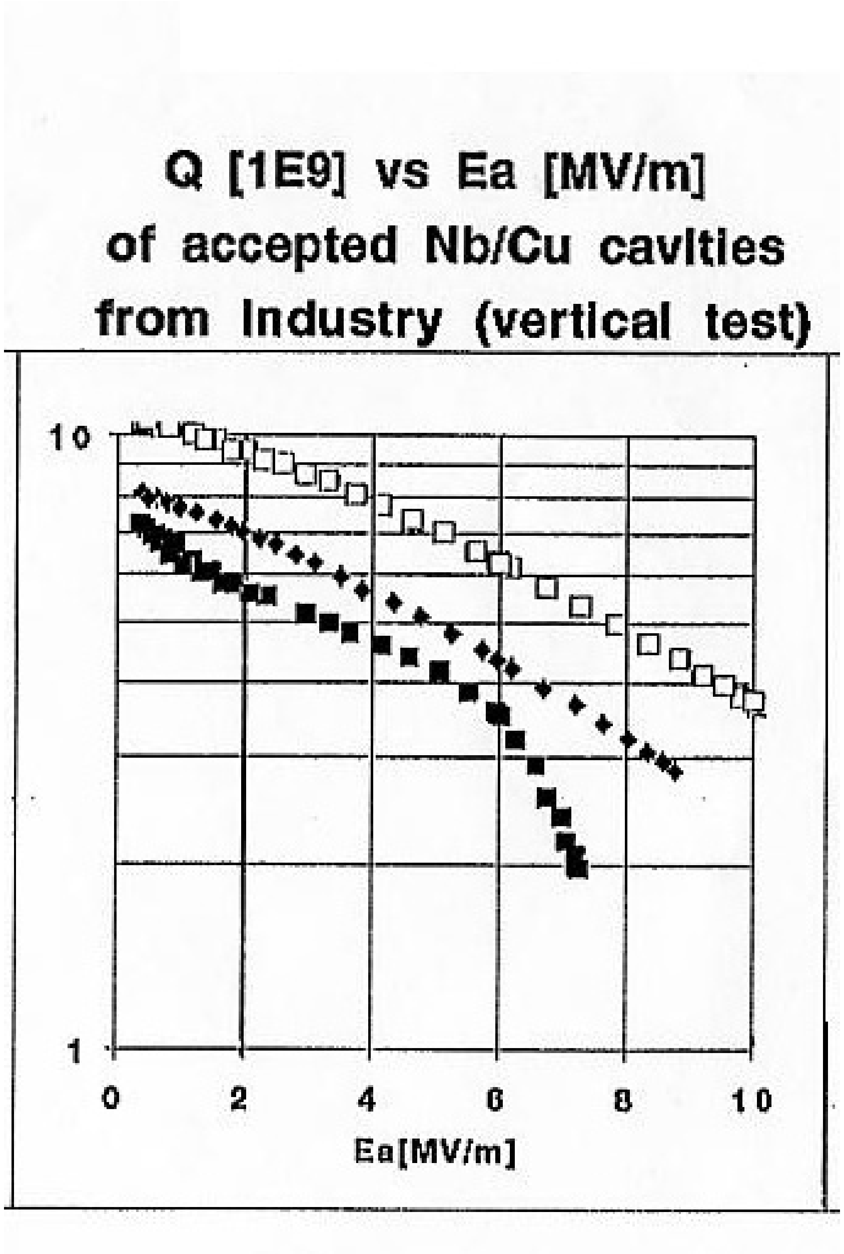
Cost reduction of 200 MHz cavities

Niobium on Copper Cavities
Fabrication

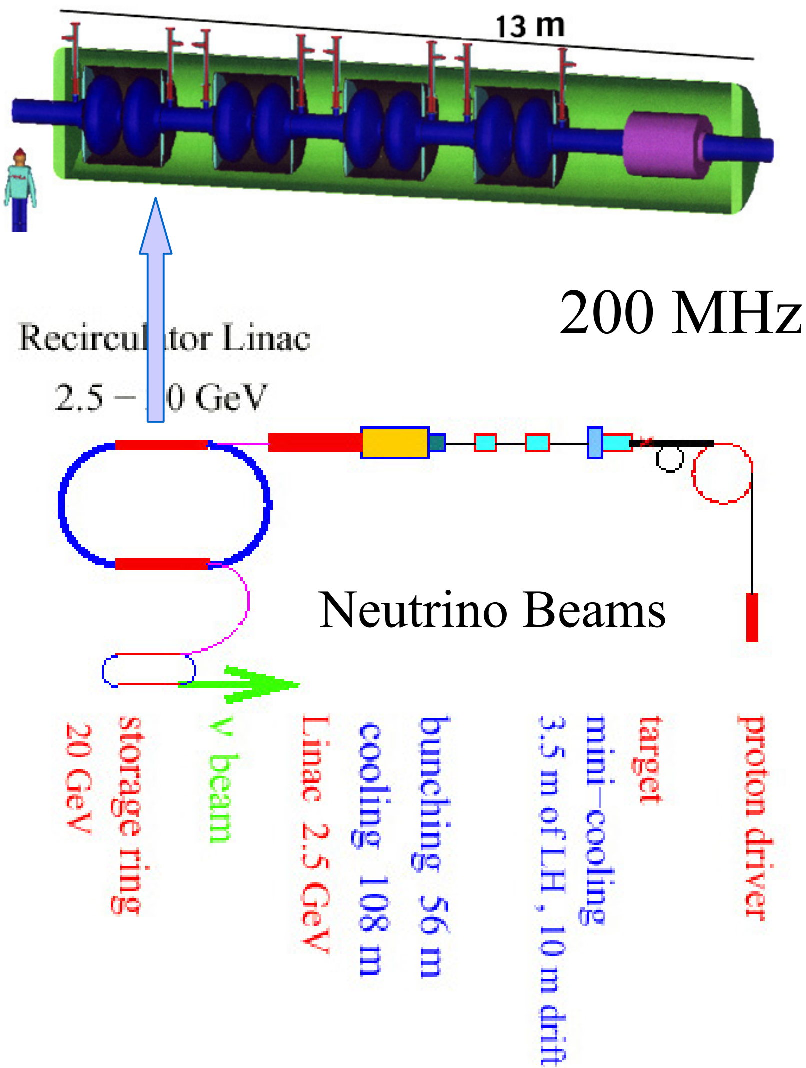




Performance of LEP Cavities 350 made



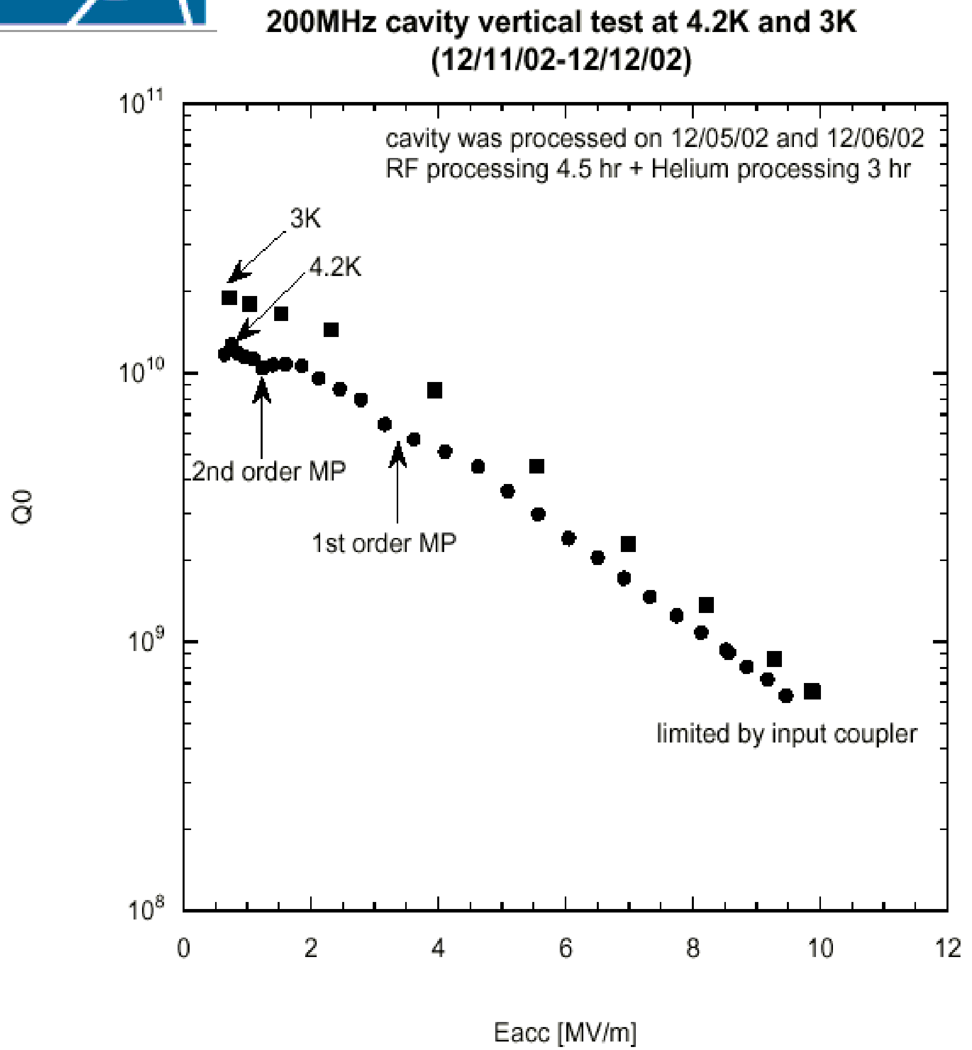
R&D For Neutrino Factory



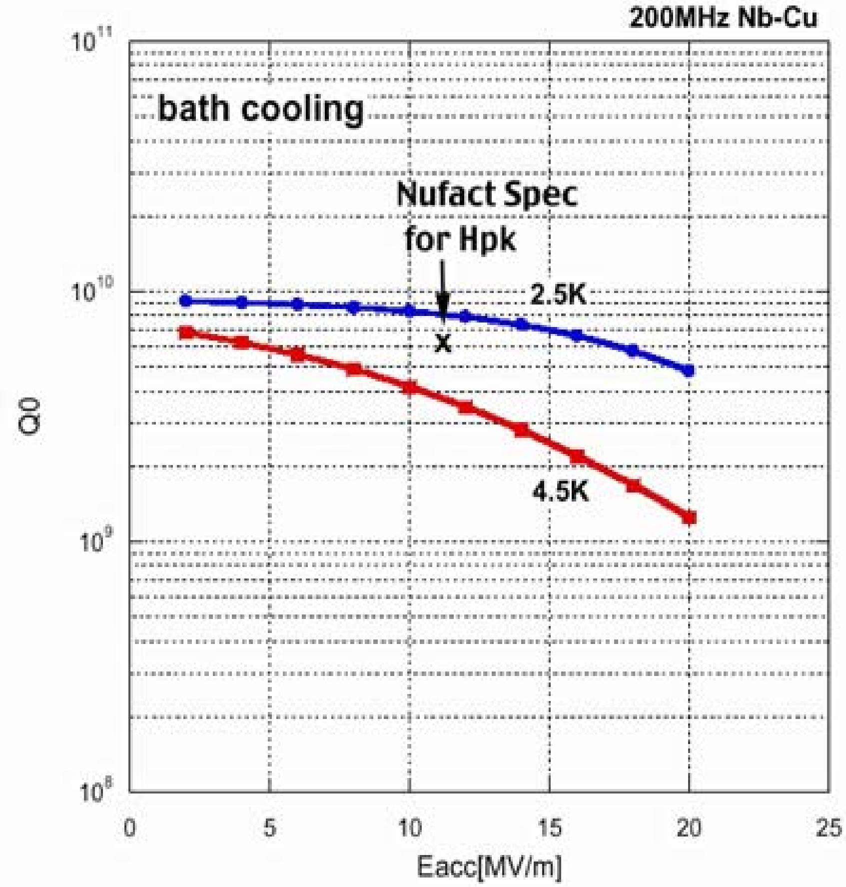
- Muons decay
- Need High Gradient ≈ 15 MV/m
- Need long pulses
  For re-circulation
- SC reduces Peak Power
- Need 500 active m
  Like LEP-II

Test Results

CORNELL



Reference cavity: LHC 400MHz Nb-Cu cavity

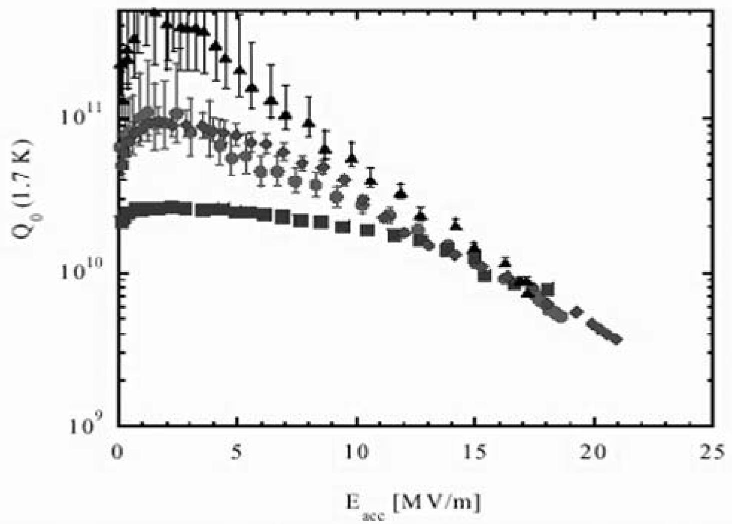


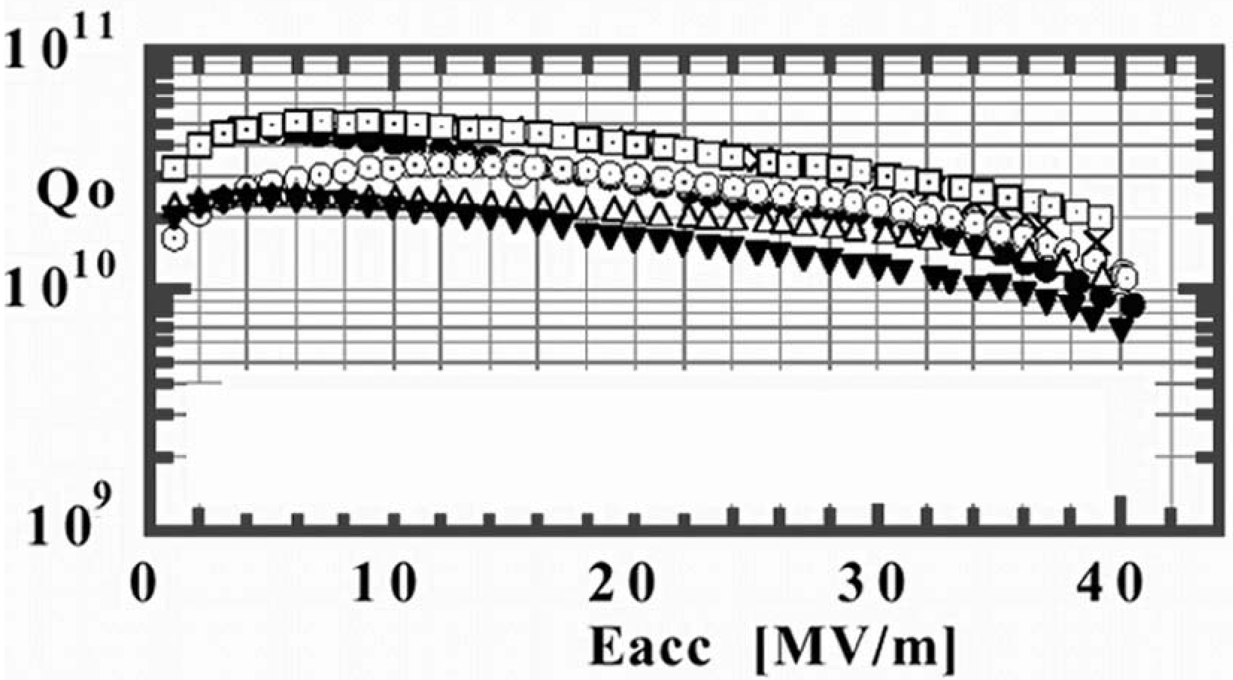
Expected from 400 MHz LHC Cavities

Need to

- Reduce Q-slope and Field emission

Compare Best Nb/Cu with Best Bulk Nb

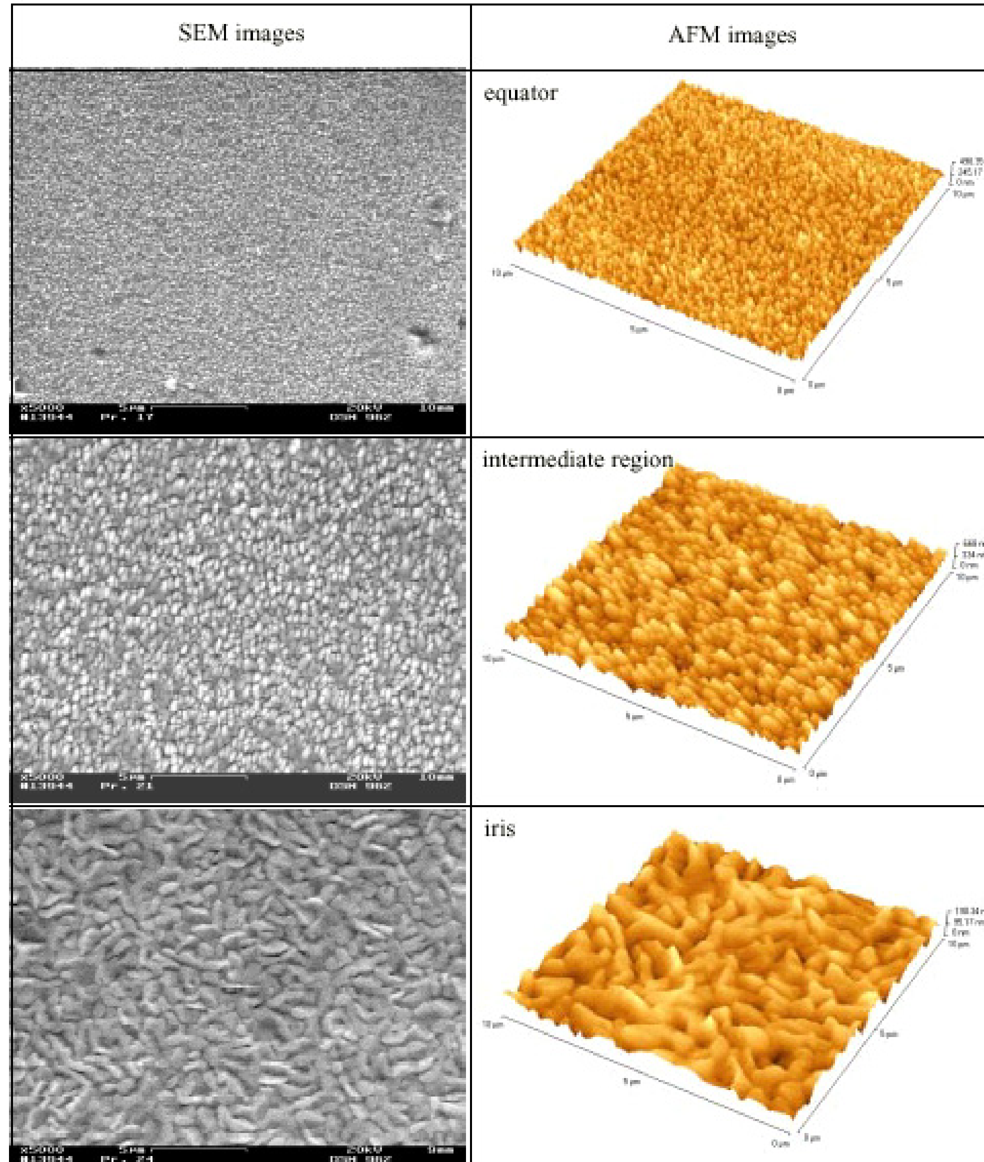




AFM Results on Surface Structure of Nb/Cu (INFN)

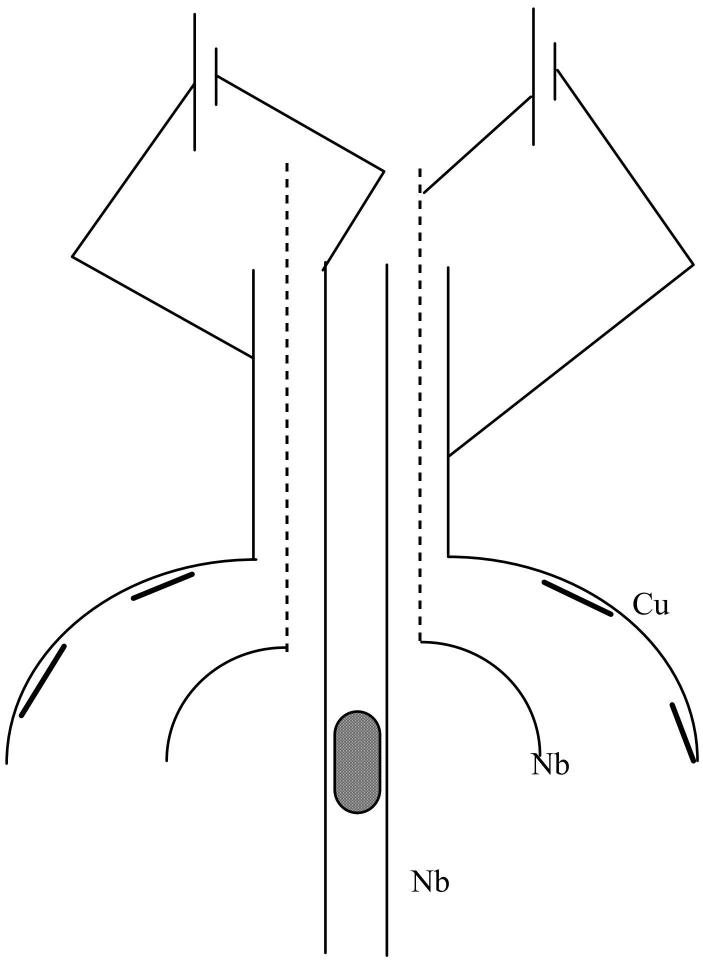
Equator

Q-slope in Nb films is related to grain structure



Iris

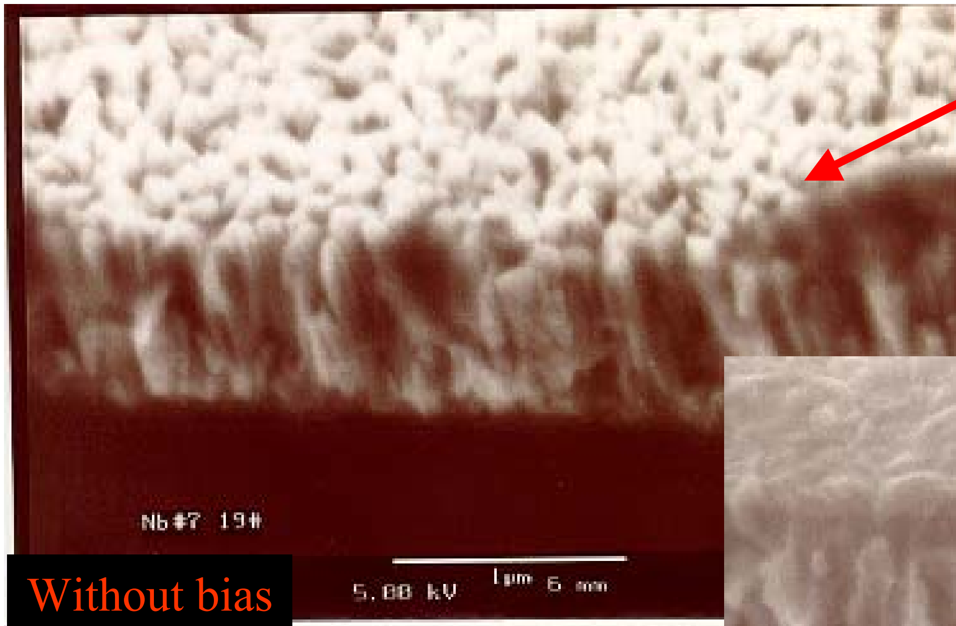
Explore Bias Sputtering Using 500 MHz Cavities



Argon Ion bombardment of Nb film should increase film smoothness

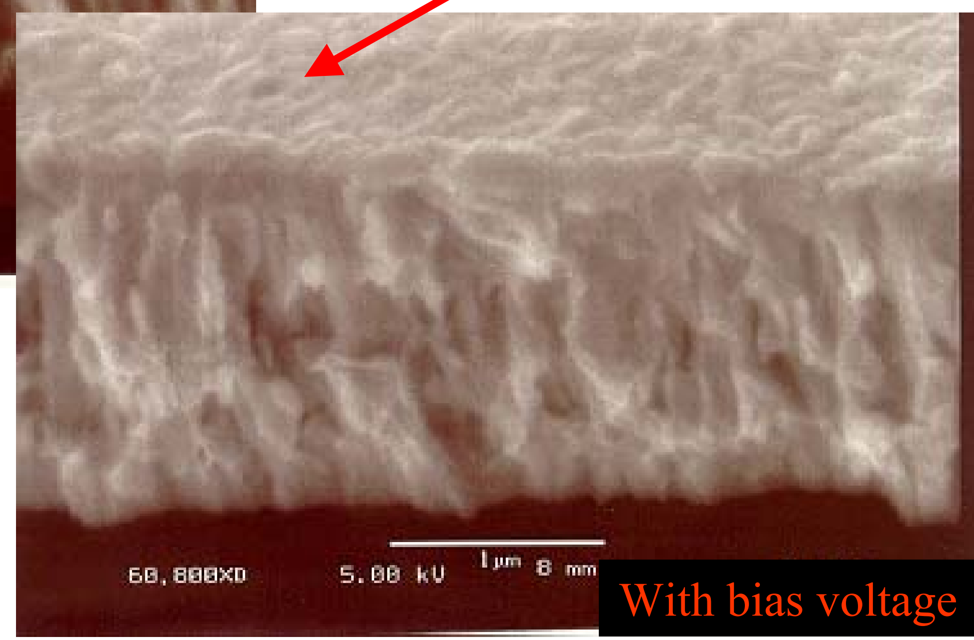
Use surface tools to examine
And compare films

Bias sputtering
Beijing Results



Columnar grains

Dense film

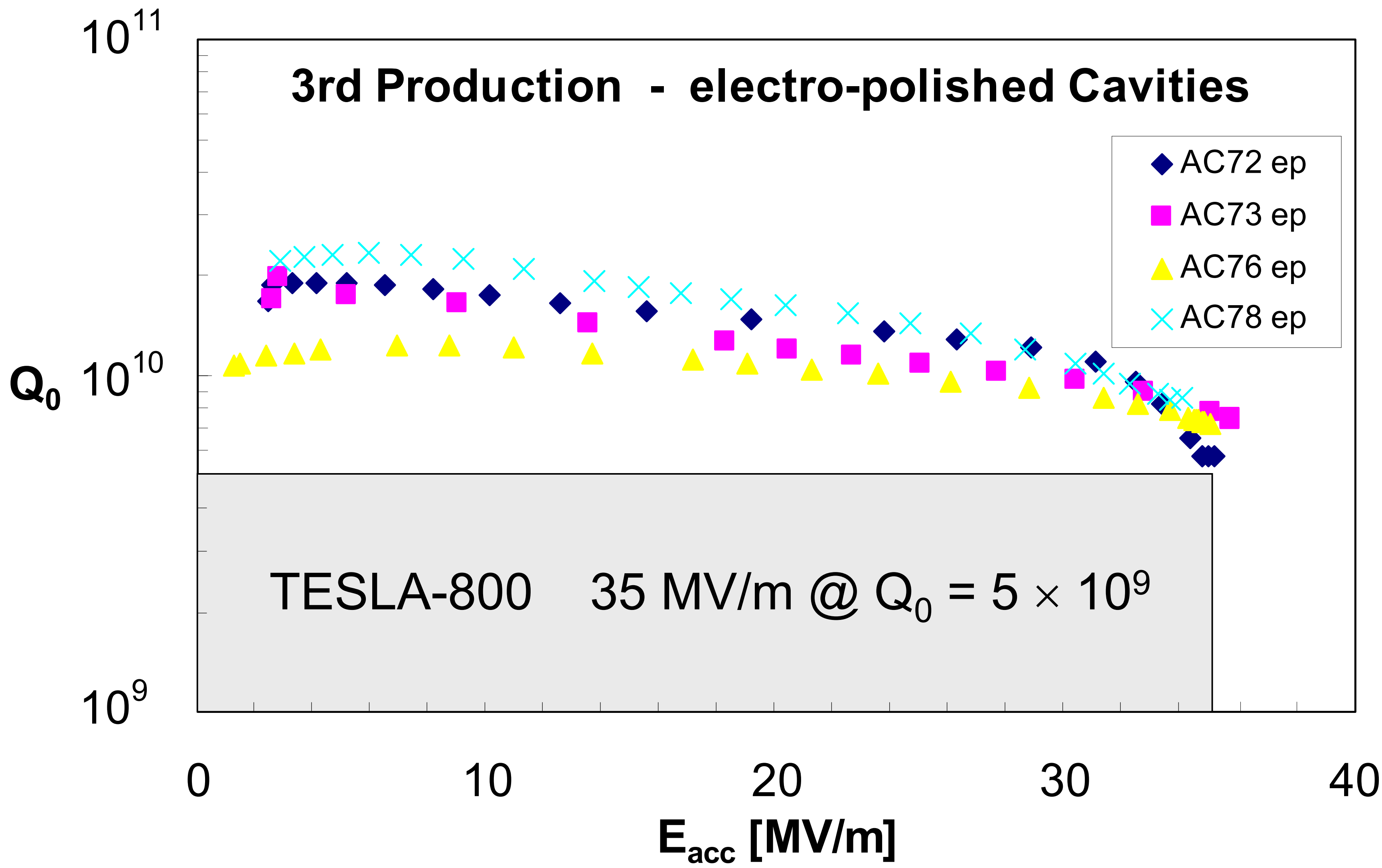


- Apply a bias voltage to substrate
- Induce substrate ion bombardment
- Can achieve defect free film

II. Gaps In Capabilities

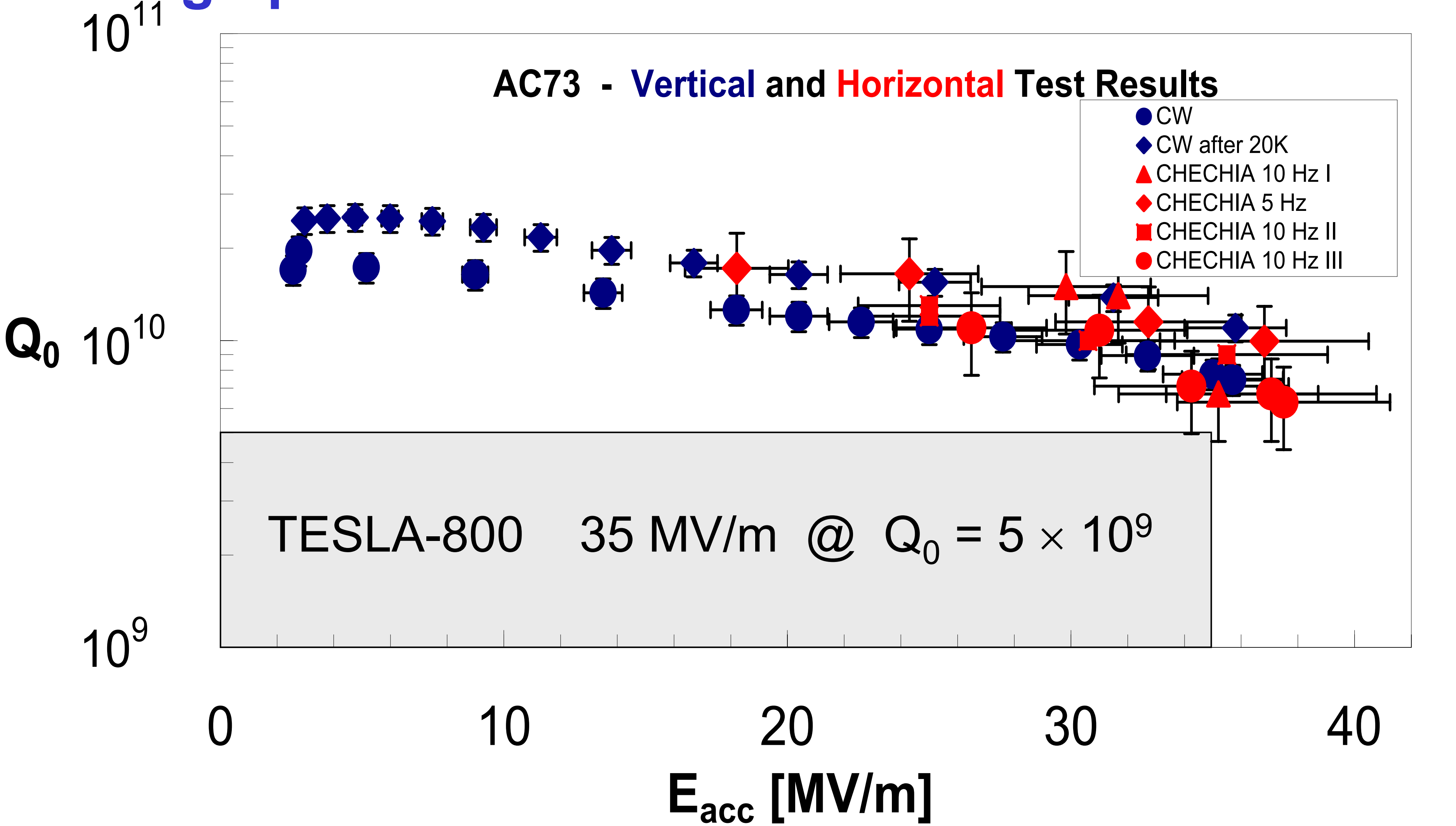
- 35 MV/m demonstrated in naked EP cavities - vertical test
- And 35 MV/m in one fully equipped cavity in horizontal test
- Q values are typically 10^10
- Need demonstration of cryomodule with 35 MV/m cavities
- Need demonstration of CW operation, Q > 10^10
- Need demonstration of high gradient, high Qext operation for low beam power applications

Highest Gradient Performance



More than 35 MV/m in CHECHIA

i.e. high power test and 1/8th of a TTF Linac module



History Lesson -1

- Demonstration of capability leads to new applications,
- e.g CESR beam test of 1500 MHz cavity lead to CEBAF switch from warm to cold
- TTF demonstration of 25 MV/m and KEK demonstration of high power coupler led to
- SNS switch to SC technology

History Lesson- 2

- Collaboration important for challenging demonstrations
- 1995: Fermilab/Cornell/DESY demonstrate 25 MV/m in 1300 MHz cavities
- TTF - large collaboration

Opportunity for a Proposal:
The Fabulous Cryomodule

Must be a collaborative effort

- Demonstrate a cryomodule with multiple goals:
- ERL light source, proton linac, linear collider
- CW operation at E > 20 MV/m
- Q = 5x10^10 at T = 1.6 K, CW
- Pulsed operation at 35 MV/m, Q = 10^10
- Variable input coupler to demonstrate limits for high Qext operation for low beam loading
- Test with beam