Summary of Superconducting RF Materials Workshop 23-25 May, 2007

and Materials Outlook

Fermilab Accelerator Physics and Technology Seminar
16 August, 2007

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Fermilab

With acknowledgment to: Genfa Wu, Claire Antoine, & Helen Edwards

** Lance Cooley is responsible for all content (and errors…)*

Workshop overview

http://tdserver1.fnal.gov/project/workshops/RF_Materials/

- May 23-24, 2007, Fermilab
- Organized by Helen Edwards, Genfa Wu, and Claire Antoine
- About 70 participants
- Purpose: encourage participation in SRF science by academia, industry, and basic science labs in a LTSW-like format
- Focused discussions organized by program committee toward topics of basic interest to SRF science, while in the context of real cavities with real deliverables

A brief history

- Regional workshops 2005 and 2006 organized by Pierre Bauer and Claire Antoine (Midwest SRF Collaboration): FNAL, UW, NU, MSU
- Materials workshop at FNAL 2001, DESY 2003 mostly Cornell – JLAB – DESY – KEK
- 13th annual International Workshop on RF Superconductivity, Beijing, October 2007
- 2007 workshop represents a national critical mass! Funding sources are now responding positively!
- Intention: continue *national* workshop annually or semi-annually

Charge from Claire Antoine
(see ATP seminar 22 Feb 2007)

- Understand basic issues
- Evolve beyond niobium's limits; open up new frontiers
- Understand physics and materials science
- Bring to bear surface science coordinated with characterization of real cavities
- Build interactions, form coordinated research activities, promote interdisciplinary studies
- Extend SRF materials community to basic science
- Expand SRF materials community to academia and industry

Workshop topics

- Fundamentals of RF superconductivity
- Materials properties and surface characterizations
- New materials
- Innovative processing of materials
- Production of niobium

Main Findings

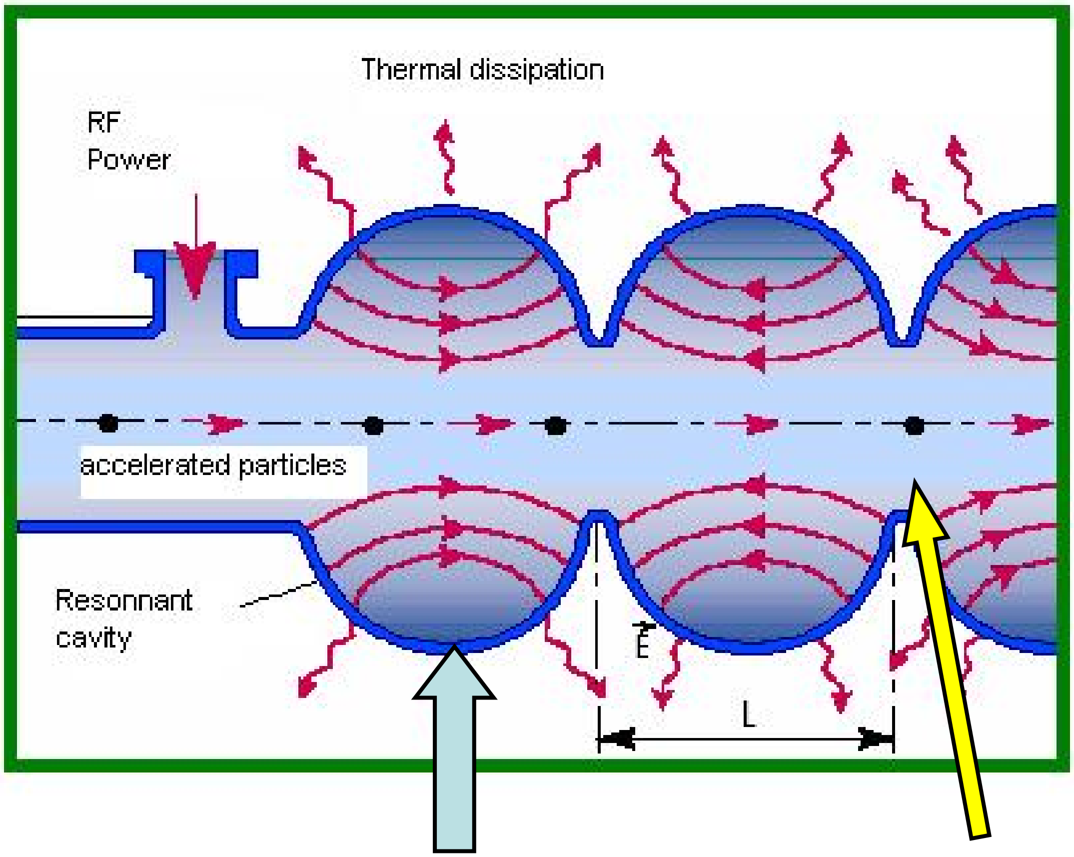
- A new era may be emerging where internal surfaces of RF cavities are engineered by design.
  - Conformal multilayers
  - Protective coatings
  - Roughness removal
  - Re-plating Nb
- Gurevich theory to break niobium monopoly can now be tested in real cavity forms

- Exciting new tools make it possible to search out problem areas and perform materials science
  - RF microscope
  - Scanned laser microscope
  - Orientation imaging microscopy
- An analog of the "short sample test" is missing
  - LANL cavity
  - U Md resonator

Main Findings, cont.

- Progress toward under-standing inter-relationships between surface structure, surface chemistry, and Nb cavity performance
  - Oxygen and oxides
  - Tantalum: relax spec?
  - QA and tracking processing history
- Alternatives to HF etching exist
  - Ion cluster bombardment
  - Plasma etching
  - Single crystals (already smooth)
- Messages to HEP:
  - Much work is bootstrapped – need support
  - New talent is being uncovered!

A basic SRF cavity…



Region of highest magnetic field

Region of highest electric field

Quality coefficient
$Q_0 \propto G / R_s$

G = geometry factor
i.e. E_{acc} depends on the shape

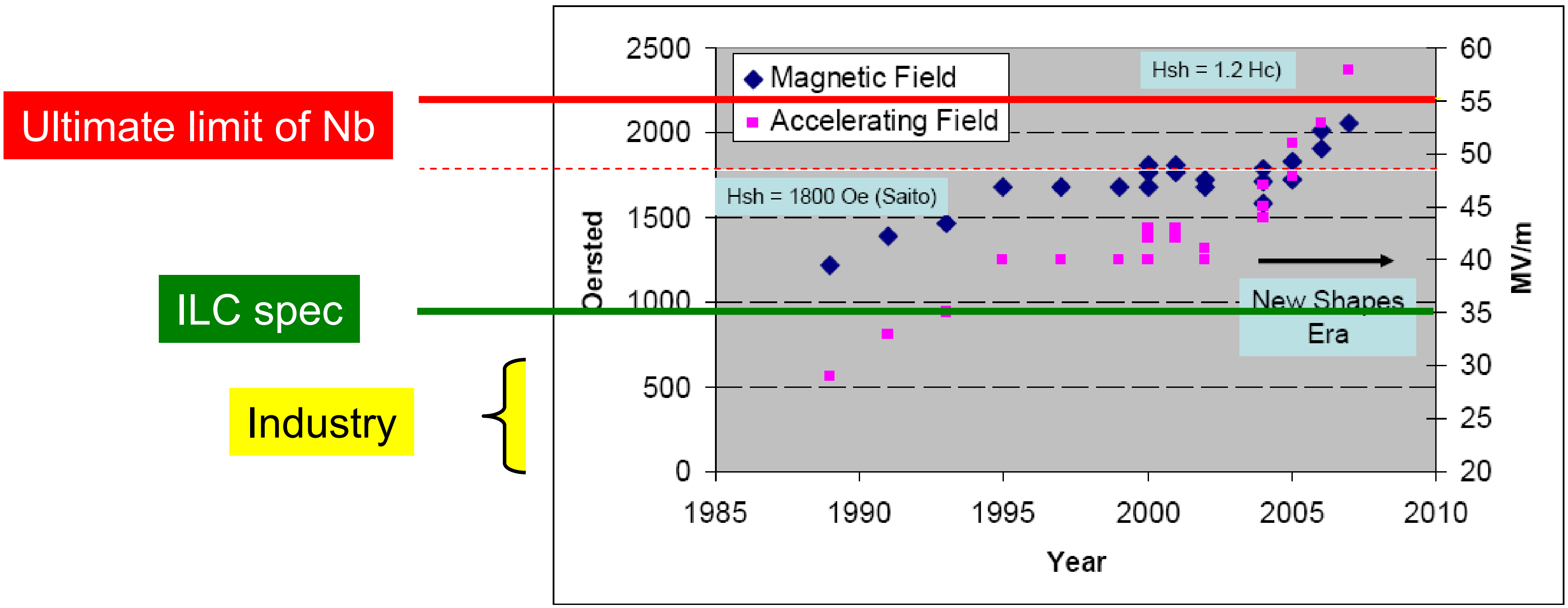
Surface resistance R_S
$R_S(Nb) \sim 1$ nΩ @ 2K
$<< R_s(Cu) \sim 100$ μΩ

$E_{surf} \sim 10^6$-10^7 V/m
$J_{surf} \sim 10^9$-10^{10} A/m^2
$H_{surf} \sim 100$ mT or more
$\lambda_L \sim 50$ nm

Graphics from C. Antoine APT seminar

SRF state of the art

- Extremely pure niobium provides the highest possible surface RF field of any material



Graphics from Singer and Padamsee

Performance metric: Q vs E

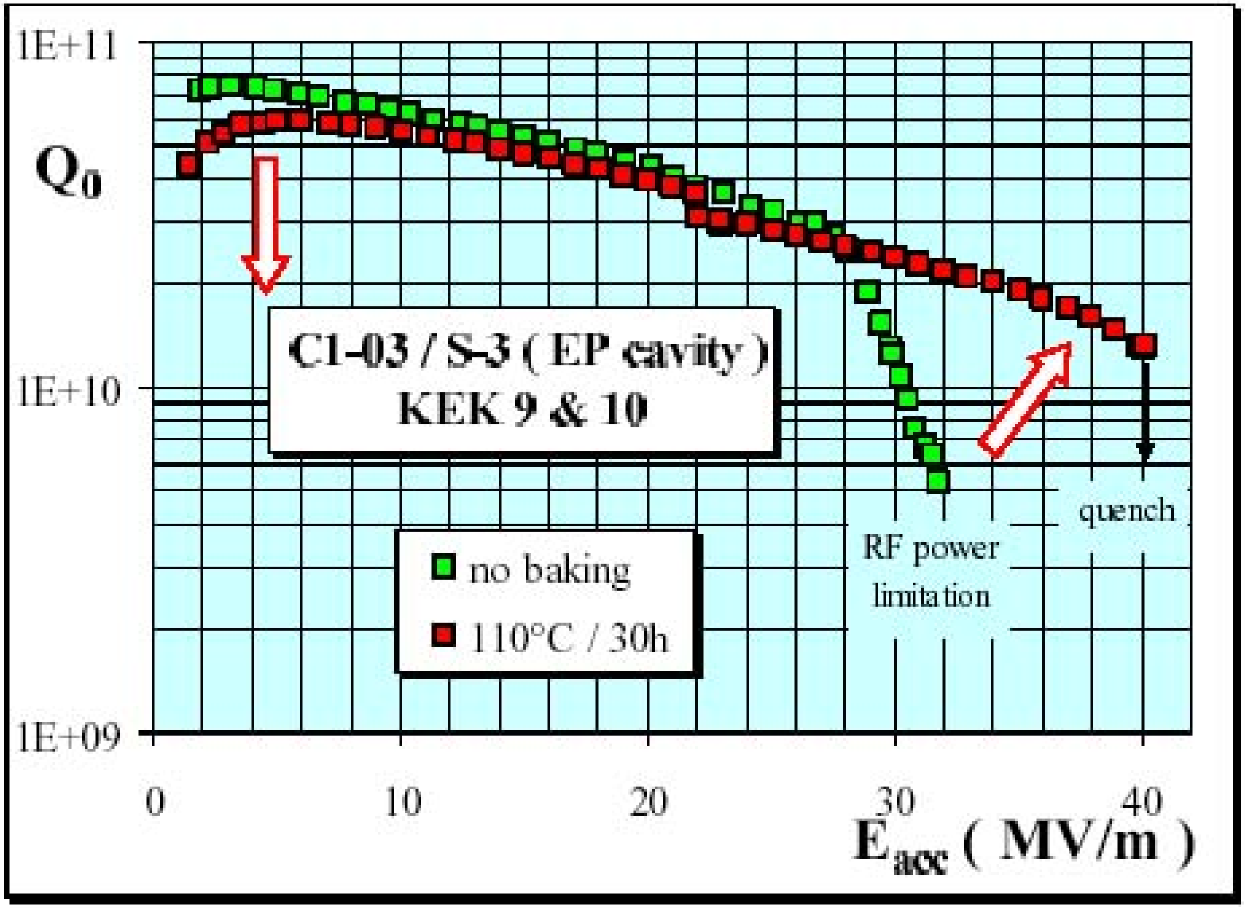


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

Plot from Padamsee talk 2

Performance is sensitive to many things, some rooted in the material and some in cavity preparation

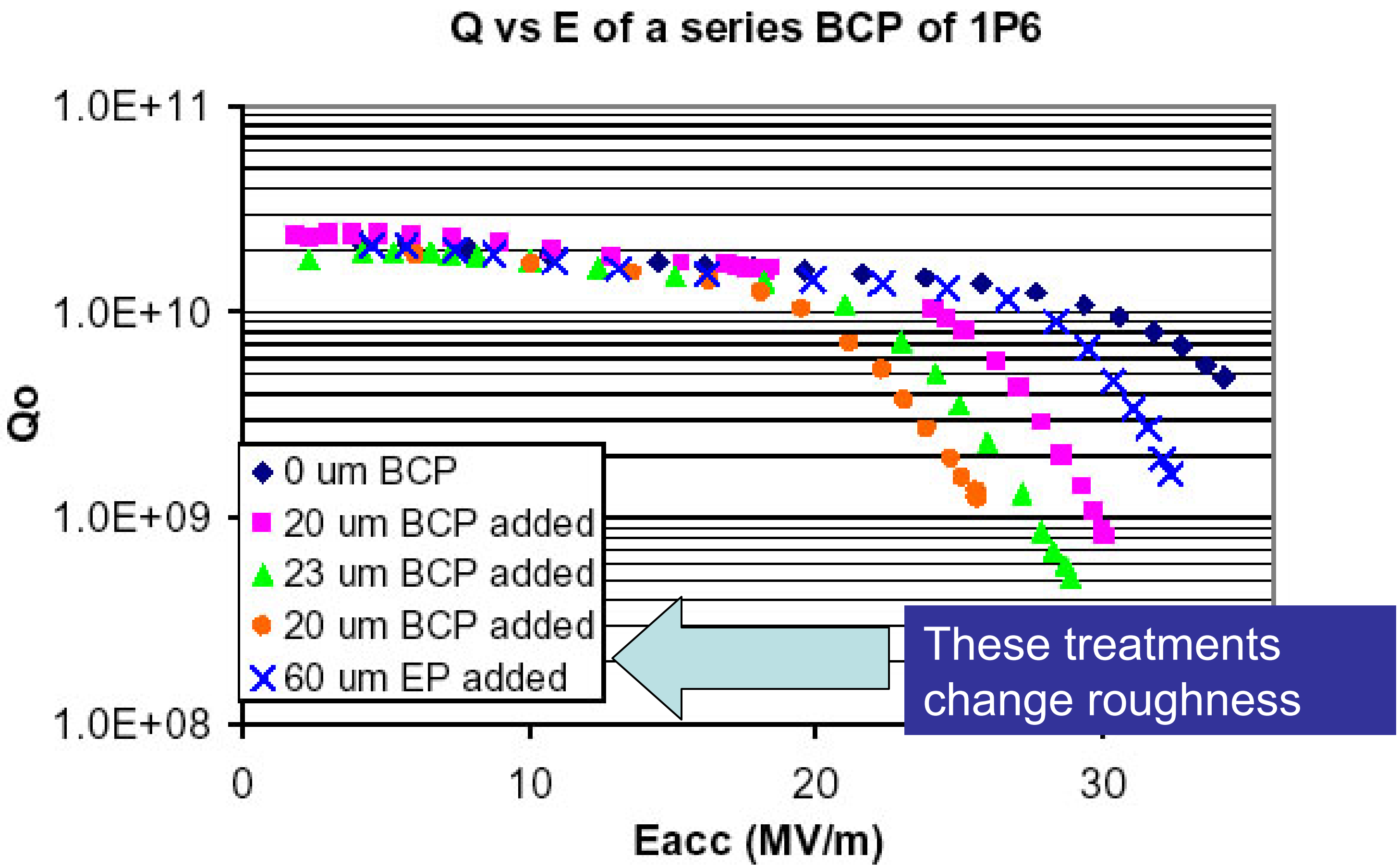


Fig. 9: Q vs. E of a series of BCP on 1P6

Plot from Padamsee talk 2

Detail of the usual process (1/2)

	WHY	COMMENT
Forming		
EB welding	*Clean welding*	*Nb gets H, C, N, O. All contaminants degrade SC @ weld Þ Q_0/10*
Ti purification	*Remove interstital contaminants*	*Needs 1400 °C in high vacuum. RRR 300-400 now commercially available*
Deep etching (**BCP**, **EP**)	*Remove damage layer (~100 µm)*	*Etchants are nasty! Need smooth and clean surface*
800°C annealing	*Remove hydrogen contamination*	*Hydrogen is a byproduct of deep acid etching*
Light etching	*Remove trace contaminants from surface layer (O, C, N)*	*Diffusion length < 10 µm*

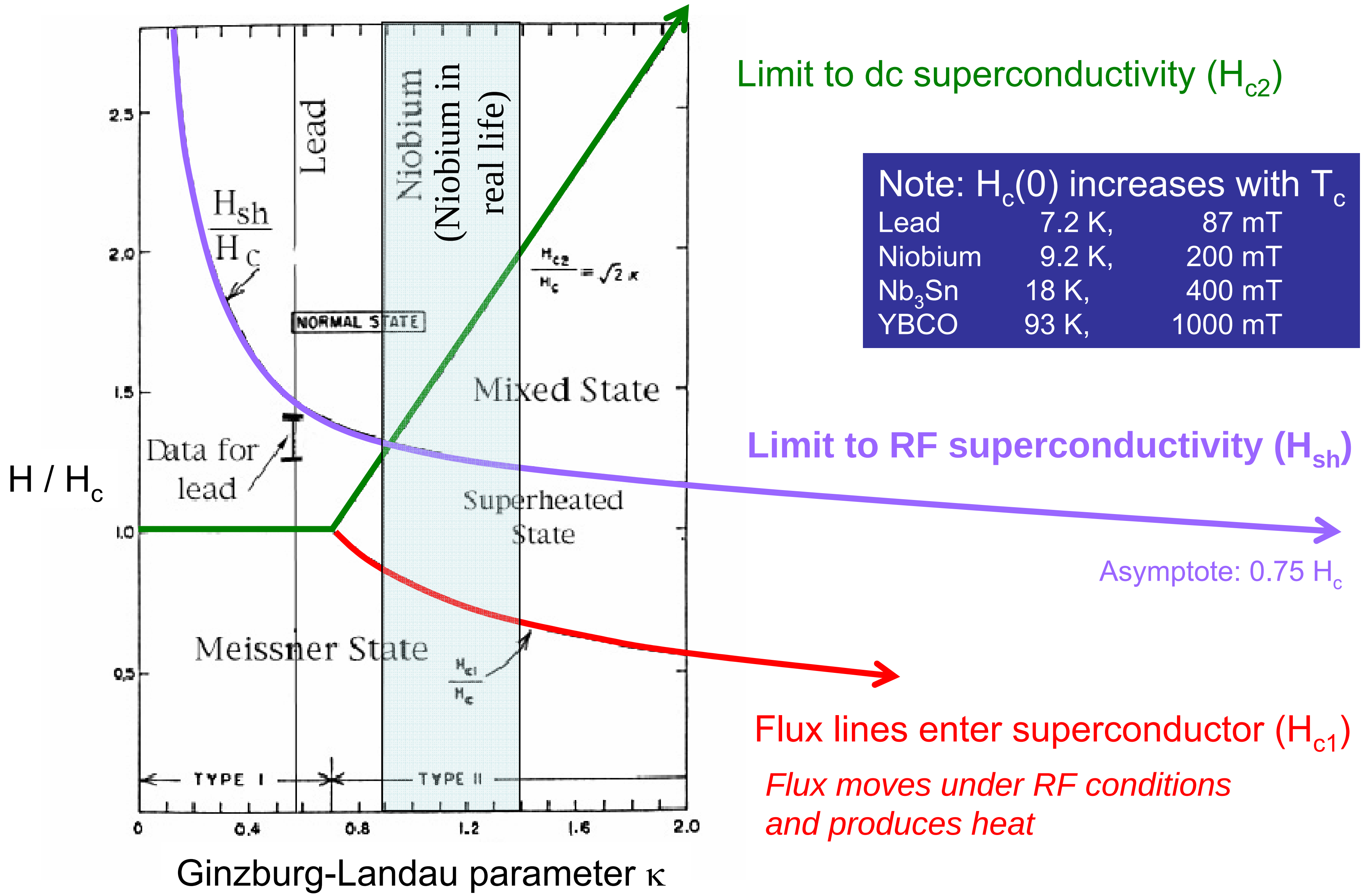
Slide from Claire Antoine

Detail of the usual process (2/2)

	WHY	COMMENT
…Light etching		
…Special rinse	*Remove sulfur*	*Sulfur particles are residues of EP, and become field emitters*
HPR	*Get rid of dust, flakes, etc.*	*High-pressure ultra-high purity water is convenient, but not sufficient*
Assembly	*Couplers, antennas, …*	***In clean room**. But re-contamination is possible (e.g from bolt threads)*
Baking, 120°C, 48h	*Diffuse oxygen away from surface?*	*Why this works is not understood. Affects 50 nm within surface*
Post processing	*Get rid of dust from assembly*	*(Experimental) Ex: dry ice cleaning, plasma*
RF test		
He processing, HPP	*Fix field emission*	*Use pulsed fields to ablate remaining junk*

Slide from Claire Antoine

Highlights – Limits to SRF (Ginzburg-Landau theory)



Flux moves under RF conditions and produces heat

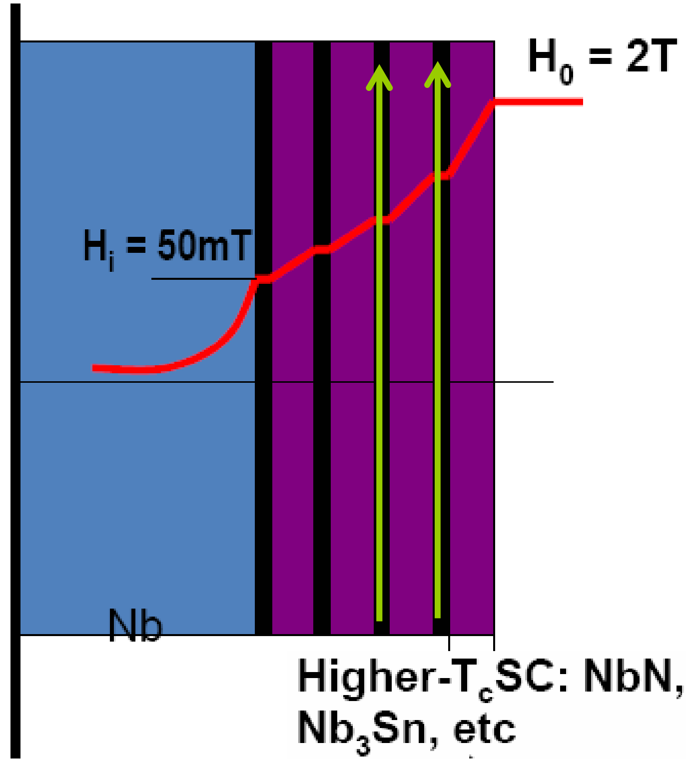
Note: $H_c(0)$ increases with T_c

Lead	7.2 K,	87 mT
Niobium	9.2 K,	200 mT
Nb_3Sn	18 K,	400 mT
YBCO	93 K,	1000 mT

Plot from Padamsee

How to use materials with higher Hc than Nb?

- Alex Gurevich (FSU): SRF is limited by flux motion at fields below H_{sh}
  - Implication: hot-spot models should explain quenches
  - Implication: build multilayers, expel flux to non superconducting layers
    - Alloys and compounds can be used
    - Thin superconductors have enhanced H_{c1}, so they resist flux entry



Example: Nb_3Sn layers with d = 30nm
λ_0 = 65 nm and H_{c1} = 2.4T

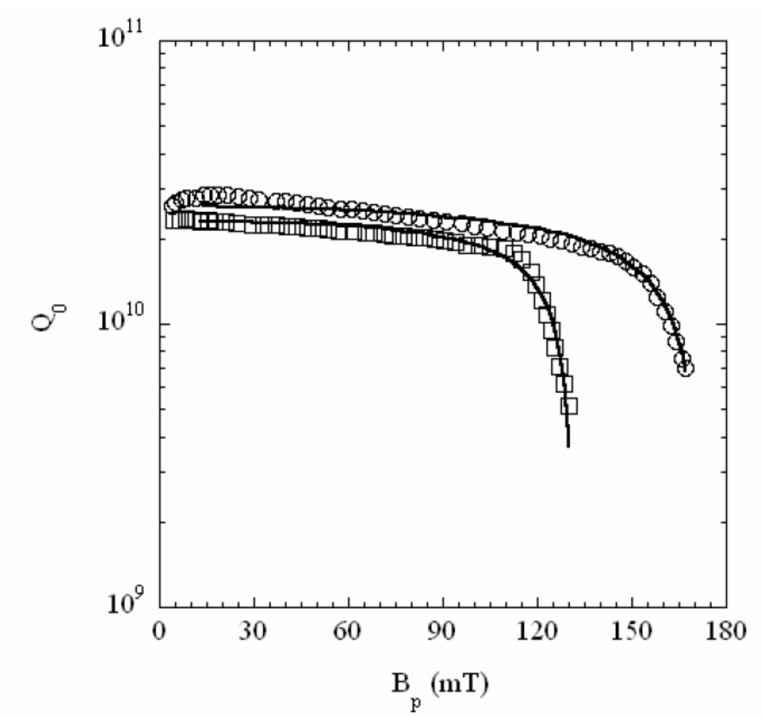
10× higher acc. field!

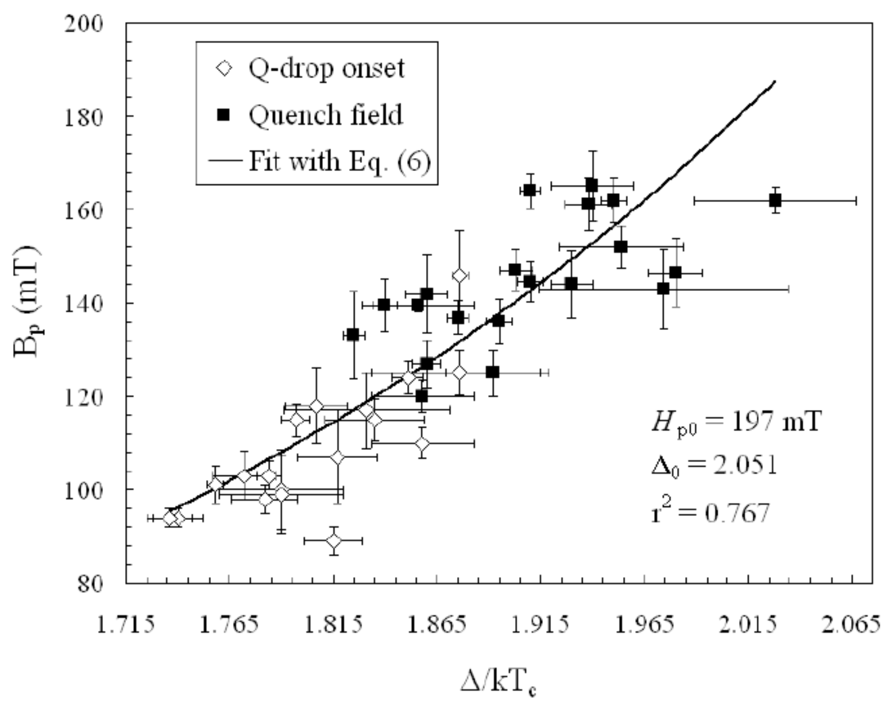
Slide from Gurevich

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 062002 (2007)

Measurement of the high-field *Q* drop in a high-purity large-grain niobium cavity for different oxidation processes

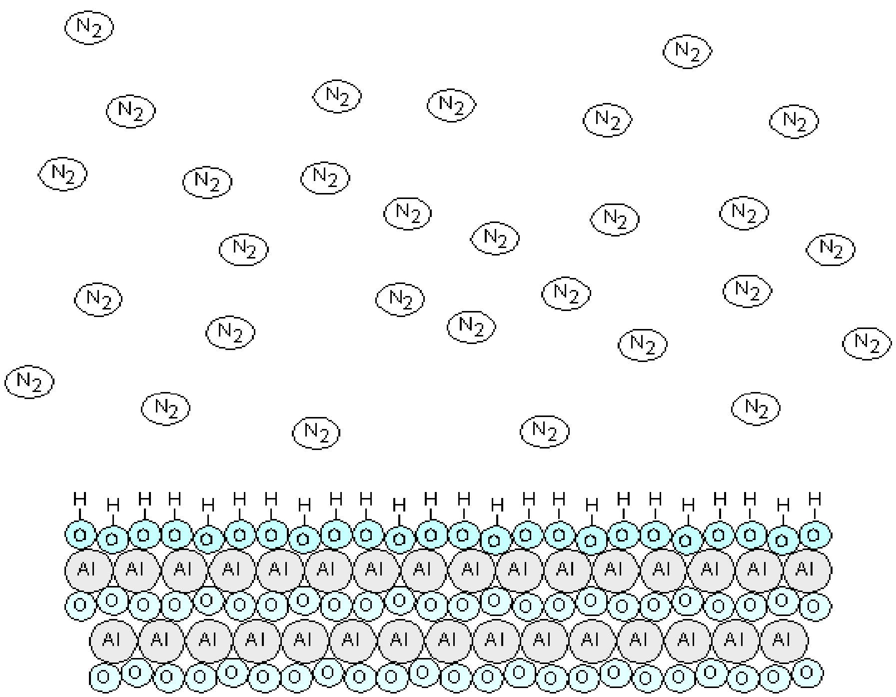
G. Ciovati,[1,*] P. Kneisel,[1] and A. Gurevich[2]
[1]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[2]*Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA*
(Received 8 May 2007; published 27 June 2007)





Fits are according to hot-spot model

Atomic layer deposition: route to coatings and multilayers? M. Pellin, J. Norem - ANL



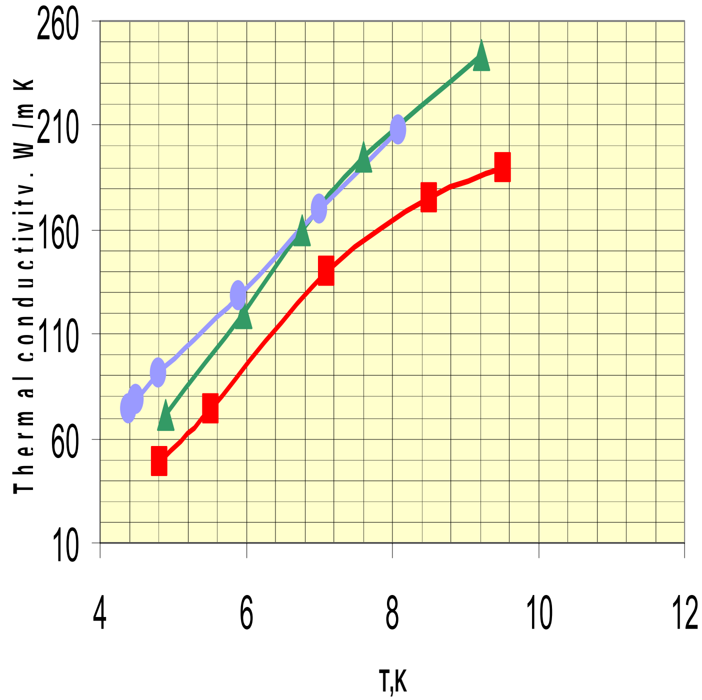
- Paired chemical-vapor reactions are used
  - Surface atoms control reactions
  - Surface atoms that stop one reaction can start another
  - Reaction products leave behind surface atoms that prevent subsequent reaction, so one and only one layer is formed at a time
  - Coating is conformal; ellipsoidal cavities can be coated

Slide from Norem

Highlights

- Pure Nb is specified for good thermal conductivity.
- Tantalum content from 200 to 1300 wt. ppm does not seem to produce a performance change when cavities are operating at ~25 MV/m.
  - Therefore, should we relax the spec to reduce cost?
- Tantalum content *does* produce a small dropoff in performance, about 10%, for ~35 MV/m cavities.
  - No Ta-rich cavity exceeded 33 MV/m

Tantalum content:
Low Medium High

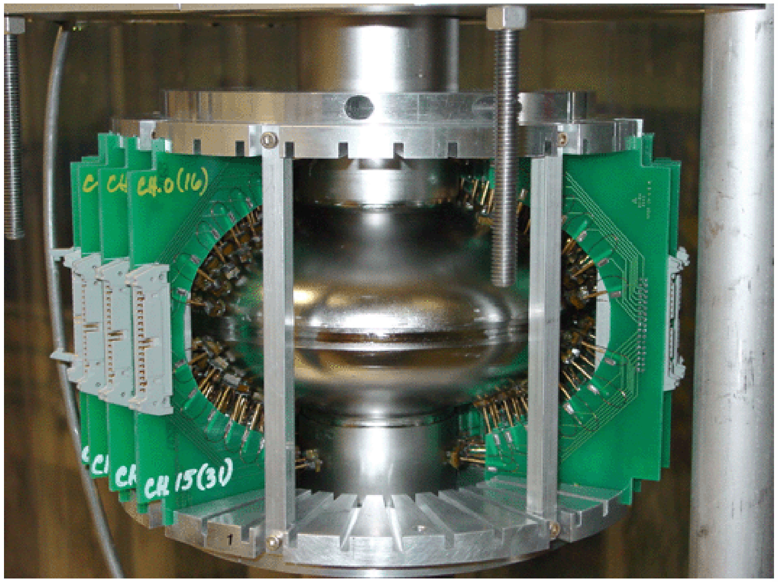


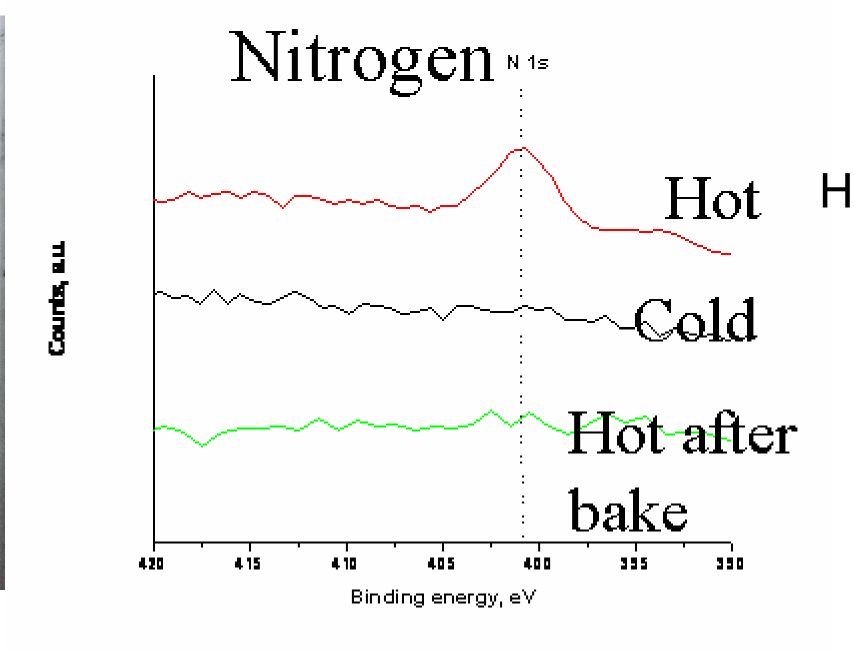
Plot from Singer

Dissection of a cavity with hot spots

Romanenko - Cornell

- Cut out hot spots to see what's wrong using advanced surface probes
- Oxygen? No.   Roughness? No.
- Evidence for nitrates – first time ever seen



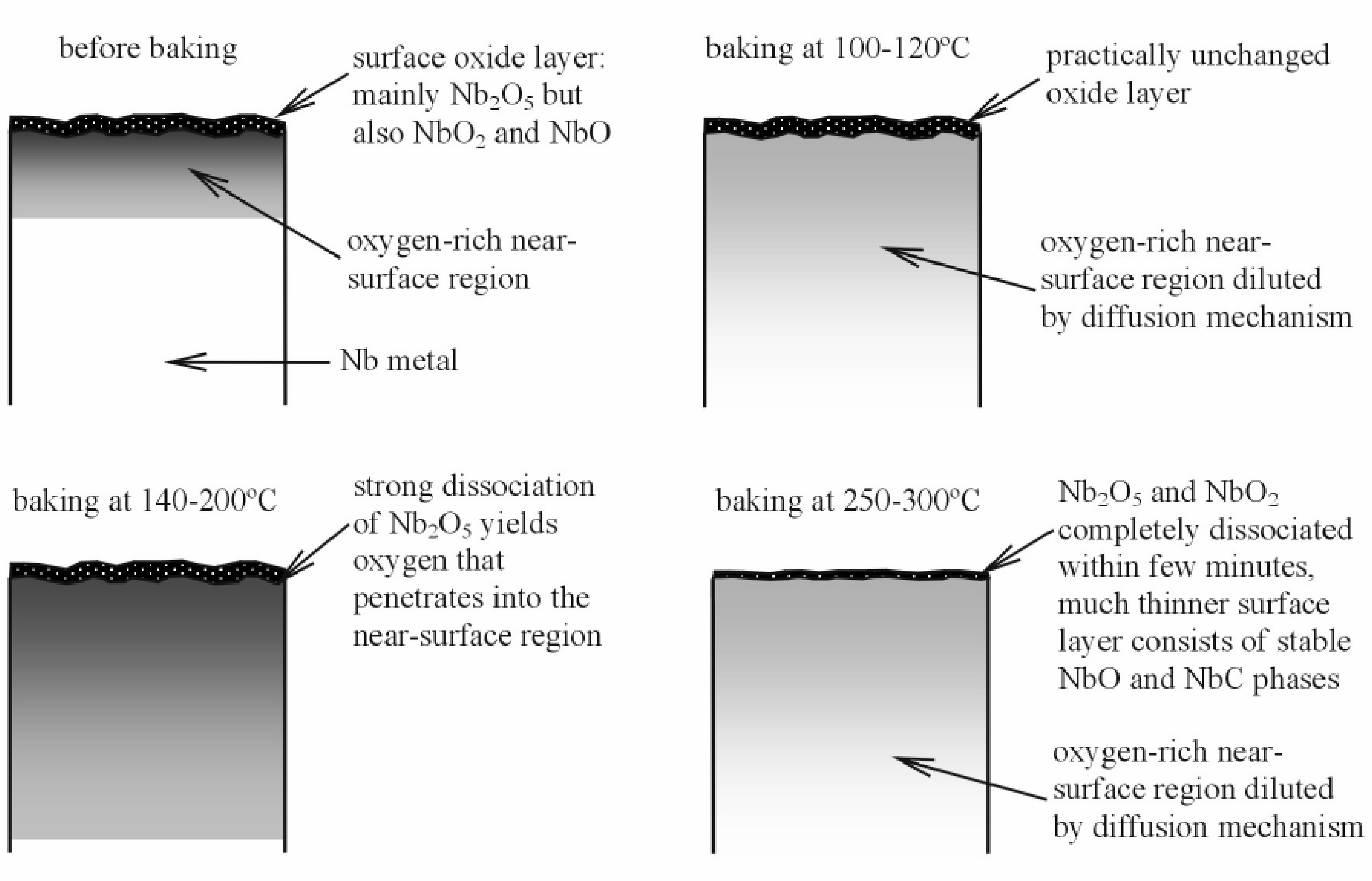


Hot spot

Plot from Romanenko

Oxygen pollution model

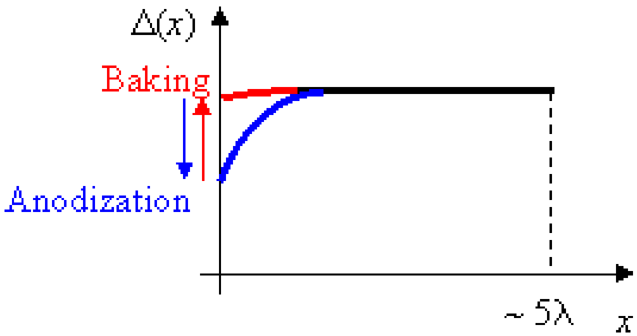
H. Safa, K. Kowalski, G. Ciovati



Graphics from Ciovati

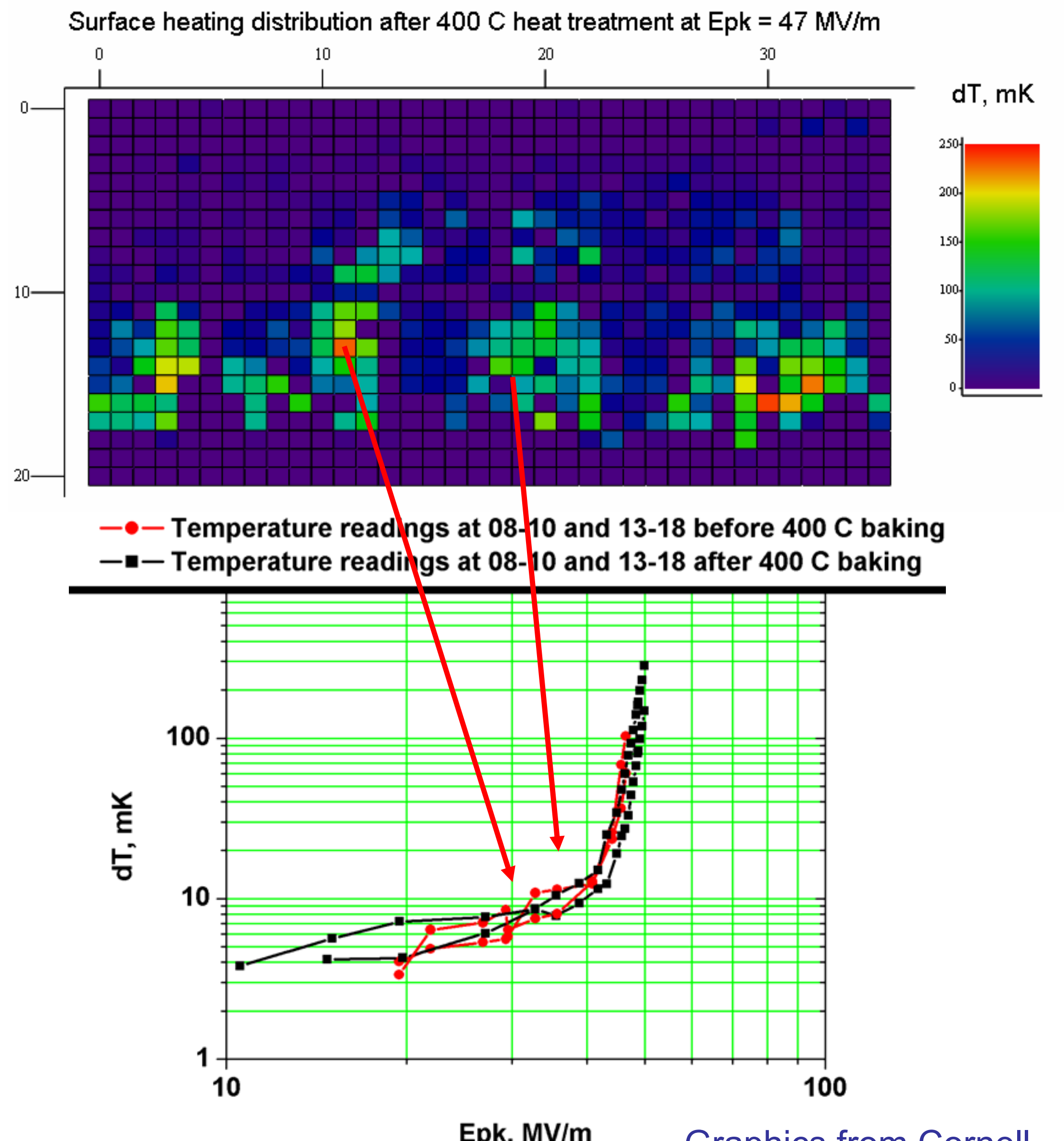
Testing the “pollution model”

Eremev - Cornell



- Baking moves oxygen but doesn’t fix hot spots

- Thus, oxygen seems not to be the cause of hot spots

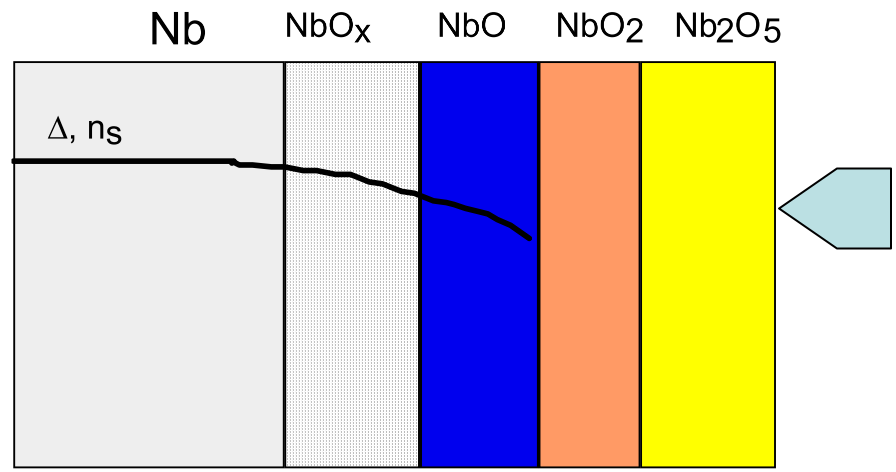


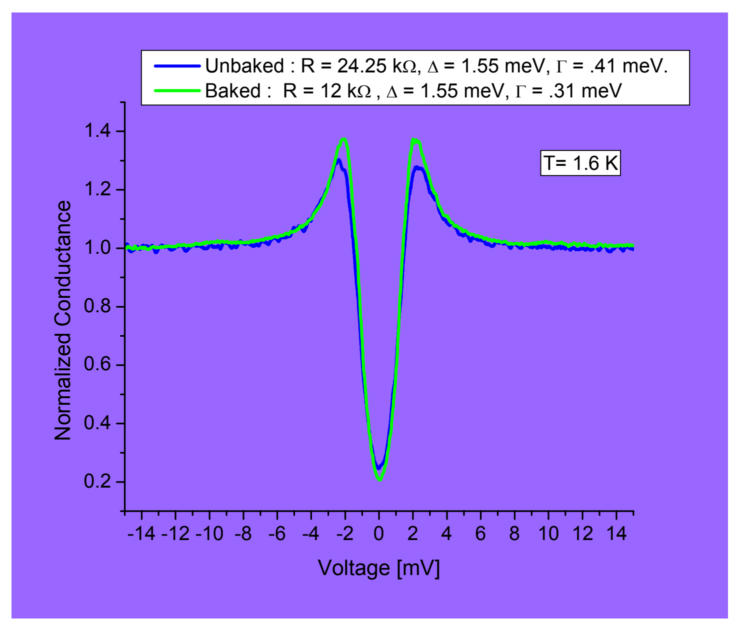
Graphics from Cornell

Testing the "pollution model"

Zasadzinski - IIT, Iavarone - ANL

- Virtually no change in the superconducting gap for tunneling through oxide or for "burying" tip – suggests oxide layer has *no* effect on superconductivity!
  - But subtle differences could matter
  - Need modeling



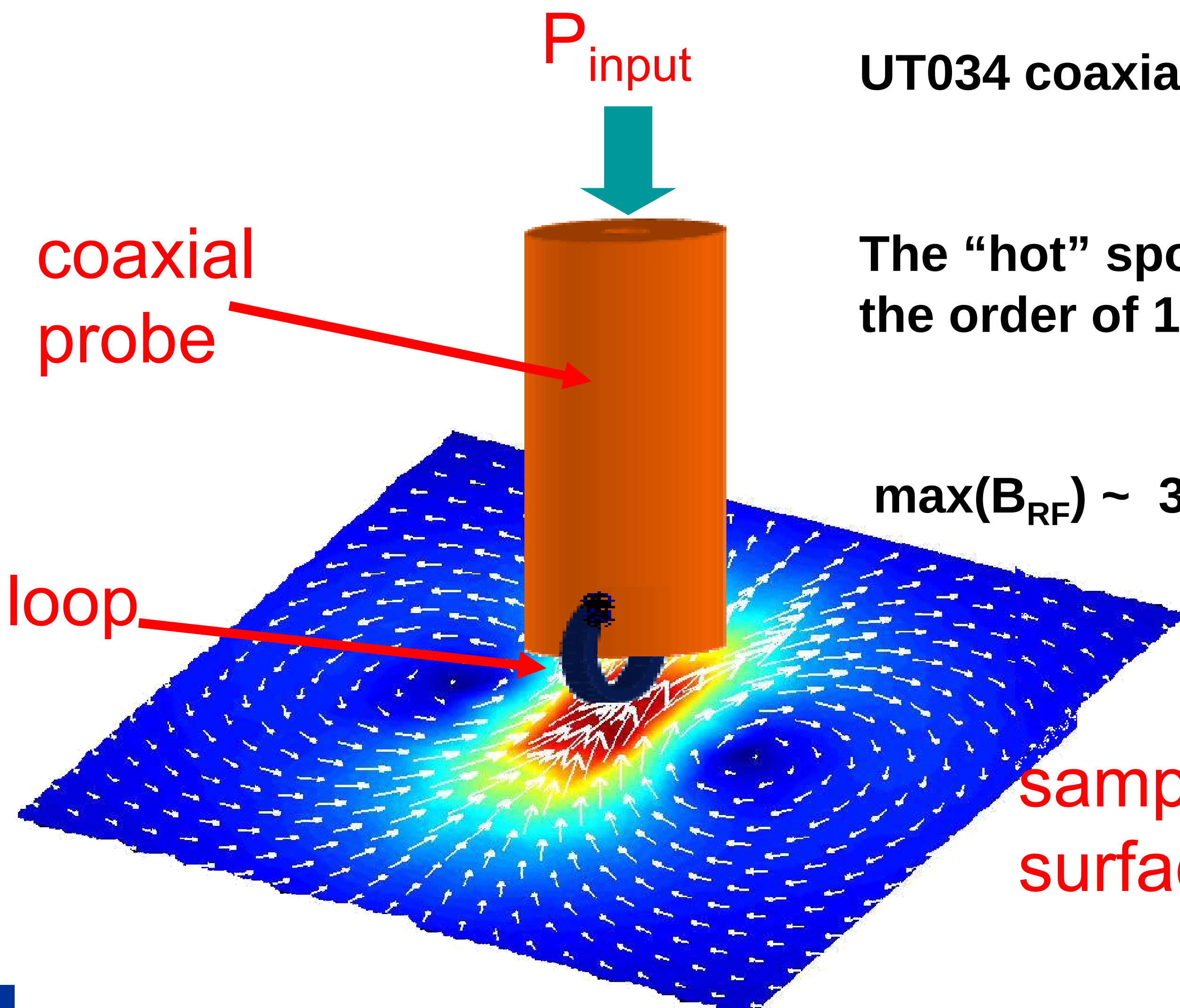


As-cleaned
Baked

Graphics from Zasadzinski

Scanning RF microscopy

Steve Anlage - Maryland



UT034 coaxial transmission line:

The "hot" spot has dimensions on the order of 100 X 500 μm

max(B_{RF}) ~ 3 mT (@ 1 W)

Graphics from Anlage

350 mT for 1 W

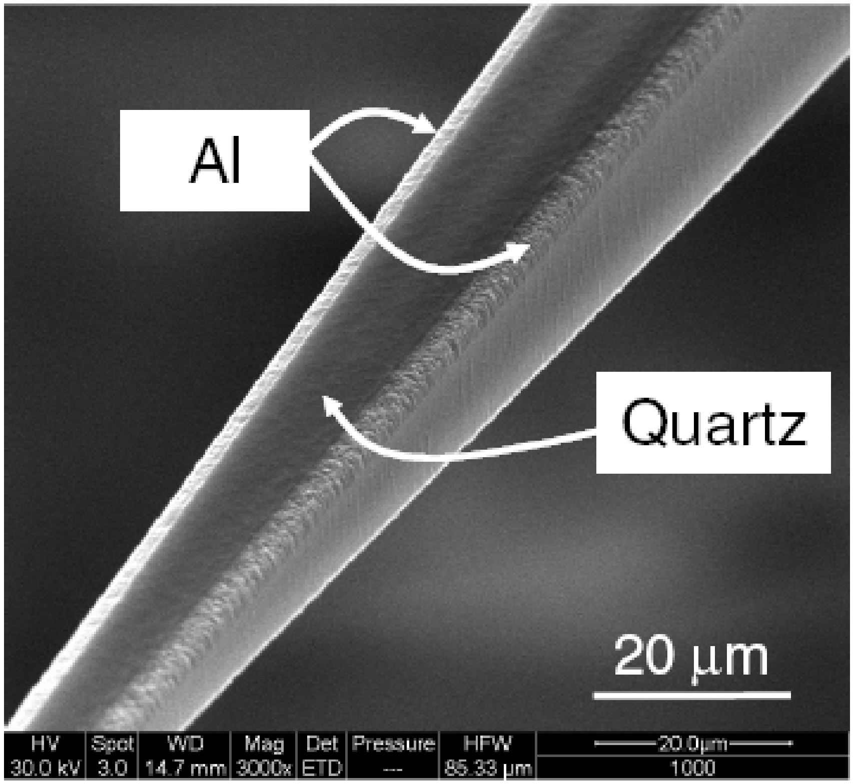
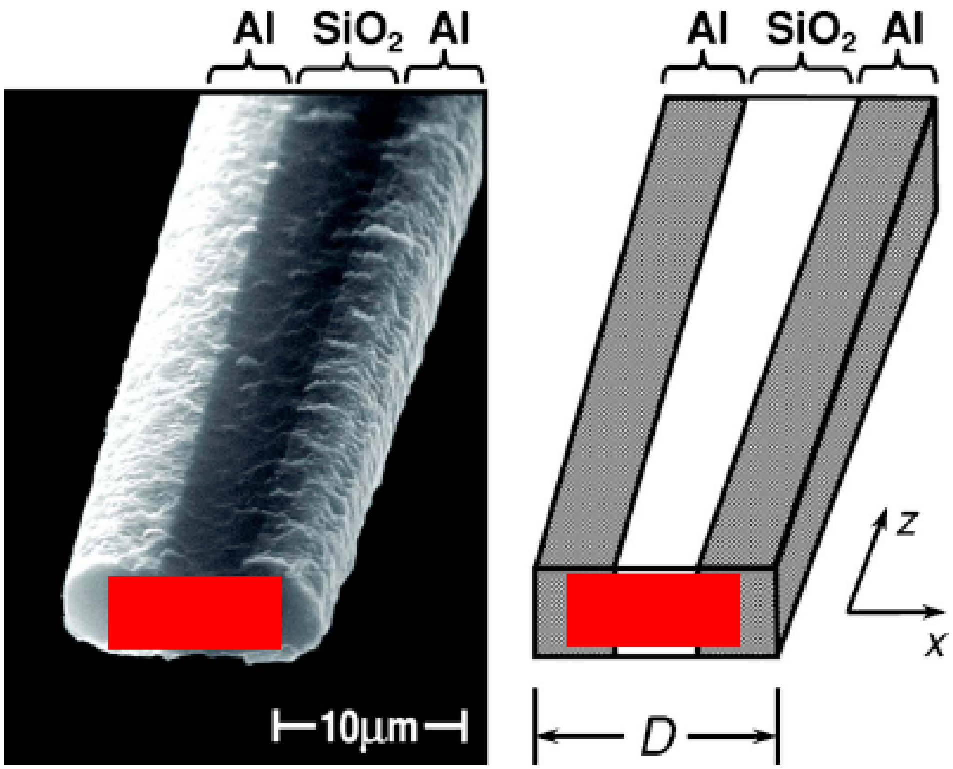


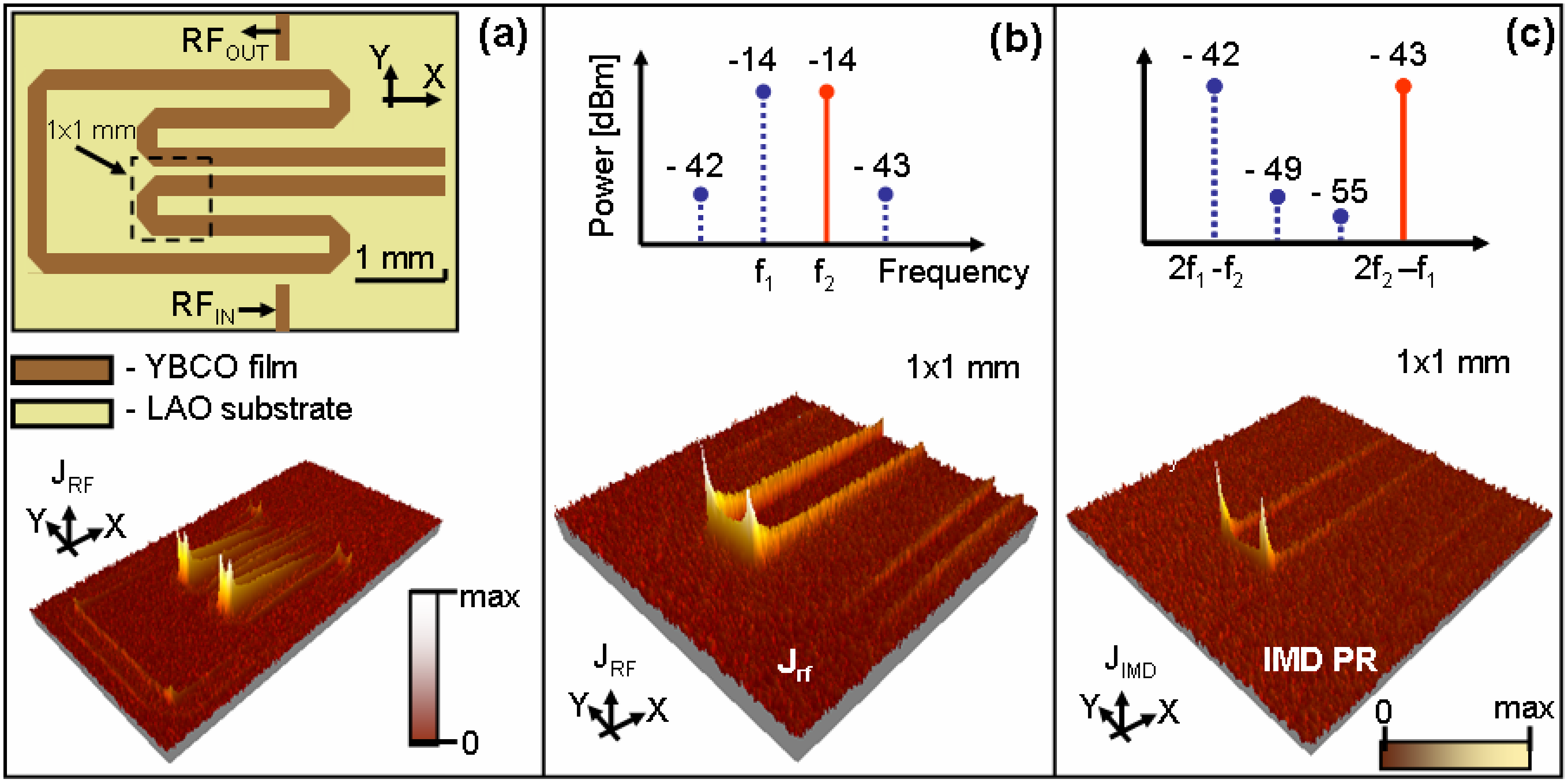
Figure 1: SEM image of a typical probe with two metal strips on the quartz dielectric support



Graphics from Anlage

Laser scanning microscopy

Steve Anlage - Maryland

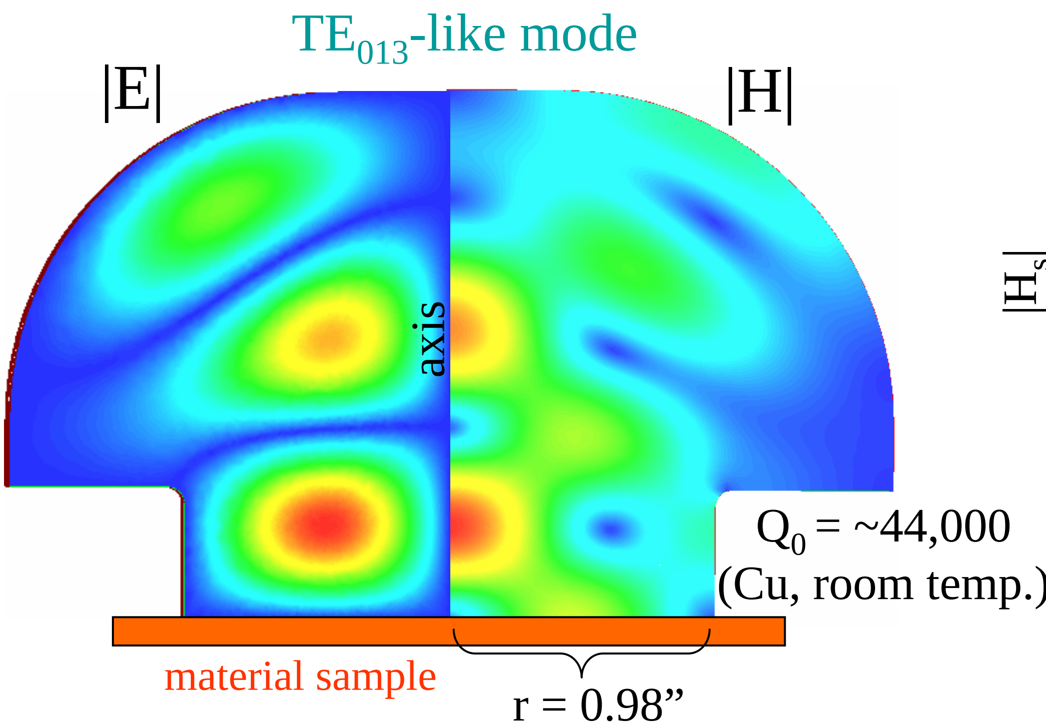


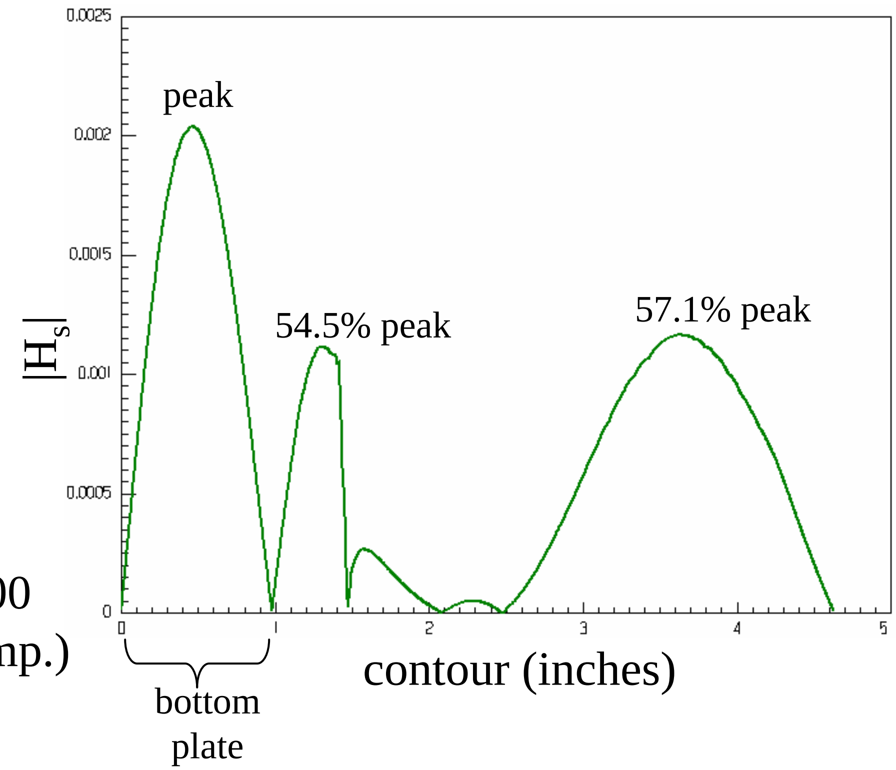
Idea: scan laser within cavity, find bad spots

Laser Scanning Microscope Image: T. Kaiser, *et al.*, Appl. Phys. Lett. 73, 3447 (1998)

Graphics from Anlage

Cavities for “short sample” tests





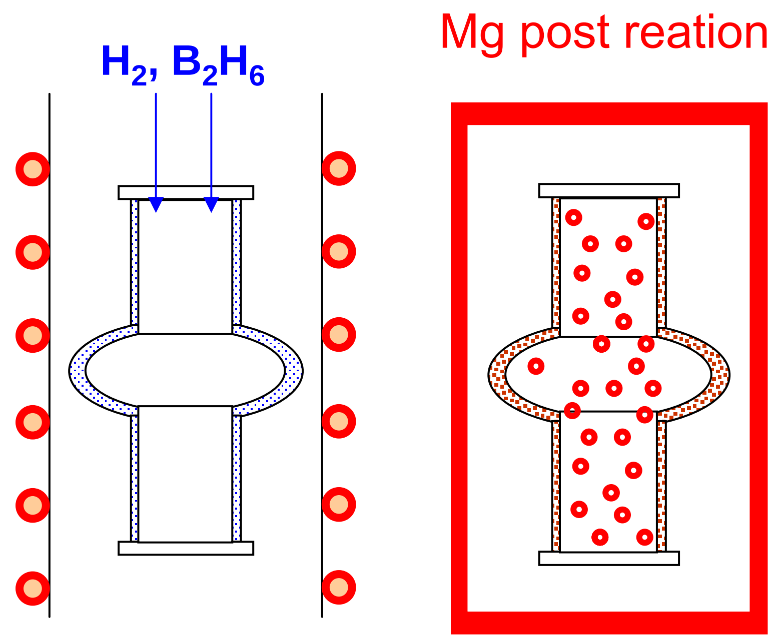
“brute force” approach
(analogous to Bitter coils)

Sami Tantawi, Valery Dolgashev, Gordon Bowden, James Lewandowski, Christopher Nantista
SLAC
Ricky Campisi*1, Tsuyoshi Tajima*2, Alberto Canabal*2
*1ORNL, *2LANL

Graphics from Tajima

New materials - Magnesium diboride
Xi - Penn State

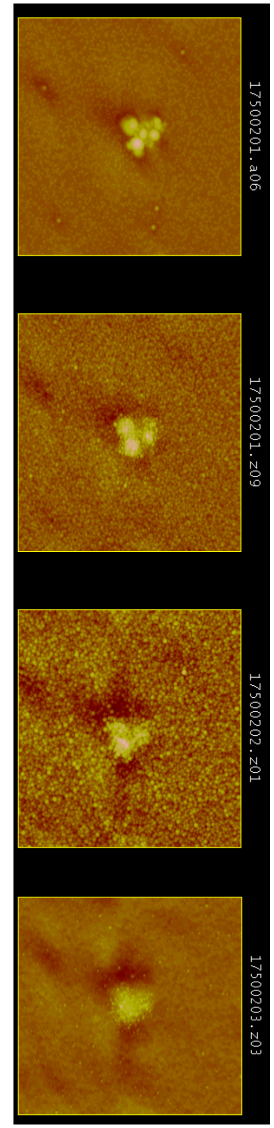
- Surface resistance is a decreasing function of T/T_c, so higher T_c helps
- MgB_2 is being made by STI for communications, and it is showing Nb-like behavior but at 20 K (so should be even better at 2 K)
- Penn State group: CVD using diborane (very clean boron source, also reduces oxygen) onto Nb single cell provided by FNAL



Graphics from Xi

Innovative Processing - avoid HF

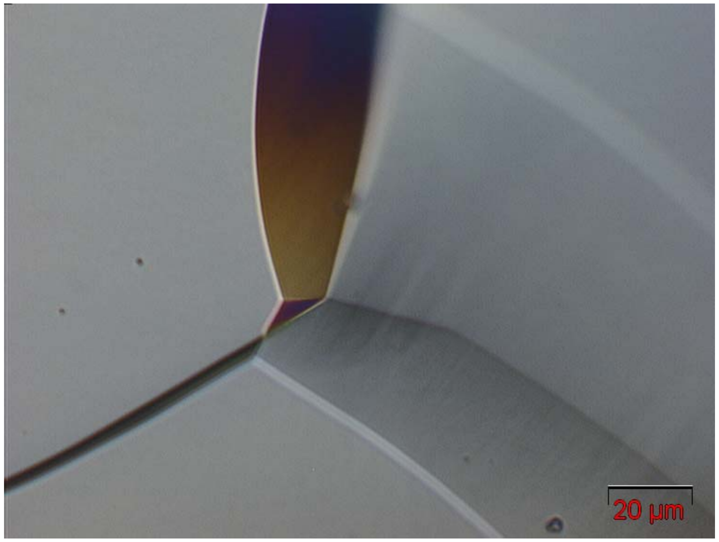
- Gas Cluster Ion Bombardment: used by semiconductor industry to clean wafers. Possible way to smooth and clean Nb
  - But will it damage Nb by “ion peening”?
  - Nb is like bubble gum, not hard like silicon.
- Plasma cleaning
  - Chemically reactive plasmas clean and smooth surface but also leave behind reaction products, e.g. NbB_2 from BF_3. Some products could be beneficial, however.
  - Electron cyclotron resonance: simple! Just hold magnet on back side of cavity
- Tumbling



Graphics from Epion Inc.

Niobium Processing

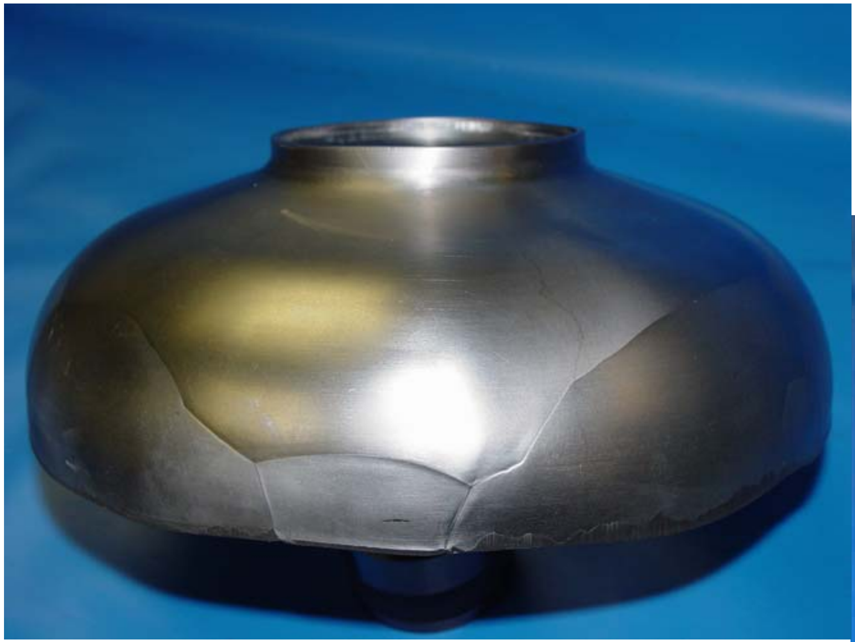
- Grain size issues
  - Small grains: good formability and low roughness upon etching, but can trap impurities in boundaries
  - Large grains: grain interiors are smooth, but big steps at boundaries (roughness) and tolerances difficult to hold
  - Single crystals: very smooth, very well behaved mechanically, but expensive. Engineering is just beginning. Do properties depend on crystallographic orientation?



Large-grained niobium sample after etching 100 µm from surface. Steps at boundaries are 2, 12, and 15 µm

Graphics from Singer

Single crystal option is more exciting.



Deep drawn half cell of large grain niobium; grain boundaries pronounced, anisotropy of properties (earing)

Deep drawn half cell of single crystal niobium

Predictable properties

Graphics from Singer

Single crystal Nb - already smooth after etch

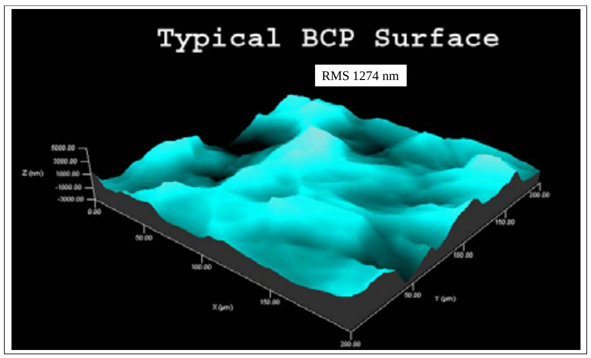
BCP provides very smooth surfaces

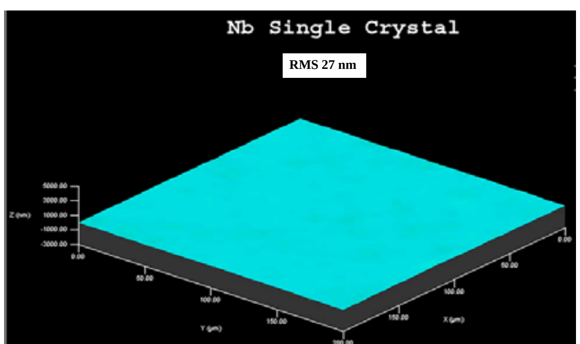
(A.Wu, Jlab)

1274 nm fine grain bcp

27 nm after ~ 80 micron bcp, SC

251 nm fine grain ep

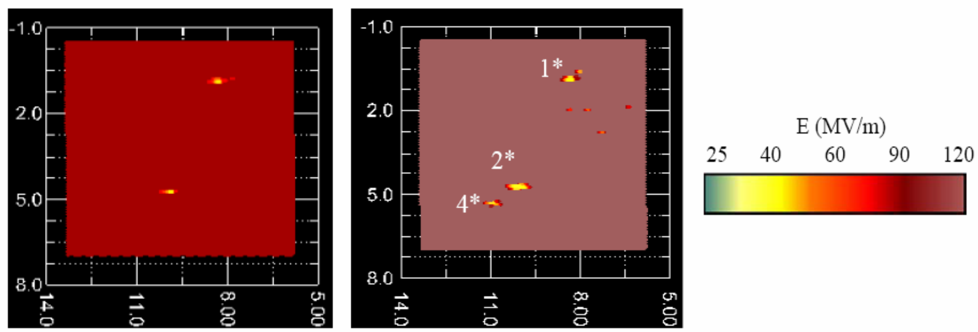




Field Emission Scanning:
A.Dangwal, G.Mueller (Wuppertal)

E = 120 MV/m, 0 emitters   E = 150 MV/m, 2 emitters   E = 200 MV/m, 4 emitters

FE scans on single crystal Nb sample after 30 μm BCP.



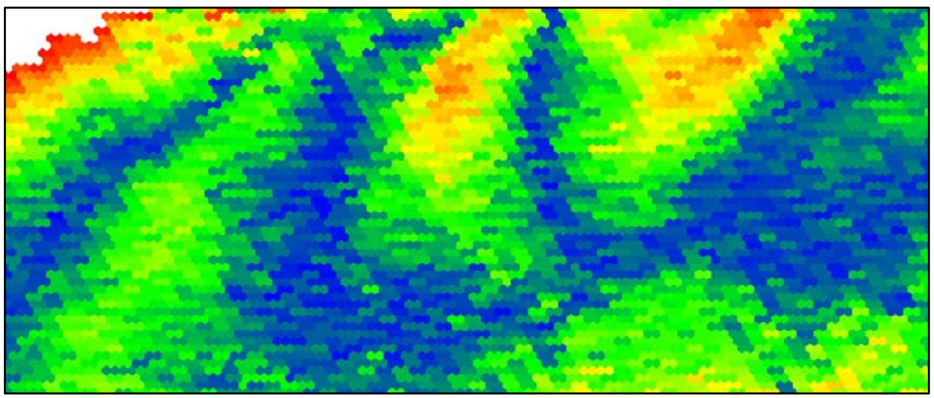
Example of similar FE scans on fine grain EP Nb sample. (left) E = 90 MV/m, 3 emitters (right) E = 120 MV/m, 8 emitters

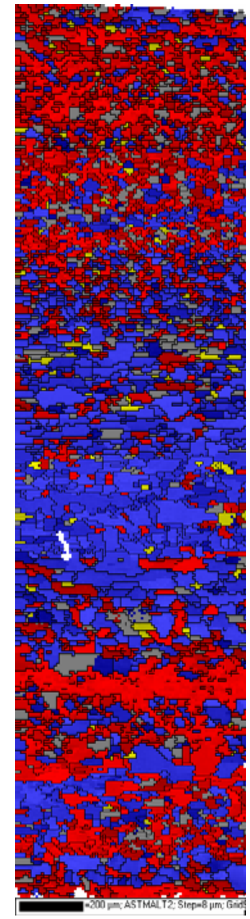
Surface quality of the BCP treated SC is better as of EP treated polycrystalline Nb

Graphics from Singer

Niobium specifications

- Sheet rolling produces different grain textures
- Shear bands produced by rolling may not be fully recovered by annealing
- Both should affect formability and performance
- Problem: present Nb spec may not contain adequate testing, and may contain conflicting requirements





Graphics from C. Compton, and HC Starck Inc.

What has happened since the workshop?

- DOE-HEP is processing academic proposals
- FNAL has provided cavities for experiments
  - GCIB (Epion, Inc.)
  - MgB_2 (Penn State)
  - ALD (ANL)
- FNAL has purchased other services related to R&D
- Interactions between basic materials groups and cavity projects have increased
- FNAL has begun making and testing its first cavities (with help from collaborations)
- Summary: “mass” and “energy” are converging!

Outlook - 1

- The workshop revealed / re-emphasized that the niobium starting material is not simply “sheet metal”
  - We may need to test every sheet until we understand the consequences of fabrication history, trace impurities, grain size, etc.
  - We will need a single cell program to limit costs
  - We need to rethink our niobium specification
- The “pollution model” remains a mystery!
  - Experiments point away from oxides / oxygen
  - Progress will continue to be empirically based
  - We need to give new, very basic science a chance to produce results and generate understanding and new ideas
    - New players, e.g. Seibener at Chicago, were stimulated by workshop
    - Old players, e.g. Kelley at NCSU, were invorgorated by workshop

Outlook - 2

- The workshop showed that there are several alternatives to reduce or remove dangerous acid processes
  - Crystals are inherently smooth
  - Tumbling, plasma cleaning, bombarding, etc. will become more active.
  - (We are pushing ideas here, too, via collaborations and other routes)
- The workshop showed that ultimate limits to SRF are closely tied to intrinsic limits of the superconductor
  - The superconductor determines a starting point, from which processing flaws subtract
  - We must perfect the starting point at all costs
  - We must also identify and limit process flaws
  - We must continue to distinguish what is due to niobium and what is a result of processing

Outlook - 3

- Thin layers / multilayers are an exciting way to break the "niobium monopoly"
  - We anxiously await the results from ALD, MgB_2, other experiments to test Gurevich's model
  - We must develop the ability to test "short samples"
    - Point RF probes @ 2 K?
    - "Brute force" RF cells?
- We must sustain the workshop's energy and its critical mass of participants!
  - Thanks to Helen, Genfa, Claire, and Pierre