High Gradient Limits in Linacs

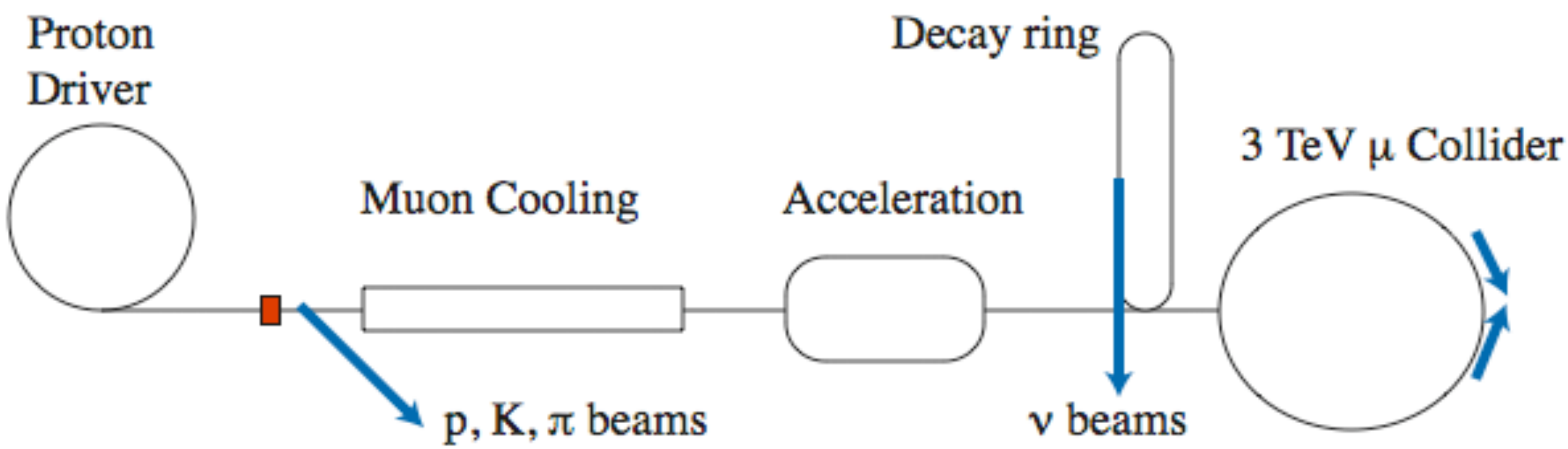
J. Norem
ANL/HEP

NFMCC meeting
FNAL
1/17/8

Neutrino Factory
Muon Collider

THE UNIVERSITY OF CHICAGO
Office of Science
U.S. DEPARTMENT OF ENERGY
Argonne NATIONAL LABORATORY

There are two High Gradient Collaborations –
1) ours in the NFMCC



- We have a ~ ten year head start.
- We are proposing solutions which could raise SC and NC gradient limits by >3X.
- We can do it all: NC, SC, DC, Hifreq.

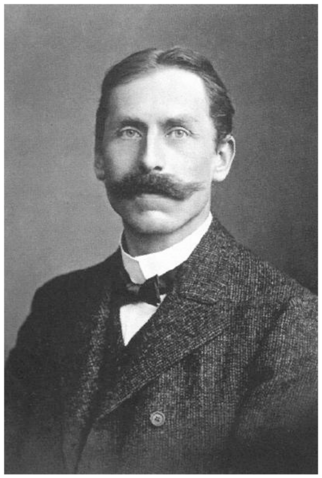
2) and a group centered at SLAC

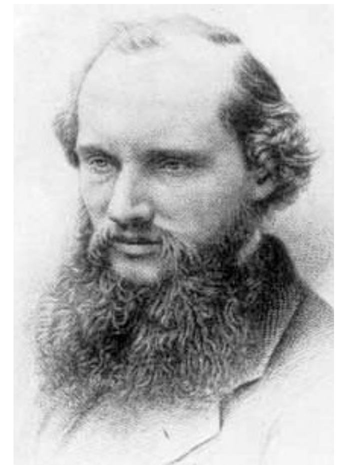
- They work with CERN/CLIC

This problem was discovered and understood 100 years ago.

Everything important was known in the first 5 years

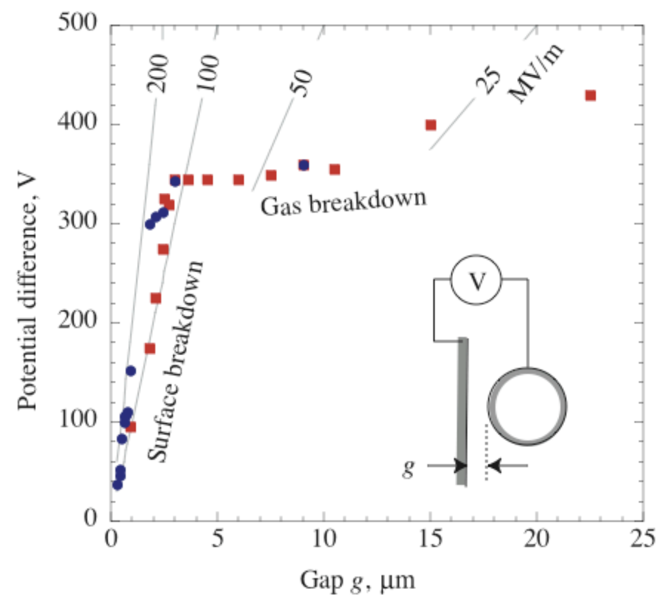
Paschen, Millikan, Michelson, Lord Kelvin





In 1904, Lord Kelvin argued that:

- Field emission is electrons (electrions),
- Electron emission may imply ion emission (damage),
- Local fields of ~ 9.6 GV/m would do this,
- Tensile strength is an important parameter,
- Better experiments are needed.



100 years of distractions have muddied the water

Breakdown / Field Emission connection.

Melting - not consistent with tensile stress

Multipactor – not consistent with high fields, forbidden by electron optics

Models without trigger fields.

Narrow range of experiments possible at high *f*.

Fowler-Nordheim Plot – ☣, Linear plot - flushes data.

Cond/Ins/Cond etc. models.

DC and *AC* FE expressions.

Plasma spots, crater clustering, “tip on tip”, “telephone pole” field enhancements.

Secrecy / isolation.

Feynman got it right.

6-11 High-voltage breakdown

We would like now to discuss qualitatively some of the characteristics of the fields around conductors. If we charge a conductor that is not a sphere, but one that has on it a point or a very sharp end, as, for example, the object sketched in Fig. 6-14, the field around the point is much higher than the field in the other regions. The reason is, qualitatively, that charges try to spread out as much as possible on the surface of a conductor, and the tip of a sharp point is as far away as it is possible to be from most of the surface. Some of the charges on the plate get pushed all the way to the tip. A relatively small *amount* of charge on the tip can still provide a large surface *density;* a high charge density means a high field just outside.

One way to see that the field is highest at those places on a conductor where the radius of curvature is smallest is to consider the combination of a big sphere and a little sphere connected by a wire, as shown in Fig. 6-15. It is a somewhat idealized version of the conductor of Fig. 6-14. The wire will have little influence on the fields outside; it is there to keep the spheres at the same potential. Now, which ball has the biggest field at its surface? If the ball on the left has the radius a and carries a charge Q, its potential is about

$$\phi_1 = \frac{1}{4\pi\epsilon_0}\frac{Q}{a}.$$

(Of course the presence of one ball changes the charge distribution on the other, so that the charges are not really spherically symmetric on either. But if we are interested only in an estimate of the fields, we can use the potential of a spherical charge.) If the smaller ball, whose radius is b, carries the charge q, its potential is about

$$\phi_2 = \frac{1}{4\pi\epsilon_0}\frac{q}{b}.$$

But $\phi_1 = \phi_2$, so

$$\frac{Q}{a} = \frac{q}{b}.$$

On the other hand, the field at the surface (see Eq. 5.8) is proportional to the surface charge density, which is like the total charge over the radius squared. We get that

$$\frac{E_a}{E_b} = \frac{Q/a^2}{q/b^2} = \frac{b}{a}. \tag{6.35}$$

Therefore the field is higher at the surface of the small sphere. The fields are in the inverse proportion of the radii.

This result is technically very important, because air will break down if the electric field is too great. What happens is that a loose charge (electron, or ion) somewhere in the air is accelerated by the field, and if the field is very great, the charge can pick up enough speed before it hits another atom to be able to knock an electron off that atom. As a result, more and more ions are produced. Their motion constitutes a discharge, or spark. If you want to charge an object to a high potential and not have it discharge itself by sparks in the air, you must be sure that the surface is smooth, so that there is no place where the field is abnormally large.

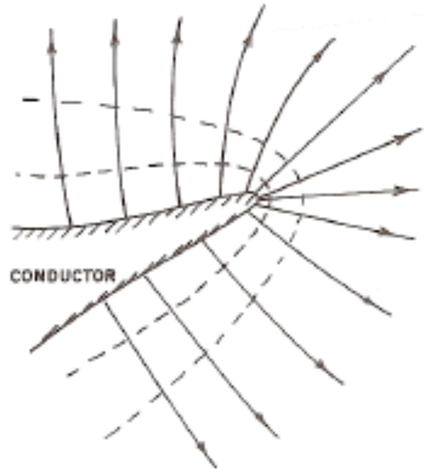


Fig. 6-14. The electric field near a sharp point on a conductor is very high.

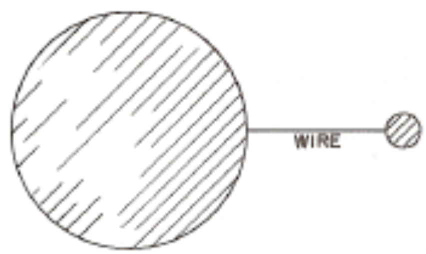
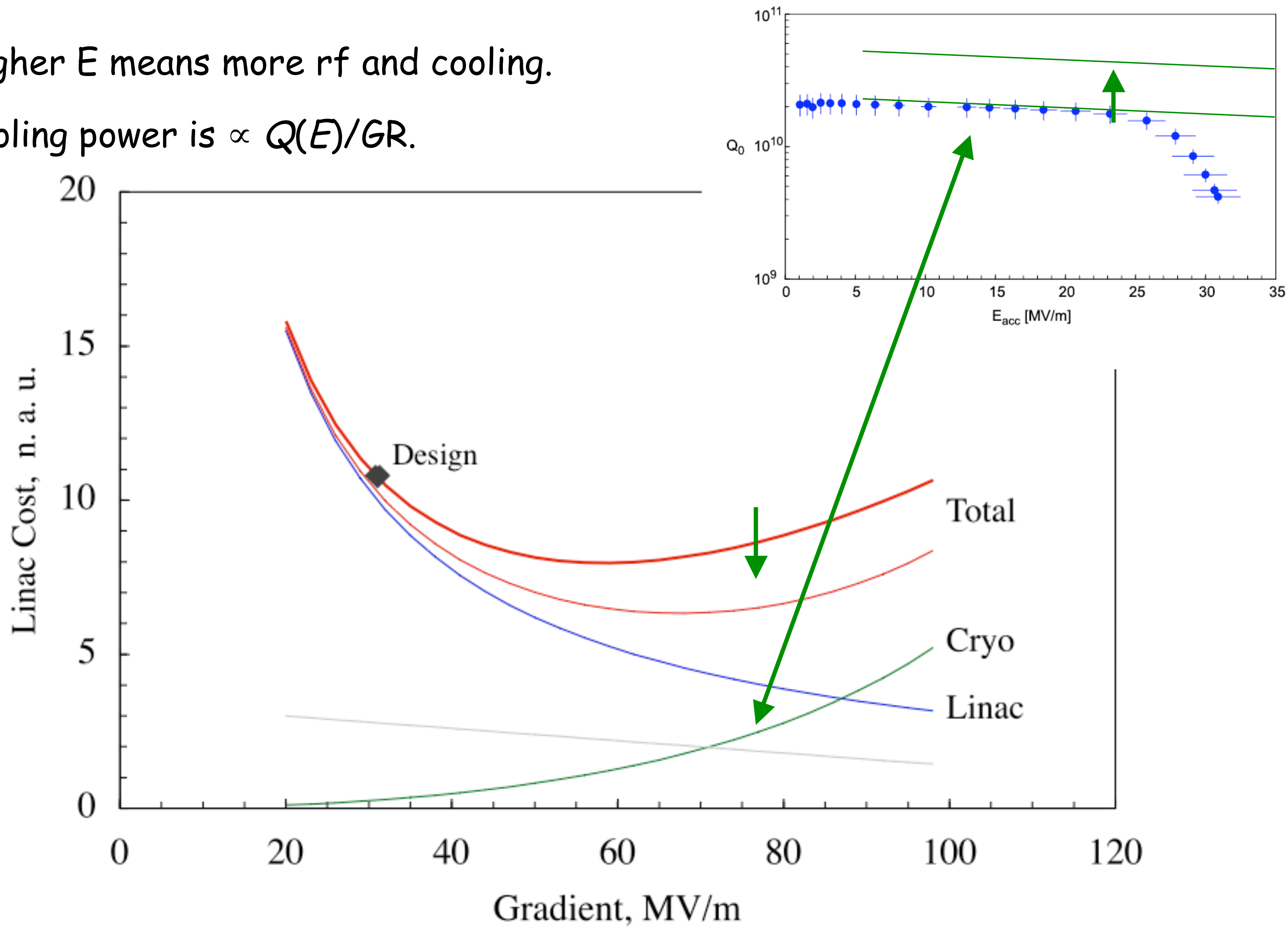


Fig. 6-15. The field of a pointed object can be approximated by that of two spheres at the same potential.

$E_{local} = E_{surf}\beta \sim 1/r$

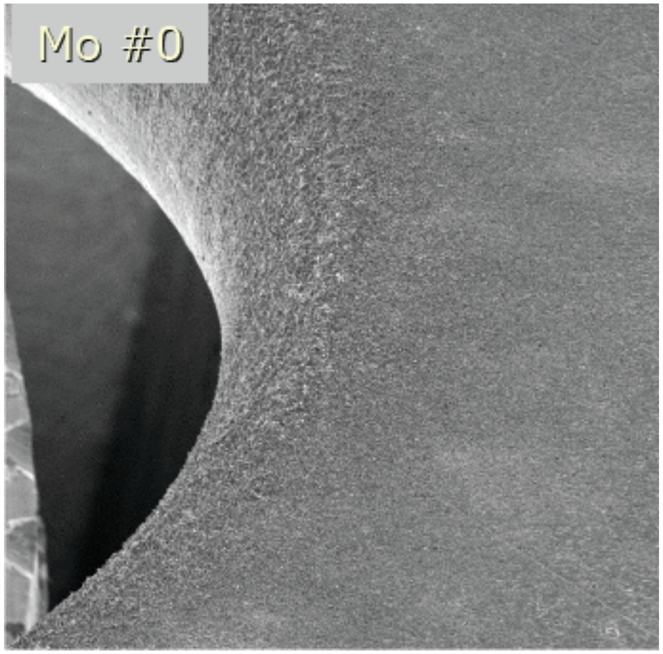
These models affect the cost of ILC . . .

- Higher E means more rf and cooling.
- Cooling power is $\propto Q(E)/GR$.



. . . and the feasibility of CLIC.

• CLIC sees damage where electric fields are highest . . .



. . . and conclude that skin currents are responsible.

Many people have contributed to our results.

<u>Normal Conducting</u>		
A. Hassanein	Plasma Phys	ANL Numerical Modeling
Z. Insepov	Fracture kenetics	ANL Numerical Modeling
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
D. Huang	RF, Instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X
P. Stoltz	Plasma modeling	Tech-X
<u>Superconducting</u>		
M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
J. Moore	ALD, expts.	MassThink LLC
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
Th. Proslier	SC theory and exp	IIT

We have been successful.

- We have accumulated good data on breakdown sites and cavity behavior.
  Unique apparatus (B~5T) permits detailed study of asperities
  Interest in Be, thin walls, gas filled, DC, intense beam loading, etc.

- We understand and model breakdown and operational limits.
  Integrated model of breakdown and gradient limits.
  Well documented: ~70 pages in refereed journals. Many other papers

- We try to expand the model to explain the worlds high gradient data
  High f, SCRF (Q-slope, field emission, etc). DC, Mat'ls Sci,

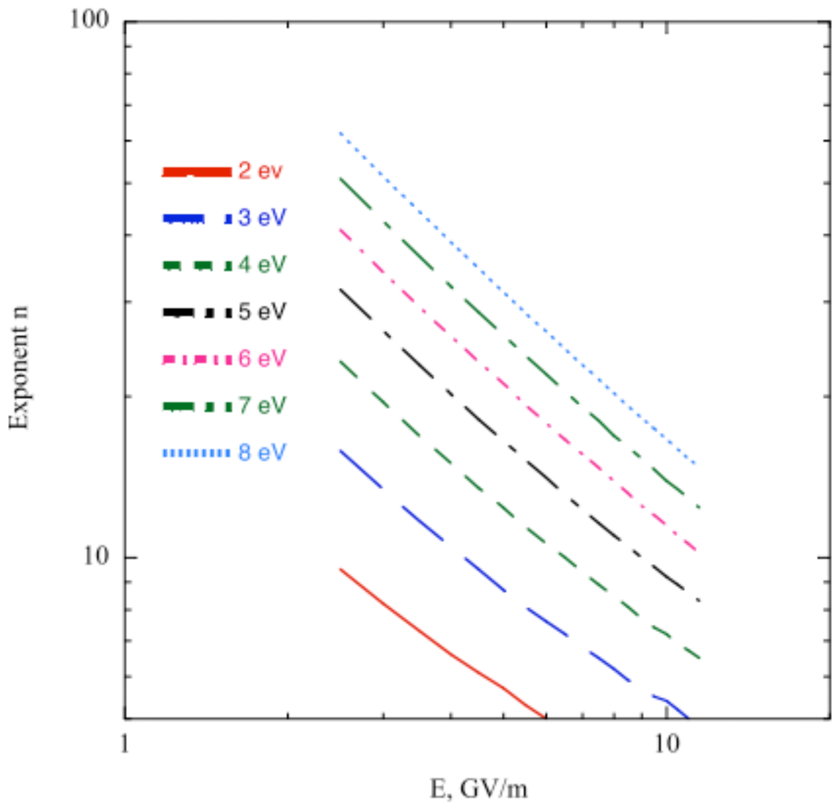
- . . and find ways to increase gradients by large factors.

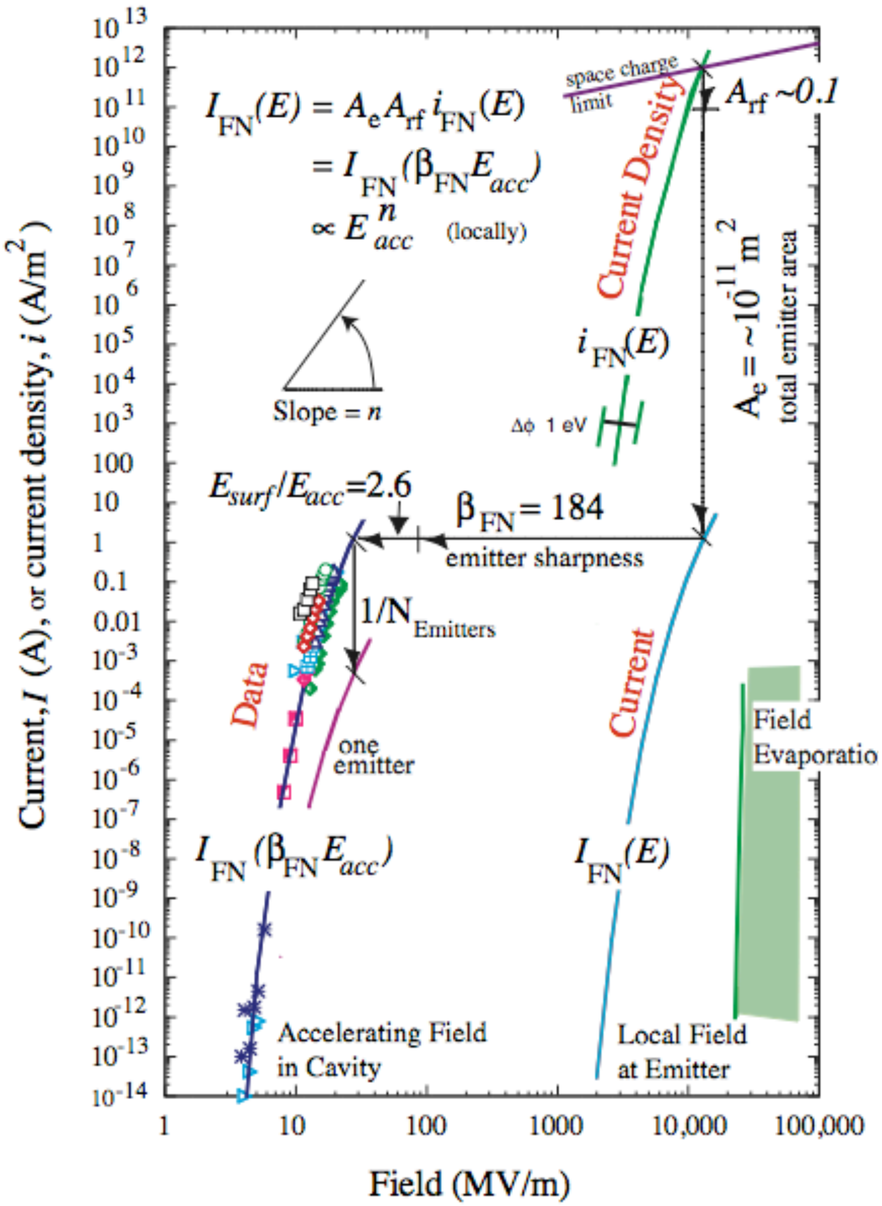
- Proposal to do Atomic Layer Deposition at Argonne Materials Science Division

- Need to understand B fields.

Basic ideas: 1) Local electric fields are easy to measure.

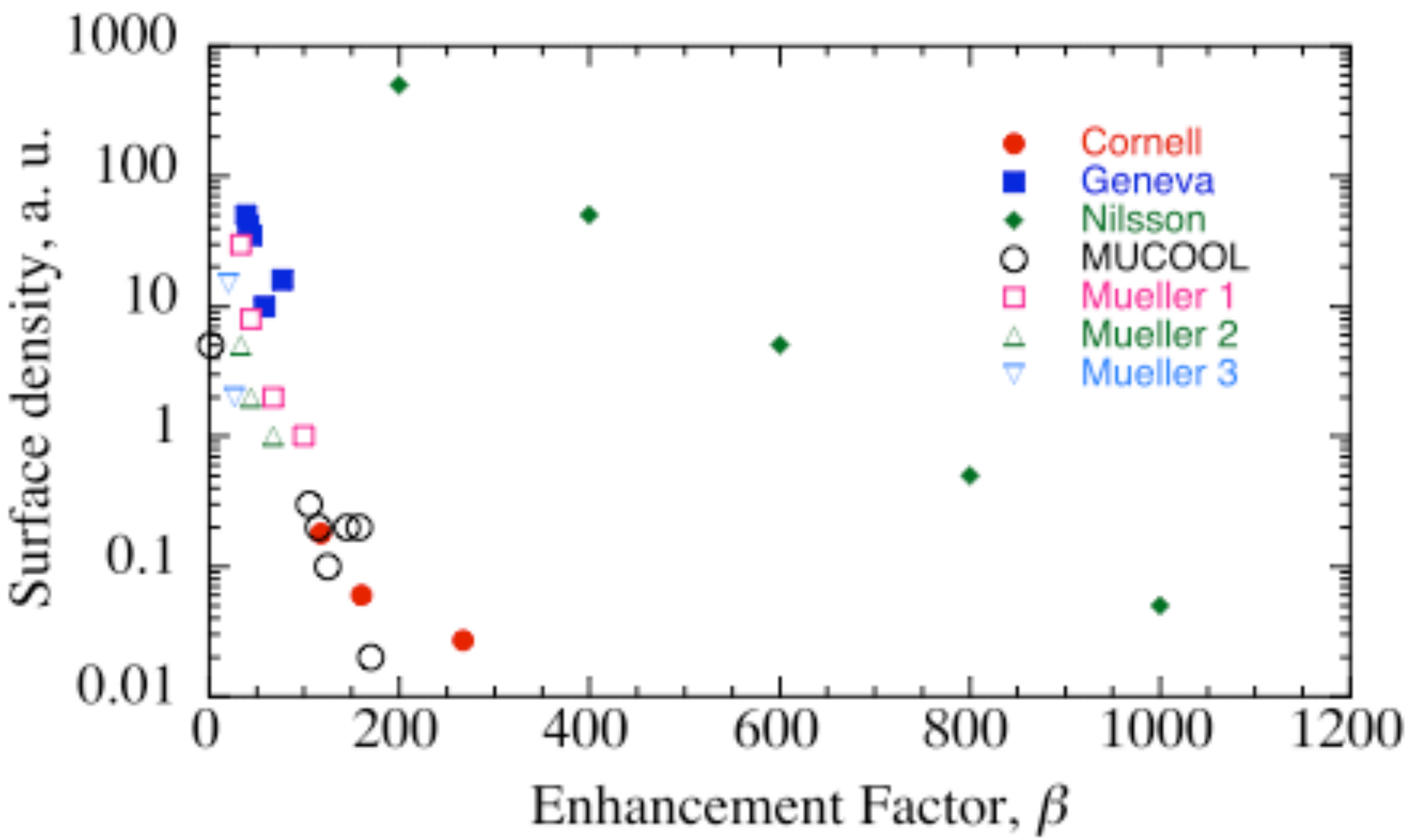
- FN can be approximated by $I = E^n$.
- The local surface field = f(n, ϕ).





Basic ideas: 2) Enhancement spectra.

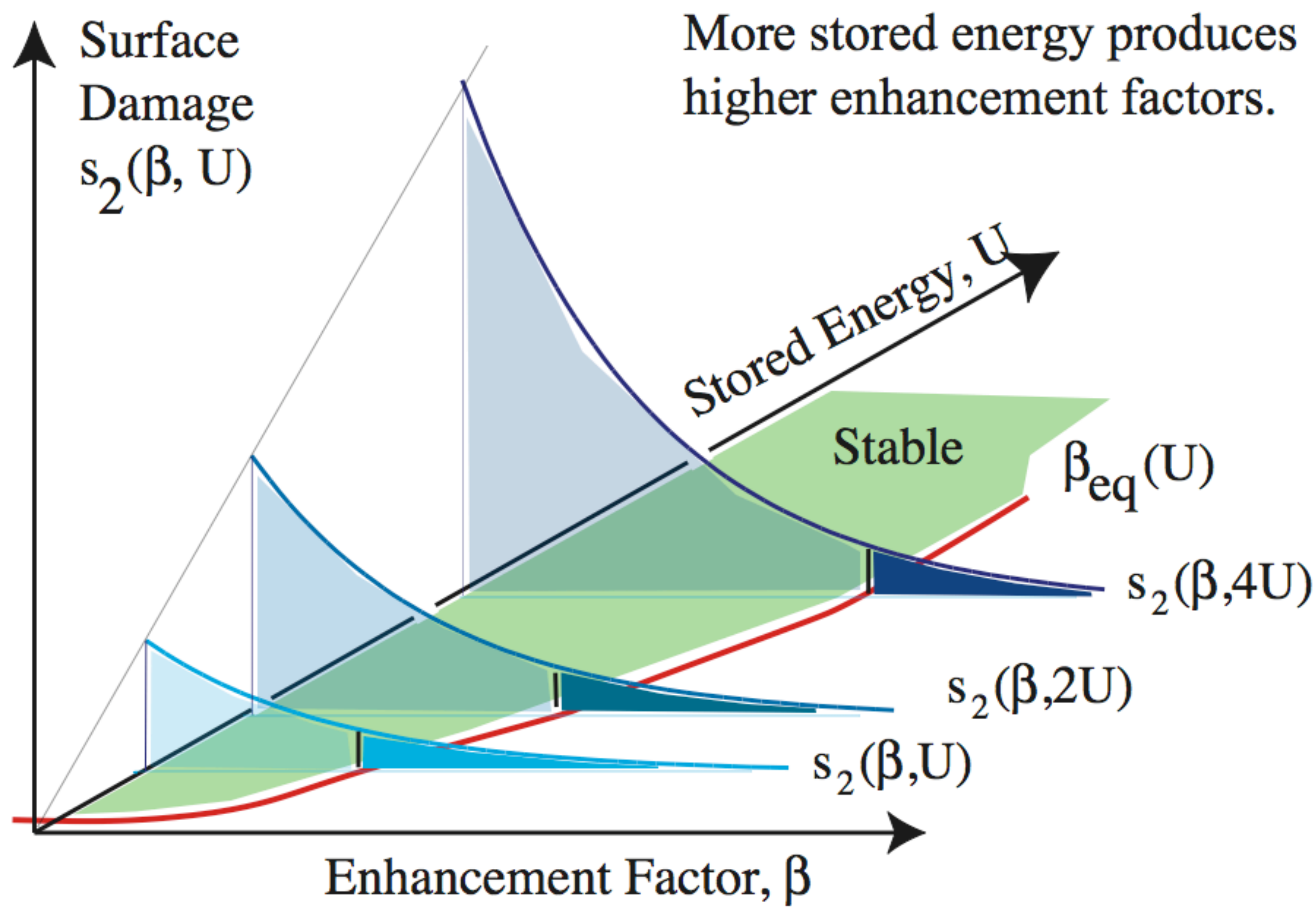
- We assume that the density of emitters looks like $Ae^{-C\beta}$.
- A wide variety of data is consistent with this parameterization.



Basic ideas: 3) Tensile stress & fatigue.

Basic ideas: 4) Surface Damage

- Accelerating fields of ~460 GeV/m have been seen in copper – <u>not really relevant</u>.
- $\beta_{eq}(U)$ defined by $\int_{\beta_{eq}}^{\infty} s_2(\beta, U)d\beta \sim c$
- If the damage goes like $e^{-C\beta}$, then $E_{max} \sim 1/\ln(U)$.



Results of the model.

We can explain pretty much all the experimental data:

- Breakdown rate
- Pulse length
- Electric field
- Materials dependence
- Conditioning status
- The fully conditioned state
- Gas type
- Gas pressure
- Magnetic fields
- Frequency dependence
- DC gaps
- Temperature dependence
- Correlated breakdown events
- Timescale of breakdown process
- Plasma spots
- Crater clustering
- PS and geometry dependence of gradient limits
- Surface heating

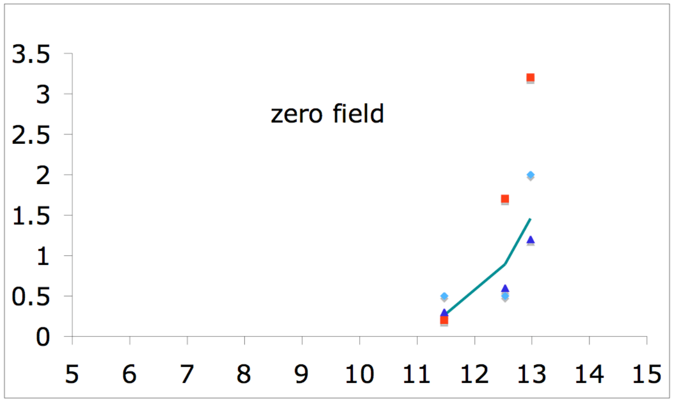
- Fatigue
- Disappearance of field emitters during breakdown
- Simple failure of atom probe tomography systems
- Surface morphology
- Superconducting systems
- Positive and negative potentials

- . . . etc.

<u>Magnetic field effects are still a problem *!*</u>

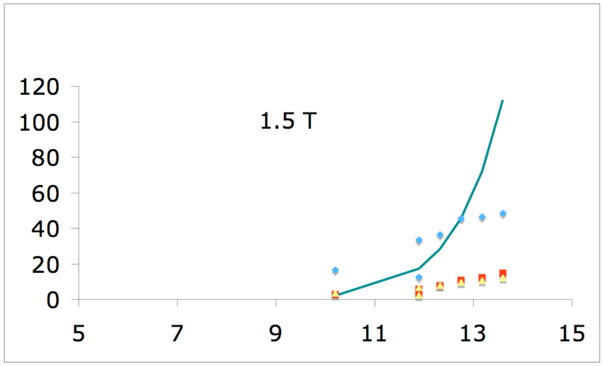
See AIP Conf. Proc. 877

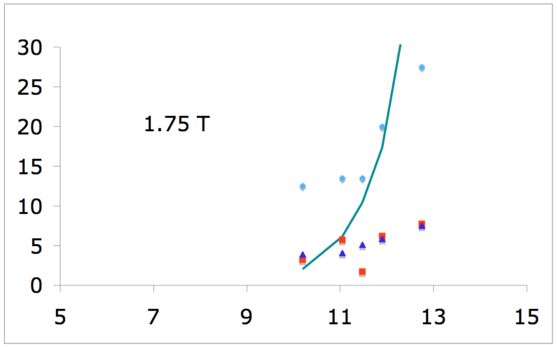
Our new data from the MTA is confusing

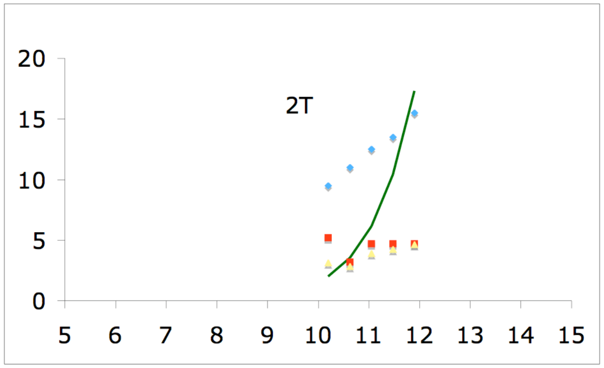


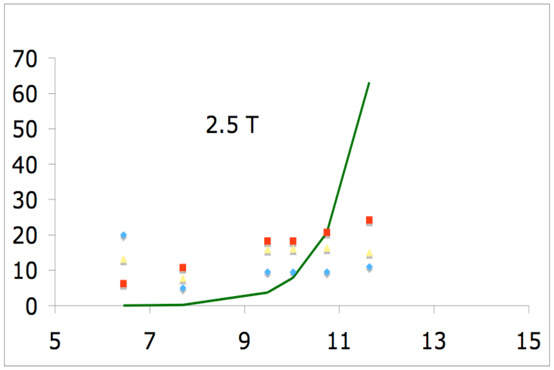
All data up to now has shown $R \sim E^{14}$.

- We don't see this when we look the 201 cavity in the solenoid field.









Many mechanisms limit gradients.

Normal Conducting

Electric fields tearing the surface apart

Skin currents heat the equator of cavities ??

Superconducting

Classical

- Heating by field emission currents
- Breakdown - High pulsed power conditioning
- Multipactor - cured by cavity shape and surface treatment
- Lorentz detuning -- electrostatic stresses approach 1 atm
- Microphonics - He bubbling distorts cavity
- Local heating - surface defects increase local resistivity

Quantum

- Quench Fields - Bmax ~ 0.2 T
- Q slope - Losses increase nonlinearly with field

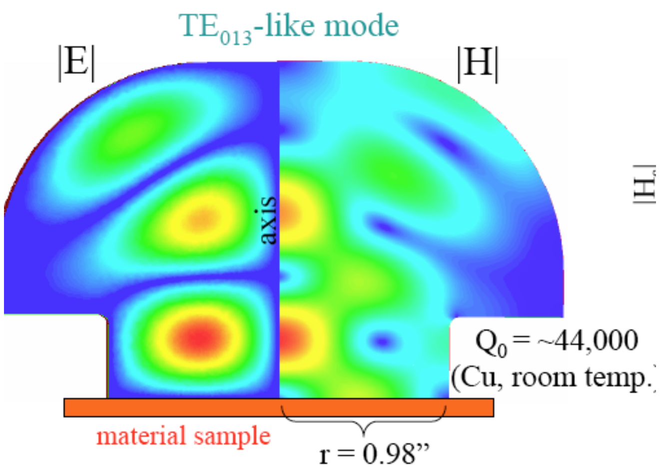
Operational

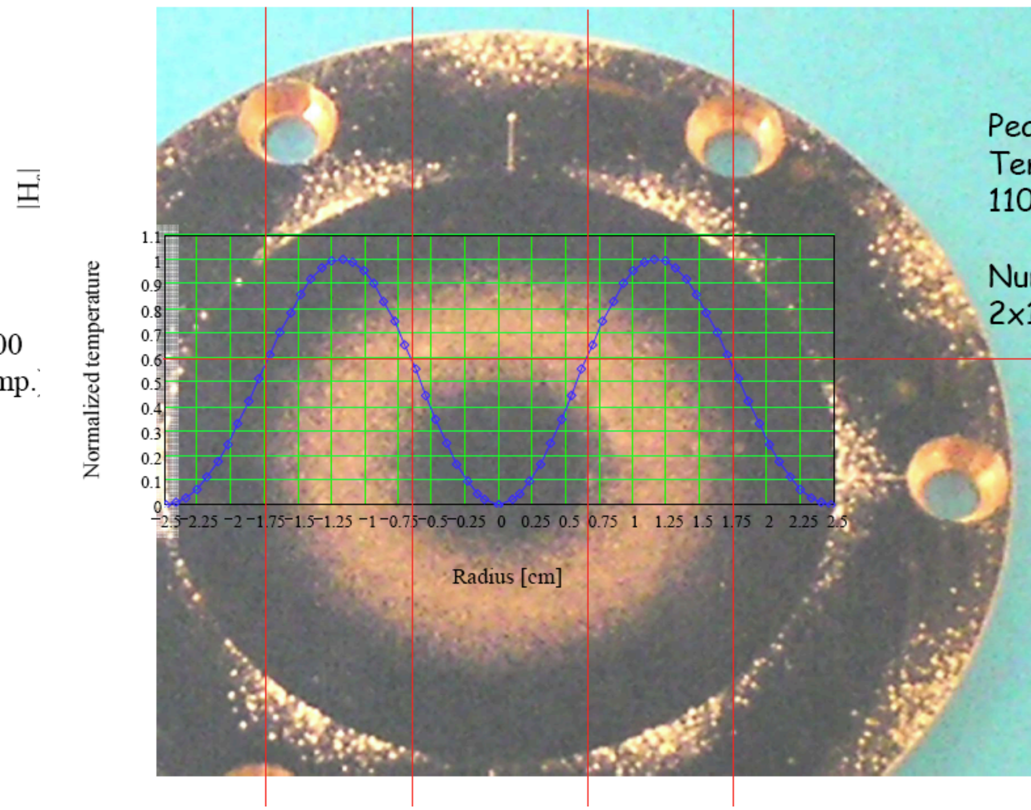
- Particulates - assembly brings contaminants
- Power use - somebody has to pay

What about pulsed heating?

- A paper by Pritzkau and Siemann in 2002 argued that surface currents will cause heat fluctuations which will cause compressional fatigue and eventually cavity failure.

- Tantawi and Dolgashev produce damage from skin currents.





Peak transient Temperature rise 110 degree Celsius

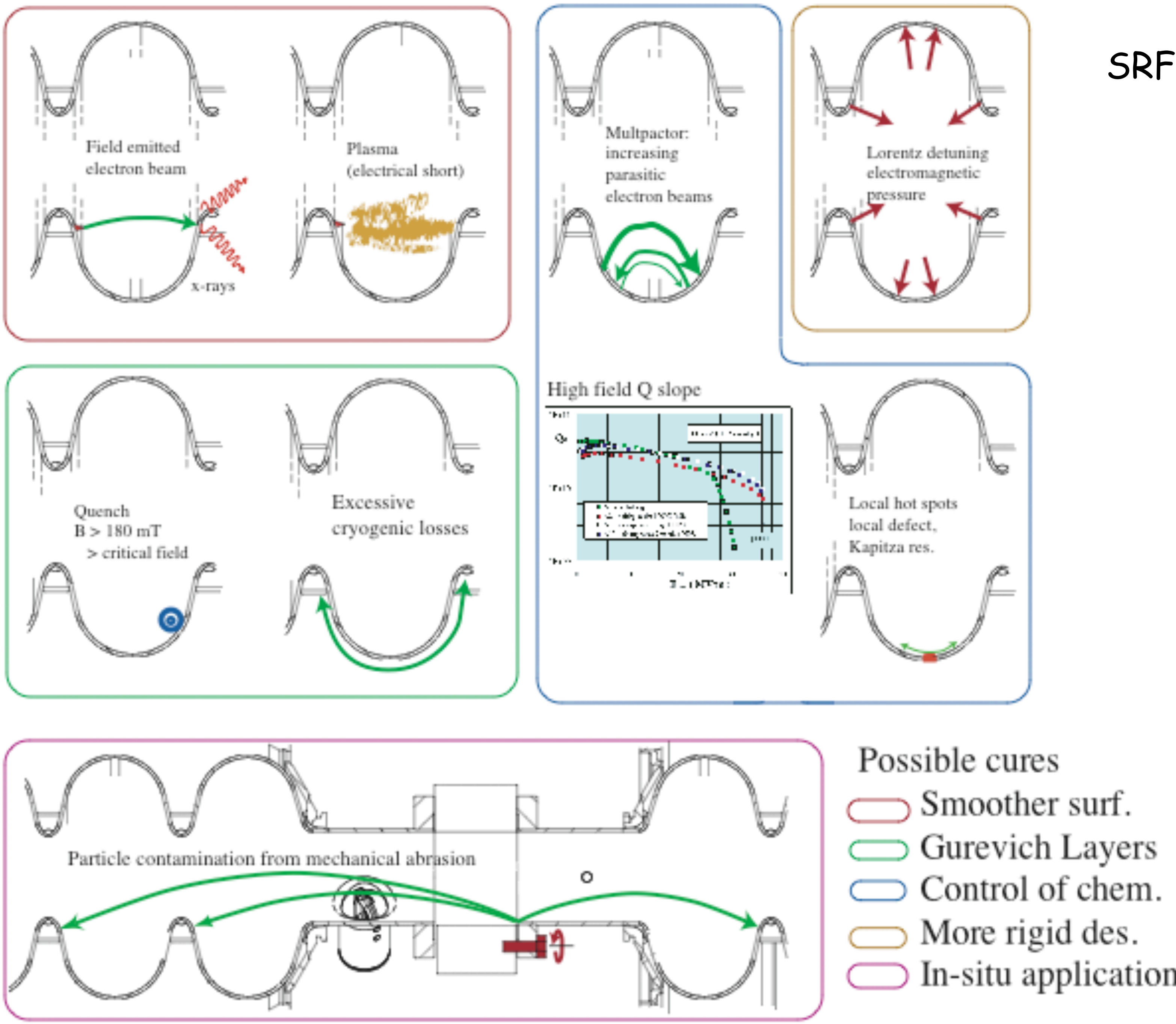
Number of pulses 2×10^6

- High temp ➜ damage

- But do cavities see this effect?

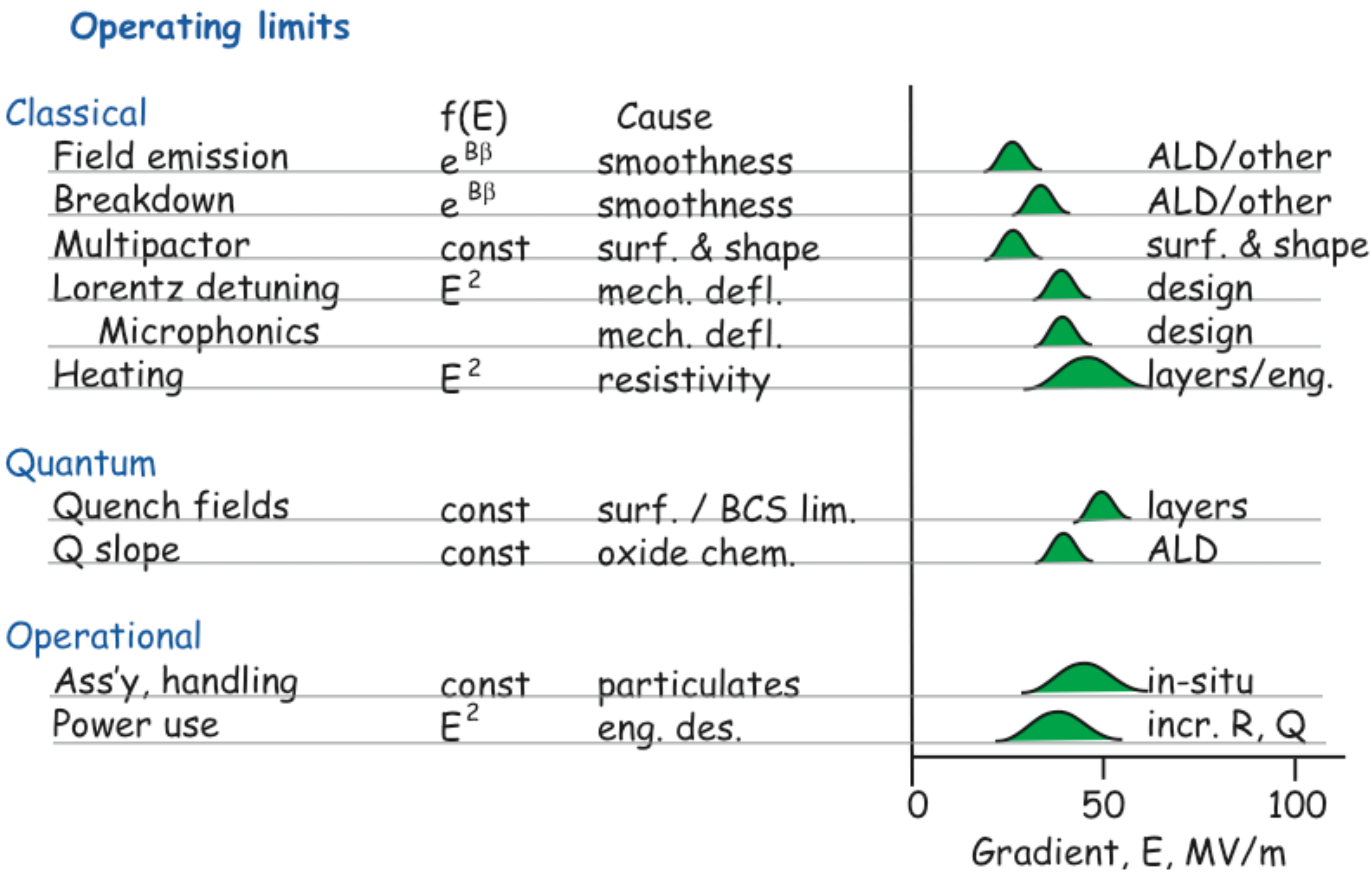
Limiting mechanisms in SCRF.

SRF2007



SCRF limits, and how far do they have to improve?

- One can estimate how much extrapolation is required.



What's New?

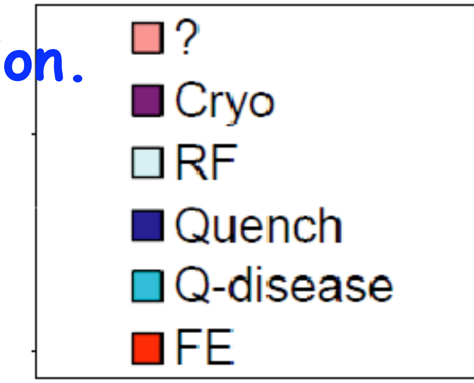
We have started our experimental ALD program
- New explanation for High field Q slope
- New way to clean SCRF materials
- Starting to look at thin layers
- Coated a cavity from JLAB
- Starting to look at binary superconductors NbN, Nb3Sn, MgBr2

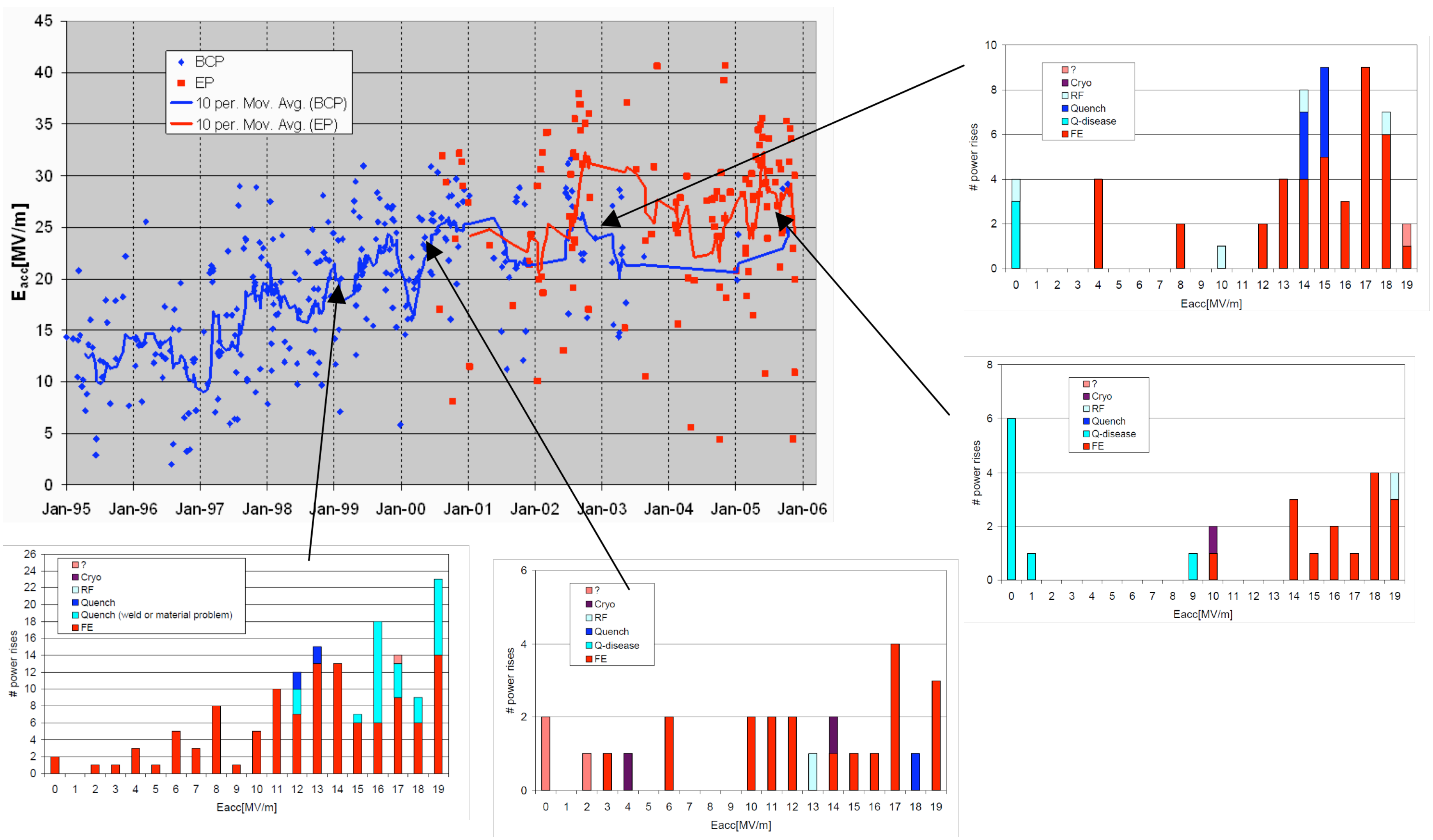
We are thinking about tests of method to make Cu cavities "breakdown-proof".
- We can make smoother surfaces that won't have high local fields.
- We can make layered structures that should not be subject to "pulse heating".
- This is applicable to
  - CLIC.
  - MUCOOL

We are continuing to look at superconducting failure modes and cures
- This is relevant to ILC and Argonne linacs (ANL internal funds).

Some problems with safety procedures and courses. . .

The <u>main</u> problem with SCRF is still Field Emission.

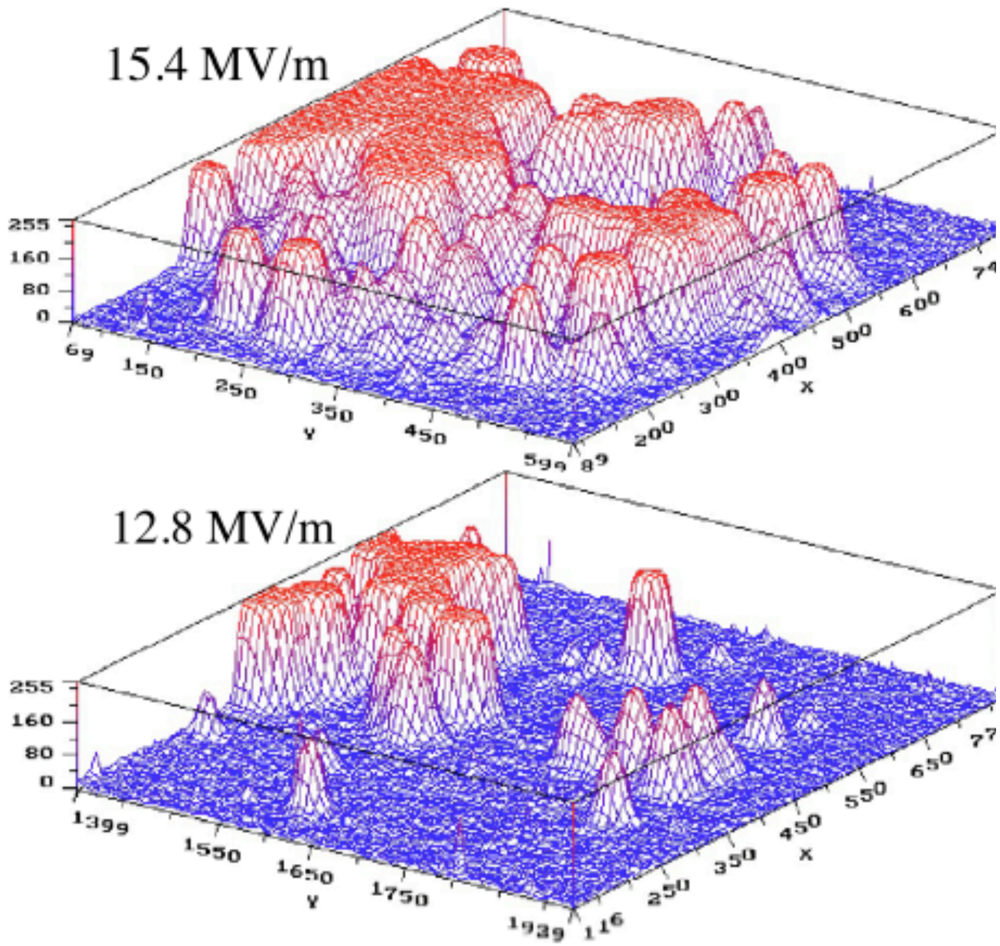


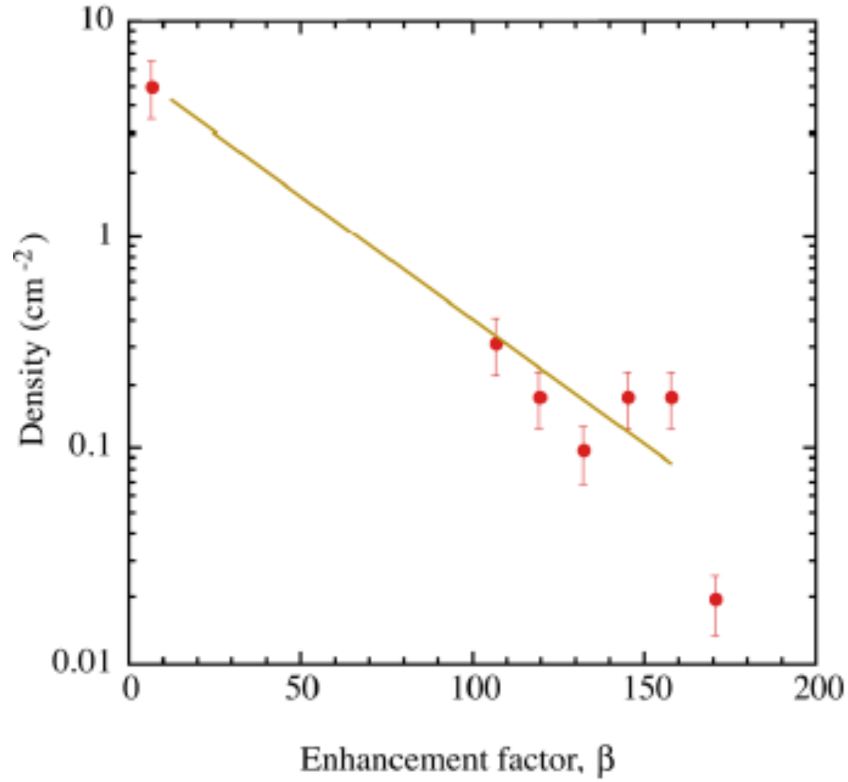


L. Lilje’s summary of DESY cavity databank. DESY. 200

Smoother surfaces should go to higher fields.

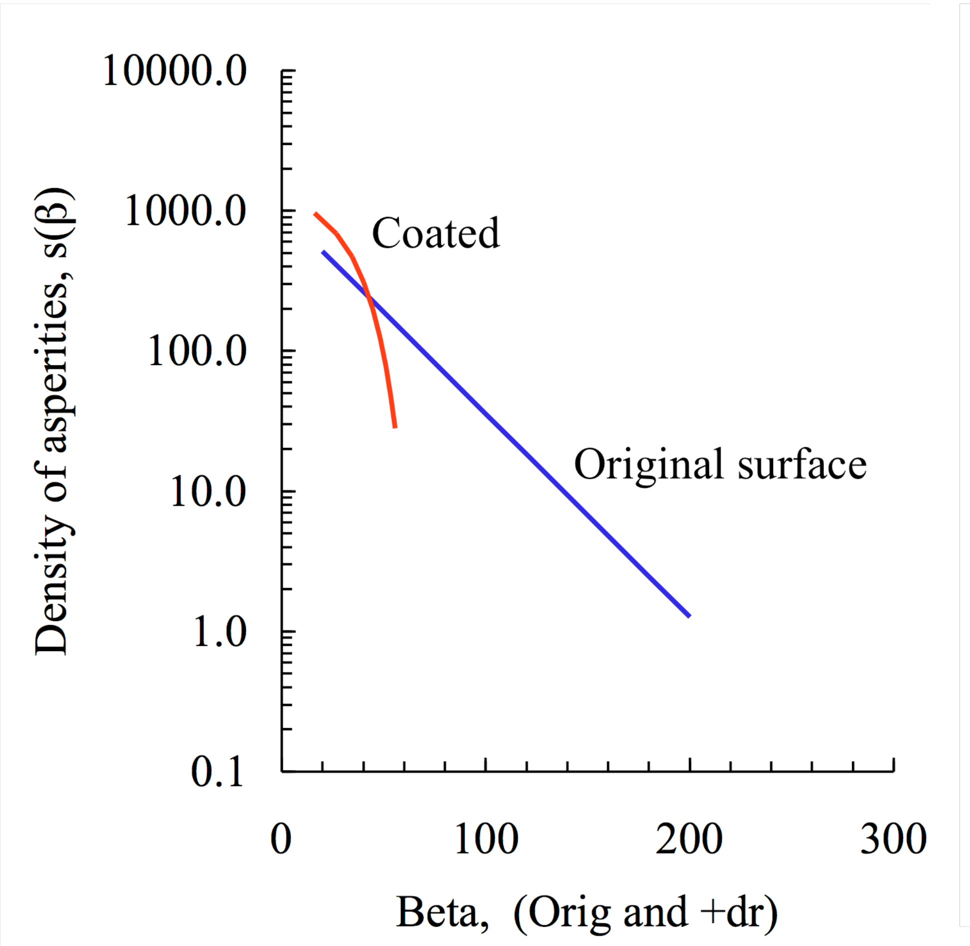
Our data from the 805 cavity show a spectrum of field emitters.

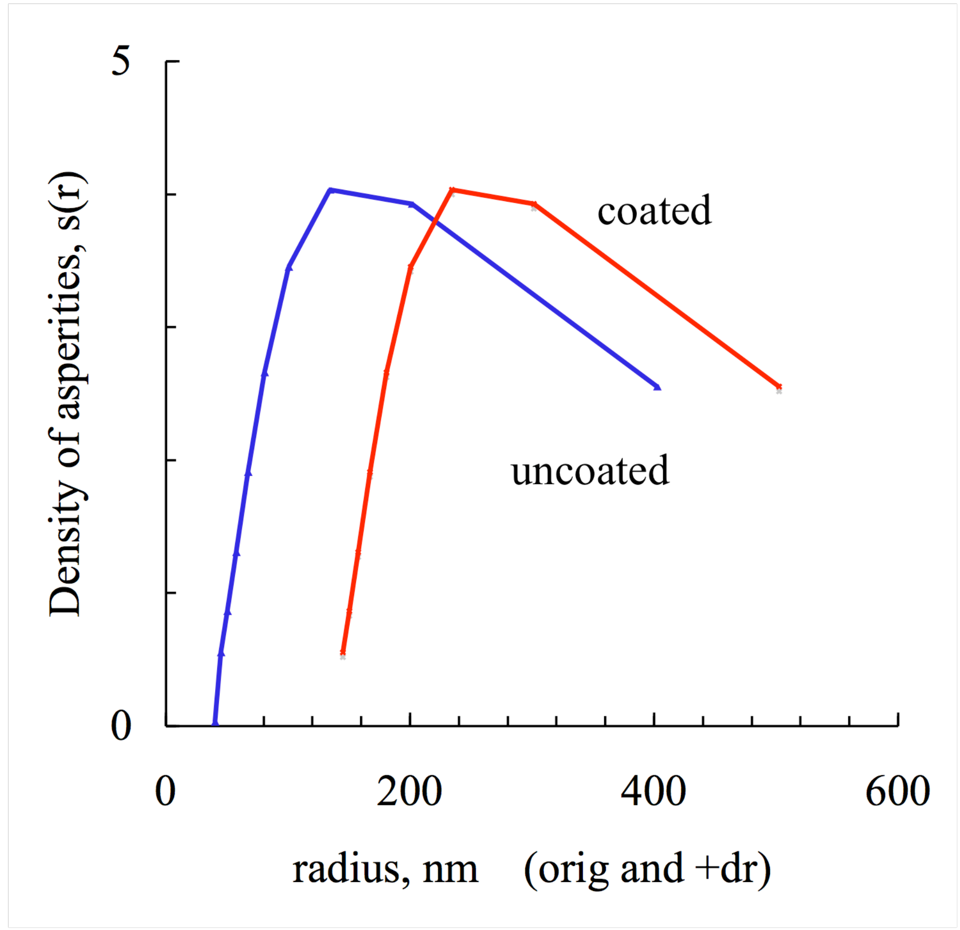




Smooth coatings can change the spectrum of enhancements.

- What is the effect of a 100 nm conducting coating?

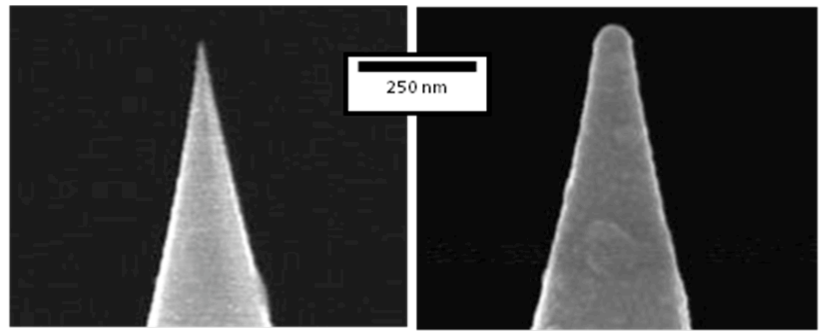




- This should give three times higher rf gradients.

ALD coatings should cure field emission and breakdown.

- ~100 nm smooth coatings should eliminate breakdown sites in NCRF.



Uncoated Si AFM tip

After 5 nm ALD ZrO_2 + 30 nm ALD Pt

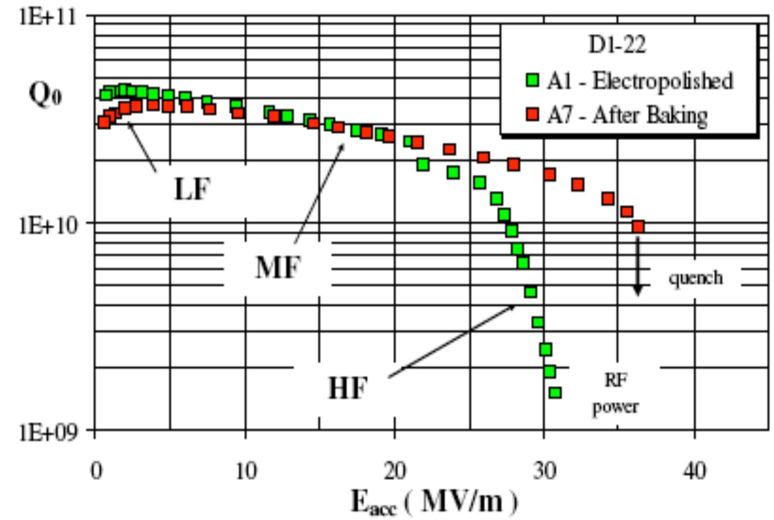
Figure 3: Scanning Electron Microscope images of nearly atomically-sharp tips, before and after coating with a total of 35nm of material by ALD. The tip, initially about 4 nm, has been rounded to 35nm radius of curvature by growth of an ALD film. Rough surfaces are inherently smoothed by the process of conformal coating.

- Copper, however, is a hard material to deposit, and it may be necessary to study other materials and alloys. Some R&D is required. This is underway.

- The concept couldn't be simpler. Should work at all frequencies, can be *in-situ*.

We have a new model of losses in SCRF systems.

- Q-Slope is an anomalous loss that appears at high gradients in SCRF systems.



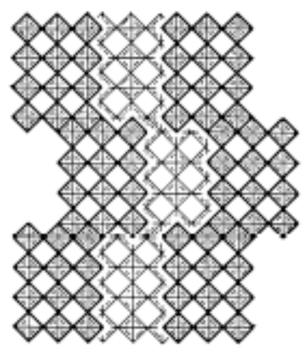
- Theoretical and experimental effort has been inconclusive.

	Q-Slope Fit	Q-Slope before baking (EP = BCP)	Q-Slope Improvem^t after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	TE_{011} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum^t Validity	Fund^al Disagreem^t Exper. ≠ Theory
Magnetic Field Enhancem^t	Y simulat. code	~~N~~ $\beta_m \neq$ $B_{C2}^S \neq$	Y $B_{C2}^S \uparrow$	Y lower β_m	-	N high β_m	-	-	Y lower β_m	N $B_{C2}^S \uparrow$	Y	D_1
Interface Tunnel Exchange	Y E^8	N $\beta_* \neq$	Y $Nb_2O_{5-y} \downarrow$	Y lower β_*	N $Nb_2O_{5-y} \uparrow$	N high β_*	~~N~~ new Nb_2O_{5-y}	~~N~~ improv^t	-	-	Y	D_2
Thermal Feedback	Y parabolic	Y ≈ thermal properties	Y $R_{BCS}\downarrow$ $R_{res}\uparrow$	N ≈ therm. propties	-	-	-	-	-	-	N C coeff.^t	-
Magnetic Field Dependence of Δ	Y expon^tial	N $B_{C2}^S \neq$	Y $B_{C2}^S \uparrow$	Y higher B_{C2}^S	-	-	-	-	-	-	~~N~~ thin film	D_1
Segregation of Impurities	?	N segregation ≠	N only O diffusion	Y surface ≠	-	Y good cleaning	N chemistry	-	-	-	Y	-
Bad S.C. Layer Interstitial Oxygen $Nb_{4-6}O$	?	Y NC layer	Y O diffusion	N	N interstitial re-appears	-	~~N~~ new bad layer	-	Y higher B_{C2}^S	N $B_{C2}\downarrow$	Y	D_1

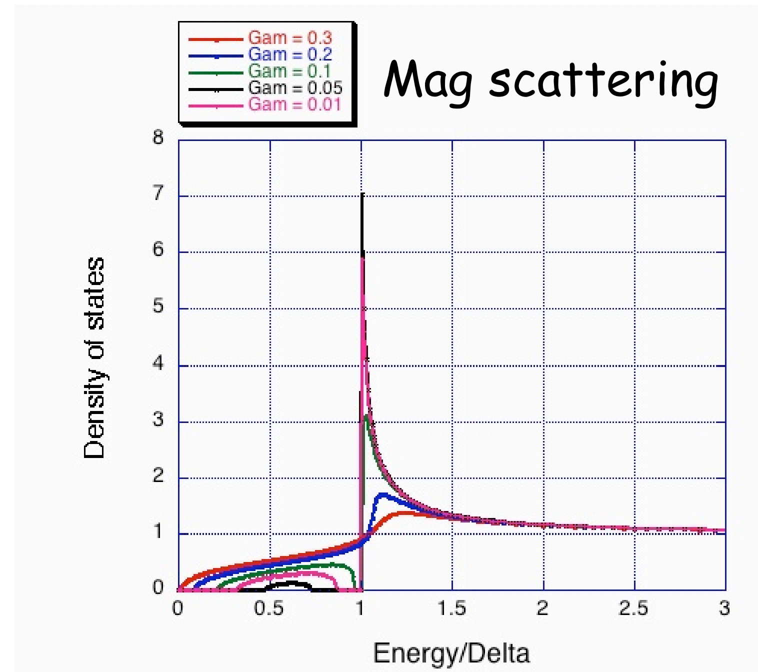
- We can present a better argument.

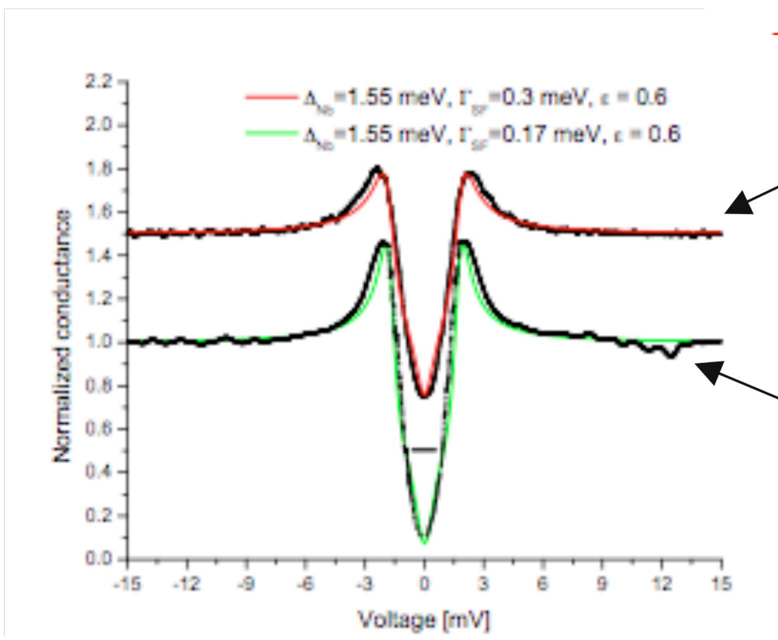
We have discovered magnetic oxides (bad) on niobium surfaces.

- John Zasadzinski of IIT believes that his point contact tunneling measurements clearly show that these magnetic oxides can break up Cooper pairs and explain high field Q-Slope.
- Described at SRF2007.
- Strange oxides are involved.



$Nb_{12}O_{29}$





Fit using Shiba theory

Baked Nb Crystal Shows reduced Magnetic scattering

We have demonstrated we can control the surface.

- Using Atomic Layer Deposition, Mike Pellin et. al. have shown that it is possible to control the oxide composition and density in the near surface region of niobium.

- We are trying to coat a JLab cavity to show that this technique will produce practical accelerator components.

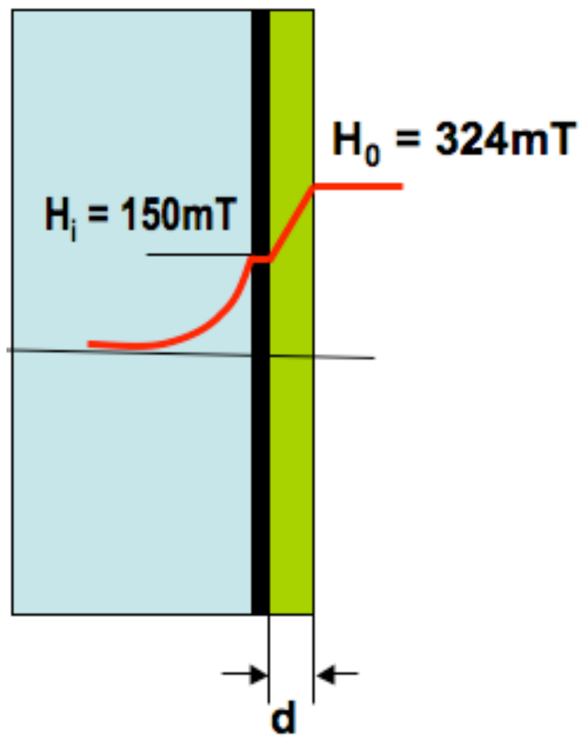
Point contact tunneling measurements show removal of oxides.

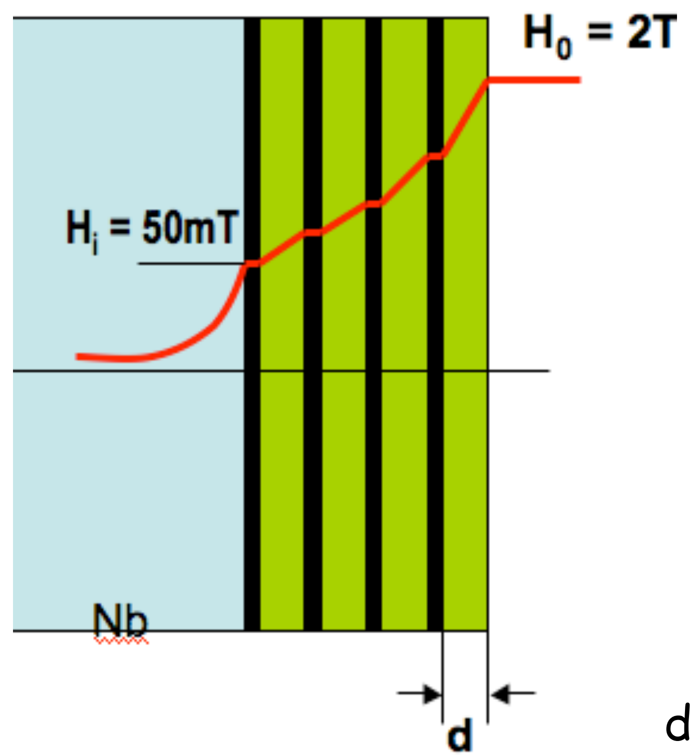
Alex Gurevich has a cure for quench fields.

The primary niobium layer is covered with an insulator and superconductor.

The top layer has high T_c, screens quench fields from the bulk niobium.

Multiple layers permit almost arbitrarily large accelerating fields.





d~30-50nm

would give E_{acc} ~ 100 MV/m

E_{acc} ~ 550 MV/m

(A. Gurevich, A. P. L. 88. 012511 (2006))

Why layered superconductors can have higher quench fields.

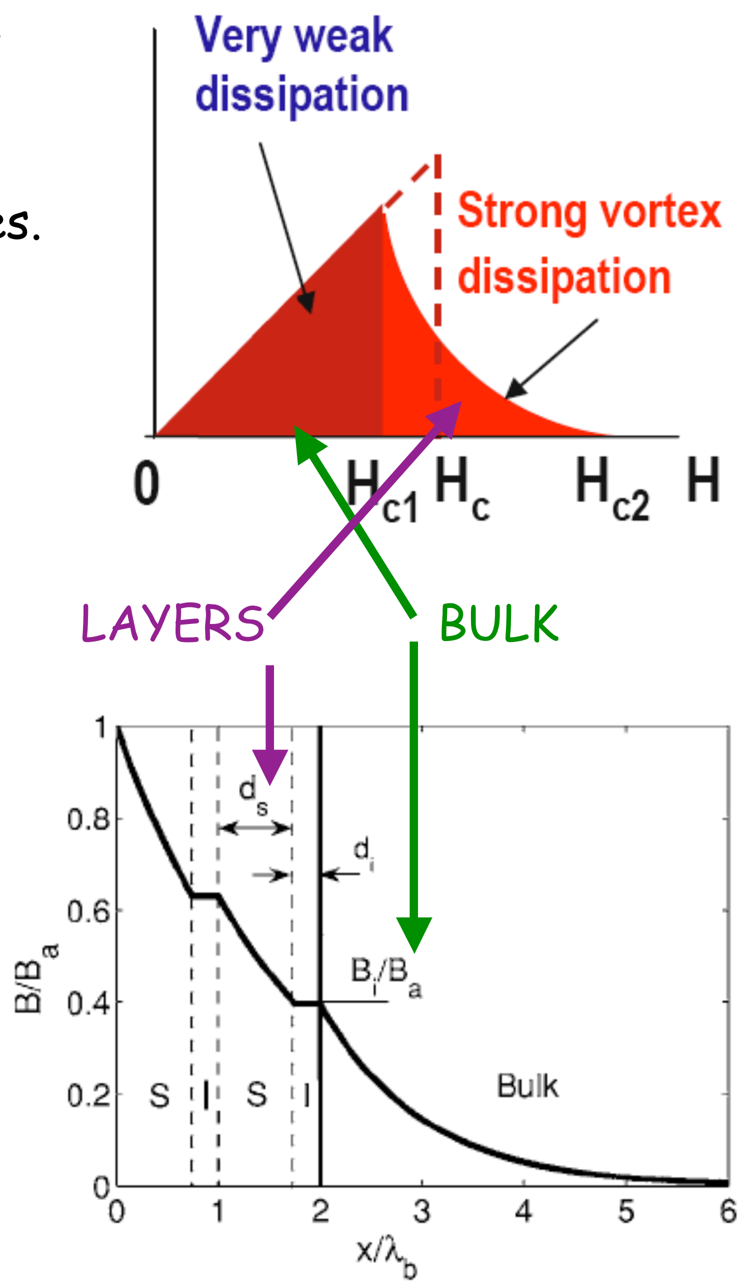
- Vortices in superconductors move in AC fields.
  ⇒ rf losses.

- Nb can reach the highest field without vortices.
  ⇒ Use as bulk material.

- Vortices aren't stable in thin layers.
  ⇒ Use layers to "screen" fields from bulk.

- This is a hard geometry to construct.
  Nb is "bulk" material, i.e. top 200 nm.
  Layers should be ~(10 – 300) nm
  Nanometer precision required for layers
  No shorts or voids in insulators.
  ALD can do it.

A. Gurevich. Appl. Phy. Let. 88 012511, (2006)



Fatigue in CLIC cavities.

- CLIC people believe:

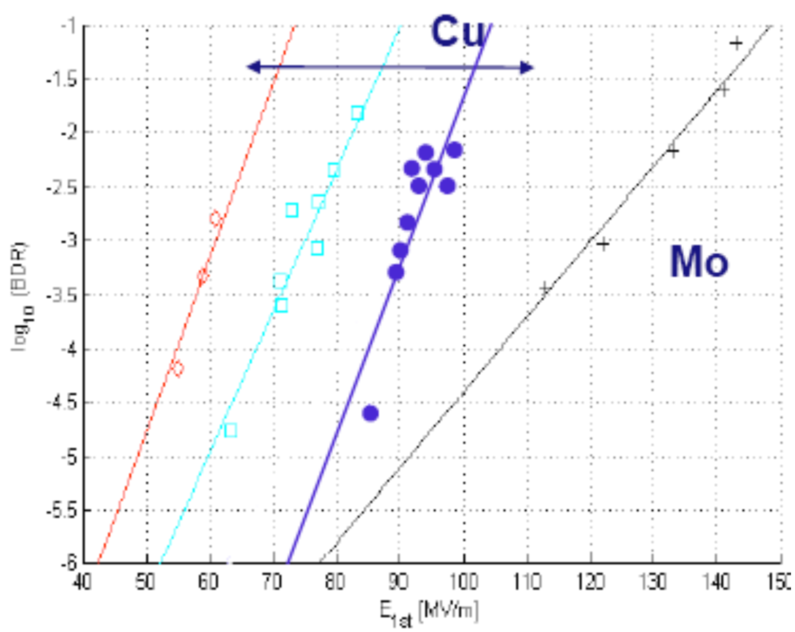
  Fatigue determines failure rate.

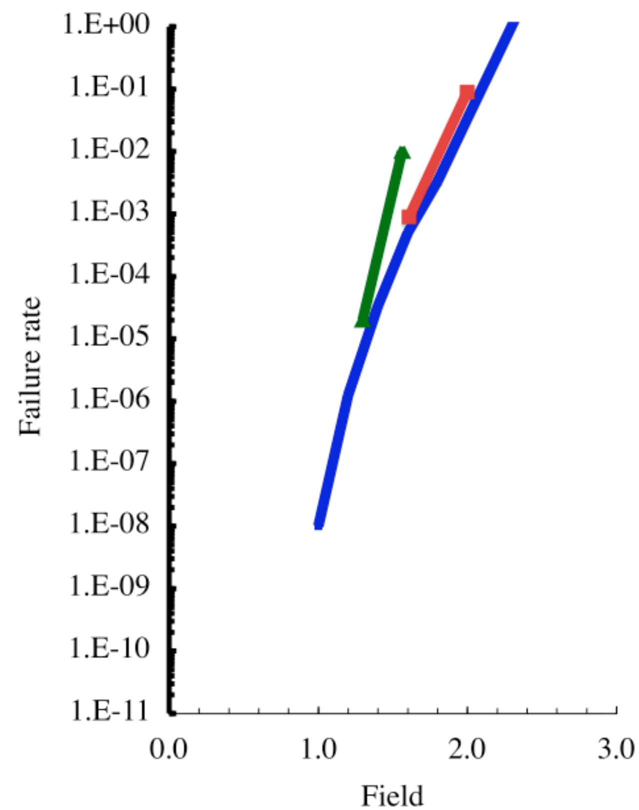
  This is correct

  They believe pulse heating causes fatigue.

  I believe tensile stress is the cause.

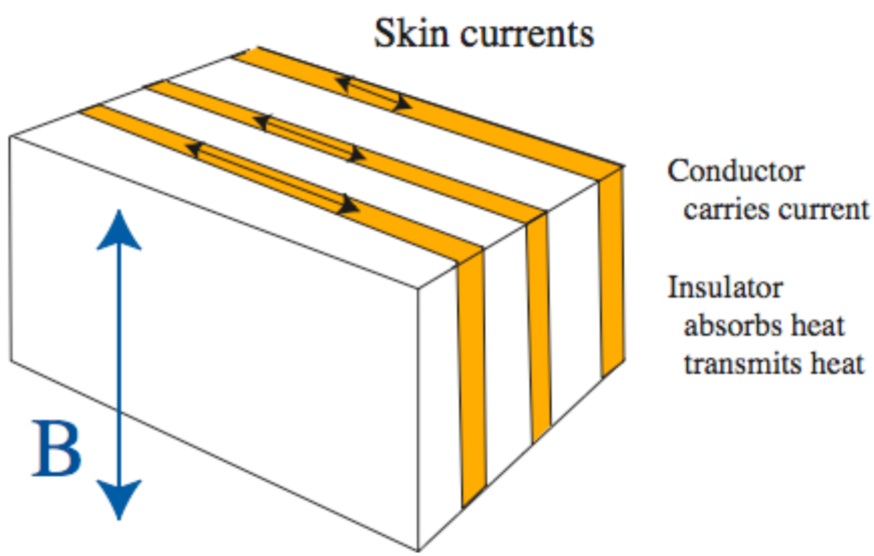
Fatigue gives the life=F(E) relation.

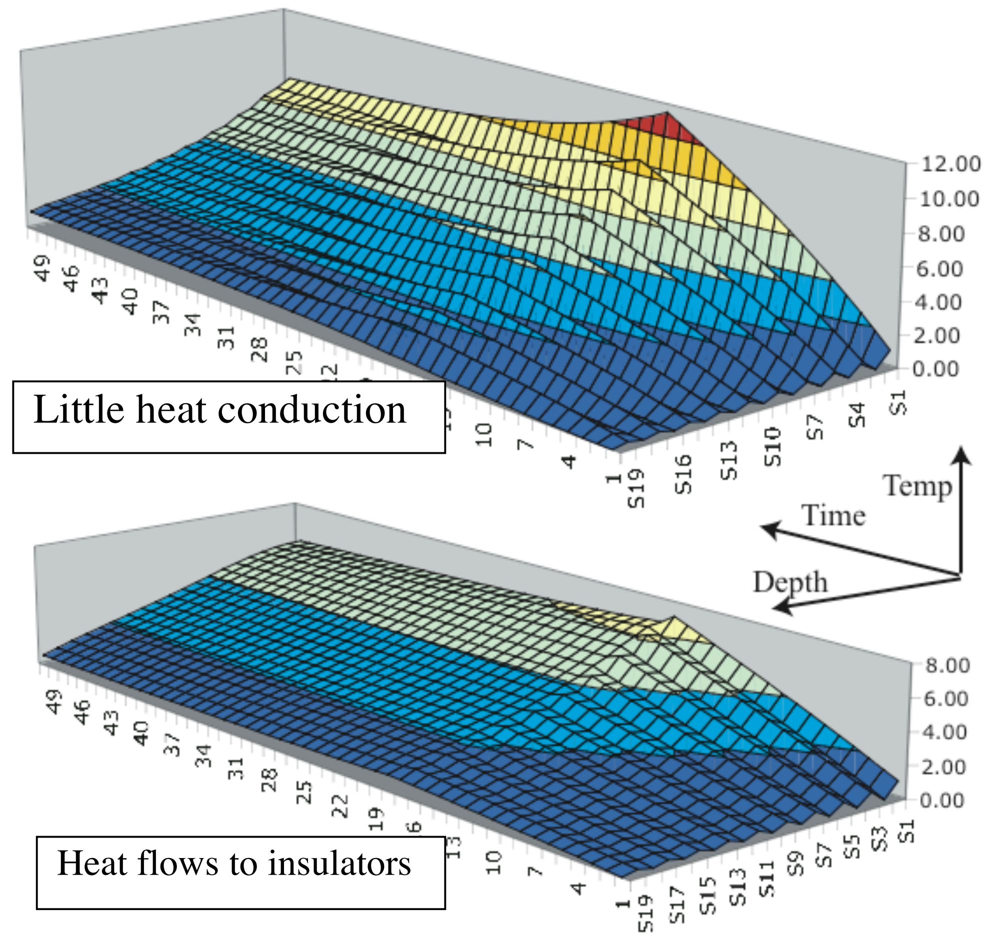




Surface layers can also cure pulsed heating, in principle.

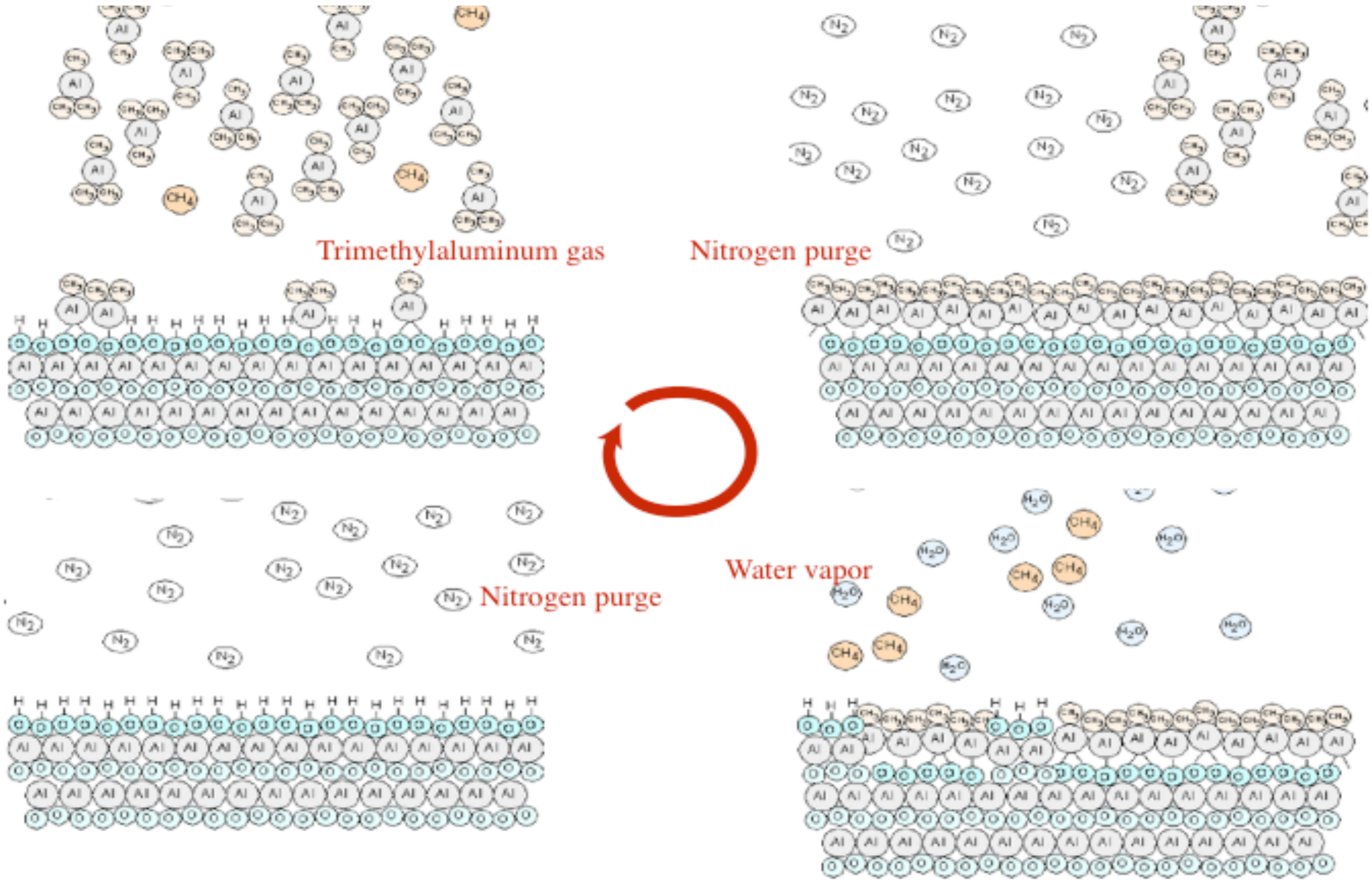
- You can build a composite material with higher specific heat.



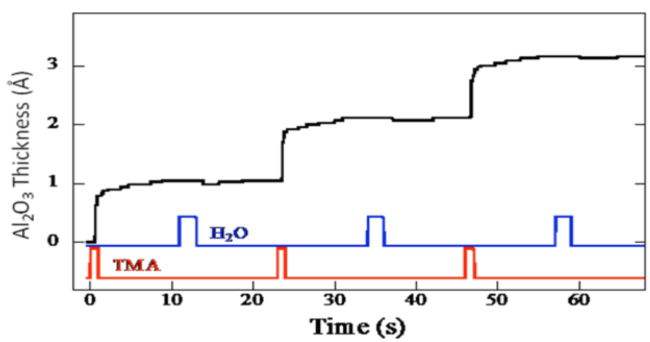


- Less thermal excursion
  Less fatigue
  Longer lifetime

Atomic Layer Deposition



Quartz
Crystal
Microbalance



- Growth Occurs in Discrete Steps

Atomic Layer Deposition (ALD)

- Atomic Layer by Layer Synthesis: a method similar to MOCVD
- Used Industrially
  - Semiconductor Manufacture for "high K" gate dielectrics
  - "Abrupt" oxide layer interfaces
  - Pinhole free at 1 nm film thicknesses
  - Conformal, flat films with precise thickness control
- Electroluminescent displays
  - No line of sight requirement
  - Large area parallel deposition
  - Large Surface area, high electric field applications
- Parallel film growth technique, (insides of large tubes).

ALD may be useful for SCRF.

- Mike Pellin & Jeff Elam (ANL/MSD) can conformally coat surfaces with monolayers of many materials. (Elam, Libera, Pellin, Zinovev, Greene, Nolan, A. P. L. **89**, 053124 (2006))

- insides of tubes

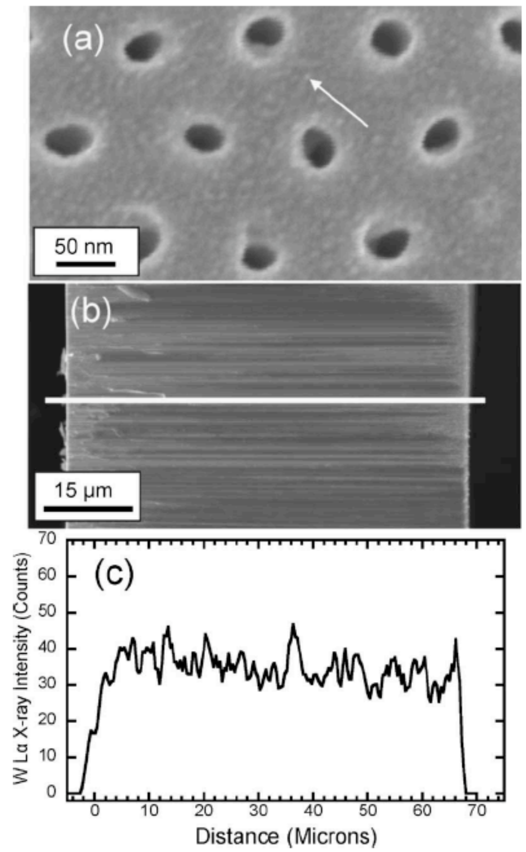


FIG. 1. Plan view (a) and cross-sectional (b) SEM images of anodic aluminum oxide membrane following ten cycles of W ALD. The white arrow indicates W nanocrystal. W EDAX line scan (c) taken from the middle of the cleaved membrane along the white line in (b).

tungsten on aerogels

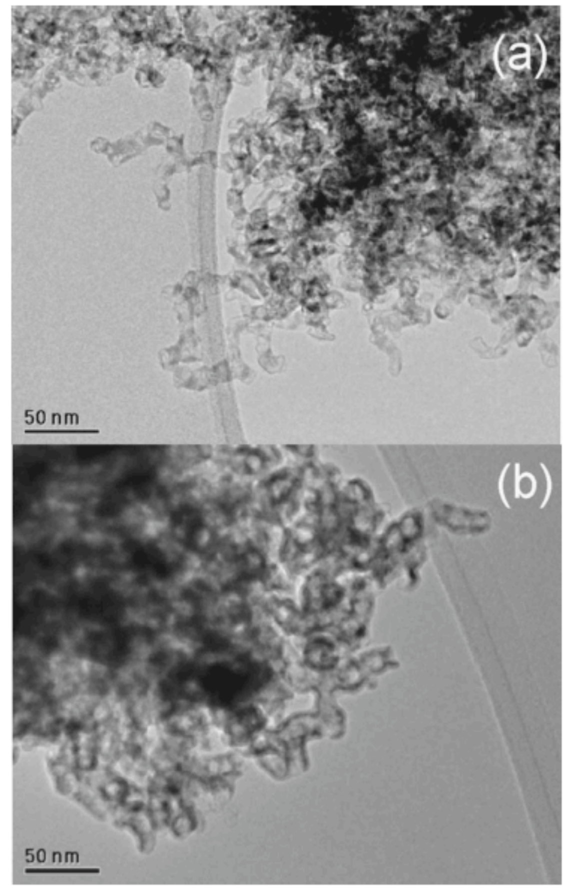
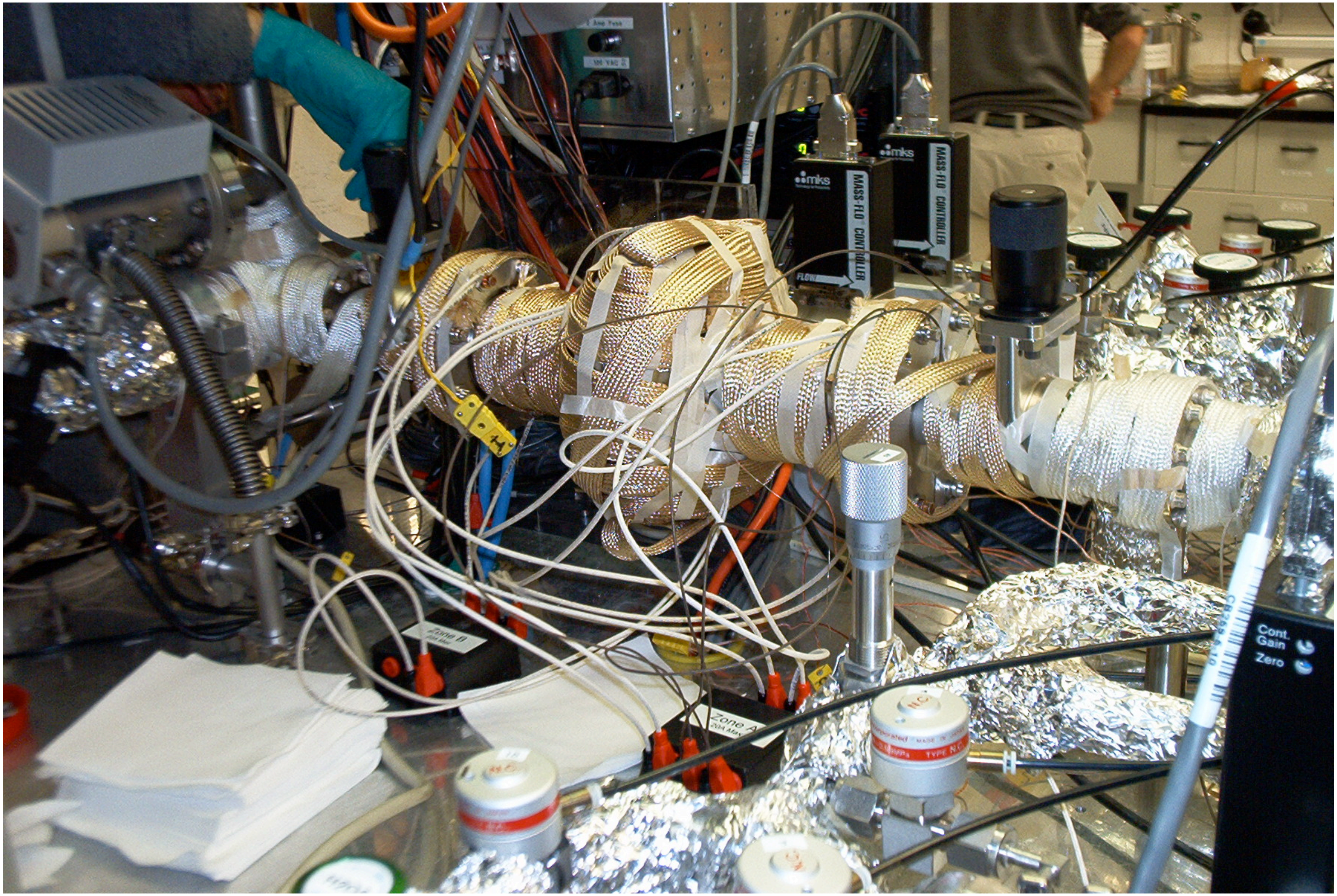
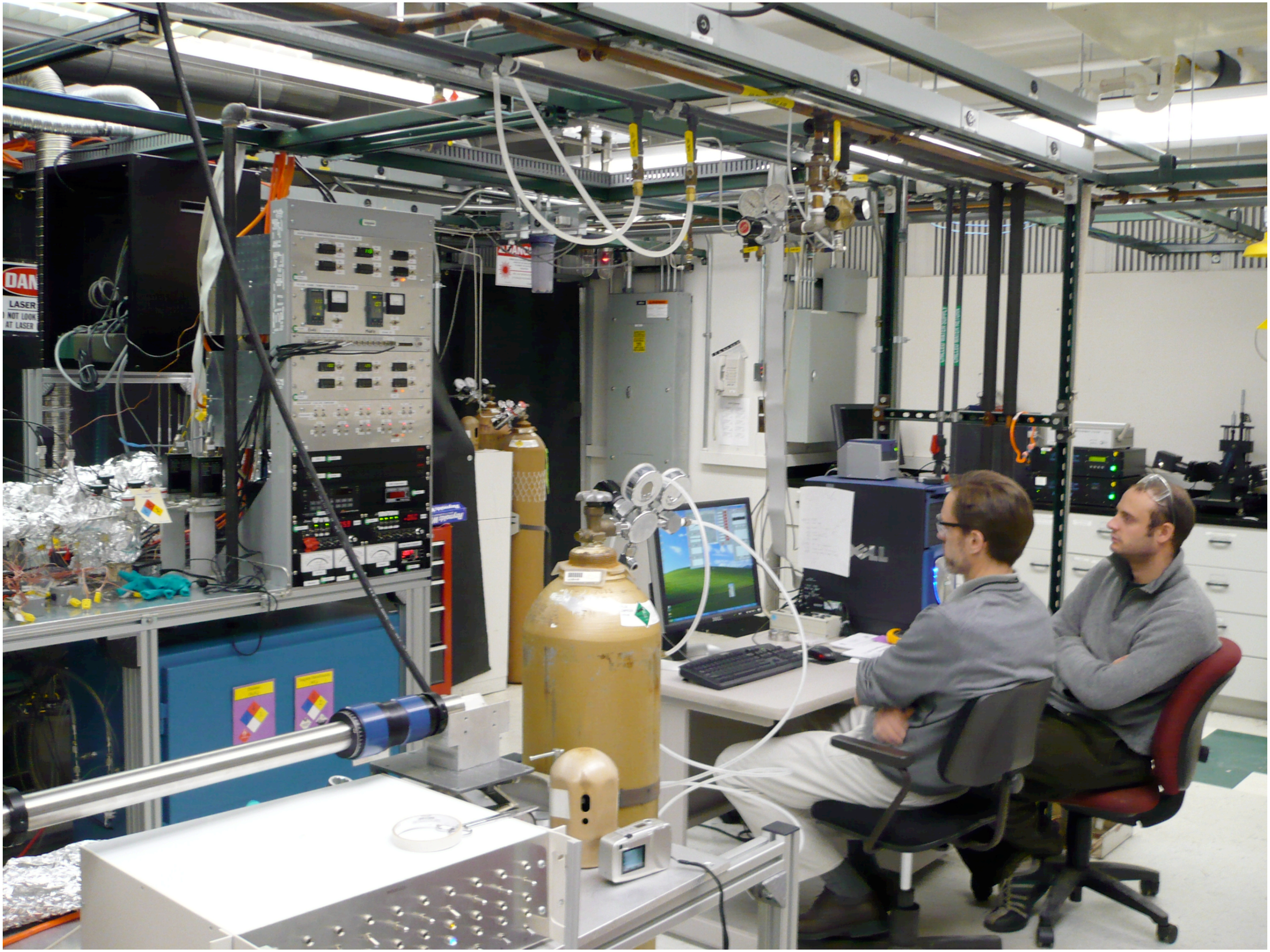


FIG. 4. TEM images of carbon aerogel following three (a) and seven (b) cycles of W ALD.

Coating a SCRF single cell cavity.




LASER

Gas filled cavities and dielectrics

- Muons Inc is doing experiments with high pressure gas rf cavities
  Perhaps crucial for muon cooling.

- Two effects of radiation damage:
  a) integrated structural damage, atomic displacements, etc. – old stuff
  b) instantaneous ionization damage – not generally considered

- Two dielectric failure modes:
  1) Resistive dissipation of cavity energy.
     Recombination times are very long (~sec)
     Loss tangent increases during radiation
       Experimentally measured

  2) “instant” loss of cavity energy due to runaway high energy δ rays.

- We will do the experiment.

Conclusions

- We have developed a model which seems to explain high gradient limits.
- We incorporate information on DC, SCRF, High f, Low f, gas filled, beams, etc.
- We also explain High field Q-Slope, SCRF surface effects.
  This work (is/is being) extensively documented.
- The model shows how to cure cavity breakdown.
- I think we can increase SCRF and NC gradients by >3X.
- Our problem is magnetic field effects, new problems with MTA data.

Bibliography

Major papers (~70 pages in refereed journals):

- X ray Spectra, Nucl. Instrum. Meth. Phys. Rev. A. **472**, 600 (2001)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0139/muc0139.pdf
  Measurements of x-rays from a single cell cavity
- Open Cell Cavity, Phys. Rev. STAB **6**, 072001 (2003)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.6.072001
  Measurements of 6 cell cavity, dark current measurements, w/wo B fields, comp. with other cavities, tensile stress
- Cluster emission, Phys. Rev. STAB **7**, 122001 (2004)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.7.122001
  Emission of clusters, thermal and field dependence,
- Breakdown mechanics, Nucl. Instrum. and Meth A **537**, 510, (2005)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0286/muc0286.pdf
  General theory of tensile stress triggered breakdown
- Magnetic fields, Phys. Rev. STAB **8**, 072001 (2005)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.8.072001
  Measurements with 805 MHz pillbox, measurement of $s_2(\beta)$
- Surface damage, Phys. Rev. STAB **9**, 062001 (2006)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.9.062001
  Relationship between surface damage and maximum operating fields.

Other papers

Recent results in: PAC, EPAC and SRF workshops . . etc.