Can We Increase the Operating Gradients of Linacs ?

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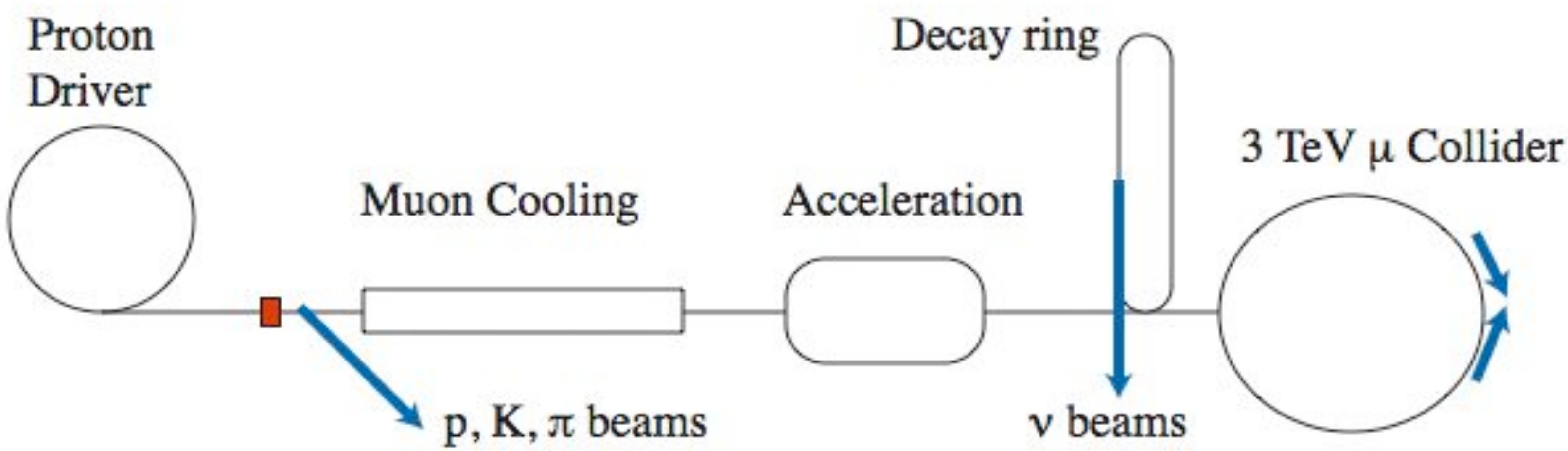
ANL/HEP

Accelerator Science and Technology Seminar
Fermilab
3/17/08

Outline

The Muon Collaboration needs better linacs.



We are developing a model that can study all aspects of breakdown. (the first?)

Using Atomic Layer Deposition we might be able to completely control the surface.

So:

- Why do rf structures fail?
- How well can we control the surface?
- What are the ultimate limits?

Many people have contributed to these results.

Normal Conducting

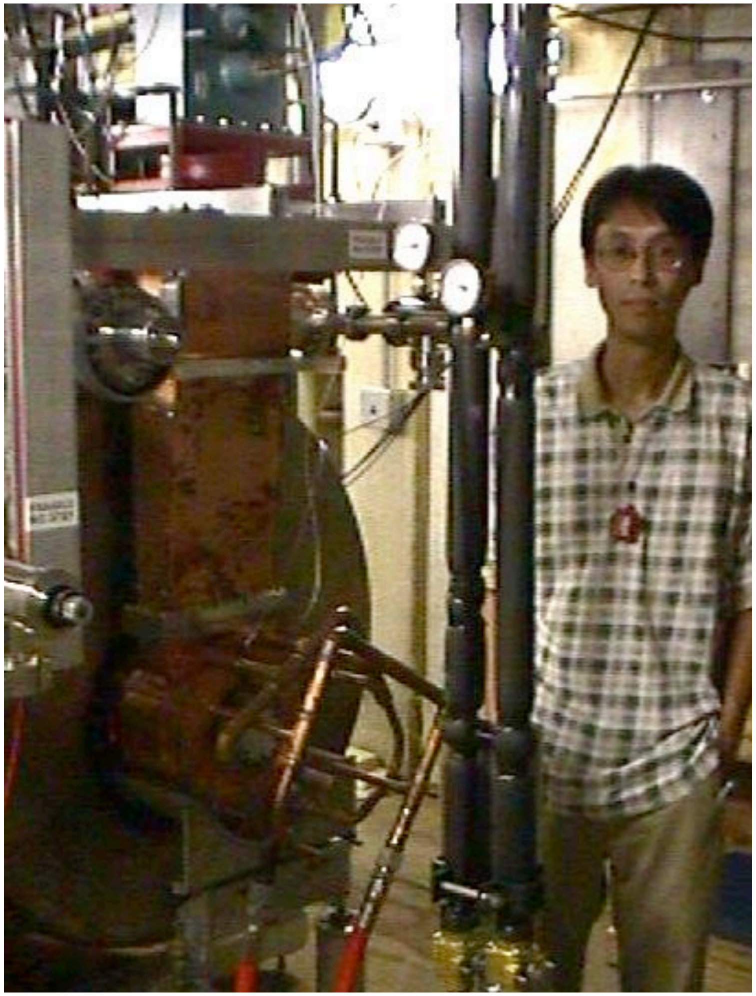
A. Hassanein	Plasma Phys	Purdue
Z. Insepov	Fracture kenetics	ANL/MCS
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
D. Huang	RF, Instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X
P. Stoltz	Plasma modeling	Tech-X

Superconducting

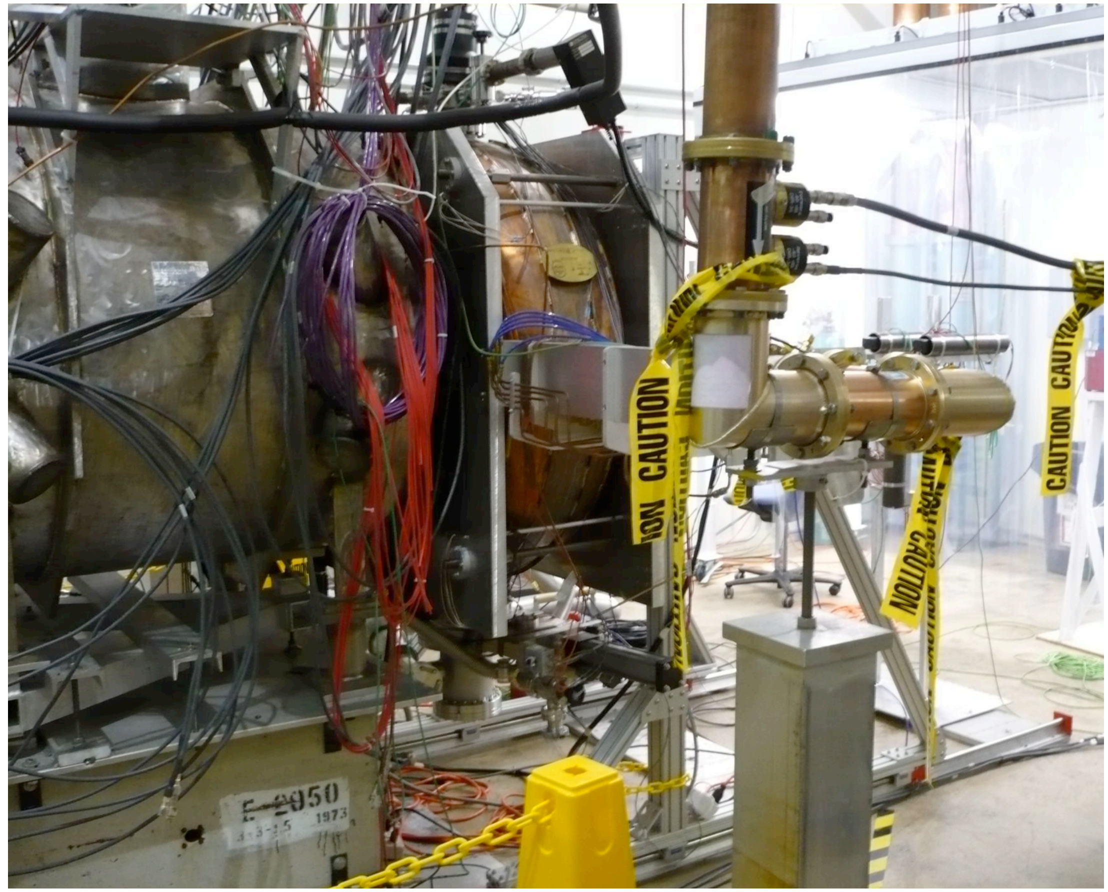
M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
J. Moore	ALD, expts.	MassThink LLC
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
Th. Proslier	SC theory and exp	IIT
L. Cooley	SCRF	FNAL
G. Wu	SCRF	FNAL

This work depends on results from Mucool Expts. at Fermilab

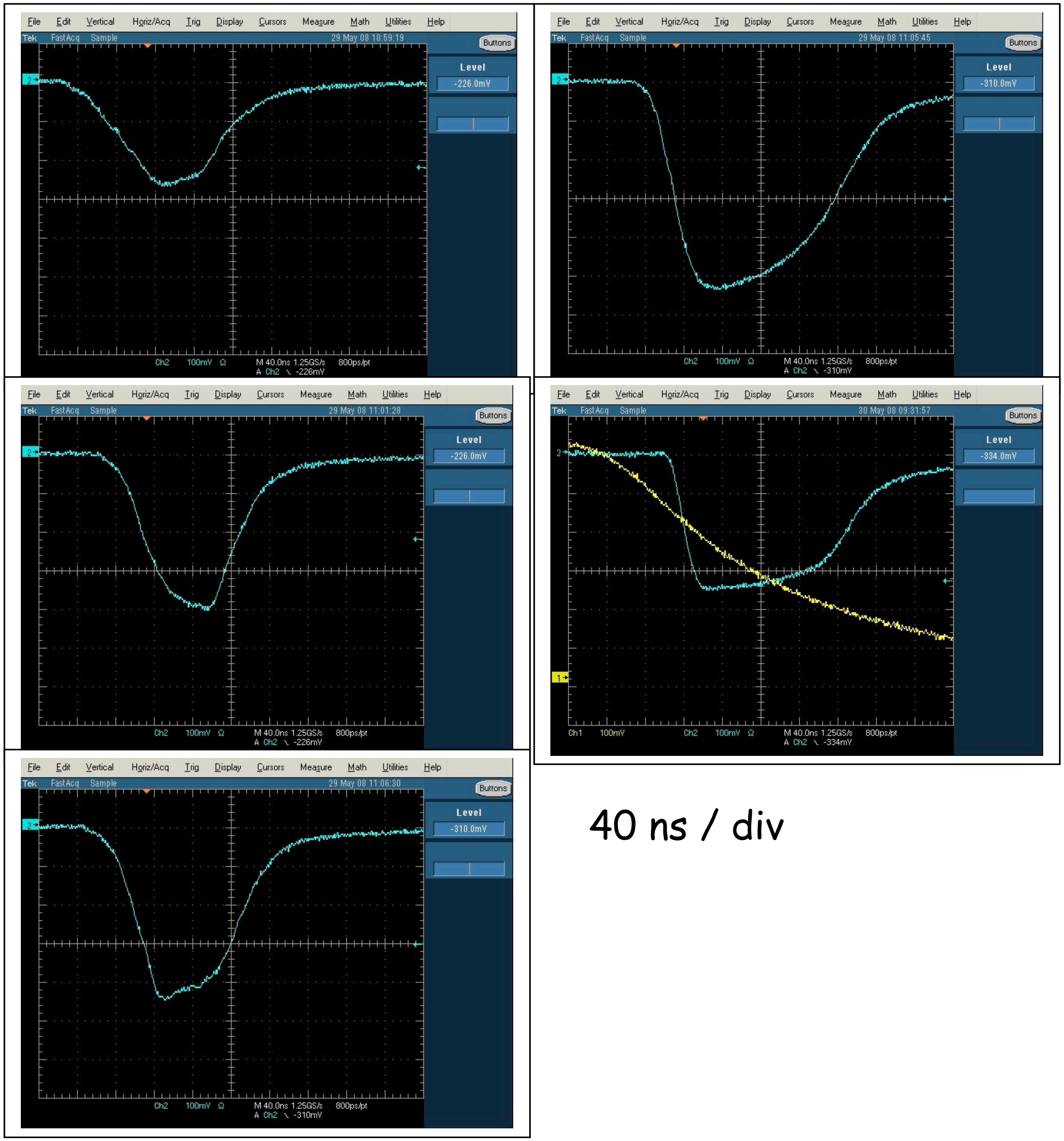
Lab G



MTA

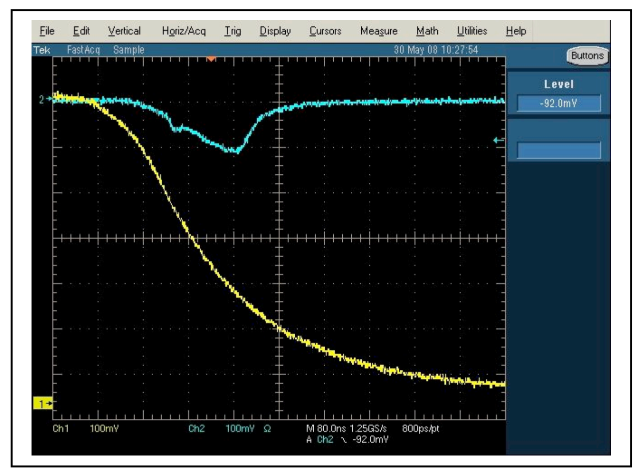


RF breakdown: x ray pulses



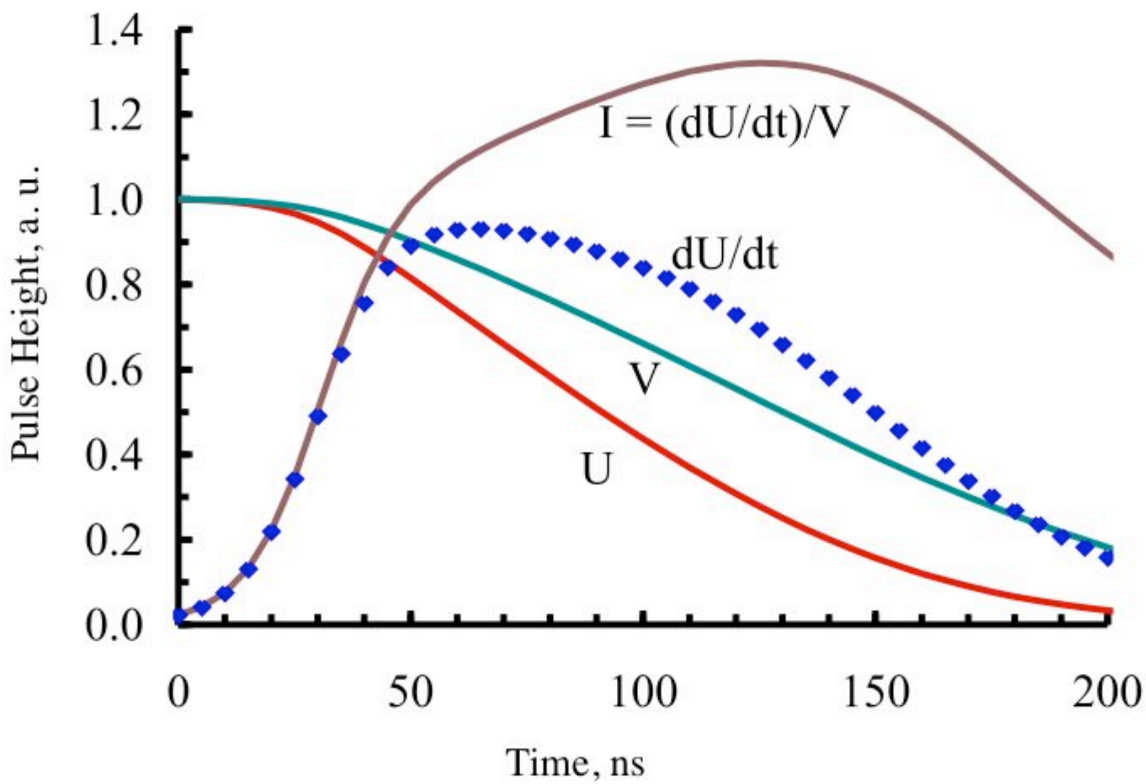
40 ns / div

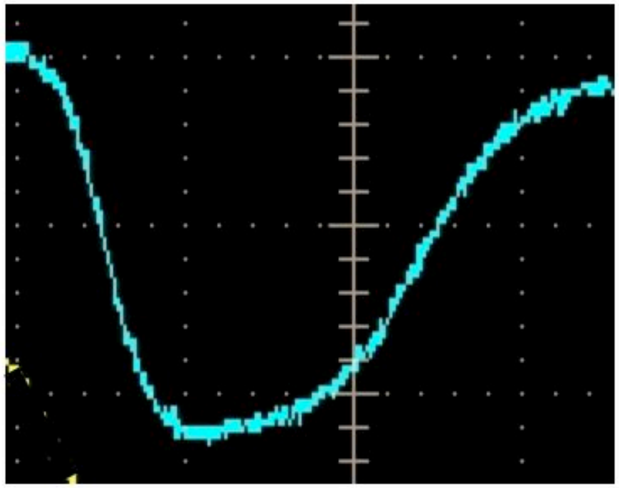
80 ns / div



What is happening?

- X ray data show how energy leaves the cavity.

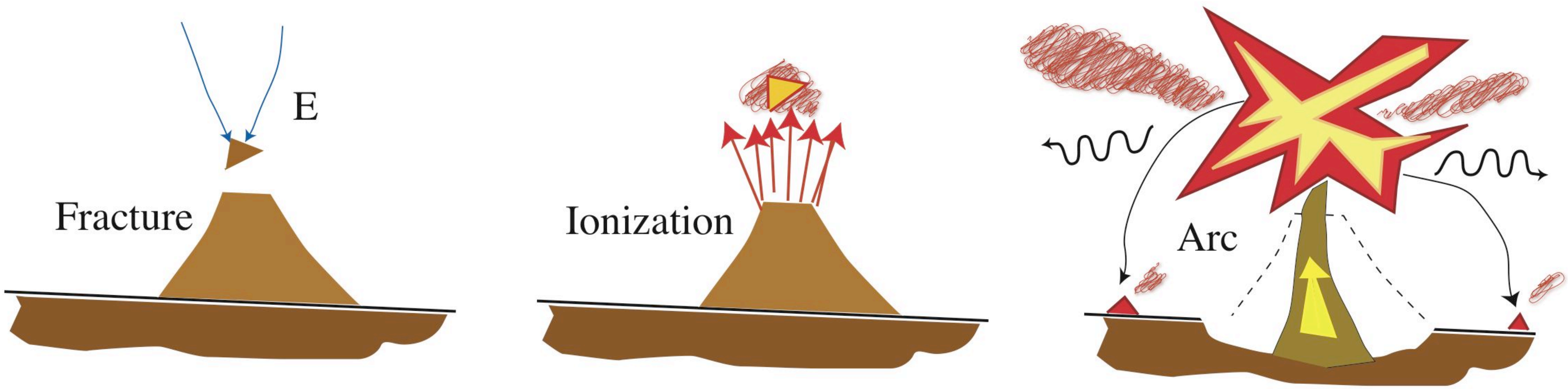




At the MTA our 805 MHz pillbox has:

- Stored Energy ~ 1 J
- Electron energy ~ 4 MeV
- Electron current ~ 4 A

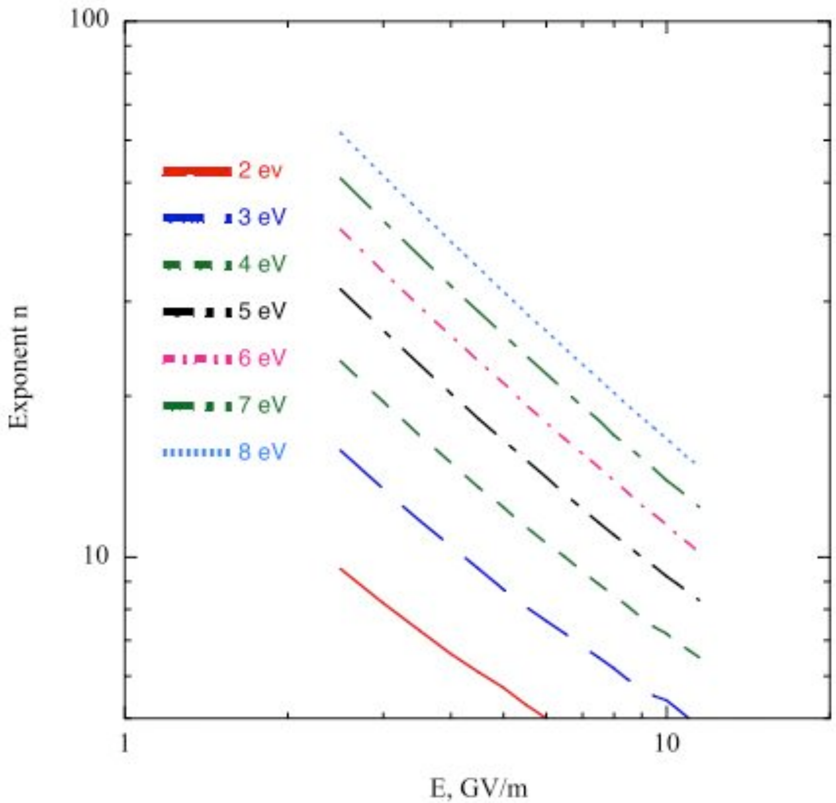
What starts the process?

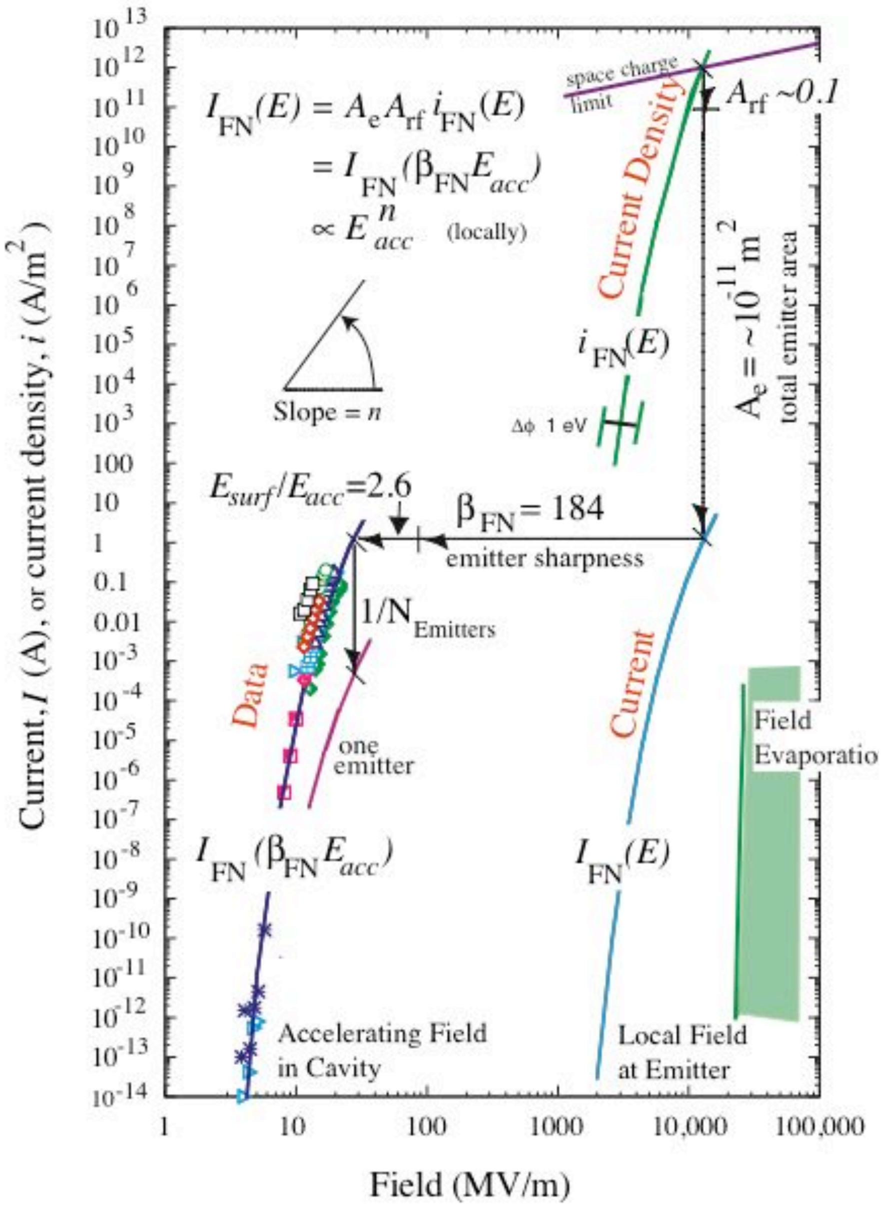


- Average fields in the cavity are 30 – 50 MV/m = E_{surf}
- X rays show small asperities have much larger fields, E_{local} ~ 7 GV/m.
- We assume an enhancement factor $\beta = E_{local} / E_{surf}$
- At 7 GV/m tensile stress is comparable to copper's tensile strength.

We can measure the local field at the emitter, with x rays.

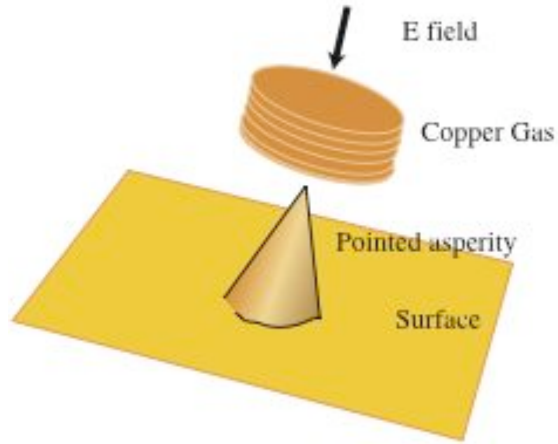
- FN can be approximated by $I = E^n$.
- The local surface field = f(n, ϕ).~7 GV/m

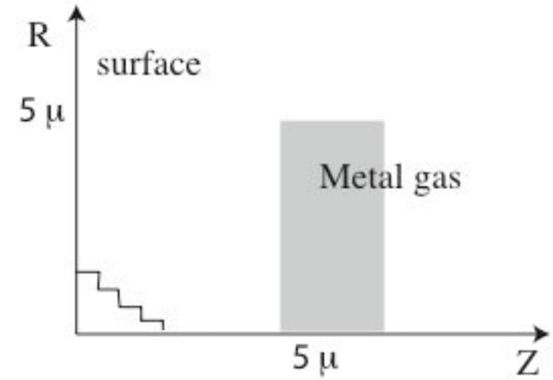




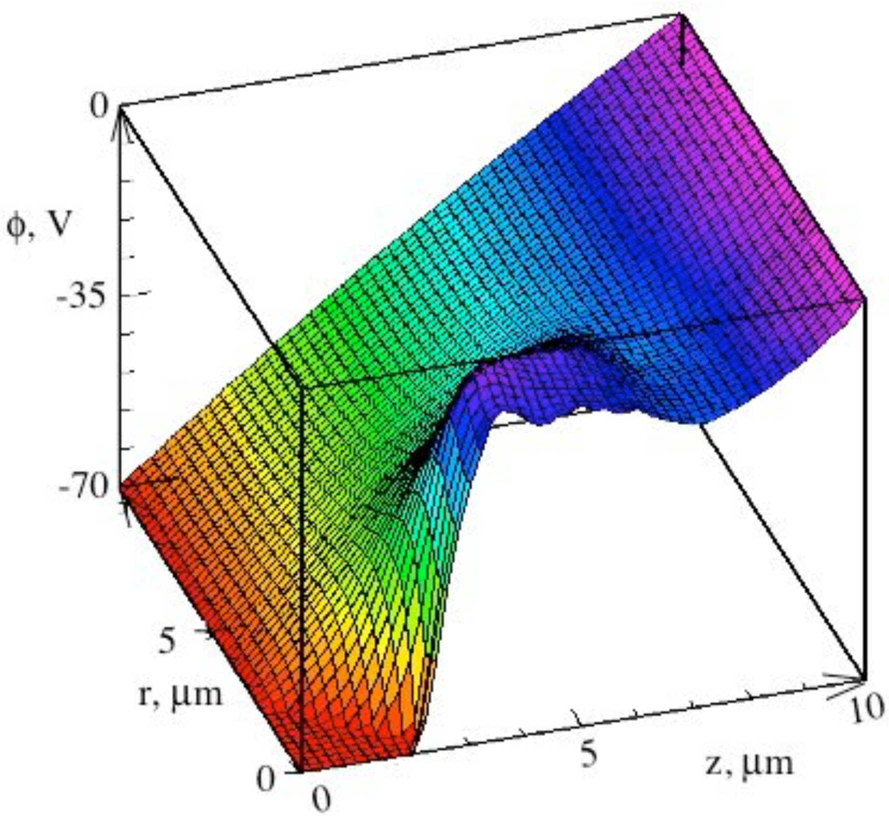
OOPIC Pro modeling

- The geometry

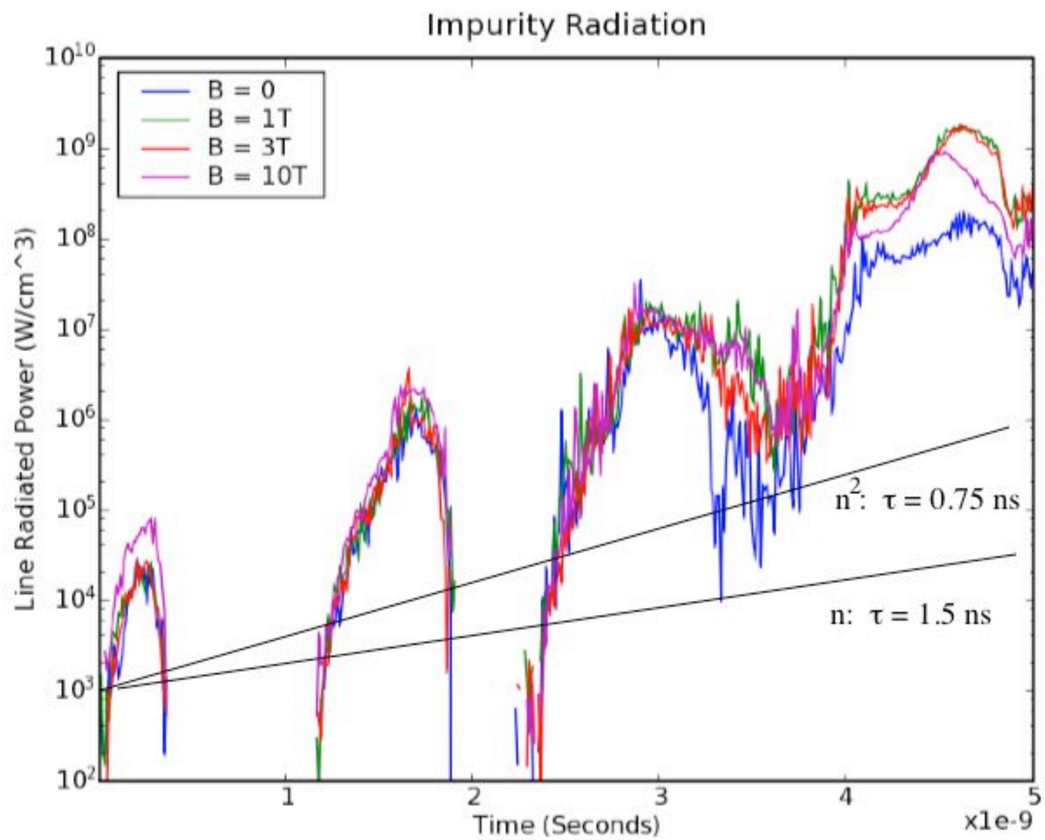




Scaler potential of local plasma

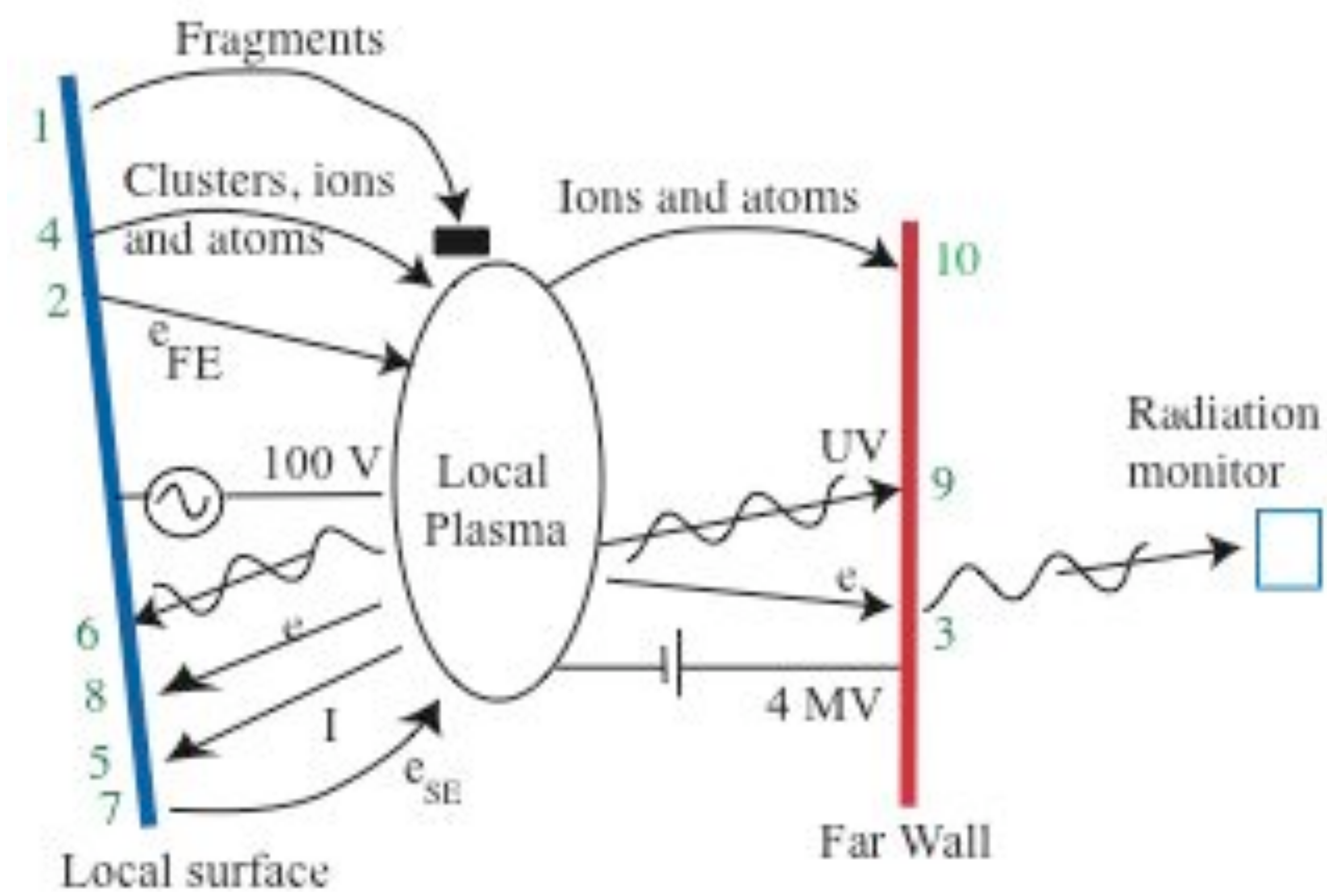


Impurity radiation during initiation

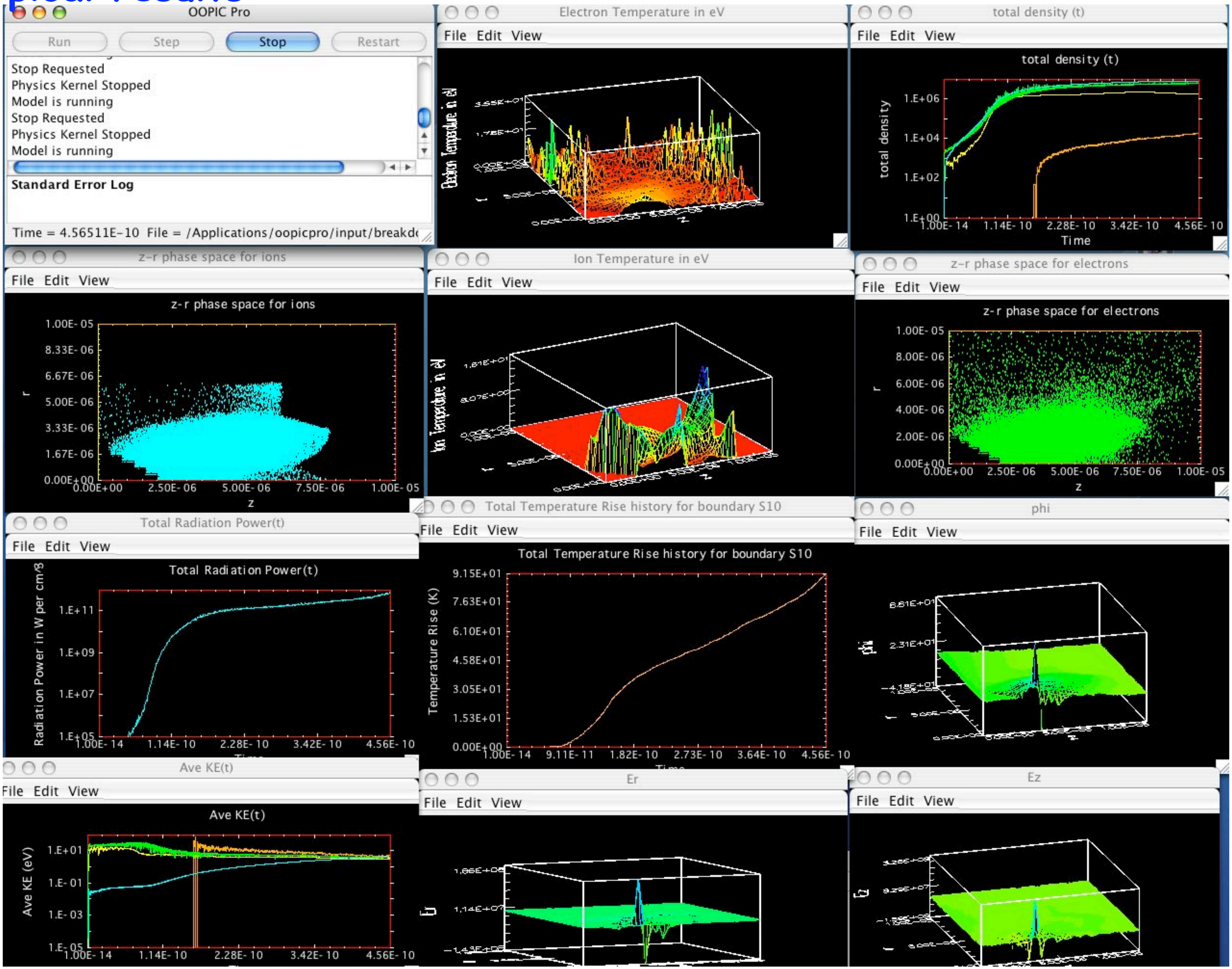


The overall model of the plasma discharge

- Fragments trigger the spark.
- These fragments are broken apart and ionized by electron collisions.
- Plasma electrons accelerate to the far wall.
- + lots of other stuff



Typical results



Factors that drive the discharge

- Immediately following the formation of the plasma, the surface field increases by a huge factor producing
  - more tensile stress
  - more field emission
  - more ion current to the wall

Factors that limit the discharge

- Space Charge Limit
  This still exists and causes the electrons to belch out of the asperity.

- Electron kinematics
  Most of the energy may go to the far wall. Electron dynamics limit how energy can be moved from EM to heat
  - Secondary emission etc
  - Low energy electrons

- Metal Injection
  Huge forces and power levels exist, but material motion constrains things.

We are adding many details into the model.

- Field emission is not so simple
  - The work function varies widely across the emitter
  - The space charge limit has been carefully measured for our emitters - and these measurements seem to contradict all modern data.
- Coulomb explosions
  - More data (not really needed) in support of the fracture model
- OOPIC modeling of plasma formation
  - Description of ionization process
  - Description of the surface electric field
  - Description of fluxes of UV, ions, electrons, metallic fluids and fragments
- Breakdown Energy and Mass flow.
  - Many Mechanisms exist
- Field Ion evaporation
- Breakdown data from Lab G and the MTA

Field emission is more than an equation.

- This process has been studied for almost 120 years.
- Simple application of the eqn. isn't always useful.

current vs. field

Barbour et. al. '53

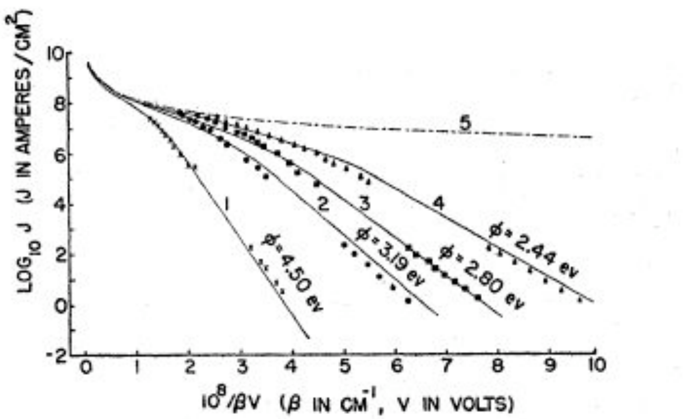


FIG. 7. Comparison of experimental data with space-charge field-emission theory (solid lines) for emitter N85. Curve 1, clean tungsten, curves 2–4, barium-on-tungsten as in Fig. 3; curve 5, Child's equation.

emission of electrons

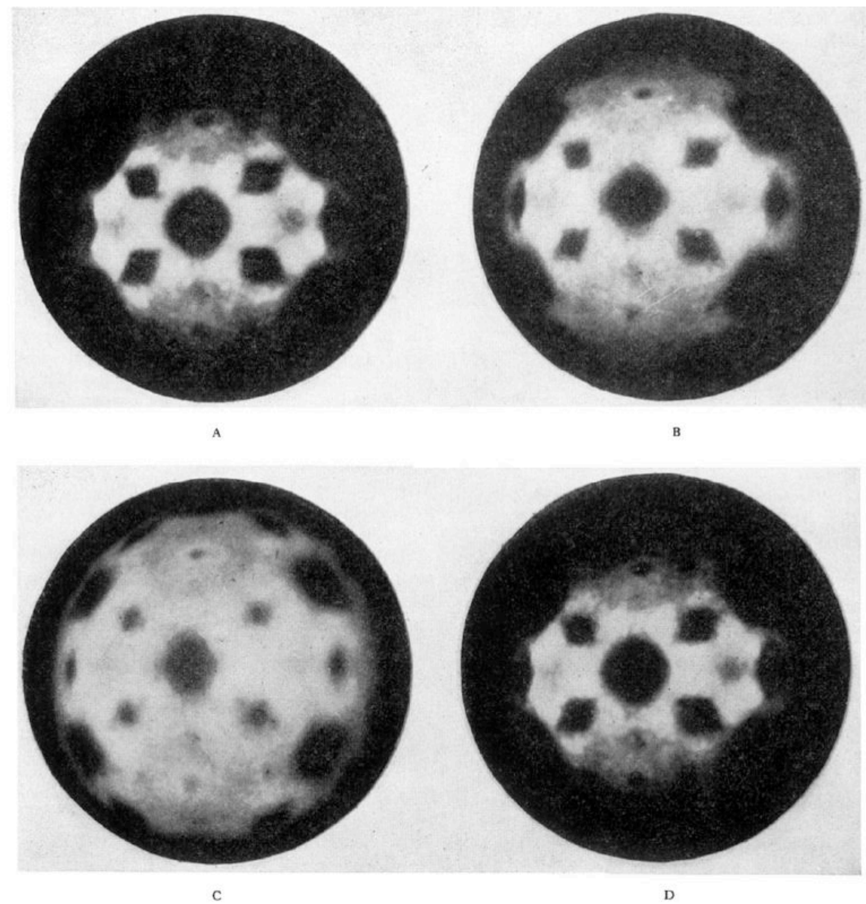


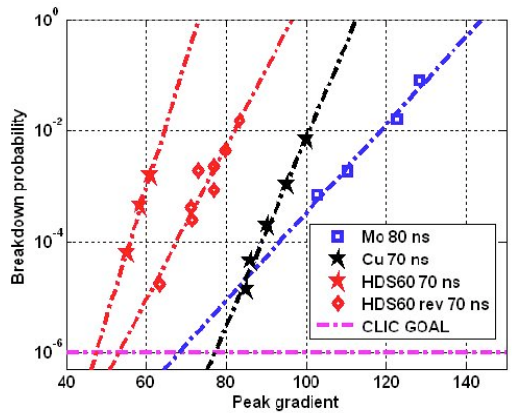
FIG. 4. Emission patterns at various currents, with constant work function $\phi = 3.19$, for emitter N85, corresponding to curve 2, Fig. 7.

- Small changes in surface materials make major changes in current yields.
- Space charge depends on geometry.

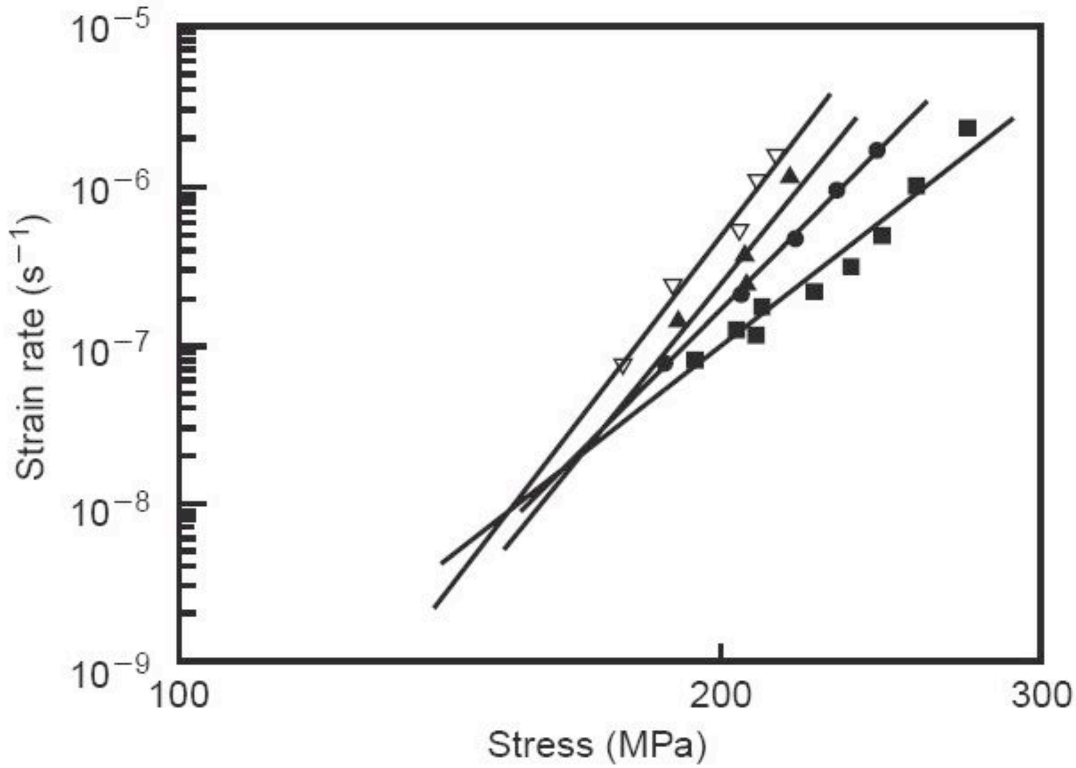
Fracture, Creep and Tensile stress

- Fatigue failure seems to explain how breakdown can occur after many cycles.

- Creep seems to explain fatigue at the atomic scale.



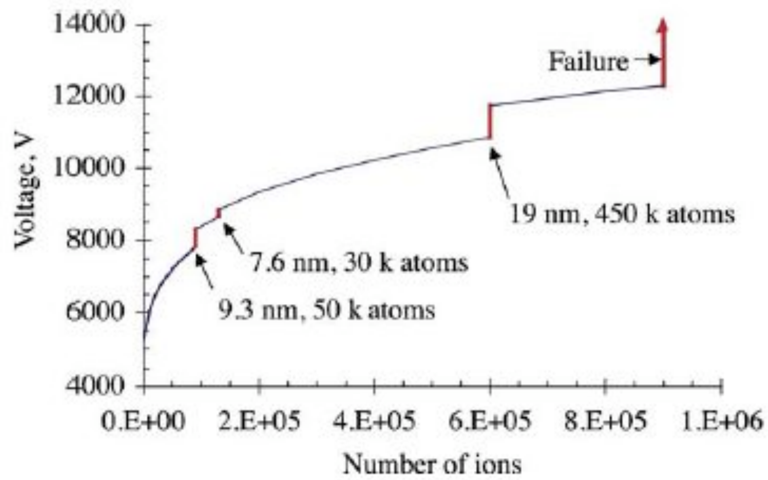
Creep rates at
0, 0.04, 0.5 and 1 Hz.

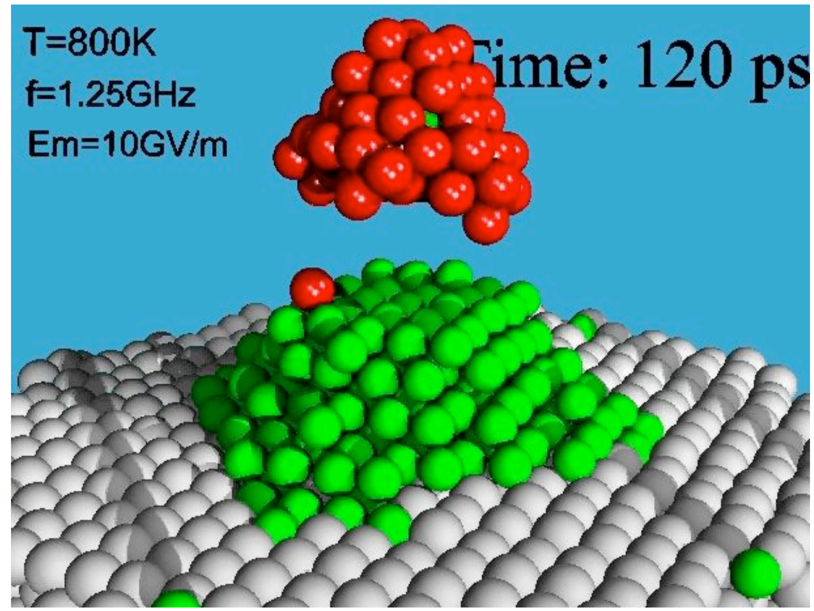


- There is a lack of data on creep and fatigue in the GHz range.

Field induced fracture is comparatively well understood.

- It is seen experimentally and modeled





Atom Probe Tomography data

The voltage is proportional to the radius

They count the atoms that come off

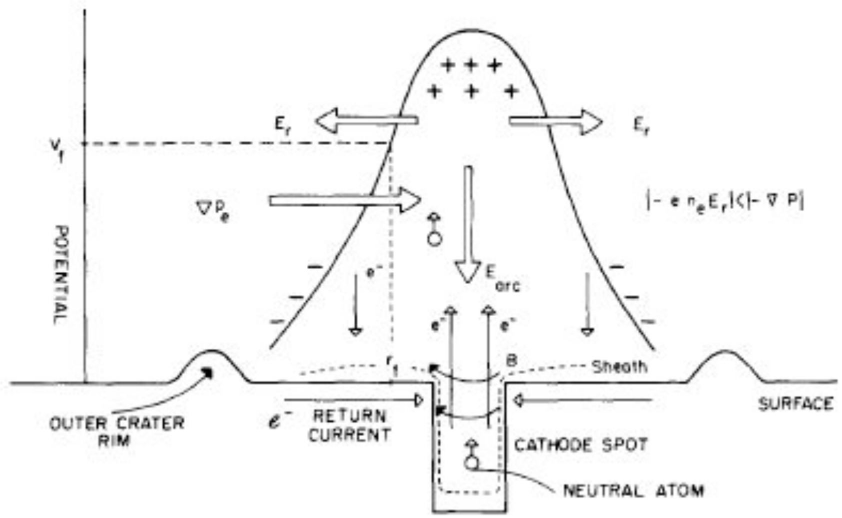
Insepov 2003

Unipolar Arcs

- Unipolar arcs were first seen (?) in tokamaks when tiny "weld beads" were found spiraling around the inner walls of these structures.

- They are driven by the sheath potential at the edge of a stable plasma.

- In tokamaks they are moved around by the electric and magnetic fields, producing their characteristic tracks.

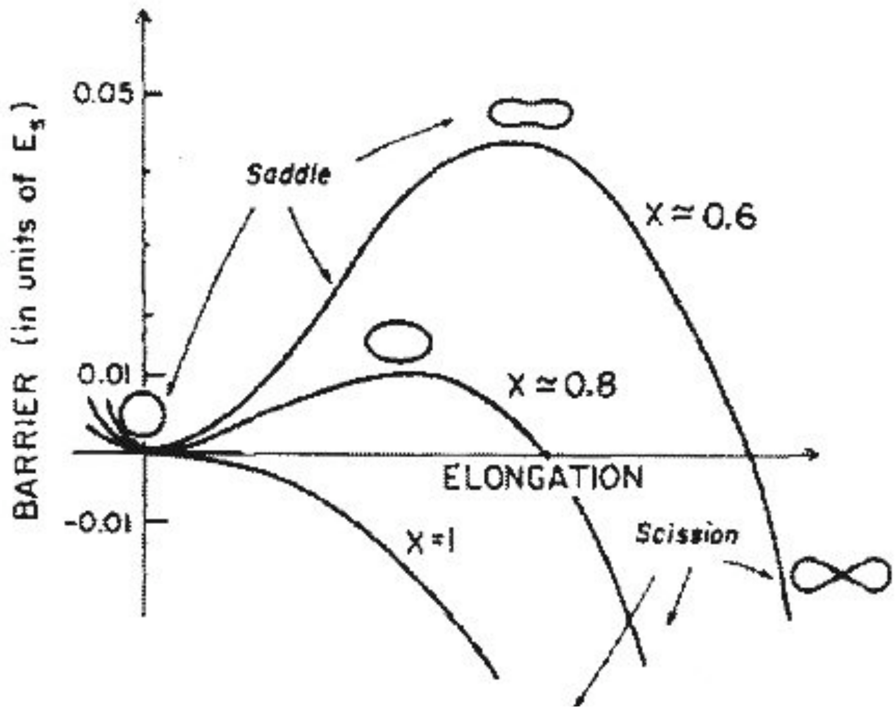


- The breakdown arcs we see are similar in some respects to unipolar arcs, however breakdown arcs are:
  - violently bipolar,
  - growing exponentially with ~ns scale time constants

Coulomb Explosions seem to be important.

- Coulomb effects in small clusters can break them apart (Rayleigh, 1882).
  $N_e/N_I = 1 \pm \delta$,
  $\delta \sim 0.01$ can give surface fields of 10 GV/m.

- Clusters are energetically unstable when $x = E_{Coulomb}/2E_{surface} > 1$,



Coulomb explosions are being modeled.

- They break up fragments above the field emitter.

- They may be seen as the cause of the initial fracture.

- This mechanism is seen experimentally and being modeled

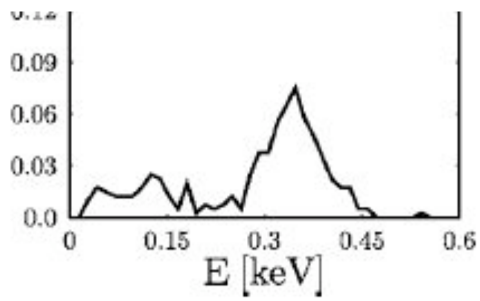
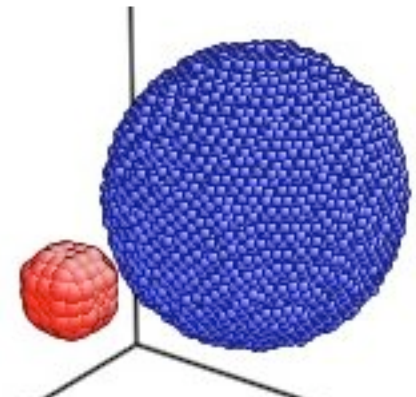
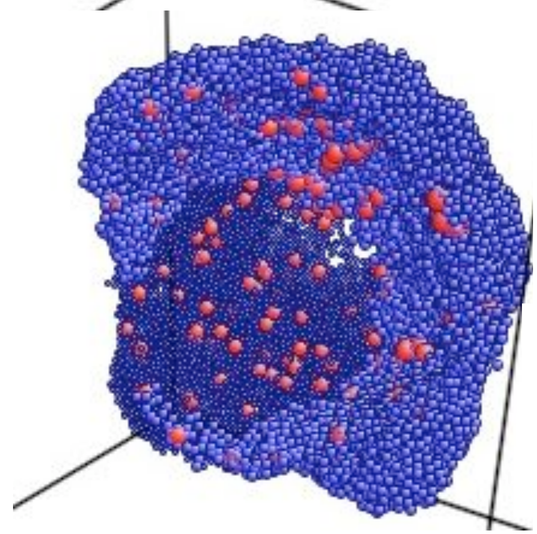


FIG. 3. Kinetic energy distributions for the different Na ions after excitation of Na_{41}^{+} with a laser of frequency ω=2.5 eV, intensity I=10^{16} W/cm^2, and $\cos^4$ pulse with FWHM of 20 fs.

Laser ionization of Na clusters



Before

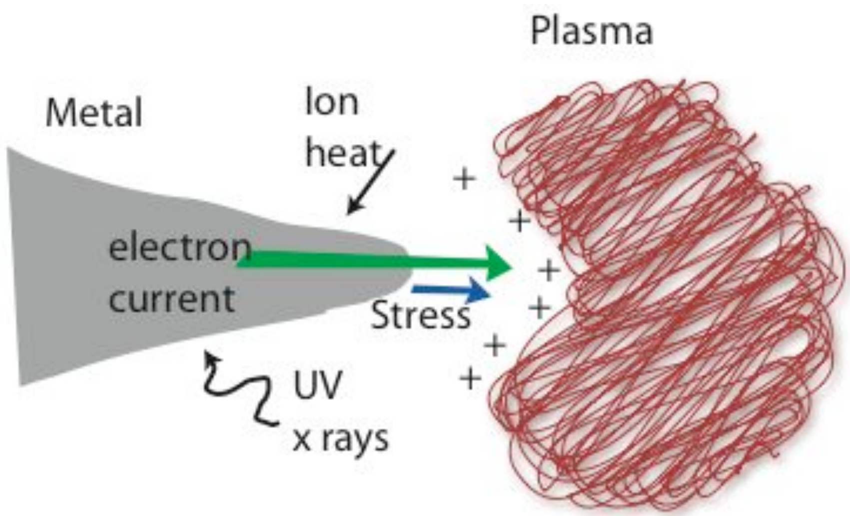


After

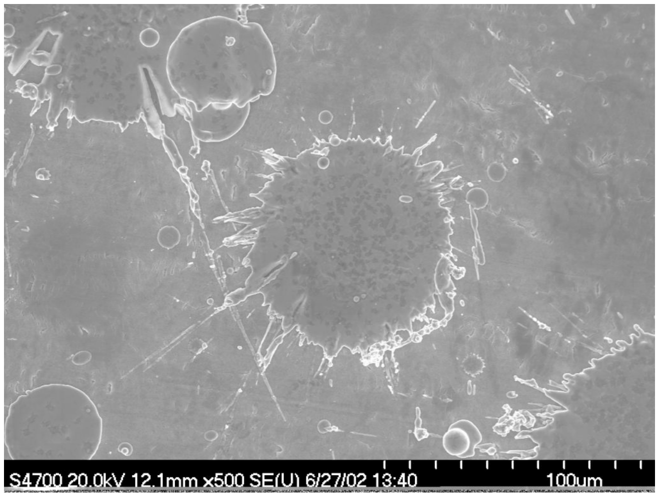
Insepov (2008)

Many mechanisms are active.

- No one understands this environment.



- Even liquid drops are accelerated.



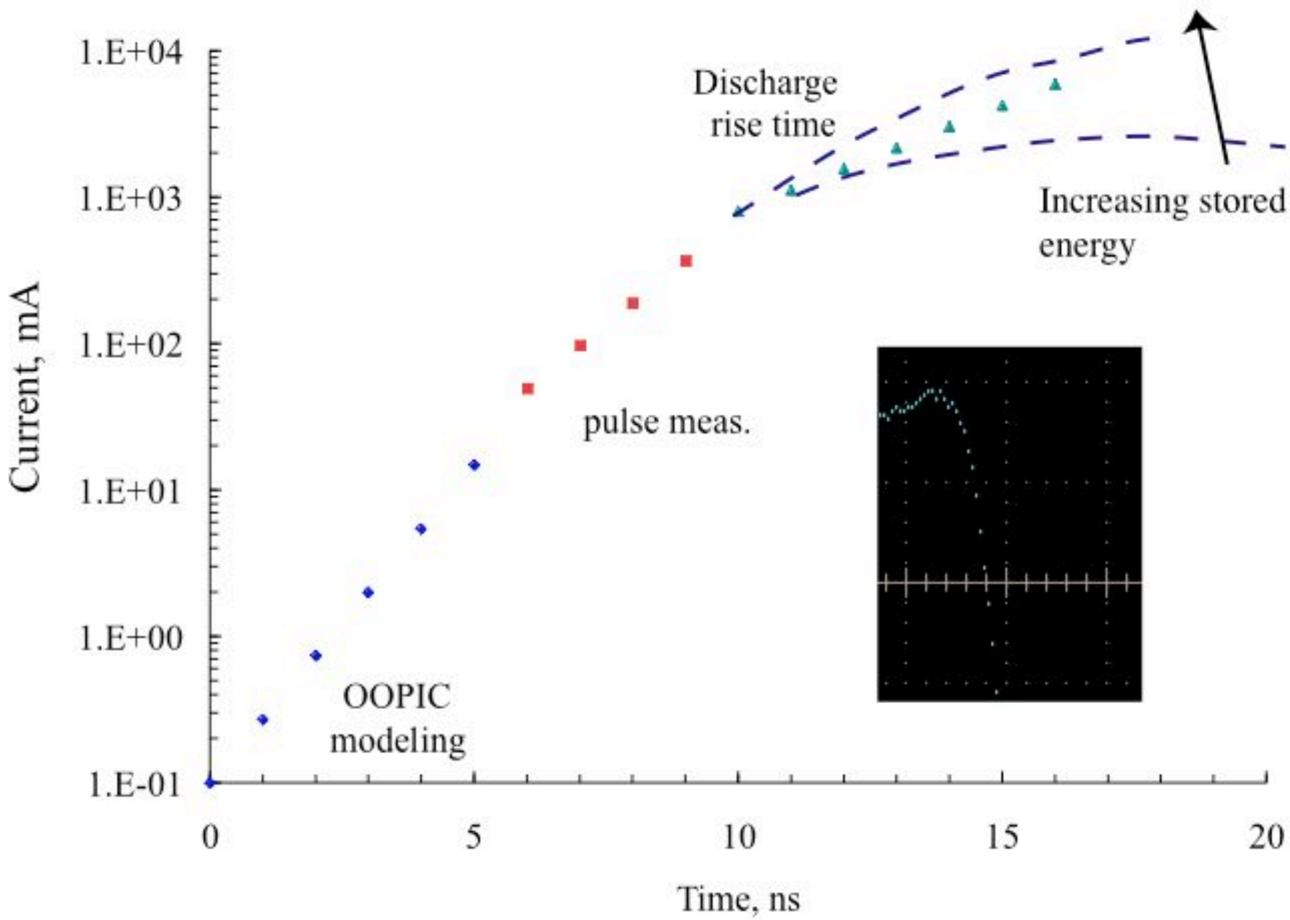
- Molecular Dynamics codes are able to model it.

Time development of a discharge

- The initial few ns have been modeled in detail in OOPIC Pro.

- The end of the breakdown event can be measured in a cavity.

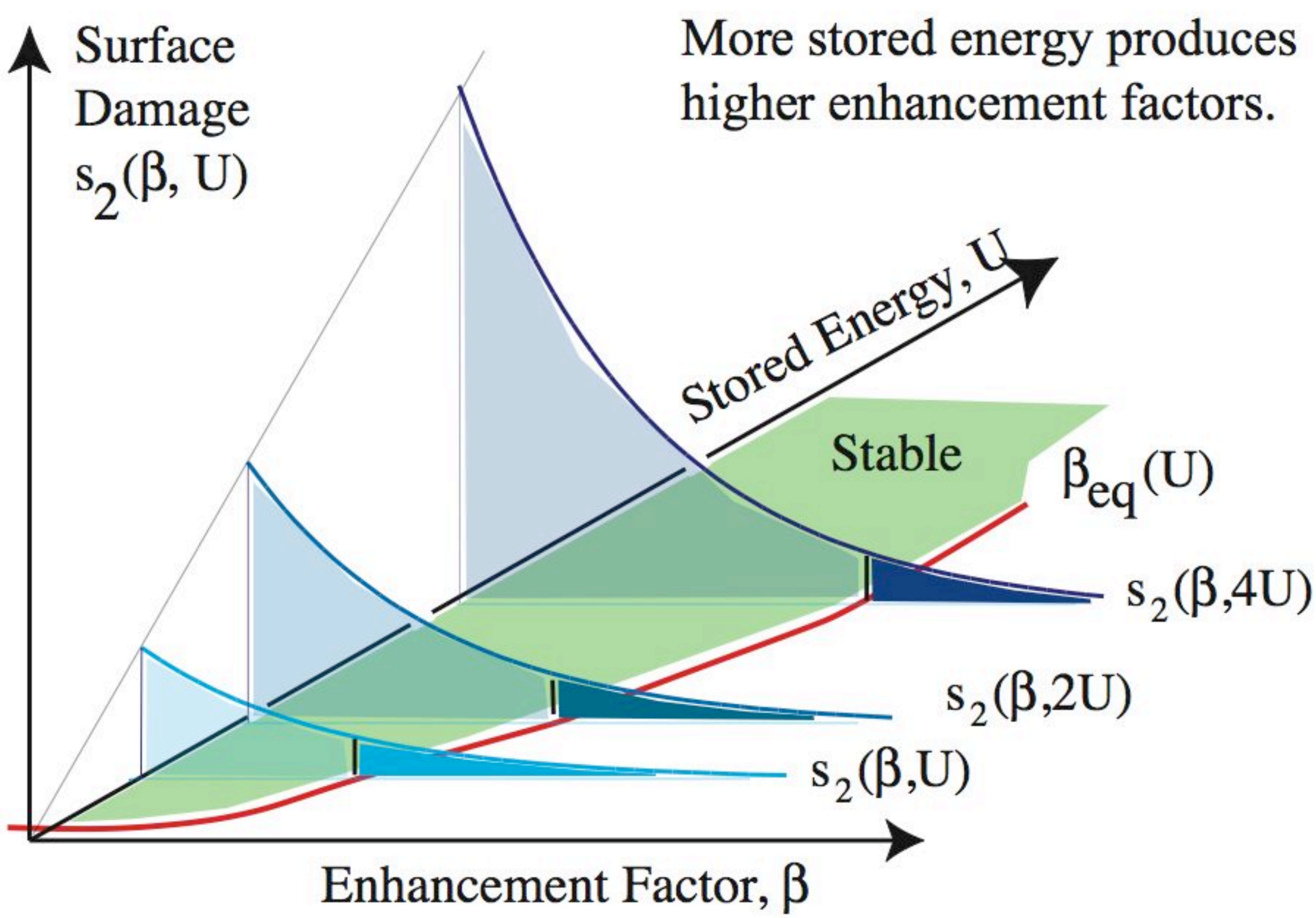
- The whole discharge can be modeled and is experimentally accessible.



Breakdown events damage the surface

- More energy => more damage

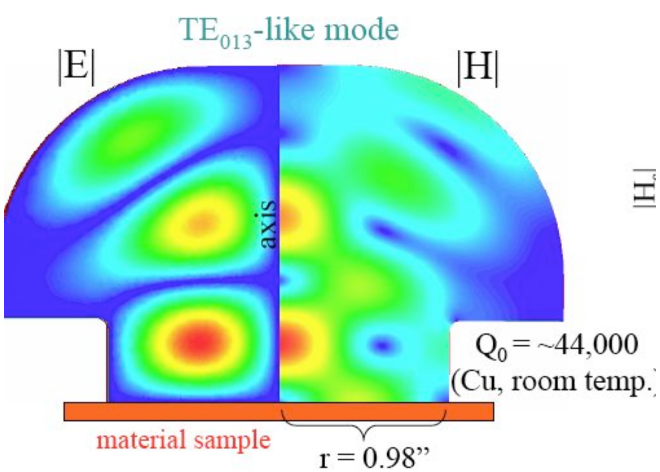
- More damage => Higher enhancement factors => Lower operating fields

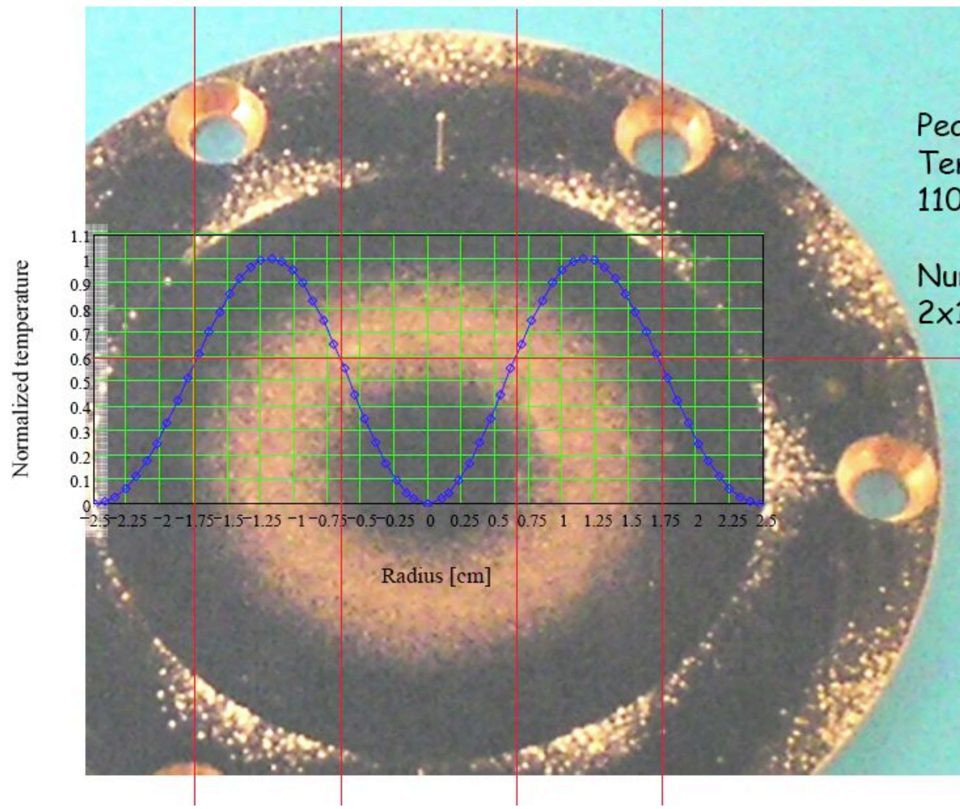


Pulsed heating can also damage cavities.

- 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?

Many mechanisms limit gradients.

Normal Conducting

Electric fields tearing the surface apart
Skin currents heat the equator of cavities

Superconducting

<u>Classical</u>

- 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

<u>Quantum</u>

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

<u>Operational</u>

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

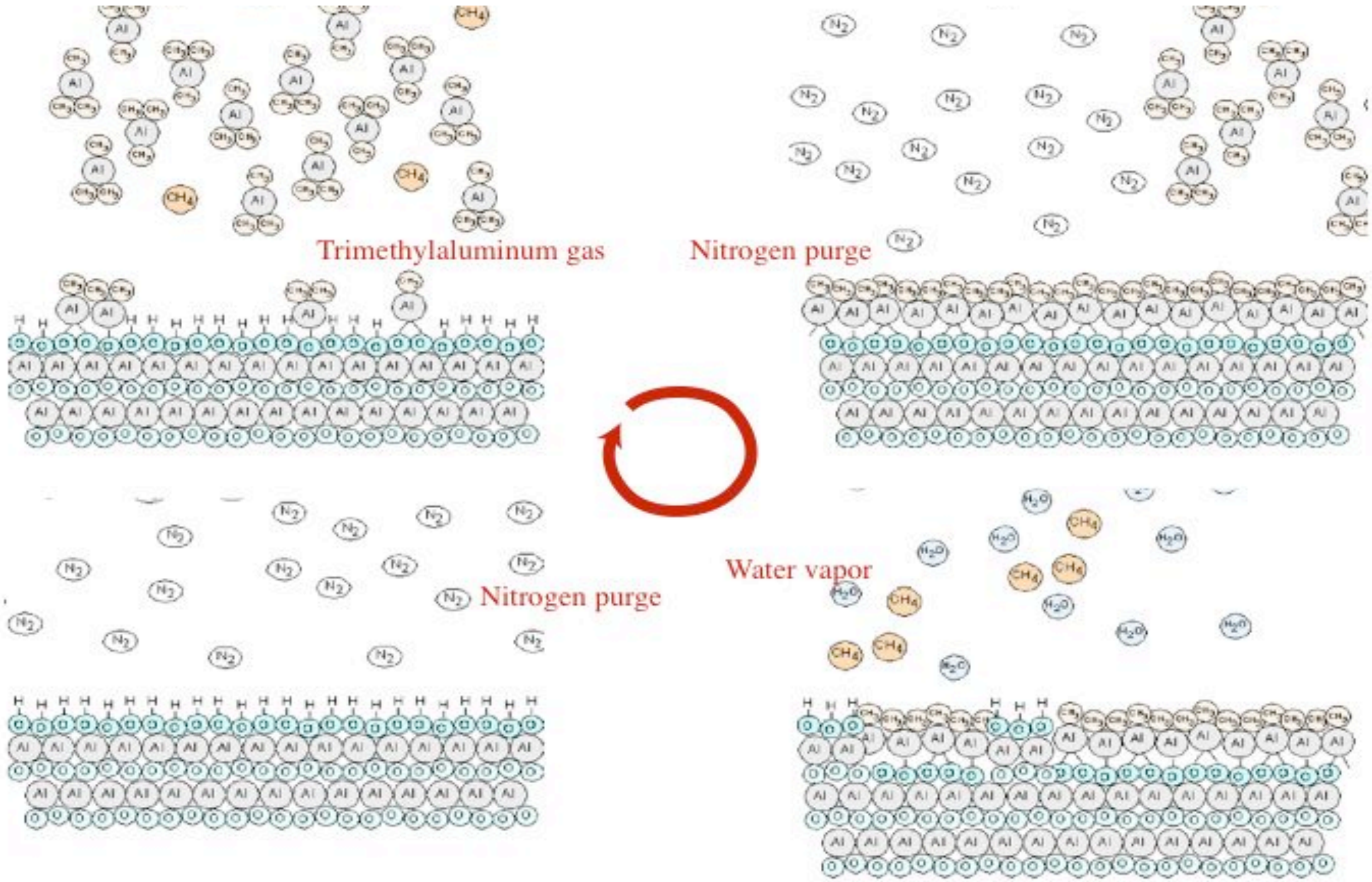
Many mechanisms limit gradients.

	CURE
Normal Conducting	
Electric fields tearing the surface apart	smooth
Skin currents heat the equator of cavities	layers
Superconducting	
Classical	
Heating by field emission currents	smooth
Breakdown - High pulsed power conditioning	smooth
Multipactor - cured by cavity shape and surface treatment	chemistry
Lorentz detuning -- electrostatic stresses approach 1 atm	substrate
Microphonics - He bubbling distorts cavity	substrate
Local heating - surface defects increase local resistivity	homogeneous
Quantum	
Quench Fields - Bmax ~ 0.2 T	layers
Q slope - Losses increase nonlinearly with field	chemistry
Operational	
Particulates - assembly brings contaminants	in-situ
Power use - somebody has to pay	high Q

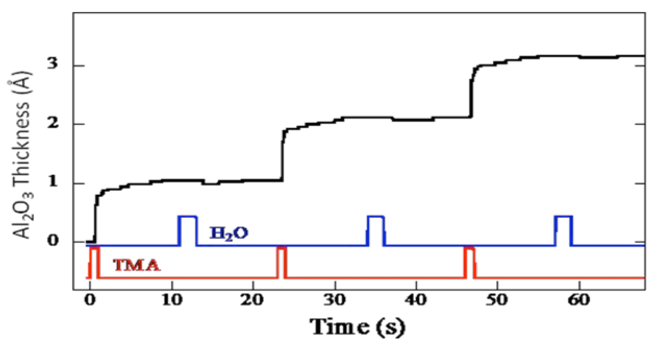
All these processes are dependent on the nature of the surface.

- There are a number of ways of improving the surfacees.
- Electropolishing copper has been shown to be useful,
- Ultra polishing with abrasives is also promising.
- Clean rooms and other SCRF technology is appropriate..

Atomic Layer Deposition may be useful.



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 produces conformal coatings.

- 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

tungsten on aerogels

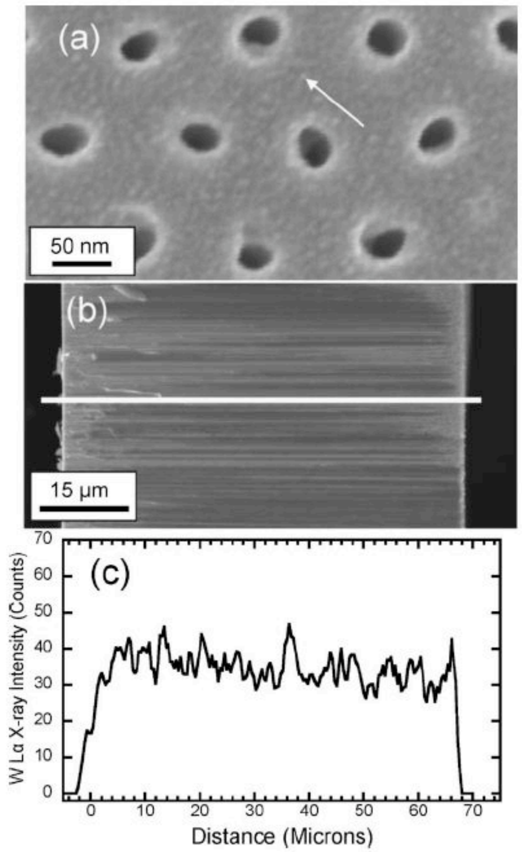


FIG. 1. Plan view (a) and cross-sectional (b) SEM images of anodic aluminum oxide membrane following ten cycles of W ALD. The white arrow indicates W nanocrystal. W EDAX line scan (c) taken from the middle of the cleaved membrane along the white line in (b).

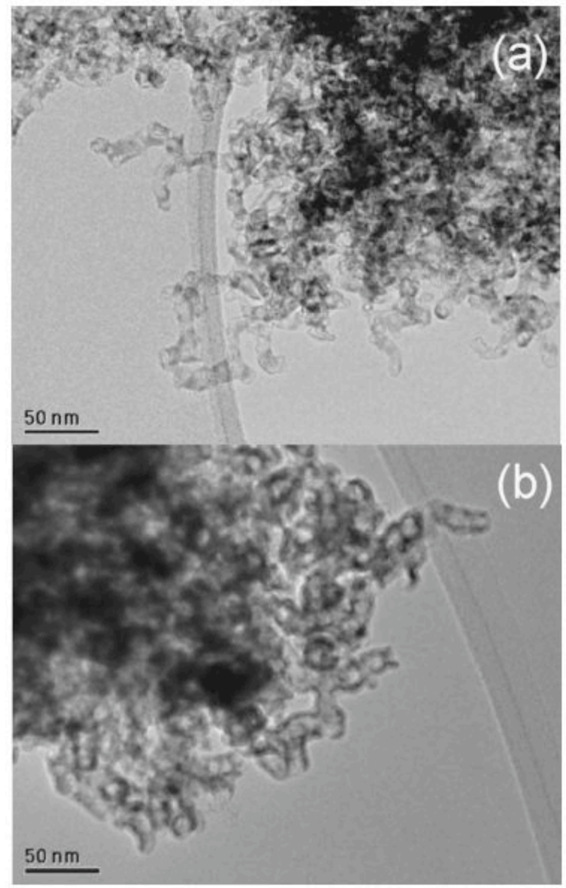
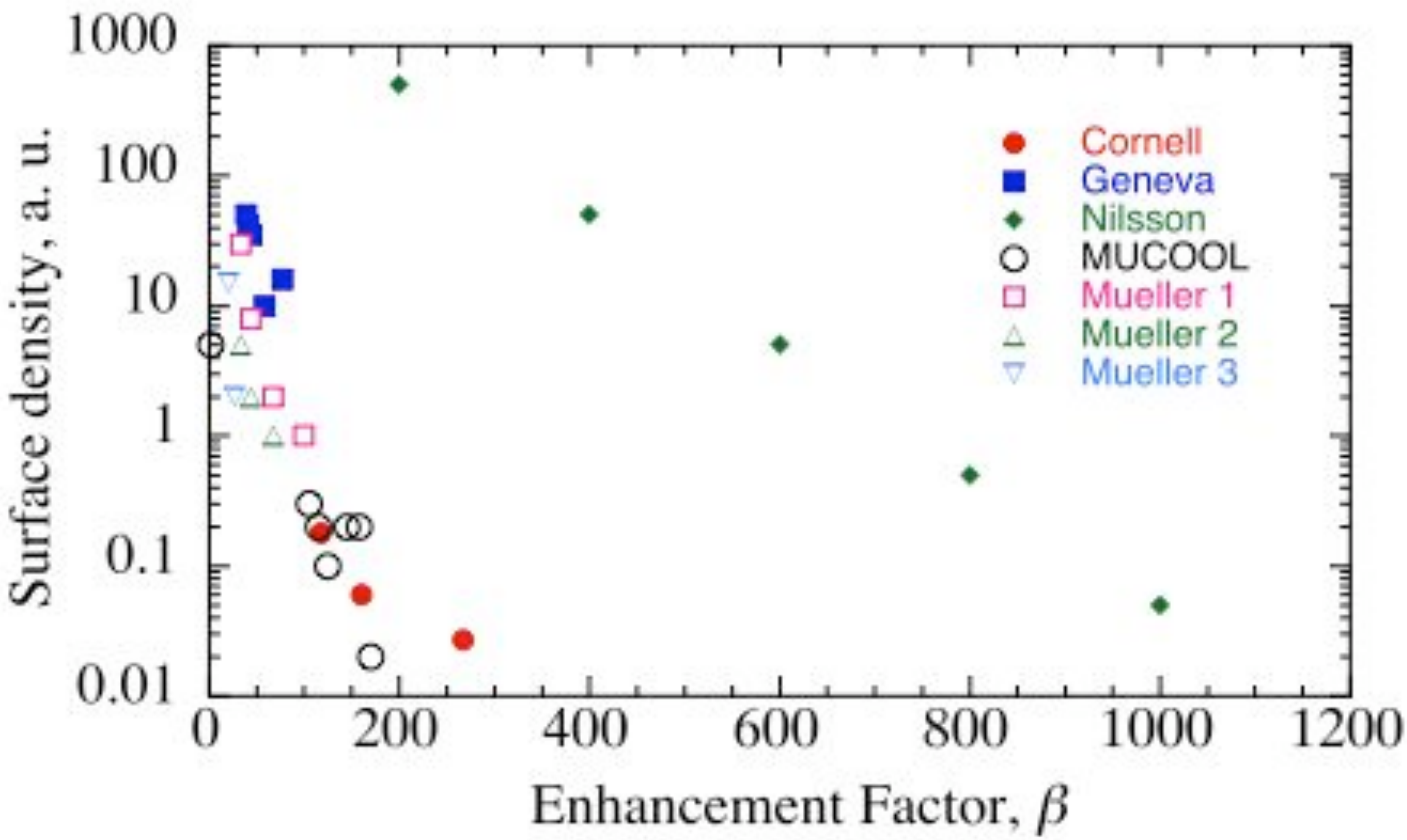


FIG. 4. TEM images of carbon aerogel following three (a) and seven (b) cycles of W ALD.

Enhancement spectra for "flat" surfaces.

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



Enhancement factors (from Feynman).

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

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

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.

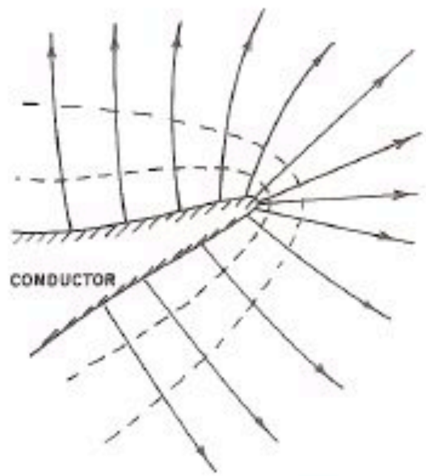


Fig. 6–14. The electric field near a sharp point on a conductor is very high.

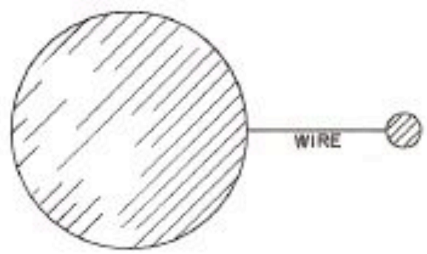
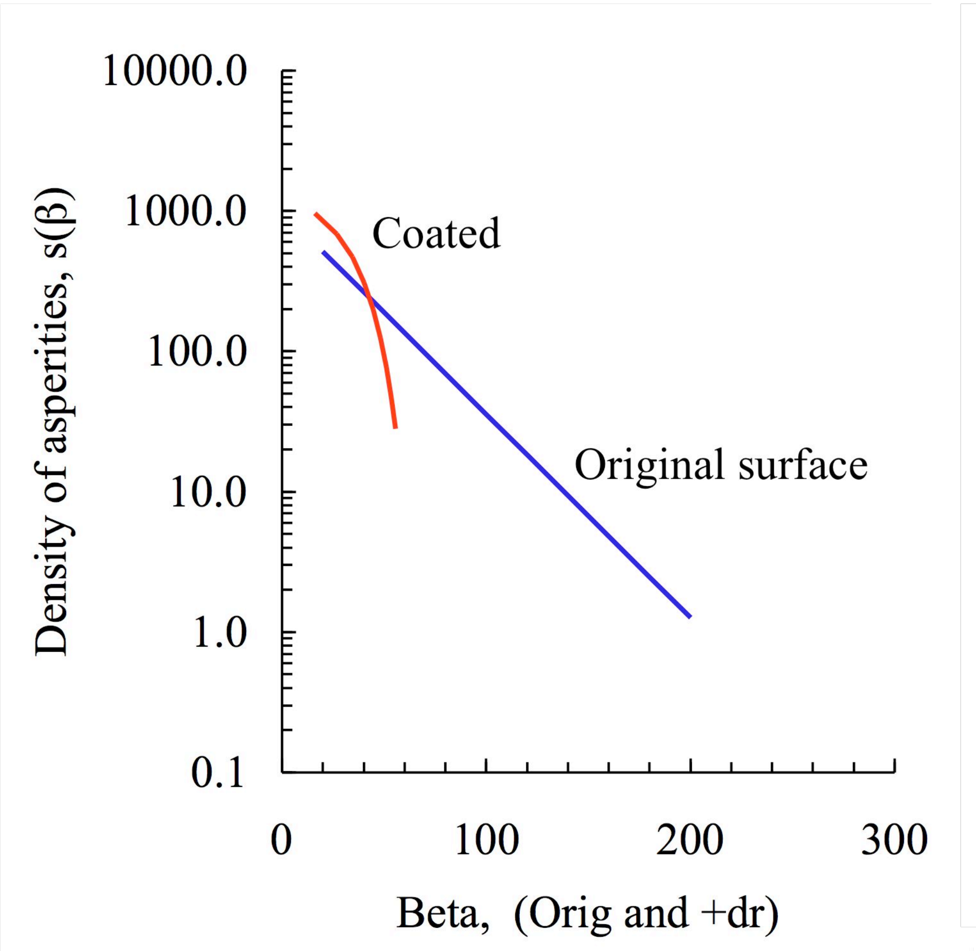


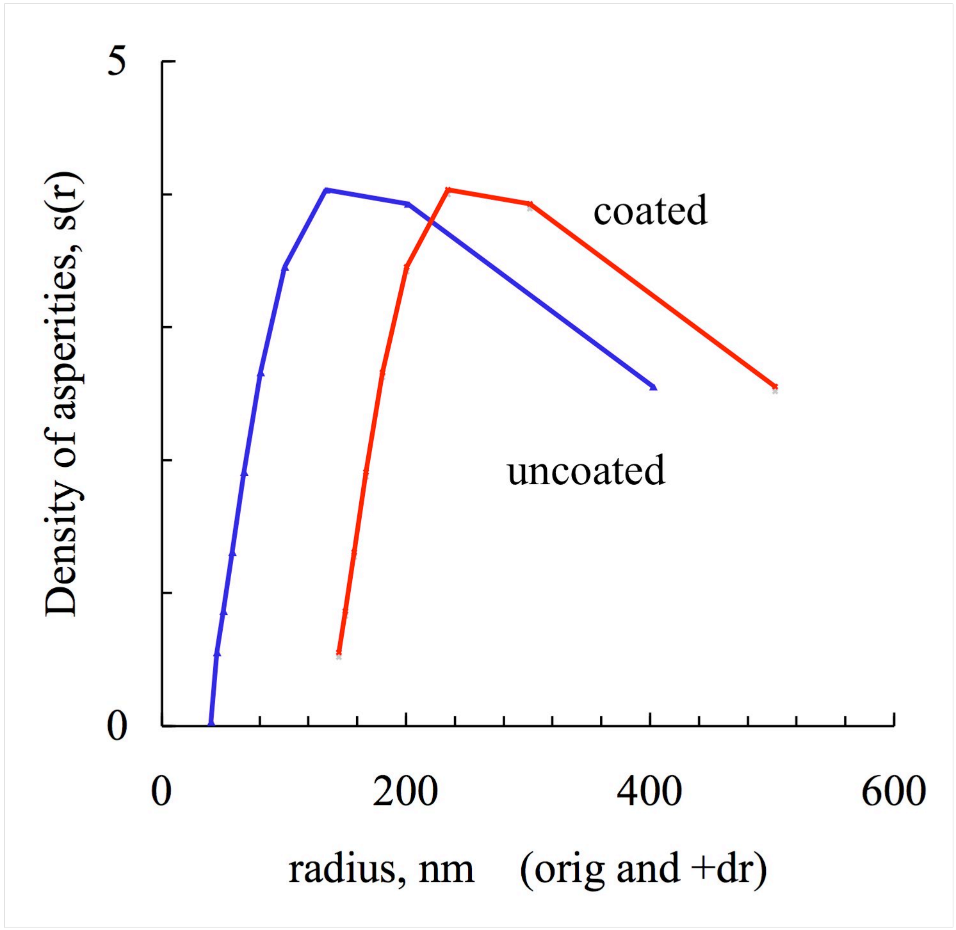
Fig. 6–15. The field of a pointed object can be approximated by that of two spheres at the same potential.

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

Smooth coatings can change the spectrum of enhancements.

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





- This example 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.

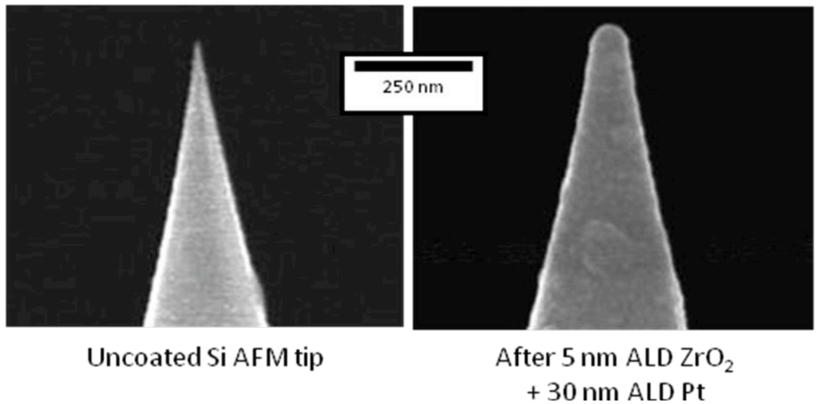


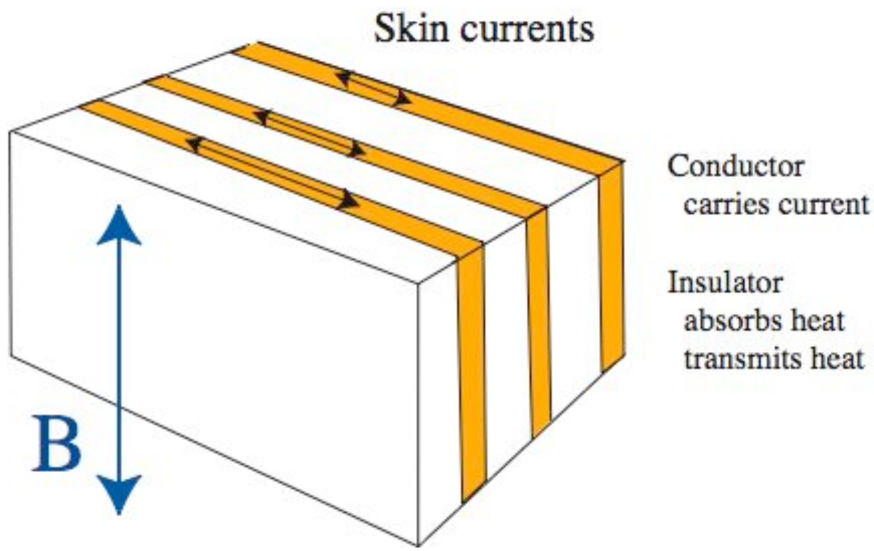
Figure 3: Scanning Electron Microscope images of nearly atomically-sharp tips, before and after coating with a total of 35nm of material by ALD. The tip, initially about 4 nm, has been rounded to 35nm radius of curvature by growth of an ALD film. Rough surfaces are inherently smoothed by the process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

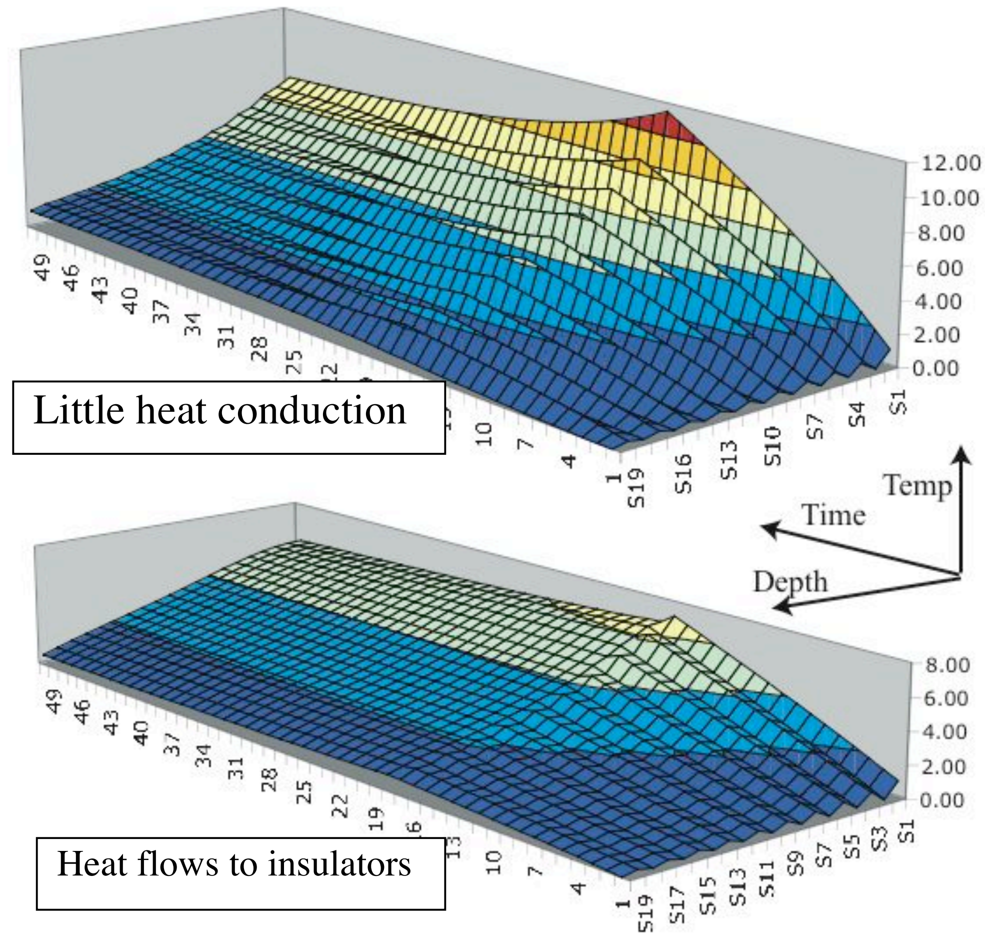
- Copper, however, is a hard material to deposit, and it may be necessary to study other materials and alloys. Some R&D is required.

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

Surface layers can address cure pulsed heating in NCRF.

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

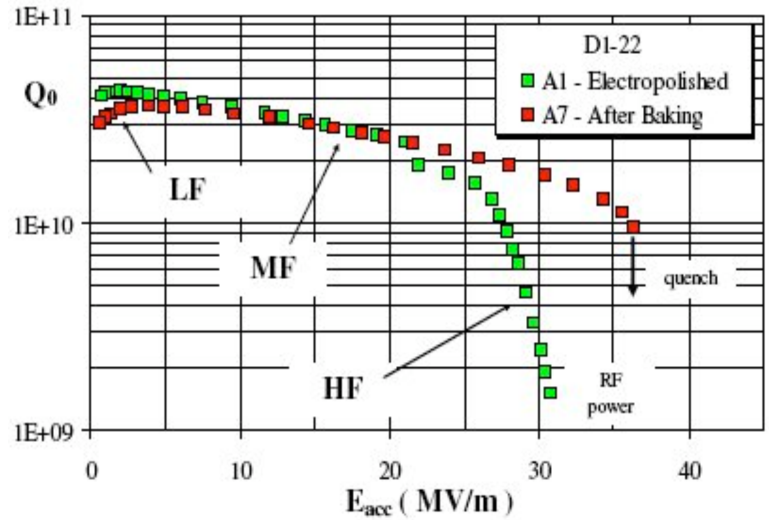




- Less thermal excursion
  Less fatigue
  Longer lifetime

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.

- We can present a better argument.

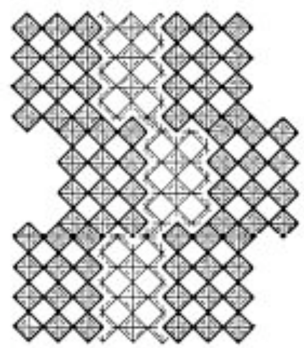
	Q-Slope Fit	Q-Slope before baking (EP = BCP)	Q-Slope Improvem^{t} after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	TE_{011} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum^{t} Validity	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 have discovered magnetic oxides (bad) on niobium surfaces.

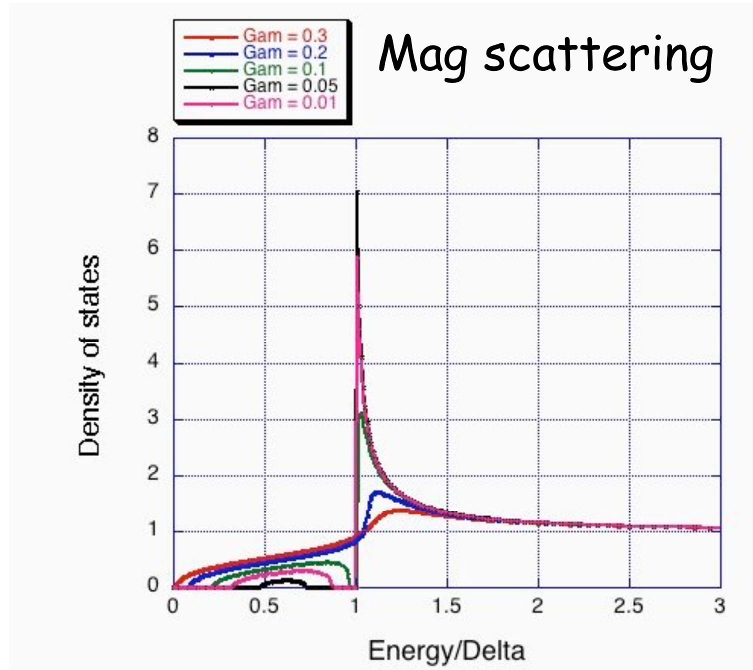
- John Zasadzinski and Thomas Proslier of IIT believe that their point contact tunneling measurements clearly show that these magnetic oxides can break up Cooper pairs and explain high field Q-Slope.

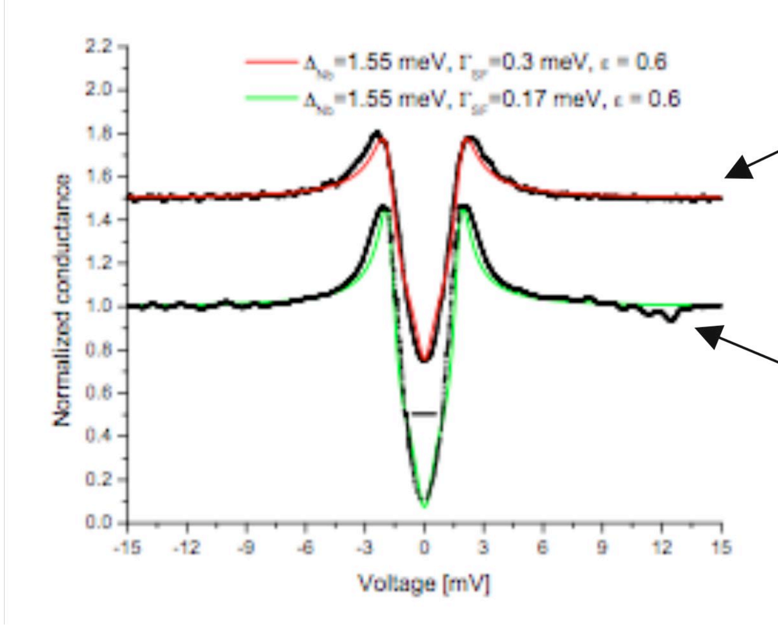
- APL paper accepted 2 days ago.

- **Strange oxides are involved.**



$Nb_{12}O_{29}$





Fit using Shiba theory

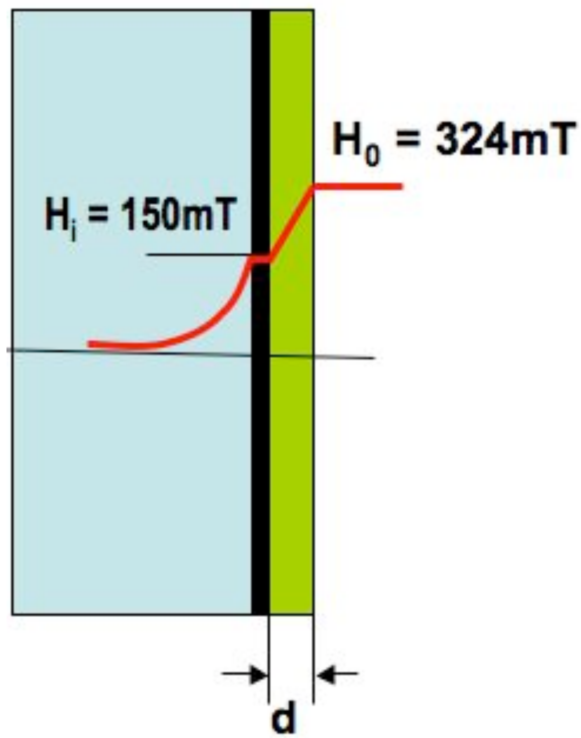
Baked Nb Crystal Shows reduced Magnetic scattering

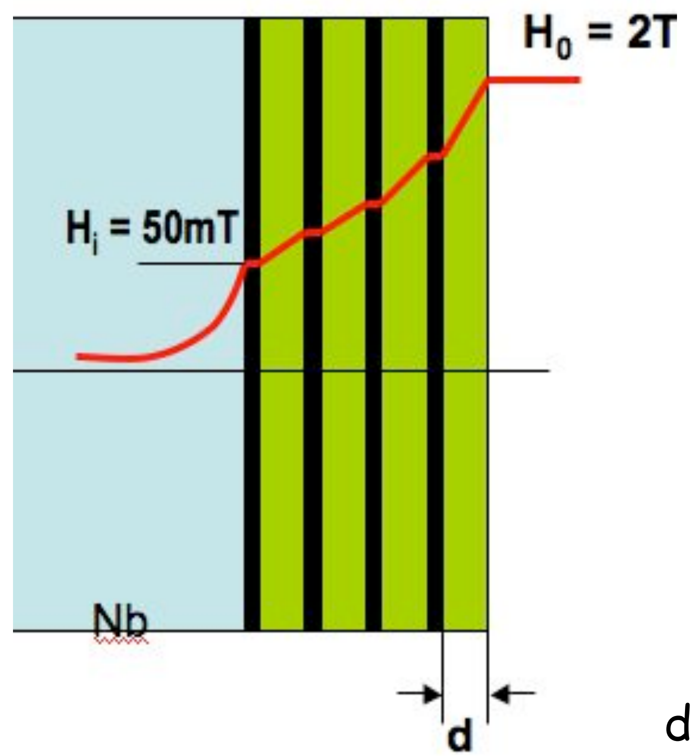
Alex Gurevich has a cure for quench fields.

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

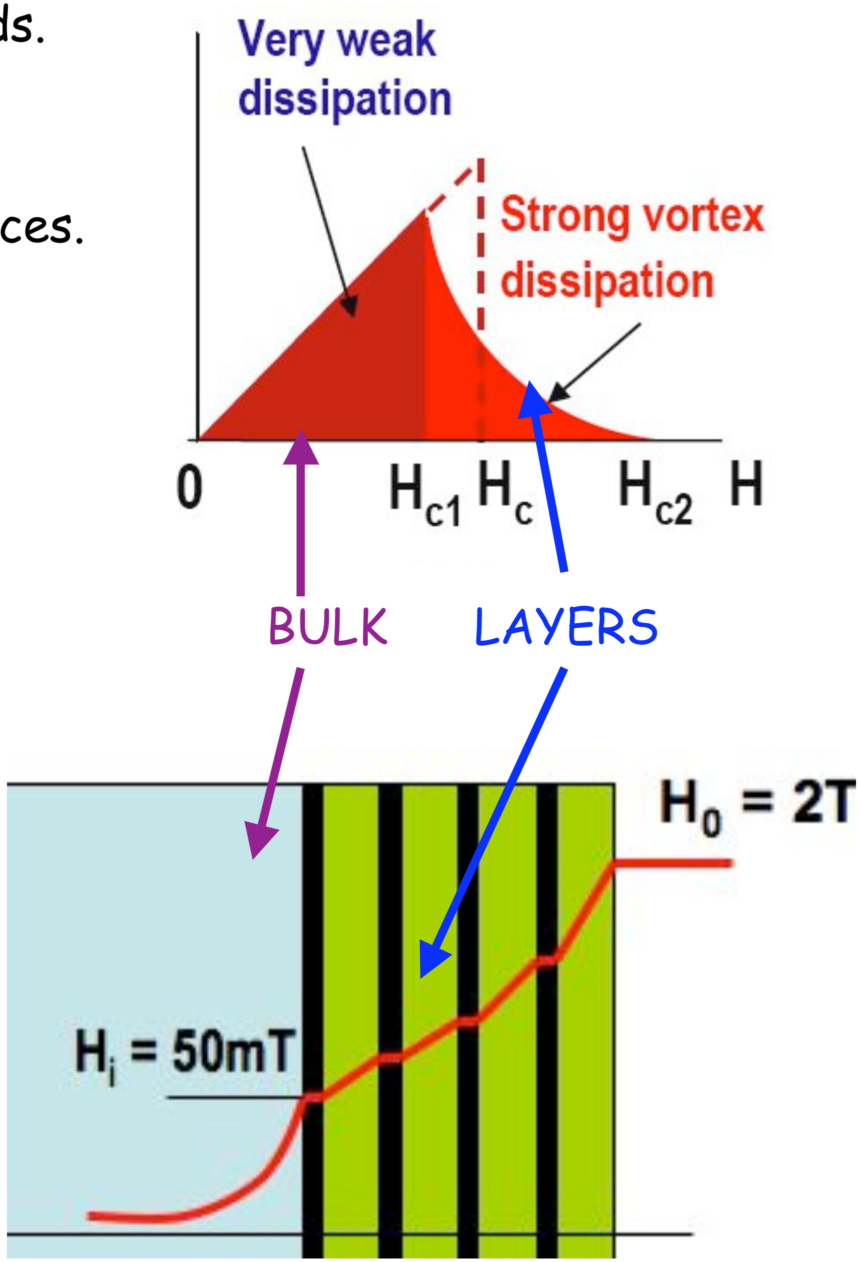
(A. Gurevich, A. P. L. 88. 012511 (2006))

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 <u>aren't stable</u> in <u>thin layers.</u>
  ⇒ Use layers to "screen" fields from bulk.

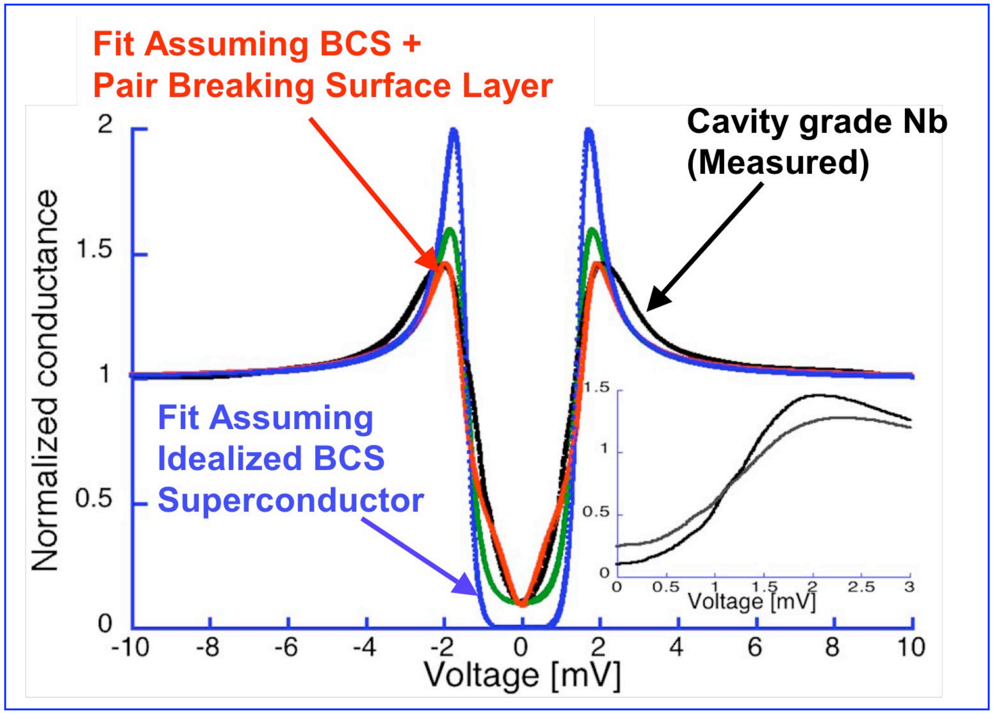


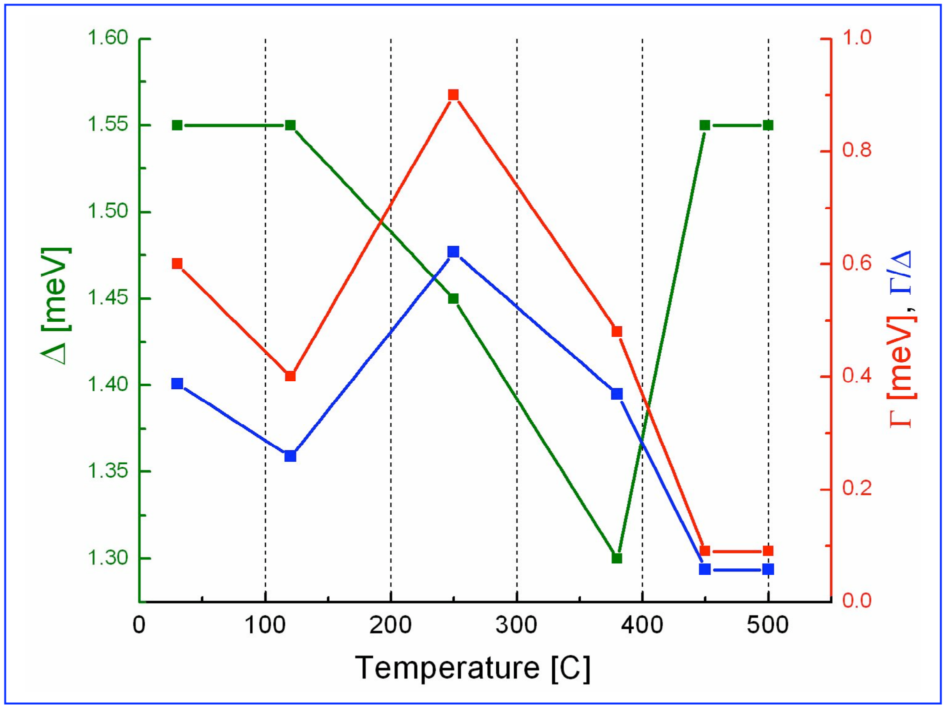
- This is a hard geometry to construct.
  Nb is "bulk" material, i.e. 200 nm.
  Layers should be ~(10 – 30) nm
  Nanometer precision required for layers
  No shorts or voids in insulators.
  ALD can do it.

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

Controlling the chemistry.

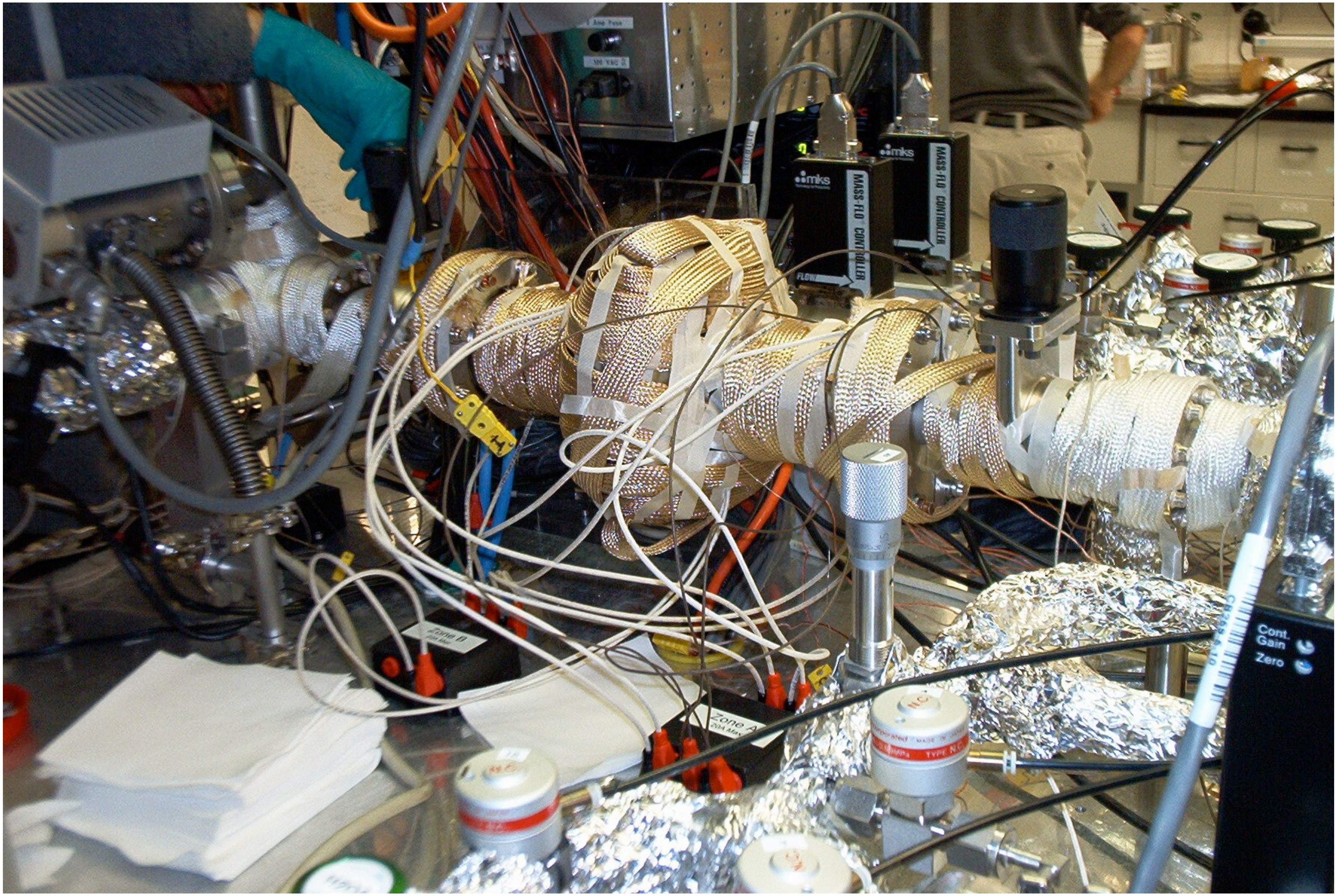
- SC properties measured by
  Point Contact Tunneling
    Measures Cooper binding energy



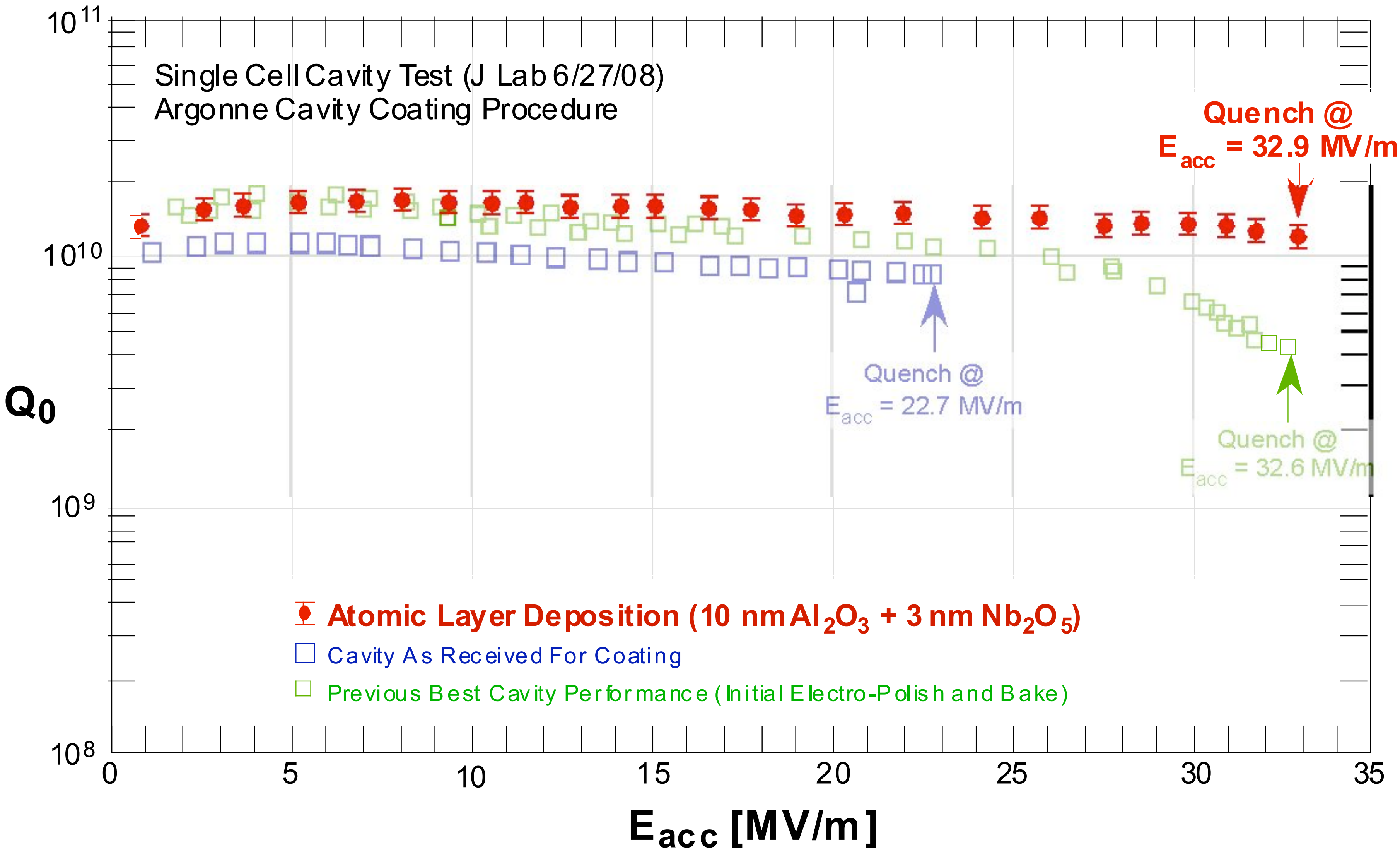


Magnetic oxides can be dissolved in bulk

We coated a SCRF single cell cavity.



And improved it.



Other efforts are underway.

- Muons Inc has an effort they are starting.
- Bob Palmer is looking at magnetic insulation.
- CERN has an active experimental and modeling program.
- There is a High Gradient Collaboration lead by SLAC.

Conclusion – things are converging