High Gradient Results from the Muon Program

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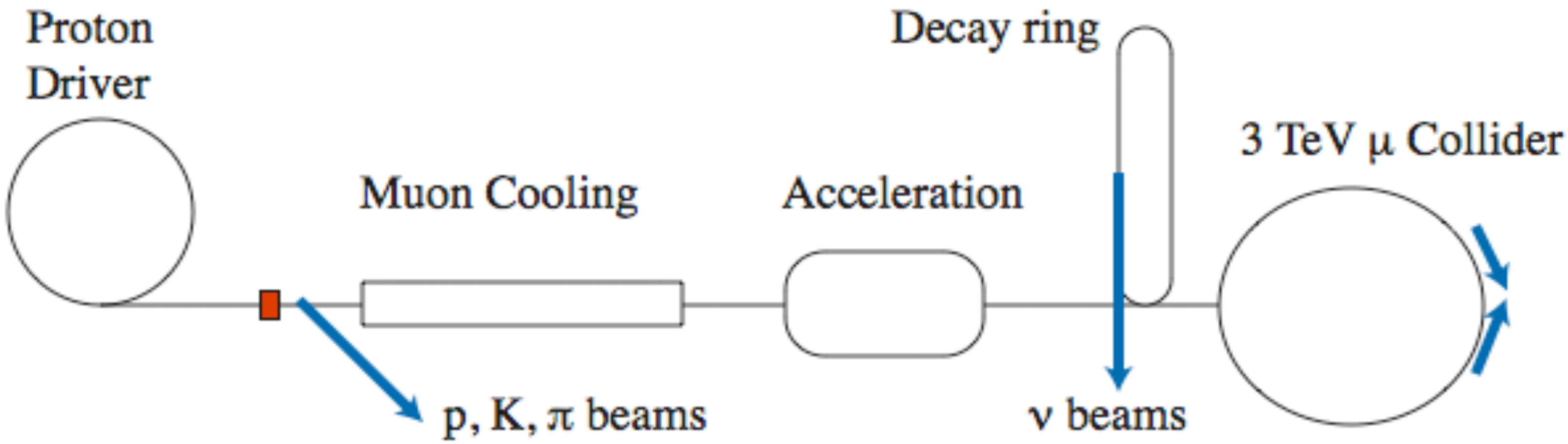
ANL/HEP

CLIC08
10/15/08

Neutrino Factory
Muon Collider

The Muon Program

A muon collider and neutrino factory would be a very useful physics tool.



The design of this system is challenging in many ways.

High gradient rf is necessary in muon cooling and acceleration.

We need more than just achieving high gradients.

Our rf program

Problems
- Our low frequency rf structures must be operated in 1 - 3 T magnetic fields

Goals
- Reduce field emission for the MICE experiment at Rutherford.
- Reduce the breakdown rate for MICE
- Increase gradients in magnetic fields for MICE and Muon Cooling

Experimental effort
- Experimental work started in summer of 2001
- We use 805 and 201 MHz cavities, 5 T solenoid
- We have a large group: ANL, FNAL, IIT, BNL, LBL, Muons Inc. JLab, Tech-X + .

Results.
- We have experimental data and have been developing models.
- ~70 pages in Phys. Rev. APL, and NIM, Many conference papers

Many people have contributed to the results presented here.

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

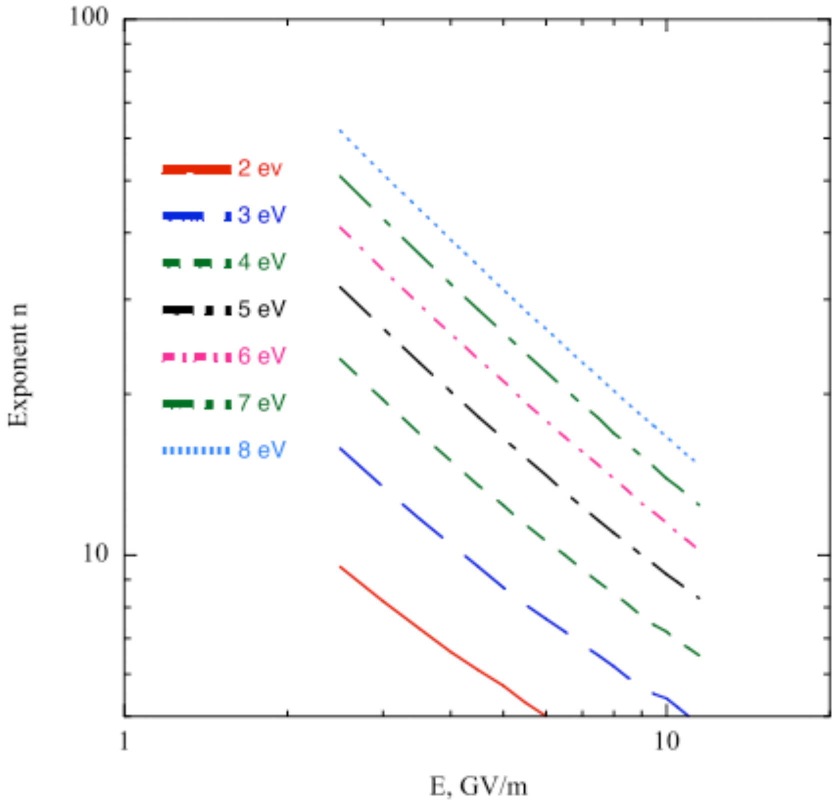
. . . .And many others

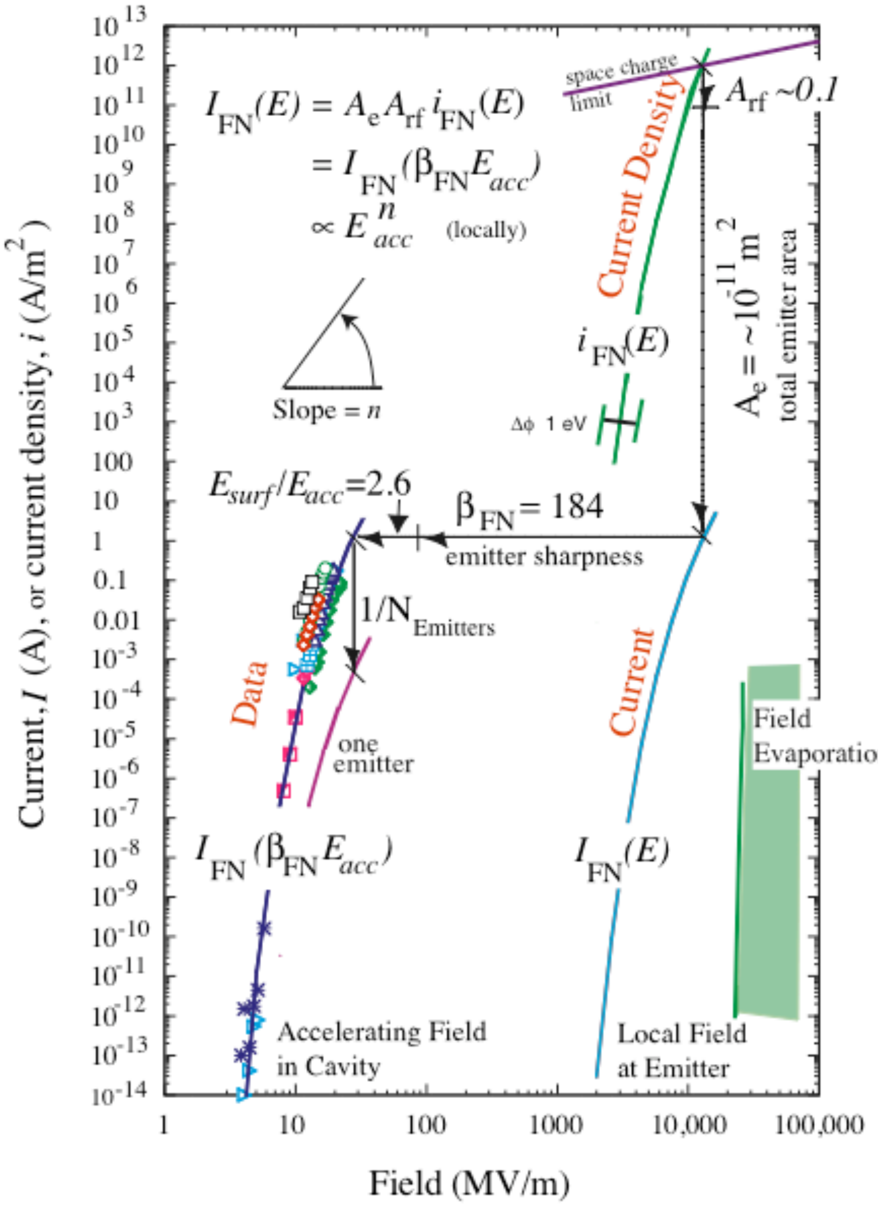
The basic science of accelerators should be better understood.

- The defining technologies (ISABELLE, SSC, NLC, ILC) were not optimized.
- Need a way to converge on a global optimum rather than local minimum
- Need complete self-consistent models that describe the process
    - Predict and explain experimental data
    - Identify and quantify problems
    - Guide the experimental program

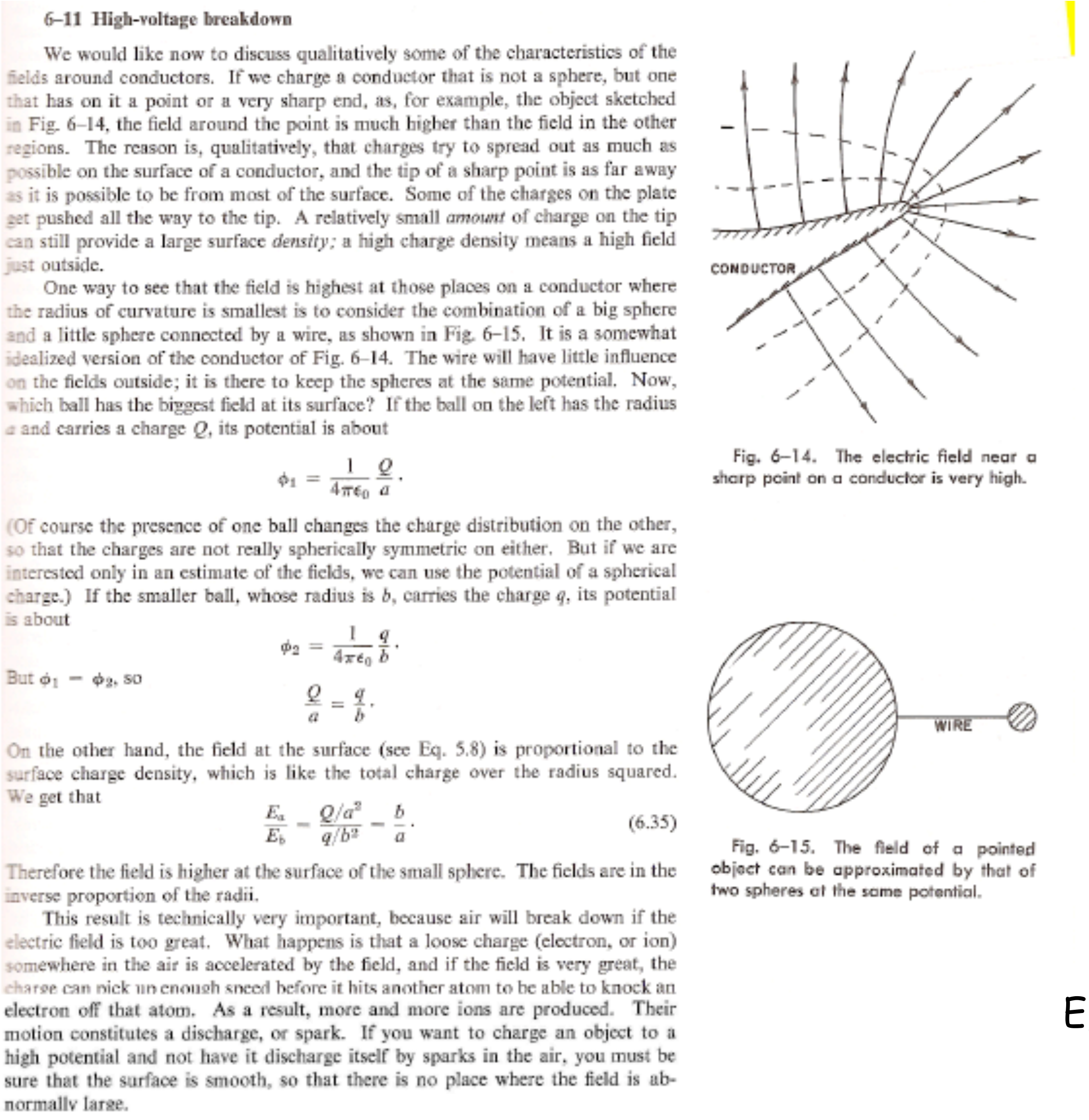
Our Muon Collaboration data started with x ray measurements.

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





Everybody knows this. (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

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

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.

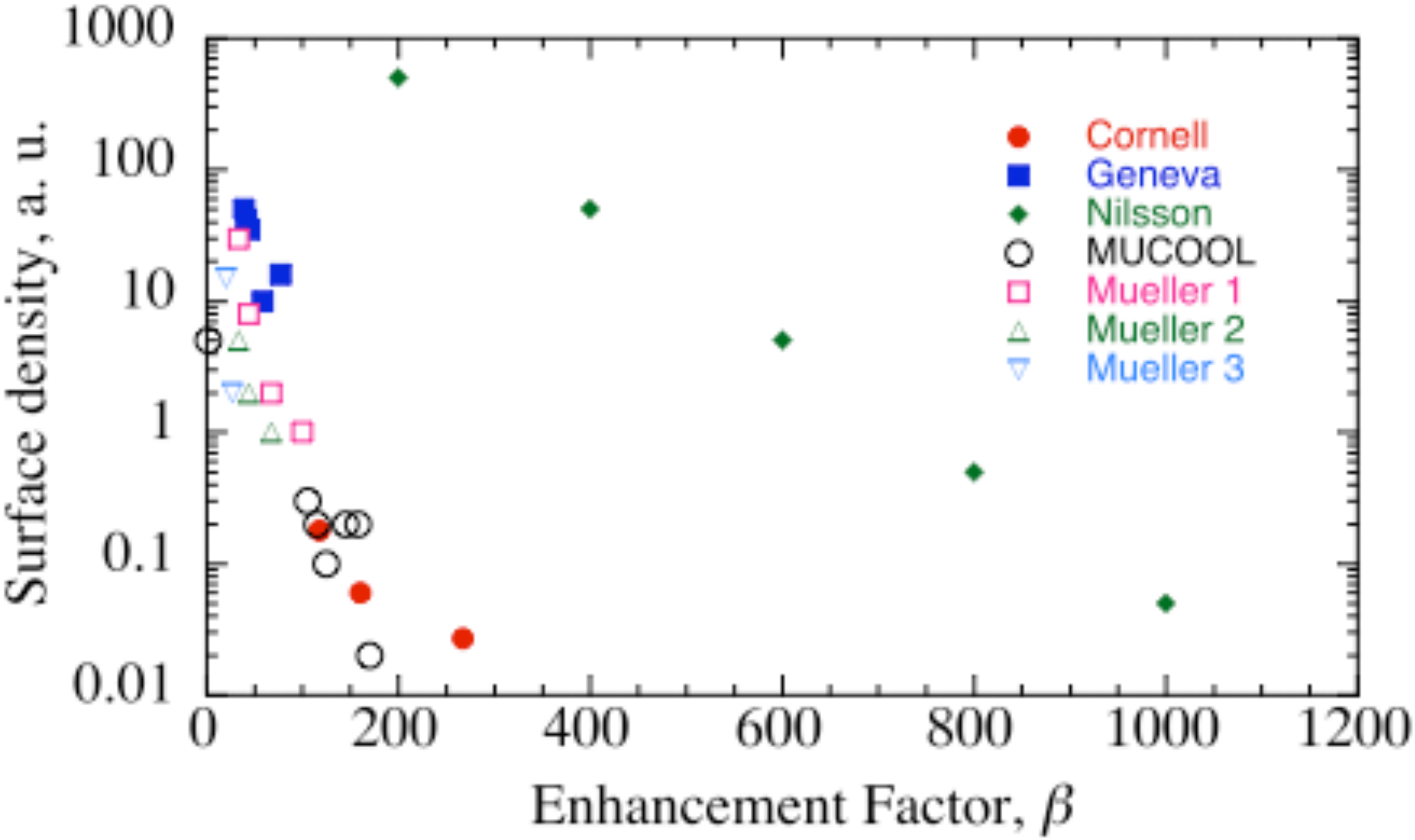
Fig. 6–14. The electric field near a sharp point on a conductor is very high.

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

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

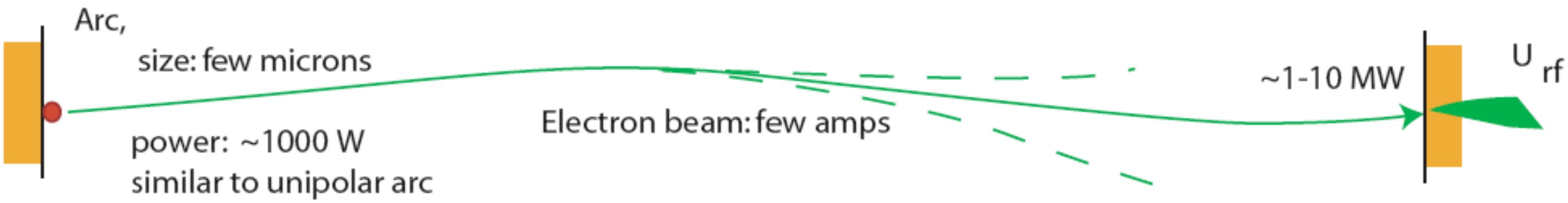
Enhancement spectra measured for "flat" surfaces.

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

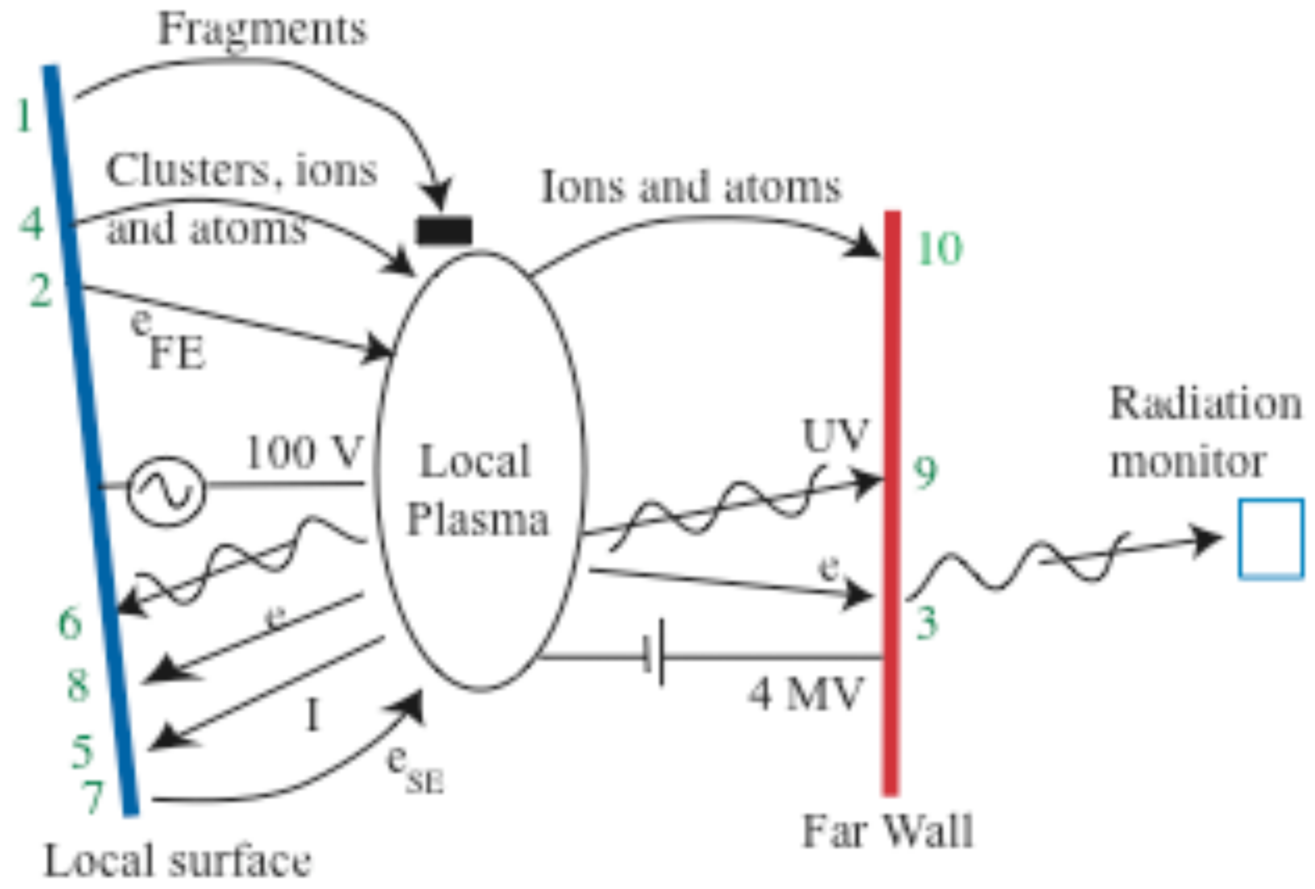


Modeling of arcs is underway.

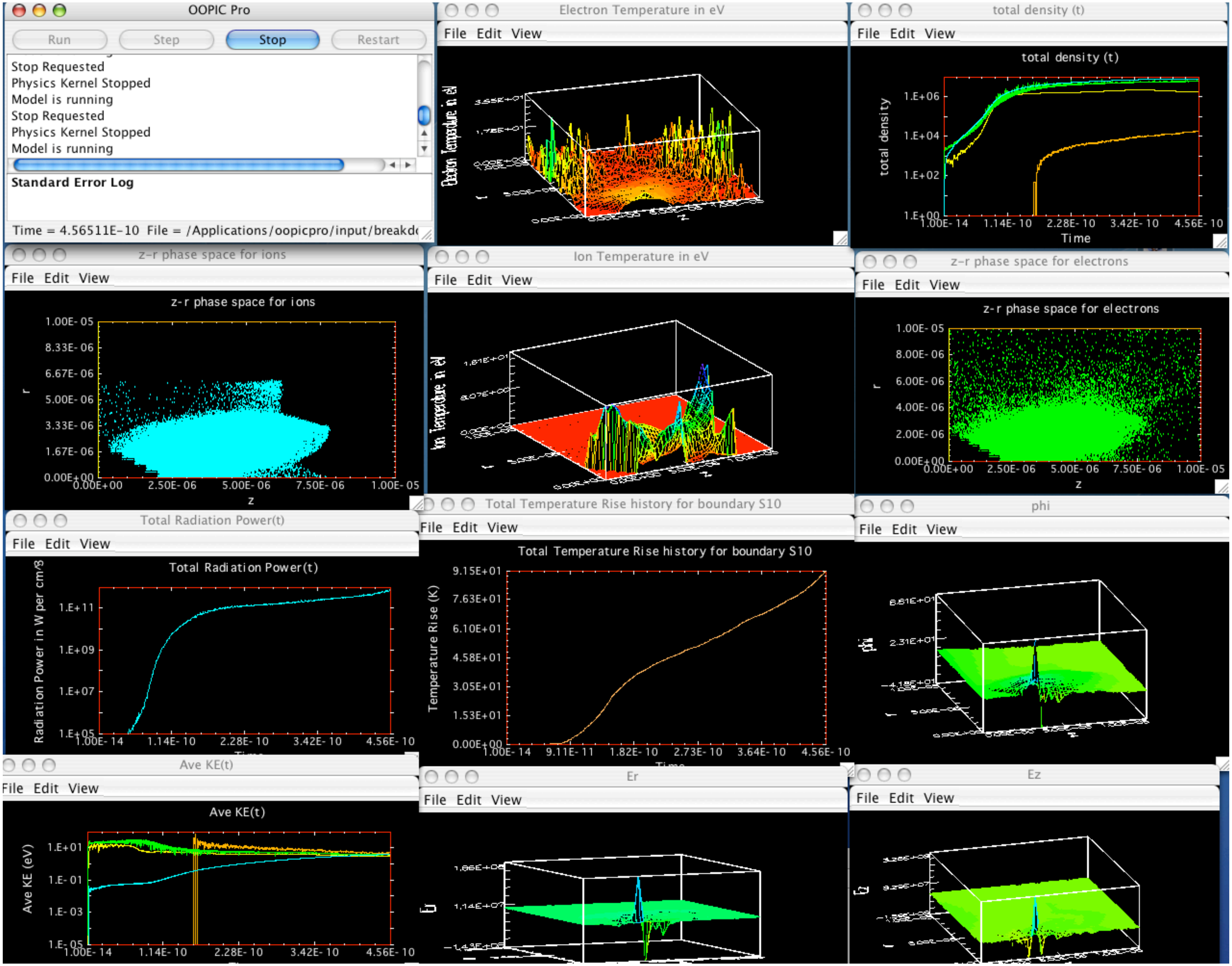
They seem to look like this:



With lots going on inside.



We have been working with Tech-X to develop OOPIC.



```
Stop Requested
Physics Kernel Stopped
Model is running
Stop Requested
Physics Kernel Stopped
Model is running
```

Standard Error Log

```
Time = 4.56511E-10  File = /Applications/oopicpro/input/breakd
```

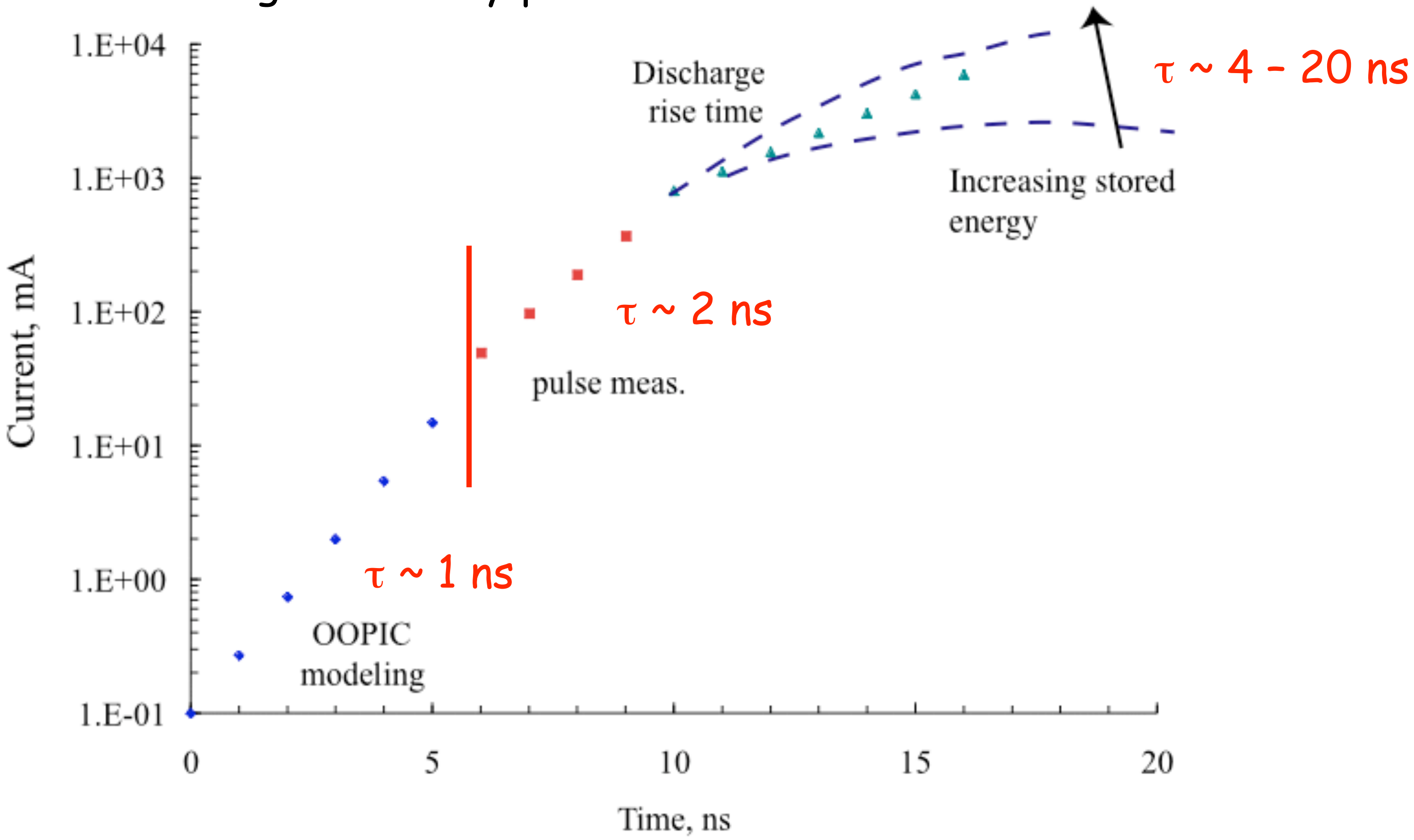
In principle, OOPIC can calculate everything about a BD event.

Modeling and data are consistent, but do not yet cover the same time period.

- The initial few 5 ns have been modeled in detail in OOPIC Pro.
- The end (high power part) of the breakdown event was measured with x rays.

Experimental data show large scatter in measured risetimes.

- Increased stored energy produces faster x ray pulses
- Earlier in the discharge the x ray pulse risetime is shorter.



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
  - we use a fragmentation model which seems consistent with the data

- Breakdown Energy and Mass flow.
  - Many Mechanisms exist

- Surface tension

- Field Ion evaporation

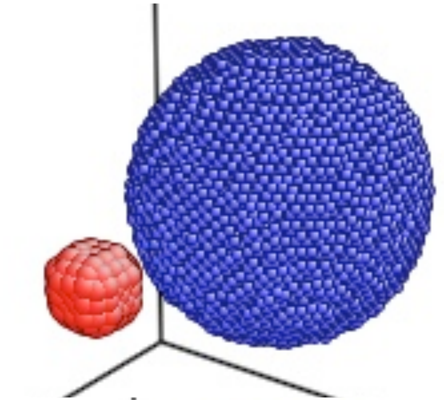
- Breakdown data from Lab G and the MTA

Molecular Dynamics (MD) seems essential.

- Electrostatic forces break up fragments and particulates.

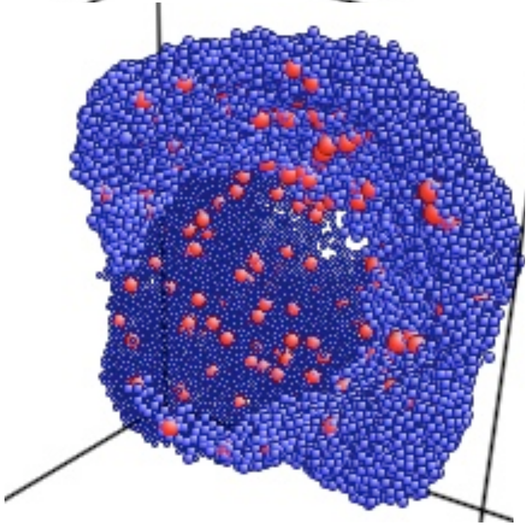
- They may be seen as the cause of the initial fracture.

- Coulomb explosions are seen experimentally and being modeled



Before

Need MD modeling describing
  Particle production Coulomb explosions
  Creep
  Surface stability
  Sputtering yields
  Surface deformation
  Timescales



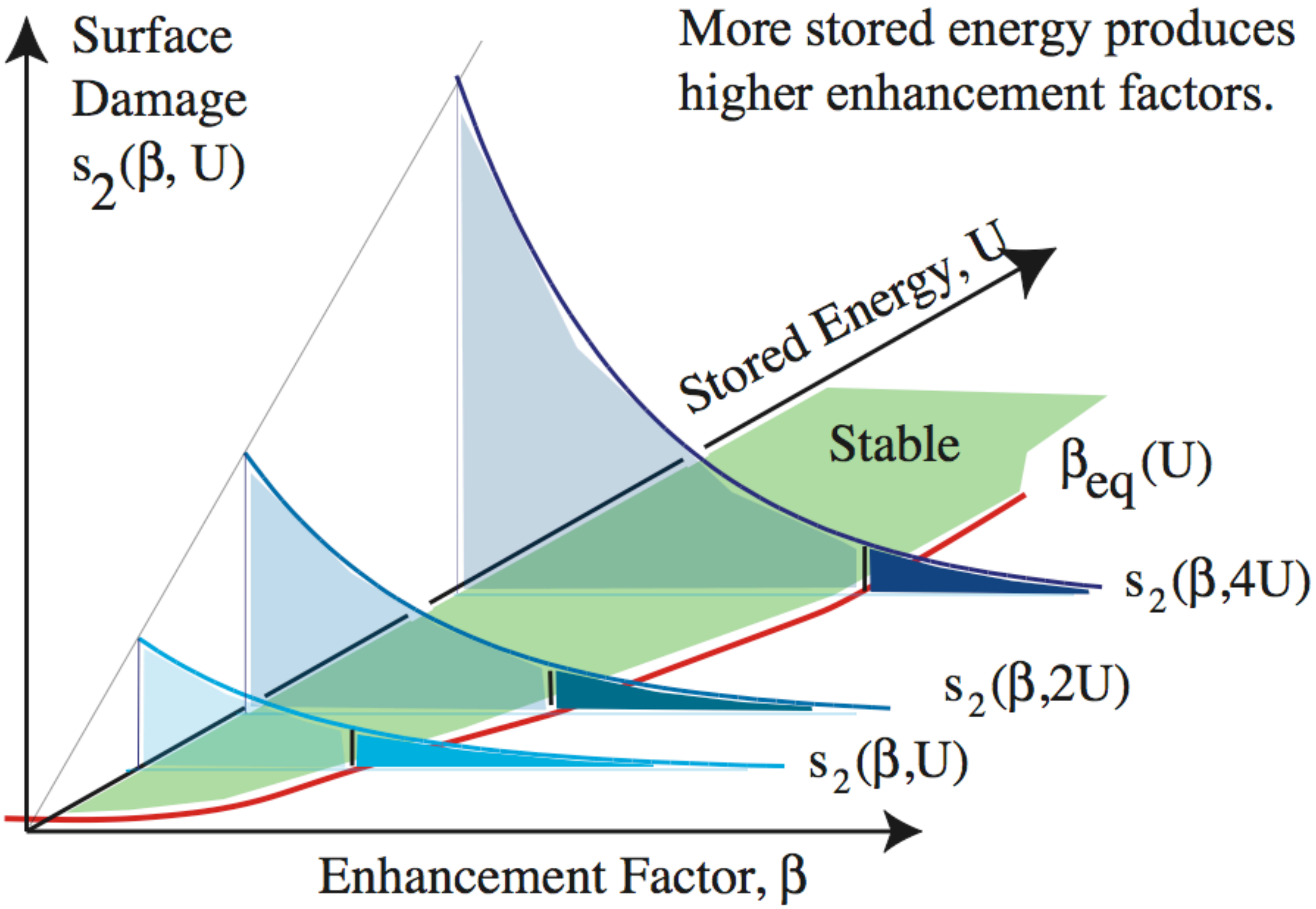
After

Insepov (2008)

An equilibrium exists between surface damage and gradient limits.

We can explain the equilibrium in terms of the enhancement spectrum of damage produced.

More damage give higher enhancements, lower maximum fields. Phys. Rev. STAB **9**, 062001 (2006)



High Gradients interact only with the immediate surface.

Since:

- Copper skin depth @ 11 GHz ~ 540 nm

- Field emitters / breakdown sites ~ 30 nm radii

- London penetration depth in Nb ~ 40 nm

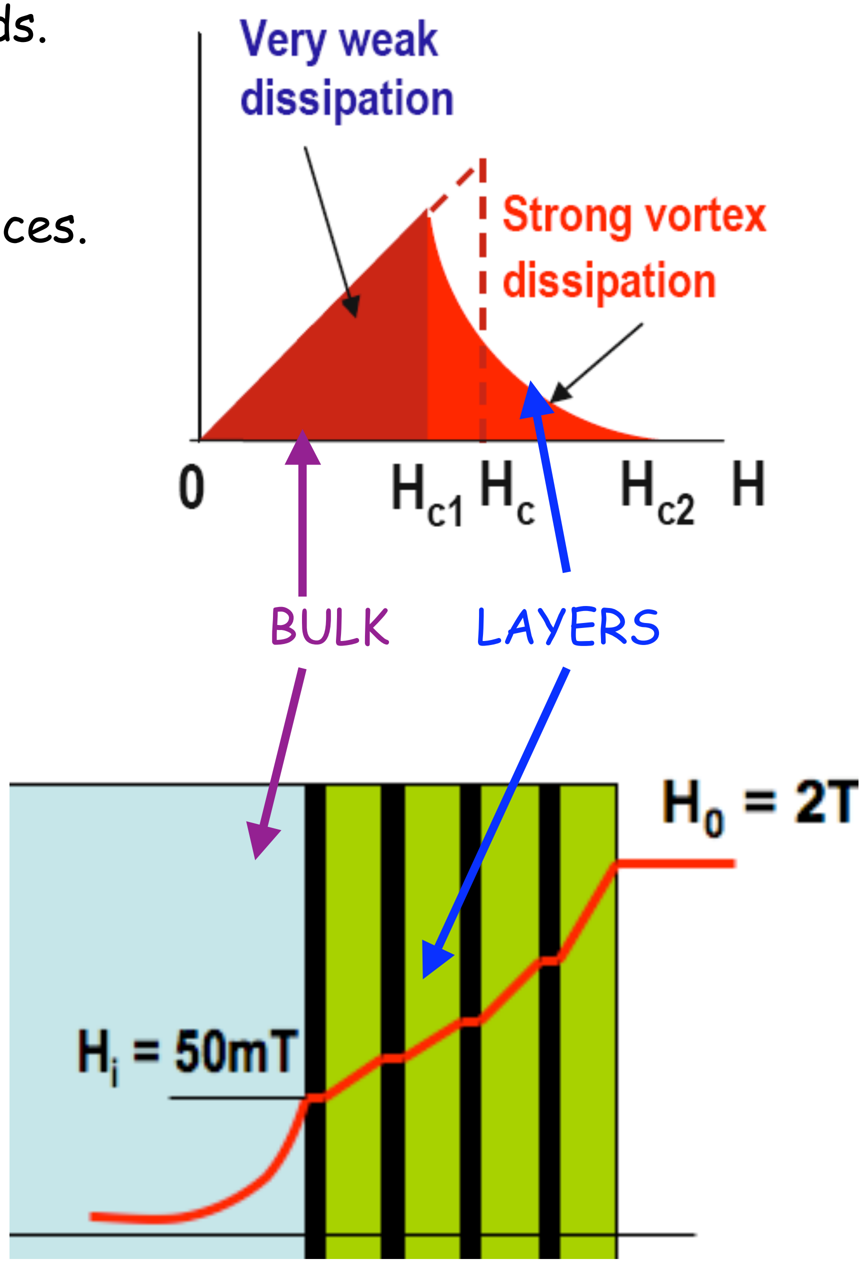
- Oxide thickness in various materials ~ 1 – 10 nm

Can one control the surface ?

What would you do if you could ?

Layered superconductors should reach 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.



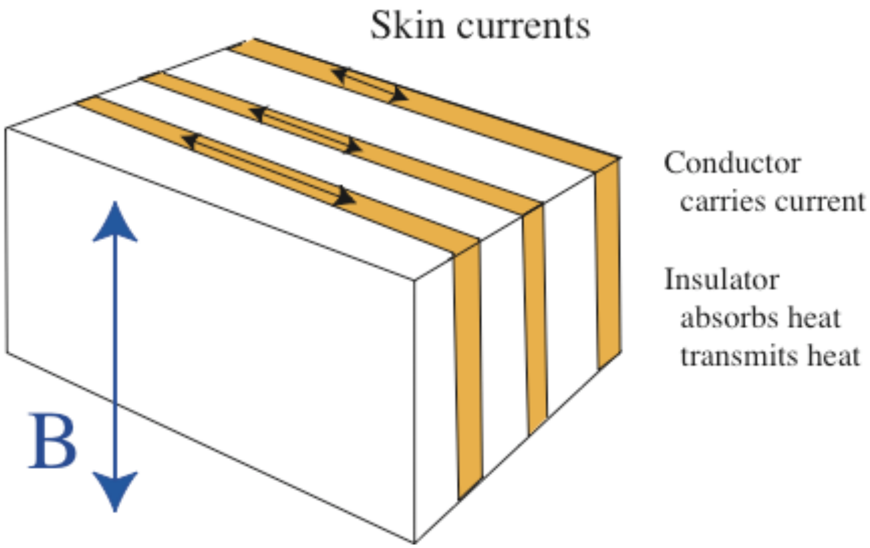
- This is a hard geometry to construct.
  - Nb is “bulk” material, i.e. 200 nm.
  - Layers should be ~(10 – 30) nm
  - Nanometer precision required for layers
  - No shorts or voids in insulators.

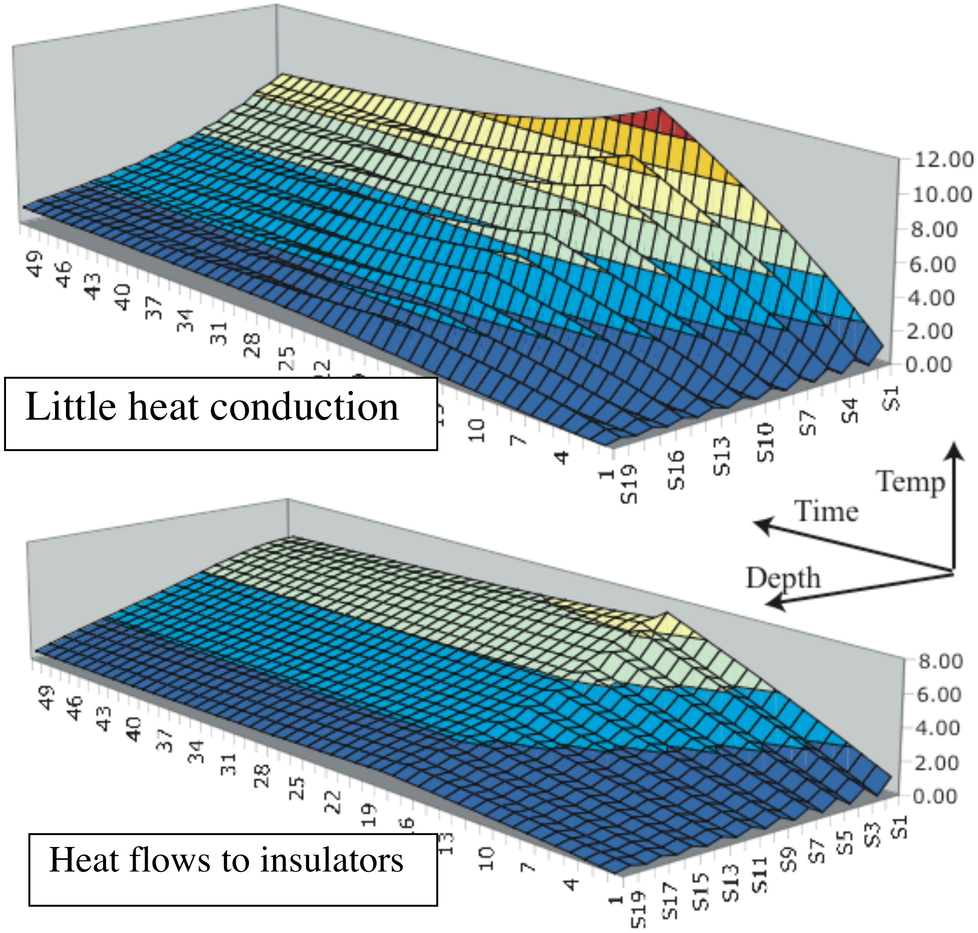
  ALD can do it.

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

Surface layers can address pulsed heating in NCRF.

- You can build a composite material with different properties.

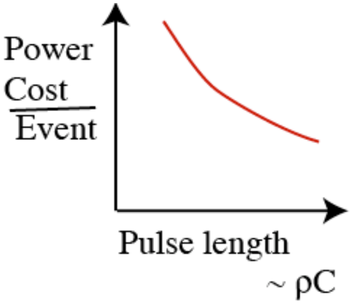




Since

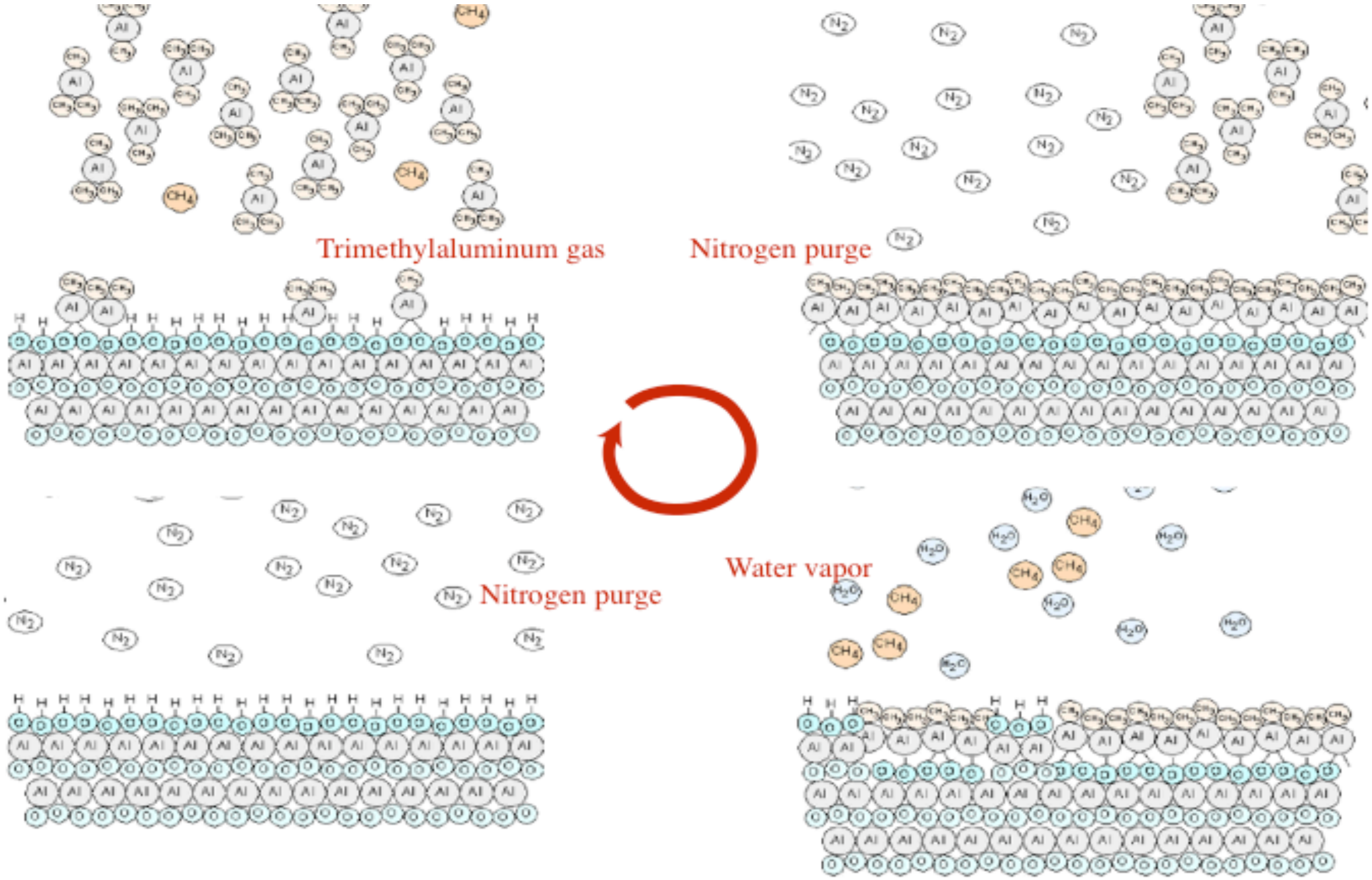
$$\Delta T = \frac{H_t^2}{\sigma\delta}\sqrt{\frac{t}{\pi\rho C_\epsilon \kappa}}$$

everything else constant $\Rightarrow t \propto \rho C$.

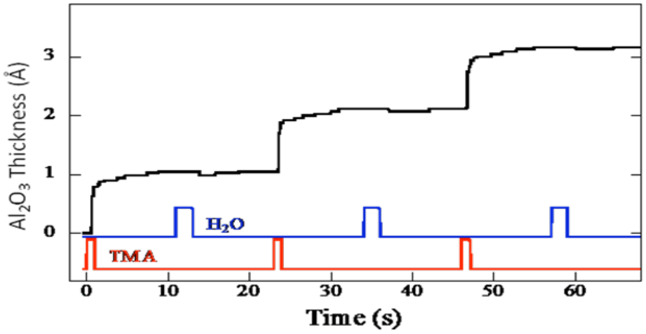


With ideal materials this must work.
What happens with nanofabricated materials?

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

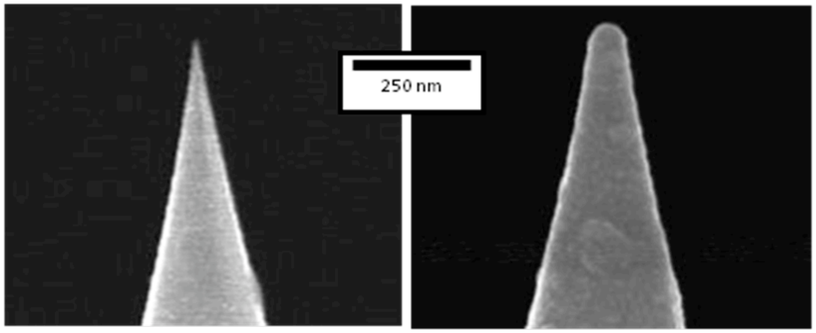
- Used Industrially
  - Semiconductor Manufacture for “high K” gate dielectrics
  - “Abrupt” oxide layer interfaces
  - Pinhole free at 1 nm film thicknesses
  - Conformal, flat films with precise thickness control

- 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 coatings should address field emission and breakdown.

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



Uncoated Si AFM tip

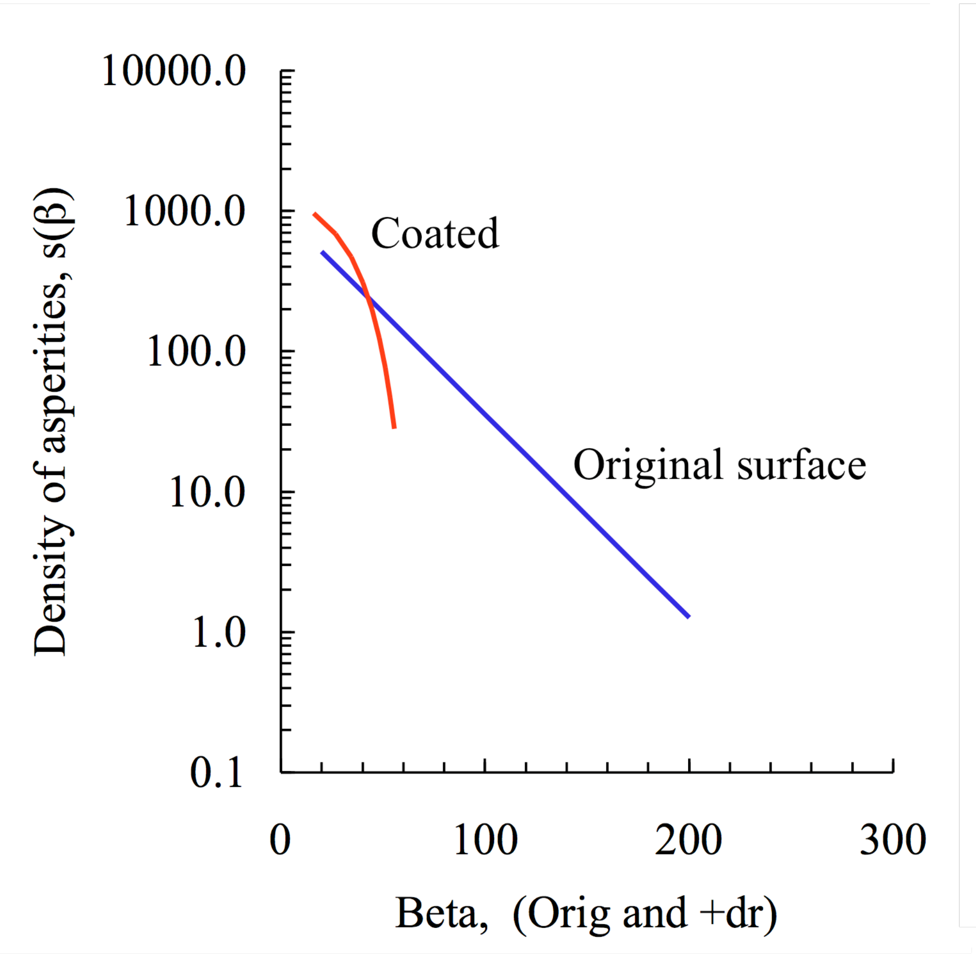
After 5 nm ALD ZrO_2 + 30 nm ALD Pt

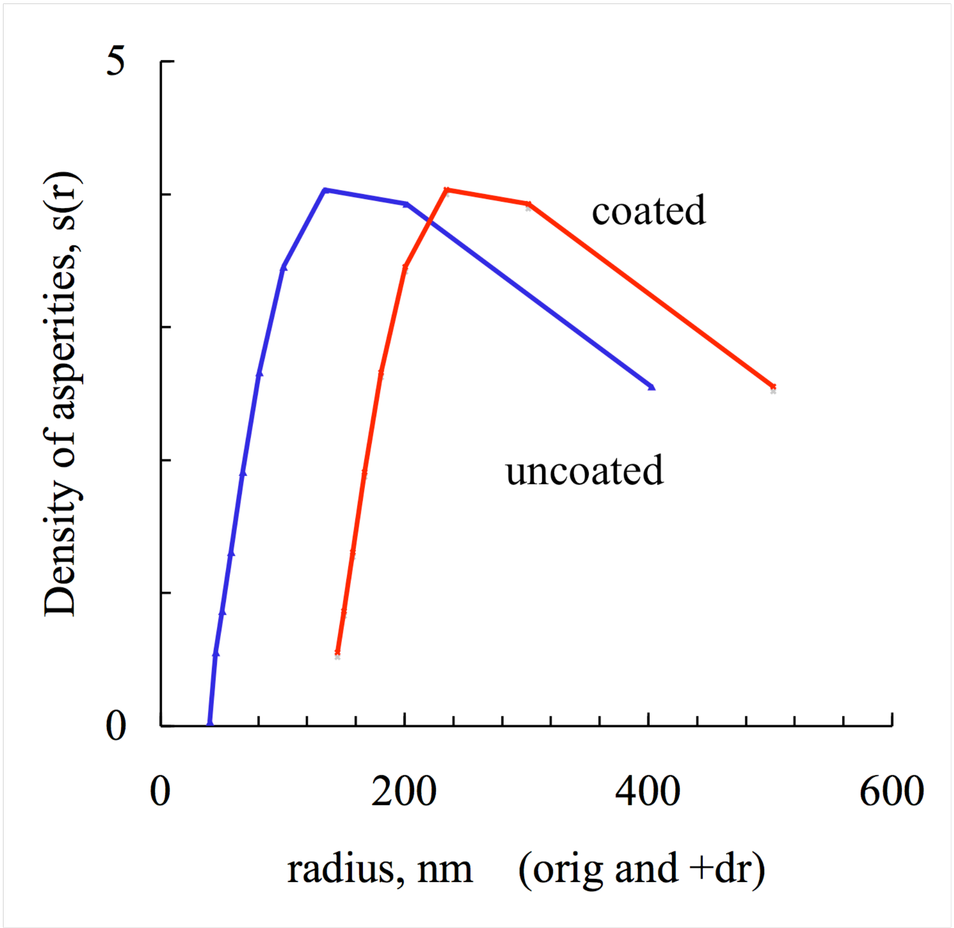
Figure 3: Scanning Electron Microscope images of nearly atomically-sharp tips, before and after coating with a total of 35nm of material by ALD. The tip, initially about 4 nm, has been rounded to 35nm radius of curvature by growth of an ALD film. Rough surfaces are inherently smoothed by the process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

Smooth coatings can change the spectrum of enhancements.

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





- This example should give <u>three times higher</u> rf gradients.

Summary

A model is being developed that can describe all the plasma properties of arcs.
- It is incomplete.
- Preliminary predictions seem to match experimental data.

The properties of metals during BD should be modeled with Molecular Dynamics.
- Coulomb explosions
- Creep
- Fracture
- Generation of particulates
- Etc.

We are beginning to look experimentally at ALD surfaces under high fields.
- Suppression of field emission
- Pulsed heating

CLIC, Muons, and SRF look at many of the same mechanisms.