Breakdown in RF Cavities

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Outline

- Basic Ideas
- Complications
- What happens in breakdown
- How to get to higher gradients

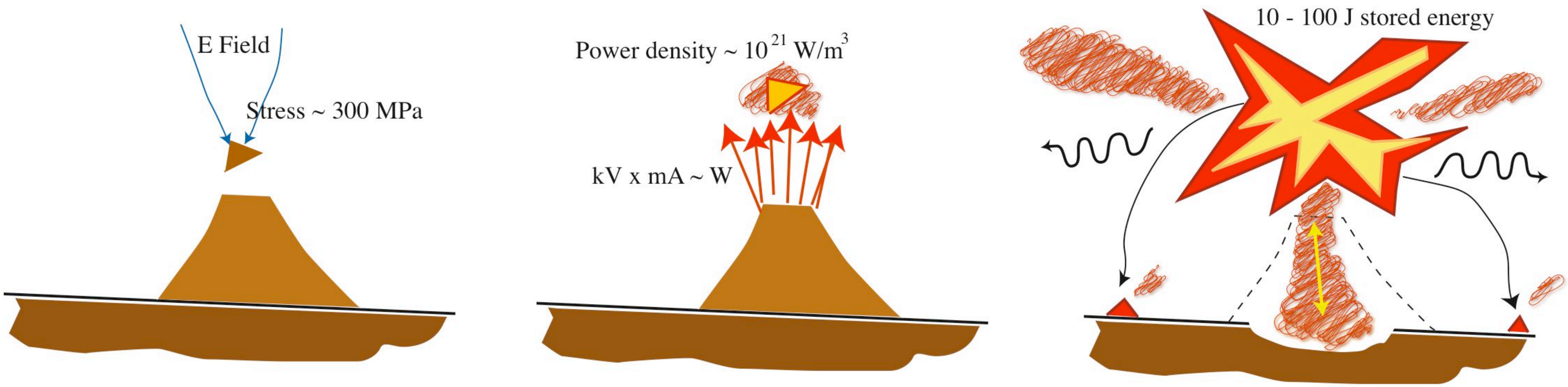
This is an early view of a more detailed paper. General mechanisms – no details.

Many people have contributed to this work.

Normal Conducting

A. Hassanein	Plasma Phys	Purdue Univ
Z. Insepov	Fracture kenetics	ANL Numerical Modeling
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Z. Qian	RF	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

But we haven't said anything about the breakdown itself.



Fracture is the trigger
$\varepsilon_0 E^2/2 = T$

Field emission produces plasma
$dE/dx = \{\ \ \}/\beta^2$

Lossy plasma absorbs energy
$s_2(\beta) = \exp(-b\beta)$

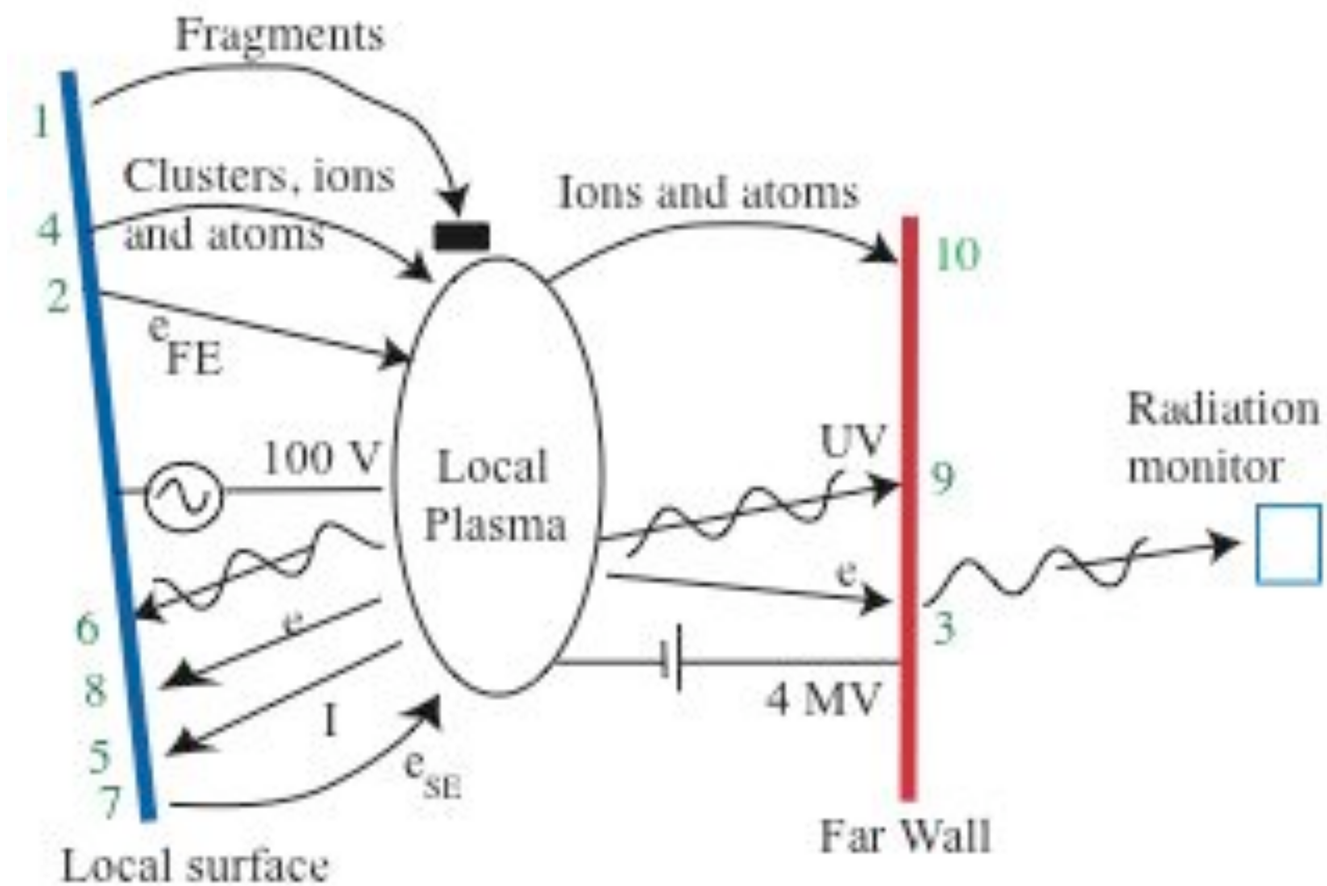
We want to know:

What happens?

What makes what happens happen?

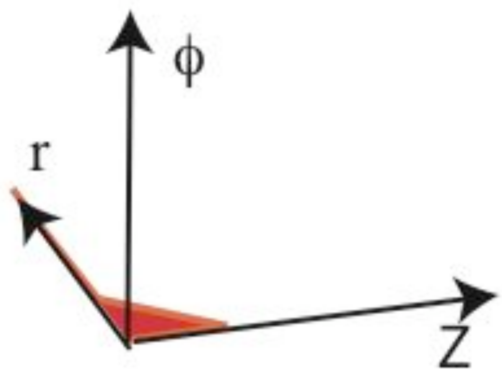
The overall model of the discharge

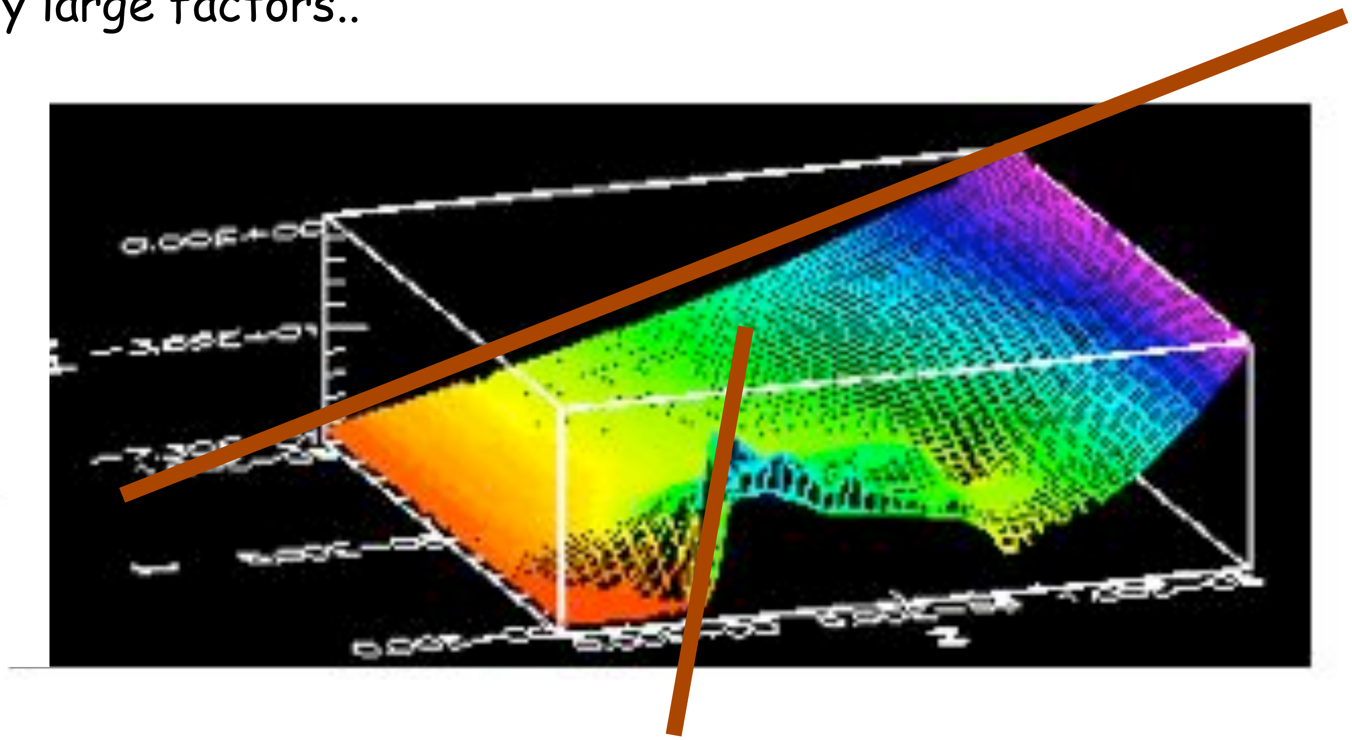
- Fragments trigger the spark.
- These fragments are broken apart and ionized.
- Plasma electrons accelerate to the far wall.
- + lots of other stuff



OOPIC Pro modeling gives the key.

- OOPIC Pro works very well, and can produce useful results.
- If ions cluster above an asperity and the electrons run away, the surface gradient can be increased by very large factors..

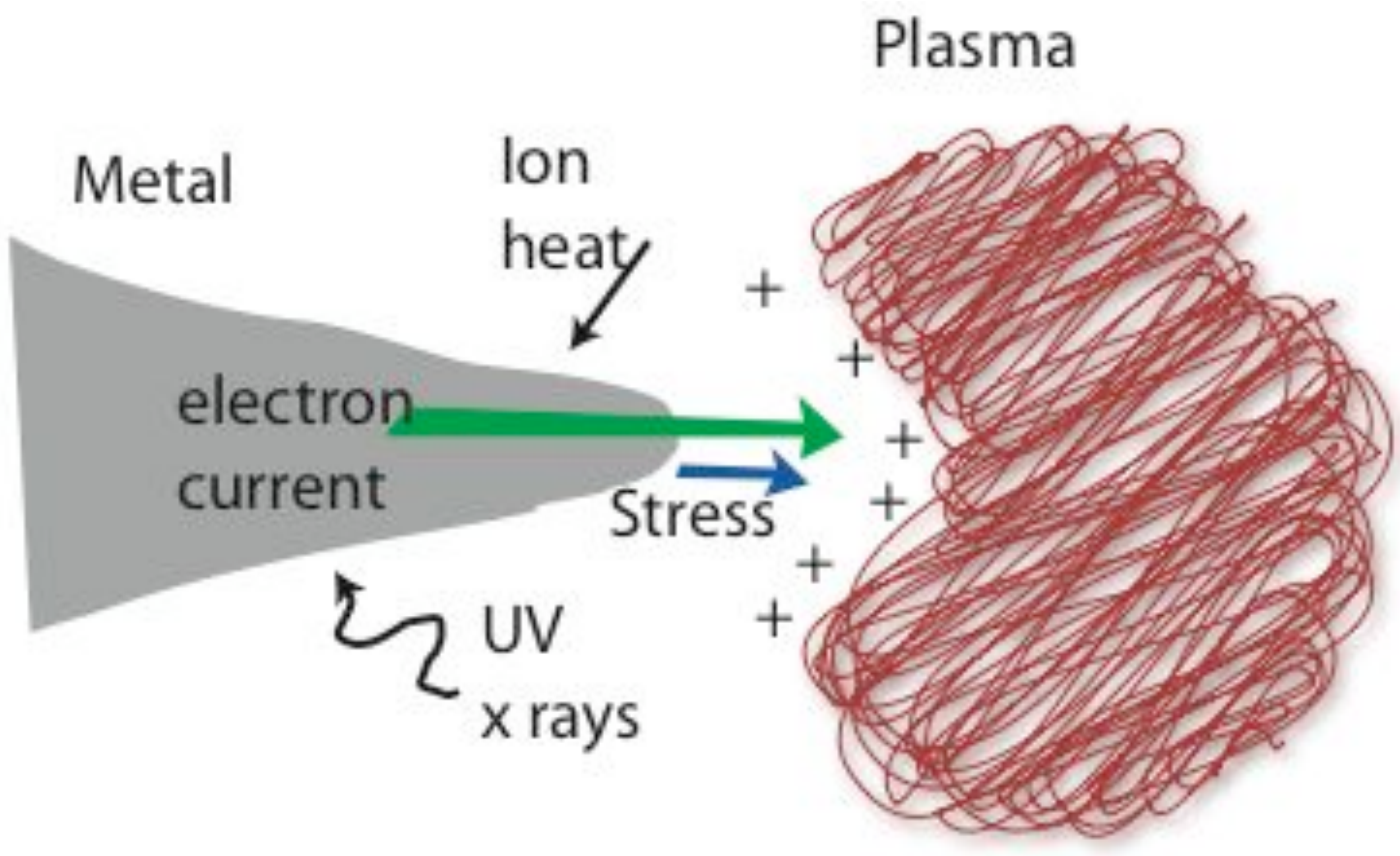




- dV/dx gives gigantic E_{surf}, which will pull <u>both</u> electrons & atoms from the surface.

Really high tensile stress and melted asperities?

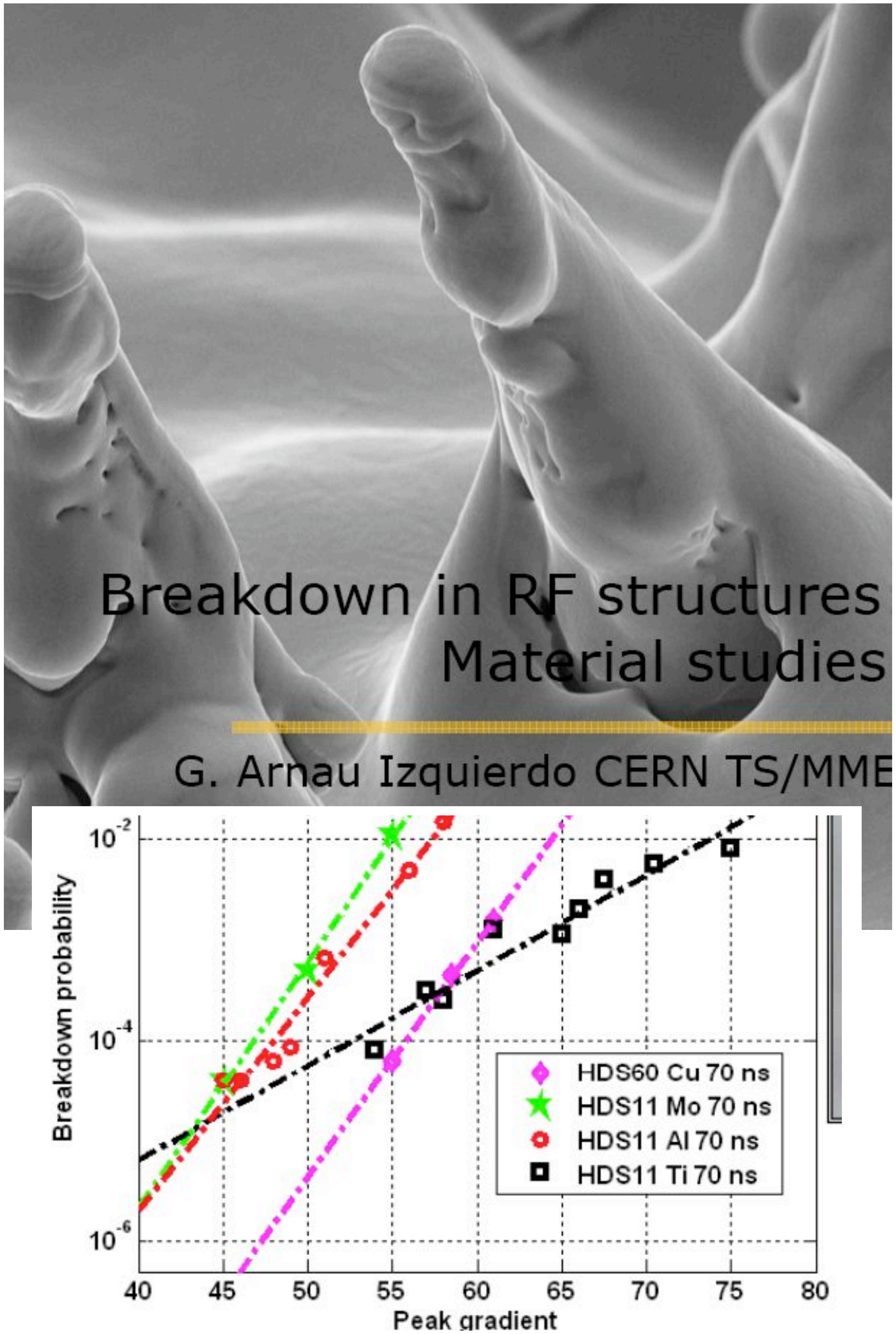
- No one understands this environment.

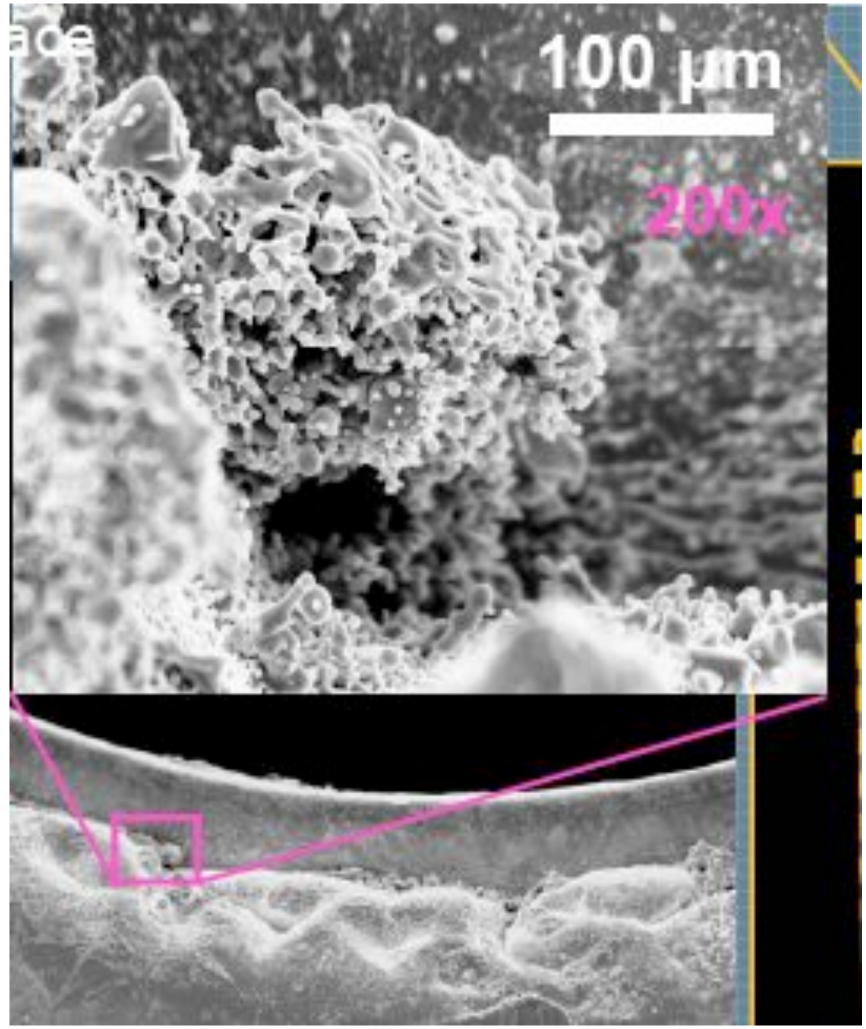


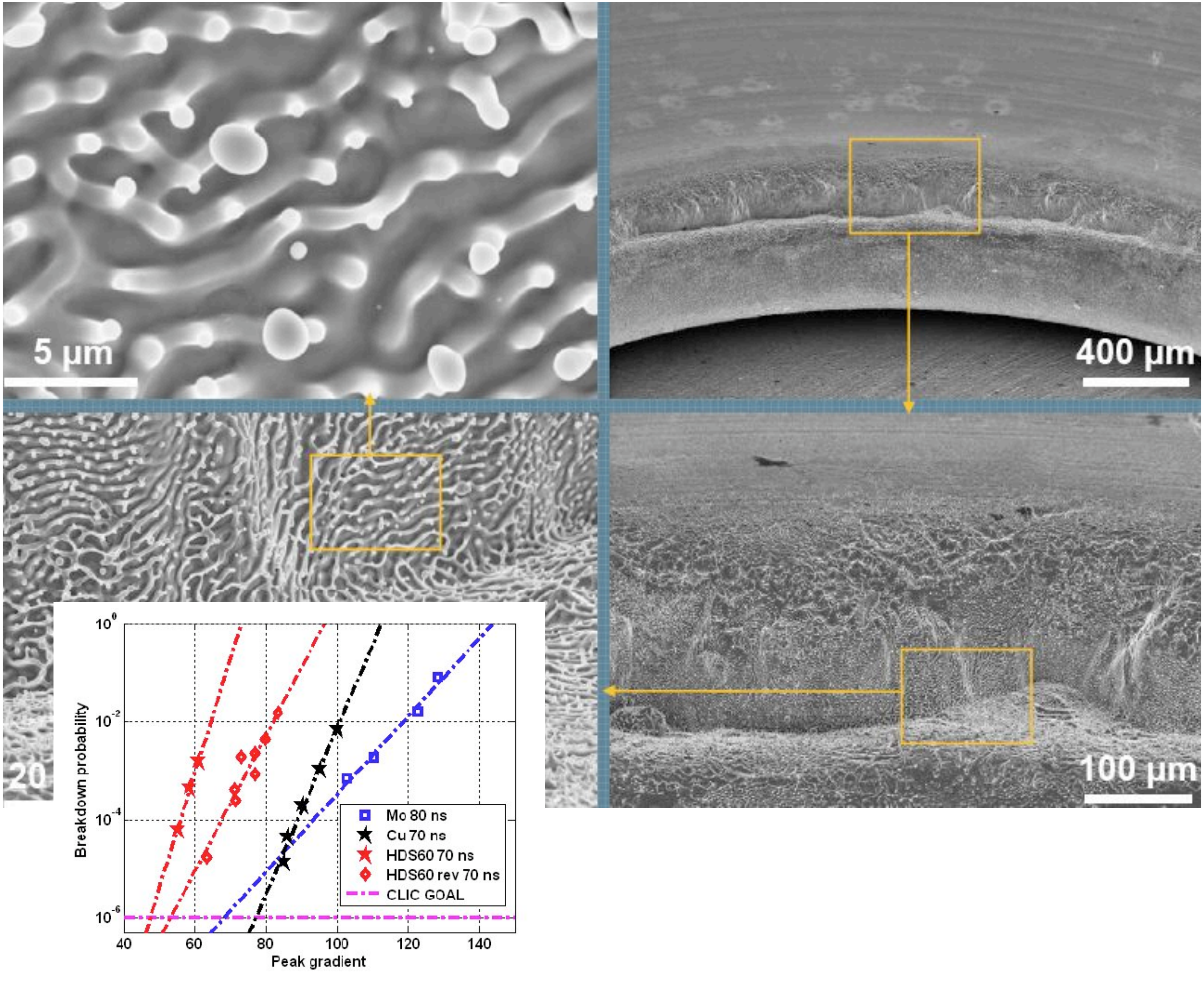
We are folding many details into the model.

- 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

CERN sees strange things in cavities and in cavity behavior.






5 µm
400 µm
100 µm
20
Breakdown probability
Peak gradient
Mo 80 ns
Cu 70 ns
HDS60 70 ns
HDS60 rev 70 ns
CLIC GOAL

Field emission is more than an equation

- This process has been studied for almost 80 years.
- Simple application of the eqn. isn't always useful.

current vs. field

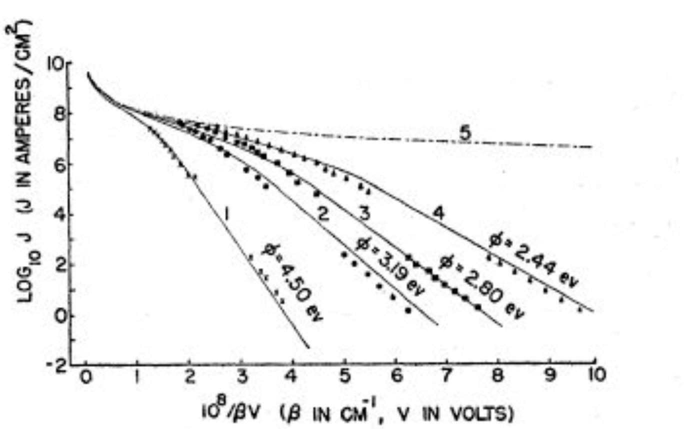


FIG. 7. Comparison of experimental data with space-charge field-emission theory (solid lines) for emitter N85. Curve 1, clean tungsten, curves 2–4, barium-on-tungsten as in Fig. 3; curve 5, Child's equation.

emission of electrons

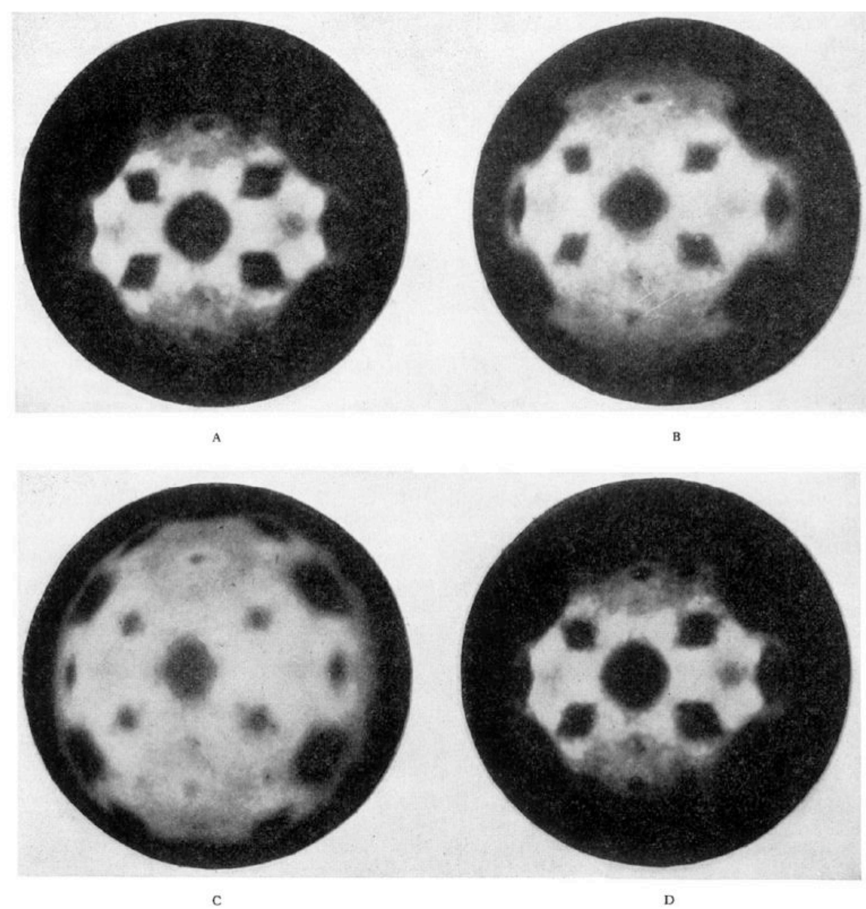
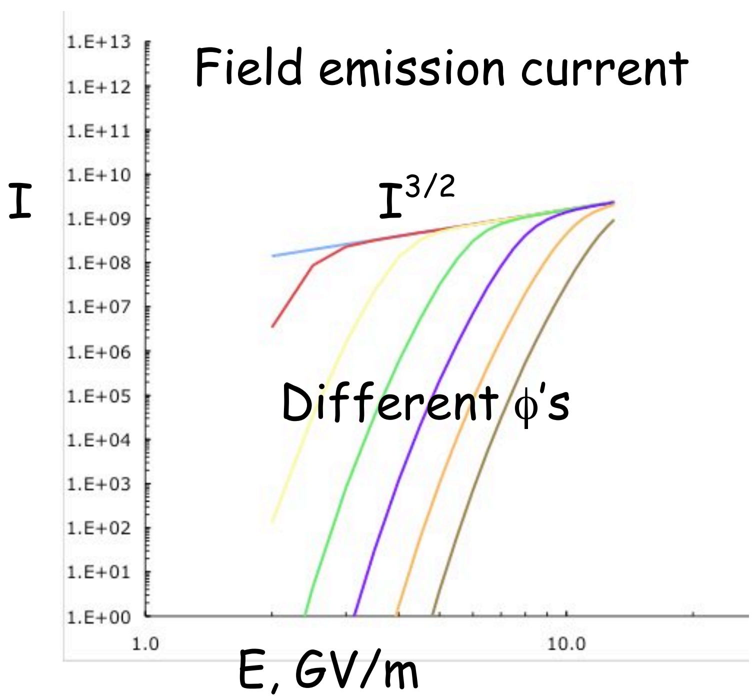


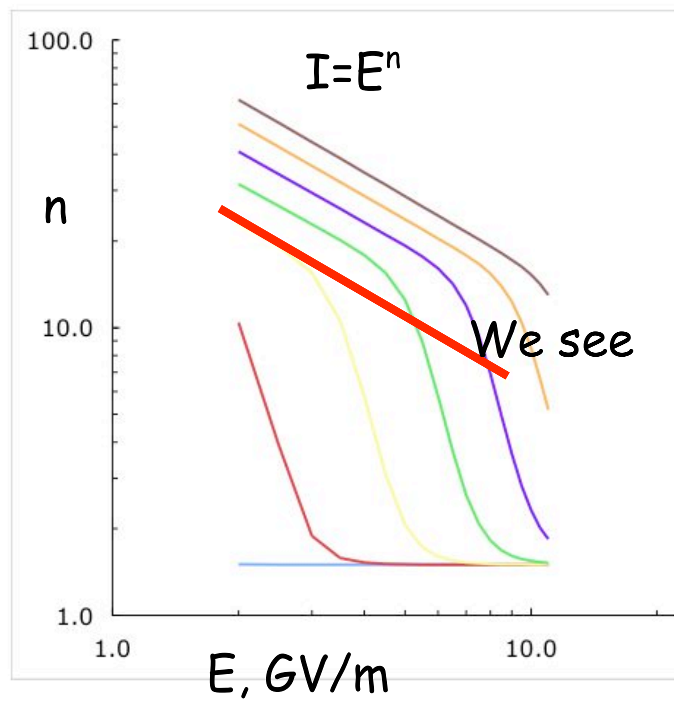
FIG. 4. Emission patterns at various currents, with constant work function $\phi = 3.19$, for emitter N85, corresponding to curve 2, Fig. 7.

- Small changes in surface materials make major changes in current yields.

Space charge

- In the 50's everyone understood space charge, because it limited vacuum tubes.
- Barbour et. al. saw space charge limit at ~ 3 GV/m. People now see 7 – 10 GV/m.





- This is a potentially serious problem, because these guys (from Linfield college OR, ~1953), always did everything right.

The solution to the problem is in the geometry.

- They are using a needle electrode in a spherical chamber, so E_{sc} is always in the direction of E_{acc}. Not true in our case.

- In our geometry, the surface asperities are small bumps on a flat surface:

  There is a $1/r$, $1/r^2$ dependence for a small distance.

  After a distance of about r, the field becomes uniform.

- Our electrons are allowed to expand freely perpendicular to the acceleration field.

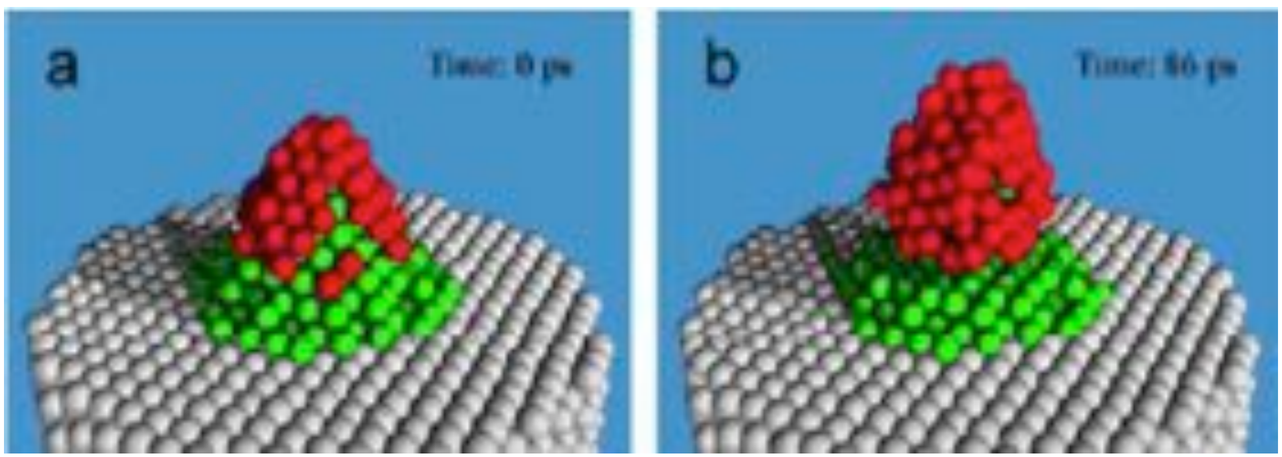
- The SC limit is still there, but at a higher current. It can most easily be evaluated by modeling

Coulomb explosions

- If metallic nanoclusters are charged, they can become mechanically unstable.
- The electric field pulls the clusters apart.
- This occurs at surface fields of 7 – 10 GV/m. (Who could have predicted that?)
- Not many electrons are required,

  A 0.01 – 0.001 excess of electrons/atom will make the cluster unstable.

  Our clusters exist in currents of ~1 Me^-/ns, where neutrality is unlikely.

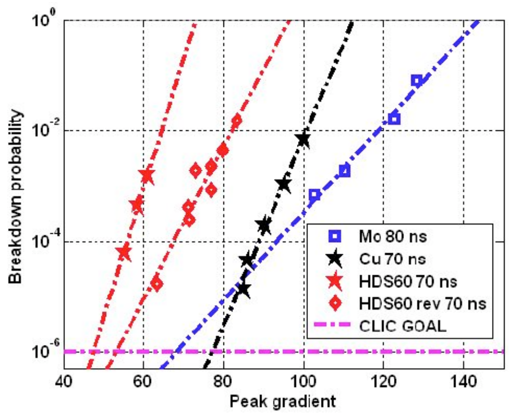


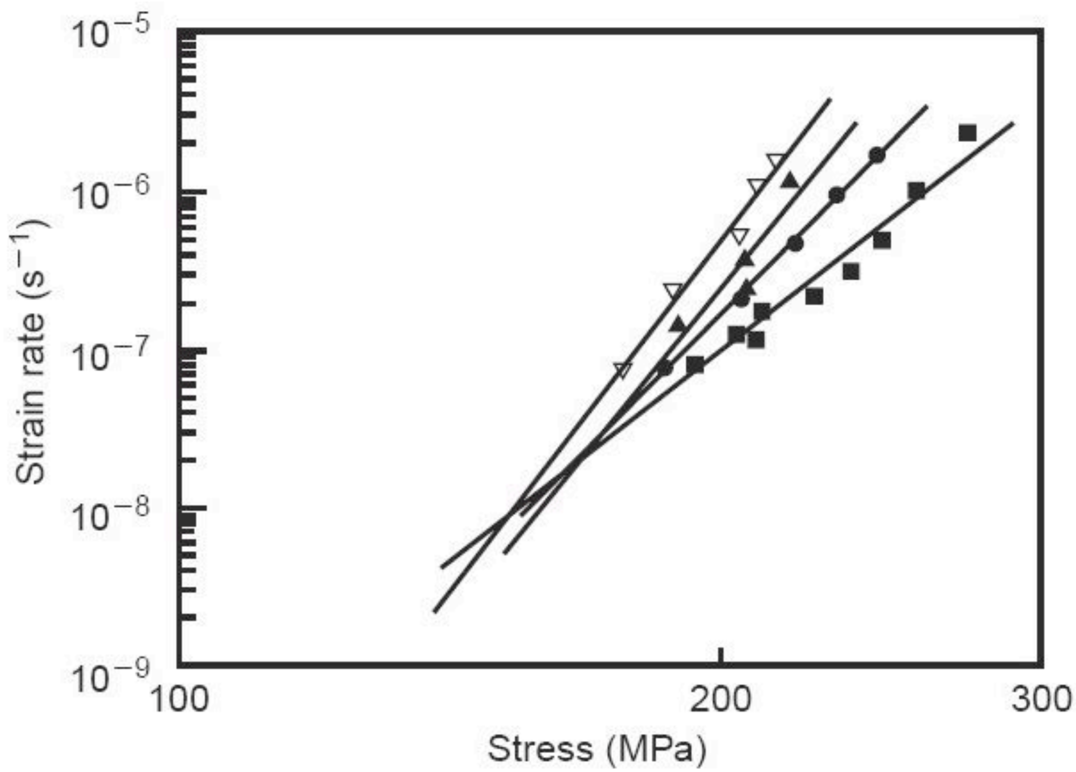
- **This is our trigger mechanism when it occurs on the surface.**

Fracture, Creep and Tensile stress

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

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



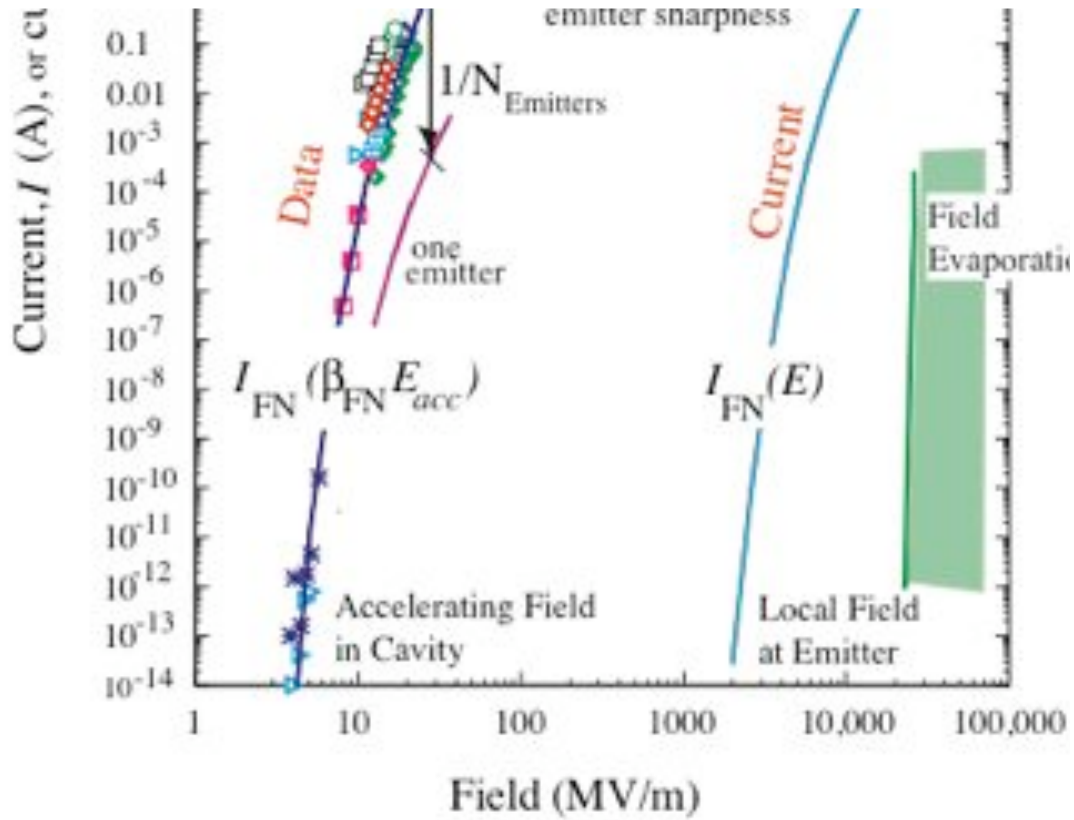


- There is a lack of data on creep and fatigue in the GHz range so we are, to some extent, flying blind.

Electroplastic, magnetoelastic effects ? ?

Field Ion Evaporation

- Usually negligible, this process can become very strong at surface fields > 10 GV/m.
- The process occurs with a field dependence of $I_i \sim E^m$, with m ~100 – 150. ! !
- This could produce a huge atomic current at these fields.



Factors that limit the discharge

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

- 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/

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

Where does all the cavity energy go?

- The plasma has a sheath potential of ~ +/- 100 V and may draw a few amps.
  Not much power.

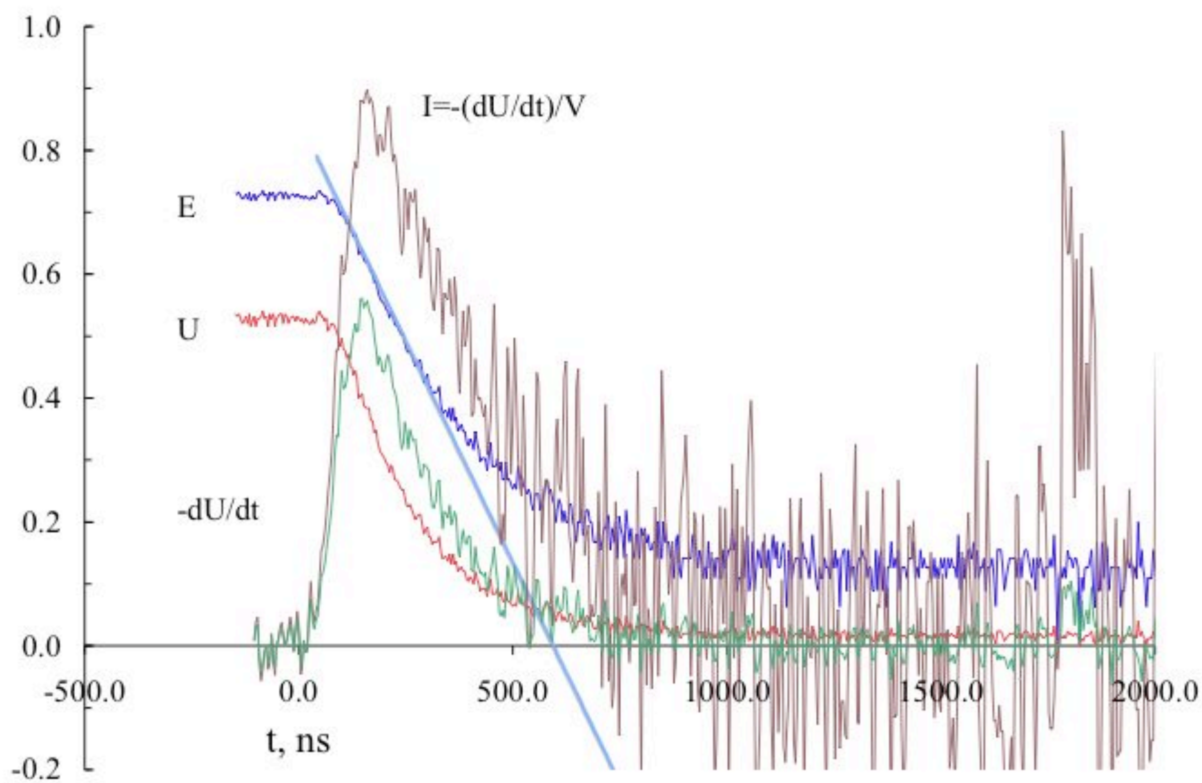
- Electrons that are accelerated out of the plasma reach ~ 4 MeV at the far wall.

- ~ 1 A of electrons in the far wall would absorb ~4 MW of power. That's enough.

We can measure:

P = IV =-dU/dt

I = -(dU/dt)/V



NOTE: Al doesn't like
this data,
We are repeating it

What terminates the arc?

- The plasma arc is driven primarily by the electric field in the cavity and will exist as long as the E field exists.

- In standing wave cavities, the currents essentially discharge the cavity to a level where the shorting mechanism is less efficient.

  As the cavity field decreases, the electrons have trouble reaching the far wall in a quarter cycle, reducing the power they can carry.

  One would expect that the location of the arc etc. would have a significant effect on the efficiency with which it could short the cavity.

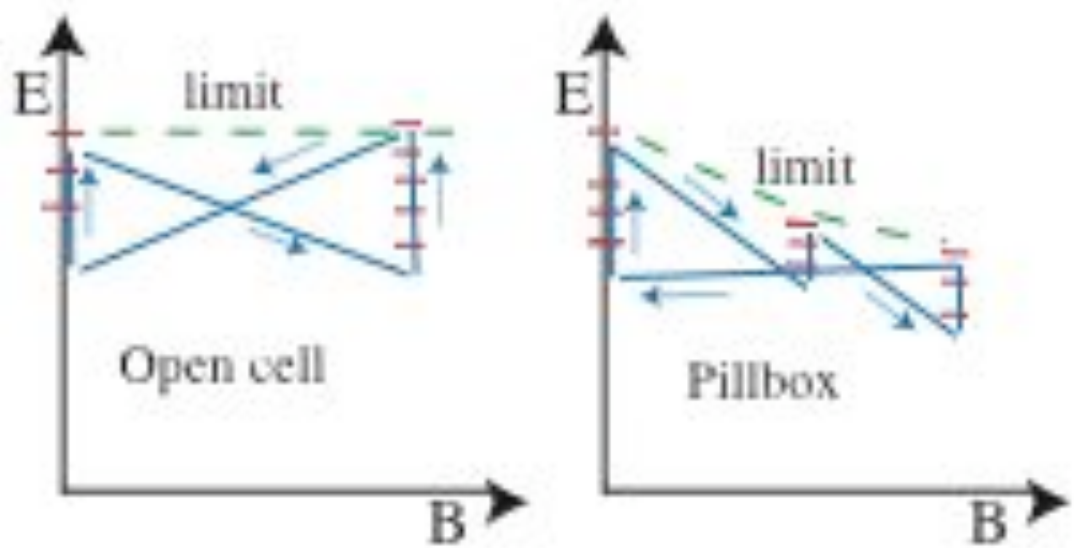
- In traveling wave cavities the shorting currents will persist as long as the cavity is powered, effectively producing an ideal load.

Useful things to do.

- Measure E at various angles to B in a simple system
- Measure dU/dt, P_f, P_r with high resolution.
- Look at spectroscopy.
- Look at effects of reversing magnetic field.
- Look for clockwise, counterclockwise effects on end pieces.
- Try to make estimates of radial extent of plasma from damage.

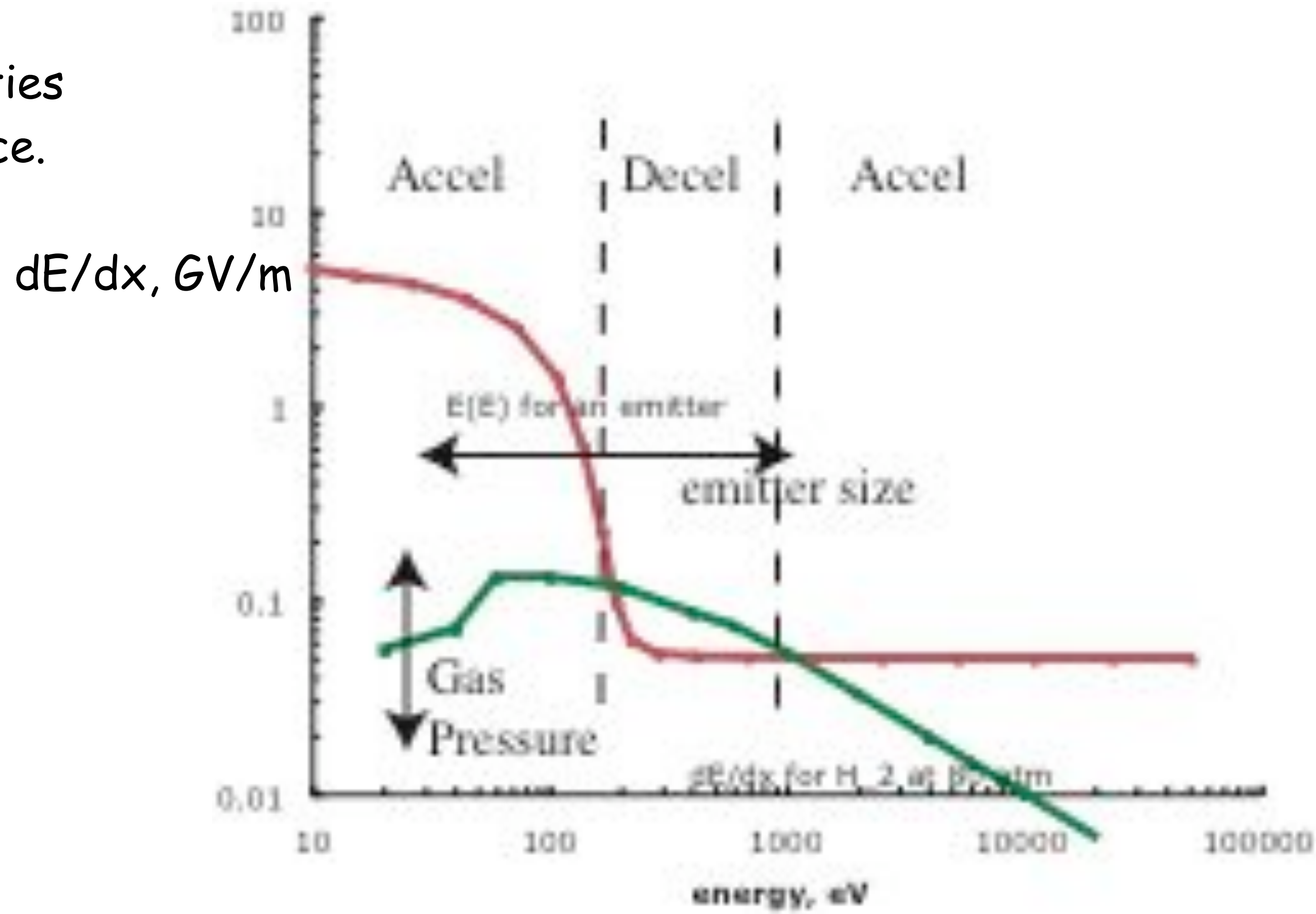
Magnetic field effects

- J x B drifts, v = E/B, but what E field should be used?
- Beams pinned to magnetic field lines
- different breakdown sites



High pressure cavities

- Looking at high pressure air in cavities
- Paschen breakdown has been solved for 150 years. (radiation effects are new !)
- Surface breakdown seems to be a function of local electric fields and dE/dx loss.
- Fields around asperities drop off with distance.



ALD coatings should cure field emission and breakdown.

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

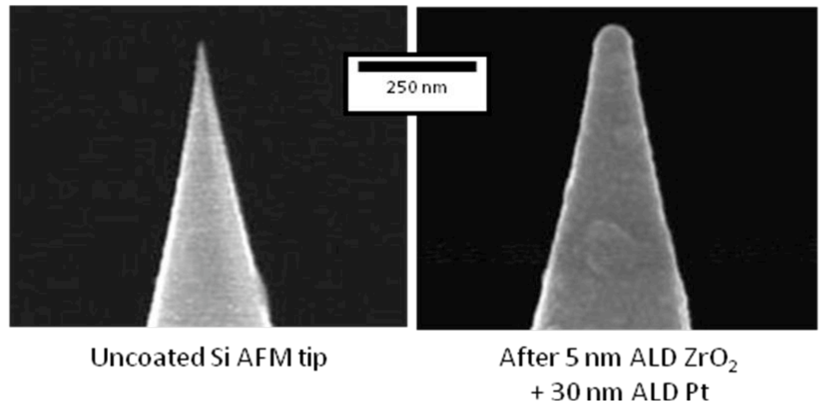


Figure 3: Scanning Electron Microscope images of nearly atomically-sharp tips, before and after coating with a total of 35nm of material by ALD. The tip, initially about 4 nm, has been rounded to 35nm radius of curvature by growth of an ALD film. Rough surfaces are inherently smoothed by the process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

Conclusions

- Breakdown is complex.
- It has been fairly straightforward to identify and propose solutions to the problems of superconducting rf systems and normal rf systems in a non-magnetic environment.
- Solving the MICE and Muon Cooling problems (B field) may be harder.

On a larger scale:

- Europeans are well funded and moving in the right direction.
- We should raise the priority for our effort.