PLANS FOR RF TESTING

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Muon Collaboration Meeting
Riverside, California
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Muon Collaboration

Around Christmas, Fermilab burned out some 805 MHz klystrons.

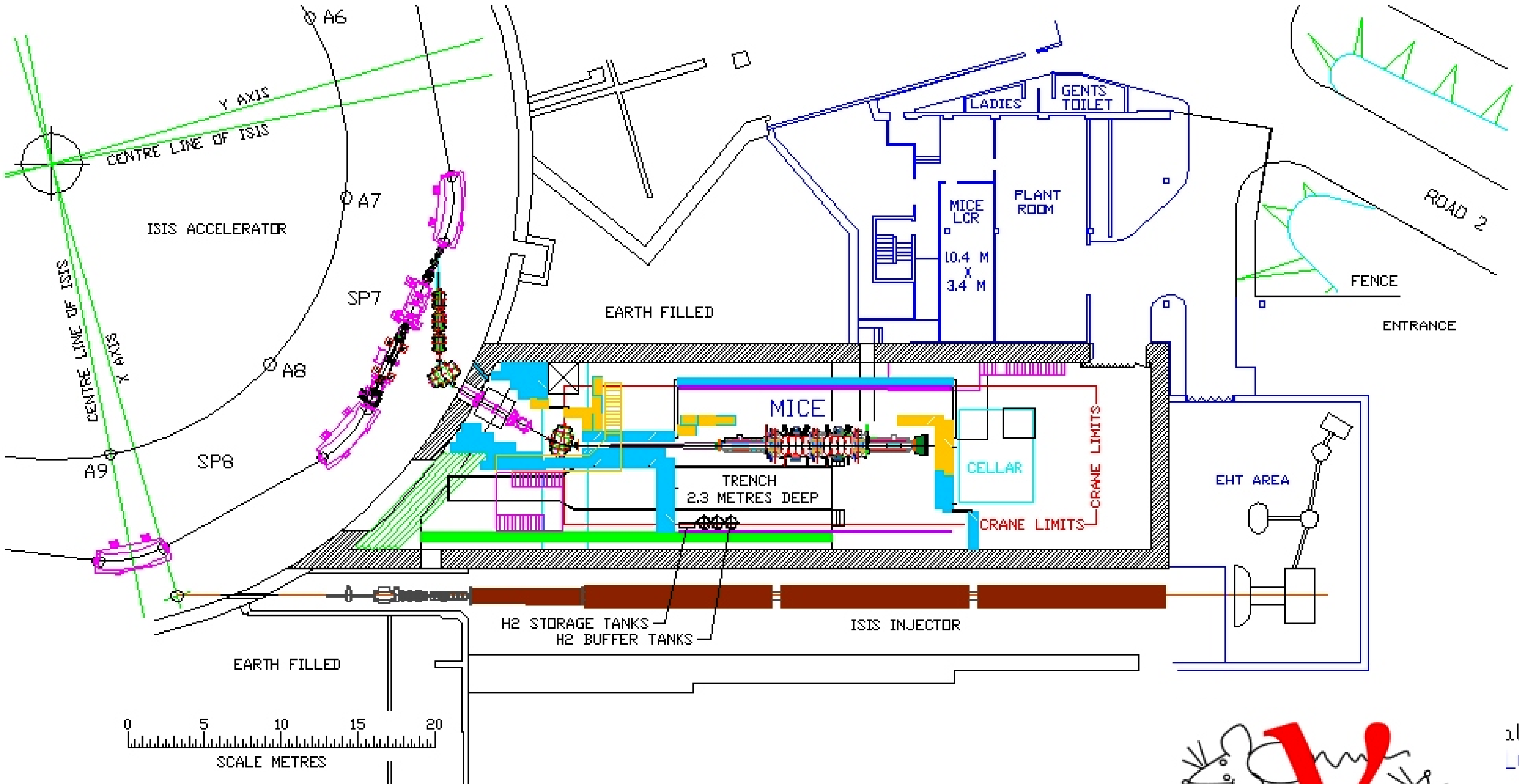
- The Lab G klystron was requisitioned as a spare.
- Lab G is off the air
- All plans are void.
- We may be back on by May.
- We are making new plans.
- End of Talk

Appendix Outline

- Introduction
- What we have learned from field emission (dark currents)
- Properties of emitters and electron (and ion) optics
- Cavity breakdown mechanisms
- Loose ends and interesting things to look at
- Conclusions

Experimental problems have high priority.

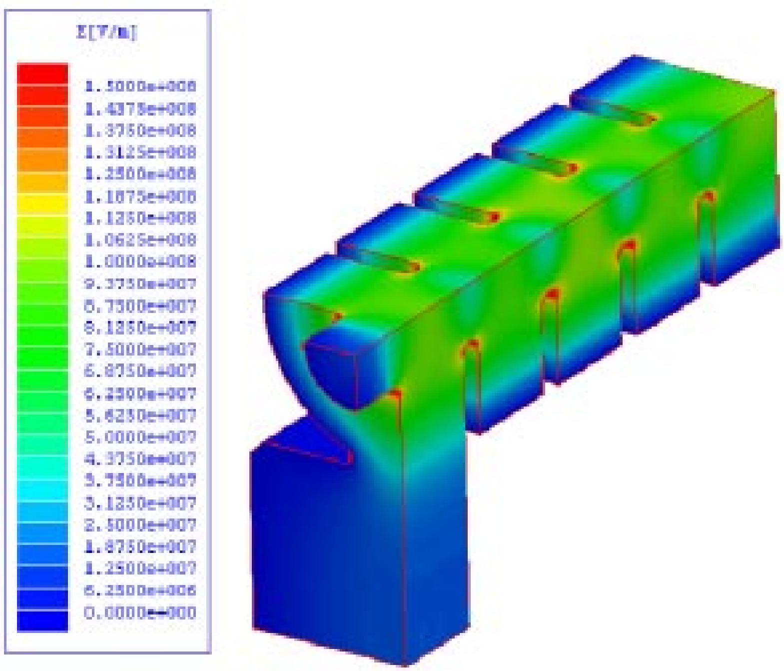
- The CCLRC has given RAL funding for design and beamlines.

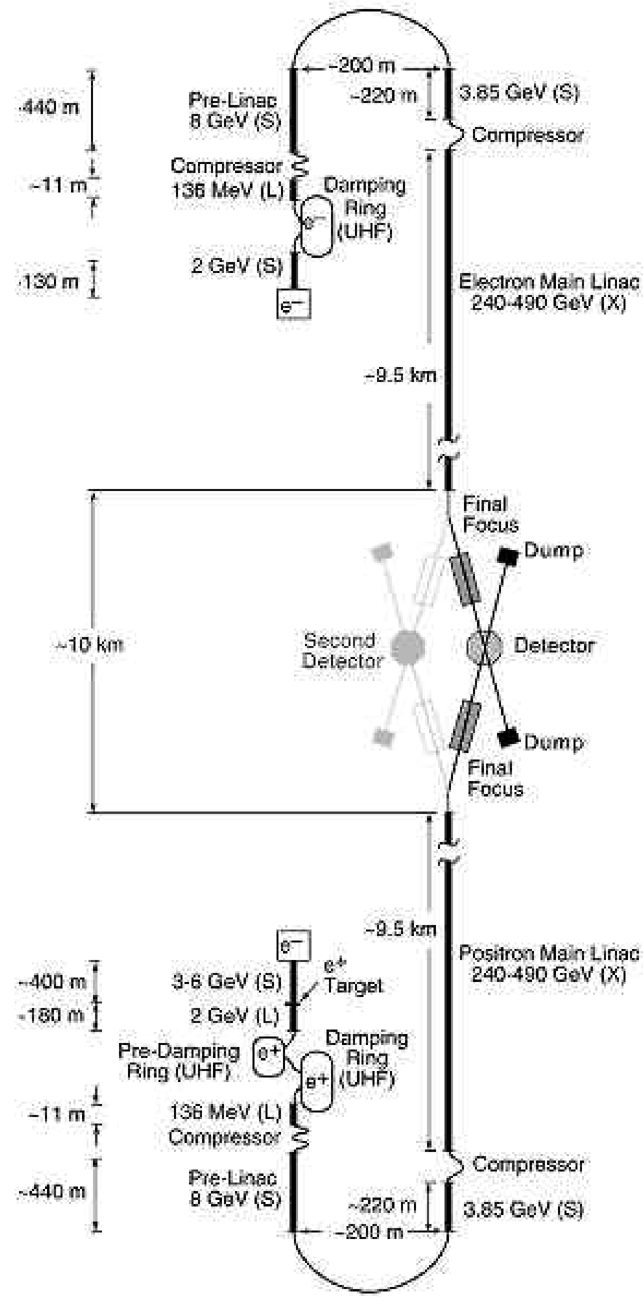


- Goal: Reduce backgrounds in spectrometers.

The work also applies to Linear Collider problems.

- The device is 30 km long, most of the active length is rf cavities.
- The cavity structures have high fields.
- Breakdown is the primary failure mode.
- It seems useful to understand the how to cope with breakdown before proposing the facility.





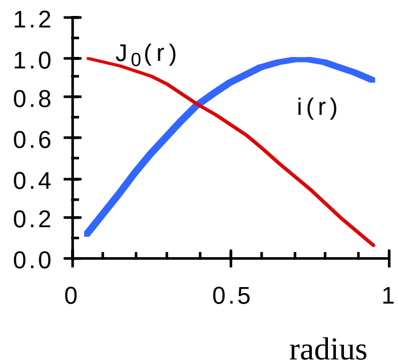
- Goal: Find the optimum material (copper?).

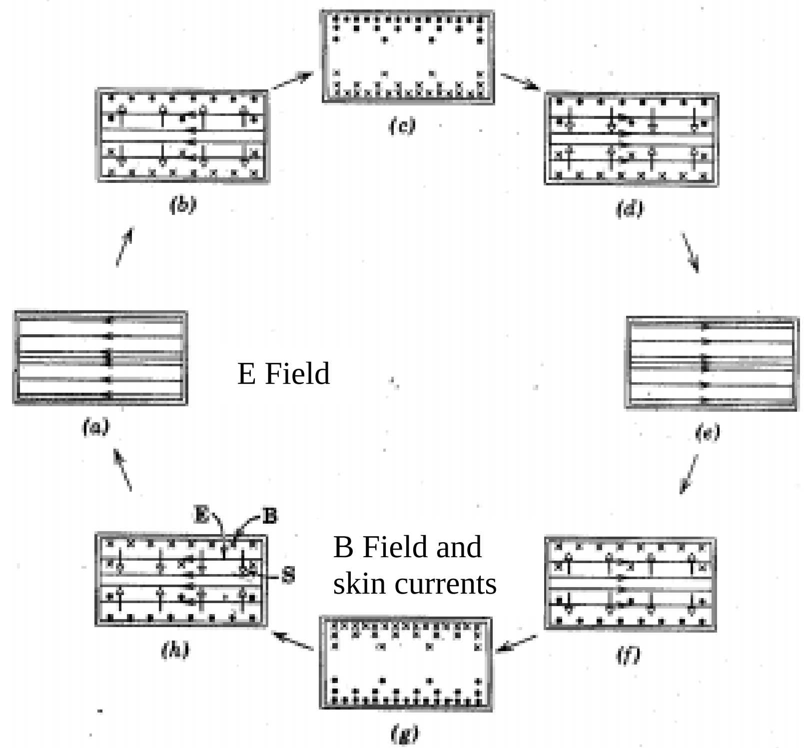
The Muon Coll. hosted a Workshop on High Gradient RF at Argonne.

- About 90 people came - from CERN, KEK, SLAC, Fermilab, BNL . . . .
- Complete review of the state of the art.
- The CERN Courier will have a summary in Feb.
- Not too much disagreement
- Interest in NLC, SCRF, and surface treatments.
- Triggers for breakdown were one of the issues.

Cavities of different sizes have similar physics.

- Electric fields and current densities are high.





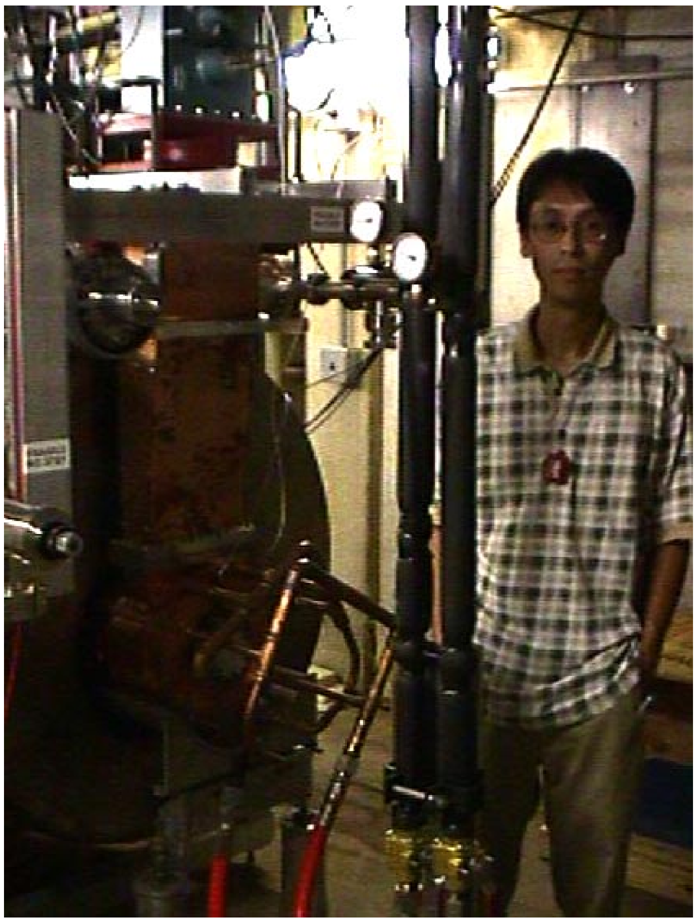
- Cavity Parameters

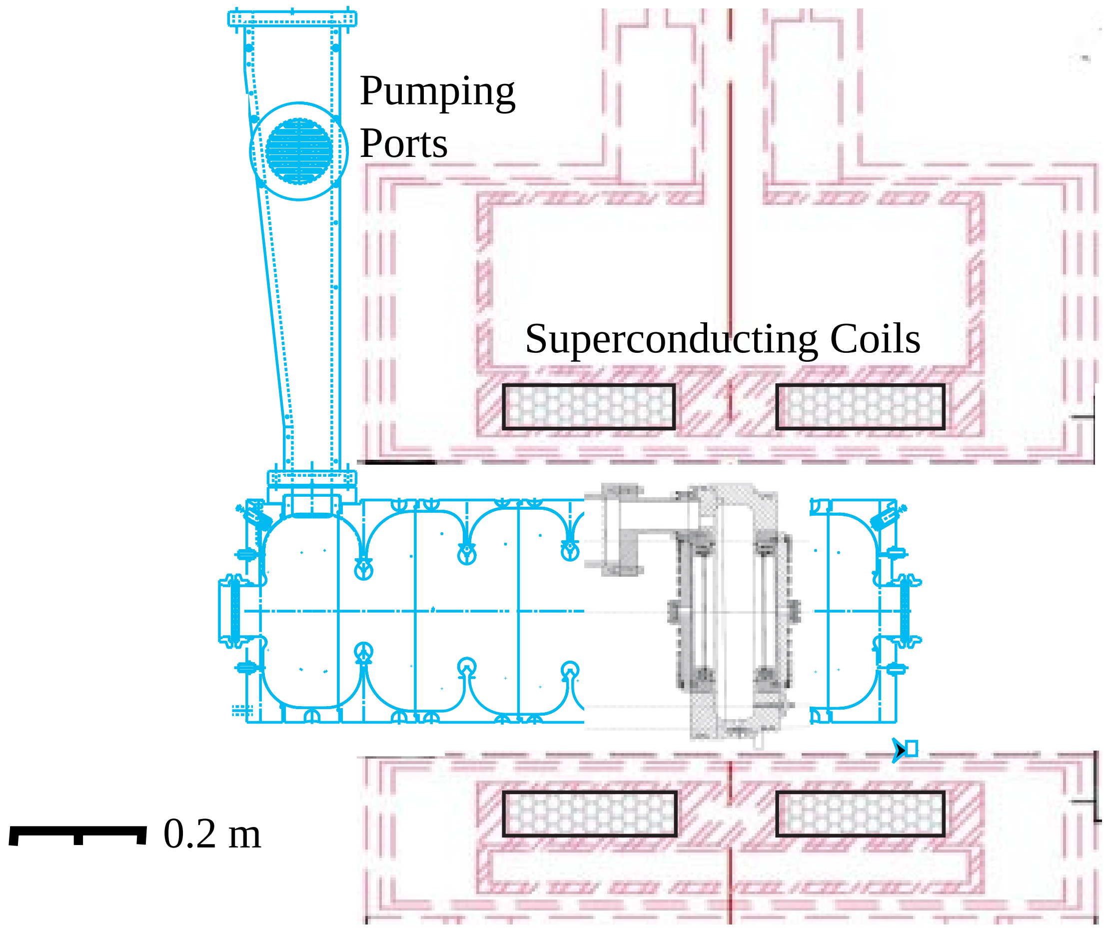
	200 MHz	Lab G	NLC	CLIC	
f =	2.00E+08	8.05E+08	1.14E+10	3.00E+10	Hz
E Field =	1.50E+07	1.50E+07	7.00E+07	1.70E+08	V/m
R =	0.75	0.19	0.013	0.005	m
L =	1.00E-01	1.00E-01	5.00E-03	5.00E-03	m
Skin depth =	4.64E-06	2.31E-06	6.15E-07	3.79E-07	m
Skin current =	1.47E+05	7.70E+04	1.20E+04	1.11E+04	A
current density =	3.36E+05	1.42E+06	1.18E+07	4.65E+07	A/cm^2
Ohmic heating =	7.66E+05	1.37E+07	9.48E+08	1.47E+10	W/cm^3
dT =	226	203	112		degC

Most of our data comes from an 805 MHz system in Lab G.

- Solenoidal and Gradient Magnetic fields

- Open cell (1 m long) and pillbox (8.6 cm long) were used
  - Open cell 6/01 - 12/01
  - Pillbox 1/02 - present





Many people were involved with dark current measurements

- Taking data

Argonne:	J. Norem
Fermilab	A. Moretti, Z. Qian, M. Popovic
U of Cincinatti	V. Wu
U of IL.	L. Ducas
IIT	Y. Torun, N. Solomey
LBL	D. Li,
CERN	P. Gruber
Imp Coll	E. McKigney

- Otherwise involved

Fermilab:	S. Geer, Tollestrup, A. Rowe
LBL	M. Zisman, M. Green
U of IL	D. Errede
Jlab	R Rimmer

and many others. . . .

- Breakdown study

Argonne	A Hassanein, I. Konkashbaev, Z. Insepov, M Pellin, F. Fradin, S. Streiffer, D, Kaufman, D. Miller

How does the cavity surface affect high gradient phenomena?

- Many studies have been done with various copper treatments, but many fewer compare different materials. Both experiments are expensive and difficult.

- How do rf and DC phenomena differ?

- What surface parameters and mechanisms are relevant?

- How much improvement is possible with surface treatments?

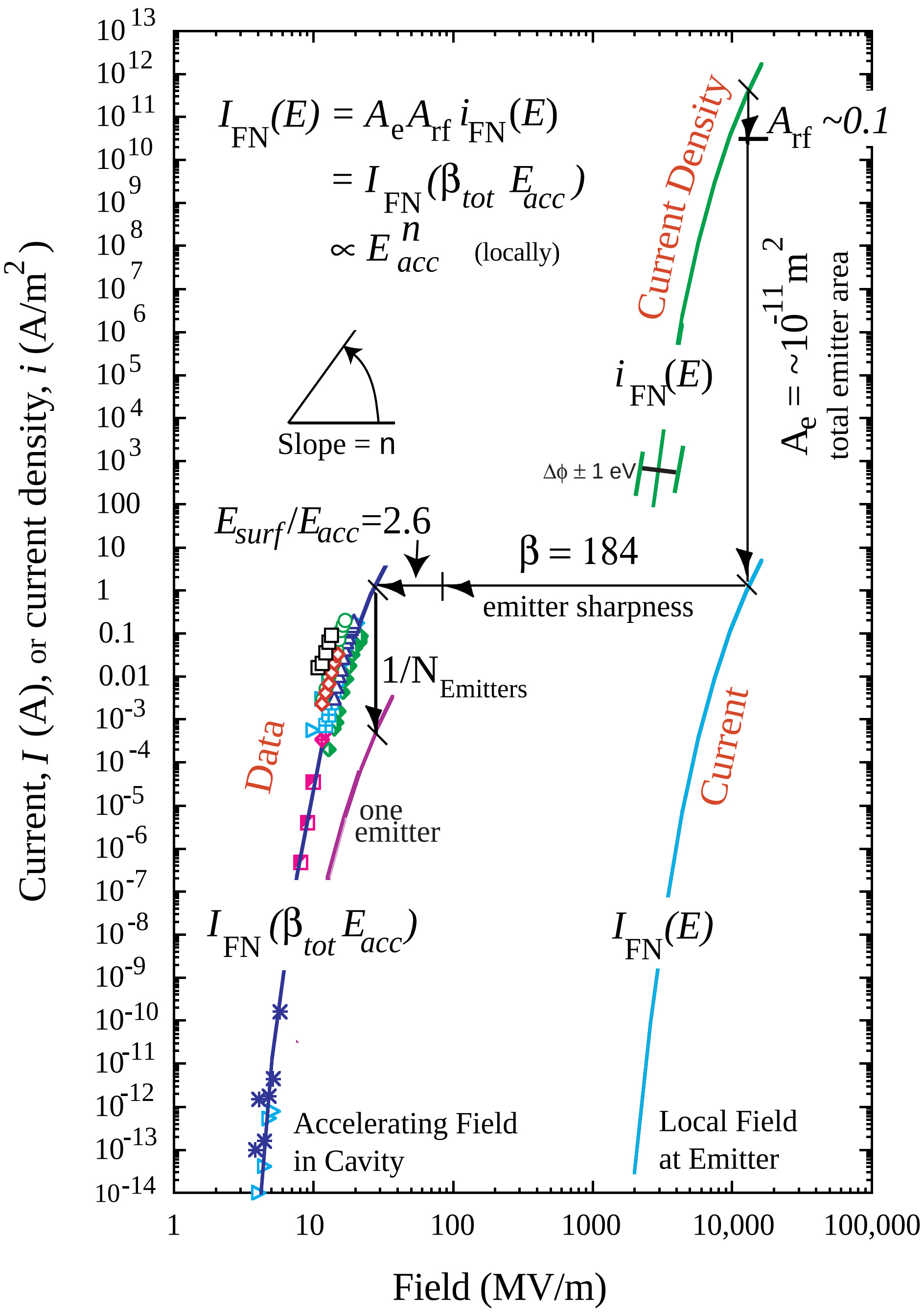
- How far are we from theoretical limits?

- What can we learn from SCRF? What are common problems? Can we tell them anything?

- What measurements should be done?
  - In-situ cavity measurements.
  - DC measurements.

Understanding Dark Currents

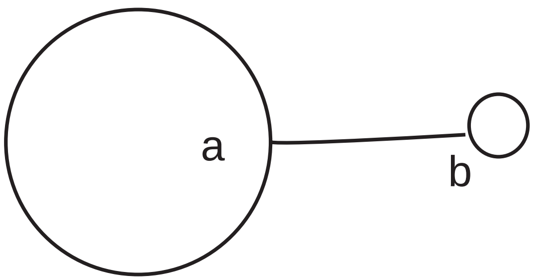
- Assume Fowler-Nordheim emission.
- Plot I vs E.
  Graphic interpretation of terms
  - RF/DC field emission ~ 0.1
  - Total emitter area, A_e
  - Enhancement factors, β
  - Total/Individual emitters
  - E_{surf} / E_{acc}
  - $n = E/I \, dI/dE$
  - Work function, ϕ
- Plotting other ways loses information
  F-N plot { $\ln(I/E^2)$ vs $1/E$ }
  nonintuitive.
  Linear { I vs E }
  imprecise

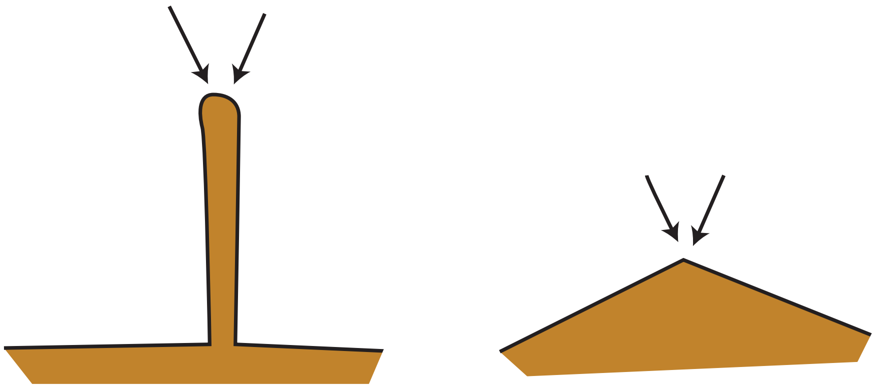


Large enhancement factors do not require conspicuous emitters.

- While "telephone pole" geometries would have high enhancement factors, this may not be the most common form of emitter.

- As shown in Feynman's Lectures, the breakdown enhancement factor is a function of the local radius, and is a result of the metallic surface being an equipotential.





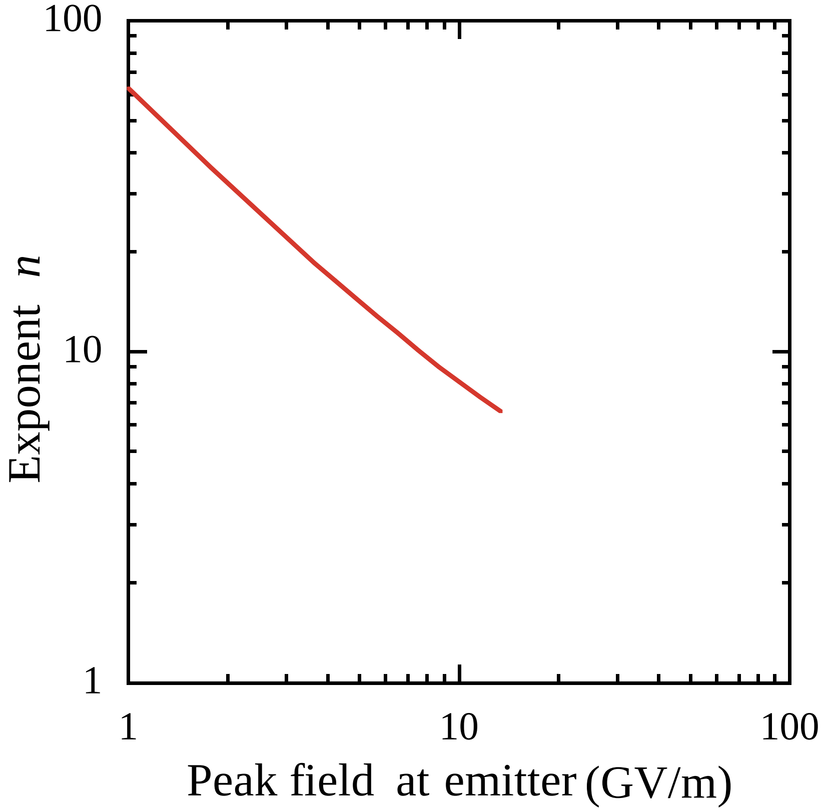
$\phi_a = \phi_b = Q/4\pi\varepsilon_0 a = q/4\pi\varepsilon_0 b \Rightarrow E_a/E_b = b/a$. The local radius is the most important thing.

- Grain boundaries, crater edges, and splashes could see very high fields, if the sharpness of the points is limited only by atomic dimensions.

- Defects in the surface can cause enhancements without any surface perturbation.

We can measure local electric field from *dI/dE*.

- The ratio *dI/dE* measures the local electric field at the emitter.
- The exponent $n = E/I \, dI/dE$, (the slope on the log-log plot), gives the field directly.
- The quantity *n* is easy to measure in a variety of environments and accelerators.



Two Mechanisms seem to be responsible for breakdown

It is an interesting exercise to assume that all breakdown phenomena are due to a few simple mechanisms. We are trying this with two. Unfortunately, neither is very well studied or understood.

1) Tensile stress exerted by the electric field on surfaces. (Breakup)

2) High current densities producing high gradients at grain boundaries and defects.

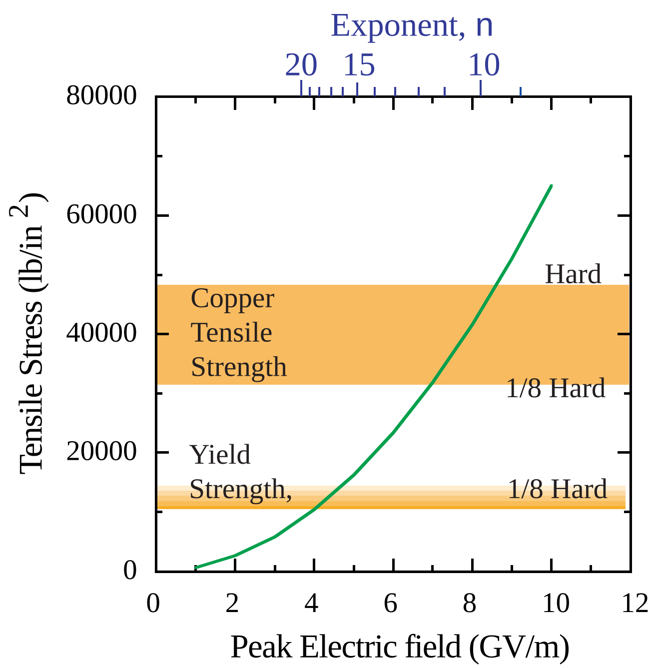
• However, **Magnetic fields** can also interact mechanically with field emission currents and cause problems within the emitters.

These two mechanisms should be necessary and sufficient to explain all the good data on breakdown in rf systems.

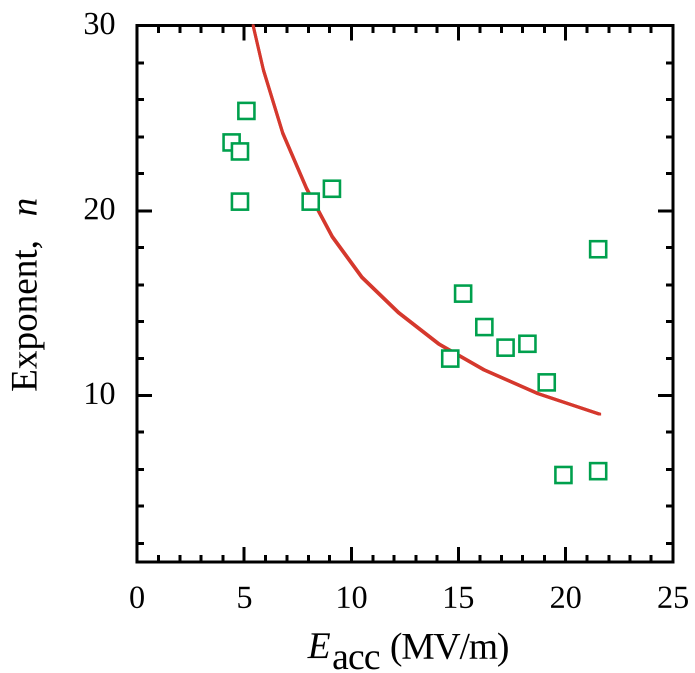
the primary cause

Tensile strength, tensile stress and breakdown

- The electric field exerts a tensile stress, $S = -\varepsilon_0 E^2/2$, on the surface. This stress can be comparable to the tensile strength of the copper.



In Lab G



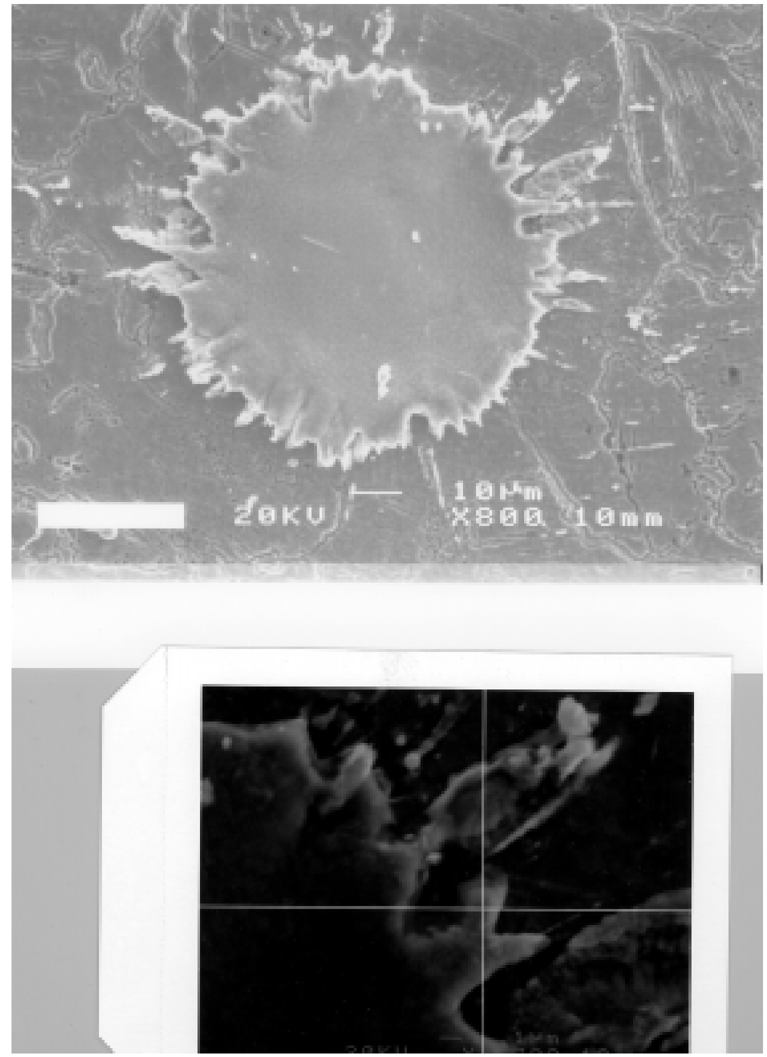
SEM photos show sharp points from splashes, and other effects.

- Splashes look alike.

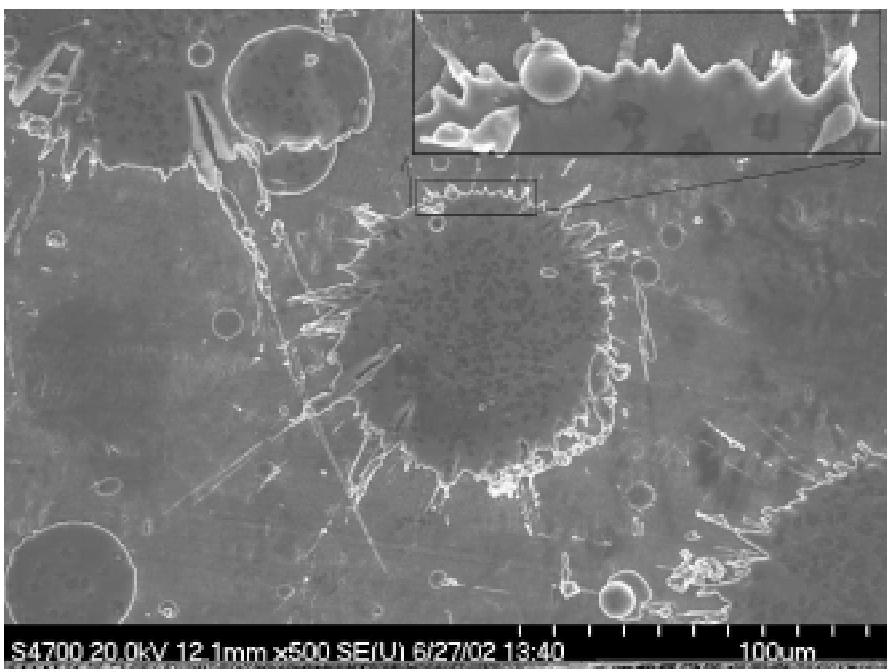
Milk

- Sizes are consistent with dark current data.

Pillbox cavity: Cu plate

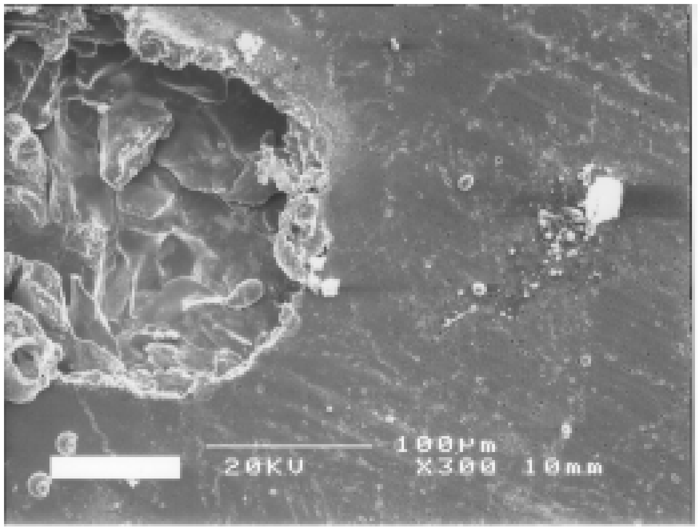


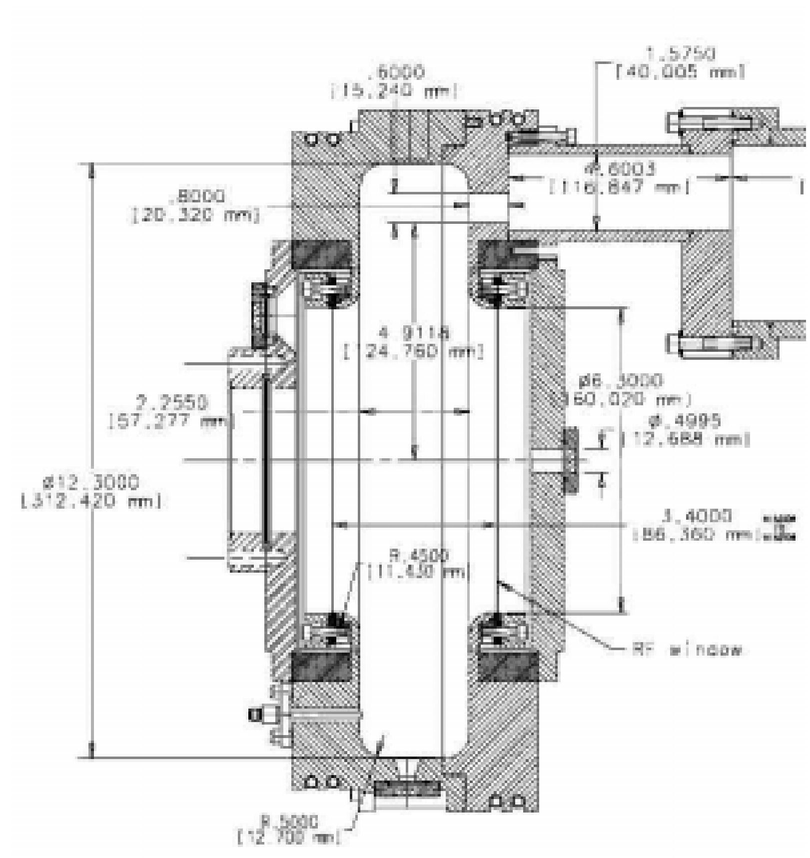
Open Cell cavity: Ti window



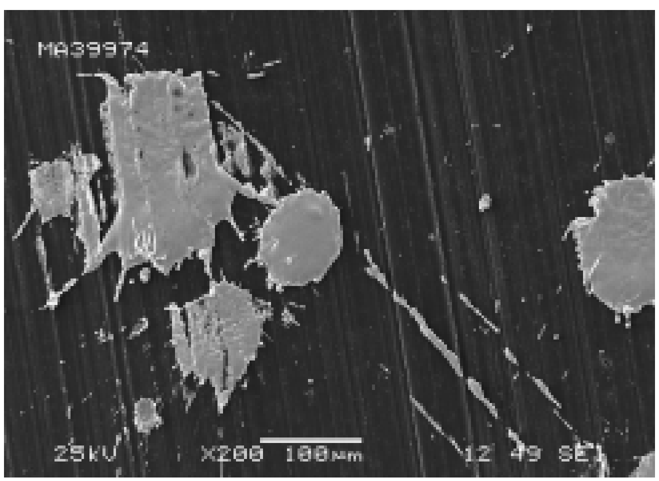
Beryllium works.

- Although covered in Cu, the Be surface seemed undamaged.
- Copper windows were pitted.



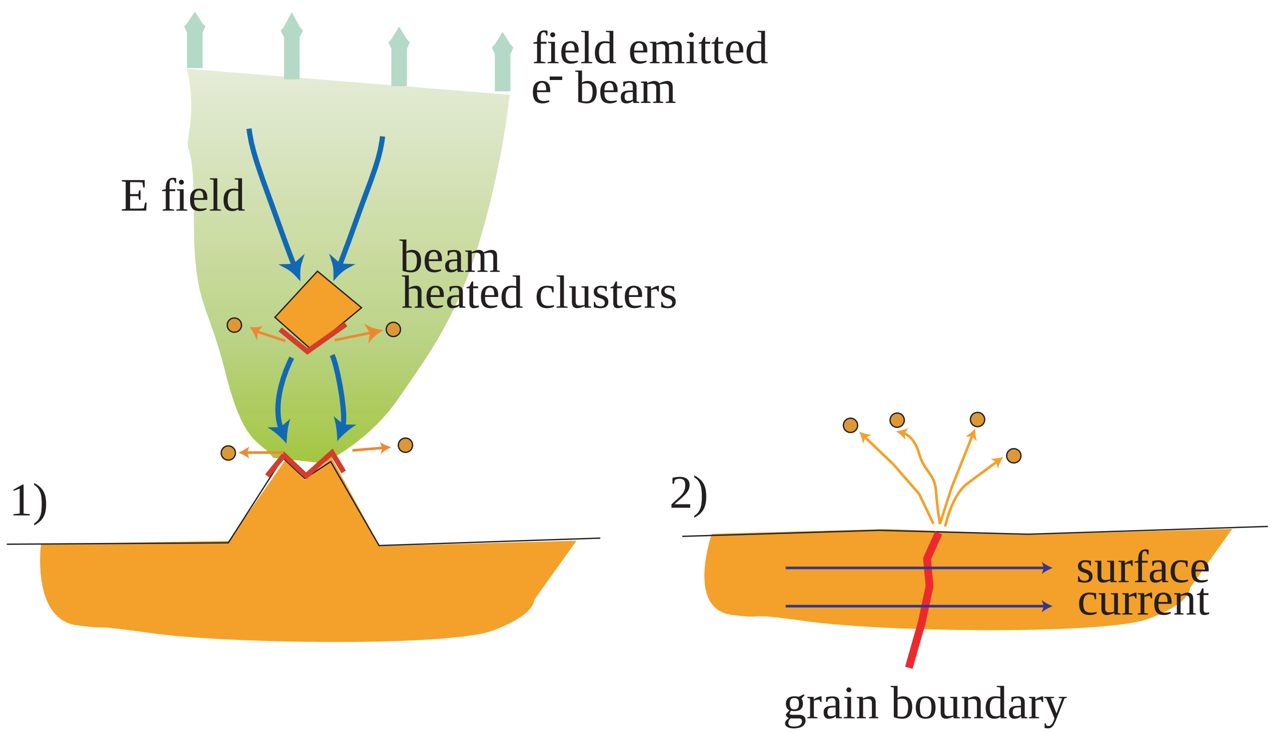


- Cu splashes on the Be window.



We can use simple models.

- While the emitter must be sharp, the cone angle is unknown, and "sharp" means hemispherical with $r < \sim 0.05\ \mu$.
- Sharp cones will get hot, but large cone angles won't.
- All aspects of the electron motion are relevant and interesting.
- Currents, even below the emitter surface, are subject to magnetic fields



The power density in the field emitted beam is enormous.

- The ranges of low energy electrons are short.
- Electric fields of 10^{10} V/m die off like $1/r^2$.

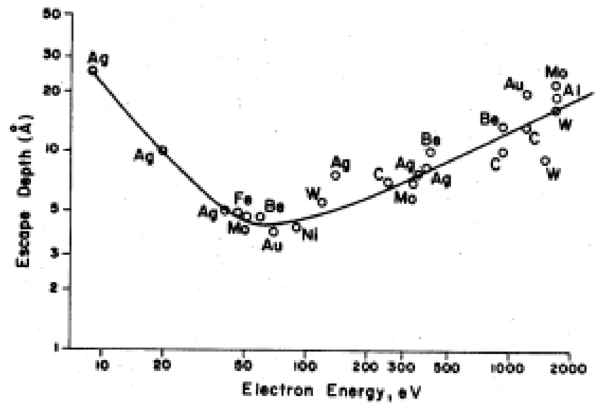
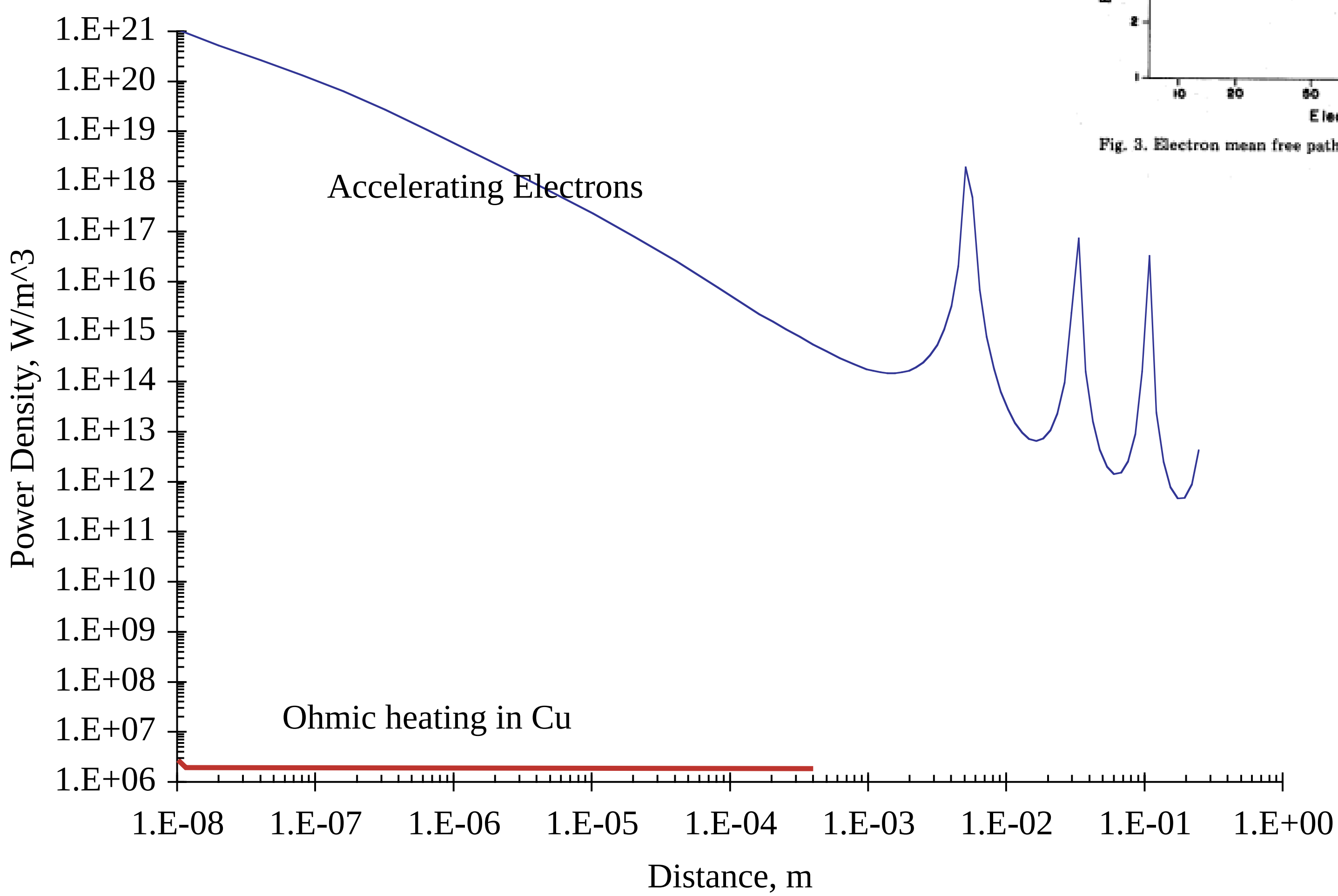


Fig. 3. Electron mean free path vs. kinetic energy in metals.



High voltages on sharp probes have been studied in materials science.

- **Negative voltage**

    Field Emission Microscope

    Electrons tunnel thru potential barrier and impact on phosphor

    - Probe radius r = 0.1 - 1 micron
    - Resolution limited by diffraction and electron wavelength effects ~ 0.002 μ.
    - Magnification = R/r ~ 1,000,000+

- **Positive Voltage**

    Field Ion Microscope (FIM)

    Gas is Ionized at surface and accelerated to phosphor screen

    - probe radius r = 0.01 0.1 microns
    - Resolution ~ 0.0002 μ
    - Gas pressure ~ 10^{-5} torr
    - Magnification of R/r ~ 1,000,000+

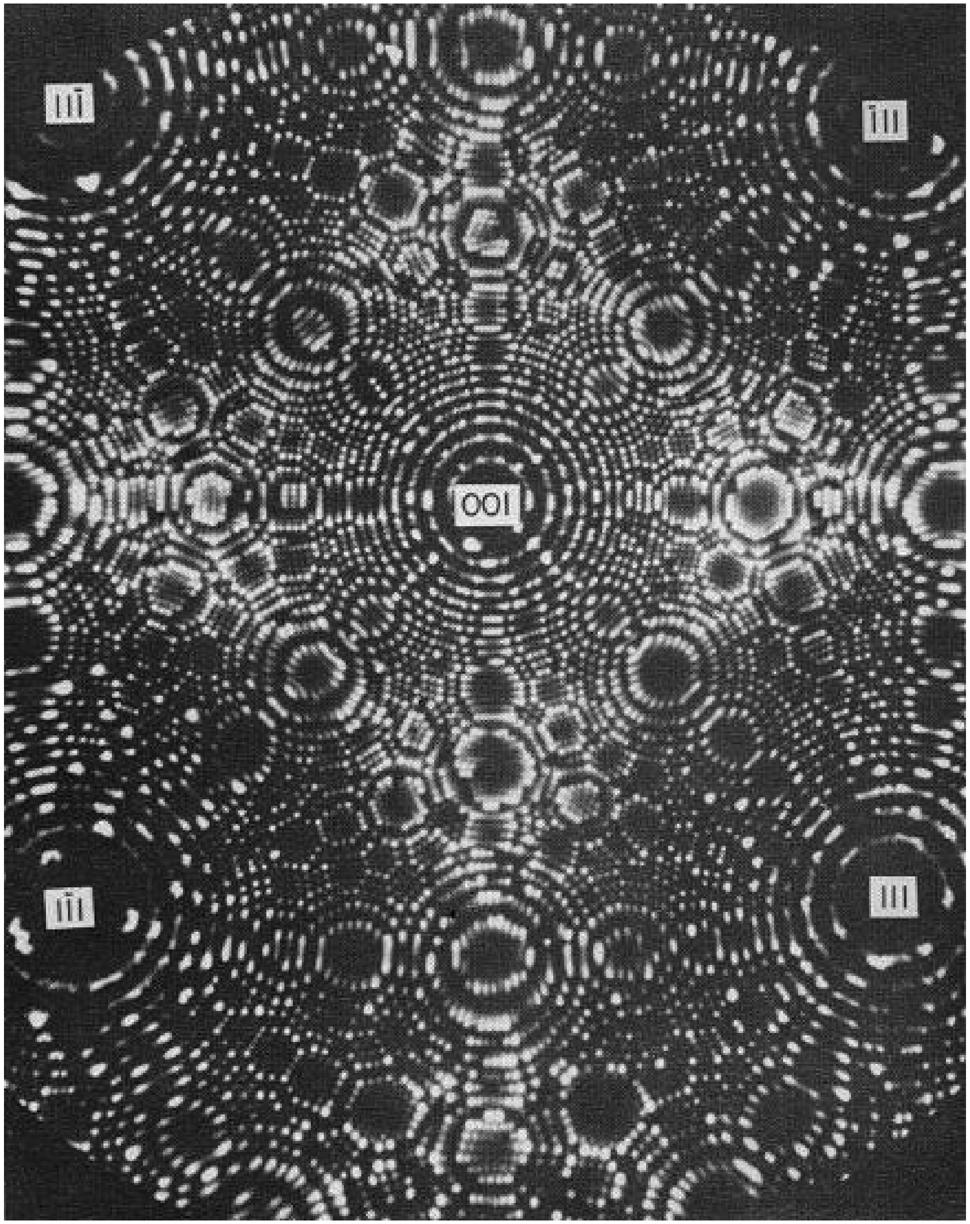
    Field Evaporation

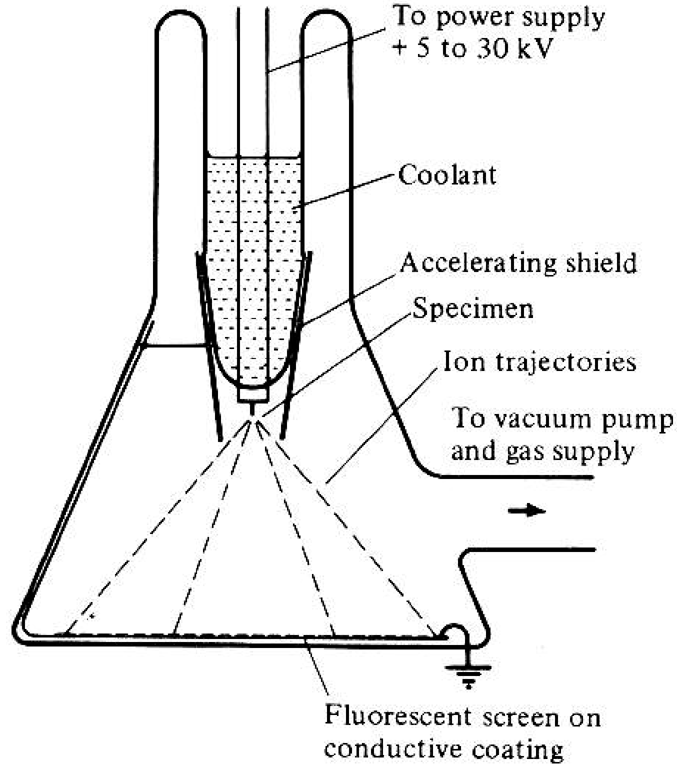
    Surface atoms are ionized and are pulled from surface to phosphor

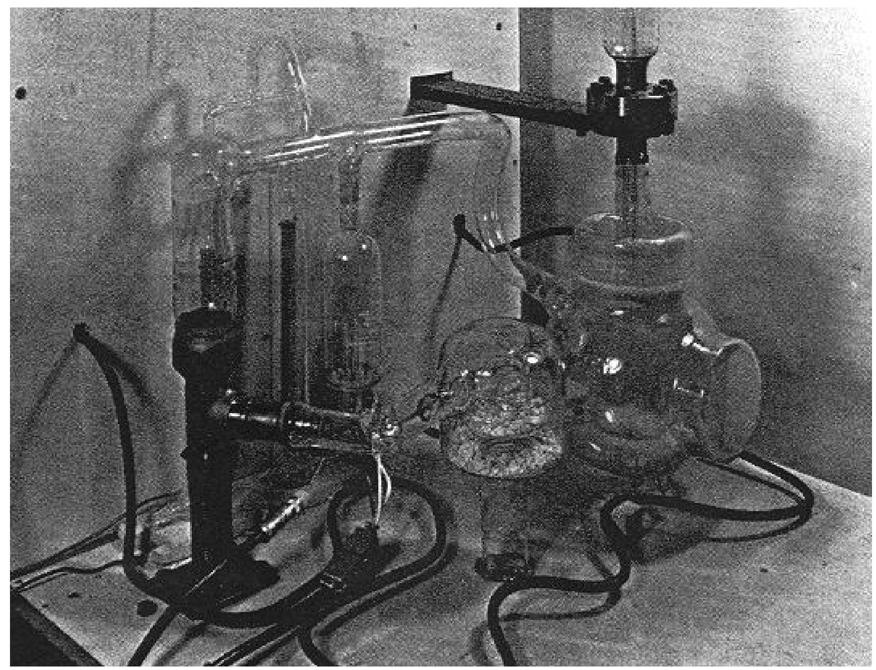
    - Optically similar to FIM
    - Process is misnamed. Tensile stresses on atoms are huge ~ 5,000,000 psi

Field Ion Microscopy and Field Evaporation

- The principle of FIM, and the setups, are simple.

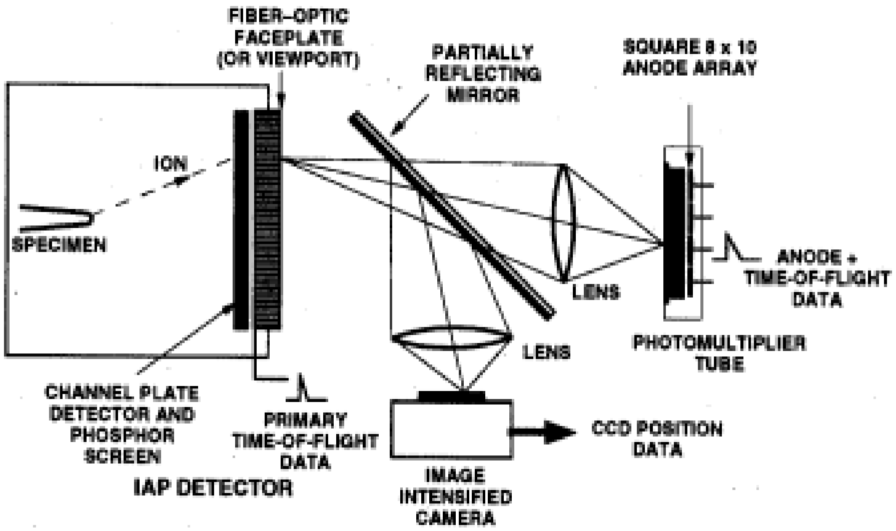


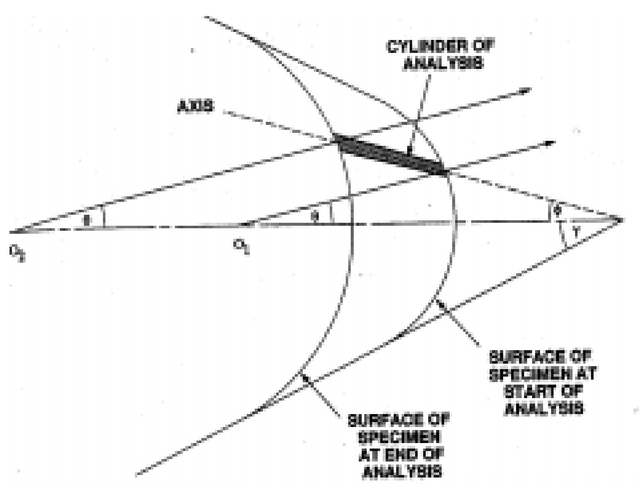




Modern systems measure atomic mass, and position in 3 dimensions.

- Mass is measured by time of flight, with good resolution.
- Position is measured optically.



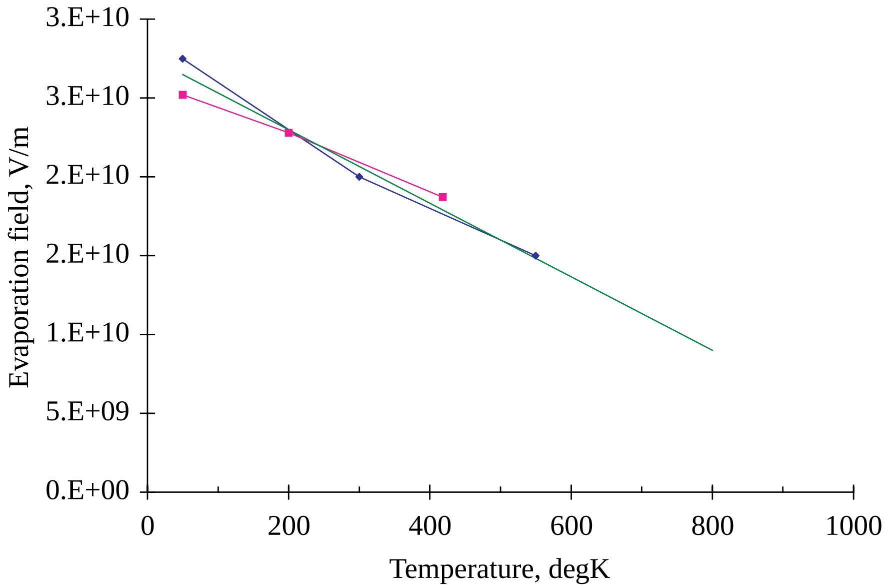


Imago, Madison Wisconsin

Field Evaporation may be responsible for breakup.

- When the electric field is high enough it pulls atoms off the surface.

- The rate of emission is very strongly dependent on electric field and temperature.

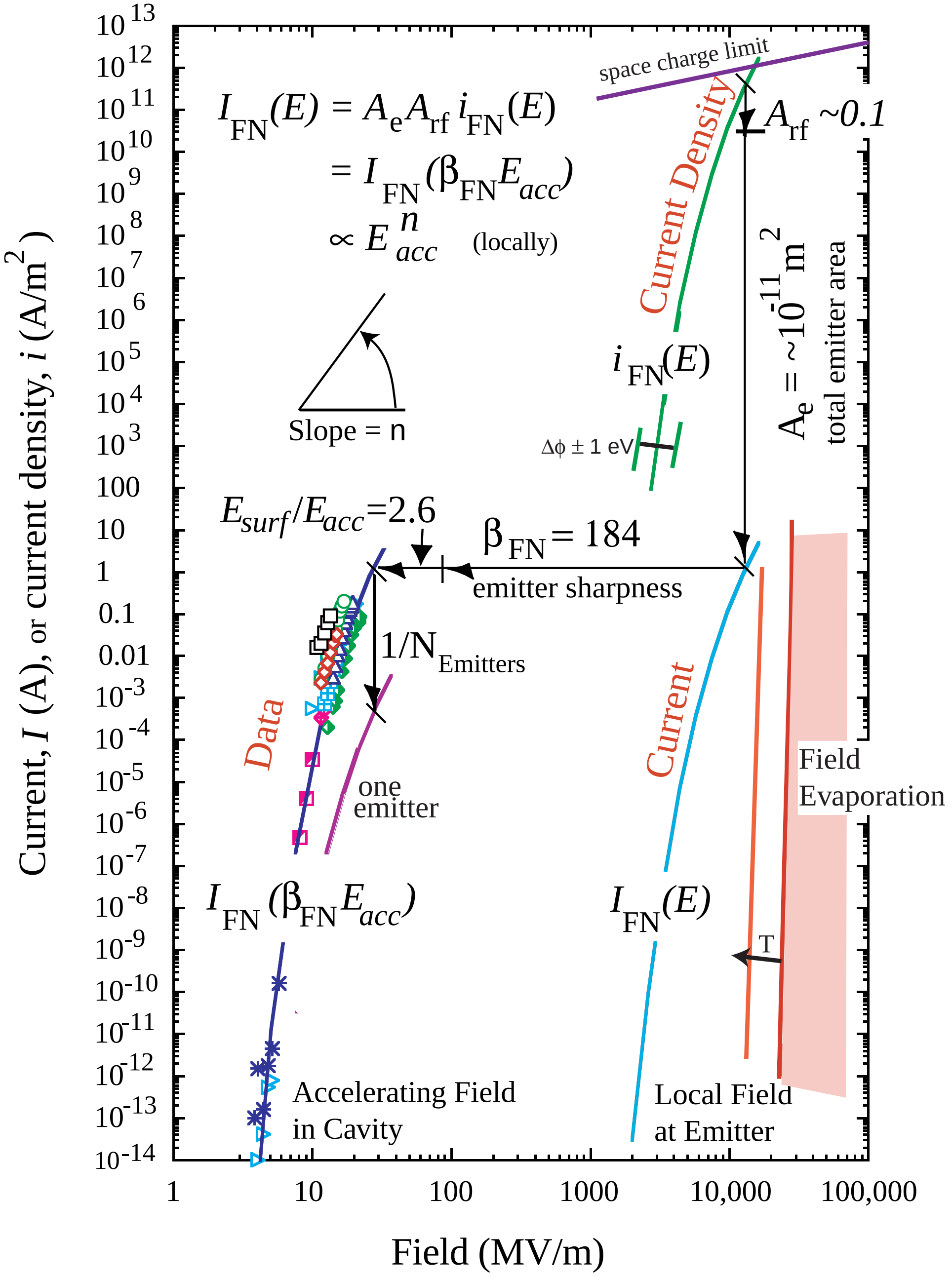


- At 300^0 C the electric tensile stress produced by the evaporation field is comparable to the tensile strength of copper at room temperature. Atomic analog of fracture??

- Field evaporation is easier to model than fracture, and otherwise equivalent.

Field Evaporation has a sharp threshold.

- The threshold is temperature dependent.
- Field emission and field evaporation are somewhat similar.
- Field evaporation goes like ~ E^{100}.



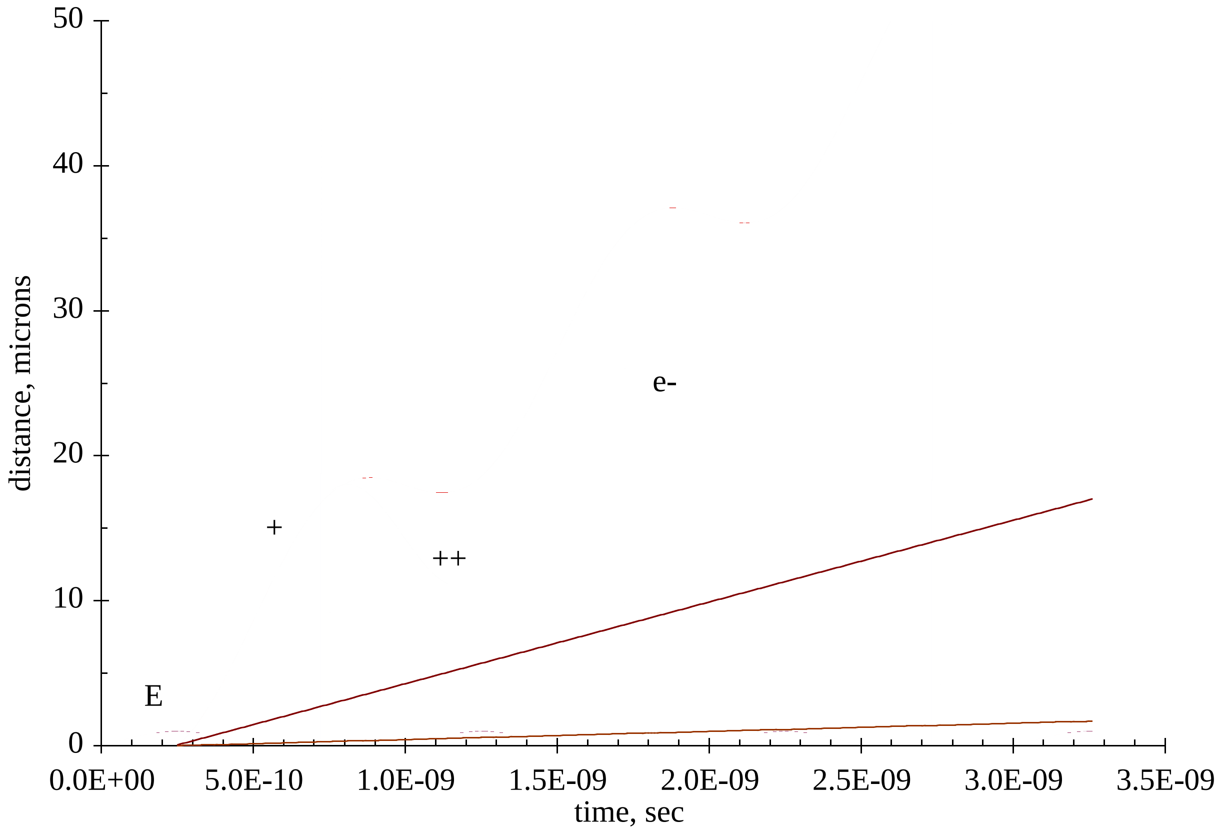
The kinematics of simple ions is complex.

- The kinetic energy from the local field is large.

  $U = Ed = (10^{10}\ \mathrm{V/m})\ (10^{-7}\ \mathrm{m}) = 1000\ \mathrm{V}$

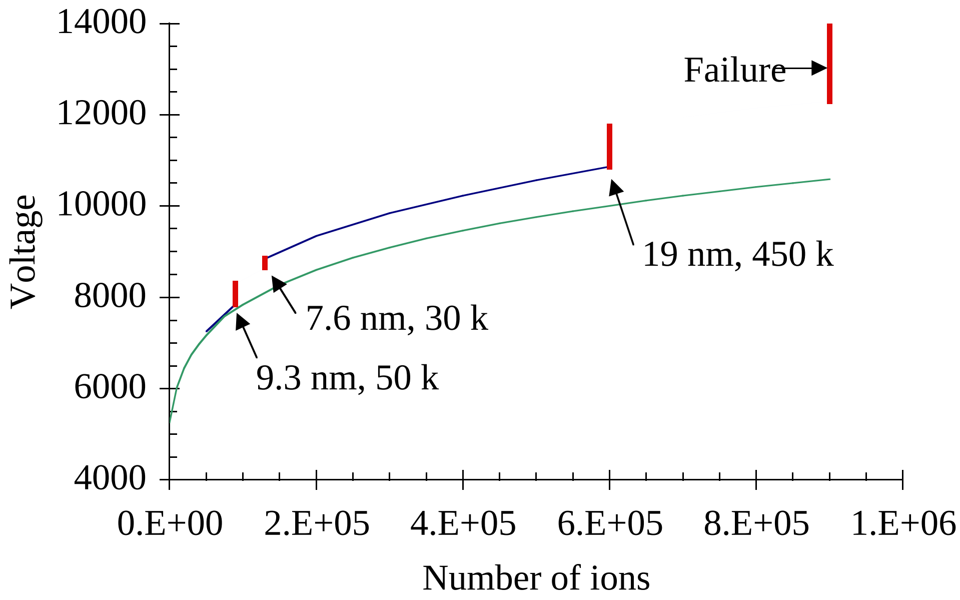
  This gives copper ions velocities of ~20,000 m/s, dominating rf motion.

- These ions may not strongly interact with the field.



We are more interested in abnormal behavior of samples.

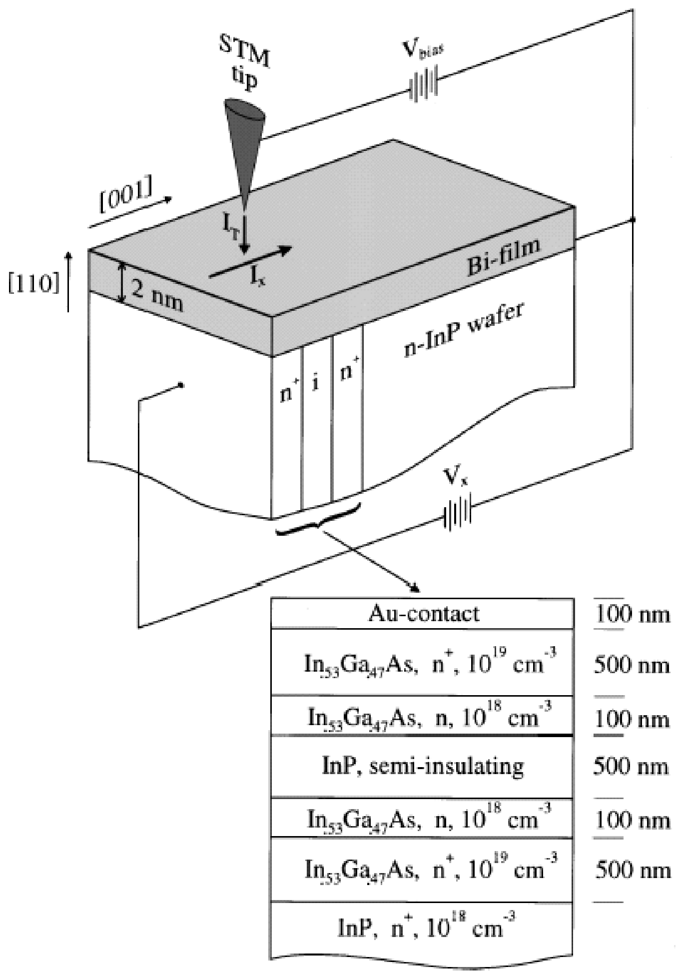
- Field evaporation is generally done slowly and carefully.
- At high gradients samples can come apart in chunks.   There is uninteresting to surface studies, and there is little data on this behavior.



- These are "sample failures". The data is thrown out.

Fields at defects and grain boundaries are high.

- Scanning tunneling potentiometer measurements show huge gradients with currents. This is a defect (actually a hole), at 4 MA/cm^2.
- Grain boundaries are less photogenic.



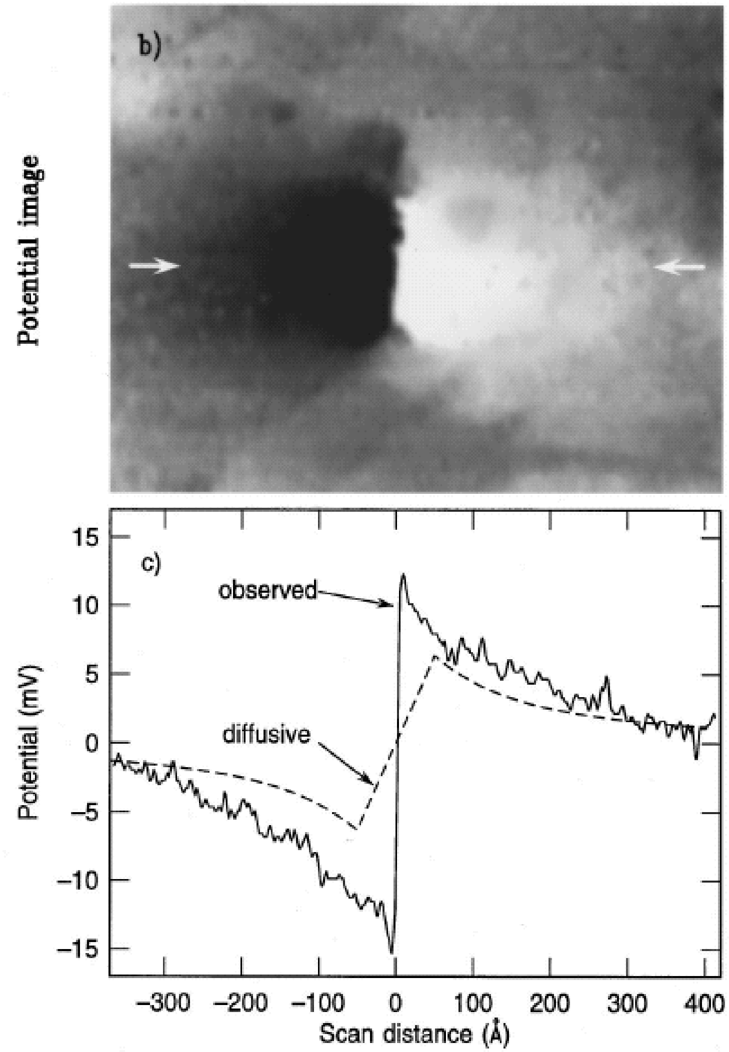


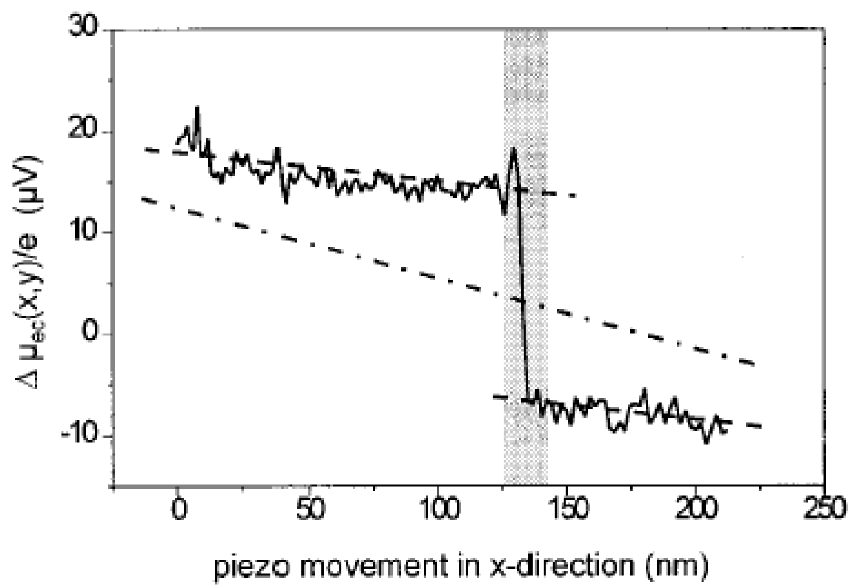
FIG. 5. (a) 640×800 Å^2 area of 30-Å-thick Bi film with a 24-Å-deep hole in the center. Pixel resolution = 3.5 Å. (b) Reduced STP potential after subtraction of a linear background. (c) Cross-sectional cut along the line marked by arrows in Fig. 5(b) (solid line), and computed curve for purely diffusive transport around the deep hole (dashed line). All three figures share the same x-axis calibration.

High currents at grain boundaries are another breakdown trigger.

- SLAC autopsies imply their problems are current related.
- Grain boundaries should have very large Ohmic losses, ~100 times bulk.
  temperatures 100 x the 100^{O}C generated in the bulk?
- Very high fields may also be present, perhaps 1GV/m.

NLC prototype cavity damage

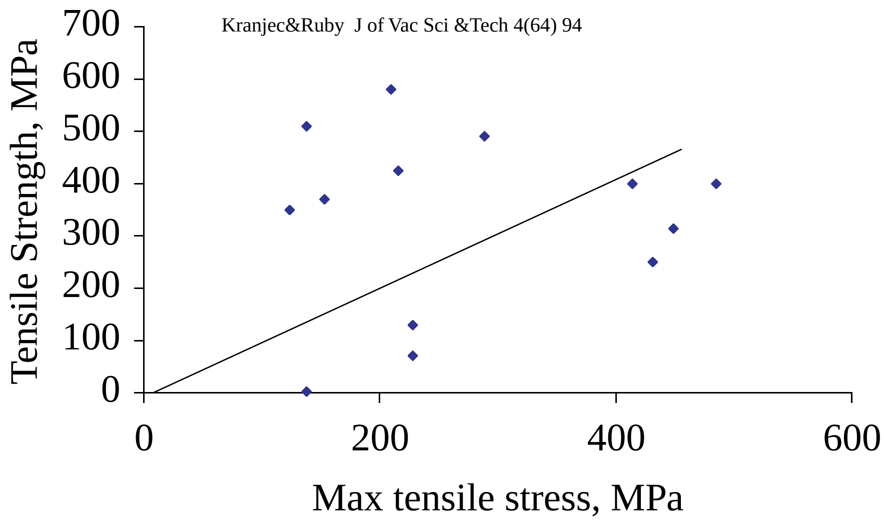
STP measurements of grain boundaries



Au sample, Schneider et al Appl Phys let 69 (96) 1327. 1546

Breakdown does not neatly correlate with tensile stress

- One old data set from a Masters Thesis at Berkeley in 1964 may be relevant.



- ... or it may not.
  - bad vacuum
  - One metal is a liquid at room temp
  - Oxides
  - Cleaning?

- We need better data on this.

Magnetic fields affect breakdown.

- We found that running with solenoidal fields required a new conditioning period.
- After running with field, the cavities required conditioning to run without.
- Torques in solid material can "unscrew" emitters
  F = ***I*** x ***B*** forces apply at the base of emitters
  Forces are strong for high current densities with a few tesla fields.

We saw more breakdown with magnetic fields, more damage in the high field area of the open cell cavity.

- Extrapolation from 1T to 5 T with the MICE cavity in the MTA?

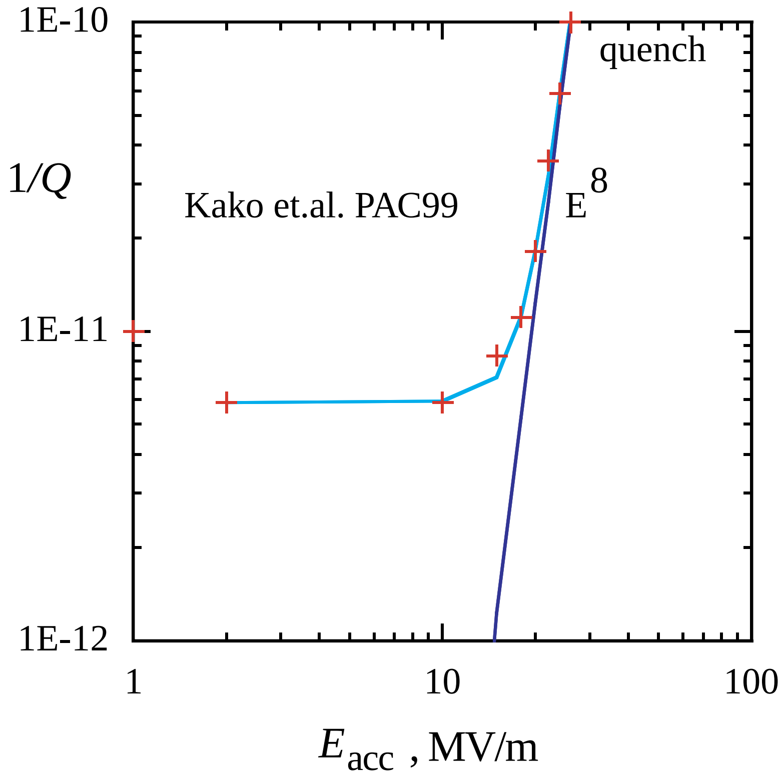
New questions

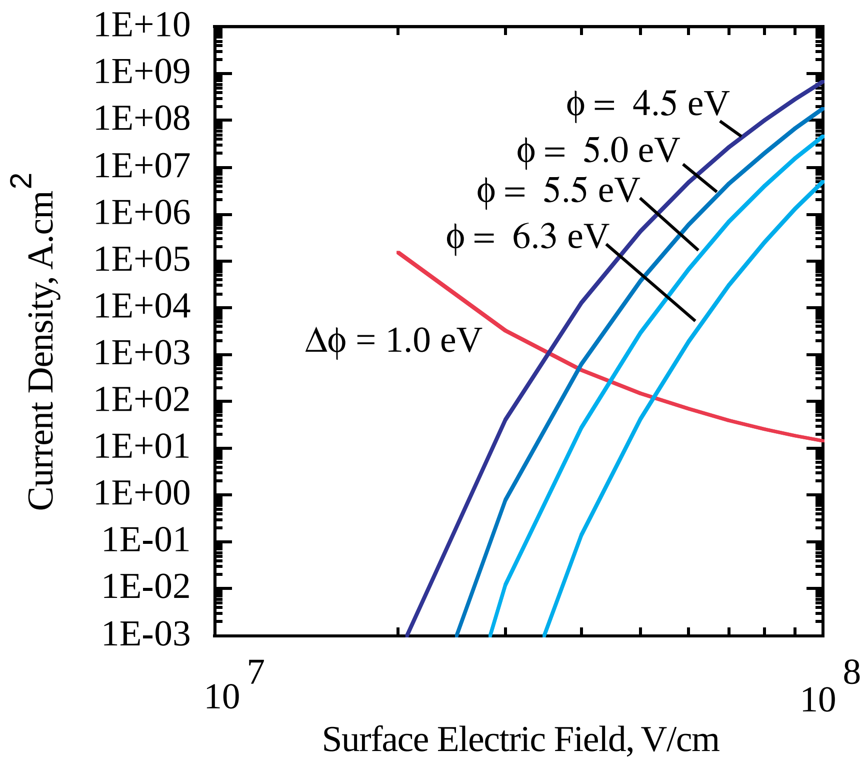
- Are these models useful?
- Can we use them to solve problems?
    - Can SCRF and normal RF cavity field emission be reduced?
    - Can cavities and DC systems be made breakdown-proof?
    - Can new and more efficient conditioning methods be developed?

The answer to all these questions may be **yes**, but more work is required.

Can normal and SCRF field emission be reduced?

- SCRF gradients can be limited by field emission.
- Although niobium and copper both have work functions around 4.5, the use of materials with work functions of up to 5.9 is, in principle, possible.
- A change in work function by 1 eV could reduce the field emitted current by factors of 10^2 - 10^5. This would permit higher surface fields or more conservative operation.



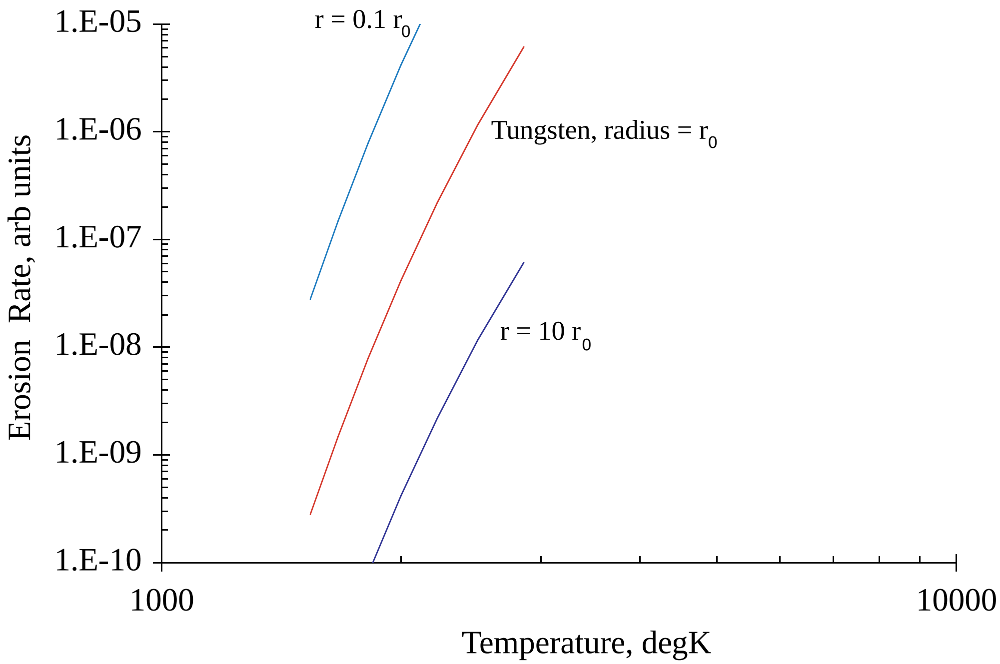


Can improved conditioning methods be developed?

- The long term stability of the surface shape is determined by the balance between surface tension and applied electric field forces. The rate at which the surface can move is determined by the temperature and the radius of the asperities. There is experimental data for tungsten.

- Running in the space charge limited regime should provide the high temperature and low electric field required to produce smoothing.

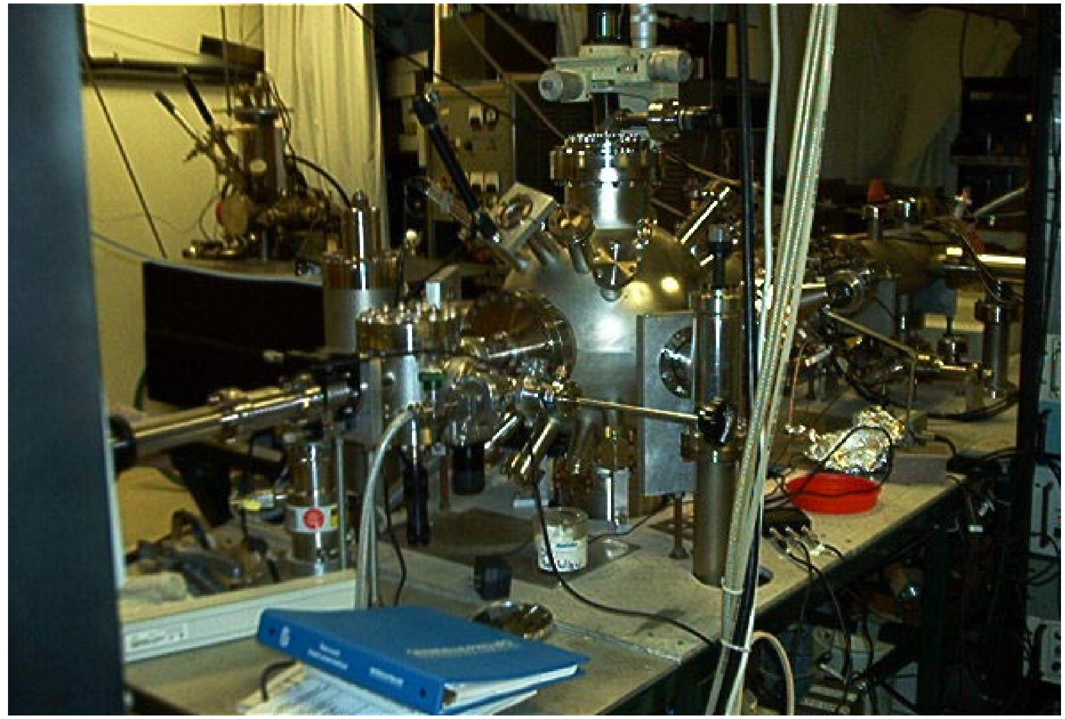
- Once smooth surfaces are achieved, it should be possible to operate with high ϕ and low field emission.



Our Proposal will have four primary elements:

1) Field Ion Microscope studies of materials at high gradients looking at:
   - clusters and fragments
   - alloys
   - gasses
   - coating application
   - work function
   - temperature dependence
   - monolayer coating stability

   to be done at Northwestern



2) Studies of high currents at grain boundaries and defects
   - how defects produce local fields and heating.

3) Simulations of breakdown triggers
   - maintaining contact with problems in Muon cooling and NLC linac technology.

4) Testing in rf cavities

Summary

- Breakdown in cavities seems to be a complex process.

- There is a need for good surface studies to understand how to produce surfaces which can operate with high gradient rf fields.

- Information is needed on
  - Conduction at grain boundaries and defects
  - Field evaporation with realistic surfaces and temperatures particularly clusters and fragments.
  - Different work functions
  - Effects of gas on surfaces
  - Comparisons between different smoothing methods
  - Coating technologies
  - Effects of monolayer coatings

- At the moment we do not know what parameters to optimize.

- This work should have a high priority.

- Funding:
  USDOE/HEP, DARPA, EPRI, NSF, ICAR ?