rf Breakdown and High Gradient Phenomena

J. Norem
Argonne

Workshop on High Gradient rf
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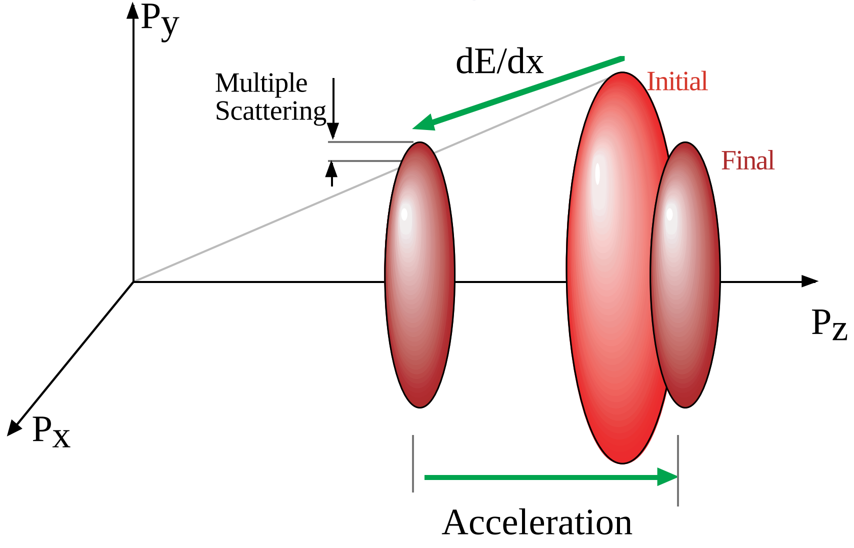
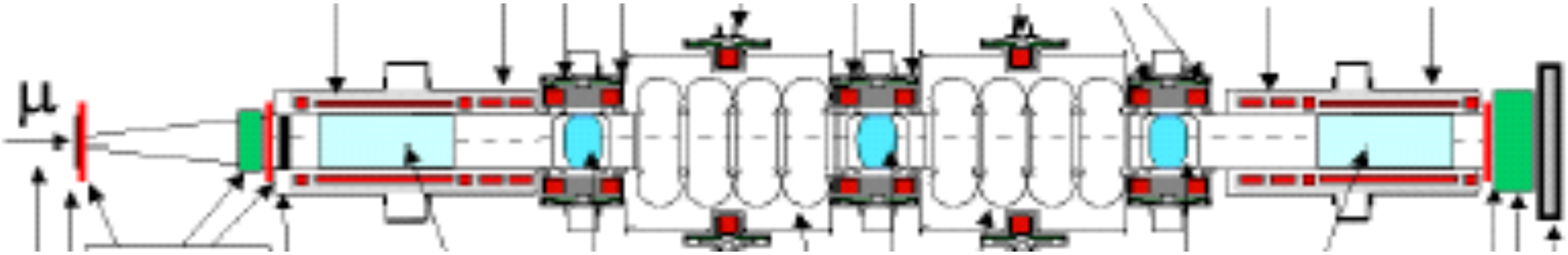
Muon Collaboration

This work is directed at Muon Collaboration problems.

- Cooling muons requires absorbers and rf.


Muon Cooling, in Phase Space

- Our Muon Ionization Cooling Experiment (MICE) cannot tolerate high backgrounds.

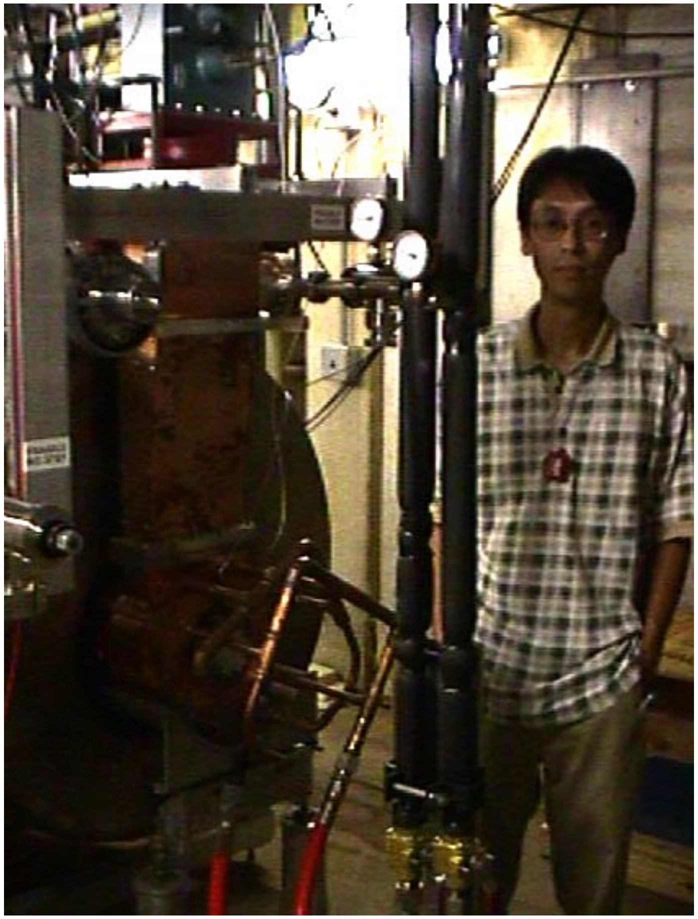


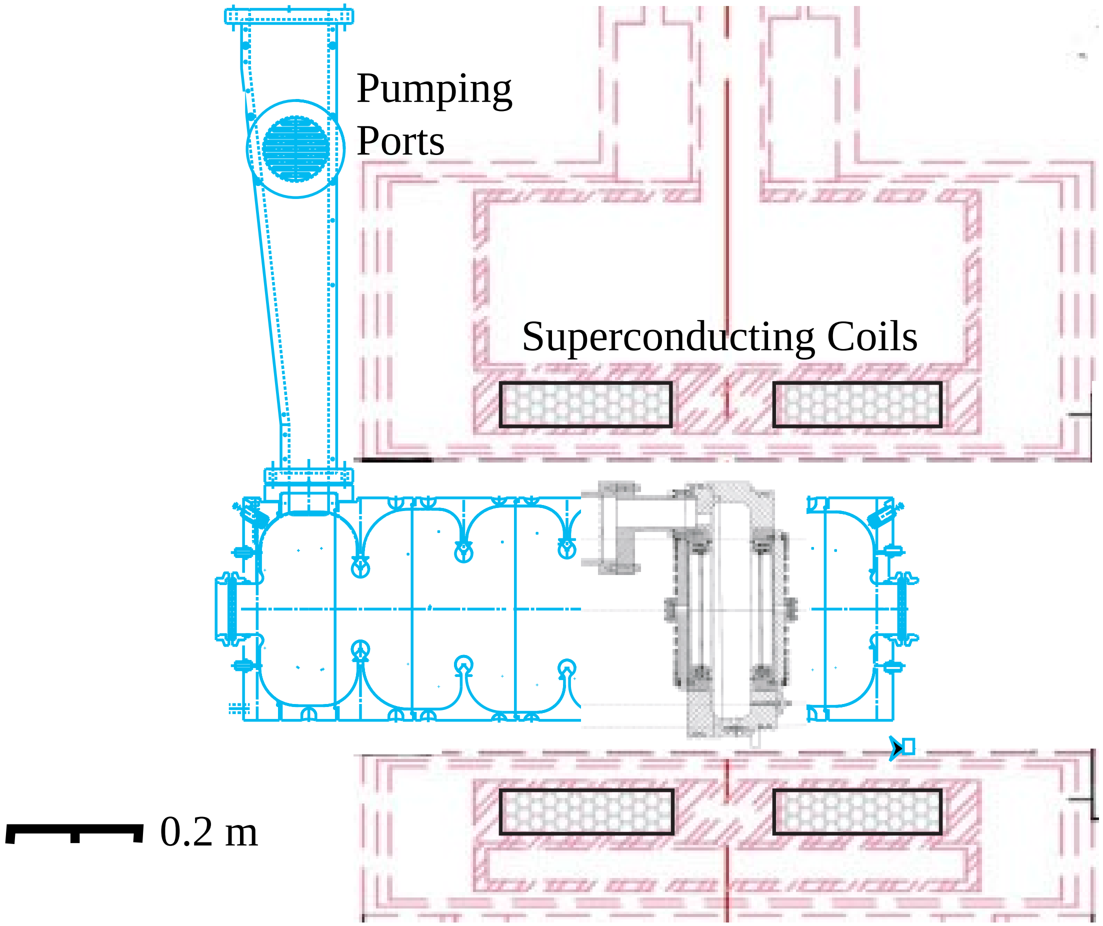
scattering measuring acceleration + absorbers = cooling measuring

Most of the data comes from the 805 MHz systemin 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 rf 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

How does the material 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.

DARK MATTER

- CONFINES THE UNIVERSE

DARK ENERGY

- DETERMINES THE FATE OF THE UNIVERSE

DARK CURRENTS

- DESCRIBE THE FUTURE OF USHEP

Apologies to M. Turner

We have looked at a Number of Issues

- Dark current yields
- Conditioning
- Magnetic field field effects
- Dark current orbits
- X-Ray Radiation levels and flux
- Usefulness of Be surfaces
- Space charge limit
- Multipactoring
- Guidance for Muon Ionization Cooling Experiment on backgrounds

Leading to

- New Models of Breakdown
- Suggestions on improving breakdown and dark current parameters of cavities

Experimental Results in Lab G

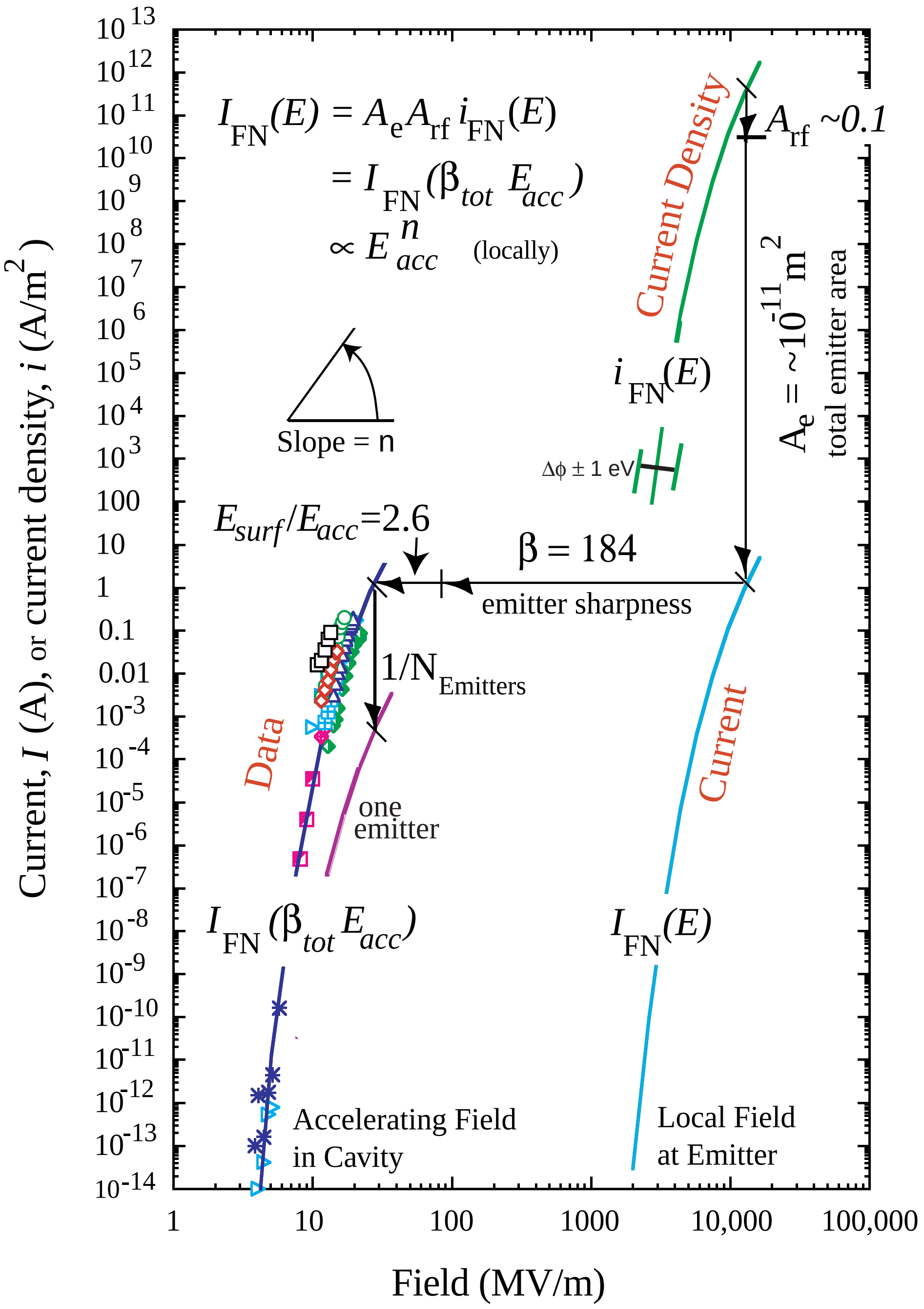
- Stable threshold for breakdown ⇒ Little long term change
- Stable dark current images ⇒ Field emitters change fairly slowly
- Dark current / x rays ⇒ Best signal
- Sharp points in SEM pictures ⇒ Likely to be emitters
- Things moving in SEM ⇒ Surfaces not mechanically stable
- Fast development of breakdown ⇒ Process is fast
- Gas emission under normal operation ⇒ Internal heating
- Similarities to SCRF ⇒ Field emission may be similar
- Magnetic field effects ⇒ B fields may be undesirable
- High dark currents under normal cond. ⇒ Electrons don't do it alone
- I vs E curve for many emitters ⇒ Electric field stress ~ Tensile strength
- Beryllium works well ⇒ Another hard material, (Mo, W, SS)

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

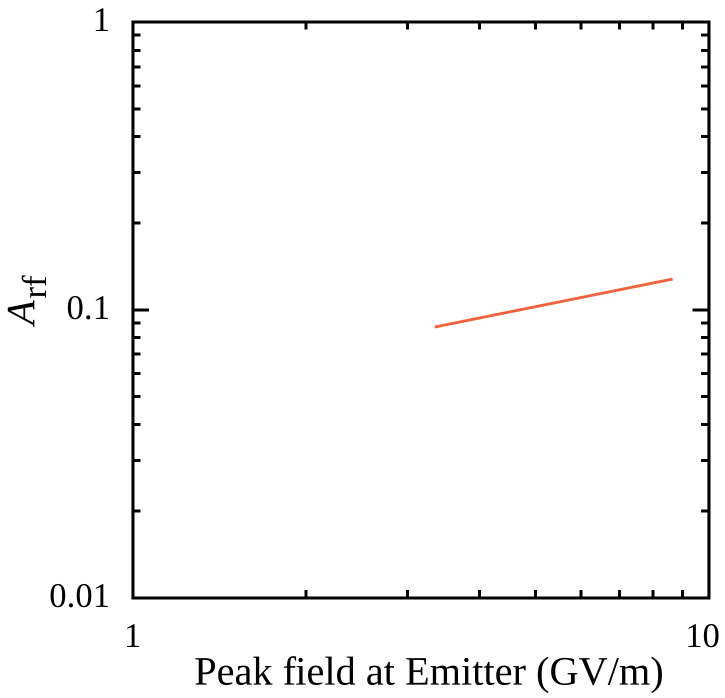


DC / RF Differences

- The only difference between rf and dc field emission seems to be duty cycle.
- Parametrizing $I \sim E^n$ makes numerical integration easy.
- Defining A_{rf} as the ratio between the rf emission and dc field emission

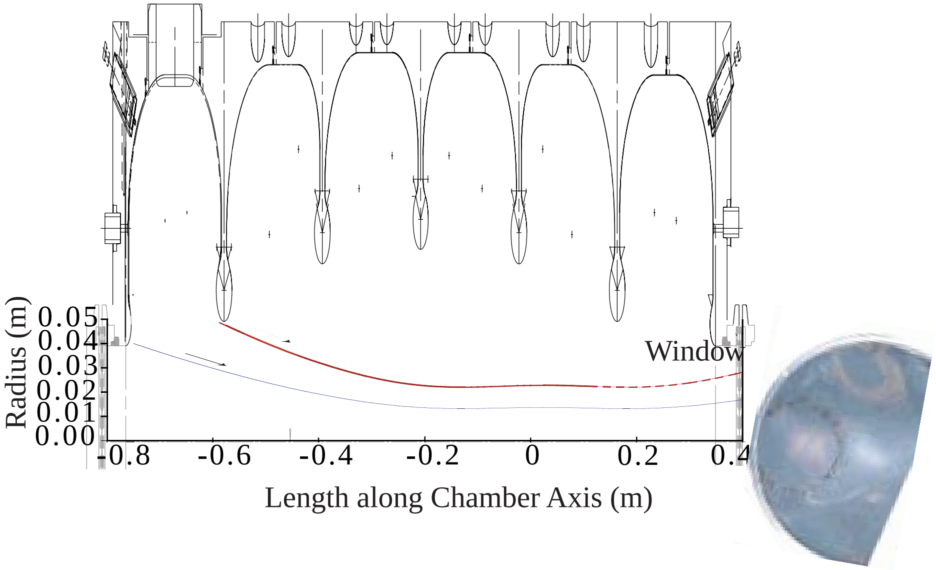
$$A_{rf} = \frac{j_{rf}}{j_{dc}} = \frac{5.7\times10^{-12}\times10^{4.52/\sqrt{\phi}}(\beta E)^{2.5}\exp(-k\phi^{1.5}/\beta E)/\phi^{1.75}}{1.54\times10^{-6}\times10^{4.52/\sqrt{\phi}}(\beta E)^{2}\exp(-k\phi^{1.5}/\beta E)/\phi} = 0.1$$

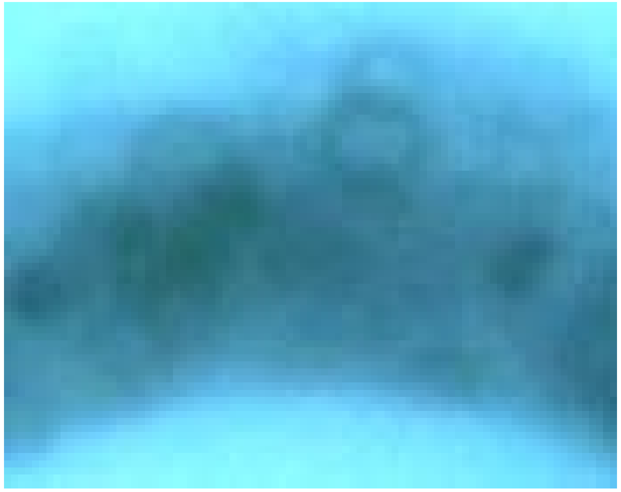
- There is a slight dependence on the field.



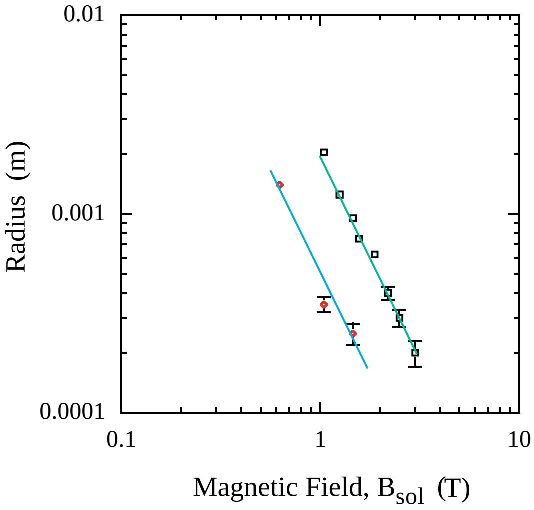
Dark current beams were easily seen in the open cell cavity.

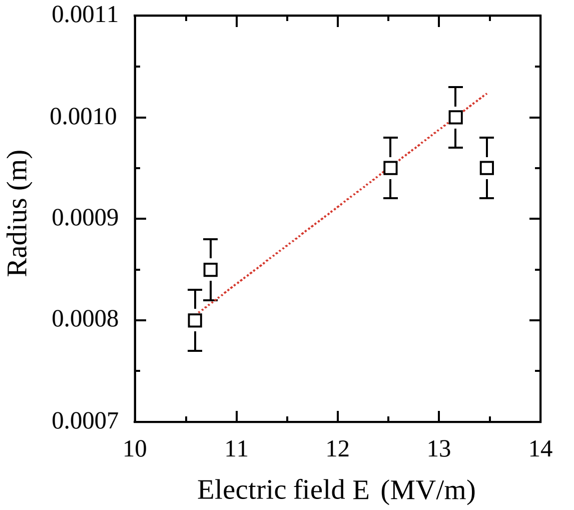
- Because of the magnetic field we could see the individual emitters. We see rings.





- The radius of the rings ~ E/B^2.





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.

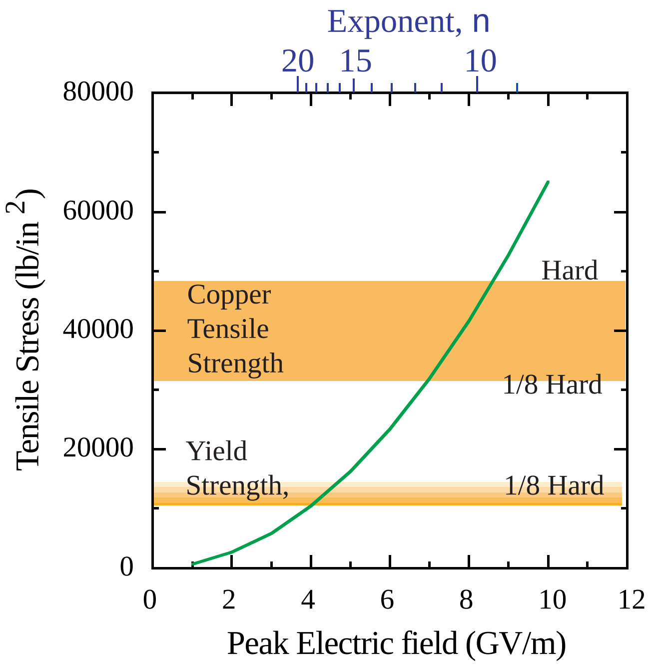
however . .

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

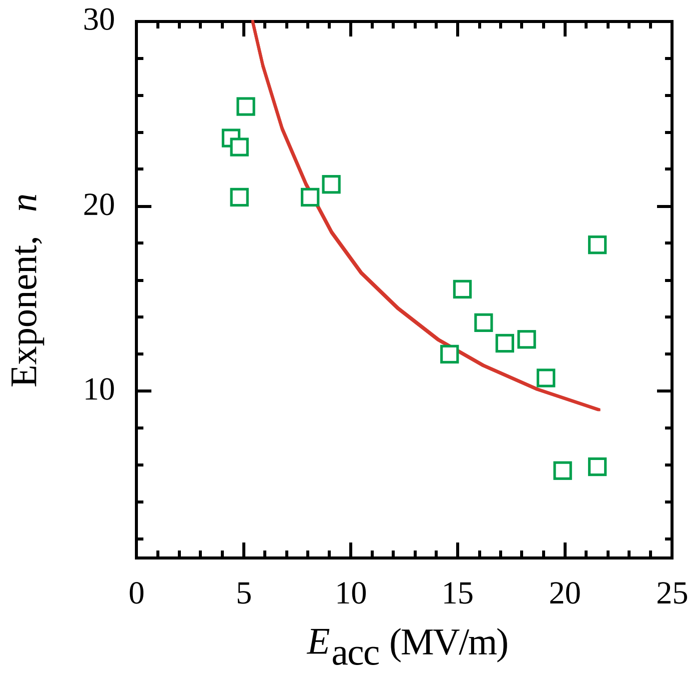
High current densities at grain boundaries and defects is primarily a problem at high frequencies.

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.



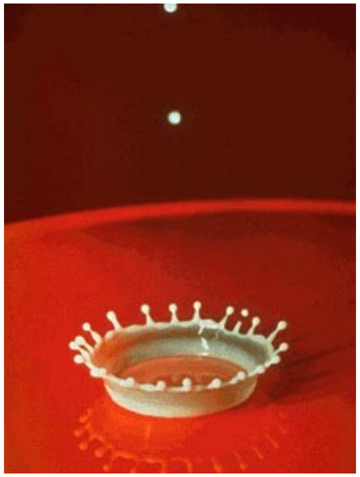
In Lab G



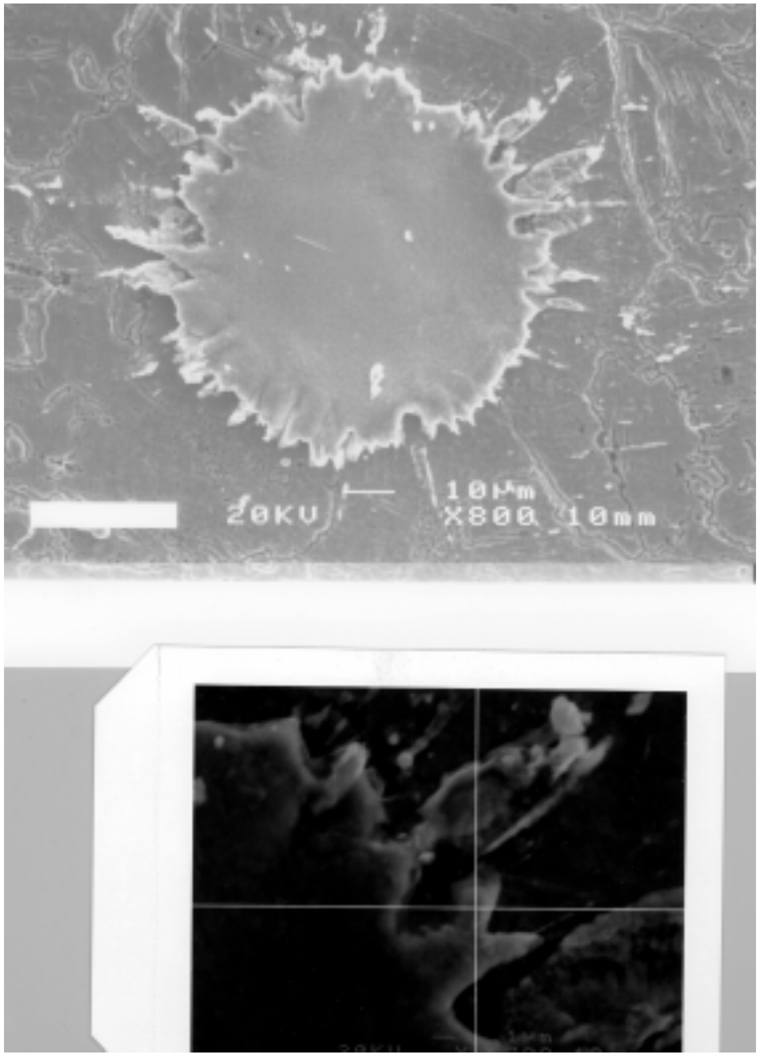
SEM photos show sharp points from splashes, and other effects.

- Splashes look alike.

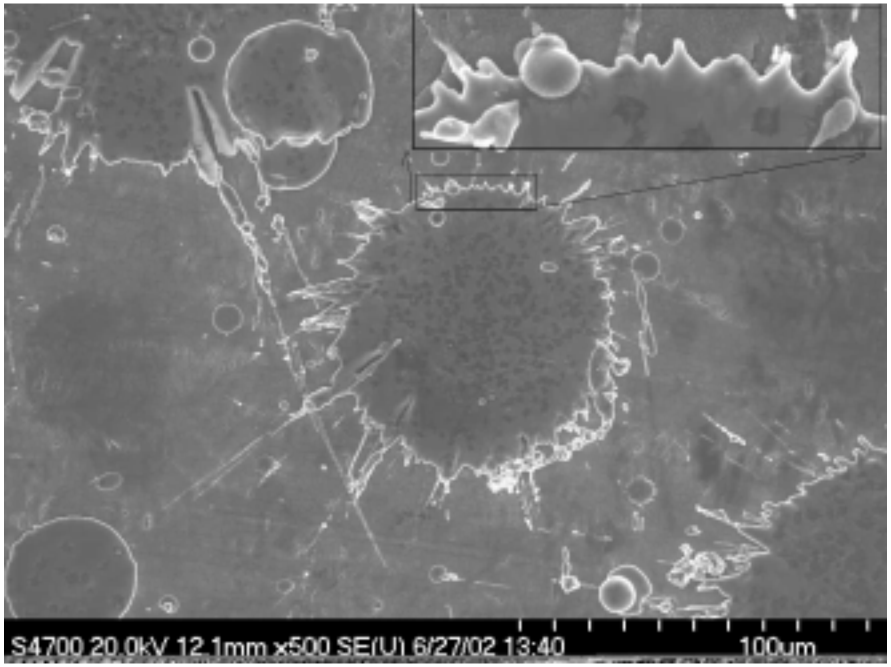
Milk



Pillbox cavity: Cu plate



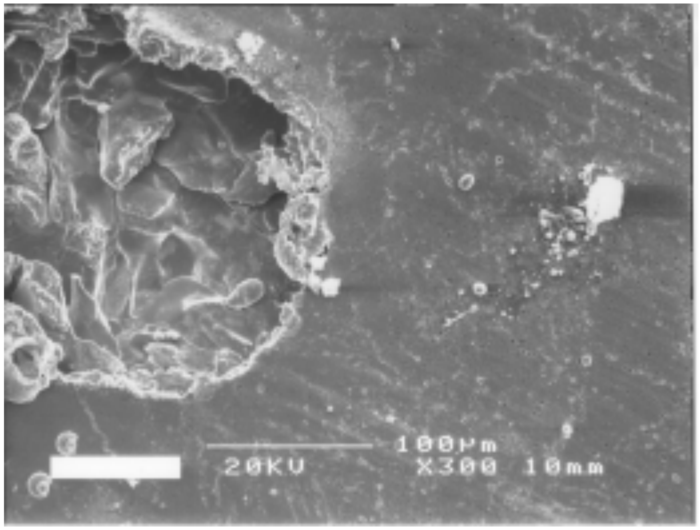
Open Cell cavity: Ti window



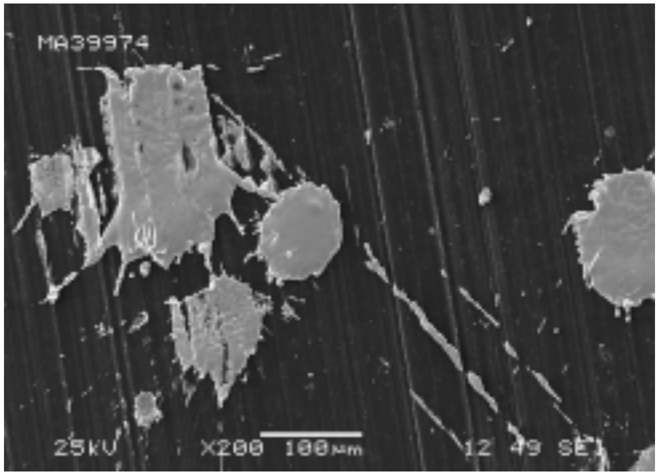
We have used Be windows in an rf cavity

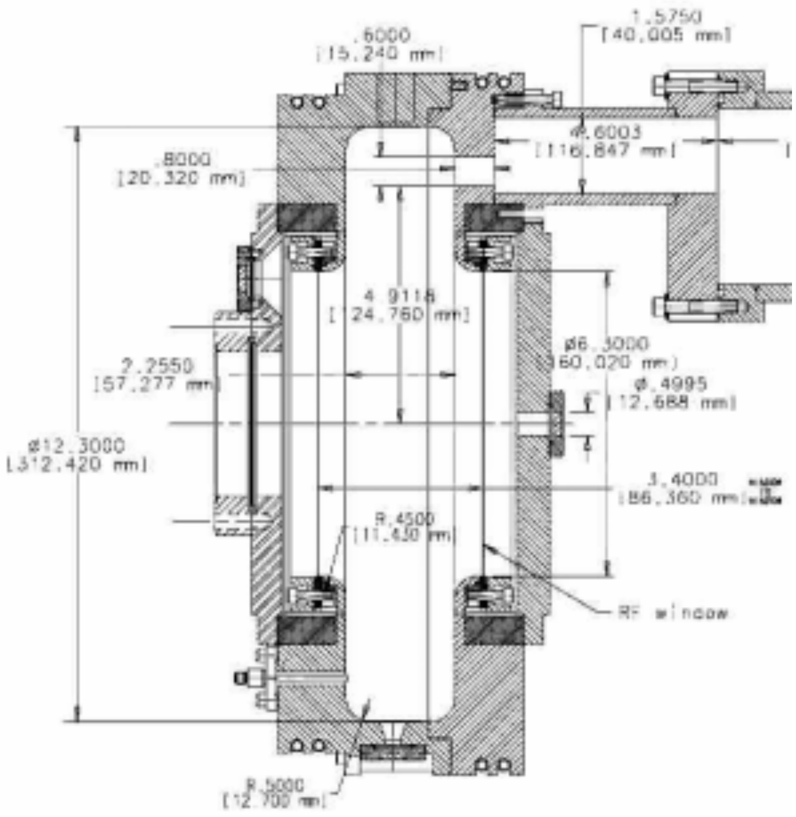
- Although covered in Cu, the Be surface seemed undamaged.

- Copper windows were pitted.



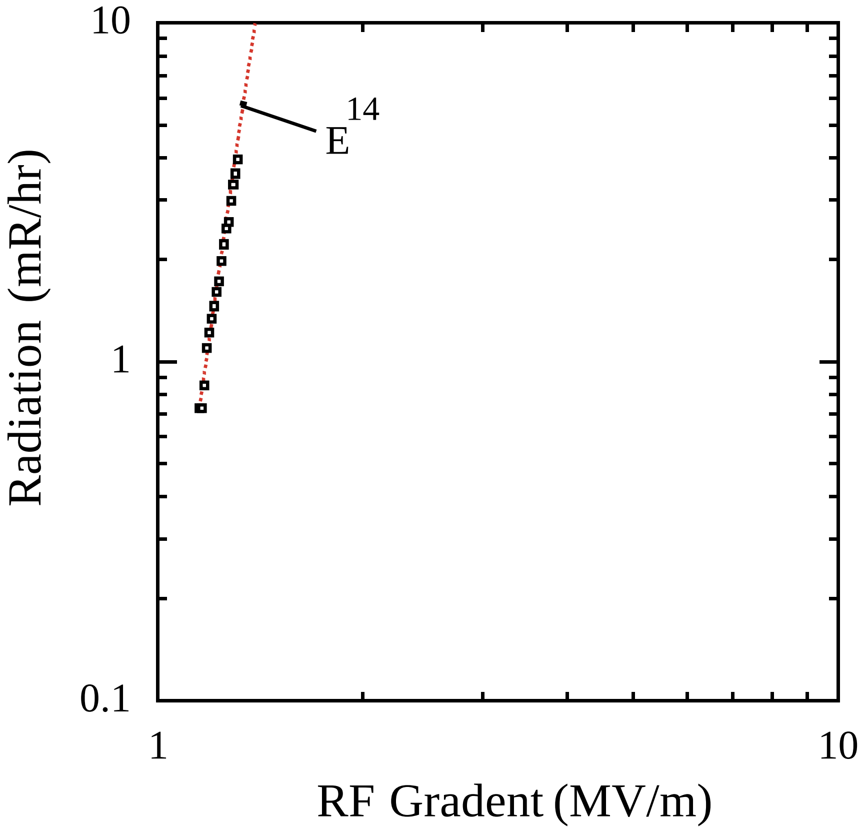
- Cu splashes on the Be window.



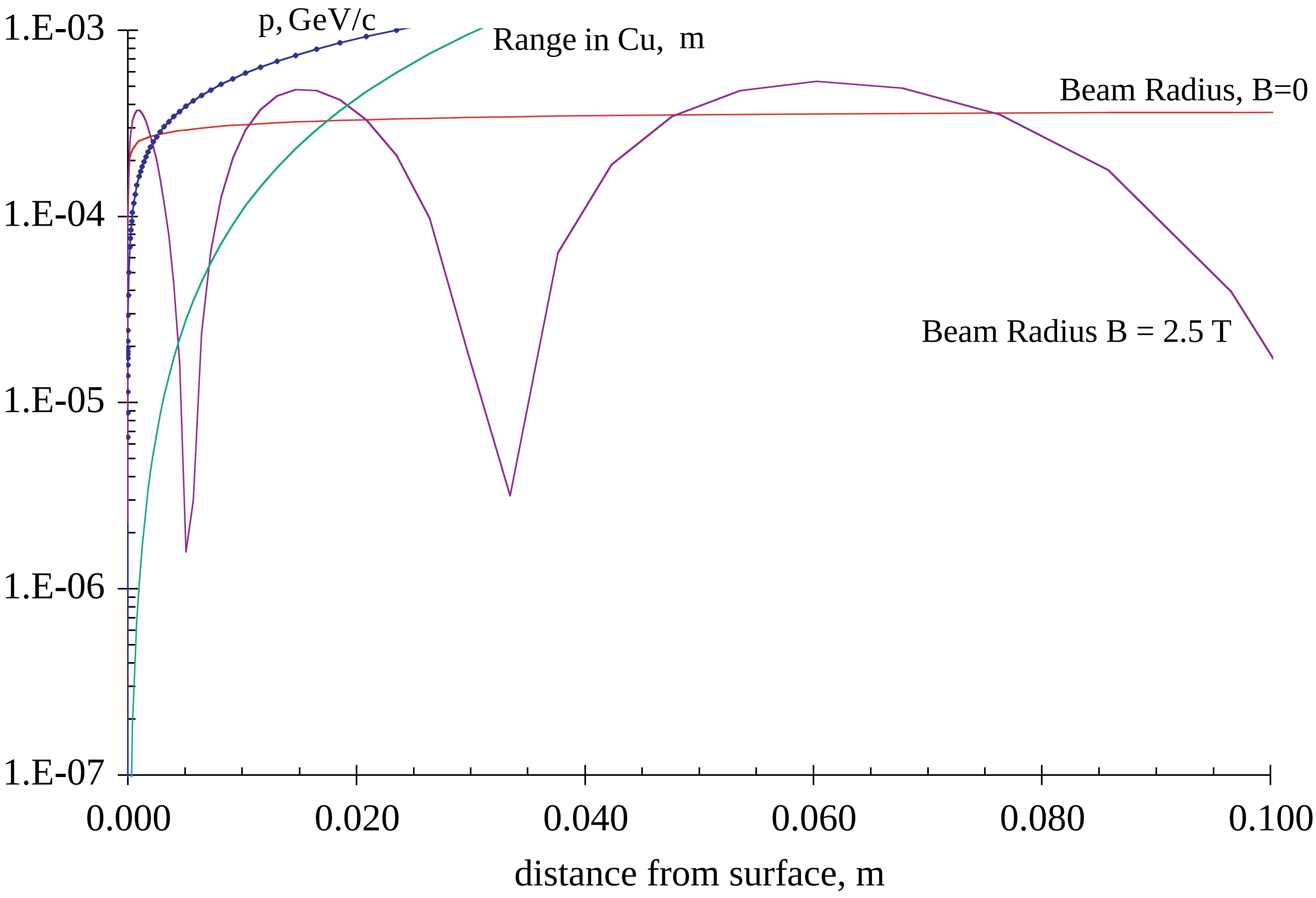


Most linacs operate with lower stresses.

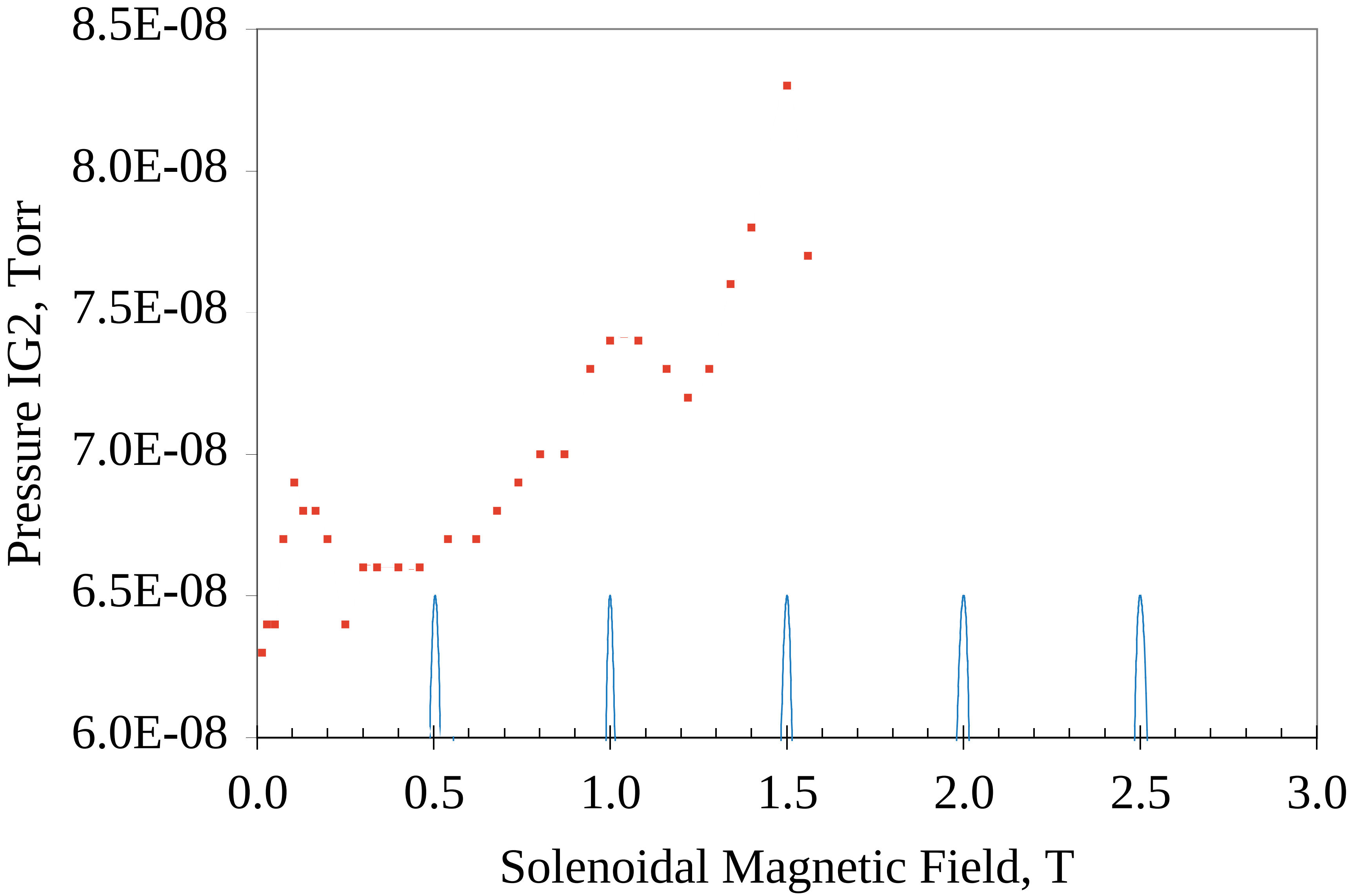
- The 200 MHz IPNS linac operates in a mode where stresses should be about half of the copper tensile strength.
- Sparking is rare.
- This seems typical.



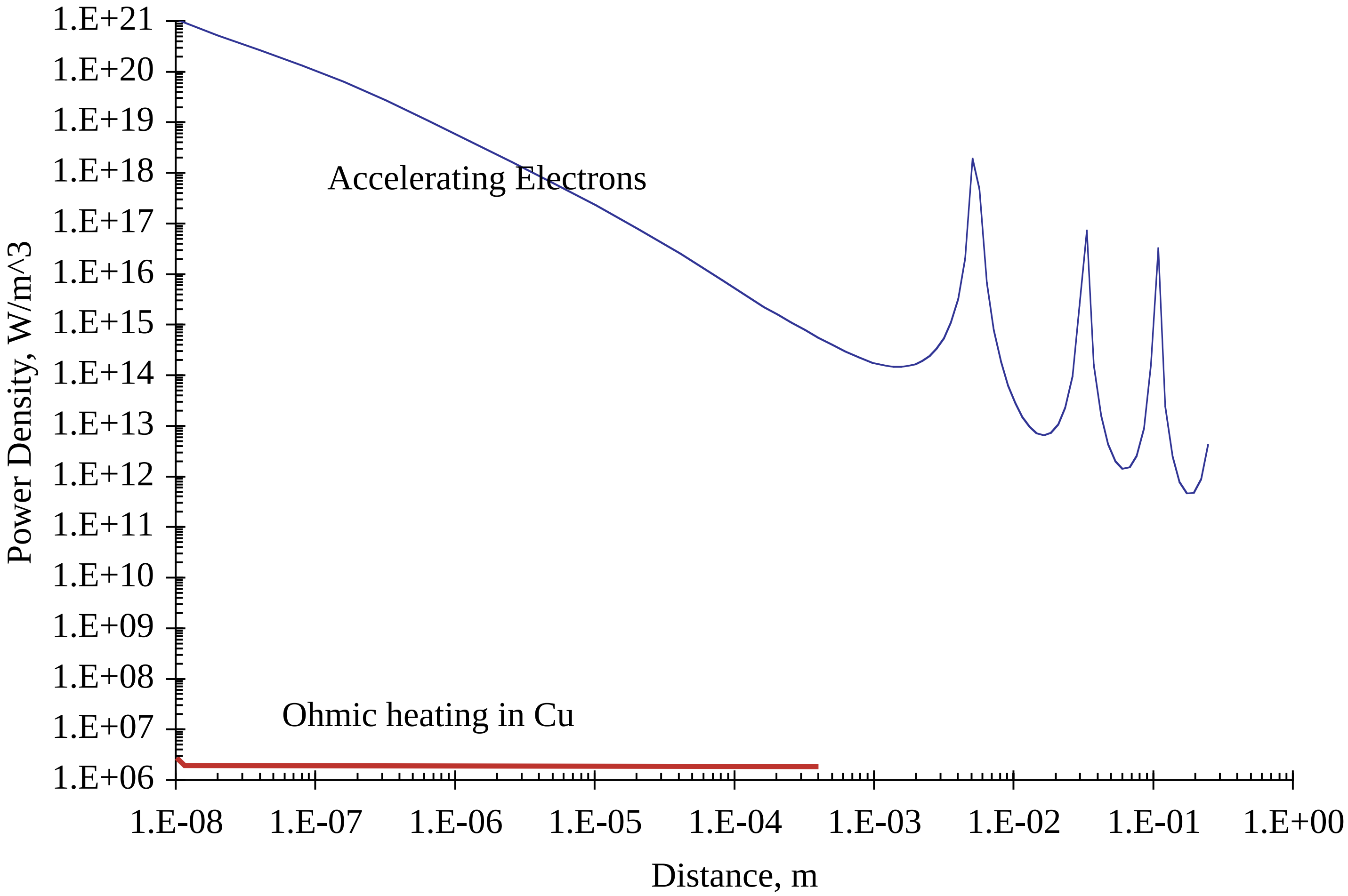
The optics of field emitted beams is complex.



Is the gas pressure related to the solenoidal field?



The power density in the field emitted beam is very high.



High Voltages on sharp probes have been studied in detail.

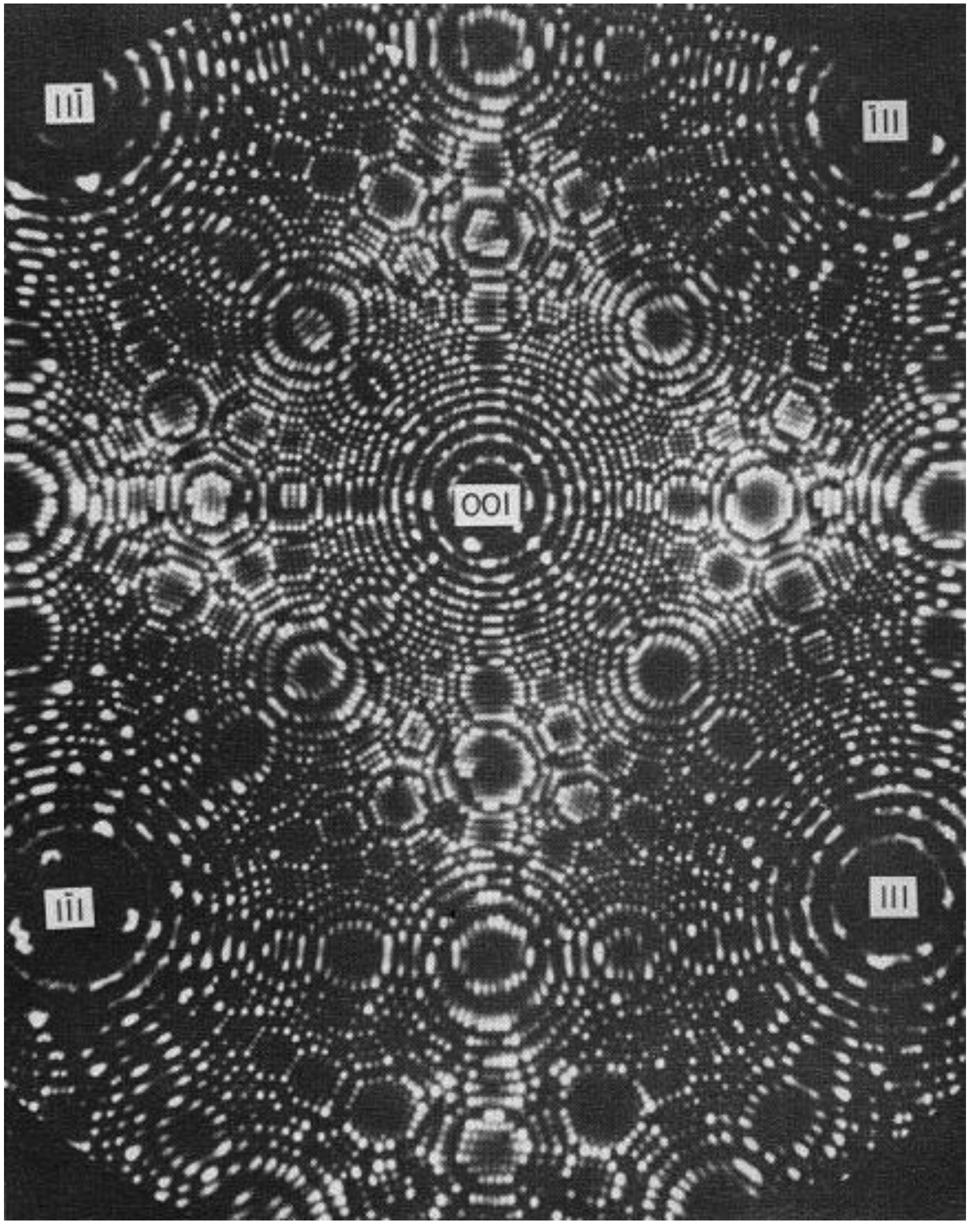
- **Negative voltage**
  - Field Emission Microscope
    - Electrons tunnel thru potential barrier and impact on phosphor
    - Probe radius *r* = 0.1 - 1 micron
    - Resolution limited by diffraction and electron wavelength effects ~ 0.002 μ.
    - Magnification = R/r ~ 1,000,000+

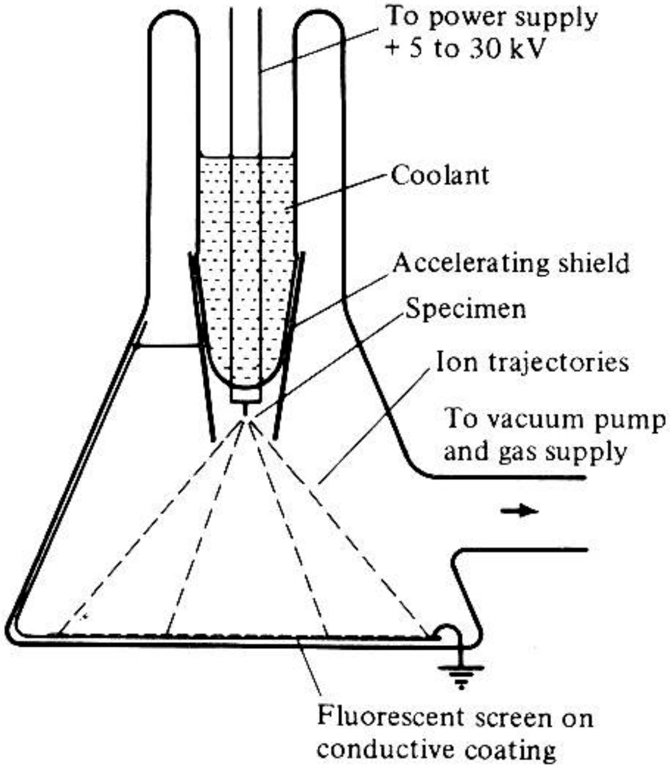
- **Positive Voltage**
  - Field Ion Microscope (FIM)
    - Gas is Ionized at surface and accelerated to phosphor screen
    - probe radius *r* = 0.01 0.1 microns
    - Resolution ~ 0.0002 μ
    - Gas pressure ~ 10^{-3} torr
    - Magnification of R/r ~ 1,000,000+

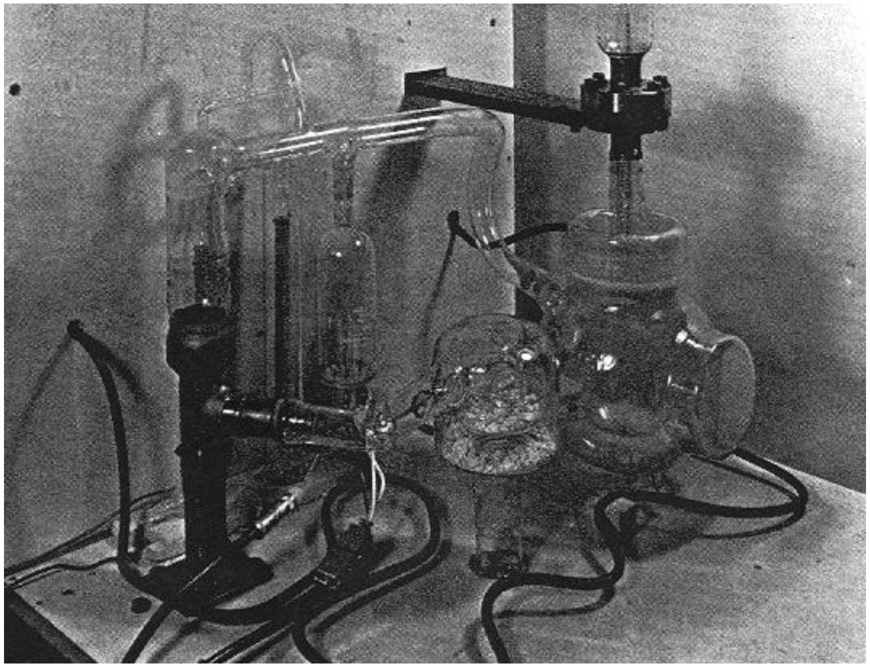
  - Field Evaporation
    - Surface atoms are ionized and are pulled from surface to phosphor
    - Optically similar to FIM
    - Process is misnamed. Tensile stresses on atoms are huge ~ 5,000,000 psi

Field Ion Microscopy and Field Evaporation

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



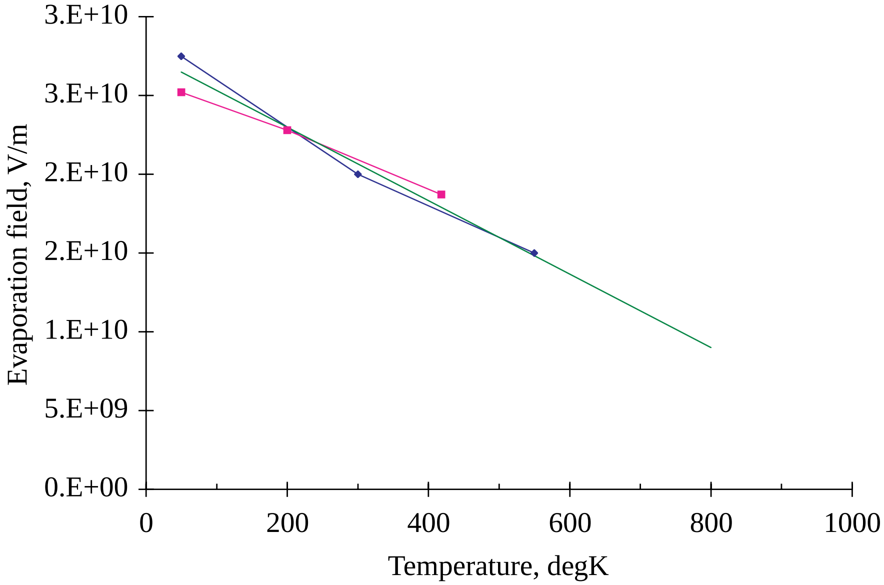




Field Evaporation may be responsible for breakup.

- 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.



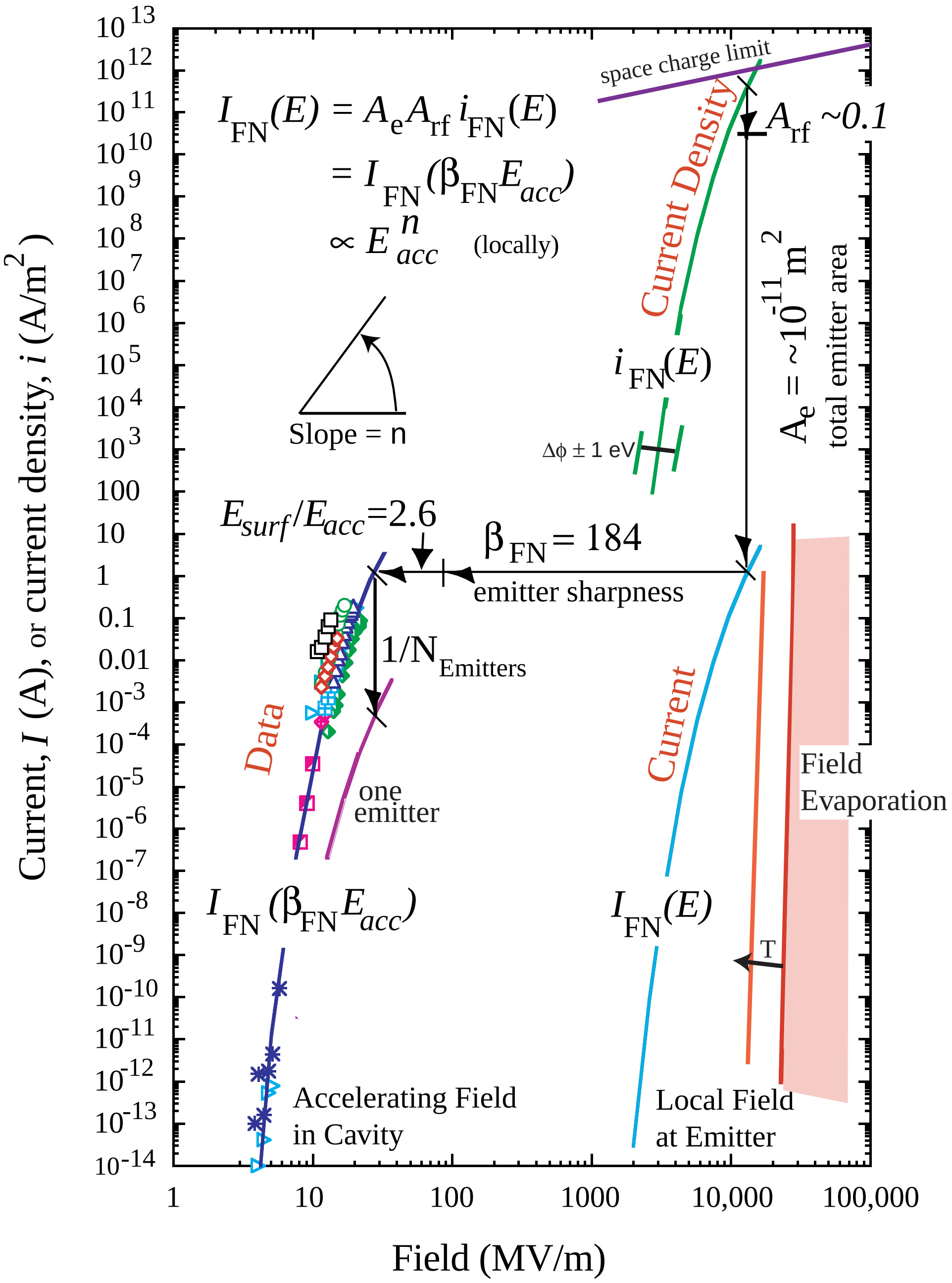
- Field evaporation rates rise rapidly with electric field.

- 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}.

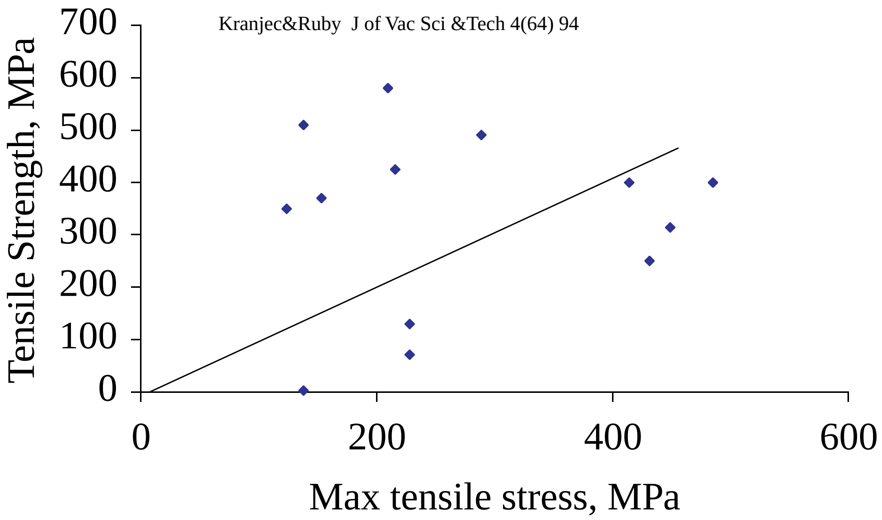


How metals bond to oxygen may be important.

Metal	MP, K	BP, K	delG/O @ 298K+
Readily reduced by H2 at RT, sorted by ease of reduction			
Au	1338	3130	oxide unstable
Pd	1825	3237	oxide unstable
Rh	2236	3970	oxide unstable
Pt	2045	4100	oxide unstable
Ir	2716	4701	oxide unstable
Os	3300	5285	oxide unstable
Ag	1234	2436	-2.697
Ru	2523	4423	-30.197
Cu	1358	2836	-30.570
Bi	545	1837	-39.317
Pb	600	2023	-45.157
Re	3453	5869	-46.747
Sb	904	1860	-49.921
Ni	1726	3187	-50.573
Co	1768	3201	-51.198
Fe	1809	3135	-60.080
Sn	505	2876	-62.146
Ge	1210	3107	-62.302
Not readily reduced by H2 at RT sorted by MP			
W	3680	5828	-63.803
Ta	3287	5731	-91.351
Mo	2890	4912	-63.702
Nb	2740	5017	-88.490
Hf	2500	4876	-126.817
V	2175	3682	-96.606
Cr	2130	2945	-84.366
Zr	2125	4682	-124.620
Ti	1943	3562	-114.243
Be	1560	2745	-138.559
Mn	1517	2335	-86.738
In	430	2346	-66.179
Ga	303	2478	-79.540

Breakdown does not neatly correlate with tensile stress

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

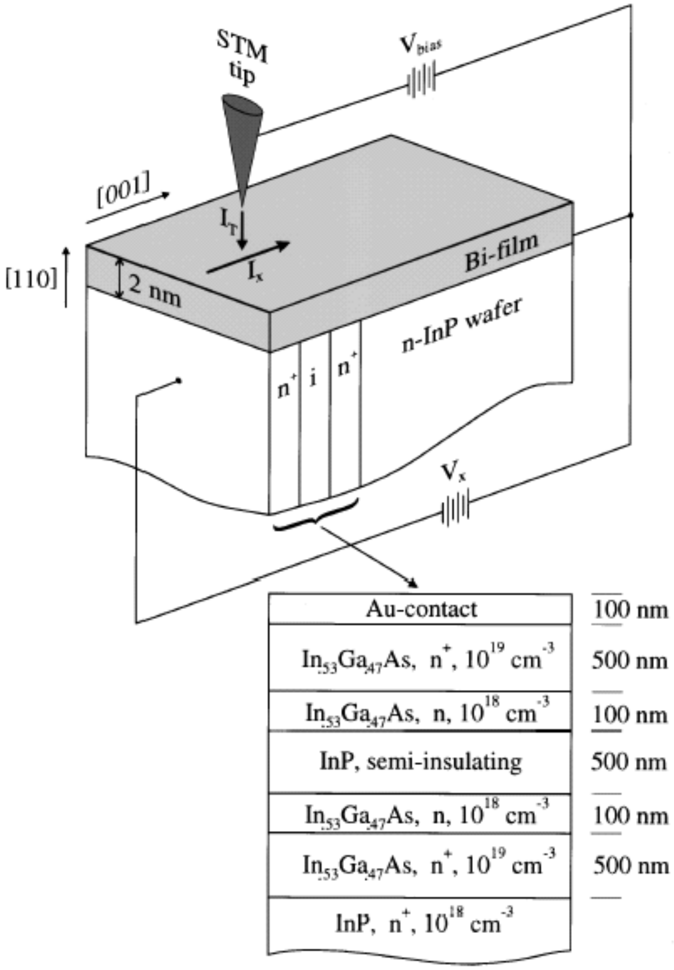


- ... or it may not.
  - bad vacuum
  - One metal is a liquid at room temp
  - Oxides
  - Cleaning?

- We need better data on this.

Fields at defects and grain boundaries are high.

- Scanning tunneling potentiometer measurements show huge gradients with currents. This is a defect (actually a hole).
- Grain boundaries are less photogenic.



Au-contact	100 nm
$In_{.53}Ga_{.47}As$, n^+, 10^{19} cm^{-3}	500 nm
$In_{.53}Ga_{.47}As$, n, 10^{18} cm^{-3}	100 nm
InP, semi-insulating	500 nm
$In_{.53}Ga_{.47}As$, n, 10^{18} cm^{-3}	100 nm
$In_{.53}Ga_{.47}As$, n^+, 10^{19} cm^{-3}	500 nm
InP, n^+, 10^{18} cm^{-3}	

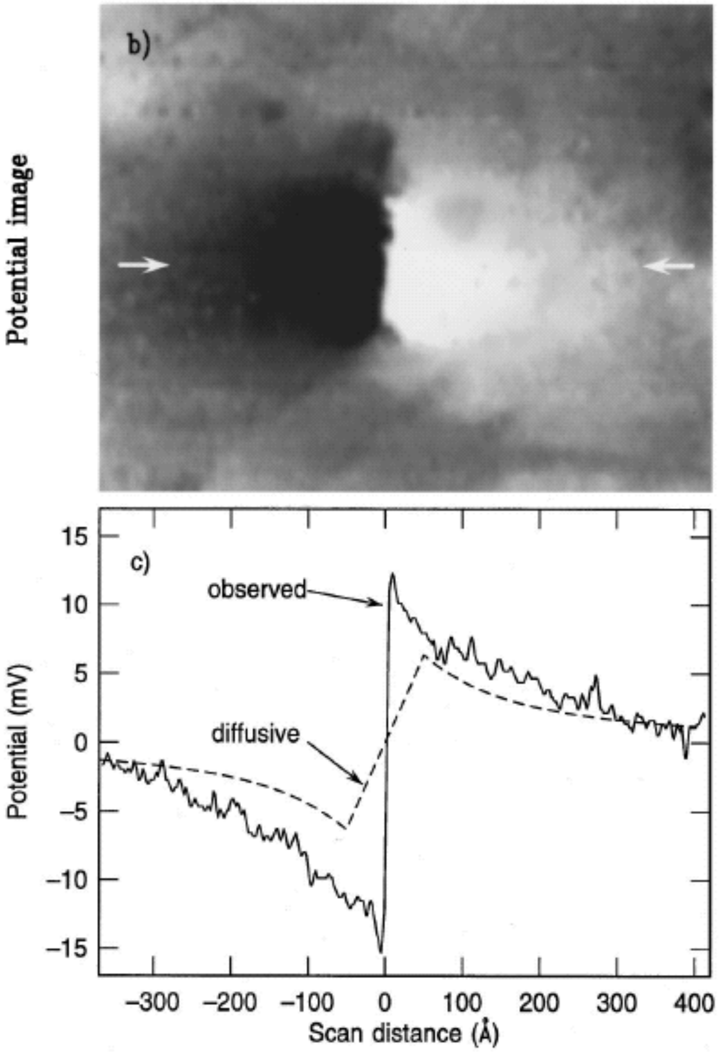
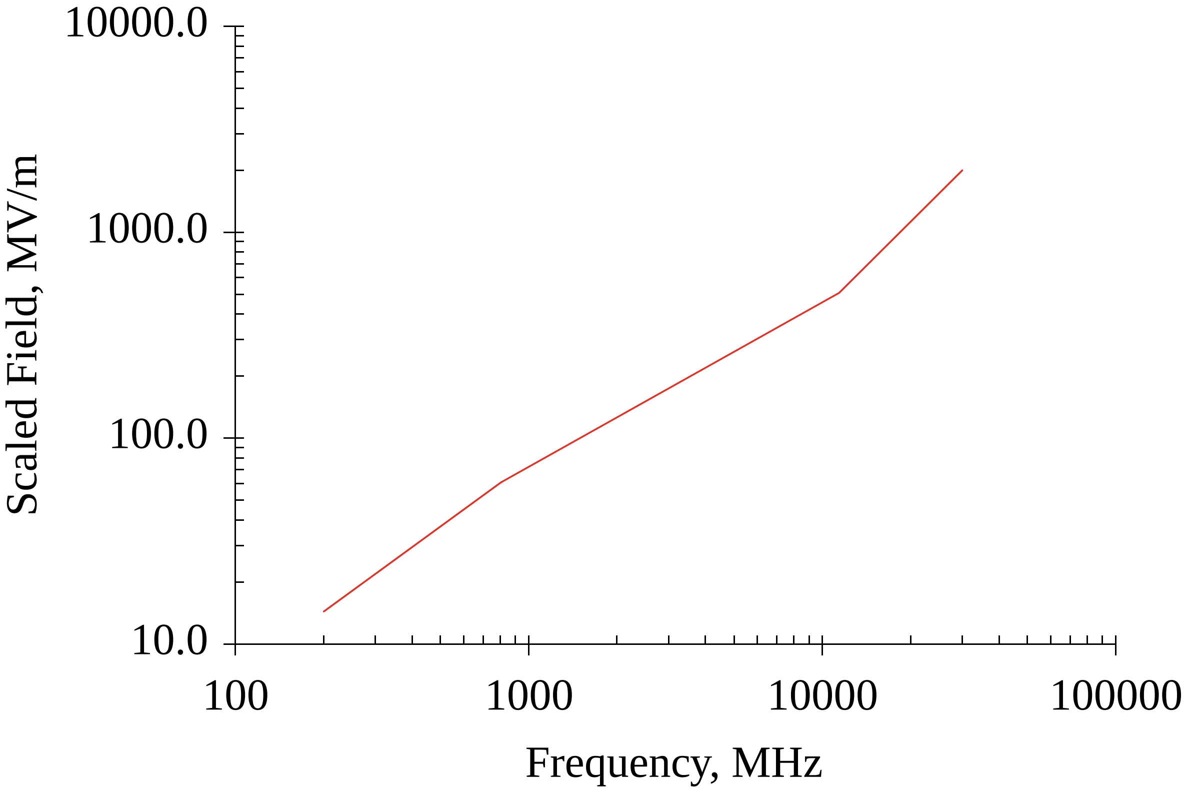


FIG. 5. (a) 640×800 Å^2 area of 30-Å-thick Bi film with a 24-Å-deep hole in the center. Pixel resolution = 3.5 Å. (b) Reduced STP potential after subtraction of a linear background. (c) Cross-sectional cut along the line marked by arrows in Fig. 5(b) (solid line), and computed curve for purely diffusive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

Current density effects increase with frequency

- Effects due to current density are not significant at low frequencies
- Grain boundary and defect effects are presumed to be proportional to current density.
- The effects in the previous page scale approximately like *f*.
- Grain boundaries seem to produce smaller fields.



Magnetic Fields Affect Breakdown

- We found that running with solenoidal fields required a new conditioning period.

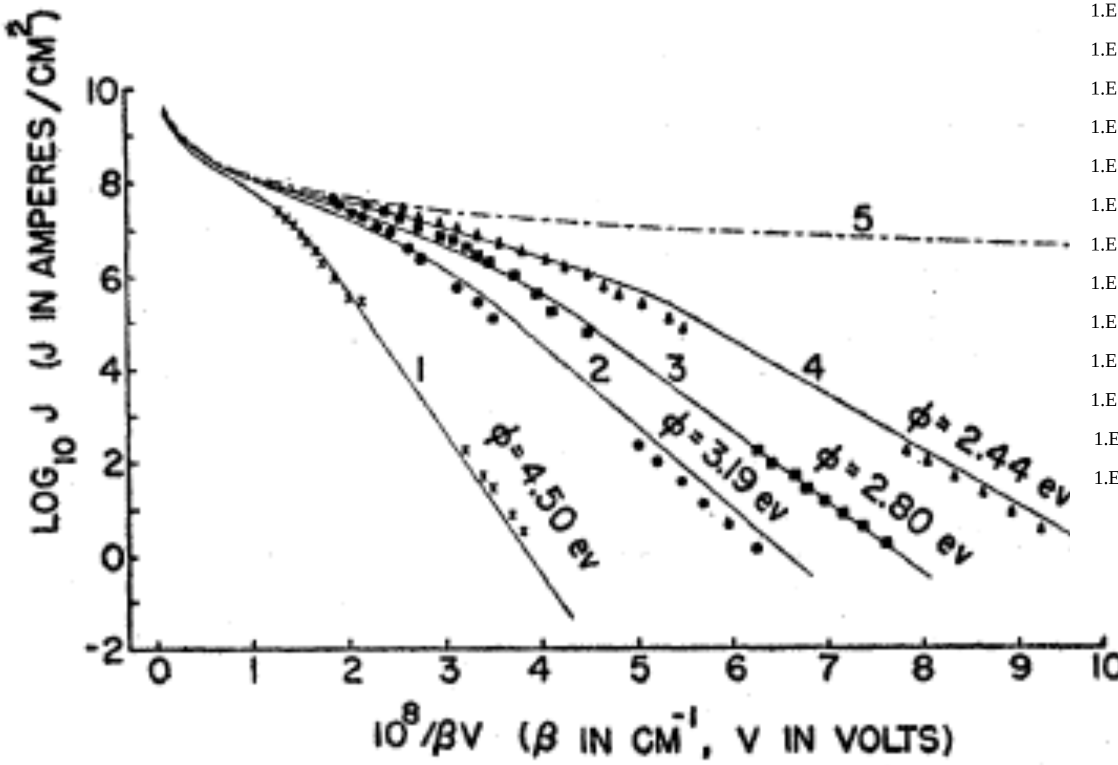
- After running with field, the cavities required conditioning to run without.

- Torques in solid material can "unscrew" emitters
  $\boldsymbol{F} = \boldsymbol{I} \times \boldsymbol{B}$ 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.

Space Charge Effects Have Been Measured a Long Time Ago

- Barbour, Dolan, Trolan, Martin and Dyke made detailed measurements with different surfaces.



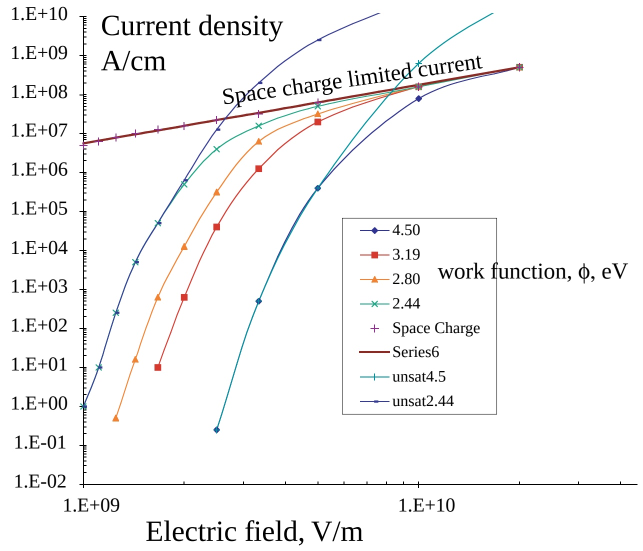


FIG. 7. Comparison of experimental data with space-charge field-emission theory (solid lines) for emitter *N*85. Curve 1, clean tungsten, curves 2–4, barium-on-tungsten as in Fig. 3; curve 5, Child's equation.

The shape of the surface can be affected by surface tension forces.

- In the study of Field Emission Microscope probes, it was noticed that the surfaces of tips became dull after some time.
- Erosion rates compared well with a model based on surface tension forces.
- The process is slow, and requires high temperatures
- Surface tension flattens surfaces.

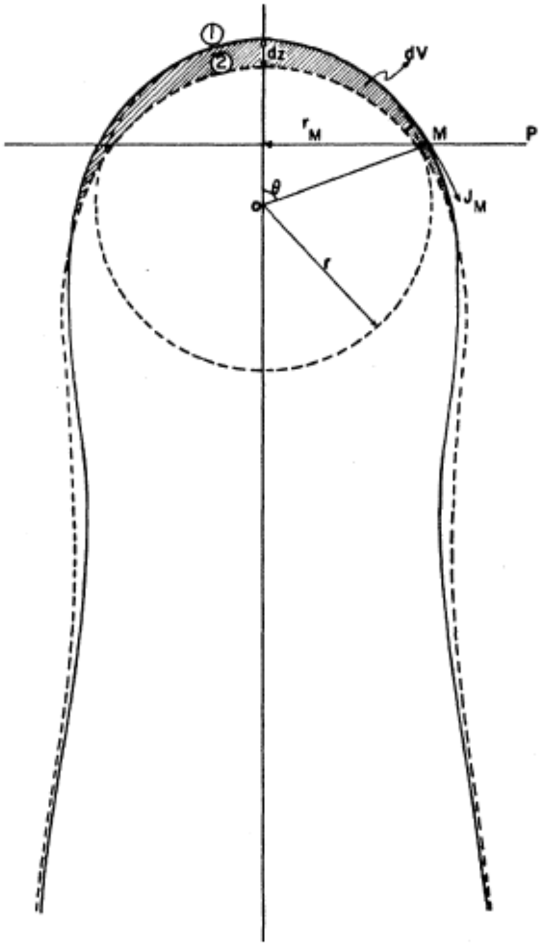


FIG. 3. Successive positions ① and ② of the field emitter surface.

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?

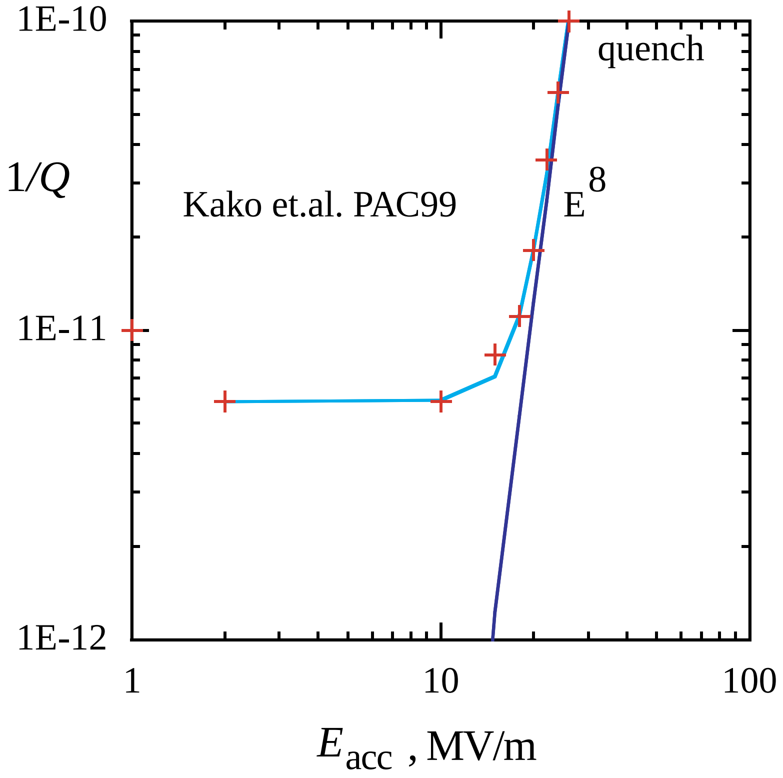
The answer to all these questions may be **yes**, but more work is required.

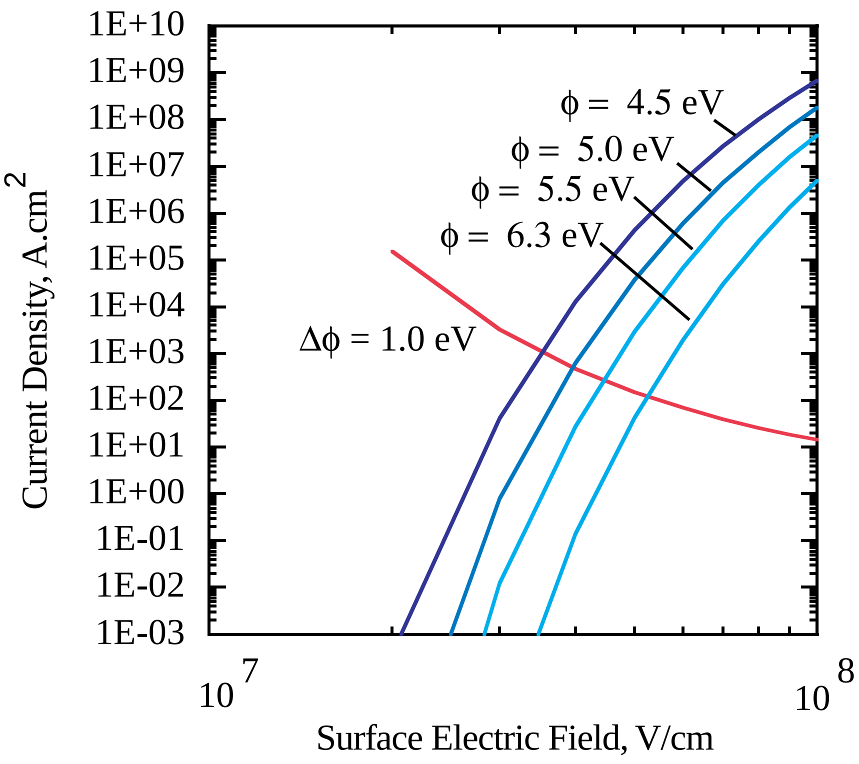
Can Normal and SCRF Field Emission be Reduced?

- 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 Cavities be made Breakdown-Proof?

- Barbour et al have shown that coating with low work function material can increase the field emission from asperities.

- At large values of field emission, space charge has been shown to limit the field emitted currents.

- The space charge limit is a loading term on the electric field, and which prevents the electric field from reaching the surface.

- When the surface electric field is limited, the surface stress is reduced.

- Tensile Stress > Tensile Strength
  $\Rightarrow$ Breakdown

  Tensile Stress < Tensile Strength
  $\Rightarrow$ No breakdown

- Data show that emitters can function at space charge limit without surface damage.
- Fig A and D are field emission photographs taken before and after high current operation and show the barium on tungsten surface is unchanged.

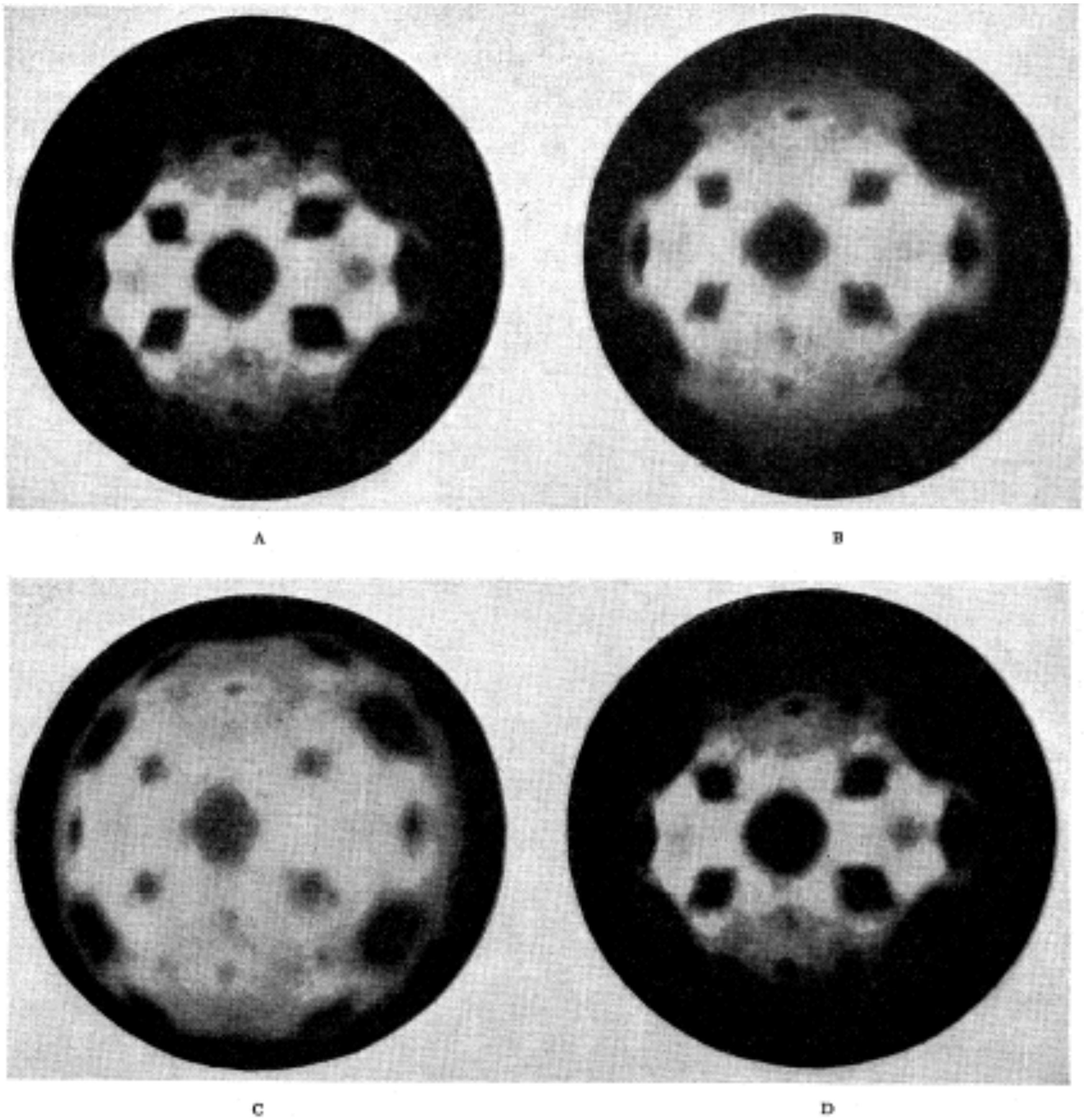


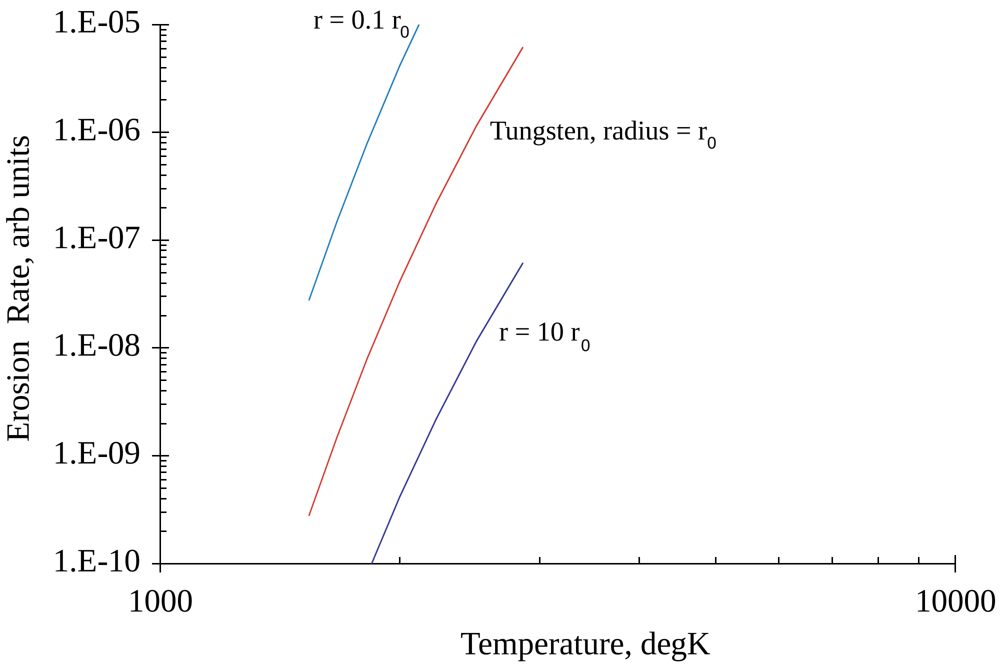
Fig. 4. Emission patterns at various currents, with constant work function $\phi=3.19$,

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.



Relevant Materials Properties (alphabetically)

- Conductivity (thermal and electronic)
- Evaporation field as a function of temperature
- Machinability
- Melting point
- Polarizability
- Secondary emission coefficient
- Surface tension
- Tensile Strength
- Reactivity, oxygen affinity, equilibrium pressure of oxygen
- Vapor pressure of metal
- Viscosity when molten
- Work function

Relevant Mechanisms (alphabetically)

- Conductivity (thermal and electronic)
- Conduction at grain boundaries and defects
- Gas Evolution
- Field emission
- Fatigue
- Field Evaporation
- Fracture
- Lorentz forces
- Melting
- Multipactor
- Space charge
- Vaporization

Summary

- 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
  - Different work functions
  - Effects of gas on surfaces
  - Comparisons between different smoothing methods
  - Coating technologies
  - Effects of monolayer coatings

- We can start looking at some questions with the Lab G cavity.
  - Do coatings help reduce dark currents?
    Can SCRF profit from this?
  - How do other materials survive sparking?

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

- This work should have a high priority.