

High Gradient RF Studies

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Aug. 4, '05



Collaborators

- Experiments in Fermilab Muon Test Area (MTA)
 - J. Norem, Argonne
 - A. Moretti, A. Bross, Z. Qian FNAL
 - Y. Torun, IIT
 - D. Li, M. Zisman, LBL
 - R. Rimmer, JLab (thanks to many who helped with the 201 MHz cavity.)
 - R. Sandstrom, Geneva University
- Modeling
 - Z. Insepov, A. Hassanein, I. Konkashbaev, ANL
- Surface studies
 - D. Seidman, J. Sebastian, K. Yoon NW
 - P. Bauer, FNAL

Ultimately, everything is limited by strength of materials and heat transfer.

H. Stevens

Outline

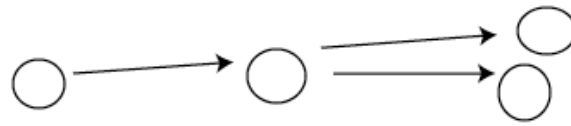
- History
- The Muon Cooling RF R&D Program
 - What we are doing
 - What x-rays tell about the local surface
 - Our Model of breakdown
 - Our experimental program
- Does our model apply to SCRF data?
- Some questions

Breakdown in gasses has been understood for a long time.

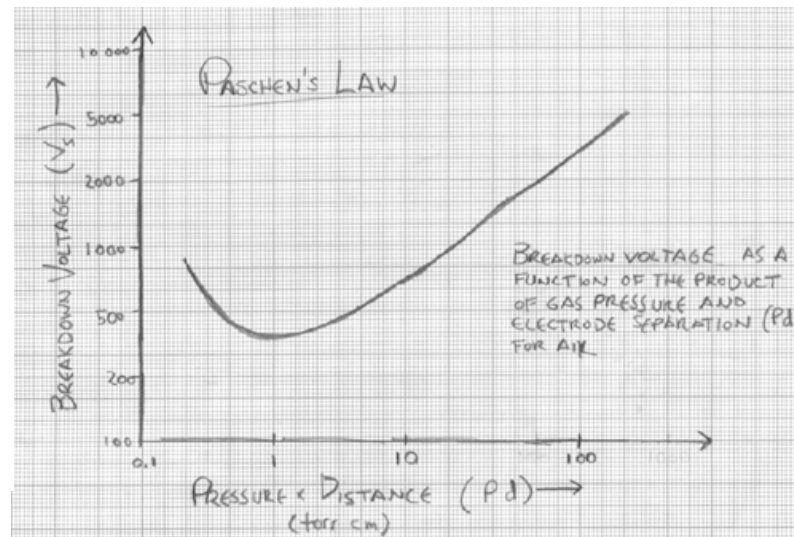
- Paschen explained it in 1889, Lord Kelvin produced the data in 1860.
- J. J. Thompson discovered the electron in 1998, which made things rigorous,



Paschen



It's an electron avalanche.



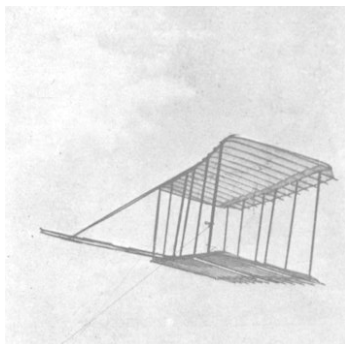
Thompson

- Can electrons be seen in the lab? What happens at small distances?

Michelson and Millikan were interested in high gradient limits.



Millikan (in 1907)



Michelson

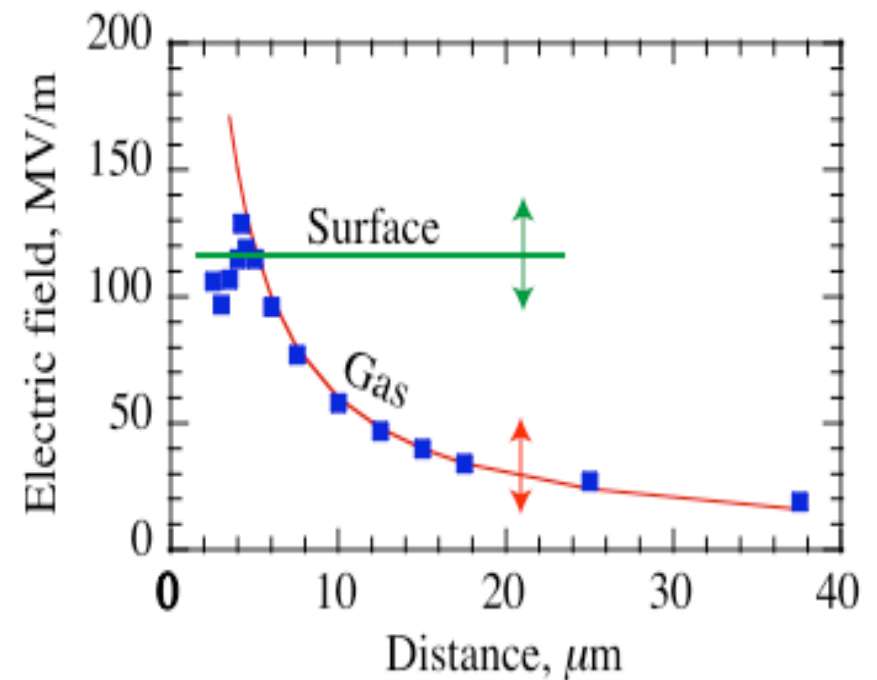
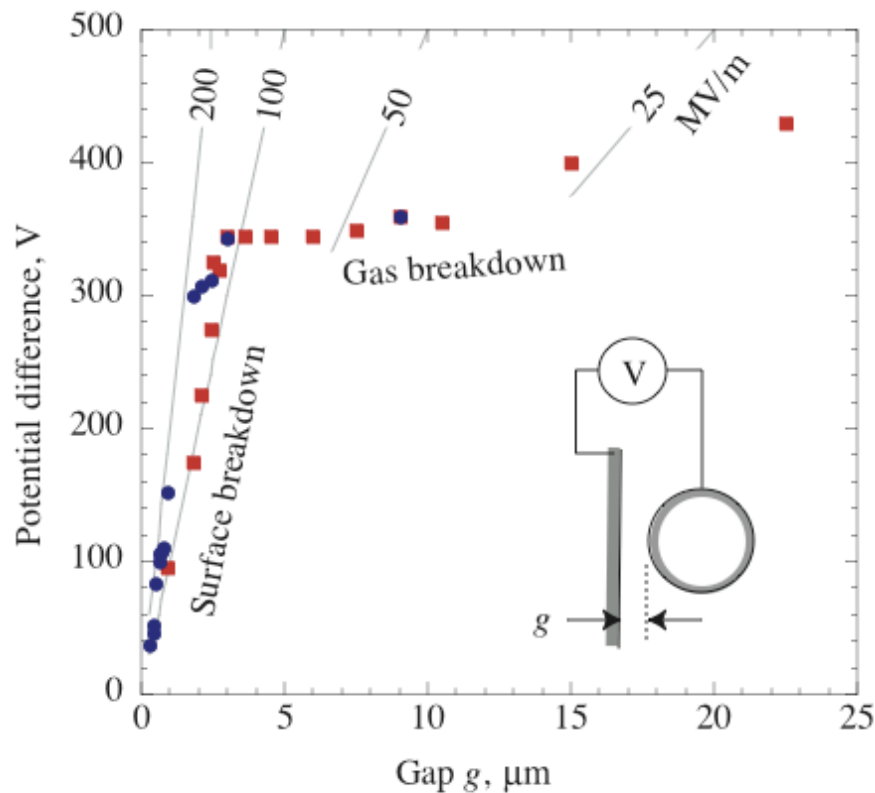


at the U of C in 1899.

The limits of avalanche breakdown.

- Breakdown at small distances is interesting - no space for an avalanche.
- Two mechanisms are easily seen.

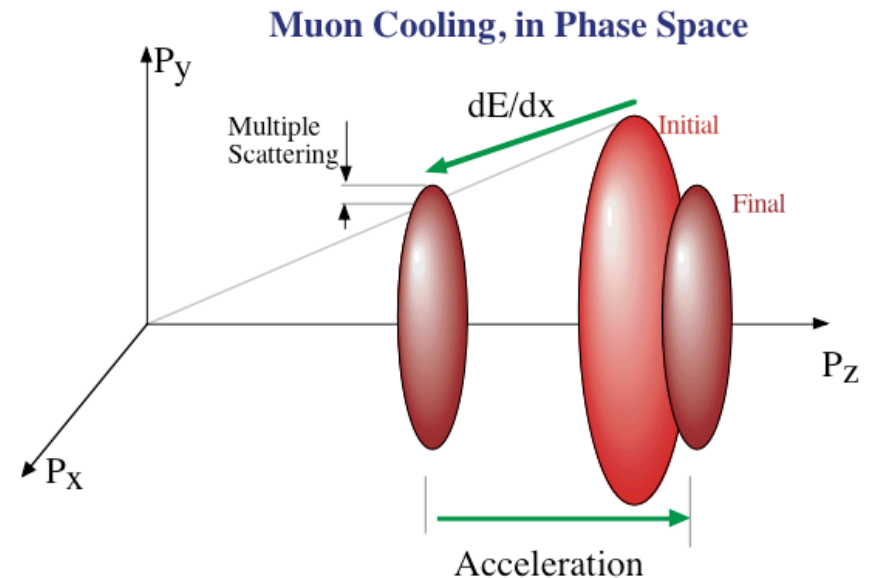
There is no better data.



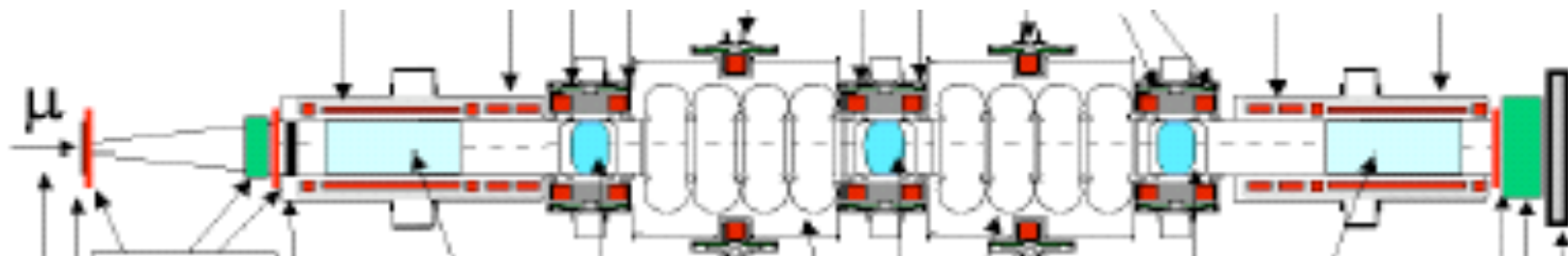
- Millikan and Michelson liked the "hot sparks", bought a vacuum pump, and invented vacuum ultraviolet spectroscopy.

Our work is directed at Muon Collaboration problems.

- Cooling muons requires absorbers and rf.



- X rays make backgrounds in the Muon Ionization Cooling Experiment (MICE)



scattering measuring acceleration+absorbers=cooling measuring

- Goals: 1) Insure we can reach full E field with 3 - 5 T solenoid.
2) Reduce backgrounds in spectrometers.

We have a program directed at understanding rf limits.

This was started to understand **muon cooling** problems.

- There are three coordinated efforts:
 - 1) Low frequency cavity studies (Muon Collaboration)
 - 2) Atom Probe Tomography (ILC and Muon Collaboration)
 - 3) Modeling (generally applicable)
- We are converging on a **general theory of vacuum breakdown**.
- We are producing unique data on high gradient environments.
- Our work should be relevant to ILC/SCRF, CLIC, DC ...
- We argue that **High Gradient Studies is one field**.

Superconducting rf, Normal Conducting rf DC vacuum breakdown	}	are limited by same mechanisms, .. at the same value of E .
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Muon Test Area: RF Tests



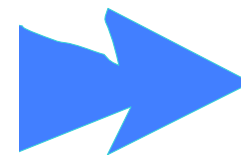
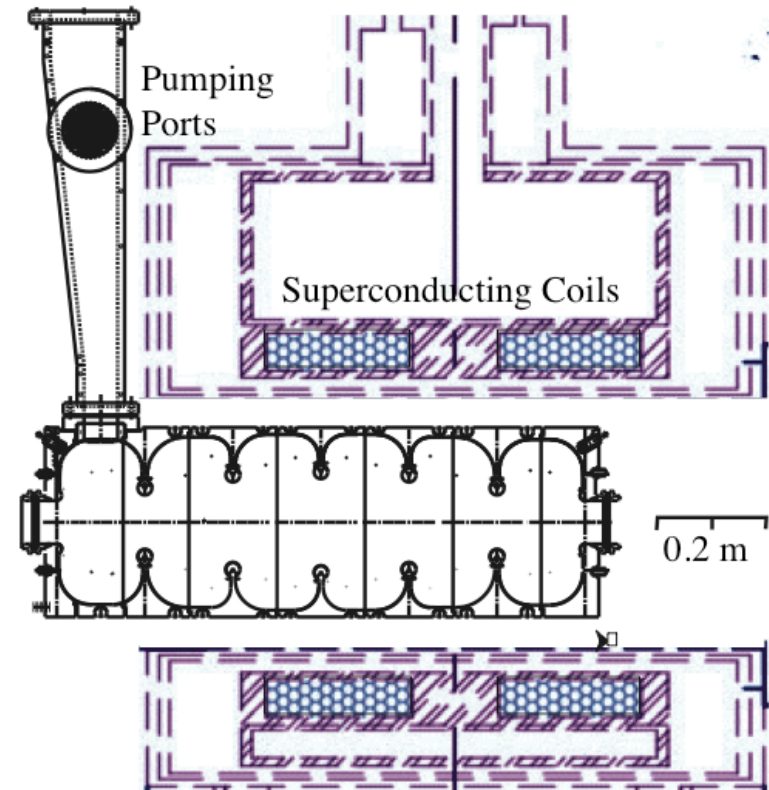
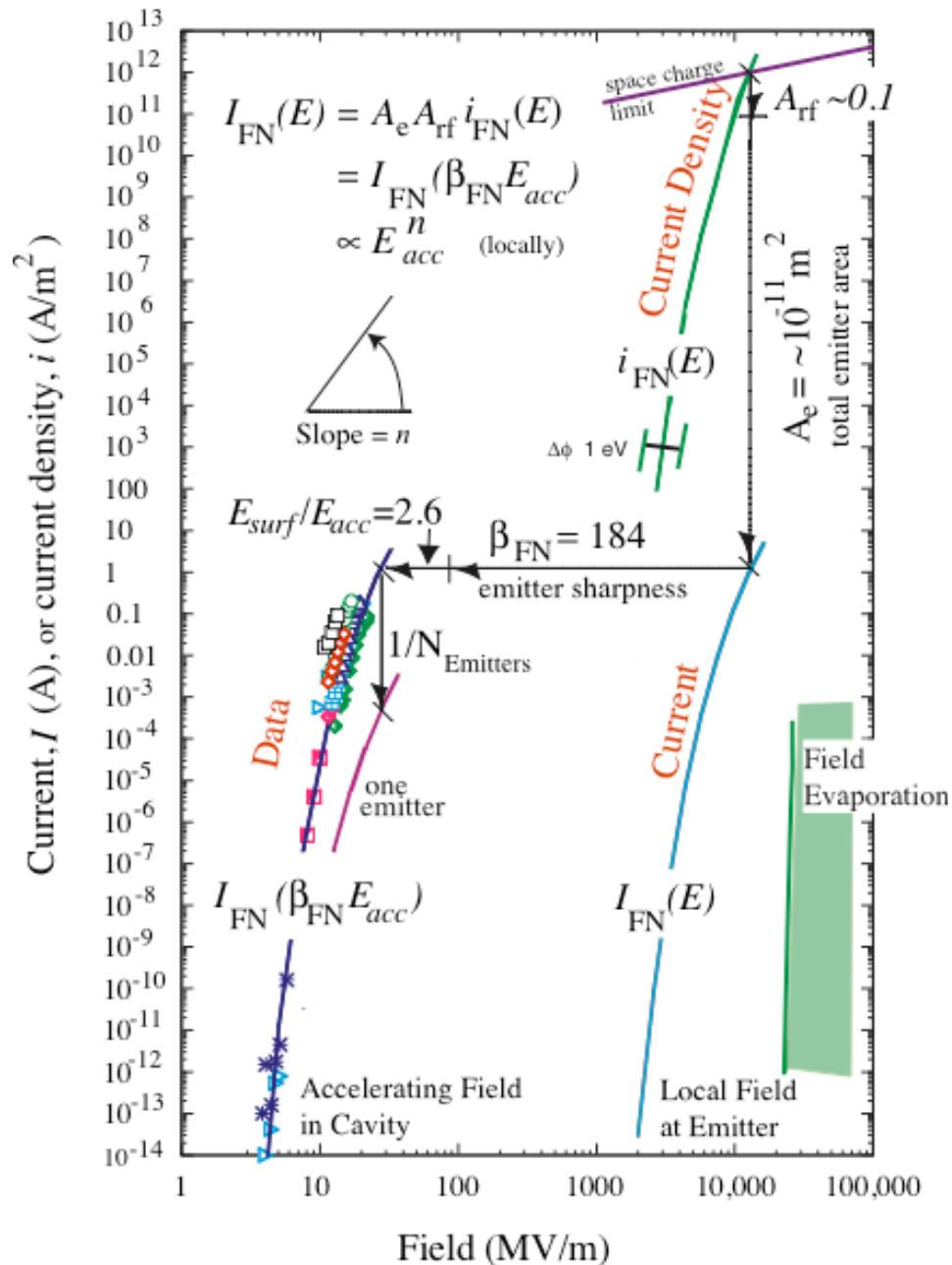
- High pressure tests started in May.
- Installation of clean room
Final connections to magnet and 805
Final cleaning of room and floor
Installation of shielding.
underway



Muon Test Area Experimental Program

- 805 MHz cavity
 - Curved windows (the flat ones were unstable)
 - Button tests of different materials (damage in different materials)
 - Magnetic field studies (we need to operate at 5T)
 - High pressure cavities (high pressures may be good)
- 201 MHz cavity
 - Conditioning and breakdown studies (needed for MICE, x ray levels, etc.)
 - Magnetic field studies (Can we reach 16 MV/m? @ 3T)
- Surface modification and control (Can we do better?)

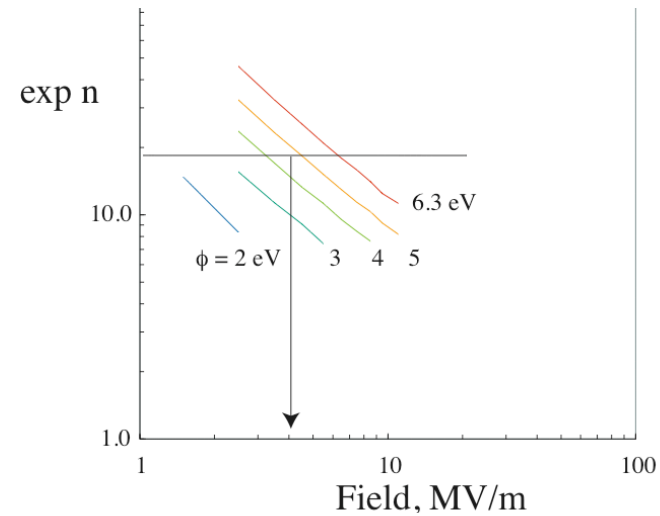
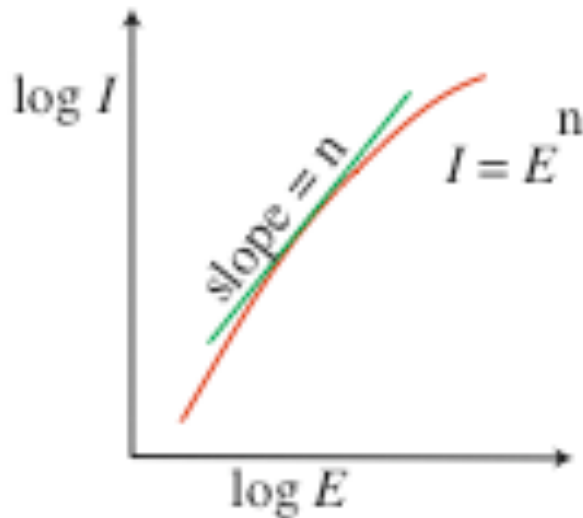
Data at Fermilab measured the local environment at emitters.



Emitter dimensions $\sim 0.1 \mu$
 Surface field $\sim 10 \text{ GV/m}$

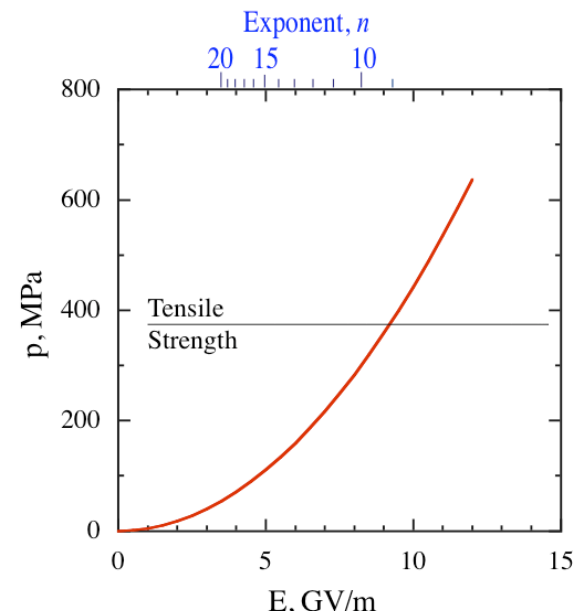
Measuring local electric fields is straightforward.

- The slope of the curve $\log_{10} I$ vs. $\log_{10} E$ gives the exponent of $I \sim E^n$.
- The value of n and ϕ , the work function, determine the local field.



- Stresses are determined by E_{local} ,

$$\sigma = -0.5 \epsilon_0 E^2.$$



Our Breakdown Model



- Electric fields produce tensile stresses that fracture the surface.

Local fields with $E > 6 \text{ GV/m}$ damage surfaces.

- Dark currents describe asperities with $E_{\text{local}} \sim 4\text{-}10 \text{ GV/m}$, dimensions $\sim 0.1 \mu$.
- At this field the electrostatic tensile stress $\sim$ tensile strength.

We see damage in **normal** rf systems

There seems to be damage in **superconducting** rf systems

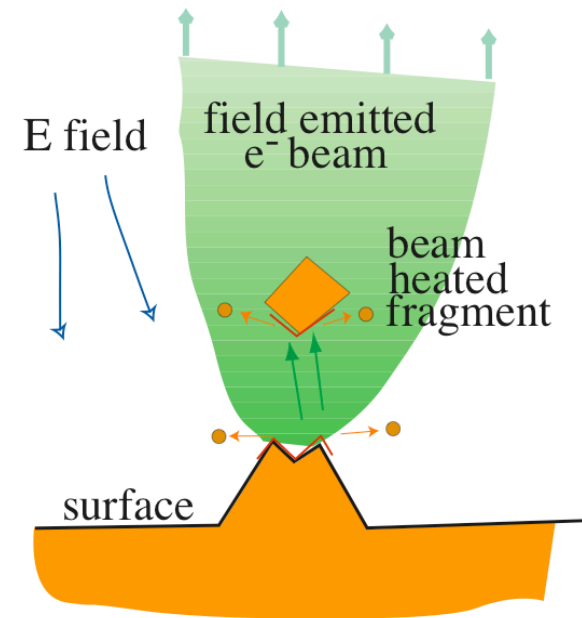
The **atom probe system** shows damage

- **The damage can trigger breakdown.**

Fragments / clusters are torn off.

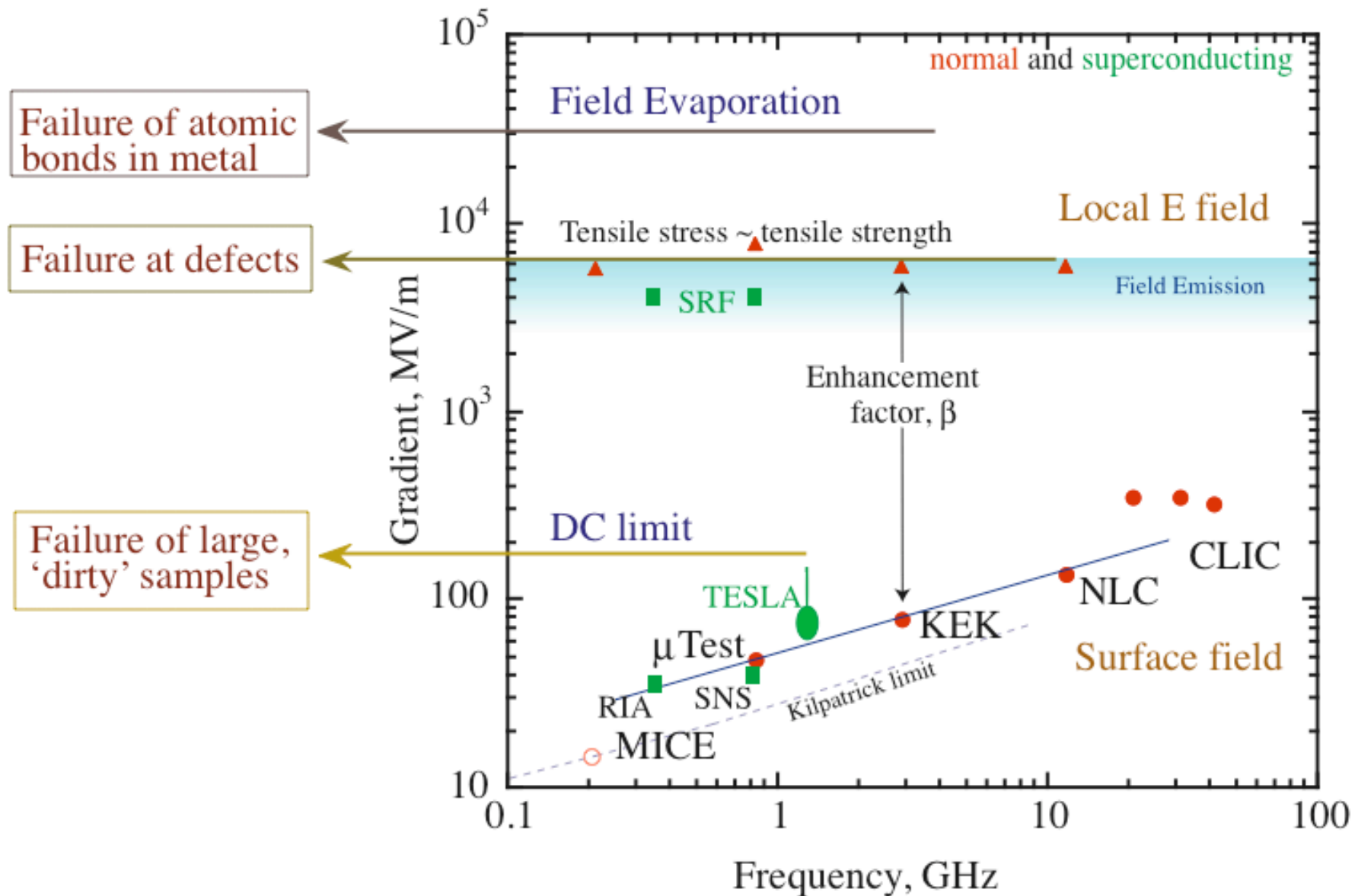
Field emitted beams vaporize fragments

Lossy plasmas short cavities.



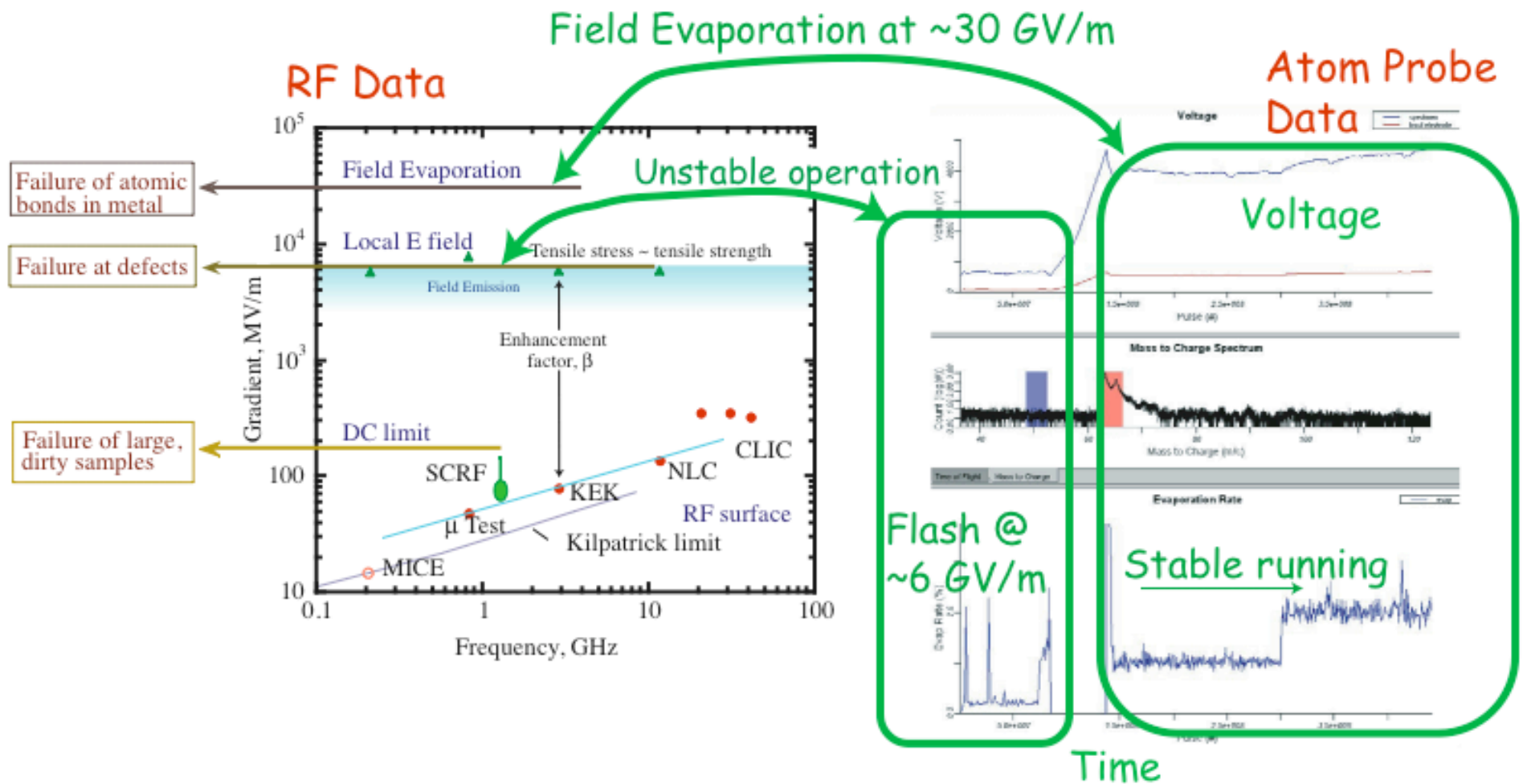
- Details in 3 recent Phys. Rev. STAB papers, a NIM paper, PAC05, EPAC . . .

Accelerating gradients are limited by local E fields.



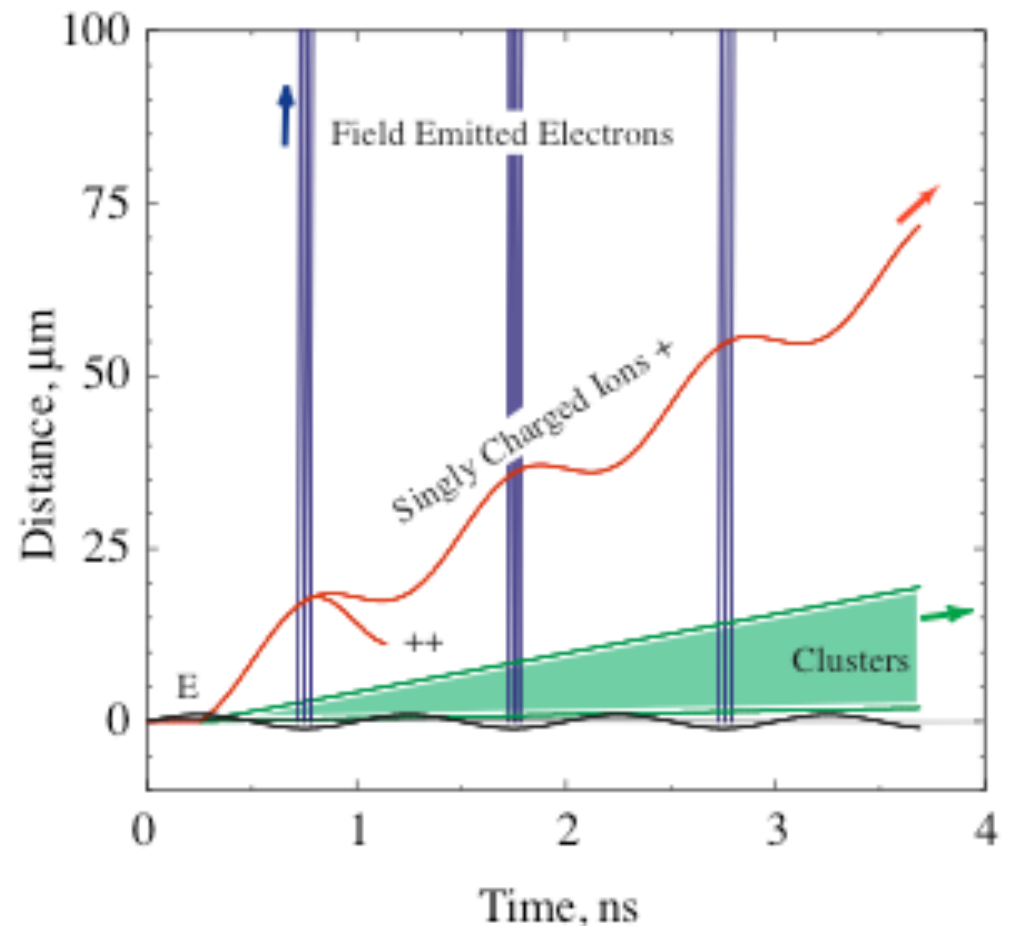
"rf breakdown triggers" are seen with Atom Probe Tomography

- LEAP data correlates with rf data. LEAP turn-on is unstable.
- Problems occur at about the right fields. (Oxide layers ?)



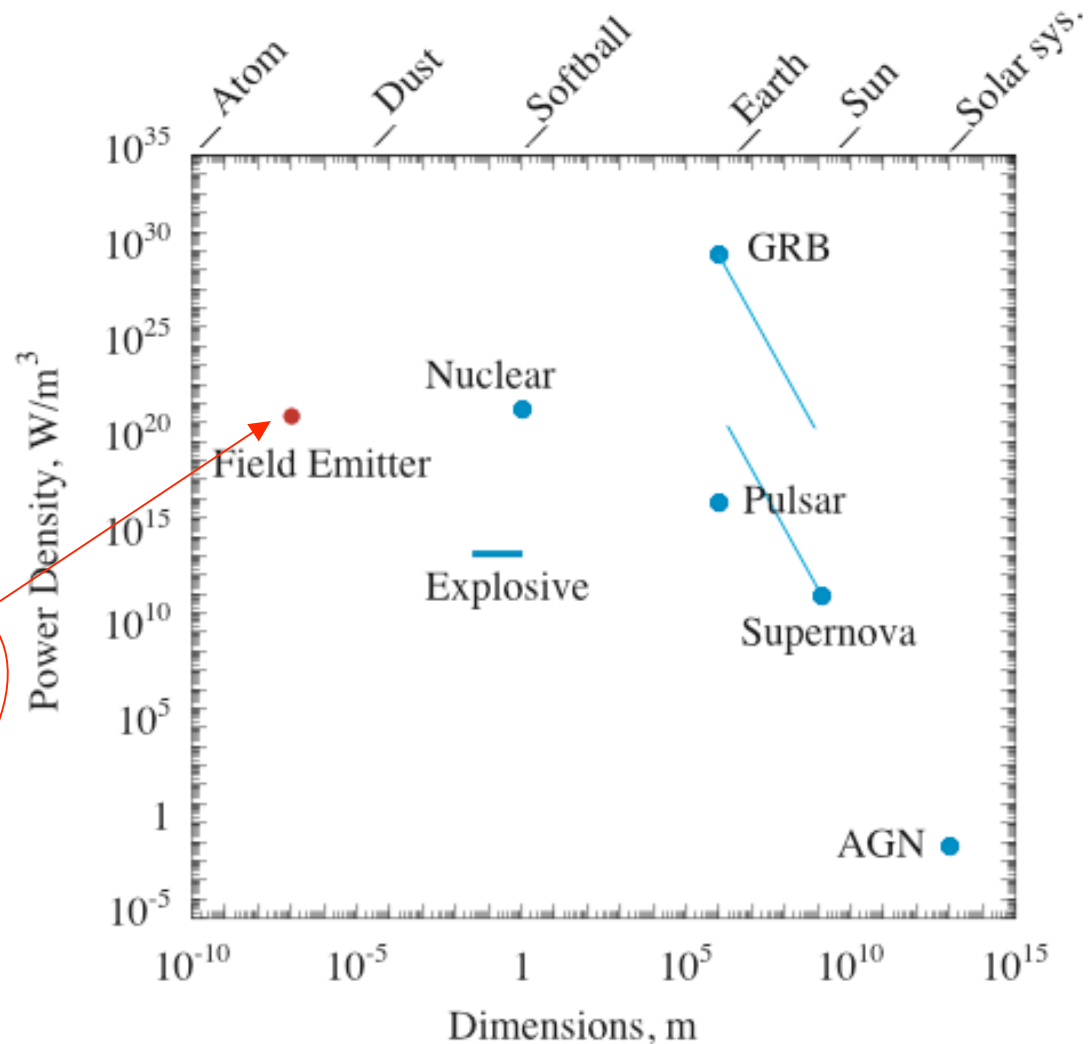
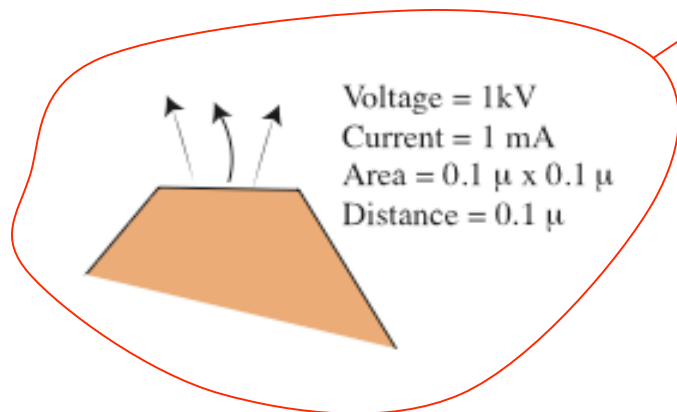
Ion Optics of fragments clusters and atoms.

- The local asperity gives single atoms enough kick to take them away from the emitter.
- Clusters and fragments move more slowly, and are heated by intense field emitted electron beams.



The highest power density in the universe ? ? ?

- Highest electric field compatible with macroscopic solids.
- Highest currents compatible with these electric fields
- Higher power density than every other "normal" phenomenon (?)
- How big are GRBs?
Supernovae?
- In the home?

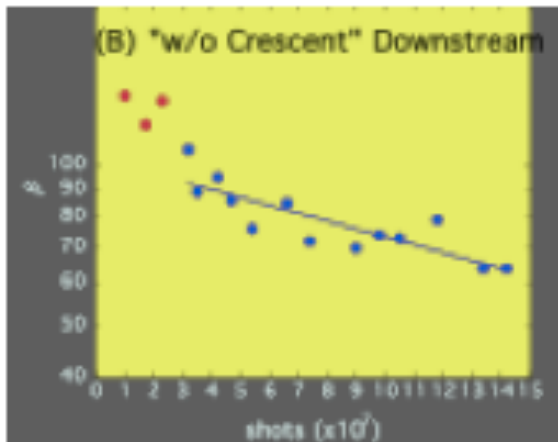


Our model is consistent with data.

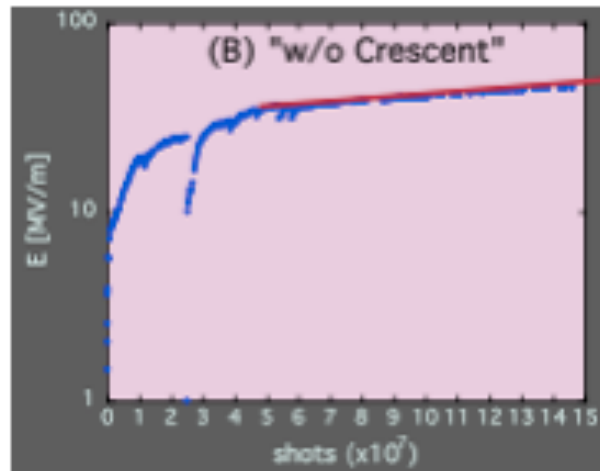
- DC to 30 GHz - breakdown occurs when tensile stress $\sim$ tensile strength.
- 10^{-11} to 10^5 Torr - weak pressure dependence.
- Different materials - harder materials better (oxides may matter - not neat).
- Temperature dependence - weak dependence is predicted.
- Secondary emitters - may determine operating fields - we have new data
- Strong magnetic fields - torques within emitters seem to dominate.
- Cavity conditioning - occurs at constant local electric fields.
- Rapid Development of spark - determined by high power density of FE e^- .
- Atom probe data - at 5 - 10 GV/m, surface layers belch and pop.
- Superconducting RF - similar mechanisms, gradient limit at $E_{\text{local}} \sim 5 \text{ GV/m(?)}$.
- Light and power switching - in the lab, and in the home.

Behavior during conditioning.

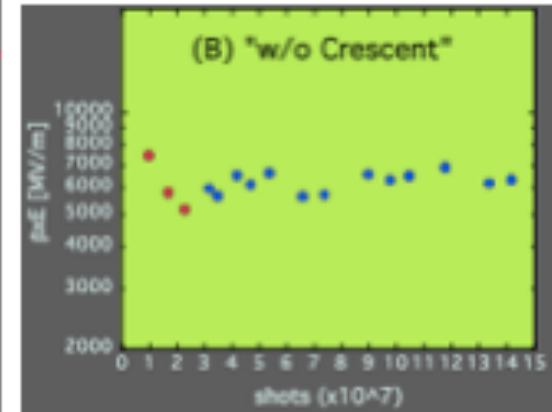
at KEK



Enhancement factor



* Surface field

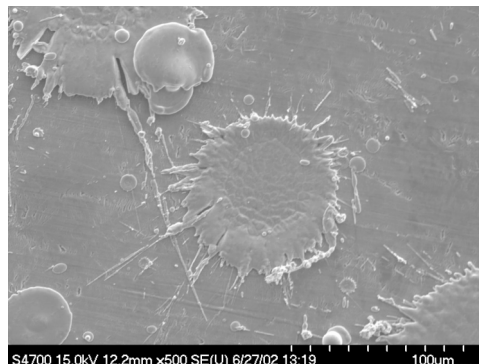


= 6 - 7 GV/m

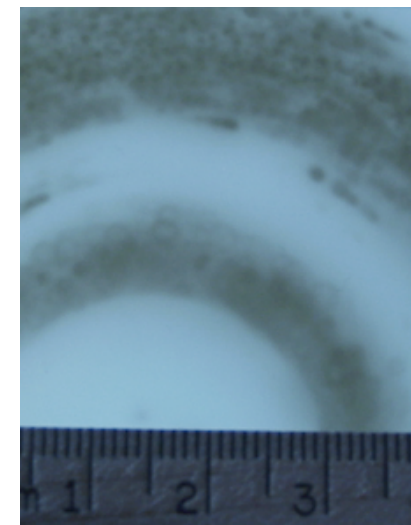
Emitters and electron beams.

- The beams we see are consistent with the surface we had in the cavity.

emitters



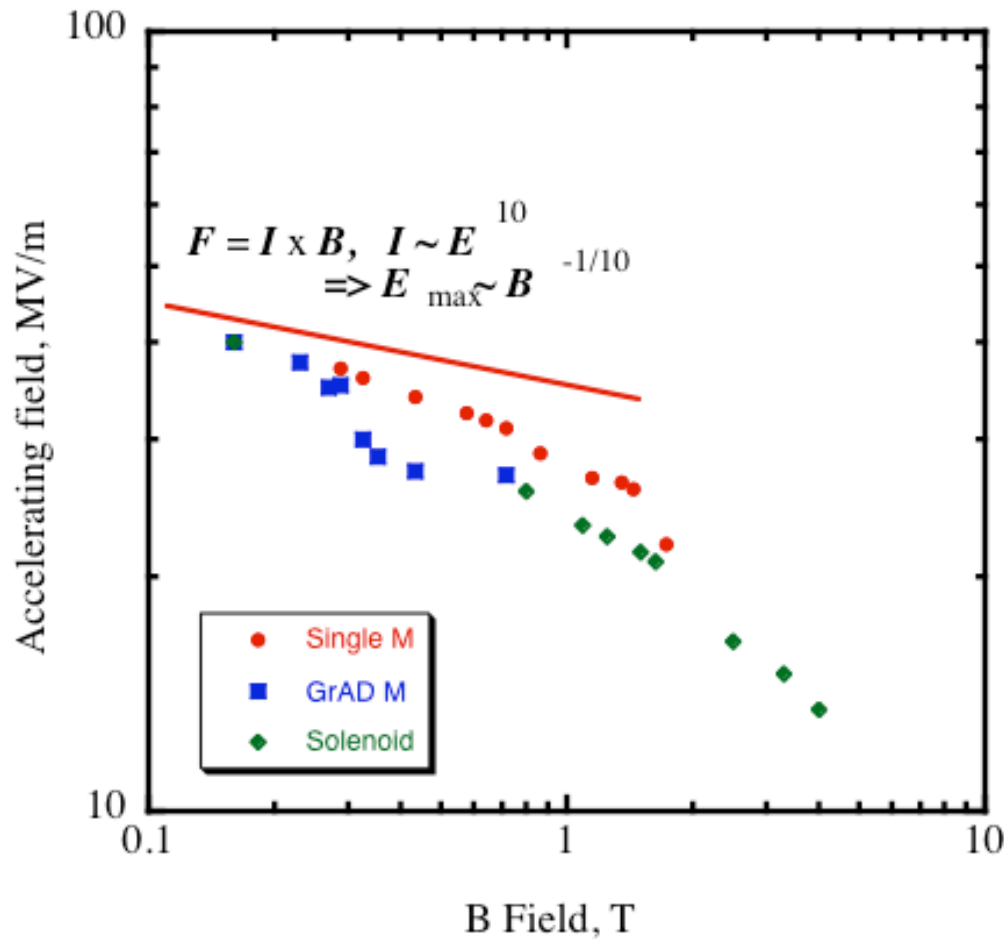
beams



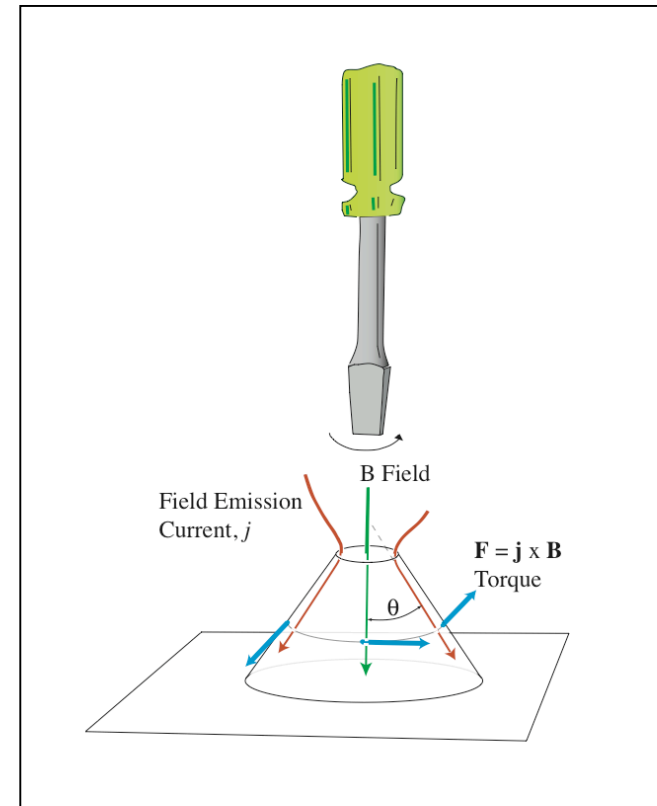
Magnetic field data is consistent with $\mathbf{J} \times \mathbf{B}$ effects.

- $\mathbf{j} \times \mathbf{B}$ forces are driven by field emission currents in the emitter.

The data

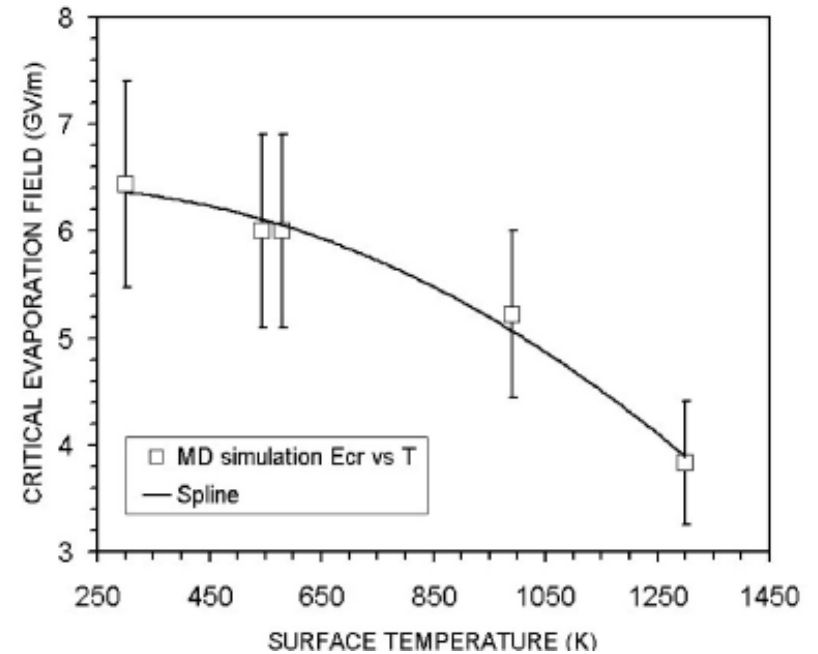
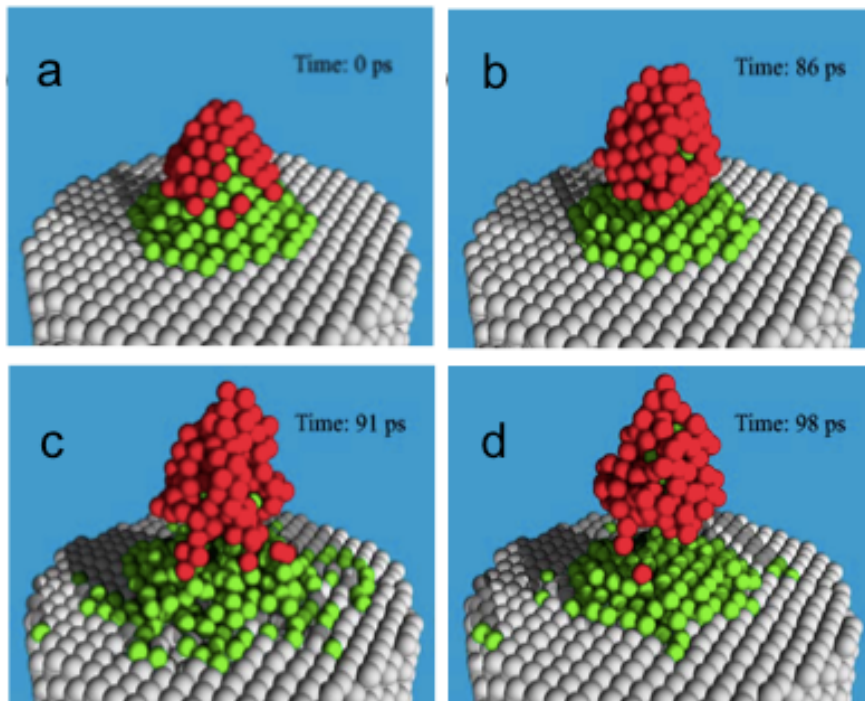


The model



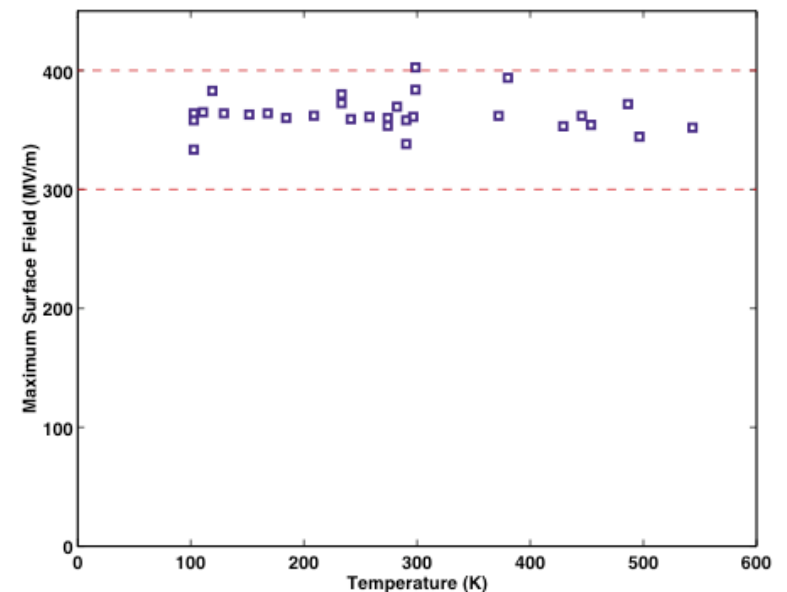
Recent modeling results

- Zeke Insepov has been modeling cluster emission using his code.



Modeling

CERN/CLIC results



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 7, 122001 (2004)

New mechanism of cluster-field evaporation in rf breakdown

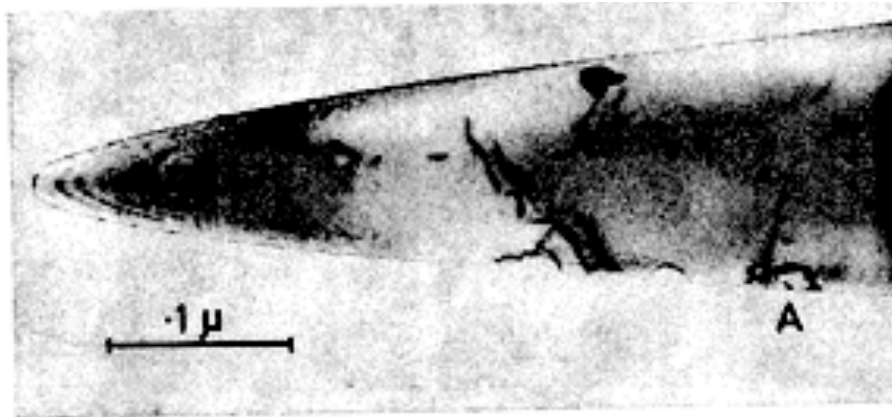
Z. Insepov, J. H. Norem, and A. Hassanein

Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA

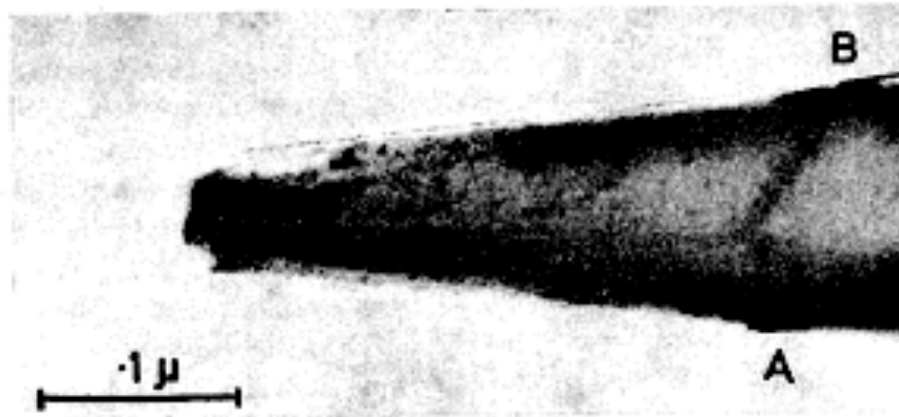
(Received 26 April 2004; published 22 December 2004)

High fields cause mechanical failures.

- Stresses cause failures in Field Ion Microscopes.
- Studies on sample stress in early '70's, (Birdseye and Smith).



(a)

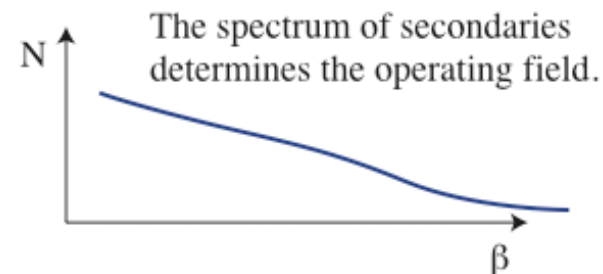
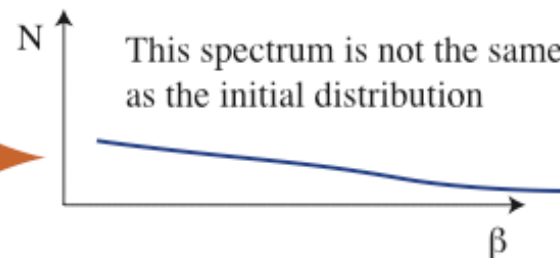
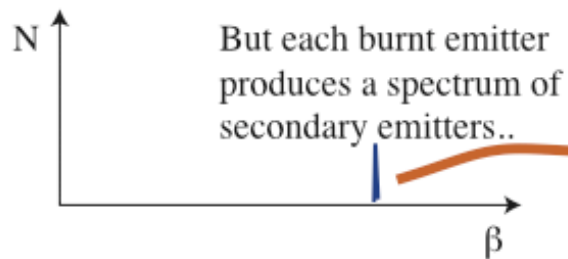
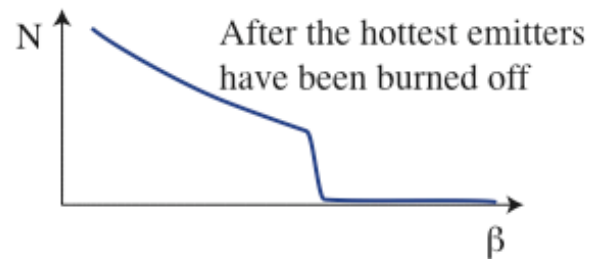
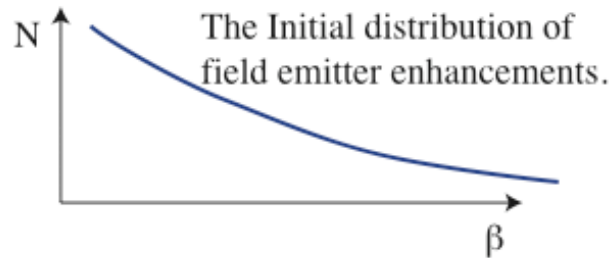


(b)

- We can see the surface under field emission conditions.

Secondary emitters.

- Secondary emitters are produced in breakdown events. We see them.

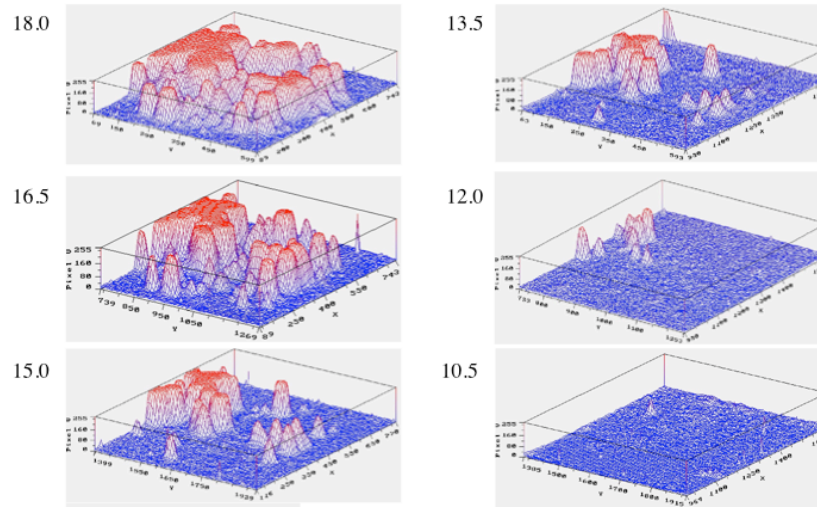


β = enhancement factor
~ sharpness ~ bump height

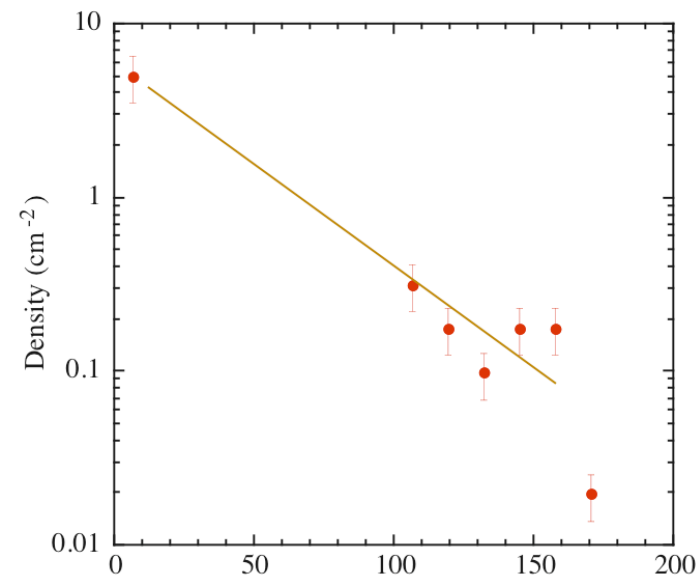
The secondary emitter spectrum – first measurements.

- Sources on an undamaged Be surface at different fields. . . .

- Emitter intensity as a function of field, in MV/m, from polaroids.



- . . . give a preliminary spectrum.



The data does not support models that involve melting.

The conventional wisdom argues that field emitted currents melt emitters. This seems to be inconsistent with data.

- There is no thermal dependence in breakdown triggers

SLAC Data

CERN Data

- Emitters can emit for months at high current densities without changing.
- Measured electric fields imply stresses equal to tensile strength of solid.
- Materials with low field emission are not better.
- Microflashes occur with positive voltage (no field emission heating) in LEAP.
- SCRF?

Consequences of the model

- Most measurable parameters depend on details of materials science.
No systematic measurements have ever been made.
- Frequency dependence is due to the surface, which is dependent on E_{stored} .
- The power density in field emitted beams is comparable to nuclear weapons.
- Atom Probe Tomography is a fantastic tool.
The technology is rapidly evolving.
Surface science is not commonly done with these machines.
Northwestern is the only university using this technology.
- Gas Cluster Ion Beams Look interesting.
- There is a lot of information in X Rays!
- The mechanisms that determines the maximum gradient in all machines (field evaporation of fragments) have never been studied systematically.

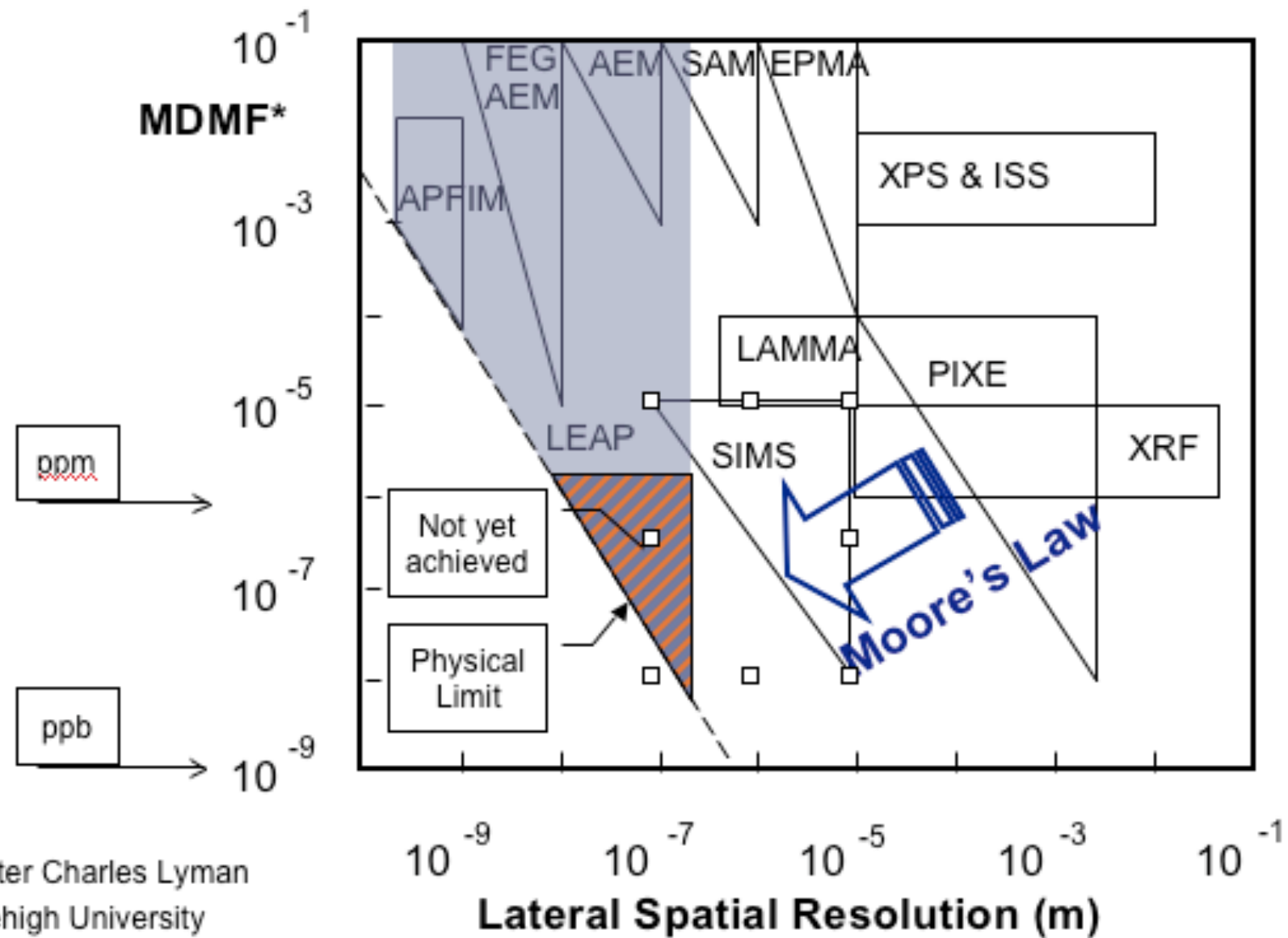
LEAP[®]



2004 Winner!



The LEAP is a giant leap forward



After Charles Lyman
Lehigh University

*MDMF = minimum detectable mass fraction (analytical sensitivity)

Atom Probe Data

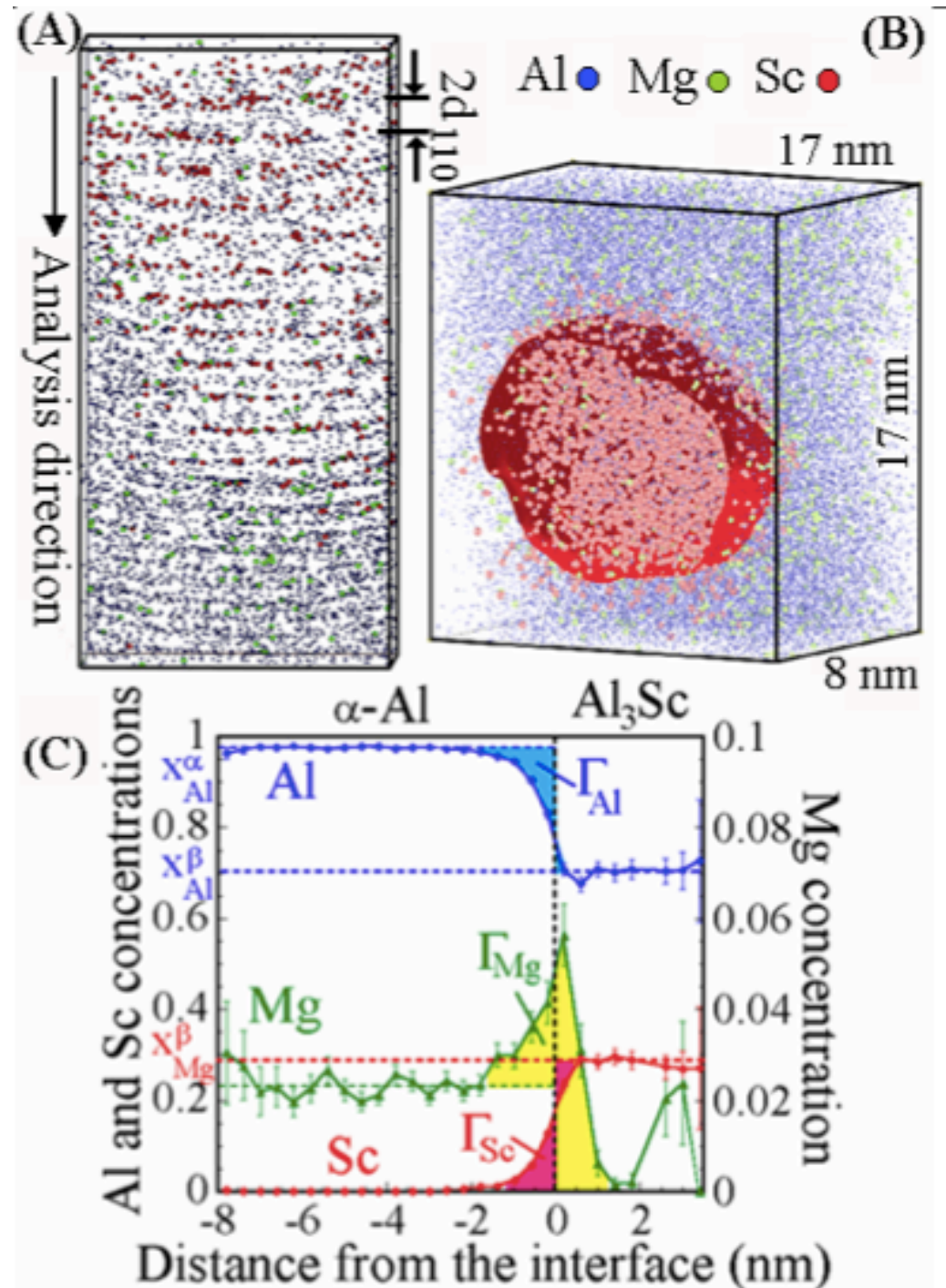
- E. Marquis D.N. Seidman PRL 2003

(A) 3D reconstruction of an Al_3Sc precipitate with a slice taken through it showing the (110) planes.



(B) 3D reconstruction of an analyzed volume from a specimen aged at 300°C for 1040 hours showing the isoconcentration surface used to delineate the $\text{Al}/\text{Al}_3\text{Sc}$ interface. Sc (Mg) atoms are in pink-red (light green), and Al is in blue.

(C) Proximity histogram showing Al, Mg, and Sc concentrations with respect to distance from the interface, which is an average for many precipitates



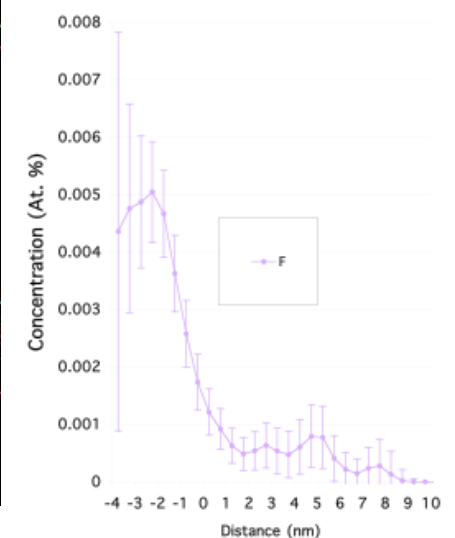
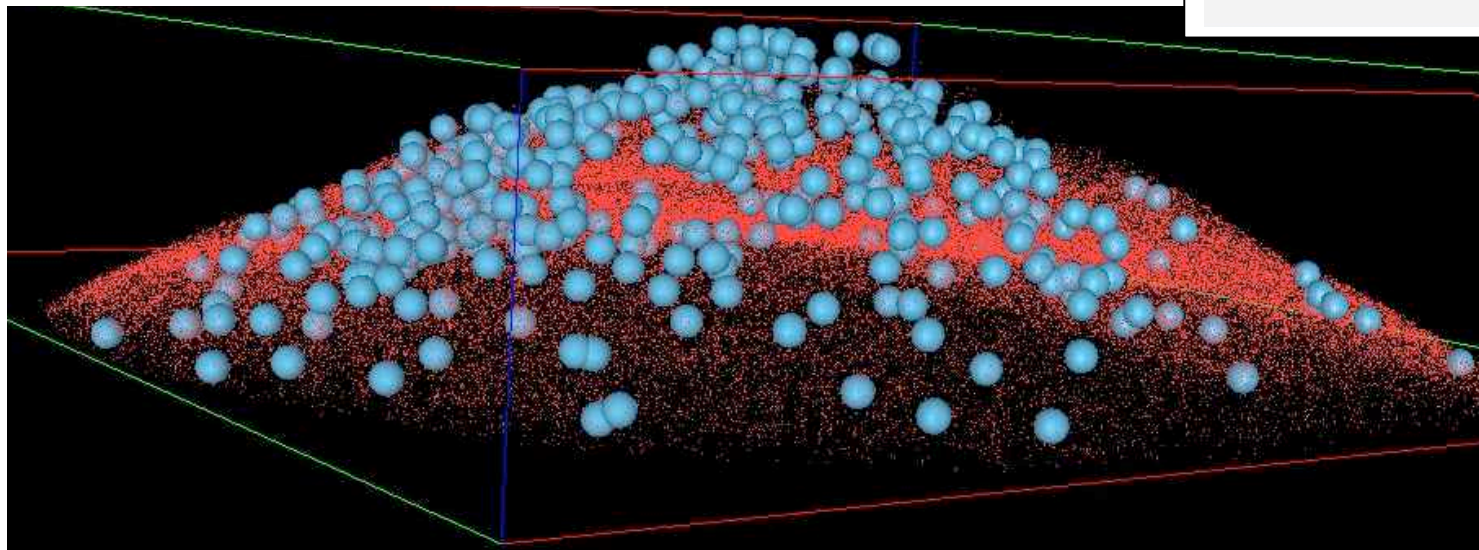
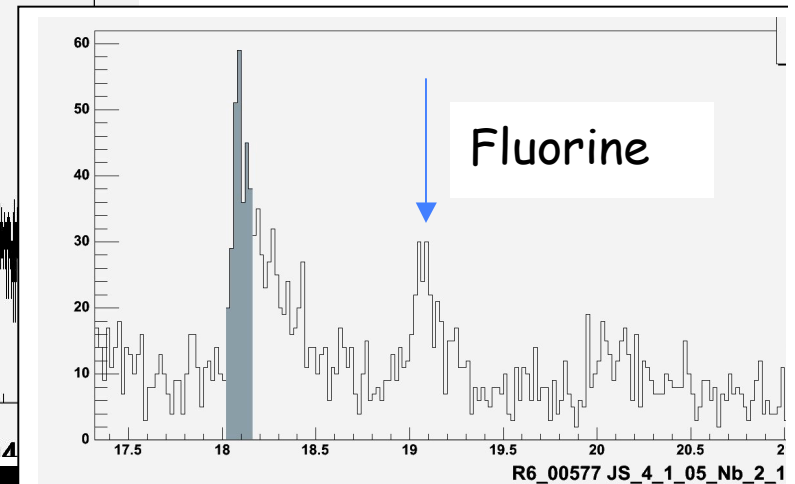
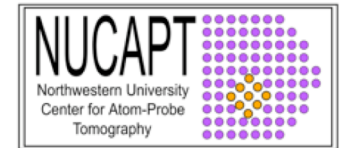
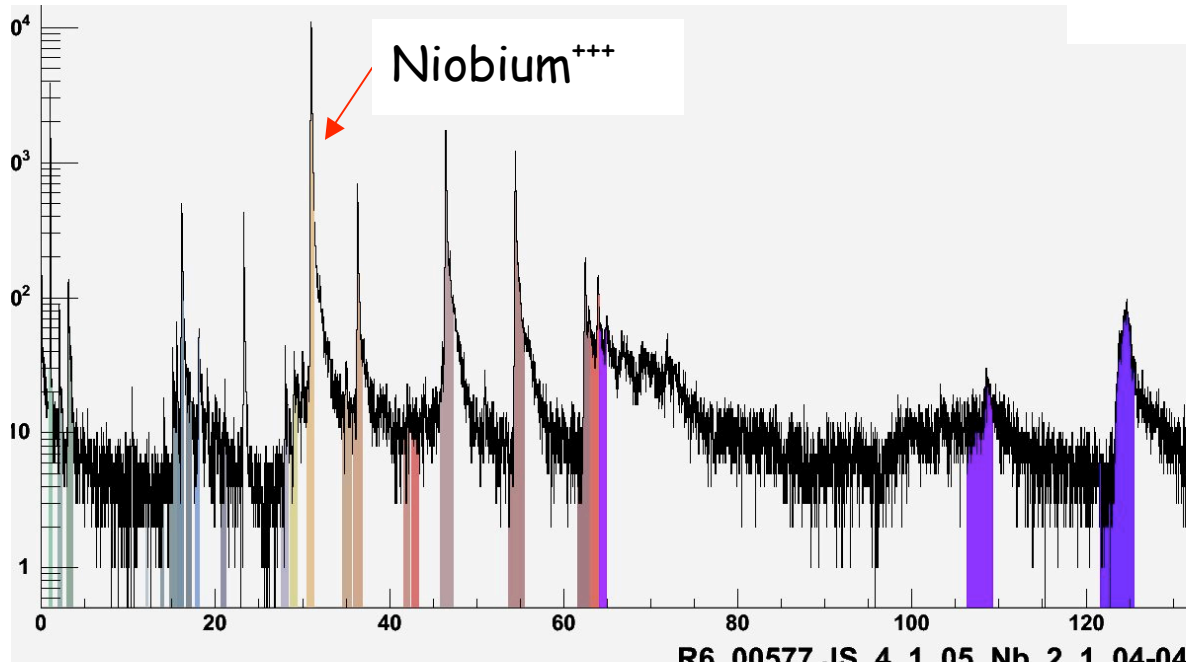
Atom Probe samples look like field emission (breakdown) sites.

- Atom Probe work is useful for two reasons:
 - 1) It provides a detailed look at high electric field on materials.
 - 2) It provides a way of looking at surface composition.

	Emitter in Cavity	Atom Probe Sample
Surface field	4 - 8 GV/m	4 - 40 GV/m
Size	~100 nm	~100 nm
Temperature	300+ K	20 - 300 K
Pulsing	200 - 12000 MHz	0.2 MHz
Stored energy	1 - 100 J	$< 10^{-6}$ J

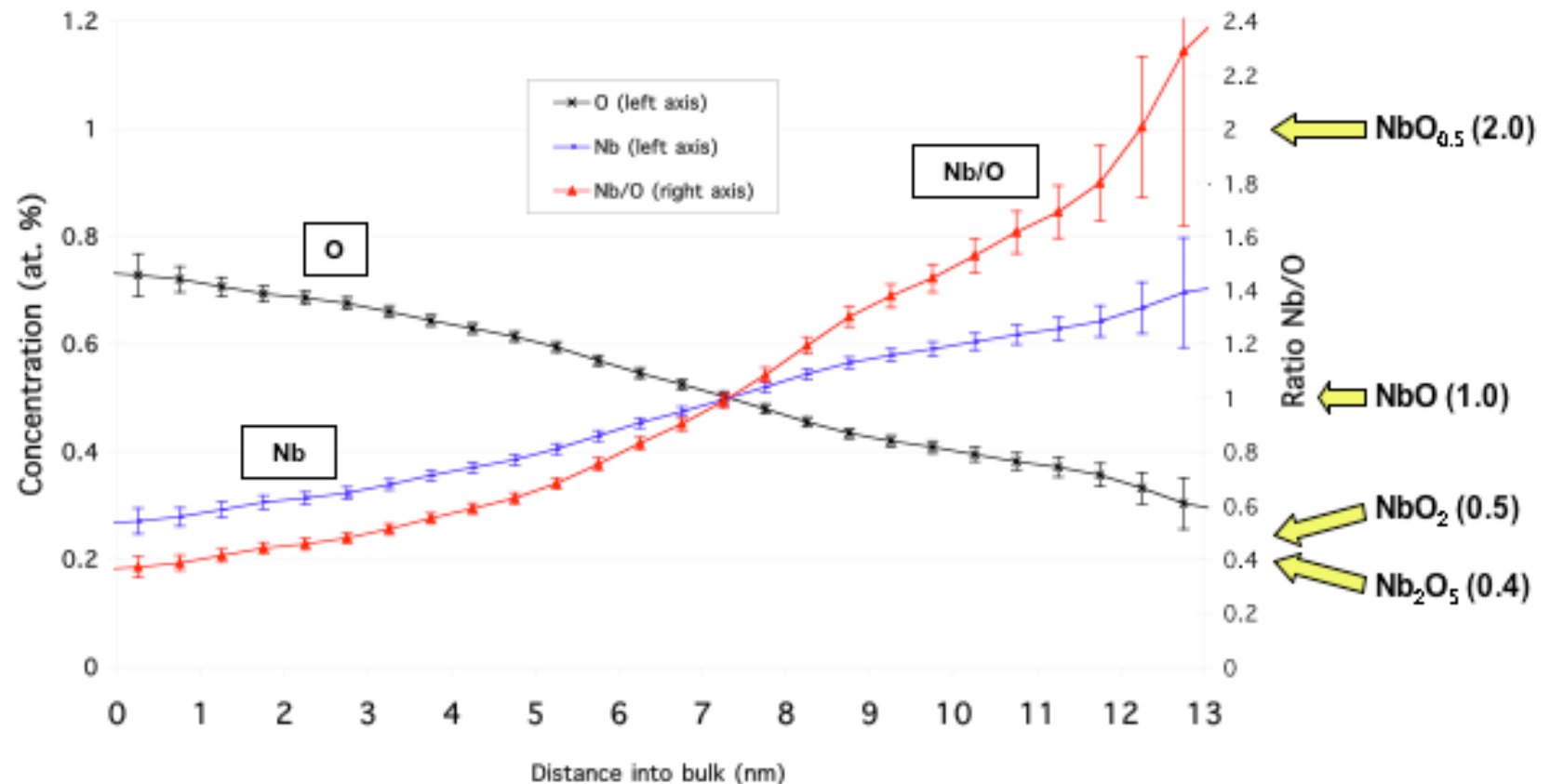
Atom Probe Data: Fluorine Contamination on Niobium

- Ions are identified by time of flight (over ~10 cm, ~1 sr).



Oxide Parameters

- We measure the density of different forms of the oxide with depth.



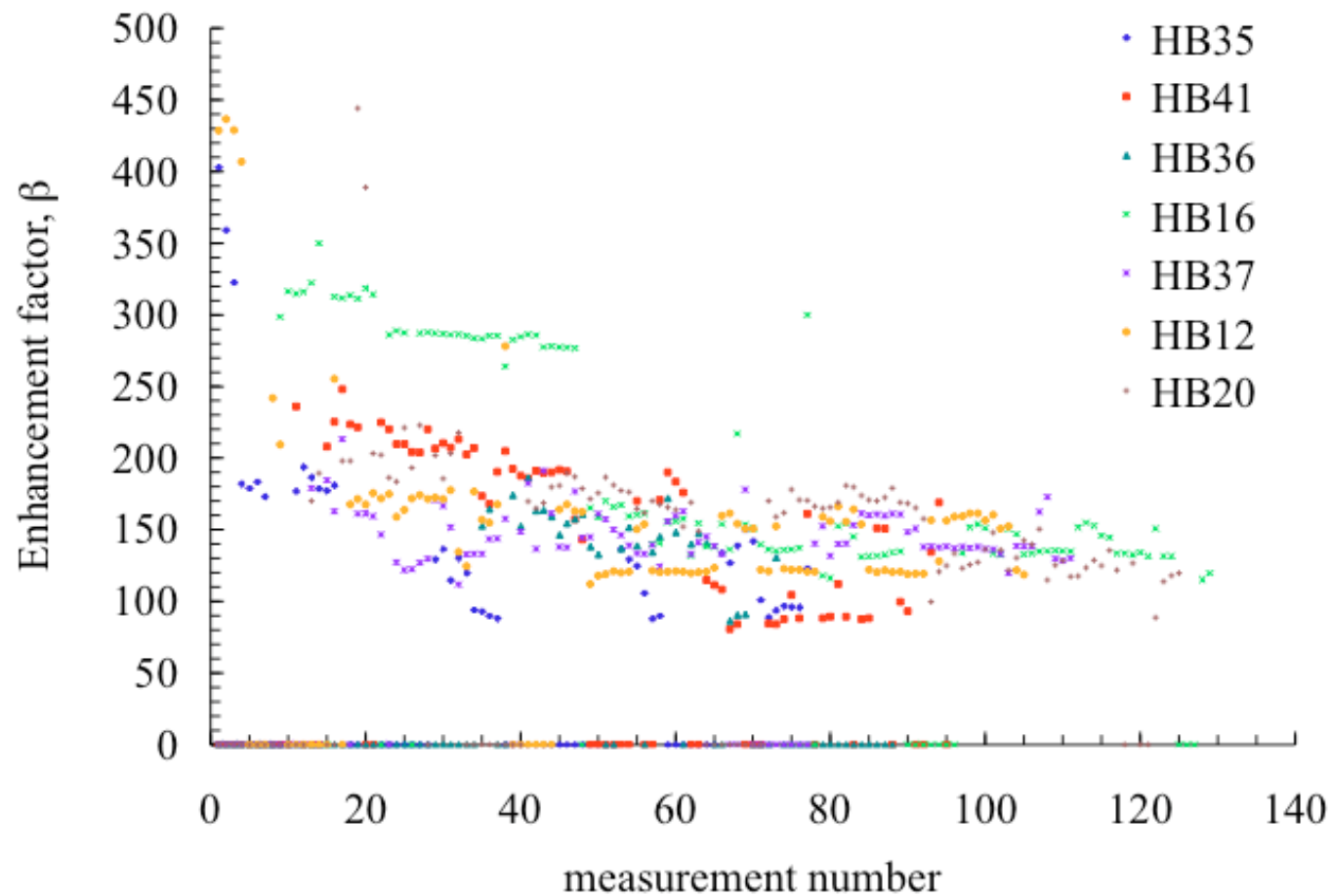
We see a clear and smooth transition from Nb_2O_5 to $\text{NbO}_{0.5}$ (= Nb_2O)

Questions

- What physical mechanisms occur at $\geq 5 \text{ GV/m}$?
What can happen over 30 years?
How does this depend on the surface?
How much control do we have?
- How do x-ray measurements on normal and SC cavities compare?
What are the parameters of emitters?
What does enhancement spectrum look like (for new and used cavities)?
Can the pattern of emitters be imaged?
- How much of experience with copper cavities applies to superconductors?
Is some SCRF cavity conditioning behavior similar?
Can the Q slope be partially due to field emission? (*losses* $\sim E^{20}$)

How similar are SCRF cavities?

- Do they condition like copper cavities?
- Preliminary data



Conclusion

- There is a lot we don't know about the limits of high gradient cavities.