RF breakdown and Gradient Limits

J. Norem
ANL/HEP

High Gradient Workshop, HG2006
CERN
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Our motivation:

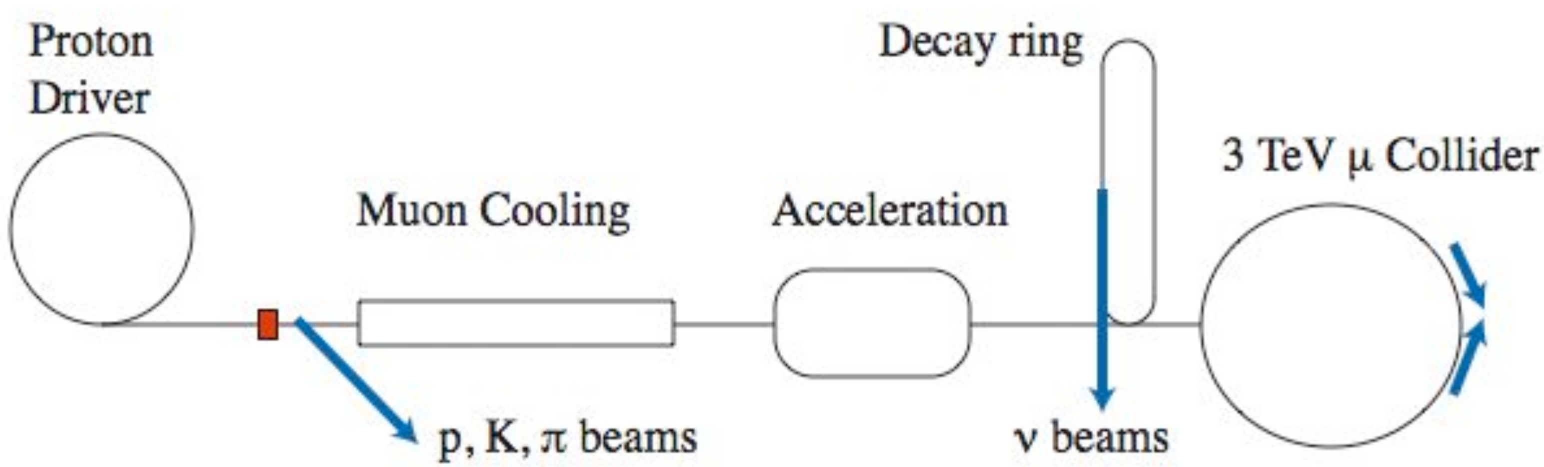
- If Muon Cooling works one can:

  + Collide leptons at 3TeV

  + produce intense neutrino beams.

  + Produce low energy meson beams for HEP

  ➜ This would support a Fermilab scale facility for years.



Muon cooling requires high gradient, low frequency RF.

- Our exp. program led to a reasonable model which we think explains **all** rf data.
- We are pursuing Atom Probe Tomography and Gas Cluster Ion Beam treatments to understand rf surfaces.
- We started the modeling effort to bring more funding into the muon work.
  We think we are 100 % successful scientifically,
  Funding ? ? ?

Bibliography

Refereed papers:

- Open Cell Cavity, Phys. Rev. STAB **6**, 072001 (2003)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.6.072001

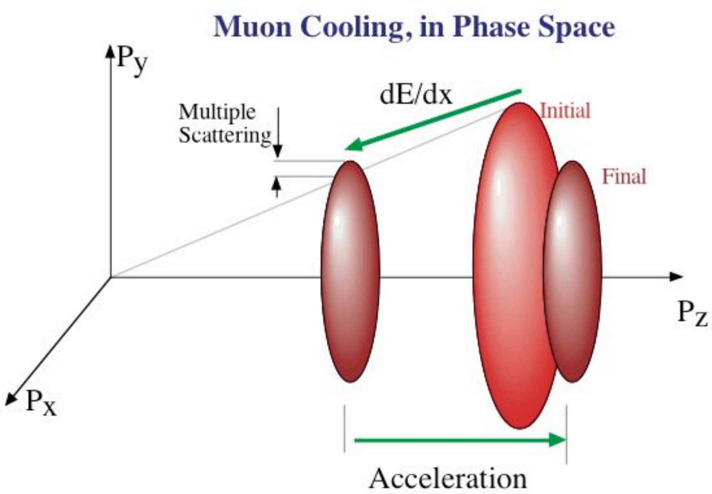
- Cluster emission, Phys. Rev. STAB **7**, 122001 (2004)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.7.122001

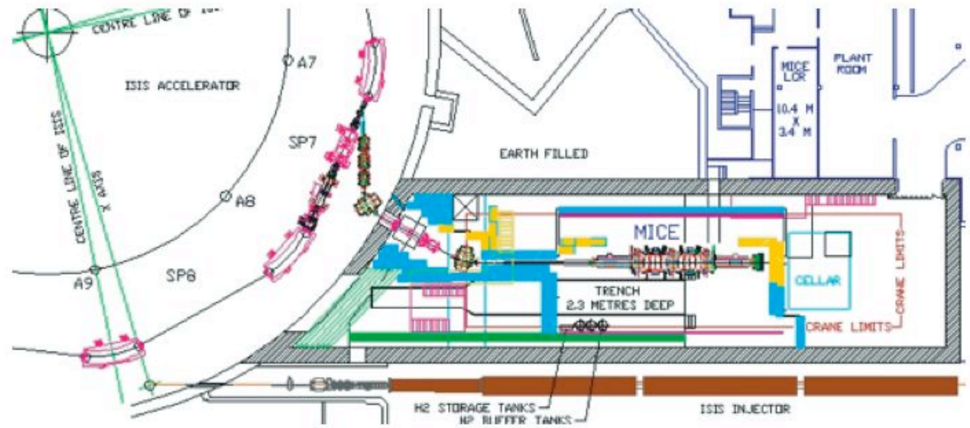
- Magnetic fields, Phys. Rev. STAB **8**, 072001 (2005)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.8.072001

- Surface damage, Phys. Rev. STAB **9**, 062001 (2006)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.9.062001

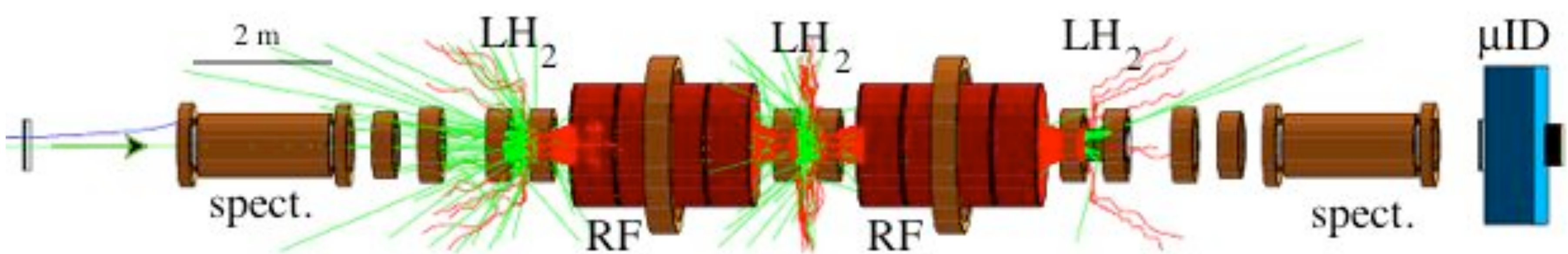
- Breakdown mechanics, Nucl. Instrum. and Meth A **537**, 510, (2005)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0286/muc0286.pdf

MuCool work is directed at MICE (at RAL).





The Muon Ionization Cooling Experiment (MICE)



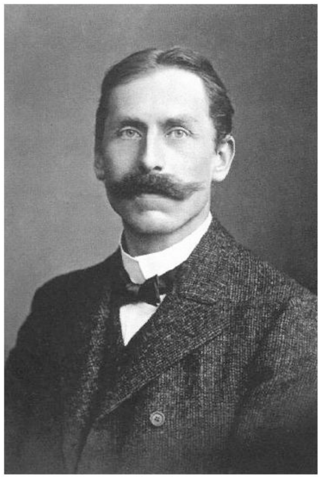
- Needs: 1) Reach full *E* field with 3 – 5 T solenoid.
  2) Reduce backgrounds in spectrometers.

- RF must be operational in 2 years.

The breakdown problem is very old.

Many have contributed - very early:

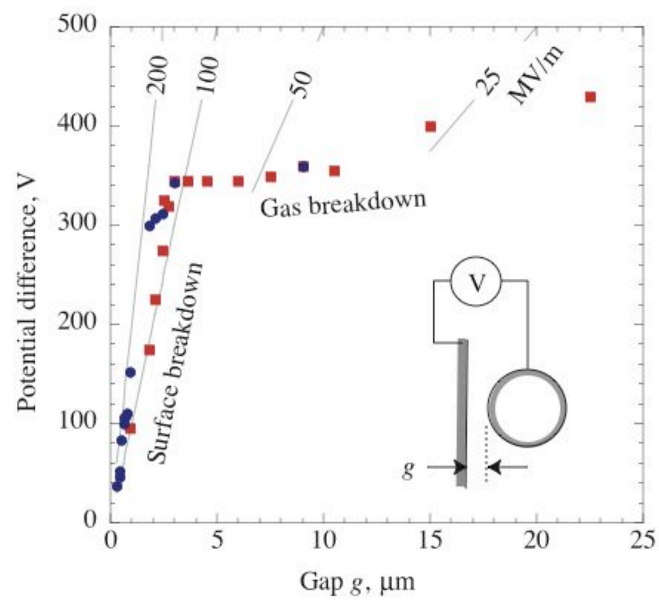
Paschen, Millikan Michelson, Lord Kelvin



In 1904, Lord Kelvin argued that:

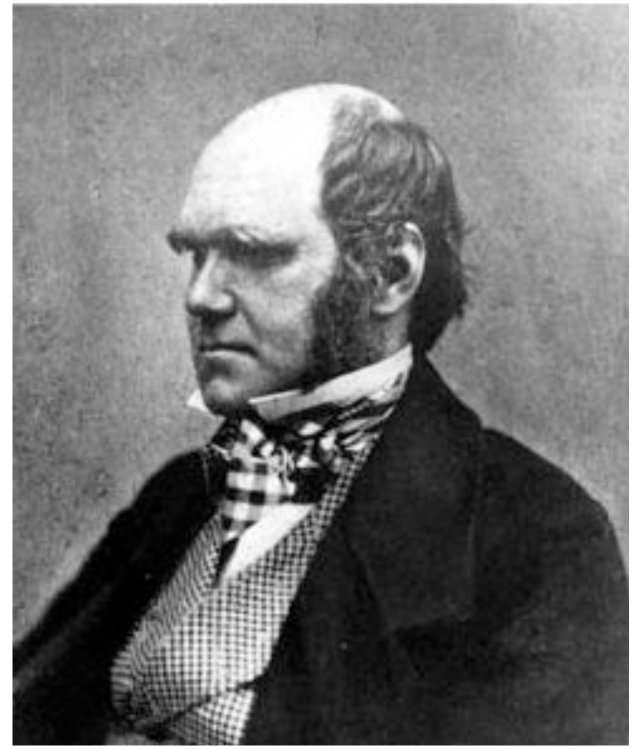
- Field emission is electrons (electrions),
- Electron emission may imply ion emission (damage),
- Local fields of ~ 9.6 GV/m would do this,
- Tensile strength is an important parameter,
- Better experiments are needed.

We agree.



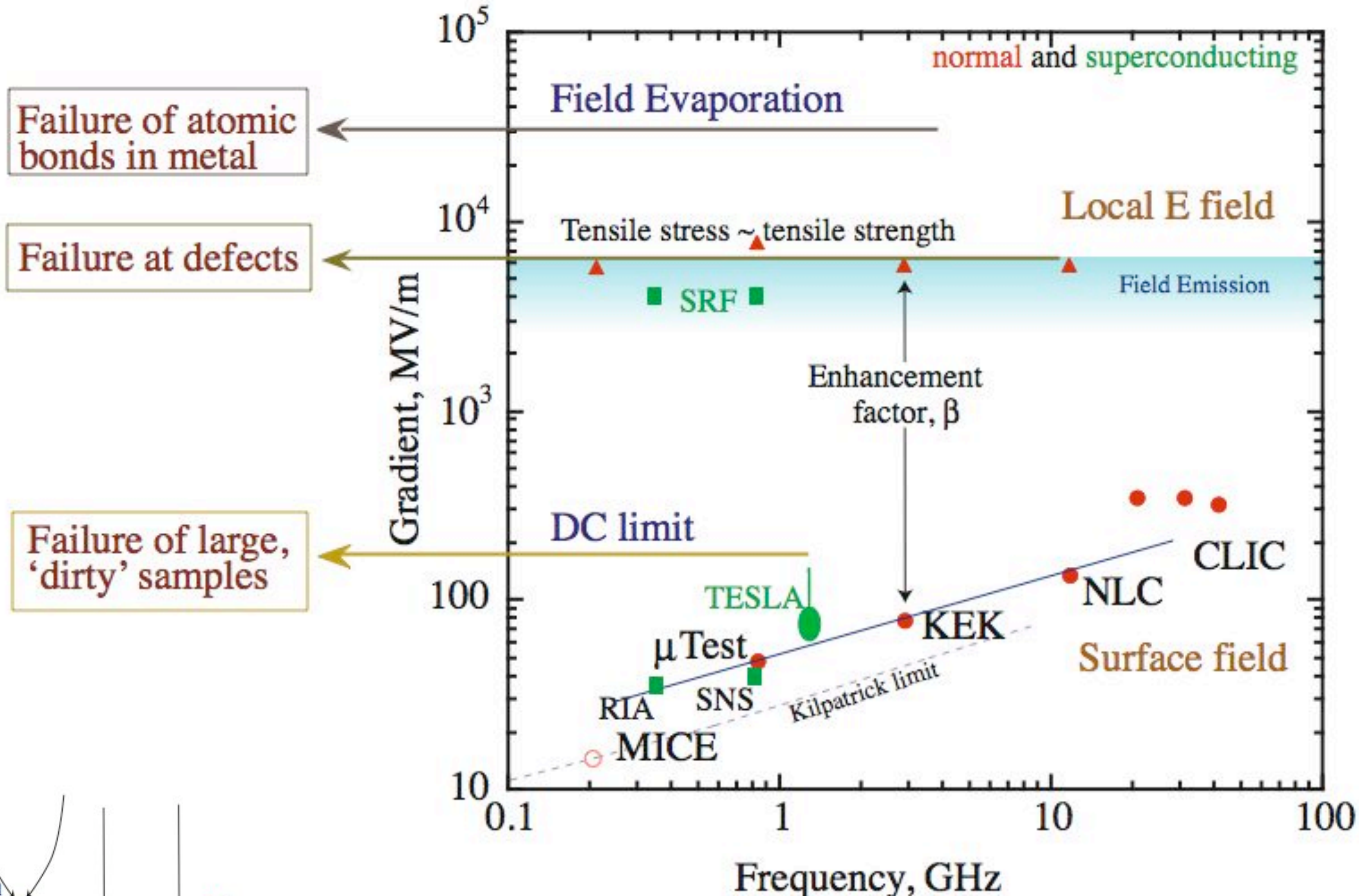
Modeling is necessary.

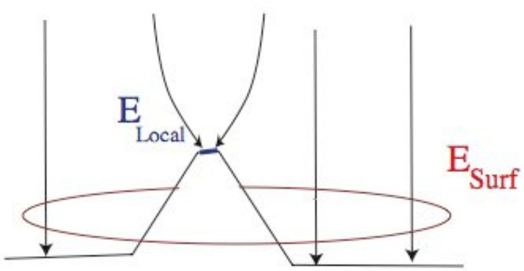
- "About 30 years ago there was much talk that geologists ought only to observe and not theorize; and I well remember someone saying that at this rate a man might as well go into a gravel-pit and count the pebbles and describe the colours. How odd it is that anyone should not see that <u>all observation must be for or against some view if it is to be of any service.</u>"



Charles Darwin, 1861

The high gradient universe.

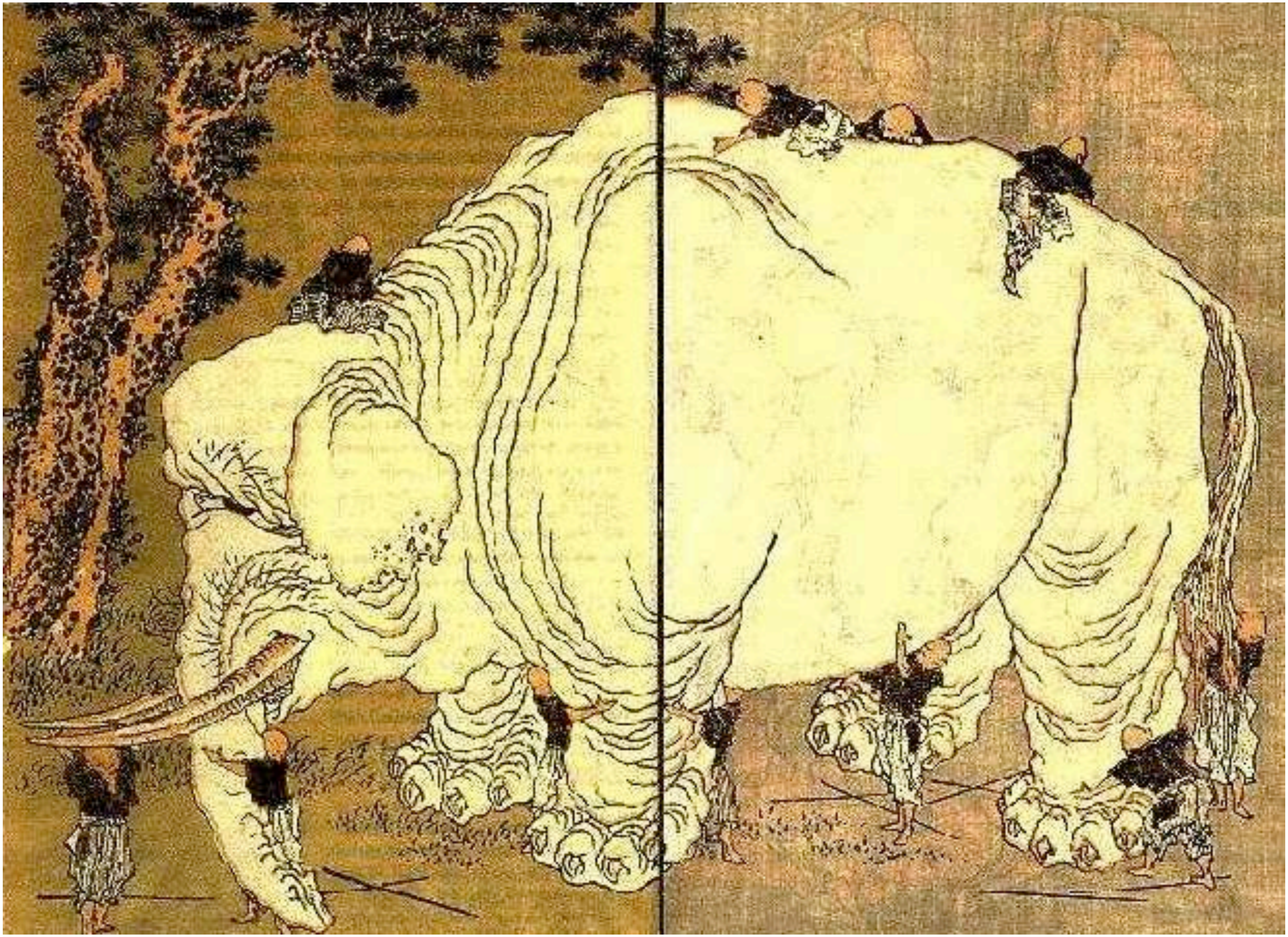




$E_{Local} = \beta\, E_{Surf}$

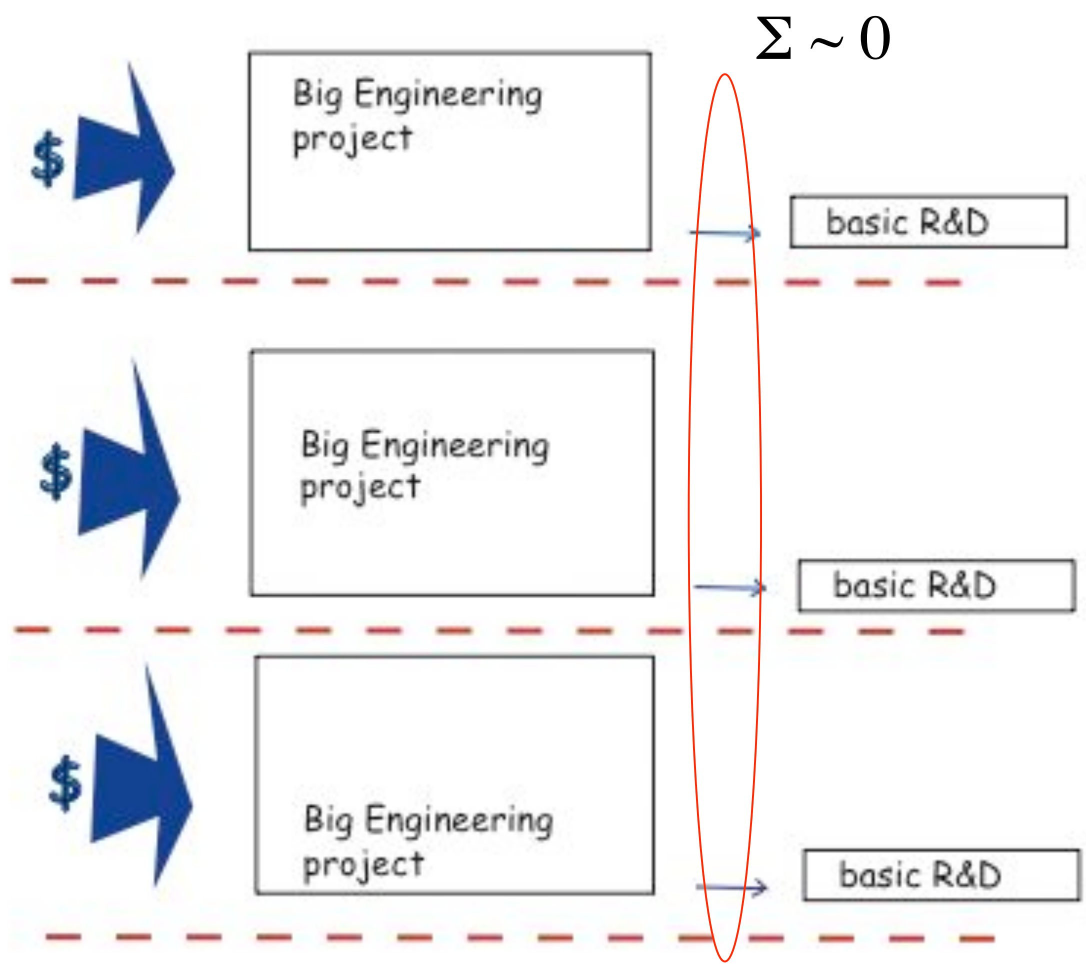
Exp. Problem: Discharges (~GW) obscure the (~W) trigger signal.

Hokusai 1818



Bureaucratic Problem: Funding is divided up.

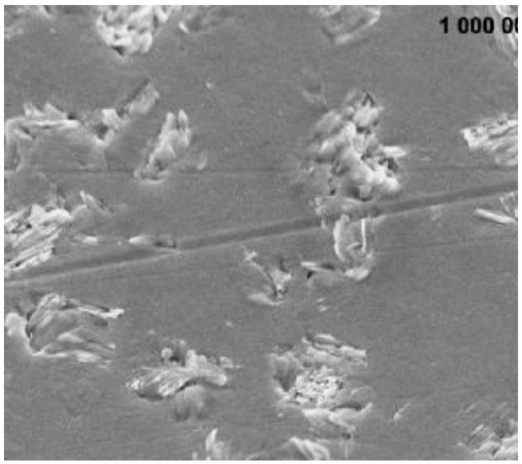
- Individual Projects are funded.
- Each decides R&D priorities separately.
- Basic R&D is not coordinated



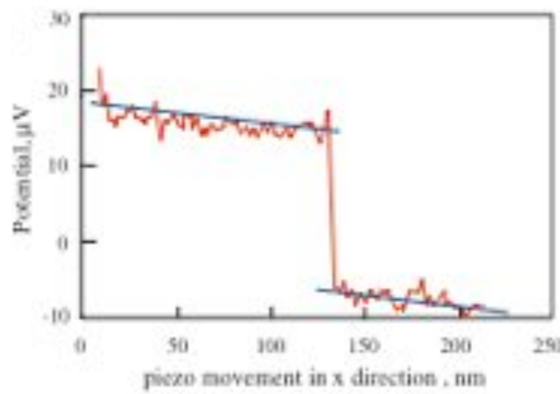
Can ILC and CLIC be limited by the same mechanism?

CLIC and ILC may be limited by the same mechanism, but the two problems cannot be studied together - and aren't studied separately.

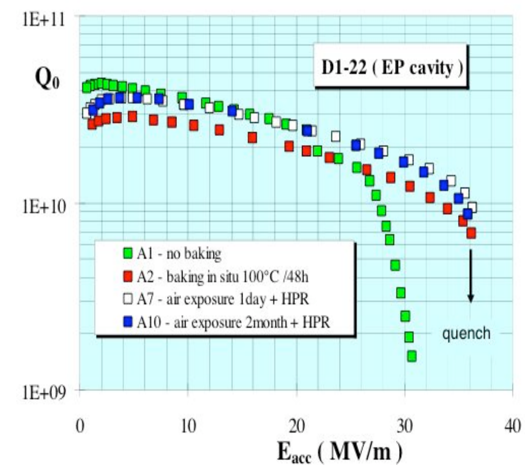
CLIC Fatique studies



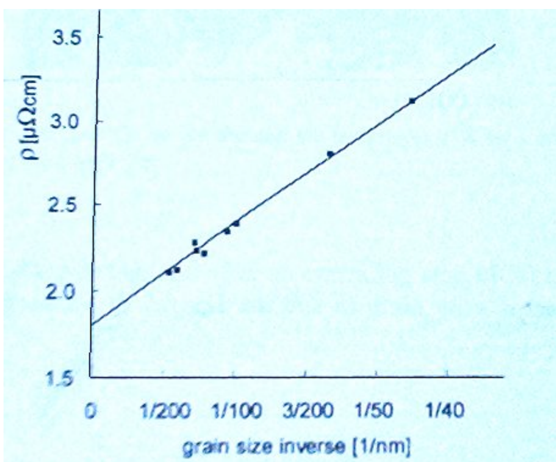
Grain boundary

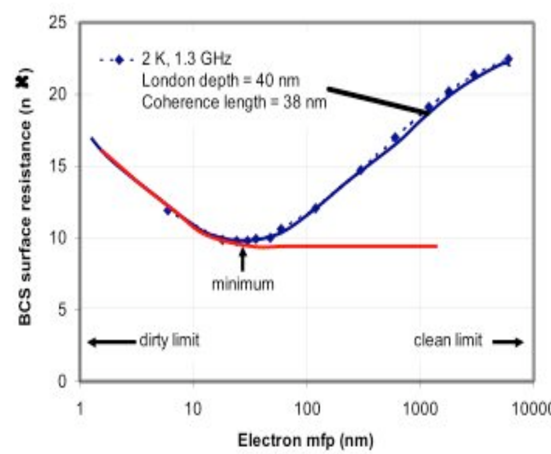


High Field Q-Slope



$\rho \sim n_{GB}$





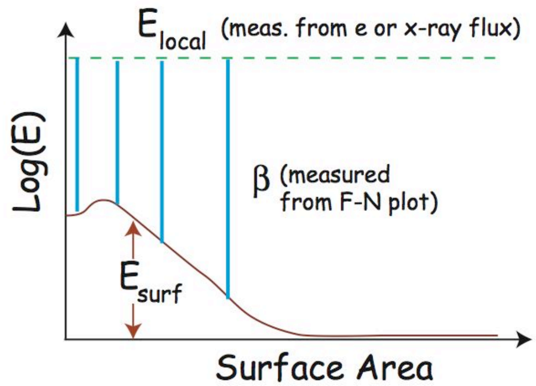
SCRF

Cultural problem: Finer Points

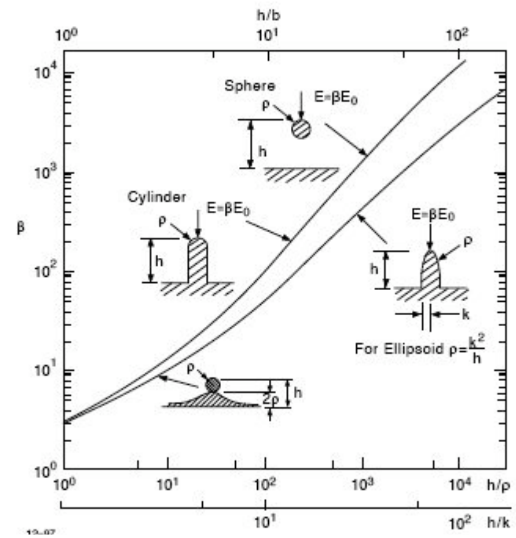
- Fowler-Nordheim plots give didfferent information - and are non-intuitive.

  We need E_{local} not β.

  E_{surf} is not a constant.



- Sharp points produce βs, not "telephone poles".



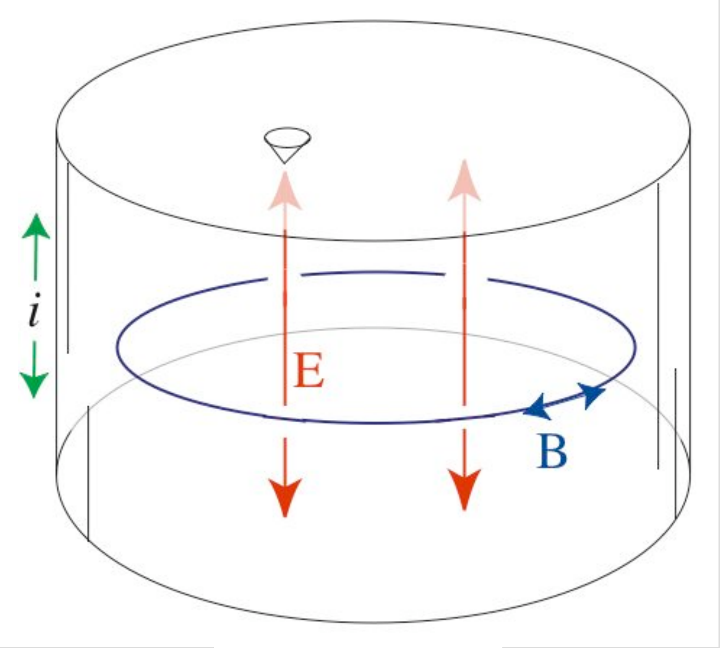
Why structures fail.

Normal metals

- Stresses from electric fields exceed material tensile strength.
  $E \sim 7$ GV/m

Superconductors

- Field emission heats cavity before tensile stress limit.
  $E \sim 4$ GV/m



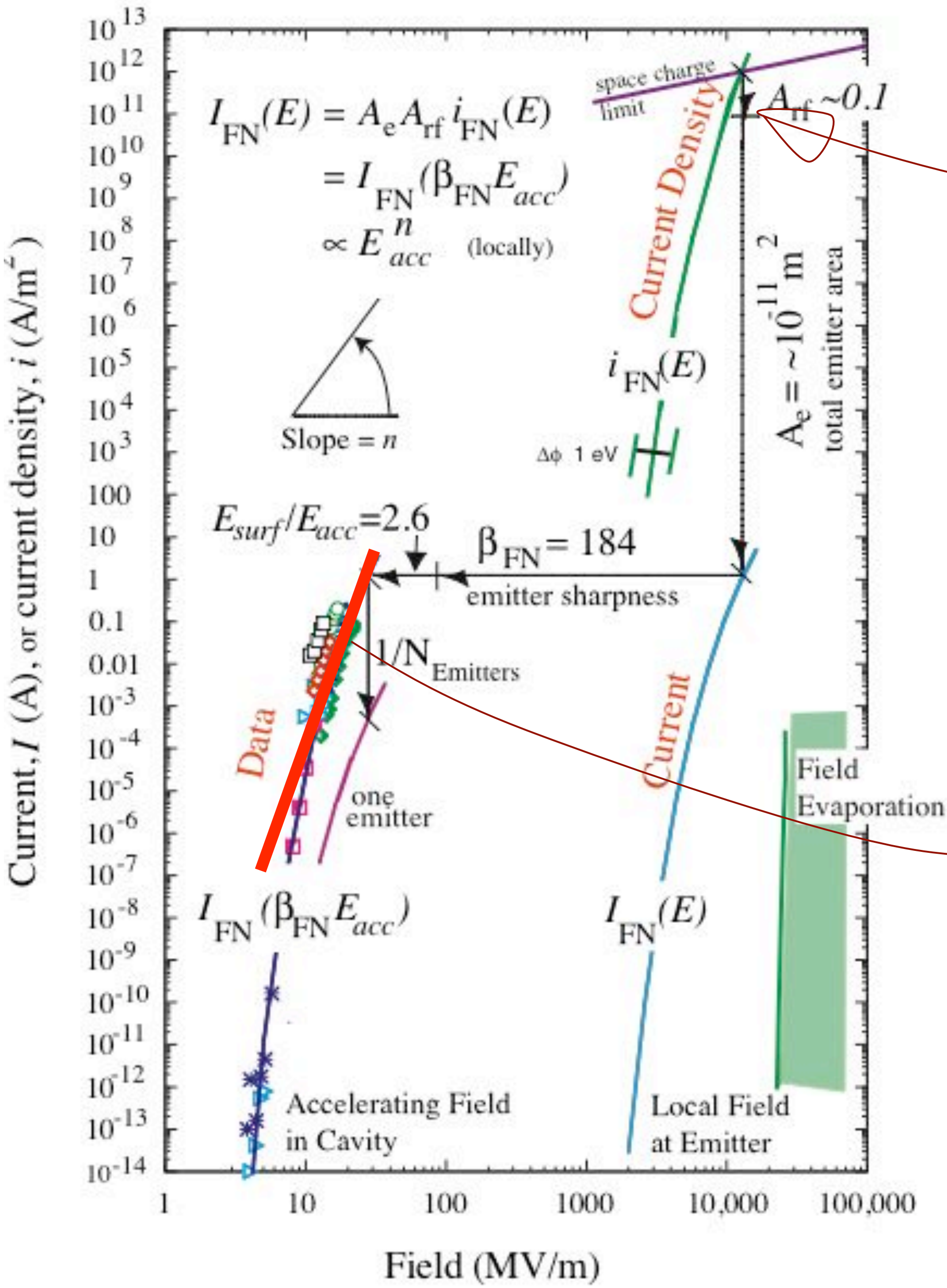
Normal metals

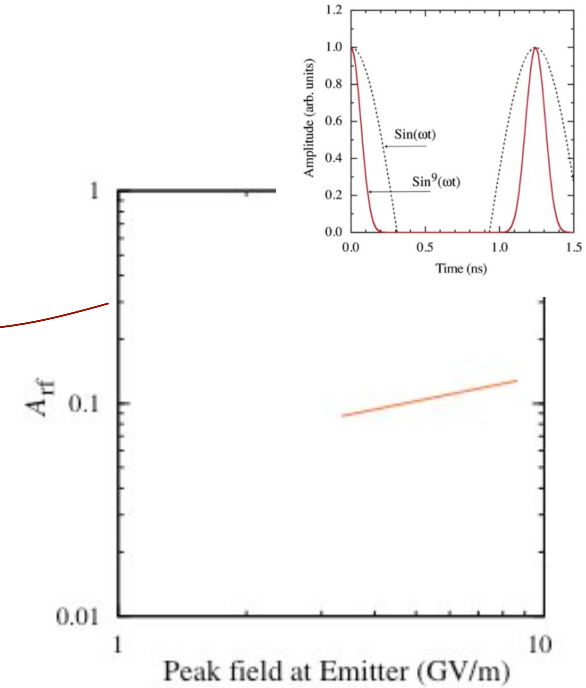
- Skin currents damage walls.
  $\Delta T \sim 100^0$

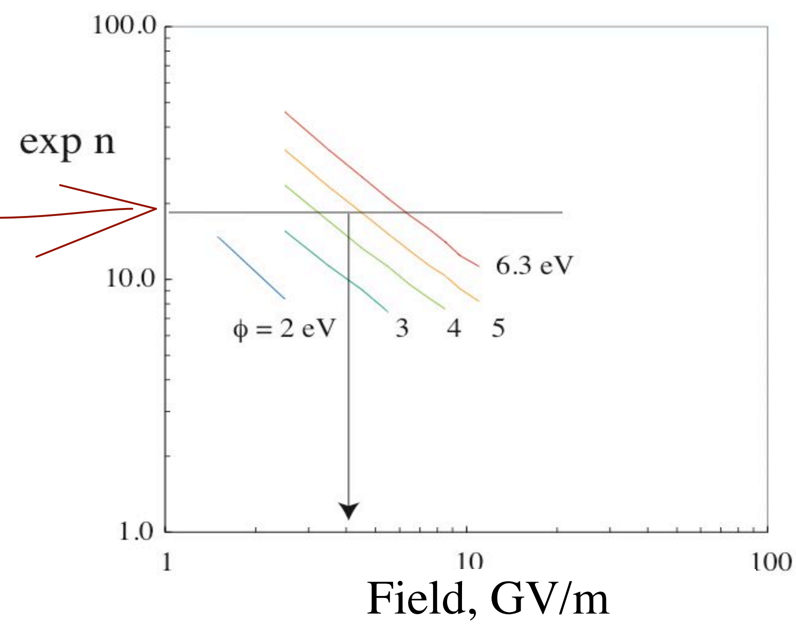
Superconductors

- $B > H_{c1}$, material goes normal
  $B \sim 180$ mT

We measure the local fields directly.



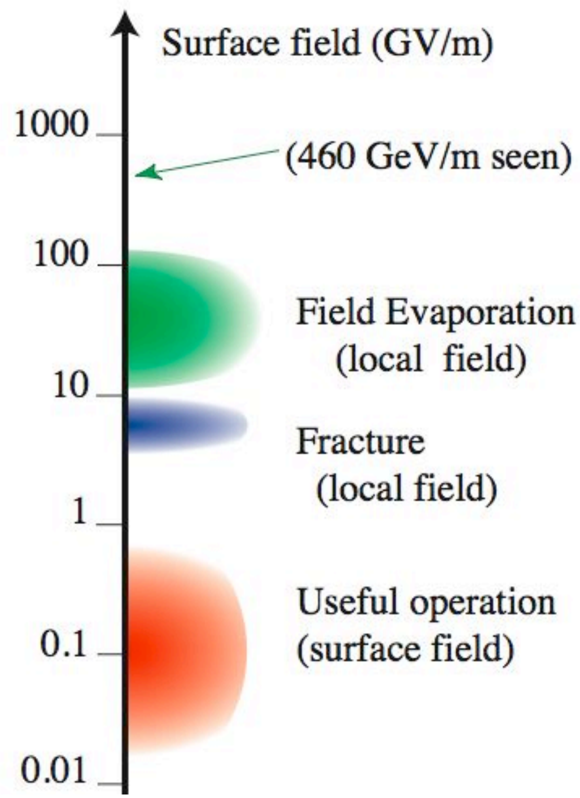




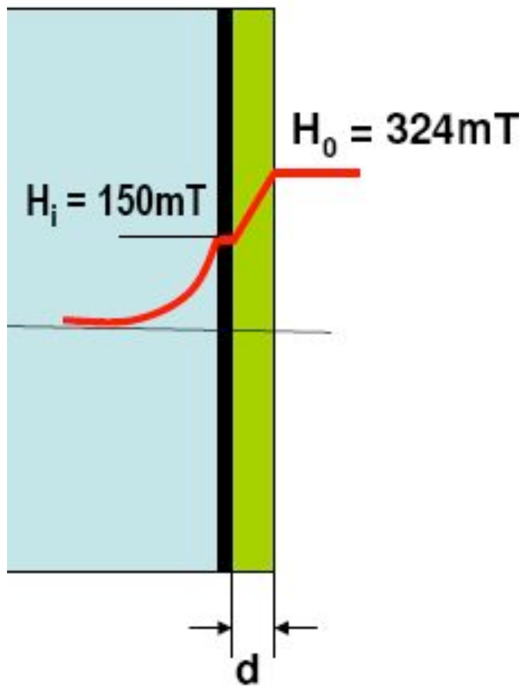
What are the limits of acceleration technologies?

- The conventional wisdom, Metals limited to 50 – 70 MV/m, seems wrong.

Normal Metal

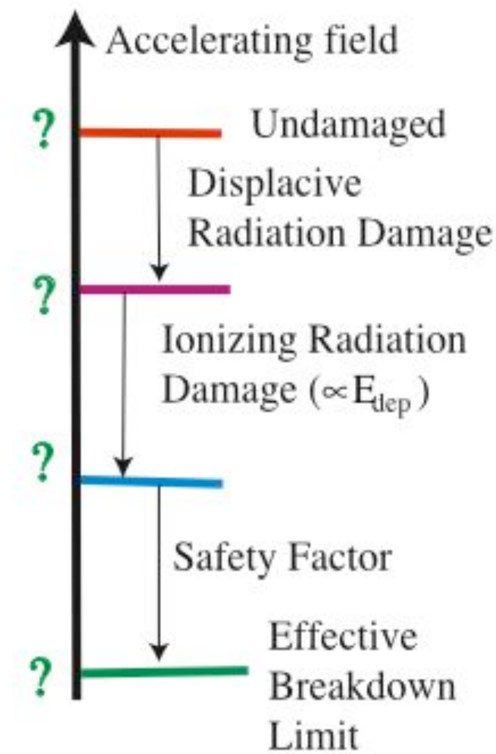


SuperConducting RF



Gurevich layers

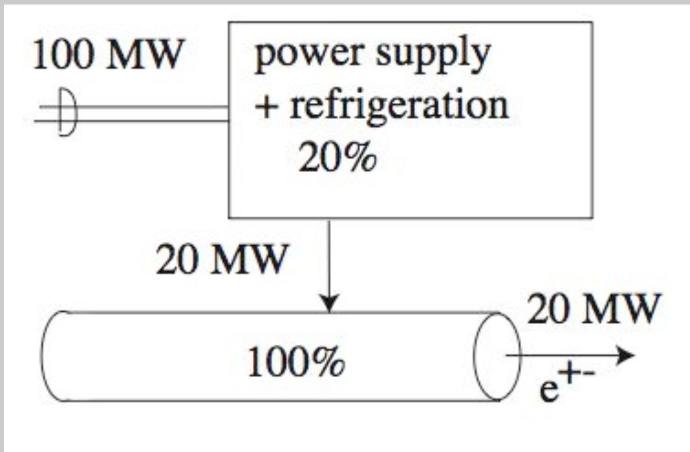
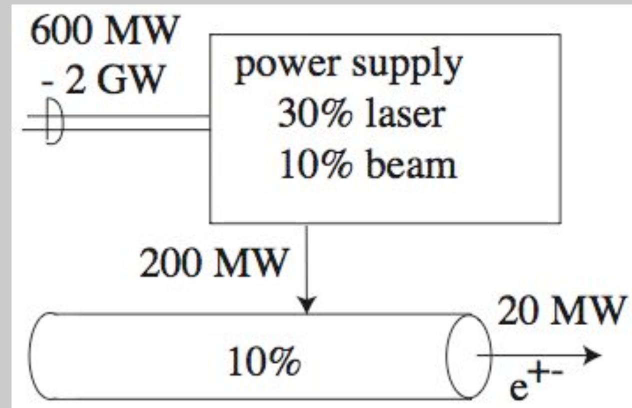
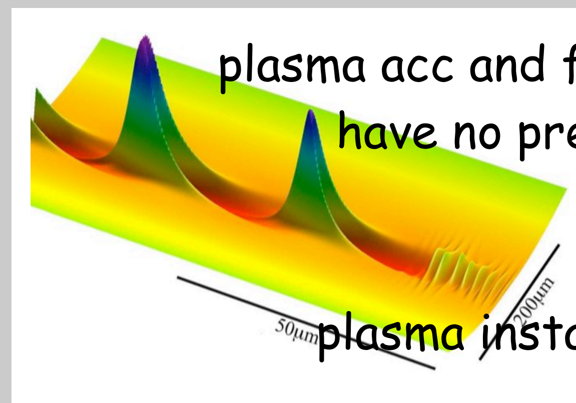
Dielectrics



- **Limits are unknown, material science needed.**

Metal surfaces required for power eff., stability, and control.

- If $\mathcal{L} = (1/2\pi E)(N/\sigma_x^*)(P/\sigma_y^*)$, high energy operation demands:

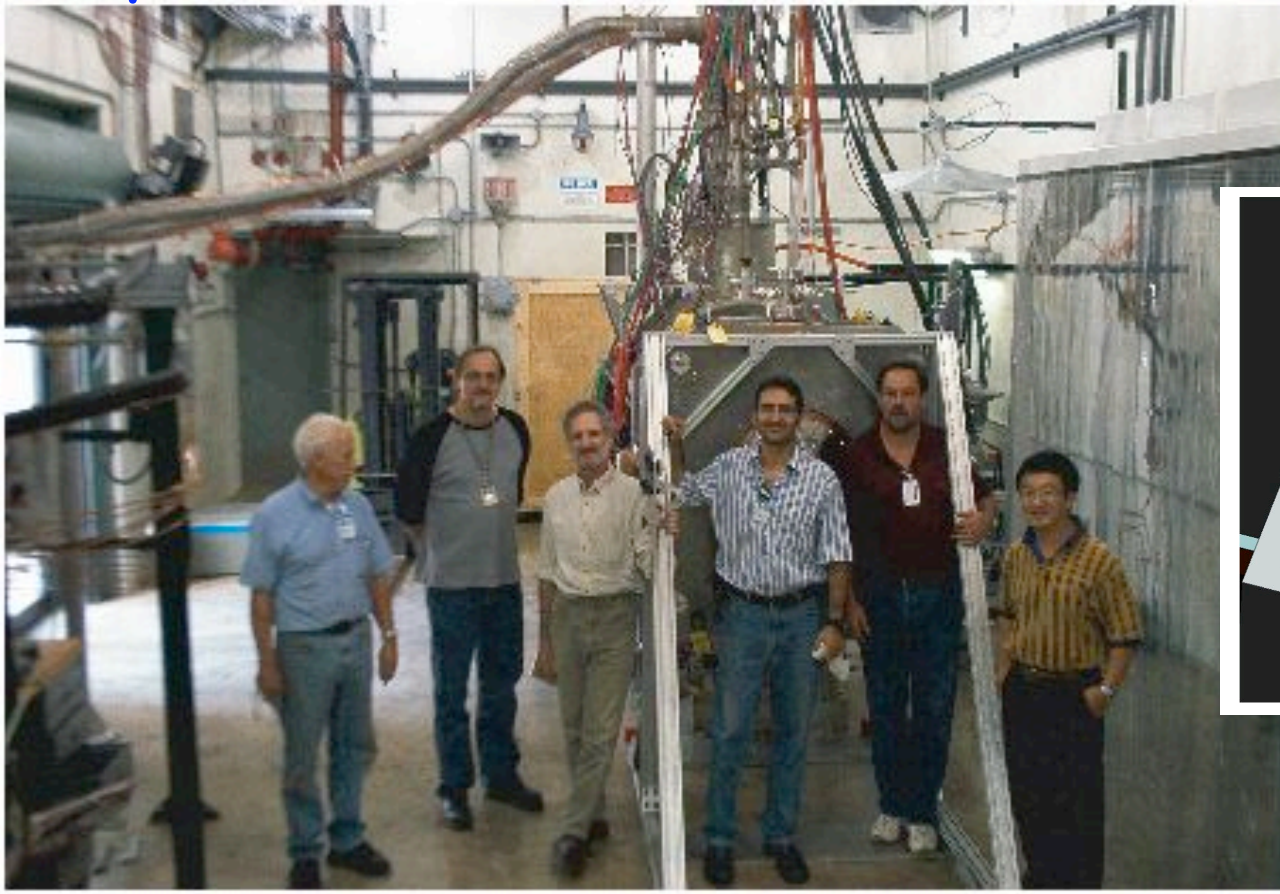
	ILC	Plasma Accelerator
• Efficiency		
• Stability	Quads and structures give 1 nm beam stability	 plasma acc and focusing have no preferred axis; plasma instabilities
• Control	FF chromatic correction and flat beams required for nm beam size	Strong aberrations limit precision, focusing str. ~ f(r,z, q)

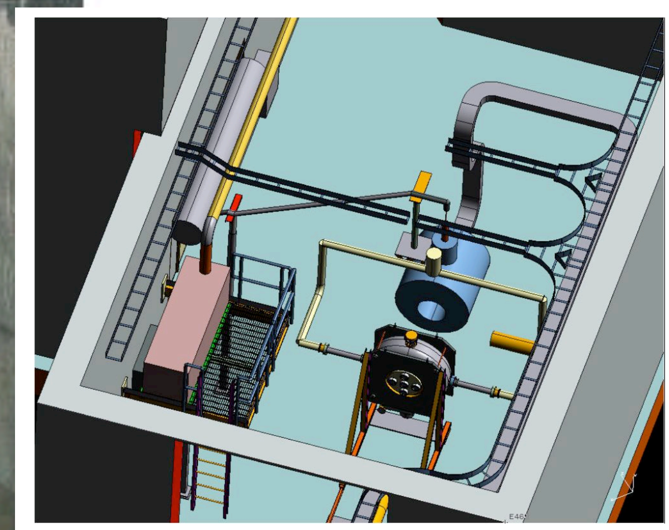
People

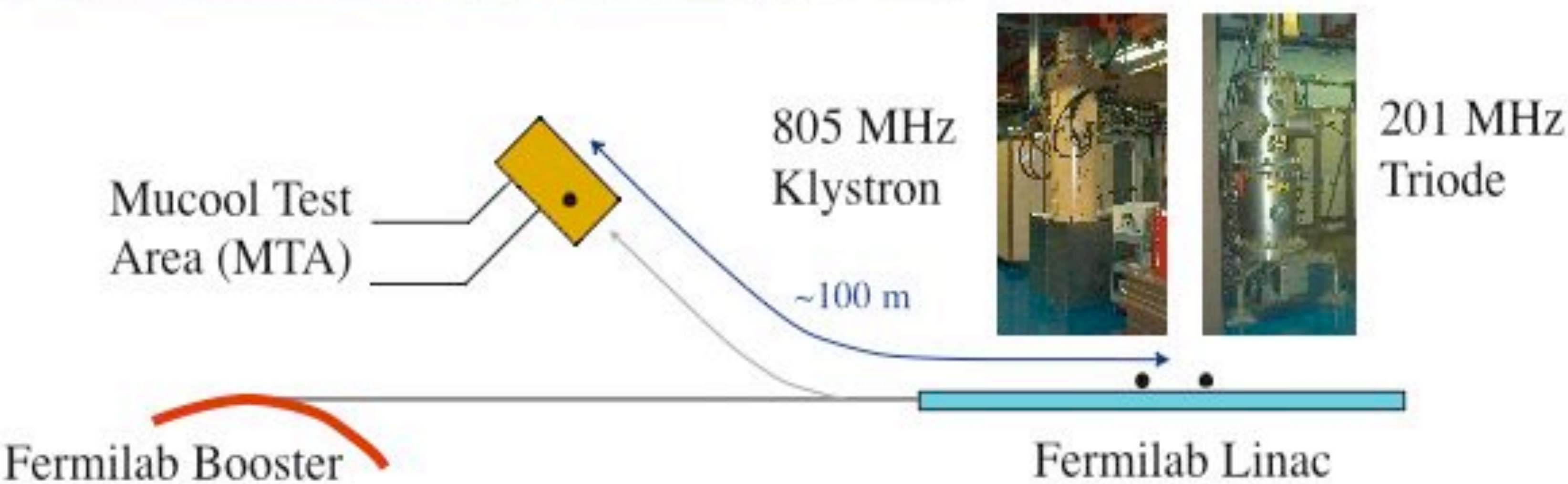
Part of the Neutrino Factory and Muon Collider Collaboration - Muon Cooling

- Experiments in Fermilab MuCool Test Area (MTA) , aimed at MICE
  - J. Norem, Argonne
  - A. Moretti, A. Bross, Z. Qian, B. Norris, FNAL
  - Y. Torun, IIT
  - D. Li, M. Zisman, S Virostek LBNL
  - R. Rimmer, JLab
  - R. Johnson, P. Hanlet, et. al, Muons Inc.
  - + many others
- Modeling of breakdown and cavity parameters
  - Z. Insepov, A. Hassanein, ANL
- Surface studies with Atom Probe Tomography at Northwestern Univ.
  - D. Seidman, K. Yoon, NW Univ.
- Plasma modeling (B and gas effects)
  - P. Stoltz, Tech-X Corp.

RF experiments are in the MuCool Test Area (MTA) at Fermilab



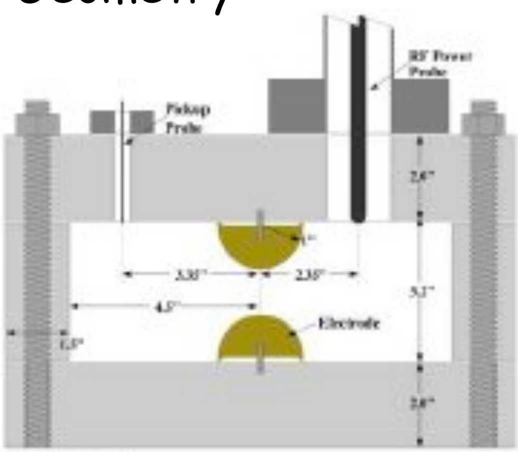




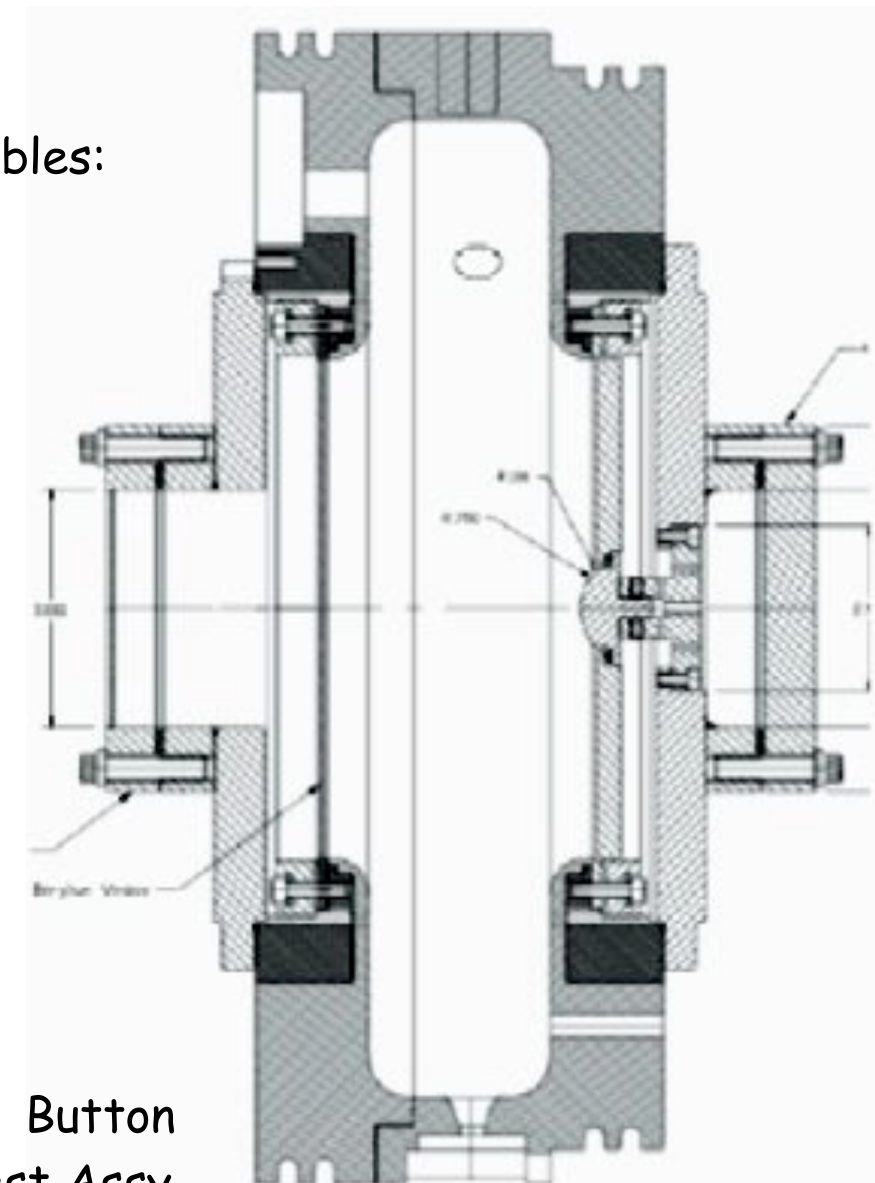
Our 805 MHz program.

We have unique hardware, can study many variables:

- Operation: 201 vs. 805 MHz.
- Magnetic field: 0 – 5 T solenoid on the 805.
- Materials: Cu, Be, SS, Mo, Mo(alloys), W, Nb
- High Pressure (Muons Inc.) H_2 and He
- Window Geometry



Muons Inc.

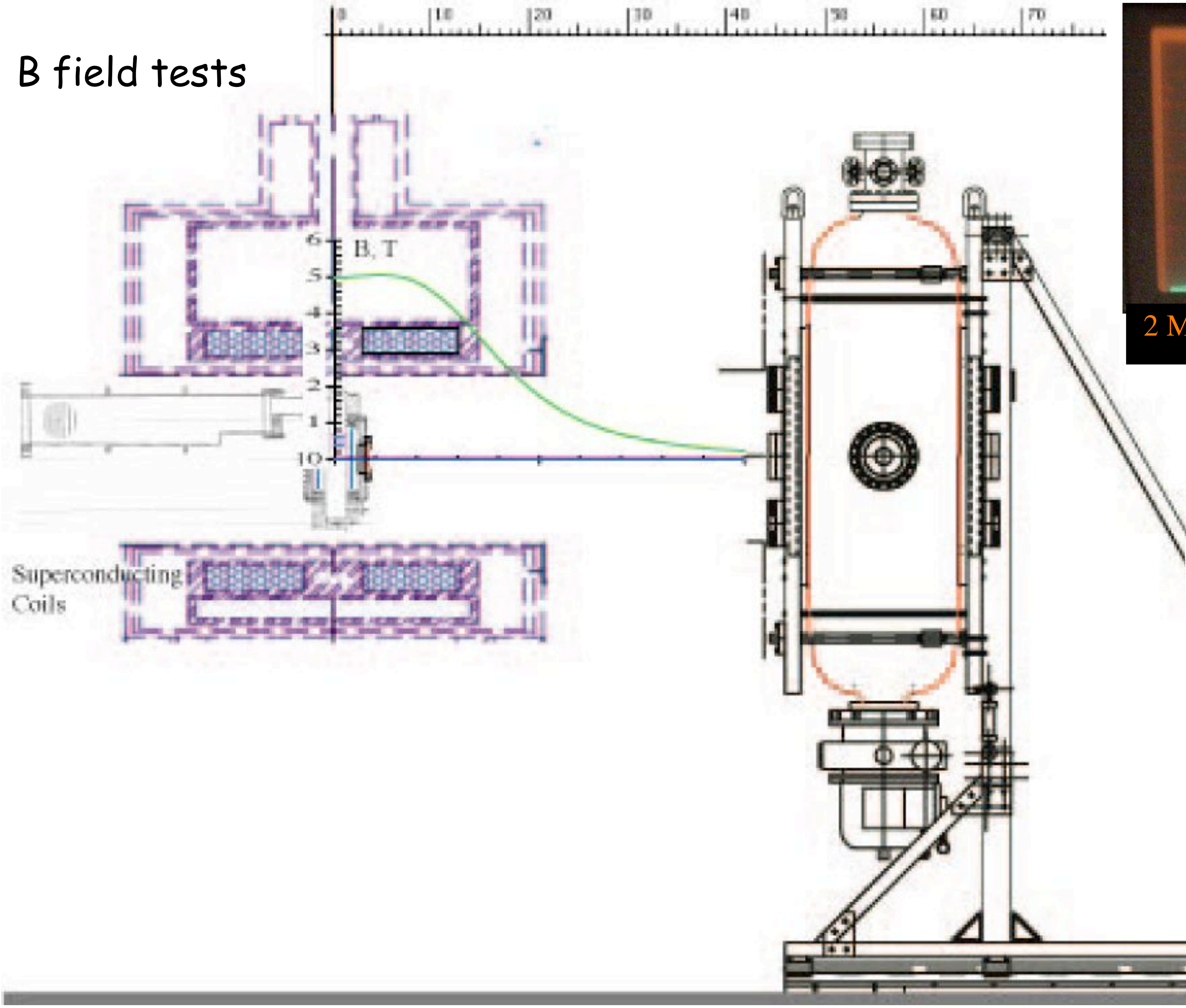


Button Test Assy.

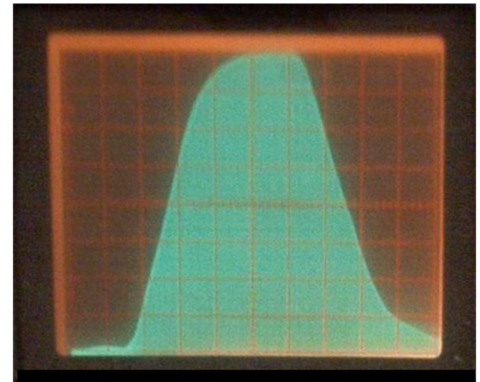
201 MHz Program.

- Conditioning / breakdown, window tests.

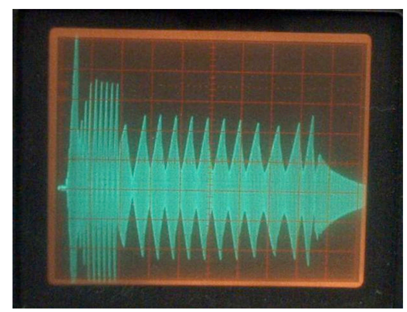
- B field tests



16 MV/m with B=0



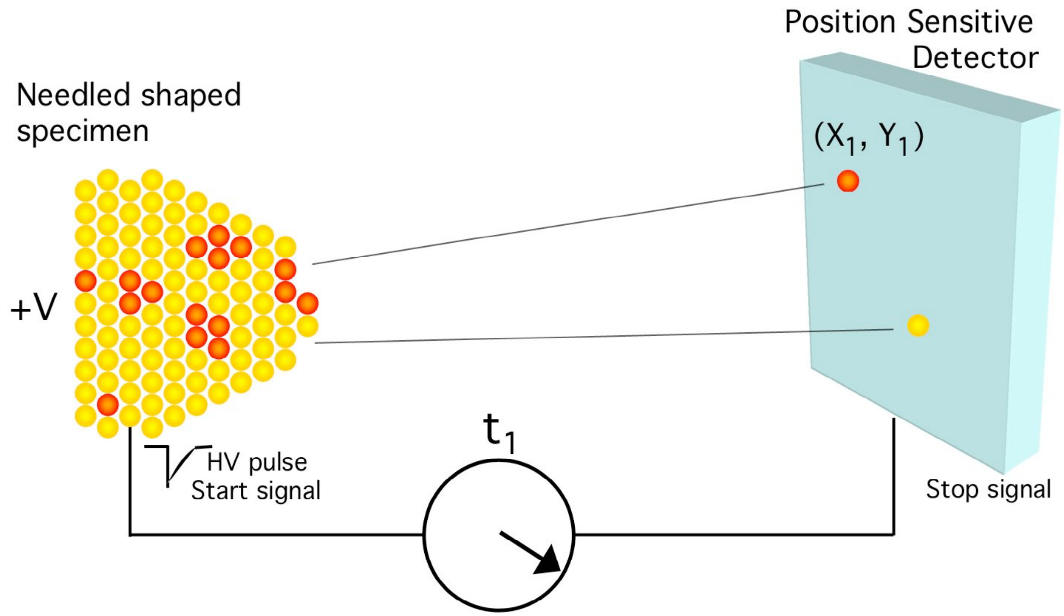
2 MV/m / div, 0.1 ms / div

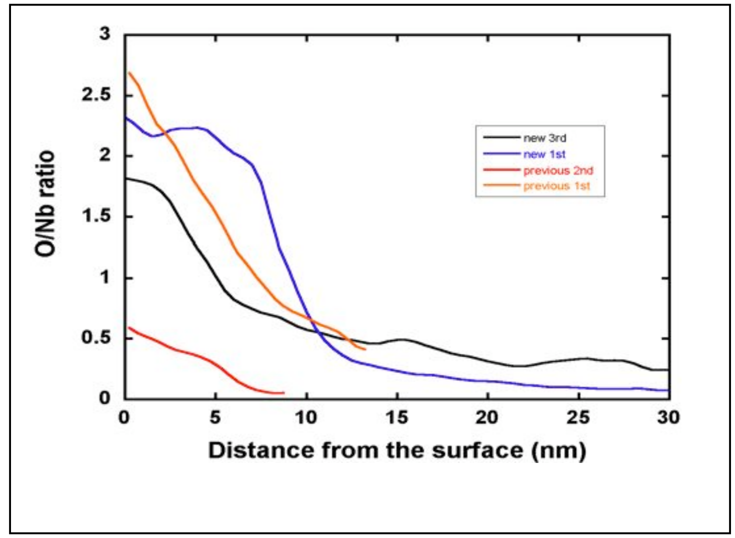


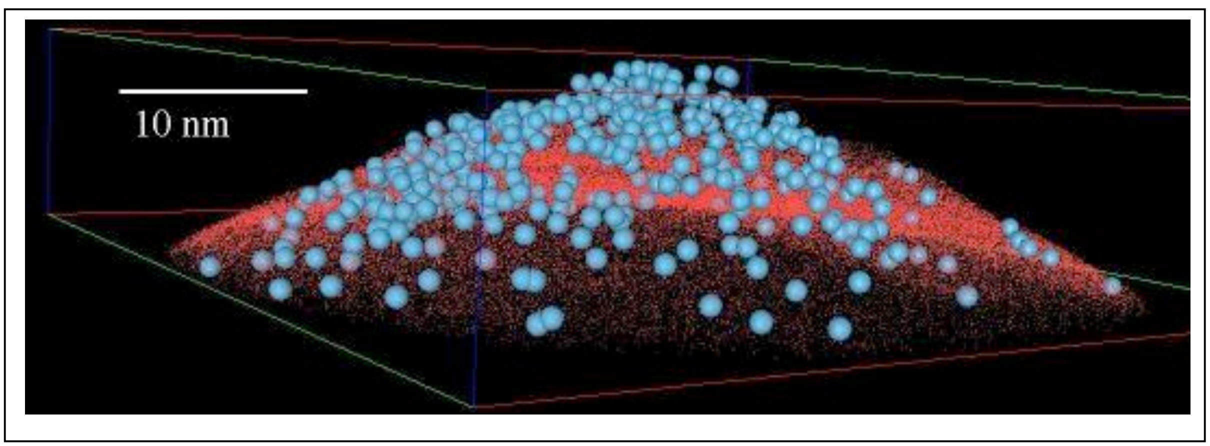
Multipactor with B

Atom Probe Tomography (at Northwestern)

- A systematic way of studying the effects of high fields on material.



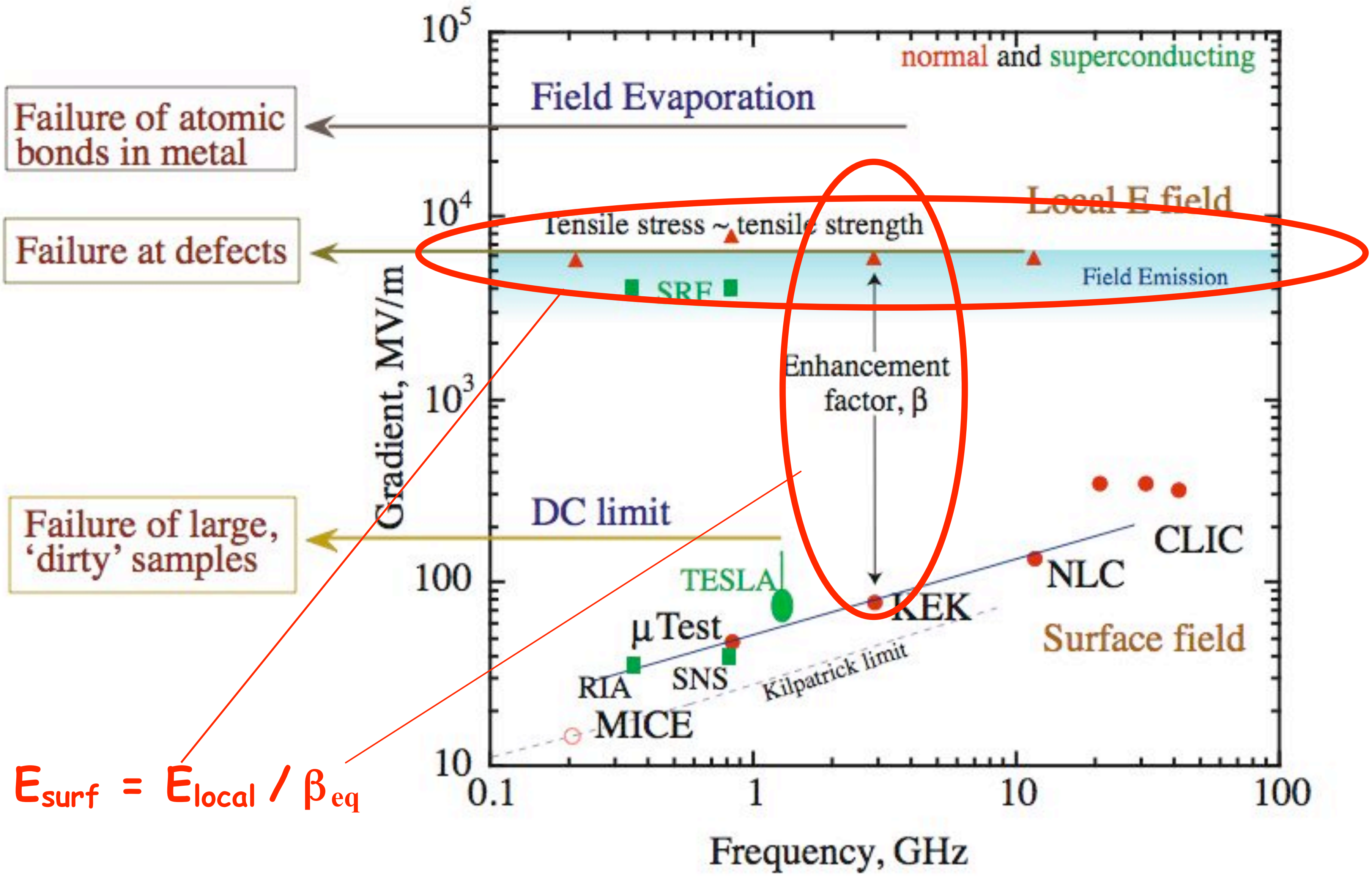




NUCAPT
Northwestern University
Center for Atom-Probe
Tomography

<u>500 GeV/m</u> accelerations !

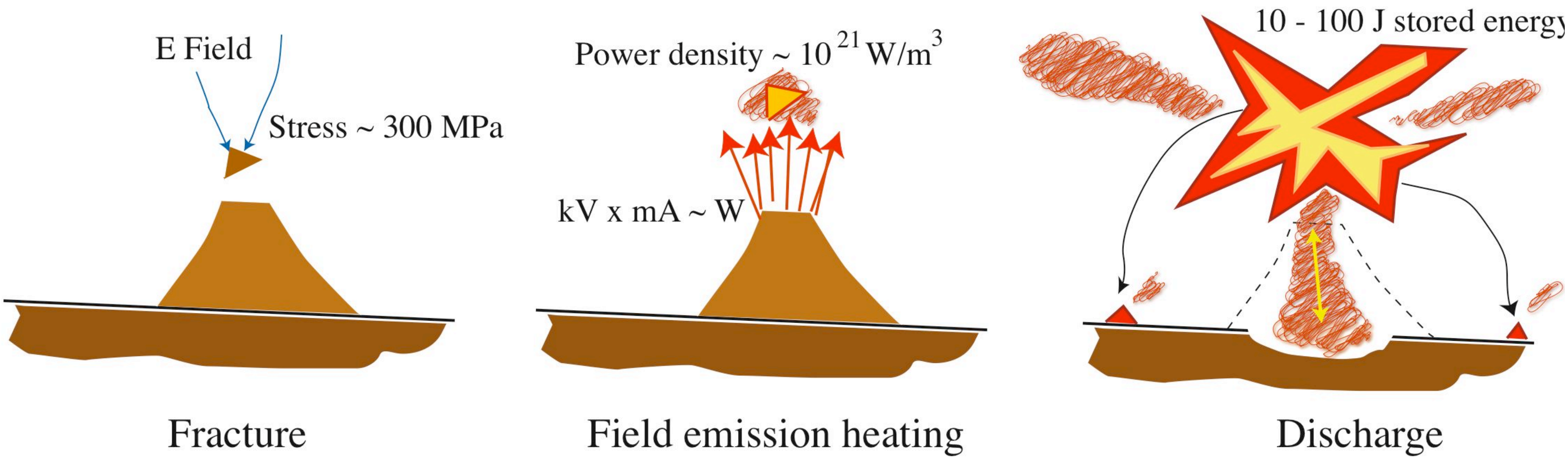
The Model: Local fields + enhancements determine everything.



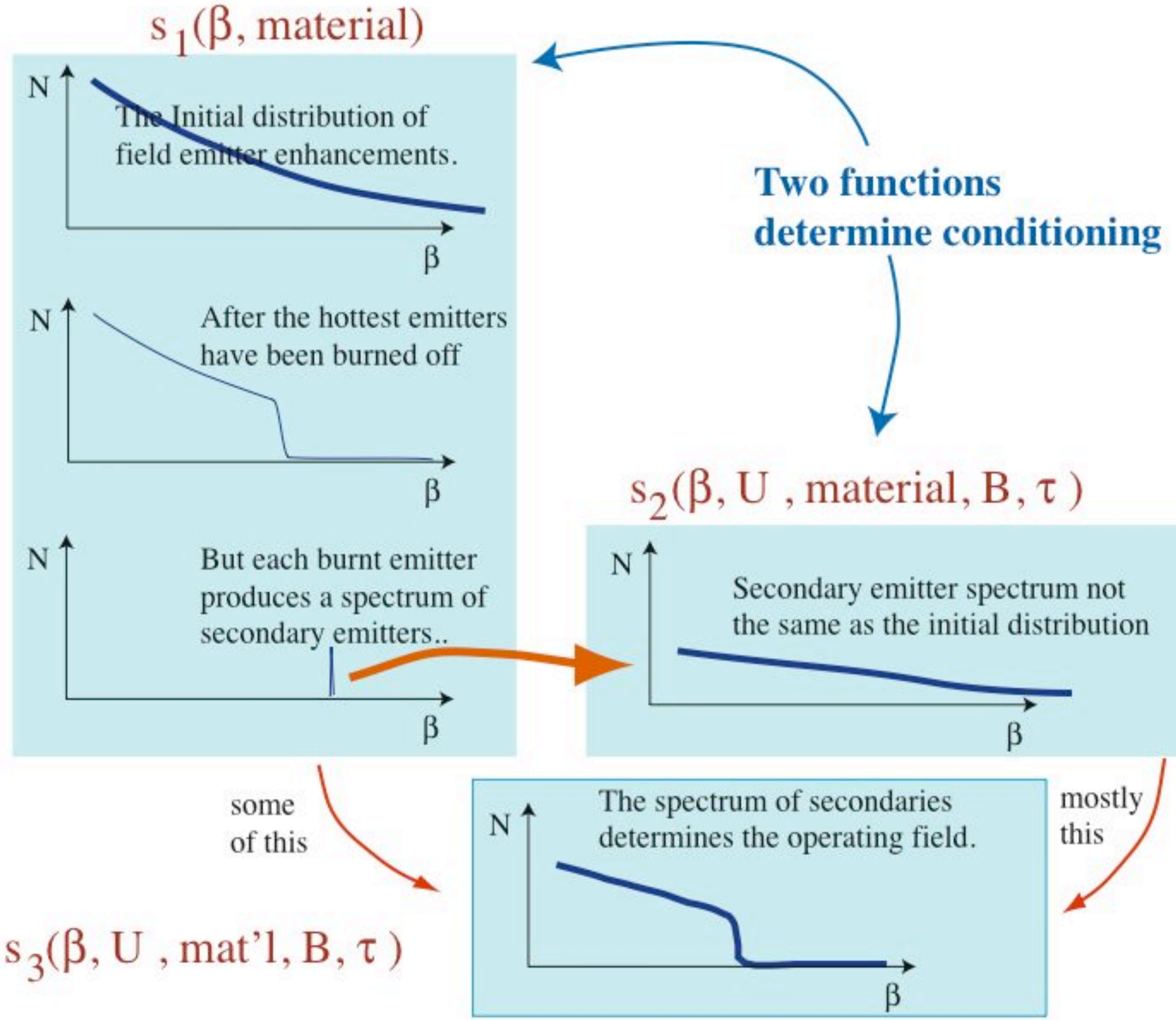
$E_{surf} = E_{local} / \beta_{eq}$

The Process of Breakdown

- Field emission is the diagnostic.
- Fracture is the trigger, $\sigma = \varepsilon_0 E^2/2$.
- Field emission heating produces a lossy plasma.
- The lossy plasma directs the EM energy to the wall.
- An equilibrium state develops between the structure and the surface.

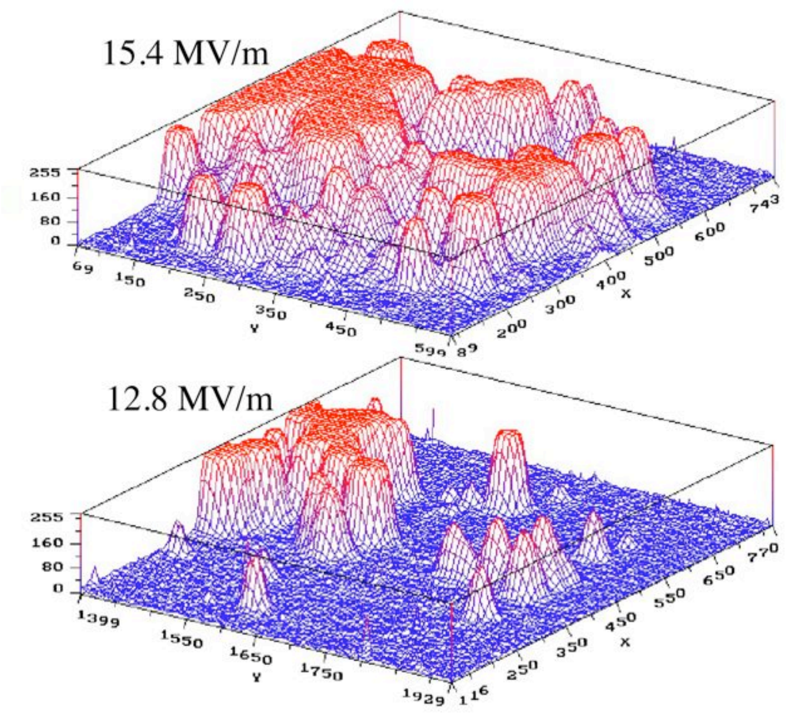


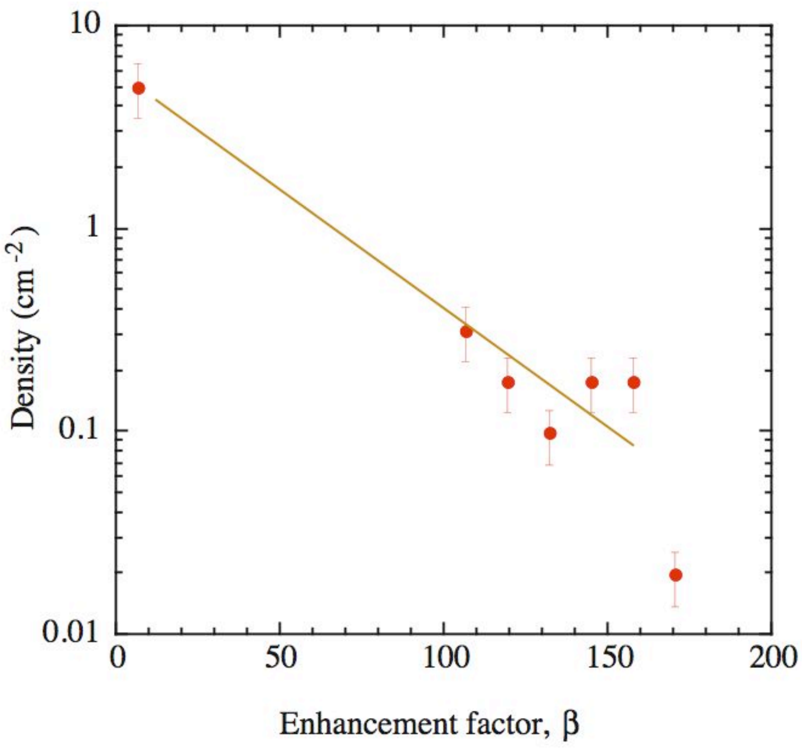
Spectra of field emitters (enhancement factors)



We have measured $s_2(\beta)$ during cavity operation.

- We looked at individual emitters, and measured spectra produced in discharges





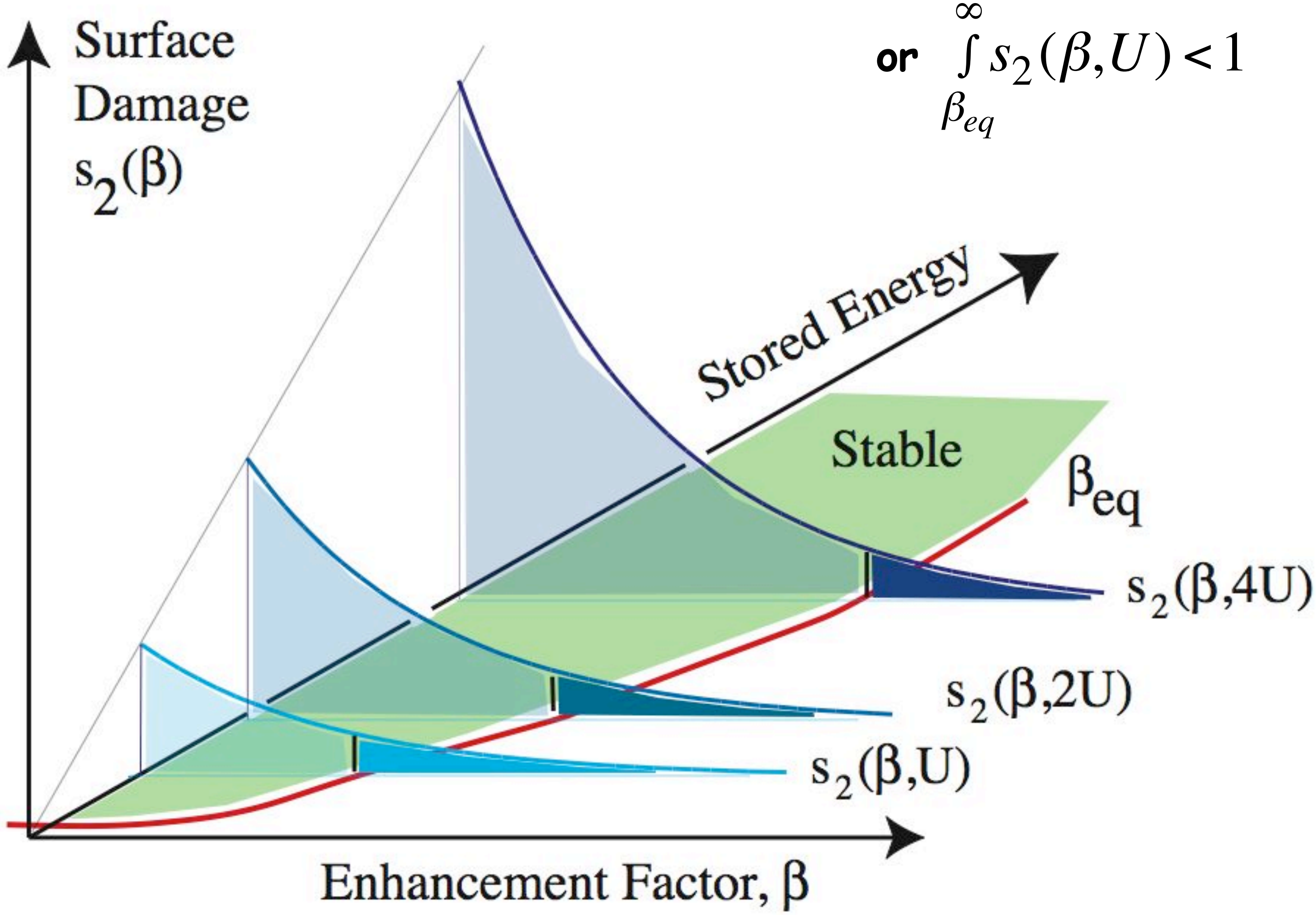
- The spectrum of enhancements seems to be a "Maxwell Boltzmann" like exponential.

- We assume the spectrum is proportional to the energy in the discharge.

The maximum operating field

- **Stable operation demands that:**

  Breakdown events cannot create more damage than they destroy.



or $\int_{\beta_{eq}}^{\infty} s_2(\beta,U) < 1$

There is a lot of data around:

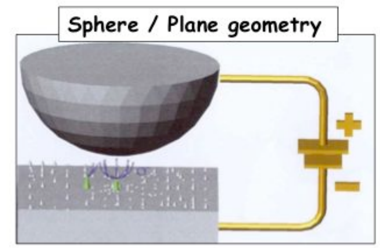
	fracture	heating	plasmadebris		Who
Breakdown rate vs. E	X	X		X	all
Breakdown rate vs. pulselength				X	S
Breakdown rate within pulse	X				CS
Materials	X		X	X	CSKF
Conditioning process	X			X	all
Magnetic fields	X	X	X	X	FMA
Breakdown timescale	X	X			all
Frequency scaling				X	all
Small gap breakdown	X				C
DC breakdown	X			X	C
Disappearance of field emitters			X		F
Fatigue	X				CF
Atom Probe Sample failure	X				A
Surface morphology	X			X	AF
Plasma spots		X			S
Crater clustering				X	SF
Correlated events, site lifetime	X				SFA
Superconducting systems				X	AF
Temperature	X				AC
High current densities in walls		X		X	FAC
Gas, type and pressure		X		X	M
Measure $s_1(\beta)$, $s_2(\beta)$, $s_3(\beta)$			X	X	AF
Triggers X					all
Special cavities	X	X		X	S
Geometry				X	all
Power supply				X	all
Lightswitches	X				all

Who is doing what: FNAL, ANL, SLAC, Muons Inc., CERN, KEK

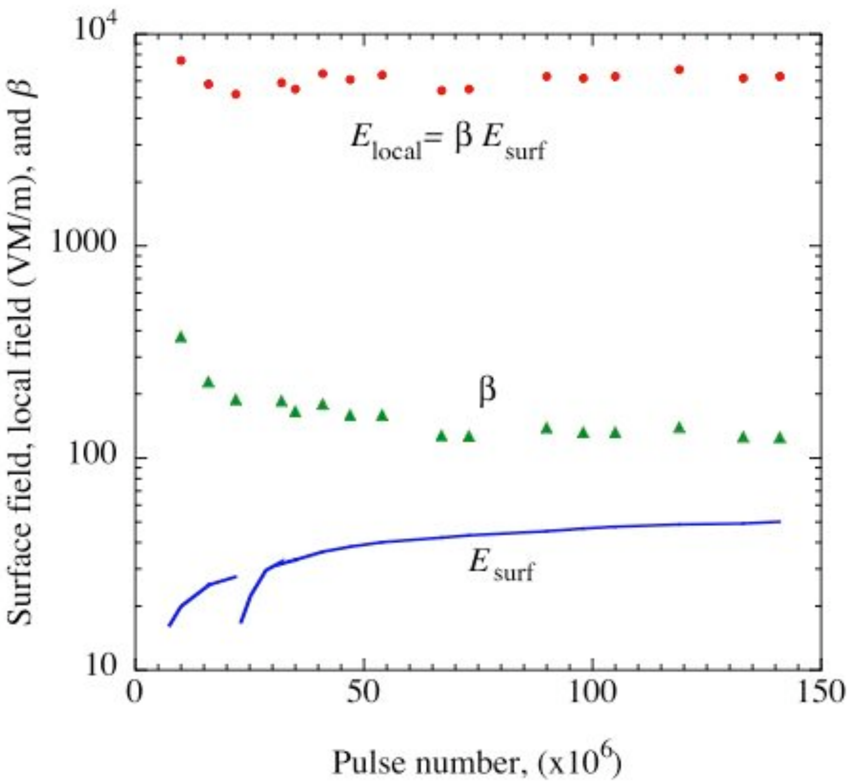
Using the model: I) Conditioning

- Breakdown occurs when E_{local} ~ 7 GV/m

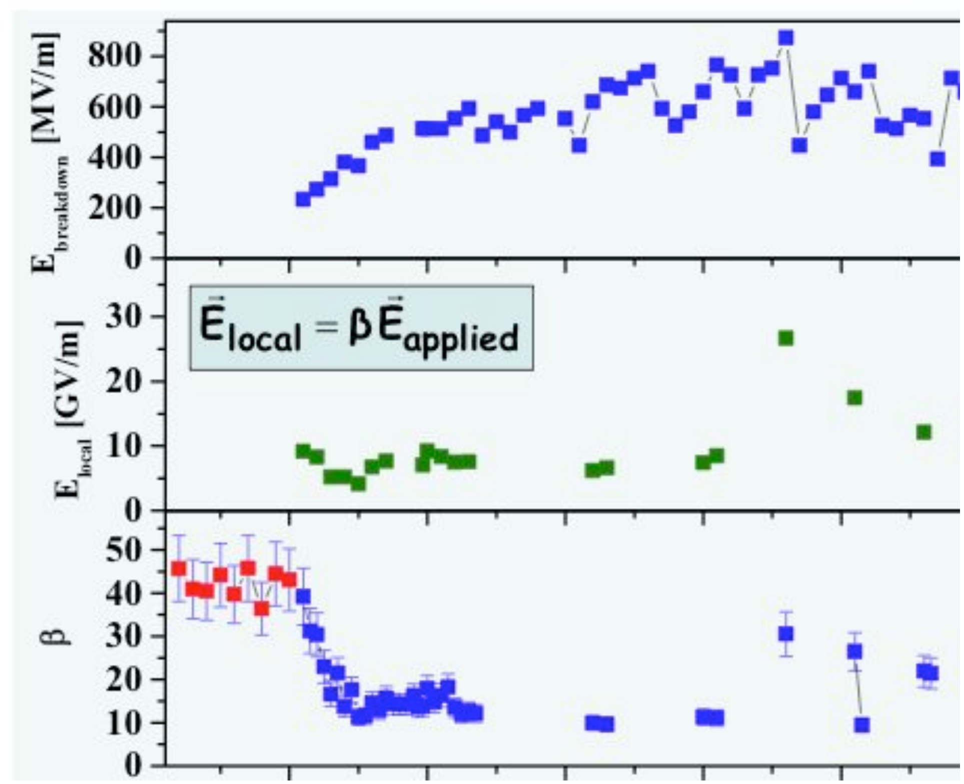
- Only the emitters change, local field is constant.



KEK linac



CERN DC test

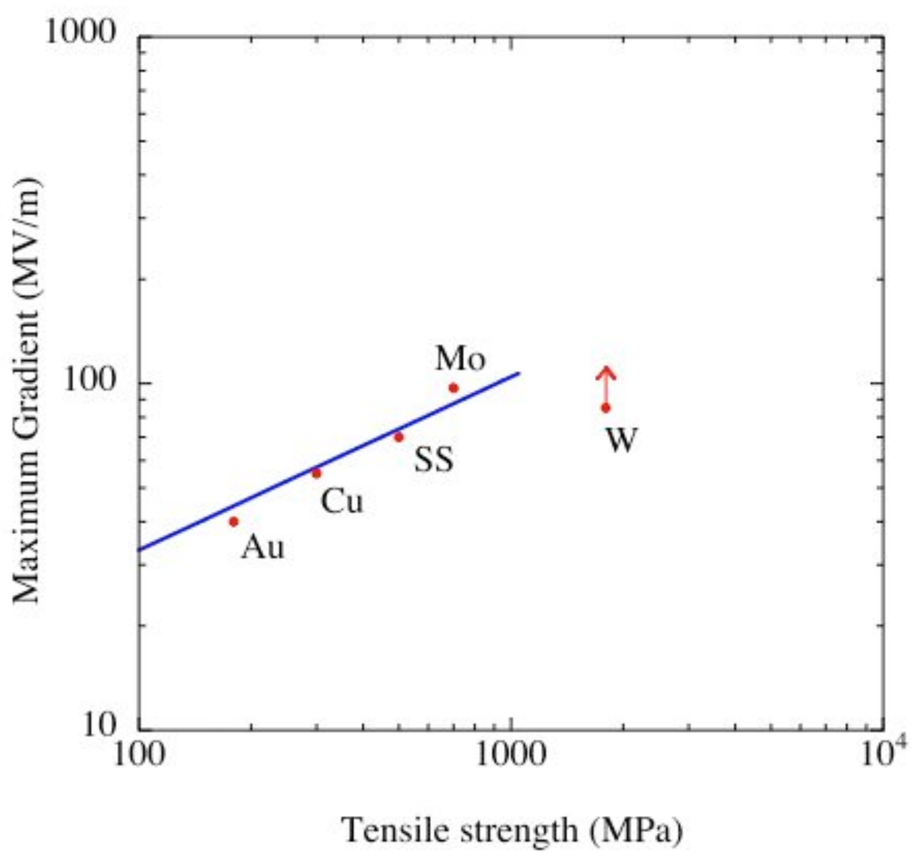


Using the model: II) Materials

- Only materials change, everything else constant.

- The model argues that tensile strength is the dominant effect.

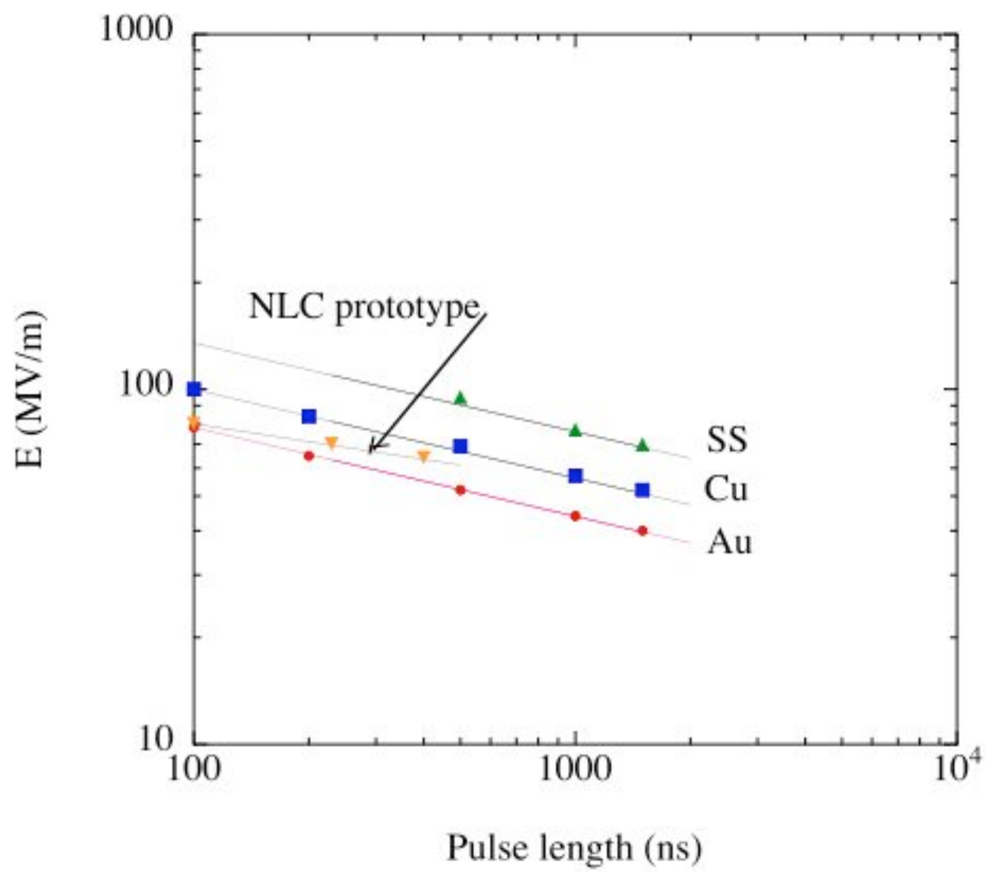
- $E_{surf} = \frac{E_{local}}{\beta} \approx -\frac{\sqrt{2T/\varepsilon_0}}{\ln(b/a)/b}$



SLAC and CERN data

Using the model: III) Pulse length

- Only pulse length changes, everything else constant.
- More damage ➜ lower gradients
- Predictions and data show no dependence on position of breakdown within pulse.

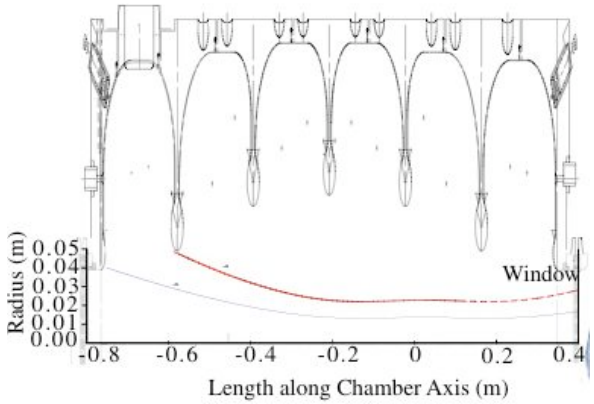


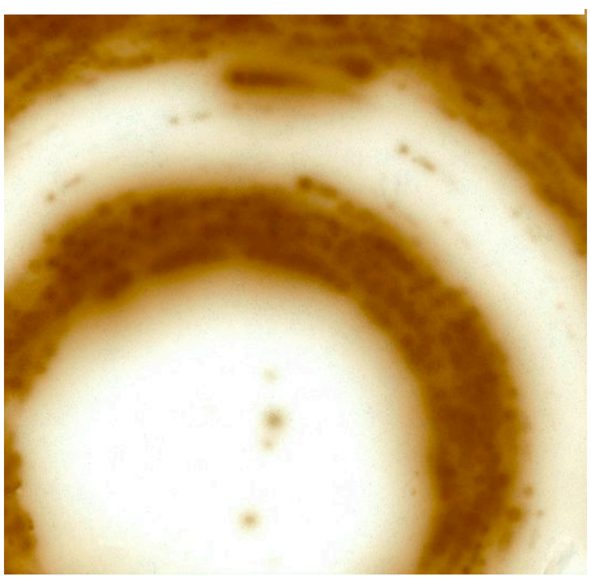
SLAC data

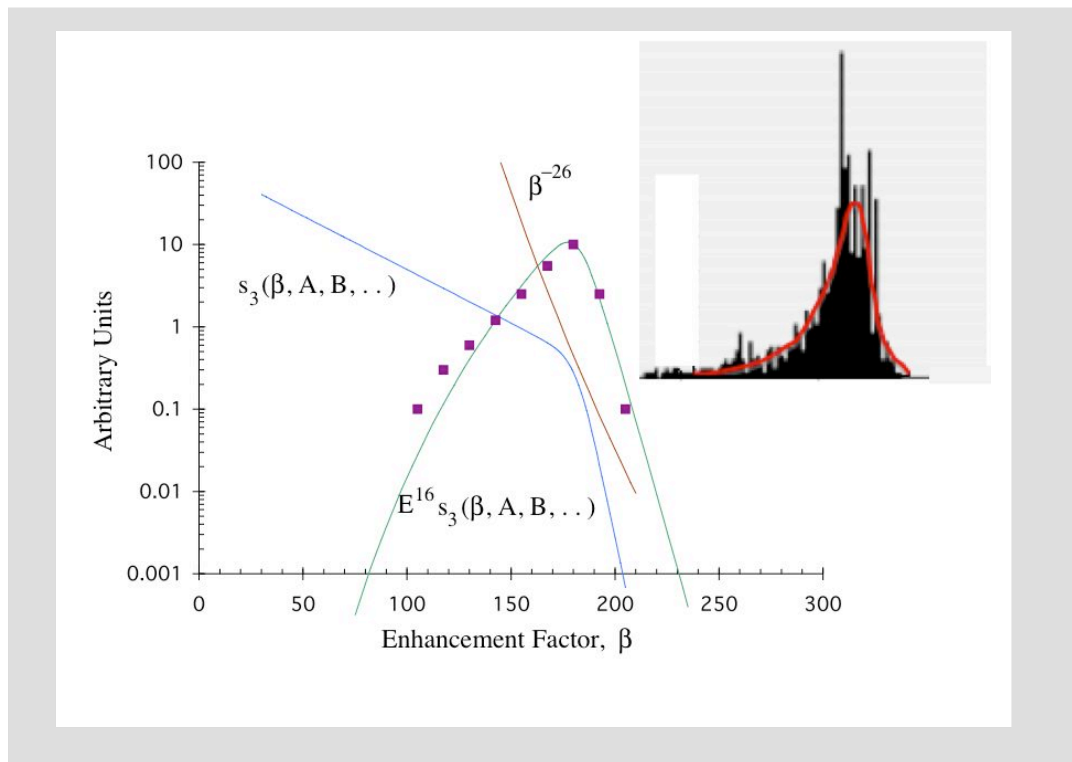
Using the model: IV) Can we see the cutoff of $s_3(\beta)$?

- When you look at emitters, they are all the same strength.
- Assume $s_3(\beta) = s_2(\beta)/(e^{(\beta-\beta_{eq})/c}+1)$ (F-D cutoff - very sharp β^{-25})
- Images of emitters . .. . show emitter strengths

optical densitometer shows cutoff
(weighted by field emission I=E^n)

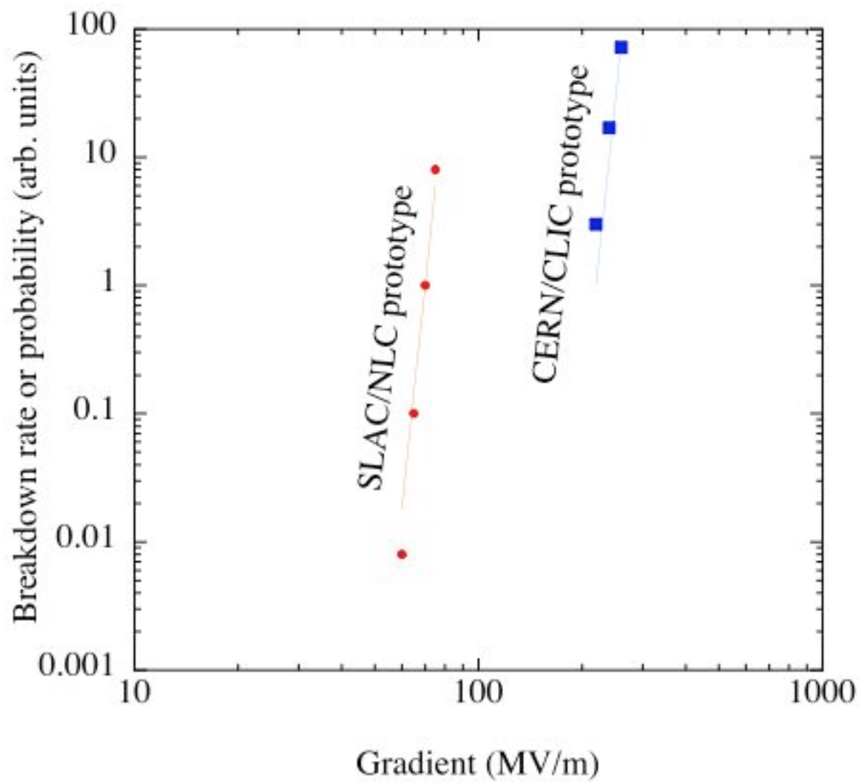






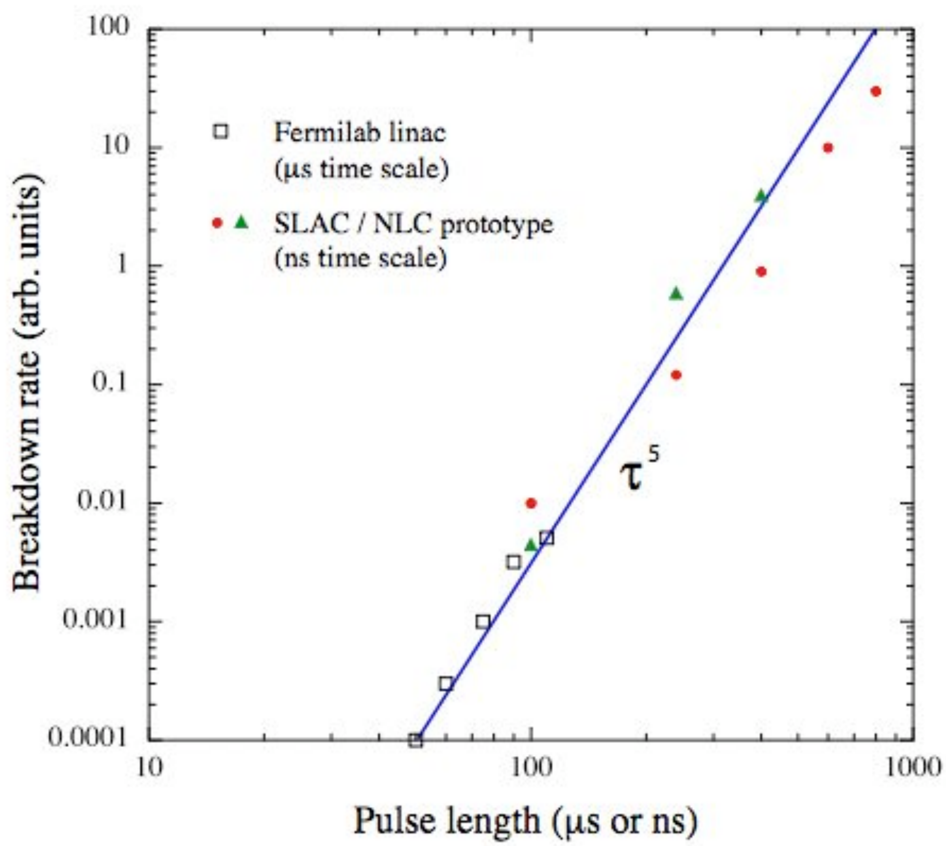
Using the model: V) Breakdown rates vs. *E*.

- These are surprisingly sharp, yet consistent with fully-conditioned state
- Thresholds go like $\sim E^{25}$.



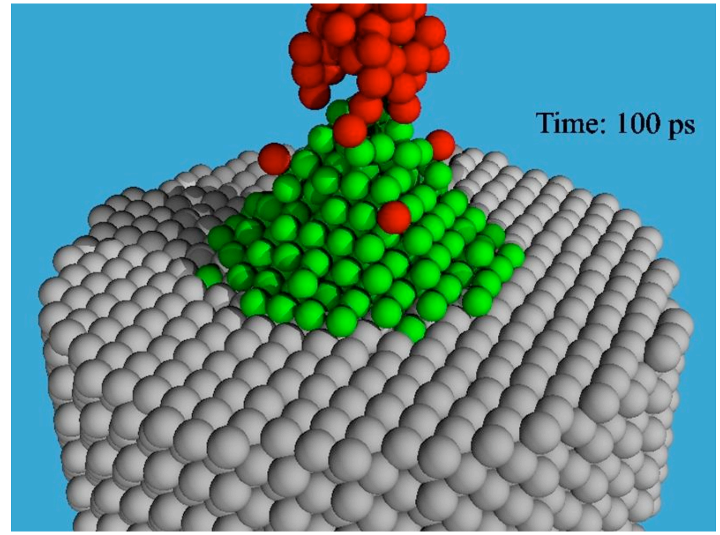
Using the model: VI) Breakdown rates vs. pulse length

- Rate vs pulselength is a function of Rate(E) and $E_{max}(\tau)$, $\left(\frac{dR}{d\tau} \sim \frac{dR}{dE}\frac{dE}{d\tau}\right)$.
- Data from the Fermilab Linac and SLAC/NLC prototype follow τ^5, as predicted.



Using the model: VII) Temperature dependence

- A molecular dynamics model predicts little temperature dependence. (Insepov)
- This is consistent with CERN/CLIC results.



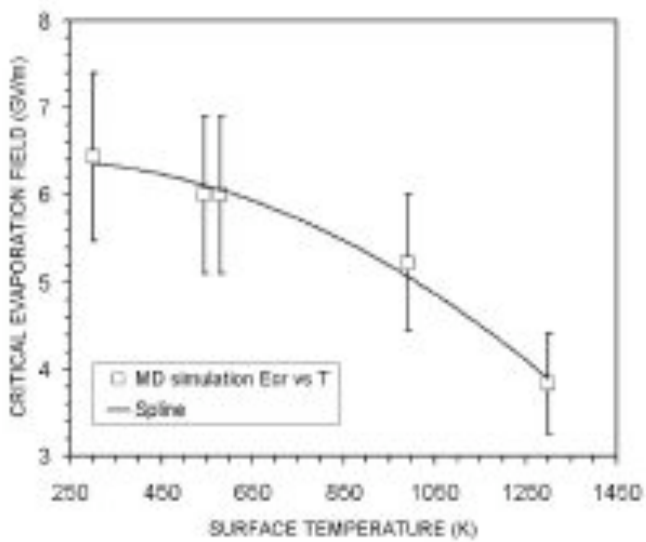


FIG. 2. Observed temperature dependence of critical evaporation field for removing cluster of ~ 200 Cu ions.

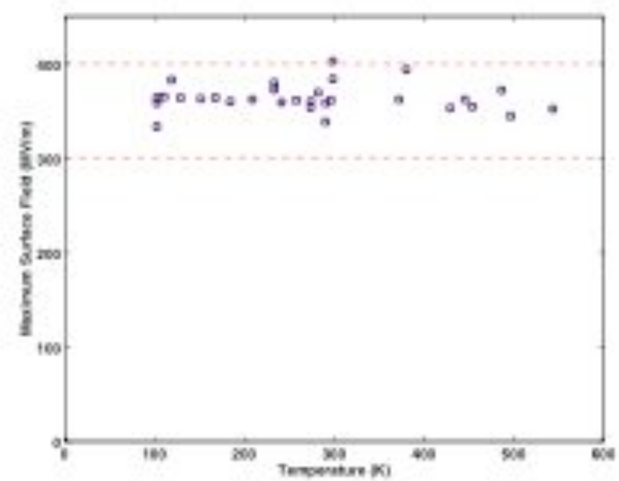
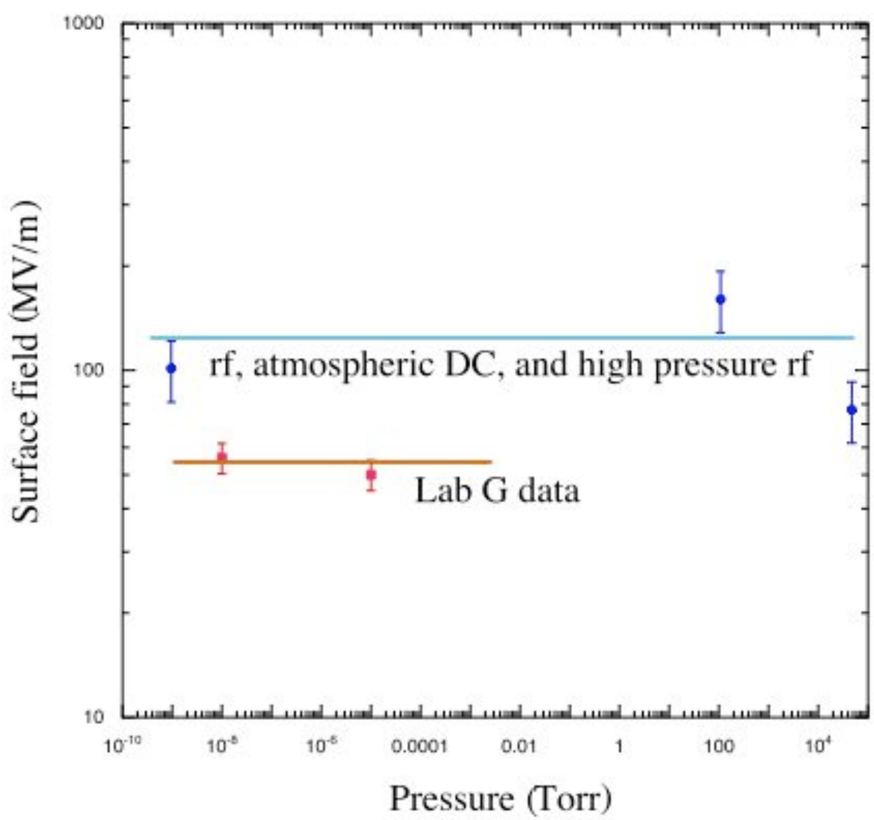


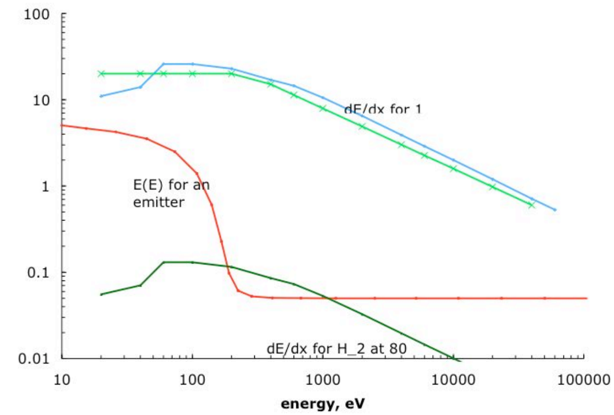
FIG. 6 (color online). Temperature dependence of maximum surface field.

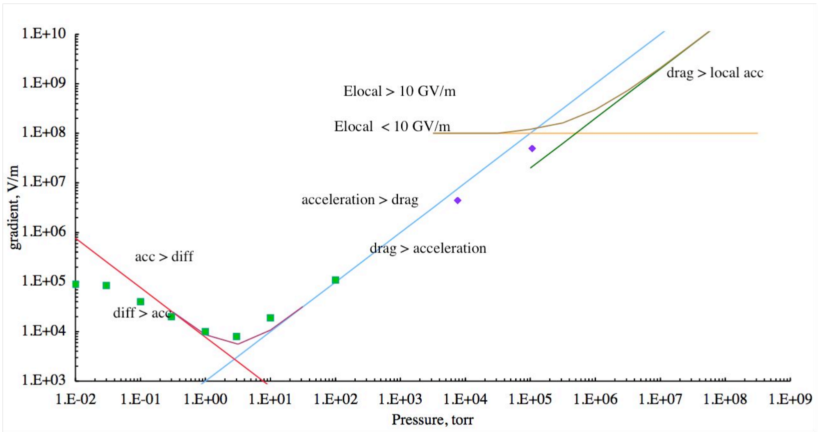
Using the model: VIII) Gas Pressure and type

- Gas pressure retards field emitted electrons heating broken fragments
  This can disrupt the trigger, for low Z gasses.

- We can also explain how SF_6 can affect breakdown.



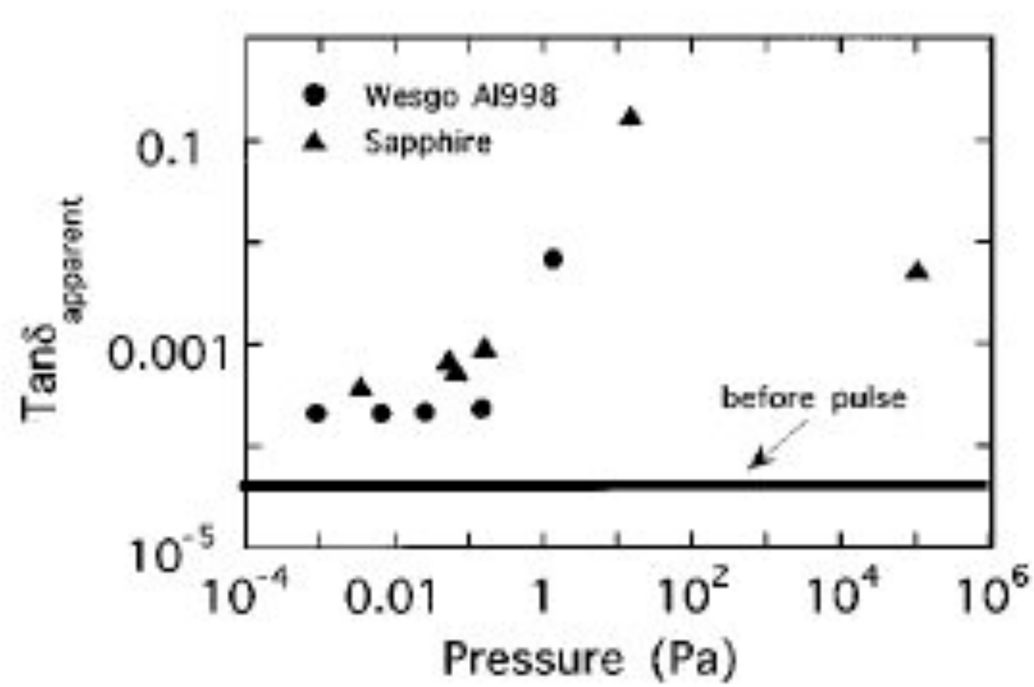




Using the model: IX) Dielectrics

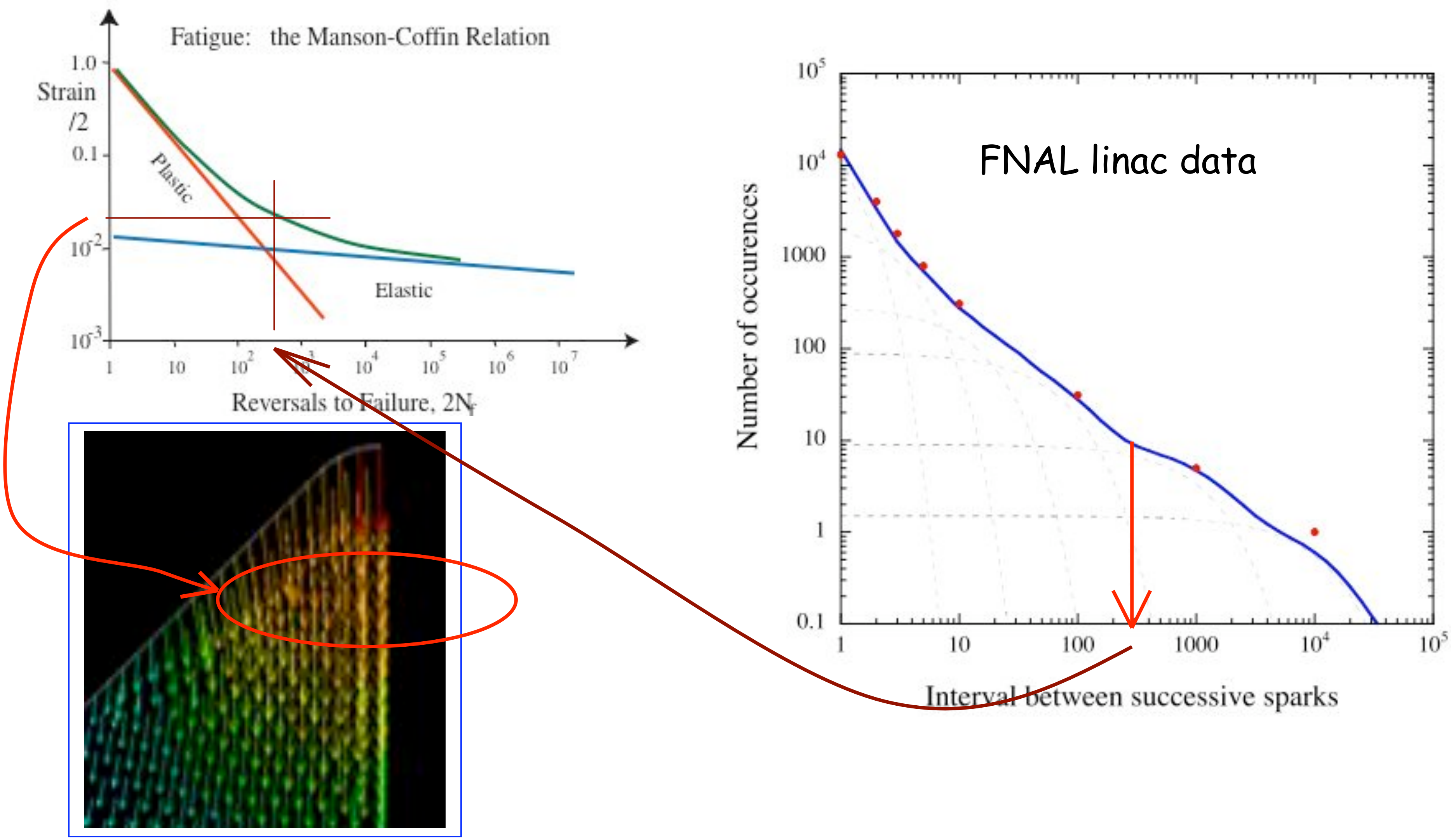
- High pressure gasses are an option for muon cooling.
- Realistic muon beams require Gas + High Gradient + Radiation
- Radiation comes two ways: 1) ionizing, and 2) displacive. 1) is our problem.
- We can measure loss tangents vs. Pressure in a radiation environment.

- Losses are radiation and pressure dependent.

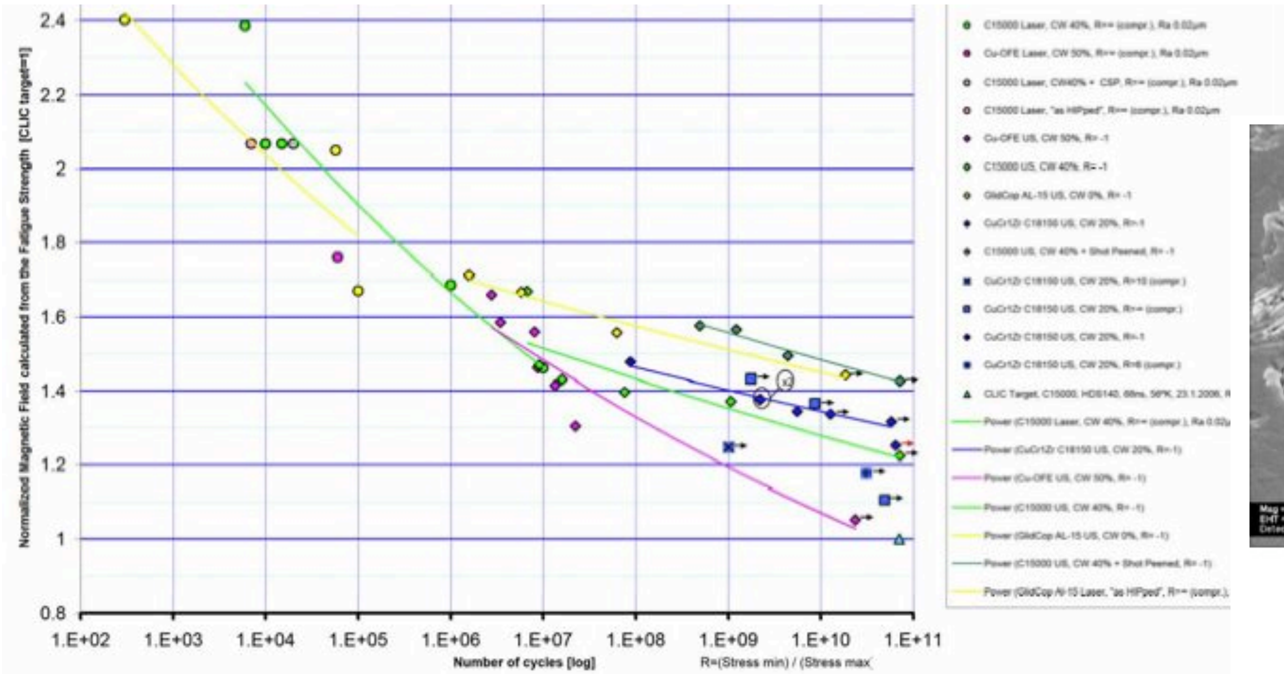


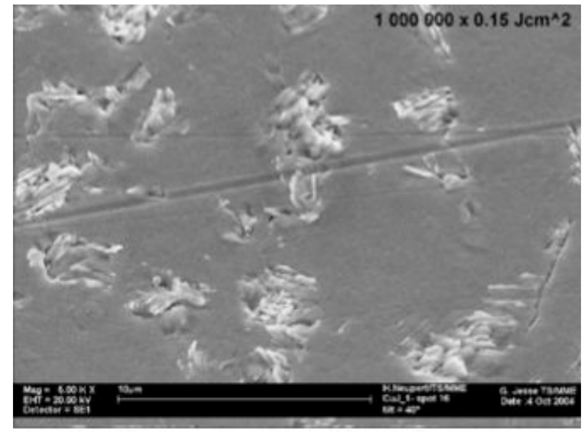
Using the model: X) Correlated breakdown events

- Correlated breakdown events measure breakdown site lifetime.
- Fatigue theory relates strain to lifetime. A spectrum of strains seems required.



. getting fatigued





Cu-OFE at 10^6 cycles, ΔT=90°C
Fatigued surface

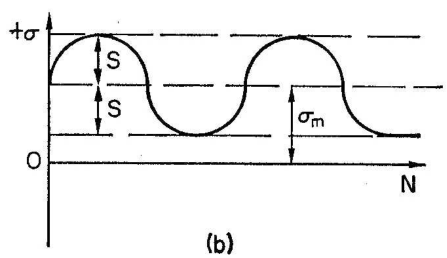


Fig. 1. Sinusoidal stress cycling, (a) about zero mean stress, (b) about a positive mean stress.

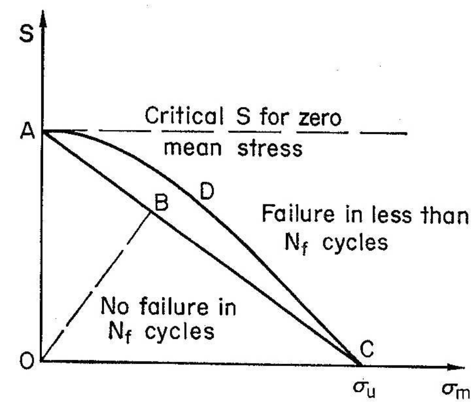
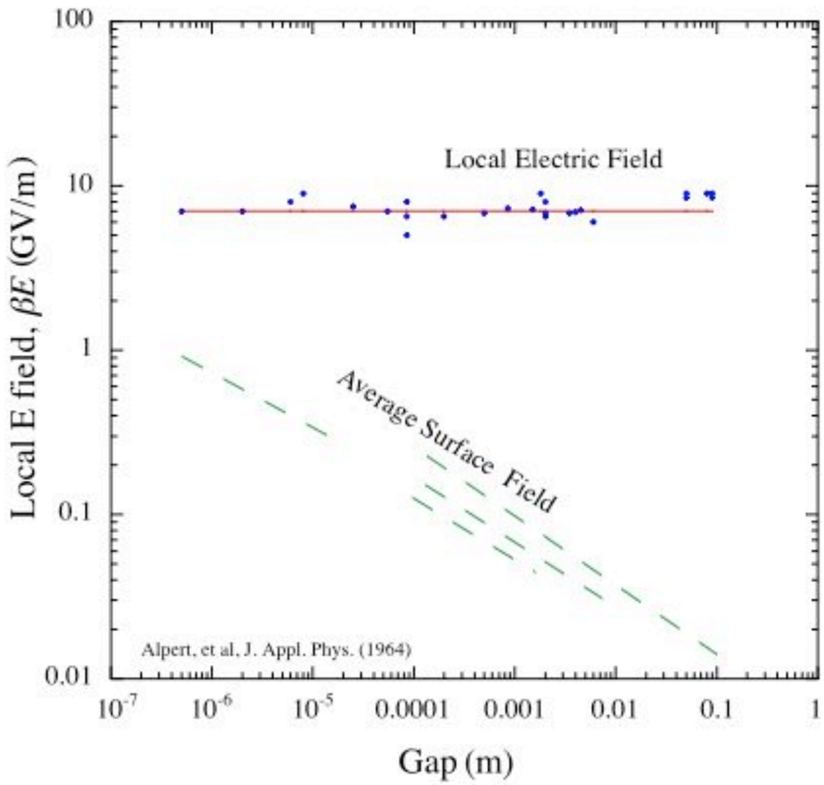


Fig. 3. The effect of mean stress. Goodman line ABC, Gerber parabola ADC.

Using the model: XI) DC breakdown

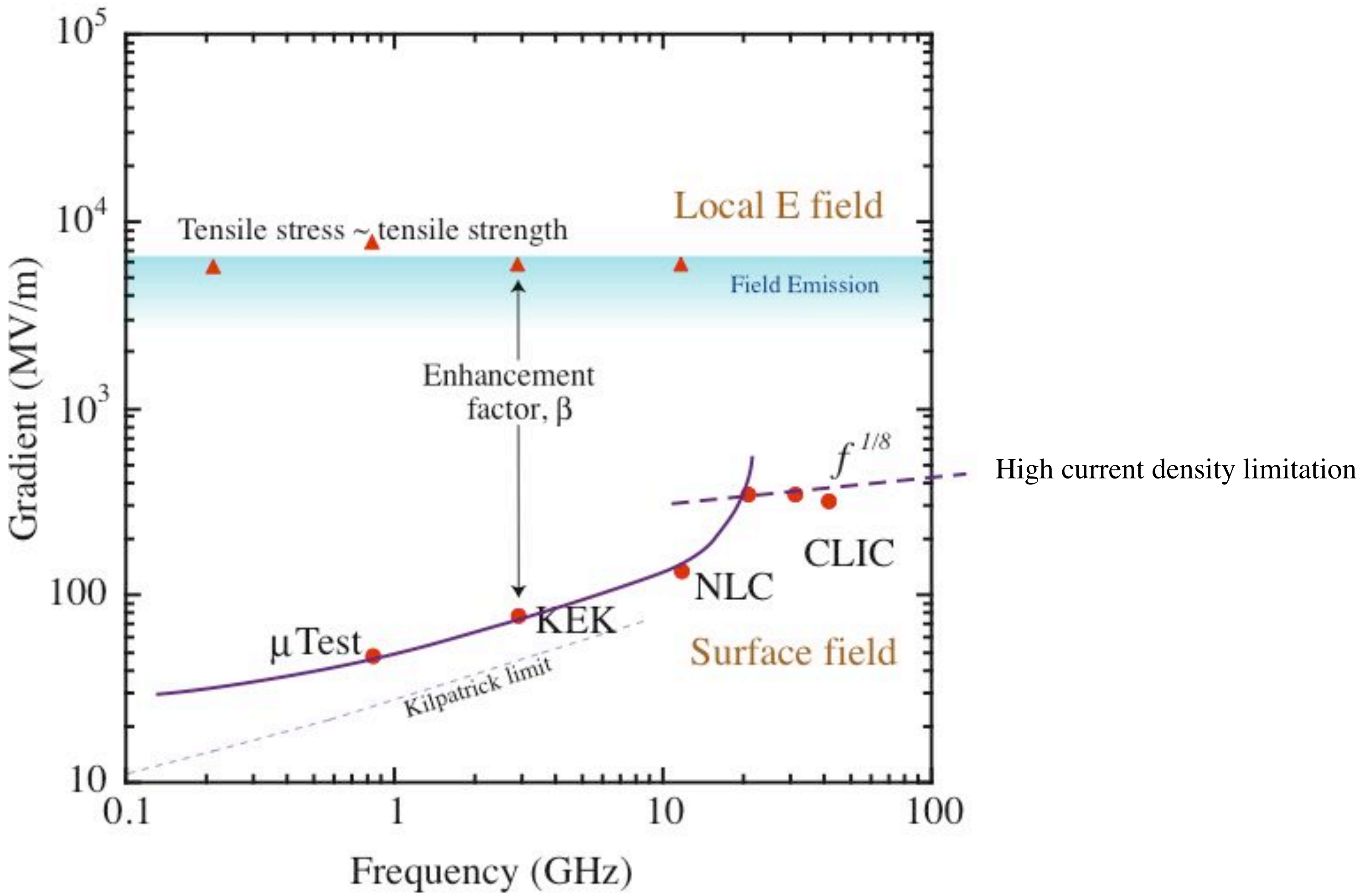
- This also fits the model, with breakdown at 7 GV/m.
- Most of this data is very old and unreliable, but they did clever things.
- Vacuum and cleaning techniques were not always well done.



Alpert et al (1964)

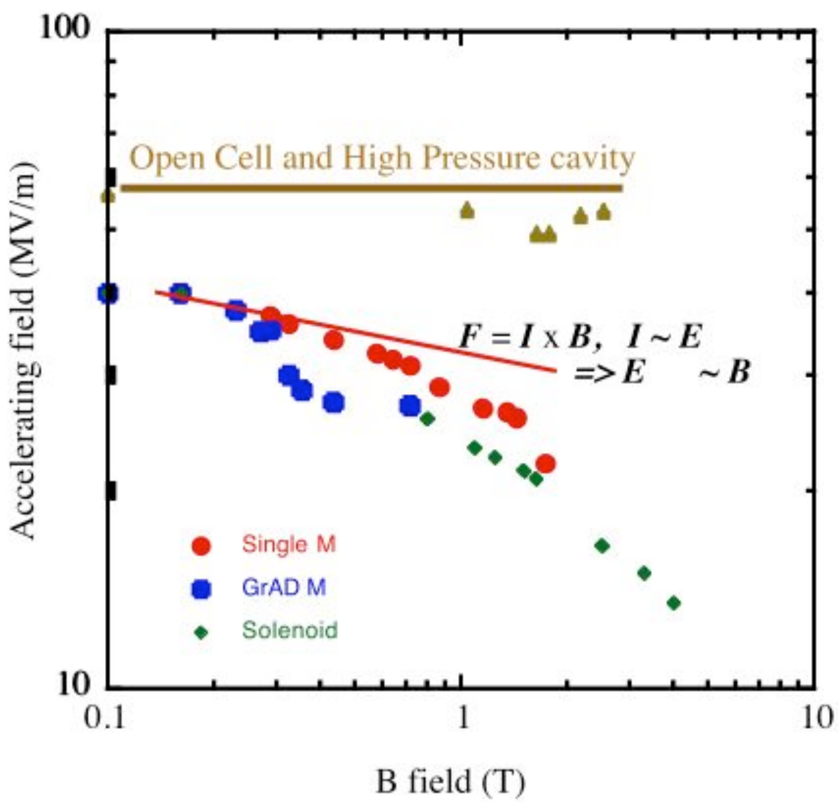
Using the model: XII) Maximum field vs. frequency

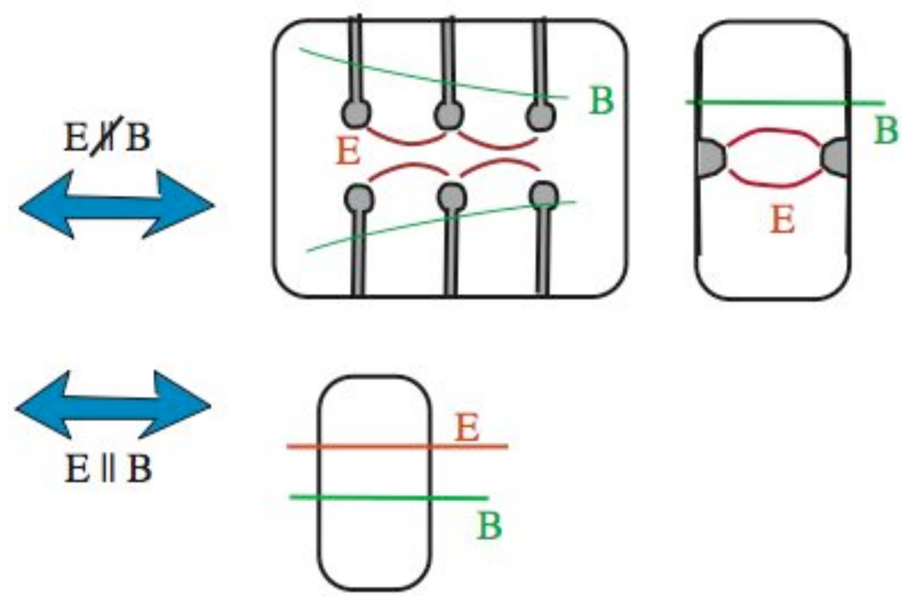
- Each cavity / PS system is unique.
- Our model gives Kilpatrick-like scaling laws.



Using the model: XIII) High Solenoidal fields

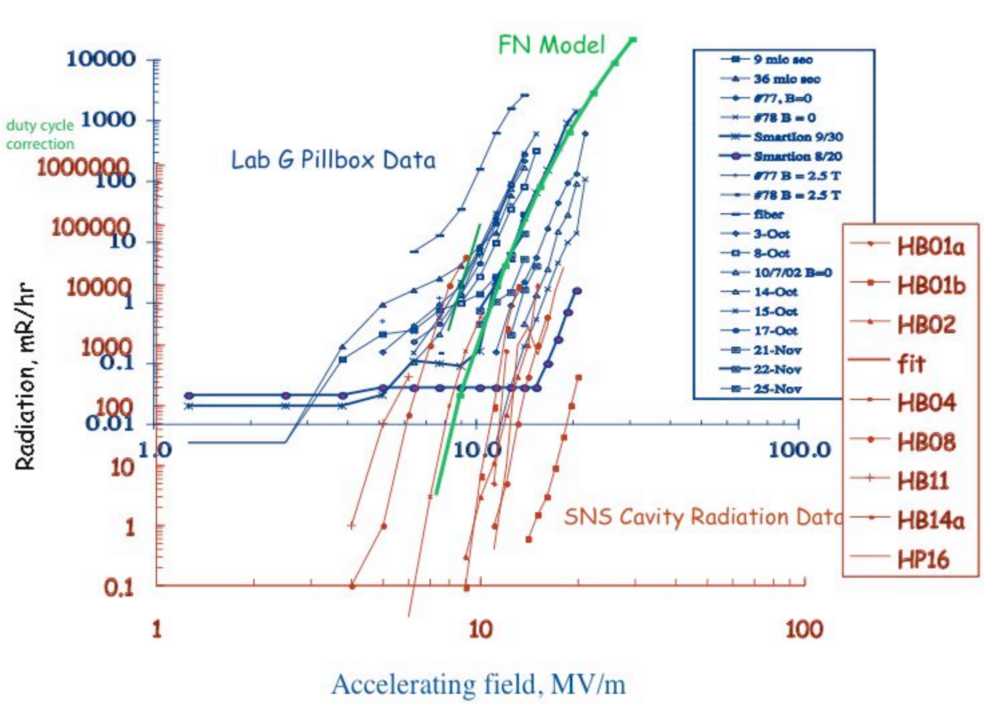
- This behavior is consistent with mechanical stress causing breakdown
- The geometry of the cavity seems to matter.
- Other effects (magnetic confinement of damage) may contribute.

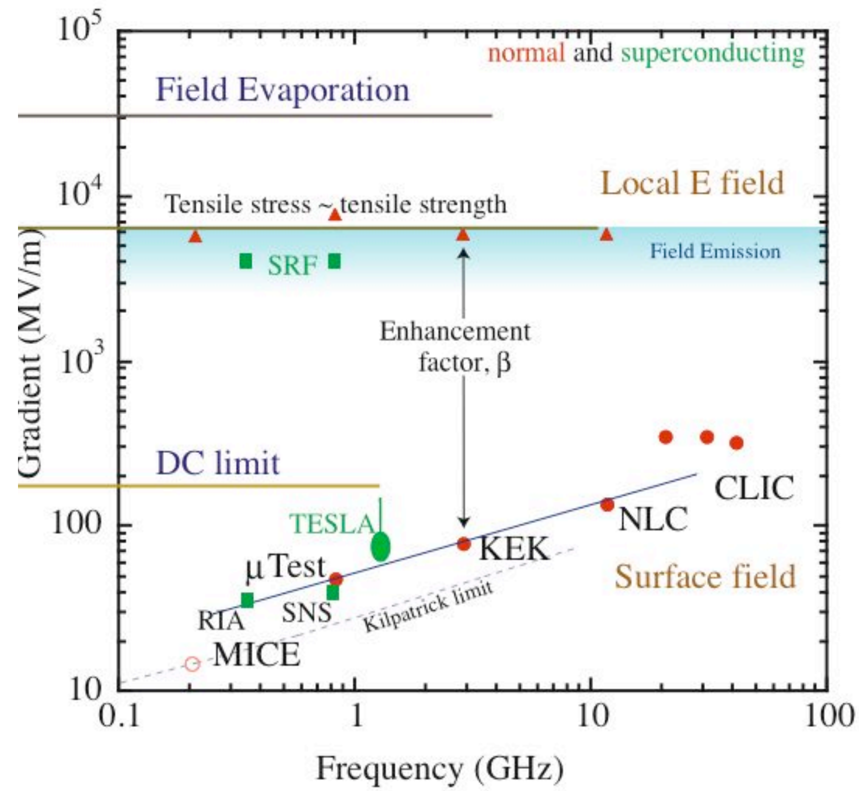




Using the model: XIV) Superconducing rf

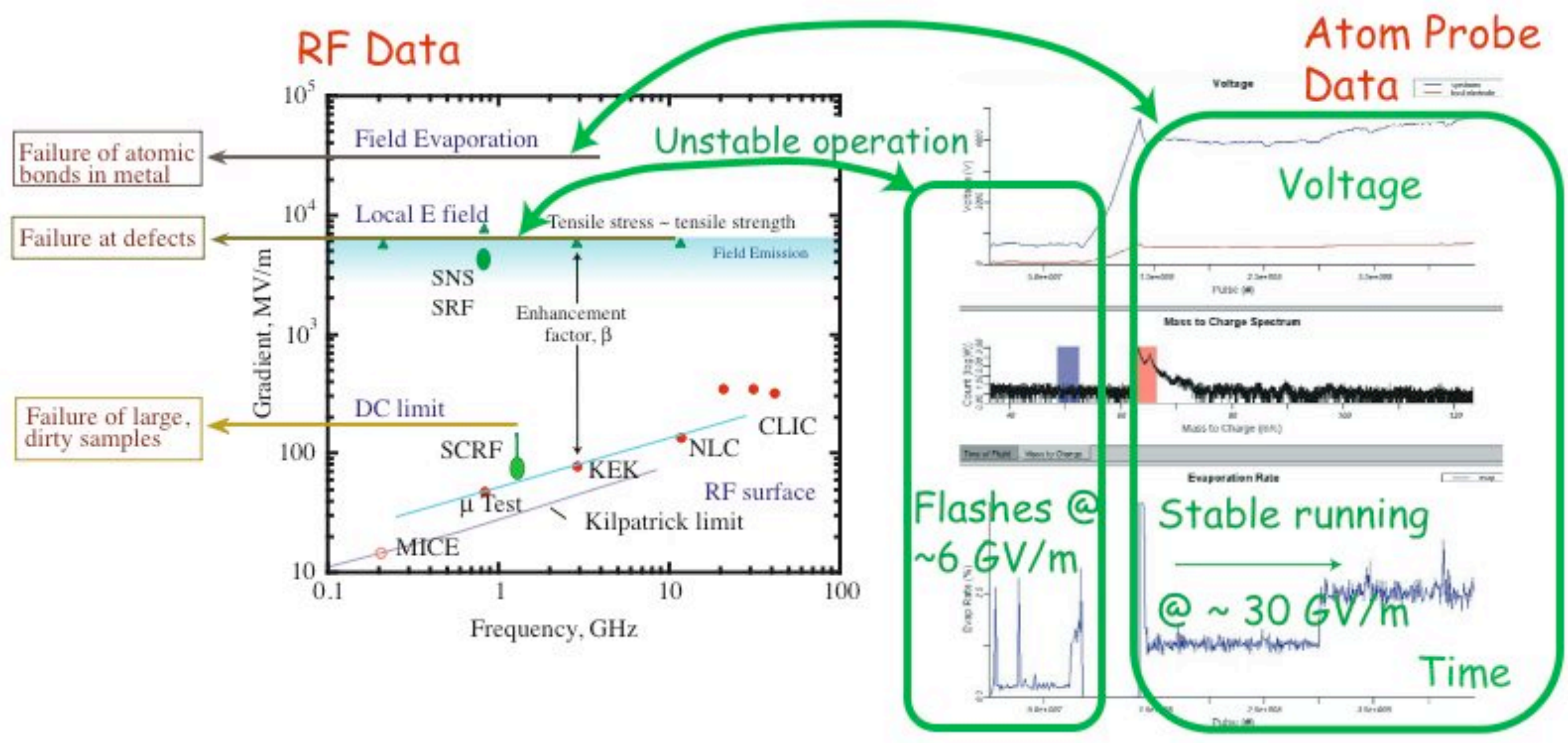
- For SCRF Emax = (4 GV/m)/ β, NCRF Emax = (7 GV/m)/ β
- Radiation levels, show SCRF for SNS has similar problems to NCRF.





Using the model: XV) Atom Probe Measurements

- Atom probe measurements show sample failure at approximately 7 GV/m.



Surface gradients of ~500 GeV/m are measured.

What needs to be done:

- MTA experiments
  Continue to study magnetic field effects, high pressure, materials
- Modeling
  Model trigger, (fracture, ionization)
  Model Plasmas with Strong *E* and *B* fields, high gas pressures
- Study fracture of materials with realistic surfaces
  Atom Probe Tomography technology ideal
  Surface modification with Gas Cluster Ion Beams
- Continue to try to understand all other experiments.

Summary

- We have developed a simple model can explain all the data.
- We are developing two new analysis techniques
  - Atom Probe Tomography
  - Gas Cluster Ion Beam surface modification
- We have seen the highest gradient in accelerator science.

- More precision is required.

More General Conclusions

- High Gradient research (high and low frequency, normal and SC) is one field.

- Gradient limits should be a science.