

RF breakdown and Gradient Limits

J. Norem
ANL/HEP

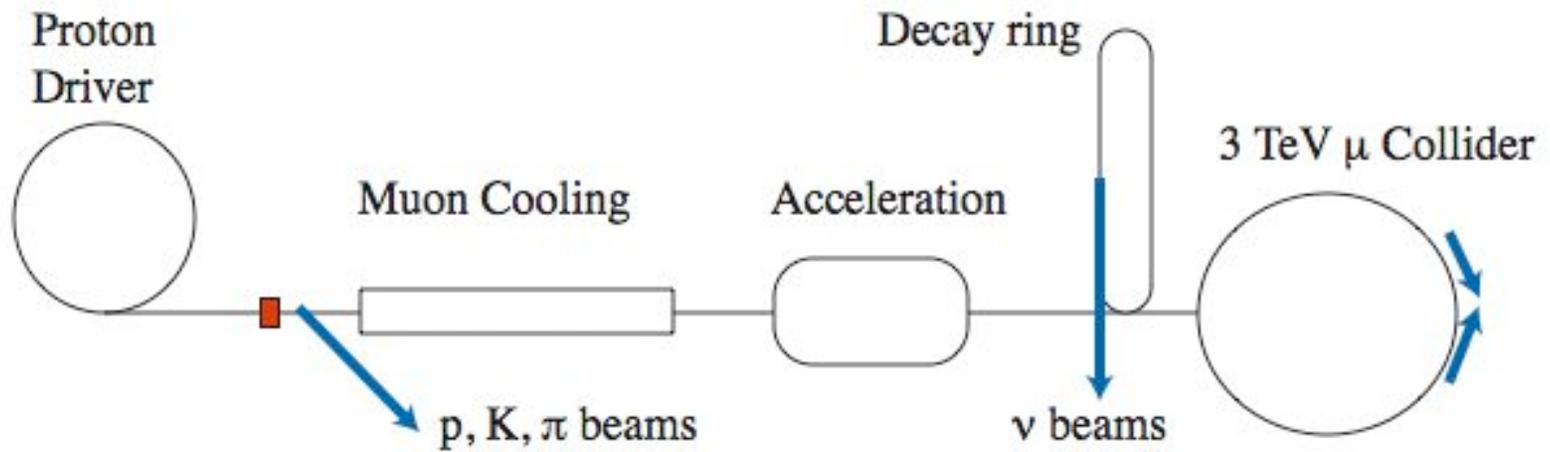
Accelerator Science and Technology
Fermilab
Sept 7, '06



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.



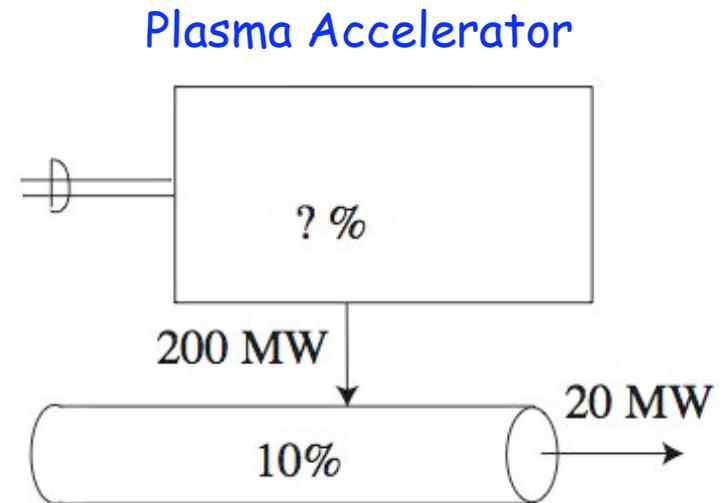
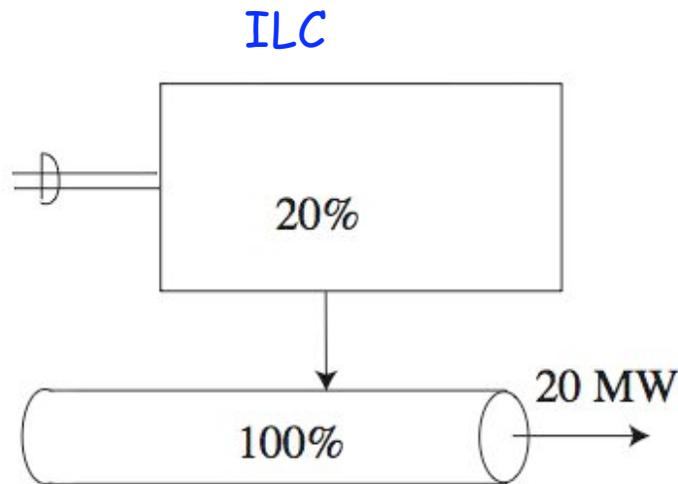
The Achilles Heel of Accelerator Designs

ISABELLE	material science (superconductor)
SSC	material science (conductor placement tolerances)
NLC	material science (rf gradient limits)
Neutrino factory/ Muon collider	material science (rf gradient limits)
CLIC	material science (rf gradient limits)
ILC	material science (rf gradient limits)
Dielectric Accel.	material science (radiation damage, gradient limits)

Metal surfaces provide power efficiency, stability, and control.

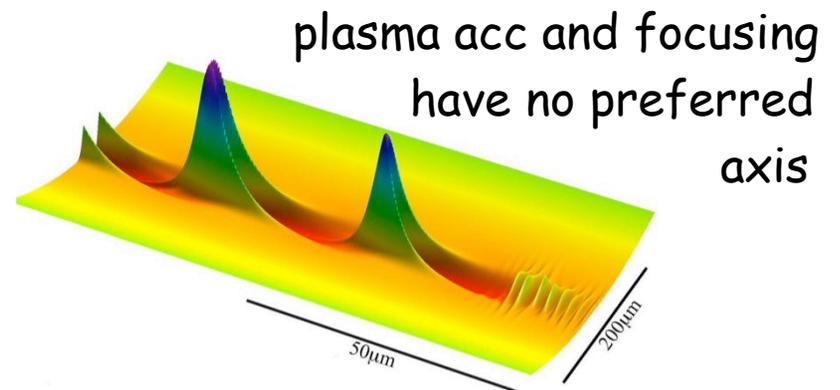
- If $\mathcal{L} = (1/2\pi E)(N/\sigma_x^*)(P/\sigma_y^*)$

- Efficiency



- Stability

Quads and structures
give 1 nm beam stability

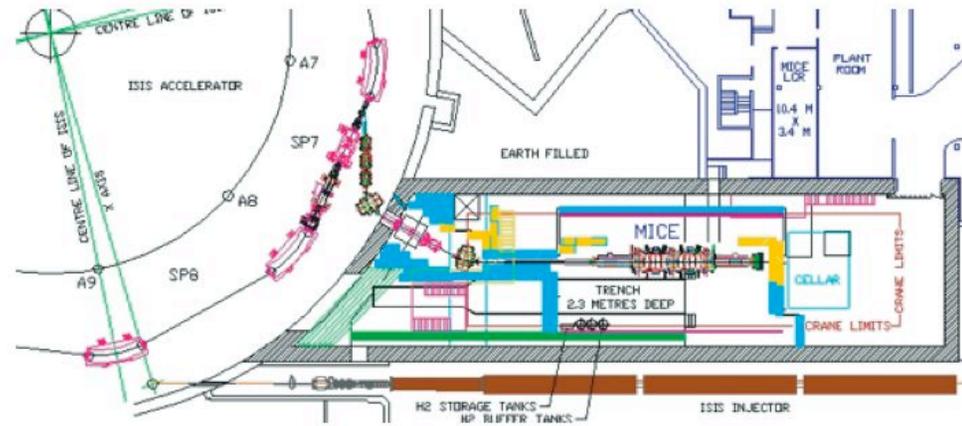
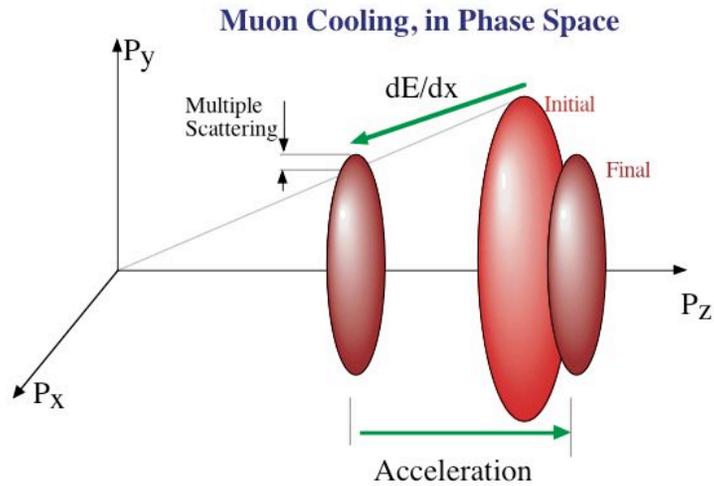


- Control

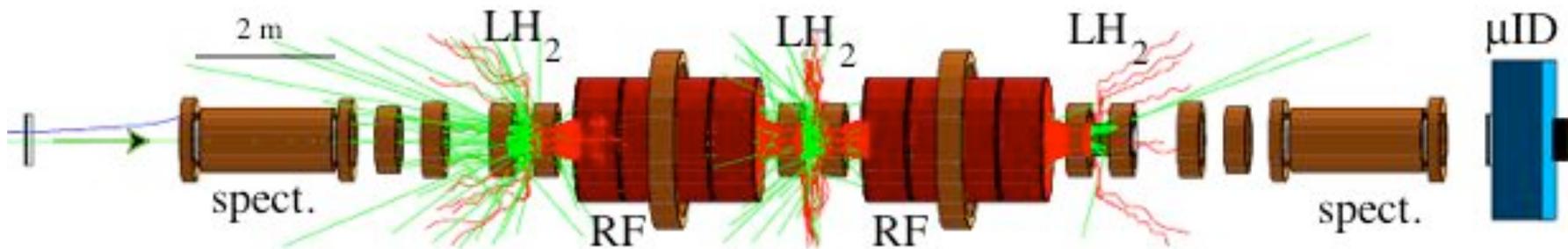
FF chromatic correction section

plasma lens aberrations

MuCool work is directed at MICE (at RAL).



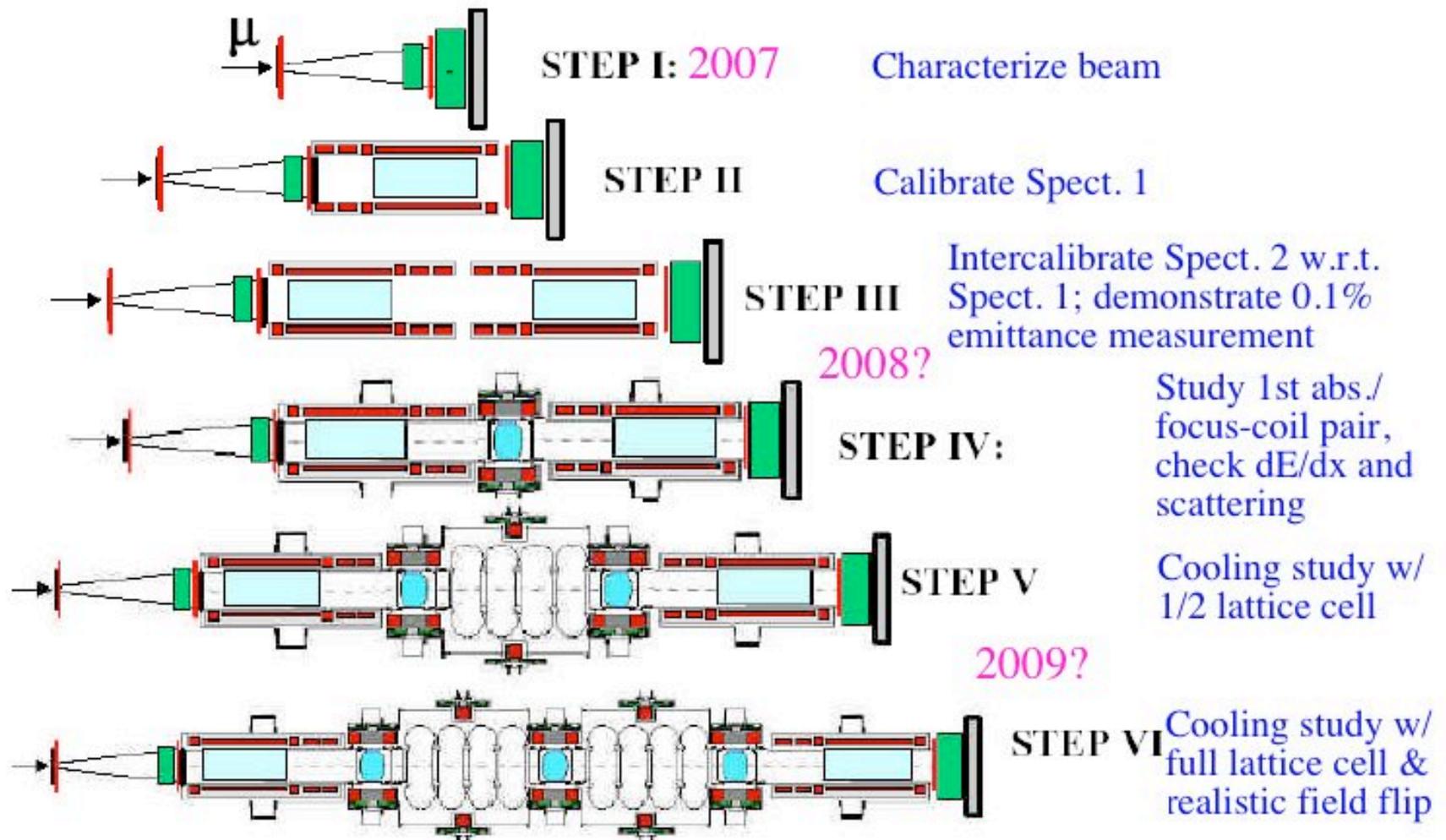
The Muon Ionization Cooling Experiment (MICE)



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

We need to understand high gradients. Now.

- MICE, and muon cooling, require high electric fields in high solenoidal fields.
- This physics/material science is not understood.



The breakdown problem is very old.

Many have contributed - very early:

Paschen,

Millikan

Michelson,

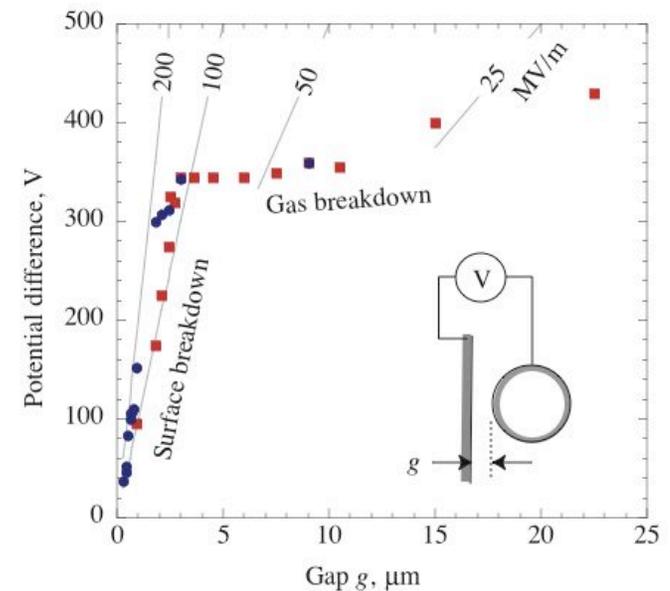
Lord Kelvin



In 1904, Lord Kelvin argued that:

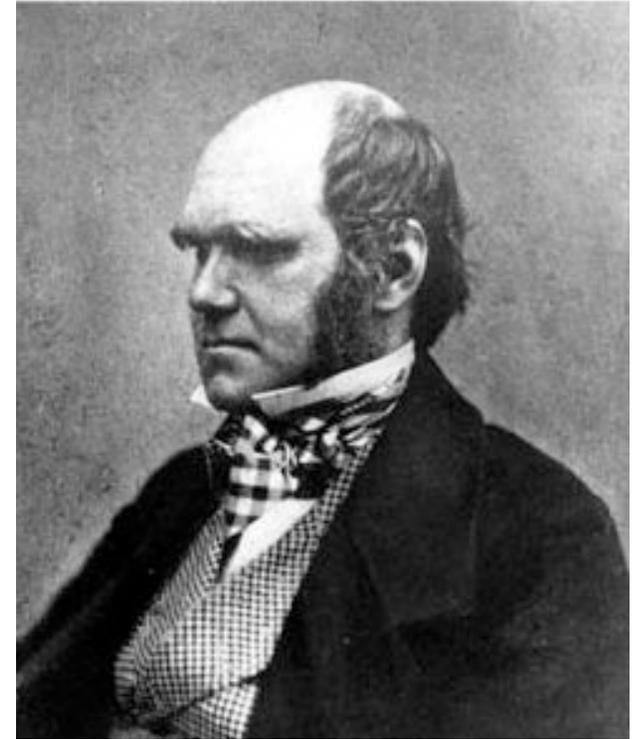
- Field emission is electrons (electrons),
- Electron emission may imply ion emission (damage),
- Local fields of $\sim 9.6 \text{ GV/m}$ would do this,
- Tensile strength is an important parameter,
- Better experiments are needed.

We agree.



Modeling is necessary.

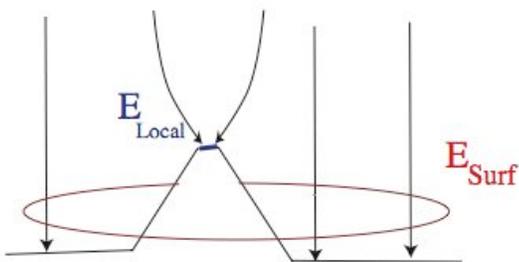
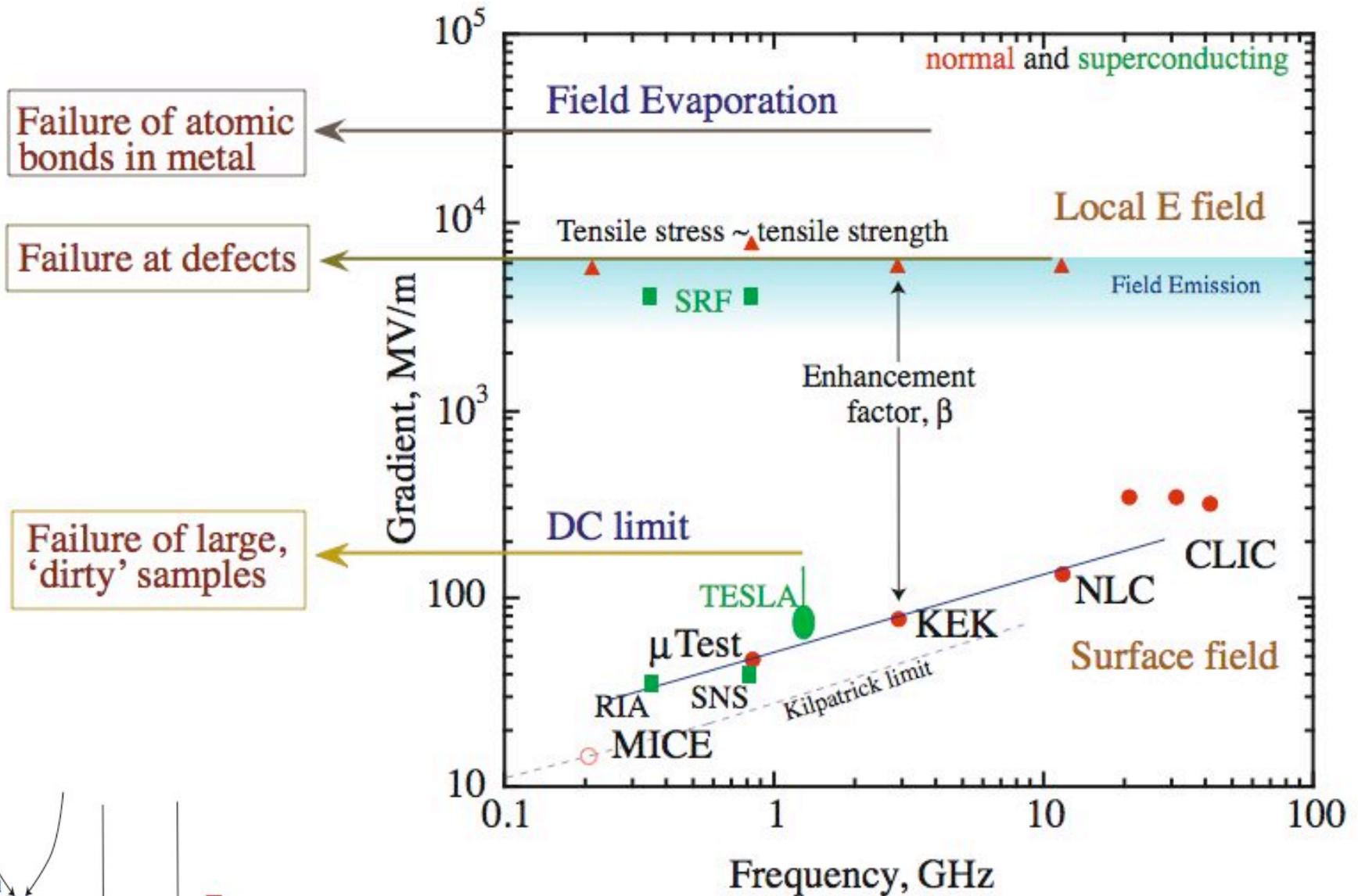
- “About 30 years ago there was much talk that geologists ought only to observe and not theorize; and I well remember someone saying that at this rate a man might as well go into a gravel-pit and count the pebbles and describe the colours. How odd it is that anyone should not see that all observation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



Charles Darwin, 1861



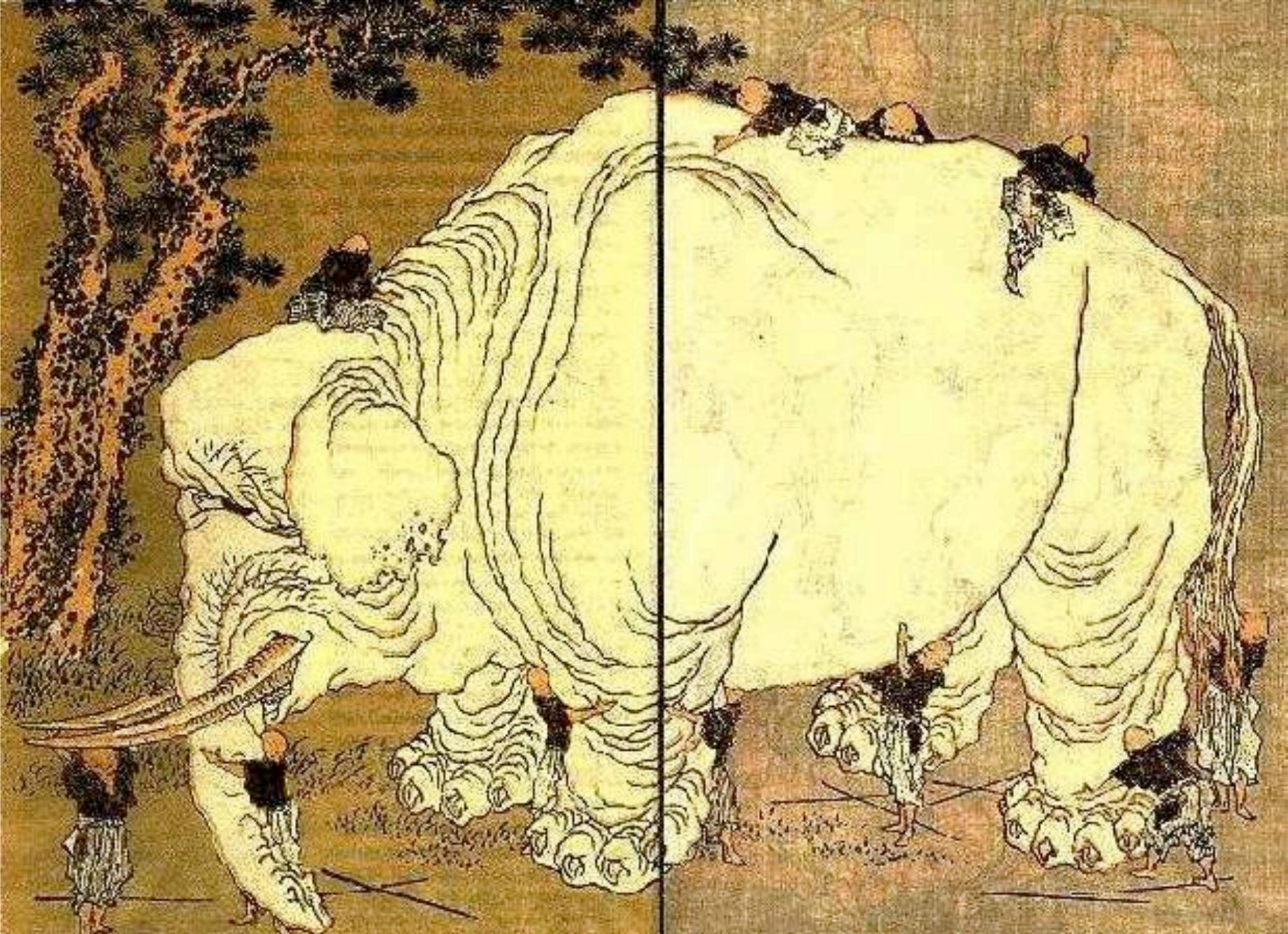
The high gradient universe.



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

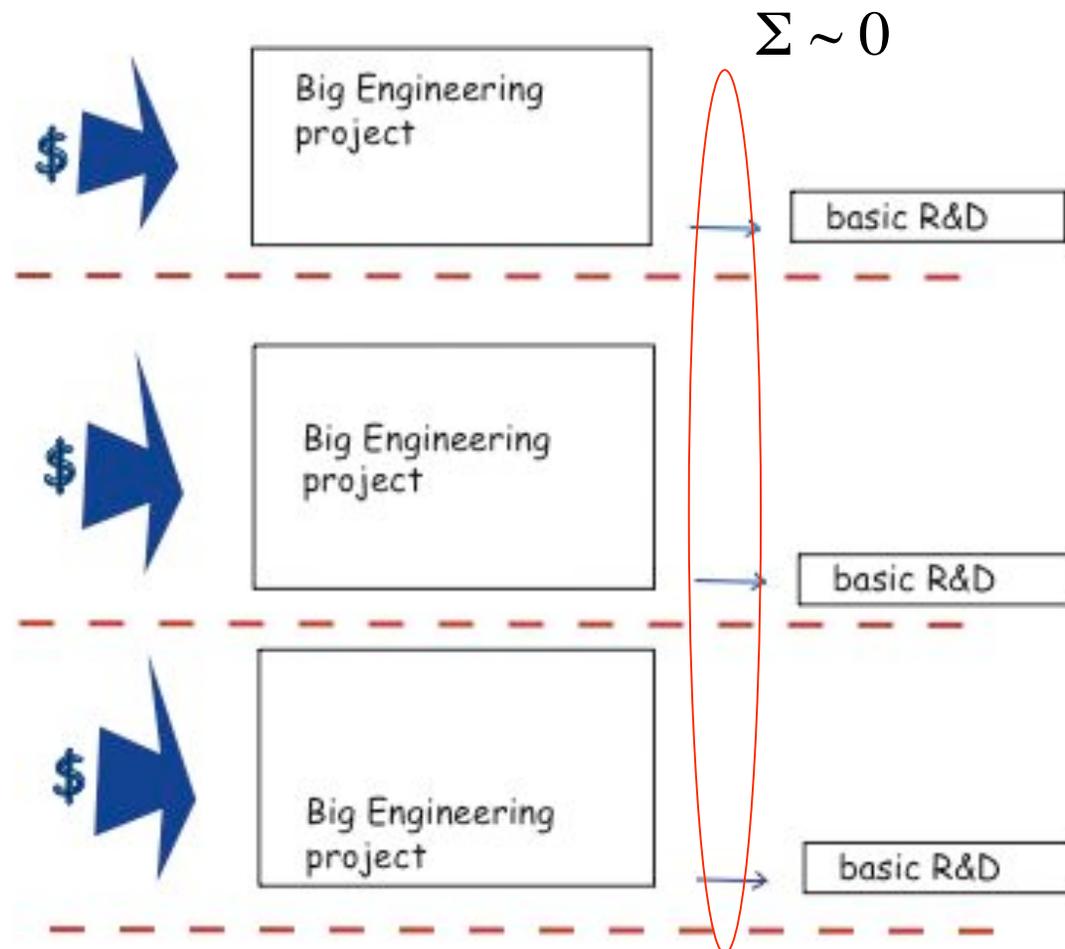
Exp. Problem: Discharges (~GW) obscure the (~W) trigger signal.

Hokusai 1818



Bureaucratic Problem: Funding is divided up.

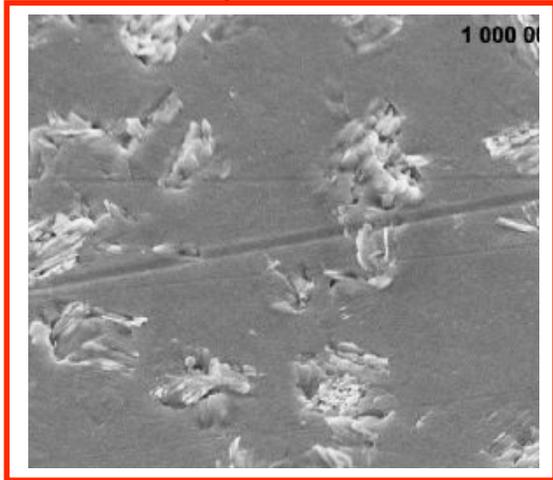
- Individual Projects are funded.
- Each decides R&D priorities separately.
- Basic R&D is not coordinated



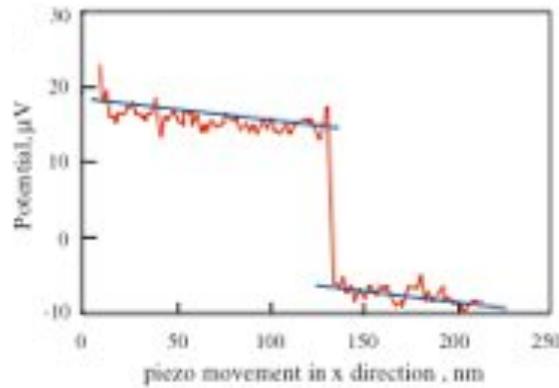
Can ILC and CLIC be limited by the same mechanism?

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

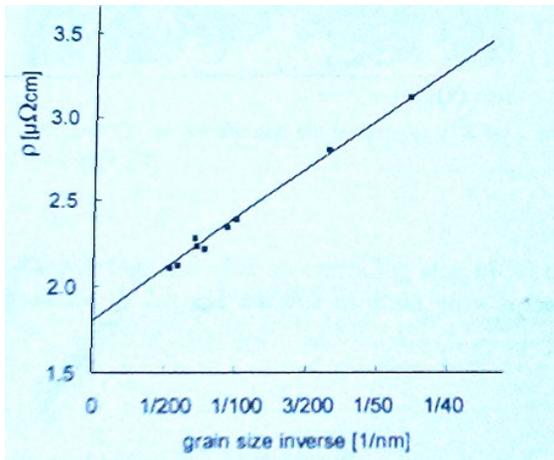
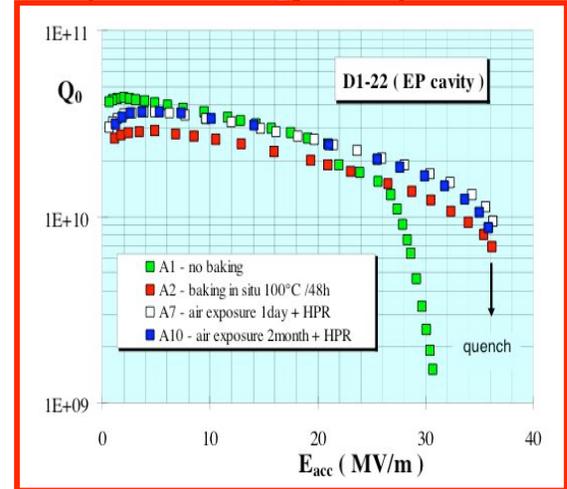
CLIC Fatigue studies



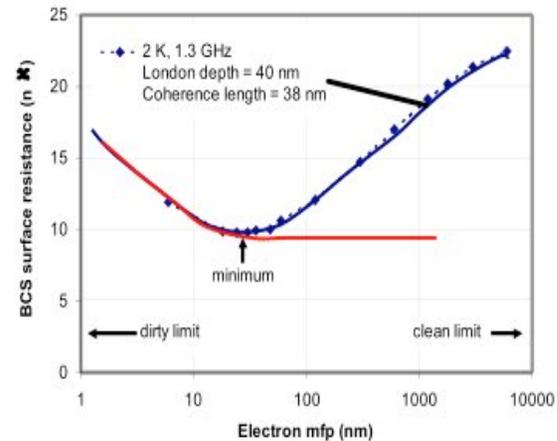
Grain boundary



High Field Q-Slope



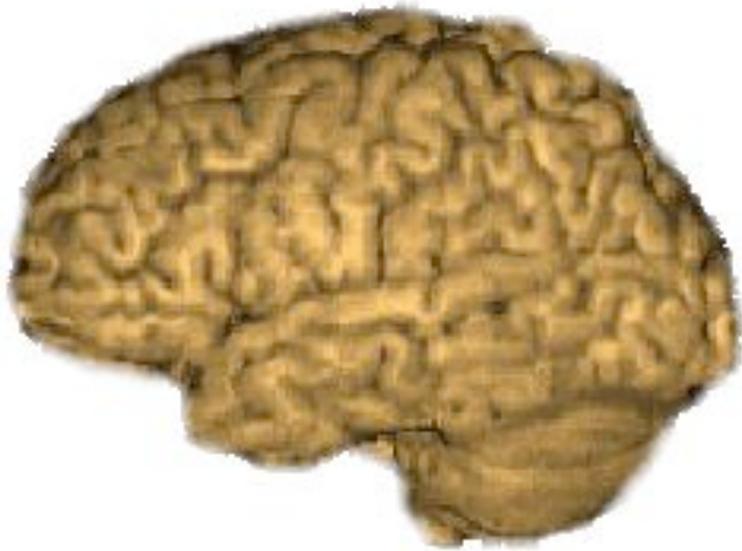
$$\rho \sim n_{GB}$$



SCRf

Cultural problem: Procedures

- Your Brain



- Your brain after a Fowler-Nordheim plot



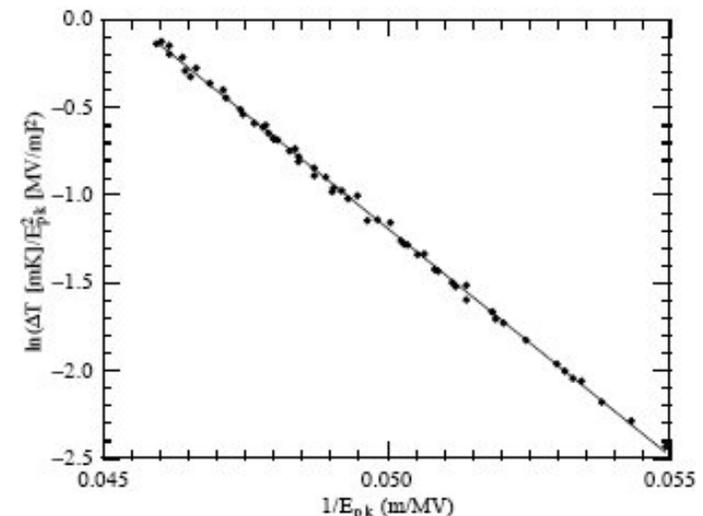
- In the F-N expression

$$j_{FN} = c_1 E^2 \exp\left(\frac{c_2}{E}\right),$$

the local surface field βE_{meas} must be used.

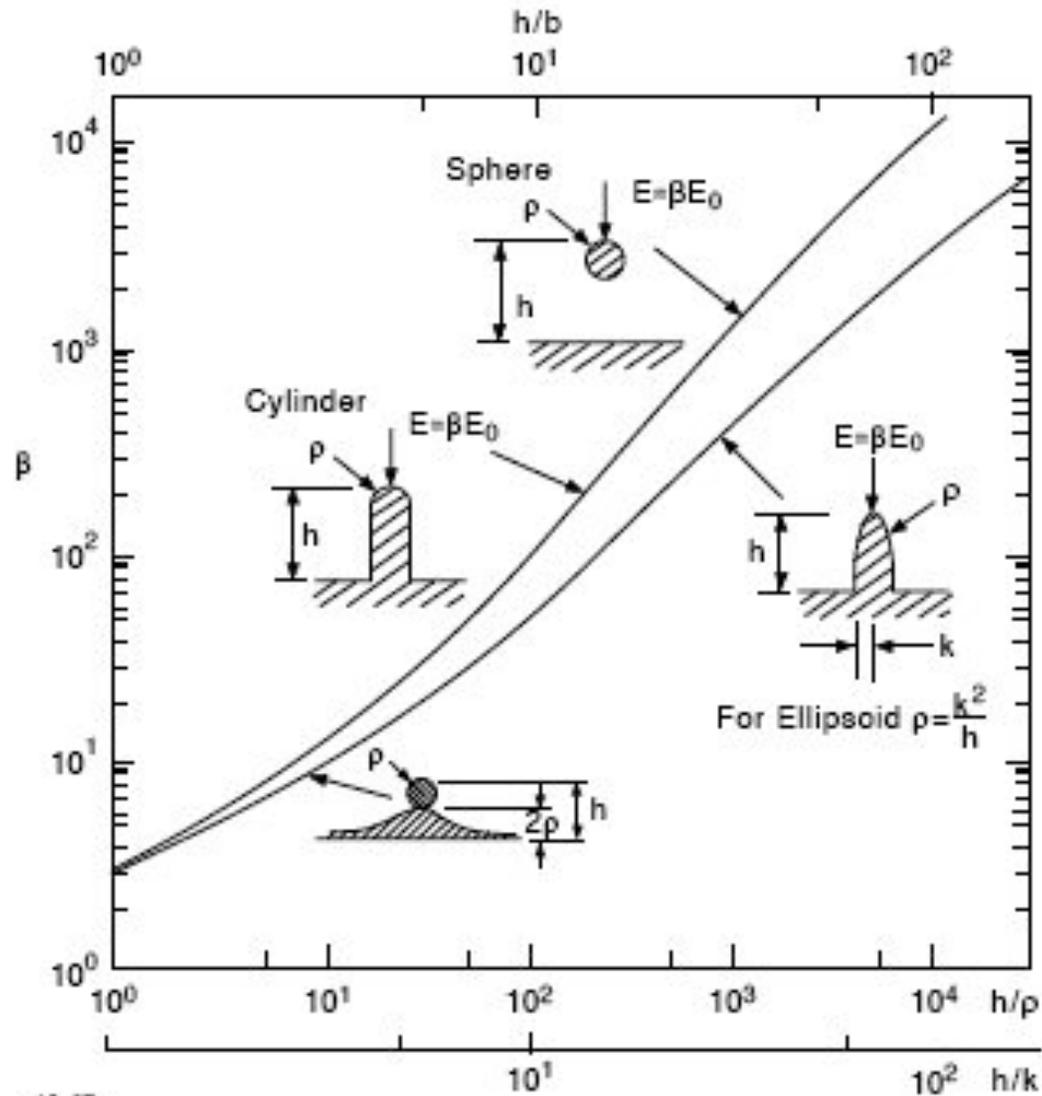
- people plot $\log_{10}(R/E^{2.5})$ vs. $1/E$.
(or $\log_{10}(R/E^2)$ vs. $1/E$)
where $\beta = 2.84 \times 10^9 \varphi^{1.5} / (\text{slope})$.

different numbers
(equally confusing)



Historical Problem: Mythology

- People don't see the "Telephone pole" emitters they expect.
- but sharp corners give high local fields.



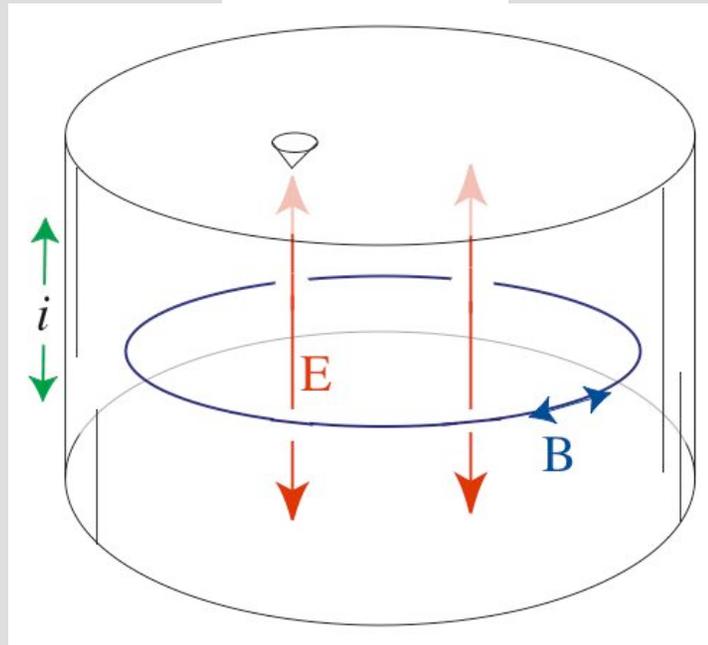
Why structures fail.

Normal metals

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

Superconductors

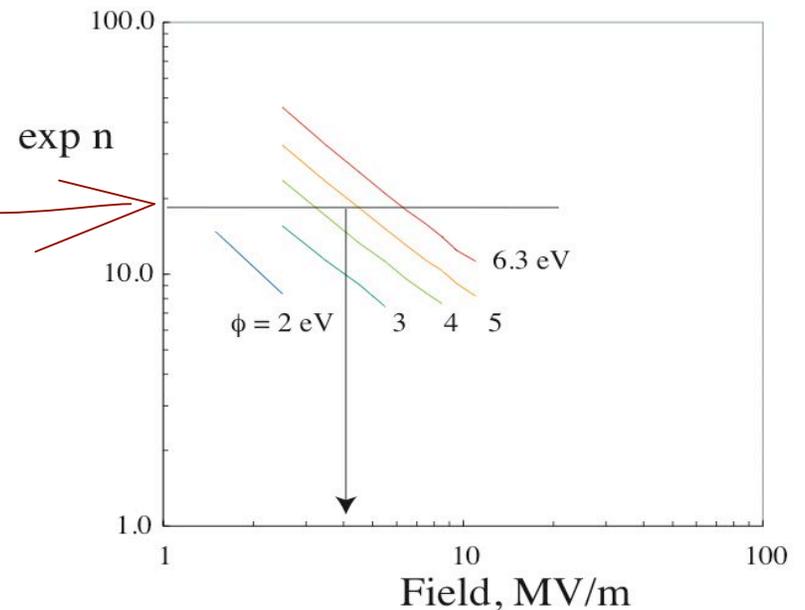
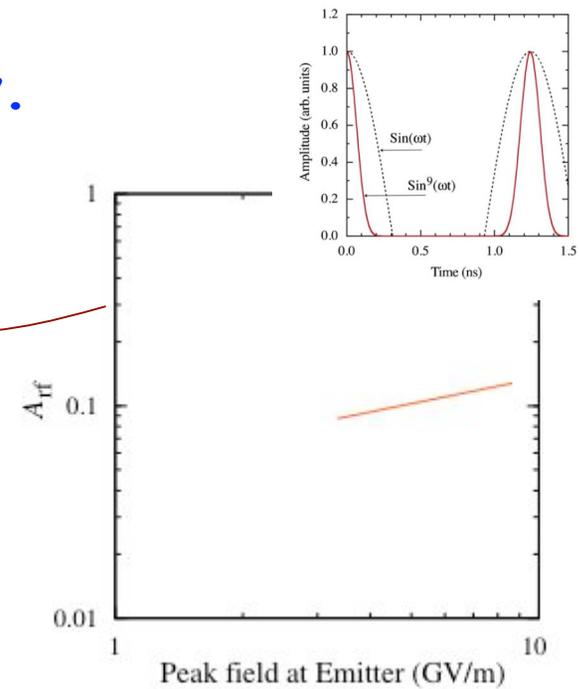
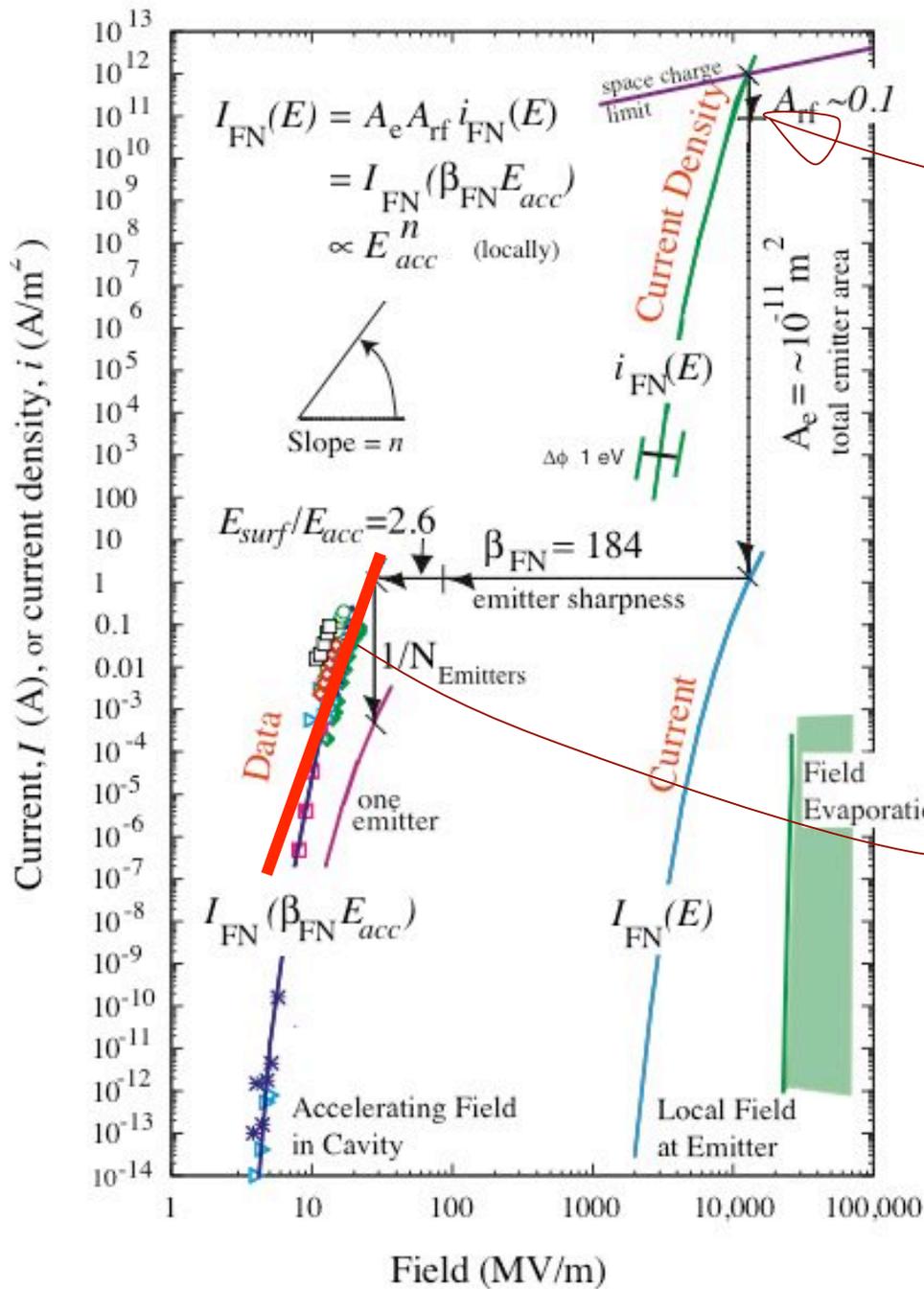
- Field emission heats cavity before tensile stress limit.
 $E \sim 4 \text{ GV/m}$



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

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

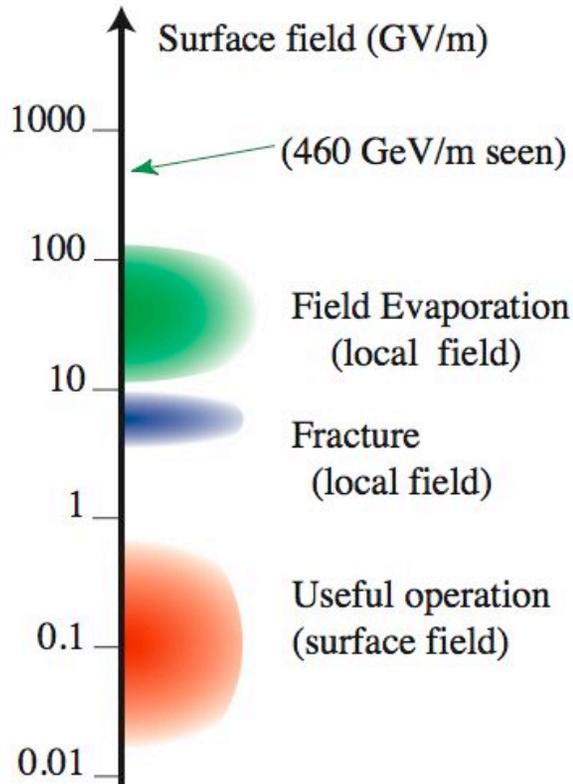
We can measure the local fields directly.



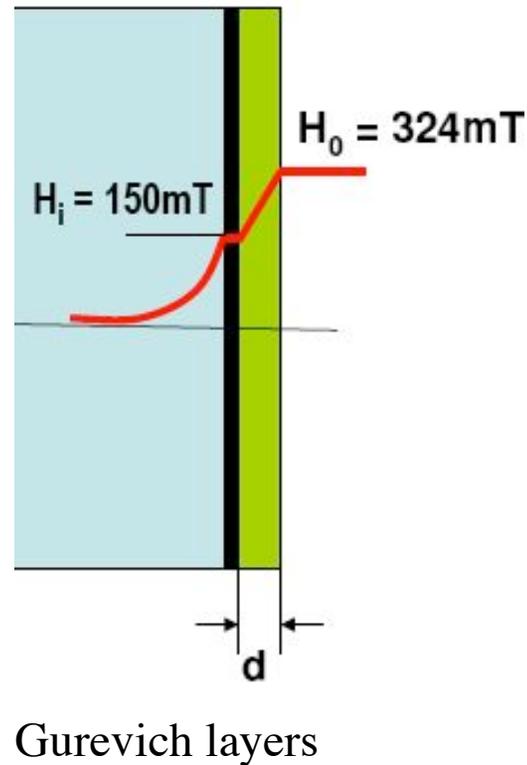
What are the limits of acceleration technologies?

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

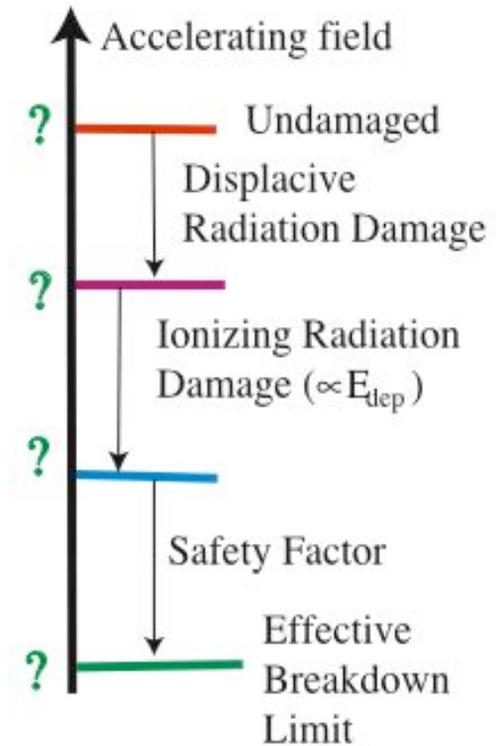
Normal Metal



Superconducting RF



Dielectrics



- Limits are unknown, material science needed.

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

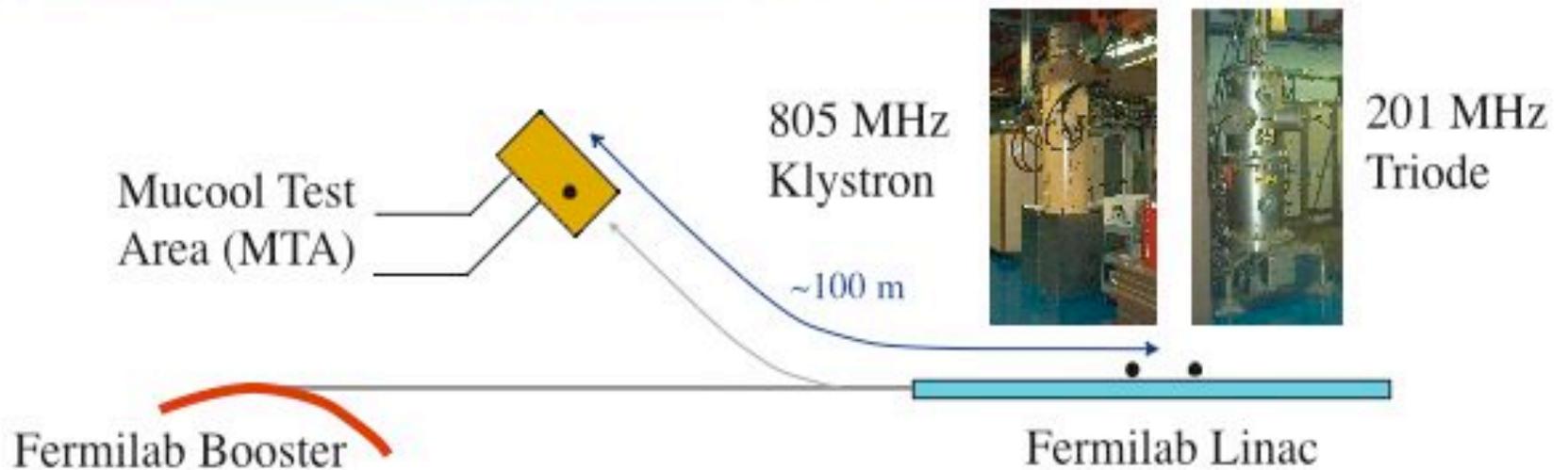
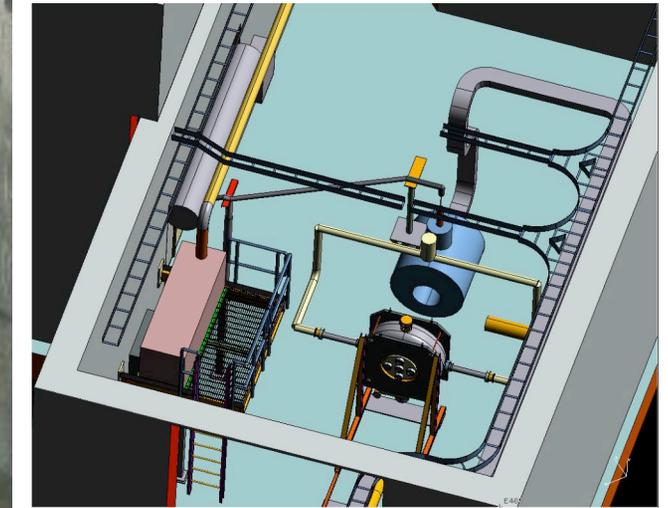
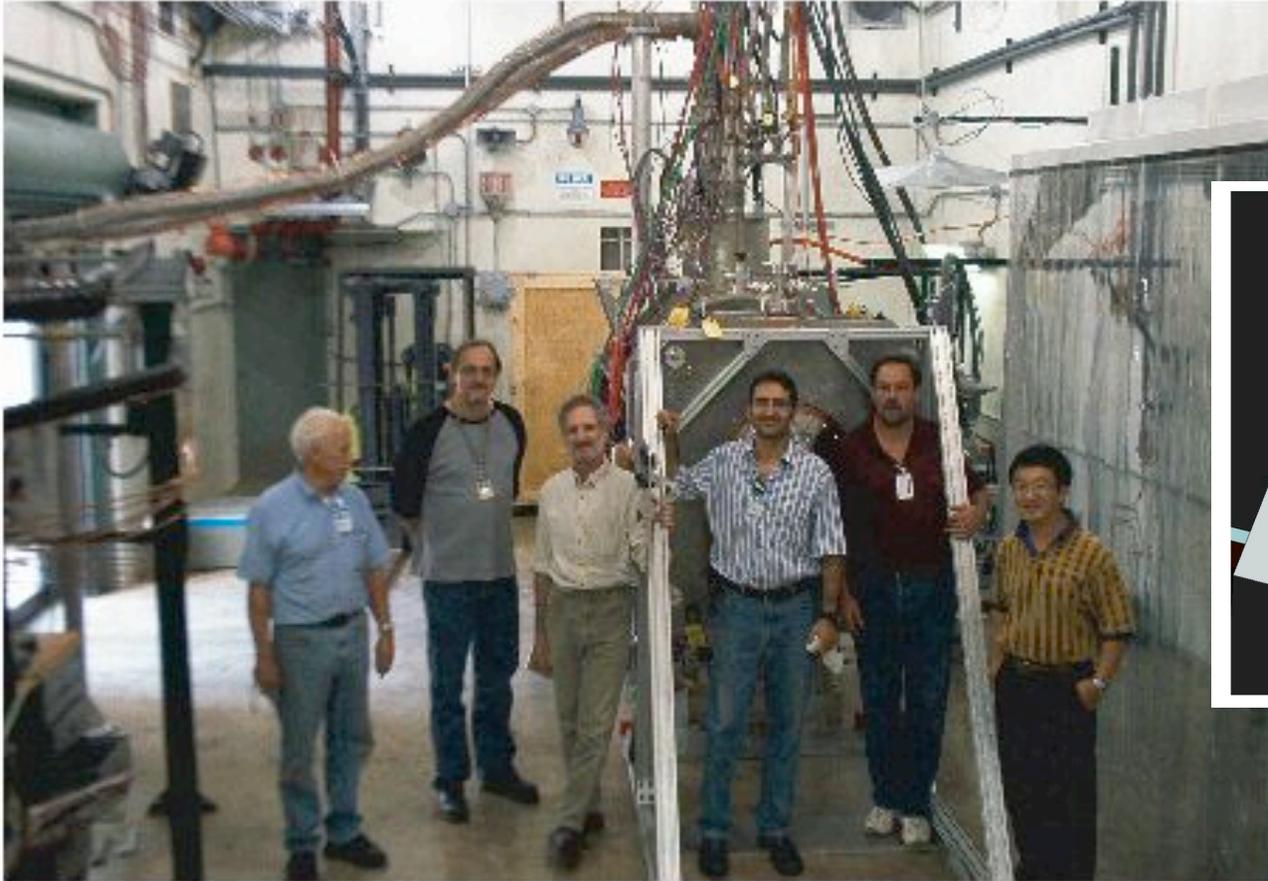
- **Surface studies with Atom Probe Tomography at Northwestern Univ.**

D. Seidman, K. Yoon, NW

- **Plasma modeling (B and gas effects)**

P. Stoltz, Tech-X Corp

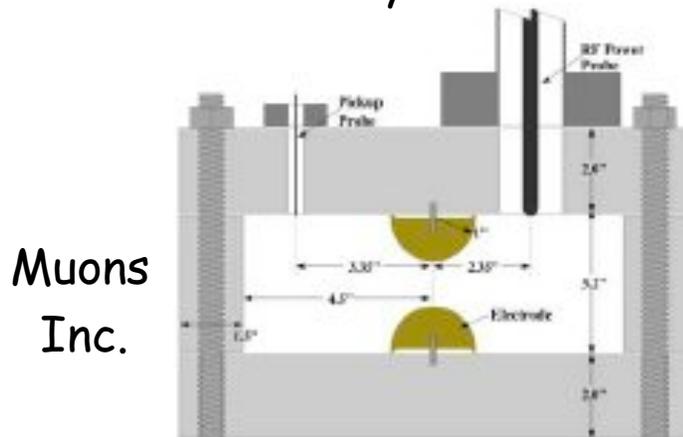
RF experiments are in the MuCool Test Area (MTA) at Fermilab



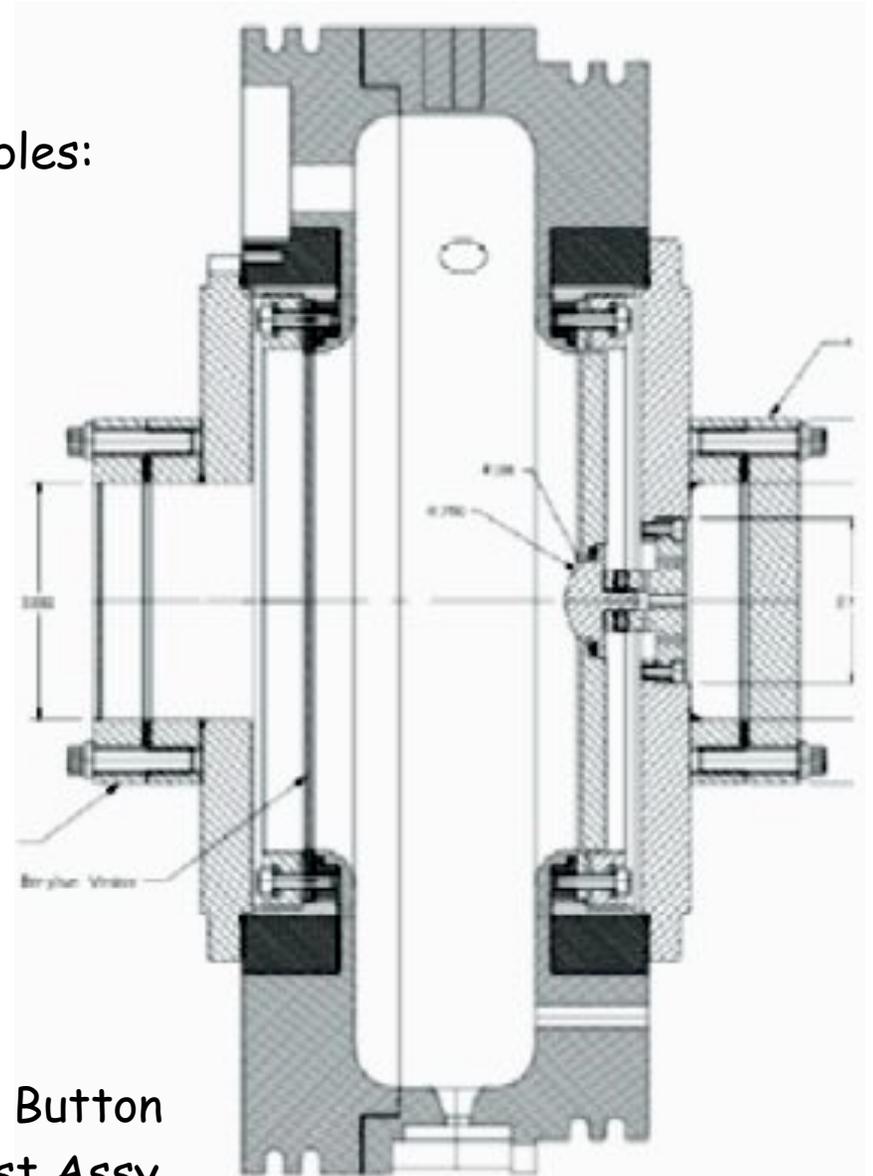
Our 805 MHz program.

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.) H₂ and He
- Window Geometry



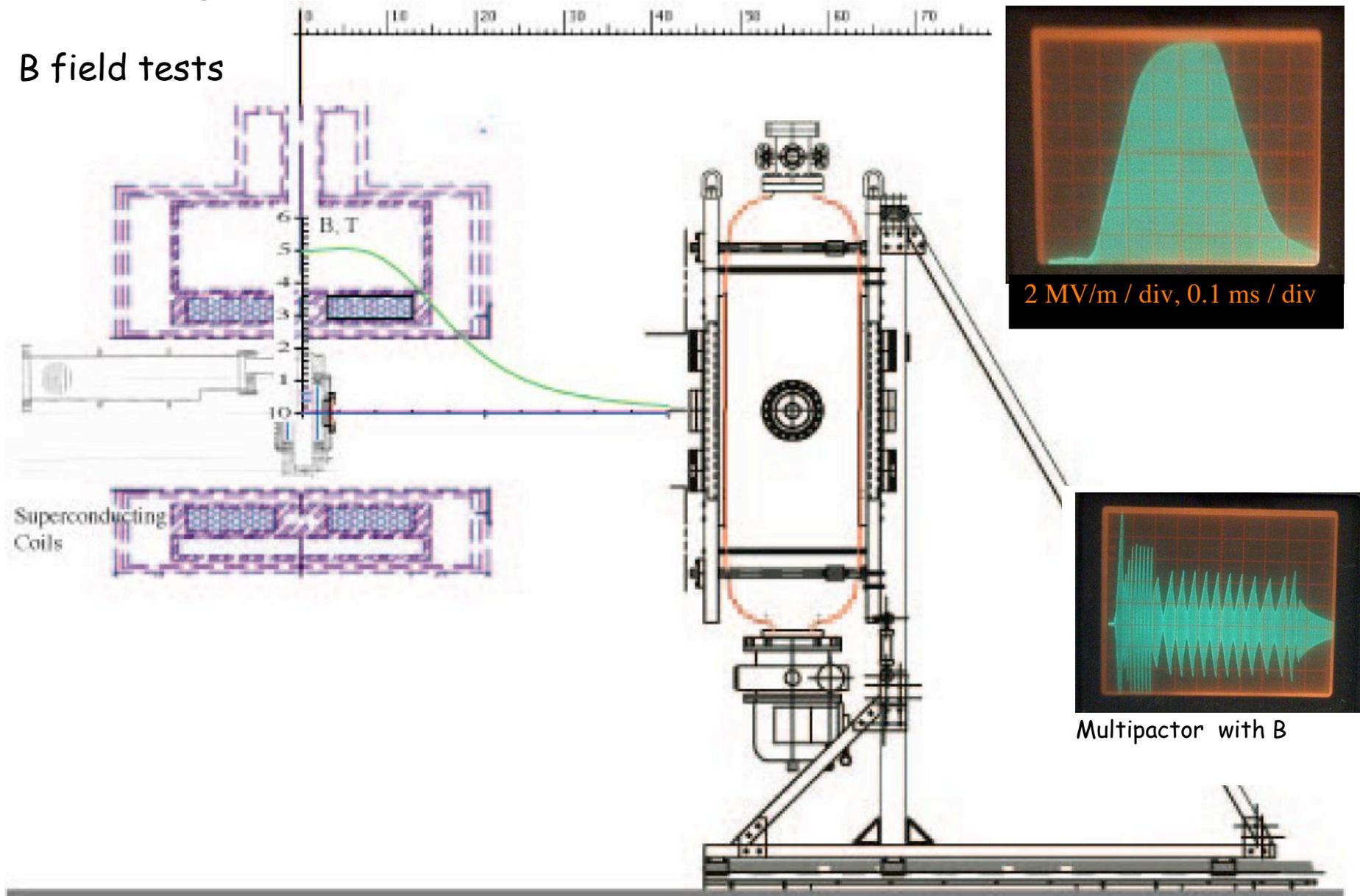
Muons
Inc.



Button
Test Assy.

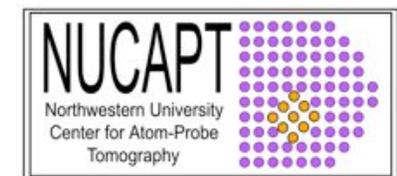
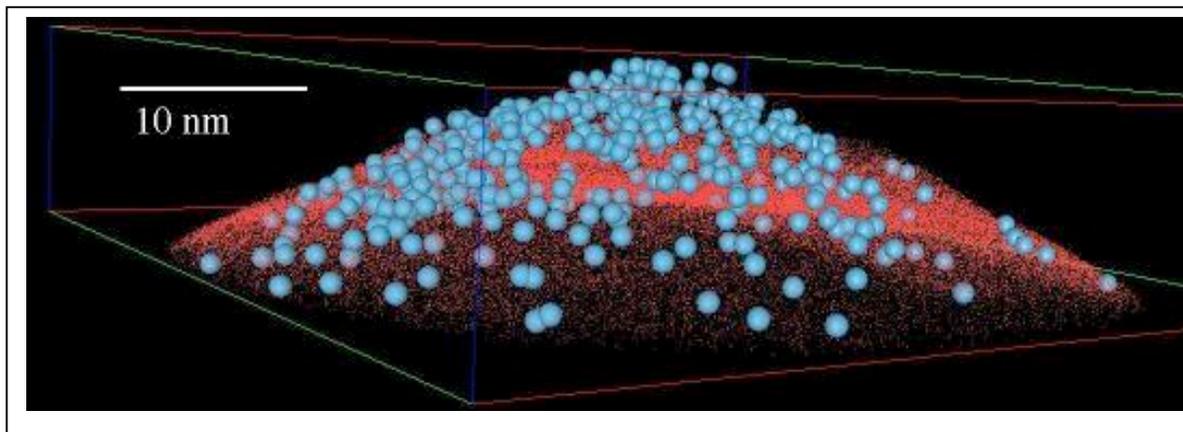
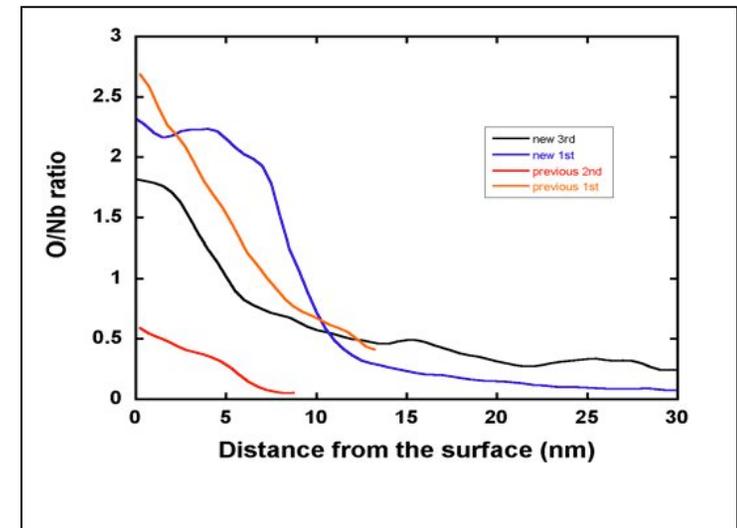
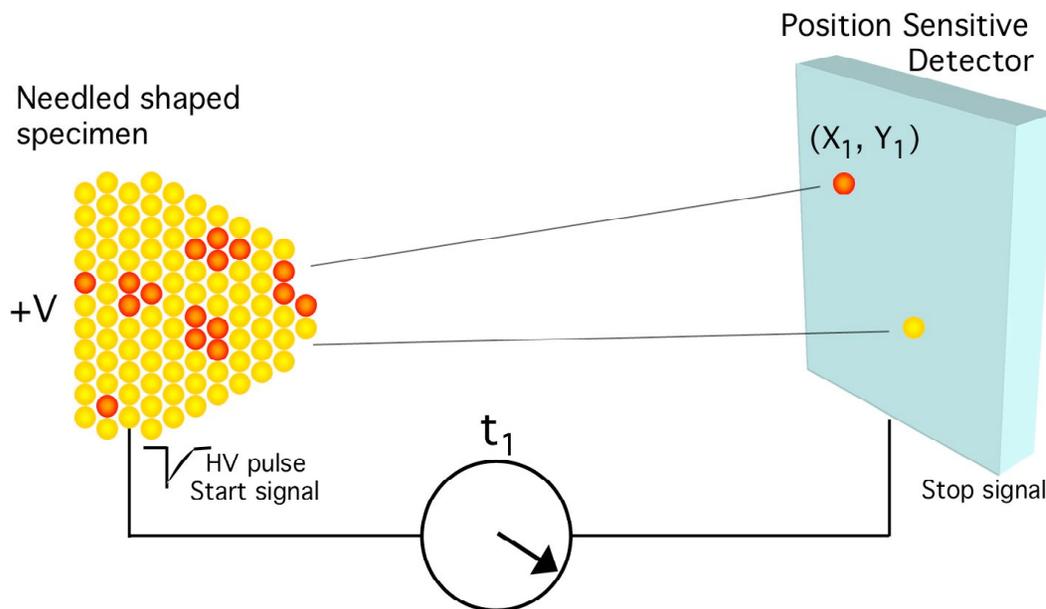
201 MHz Program.

- Conditioning / breakdown, window tests.
- B field tests



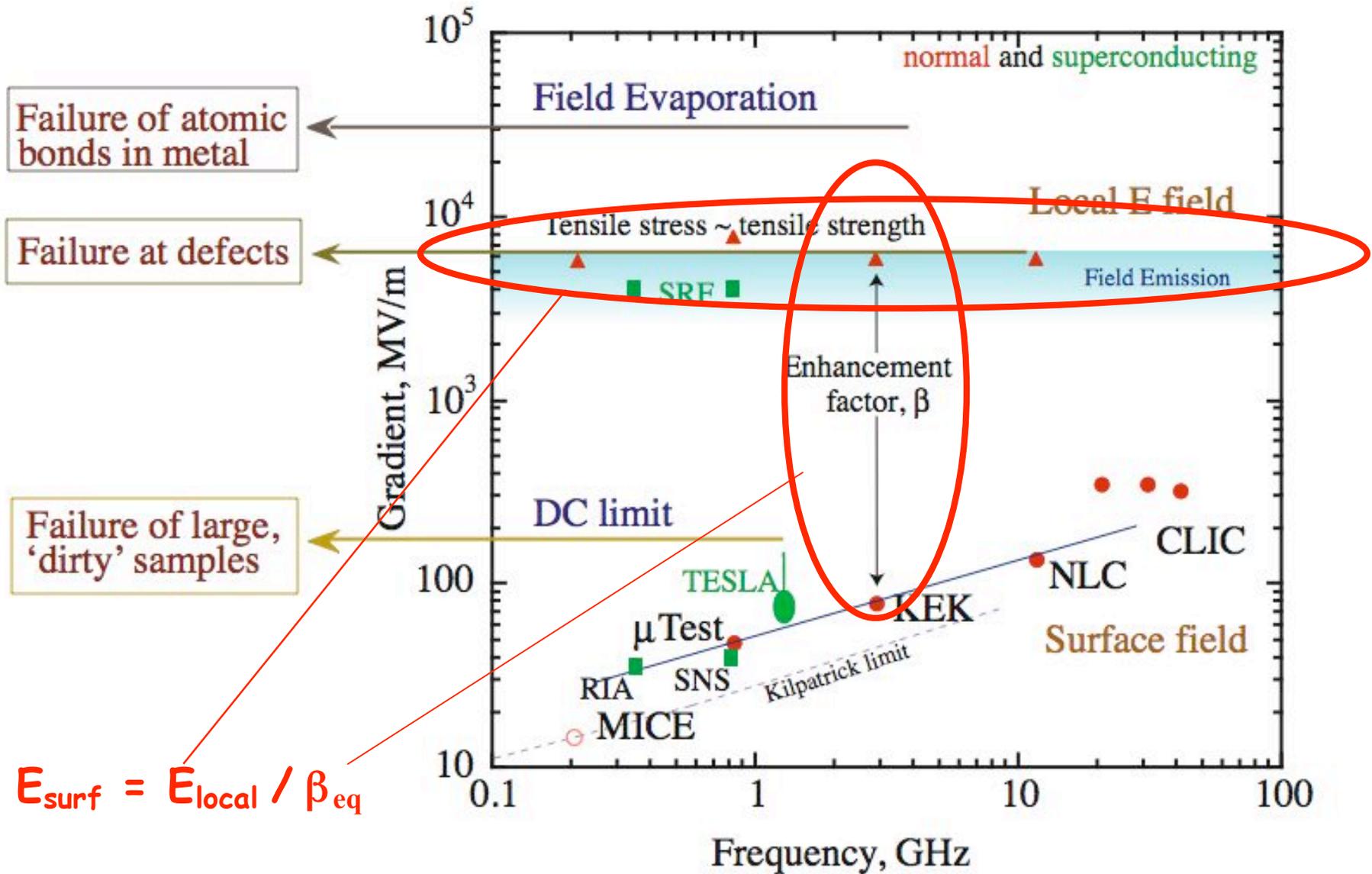
Atom Probe Tomography (at Northwestern)

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



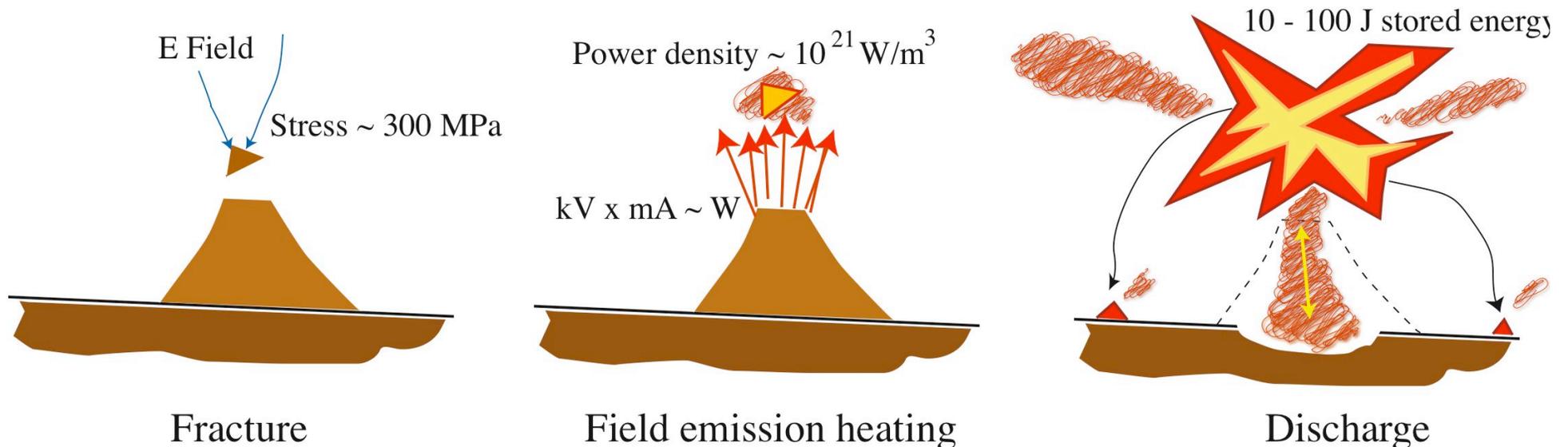
500 GeV/m accelerations !

The Model: Local fields + enhancements determine everything.

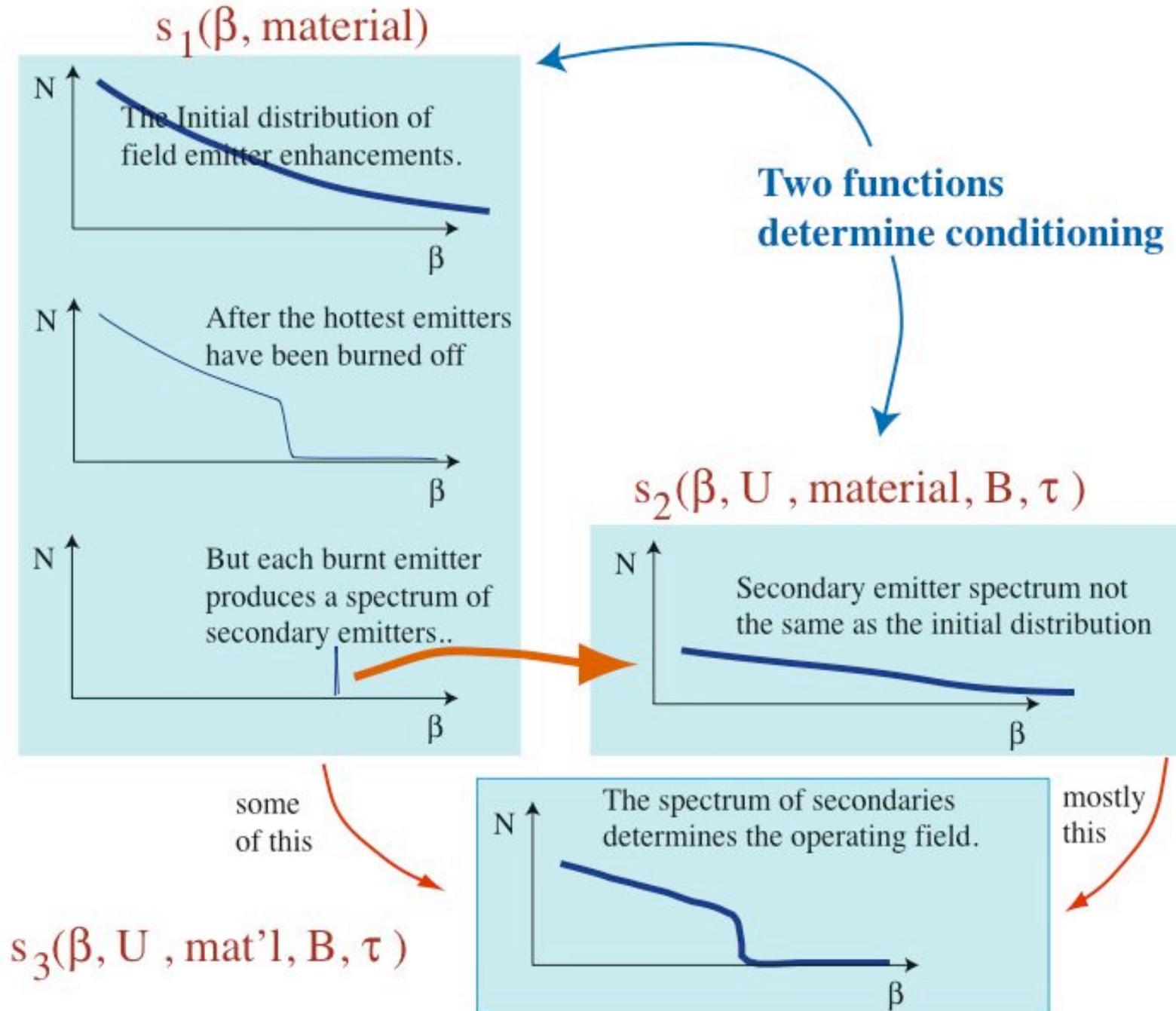


The Process of Breakdown

- Field emission is the diagnostic.
- Fracture is the trigger.
- Field emission heating makes a lossy plasma.
- The lossy plasma directs the EM energy to the wall.
- An equilibrium state develops between the structure and the surface.

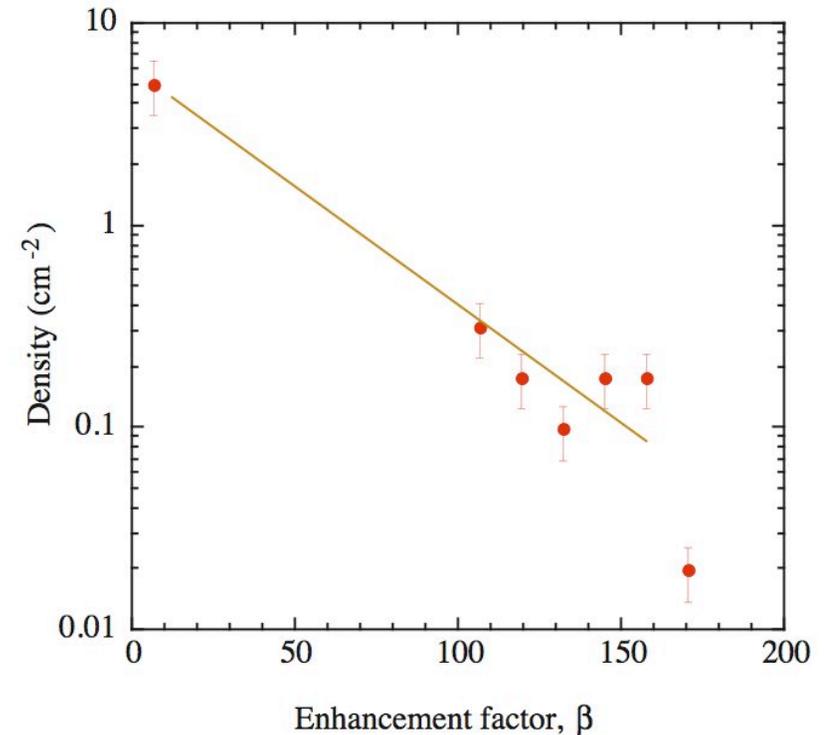
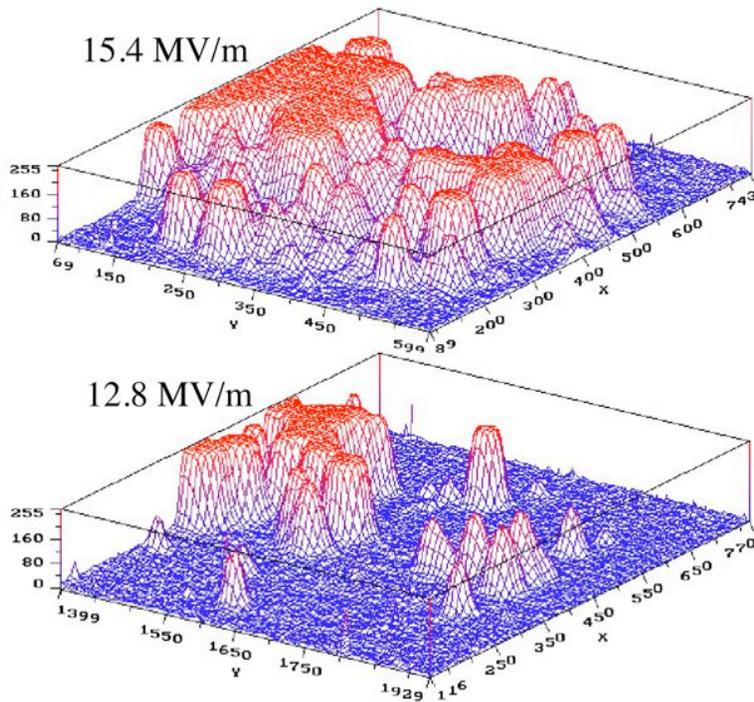


Spectra of field emitters (enhancement factors)



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

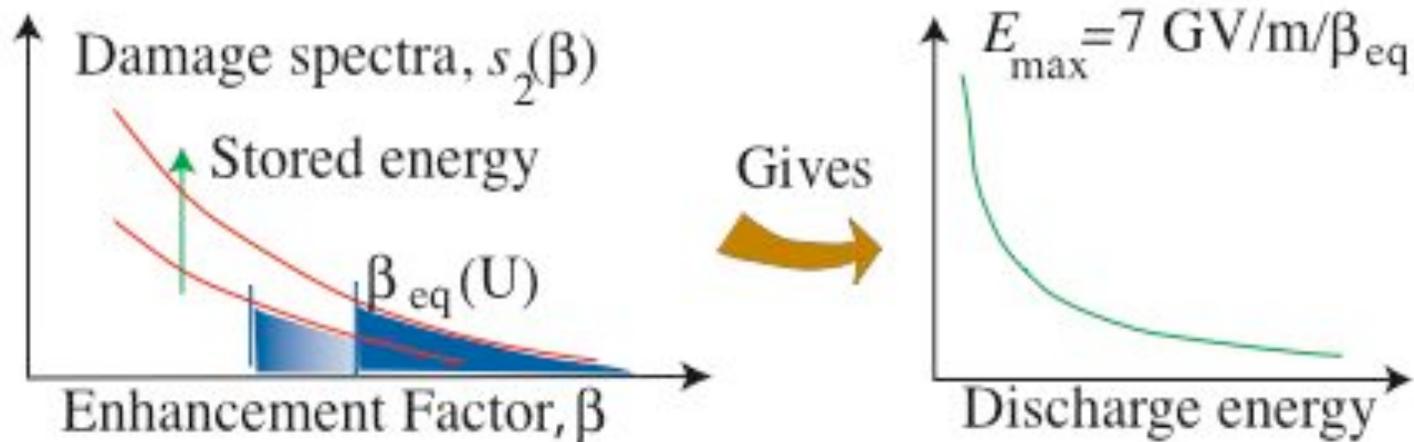
- We looked at individual emitters, and measured spectra produced in discharges



- From the emitter intensities at different fields we can measure the spectrum of field enhancements

The maximum operating field

- Stable operation demands that:
Breakdown events cannot create more damage than they destroy.
- This constraint relates the maximum β and the discharge energy.



- The damage spectra seem to be defined by $s_2(\beta, mat'l, U_{dis}, geom. \dots) \sim U_{dis} e^{-a\beta}$
so one can find β_{eq} from the constraint that $\int_{\beta_{eq}}^{\infty} s_2(\beta, mat'l, U_{dis}, geom \dots) d\beta = p$.
- Thus if $s_2(\beta) = Ue^{-b\beta}$, then $\beta_{eq} \sim -\ln(b/U)/b$.

A Theory for the RF Surface For Metals at the Destructive Breakdown Limit

*Perry Wilson
SLAC*

By destructive breakdown we mean a breakdown event that results in surface melting over a macroscopic area in a high E-field region. A plasma forms over the molten area, bombarding the surface with an intense ion current ($\sim 10^8 \text{A/cm}^2$), which is equivalent to a pressure of about a thousand Atmospheres. This pressure causes molten copper to migrate away from the high-pressure region near the iris tip, resulting in a measurable change in the iris shape.

The four Stages of breakdown

1. The formation of plasma spots and individual craters in high field regions on the metal surface.
2. Setting up the conditions for surface melting—crater clustering.
3. Prediction for the surface field at the threshold for destructive breakdown.
4. From surface melting to destructive breakdown.

There is a lot of data around:

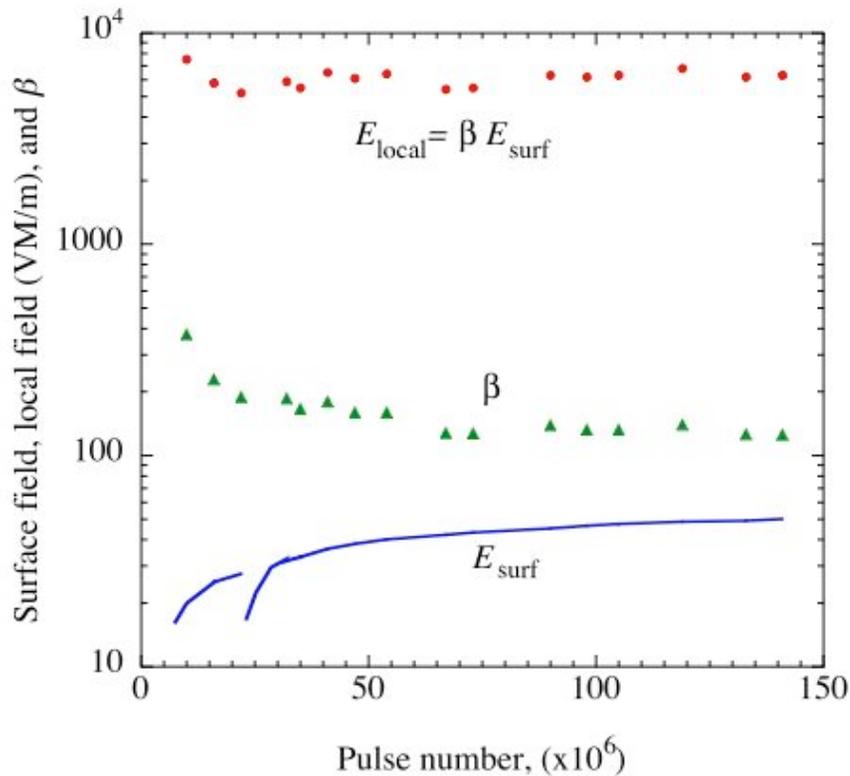
	fracture	heating	plasmadebris		Who
Breakdown rate vs. E	X	X		X	all
Breakdown rate vs. pulselength				X	S
Breakdown rate within pulse	X				CS
Materials	X		X	X	CSKF
Conditioning process	X			X	all
Magnetic fields	X	X	X	X	FMA
Breakdown timescale	X	X			all
Frequency scaling				X	all
Small gap breakdown	X				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

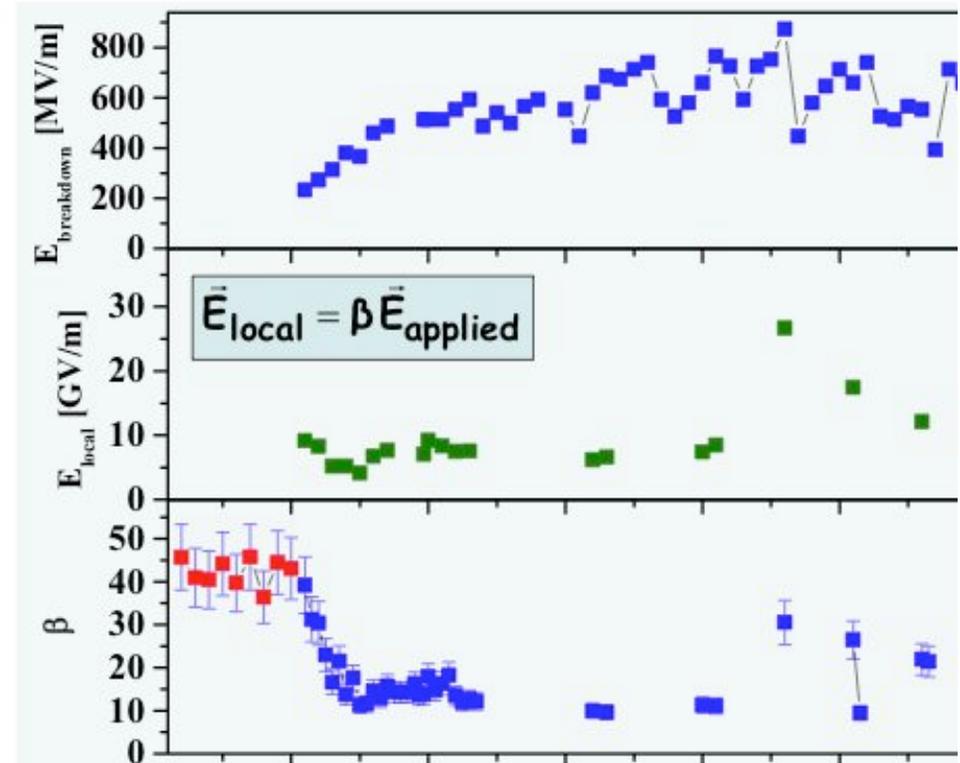
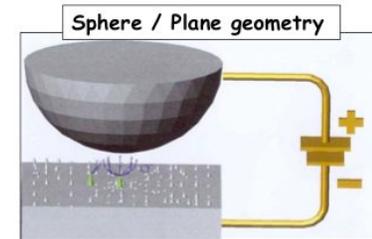
Using the model: I) Conditioning

- Breakdown occurs when $E_{\text{local}} \sim 7 \text{ GV/m}$
- Only the emitters change, local field is constant.

KEK linac



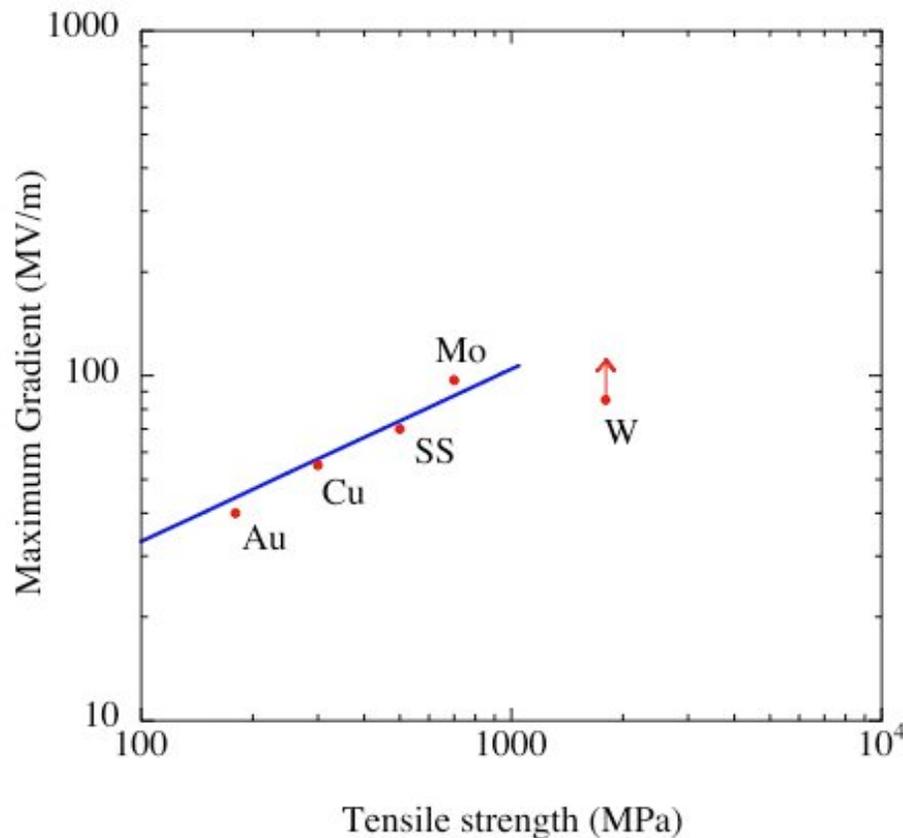
CERN DC test



Using the model: II) Materials

- Only materials change, everything else constant.
- The model argues that tensile strength is the dominant effect.

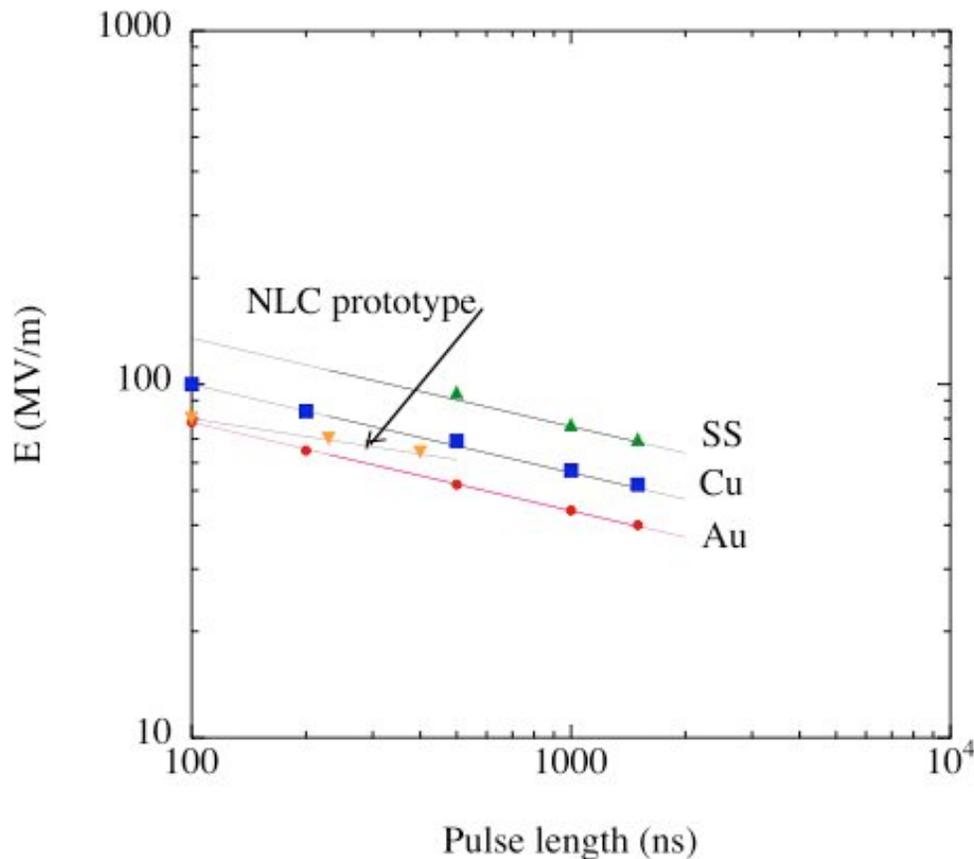
$$E_{surf} = \frac{E_{local}}{\beta} \approx -\frac{\sqrt{2T/\epsilon_0}}{\ln(b/a)/b}$$



SLAC and CERN data

Using the model: III) Pulse length

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

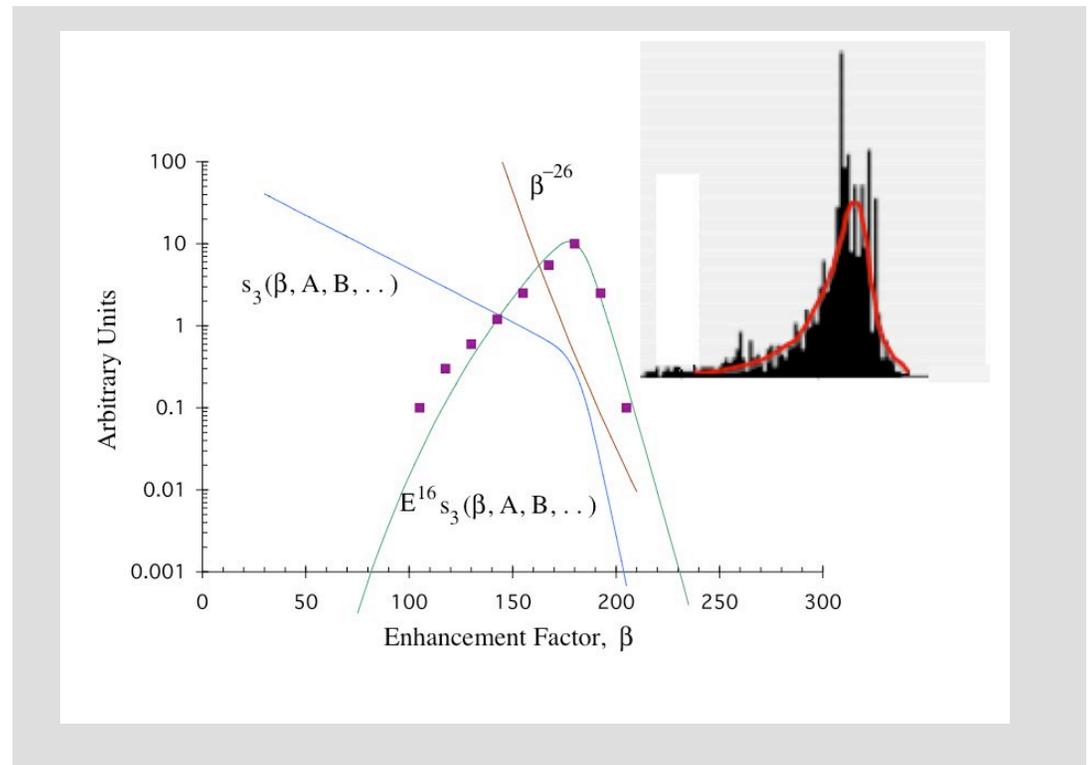
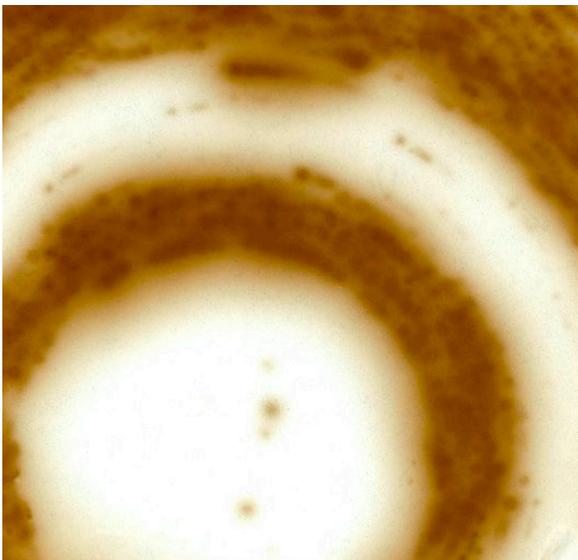
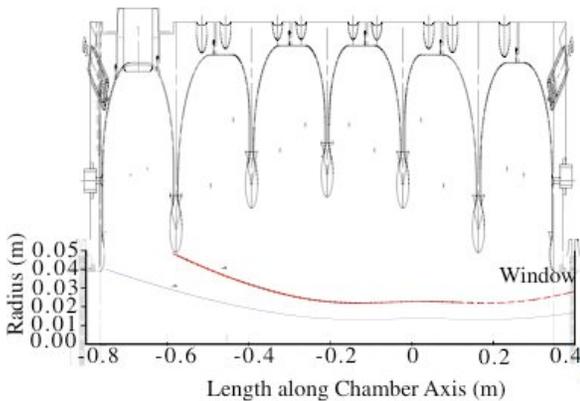


SLAC data

Using the model: IV) The fully-conditioned state

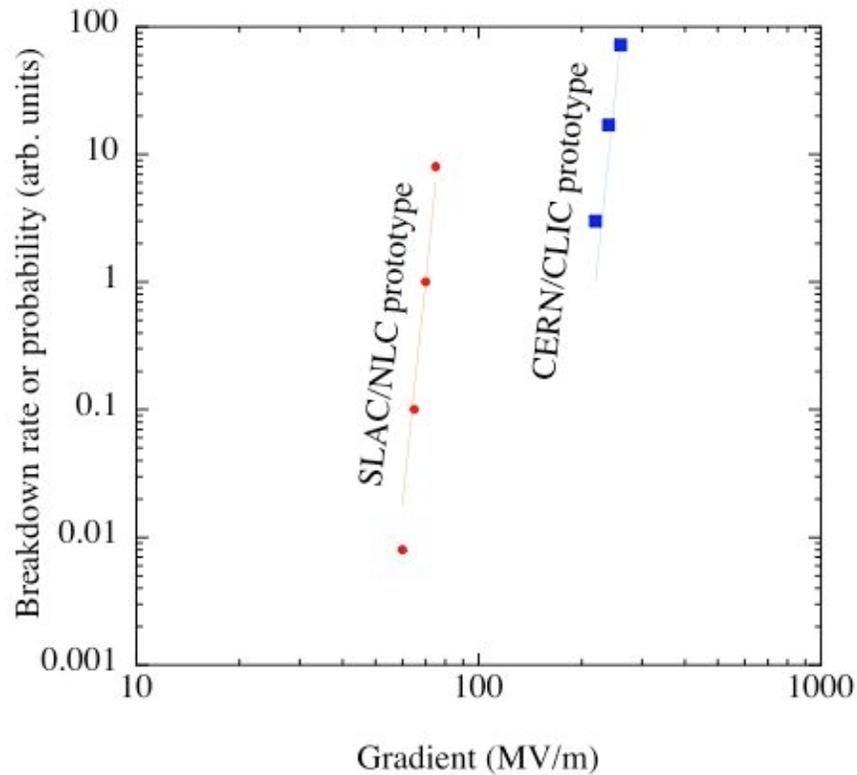
- When you look at emitters, they are all the same strength.
- Assume $s_3(\beta) = s_2(\beta) / (e^{(\beta - \beta_{eq})/c} + 1)$ (F-D cutoff - very sharp β^{-25})

- Images of emitters show emitter strengths
 optical densitometer shows cutoff
 (weighted by field emission $I = E^n$)



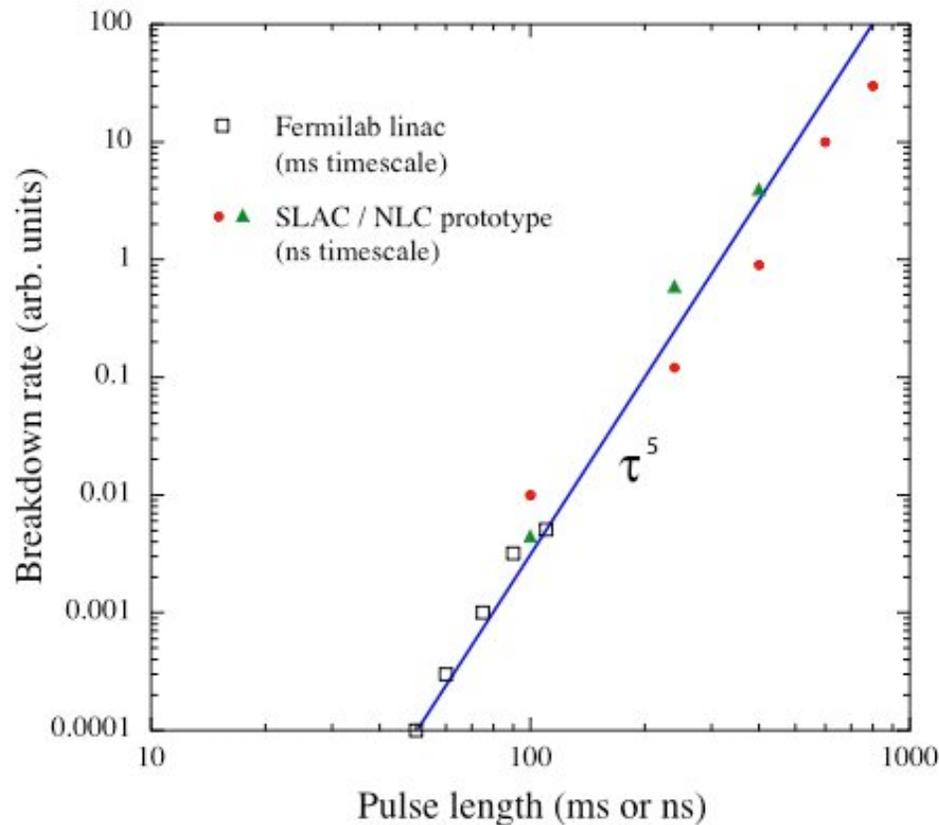
Using the model: V) Breakdown rates vs. E .

- 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.

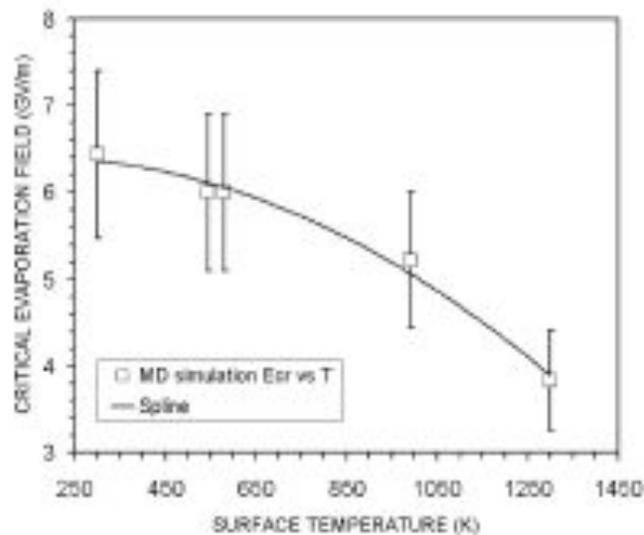
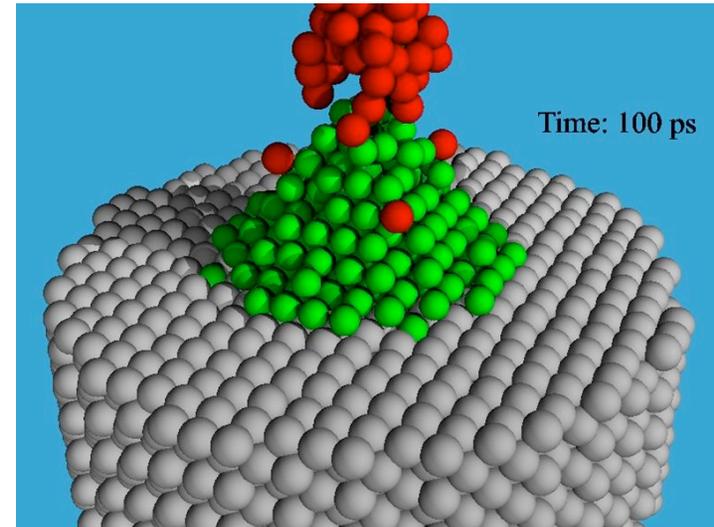


FIG. 2. Observed temperature dependence of critical evaporation field for removing cluster of ~ 200 Cu ions.

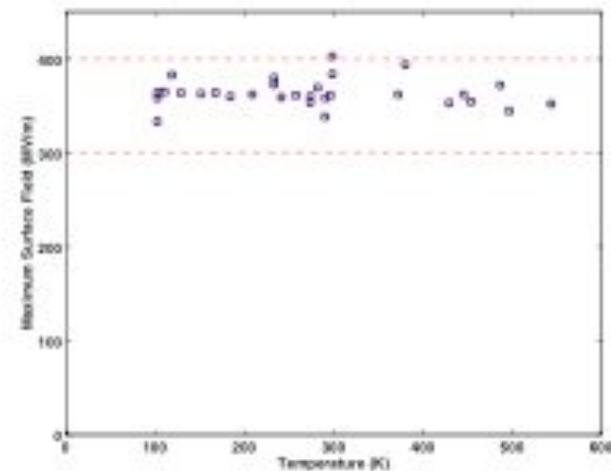
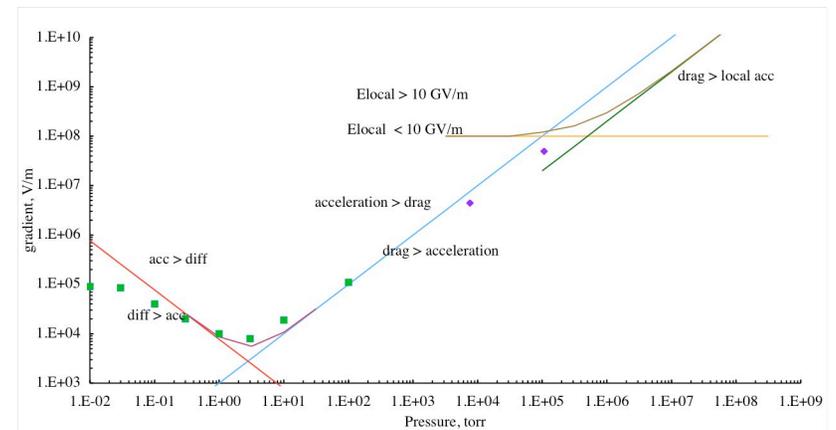
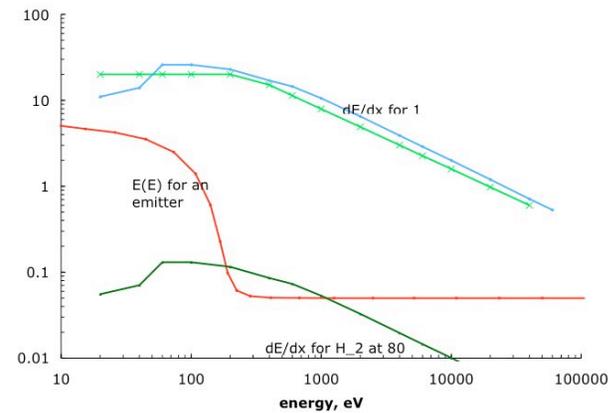
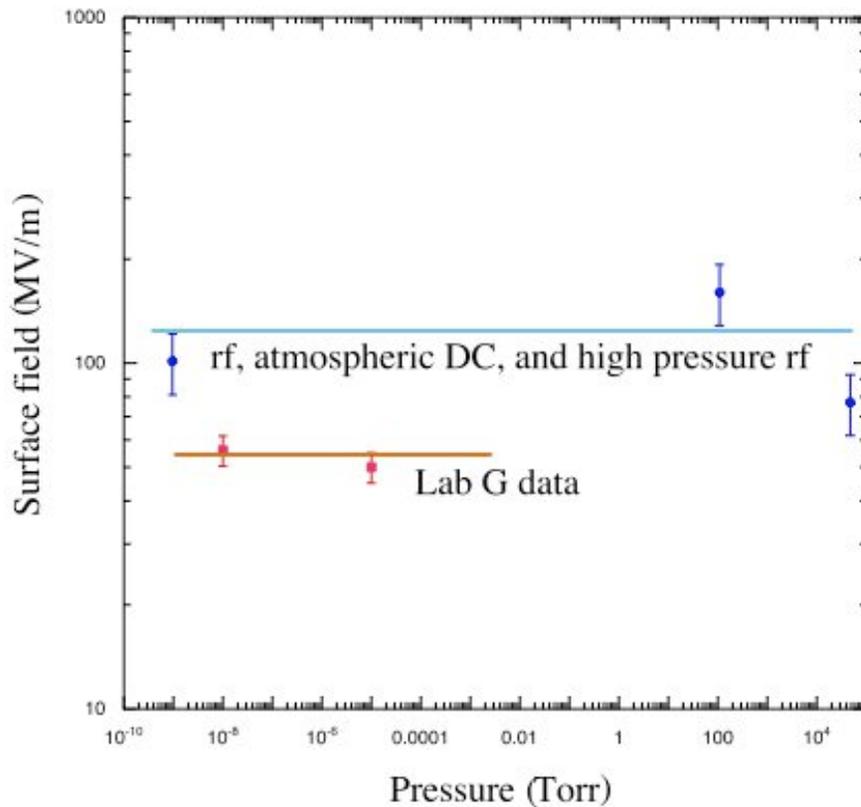


FIG. 6 (color online). Temperature dependence of maximum surface field.

Using the model: VIII) Gas Pressure and type

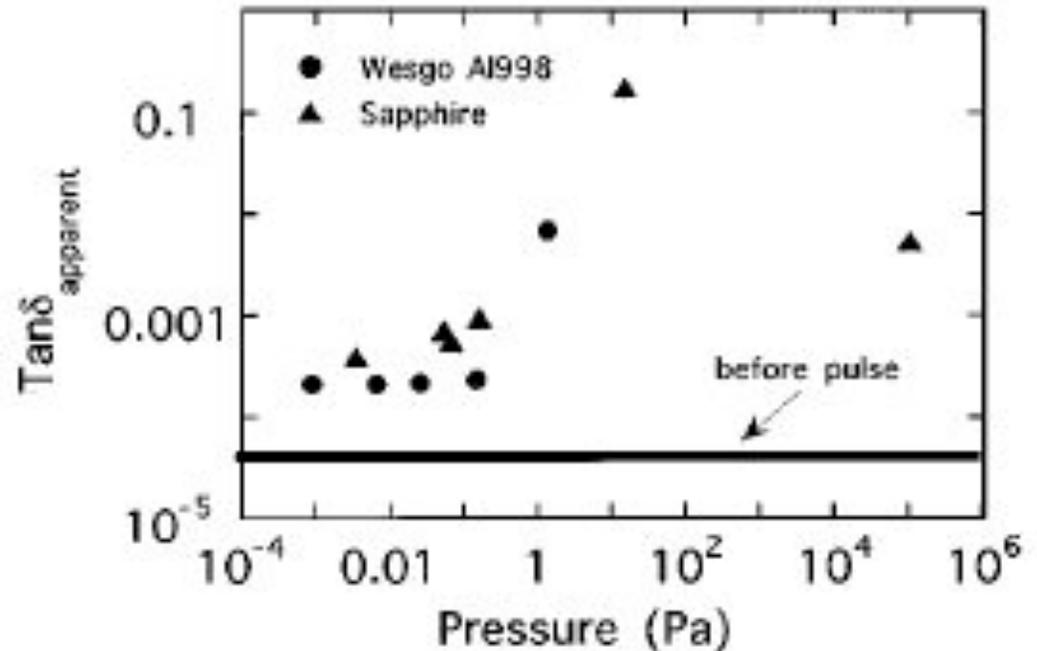
- Gas pressure retards field emitted electrons heating broken fragments
This can disrupt the trigger, for low Z gasses.
- We can also explain how SF_6 can affect breakdown.



Using the model: IX) Dielectrics

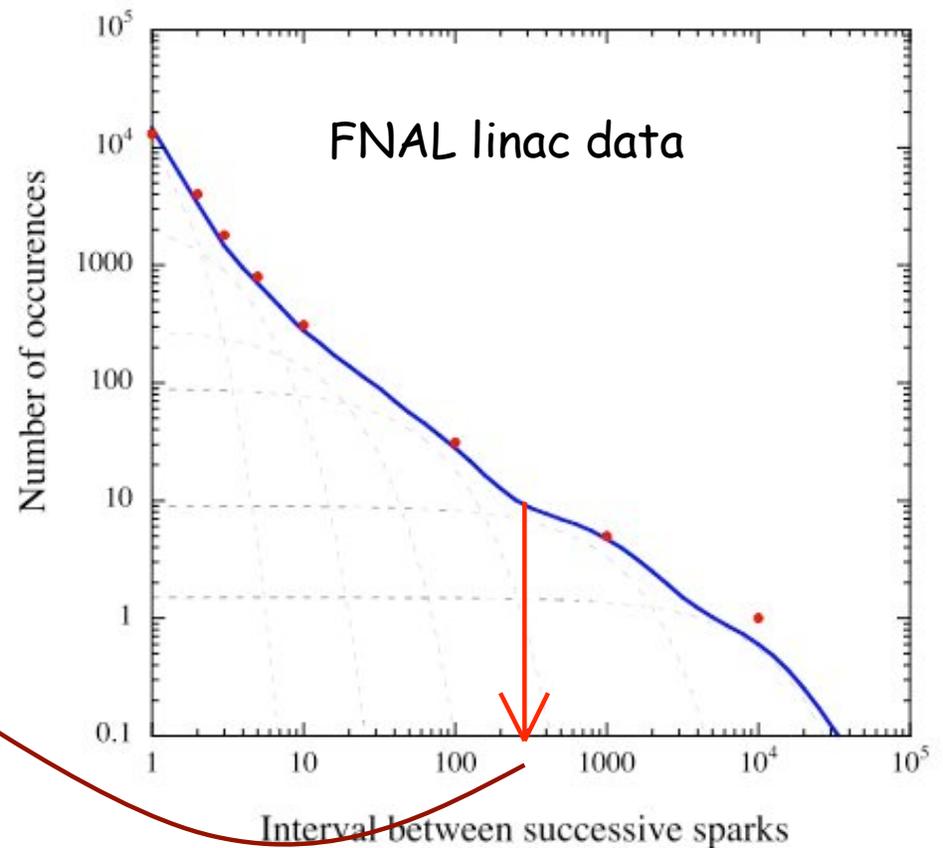
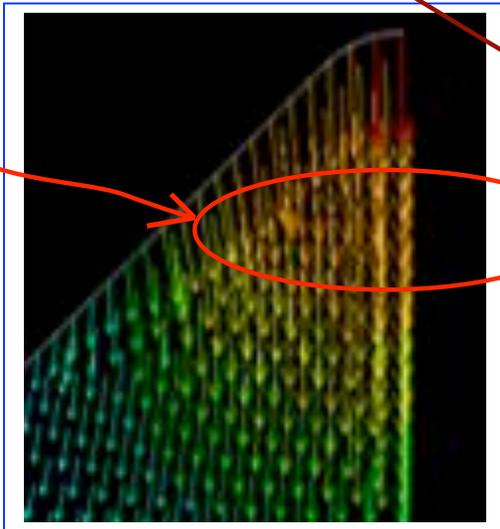
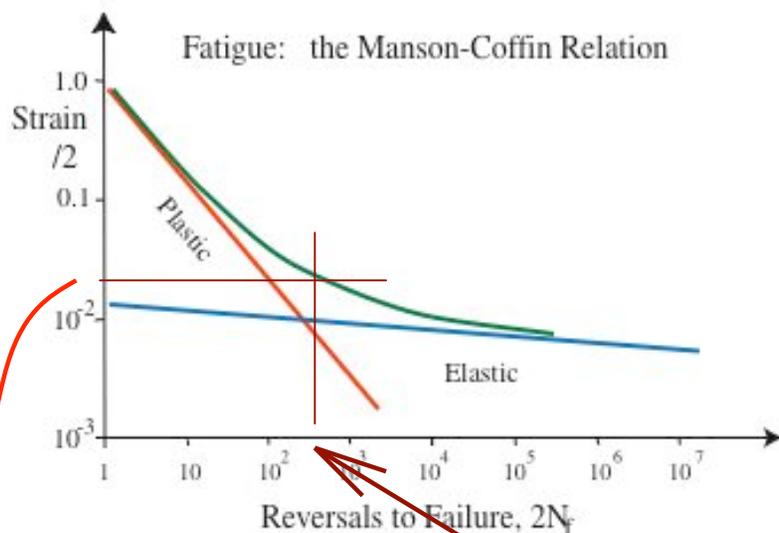
- High pressure gasses are an option for muon cooling.
- Realistic muon beams require Gas + High Gradient + Radiation
- Radiation comes two ways: 1) ionizing, and 2) displacive. 1) is our problem.
- We can measure loss tangents vs. Pressure in a radiation environment.

- Losses are radiation and pressure dependent.

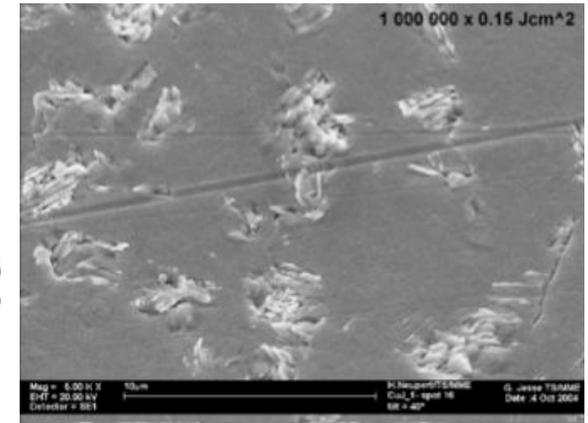
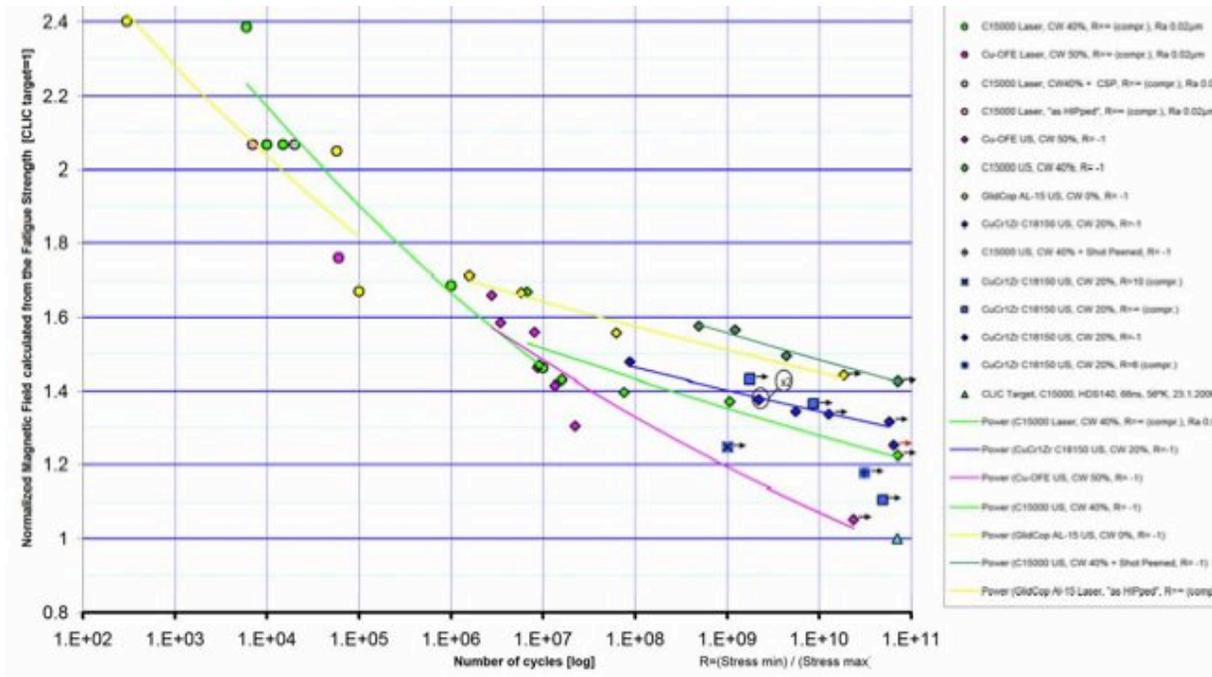


Using the model: X) Correlated breakdown events

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



. getting fatigued



Cu-OFE at 10⁶ cycles, $\Delta T = 90^\circ\text{C}$
Fatigued surface

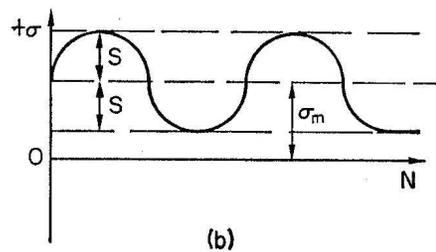


Fig. 1. Sinusoidal stress cycling, (a) about zero mean stress, (b) about a positive mean stress.

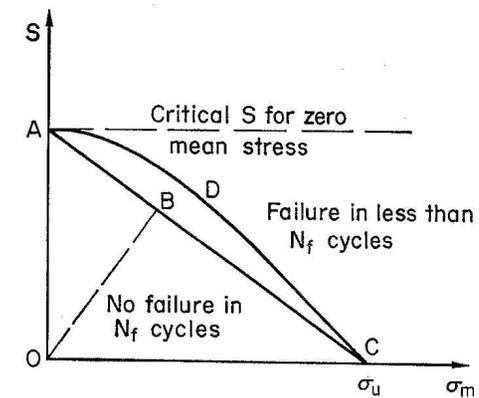
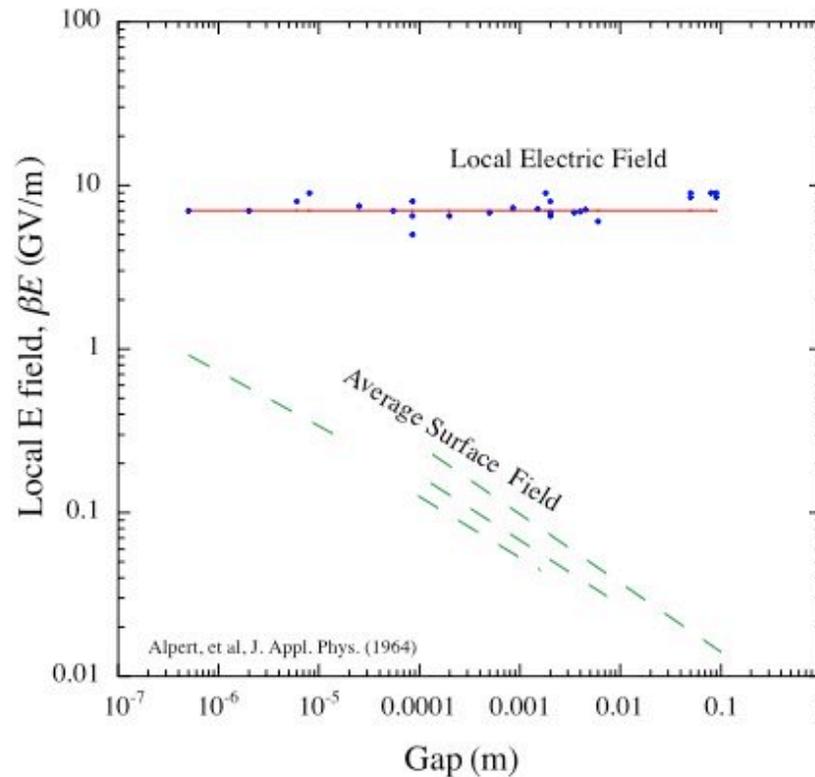


Fig. 3. The effect of mean stress. Goodman line ABC, Gerber parabola ADC.

Using the model: XI) DC breakdown

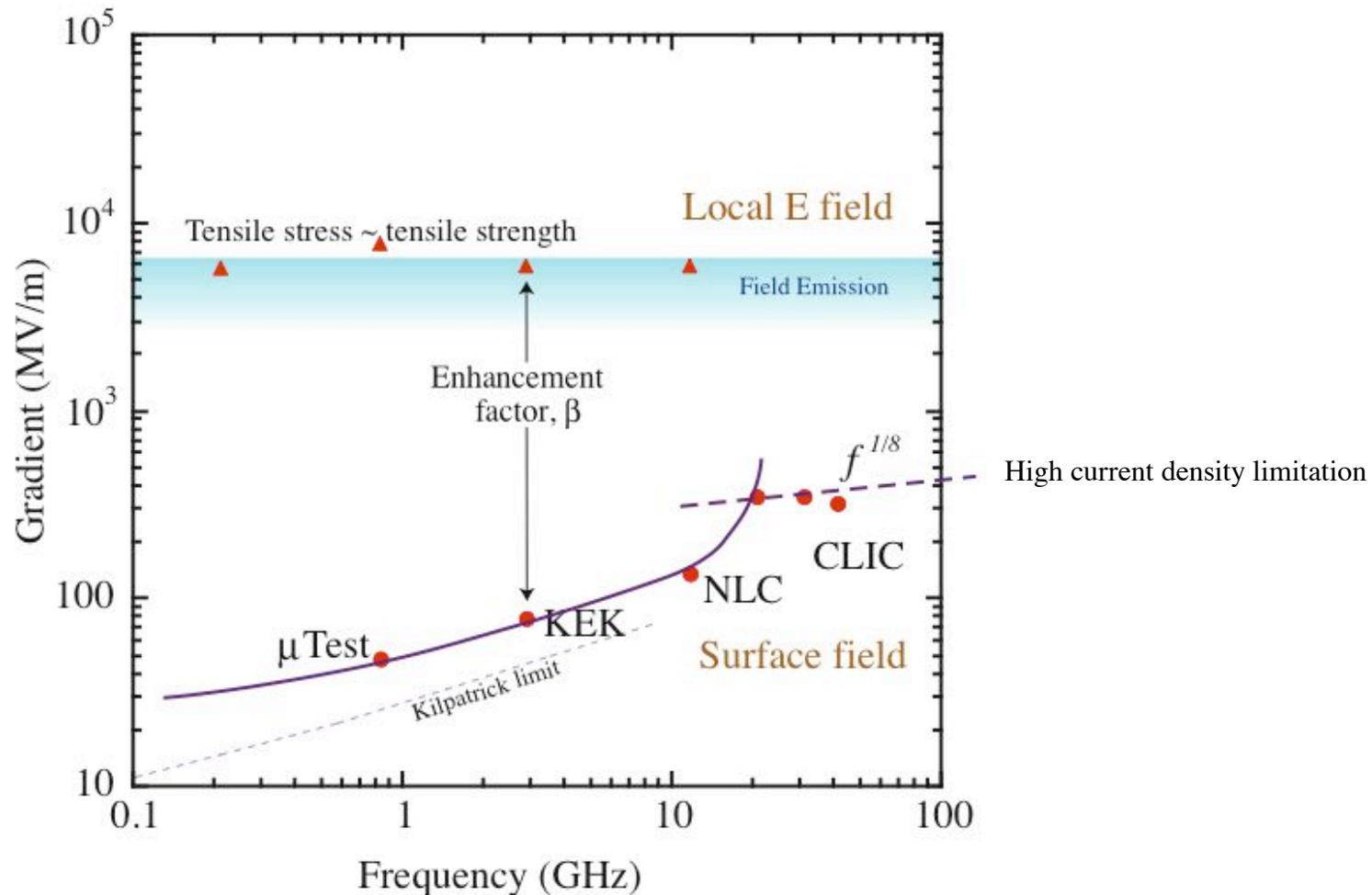
- This also fits the model, with breakdown at 7 GV/m.
- Most of this data is very old and unreliable, but they did clever things.
- Vacuum and cleaning techniques were not always well done.



Alpert et al (1964)

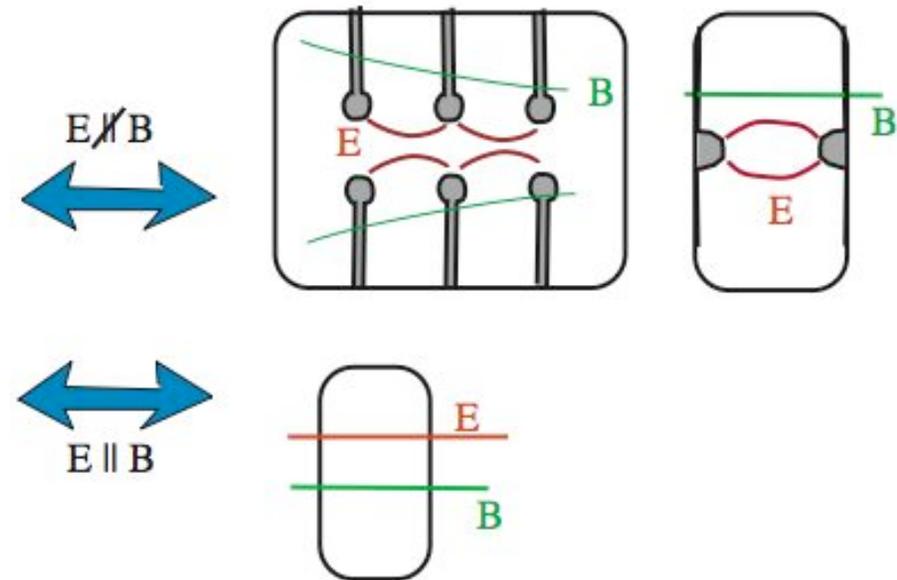
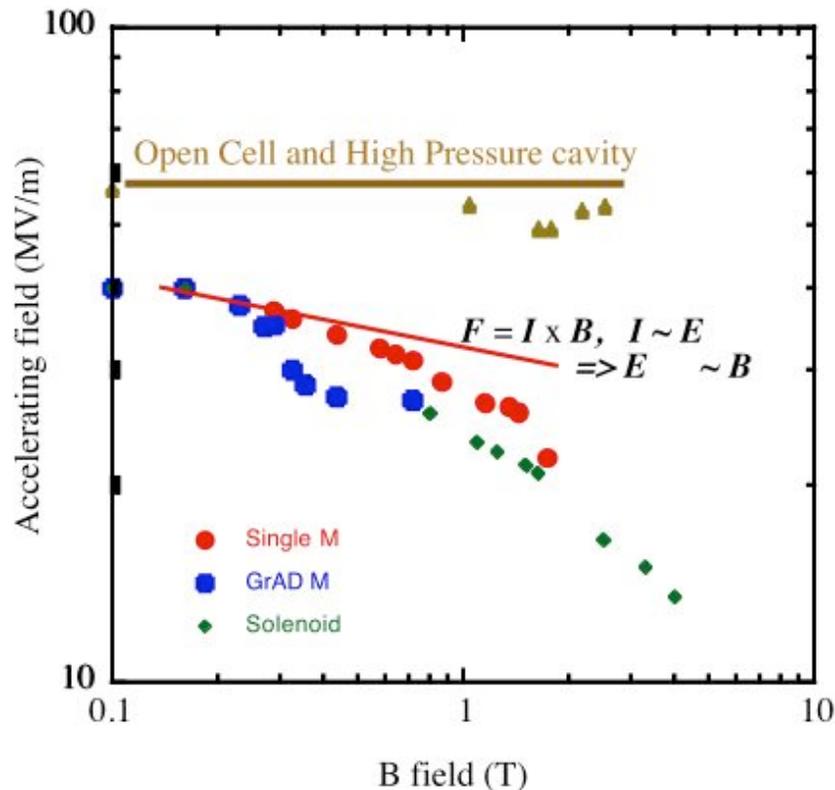
Using the model: XII) Maximum field vs. frequency

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



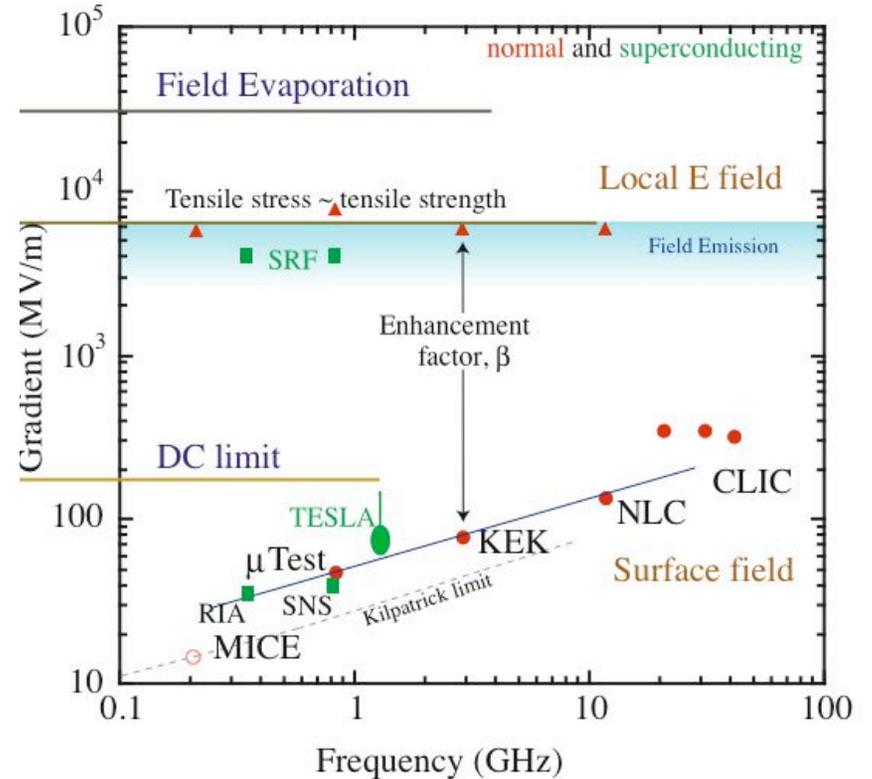
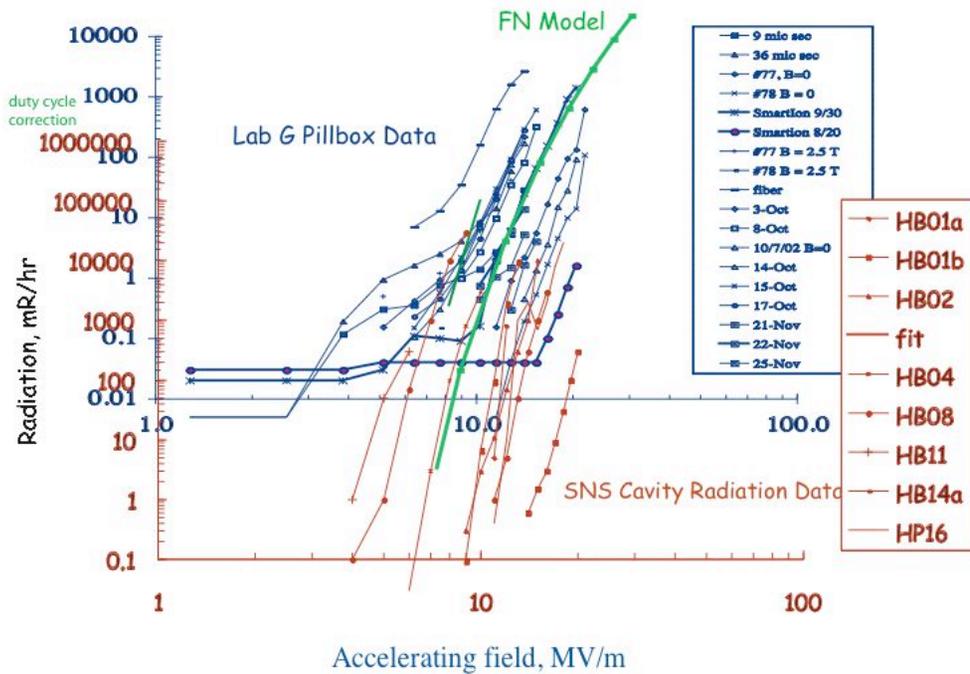
Using the model: XIII) High Solenoidal fields

- 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.



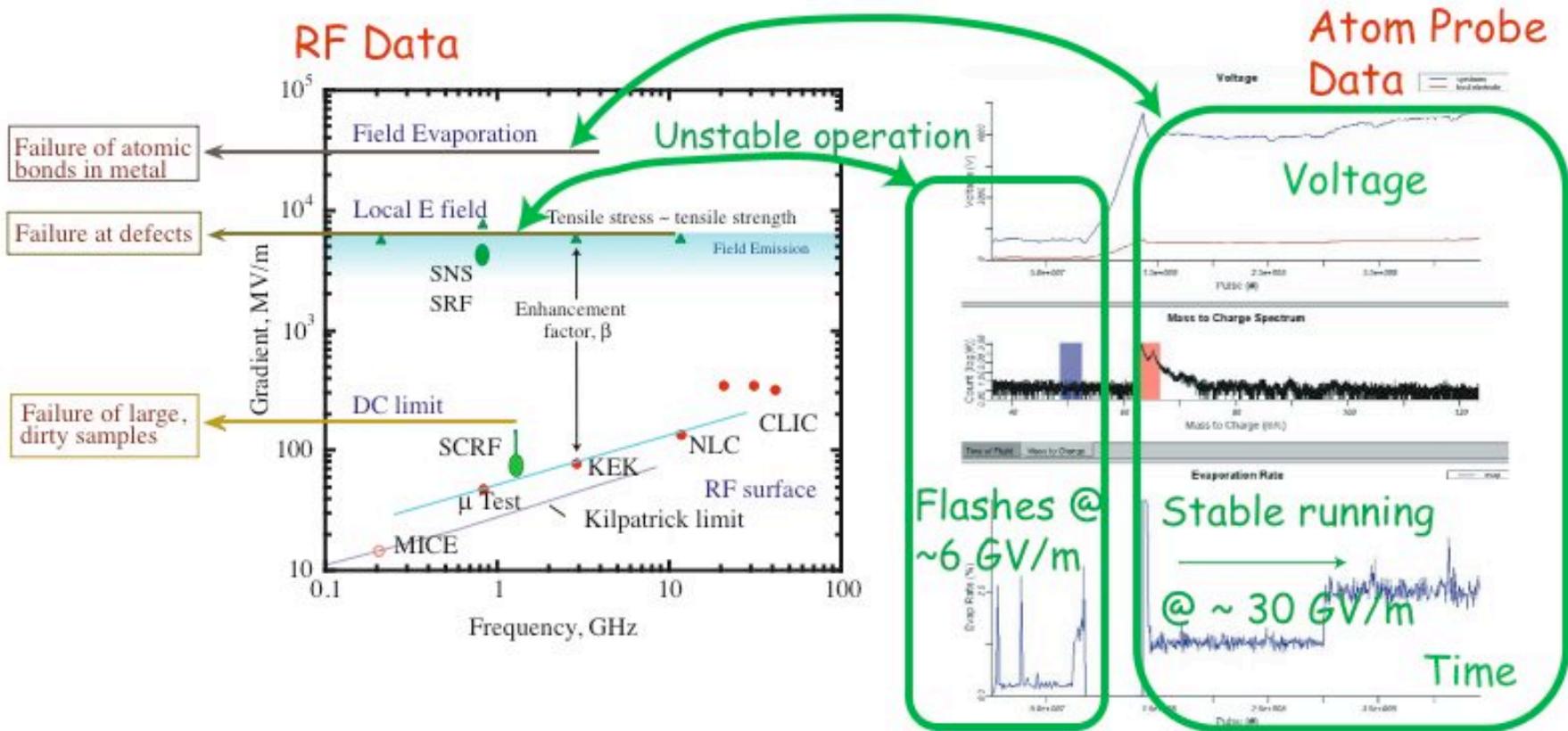
Using the model: XIV) Superconducting rf

- For SCRF $E_{max} = (4 \text{ GV/m}) / \beta$, NCRF $E_{max} = (7 \text{ GV/m}) / \beta$
- 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.

A New Entity

- The US Collaboration on High Gradient Research for a Multi-TeV Linear Collider, which seems to be aimed at developing, and optimizing CLIC technology has been formed in the past year.
- Ron Ruth, at SLAC, is the Spokesman.
- Membership consists of:
 - Labs: ANL, LBNL, NRL, SLAC
 - Universities: U of Md, MIT, UCLA, U of Colo.
 - Business Associates: Omega-p, Calabazas Creek Res, Tech-X, Euclid, CPI
 - Foreign Associates: CERN, KEK
- The collaboration itself will have no direct funding, and proposals and funding will be handled as separate projects.

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.

Specific Conclusions

- A simple model can explain all the data.
- 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.

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