Progress in Understanding High Gradients*

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High Gradient RF
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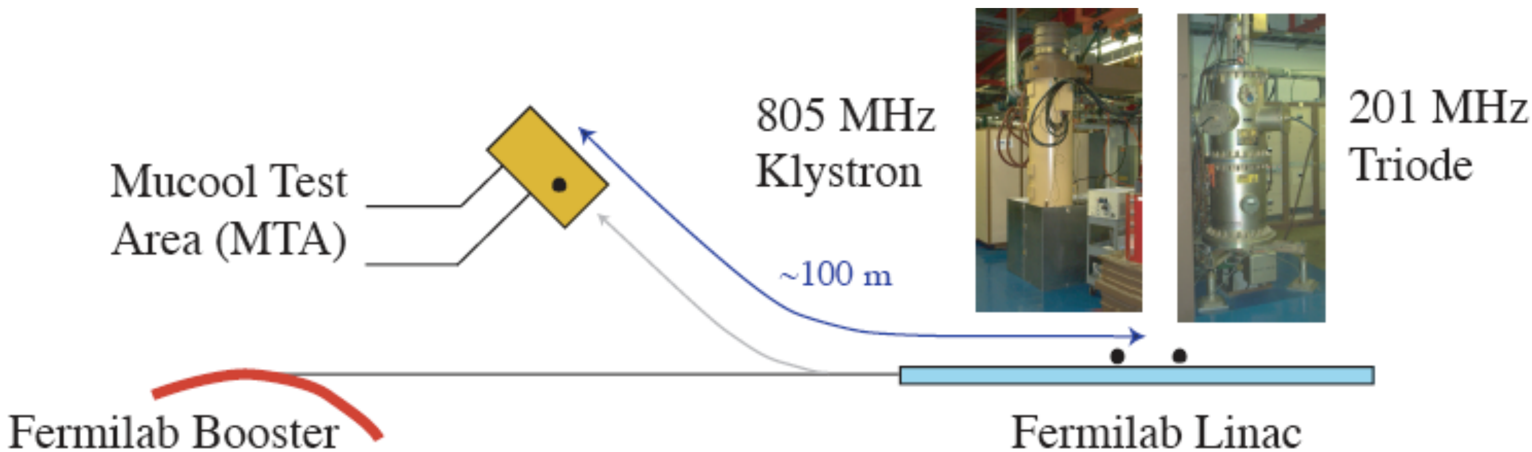
* The physics in this talk will be part of an article to be submitted to Phys. Rev STAB.

The Muon Collaboration has a program in high gradient R&D.

- Muon cooling requires low frequency, high gradient cavities – in solenoids.
- Since 2001 we have had an experimental program – with theoretical modeling.
- We just moved to a new experimental area, with access to FNAL / LINAC power.

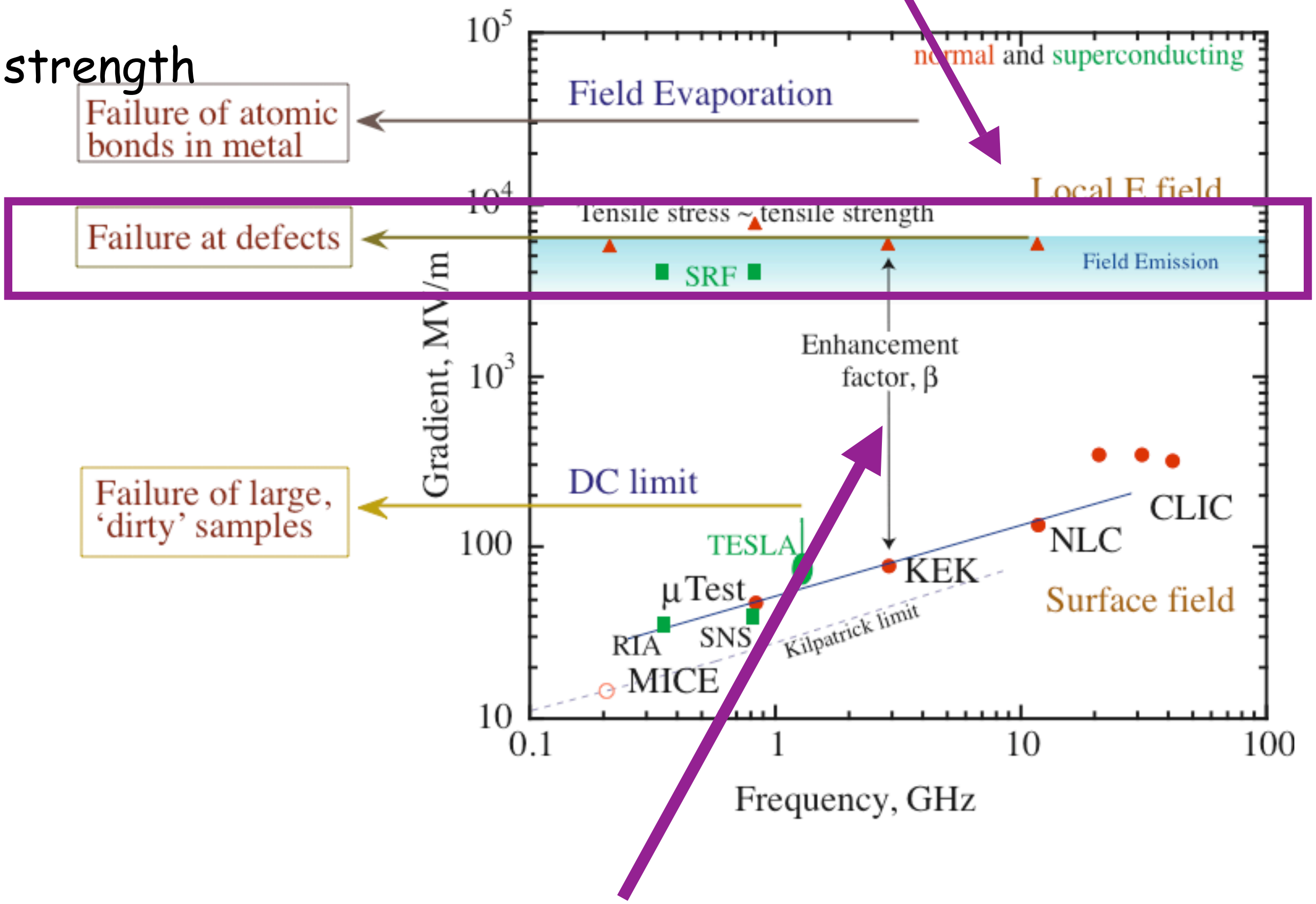


Results

- This program helped justify the MICE experiment, which needs these results.
- We have published a model of breakdown triggers, and have a general theory.
  New experimental results: Highest field seen ~110 GV/m, Oxide effects.
- A complete understanding of breakdown / gradient limits underway.

The problem of rf gradient limits

- We understand breakdown as mechanical failure of emitters at ~7 GV/m.
- Tensile stress = tensile strength

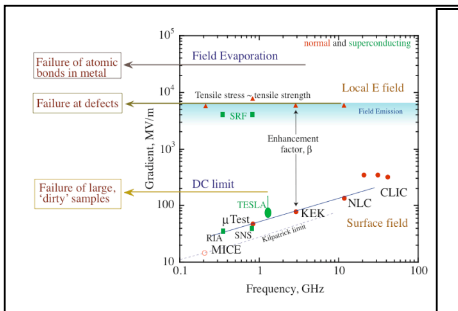


- We want to know what determines the value of β, - which determines E_{surf}.
- There are lots of variables: *f*, *P*, *U*, *mat'l*, *τ*, *geom.*, *vac.*, *conditioning . . .*

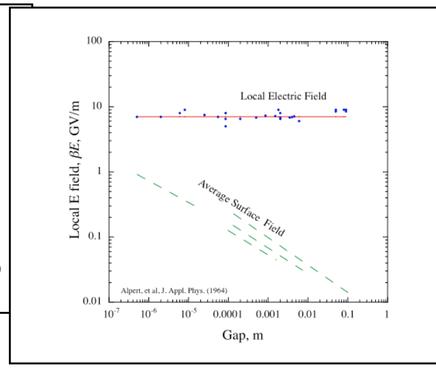
There are a number of mechanisms at work during breakdown.

- We think mechanical stress triggers breakdown events,
- Parameters that **are not** involved in breakdown triggers:

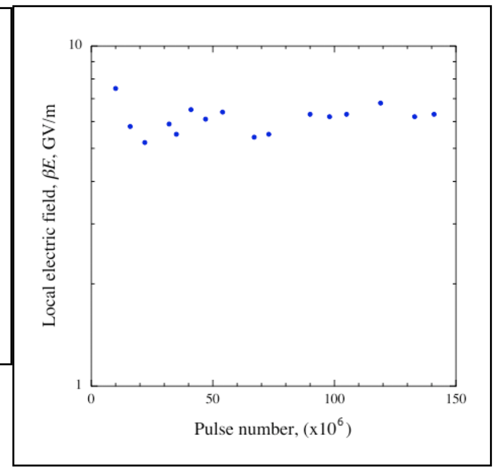
Frequency



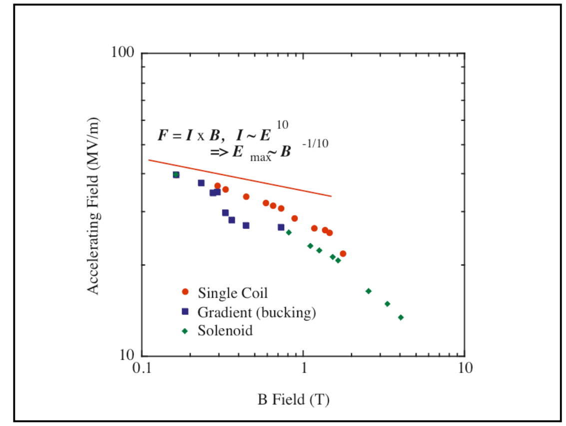
gap length



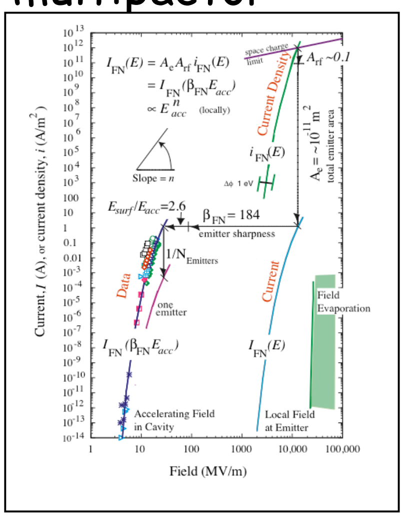
state of conditioning



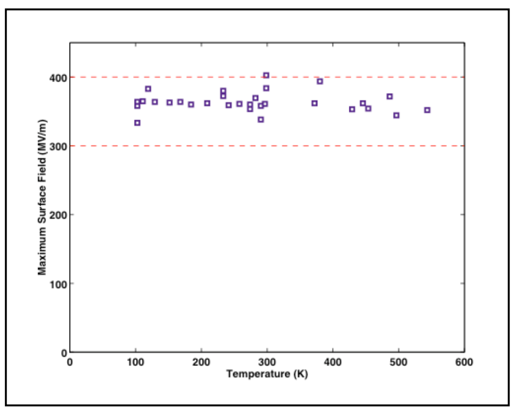
small B fields



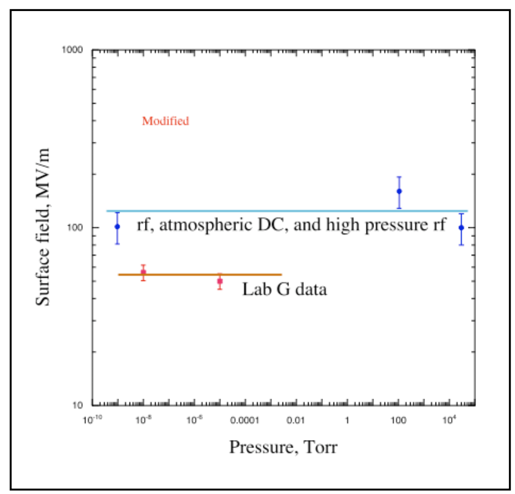
multipactor



temperature

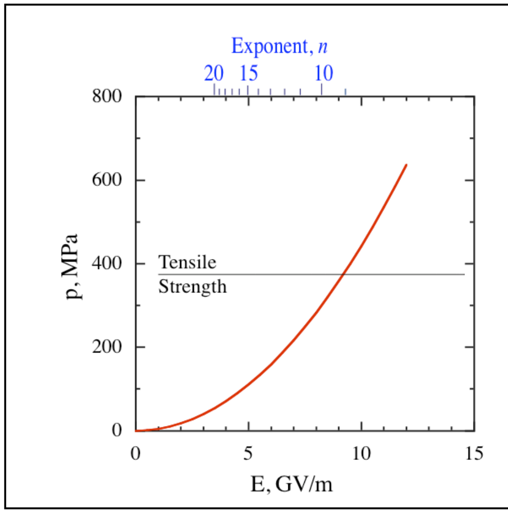


pressure

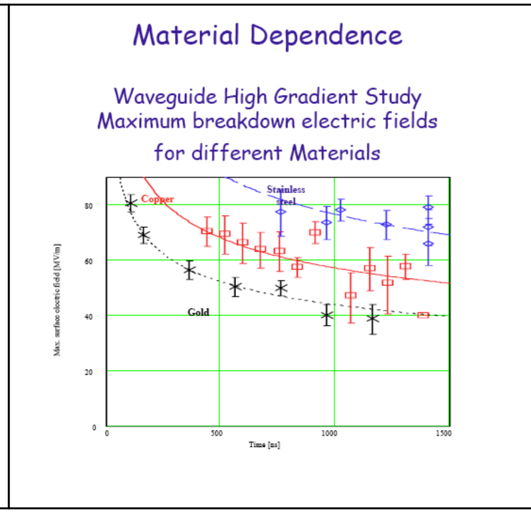


- Things that **do** matter.

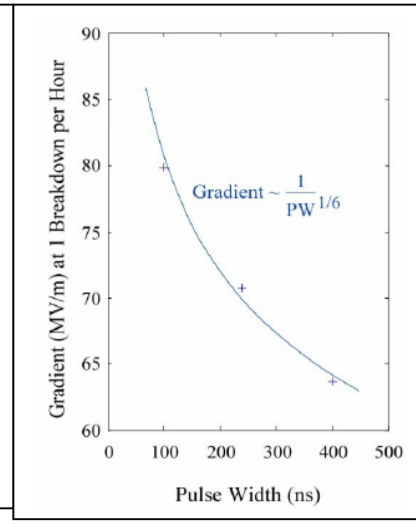
Local electric fields



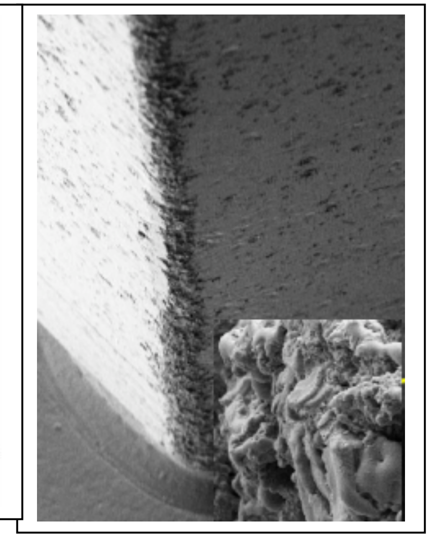
material



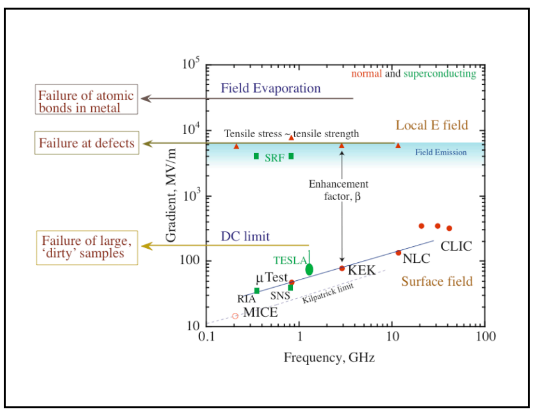
pulse leng



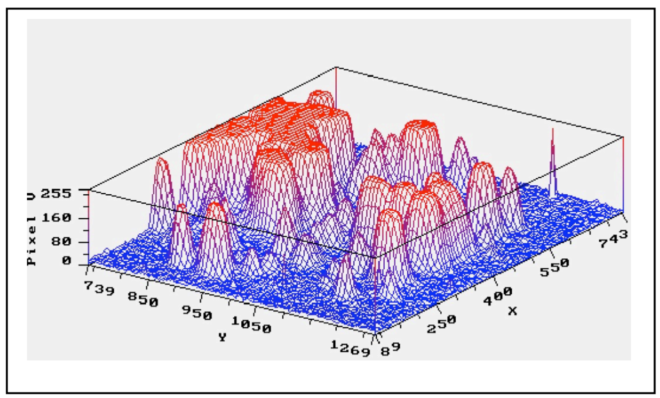
high surface currents



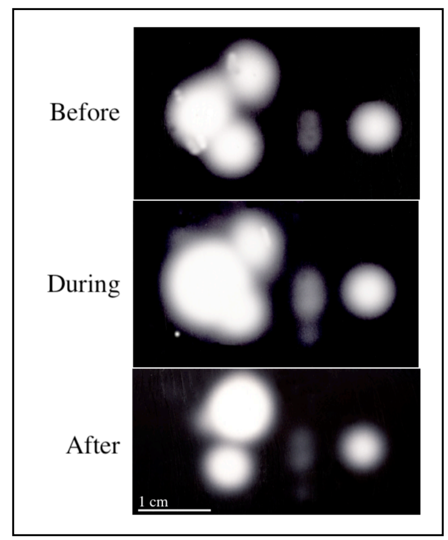
stored energy/power/geom.



β's from 2nd emitters



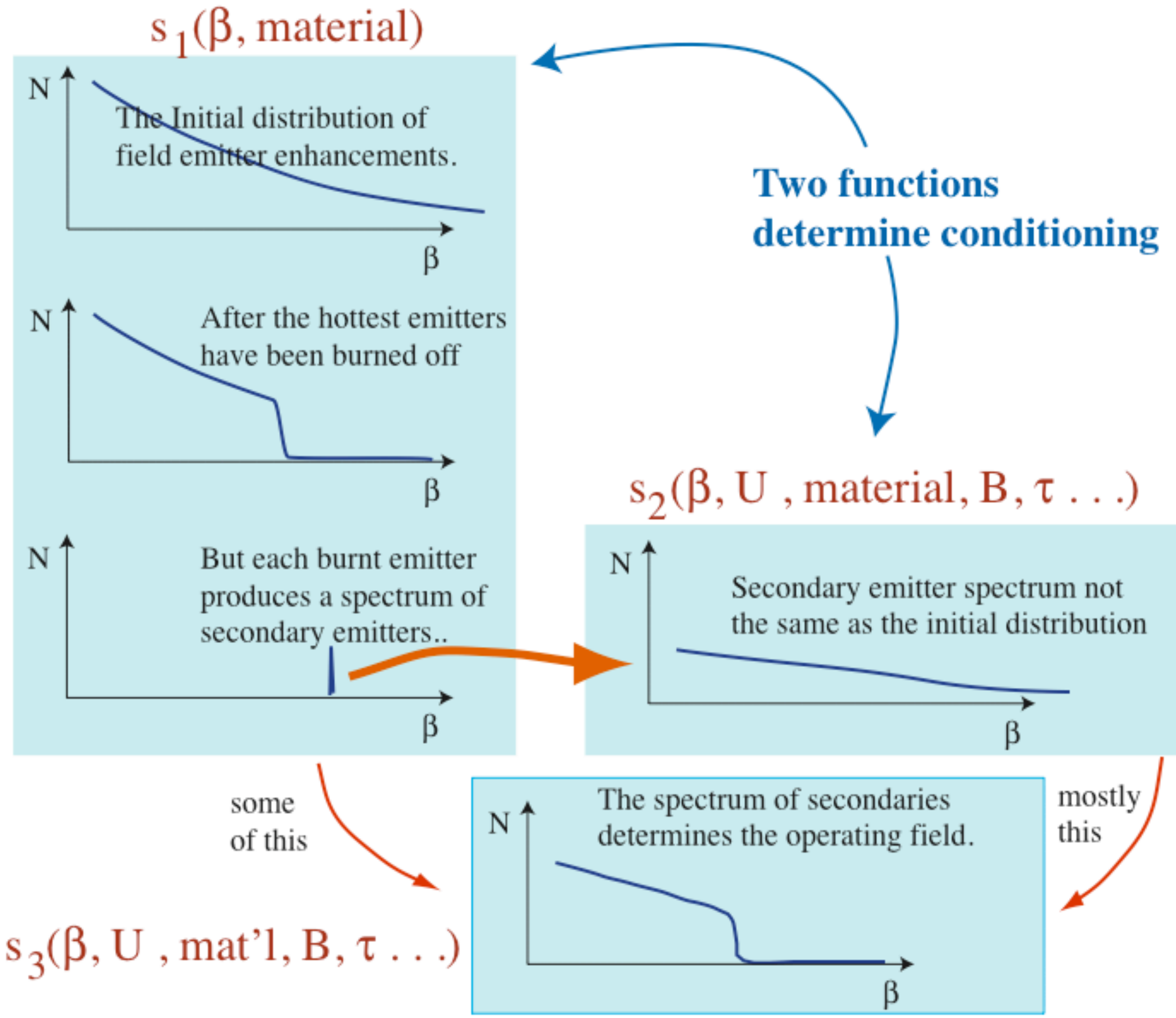
active asperities



- Field emission is not required, but may be there.

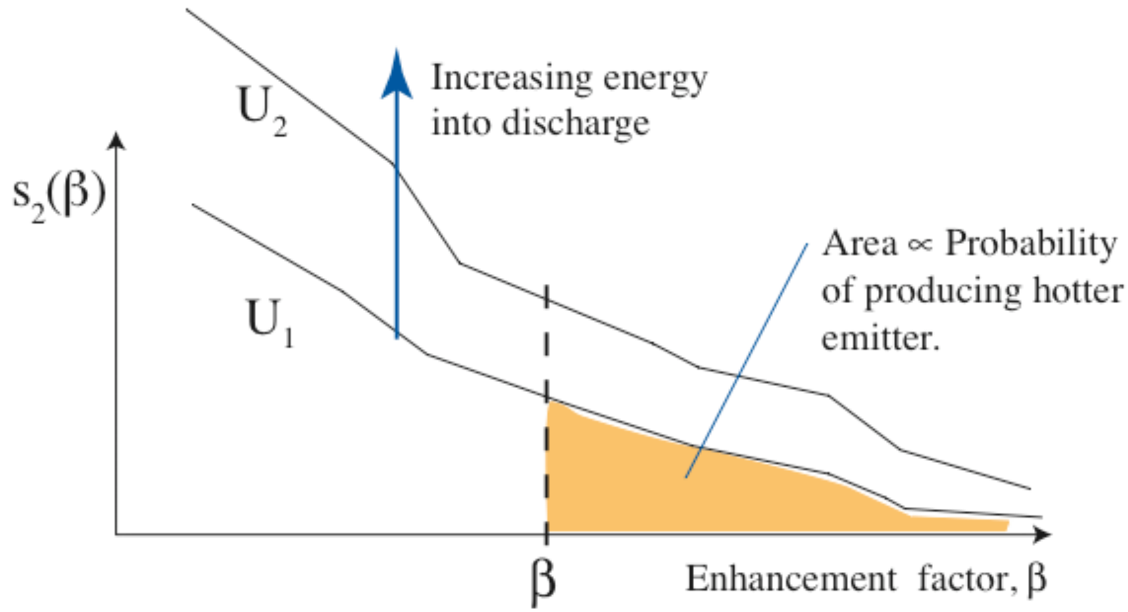
Secondary emitters seem to determine E_{max}.

- The operating field is determined from secondary emitters, $s_2(\beta.\ mat'l,\ \tau,\ ..)$.



Stable operation cannot generate high field enhancements.

- The cavity cannot operate at fields where a breakdown event produces higher β's than the one which was destroyed.
- E_{max} is defined by the constraint that the probability for producing higher β's is ~ 1.
- This is simple and reasonable.



- Specifically,

$$\int_{\beta}^{\infty} d\beta \; s_2(\beta, material, \tau) \approx c$$

solve for β_{max},

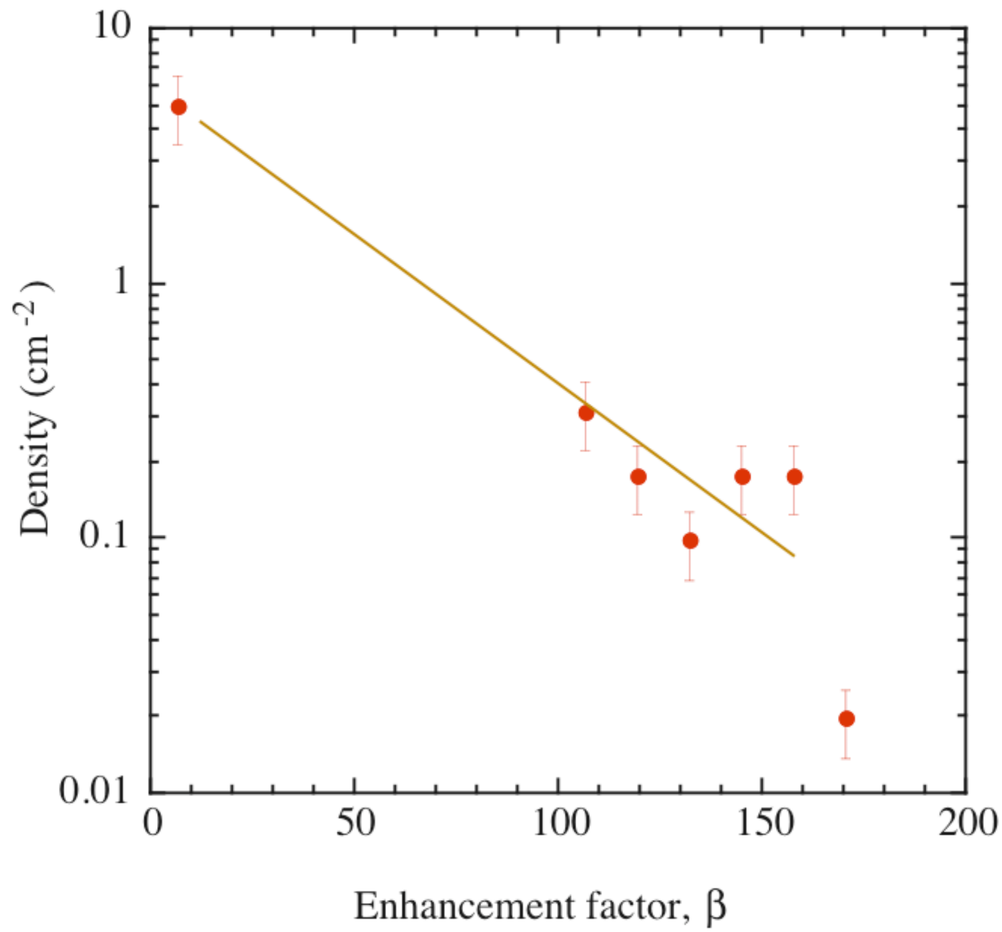
$$E_{max} = 7 \text{ GV/m}/\beta_{max}$$

The secondary emitter spectrum, $s_2(\beta)$, is not well measured.

- We made the only measurement, in an 805 MHz pillbox cavity.

- Others have "sort of" measured $s_1(\beta$
  Results don't agree
  and are badly interpreted

- This can, and should, be done better
  We know how.



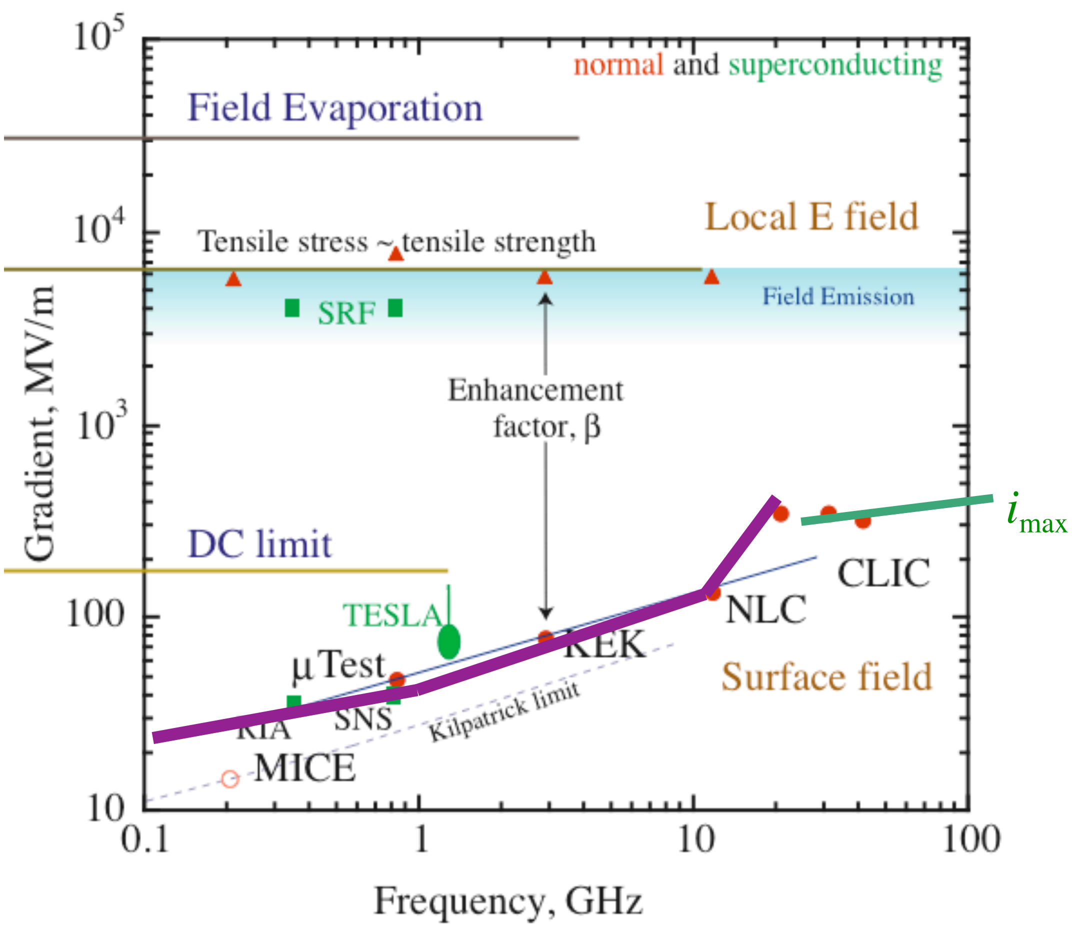
- How to parameterize $s_2(\beta)$ from the

  It seems factorizable.

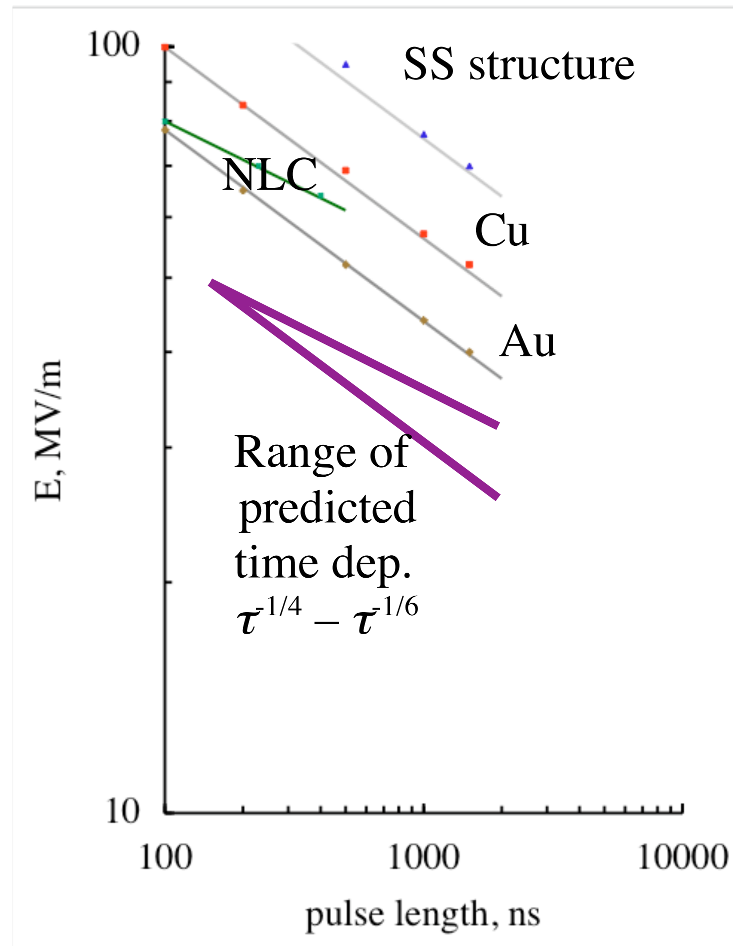
  $s_2(\beta, \tau, mat'l, U, A \ldots) = c\ \tau\ U\ A\ f(mat'l)\ s_2'(\beta \ldots)$

Some early results:

Frequency dependence
(every cavity/PS system is different)



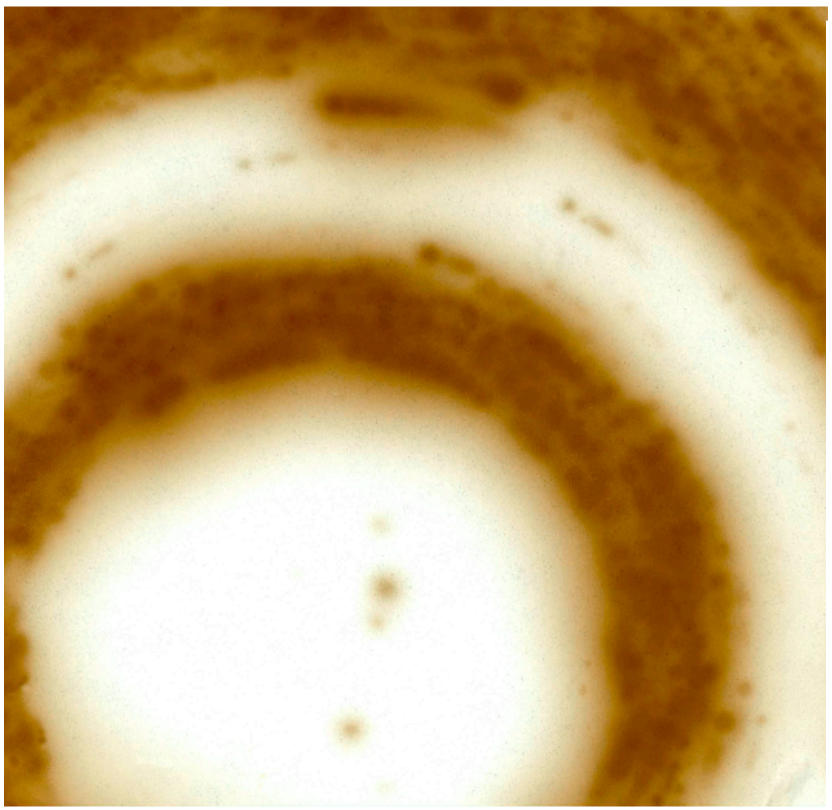
Pulse length dependence

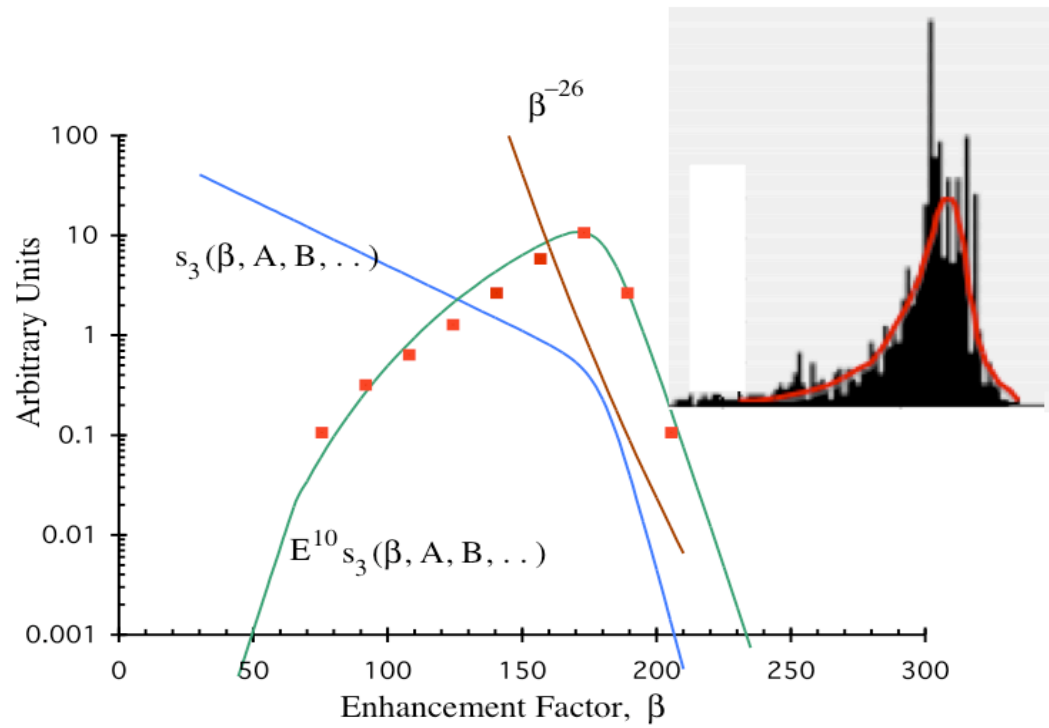


- We need a variety of data to factor out the contributions of different parameters.

Emitter density can predict breakdown rates.

- Glass slides give a picture of the breakdown rate.
- Optical densities measured in Lab G can measure $s_3(\beta. .)$.
- Results are consistent with Breakdown rate vs. *E*.





Idea	Evidence	Required work
Mech. Fail. ⇒ triggers	$I_{FE}(E)$ ⇒ Unstable envir. Emitters disappear	Systematic study of local fields Modeling of breakdown triggers Database of operating conditions
Tensile stress as cause	Failure at -400 MPa Atom probe failures No thermal dependence	Atom probe studies of high *E* Understanding: *T, f, history* Material / surface studies Submonolayer cavity coatings
$s_2(\beta, . . .) \Rightarrow E_{acc}$ $s_3(\beta, . . .) \Rightarrow R_{bd}(E)$, etc.	predictions of E_{acc}, τ^n plausibility & simplicity Emitters from Open Cell Breakdown rate vs *E*	Measurement of $s_1(\beta)$ and $s_2(\beta)$ Parametric studies τ, *P* , *mat'l* Cavity measurements Field emission microscopes Material studies and modeling Energetics of breakdown event Modeling Can snubbers increase E_{acc} ?
Current density limits	NLC couplers cooked STP data	High current densities on defects Modeling

Conclusions

- Cavity damage limits gradients.   Can we control this?
- It seems possible to predict everything from secondary emitter spectra.
- Low frequency cavities: give unique data - the key to scaling laws.
- We have aggressive High Gradient R&D program – 805 & 201 MHz data.
- **This model should be necessary and sufficient**, (complete ?).
- A 105 year old Physics Problem solved. (?)

- "With enough parameters you can fit an elephant, with a few more he can wiggle his trunk." E. Wigner