Progress in Understanding Gradient Limits

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ANL/HEP

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Outline

- An evolvong model for vacuum breakdown
  - New data on triggers
  - Ionization of fragments
  - Unipolar arcs seem to be the mechanism that attacks the surface
  - Capillary waves give useful information
  - Cooling, cracks and field enhancements: damaged surfaces produce BD sites
  - Gradient limits from enhancement spectra
  - Magnetic field effects are complex
- A model for breakdown of the scientific method
  - F-N plots
  - Telephone Poles
  - Ohmic heating
  - Pulse heating
  - Peer review
  - Management
- Experimental tests
- Conclusions

Many people have contributed to this work.

Normal Conducting

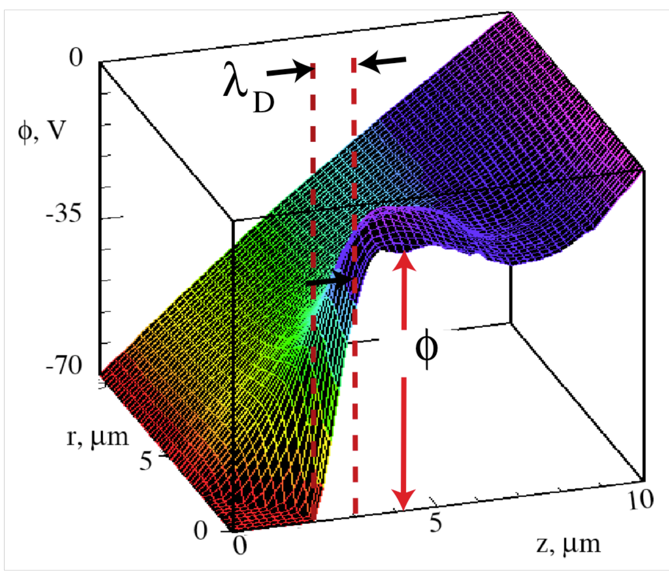
A. Hassanein	Plasma Phys	Purdue
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
D. Huang	RF, Instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X

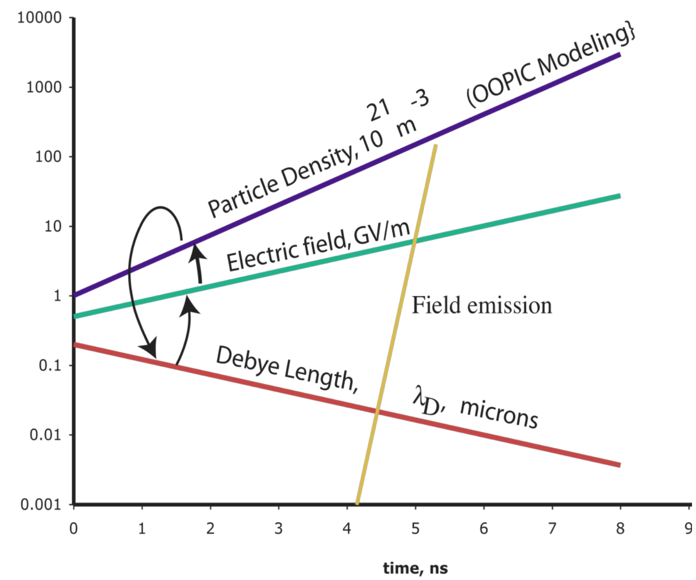
Superconducting

M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
L. Cooley	SCRF	FNAL
G. Wu	SCRF	FNAL

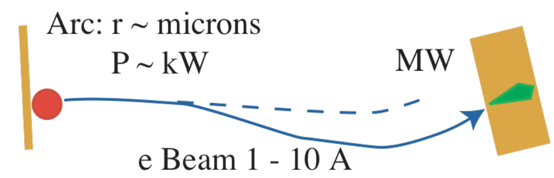
The breakdown model.

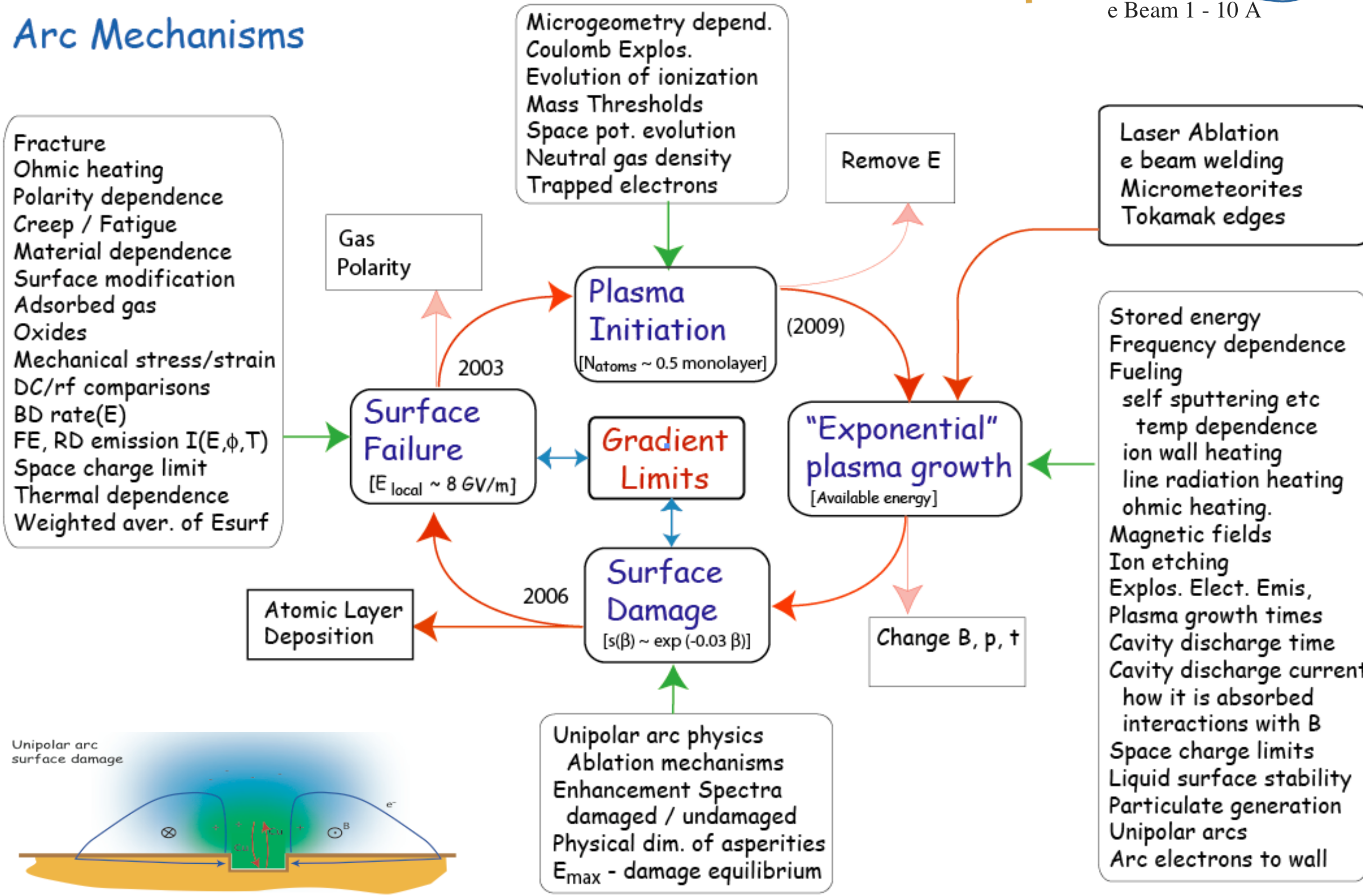
- Coulomb explosions trigger breakdown - fatigue (creep) and Ohmic heating help.
- Breakdown arcs are initiated by FE ionization of fracture fragments.
- The arcs produced are small, very dense, cold, and charged +(50-100) V to surface.
- Small Debye lengths, $\lambda_D = \sqrt{\frac{\epsilon_0 KT}{n_e q_e^2}} = \sim\text{nm}$, produce fields, $\boldsymbol{E} = \phi/\lambda_D \sim$ GV/m.
- High electric fields produce micron-sized unipolar arcs.
- Unipolar arc energy produces craters and cracks with high field enhancements.





More details (mere details).

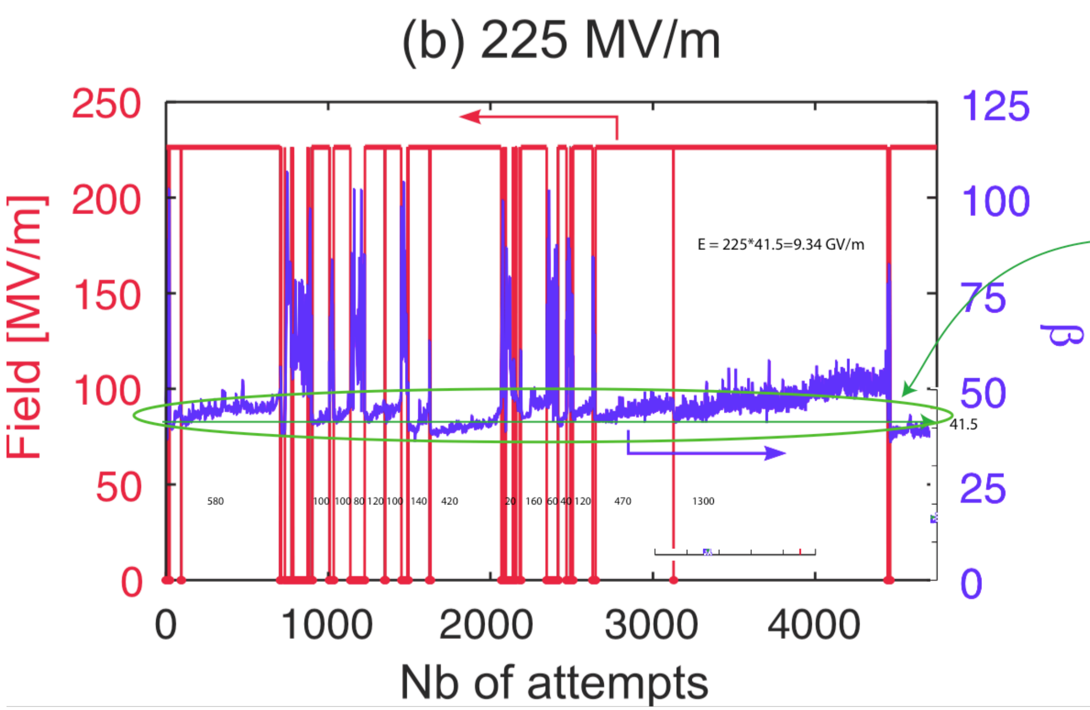




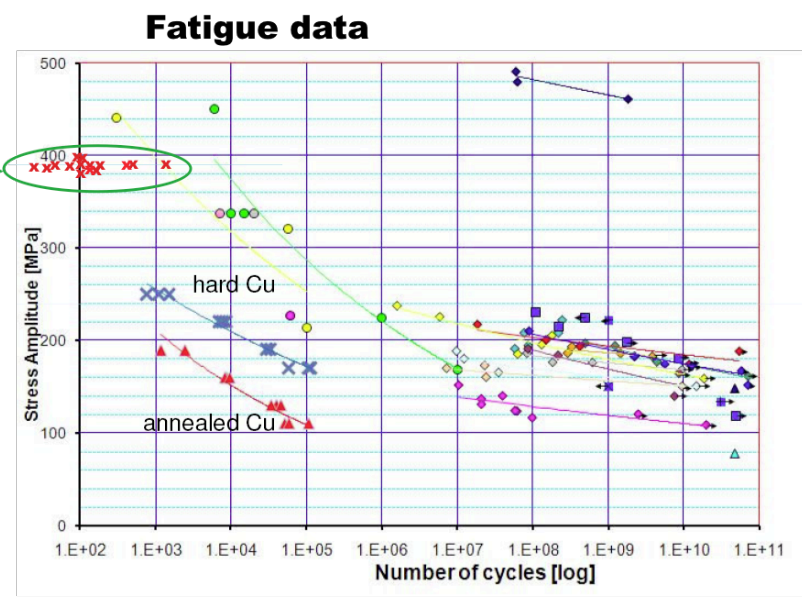
New data from CERN

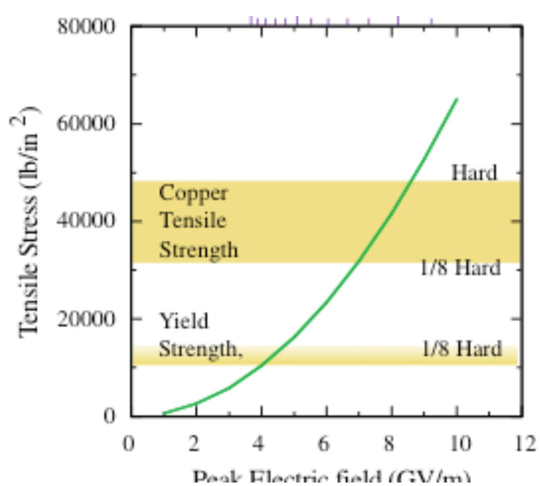
- New data from CERN spark gap imply triggers are due to mechanical forces.

° They don't make this argument, for some reason.



$P = E^2\varepsilon_0/2 = 386$ MPa

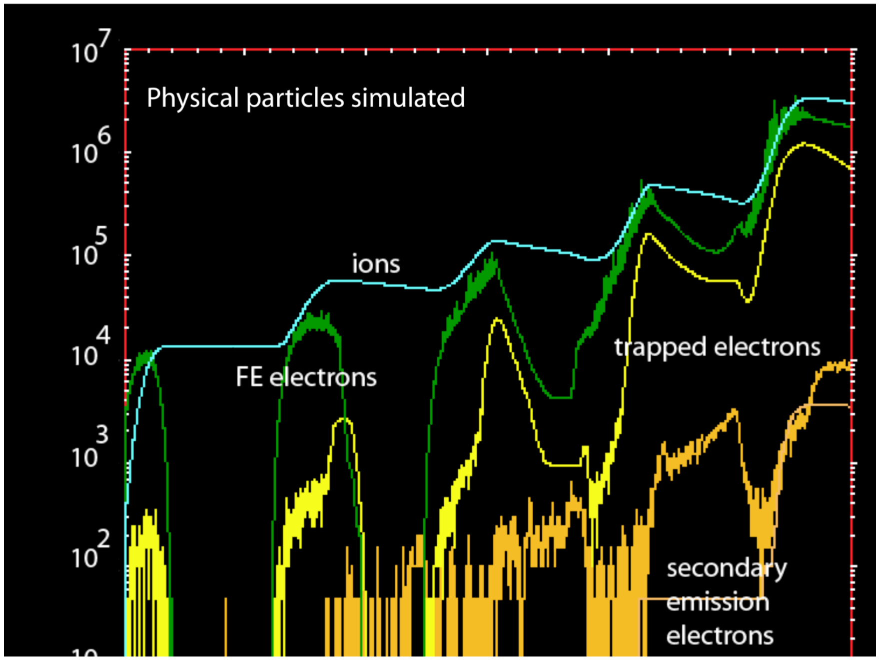


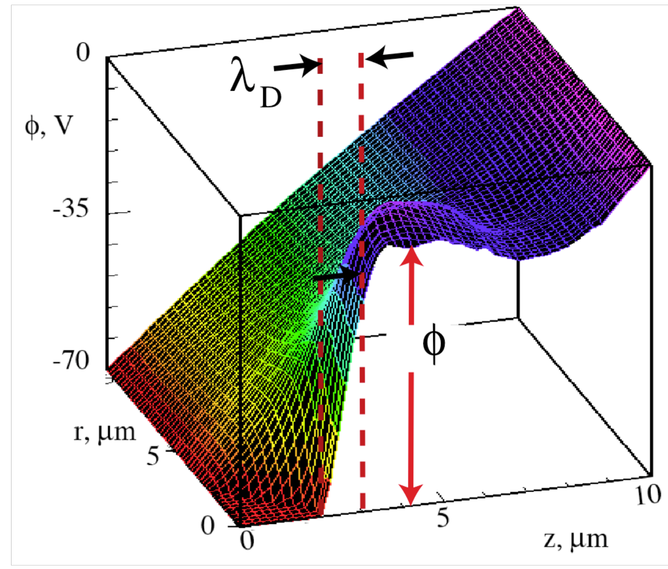


- We have been saying this for a long time.

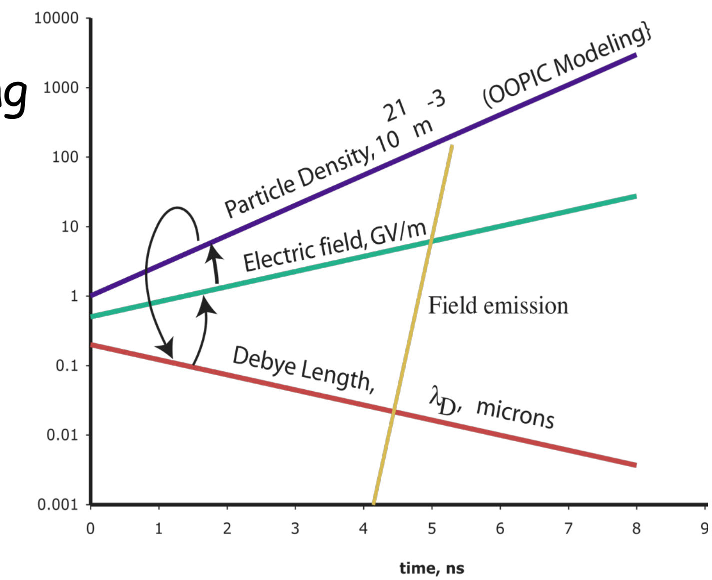
Ionization of fragments

- Surface parameters are determined by the sheath potential and the Debye length.





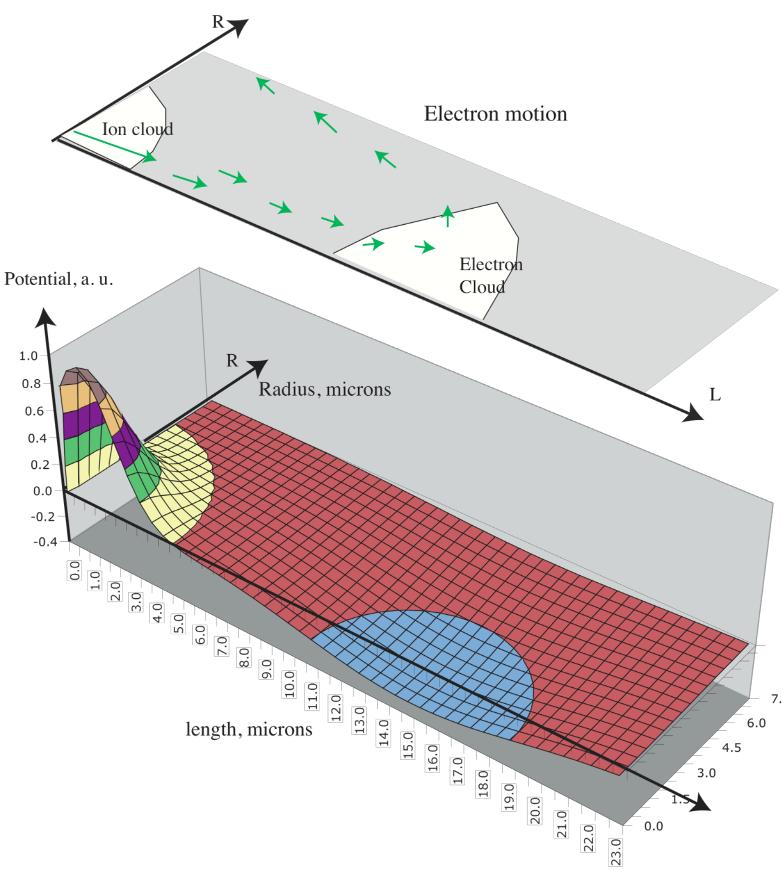
- The surface field is continuously increasing, changing the surface conditions and becoming more extreme.
  $E_{surf} \sim \phi/\lambda_D \sim$ GV/m

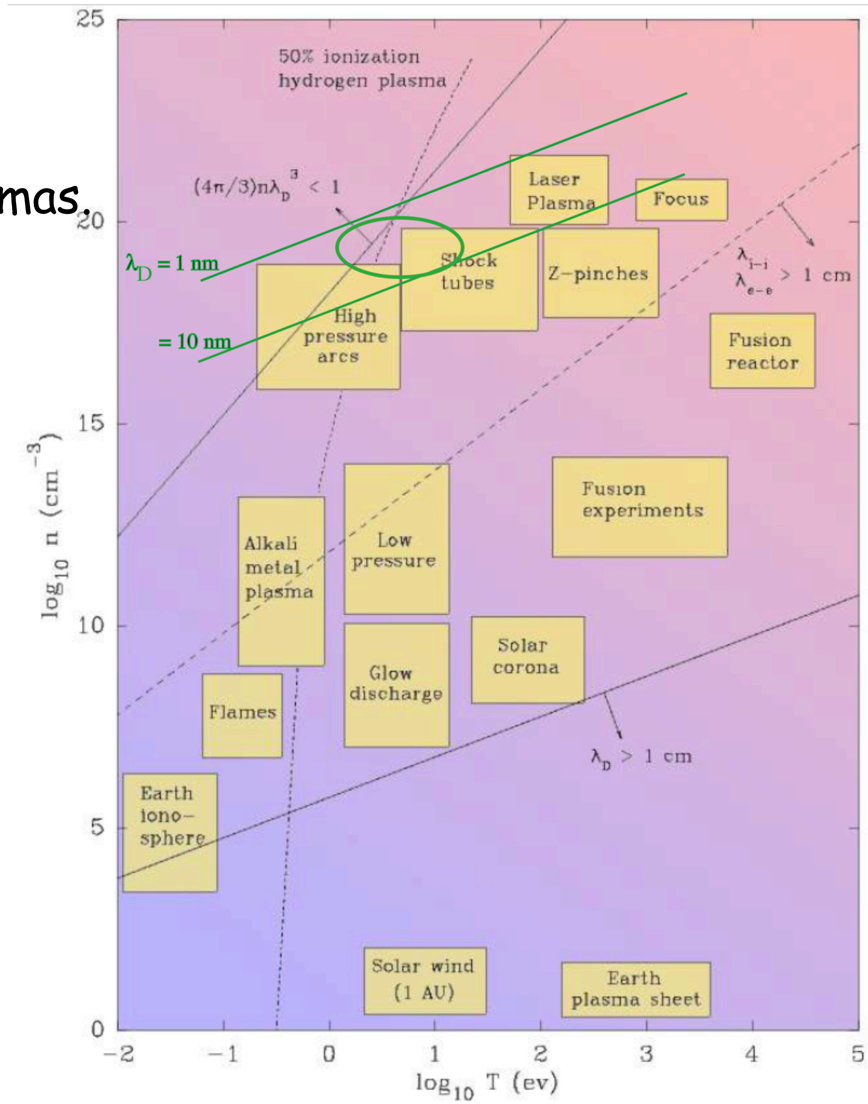


- These conditions seem to define the unipolar arc, which is not otherwise rigidly defined.

Unipolar arcs have not been well studied

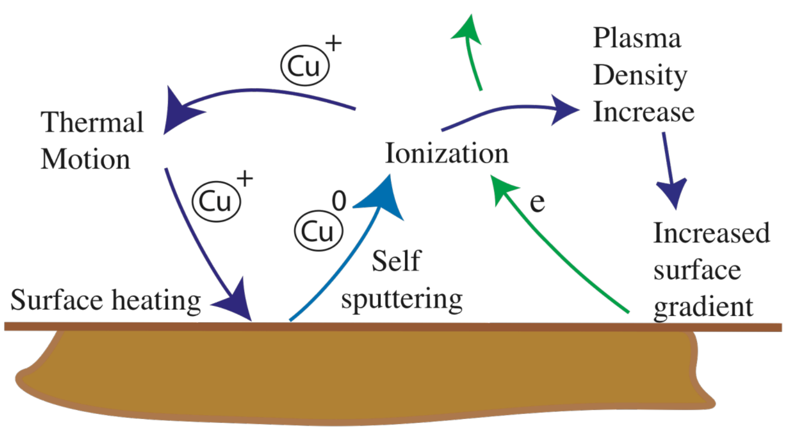
- A lot of effort went into this work in the '70s and '80s, not much since.
- In spite of this lack of effort:
  The fusion community considers them basic.
  This physics may be critical to ITER.
- Numerical meth. now exist for non Debye plasmas.



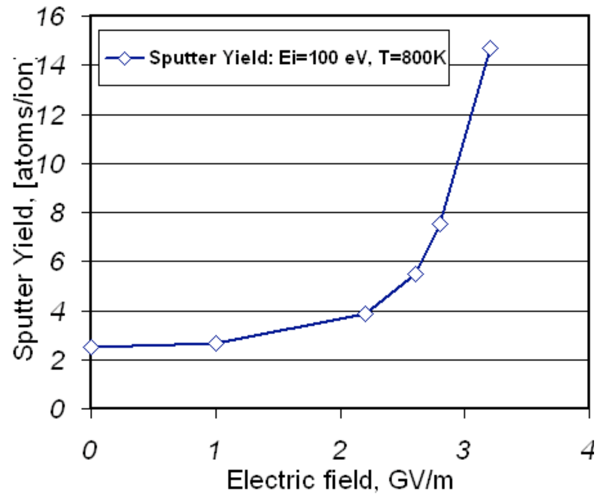


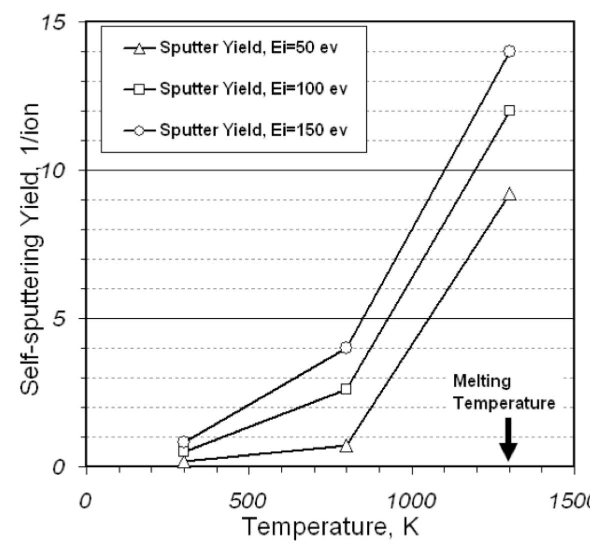
Unipolar arcs attack surfaces,

- . . . and they do it very efficiently.
- Numerical modeling of self-sputtering at high fields and high temperatures shows high secondary atom yields, but codes give surface temperatures of ~10000 degC so the surface could not survive.
- Erosion rates on the order of, $r = n_I \, v_I \, Y(\lambda_D, \phi, T_{surf}) / V_A$ are ~ 1 m/s.



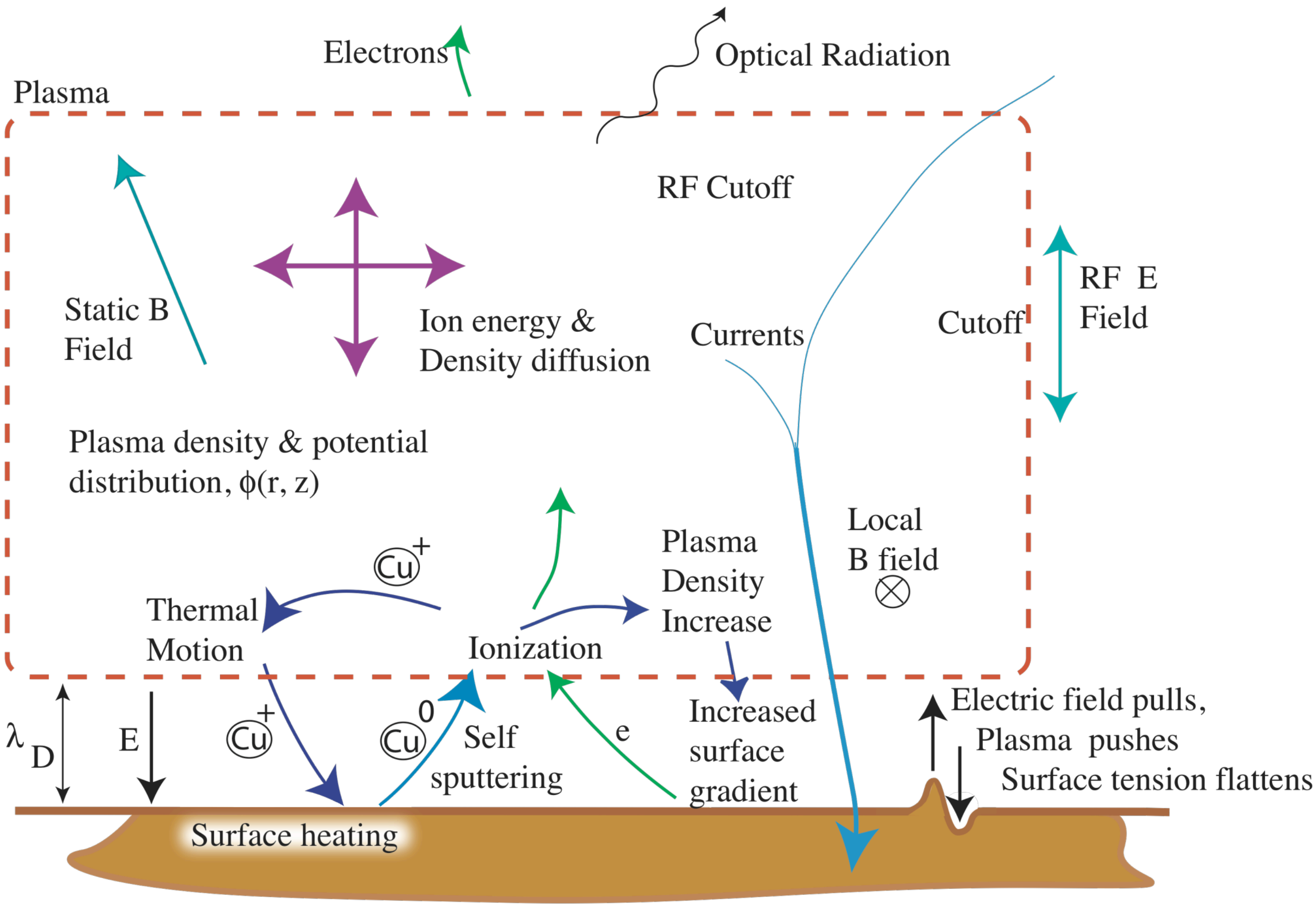
Self-sputtering yield of a charged by plasma copper surface





The unipolar arc is complex

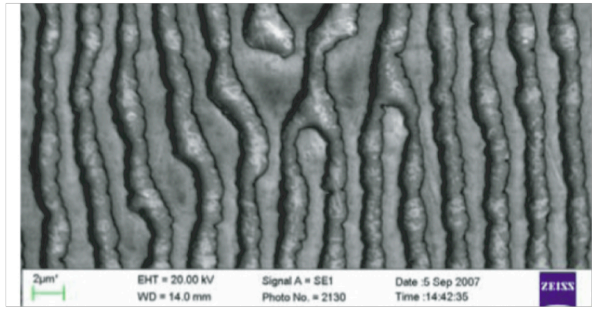
- The surface electric field defines the environment.

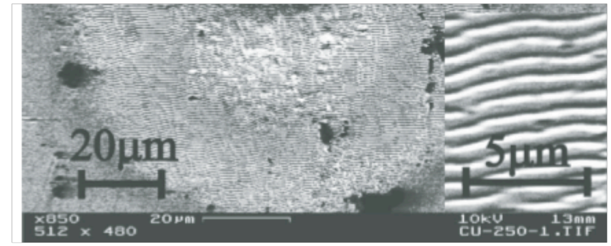


Capillary waves measure the surface environment

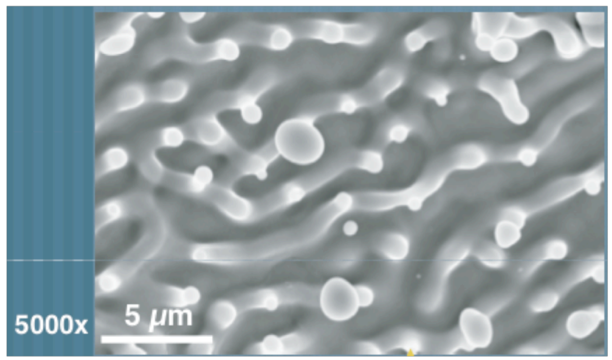
- Electrohydrodynamic spinodal decomposition of capillary waves can measure E_{local}.
- We get $E_{surf} \sim 1$ GV/m
- Wavelength ~ 2 μ.
- More precision requires $p_T = p_{Elect} - p_{plasma}$

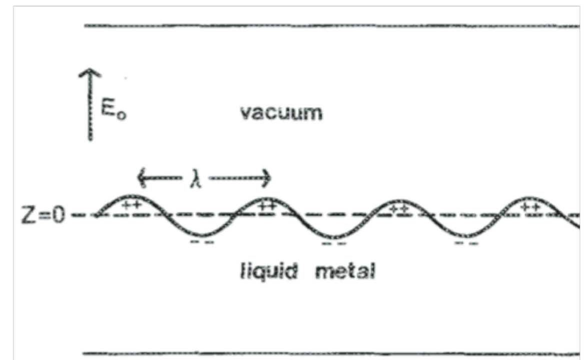
Laser material interiactions by Getvilas. et al. (2009) and J. Wang and Guo (2005)



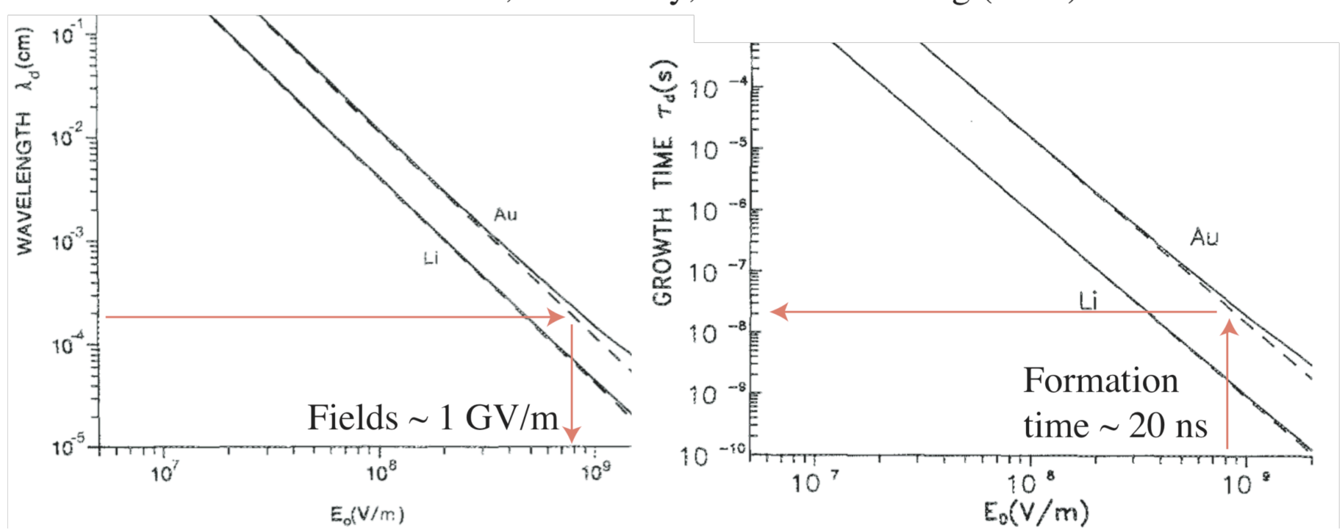


and surface waves in CLIC prototype Cu cavities (Izquierdo, 2008) . . . . .



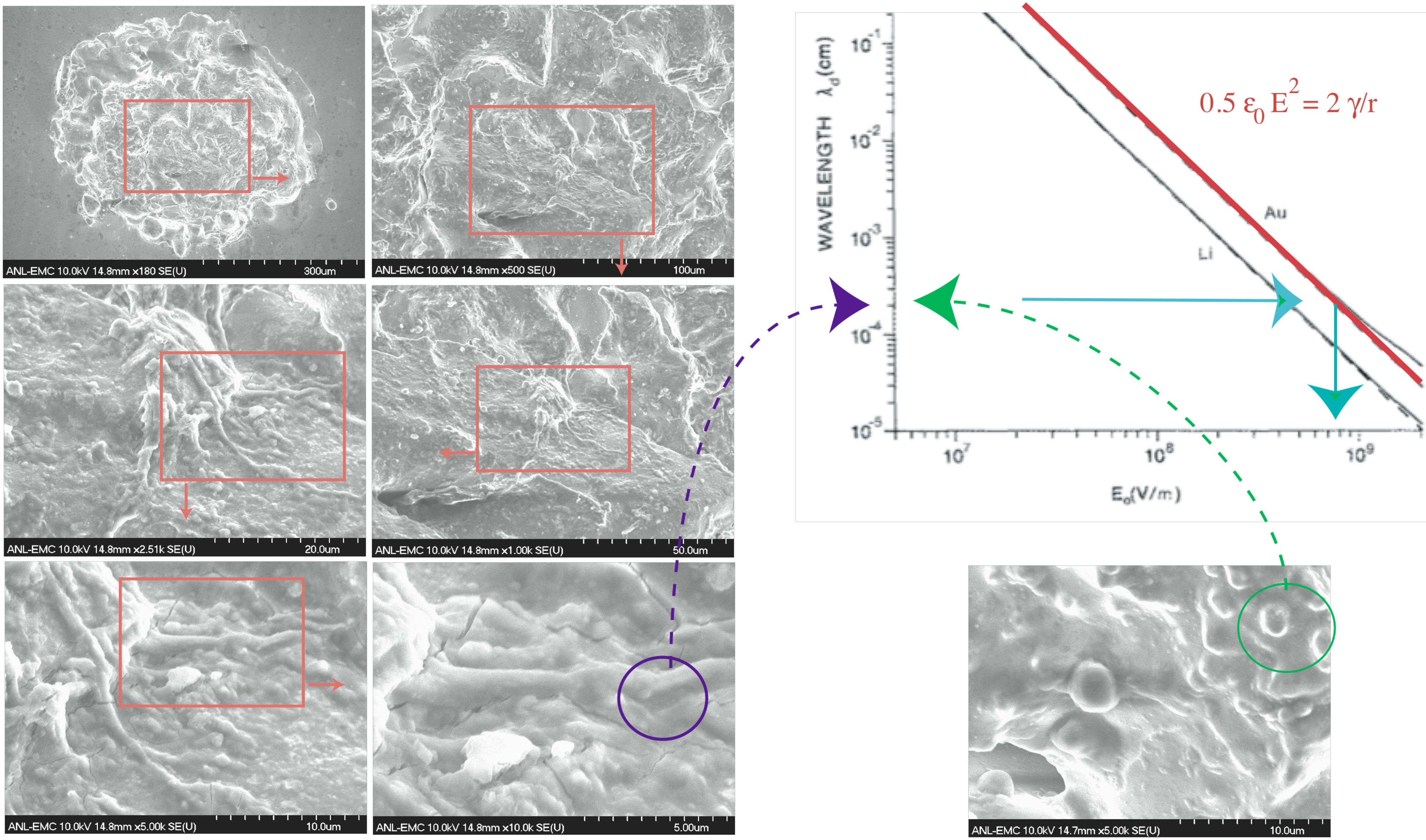


seem to follow the model of He, Miskovsky, Cutler and Chung (1990).



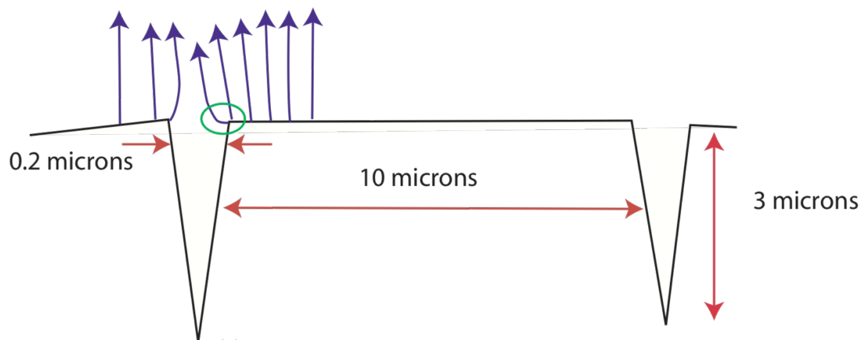
We see the 2 micron structure, as do others.

Things are chaotic at larger dimensions, smoother at smaller ones.



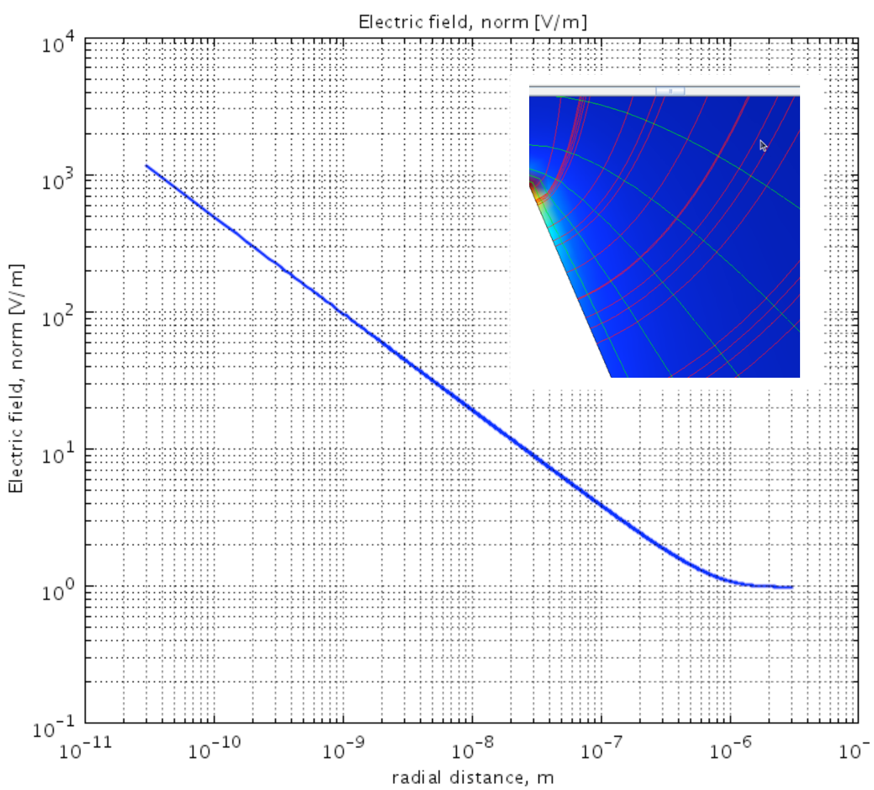
Cooling, cracks and β's:

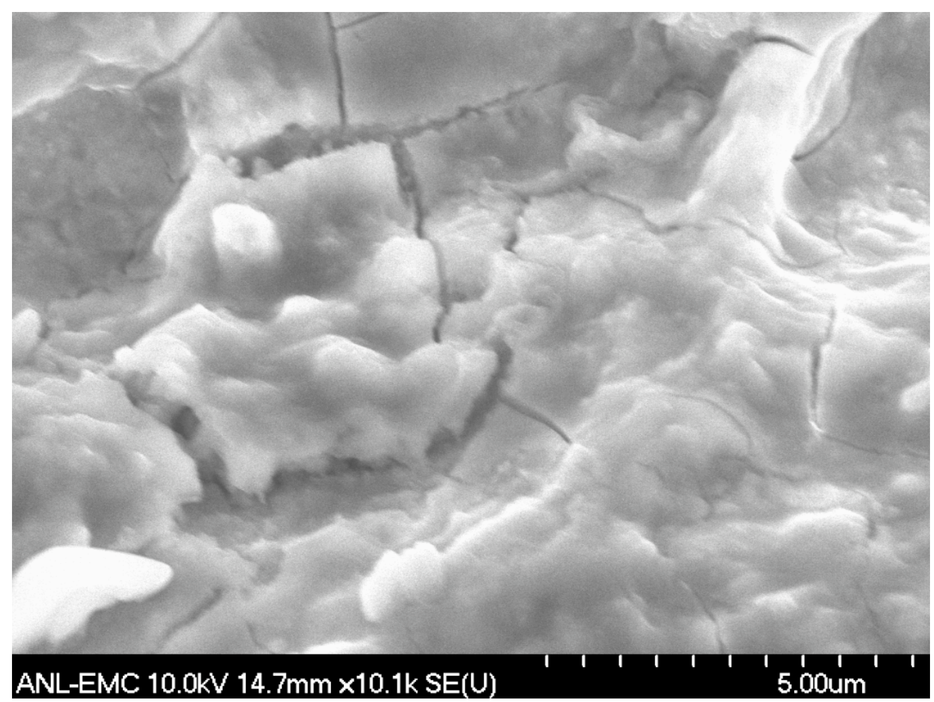
- Melted copper (~3 μm thick, at ~1000 degC) cools and cracks.
  Crack width: $dx \sim (17 \times 10^{-6}) * 1000 * x \sim 2\% x$, $x = 10\ \mu \Rightarrow dx \sim 0.2\ \mu$.



Can be modeled by a cone.

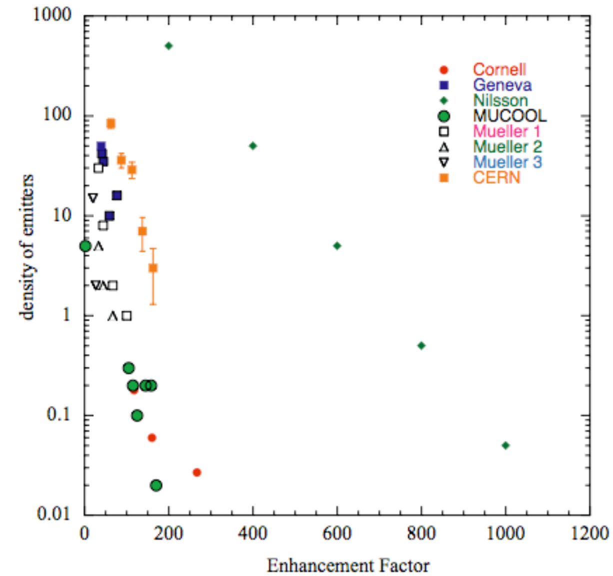
- Corners are atomically sharp, have high βs, and there are lots of them.



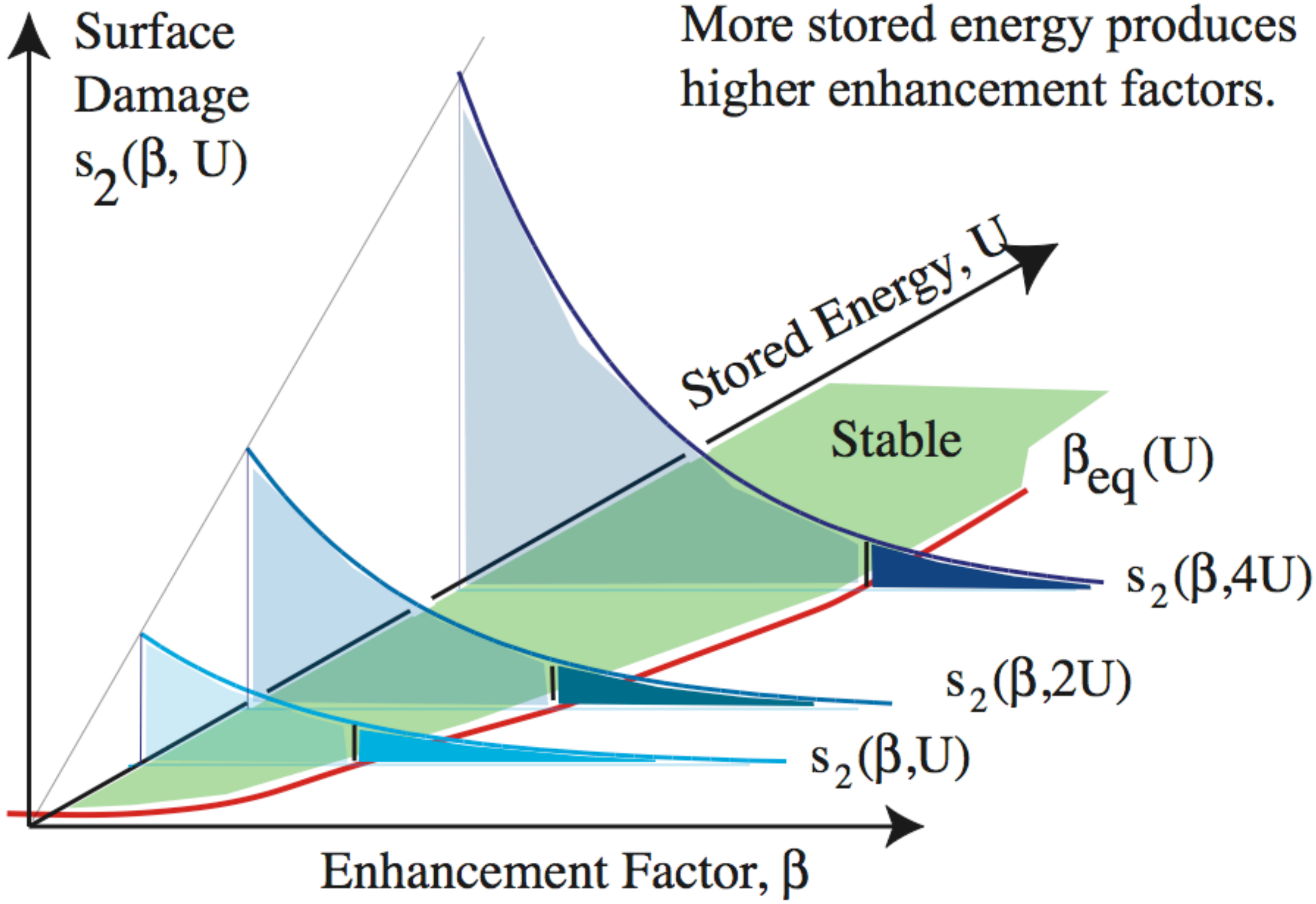


radient limits result from enhancement spectra.

- We have said this before.



More stored energy produces higher enhancement factors.



Magnetic effects are complex.

- The primary effects of the magnetic field seems to be confining the plasma.

- Larmor orbits for electrons and ions are given by:

$$\rho^{-}_{[mm]} = 0.0035\frac{\sqrt{W_e}}{B}, \qquad \rho^{+}_{[mm]} = 0.16\frac{\sqrt{AW_i}}{zB}$$

  Electrons are confined to a few microns

  Ion orbits are larger, but ions move so slowly orbits don't matter.

- OOPIC shows this plasma confinement, but results have to be done for different magnetic field geometries. Seth and Sudhakar at Tech-X are calculating plasma effects with VORPAL.

- The electron beams that short the cavity have all the cavity energy and are also affected by the magnetic field and will also produce damage.

- j x B effects should not contribute to this geometry.

Why is it taking so long to understand this process?

The physics of arcs is <u>a "breakdown" of the scientific method.</u>

- Much work has been guided by misleading assumptions.
- Good papers don't always lead to good directions.
- Powerful forces support the conventional wisdom.
- People have fixated on simple problems, complete models are more constrained.

Fowler-Nordheim plots

- Evidently the same year as the Fowler-Nordheim model was published, Fowler first began to graph data in the form $\ln(I/E^{(2 \text{ or } 2.5)})$* vs 1/E, the slope of this line being equal to the enhancement factor.

- This confused everyone for the next 80 years.

- The Fowler Nordheim plot:
  makes the enhancement factor look like some arcane mathematical residue.
  diverts attention from the local electric field, which is fundamental.
  destroys any intuitive understanding of the experimental conditions.

- While these plots may have been useful in the slide rule era, with computers we can plot both the FN predictions and data on the same log-log plot, and trivially find the local fields, emitter area and field enhancements, and reasonable estimates of experimental errors in determining these quantities.

* Probably should be $E^{2.38}$ for rf, E^2 for dc.

Telephone pole shaped surface structures.

- The standard reference on β factors is F. Rohrbach's CERN yellow report 71-28.
- The results on telephone poles, and ellipsoids are widely quoted.
- These structures are not seen, however, causing some concern.
- Modifications to the theory (tip-on-tip) models, are assumed in SRF work. Particle contamination contributes. They ignore the telephone pole model.
- In fully conditioned Cu cavities, particle contamination doesn't obviously contribute.

- Since no one seems to understand βs from the Fowler Nordheim plot, and no one saw the telephone pole emitters described by Rohrbach, the assumption was that arc triggers are an "unsolvable mystery".

Ohmic heating

- Ever since the papers by Dyke, Trolan, et. al. in the early 50's showed that Ohmic heating could be responsible for failure of tungsten needles at high field emission, Ohmic heating has been the "standard model" for breakdown triggers.

- The problem is that Ohmic heating in needles and in realistic geometries is quite different. In needles the heating is more or less constant throughout the length and there is negligible heat conducted away.

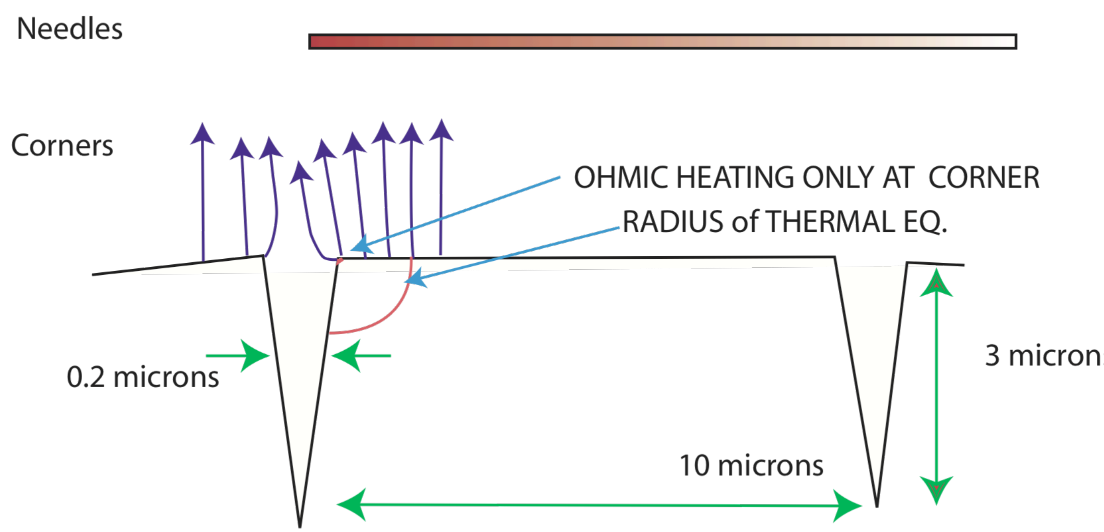
- With wider cone angles, however, the amount of heating decreases and thermal conduction can become huge. We assume 90^{o}.

- In the corners described above, heating occurs only within a few nm of the tip, and thermal diffusion lengths are:

  $(Dt)^{0.5} \sim (1E\text{-}4 * 1\ ns)^{0.5}$

  $\sim 0.3\ \mu m$

- Thus heating is reduced by $\sim 10^{6}$.



Pulse heating

- The paper by Pritzkau and Siemann in 2002 caused increased interest in heating and damage by skin currents in rf cavities.
- Unfortunately, that paper, and others, have not shown that pulse heating unambiguously degrades the limiting gradients.
- At the same time experiments with “photonic band gap” (? ?) structures have shown that pulse heating only seems to matter at acceleration fields twice the electric field limit.
- Electric breakdown occurs at irises, pulse heating occurs at the equator.
- Damage seems to occur at irises.
- Draw your own conclusion.

Scientific Momentum

- In my experience, (~70 pages on this subj. in refereed journals), the referees in this field can be erratic and misinformed. All support the conventional wisdom.

  Phys. Rev. STAB standards seem to be slipping.

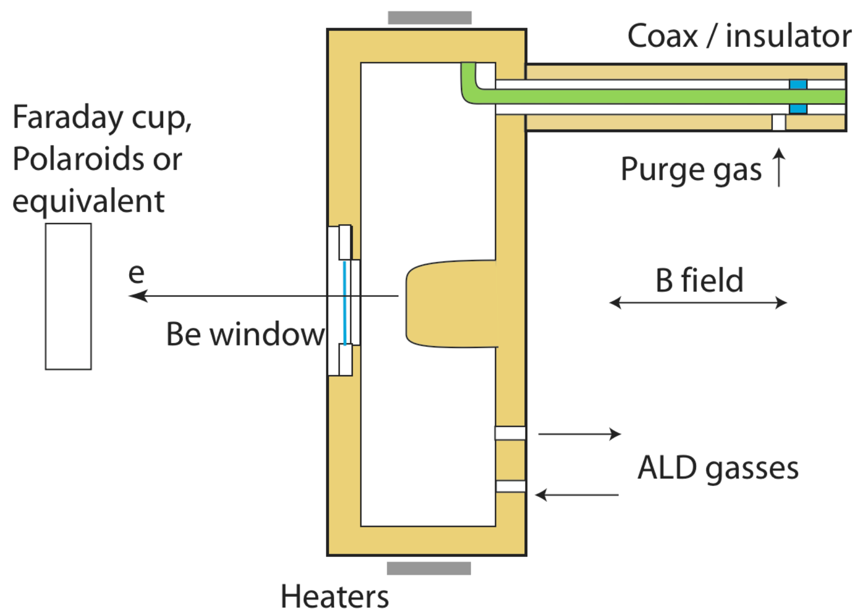
  Maybe arXiv.org is the way to go.

- For some reason the Muon effort is not connected any way with the DOE high gradient effort.

  I don't see any benefit of closer collaboration.

"Breakdown Proof": proof-of-principle and RF cavity tests

- The primary experimental question the radius of the field emitter / arcing site.
- We are considering an experiment that uses pre-sharpened pins that we can sequentially coat and measure the field emission current. Depositing a known thickness of material conformally on the tips we should be able to "turn off" field emission, and measure the radius of the emitter (breakdown site).
- We can also do this in-situ in a cavity. The experiment would involve
  - First: Condition the cavity & measure the dark currents at maximum gradient.
  - Then: Coat the cavity with ALD using known thickness of different metals.
  - Measure the maximum gradient as a function of ALD coating thickness.
- The cavity might look like this.



Progress with ALD

- Thomas has been able to produce ALD coatings with T_c of 8.5 K, comparable with what one would expect from thin Nb layers.
- The coatings have high impurity levels, primarily Oxygen.
- Eliminating these impurities should be straightforward.
- We are finding differences in the Zero Bias Conductivity for Hot Spots taken from failed cavities. This tends to confirm the argument that cavities can fail due to magnetic impurities.
- We are buying a Plasma Enhanced ALD system, for the production of pure metals.

Conclusions

- We are presenting another iteration of our model, with new details:
  - Unipolar Arcs
  - Self sputtering under extreme conditions
  - E_{surf} measured by electrohydrodynamic spinoidal decomposition of capillary waves
  - Crack formation
  - High enhancement factors
  - Useful ALD tests.
  - and some other things
    - Much of this has been published or submitted, some is being written up.
- We argue against many traditional assumptions (old wives tales) in this field.
- We describe a proof-of-principle experiment for "Breakdown Proof" cavities.
- All this work is relevant to SRF, CLIC etc.
- We are hosting a workshop on Unipolar Arcs.
- Continued refinement of the model is necessary.