Modeling Arcs

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Outline

Our model tries to converge on something simple

Active Issues:

- Measuring Surface fields using surface morphology
- Self-sputtering
- The formation of high β asperities
- External B fields
- Unipolar arcs
- Our experiment

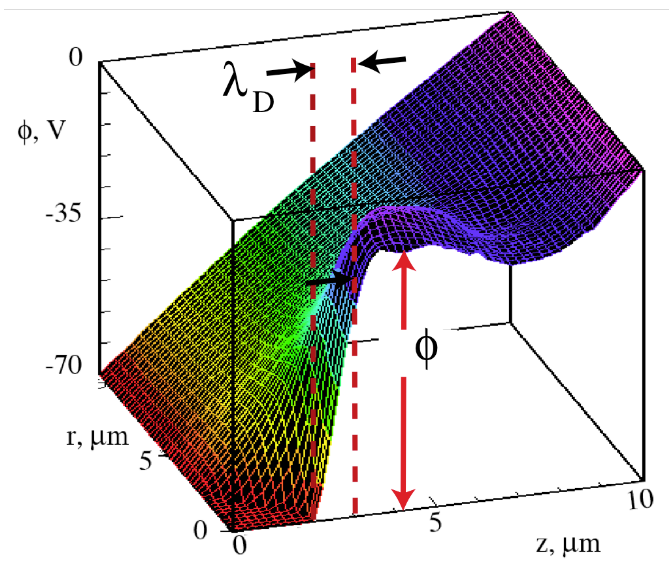
Comments on the Workshop on Unipolar Arcs:

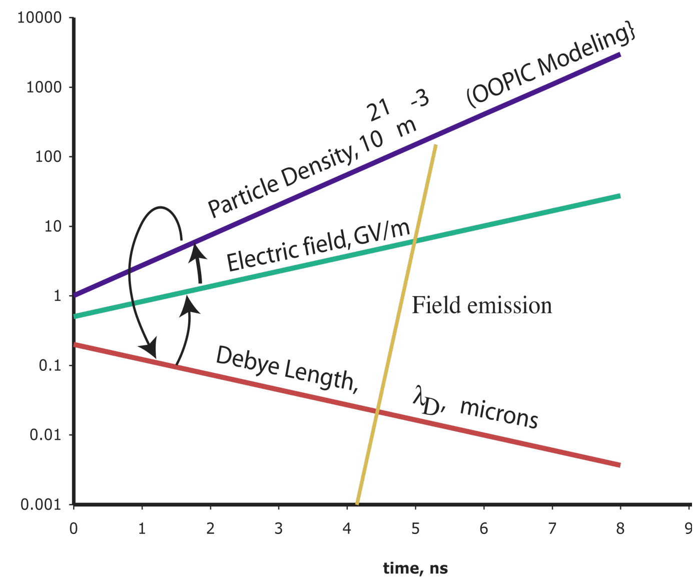
Where we differ from others:

Conclusions

The model is driven by electric fields.

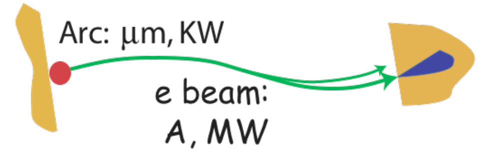
- Coulomb explosions trigger breakdown - fatigue (creep) helps.
- Breakdown arcs are initiated by field emission ionization of fracture fragments.
- The arcs produced are small, very dense, cold, and charged +(50-100) V to surface.
- Increasing surface fields increase density, which further increases surface fields..
- Small Debye lengths, $\lambda_D = \sqrt{\frac{\epsilon_0 KT}{n_e q_e^2}} = \sim\mathrm{nm}$, give, $\boldsymbol{E} = \phi/\lambda_D \sim$ GV/m.
- Unipolar arc behavior produces craters and cracks with high field enhancements.





Details

Arc Mechanisms



Fracture
Ohmic heating
Polarity dependence
Creep / Fatigue
Material dependence
Surface modification
Adsorbed gas
Oxides
Mechanical stress/strain
DC/rf comparisons
BD rate(E)
FE, RD emission I(E,ϕ,T)
Space charge limit
Thermal dependence
Weighted aver. of Esurf
Hollow beams

Microgeometry depend.
Coulomb Explos.
Evolution of ionization
Mass Thresholds
Space pot. evolution
Neutral gas density
Trapped electrons

Gas
Polarity

Remove E

Laser Ablation
e beam welding
Micrometeorites
Tokamak edges
Classical Unipolar Arc

Plasma Initiation
[N_{atoms} ~ 0.5 monolayer]

Surface Failure
[E_{local} ~ 8 GV/m]

Gradient Limits

"Exponential" plasma growth
[Available energy]

Surface Damage
[s(β) ~ exp (-0.03 β)]

Atomic Layer Deposition

Change B, p, t

Stored energy
Frequency dependence
Fueling
- self sputtering etc
  - temp dependence
- ion wall heating
- line radiation heating
- ohmic heating.

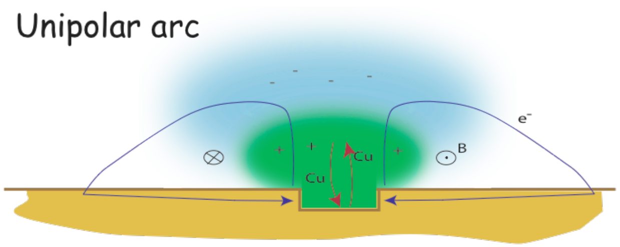
Magnetic fields
Ion etching
Expl. Elect. Emis, ectons
Plasma growth times
Cavity discharge time
Cavity discharge current
- how it is absorbed
- interactions with B

Space charge limits
Liquid surface stability
Particulate generation
Unipolar arcs
Arc electrons to wall

Unipolar arc physics
- Ablation mechanisms

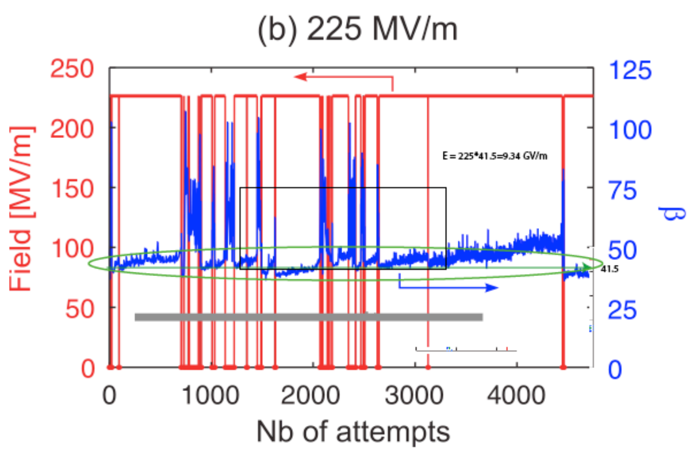
Enhancement Spectra
Crack formation
Physical dim. of asperities
Emax - damage equilibrium

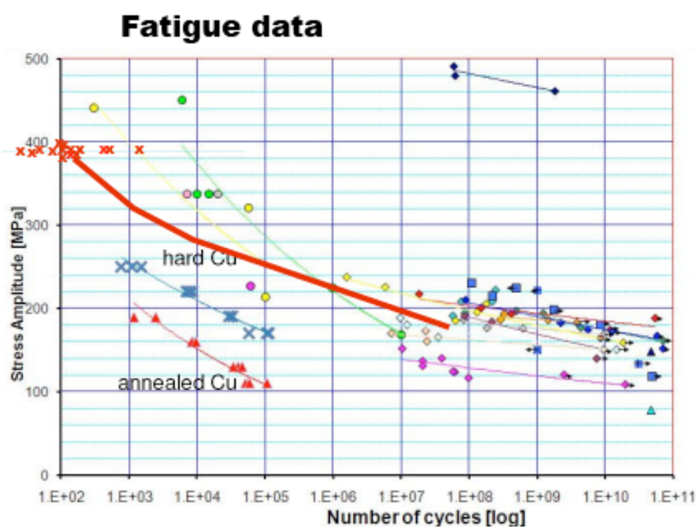
Unipolar arc

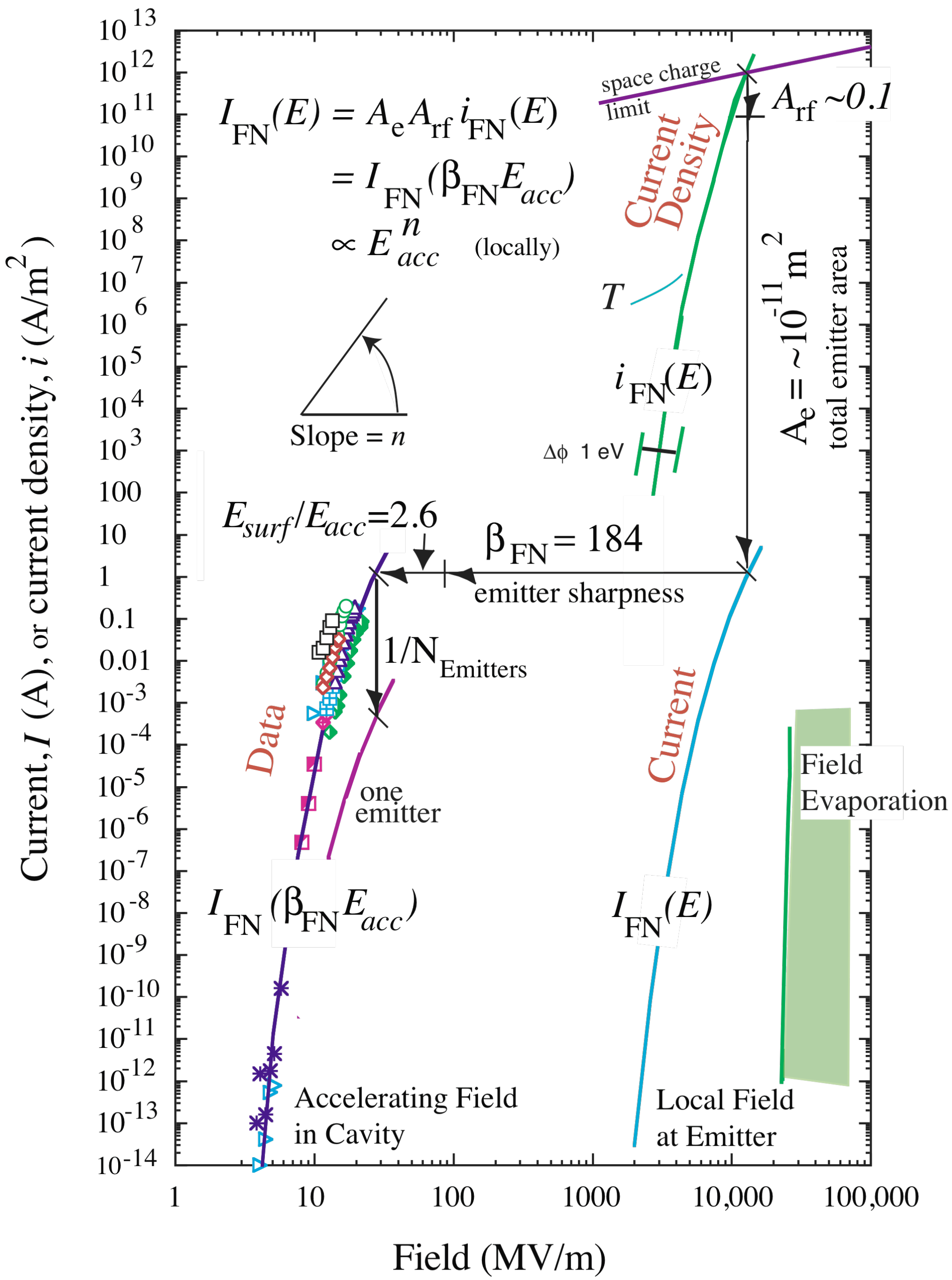


X rays show that cavities break down at E_{local}~ 7-10 GV/m

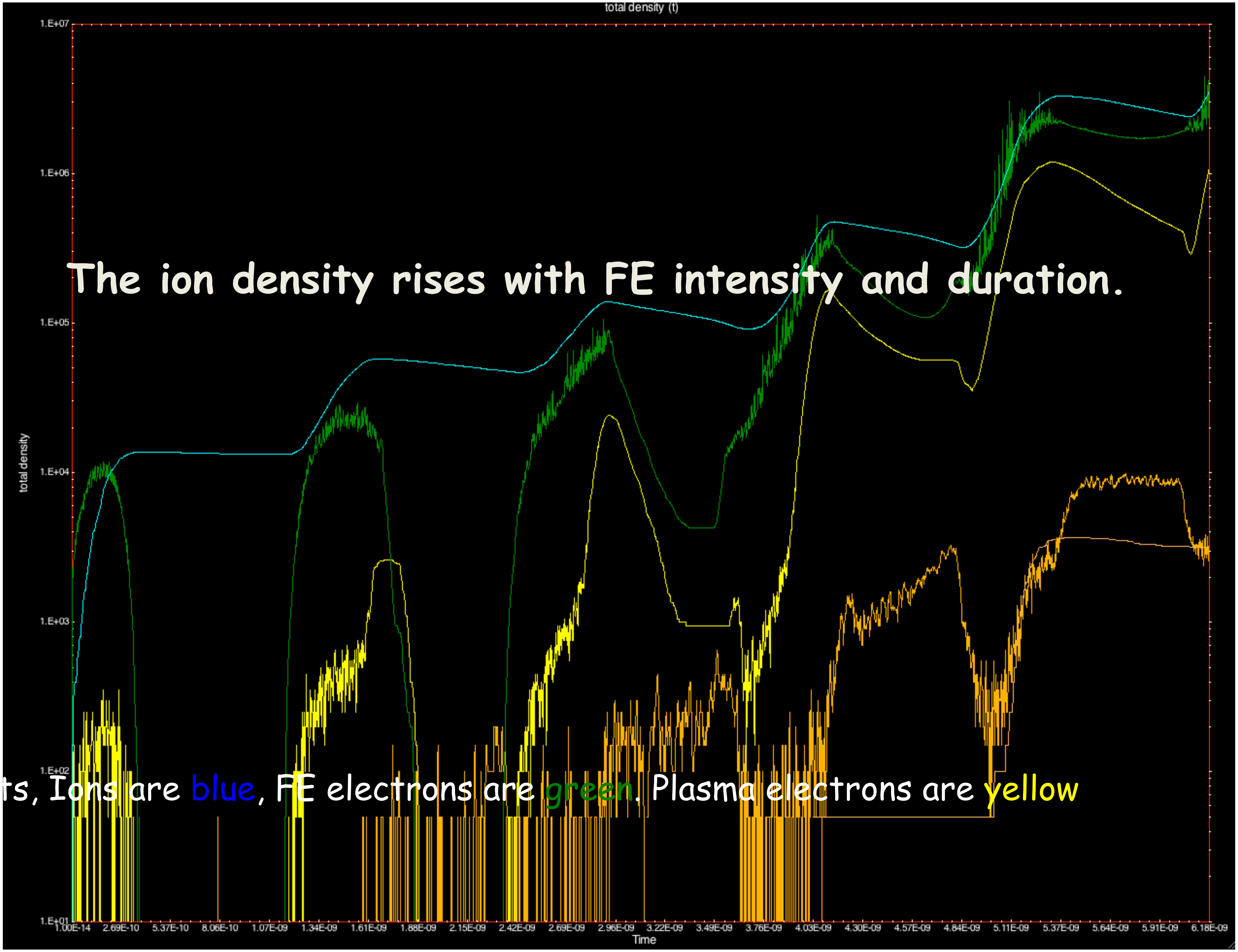
- Breakdown sites are highly stressed.
- E_{local} is close to the evaporation field.
- Recent CERN data => fatigue





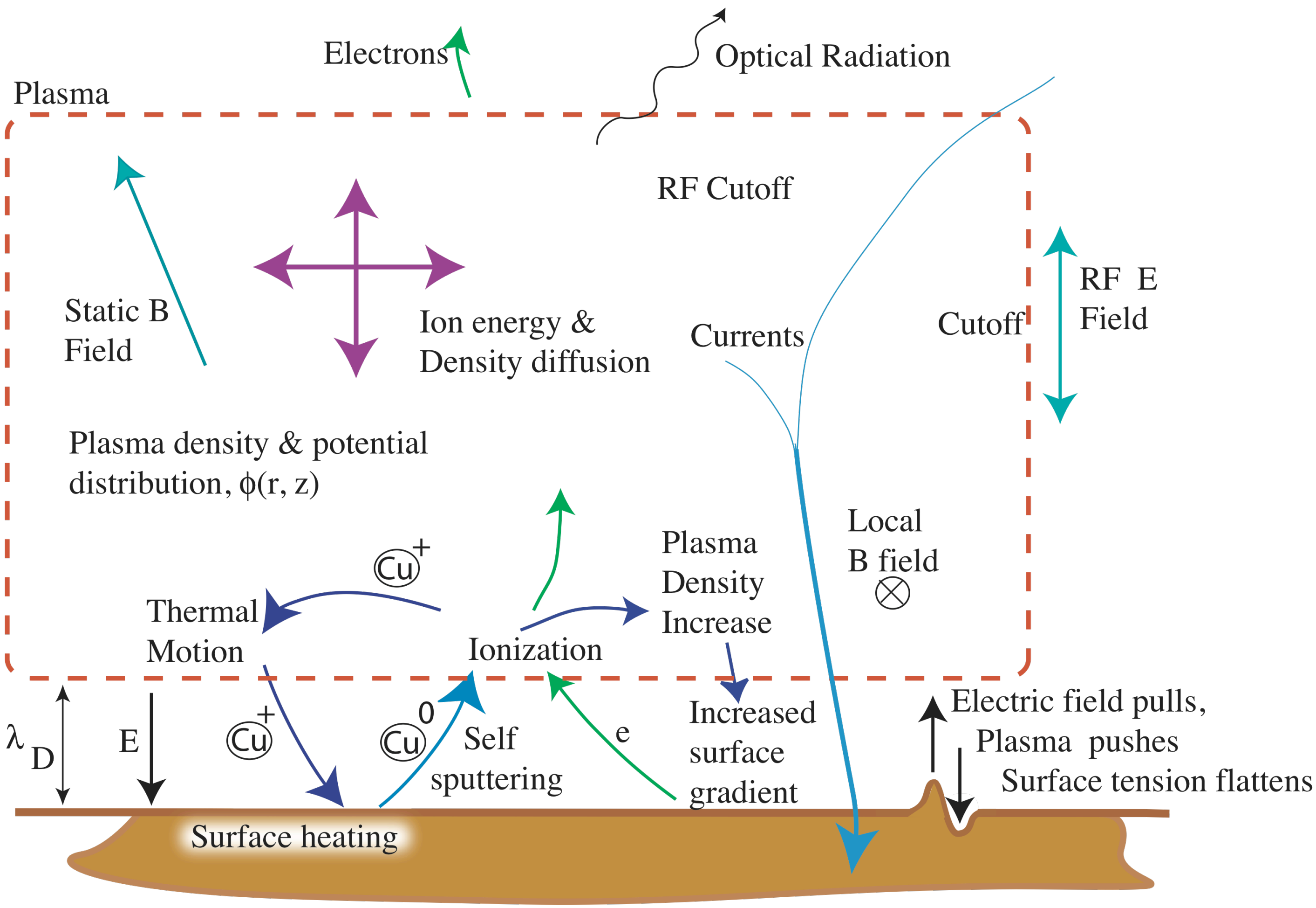


OOPIC Pro 2.5D modeling shows how arcs start (805 MHz).



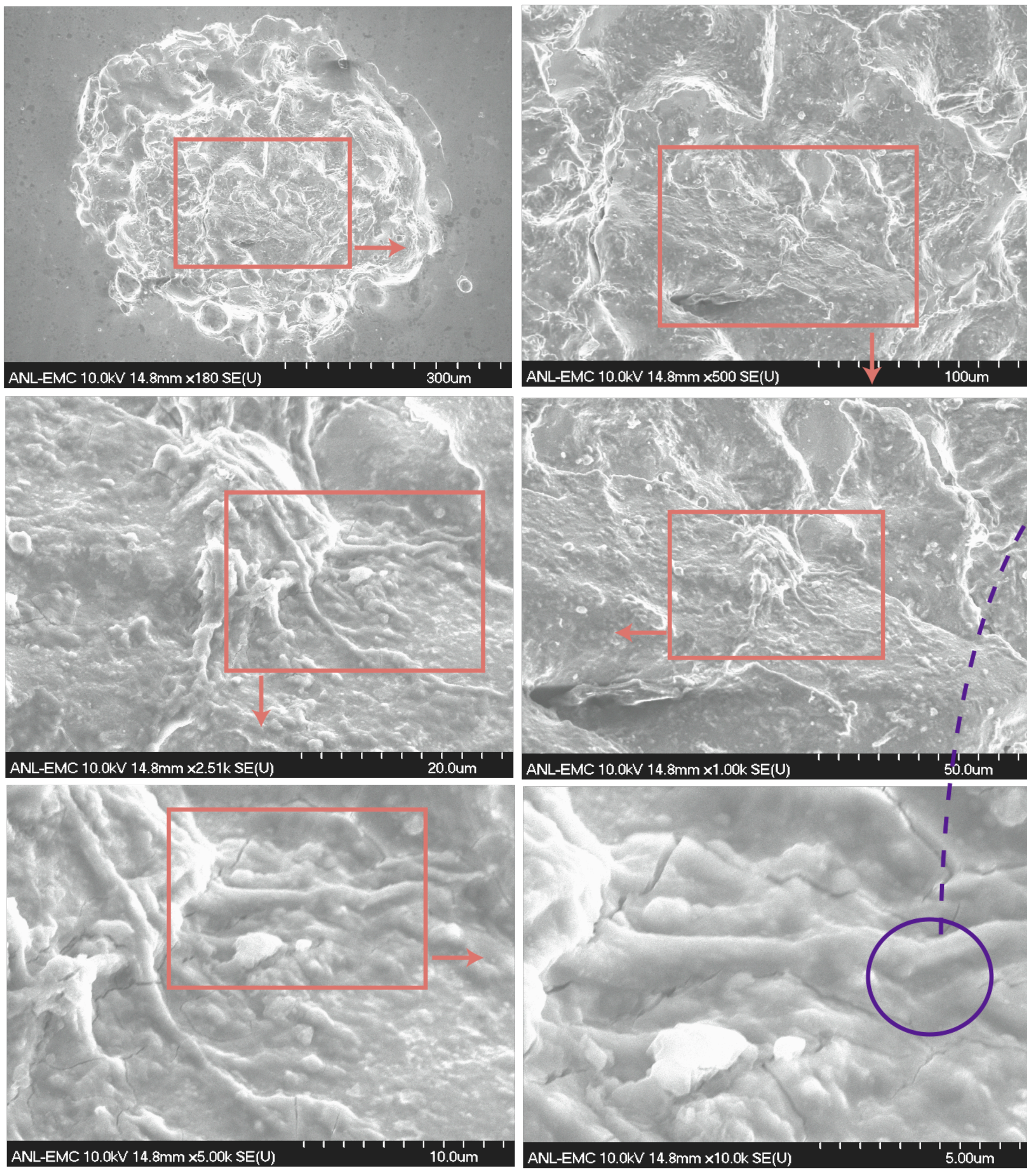
The arc is complex

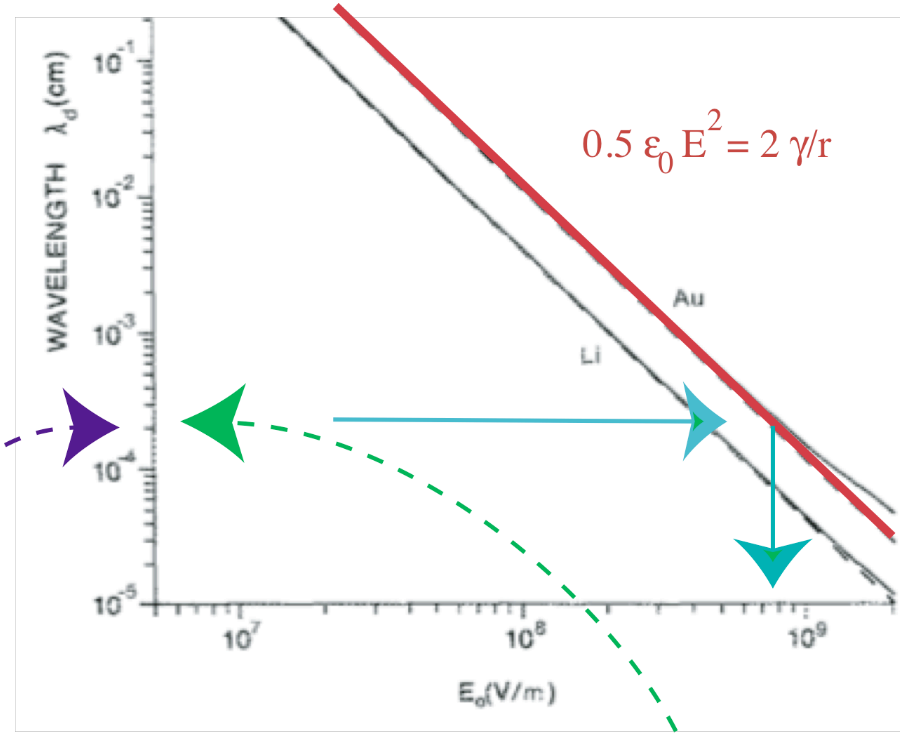
- The surface electric field defines the plasma thru sputtering and field emission.
- Inertial confinement of ions and quasi-neutrality constrain its evolution.

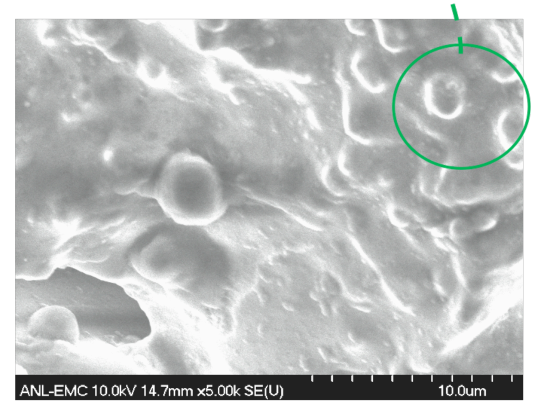


Capillary waves can measure surface fields (Tonks-Frenkel inst.).

- Dimensions of structures imply $E_{surface} > 1$ GV/m, if $P_{surface\ tension} = P_{Electrostatic}$.





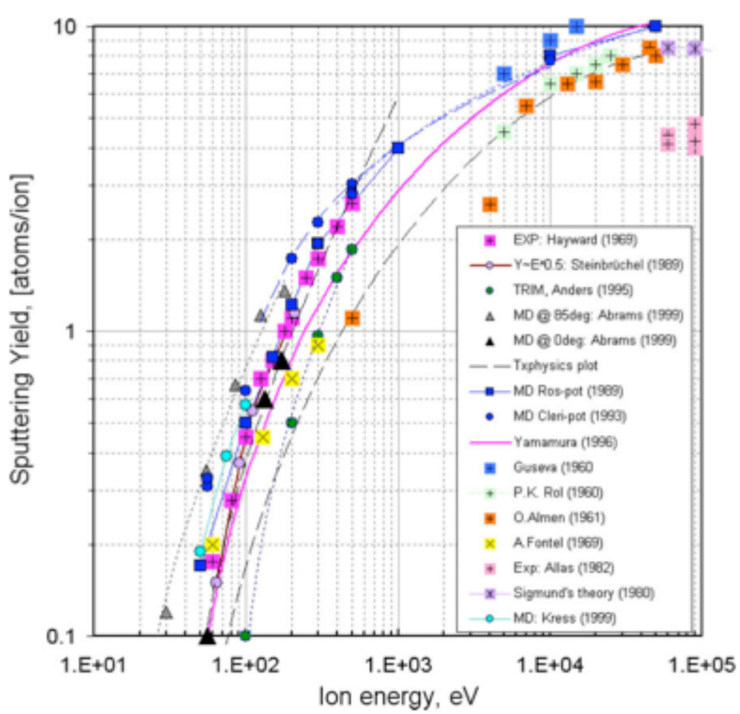


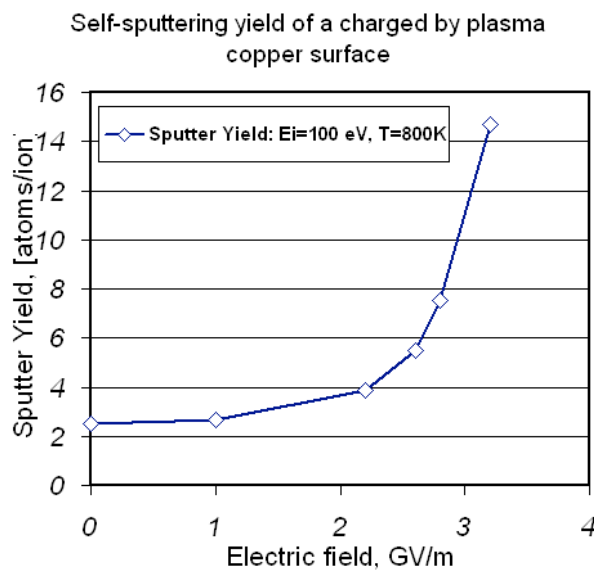
High temperatures and fields increase self-sputtering.

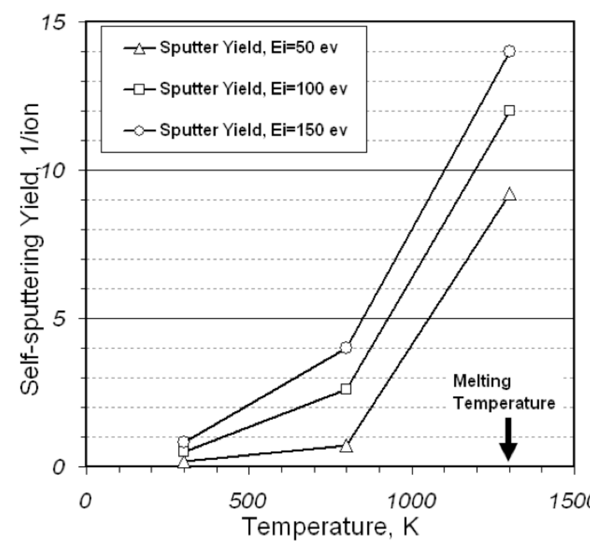
- Self-sputtering rates determine surface erosion, and the plasma density. Fast development of the plasma requires self-sputtering rates above 10, which are not usually seen at low (~100 eV) ion energies.

- These rates have not been previously calculated for liquids above their melting point or for environments with high local fields. We use MD, and see high yields.

- Erosion rates on the order of, $r = n_I v_I Y(\lambda_D, \phi, T_{surf}) / V_A$ are ~ 1 m/s.

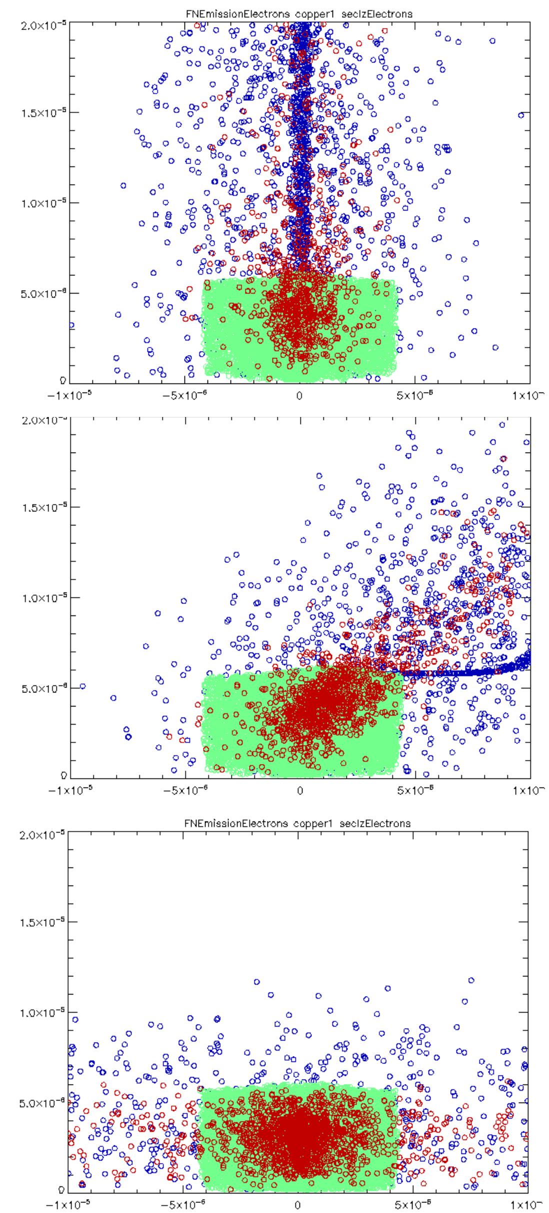






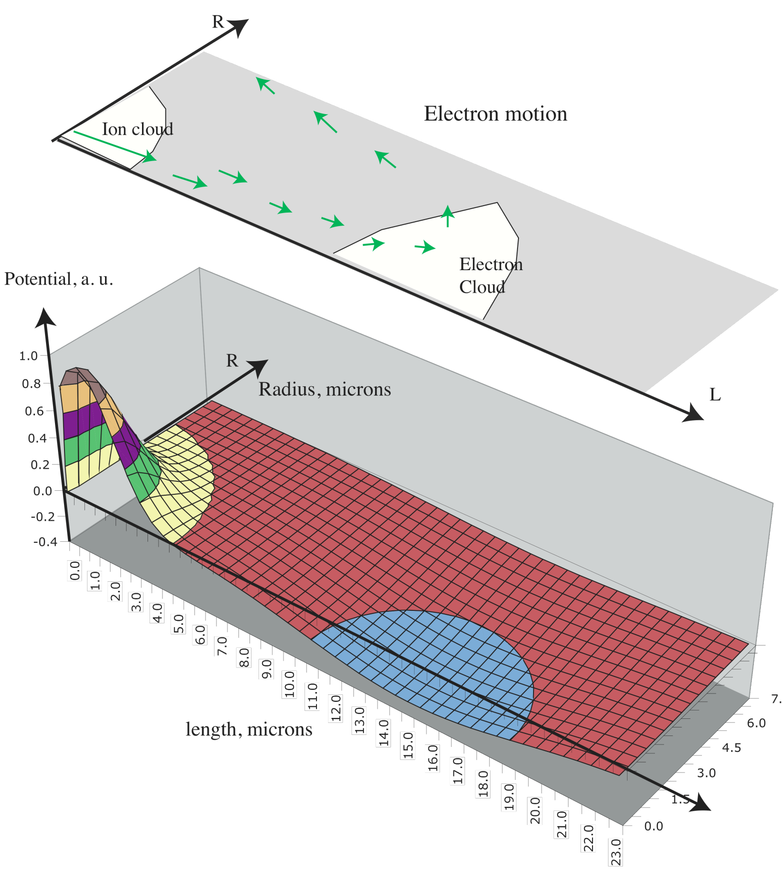
Magnetic effects are complex.

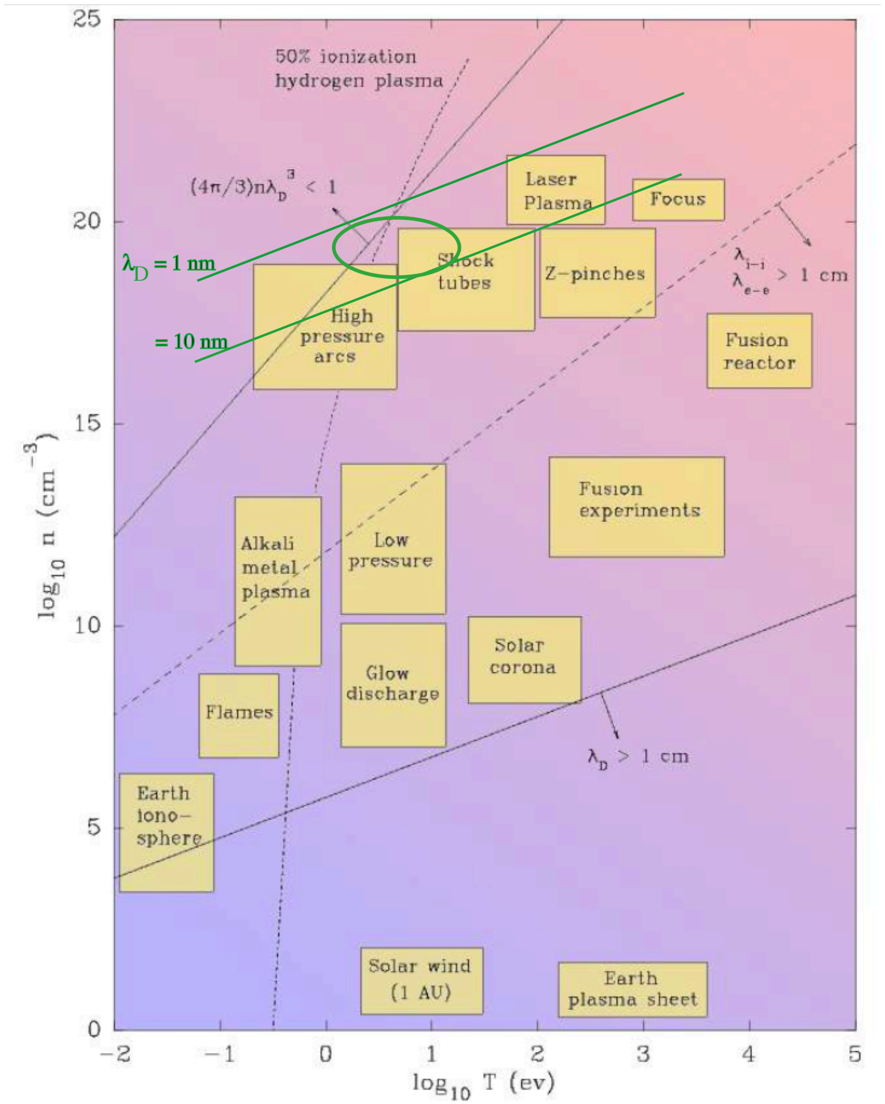
- The primary effect of the magnetic field seems to be confining the plasma.
- OOPIC shows this plasma confinement.
- New VORPAL data will show ExB effects
- First data, with vertical E field shows results for B parallel to E, B at 45 degrees and B perpendicular to E. gas occupies the region shown in green.



Unipolar arcs are not well understood.

- A lot of effort went into this work in the '70s and '80s, not much since.
- These arcs seem to occur in non-Debye (very dense) plasmas.
  - We are exploring modeling methods.
  - "Chicken track" arc damage.
- Unipolar arcs could be transients.

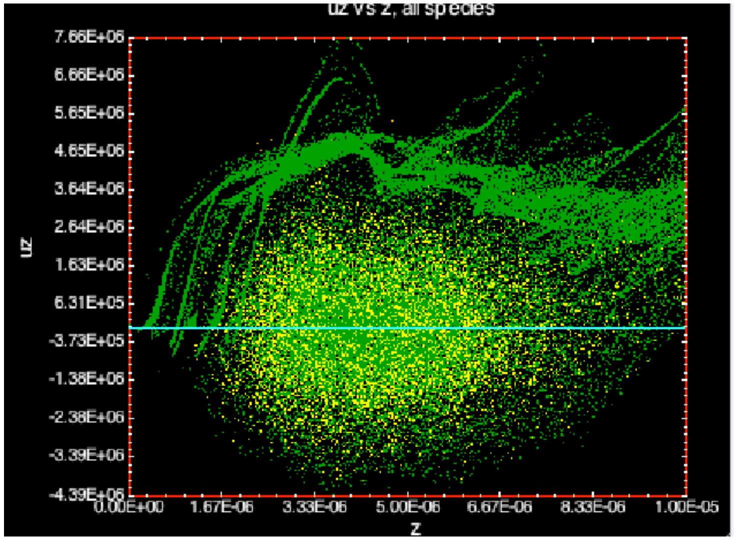




Field emission and Unipolar Arcs

- Exponential growth must eventually be terminated.
- As the plasma density increases, the plasma potential and excess charge density remain roughly constant, eventually reaching a condition where a large area is seeing *E* fields (~5 GV/m) capable of high current density field emission.
- The combination of large surface area and high fields seem to imply currents that could short the plasma potential on the order of ns.
- The figure shows that FE ~ Trapped electrons, and,

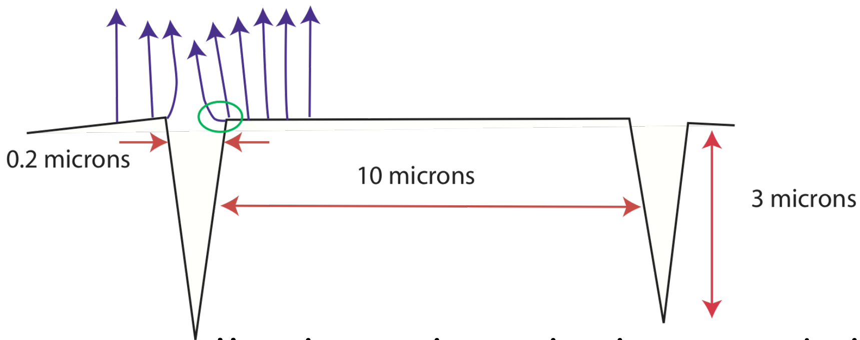
  $n_{e,FE} \sim n_{e,trapped} \gg (n_I - n_{e,trapped})$



- These currents would create high magnetic fields pulses, high frequency structure in all plasma parameters. They would also terminate and perhaps "quantize" the arc. (ectons?). Is this a unipolar arc?

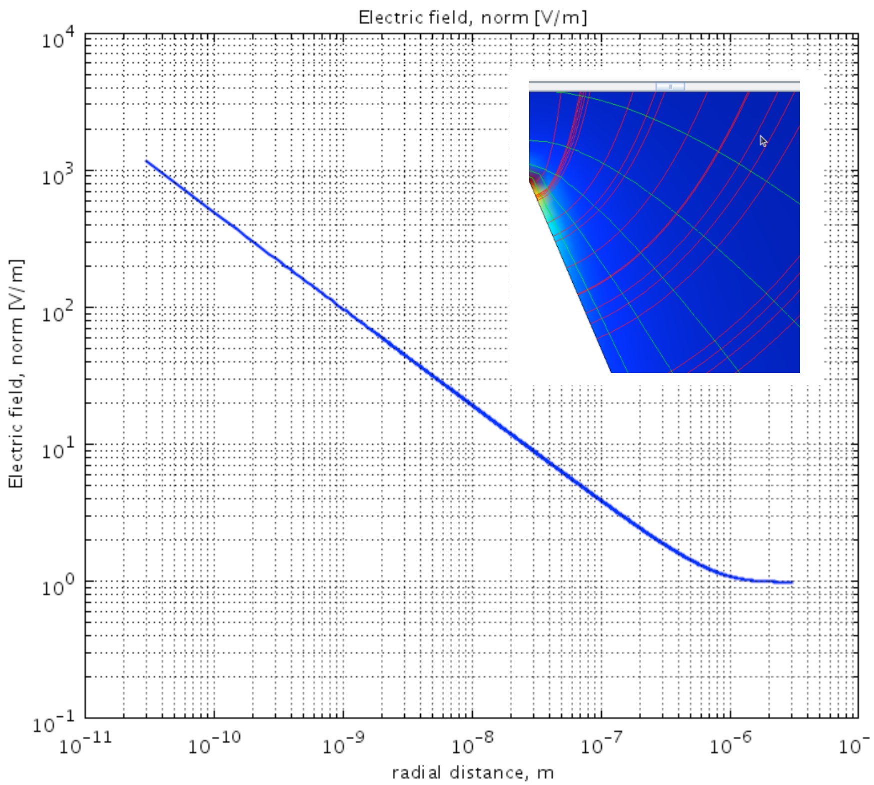
Cooling, cracks and β's:

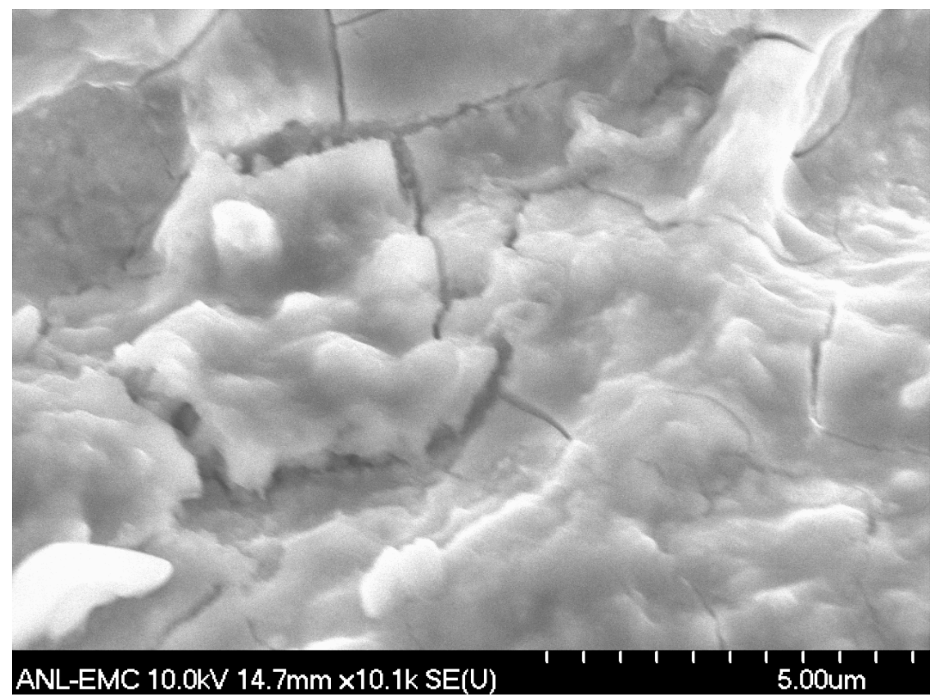
- Melted copper (~3 μm thick, at ~1000 degC) can cool and crack.
  Crack width: $dx \sim (17 \times 10^{-6}) * 1000 * x \sim 2\% \, x$, $x = 10\ \mu \Rightarrow dx \sim 0.2\ \mu$.



Can be modeled by a cone.

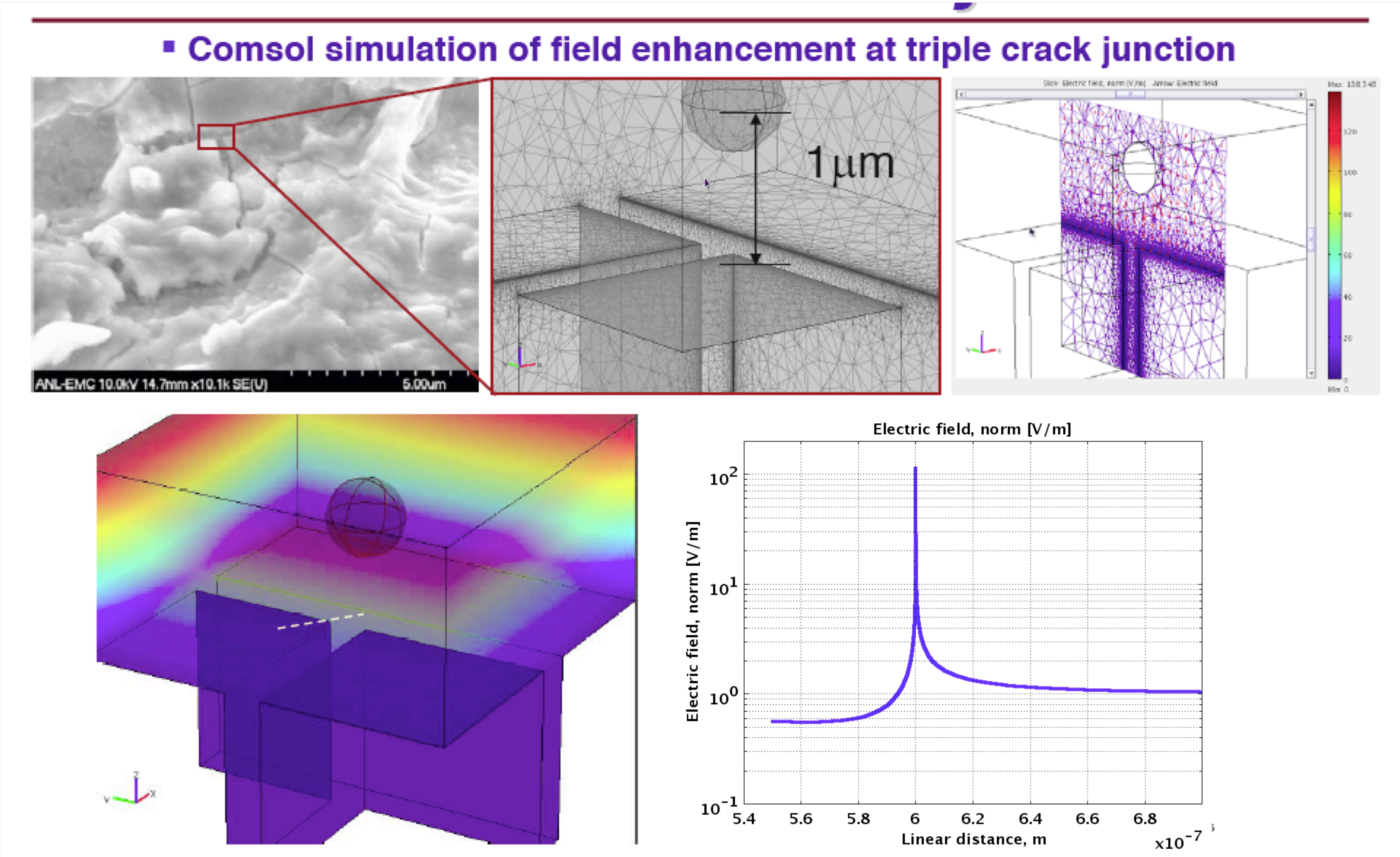
- Corners are atomically sharp, have high βs, and there are lots of them.





Modeling field enhancements.

- We have been modeling, cracks, junctions, edges and other shapes.



Ohmic heating

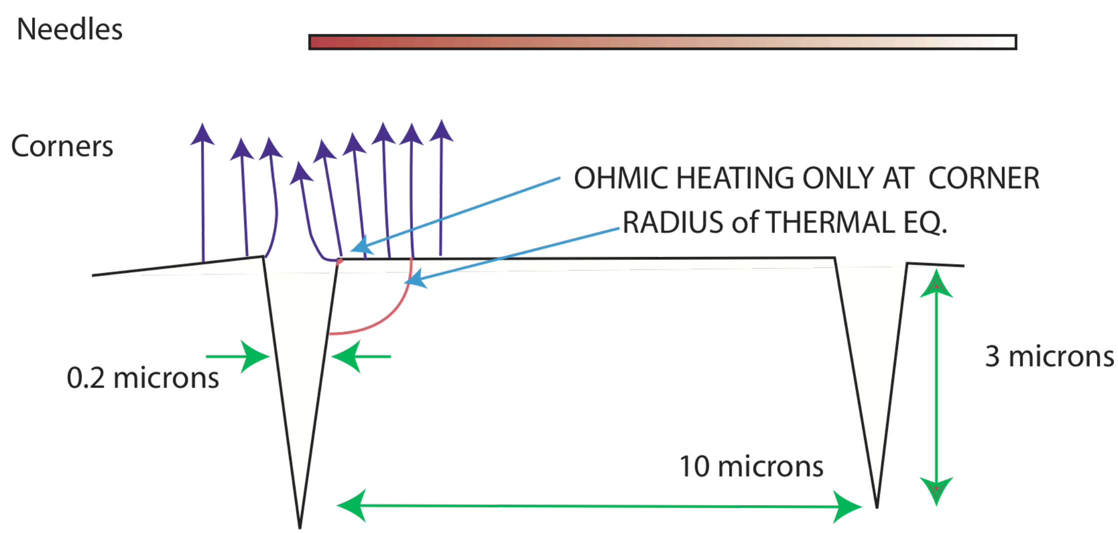
- Ohmic heating has been the "standard model" for breakdown triggers since the papers by Dyke, Trolan, et. al. in the early 50's showed that Ohmic heating could be responsible for failure of tungsten needles at high field emission.

- In needles, the heating is more or less constant throughout the length, with 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:

$$r = (Dt)^{0.5} \sim (1E\text{-}4 * 1\ ns)^{0.5}$$
$$\sim 0.3\ \mu m$$



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

Other applications of arcing

We are beginning to develop parameter sets for these cases:

- Tokamak edge plasmas

  Large surface area and long DC pulses.

  This model predicts that breakdown will occur when the local surface field is greater than 5 – 6 GV/m.

  $(\phi/\lambda_D)\beta$ ~ 6 GV/m

  With a 100 eV sheath potential, and λ_D ~ 6 μm gives,

  β ~ (6 GV/m)(6e-6m)/(100 eV) ~ 400,

- Laser Ablation, micrometeorite impacts

  Tiny areas and very short DC pulses.

  Arbitrarily dense plasmas can appear over essentially smooth surfaces, and arcs must trigger more quickly. With λ_D ~ 0.1 μm,

  $(\phi/\lambda_D)\beta$ ~ 11 GV/m,

  we assume this would imply a constraint on the plasma parameters like,

  ϕ ~ (11 GV/m)(1e-7m)/30 ~ 40 eV

- These arcs would have similar parameters and would develop as described above

We differ with other models:

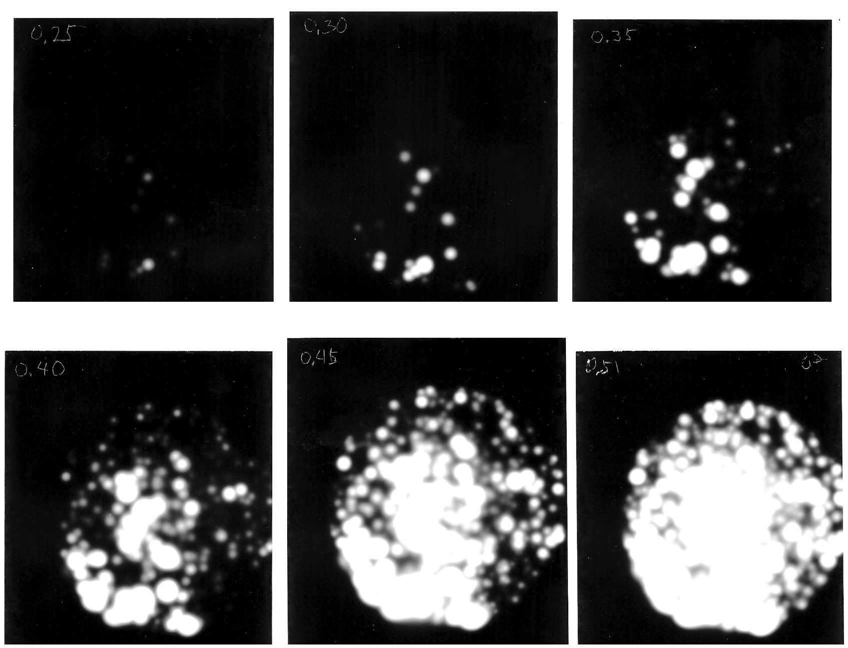
Lord Kelvin, '04:	We spell "electron" correctly.
J. Anderson, '20:	First exploding wire paper (?), We assume Coulomb explosion.
R. H. Fowler, '29:	F-N model is great, F-N plots have confused everyone.
W.P. Dyke. '52:	Needles resistively heat, realistic geometries don't.
F. Rohrbach, '71:	Whiskers not seen.
F. Schwirzke, '93:	Unipolar arcs seem to be (terminal) transients.
G. Mesyats, '97:	Driving force is surface field, Ohmic effects not dominant.
I. Beilis, '95;	Numerical modeling few mechanisms, not kinetic eqns.
R. Siemann, '03:	Arcing at irises => B field not involved.
R. Palmer, '09:	Our model describes arcs under all conditions.

Test of "Breakdown-Proof" Cavities

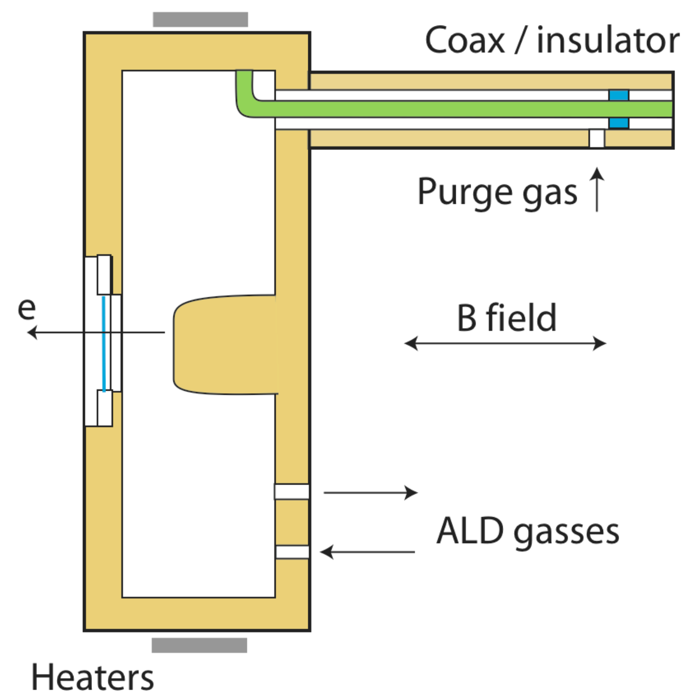
- Atomic Layer Deposition can conformally coat emitters & breakdown sites during operation, increasing local radii, reducing the local field, $E_l \sim 1/r$, field emission, $\sim E_l^{14}$, and breakdown rate $\sim E_l^{30}$. As little as a few nm might do it.

- The experiment will be done in the Fermilab MTA.

- We can monitor field emission patterns with Polaroid film or other instrumentation as shown in old data (increasing field) for a similar geometry.



The cavity



Workshop on Unipolar arcs

- In the 1980's and '90's unipolar arcs were actively studied in many environments primarily in the tokamak community. They were considered to be the primary damage mechanism for tokamak walls, but they were described as "ubiquitous" because their characteristic "chicken track" damage was seen in many places.

- Since 1997 there has been very little study of this mechanism, or arcing in general. High power tokamaks now use divertors, and interest has shifted.

- We wanted to find out what interest there was in these arcs in different fields.
  - DC arcs
  - RF antennas in tokamaks
  - Arcs and hot spots / edge limited modes
  - Accelerators
  - Programmatic fusion priorities
  - Modeling
  - Other examples.

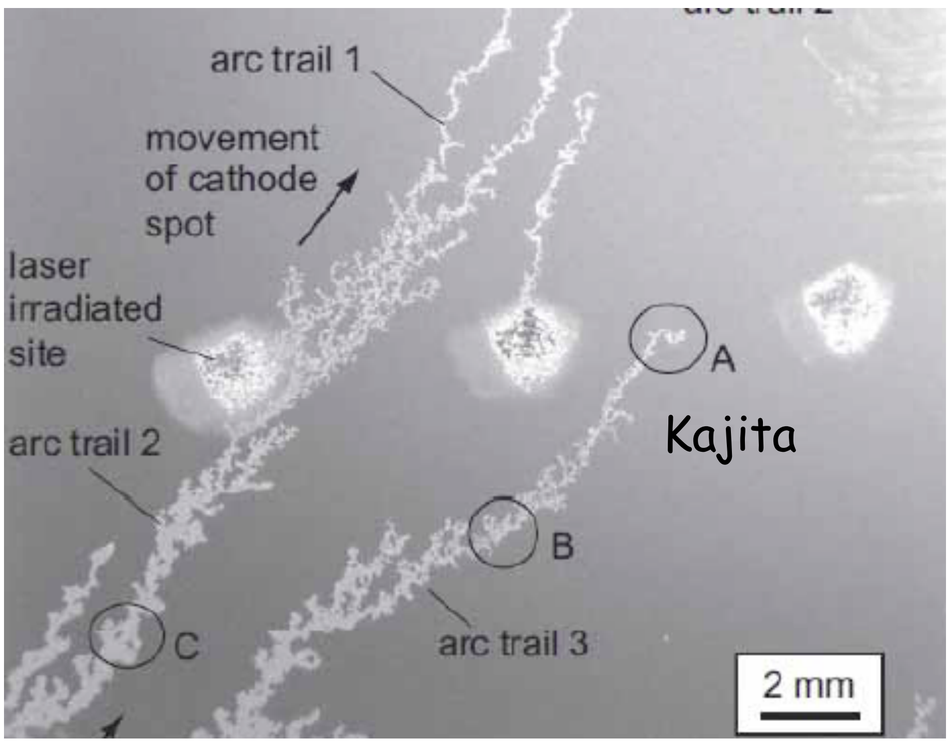
- The problems are different, but the same physics seemed to be involved.

We had participation from many fields.

- The talks are on the web. It is hard to neatly summarize
  https://twindico.hep.anl.gov/indico/conferenceDisplay.py?confId=69

  S. Kajita and C. Castano reported recent measurement of Unipolararcs
  A. Anders and G. Norman discussed general arc theory
  J. Norem and J. Brooks described arcing in accelerators and fusion devices.
  Z. Insepov, L. Cooley, Y. Raitses and J. Caughman described details of arcs
  R. Smirnov, S. Veitzer and P. Crozier described modeling techniques.

- This was followed by discussion of a general strategy for R&D.



Conclusions

- Our picture of arcs is becoming simpler and more general.
  We find electrostatic fields can both trigger and drive arcs

- We are exploring new applications and constraints on our model, with a number of papers underway

- Construction on the experimental equipment should start this year.

- Our work using ALD to understand SRF is also productive.

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Anderson, Astrophysical Journal, 51, 37 (1920)

The mechanical effects of exploding wires are interesting. Some of these have been described by Singer[1] and by F. E. Nipher.[2] If a glass tube with open ends be slipped over the wire the explosion breaks the tube into fragments, which are scattered all over the room; if the ends of the tube are closed by cork stoppers and the tube filled with water, the water disappears completely and the tube is broken into powder so fine that it is sometimes difficult to recognize it as glass. With the wire a few millimeters below the free surface of water in a large glass jar, the sound-wave transmitted through the water by the explosion thoroughly wrecks the containing vessel.. The apparent absence of any heat effect is also quite striking. A No. 40 B. and S. gauge (0.080 mm) copper wire with double cotton insulation may be exploded, and in most cases the insulation remains nearly unchanged. Tissue paper wrapped tightly around the wire is torn into small bits, but not burned or even charred.

[1] *Philosophical Magazine*, 46, 161, 1815.

[2] *Experimental Studies in Electricity and Magnetism*. Blakiston, 1914.