ALD status and plans

J. Norem, ANL/HEP

Friday MAP Mtg.
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Muon Accelerator Program

Argonne NATIONAL LABORATORY

Outline

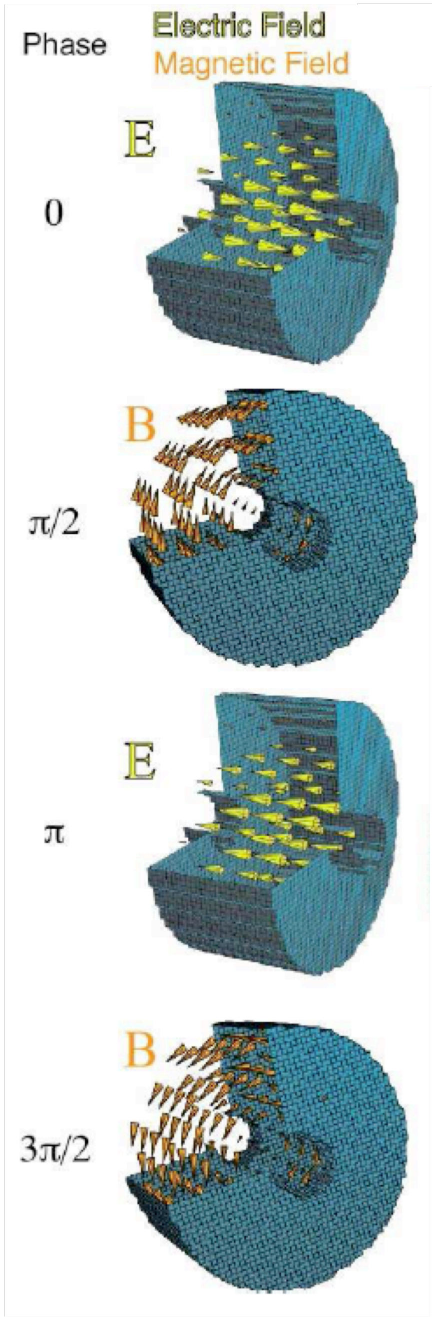
General ideas

Survey of effort

Causes and “cures”

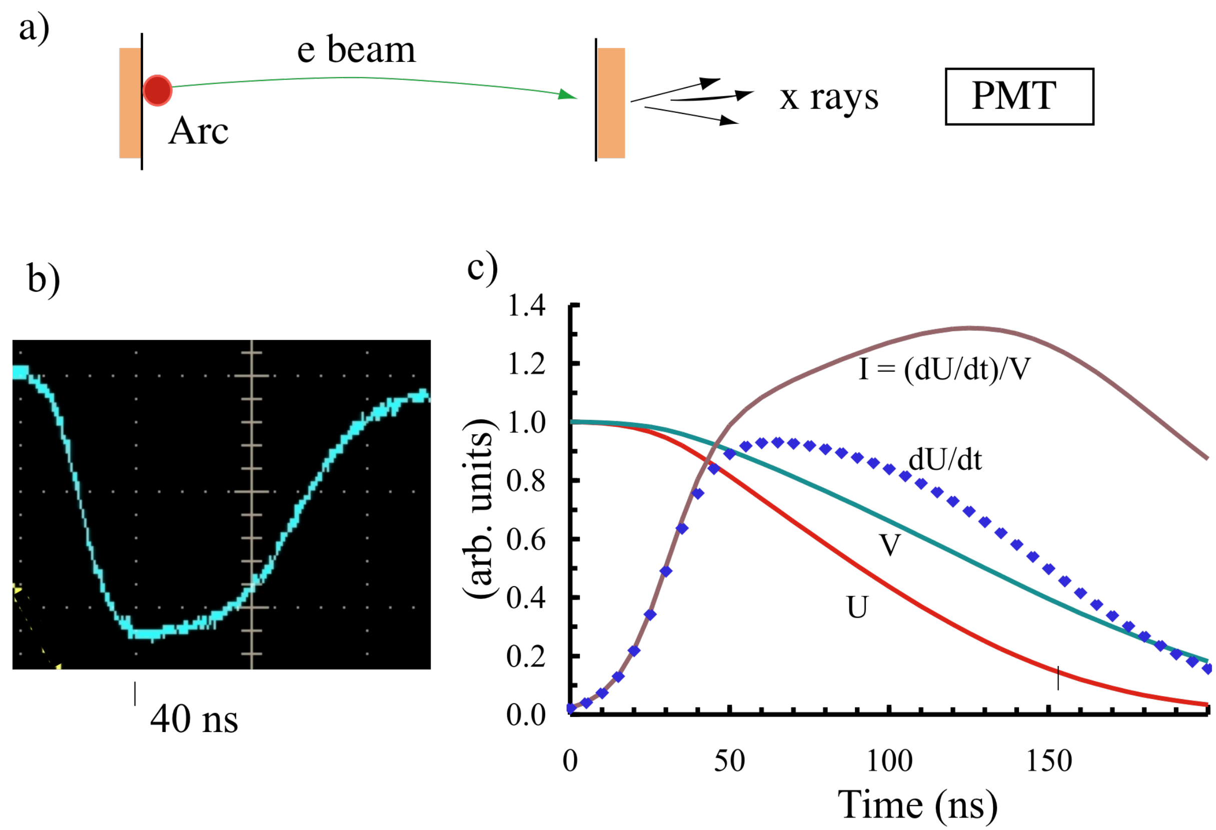
We look at arcs in linac rf cavities.

Linac cavity



Breakdown event

- We primarily look at x rays from shorting currents.
- Stored energy, Fields & currents calculated.



This is a strange branch of science.

The physics is crucial to accelerator gradient limits,
Relevant to Tokamak stability and efficiency,
Studied for > 110 years in lab plasmas,
Given high priority and good experimental budgets,
Many workshops and applications.

But there is no agreement on what is happening.

- Triggers
- Damage
- Cures

What's the problem?

- The process is multidisciplinary
- Lots of data
- Misleading ideas
- Easy to fit a few points
- . . a local "breakdown" of science?

110 years of Vacuum Arcs have not produced understanding

1880's	Paschen,	Gas Breakdown
1900	Michaelson	Surface (Vacuum) Breakdown identified
1904	Lord Kelvin	Tensile stress model
1929	Fowler Nordheim	Quantum Mechanics of field emission
1929	Fowler	Fowler-Nordheim plot, $\ln(I/E^2)$ vs. $1/E$
1952	Dyke et al,	Breakdown measurements
1963	Alpert,	Breakdown is independent of gap
1973	Rohrbach,	Field enhancements
1980's	Mesyats	Explosive Electron Emission (EEE) and Ectons
2002	Siemann	Pulsed heating

The conventional wisdom,

Arcs are caused by whiskers of metal that are heated by field emission currents.

is not convincing. (no whiskers)

Data is sparse and clustered -

How do you compare 200 ns rf pulses with DC data ?

Clean/dirty, dc/rf, small /large gap, positive/negative polarity etc

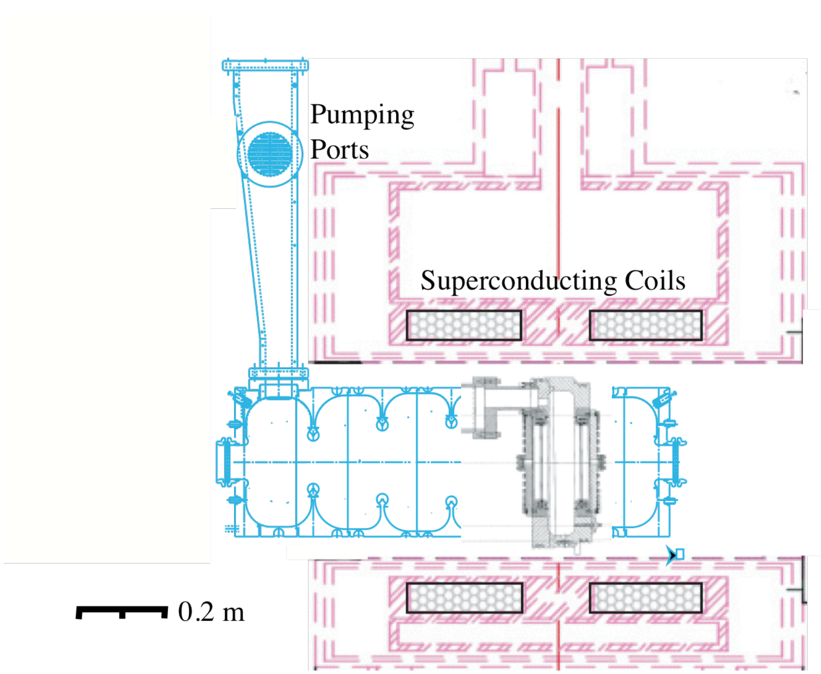
Need a model to understand the data. The model should be:

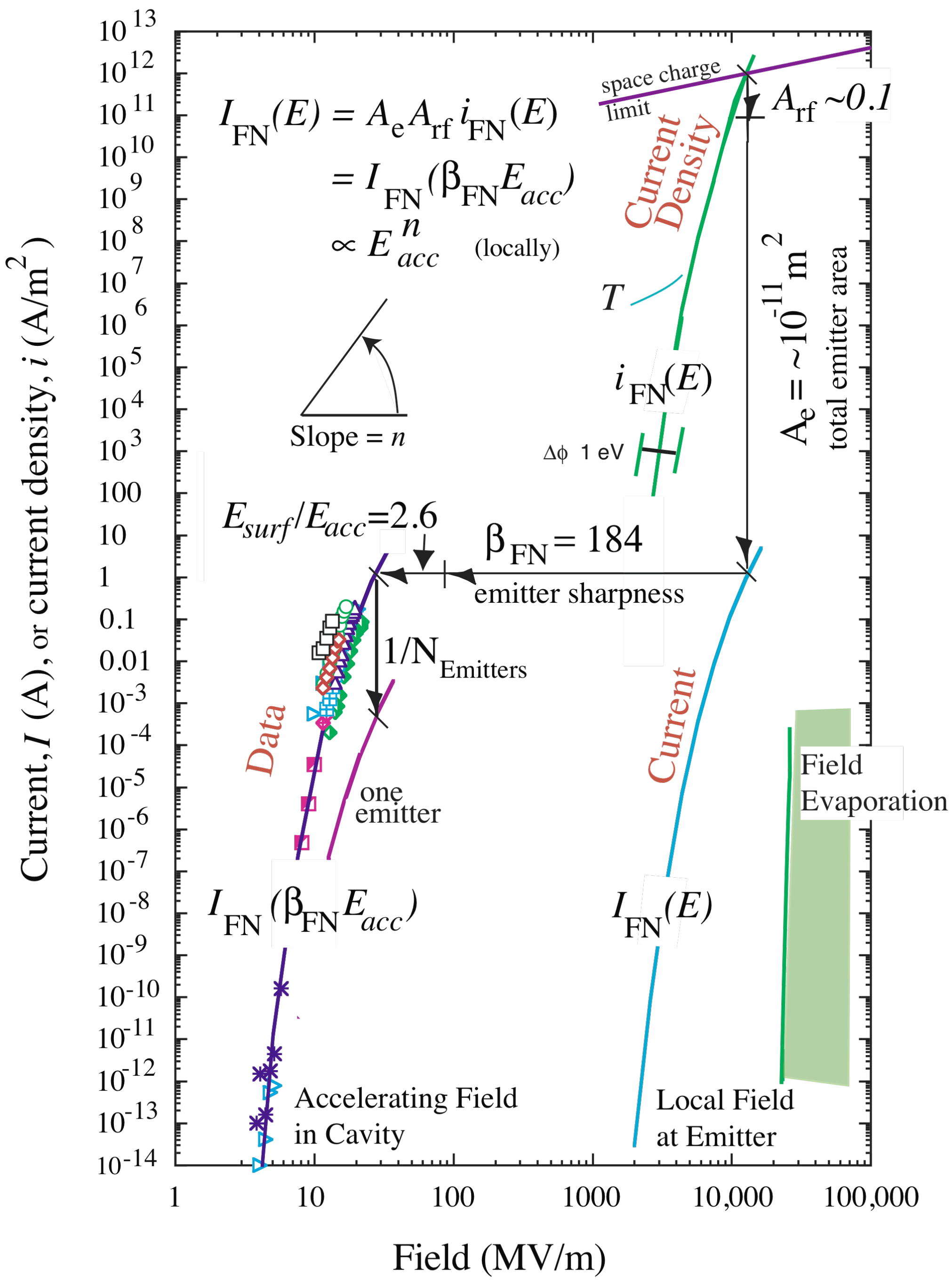
- simple,
- self consistent
- general, all polarities, gap lengths, etc.
- can explain 100 years of data
- and point to a solution

We rely on numerical simulations.

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

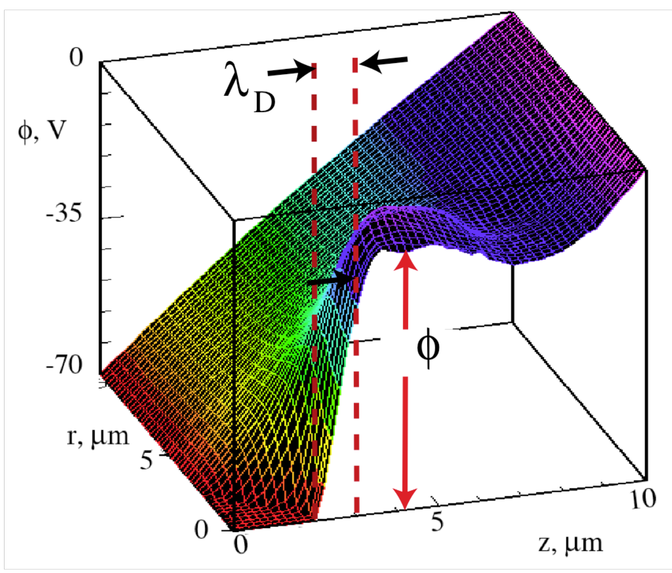
- Breakdown sites are highly stressed.
- E_{local} is close to the evaporation field.
- E_{local} ~ 7 – 10 GV/m seen by everyone.
- E_{local} ~ 67/(n-2) if $J \sim E^n$ and ϕ is ok. (Torun)

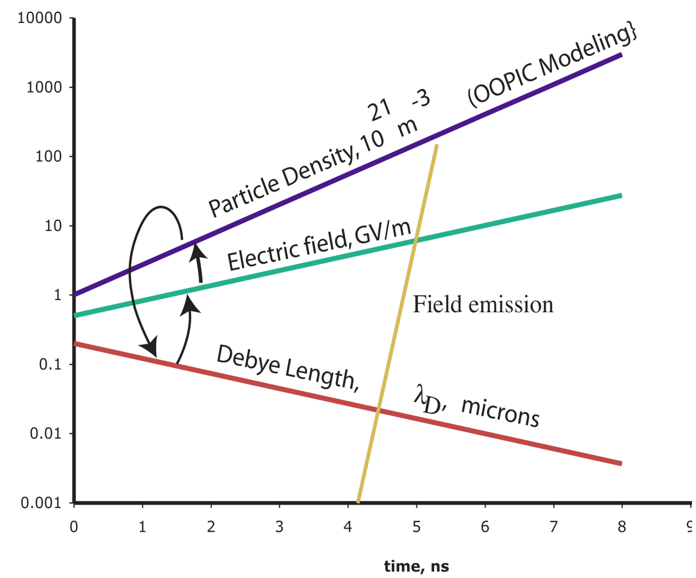




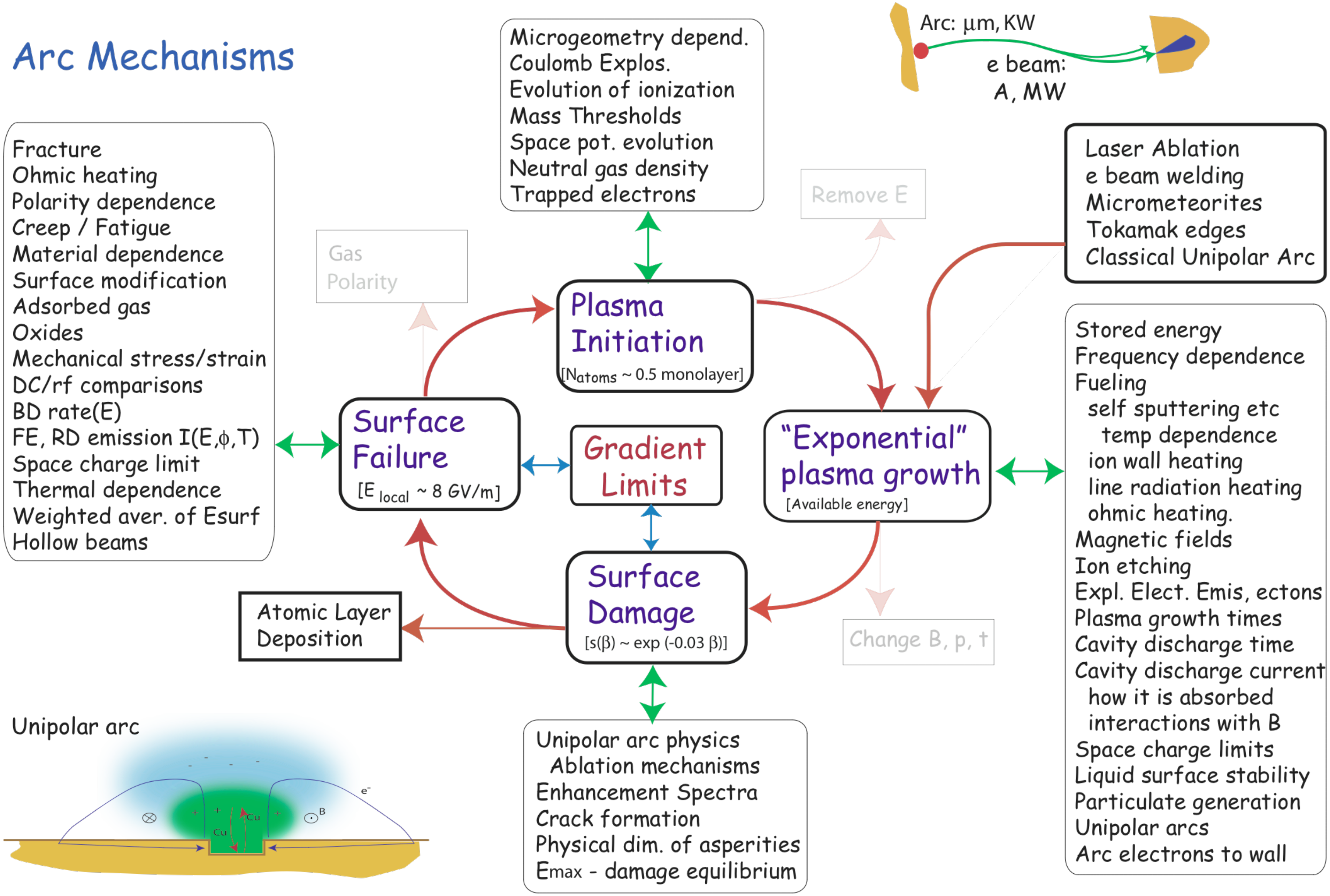
Our arc model.

- Coulomb explosions trigger breakdown - fatigue (creep) helps.
- Breakdown arcs are initiated by field emission ionization of fracture fragments.
- The plasmas produced are small, very dense, cold, and charged ~75 V to surface.
- Increasing surface fields increase density, which further increases surface fields..
- Small Debye lengths, $\lambda_D = \sqrt{\dfrac{\epsilon_0 KT}{n_e q_e^2}} = \sim\mathrm{nm}$, give, $\boldsymbol{E} = \phi/\lambda_D \sim$ GV/m.
- Unipolar arc behavior produces craters and cracks with high field enhancements.

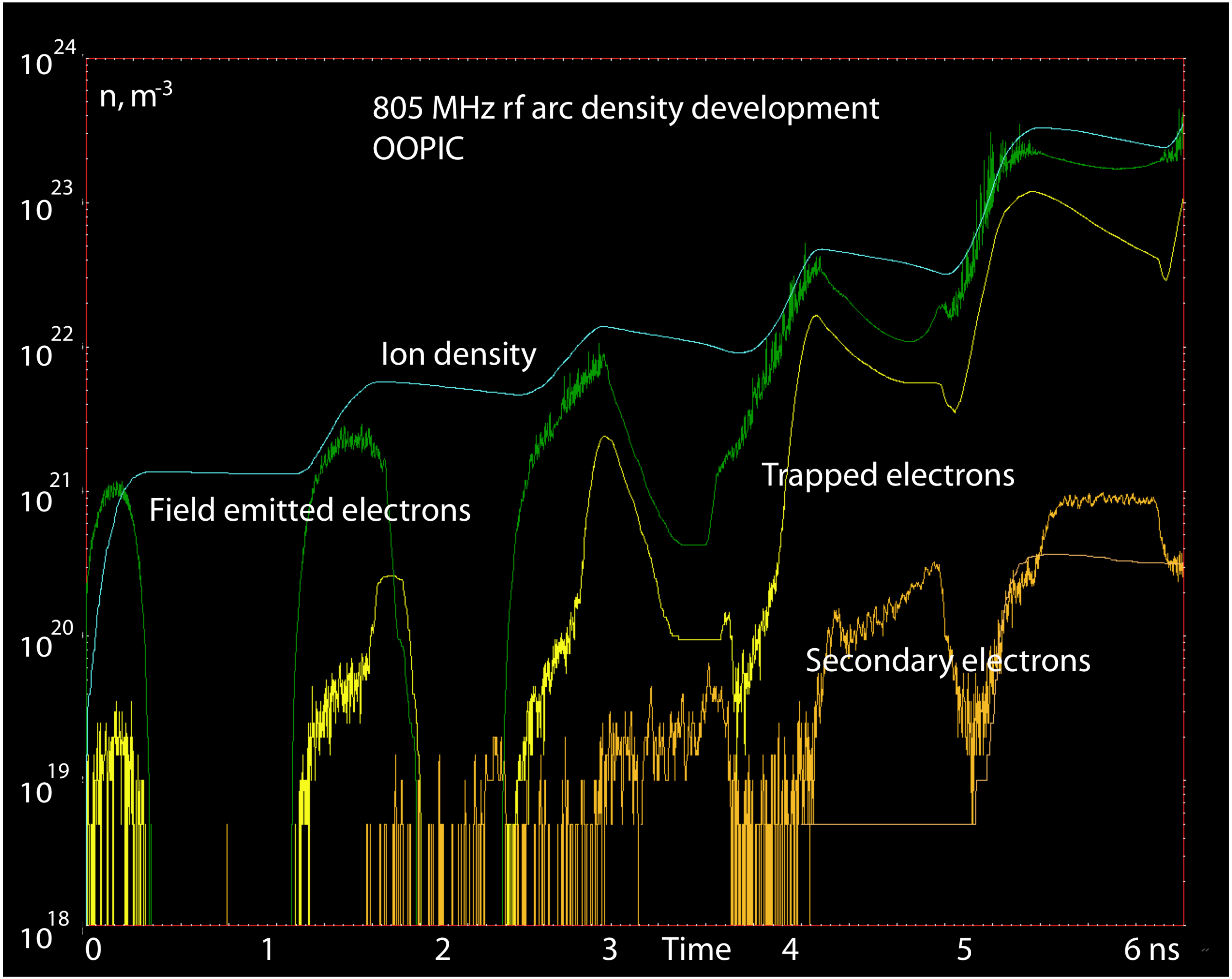




Considering the whole cycle adds more constraints.



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

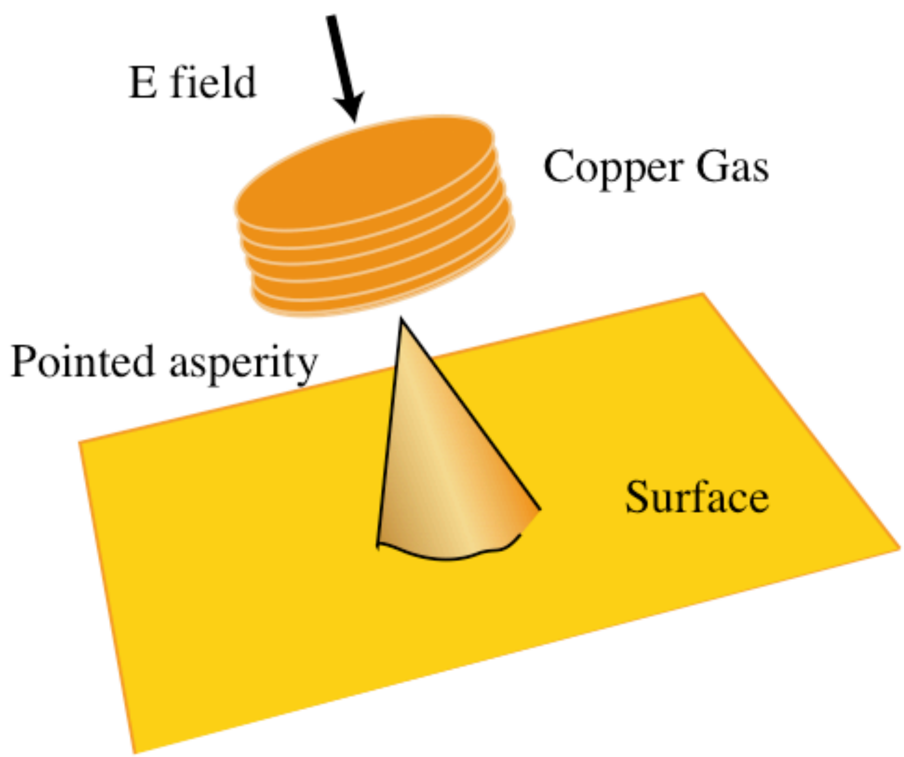


Particle-in-Cell (PIC) codes can describe plasma development.

We have been using a simple geometry.

The arc development does not strongly depend on the geometry.

The density of the gas does matter.



The surface field seems to drive the arc.

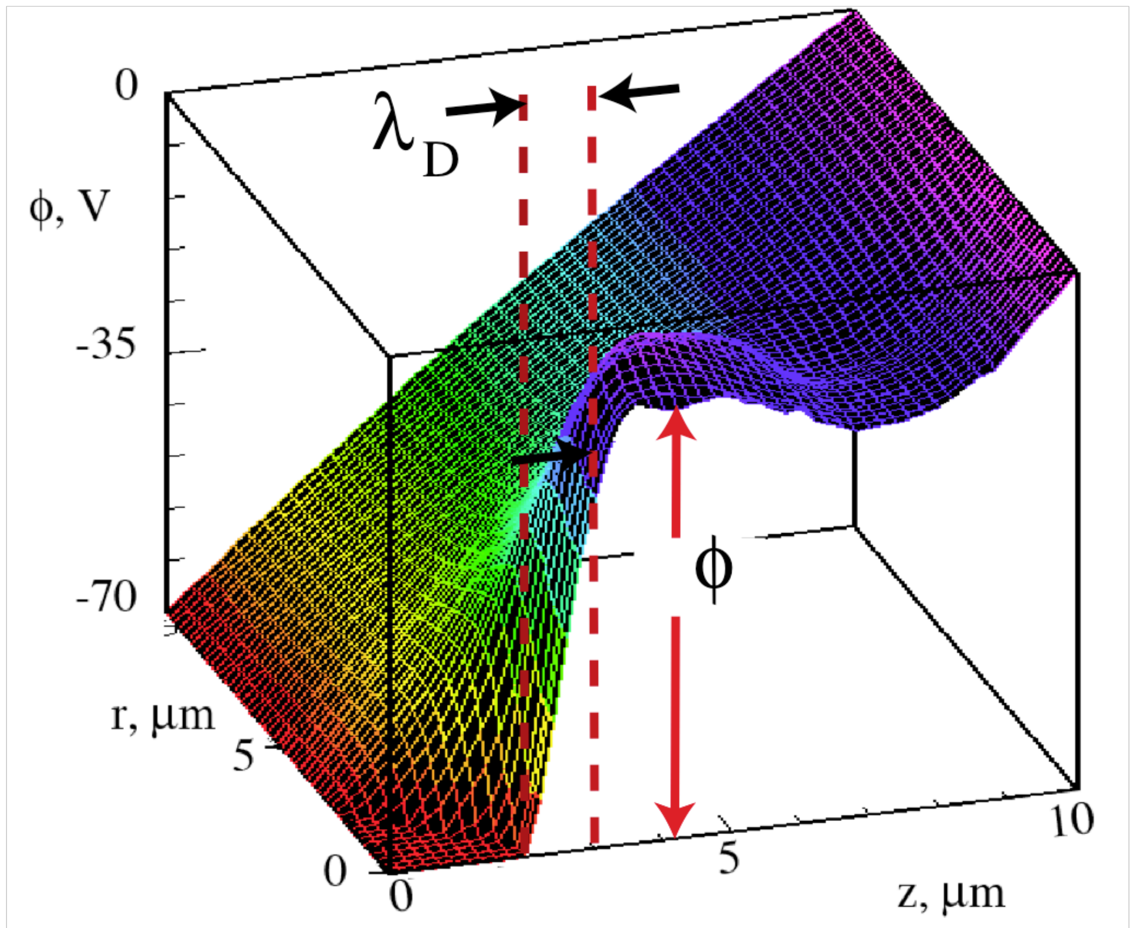
Surface field = (potential, ϕ) / (Debye length, D_λ):

At breakdown: Applied field = ~70 V/10 μm = 7 MV/m

At higher densities: Local surface field = ~ 70 V/ 1 μm = 70 MV/m

As the density increases, the field increases, (driving density increases . .) etc.

early in the arc

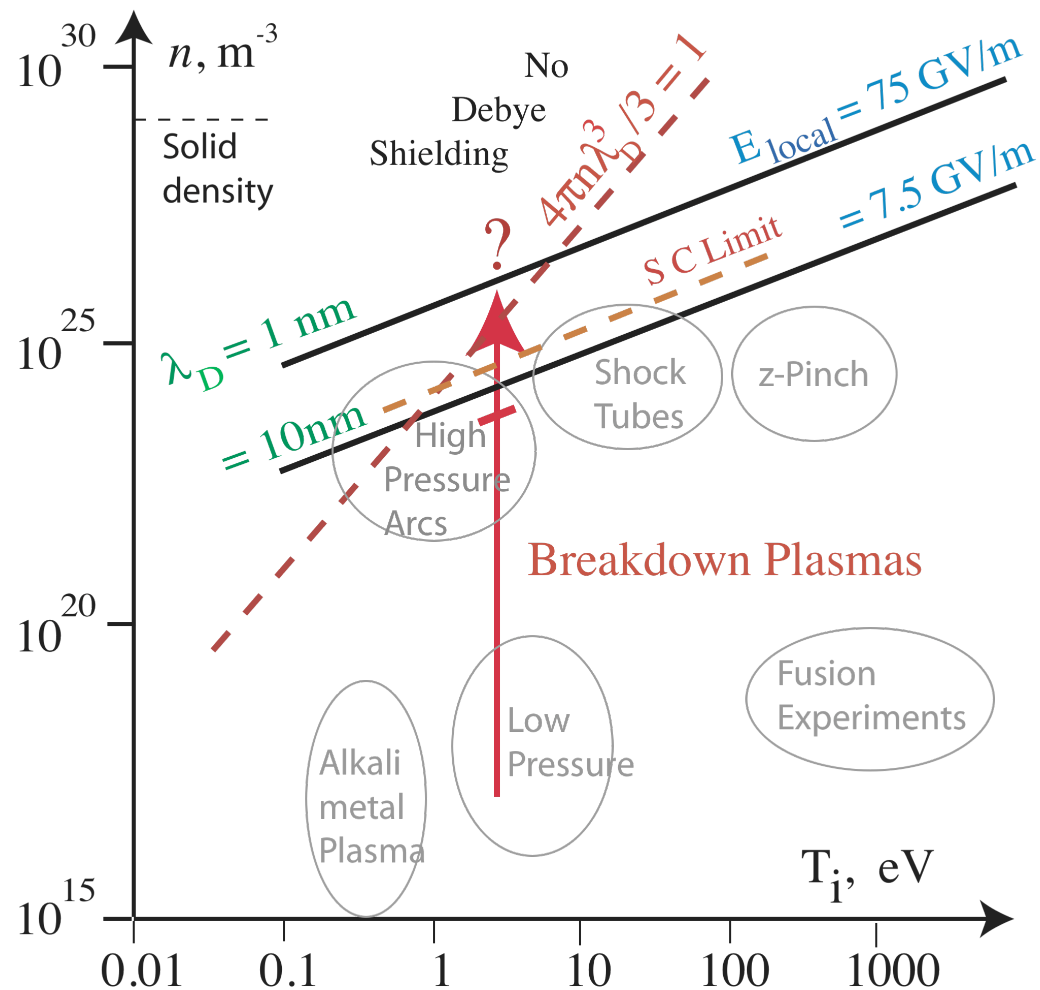


As the density increases, the plasma becomes hard to describe.

- "Plasmas" are defined by:

✔ $\lambda_D < L$ (size)
✖ $N_D >>> 1$ (screening)
✔ $\omega_p \tau_c > 1$ (collisionality)

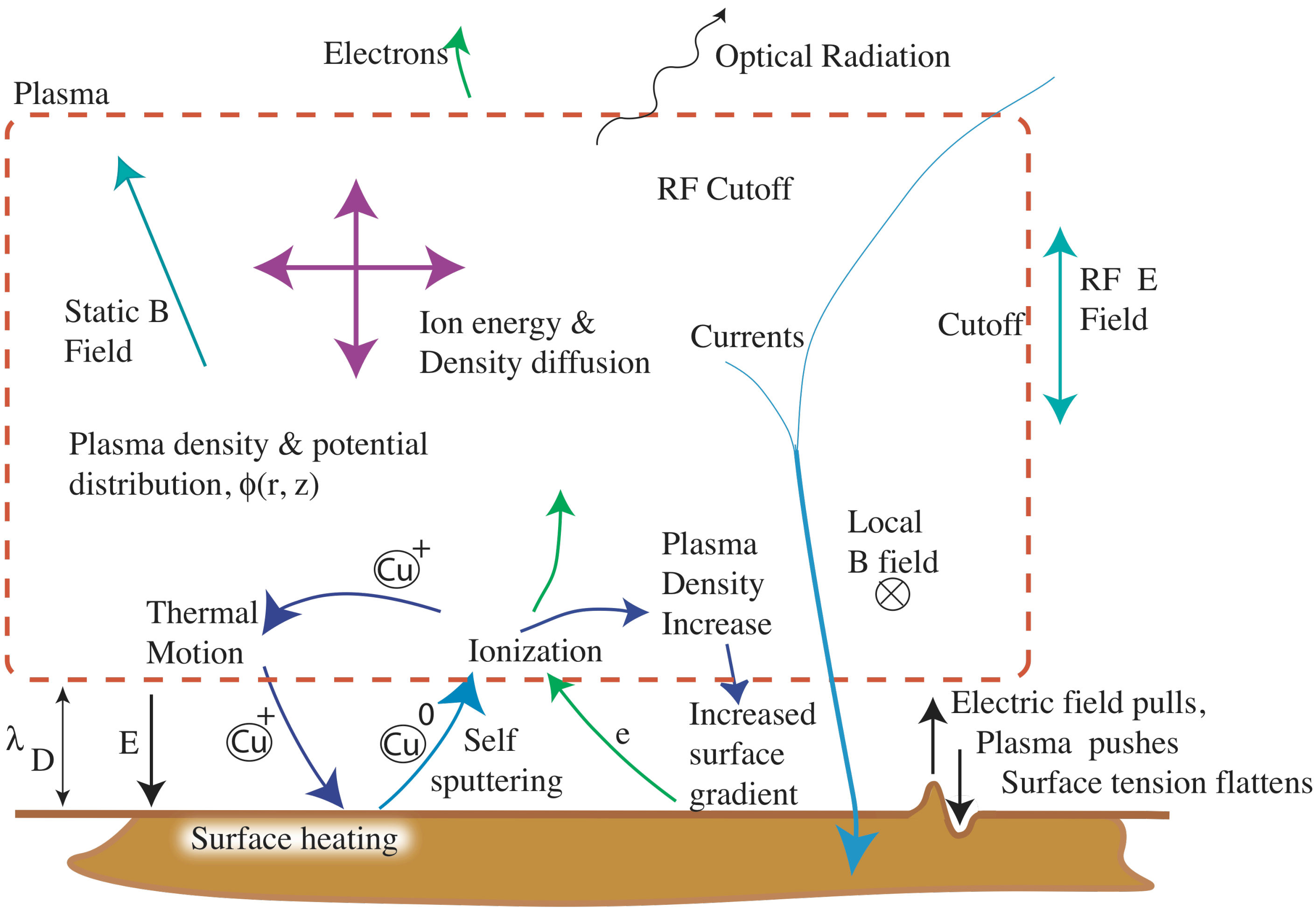
We see very high densities
very high surface fields



These plasmas have not been studied in a self-consistent way.

The arc is a complex environment.

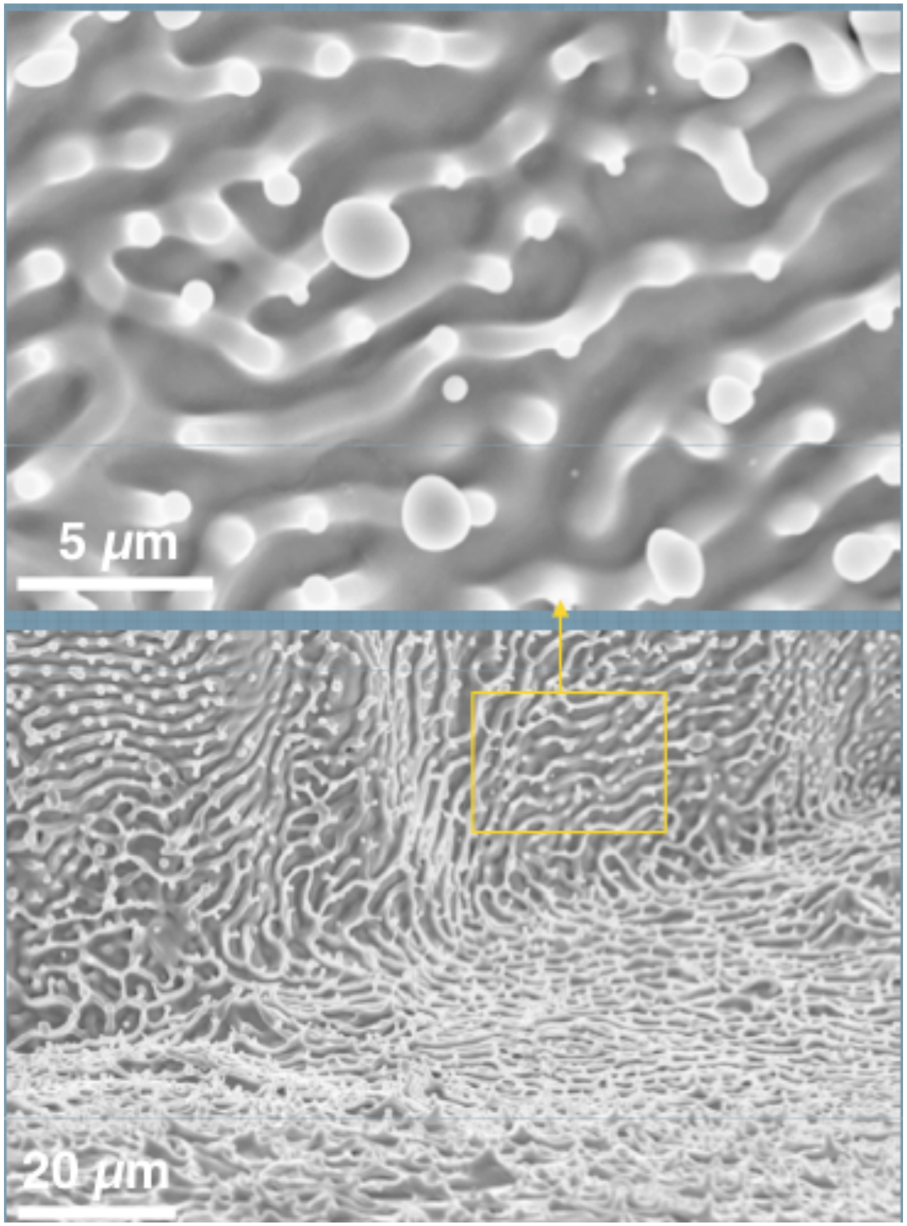
- The surface electric field defines the plasma thru sputtering and field emission.
- Inertial confinement of ions and quasi-neutrality constrain its evolution.



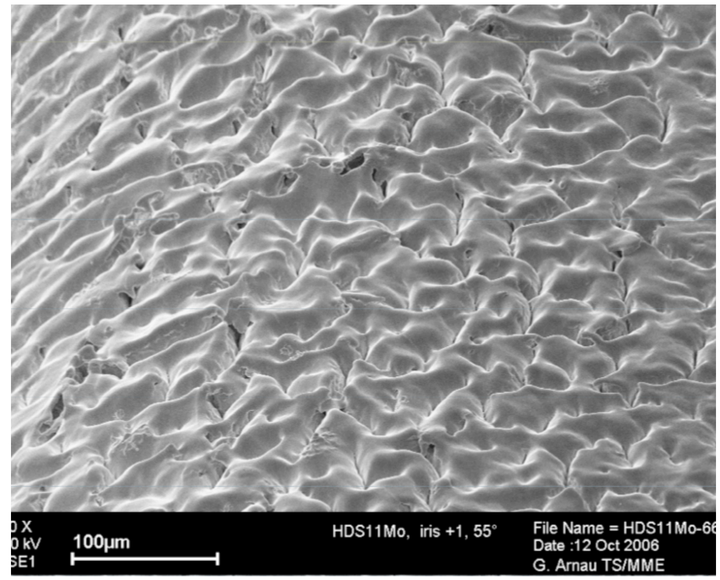
Strange patterns appear in arc damage

CERN X band structures (really highly damaged):

They have seen this,



but mostly they see this.

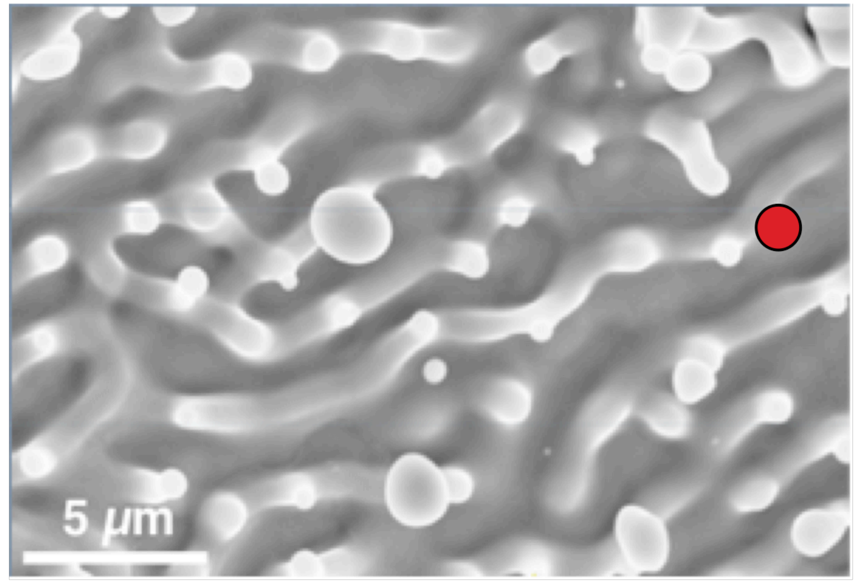


Spinodal decomposition

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

- Dimensions of structures imply $E_{surface} > 1$ GV/m, if $P_{surface\ tension} = P_{Electrostatic}$.
- bubble gives size where $E_{surface} = 1$ GV/m.
- This field is consistent with PIC code estimates, and newer images show similar effects.

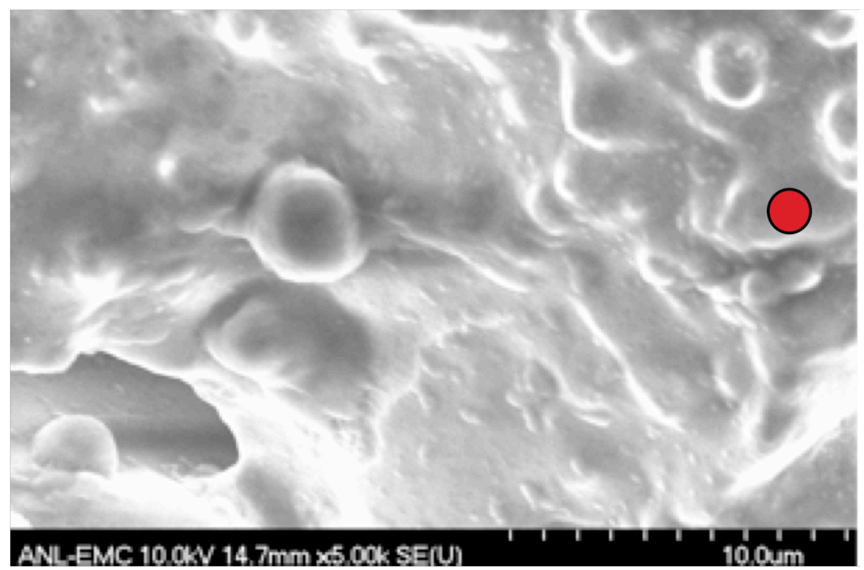
a)



- Top: CERN CLIC module

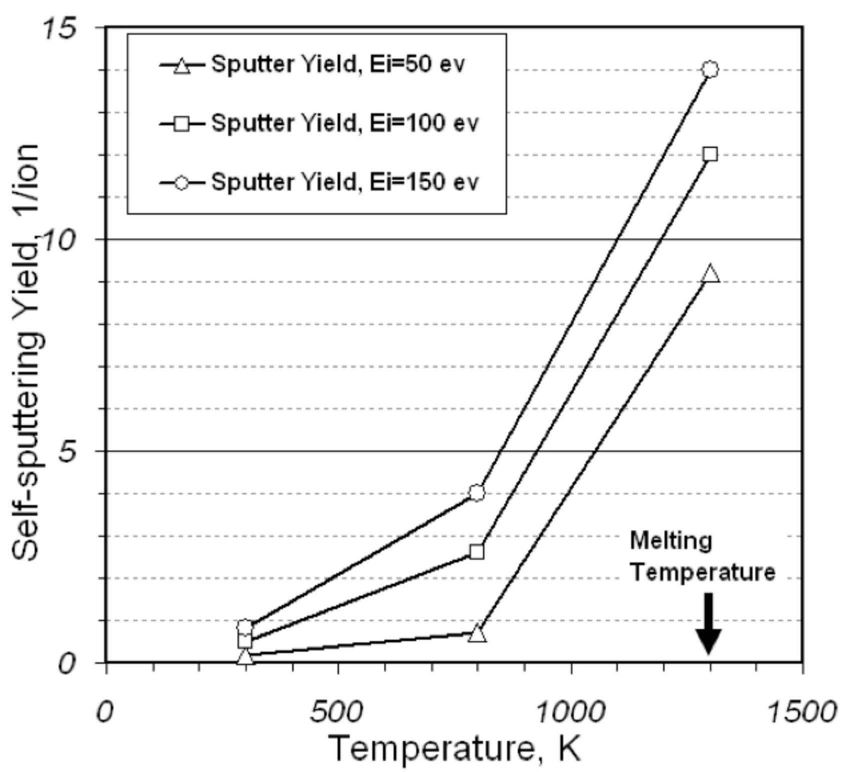
  Bottom: Pillbox arc

b)



High temperatures and fields increase self-sputtering.

- Self-sputtering rates determine surface erosion..
- We calculate self sputtering from molecular dynamics
- Very high rates.



Magnetic fields affect the arc.

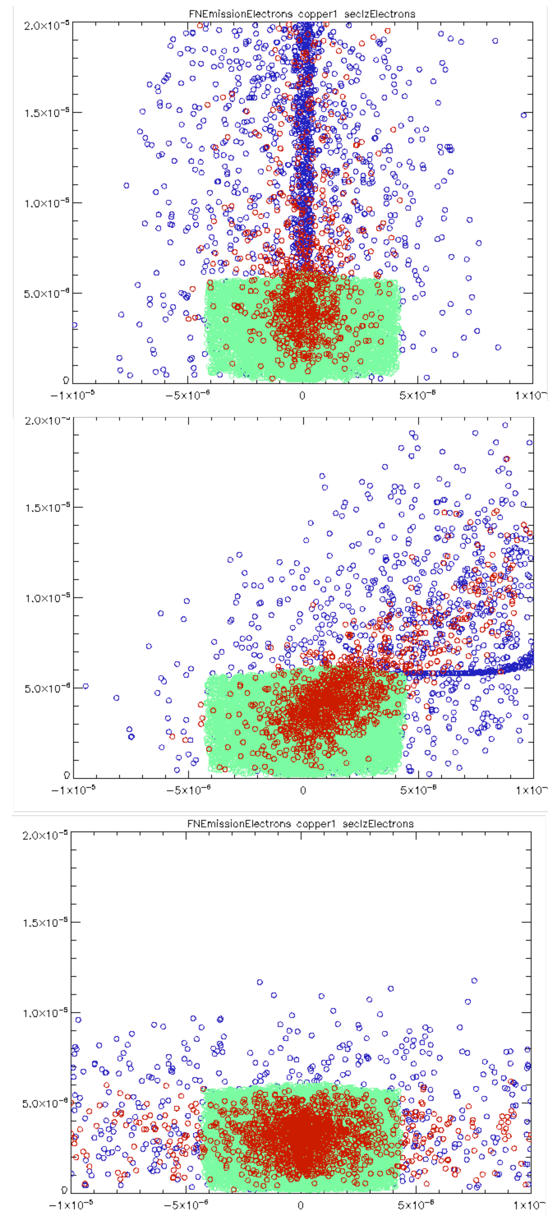
- The primary effect of the magnetic field seems to be confining the plasma.

- OOPIC shows this plasma confinement.

- New VORPAL data will show ExB effects

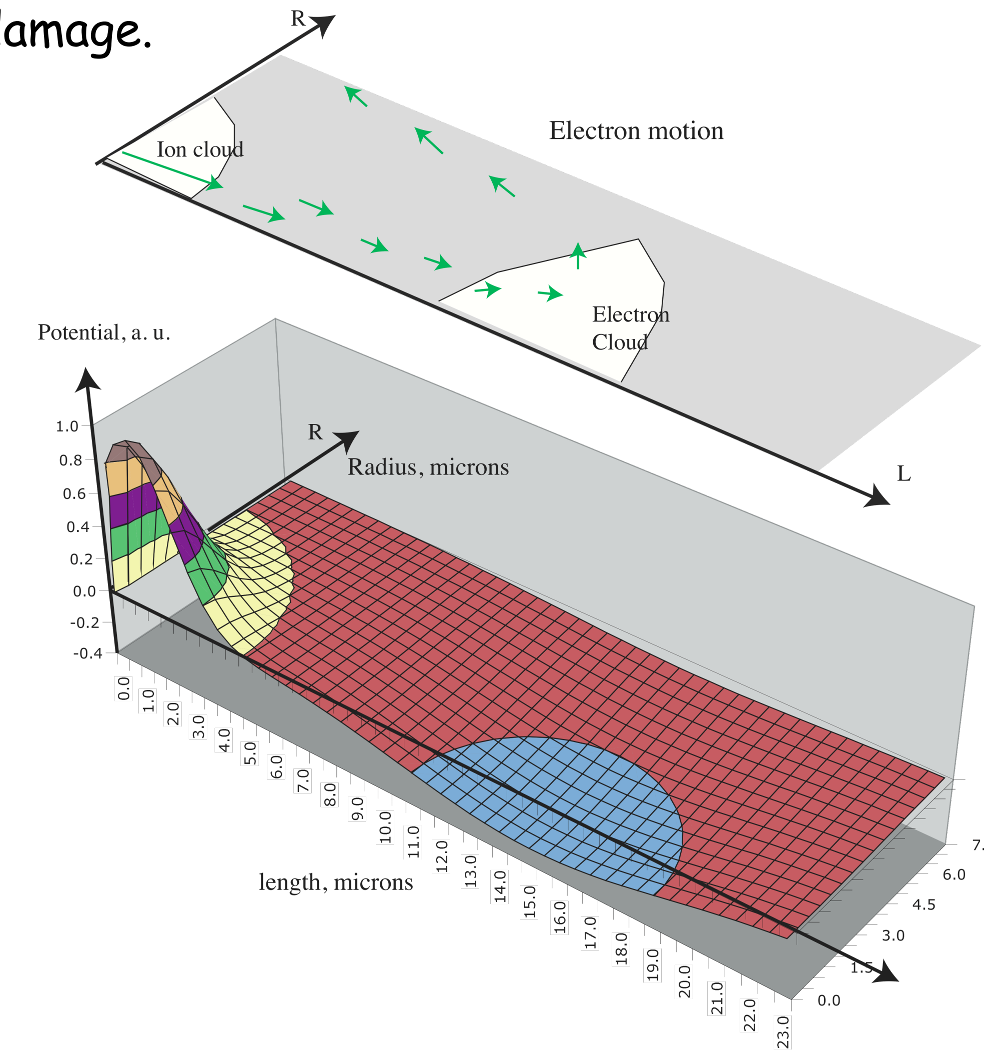
- First data:
  B parallel to E,
  B at 45 degrees
  B perpendicular to E.

  gas occupies the region shown in green.



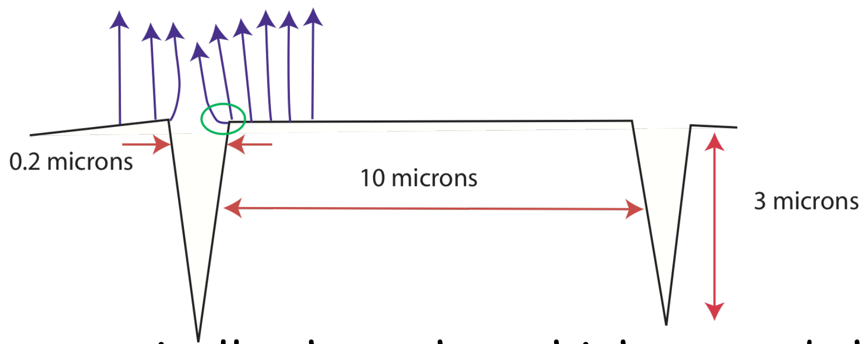
In tokamaks, unipolar arcs were studied 20 years ago.

- Lately, tokamak physics is moving in a different direction.
- These arcs seem to occur in non-Debye (very dense) plasmas.
  - Seen in laser ablation and other arcs.
  - Characteristic "chicken track" arc damage.
- Unipolar arcs are defined by:
  - Dense plasma
  - No Anode
  - Surface damage



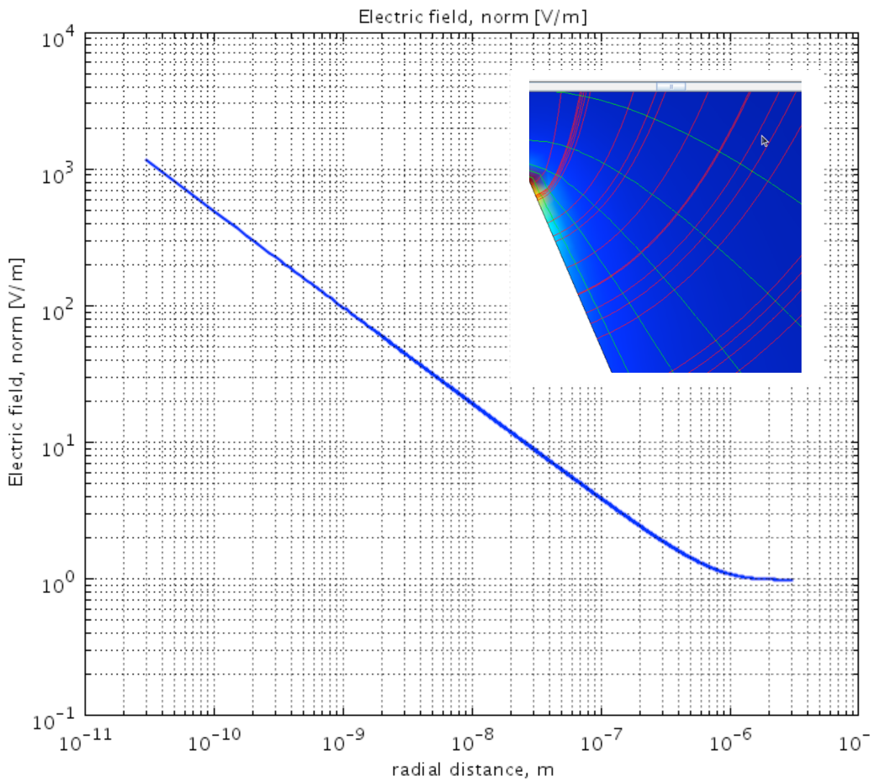
Cooling, cracks and β's:

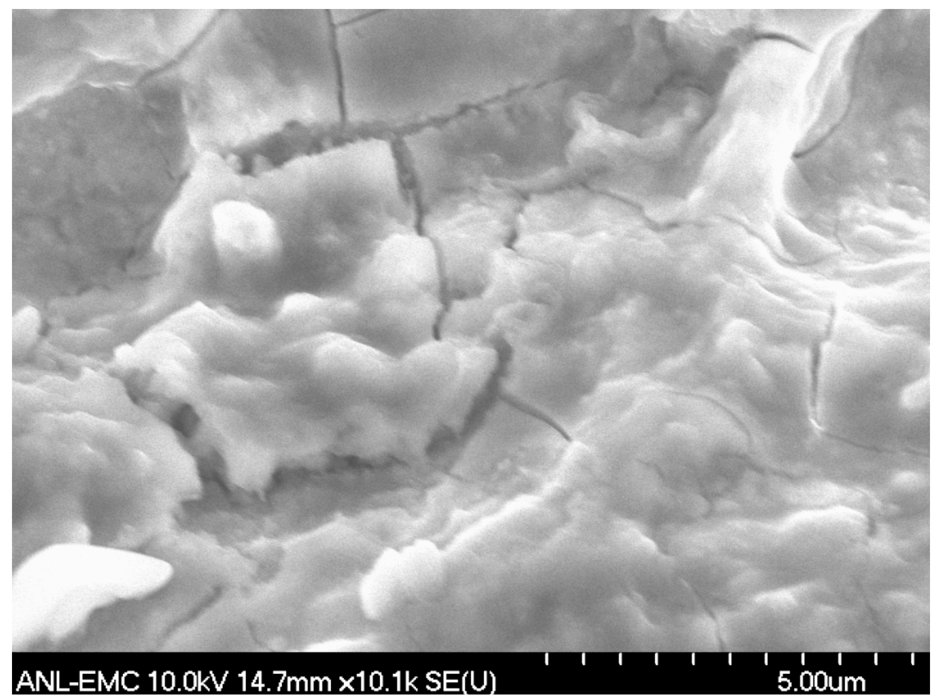
- Melted copper (~3 μm thick, at ~1000 degC) can cool and crack.
  Crack width: dx ~ $(17 \times 10^{-6}) * 1000 * x$ ~ 2% x, x = 10 μ => dx ~ 0.2 μ.



Can be modeled by a cone.

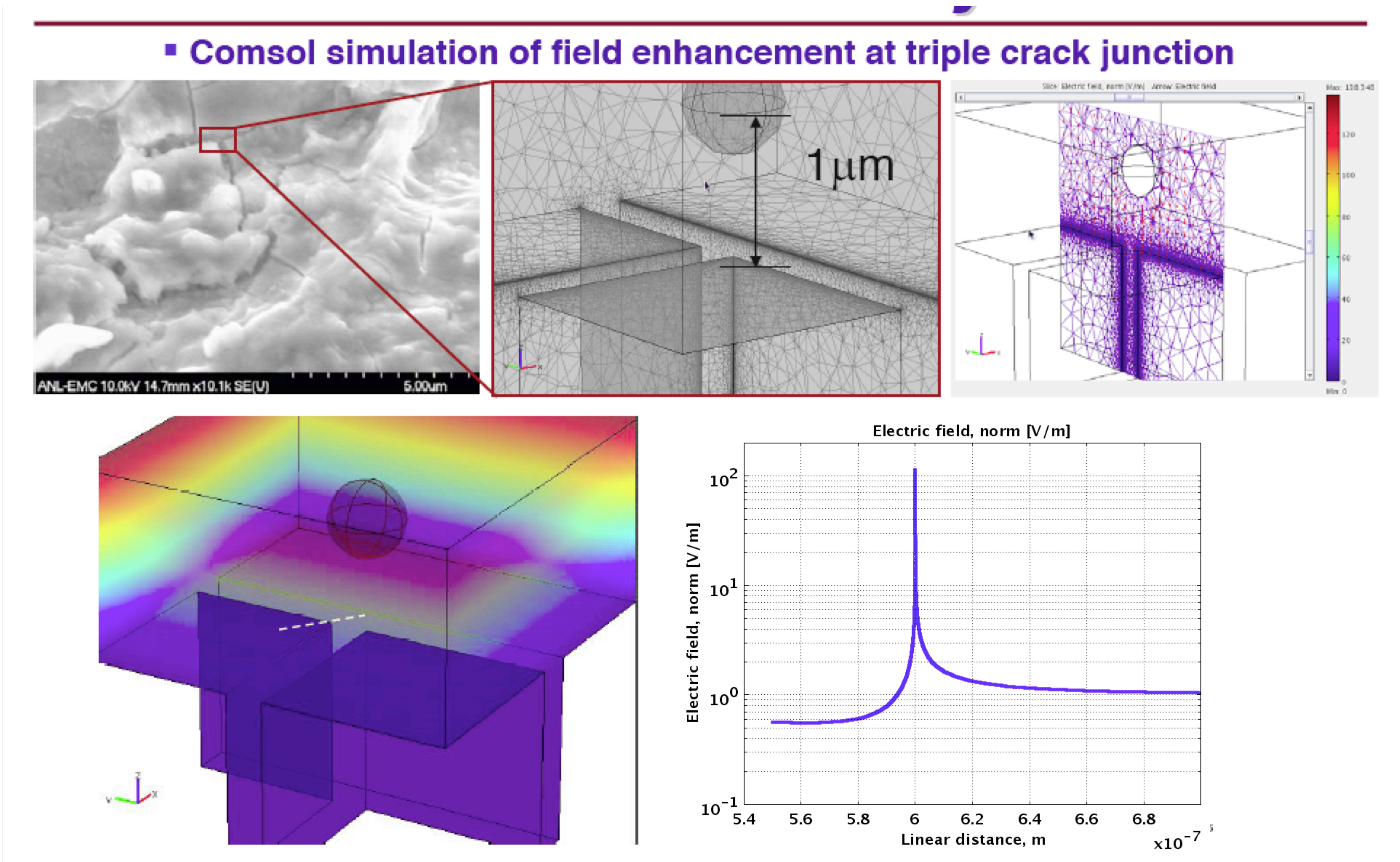
- Corners are atomically sharp, have high βs, and there are lots of them.





Modeling field enhancements.

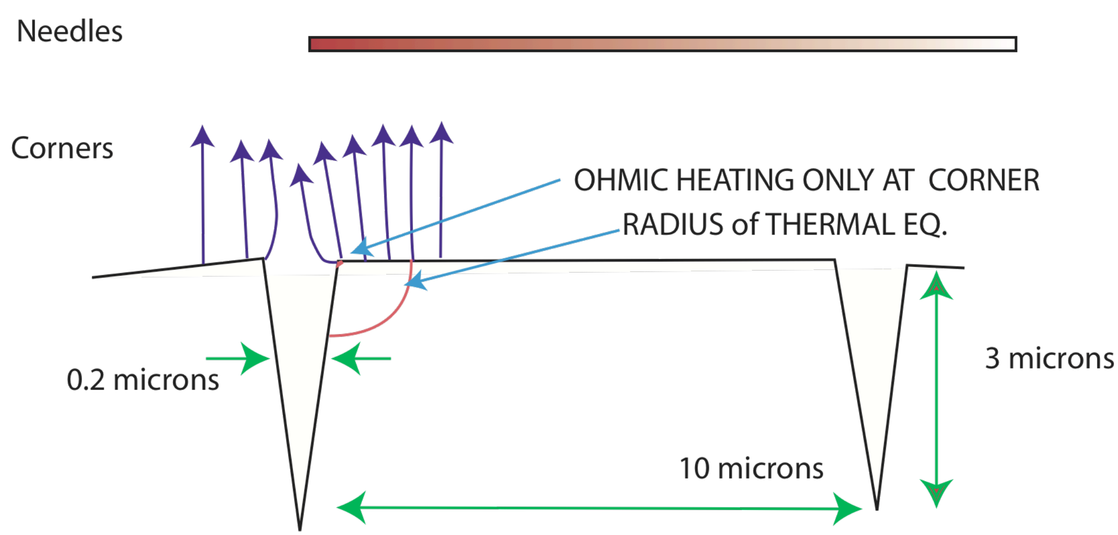
- We have been modeling, cracks, junctions, edges and other shapes.



Ohmic heating

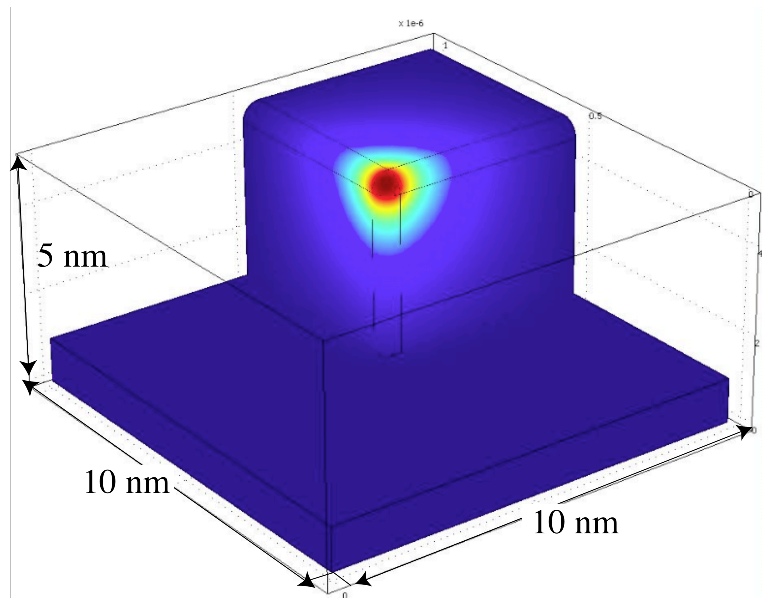
- Needles can Ohmically heat up, corners don't.

- In the corners described above, heating occurs only within a few nm of the tip, and thermal diffusion lengths are:
  $(Dt)^{0.5} \sim (1E\text{-}4 * 1 \text{ ns})^{0.5}$
  $\sim 0.3\ \mu\text{m}$



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

- Tiny corners cool off in a few × 10^{-14} sec.



Simple conclusions from modeling:

- Electric fields cause breakdown,
- Electric fields drive the arc.
- The surface geometry matters, at least initially.
- Material and plasma properties enter in complicated ways.
-

We find that we disagree with people, but not data.

- Fowler's interpretation of Fowler-Nordheim.
  Fowler: Calculating the slope of the line $\ln(I/E^2)$ vs $(1/E)$ gives β (irrelevant ?)
  Us: Calculate E_{local} directly from I or Rad ~ E^n (fundamental)

- Exploding wires:
  All assume that "whiskers" overheat and produce plasmas.
  These models include a variety of partisans,
  The current favorite is the Explosive Electron Emission (EEE) or Ecton model.
  However:
  No one has ever seen a whisker, either in rf or lab arc expts (~ one exception ?)

- Initially clean cavities
  Cavities eventually reach an equilibrium that does not depend on the initial state.

- Pulse heating

  It has been shown that high skin currents can affect cavity walls.

  Damage away from the iris can be due to arcing at joints.

- Reactive power

  This model assumes the existence of whiskers, significant B_{rf} near the iris and whisker dimensions > skin depth.

- High pressure RF

  In June '04 I argued that high-pressure hydrogen would not retard arcing.

  Loading by high energy (>1keV) δ's and low energy electrons are problems.

- Magnetic insulation

  Our highest surface gradients were reached with B ~ 4 T.

  $E \perp B$ seems to make arcs hotter, and burn longer,

  No improvement in gradient.

- Be (and other metals)

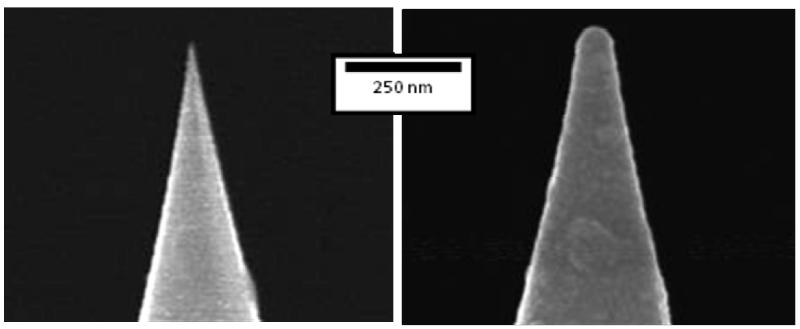
  We have already tested Be vs. Cu and found them to be equal.

  There are a lot of other metals to be tested.

Can we make "breakdown-proof" NCRF cavities?

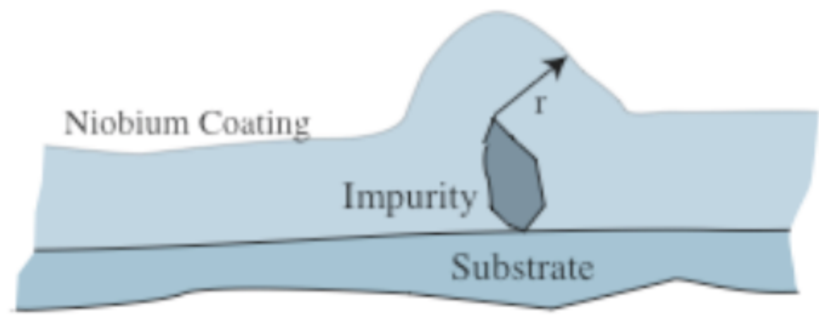
All our experimental data implies breakdown sites are <30 nm asperities.
Since $E \sim 1/r$, can we bury breakdown sites and lower local fields ?

We have shown that we can round tips
Using ALD. We need to do it in-situ.



Uncoated Si AFM tip

After 5 nm ALD ZrO_2
+ 30 nm ALD Pt



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ALD can be done in the Fermilab MuCool Test Area (MTA)

Procedure:

Condition cavity normally to whatever limit it goes to.

Coat with ~100 nm of metal to bury active asperities.

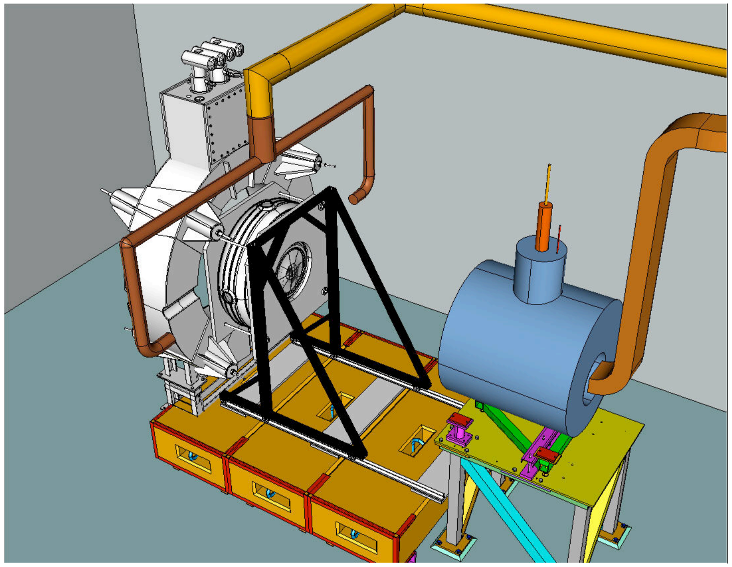
Retest with and without magnetic field.

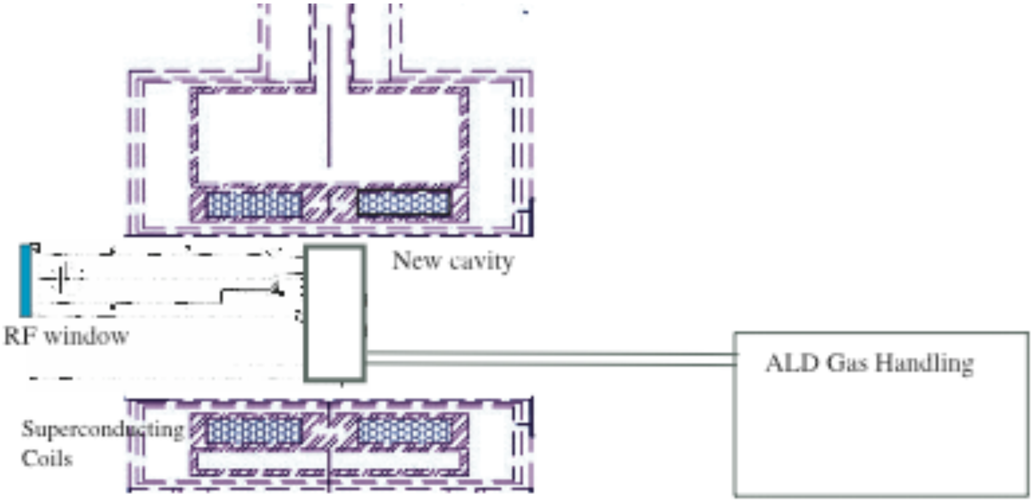
Must be done in-situ to avoid particulate contamination.

Coating of windows may be a problem, and we are developing solutions.

Particle free valves which can protect the windows.

Cooling the window can prevent measurable deposition. Needs testing.

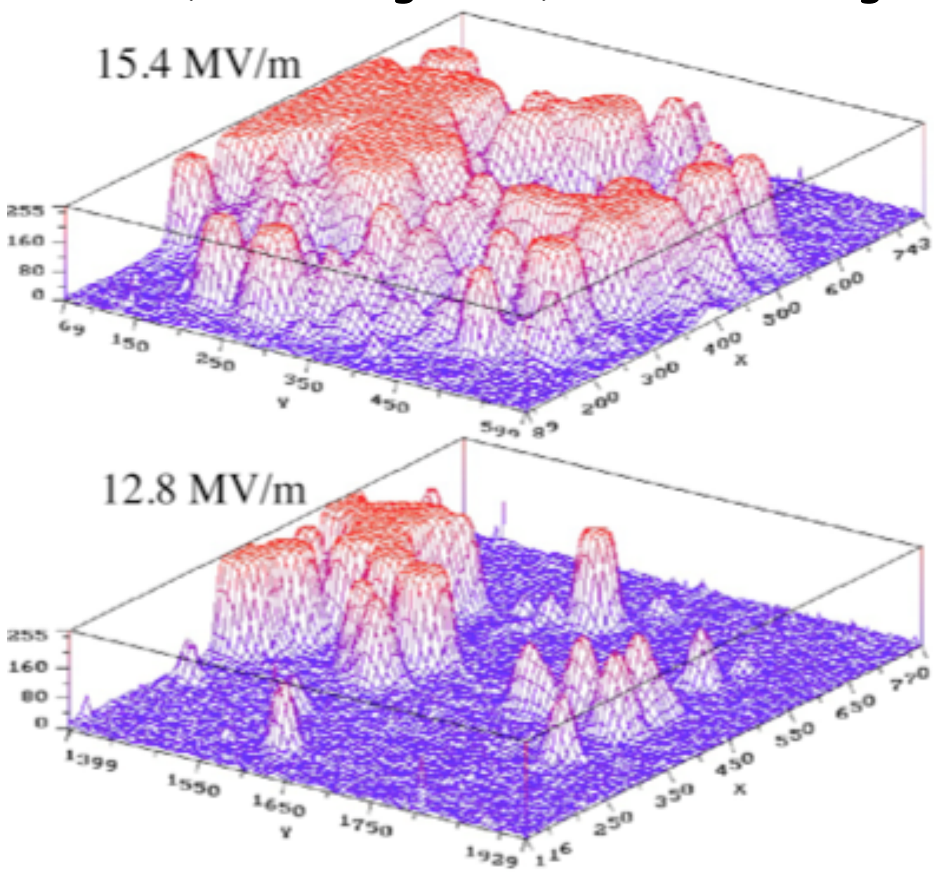




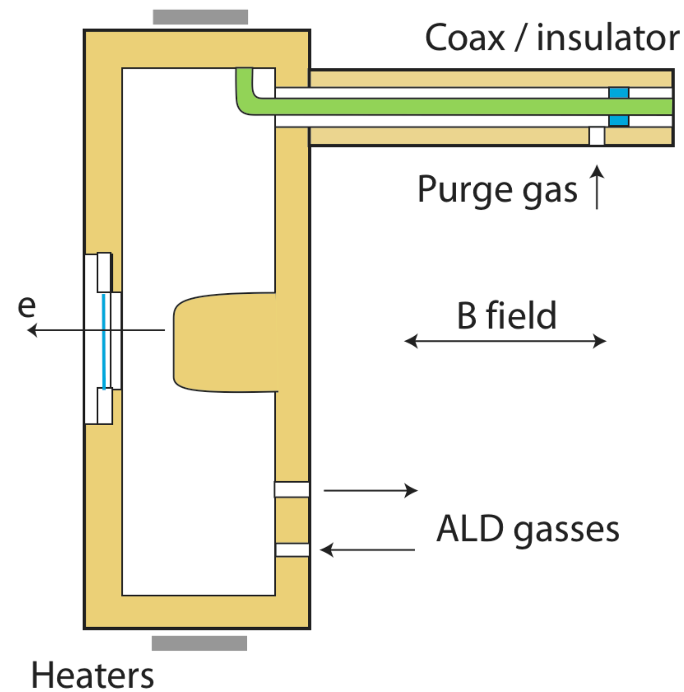
Test of "Breakdown-Proof" Cavities

- 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.

- 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



Summary

We have a consistent model of vacuum arcs.

It seems simple and general,

. . . and compatible with all the data.

We disagree with the conventional wisdom in many ways.

ALD should have a high status.