# Modeling RF Breakdown

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Relying Heavily On;
experimental data from the Muon Accelerator Program
modeling done by Veitzer/Mahalingam & I. Morozov

MeVArc2017 Workshop, Jerusalem
3/23/17

# Outline:

We are trying to develop a generally applicable model.
Our work hasn't been widely presented.
Insepov is planning to continue.

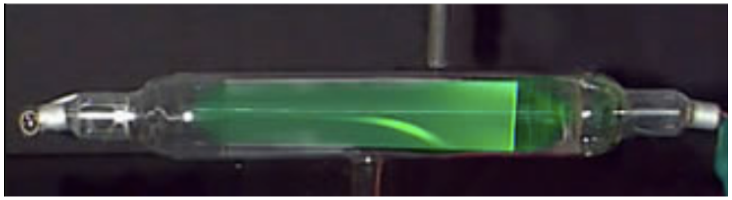
The talk:

History: What did we learn 1900 - 2000?
Our "Simple" model
Comparing and Contrasts
Conclusions:

# History

**1889** Paschen describes avalanche breakdown of gasses.

**1889** J. J. Thomson discovered the electron.



**1893** The first issues of Physical Review.

**1901** Vacuum breakdown discovered in Chicago. (Earhart, PhD Thesis)

**1904** Lord Kelvin explains vacuum breakdown

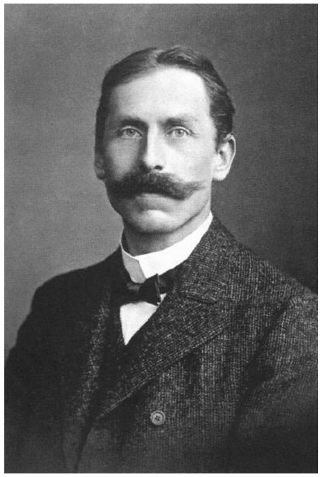
**1928** Fowler Nordheim describe field emission.

**1950** Dyke and coworkers study breakdown with W needles.

**1961** Alpert summary

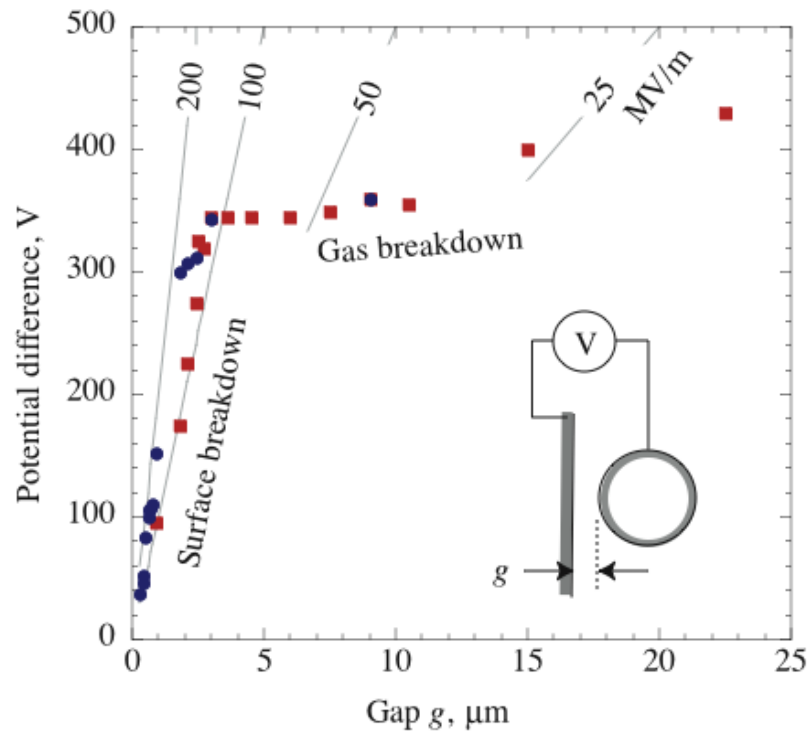
# 1901 Vacuum breakdown isolated - without vacuum pump.

Paschen, Millikan Michelson,



Discovery of vacuum breakdown

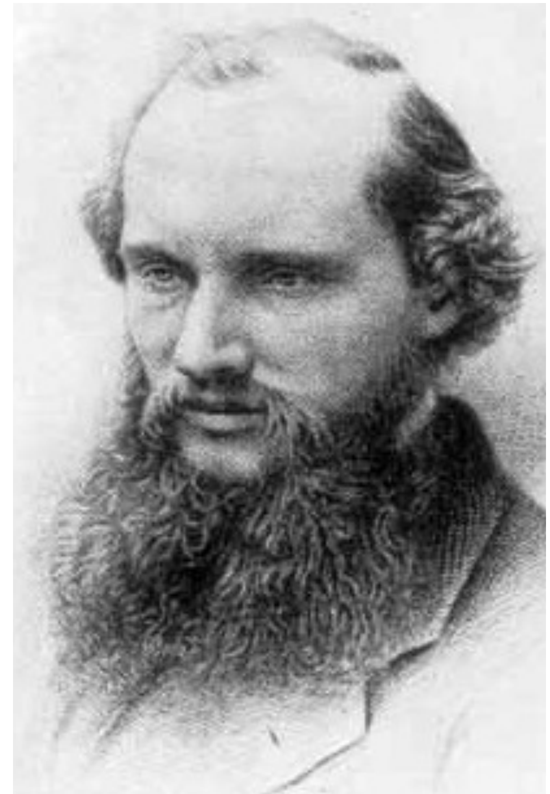
- They wanted to know small gap BD behavior.
- Mean free path for ionization is larger than gap.
- Breakdown occurs at very low voltages.
- BD occurs at ***E*** ~ 100 MV/m.
- It is dependent on electrode material.
- BD is independent of gas pressure or type.



# 1904 Lord Kelvin's estimate of $E_{local}$ from tensile strength.

Lord Kelvin argued that:

- Field emission is electrons (electrions),
- Electron emission may imply ion emission (damage),
- Tensile strength is an important parameter
  ~9.6 GV/m required to tear metals apart.
- Better experiments are needed.



out. But it may be true, and probably is true in many cases of the loss of resinous electricity from a solid, that the forces called into play may be great enough to tear away the atom, with or without its electrion or electrions, out of its place in the solid. This, however, would not contribute to the transference of electricity from the solid: in other words, Varley's torrent may contain non-electrified particles, or vitreously electrified particles, along with his negatively electrified particles which we now believe to be atoms of electricity.

## 1928 Fowler and Nordheim field emission published.

Although quantum mechanics was studied extensively, this was one of the first applications where the theory could be used to solve an otherwise insolvable problem.

## In '50's, Dyke and coworkers studied BD with W needles.

They were looking at failure of SEM sources at Linfield College in Oregon. Their data implied BD was caused by Joule heating in the needle/ fencepost/telephone pole/unicorn horn geometries.

Local fields are enhanced by geometrical factors,

$$E_{local} = \beta\, E_{acc}$$

Needles with high $\beta$s are **never** seen.

# 1961 Alpert: Vacuum BD required ~10 GV/m for all gaps.

The physics of BD triggers does not depend on the gap distance.

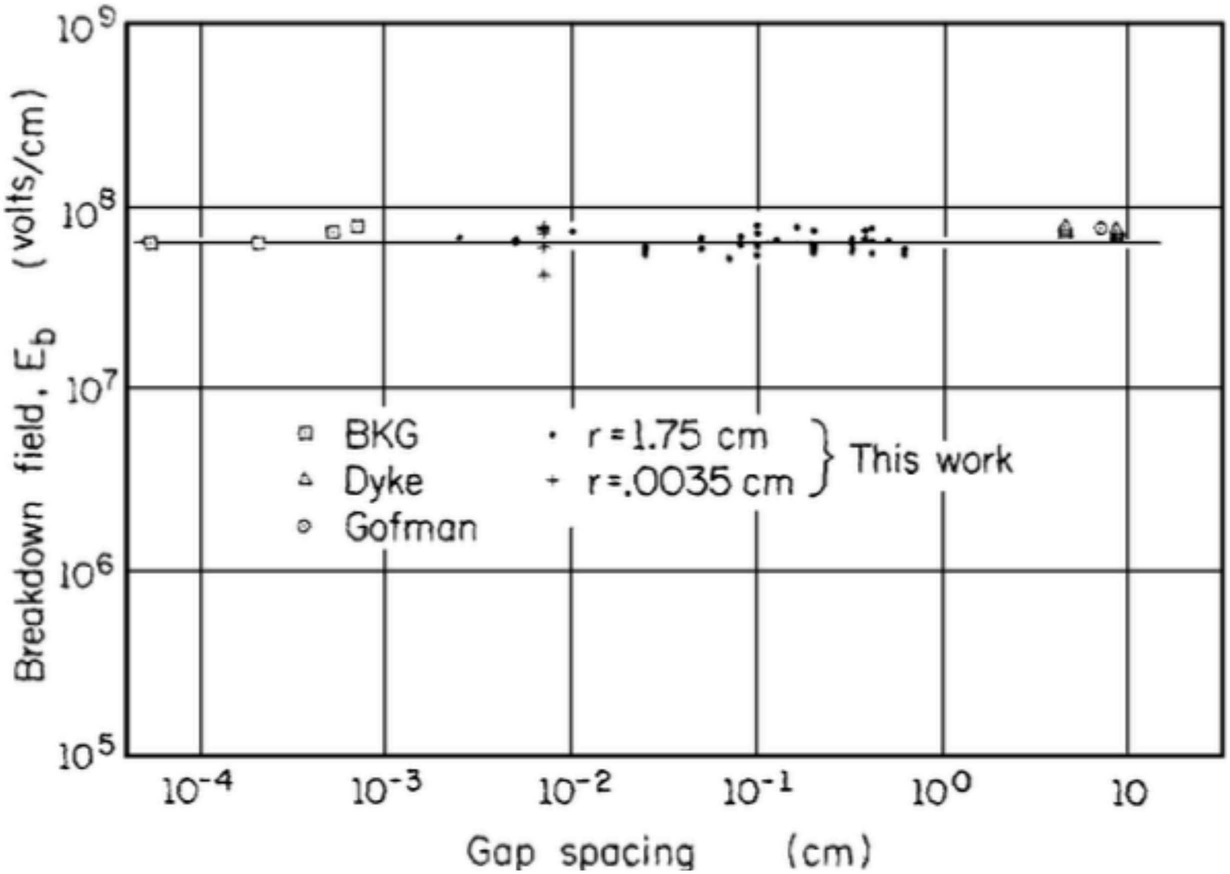



FIGURE 10. Breakdown field vs gap spacing. For each point, the breakdown field is the product of the breakdown voltage and the proportionality constant *K*, determined from the Fowler–Nordheim plot for prebreakdown current vs voltage.

# By 2001 this had not yet converged on a picture of arcs.

(even after 100 years)

"As will become clear in the following, the discussion on the physical nature and parameters of cathode spots is not yet settled. In the literature the theoretical treatment prevails, but many theories are built on unsafe experimental ground. In a competent paper, Ecker (1980) lists most of the uncertainties and uses inequalities instead of equations. This leads to possible *existence areas* in the parameter space. His example has not been followed by later authors, who give seemingly exact solutions, but remain contradictory in many aspects. The reason is the complexity of the spot and the extreme physical conditions (temperature, pressure, non-stationarity). Also, the interpretation of measurements is sometimes heavily disputed by the experimenters. Therefore, at present no model is generally accepted, and this review cannot avoid a personal view."

Juttner, 2001

# Why did this work not converge on a model?

There are many experimental problems:

Many parameters, rapid changes, wide (~$10^6$) ranges, small sizes

Many metals, power systems, gaps . . .

Wide variety of damage seen

Multidisciplinary

Experiments on micron-sized plasmas are difficult.

Some problems in explaining data

There are more variables than measurable parameters.

All stages have to be modeled to understand any one of them.

Setups are unique and hard to compare.

People were satisfied explaining their own data.

# Our effort: Can tracking chambers work near an rf cavity?

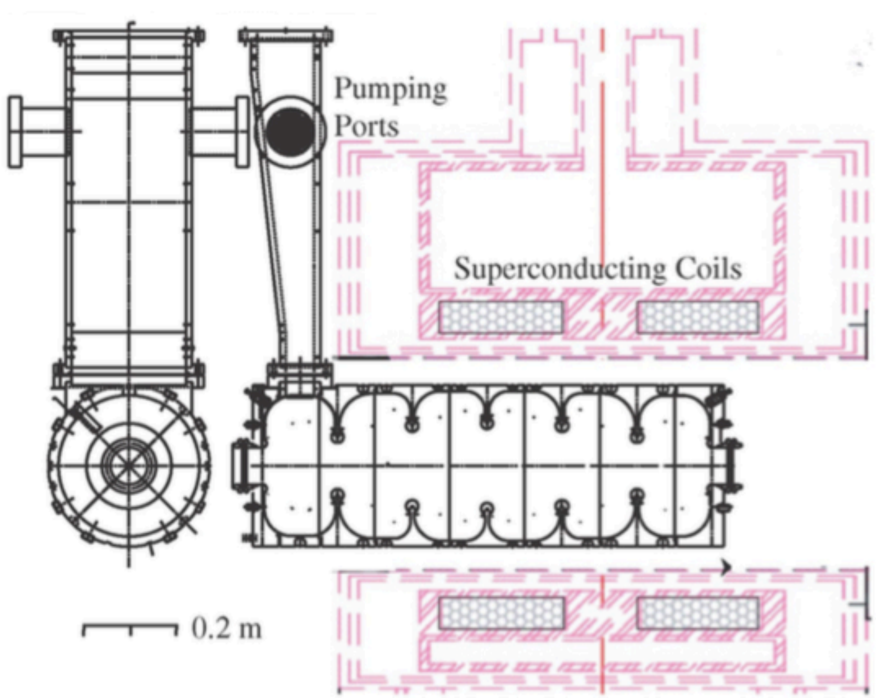
**2000** The design of the Muon Ionization Cooling Exp. was defined.

Could x-rays from rf cavities blind tracking chambers?

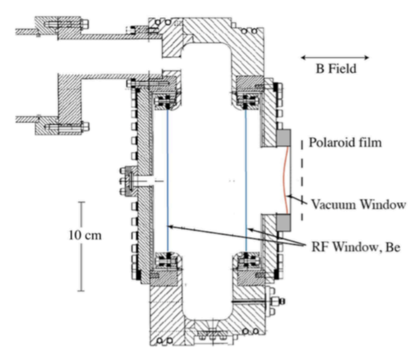
In 2001 an effort to understand the backgrounds was started.

We measured field emission and x rays from 805 and 201 MHz cavities.

the open cell cavity in the SC magnet

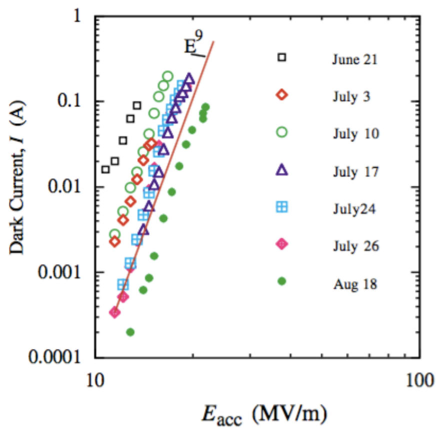



the pillbox cavity



# We measured xrays, FE and BD in rf cavities:

Field Emission currents under many conditions, including.




Conditioning

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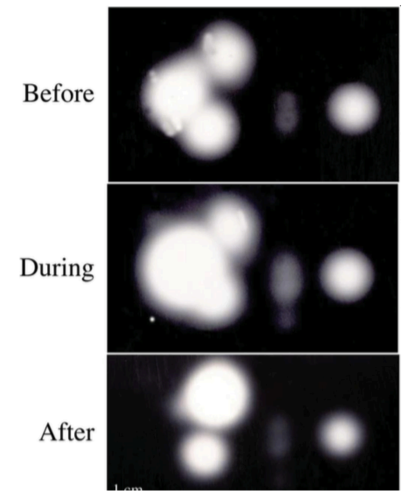
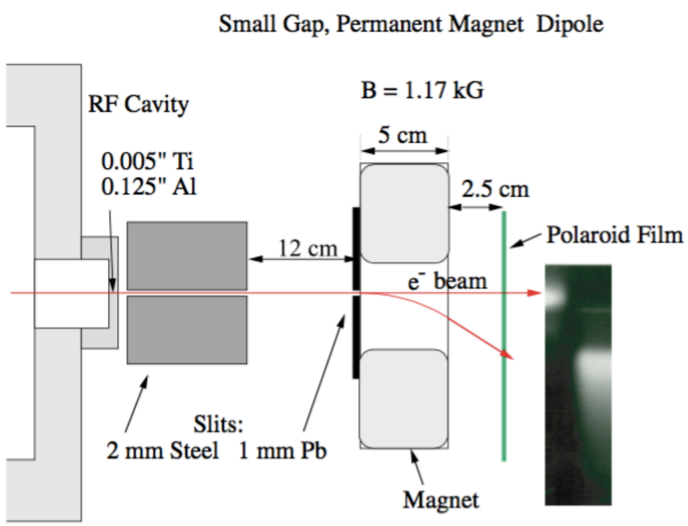
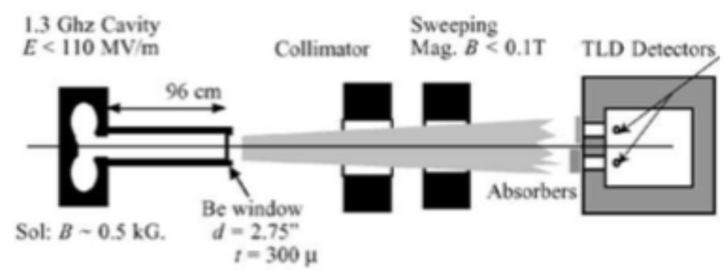
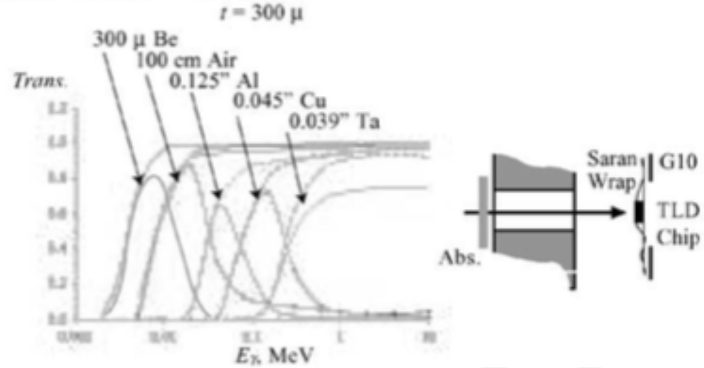
Breakdown




Energy spectrum of e's and $\gamma$'s.

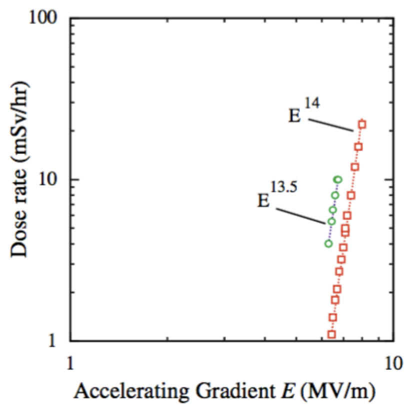


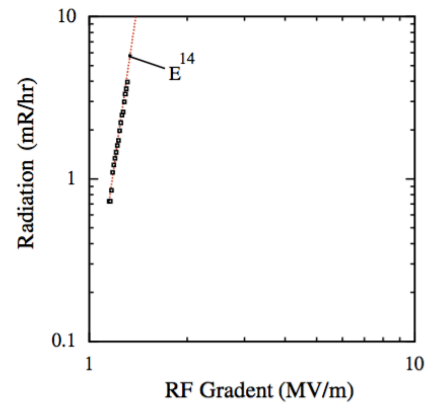



X ray fluxes and angles at a number of linacs.

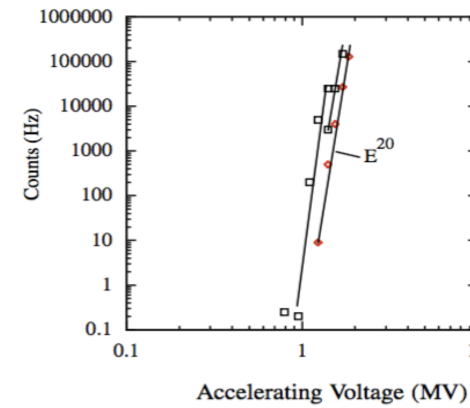
ISIS



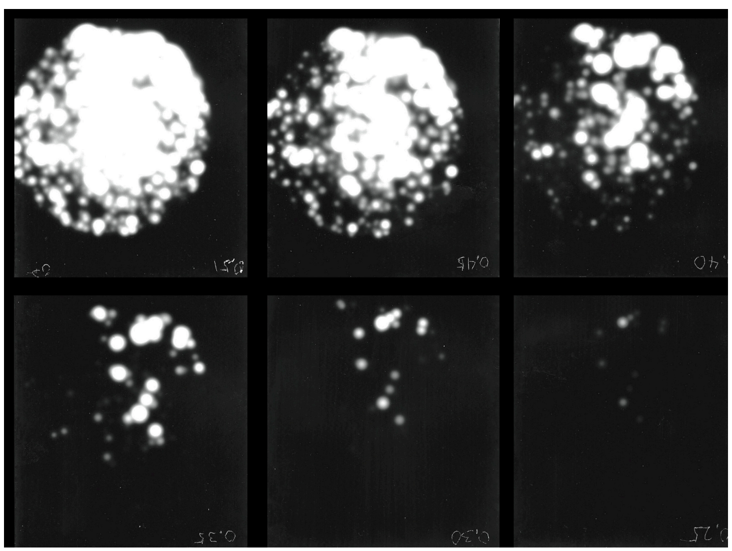

IPNS

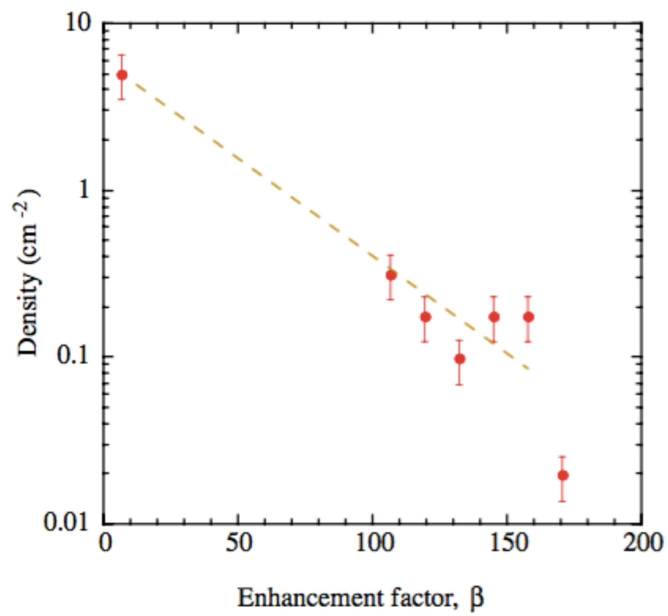



CESR




Enhancement factors and their spectrum, $n_\beta(\beta,t)$ / $n_{damage}$.



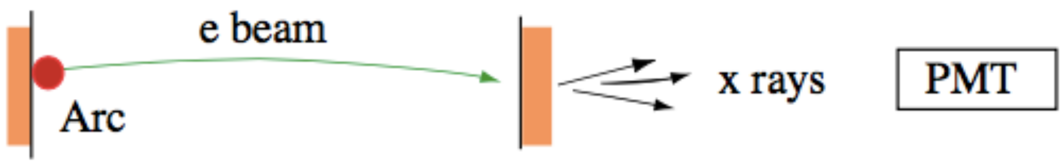


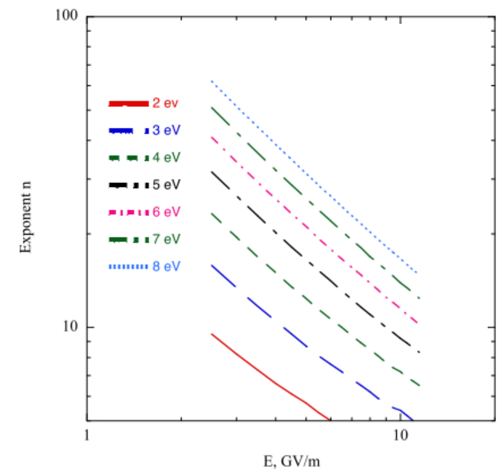

etc. . .

.,

# . . . . with the conclusions:

If B~0, arcs are asymmetric, with local plasma, and shorting current.




Local fields can be calculated from $n$, where

$$I_{FE} \sim E^n.$$

Breakdown is due to Coulomb explosions at ~10 GV/m.

Breakdown seems to be a one surface phenomenon.

Our ~ 1 m long cavity couldn't communicate with the other end.

Polaroid pictures showed single surface BD.

Field enhancements are real.

We see in SEM images what we measured with field emission.

Individual experiments/setups cannot sufficiently constrain models.

Field emitters seemed to be very small.

Local fields ~ 10 GV/m seemed to be present in all BD events.

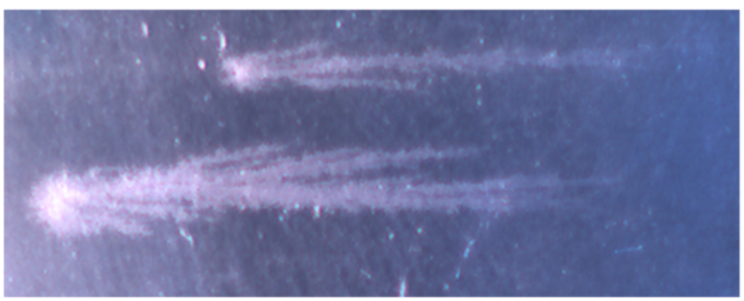
Tensile strength and electromigration explained everything

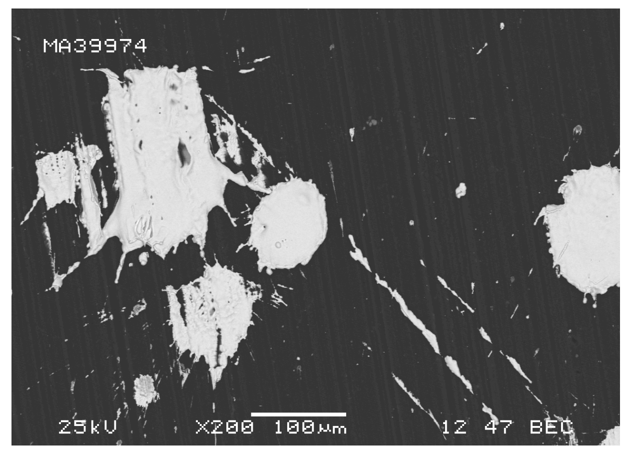
10 GV/m ~ Tensile strength of copper.

Both the plasma and the shorting current (with hi B) could damage surfaces.

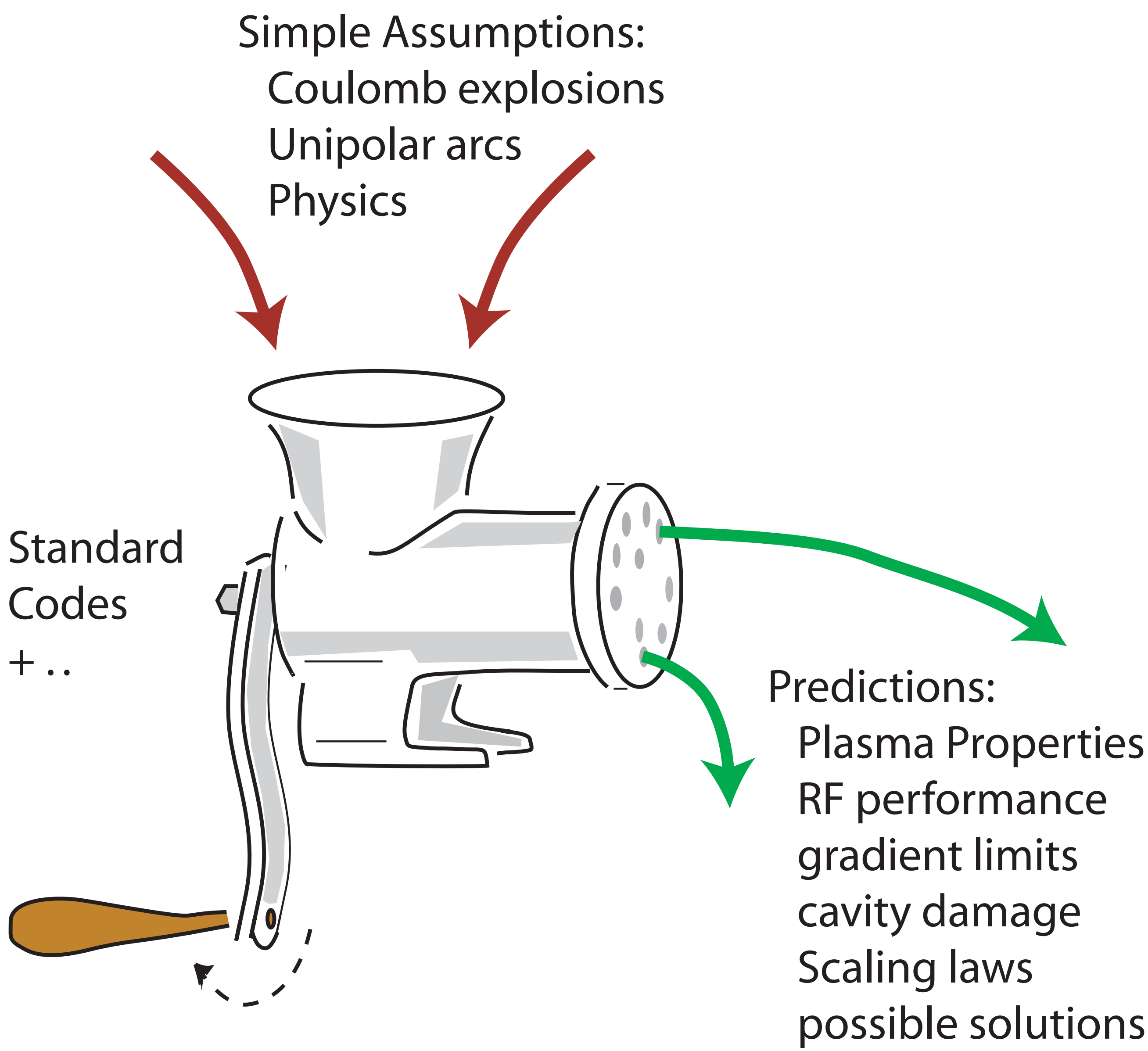
In magnetic fields the arcs can be symmetric.

Damage depends on the plasma properties.    (some strange ones)





# A Model is Basically a Set of Assumptions.



# Our simple model seeks to explain all the data.

The model must consist of four stages and must be internally consistent, experimentally accessible, and very generally applicable:

**Surface failure**:

**What triggers BD?** What are the fields, areas current densities ? What kind of damage sites are required?

**Plasma initiation**:

**How is a plasma formed?** What conditions are required? What are the growth times, densities, etc.?

**Plasma evolution**:

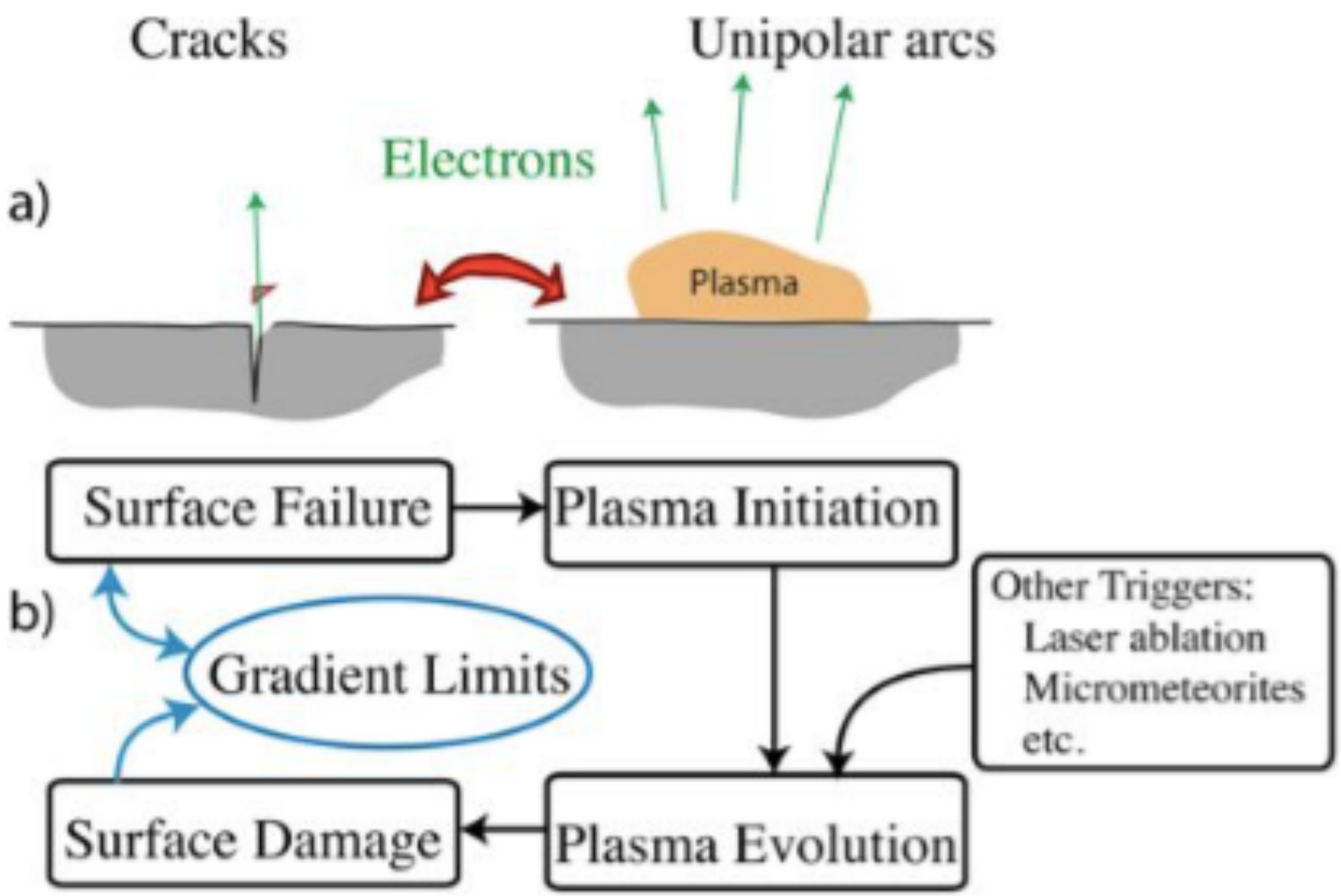
**What are the properties of the plasma?** What fuels, quenches it? What damage will it produce?

**Surface damage**:

**How do plasmas damage surfaces?** Hydrodynamics/thermal modeling, electrostatic, plasma pressure, surf tension interactions

The model should be able to generate all experimental properties.

# Four stages and two ideas define our model.




Insepov and Norem, J. Vac. Sci. Technol. A **31** 1302 (2013)

# Surface failure

Asperities fail if E ~ 10 GV/m, $j \sim 10^{11}$ A/m$^2$:

Electrostatic stress ~ tensile strength

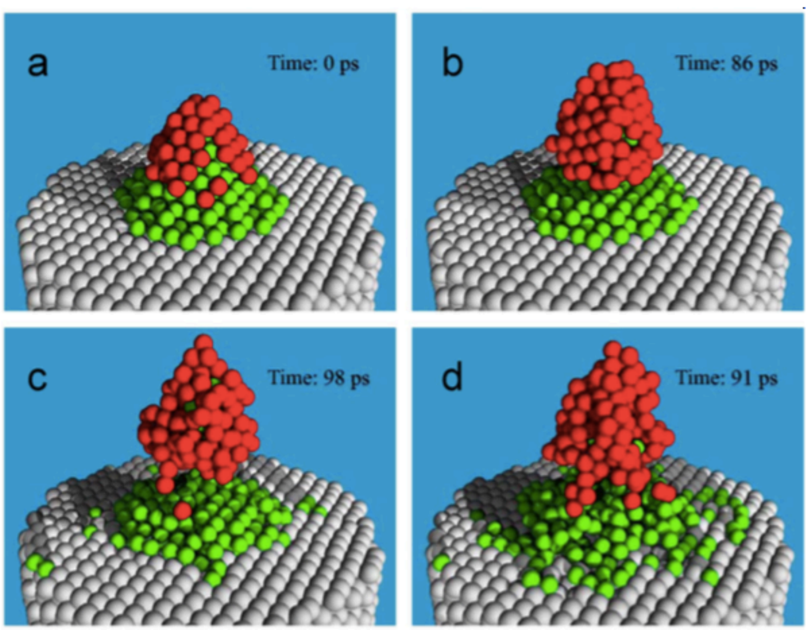
Electromigration sharpens asperities.

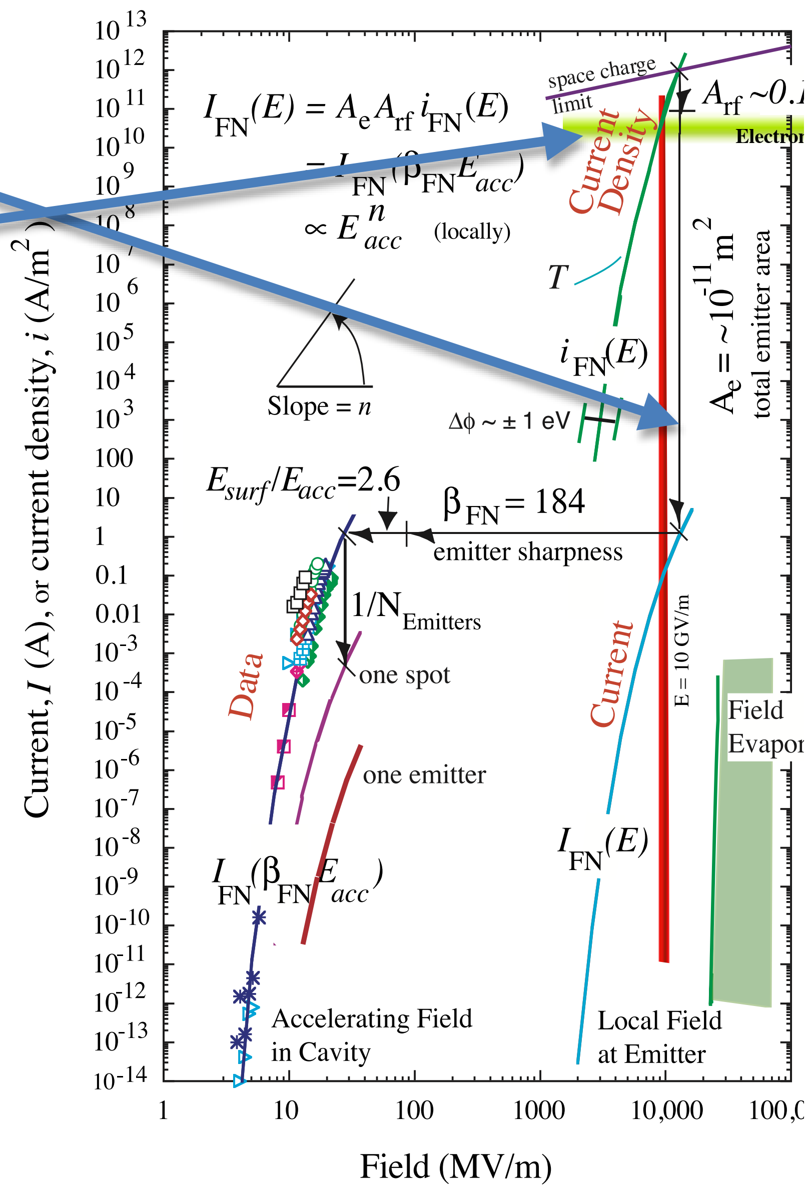
Electromigration was suggested by

C. Antoine, F. Peauger, and F. Le Pimpec

MD modeled asperity breakup.

Heating not necessary.



# Plasma Initiation

( + S. Veitzer, S. Mahalingam: Tech-X)

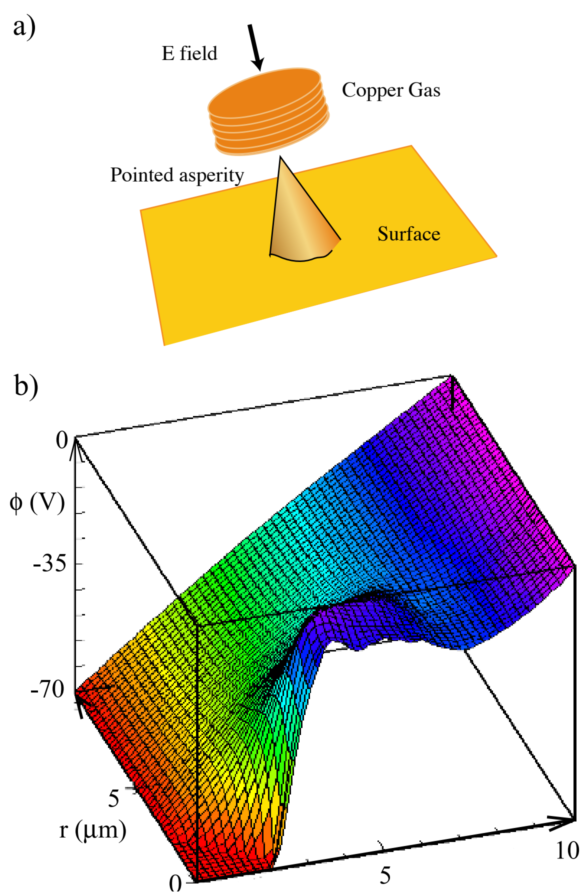
The region above the asperity contains ions, neutrals and FE electrons.

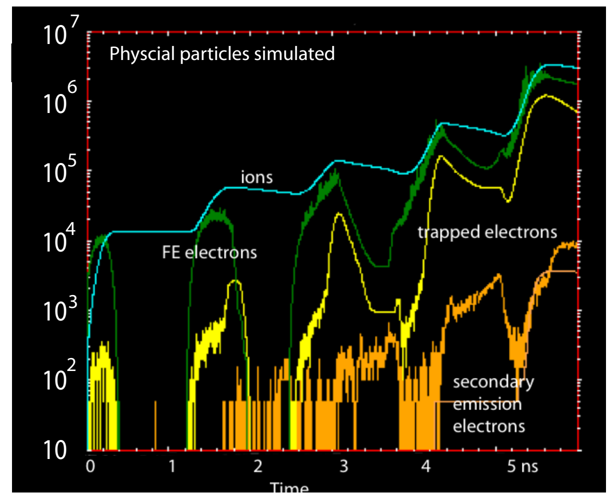
OOPIC Pro: FE electrons ionize the neutrals, with electrons swept away.

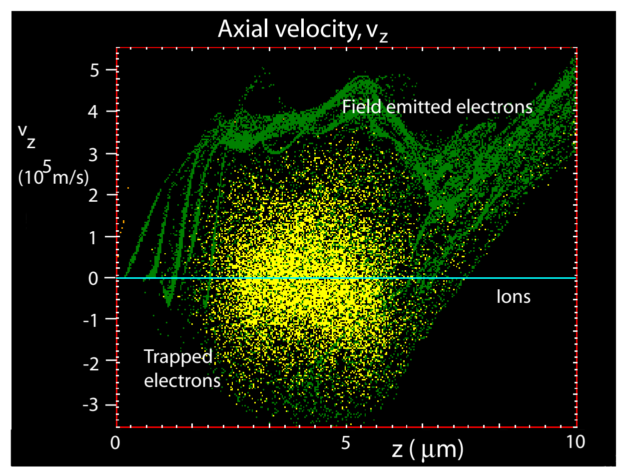
The remaining ions increase the field on the asperity, increasing FE.

the geometry

the potential



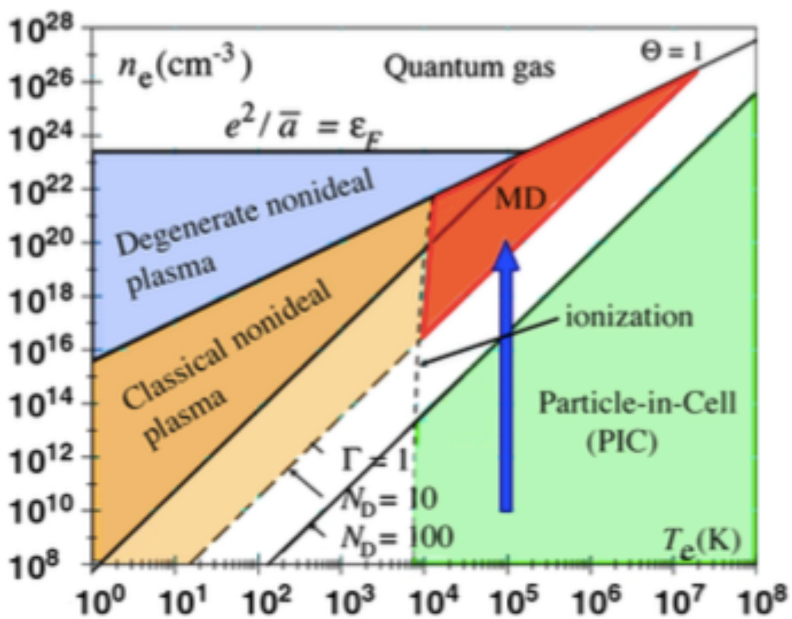
# Plasma Evolution

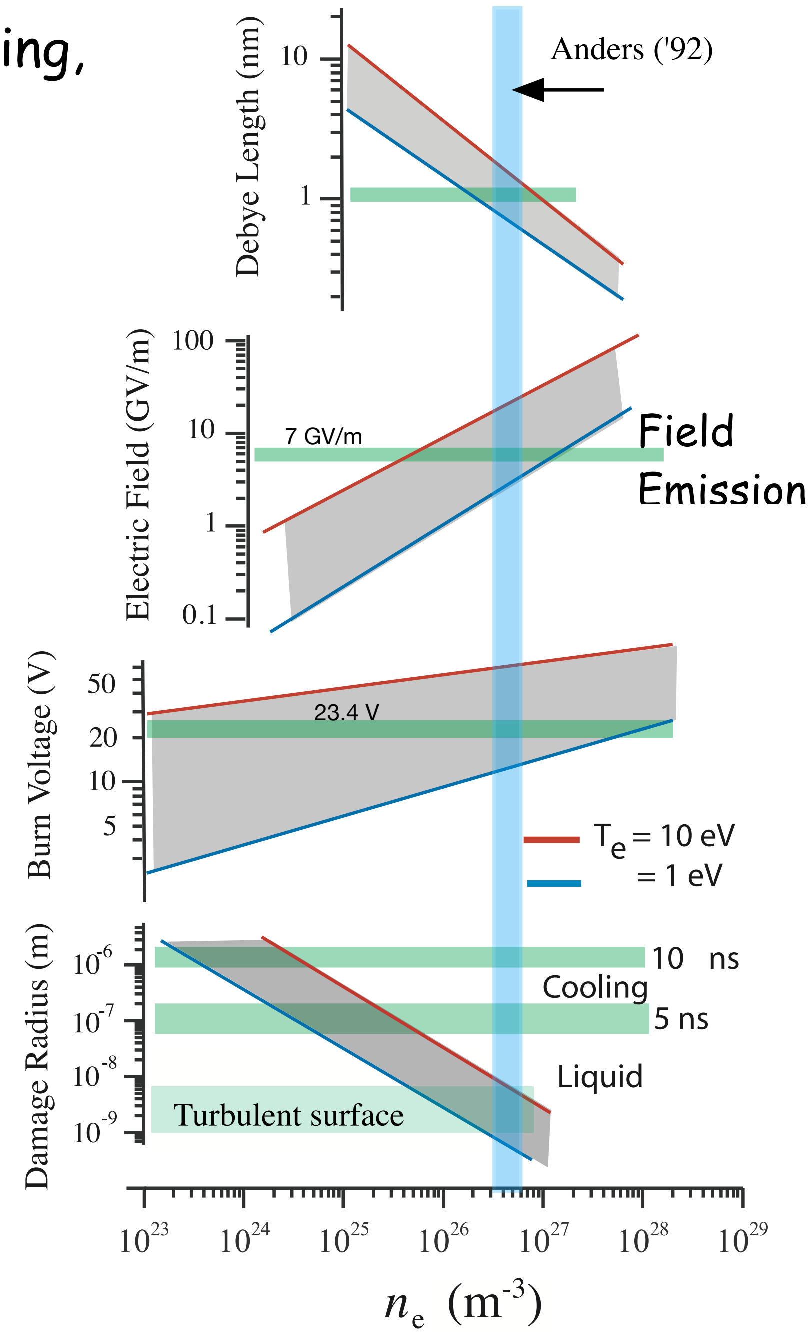
( + I. Morozov)

The plasma sheath drives FE & self sputtering, melts the surface & fuels the plasma.

Fowler Nordheim emission produces the currents that short the gap/cavity.

We looked at the properties of the sheath with Molecular Dynamics.

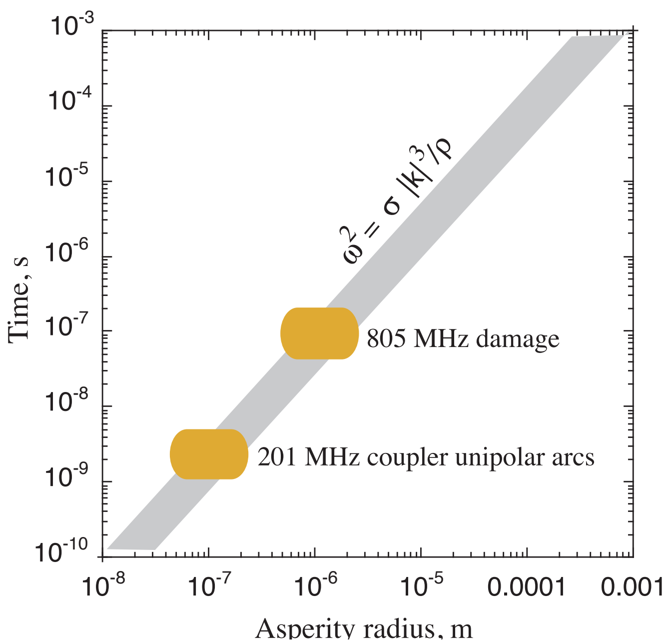


# Surface Damage

The plasma pressure + E field produces a turbulent liquid metal surface.

The damped capillary wave equation governs how the surface relaxes.




The liquid surface freezes from the outside, contracting as it cools.

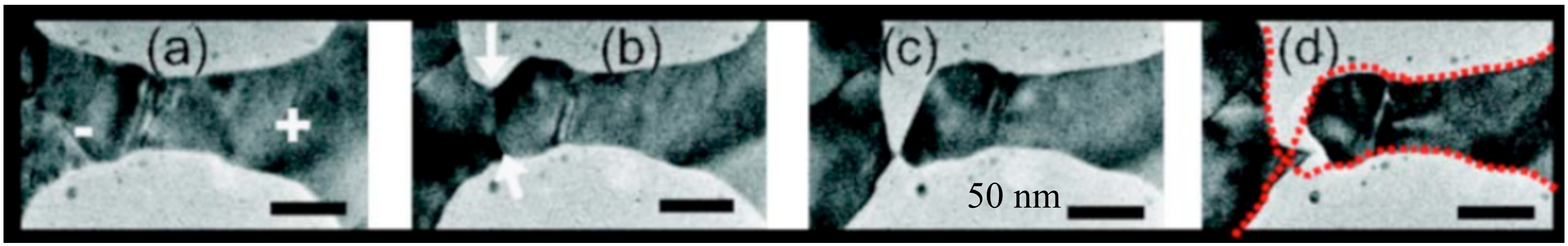
Cracks can form near the center, as the thermal contraction is localized, high $\beta$s are produced.

# Electromigration has been studied in circuit failure analysis.

Electromigration occurs at lower current densities than melting.

Electromigration damage **<u>was</u>** a common cause of circuit failures.

Hard to model, but a video shows the real thing *!*




YouTube video:  search "Delft gold electromigration"
and described in Heersche *et al*,   Appl. Phys. Lett. **91**, 072107 (2007).

Problems occur for current densities > $3 \times 10^{10}$ $A/m^2$, within the range of Fowler-Nordheim emission.

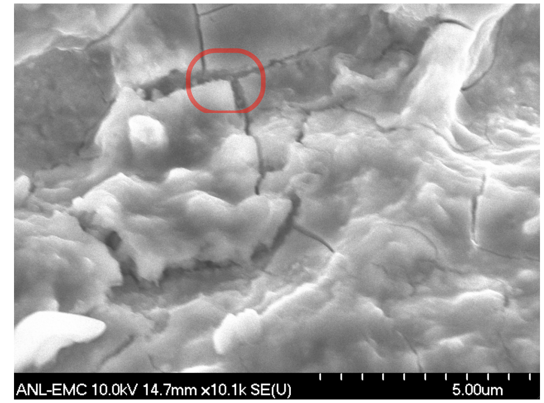
# High field enhancements come from crack junctions.

Cracks form when solid surfaces cool.

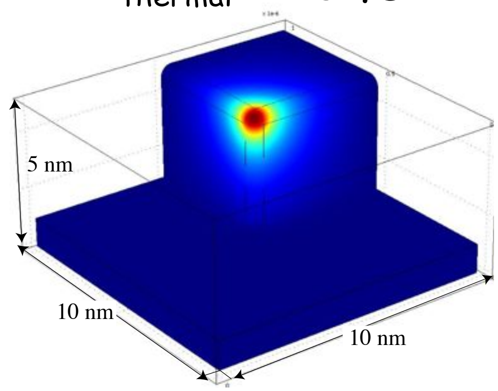
Two stages of cracking produce ~90 deg cracks.

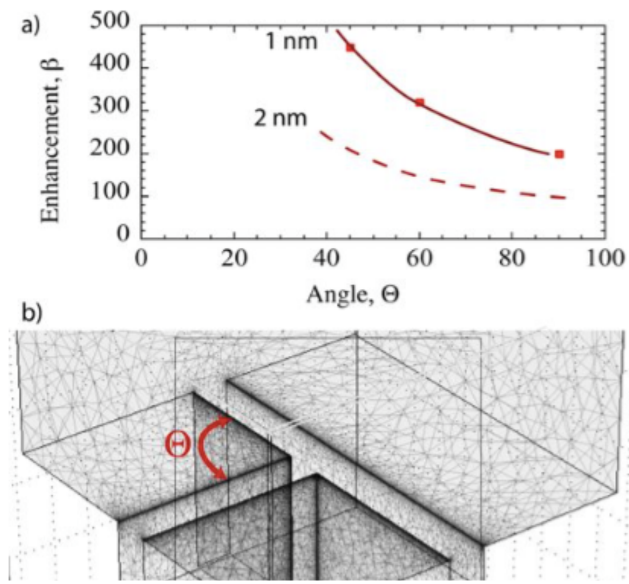
Any sharp points can produce high $\beta$s.

a)




$\tau_{thermal}$ ~ 10 fs



# Unipolar Arcs

Described by A. E. Robson and P. C. Thonemann, in 1959.

Important in tokamak studies 1970 – 1990, before divertors.

Anders and Juttner also studied these arcs ~1990.

The plasma and plasma/wall properties are determined by the sheath.

We have shown that the sheath can fuel, maintain and quench the plasma.

FE explains shorting currents.

The parameters of the nonideal plasma must be determined from MD.

MD shows however, that nonideal corrections are small.

# How does our model compare with other work?

Local electric field ~ 1/radius of curvature (Feynman Lectures)

The “Fowler-Nordheim plot”, $\ln(I/E^2)$ vs $1/E$, is unnecessarily confusing.

The common reference books do not model electromigration, Coulomb explosions, nonideal plasmas, capillary waves, how to produce high $\beta$ asperities, or plasma formation

# SLAC Pulsed Heating

Although they don't study arcing either experimentally or modelling, around 2001, SLAC found that surface currents in the walls caused damage in the surface itself and they began to argue that this damage was involved in breakdown

The primary result of pulsed heating seems to be a reduction in the Q of the cavity, which may be a significant constraint on long term, high gradient operation.

We explain the slope of the lines BDR ~ $E^{28}$ as

BDR ~ $j^2$, with $j \sim E^{14}$.

# European Modeling Efforts

The CERN/CLIC effort has inspired a large and productive modeling effort.

We find that when our assumptions disagree with theirs, it can lead to different predicted results, sometimes by very large factors. This seems to be a result of inadequately constrained assumptions, which seem to be in turn a result of the large number of variables involved.

## Interesting Experimental Topics:

The model points to interesting experimental studies, for example:

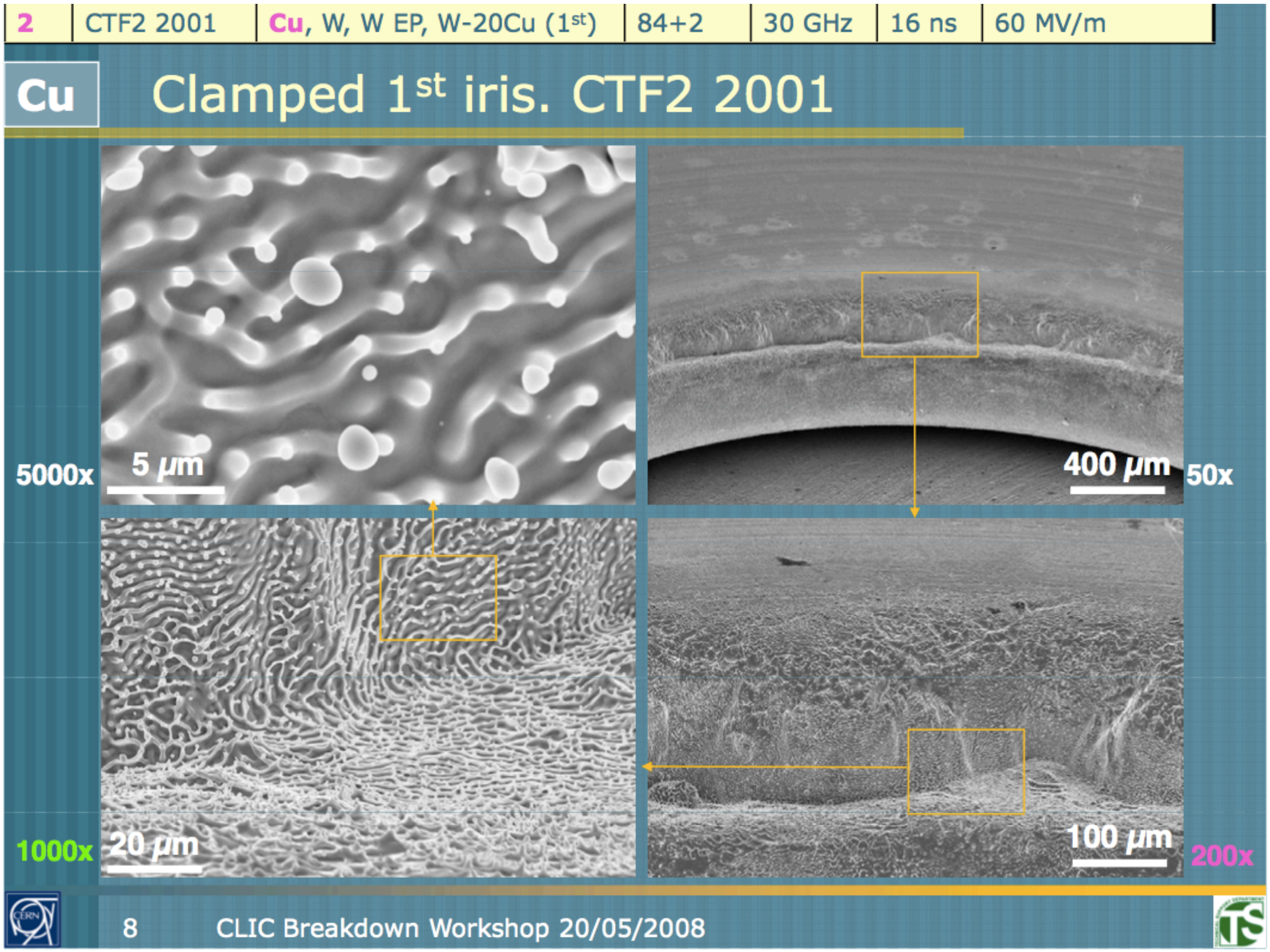
1) Field emission and the surface fields are related. RF arcs may be quite different from DC arcs.

2) Our model applies only to vacuum systems. What if there is a pre-existing plasma?

3) How is the damage that triggers breakdown related to other high voltage effects such as corona discharge?

# 1) Does the FN current density depend on arc parameters?

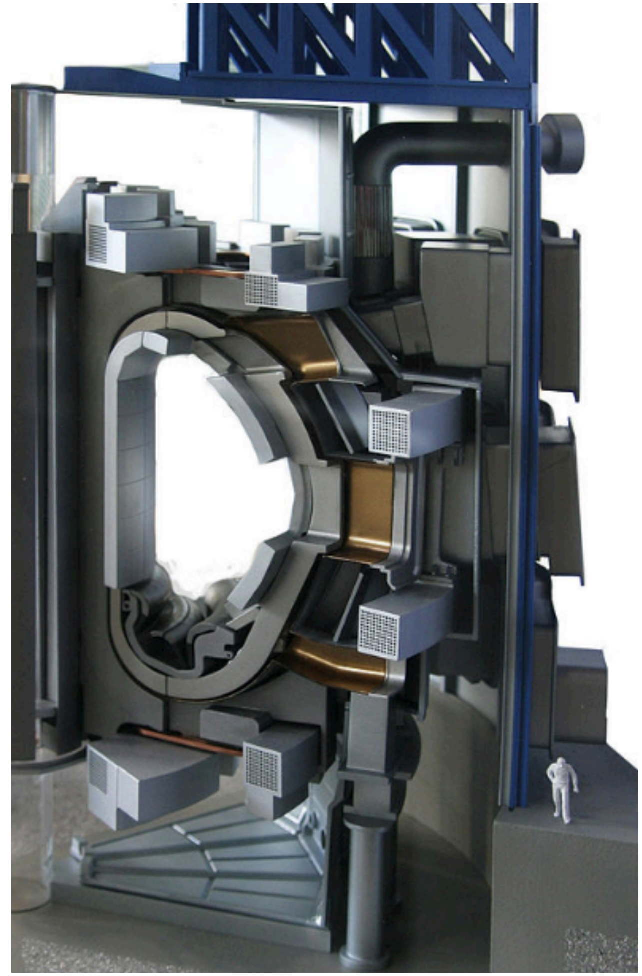
Perhaps in DC arcs, ions compensate space charge better, implying higher current densities than in RF arcs. This would mean DC arcs were small, RF arcs were larger and comparatively passive - spinodal decomposition.




Gonzalo Izquierdo

## 2) ITER and Edge Plasmas

The ITER tokamak under construction in France should be able to generate 500 MW of fusion power.



The design requires minimal arcing at the wall because:

- Impurity radiation cools the plasma.
- Impurities can constrict the plasma current.
- Breakdown limits the rf heating power.

Like accelerator science, arcs in tokamaks are not accessible or easily studied.

The fusion community does not fully understand the breakdown process and it may be possible to produce a productive collaboration on the physics of arcing.

## 3) Corona on grids

The world loses ~100 B$ worth of power every year due to corona losses on power grids. The mechanisms are fairly well understood but there don't seem to be any simple 'cures'. The power companies solution is to: 1) monitor users more closely and generate less excess power and 2) add 7% to your power bill.

The physics of corona loss is very similar to the pre-breakdown conditions described here. Are there technical modifications that can help reduce these losses? Small changes could produce significant savings.

## Conclusions

There is over 100 years worth of data to explain.

Lots of good data from Illinois.

Our model disagrees with much of the conventional wisdom.