# Do Cracks and Unipolar Arcs explain vacuum breakdown and gradient limits?

J. Norem[1] Z. Insepov[2,3]

Relying Heavily On;

experimental data from the Muon Accelerator Program at Fermilab

modeling done by Veitzer/Mahalingam & I. Morozov

MeVArc2018

San Juan, Puerto Rico

5/21/18

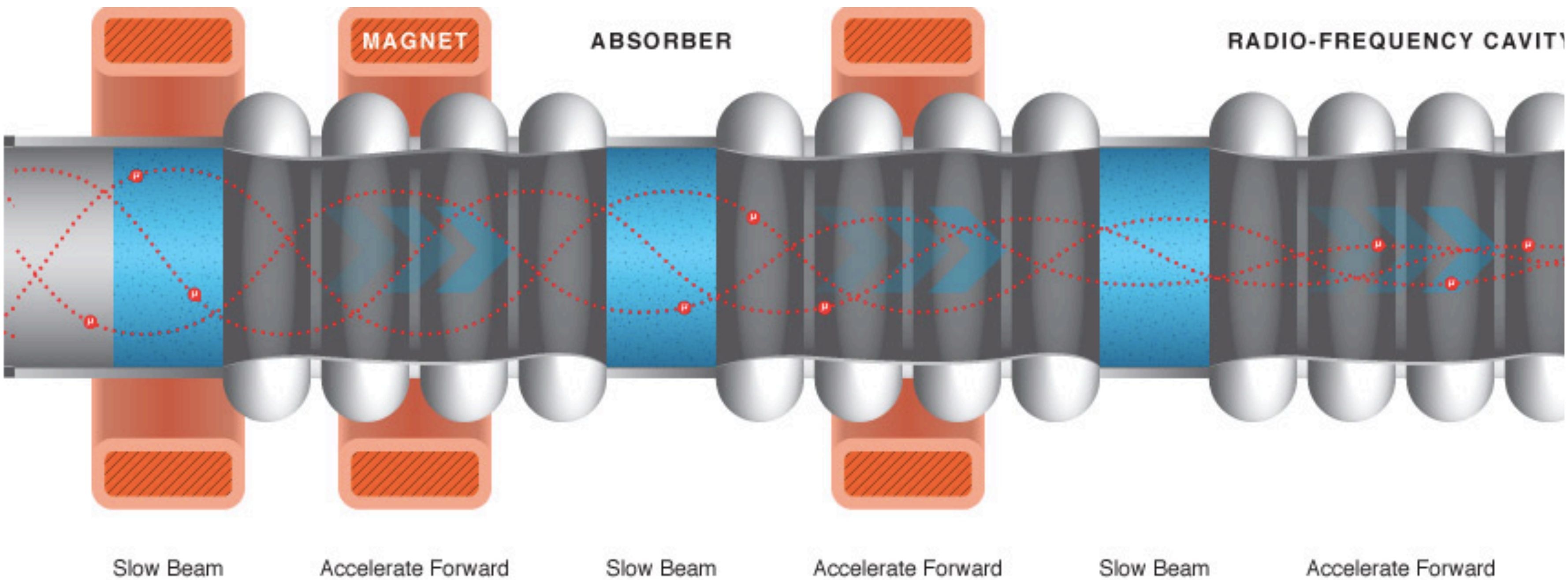
[1] ANL retired

[2] Purdue University

[3] Nazarbayev University

# Fermilab 2001: MuCool started rf studies.

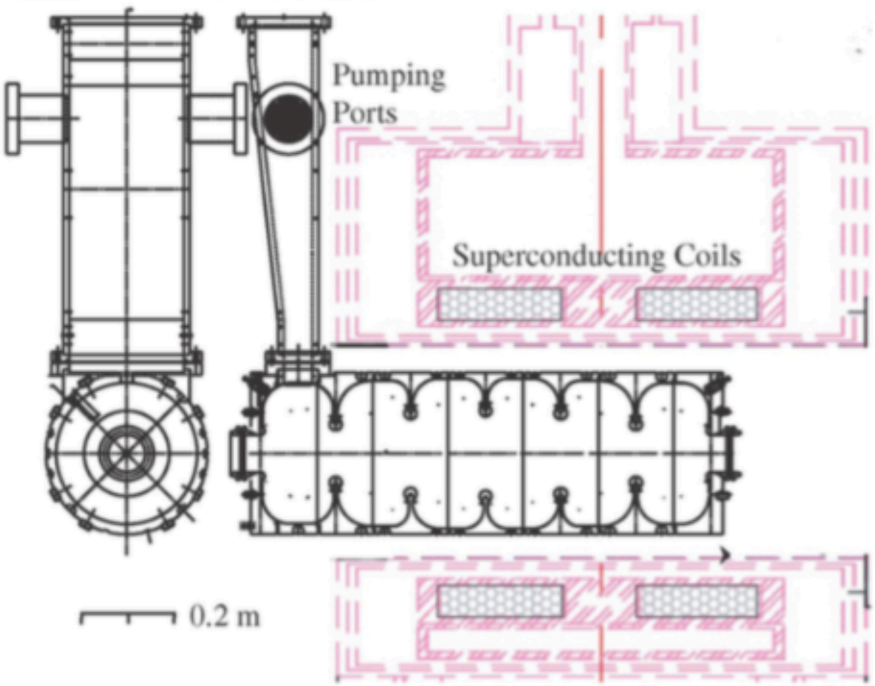
An experiment demonstrating muon cooling at Rutherford Lab required rf cavities and particle detectors very close together. It was not clear that tracking detectors would work with rf x ray backgrounds.



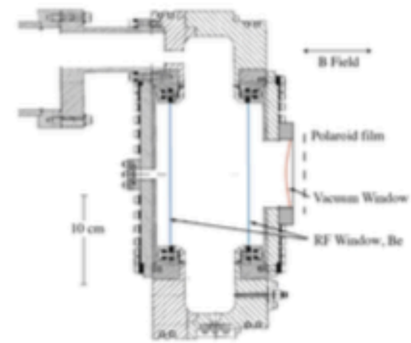

High magnetic fields were an additional complication.

# A Test Assembly used 805 MHz RF in a 5 T Field.

the open cell cavity in the SC magnet




the pillbox cavity




The program, which ended in 2017, measured every available aspect of x ray production. We tried to combine this with data from other labs.

# There were a number of Questions:

Where did the x rays come from ?

Relativistic dark currents produced in the cavities, hitting solids.

Why were x ray fluxes proportional to the (electric field)$^{14}$ ?

The dark currents were produced from field emission, which has this dependence at surface fields around 10 GV/m.

What were the sources of dark currents ?

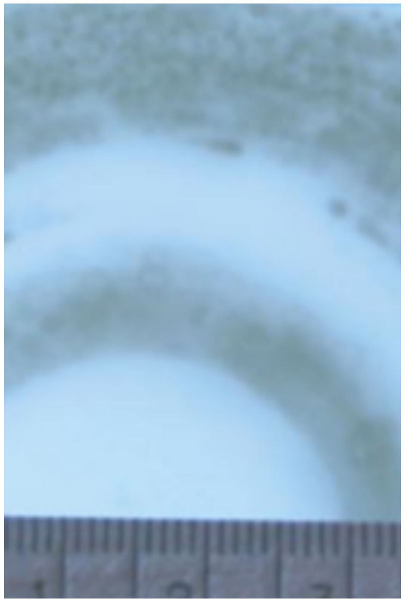
We imaged the currents and discovered hundreds of sources.

Could we operate with the x ray backgrounds ?

Yes.  Slightly reducing the field eliminated the BG.

Were other metals better than copper for rf cavities ?

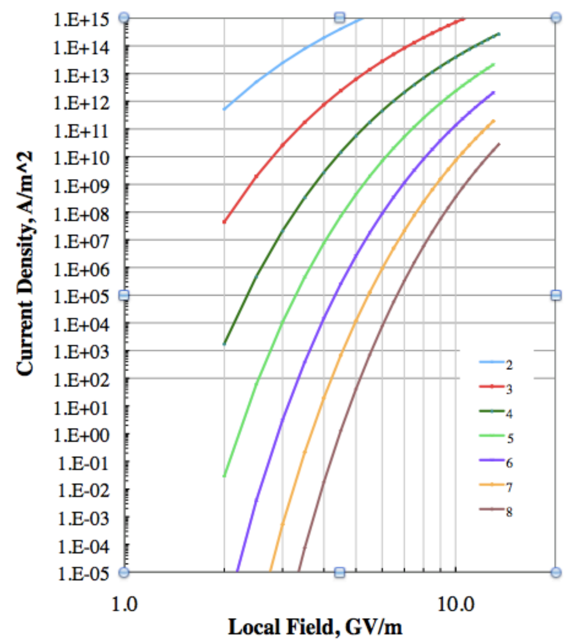
Yes, Be seemed better than copper in many respects.



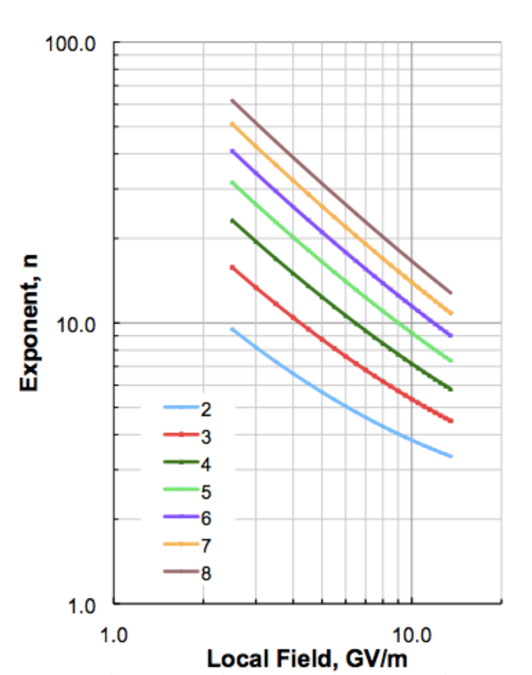
# Understanding x rays seems to be the key.

We saw x ray fluxes ~ $E^{14}$, which implies E ~ 10 GV/m, which then implies electric tensile stress ~ tensile strength.

Field Emission ($\phi$, eV)




n (E)




Should correct for surface contamination and other effects.

Data from SLAC/NLC, ISIS, CESR, and ANL/IPNS, also showed E ~ 10 GV/n

# 1900–2000: References Summarize an Active Field.

Thousands of excellent papers have been written summarizing arc experiments. A number of books summarize this literature:

The Handbook of Vacuum Arc Science and Technology (1993)
    Boxman et al. (ed), 730 pages, (Plasma Spot chapter, 413 references.)

High Voltage Vacuum Insulation, Latham (1981, 1995 & 2006)
    Summarizes modeling.

Pulsed Electrical Discharges in Vacuum, Mesyats (1989)
    Mesyats argues for Explosive Electron Emission (EEE).

Cathodic Arcs, Anders (2008)
    Anders is the most complete, stresses applications.

Vacuum Microelectronics, Brodie and Spindt (1992) (elect. & elect. Phys, V 83)
    Describes physics and applications

Vacuum arcs, Theory and Applications, Lafferty (1980)
    Excellent reference on industrial applications

Good papers: Michelson/Millikan, Kelvin, Alpert, Feynman, Anders

# The literature does not present a complete picture of arcing

In 2001 Burkhard Juttner published a paper emphasizing the incomplete nature of modeling and theory.

About the same time, Perry Wilson told me that he studied the Handbook of Vacuum Arc Science, and found that it left him with many open questions.

We also found the literature confusing. Two points:

Ohmic heating is supposed to be important, but is very geometry dependent. Limits on $j$: (~$10^3$ A/cm$^2$, ANL) to ($10^6$ A/cm$^2$, ICs). Ohmic power ~ $I^2$ varies by $10^6$. Difficult to make predictions.

These six books do not model electromigration, Coulomb explosions, plasma formation, plasma sheaths, nonideal plasmas, surface damage mechanisms, capillary waves, surface tension, vapor pressure of metals at high temperatures or production of high $\beta$ asperities. We find these mechanisms very important.

# Our model tries to explain all the data.

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

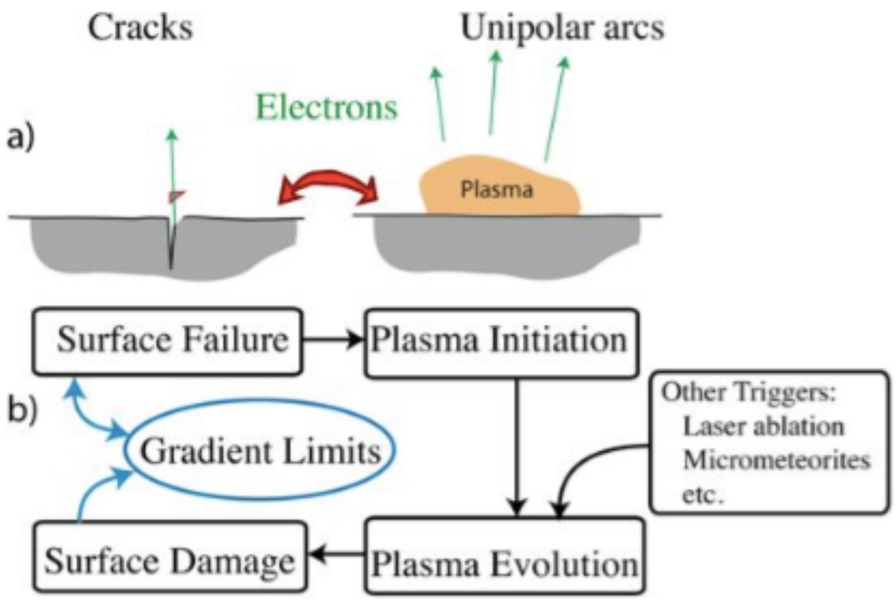
**1) Surface failure**:
- **What triggers BD?** What are the fields, areas current densities ? What kind of damage sites are required?

**2) Plasma initiation**:
- **How is a plasma formed?** What conditions are required? What are the growth times, densities, etc.?

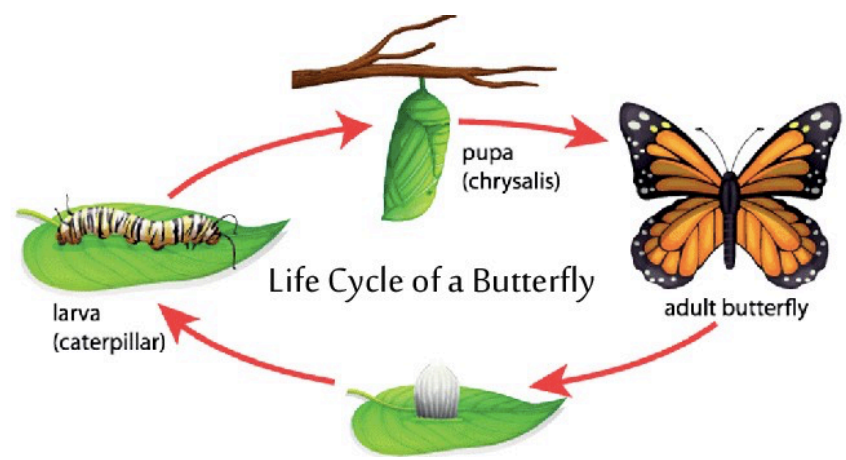
**3) Plasma evolution**:
- **What are the properties of the plasma?** What fuels, quenches it? What damage will it produce?

**4) Surface damage**:
- **How do plasmas damage surfaces and produce high $\beta$s?** Surface hydrodynamics/thermal modeling/crack formation

# Four stages and two phases define our model.




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



# 1) Surface failure

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

Electrostatic stress ~ tensile strength

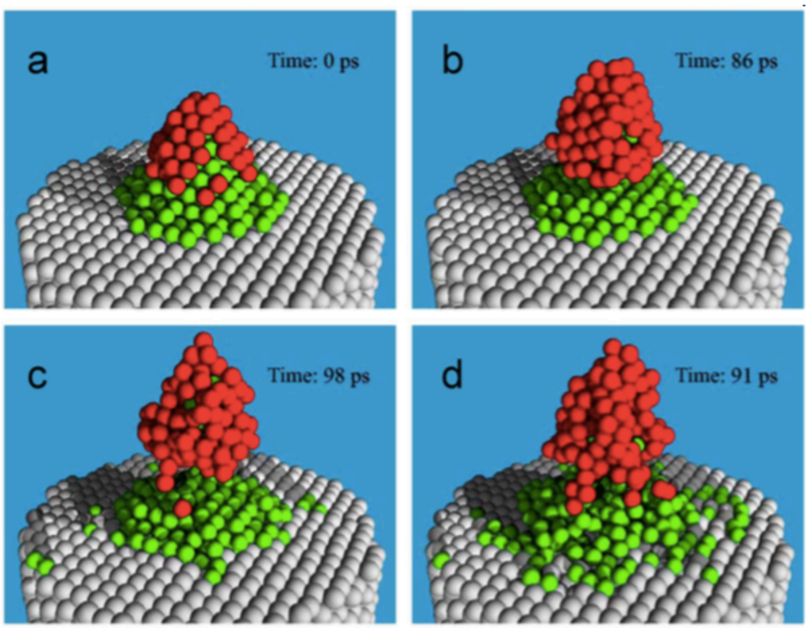
Electromigration sharpens asperities.

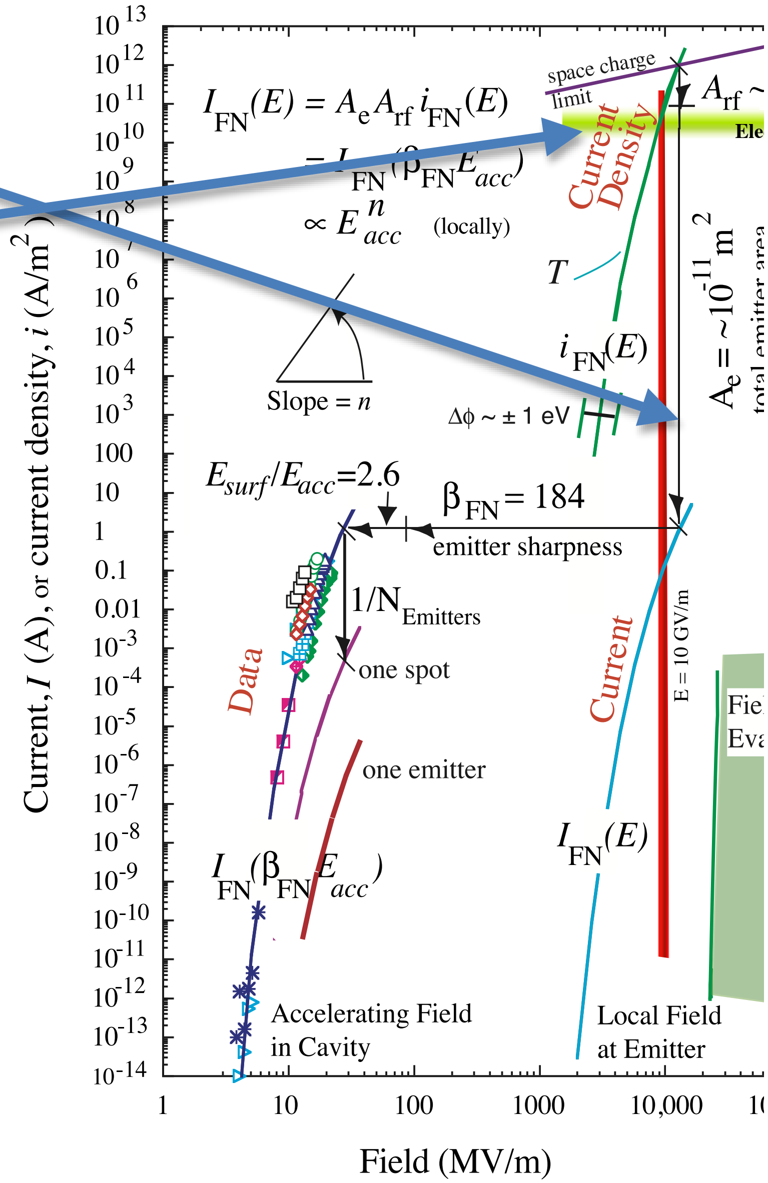
Electromigration was suggested by

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

MD modeled asperity breakup.

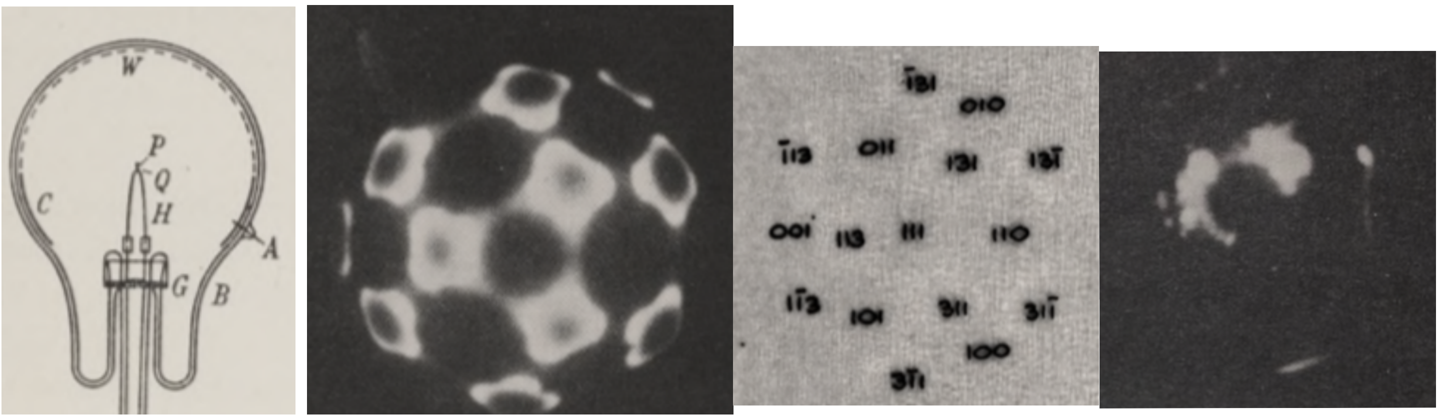
Heating not necessary.



# Electromigration is the "evil twin" of Ohmic heating.

It's hard to model, but clearly seen and understood in 1940 !




Benjamin and Jenkins
Proc of Roy. Soc,
**176**, 262 (40)

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

Ohring: Reliability and Failure of Electronic Materials and Devices

> "We have already noted that virtually all failures in electronic material and devices are the result of physical movements of atoms or charge carriers from benign locations associated with normal behavior to other sites where they contribute to creating or enlarging defects that lead to component malfunction."

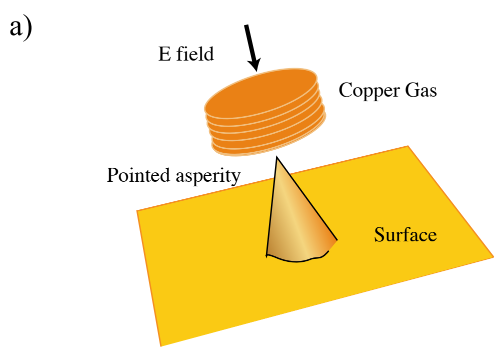
# 2) Plasma Initiation ( + S. Veitzer, S. Mahalingam: Tech-X)

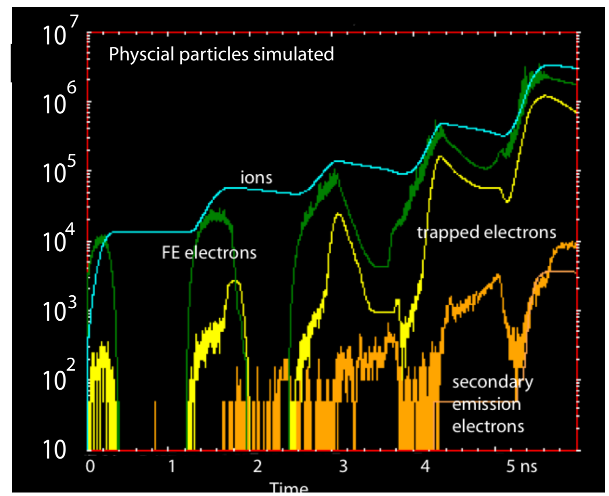
The region above the asperity contains ions, neutrals and FE electrons.

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

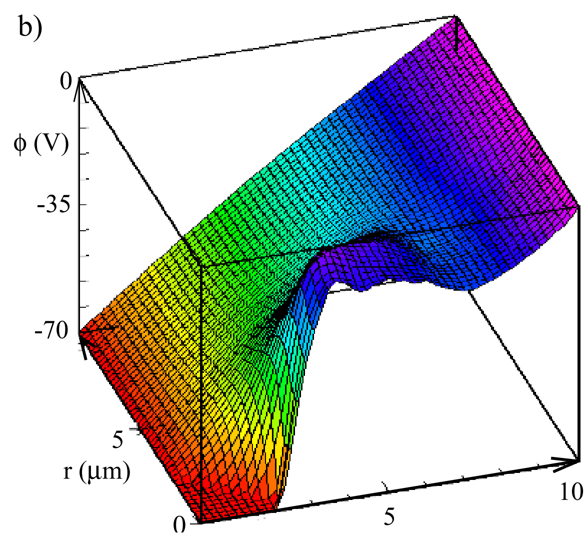
The remaining ions increase the field on the asperity, increasing FE.

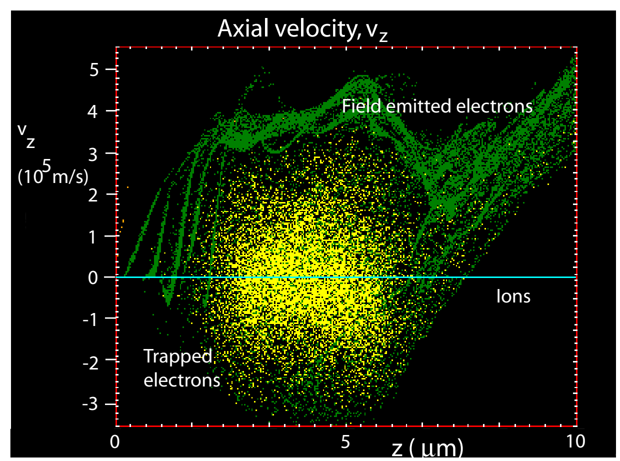
the geometry




the potential

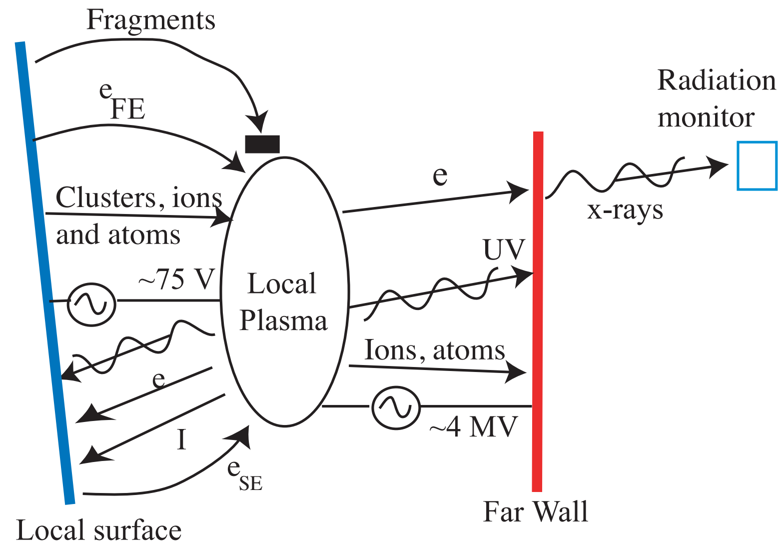


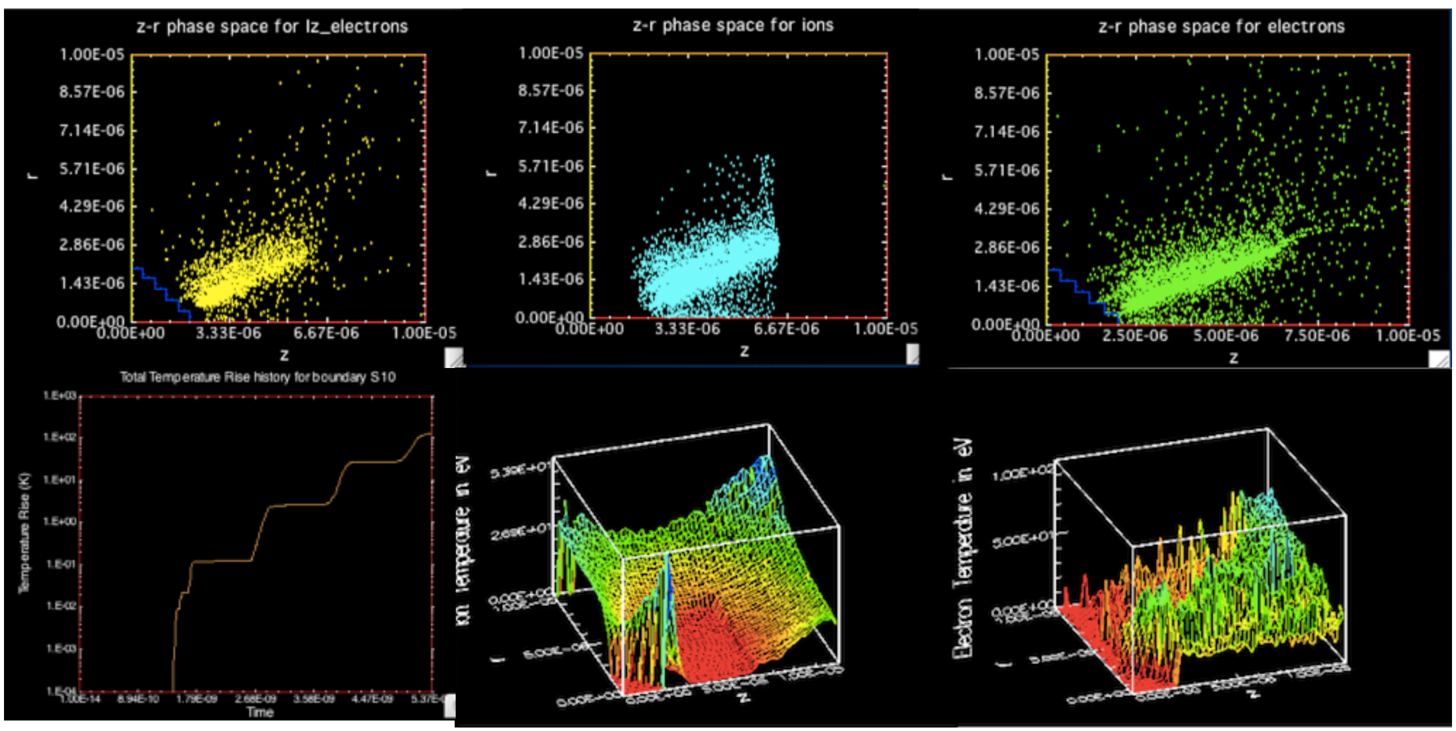



# Plasma Initiation can be modeled with PIC codes.

The low-density plasma can be modeled by particle-in-cell (PIC) codes, which keep track of many mechanisms.

OOPIC calculates everything.



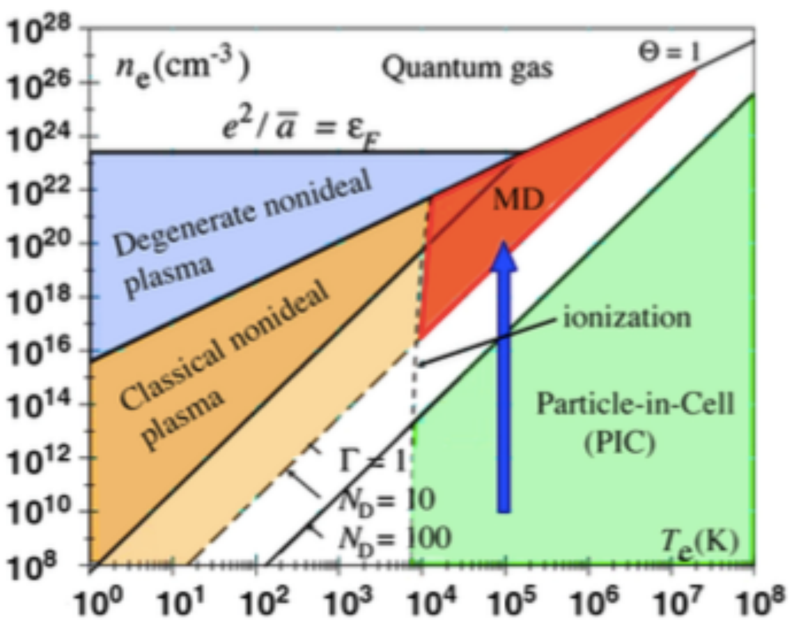
# 3) Plasma Evolution

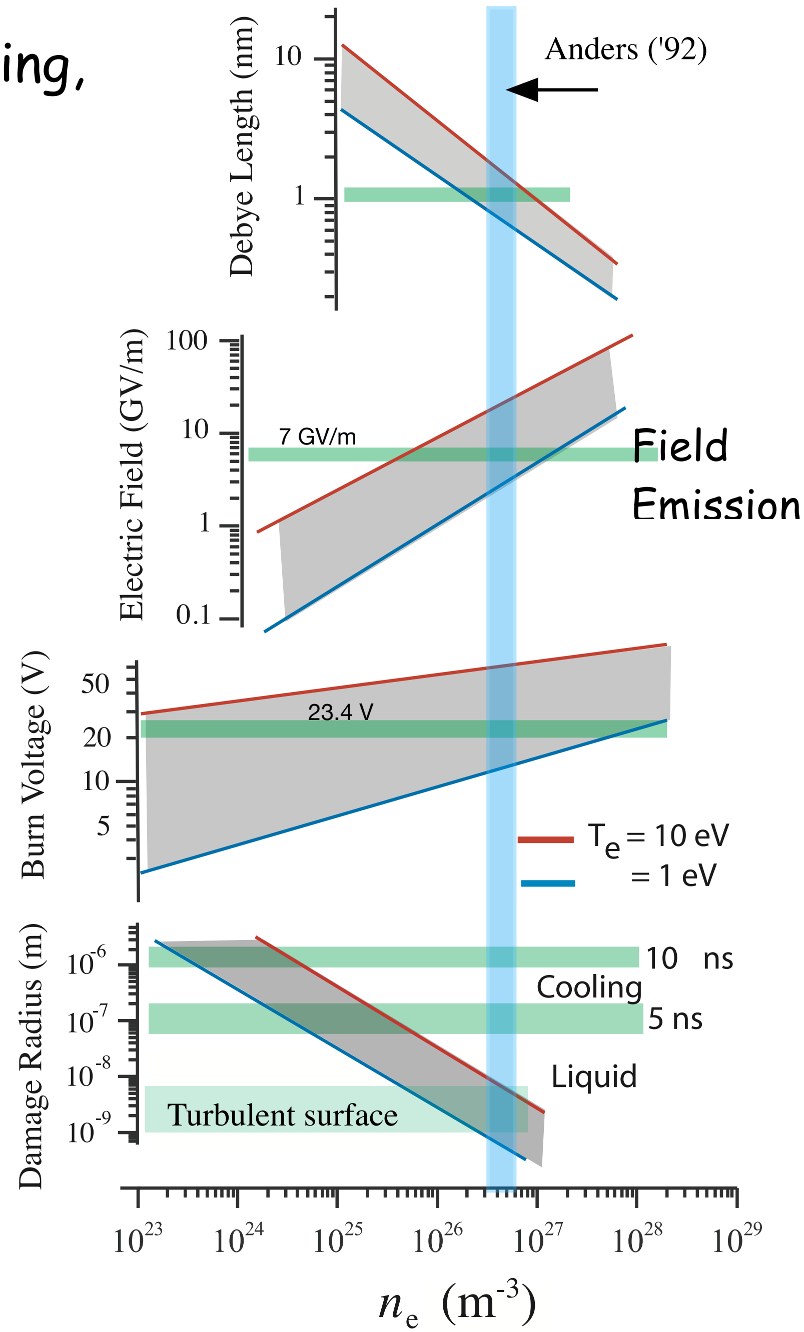
( + I. Morozov)

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 studied the properties of the sheath with Molecular Dynamics.



# Unipolar Arcs

Unipolar arcs are powered by the sheath potential, Described by A. E. Robsoı and P. C. Thonemann, in 1959. Important in tokamak studies 1970 – 1990. Sheaths produce hot surfaces (4000K ?), self-sputtering & vapor pressure (evaporation) produce plasma oscillations, and shorting currents.

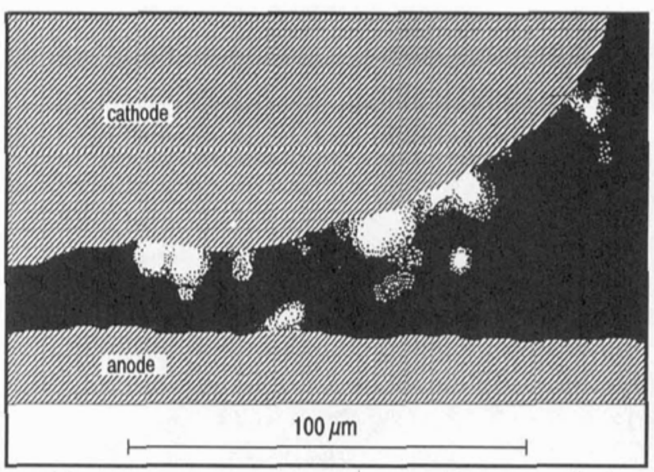



Fig. 10: Absorption picture of Cu-spots, 90 A, taken 232 ns after ignition with 0.4 ns exposure time [19]

Juttner 2001

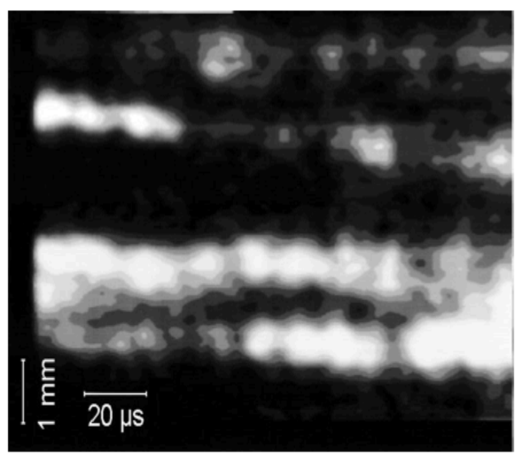
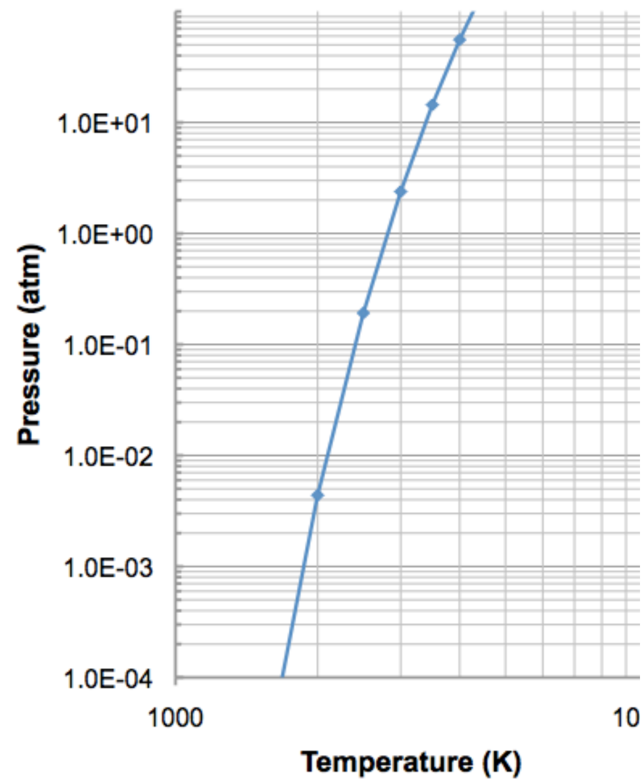



Figure 5. Fluctuating streak traces of four coexisting spots during an arc of 360 A with an extended Cu cathode (Beilis *et al* 1997).

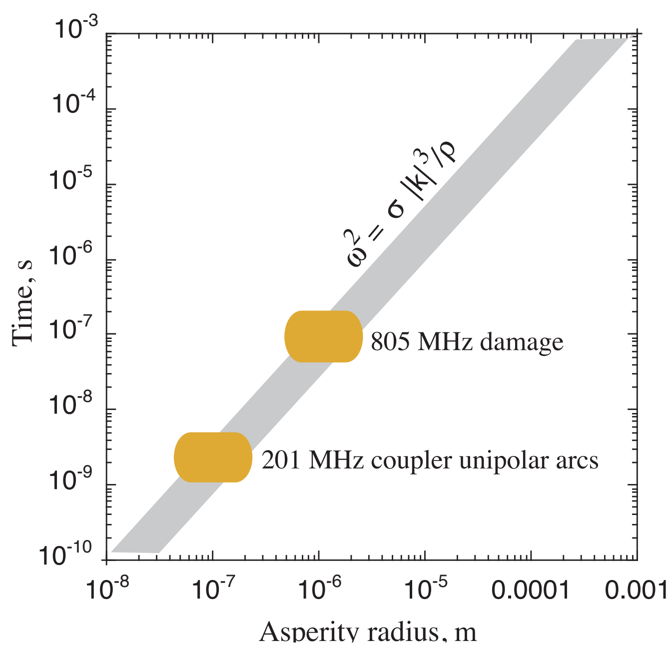
. . .and vapor pressure



# 4) 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 (~200) can be produced.

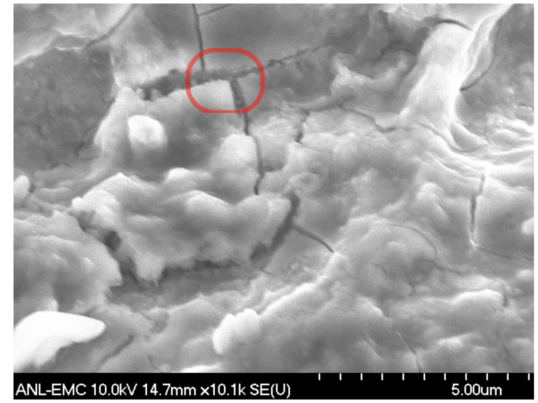
# High field enhancements come from crack junctions.

Cracks form when solid surfaces cool.

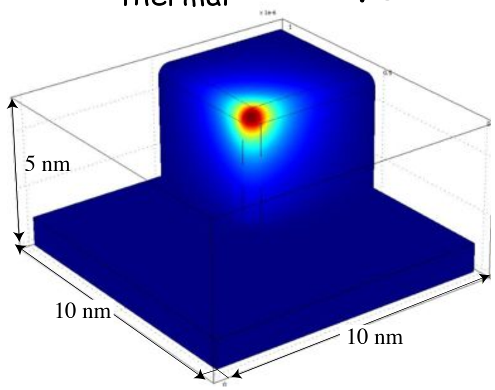
Two stages of cracking produce ~90 deg cracks.

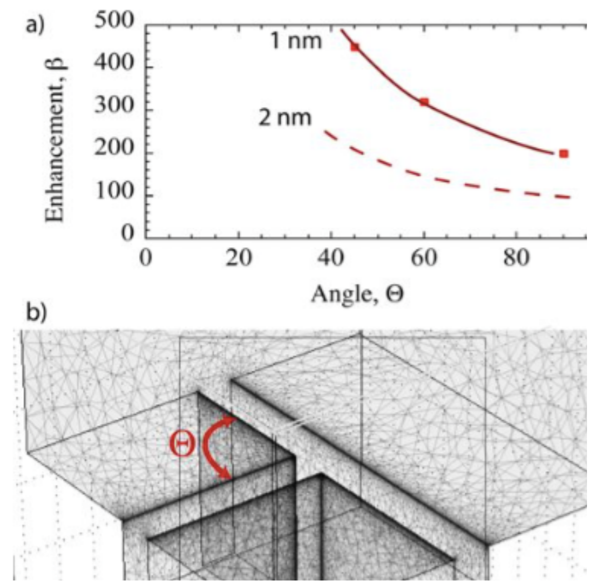
Any sharp points can produce high $\beta$s.

a)




$\tau_{thermal}$ ~ 10 fs



# Mechanisms that should be considered:

Surface failure: Coulomb explosion, Ohmic heating, Surface tension, electromigration, electric tensile stress, fatigue

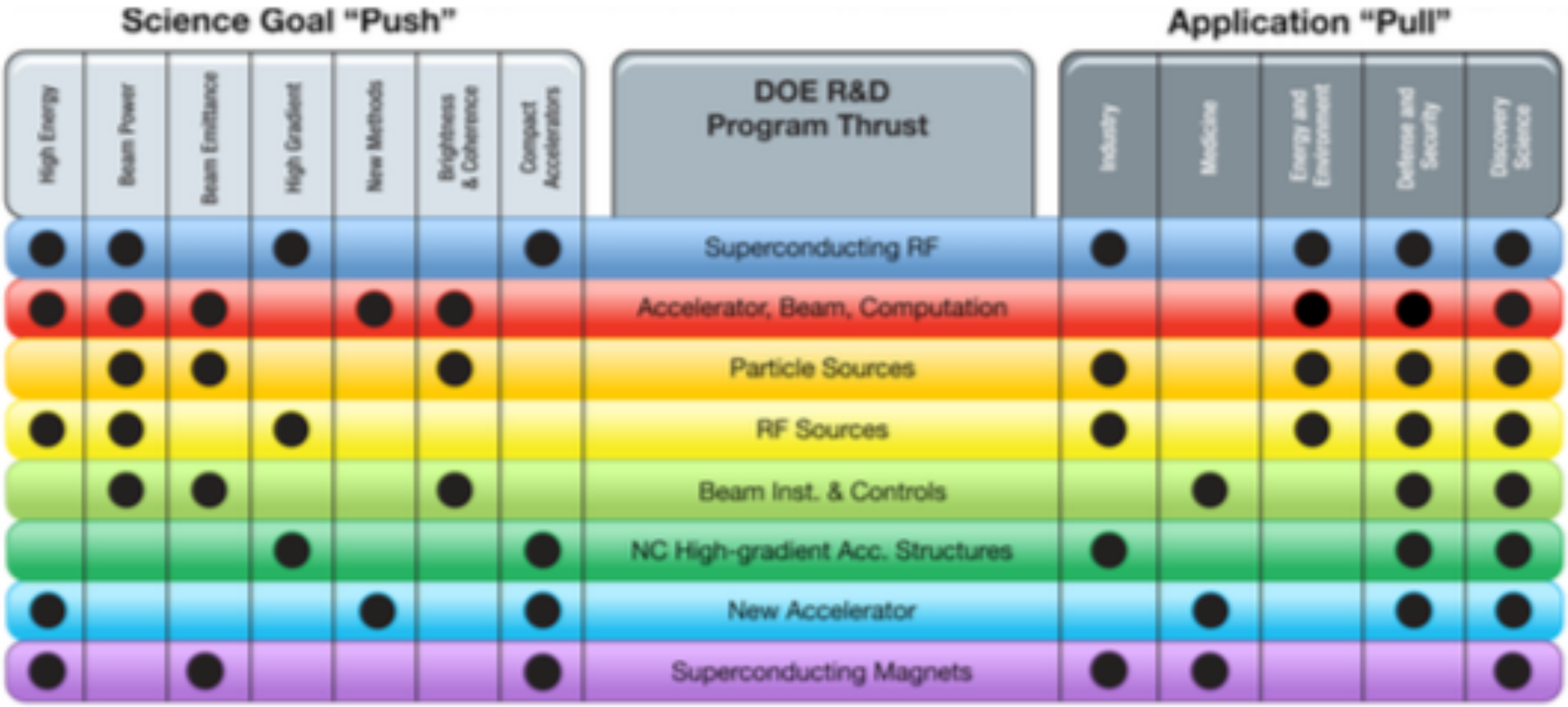
Plasma initiation: Field Emission, geometry, plasma enhanced surface fields, energy and particle flow, neutral gas density, trapped and free electrons plasma size

Plasma evolution: Plasma evolution, self-sputtering, heating, evaporation, non Debye plasmas, surface heating

Surface damage: Cooling, surface tension, capillary waves,

# Other applications: Accelerators

Many application of accelerators are being considered by DOE/HEP.

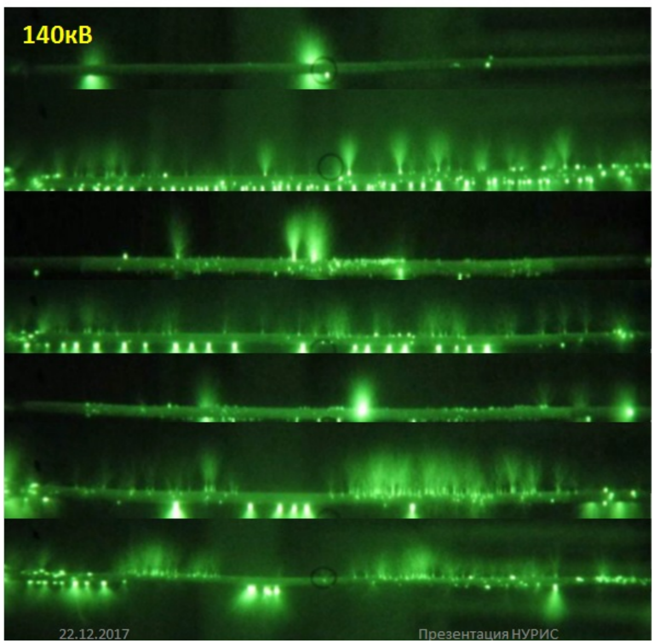



Proton therapy, flu gas mediation, beam driven thorium reactors, industrial uses

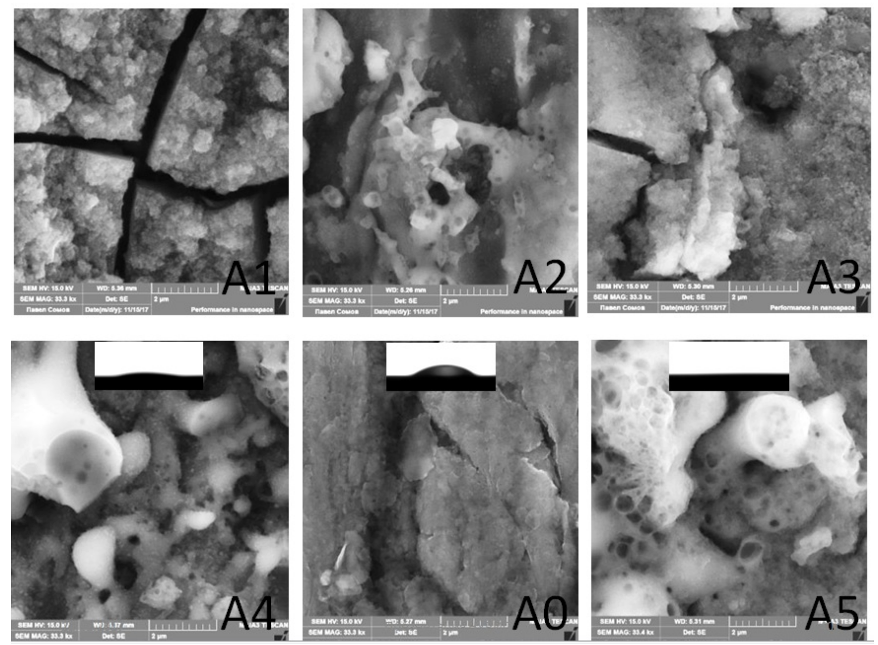
# Other applications: Power Grid

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 seer 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 bil

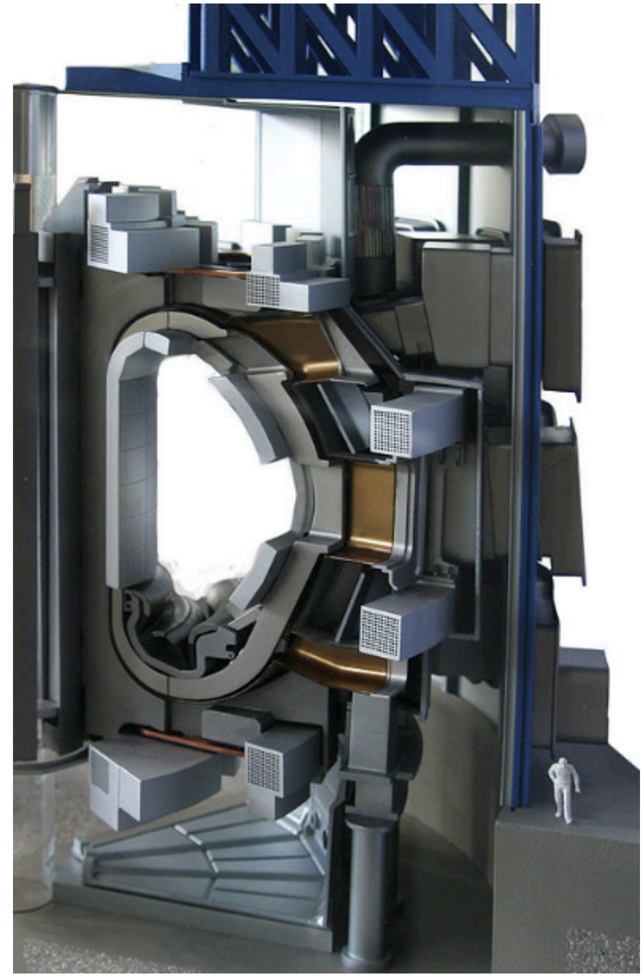
Zeke Insepov has found coating wires reduces corona losses.




2A0 dry we
2A0 rain
2A1 dry
2A1 rain
2A4 dry
2A4 rain
2A5 dry
2A5 rain



# Other applications: Fusion



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 and disrupt the plasma current.

Breakdown limits the rf and neutral beam heating power.

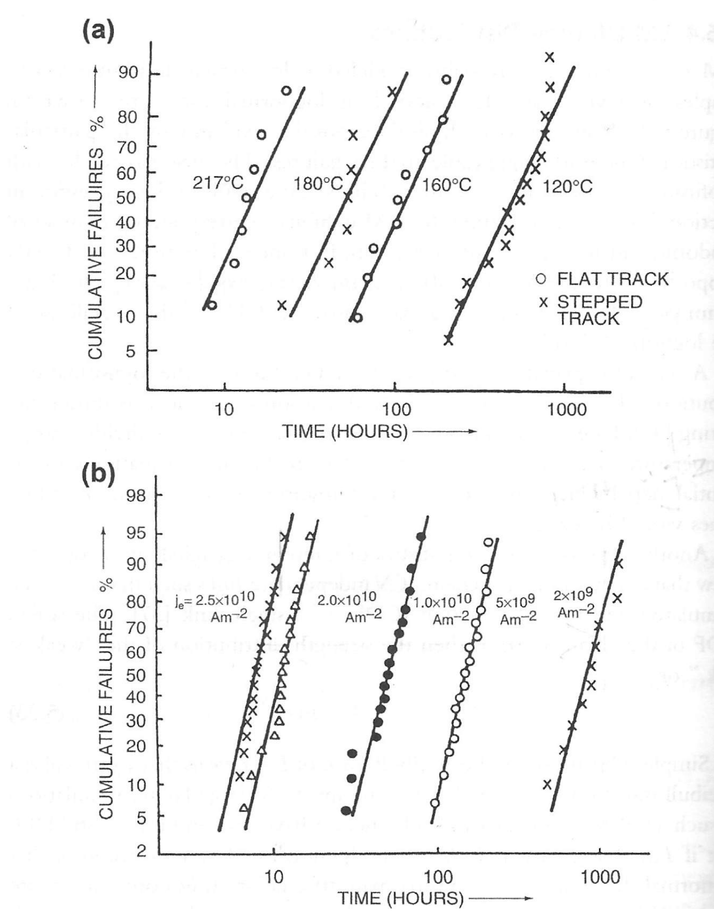
Shin Kajita described how helium implantation produces "fuzz" on the surfaces of plasma facing components (MeVArc 2017).  Grazing incedence of field lines complicates thi

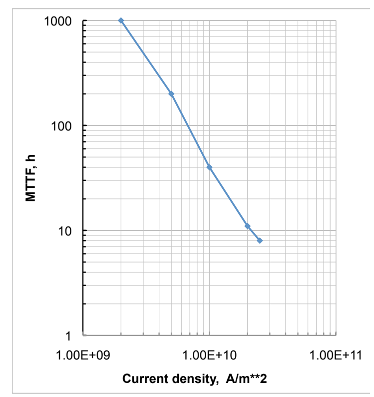
# Other applications: Failure analysis of Electronics

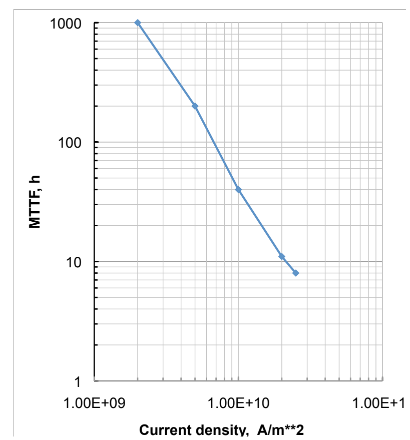
Black's equation describes Electromigration.

$$MTTF = \frac{A}{j^n} e^{\left(\frac{Q}{kT}\right)}$$

from Ohring, *Reliability and Failure of Electronic Materials and Devices*



## Conclusions

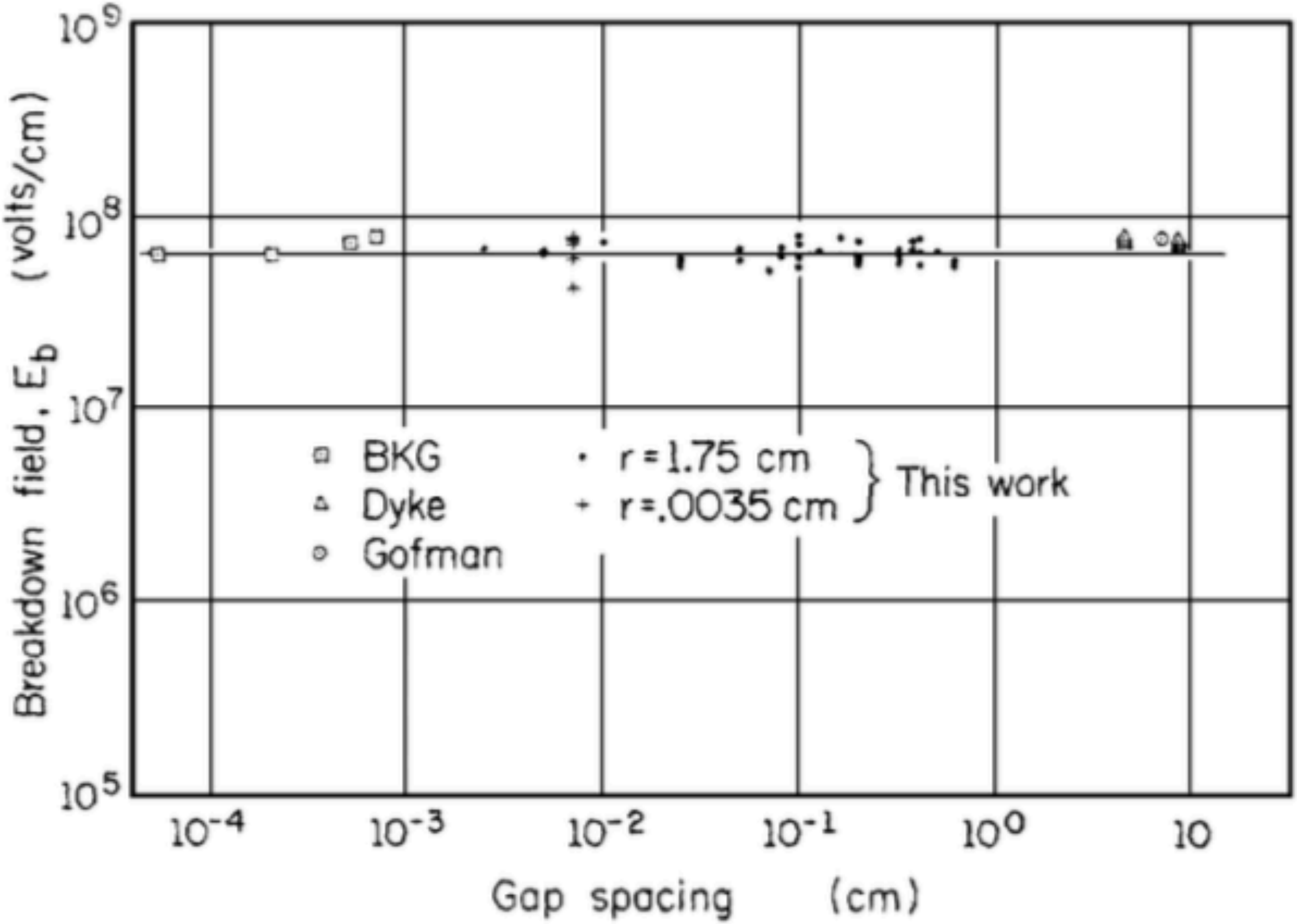
This model explains everything we see.

It predicts many things, like breakdown voltages to a few %.

No need for pulse heating, subsurface strain or anode effects.

Many applications in critical fields: power transmission, fusion, IC failures.

A huge literature is relevant.



10^9
10^8
10^7
10^6
10^5
(volts/cm)
Breakdown field, E_b
BKG
Dyke
Gofman
r = 1.75 cm
r = .0035 cm
This work
10^-4
10^-3
10^-2
10^-1
10^0
10
Gap spacing (cm)