Modeling RF Breakdown

J. Norem (+ Z. Insepov)

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

ASD Seminar
3/8/17

Outline:

Two Questions:

How do vacuum arcs work?

Why is it taking so long to find out?

History: What did we learn 1900 - 2000?

Our model

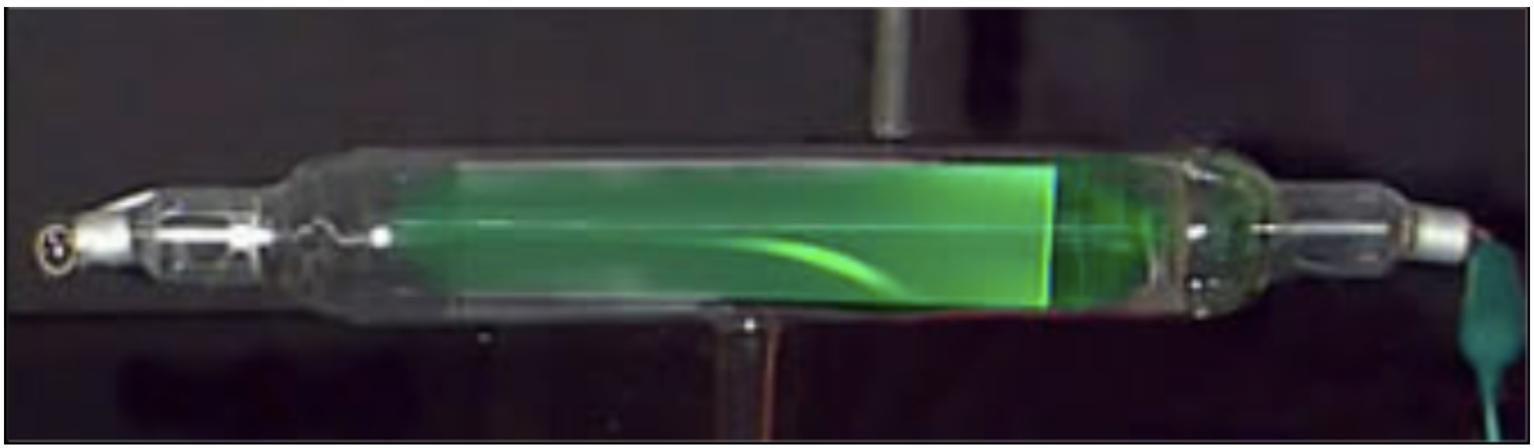
Comparing and Contrasts

Conclusions:

History – the 19th Century

1889 Voltage breakdown has been known for some time. Gas breakdown was first understood by Paschen, who proposed the idea of avalanche breakdown. Gas was ionized by collisional ionization.

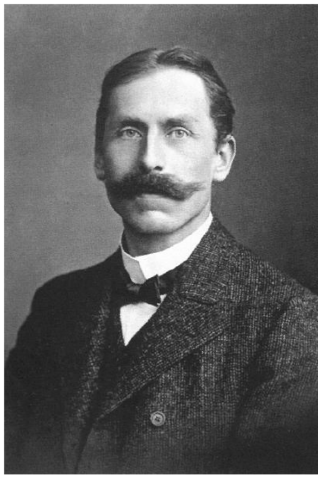
A component of this argument was also discovered in 1889 when J. J. Thomson discovered the electron, and showed that it was negative and responded to electromagnetic fields in predictable ways.



1893 The first issues of Physical Review came out, providing a place for other notable discoveries.

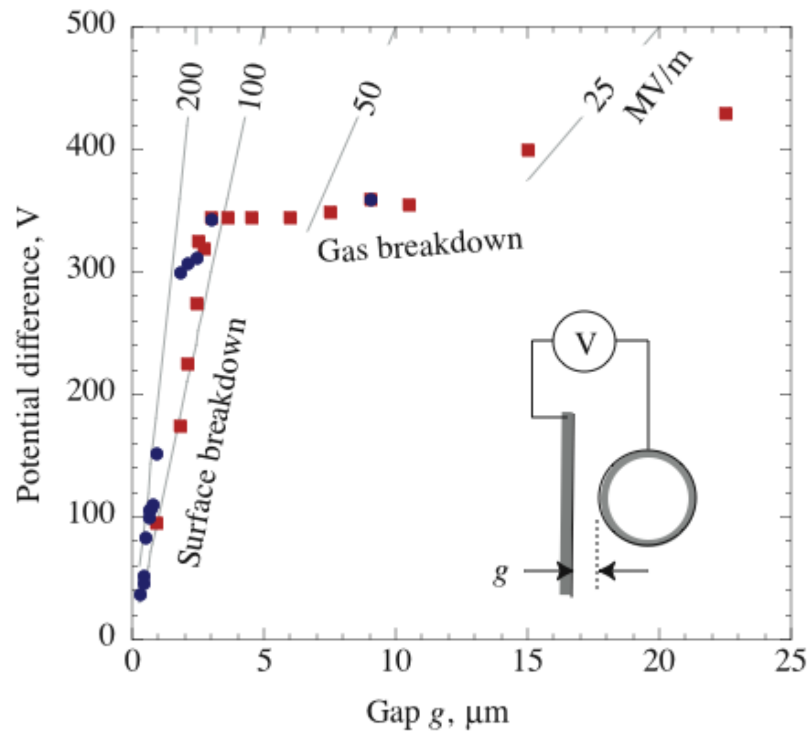
1901 Vacuum breakdown isolated - without vacuum pump.

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 $\boldsymbol{E} \sim 100$ MV/m.
- It is dependent on electrode material.
- BD is independent of gas pressure or type.



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

In 1904, 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,

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

People started looking for needles with high βs - unsuccessfully.

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

This paper reviews the available data and models available from μm to 10 cm.

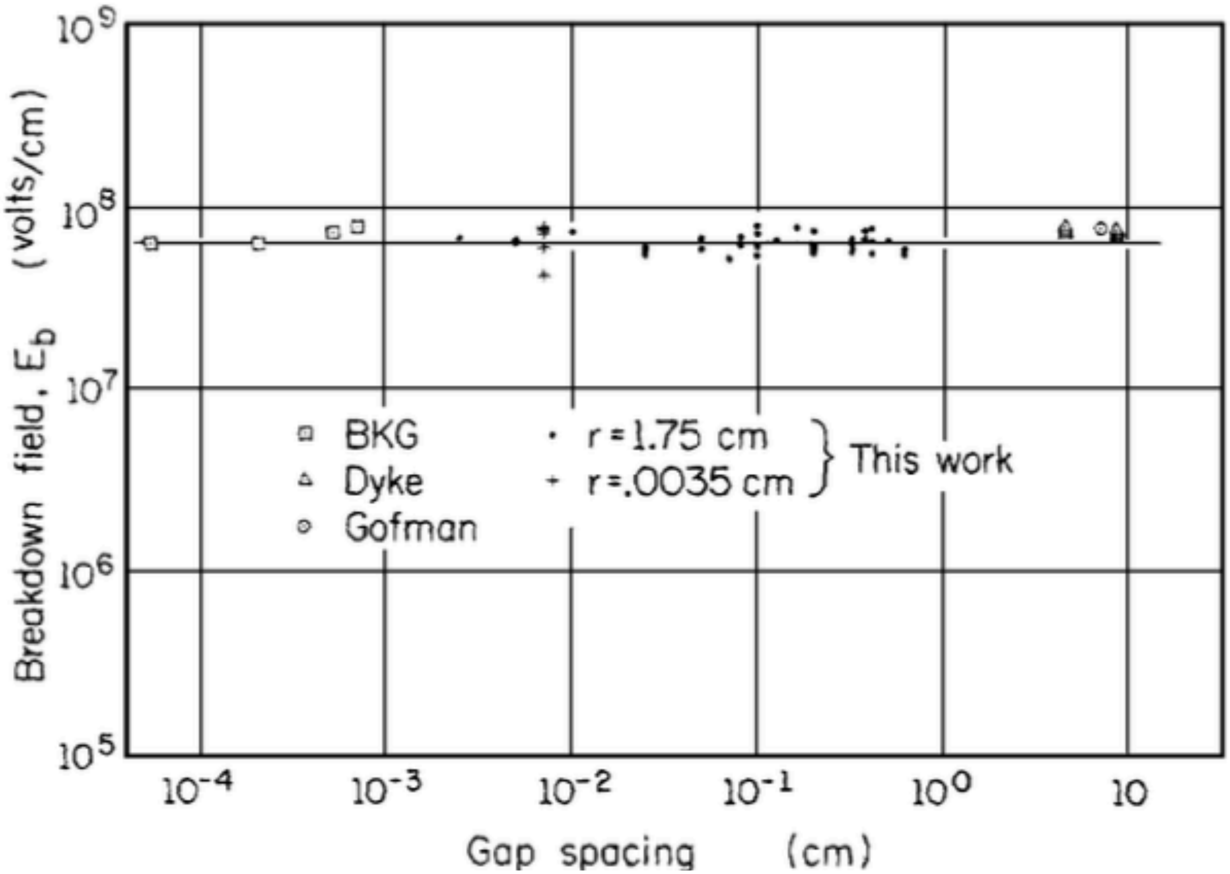


FIGURE 10. Breakdown field vs gap spacing. For each point, the breakdown field is the product of the breakdown voltage and the proportionality constant K, determined from the Fowler–Nordheim plot for prebreakdown current vs voltage.

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

(even after 115 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

Some papers worth reading

Earhart / Hobbs	First discussion of "vacuum breakdown"
Lord Kelvin	Prediction of breakdown field Measured at CERN as 10.2 GV/m in 2006
Fowler Nordheim	Barrier penetration
Alpert *et al*	Careful analysis of large gap BD and modeling

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 comparing data

- More variables than measurable parameters.
- All stages have to be modeled to validate any one of them.
- Setups are unique and hard to compare.
- People were satisfied explaining their own data.

These issues seemed to be relevant to vacuum breakdown only,

- SCRF evolved more cooperatively

FNAL: Can tracking chambers be near an rf cavity?

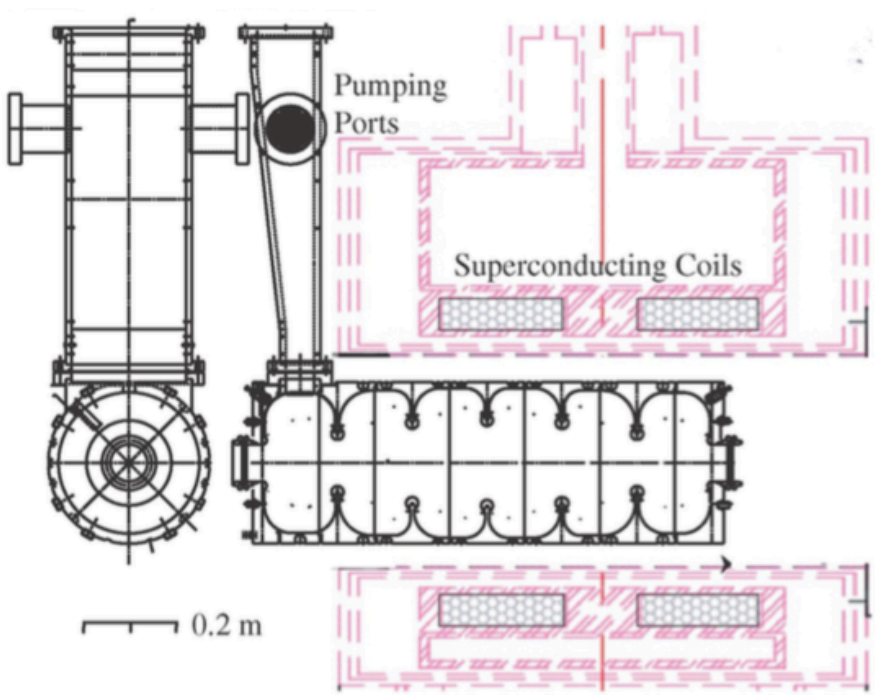
2000 The design of the Muon Ionization Cooling Exp. was defined.

Could x-rays from rf cavities blind tracking chambers?

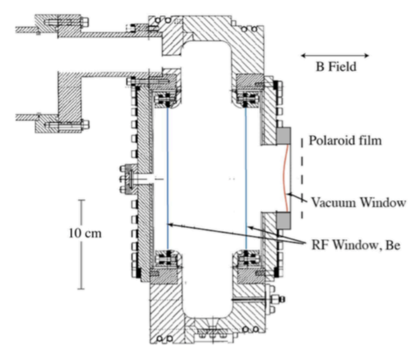
In 2001 an effort to understand the backgrounds was started.

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

the open cell cavity in the SC magnet

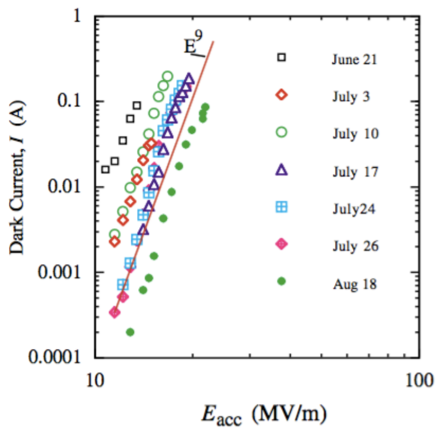


the pillbox cavity



We measured xrays, FE and BD in rf cavities:

Field Emission currents under many conditions, including.



Conditioning

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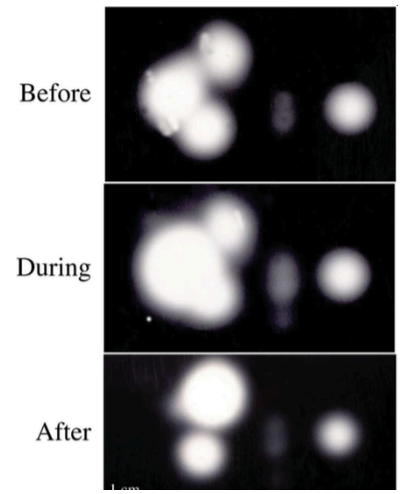
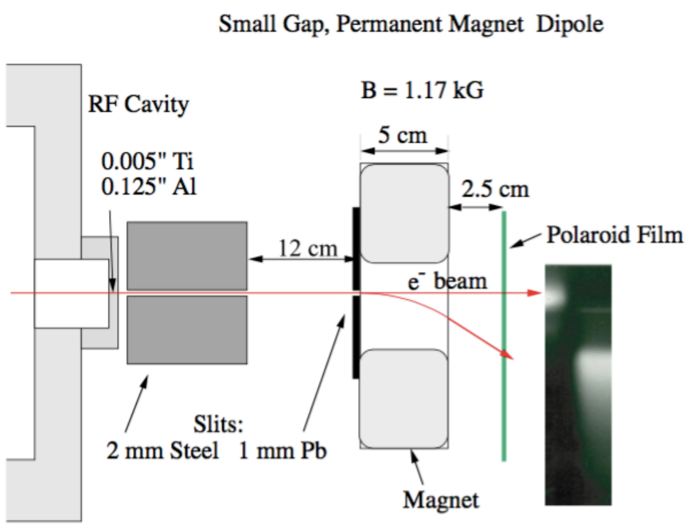
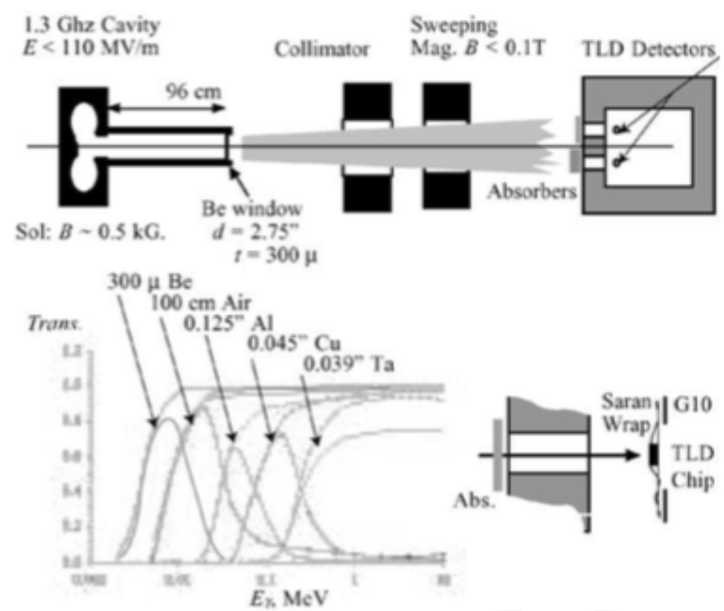
Breakdown



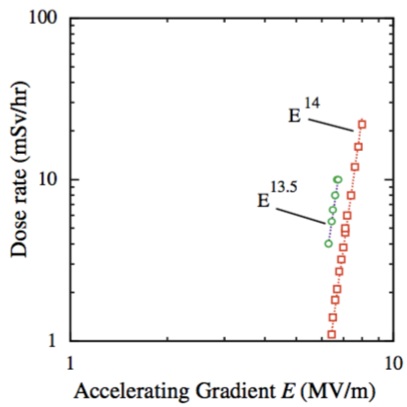
Energy spectrum of e's and γ's.



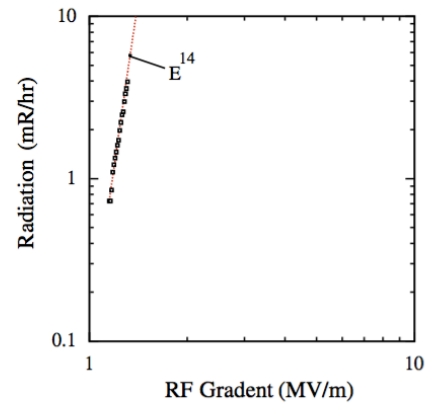


X ray fluxes and angles at a number of linacs.

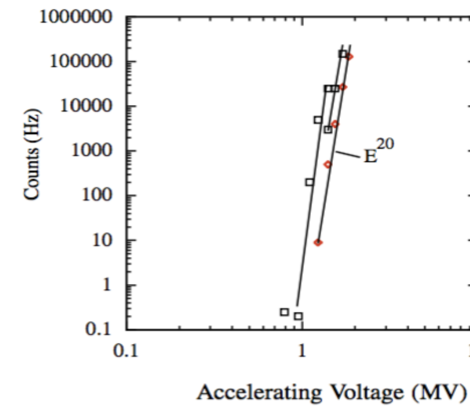
ISIS



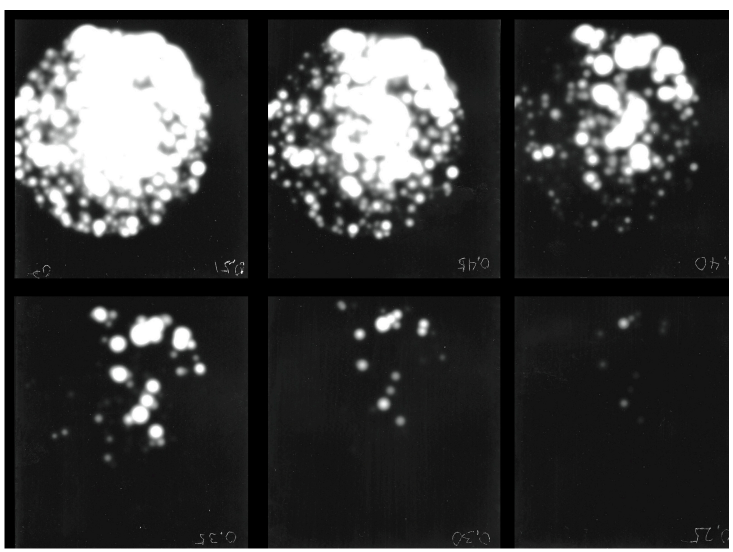
IPNS

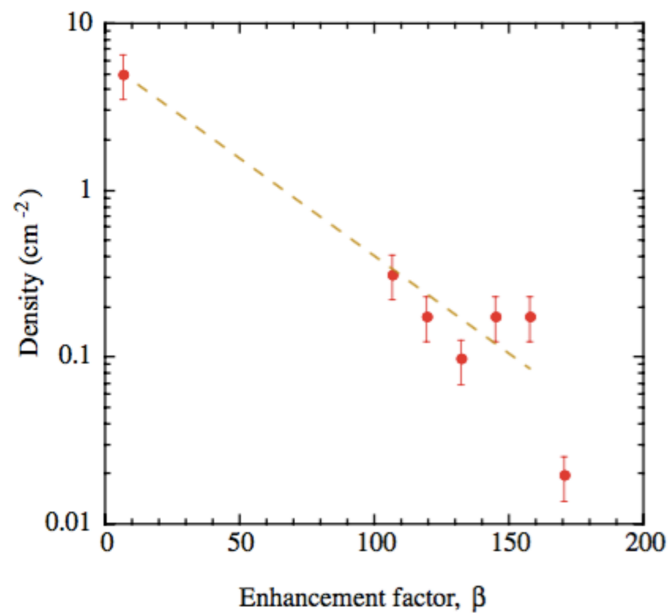


CESR



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



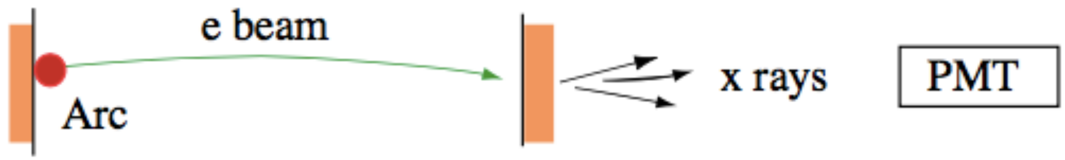


etc. . .

.,

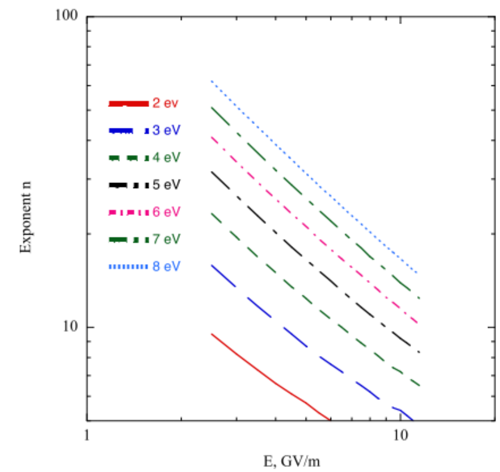
. . . . with the conclusions:

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.

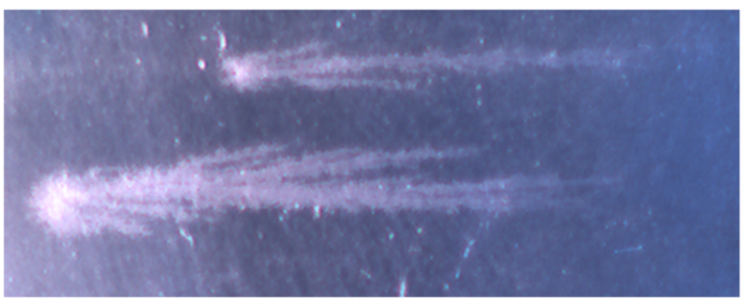
Field emitters seemed to be very small.

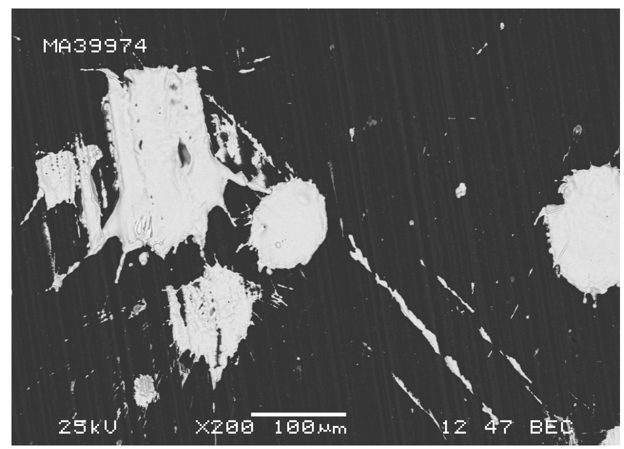
Local fields ~ 10 GV/m seemed to be present in all BD events.
Tensile strength and electromigration explained everything
10 GV/m ~ Tensile strength of copper.

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

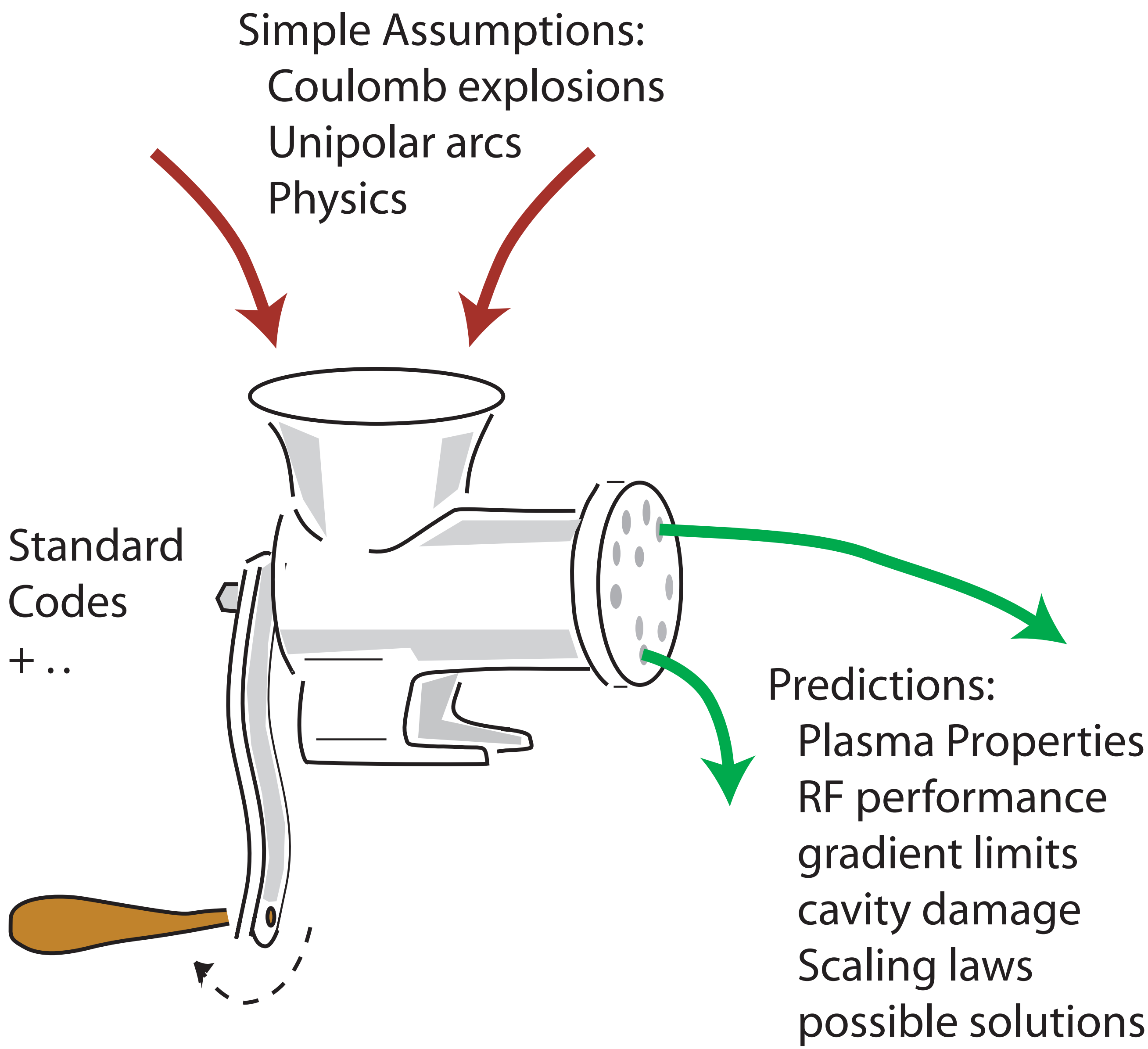
In magnetic fields the arcs can be symmetric.

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





Model is Basically a Set of Assumptions.



A Simple Model Seems 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:

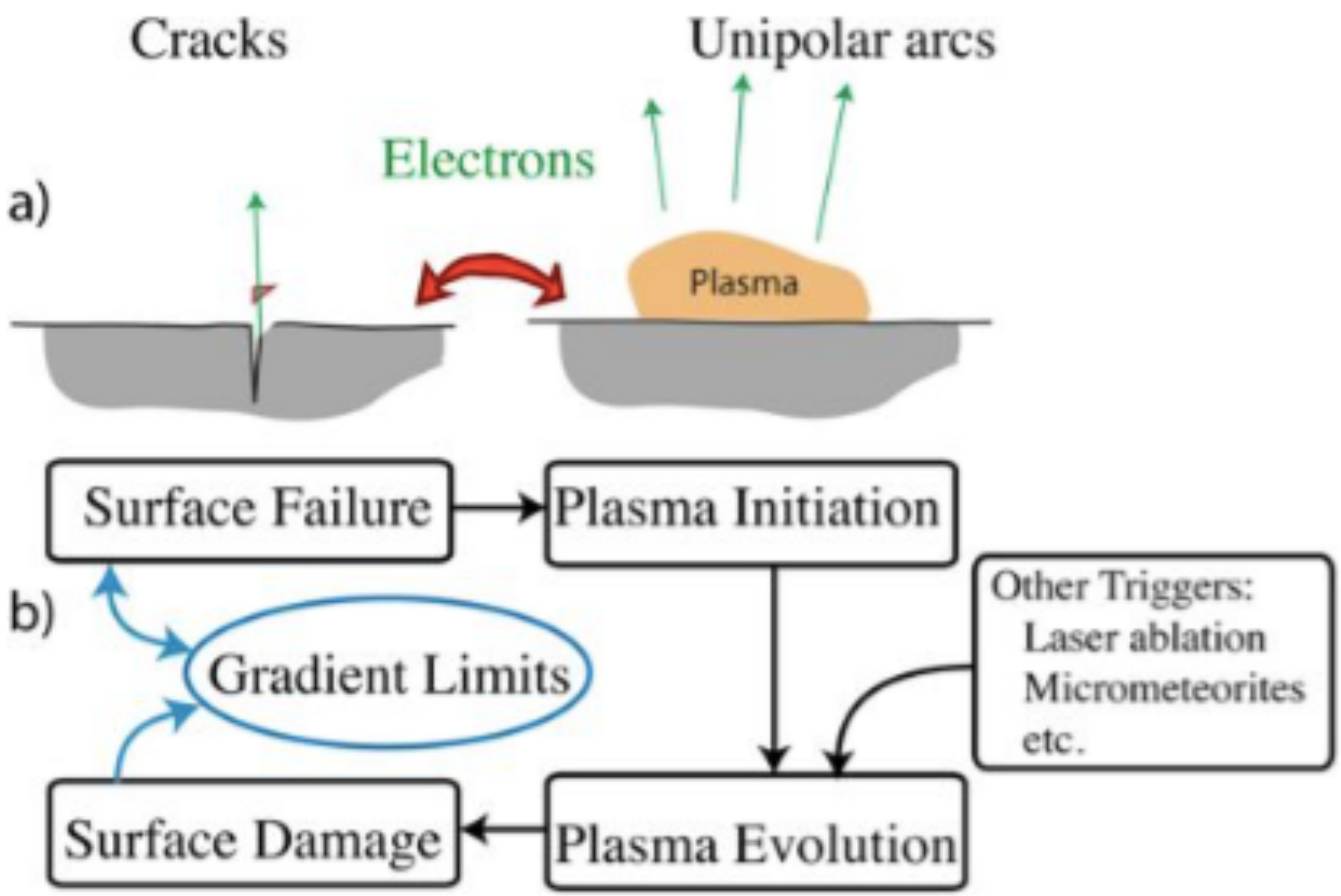
What are the properties of the plasma? What fuels, quenches it? What damage will it produce?

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 define breakdown.



Surface failure

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

Electrostatic stress ~ tensile strength

Electromigration sharpens asperities.

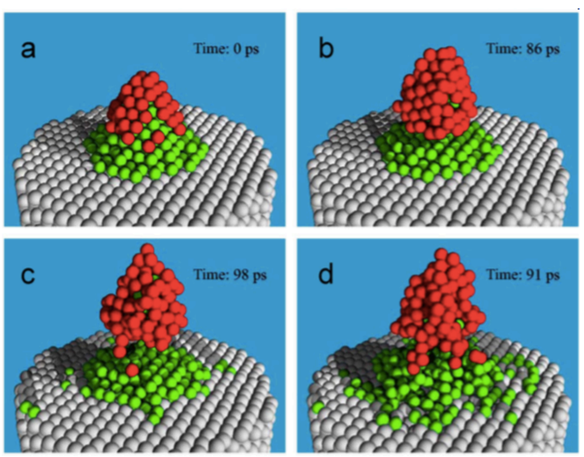
Electromigration was suggested by

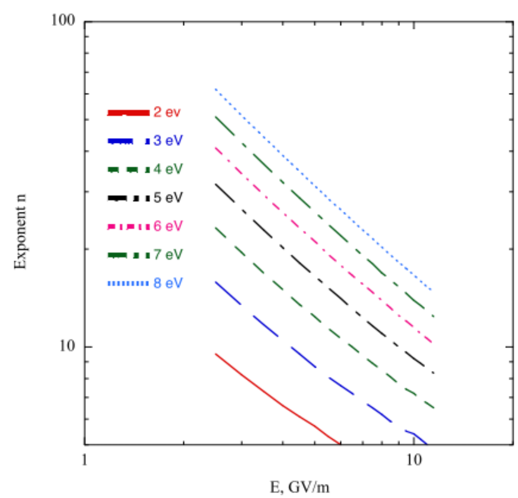
C. Antoine, F. Peauger, and F. Le Pimpec

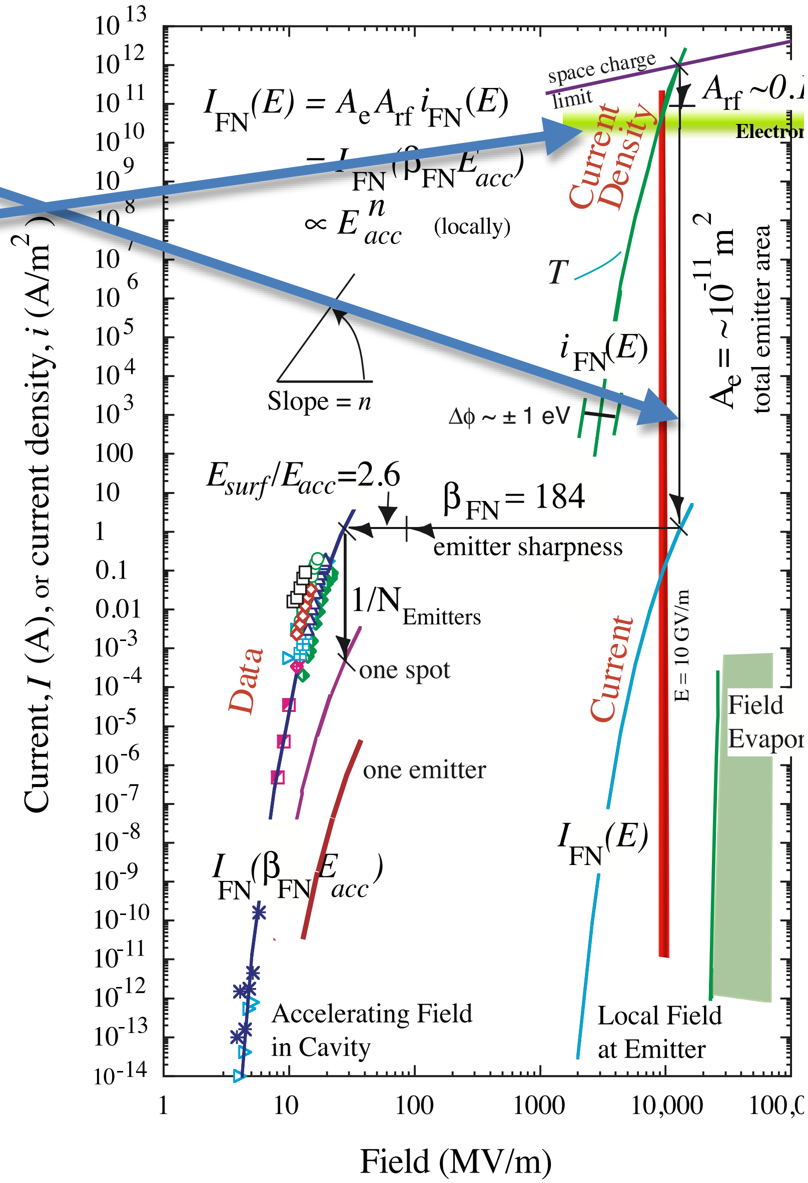
MD modeled asperity breakup.

FE electrons, ions and neutrals are emitted.

Heating not necessary.



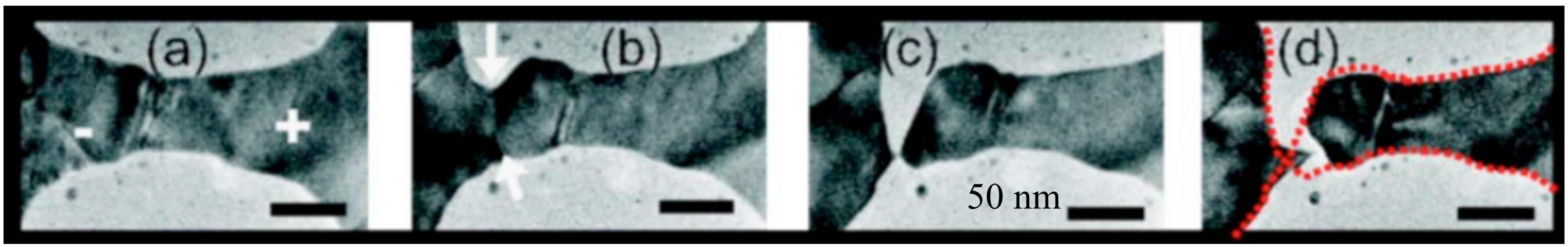




Tensile stress is "straightforward", electromigration is not.

We couldn't find information on electromigration in breakdown,
. . however there are mountains of data relating it to reliability and failure of electronic materials and devices.

High current densities erode Au and Cu contacts and also arc. Video !



This series is part of a YouTube video - search "Delft gold electromigration" and described in Heersche *et al*,   Appl. Phys. Lett. **91**, 072107 (2007).

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

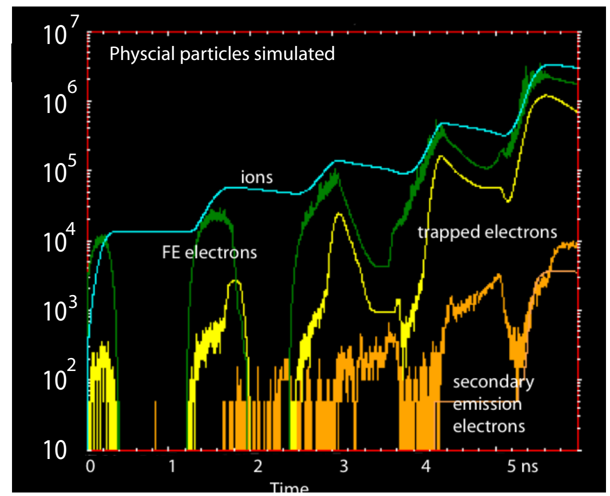
Plasma Initiation

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

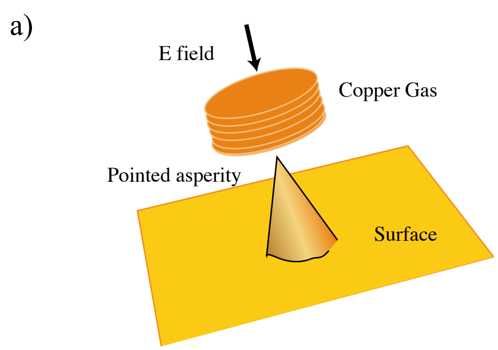
The region above the asperity contains ions, neutrals and FE electrons.

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

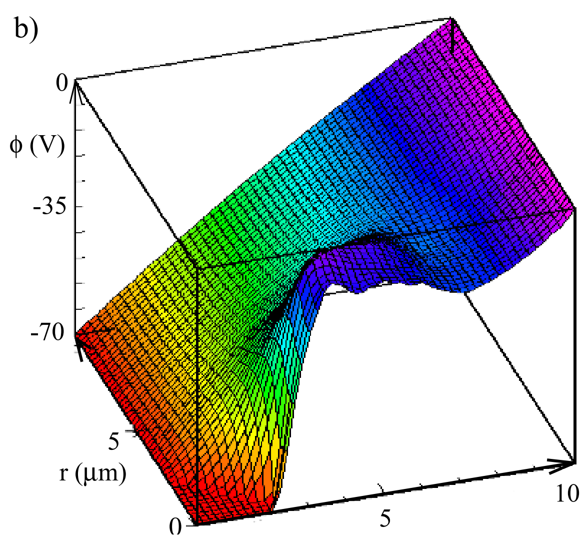
The remaining ions increase the field on the asperity, increasing FE.

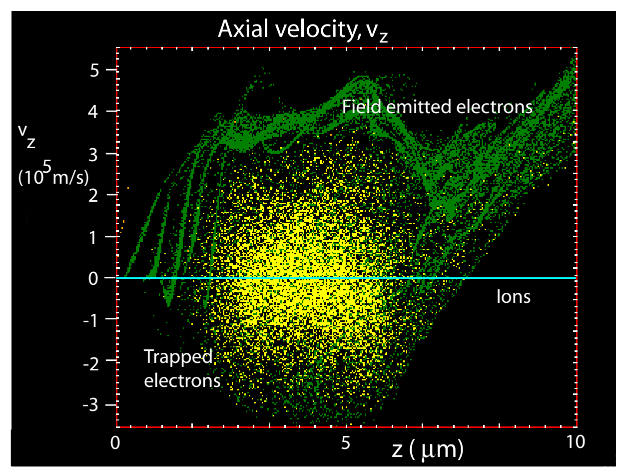


the geometry



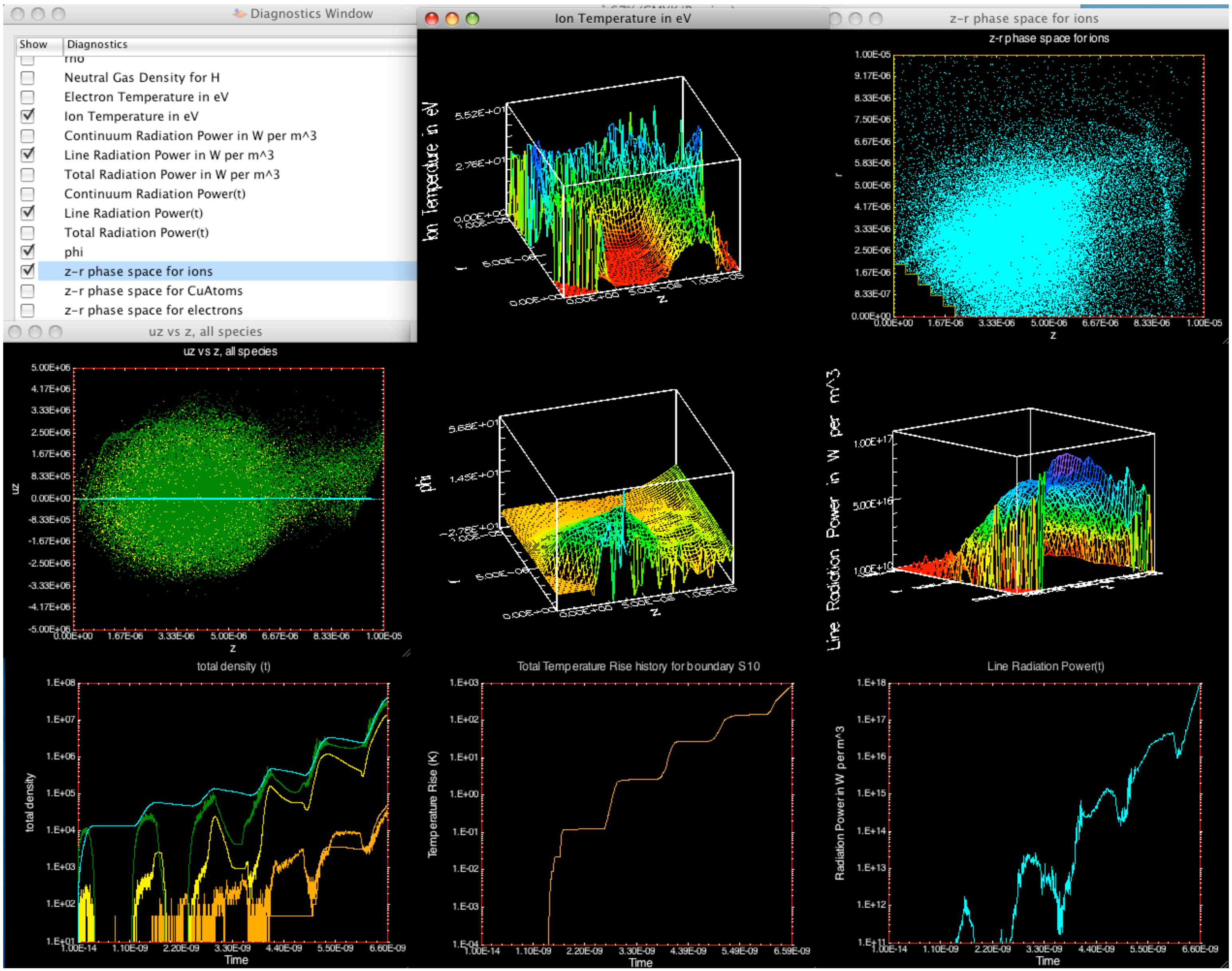
the potential





OOPIC Pro, from Tech-X, is based on a Berkeley plasma code.

It can produce many useful color plots and videos.



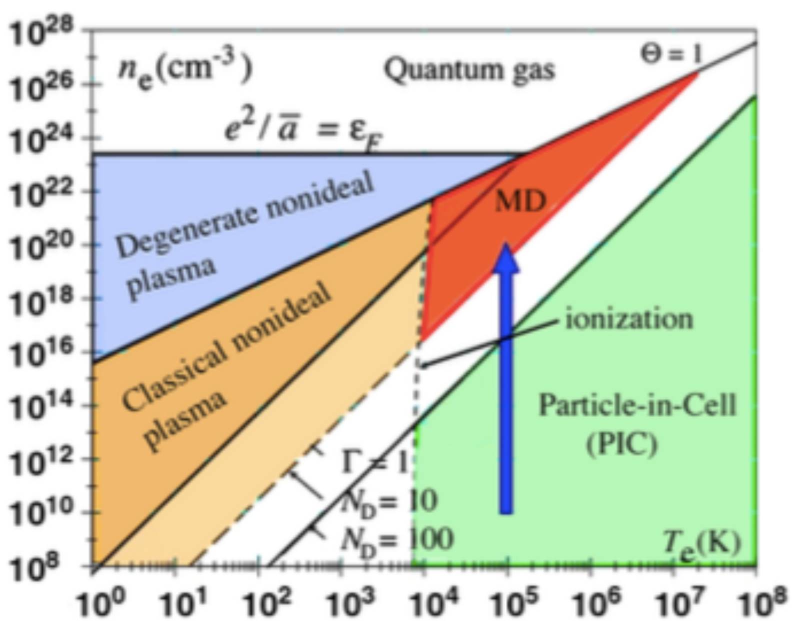
Plasma Evolution

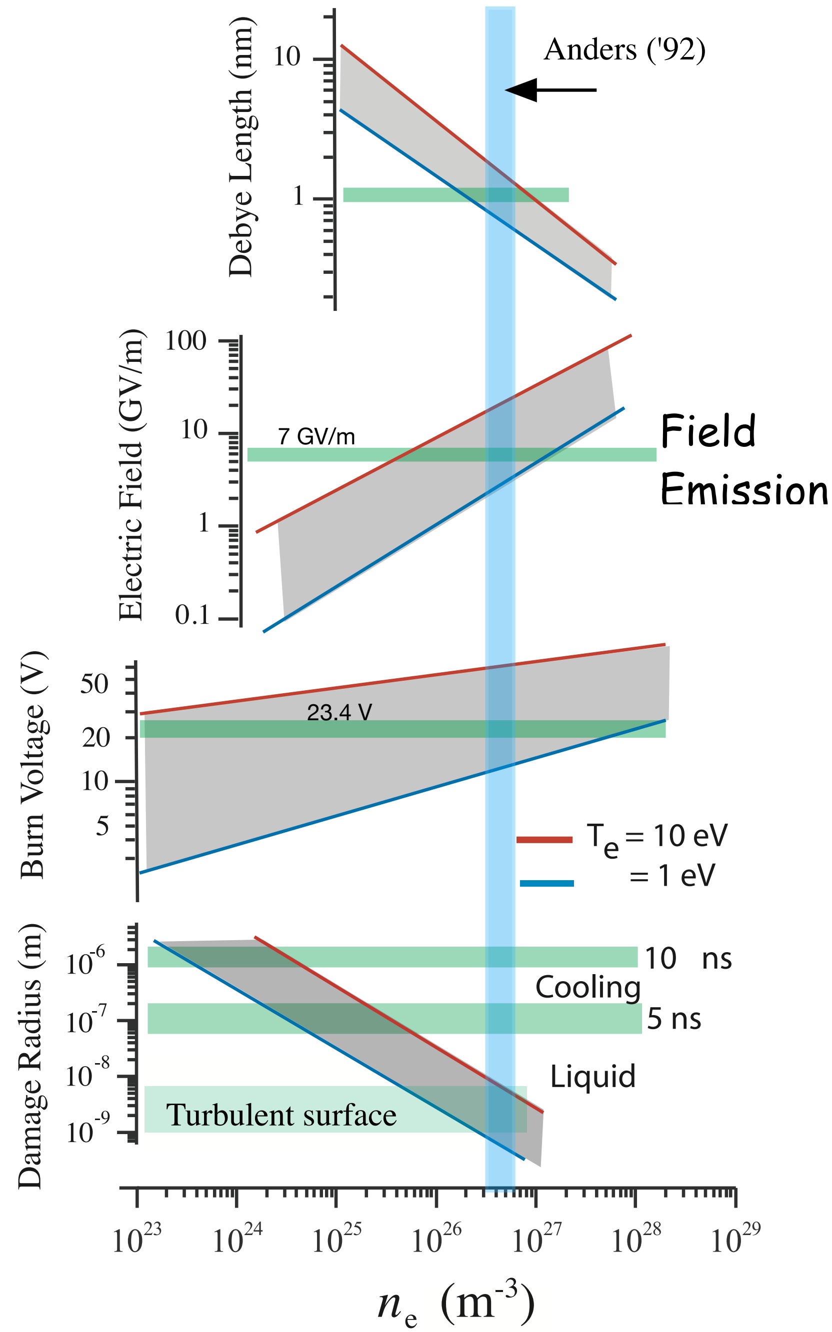
(I. Morozov)

The plasma sheath fuels the plasma, melts the surface and drives FE.

Fowler Nordheim emission produces currents that short the sheath.

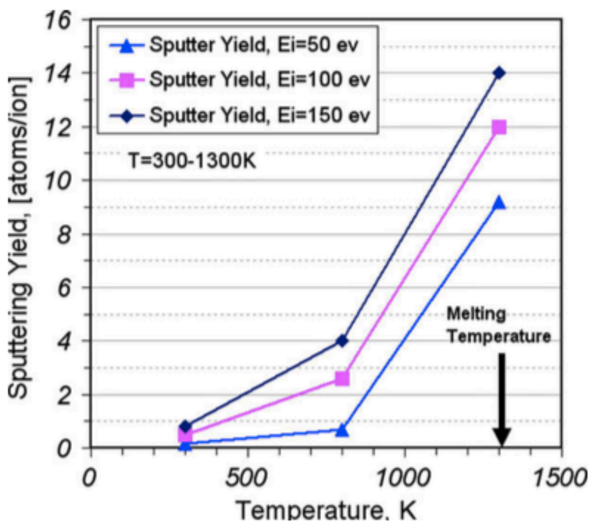
Plasma pressure, electric tensile stress and surface tension make the surface chaotic.





Complications . . .

Self sputtering is responsible for raising the plasma density



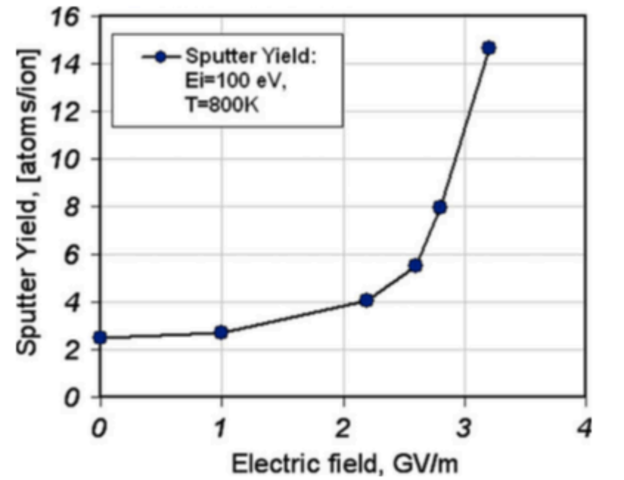


Fig. 6. Dependence of the copper self sputtering yields on the strength of electric

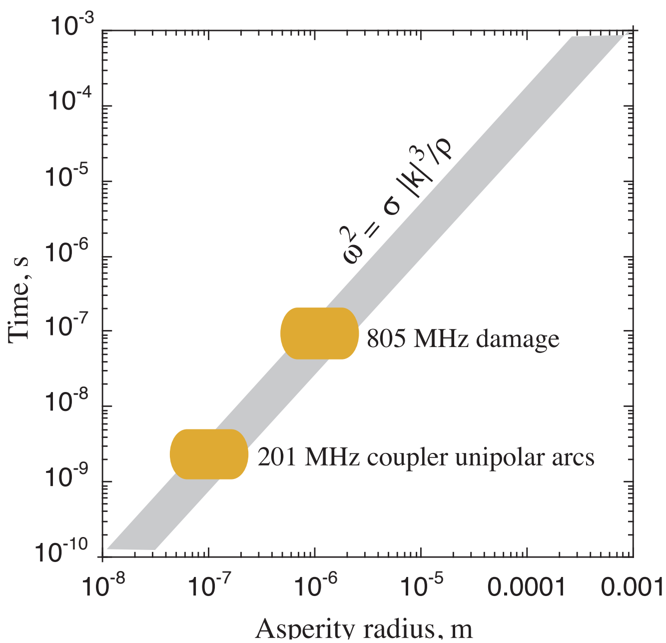
Molecular Dynamics (MD) must be used for nonideal plasmas, where the electrostatic energy is greater the kinetic energy. PIC codes aren't reliable,

Shorting currents are produced by field emission, and may vary over many orders of magnitude depending on the electric field at the surface of the metal.

Surface Damage

The plasma will produce a turbulent liquid metal surface.

The damped capillary wave equation governs liquid surface.



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

Cracks can form near the center, as the thermal contraction is localized.

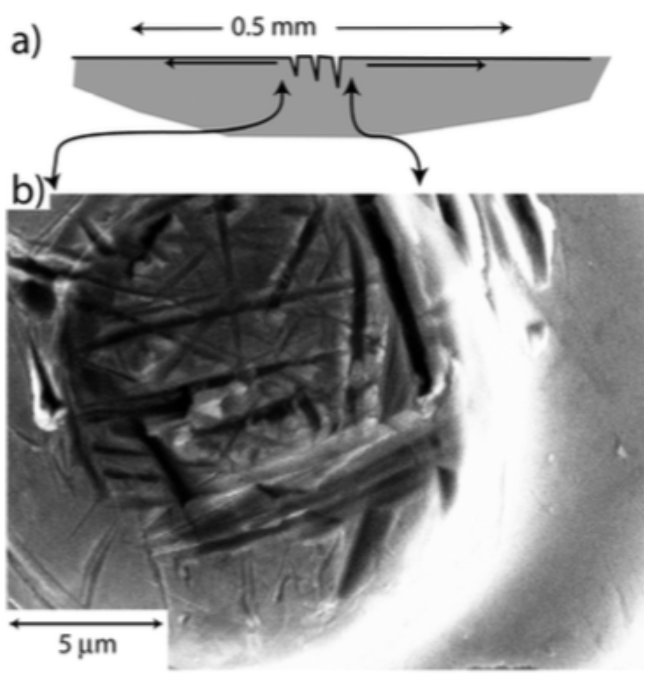
Where do β~200 asperities come from?

After the arc is over the liquid metal is smoothed by surface tension.

Cooling times before solidification determine the scale of the damage.

The surface crusts over and cracks appear when it contracts.

in cavities



in the desert

Cracks and points are common.

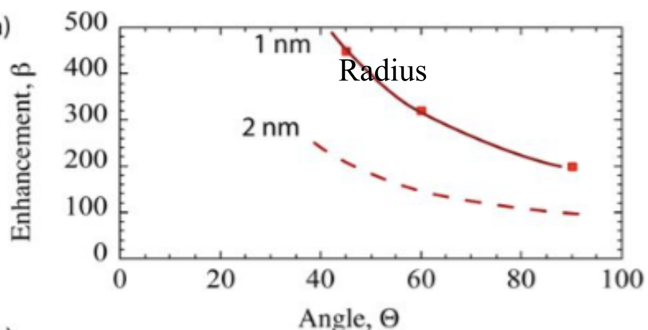
Cracks form when liquid surfaces cool.

Two stages of cracking produce ~90 deg cracks.

Co-linear B fields produce round damage, concentric central cracking (and higher βs).

However any sharp points can produce high βs.

a)



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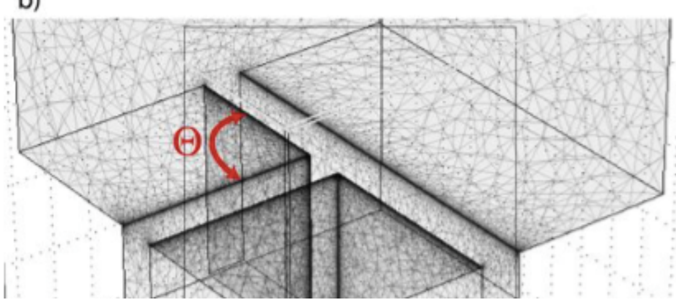
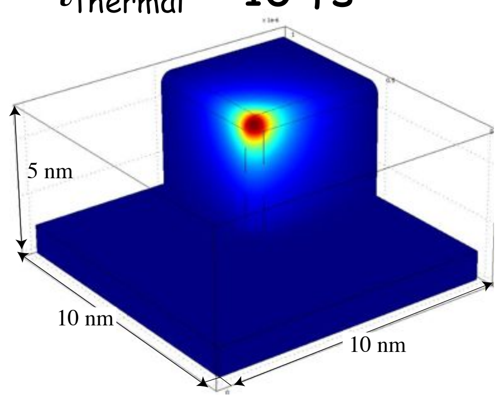


$\tau_{thermal}$ ~ 10 fs



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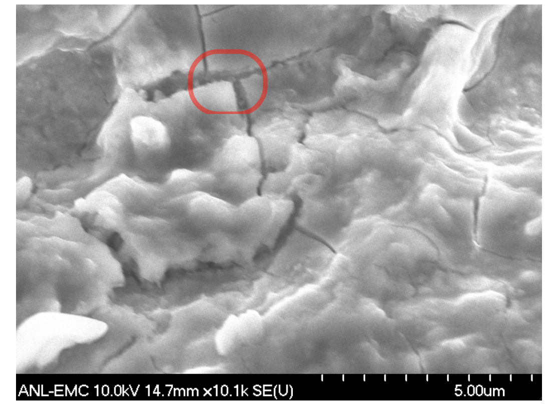

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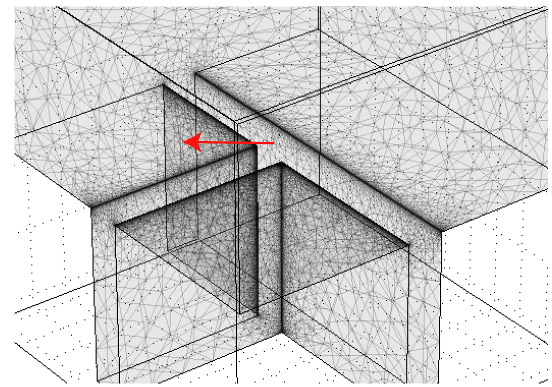
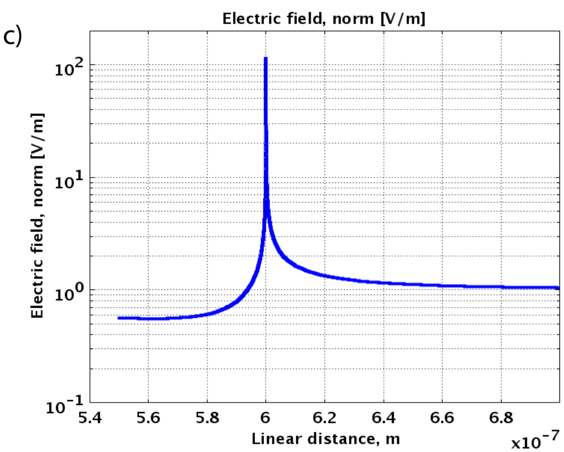


c)



Unipolar arcs (plasma spots) **are also common.**

:

Quasi-stable, local plasmas maintained by ext. gradients and sheath potential. Not actively studied (except by us and Kajita).

- Small: 10 – 100 μ
- Potentials: < 60 V
- Current Densities: 10^7 - 10^{12} A/m^3
- Dense: 10^{26} – 10^{27} m^{-3}
- Debye length: ~ 1 nm
- Surface E field: 7 – 10 GV/m
  - forces ~ tensile str. – unipolar arcs stick tightly
  - FN field emission - unipolar arcs emit high currents
  - Very high plasma pressures - unipolar arcs damage surfaces
  - High self-sputtering - unipolar arcs maintain themselves

The arcs were extensively studied in small limiter tokamaks 20+ years ago, by F. Schwirzke and R. J. Taylor and others

Unipolar Arcs

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

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 electrons can produce shorting currents.

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

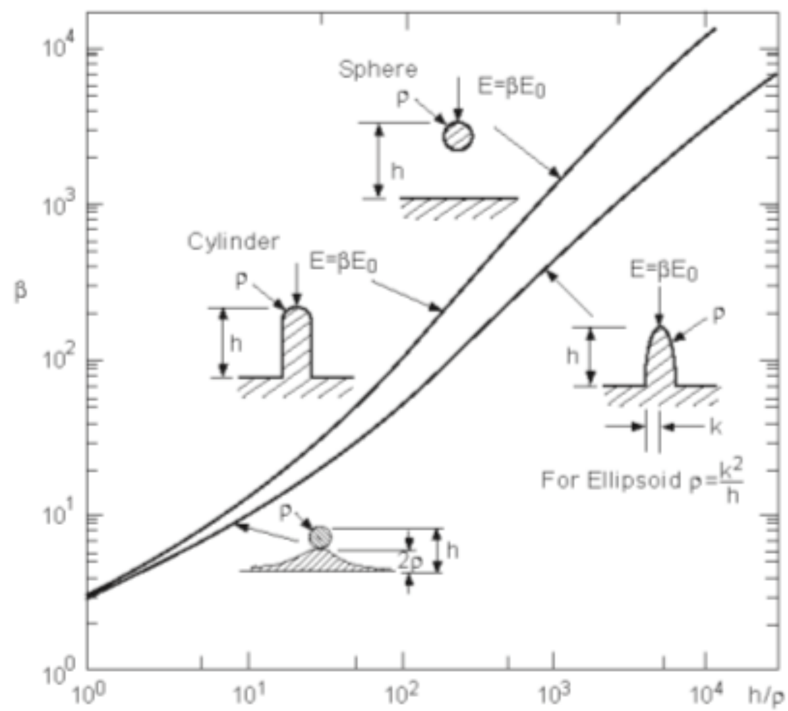
MD shows however, that nonideal corrections are small.

How does our model compare with other work?

Narrow lines on plots imply that effects like electromigration and Coulomb explosions have sharp thesholds, in fact, for rough surfaces these effects can vary over >10 within a few nm. (see Feynman Lectures)

Many use the "Fowler-Nordheim plot", i.e. $\ln(I/E^2)$ vs 1/E to check data and evaluate parameters. We think this is a bad idea, destroying ones natural intuition, knowledge of experimental errors and physical & material limits.

Following Dyke et al, many have assumed that field enhancements are due to whiskers/rods/"fenceposts". They are not seen.



There are a number of reference books

The Handbook of Vacuum Arc Science and Technology (1993 - 2012)
Boxman, Sanders, Martin

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.

None of these books discusses electromigration, Coulomb explosions, nonideal plasmas, capillary waves or how to produce high β asperities, plasma formation,

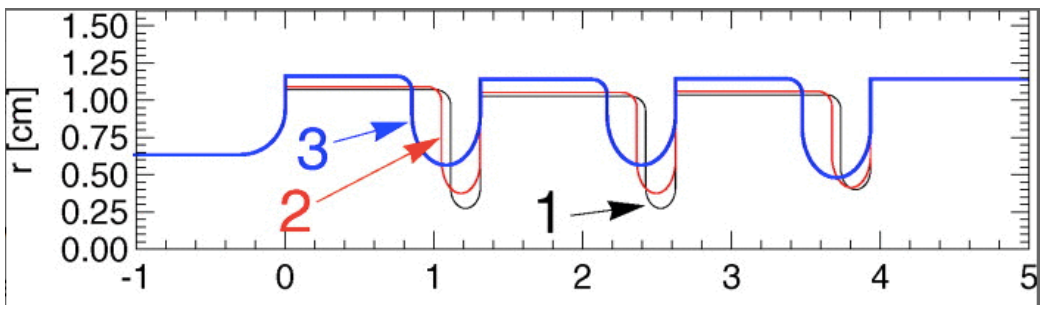
SLAC Pulsed Heating

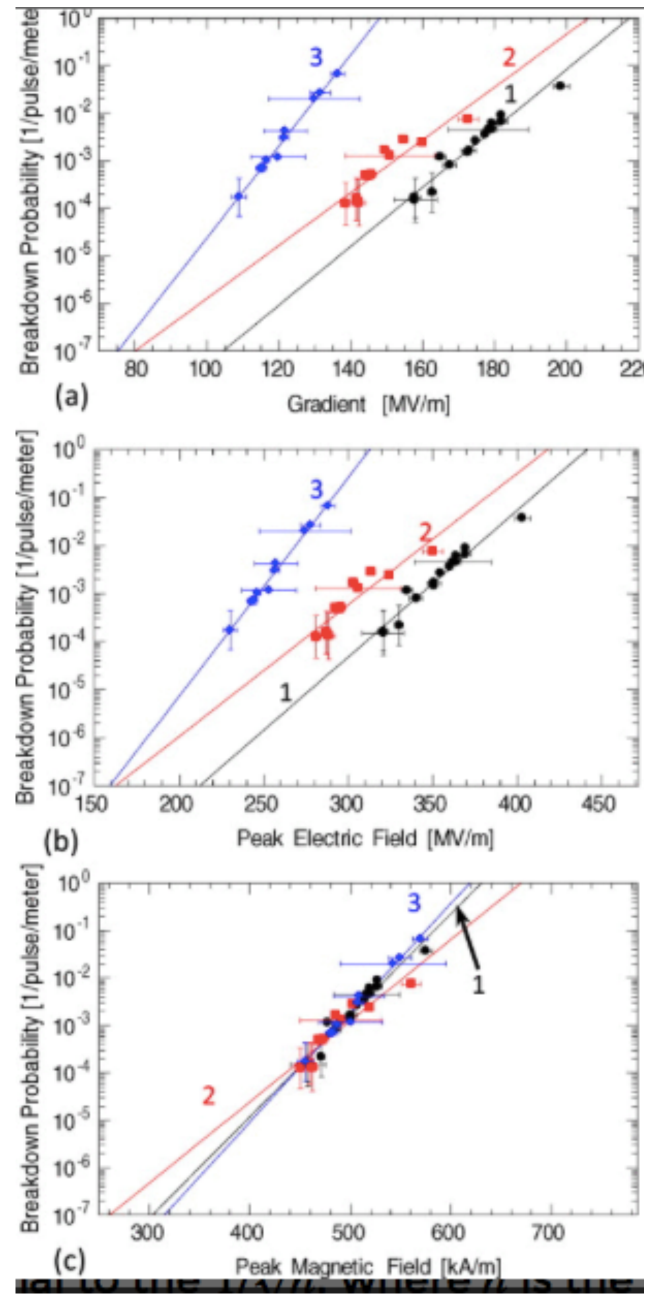
Although they don't study arcing as such, either experimentally or models, around 2001, SLAC found that surface currents in the walls caused damage in the surface itself and they began to argue that this damage was involved in breakdown, even using the terms interchangeably.

Pulsed Heating Damage does exist and Breakdown does exist, but we find the evidence that Pulsed Heating significantly affects breakdown thresholds to be surprisingly weak and indirect.

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.

Breakdown Rates are not well understood or easily calculated. Using them to compare widely different geometries seems unreliable.





We explain the slope of the lines BDR ~ E^{28} as BDR ~ j^2 where $j \sim E^{14}$.

Questions:

Where is Peak magnetic field measured?

How does change in Q alter efficiency?

CERN Small Gap Experiments

CERN has been measuring beakdown parameters with small gaps.

They use gaps of ~20 μm and voltages of ~2 kV.

They have not repeated the Earhart / Hobbs results at low voltages.
This gives a misleading impression that large voltages are required.

They seem not to have measured breakdown thresholds in cavities.

European Modeling Efforts

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

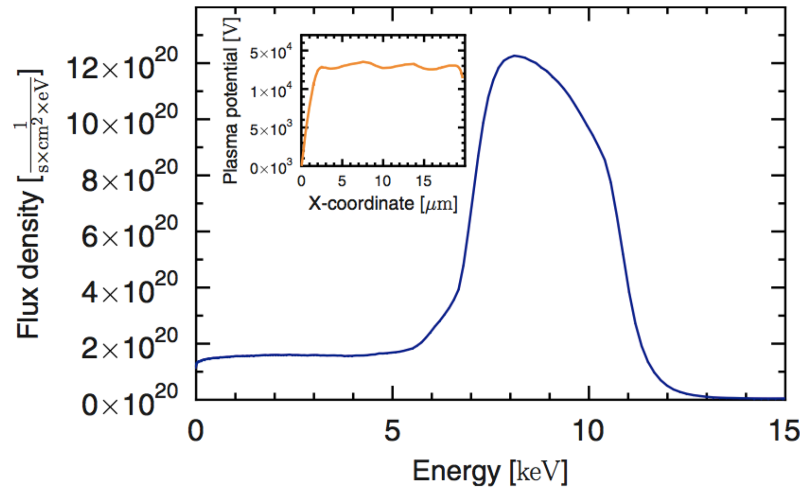
We find that we disagree with many of their conclusions.

Although the long term goal of this work is largegap+RF+vacuum+breakdown, much of their experimental and modeling work is devoted to small gap, DC, gas breakdown, and their conclusions may not apply to accelerators.

For example, for many years they modeled vacuum breakdown by adding gas until a classic gas avalanche occurred. They also assume that huge potentials (~10 kV) can be supported by plasma sheaths, and these plasma sheaths determine the properties of the breakdown, plasma pressure and surface effects.

Helsinki/CERN modeling produce large sheath potentials, we see 20 – 30 V.

They consider 10 keV ions, we use plasma pressure & E fields to explain damage.



They use thermodynamics to explain BDR, we consider huge forces on nanoscale asperities.

They consider invisible pre-existing subsurface defects, we consider sharp points that we see. We can explain what they see.

They consider specific mechanisms, we model every stage of the arc.

Our model generalizes to other environments and other fields.

We assume plasma pressure produces damage.

Our model precludes the damage they assume.

Interesting Experimental Topics:

There are a large number of profitable experimental studies, for example:

1) Field emission and the surface fields are related. RF arcs seem to be larger than DC arcs, Why?

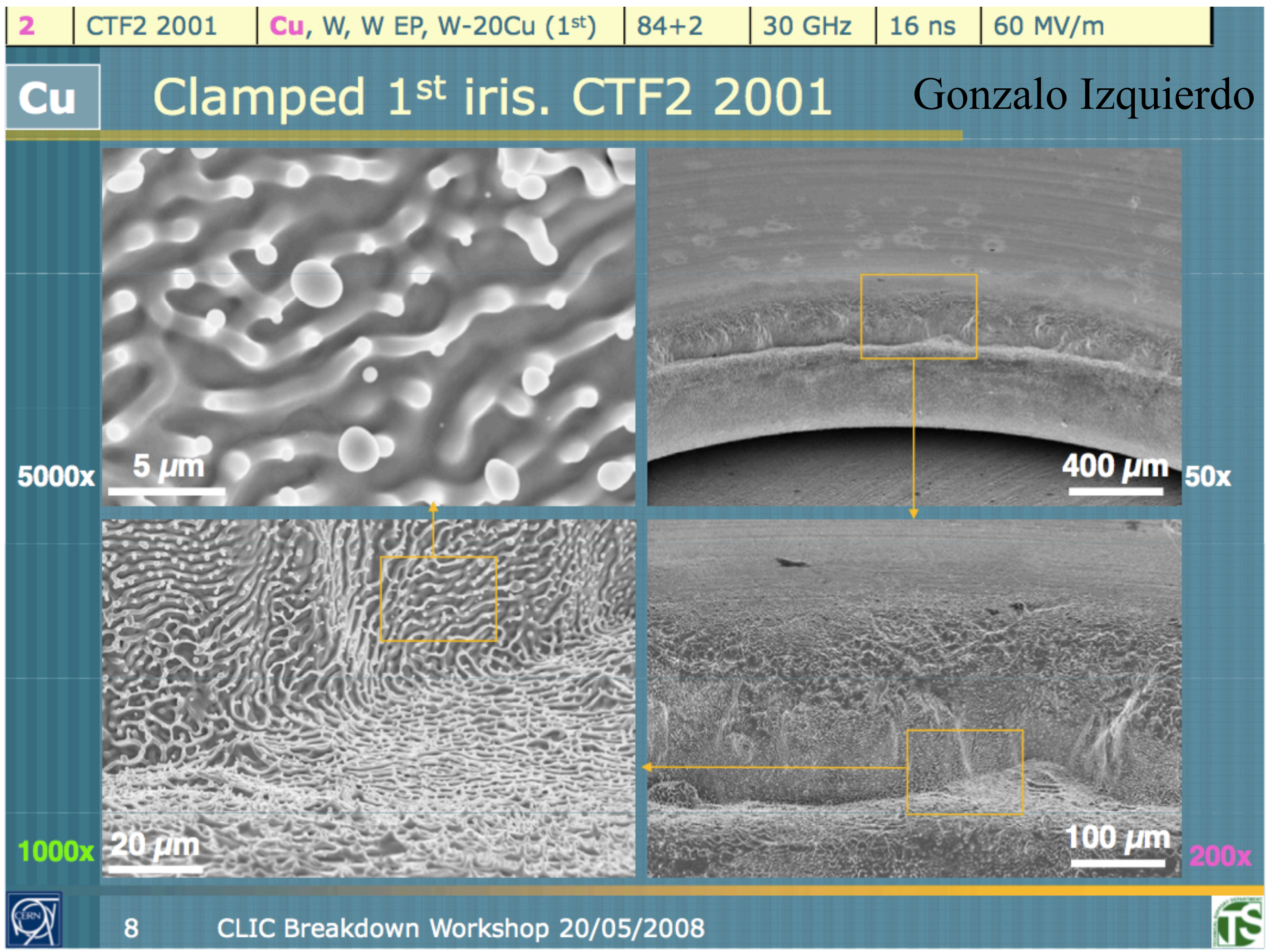
2) Our model applies only to vacuum very low pressure systems. What if there is a pre-existing plasma?

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

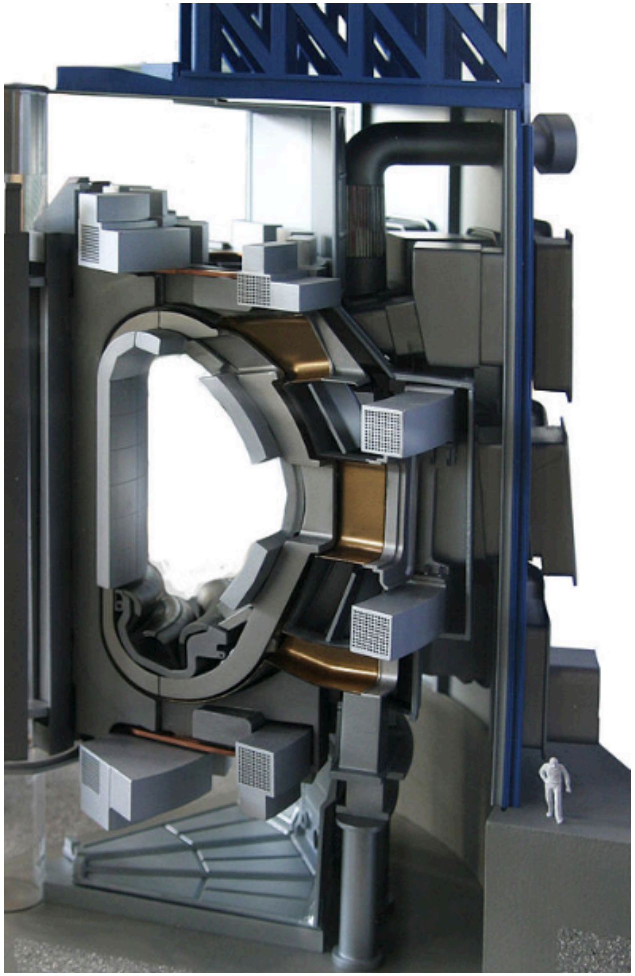
1) Does the FN current density depend on arc parameters?

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 large and comparatively passive.

CERN data implies quiescent plasmas limited by space charge.



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) have the users pay for the losses.

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.

We disagree with much of the work from CERN and SLAC.