Modeling Arcs

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rf2011
Newport R. I.
June 1-3, 2011

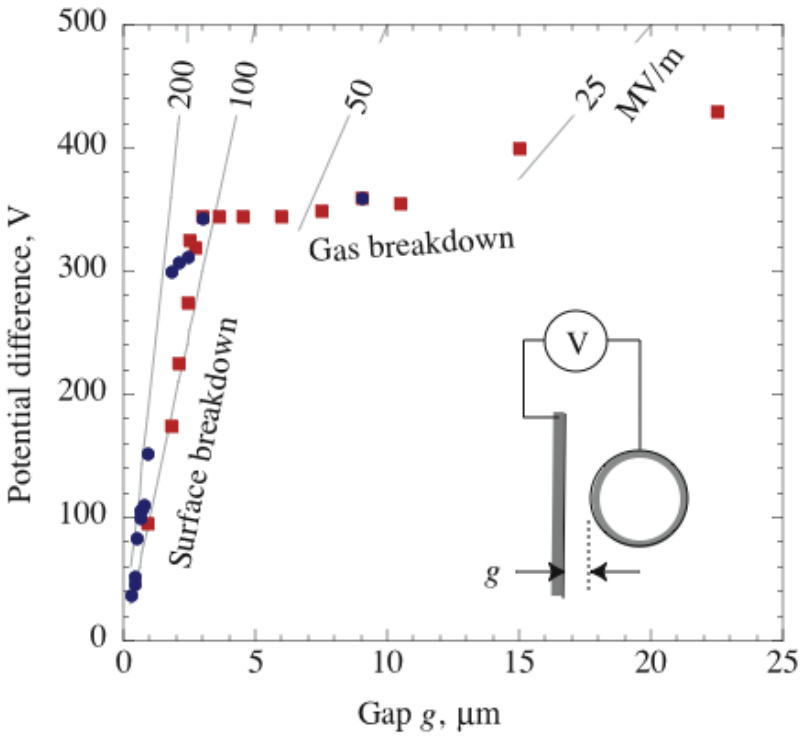
Muon Accelerator Program

Argonne NATIONAL LABORATORY

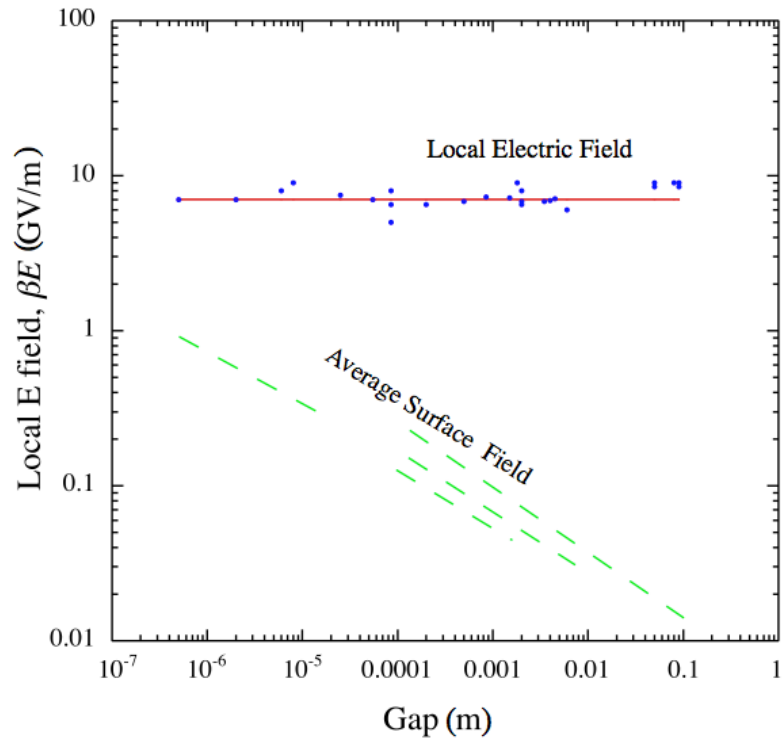
Vacuum arcs are defined by very old data

Old data define the problem:

1900-1904



1964 summary



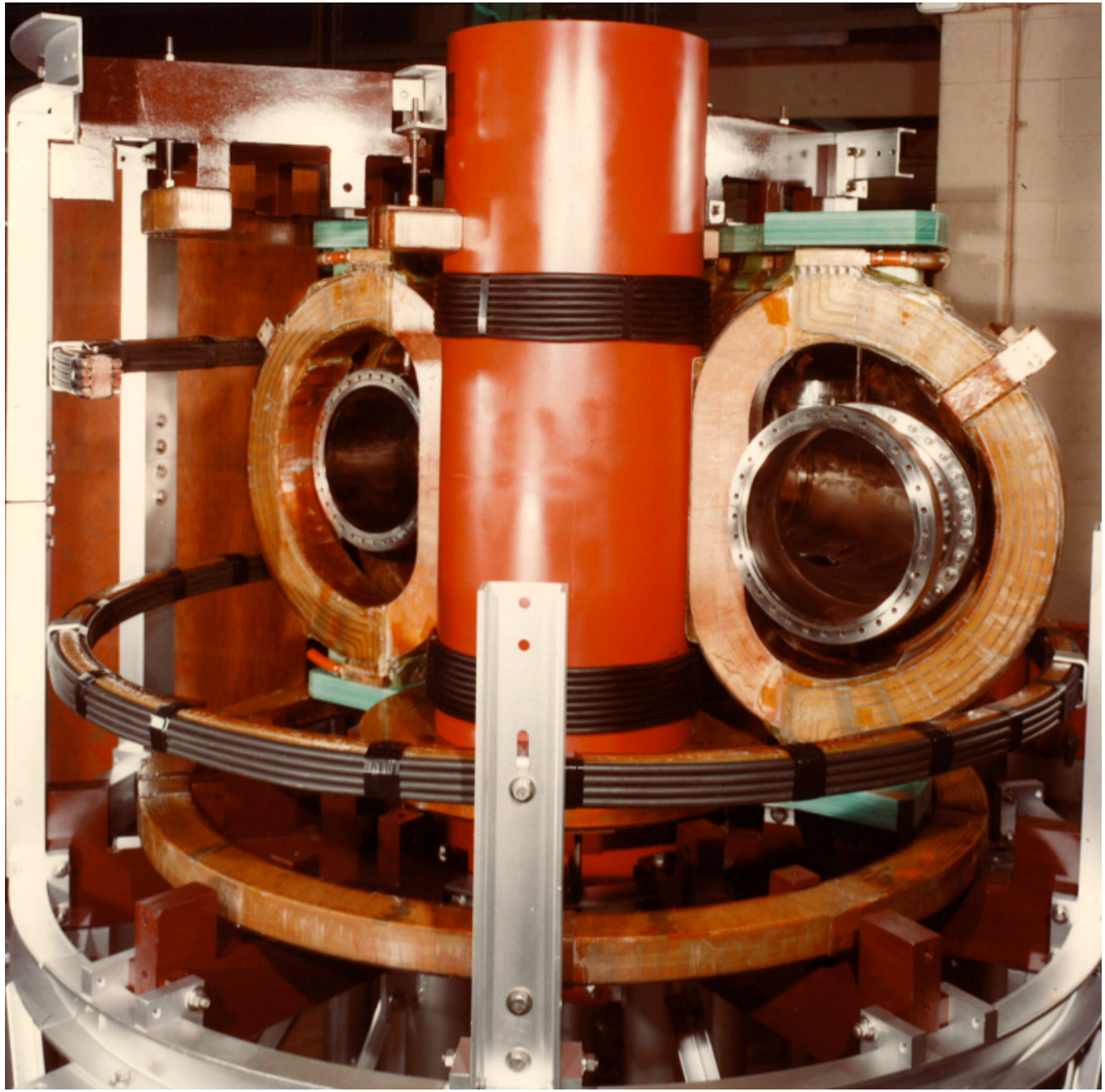
According to this data, vacuum arcs:

- are different from gas breakdown (Michelson and Millikan),
- are a single-surface phenomenon (Alpert et. al.).

Lord Kelvin showed in 1904 that breakdown should occur at E_{local} ~ 10 GV/m.

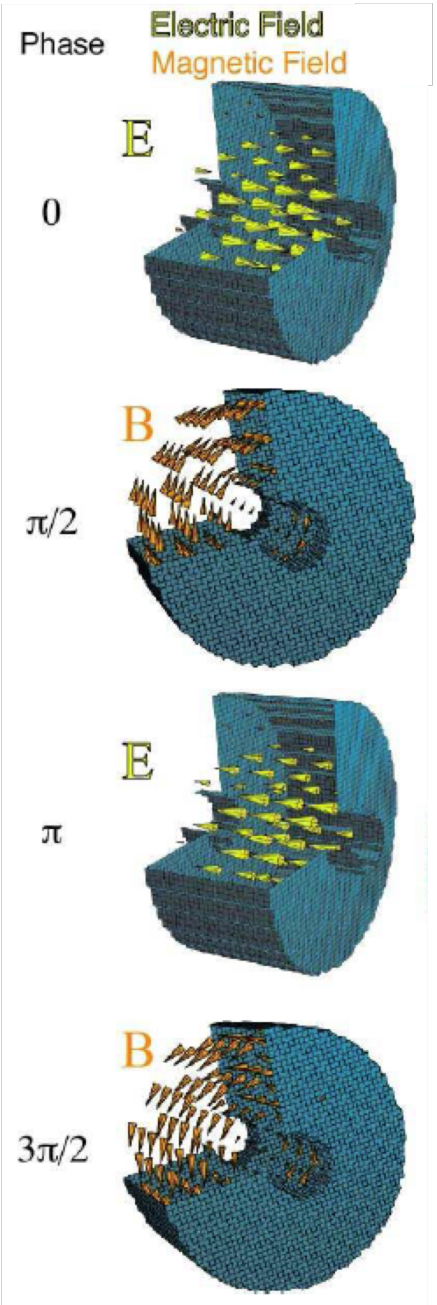
There has long been interest in plasma/materials at Argonne.

- The APEX tokamak was built to look at Be wall effects.
- operated ~ 3 years.
- on exhibit at museum for many years
- Present effort is aimed at accelerator gradient limits.
  - Experiments at FNAL
  - Modeling at Argonne.



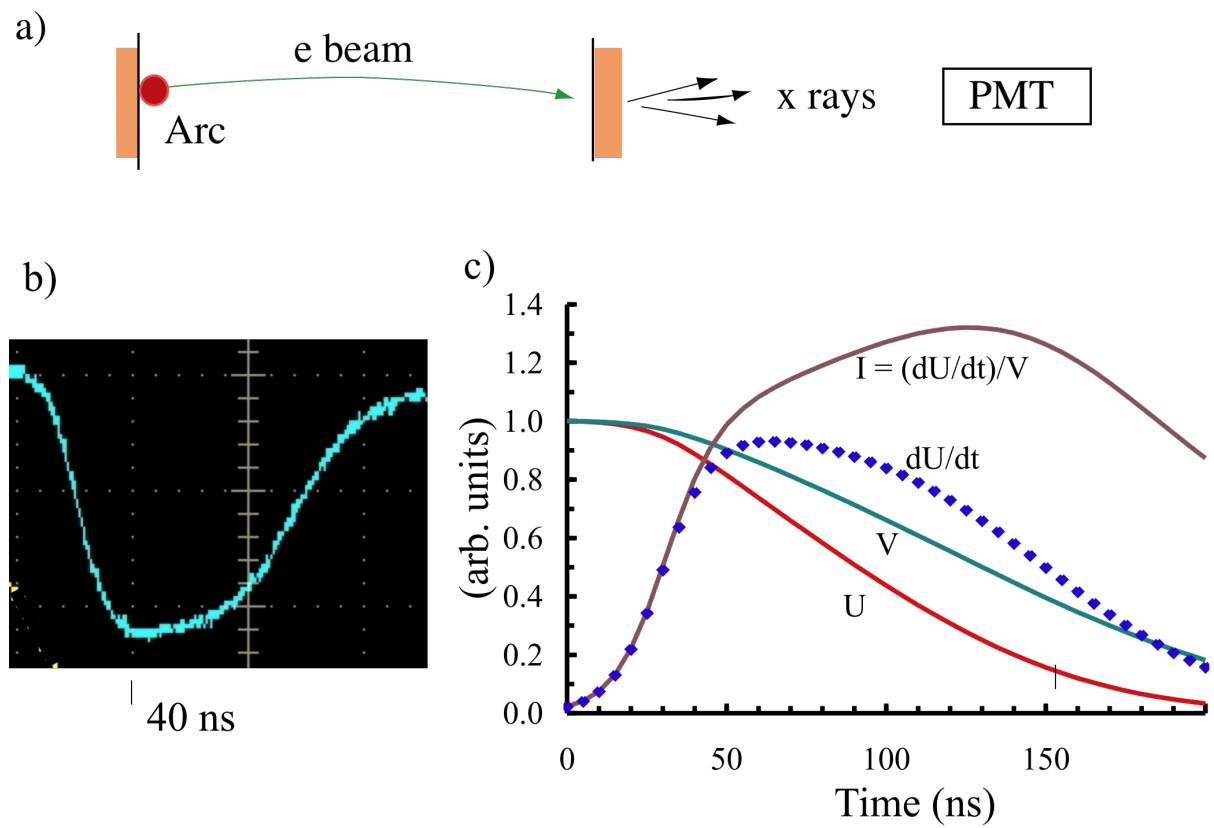
We look at arcs in linac rf cavities.

Linac cavity



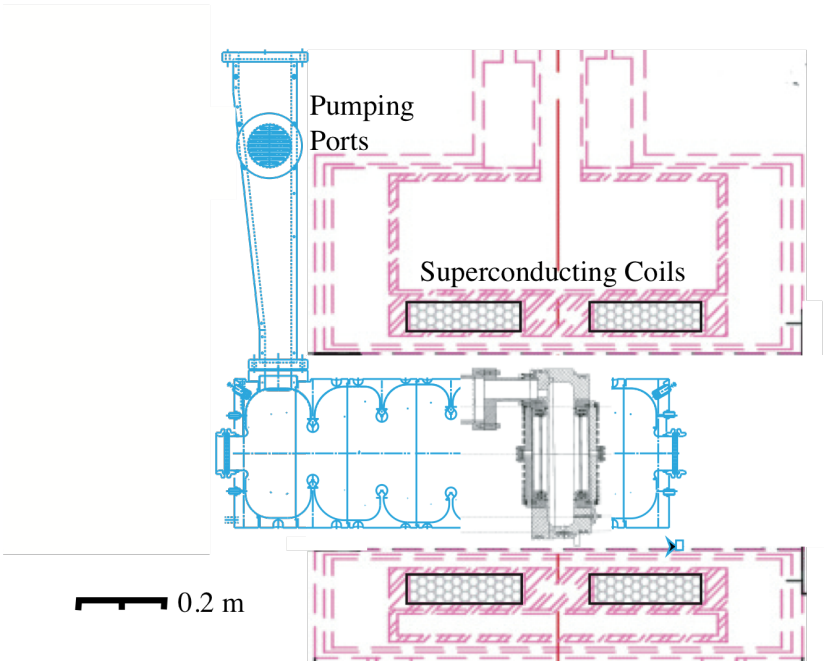
Breakdown event

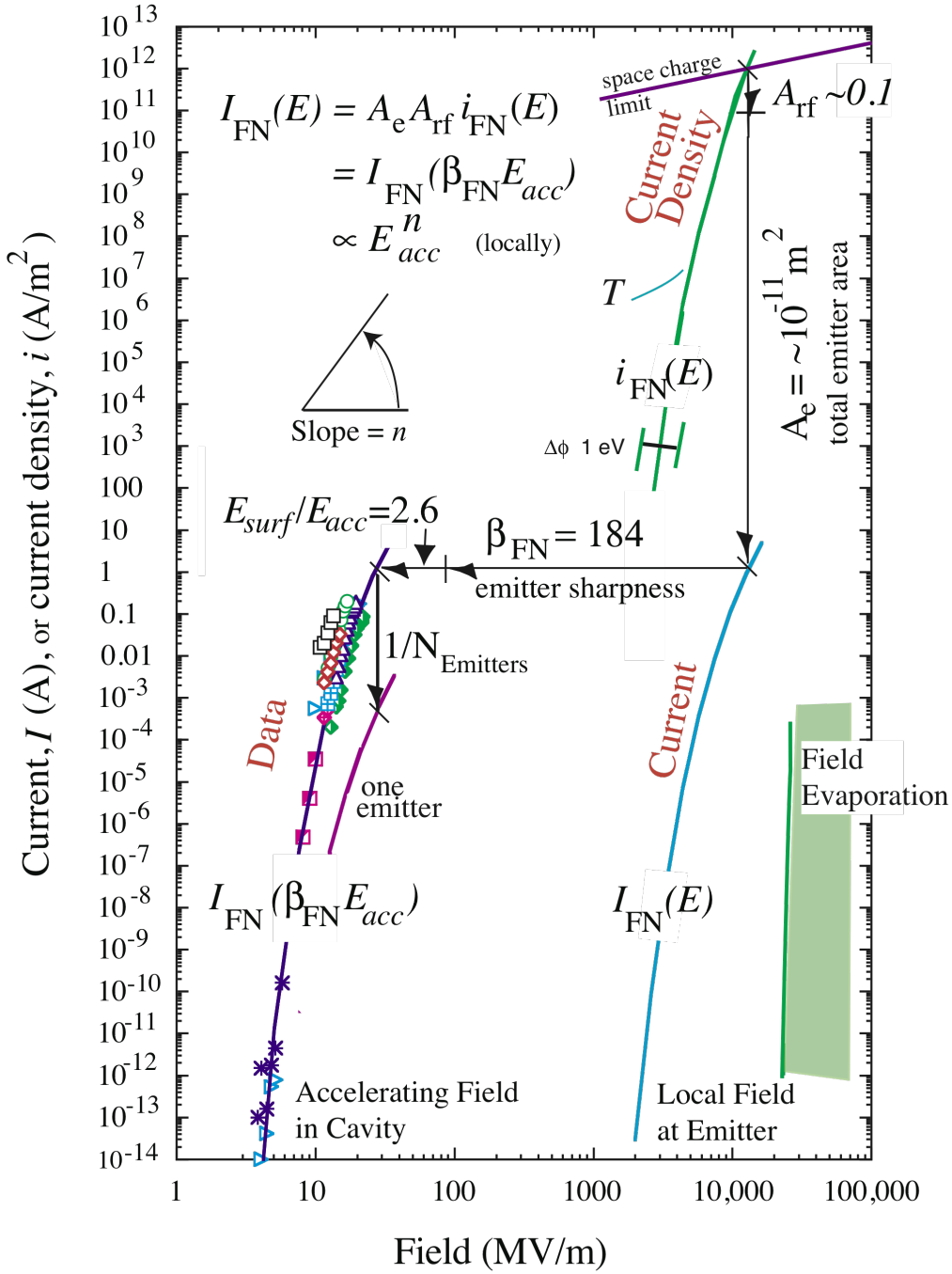
- We primarily look at x rays from shorting currents.
- Stored energy, Fields & currents calculated.



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

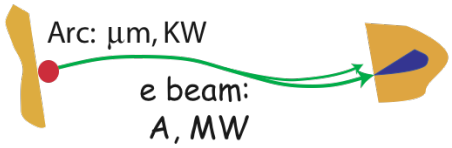
- Breakdown sites are highly stressed.
- E_{local} is close to the tensile strength.
  $\varepsilon_0 E_{local}^2/2 \sim \sigma$
- Our experiments involve rf cavities with and without magnetic fields.





We are trying to understand what mechanisms dominate.

Arc Mechanisms



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

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

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)]

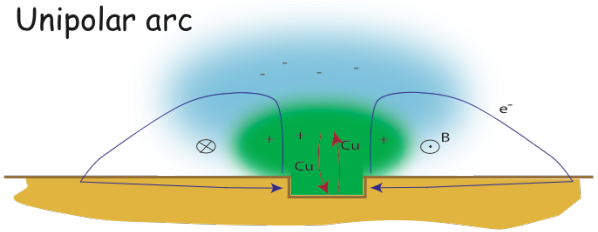
Atomic Layer
Deposition

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

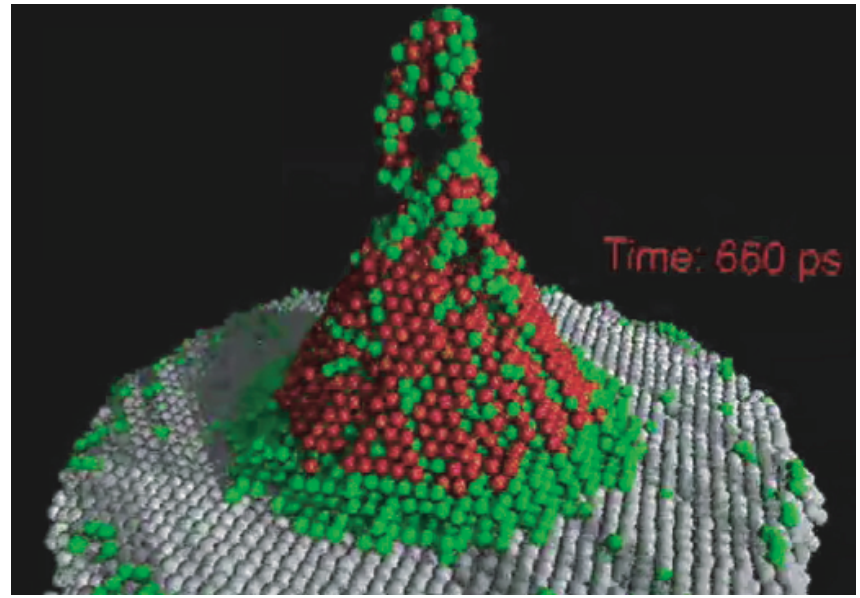
Unipolar arc



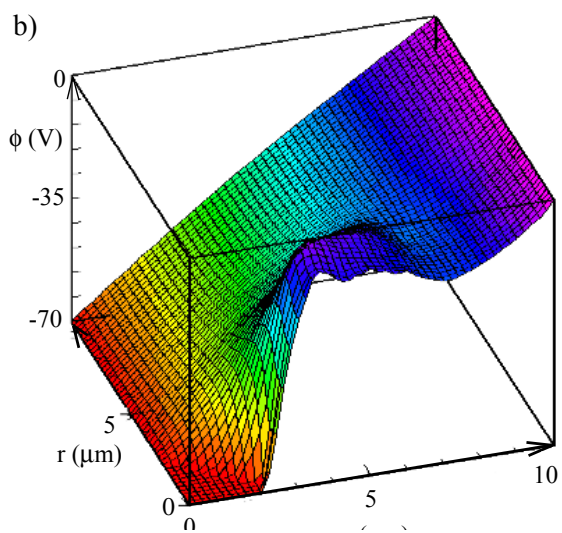
We think that Coulomb explosions and unipolar arcs are crucial.

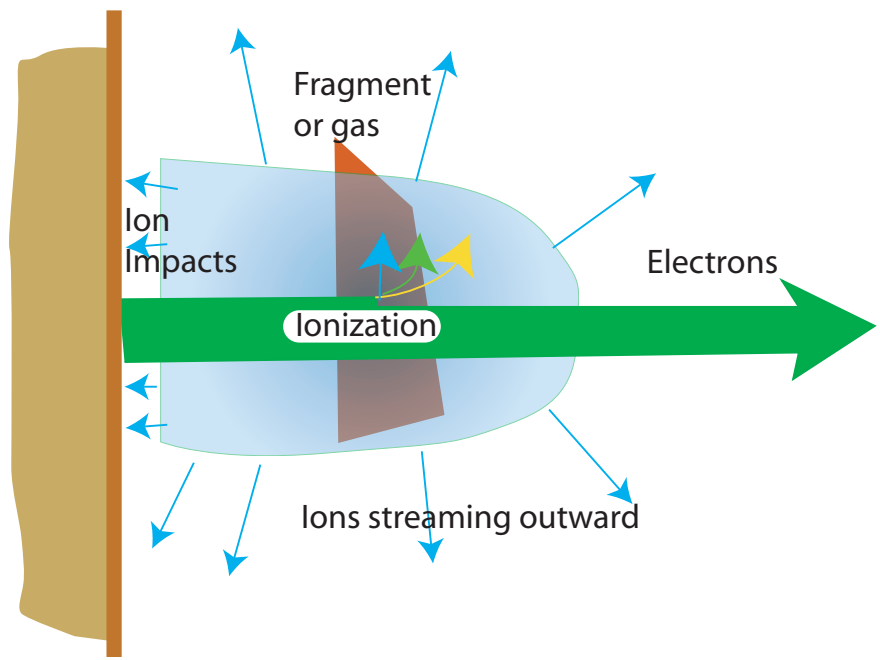
Our picture from Molecular Dynamics (MD):

Coulomb explosions trigger arcs.
(Coulomb force > atomic bonds)

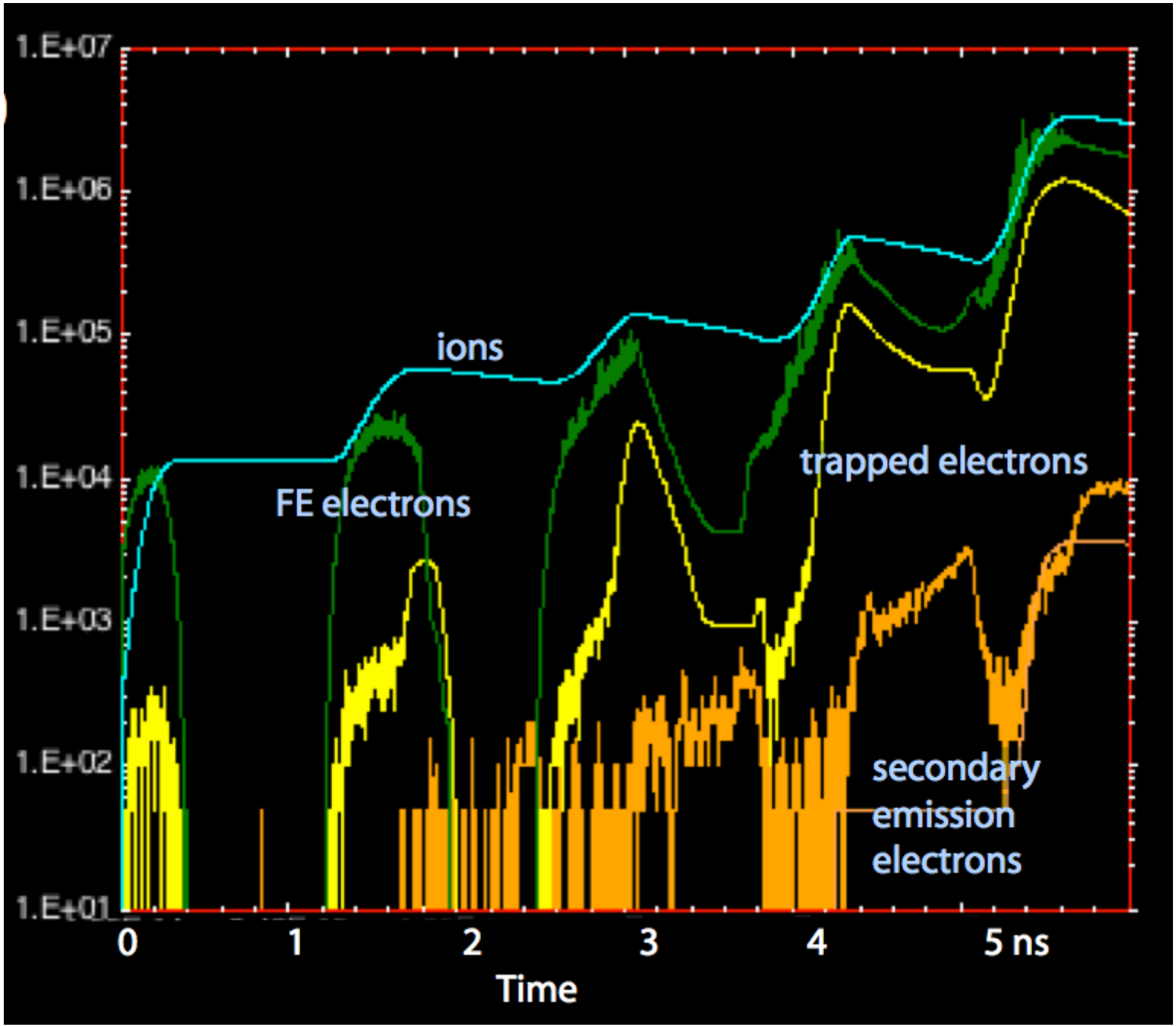


Unipolar arcs evolve.





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

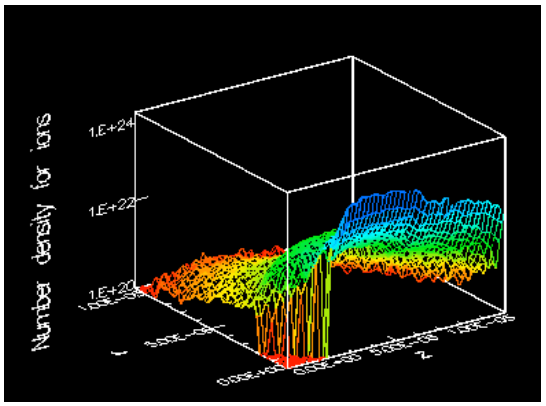


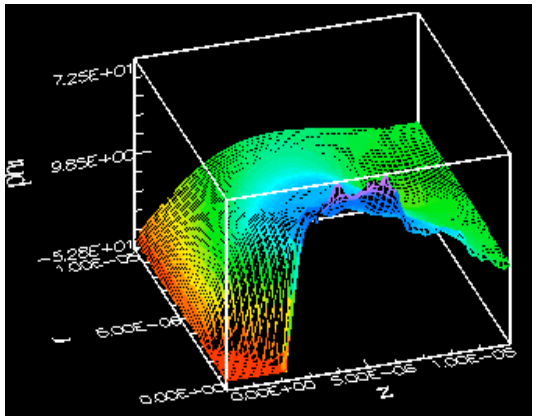
OOPIC Pro results.

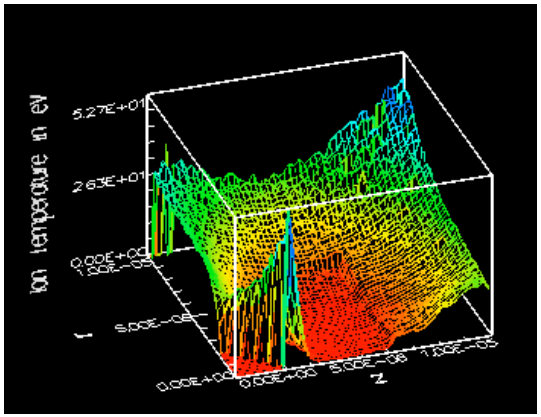
Dimensions matter

OOPIC Simulations (at ~ 6 ns), $r_{max} = Z_{max} = 10$ microns

Ion Density, Phi, T_I







Arc dimensions a few microns.

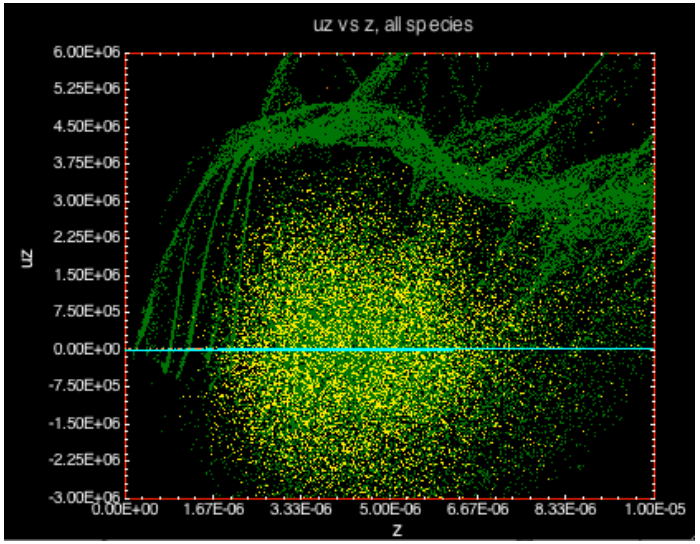
The arc is at the cathode.

Primary electron current

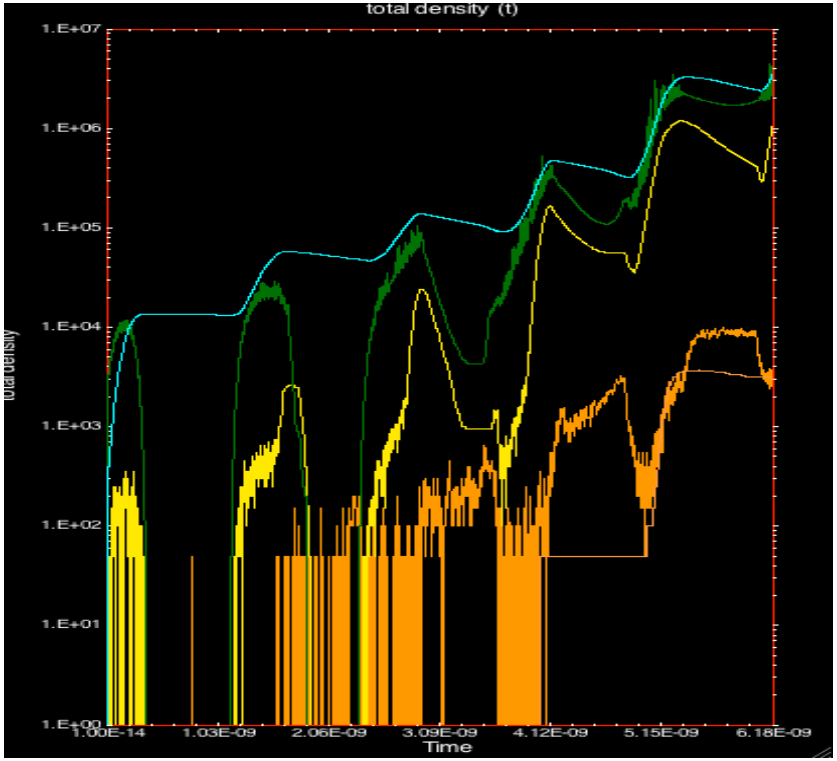
Space charge limit can be seen in v_z vs z

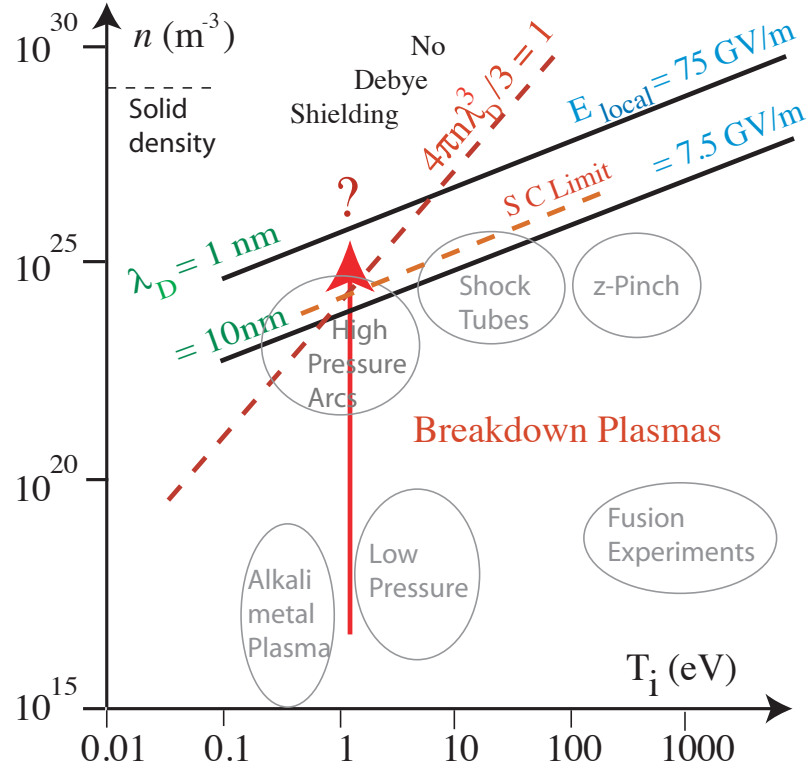
Plasma functions as a virtual cathode

Collision length remains constant ~ 10 μ

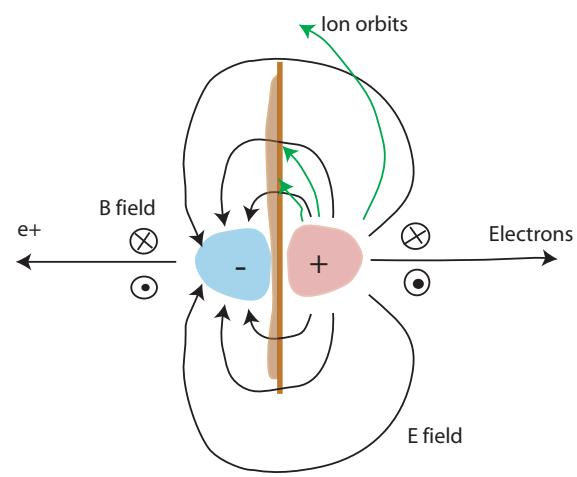


The density rises until the plasma becomes non-Debye.



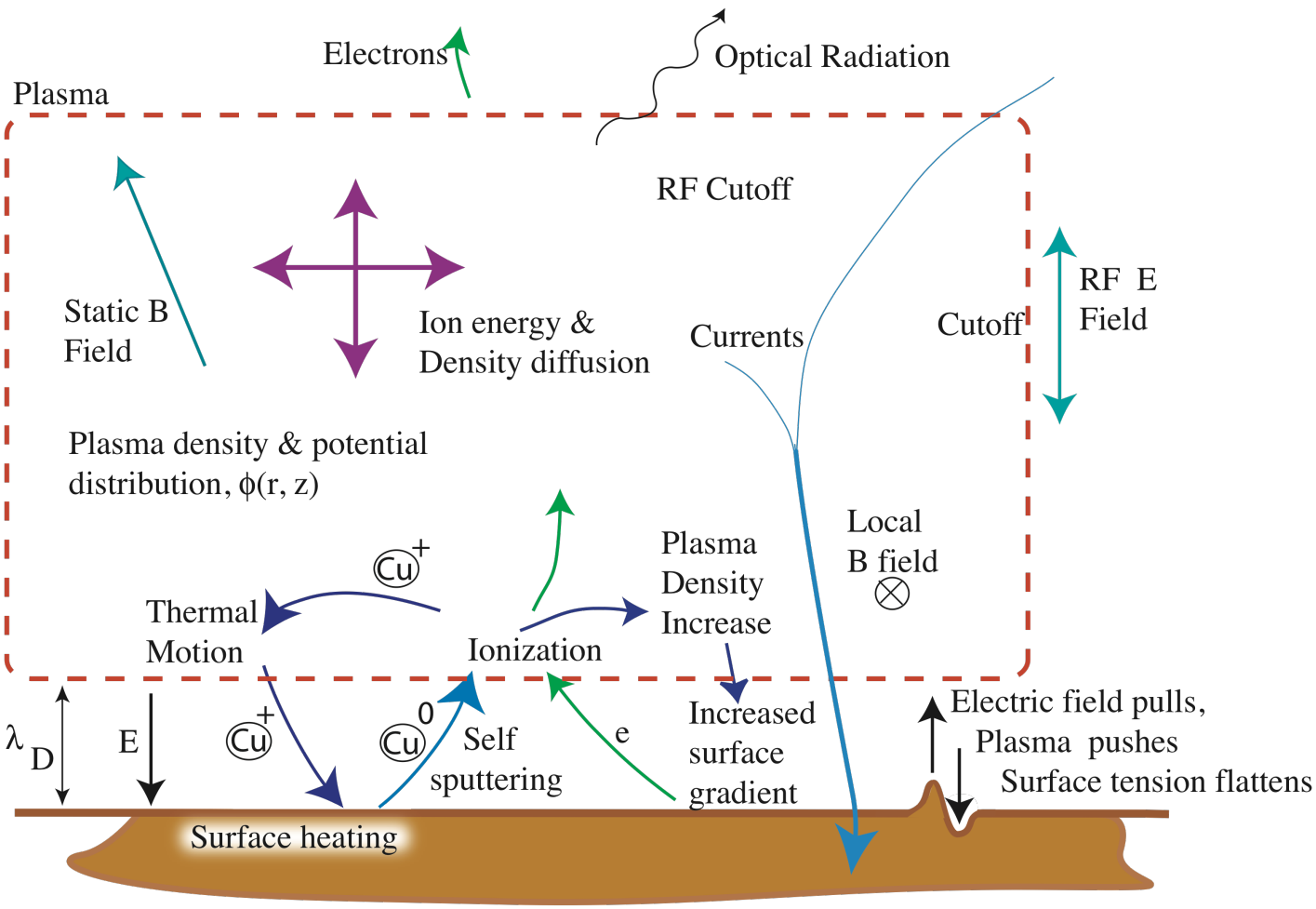


The electric field distribution can be calculated.
giving plasma pressure.



The arc is complex

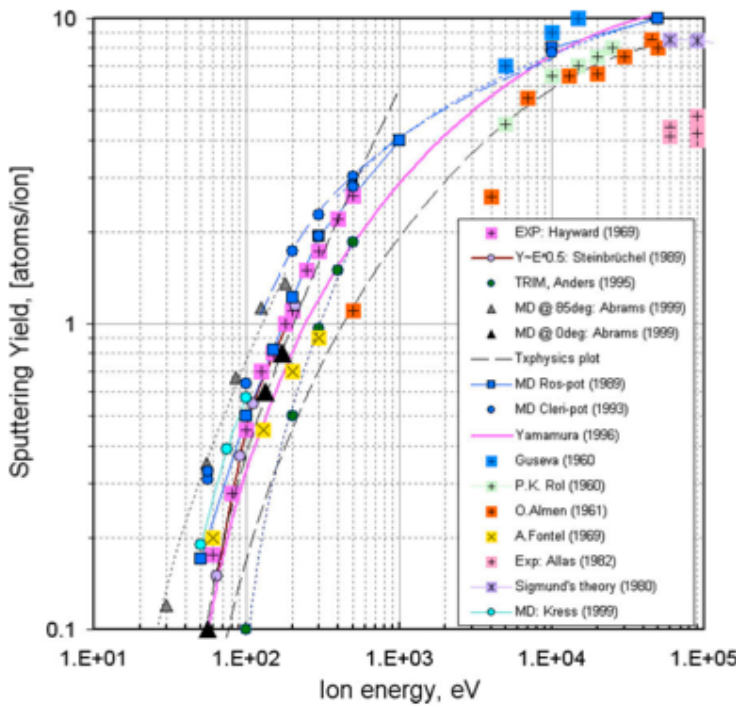
- The surface electric field defines the plasma thru sputtering and field emission.
- Inertial confinement of ions and quasi-neutrality constrain its evolution.

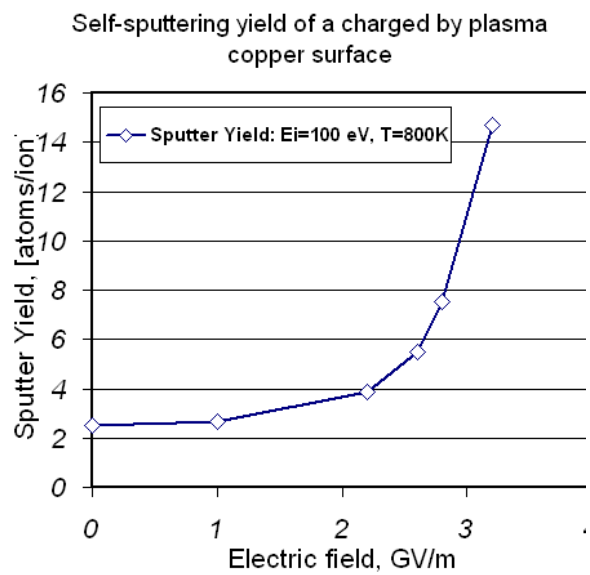


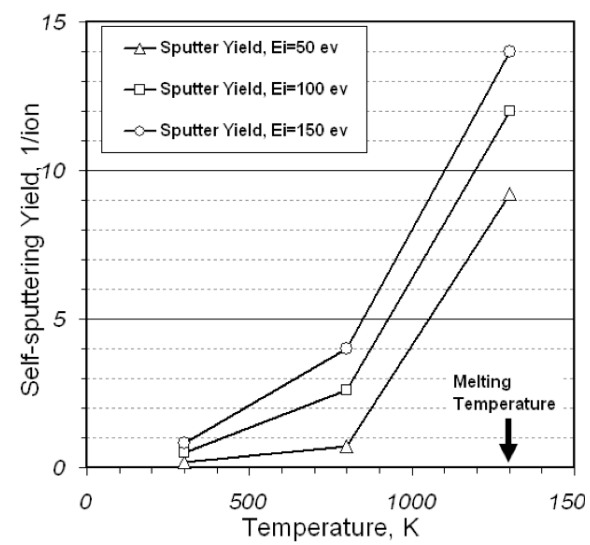
High temperatures and fields increase self-sputtering.

- 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 calculate high self-sputtering yields using Molecular Dynamics.







This plasma is a NON Local Thermal Equilibrium (LTE) plasma

- Ion & Electron Temperatures are very different
  - Ions are essentially thermal (T ~ 0), but stream in the electric field
  - Electrons stream through the plasma, but some are trapped.

Liquid surface deformation

- Surface tension flattens surface
- Electric tensile force pulls on surface, may be inhomogeneous
- Plasma pressure pushes on surface
- Spinodal decomposition causes ripples, can measure plasma surface properties
- Non-Debye plasma properties are not understood

Plasma pressure is significant, $p=nkT$,

- Generates particulates: Chapt 6 of Anders "Cathodic arcs"
- Surface heating comes primarily from ion current
- Plasma pressure forms small craters.

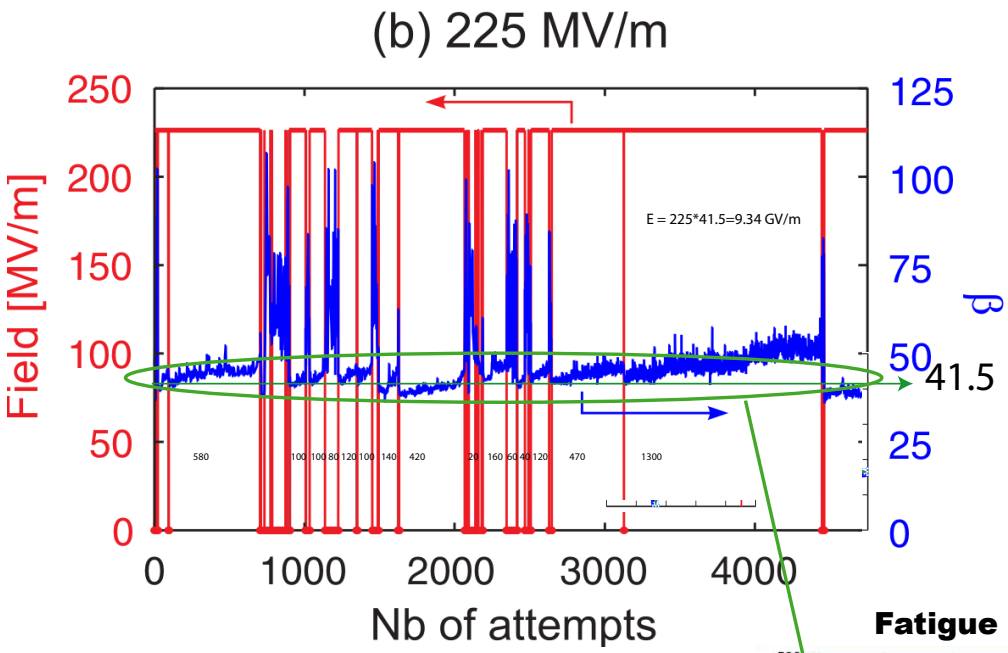
Power balance

- Ion, electron fluxes change rapidly
- Radiation flux goes like n^2
- Surface heating is large and localized
- Distribution of energy can be calculated.

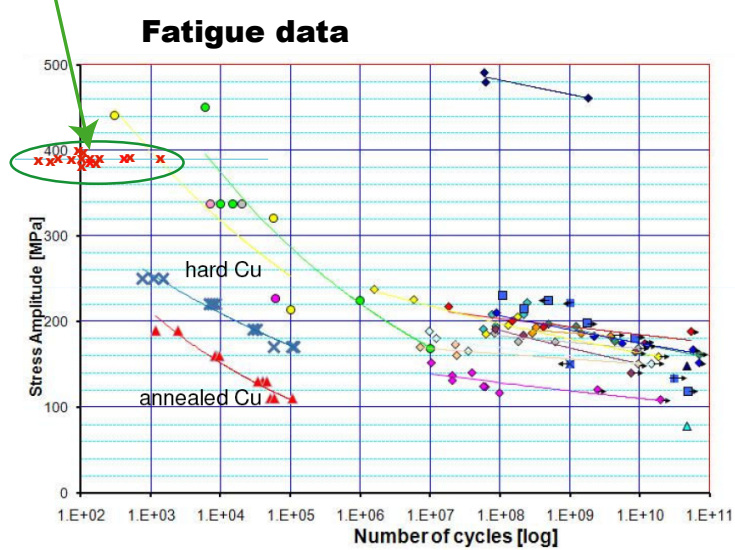
Fatigue can contribute.

Coulomb explosions are compatible with fatigue

CERN small gap data consistent with fatigue.



$P = E^2\varepsilon_0/2 = 386$ MPa



Field enhancements, β, are a source of confusion.

Fitting historical field emission data seems to give a wide range for β and A.

$2 < \beta < 1000$

$1\ nm^2 < A <$ many μ^2

(This wide range is not seen in cavities however.)

These values are not compatible with a whisker model of enhancement factors.

The validity of the Fowler-Nordheim field emission model (and quantum mechanics) has been questioned.

We look at very small structures:

Emitters are small, ($A \sim 1\ nm^2$) with natural βs around 100.

They are formed at crack junctions and spattered particulates.

If they sit on other structures, their βs can be much larger.

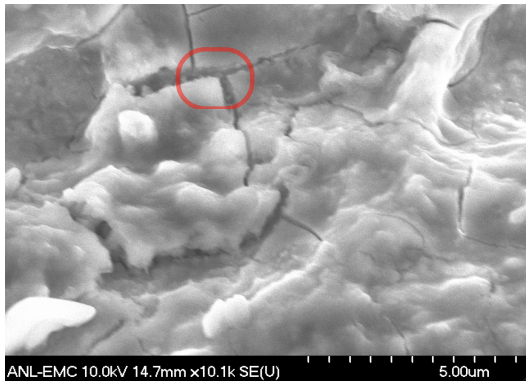
If there are lots of them, the combined A will be much larger.

Surfaces are rough, so lots of structures to sit on and lots of spatters/cracks.

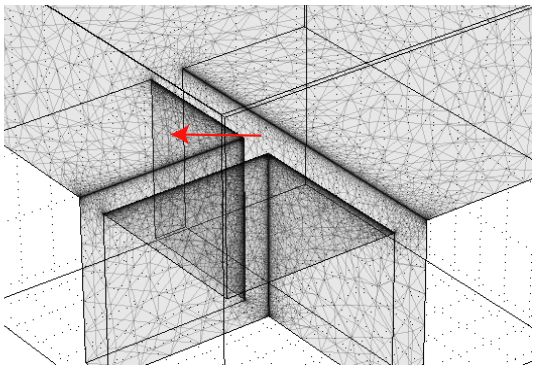
Cracks can provide high enhancements.

SEM showing cracks

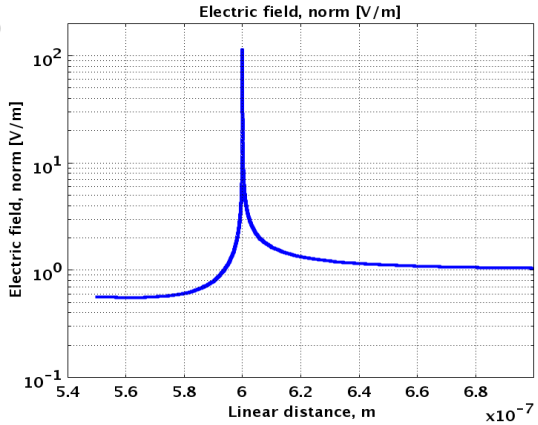
a)



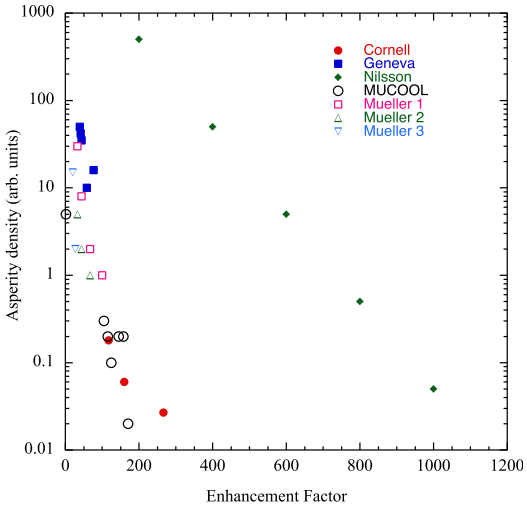
b)



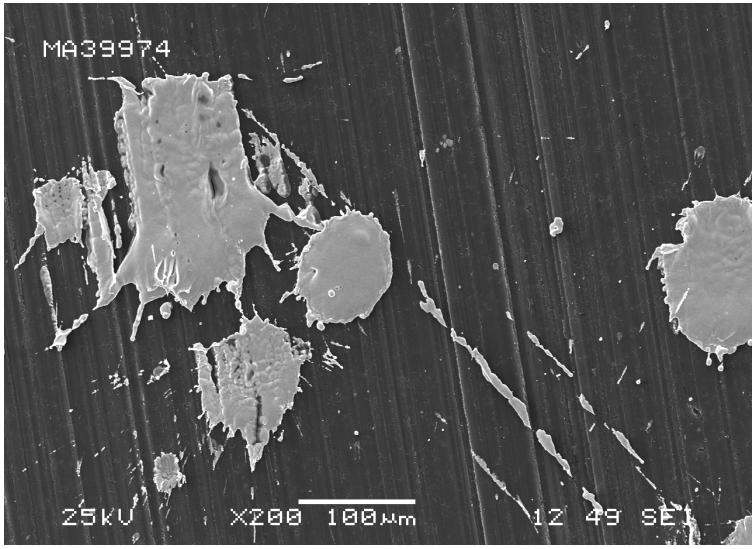
c)



$n(\beta) \sim \exp(-\beta/40)$



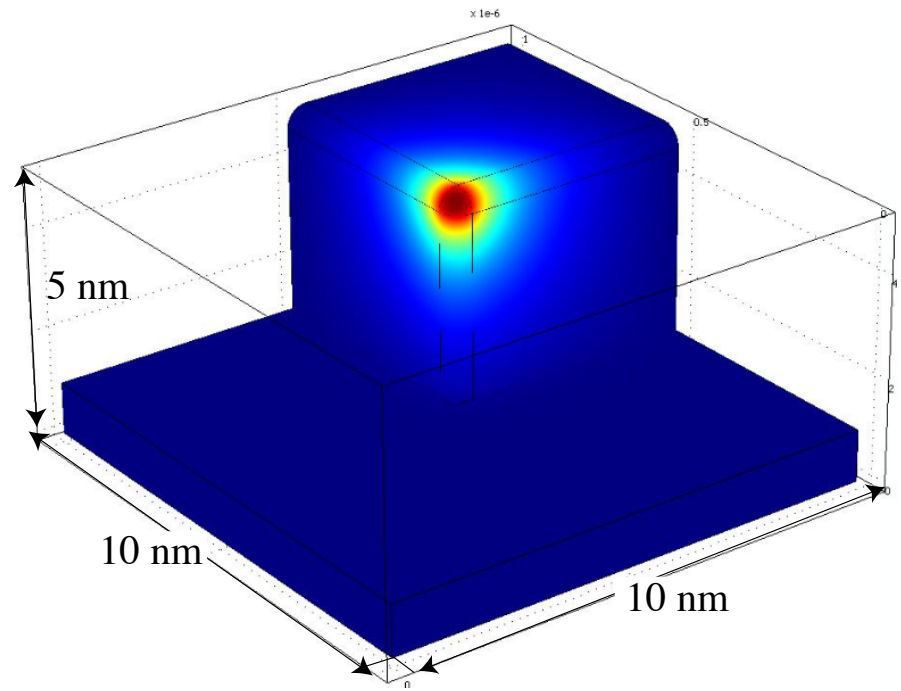
Particulates can also produce corners.



Many types of damage can produce these corners.

Damage
- Cracks
- Particulates, splashes
- Oblique ion fluxes and ripples
- Damage from shorting currents
- Erosion

We assume breakdown sites must be blunt
- Time const for cooling ~10 fs
- Heated volume is small ~ 1 nm^3.
- Large heat sink ~ 0.1 μ^3 (@ ns)
- VERY hard to heat

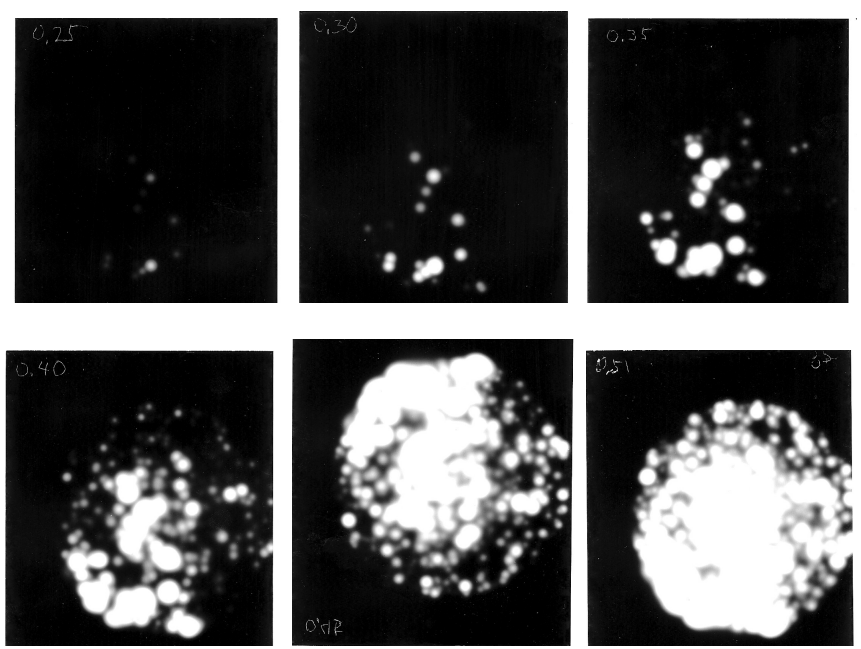


If breakdown sites are small, they can be covered.

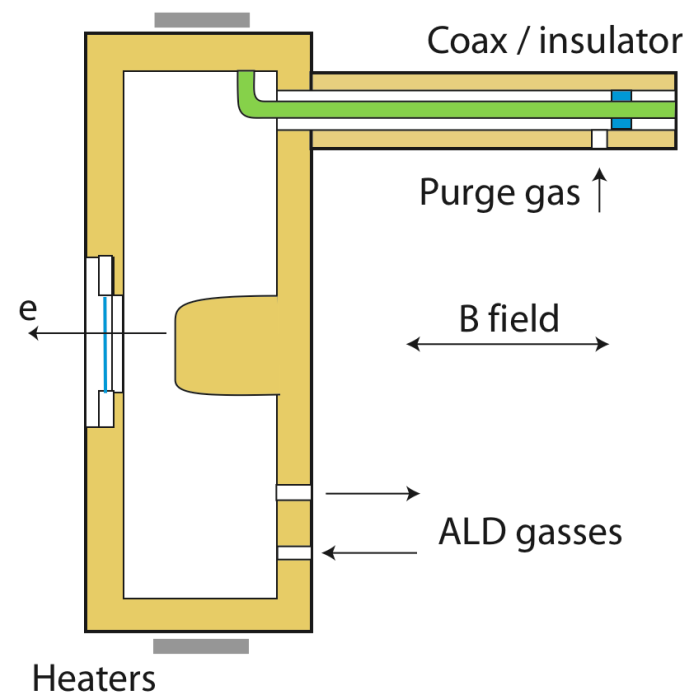
- Atomic Layer Deposition can conformally coat emitters & breakdown sites during operation, increasing local radii, reducing the local field, $E_l \sim 1/r$, field emission, $\sim E_l^{14}$, and breakdown rate $\sim E_l^{30}$. As little as a few nm might do it.

- 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.



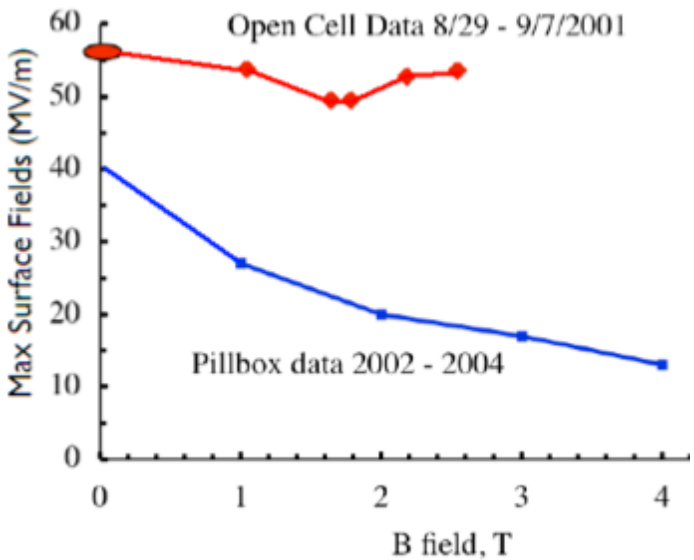
The cavity

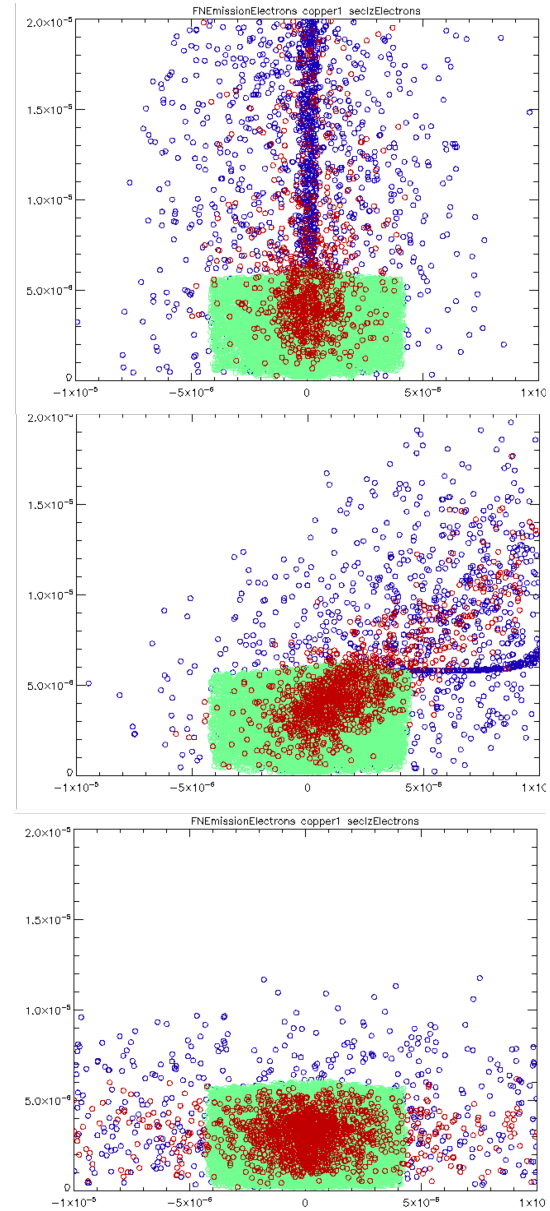


Magnetic field effects are complex.

- Experimental data is ambiguous: two shapes

Simulations difficult

- 



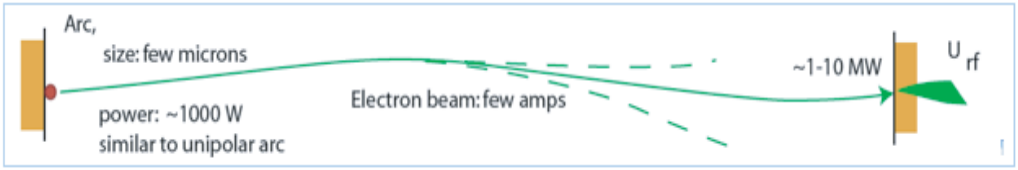
- VORPAL results will show ExB effects

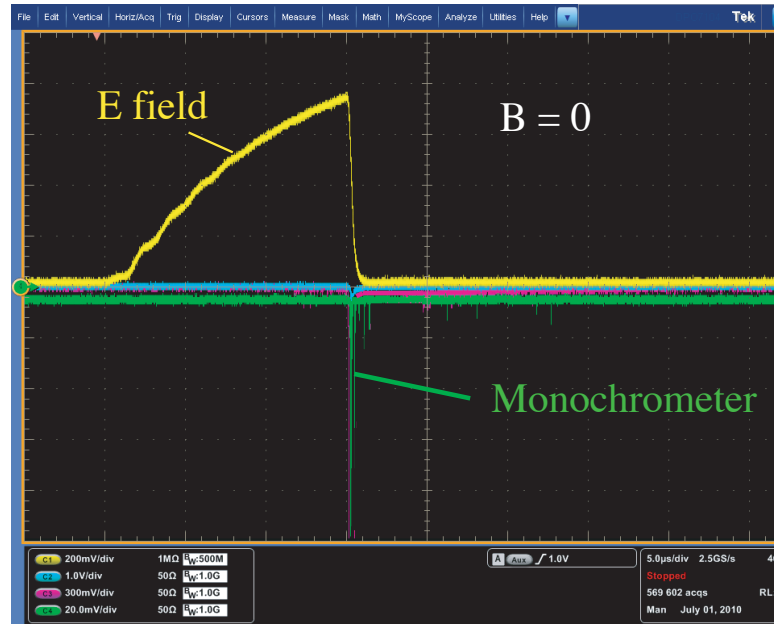
- Larmor focusing of electrons, $r_L = 0.3\ [\mu]\ W_{eV}^{1/2}$
  If ***E*** || ***B***, arc is more compact, damaging,
  If ***E*** || ***B***, or ***B*** = 0 arc is more spread out

We see two types of arcs:

Killer arcs:

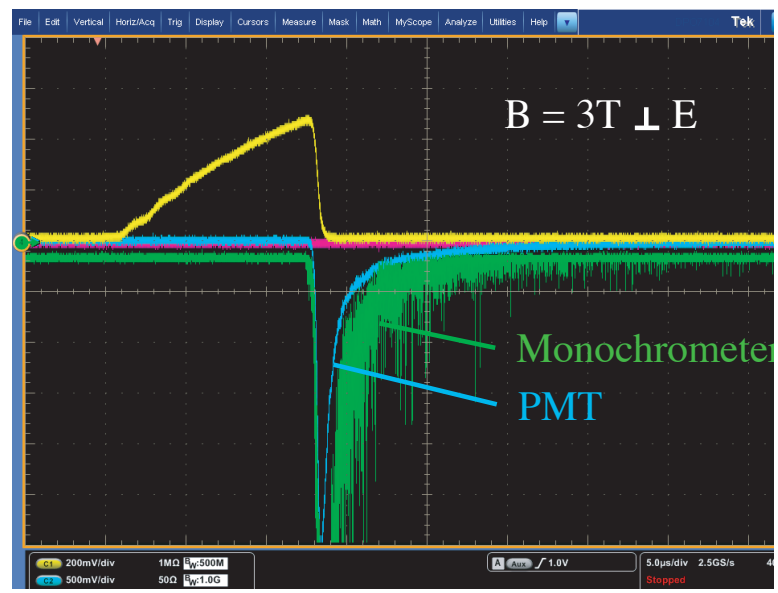
arcs short cavity
remove driving fields
arcs die quickly
small (~5μ ?) arc pits





Parasitic arcs:

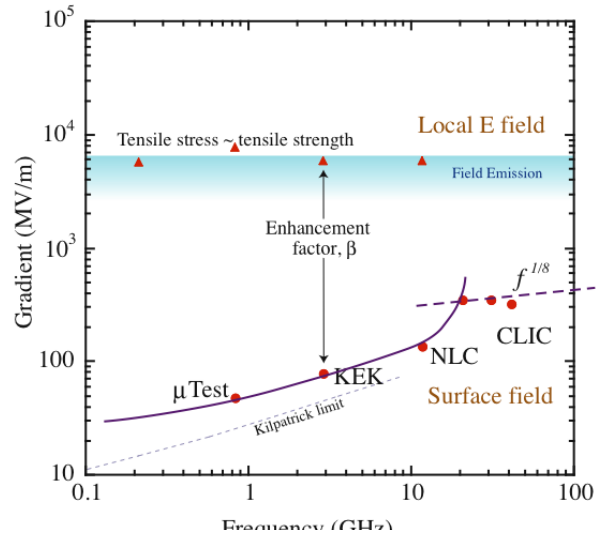
arcs cannot short cavity
driving fields persist longer
radiation losses?
arcs get bigger (~cm) and hotter
can last even after the field is gone
larger region of arc damage

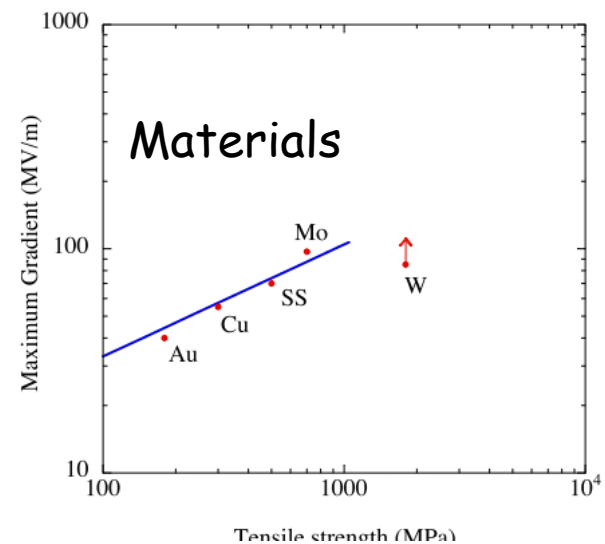


The model predicts gradient limits.

Conditioning modeled
We can calculate the Kilpatric limit
Gap dependence: there is none
Frequency dependence,
BDR(E) can be due to a number of causes
    Ohmic
    Electromigration
    Fatigue
    Are all indistinguishable, give BDRate ~ E^{30}.
Gas pressure scaling: there is none
Temperature dependence: there is none
Pulse length dependence: depends on energy.
Material dependence: depends on tensile str.
    noble metals only
Correlated breakdown rate: complex problem

And more . . .





We find the unipolar arc is not static.

This is a little different from Schwirzke's picture.

Arcs seem to be inherently unstable.

Many candidates for a termination mechanism

- Emitter melting
- non-Debye hiccup
- n_i/n_e imbalance
- radiation cooling,
- Satellite arc has more favorable energetics . . .

Secondary sources appear nearby

- Close: Ripples due to ion motion
- Far: splashes from liquid particulates
- Either way, fractal motion results

There are large efforts to look at accelerator gradient limits.

High Gradient Collaboration (SLAC)

http://www-conf.slac.stanford.edu/hg2011/

Compact Linear Collider (CLIC) Collaboration (CERN)

http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=75380

Muon Accelerator Program (Fermilab)

http://map.fnal.gov/

Workshop on Unipolar Arcs, Argonne Jan. 2010

https://twindico.hep.anl.gov/indico/conferenceDisplay.py?confId=69

Workshop "Mechanisms of Vacuum Arcs" in Helsinki Finland, June 27 – 30 2011

http://beam.acclab.helsinki.fi/hip/mevarc11/programme.php

This work involves:

- Material studies
- rf testing
- Small gap measurements
- Modeling

The problem may require a more focused effort.

Evidently small computers / clusters can't do 3 D magnetic fields.

But we also want to understand:

- Hydrodynamics and surface damage
- Pre-existing plasmas
- Beginning-to-end simulations
- Creation of satellite arcs
- Non-Debye plasmas
- Multipactoring
- Usefully accurate experimental predictions

On the other hand, most of the required information is available

- Sputtering yields
- Material properties
- PIC codes

Do we need more computing power?

Conclusions

The next generation of both tokamaks and accelerators depends on this physics.

We think we can calculate all aspects of arc properties (with limited precision).

- We have produced many predictions
- Some problems are very difficult (3D PIC /w B fields)
- We believe these methods have general applicability.

Vacuum arcs and gradient limits have been considered an insolvable problem.

- Any experiment seems to have more variables than data points.
- Time to re examine everything.

Arc problems associated with tokamaks and accelerators are very similar.

- I think a collaboration would be useful.
  - More precise modeling
  - Wider range of experiments