Vacuum Arcs and Gradient Limits

Z. Insepov , J. Norem, ANL/HEP
D. Huang, IIT
S. Vietzer, S. Mahalinham, Tech-X

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Outline

We need to understand gradient limits.
- Critical for many fields
- Seems vital to optimize accelerator designs
  - What frequency ?
  - What material properties ?, Materials ?

Description of simple (elegant ?) model
- A few simple mechanisms
- No variables
- Everything can be calculated
- We try to understand <u>all</u> arcing data
- Many Predictions

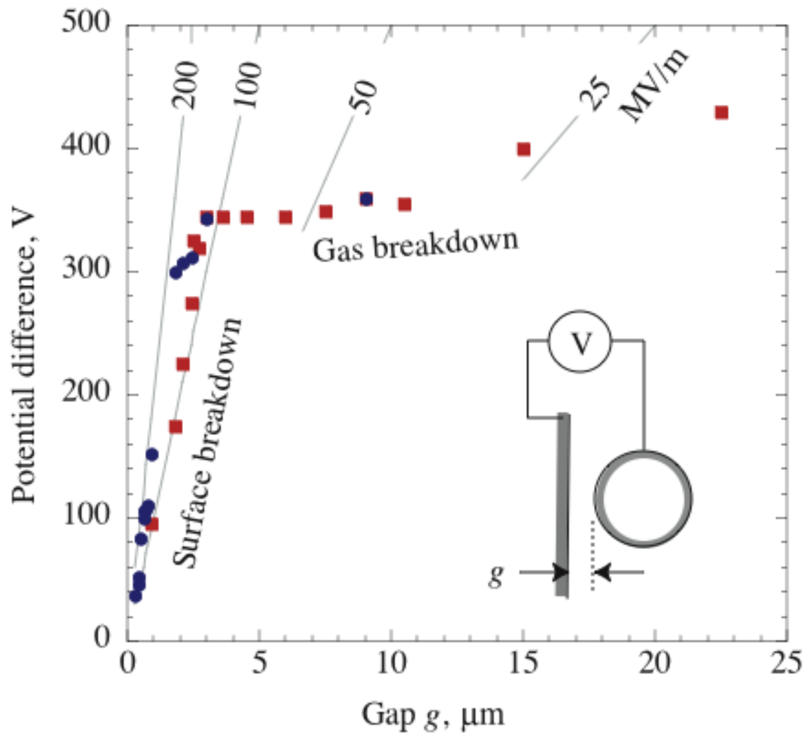
Details for much of this work have been numerically simulated.
- Everything looks simple, but calculations can be difficult.

What's next?

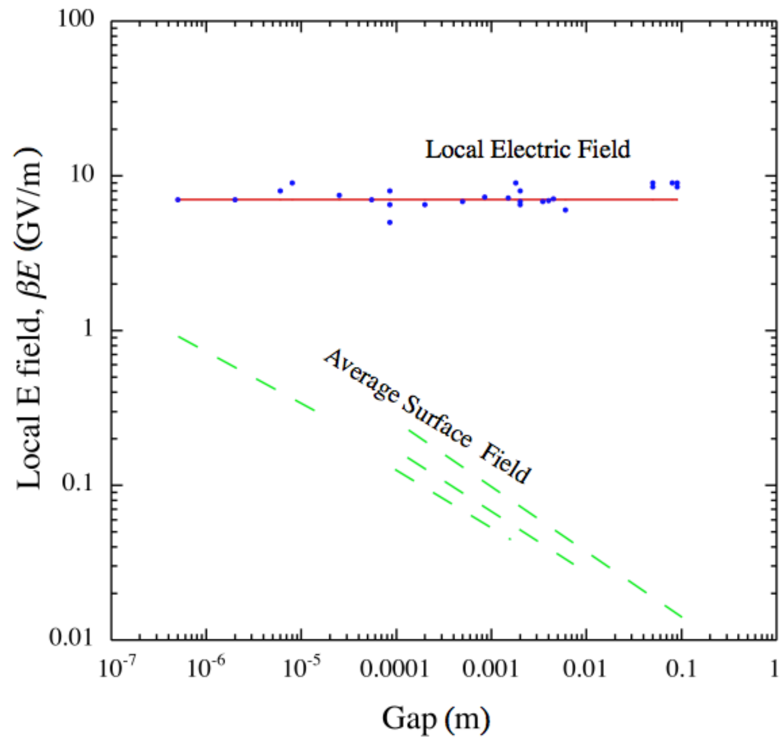
Vacuum Arcs

Old data define the problem:

1900-1904



1964 summary

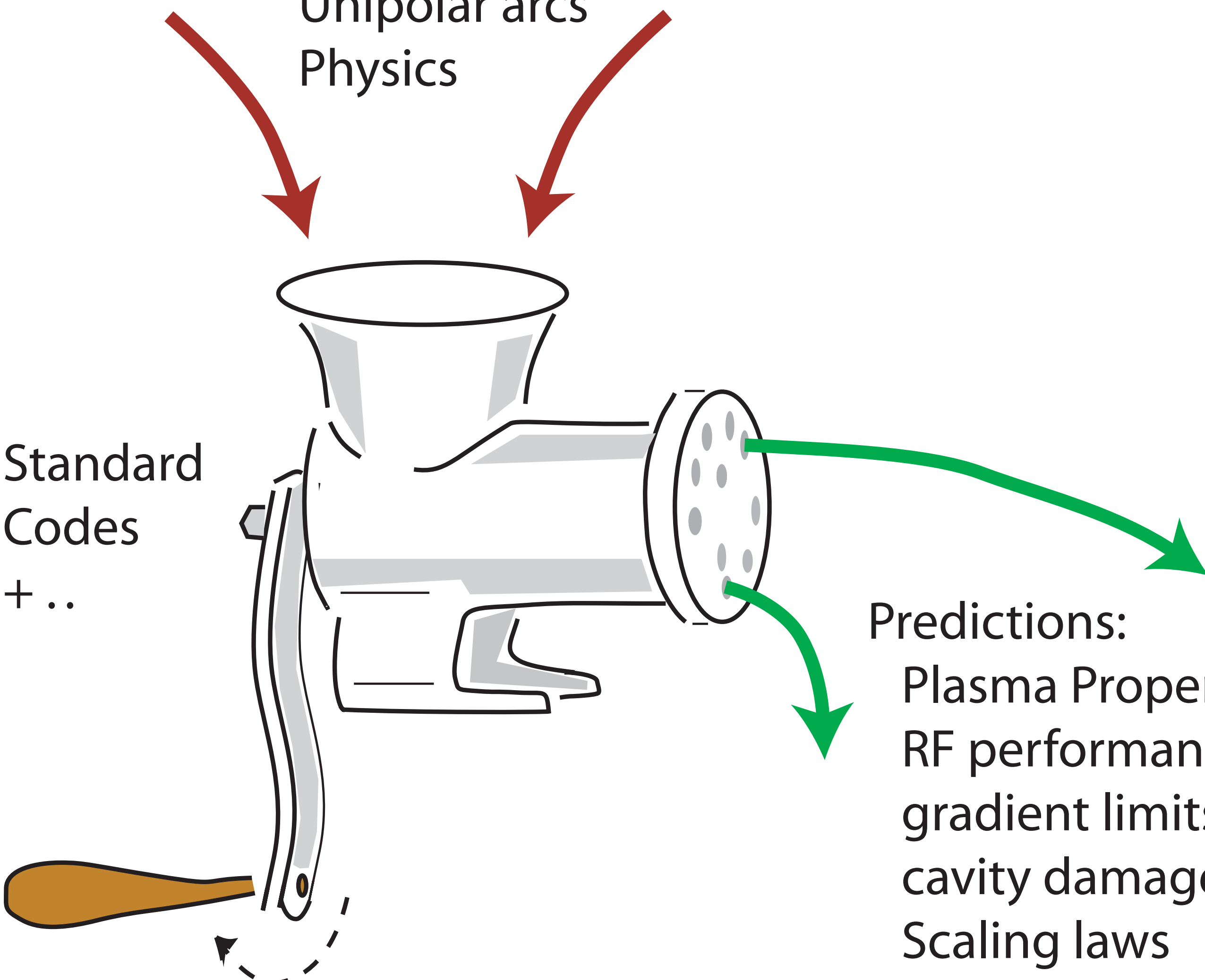


According to this data, vacuum arcs are: 1) different from gas breakdown (Michelson and Millikan) and, 2) are a single-surface phenomenon (Alpert et. al.).

They are not generally understood.

Our Model

Simple Assumptions:
- Coulomb explosions
- Unipolar arcs
- Physics

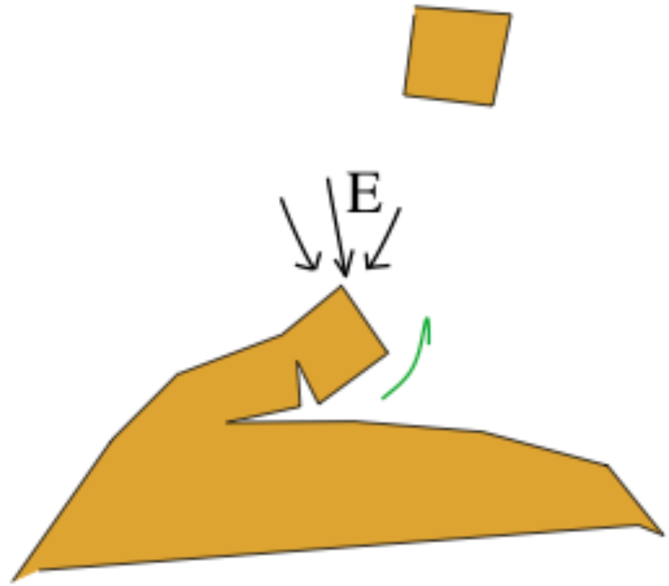


Standard
Codes
+ . .

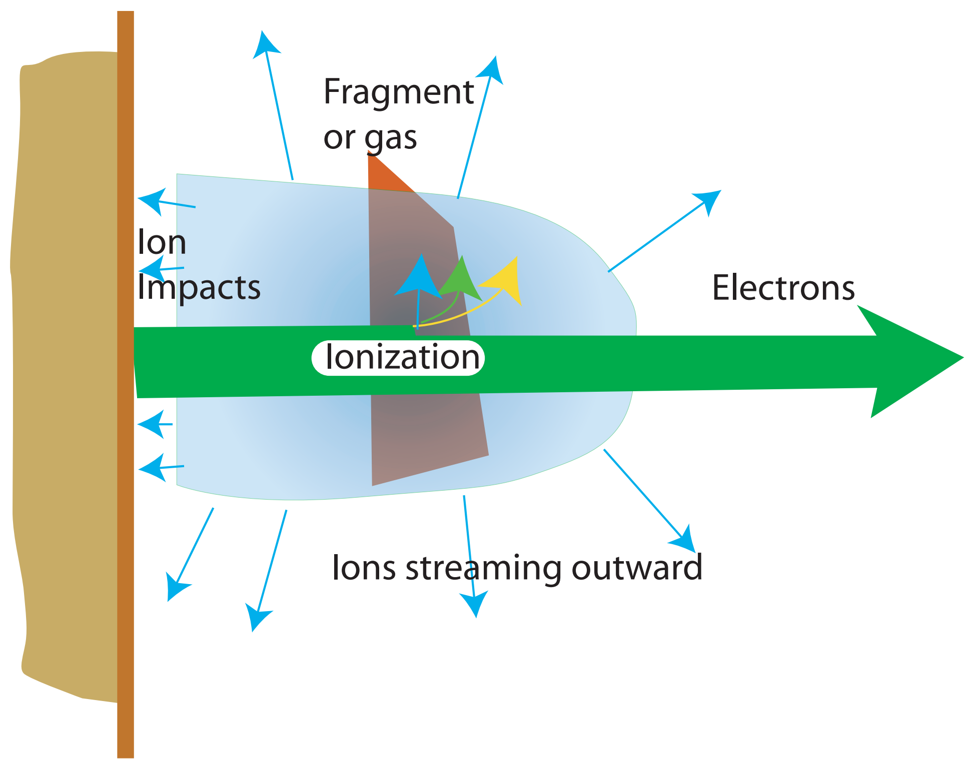
Predictions:
- Plasma Properties
- RF performance
- gradient limits
- cavity damage
- Scaling laws
- possible solutions

Assumptions

Coulomb Explosions



and Unipolar Arcs



Triggers for vacuum arcs

All vacuum arcs seem to look the same.

- Single surface phenomena (Alpert et al)
- Breakdown at ~10 GV/m surface field (Alpert, MTA, many others)
  - Tensile stress ~ tensile strength
  - Fatigue (creep) can contribute
- Our highest surface electric fields were with 3 – 4.5 T magnetic fields

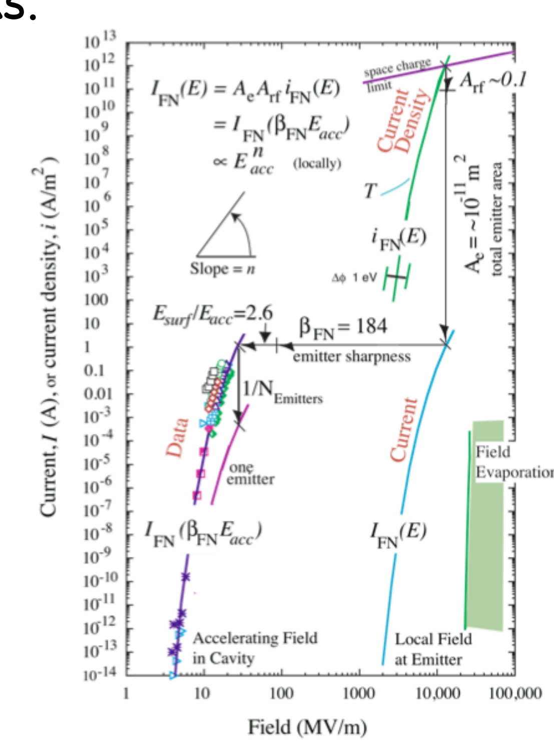
Compatible with

- Fatigue, Electromigration (Antoine, Peauger), minor heating
- Other arcs, Laser ablation, Lab plasmas, DC arcs, tokamaks.

No whiskers seen either in rf or DC expts.

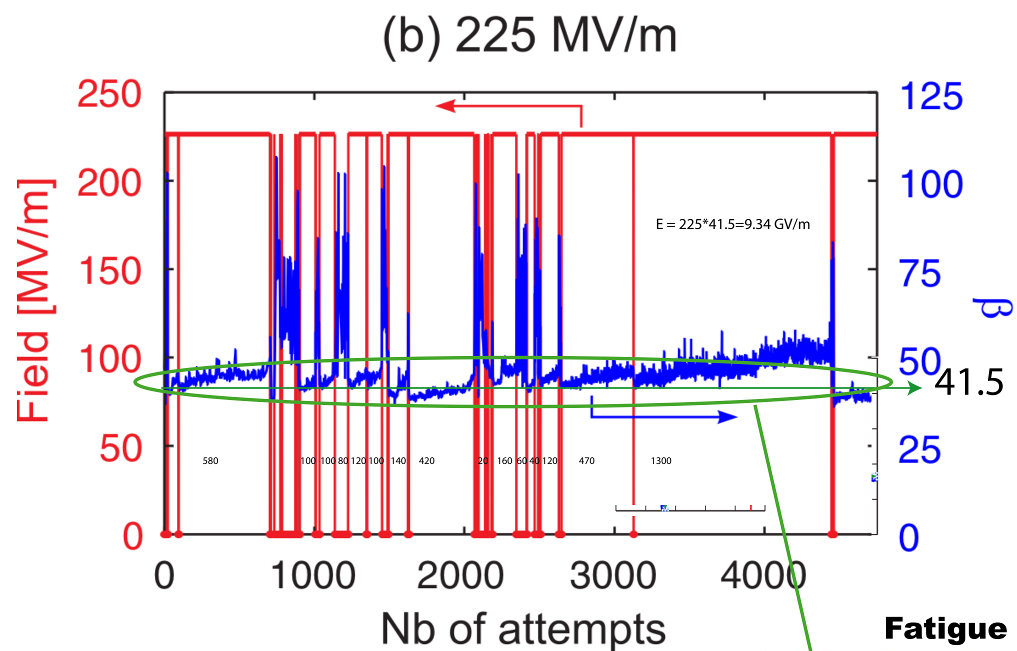
- Small emitters we see don't heat, EEE
- Pulse heating ~ 0, if $d_{\text{breakdown site}}$ << skin depth
- Breakdown is fully 3D, not 1D.
- Vacuum breakdown is not gas breakdown
- We do not see any keV ions anywhere.

E_{local} ~ 10 GV/m @ 805 MHz

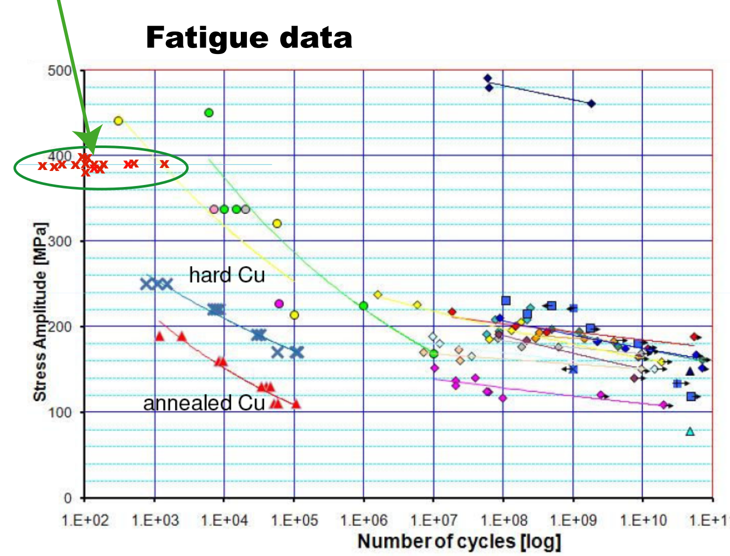


Coulomb explosions are compatible with fatigue

Breakdown numbers from CERN small gap experiment.



$$P = E^2 \varepsilon_0 / 2 = 386 \text{ MPa}$$

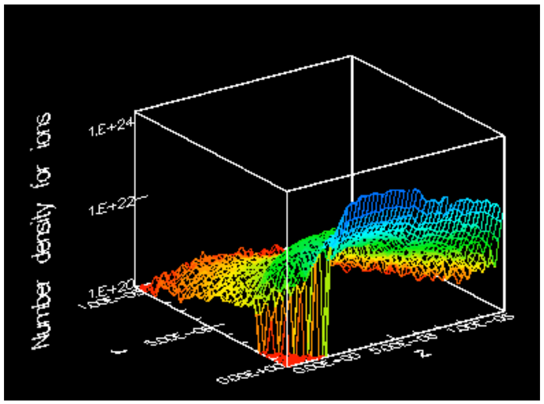


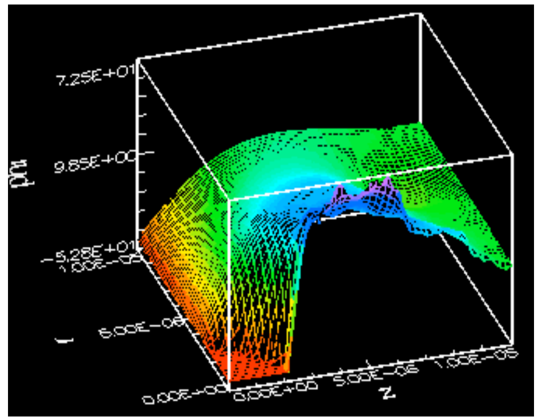
Unipolar arc properties

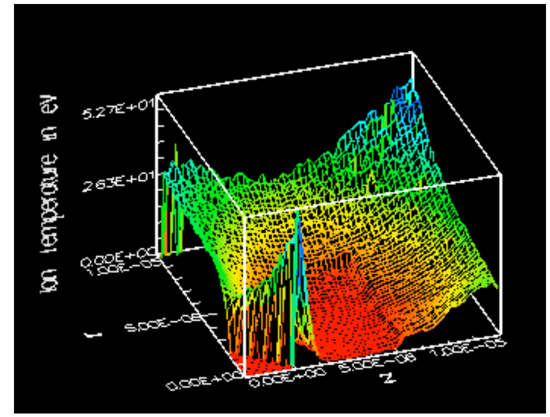
Dimensions matter

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

Ion Density, Phi, T_I



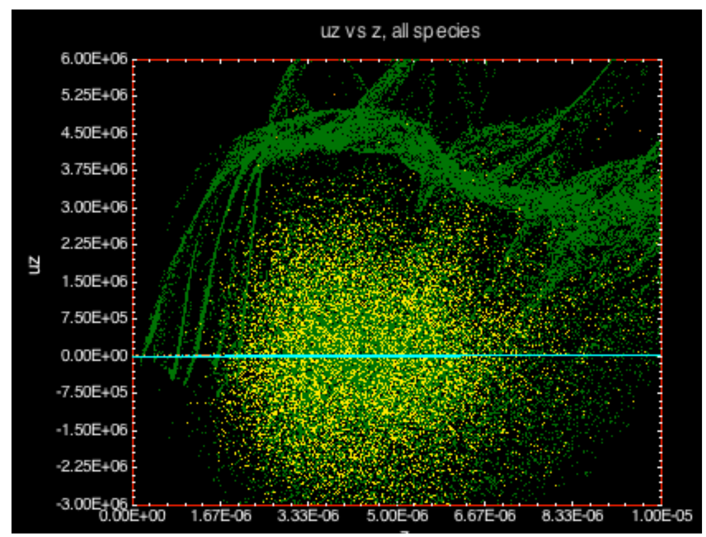




Arc dimensions a few microns.

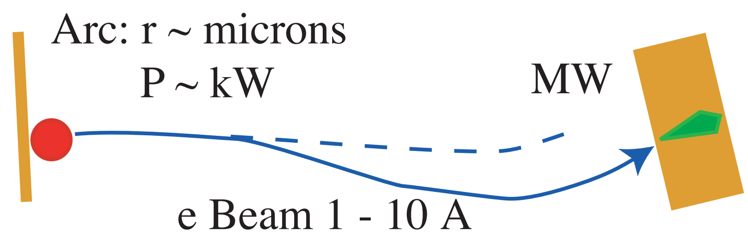
Primary electron current

- Space charge limit can be seen in v_z vs z
- Plasma functions as a virtual cathode
- Collision length remains constant ~ 10 μ

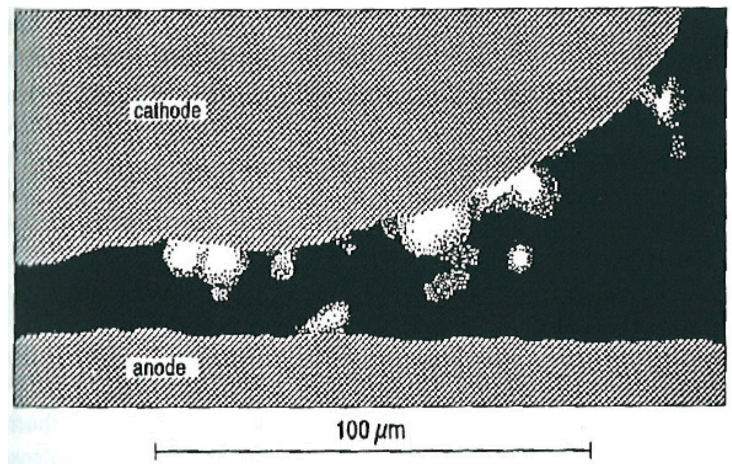


These (few micron) dimensions are consistent with a lot of data.

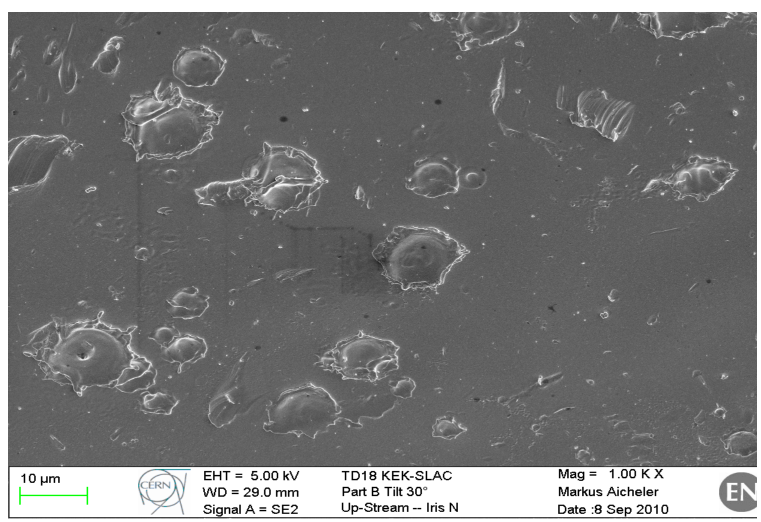
Our picture, from OOPIC



Boxman, Martin, Sanders,
Ch 3, Fig 22



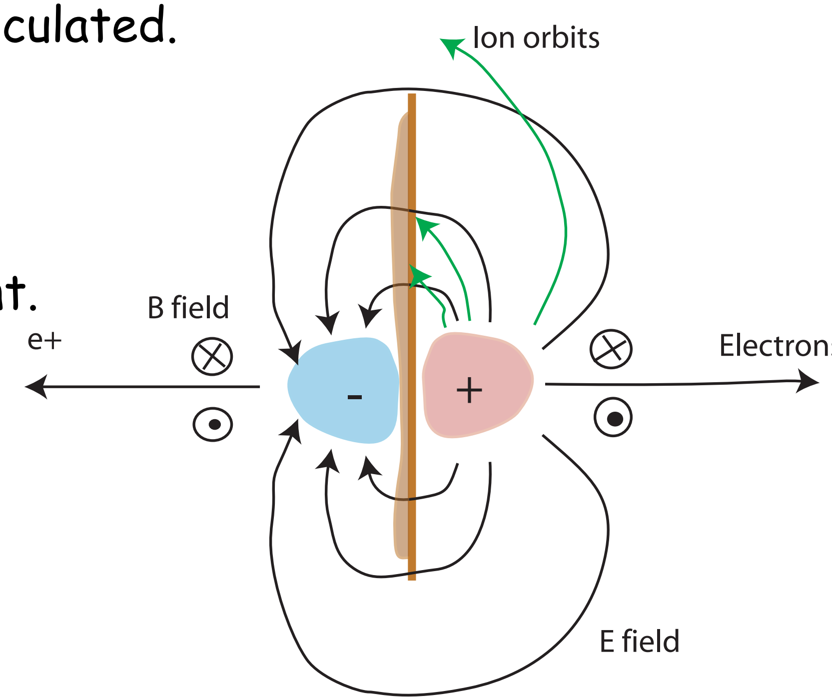
CERN and SLAC
(Aicheler CERN '10)



. . etc.

Electric field Distribution can be easily calculated.

- Image charge gives boundary conditions
- Ion motion determined by ϕ and E(r,z)
- Radial dist of E, inc ion angle
- Exact dimensions of plasma are important.

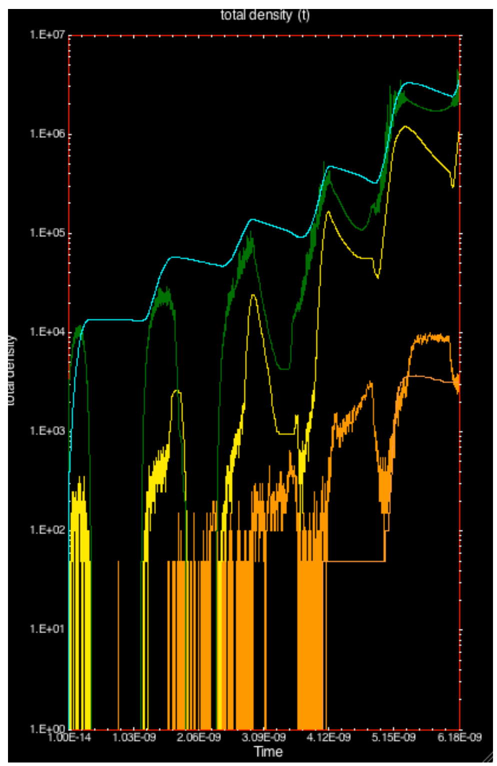


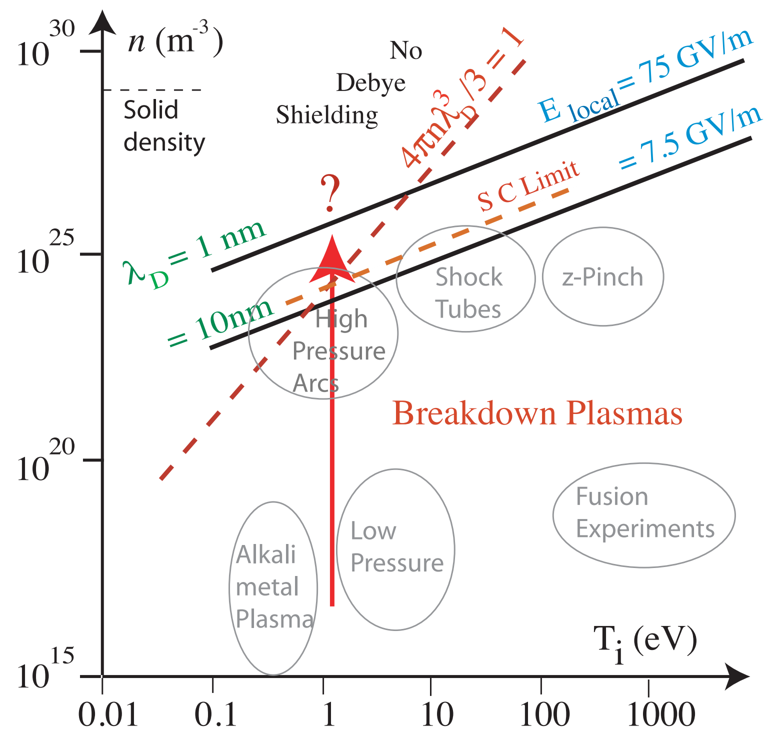
Time development:

- n vs. time for arc
- Trapped plasma develops
- $E_{average} = \phi / \lambda_D$ (increases)
- Non-Debye plasma ? ?

Increase in E drives

- arc evolution
- currents
- density increase





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

- Ion & Electron Temperatures are very different
  - Ions are essentially thermal ($T \sim 0$), 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

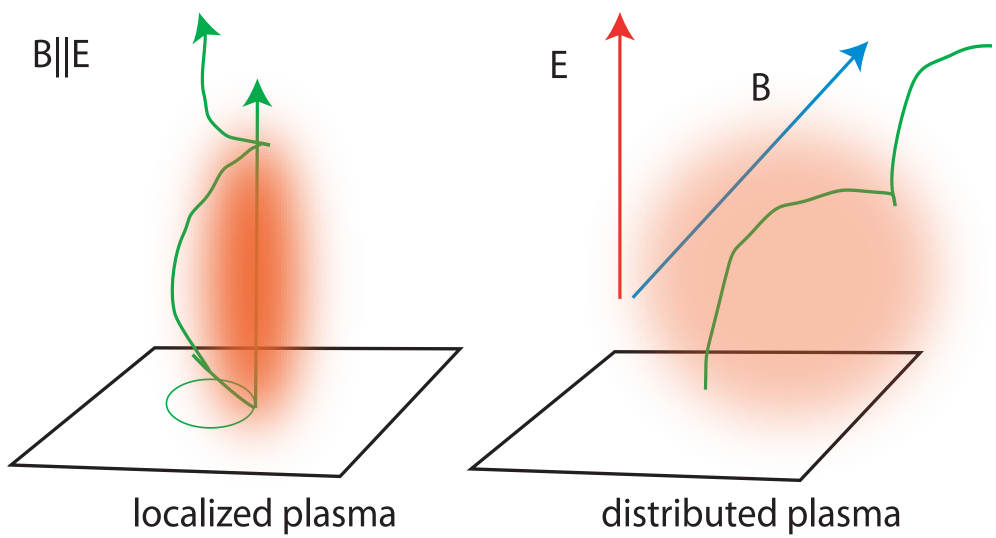
- Ion, electron fluxes change rapidly
- Radiation flux goes like n^2
- Surface heating is large and localized
- Distribution of energy can be calculated.

B Field effects electrons and should change gradient limits.

- Arc behavior is a function of ***B***.
- Focusing of shorting currents is evidently not harmful
  - Best gradient obtained with High collinear B field
- Larmor focusing of electrons, $r_L = 0.3\ [\mu]\ W_{eV}^{1/2}$
  - If ***E*** || ***B***, arc is more compact, more damaging,
  - If ***E*** || ***B***, or ***B*** = 0 arc is more spread out

This mechanism should explain the B field dependence in muon accelerator cavities.

High local fields (megagauss) are seen



Ion radius much larger

- less pressure
- fewer particles, etc.

B fields are tough simulation problem

- Requires VORPAL (or LSP)
- Evidently parallel processing
- We are trying to organize something.

Self-sputtering fuels the arc and can make it self-sustaining.

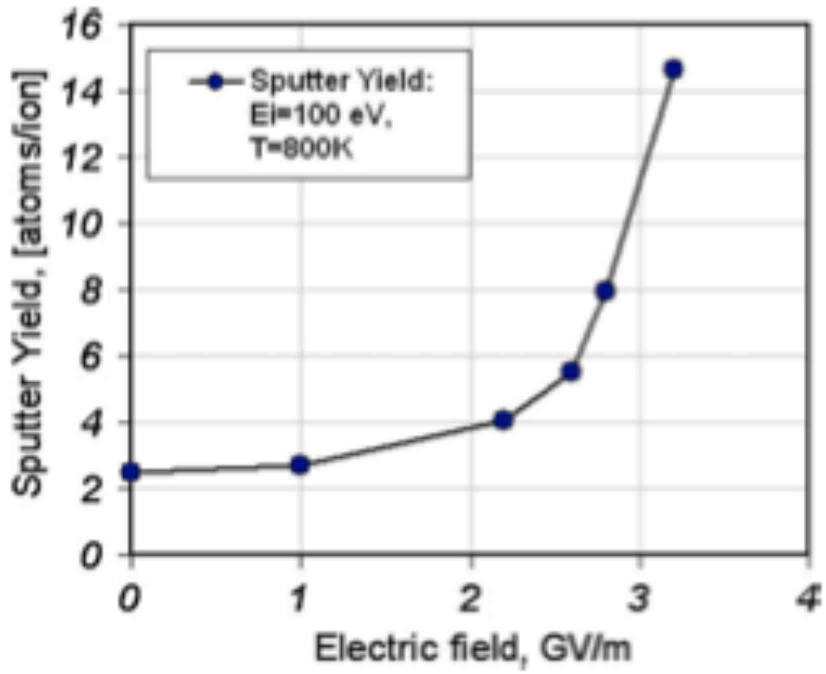
High E and T increase self-sputtering above 10 at low energies.

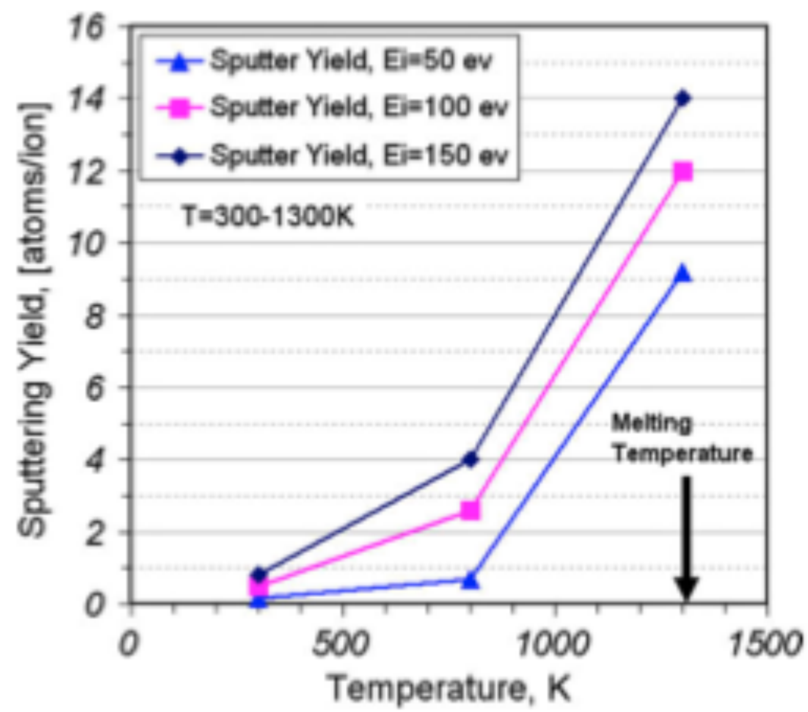
Grain orientation also seems to matter

We have calculations, are starting experiments

Electron sputtering also produces shorting currents.

Arcs must be self-sustaining in many non-accelerator environments.





We believe a unipolar arc is essentially a transient –

- 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, . . .
  - Secondary sources appear nearby
    - Close: Ripples due to ion motion
    - Far: splashes from liquid particulates
    - Either way, fractal motion results

Space potential / sheath potential

- Plasma is polarized because ions move more slowly than electrons
- This would happen in free space or near a metallic boundary
- Near a boundary the potential is essentially a normal sheath, even if nonthermal.

Ghost arcs (CERN) should be relics or precursors of Unipolar arcs.

Enhancement factors seem to be a source of confusion.

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

$2 < \beta < 1000$

$1\ \text{nm}^2 < A <$ 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 Fowler-Nordheim (and quantum mechanics) has been questioned.

We have a simple solution:

Emitters are small, ($A \sim 1\ \text{nm}^2$) 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.

Fowler-Nordheim should be OK, as is Quantum Mechanics.

Damage

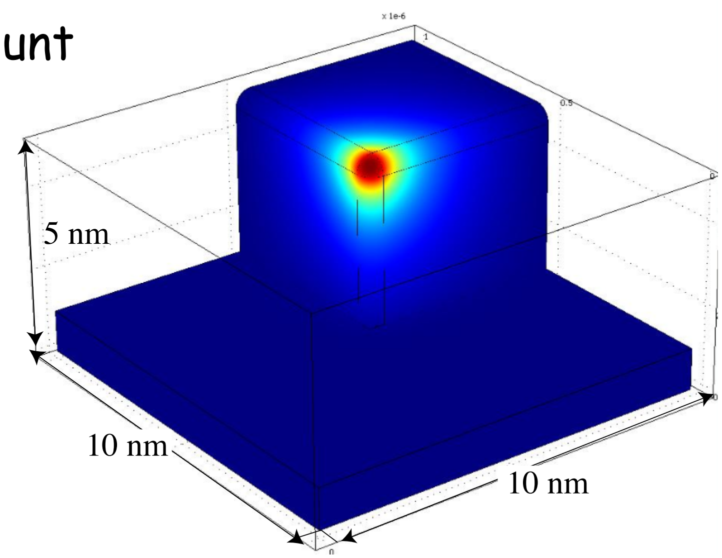
Damage mechanisms

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

The spectrum of *n*(β) is known, in many environments.

Nobody sees whiskers, so breakdown sites must be blunt

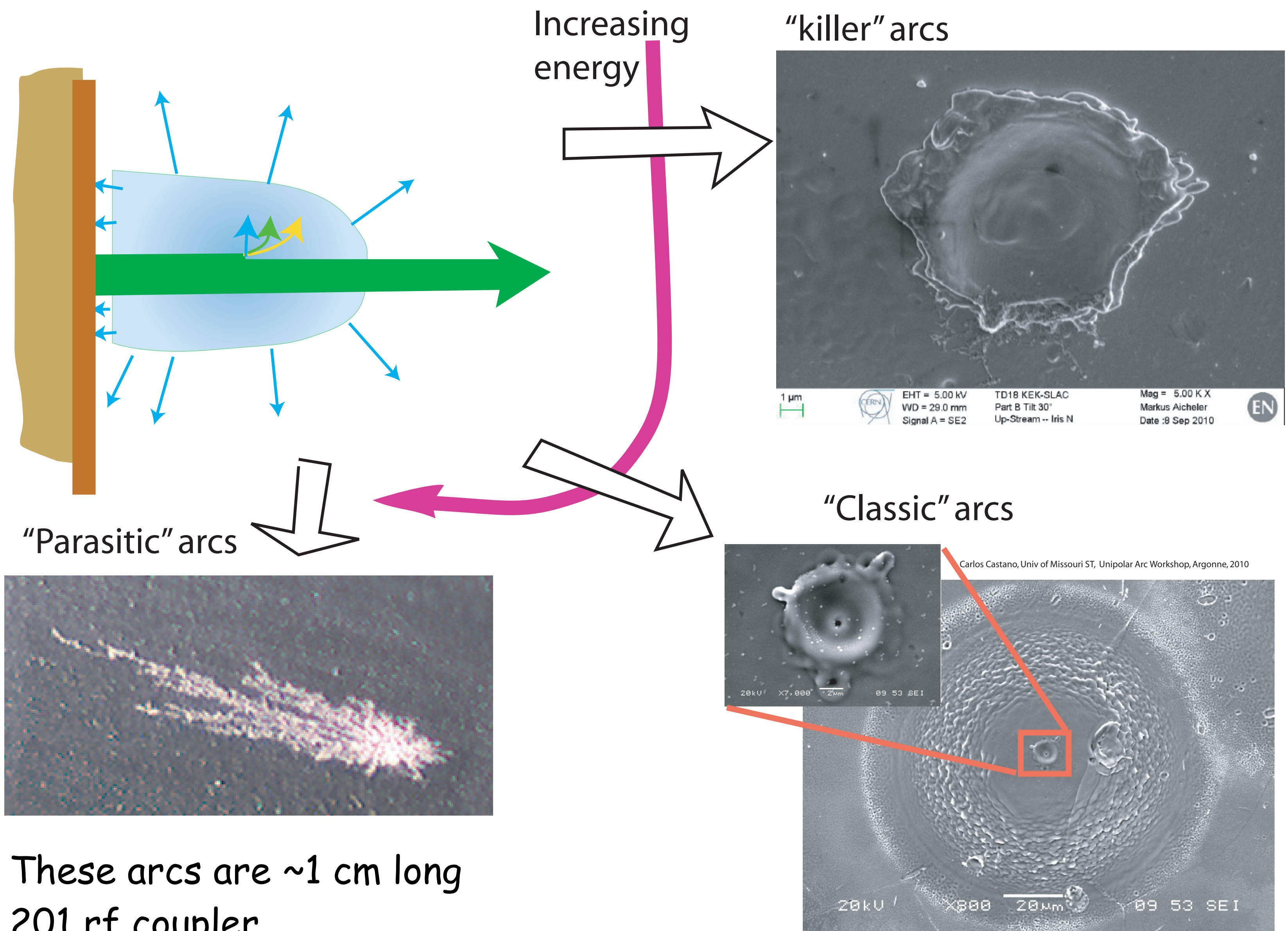
- Thermal properties of blunt corners
  - Time const for cooling ~10 fs
  - Heated volume is small ~ 1 nm^3.
  - Large heat sink ~1 μ^3 (@ ns)
  - VERY hard to heat



Two types of arcs

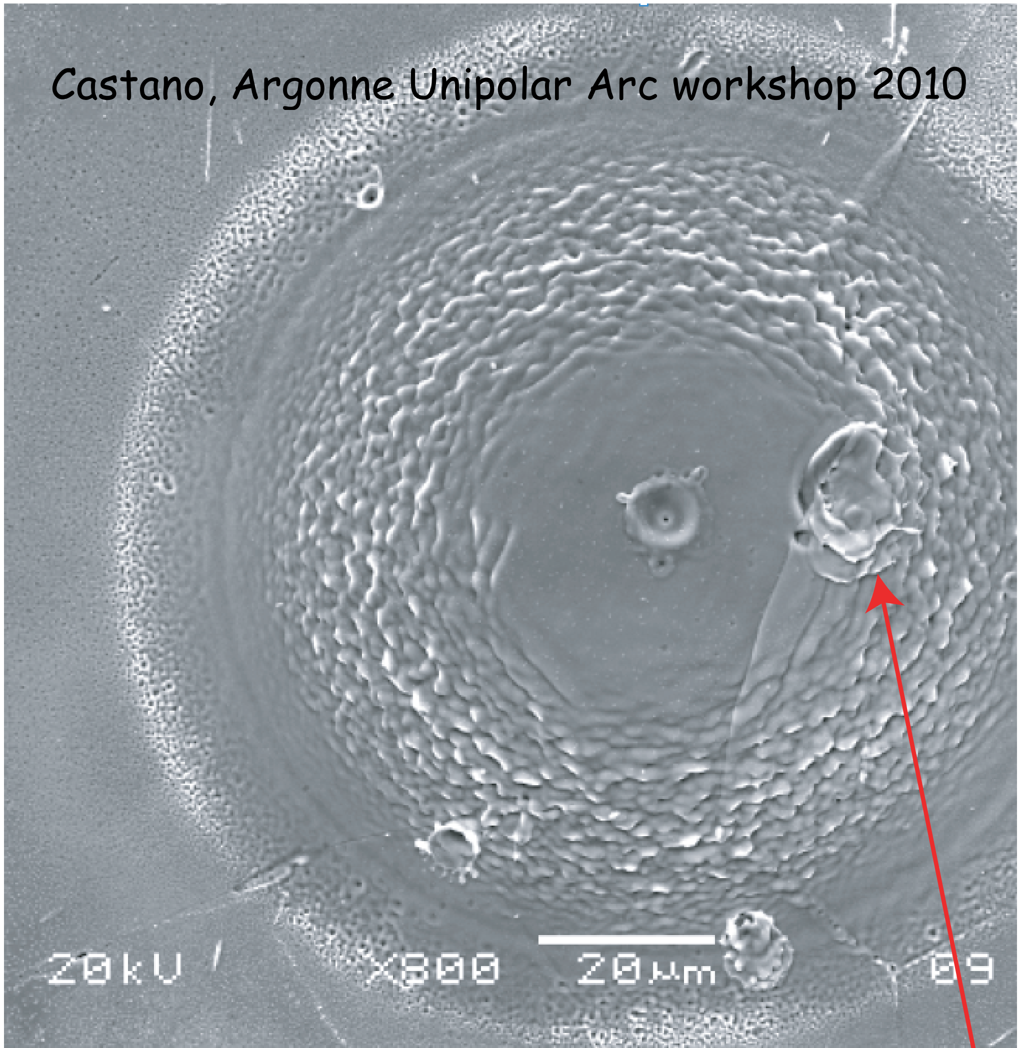
- **Killer** – arc current shorts potential, removes power source.
- **Parasitic** – arc removes energy from plasma slowly

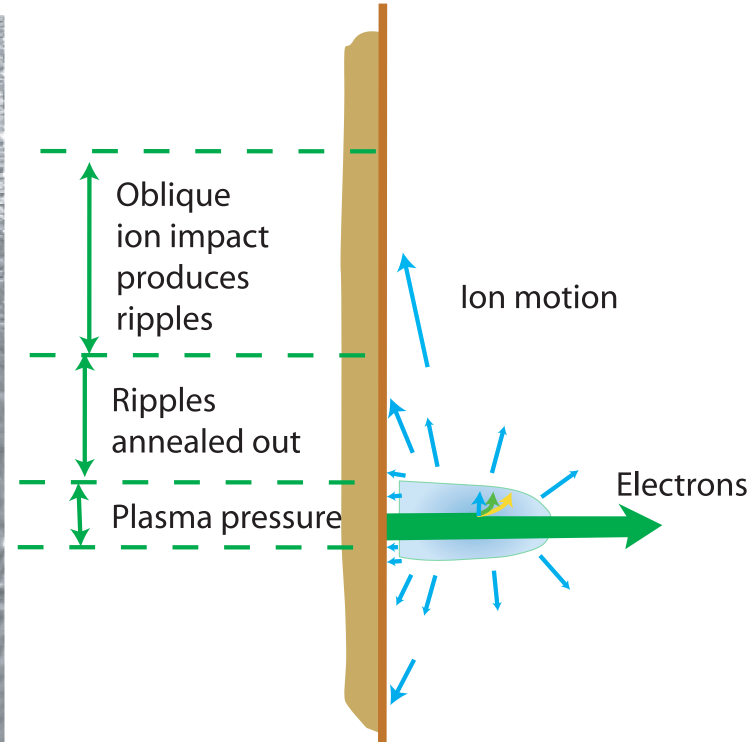
Effects of increasing Arc energy

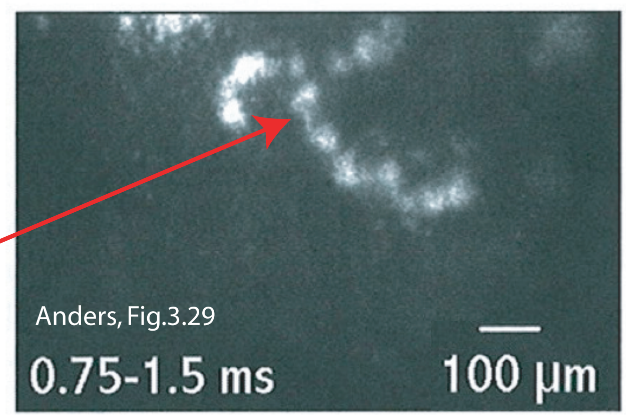


These arcs are ~1 cm long
201 rf coupler

Arc damage mechanisms







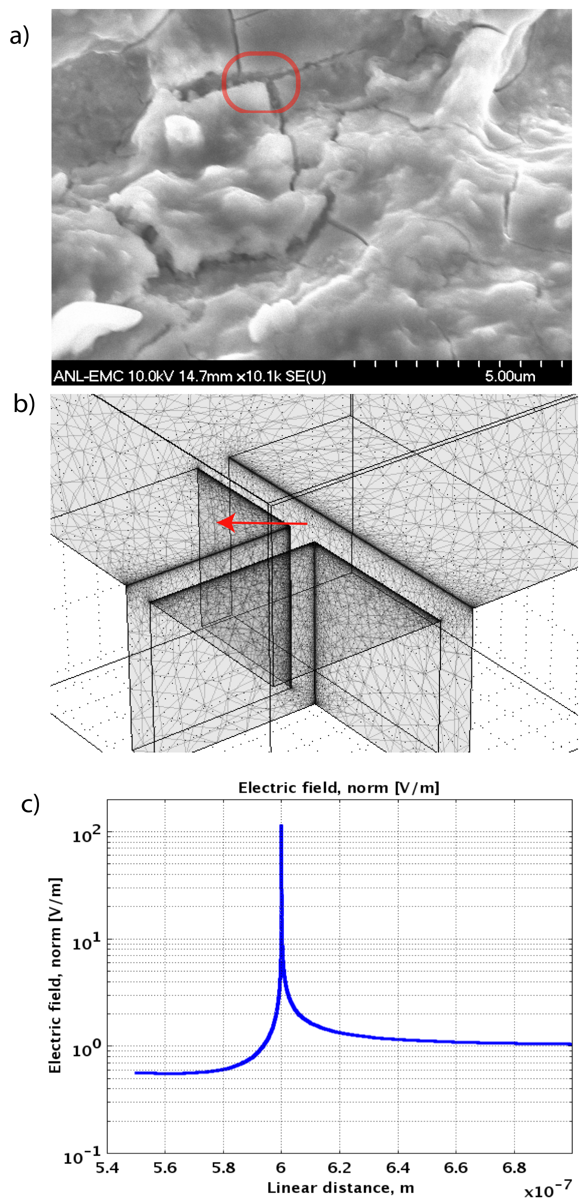
Secondary breakdown sites ~25 mm from primary site consistent with fractal arc motion

Cracks

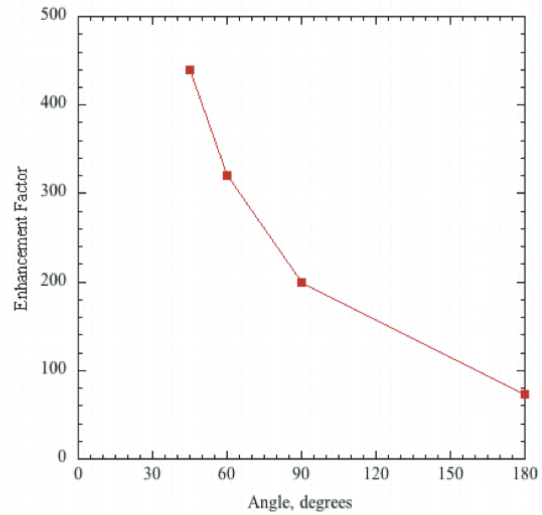
n(β) from angle dependence could be derived if needed.

Sharp crack angles have high *β*s but are uncommon.

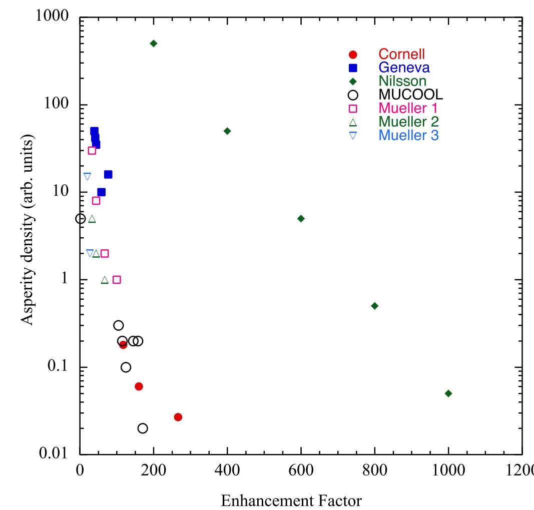
SEM showing cracks



β(crack angle)



n(β)

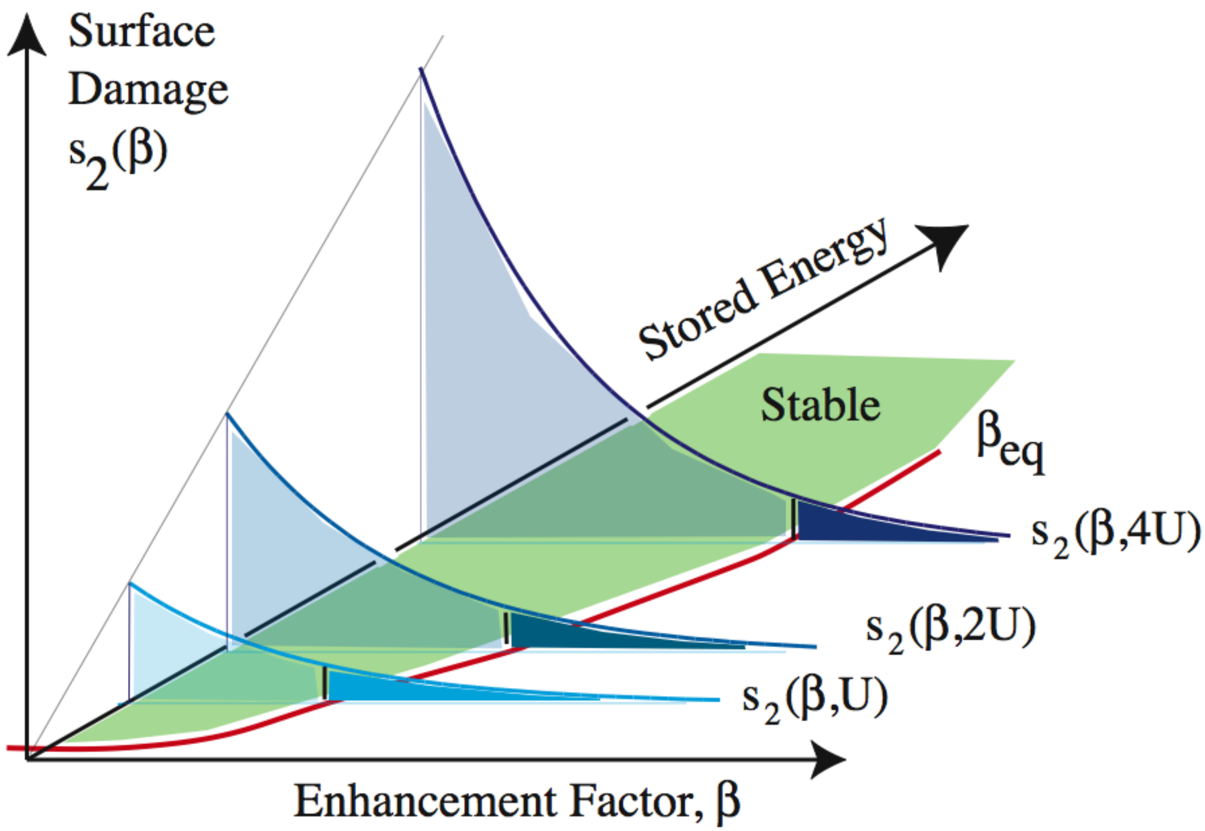


Particulates can also explain this effect.

Gradient limits

Gradient limits represents an equilibrium obtained from two effects:

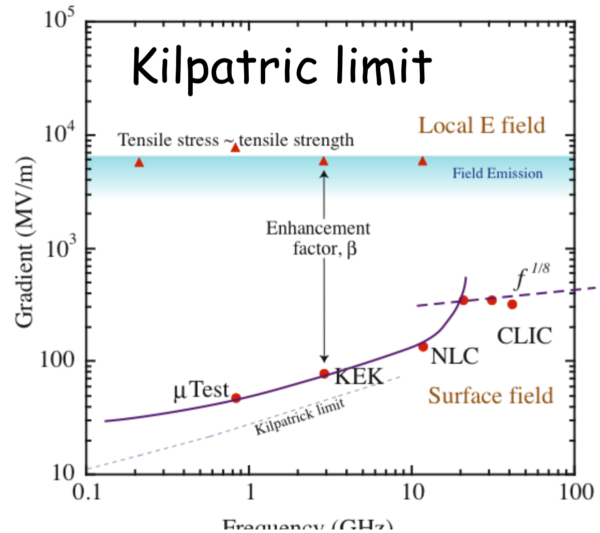
1) More energy in the arc produces more damage. (They are proportional.)
2) Because of the spectrum of enhancements drops off exponentially, damage rises logarithmically with arc energy.

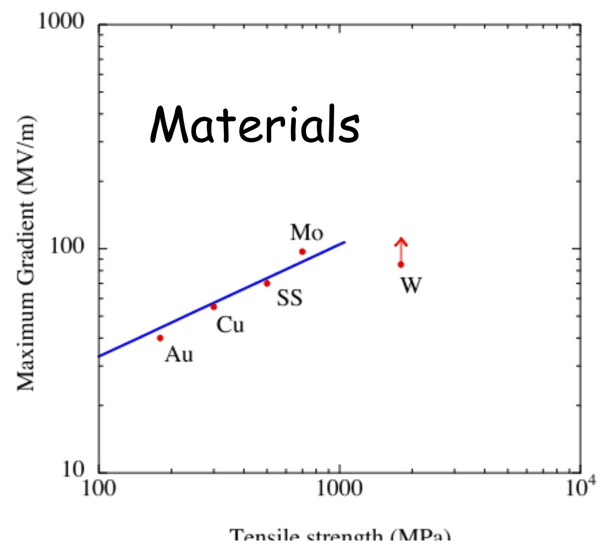


We published a paper in '05 describing how damage causes gradient limits, with a number of predictions and examples.

Conditioning
We can calculate the Kilpatric limit
Gap dependence: there is none
BDR(E) can be due to a number of causes
    Ohmic
    Electromigration
    Fatigue
    Are all indistinguishable, give BDR ~ 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 . . .





Active Effort

Thermodynamics of breakdown sites

B field effects in vacuum arcing

Sputtering and self-sputtering dependence on many parameters

Differential erosion depends on grain orientation

Surface electric fields in arcs.

How does background plasma affect gradient limits?

Non-Debye, non-LTE plasma interactions with materials.

Conclusions

We feel we can calculate all aspects of arc properties in a realistic way.

- We have produced many predictions
- We are working on many aspects of the problem
- Some problems are very difficult (3D PIC /w B fields)

We feel that we can predict any quantity with useful precision.

- We believe our methods have very general applicability.

Vacuum arcs and gradient limits seem to be considered an insolvable problem.

- Little interest, little support
- History (SSC, NLC, ILC) implies we need to know how things work.
- There seem to be different ideas, we should have vigorous debate.
- If pulse heating is real, Vacuum arcs must be the damage mechanism