Understanding Vacuum ARCS

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

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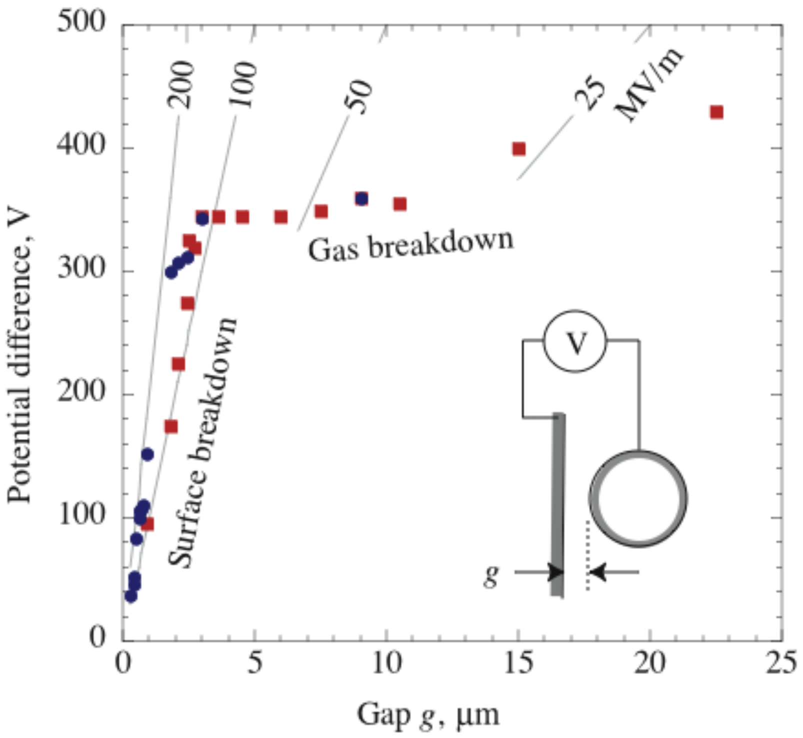
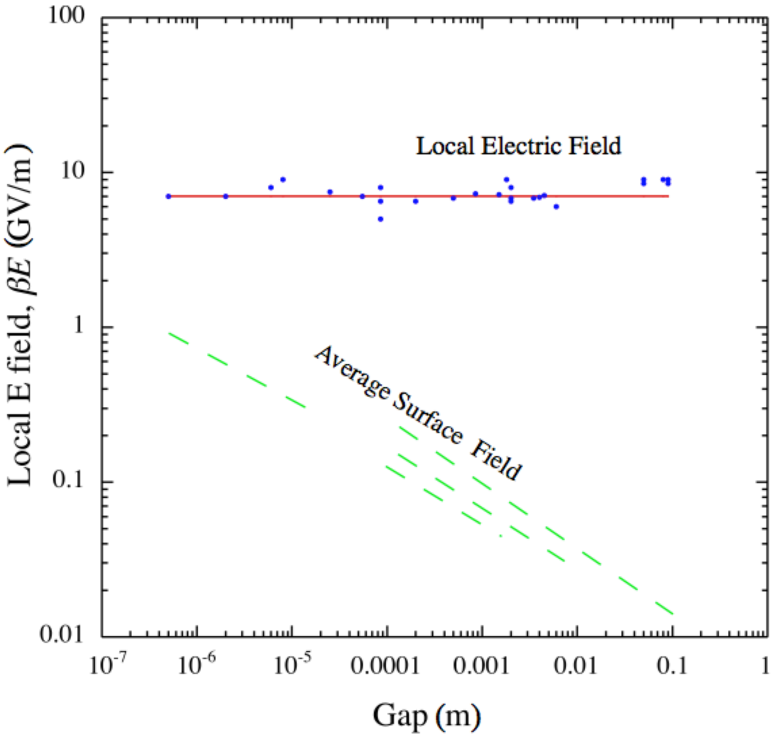
Vacuum Arcs

Old data define the problem:

1900-1904



1964 summary



According to this data, vacuum arcs:

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

Outline

After the review in August the word came back we should follow CLIC more closely.

Is CLIC ahead of us?

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?

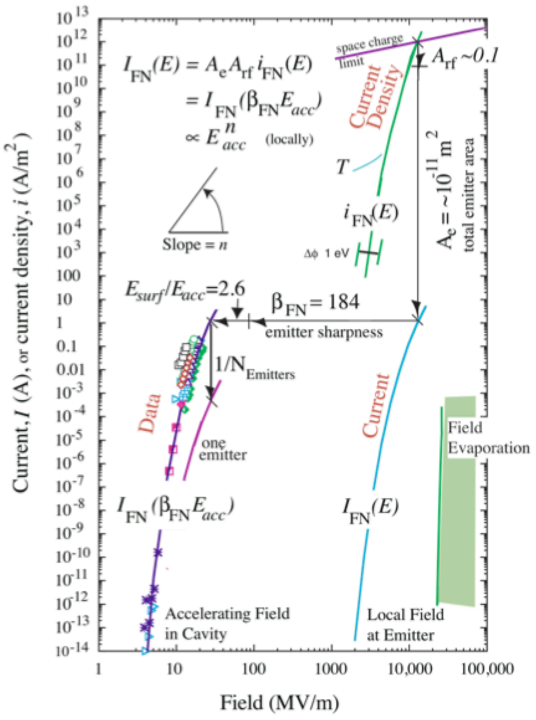
Triggers for vacuum arcs

All vacuum arcs seem to have the same trigger mechanism.
- Single surface phenomena (Alpert et al)
- Breakdown is at **~10 GV/m local 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

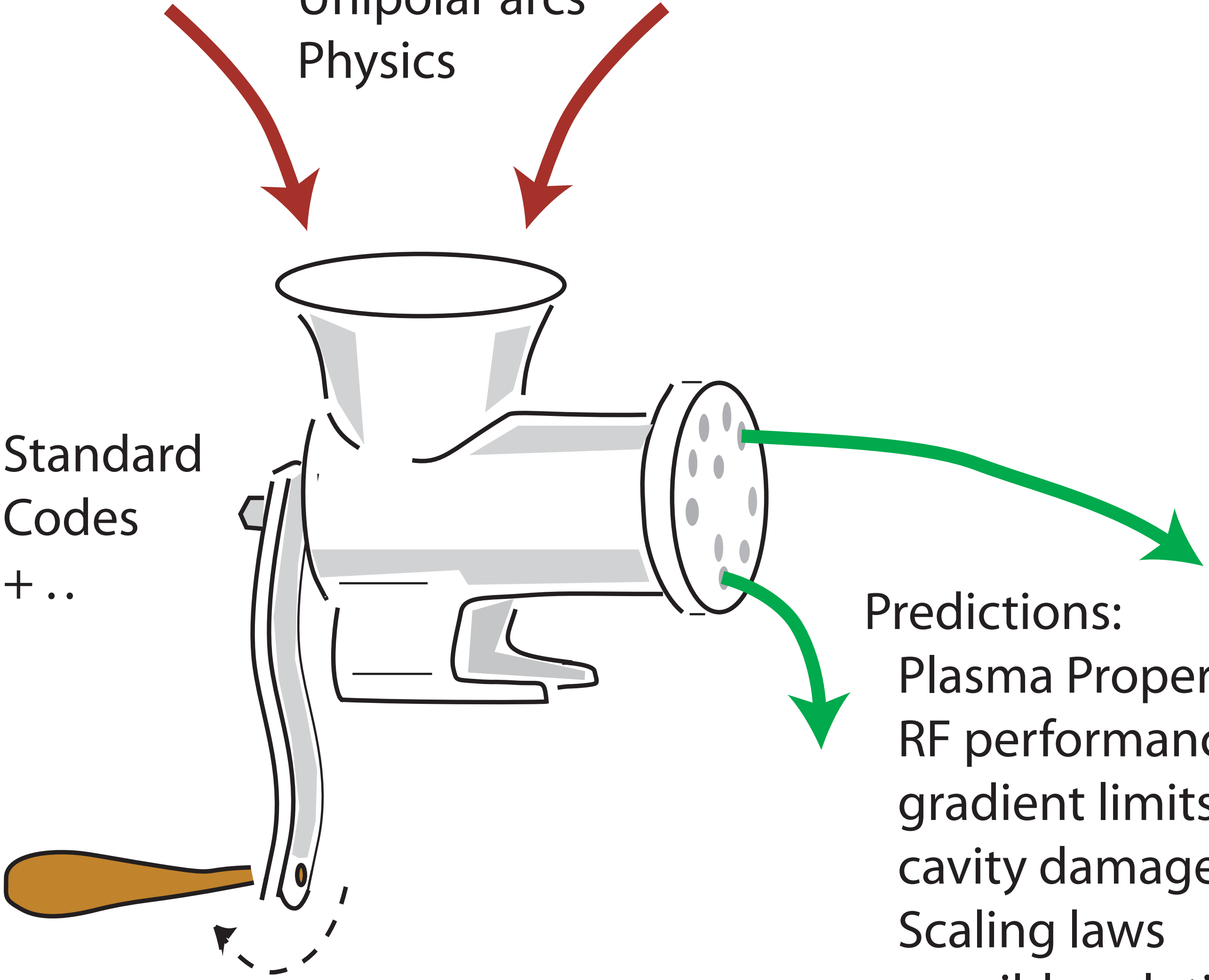
Compatible with
- Fatigue, Electromigration (Antoine, Peauger), minor heating
- Other arc data, Laser ablation, Lab plasmas, DC arcs, tokamaks.

Data shows:
- Be and Cu have equal BD fields when tested together.
- High pressure cavities can have problems with beams
- Magnetic insulation seems to make arcs hotter.
- Our highest E fields were with ~4 T B fields.

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



Our Model



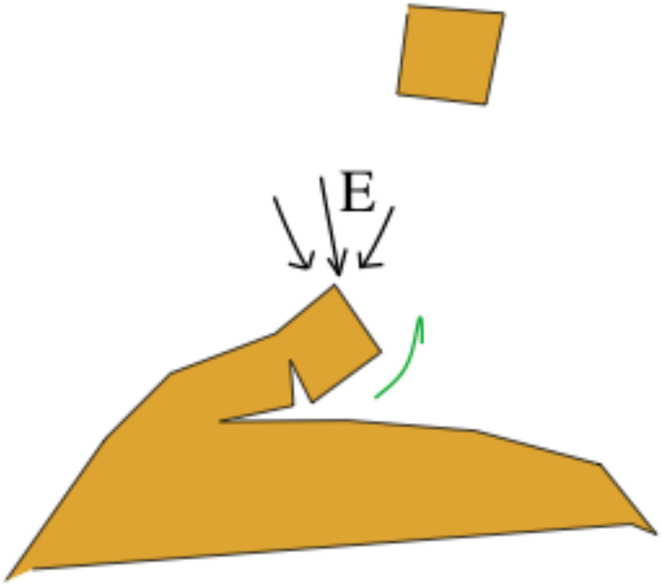
Simple Assumptions:
- Coulomb explosions
- Unipolar arcs
- Physics

Standard
Codes
+ . .

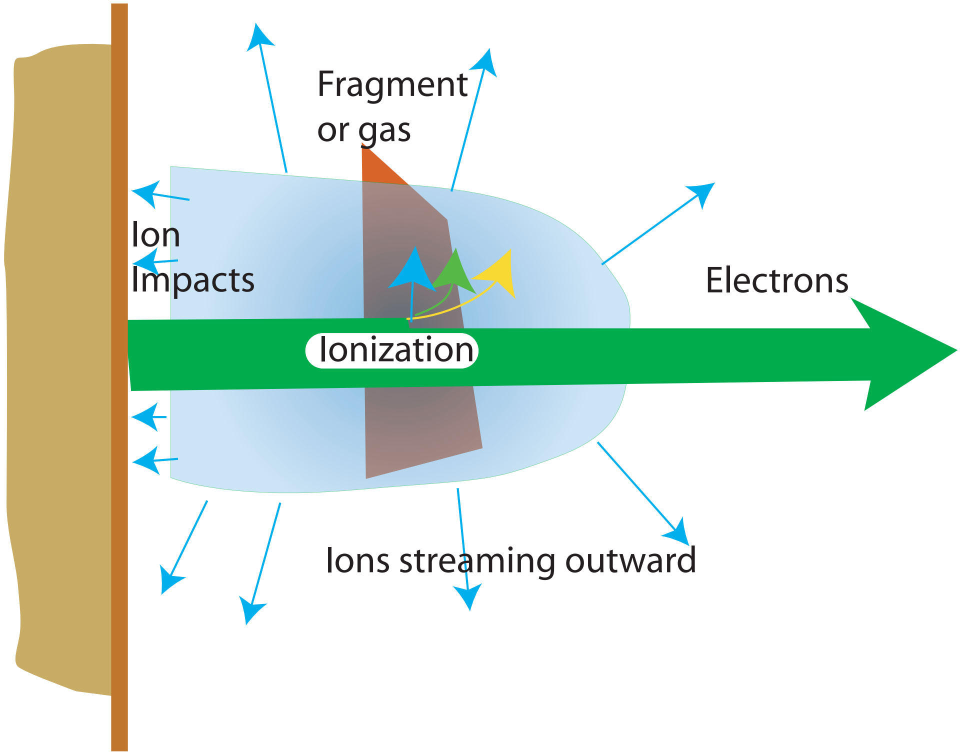
Predictions:
- Plasma Properties
- RF performance
- gradient limits
- cavity damage
- Scaling laws
- possible solutions

Assumptions

Coulomb Explosions



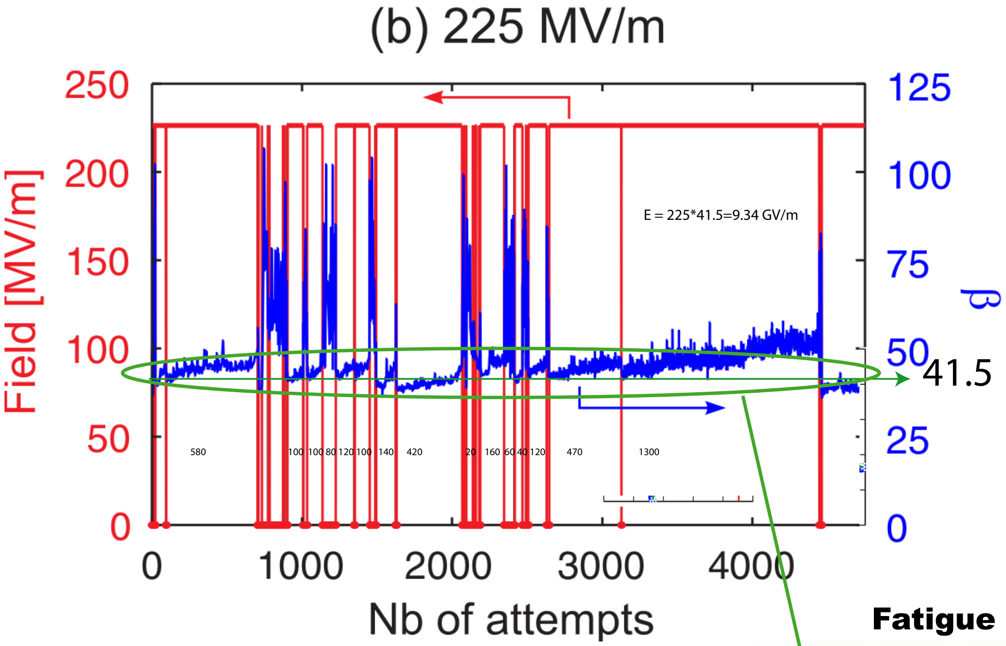
and Unipolar Arcs



We agree with European data

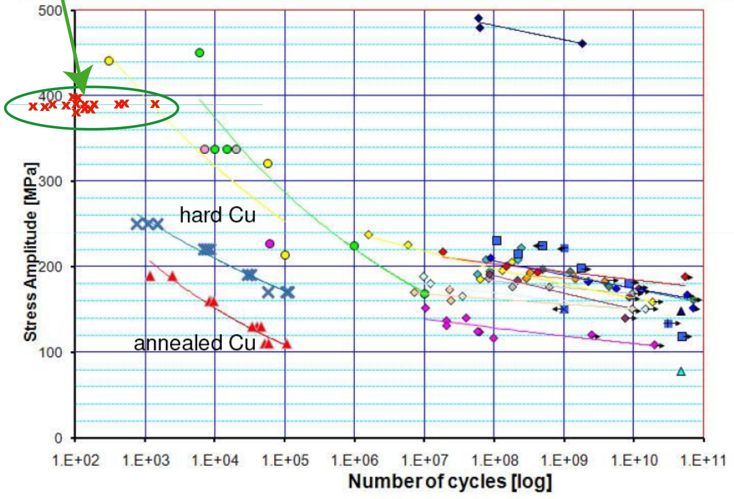
Coulomb explosions are compatible with fatigue

Breakdown numbers from CERN small gap experiment.



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

Fatigue data

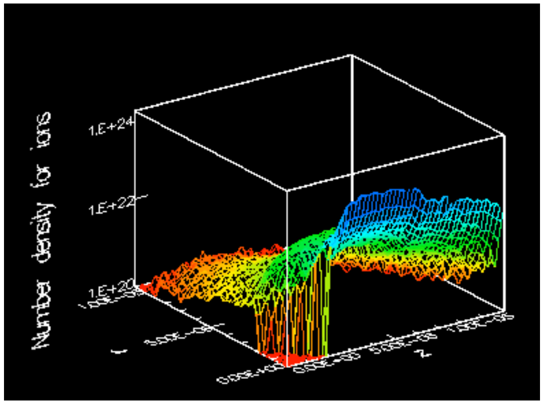


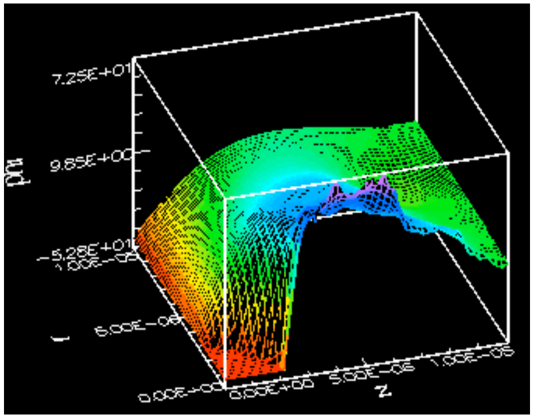
Unipolar arc properties

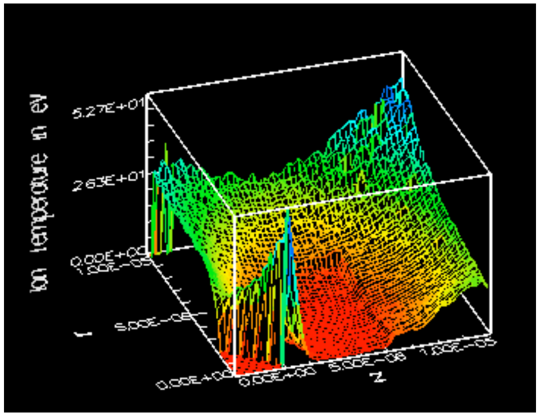
Dimensions matter

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

Ion Density, Phi, T_I







Arc dimensions a few microns.

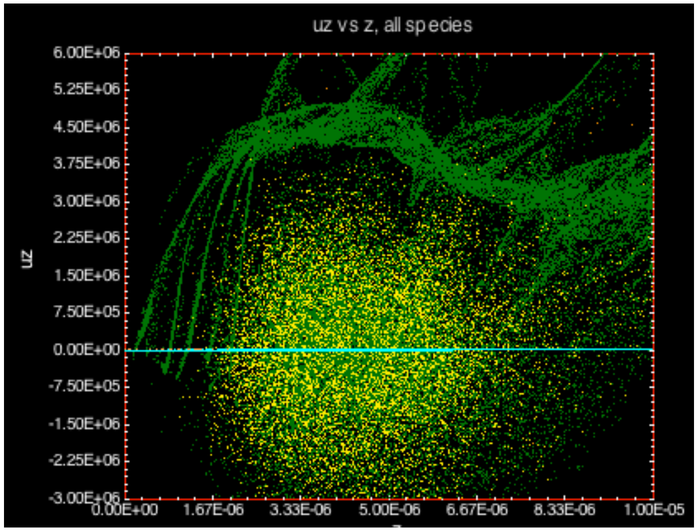
The arc is at the cathode.

Primary electron current

Space charge limit can be seen in v_z vs z

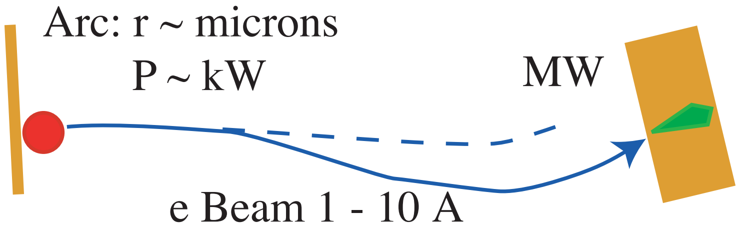
Plasma functions as a virtual cathode

Collision length remains constant ~ 10 μ



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

Our picture, from OOPIC



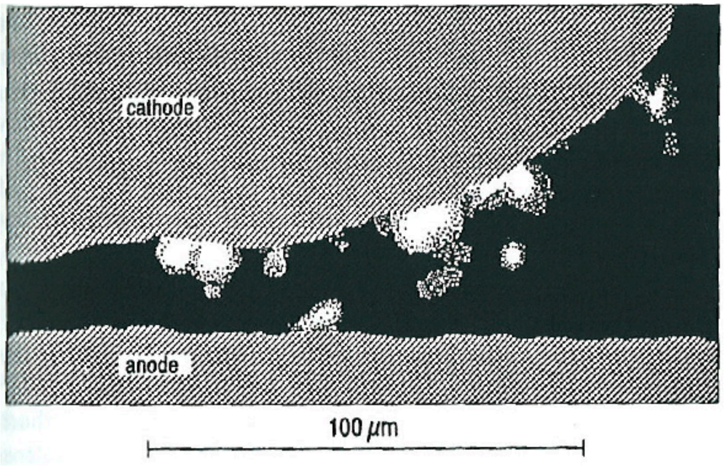
Arc: r ~ microns

P ~ kW

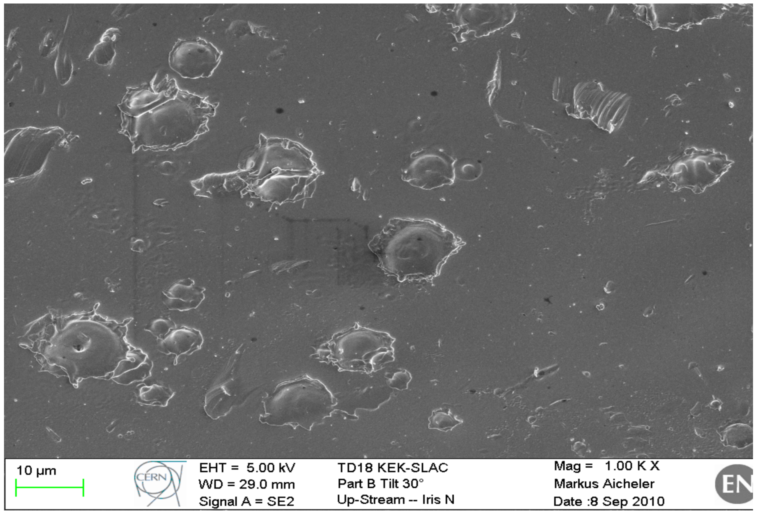
MW

e Beam 1 - 10 A

Anders, Fig 3.28,



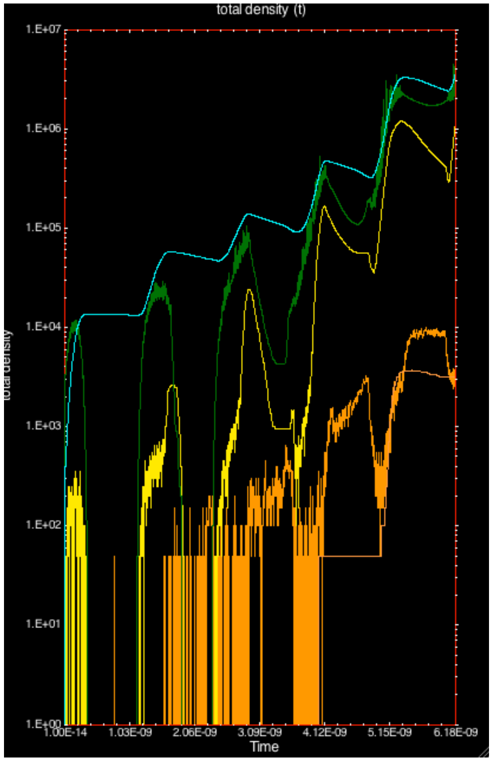
CERN and SLAC
(Aicheler CERN '10)

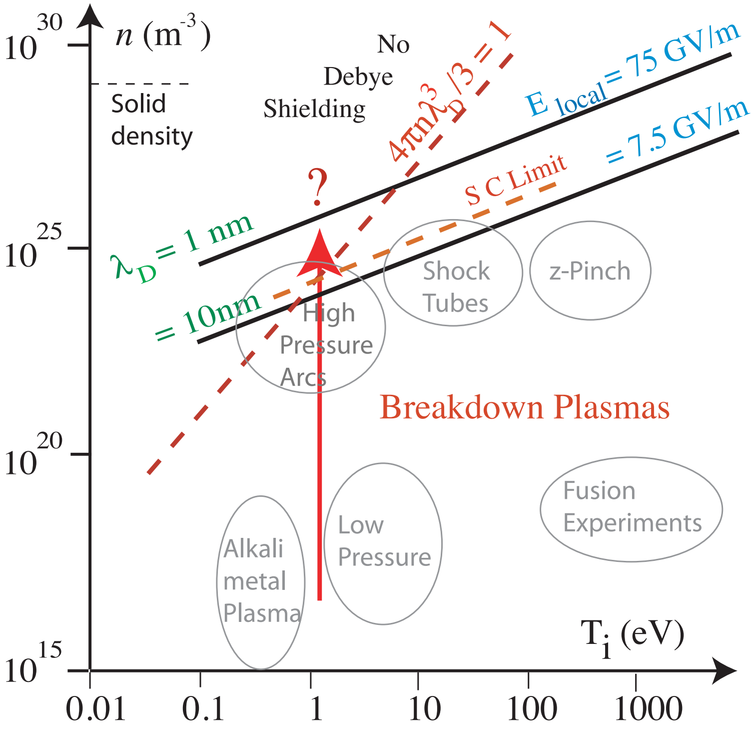


. . etc.

Time development:

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



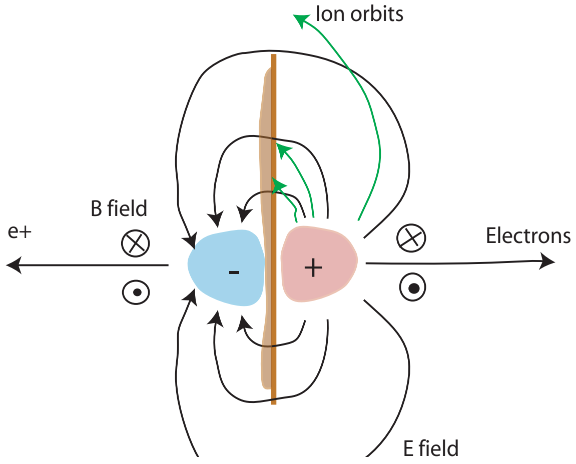


Increase in E drives

- arc evolution
- currents
- density increase

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.



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.

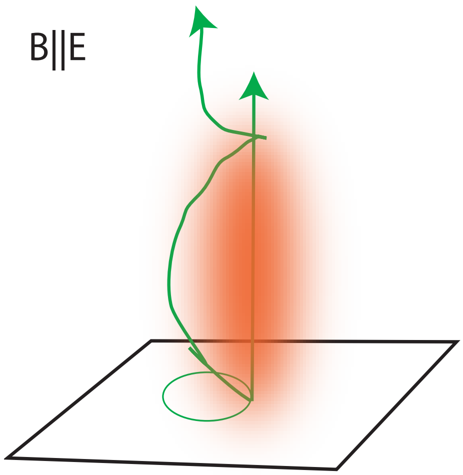
B Field effects electrons and should change gradient limits.
- Arc behavior is a function of ***B***.
- Focusing of shorting currents is evidently not harmful
  - Best gradient obtained with High collinear B field
- Larmor focusing of electrons, $r_L = 0.3\ [\mu]\ W_{eV}^{1/2}$
  - If ***E*** || ***B,*** 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.

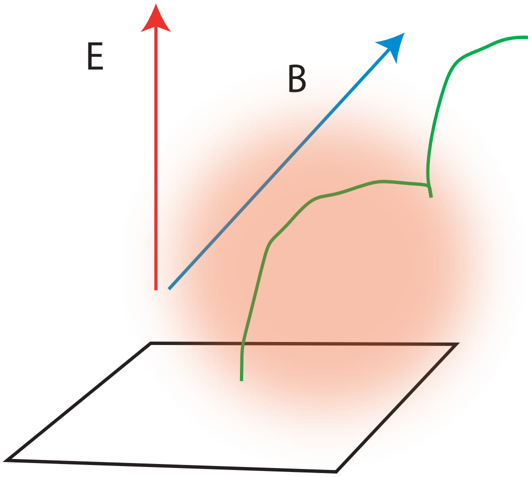
High local fields (megagauss) are seen

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.



localized plasma



distributed plasma

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

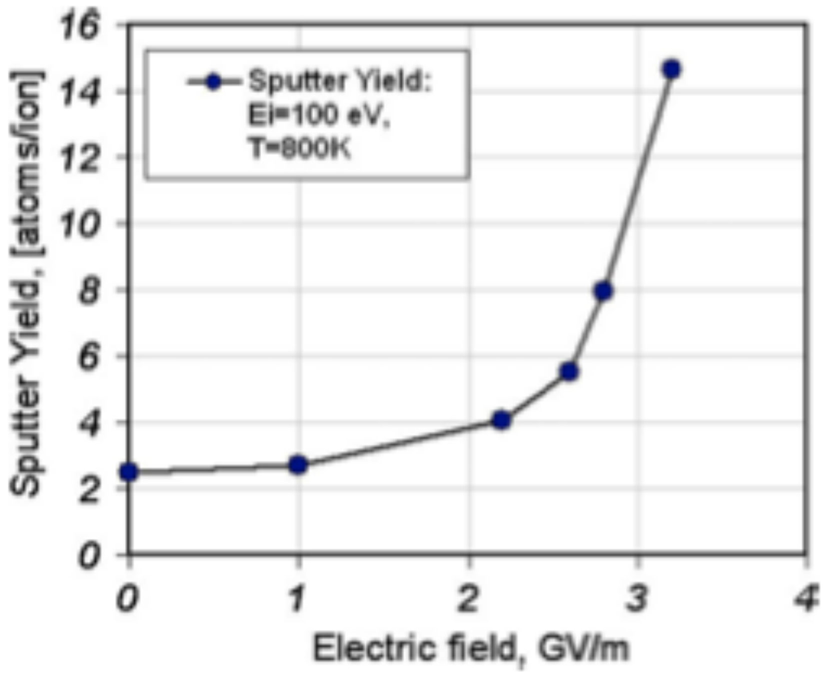
High E and T increase self-sputtering above 10 at low energies.

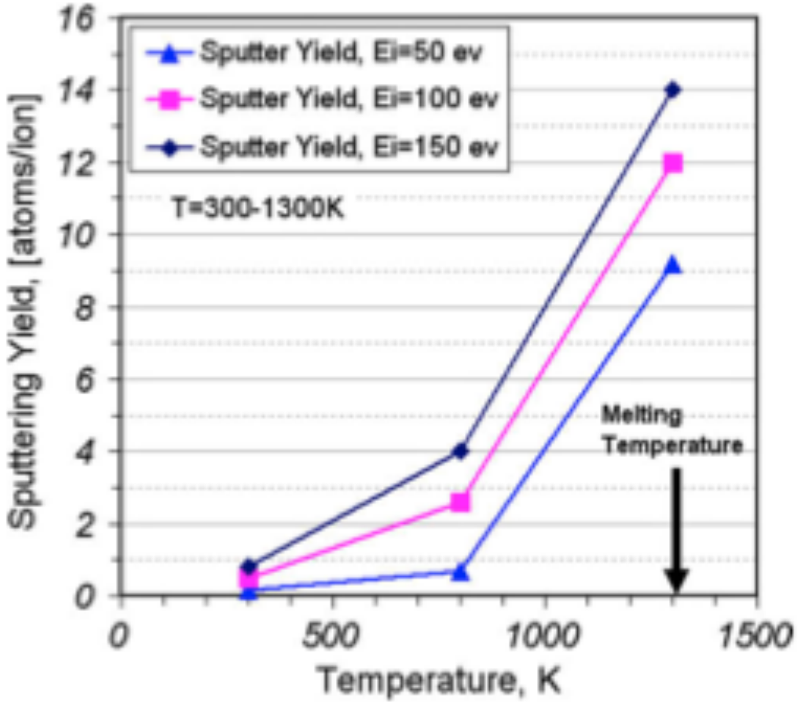
Grain orientation also seems to matter

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,
    - Satellite arc has favorable energetics . . .
  - 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.

$2 < \beta < 1000$

$1\ \mathrm{nm}^2 < A <$ 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, ($A \sim 1\ \mathrm{nm}^2$) 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.

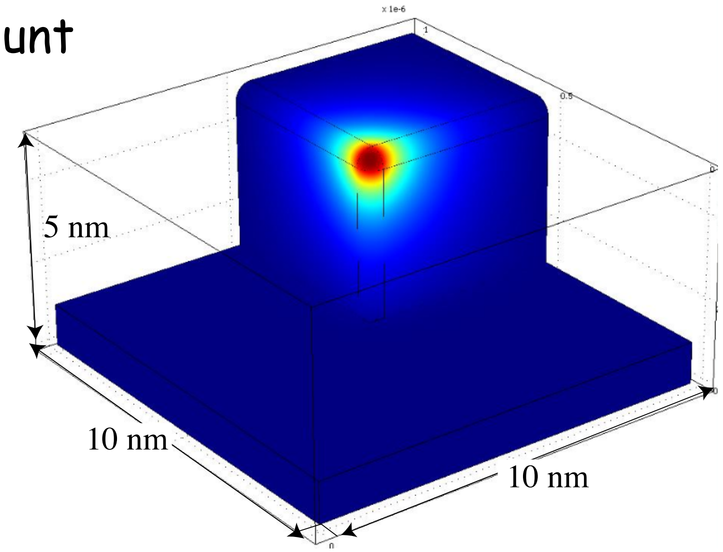
Fowler-Nordheim should be OK, as is Quantum Mechanics.

Damage

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

The spectrum of $n(\beta)$ 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

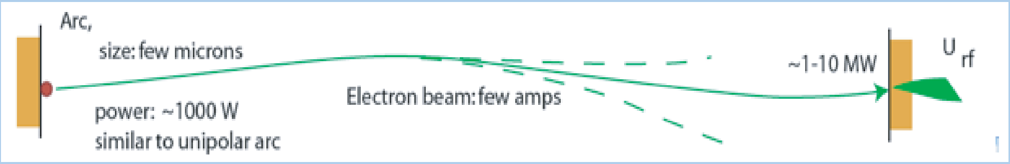


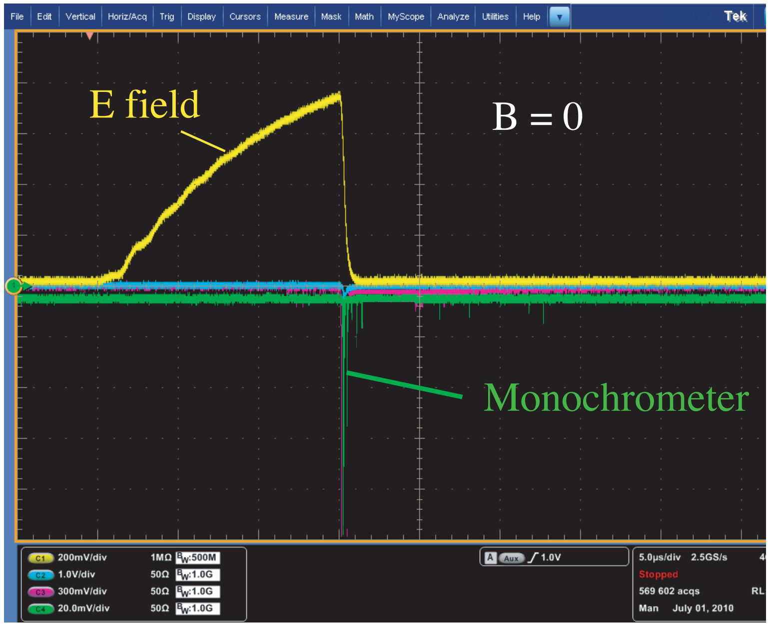
Two types of arcs
- **Killer** – arc current shorts potential, removes power source.
- **Parasitic** – arc removes energy from plasma slowly

Two types of arcs:

Killer arcs:

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

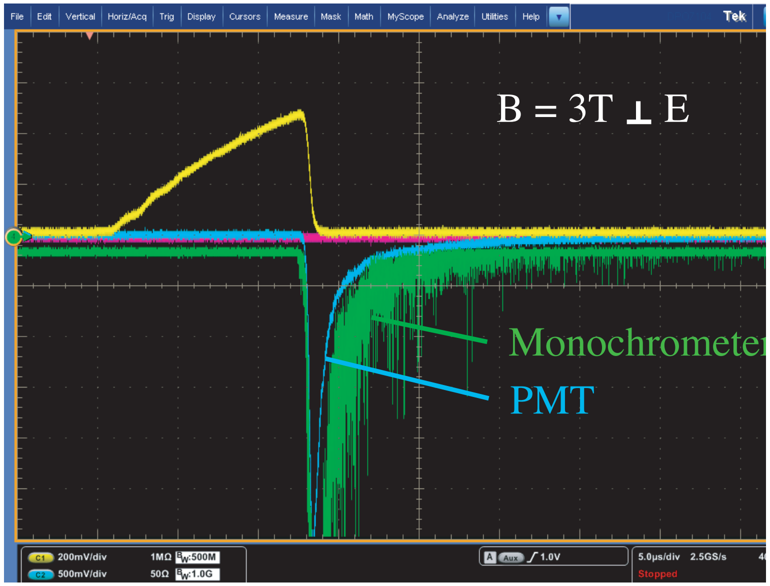




C1 200mV/div 1MΩ BW:500M
C2 1.0V/div 50Ω BW:1.0G
C3 300mV/div 50Ω BW:1.0G
C4 20.0mV/div 50Ω BW:1.0G
A Aux ⨍ 1.0V
5.0μs/div 2.5GS/s
Stopped
569 602 acqs
Man July 01, 2010

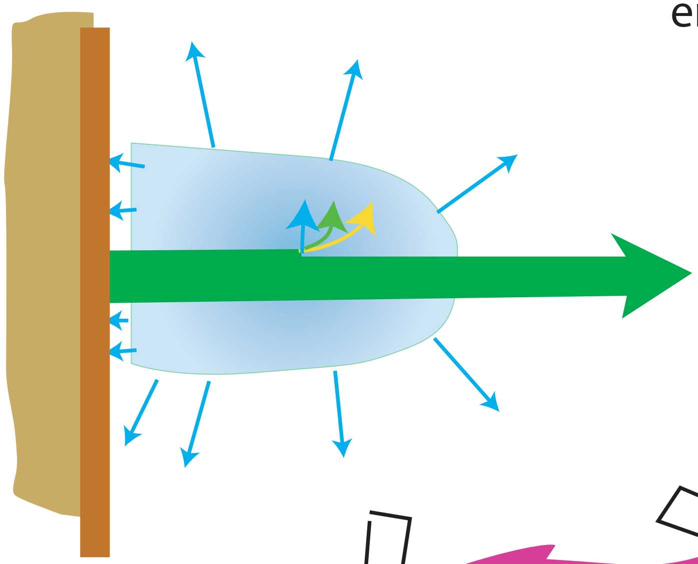
Parasitic arcs:

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



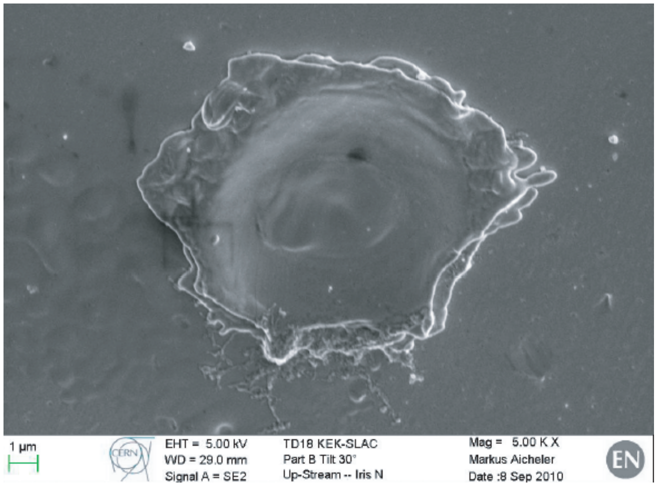
C1 200mV/div 1MΩ BW:500M
C2 500mV/div 50Ω BW:1.0G
A Aux ⨍ 1.0V
5.0μs/div 2.5GS/s
Stopped

Effects of increasing Arc energy

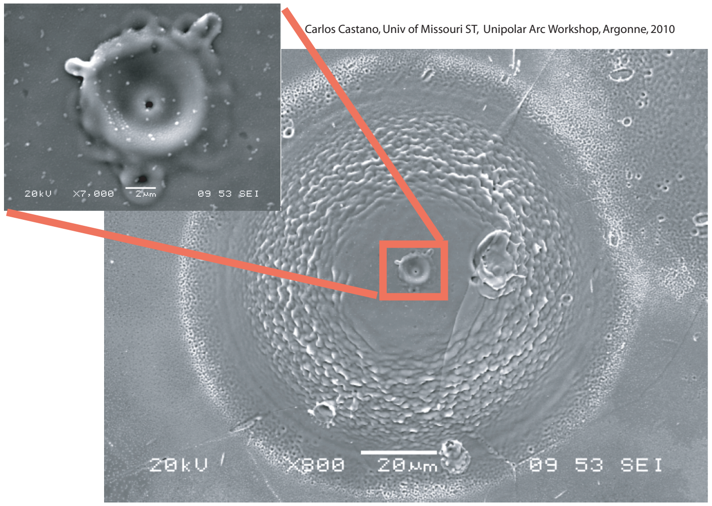


Increasing energy

"killer" arcs



"Classic" arcs



Carlos Castano, Univ of Missouri ST, Unipolar Arc Workshop, Argonne, 2010

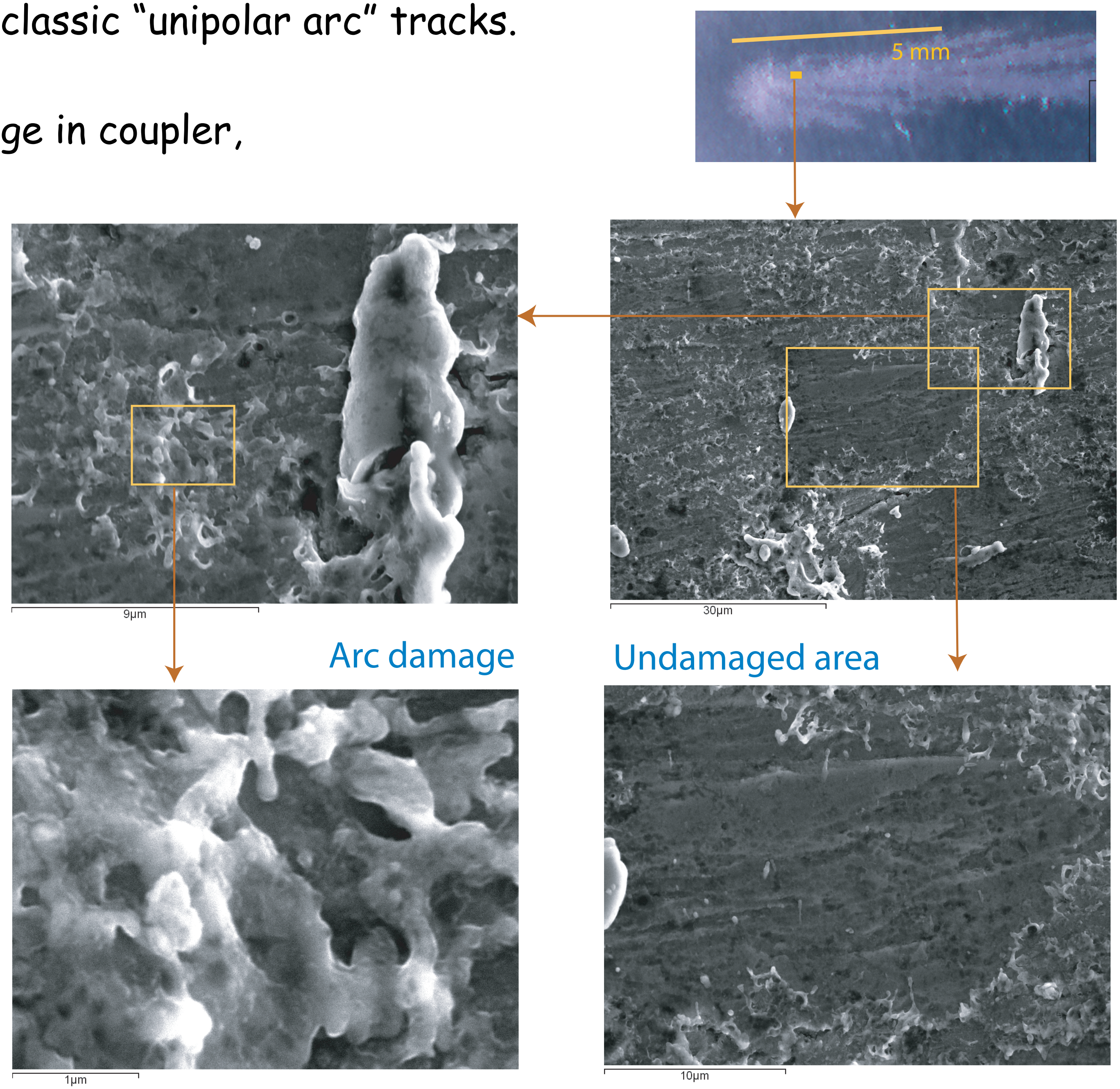
"Parasitic" arcs

These arcs are ~1 cm long
201 rf coupler

New SEM pictures of the 201 Coupler Damage.

These seem to be classic “unipolar arc” tracks.

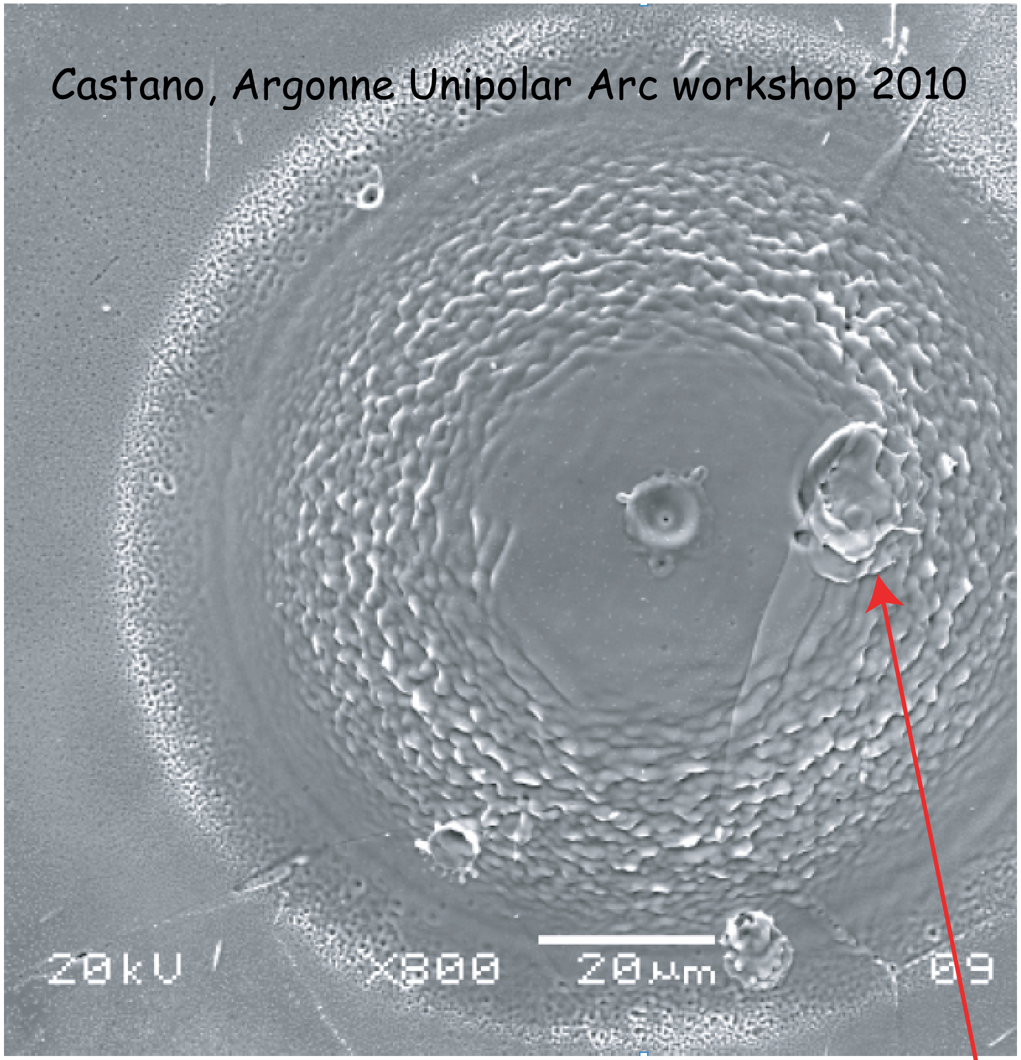
Parasitic arc damage in coupler,



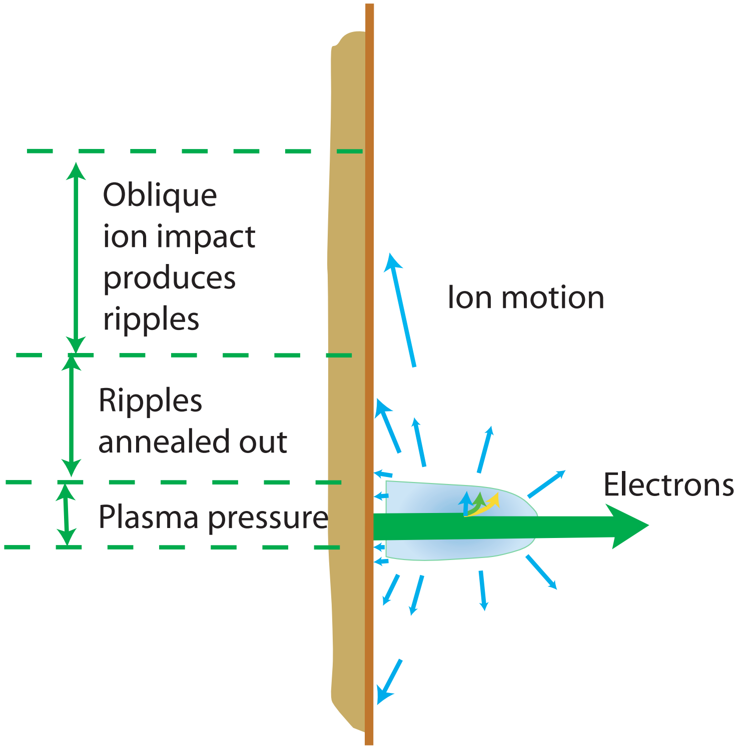
Arc damage

Undamaged area

Arc damage mechanisms



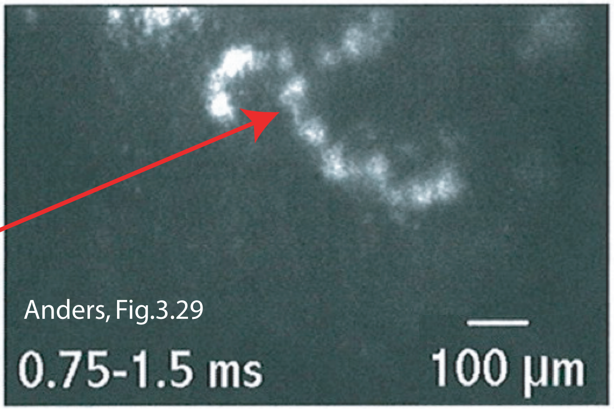
Castano, Argonne Unipolar Arc workshop 2010



Oblique ion impact produces ripples

Ripples annealed out

Plasma pressure



Anders, Fig.3.29

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

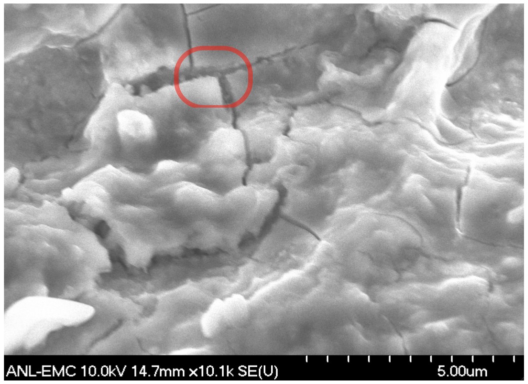
Cracks

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

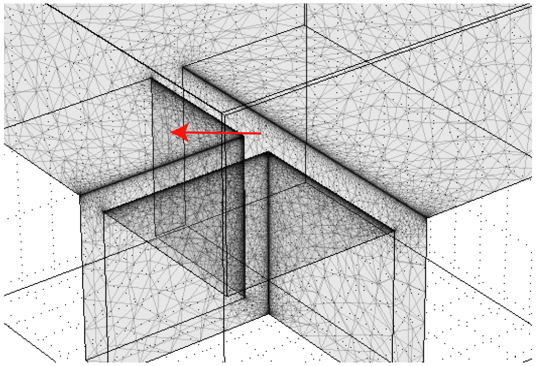
Sharp crack angles have high *β*s but are uncommon.

SEM showing cracks

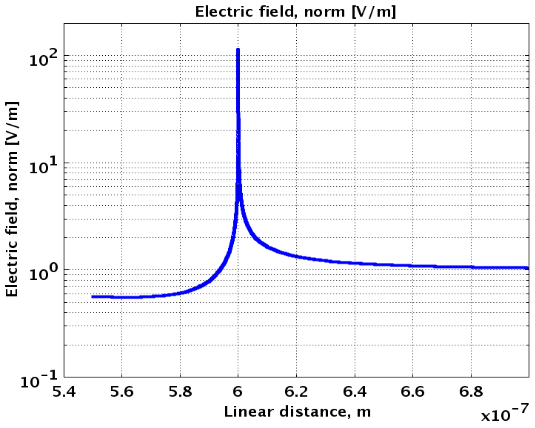
a)



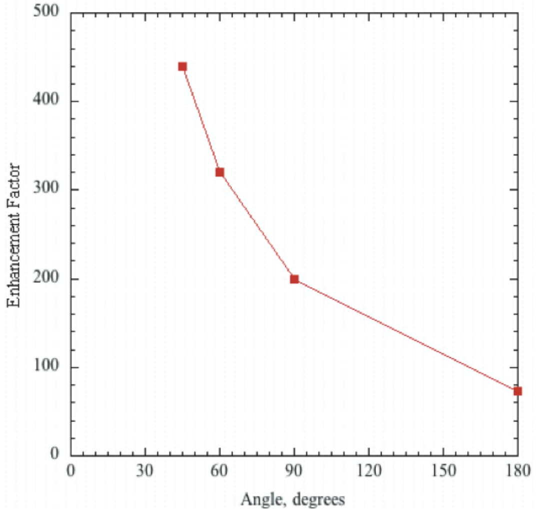
b)



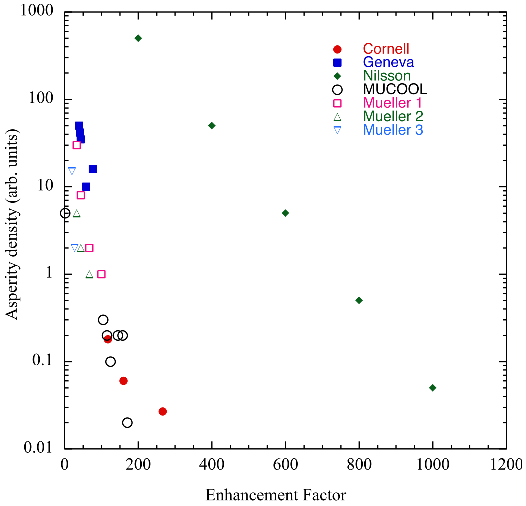
c)



β(crack angle)



n(β)

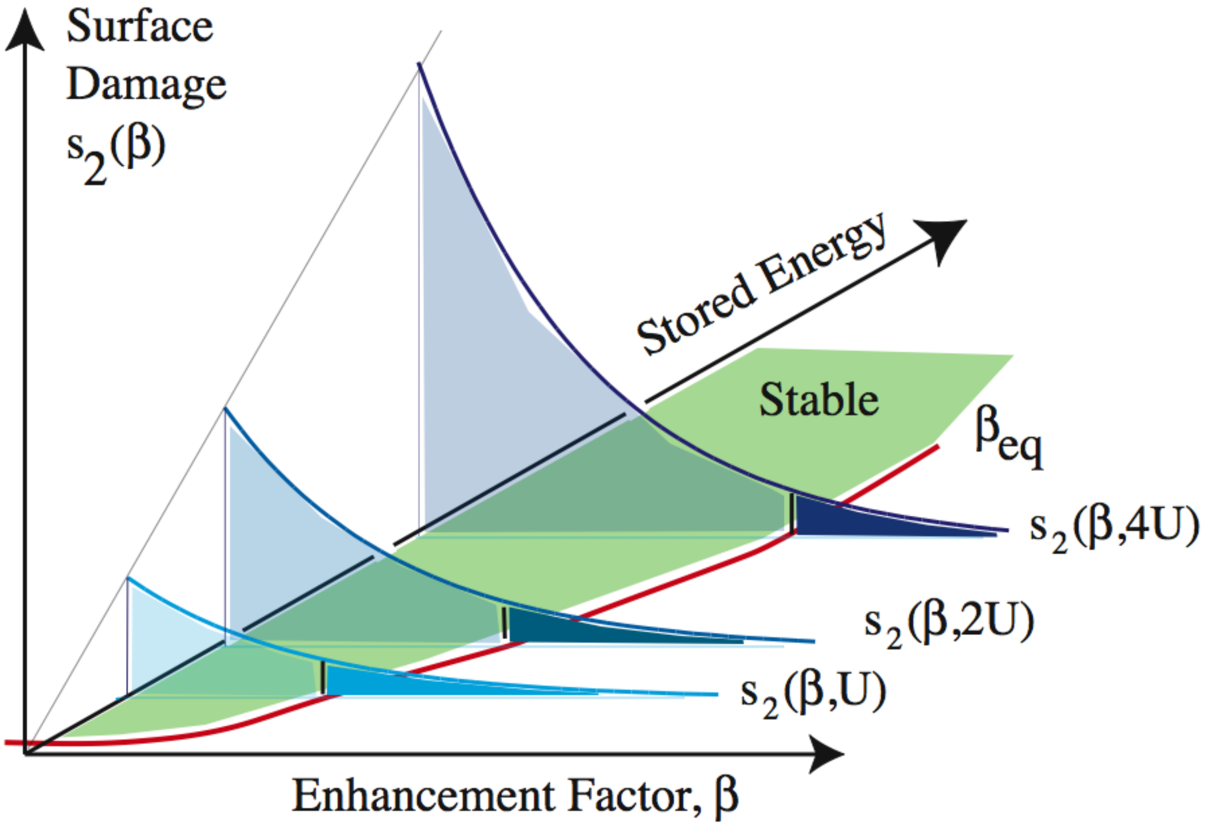


Particulates can also explain this effect.

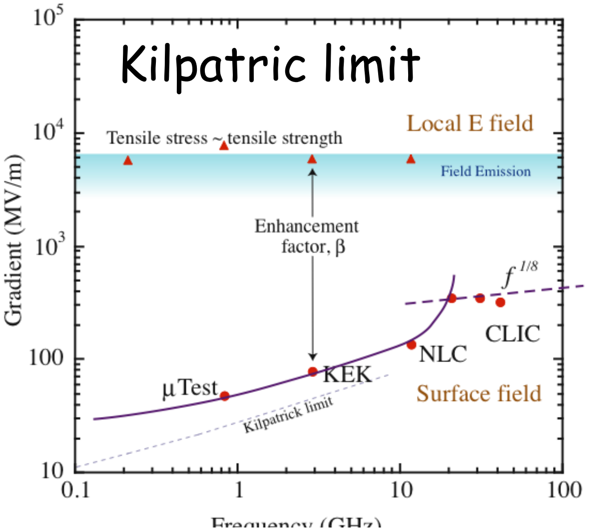
Gradient limits

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, enhancements rise (and gradients fall) logarithmically with arc energy.



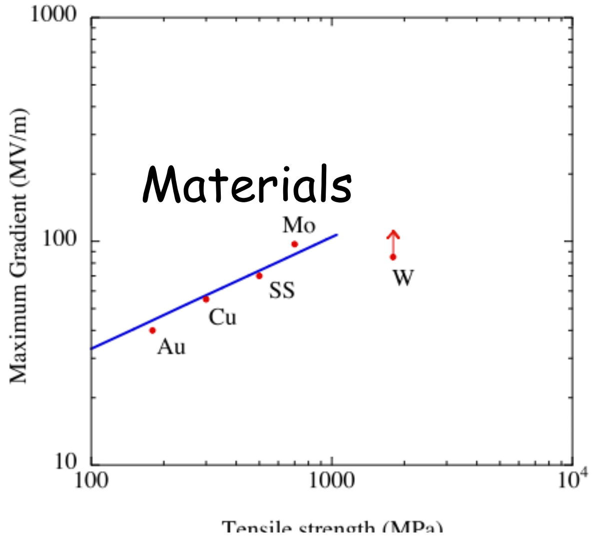
We published a paper in '05 describing how damage causes gradient limits, with a number of predictions and examples.



Conditioning modeled
We can calculate the Kilpatric limit
Gap dependence: there is none
Frequency 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 . . .



Initial tests with ALD W. (Is W optimum?)

Made from WF_6 and Si_2H_6

Composition of sample coating:

W	84.88% +- 0.110%
Si	9.217% +- 0.039%
O	4.816% +- 0.028%
C	0.964% +- 0.012%
Cu	0.012% +- 0.004%

Measured tensile strength of 50 nm coating > 3000 MPa

Compares with bulk W ~ 1500 MPa, Cu ~ 300 MPa

Adhesion and conductivity will be varied and measured by a number of techniques.

Cavity design under study.

Coating alternatives under study.

Active Effort

Thermodynamics of breakdown sites

Exploring ALD coating properties.

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.

We differ from European modeling (old and new) in many ways.

No whiskers seen either in rf or DC expts.

- For realistic geometries, emitters don't heat
- Contradicts Explosive Electron Emission (EEE) model

Confusing gas and vacuum breakdown seems common.

- CERN modeling uses plasma that spans a 20 μm gap and is equi-potential
- All their potential drop (many kV) is in the sheath
- Breakdown conditions seem dependent on gap

We do 3D simulations they do 1D

Calculations of rf B field heating emitters / breakdown sites

- Emitters must be << skin depth
- Really hard to heat emitters this way

Conclusions

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

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

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

- Little interest, little support
- History (SSC, NLC, ILC) implies we need to know how things work.
- This field may be starting to converge.