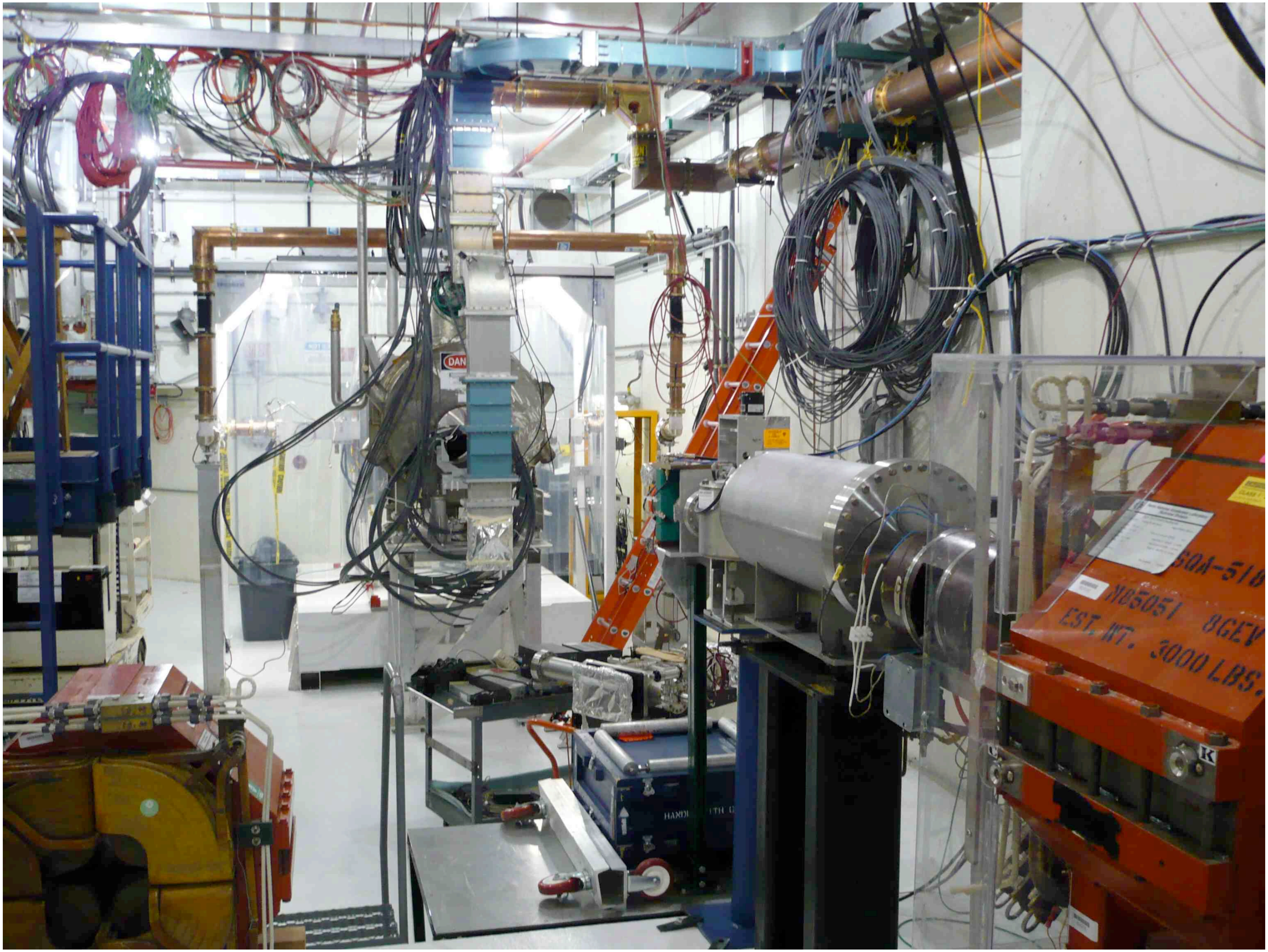
Modeling Breakdown and Gradient Limits

J. Norem & Z. Insepov
ANL/HEP

CLIC 09
Oct. 15 09

We study rf gradient limits at the Fermilab Muon Test Area.



Many people have contributed to this work.

Normal Conducting		
A. Hassanein	Plasma Phys	Purdue
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
D. Huang	RF, Instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X
Superconducting		
M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
Th. Proslier	SC theory and exp	IIT
L. Cooley	SCRF	FNAL
G. Wu	SCRF	FNAL

What determines the operational rf gradient limits (NC & SF)?

- Accelerator performance is limited by arcing.

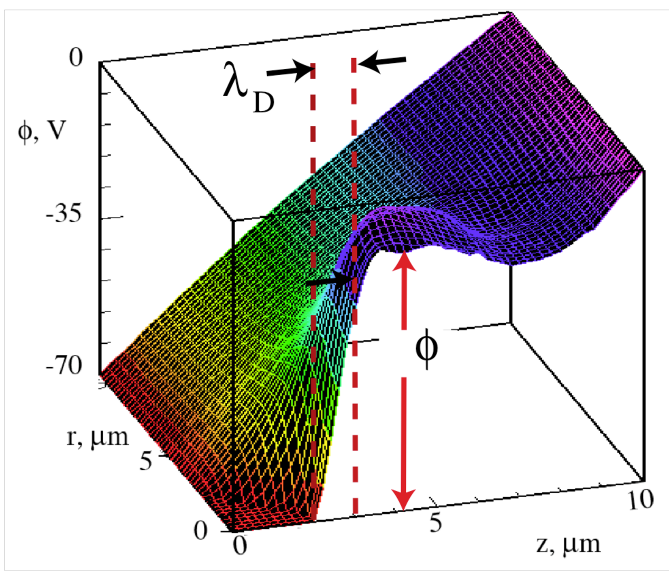
- The arcing problem is very old and not adequately described anywhere.
  (even after ~110 years, - A "breakdown" of the scientific method?)
  Data is sparse and clustered, hard to compare.

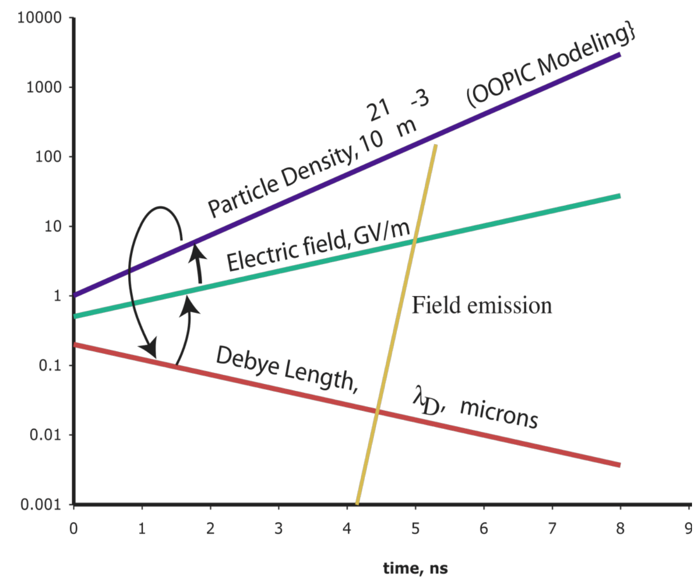
- Our basic assumption is that all arcs have a lot in common:
  Warm accelerator, SRF, Tokamak, laser ablation, cathodic arcs, large/small gap, lightswitches, micrometeorites, +/-, e-beam welding, high pressure, cavities, RF to DC, (ball lightning ?)

- We want a model that:
  is simple,
  can explain all features of the discharge in detail,
    including accelerator gradient limits,
  in all environments,
  and can point the way to a solution.

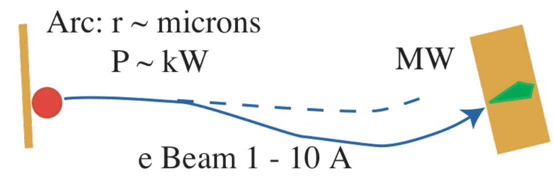
The breakdown model.

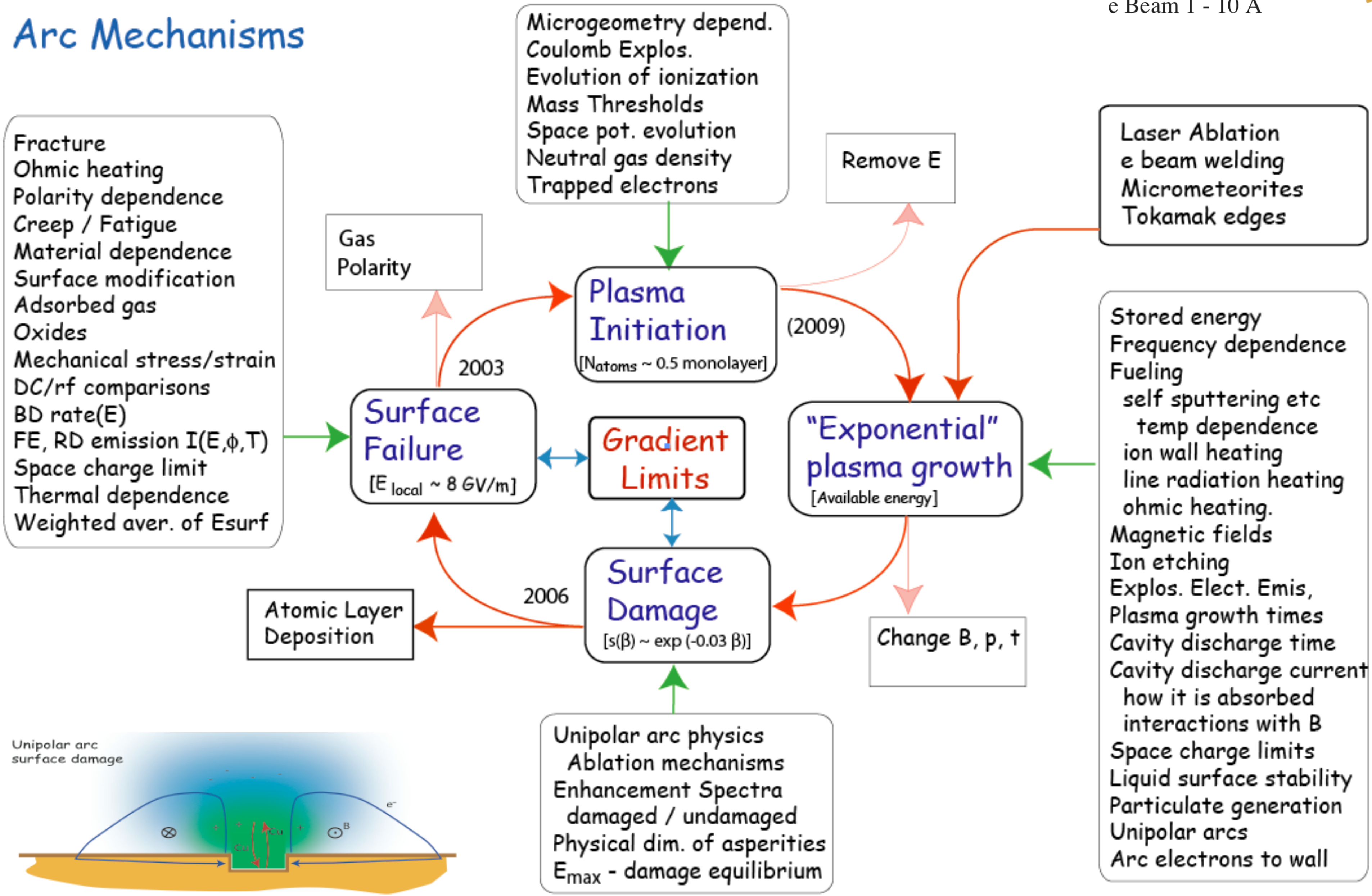
- Coulomb explosions trigger breakdown - fatigue (creep) and Joule heating help.
- Breakdown arcs are initiated by FE ionization of fracture fragments.
- The arcs produced are small, very dense, cold, and charged +(50-100) V to surface.
- Small Debye lengths, $\lambda_D = \sqrt{\dfrac{\epsilon_0 KT}{n_e q_e^2}} = \sim\mathrm{nm}$, produce fields, $\boldsymbol{E} = \phi/\lambda_D \sim$ GV/m.
- High electric fields produce micron-sized unipolar arcs.
- Unipolar arc energy produces craters and surface roughness.



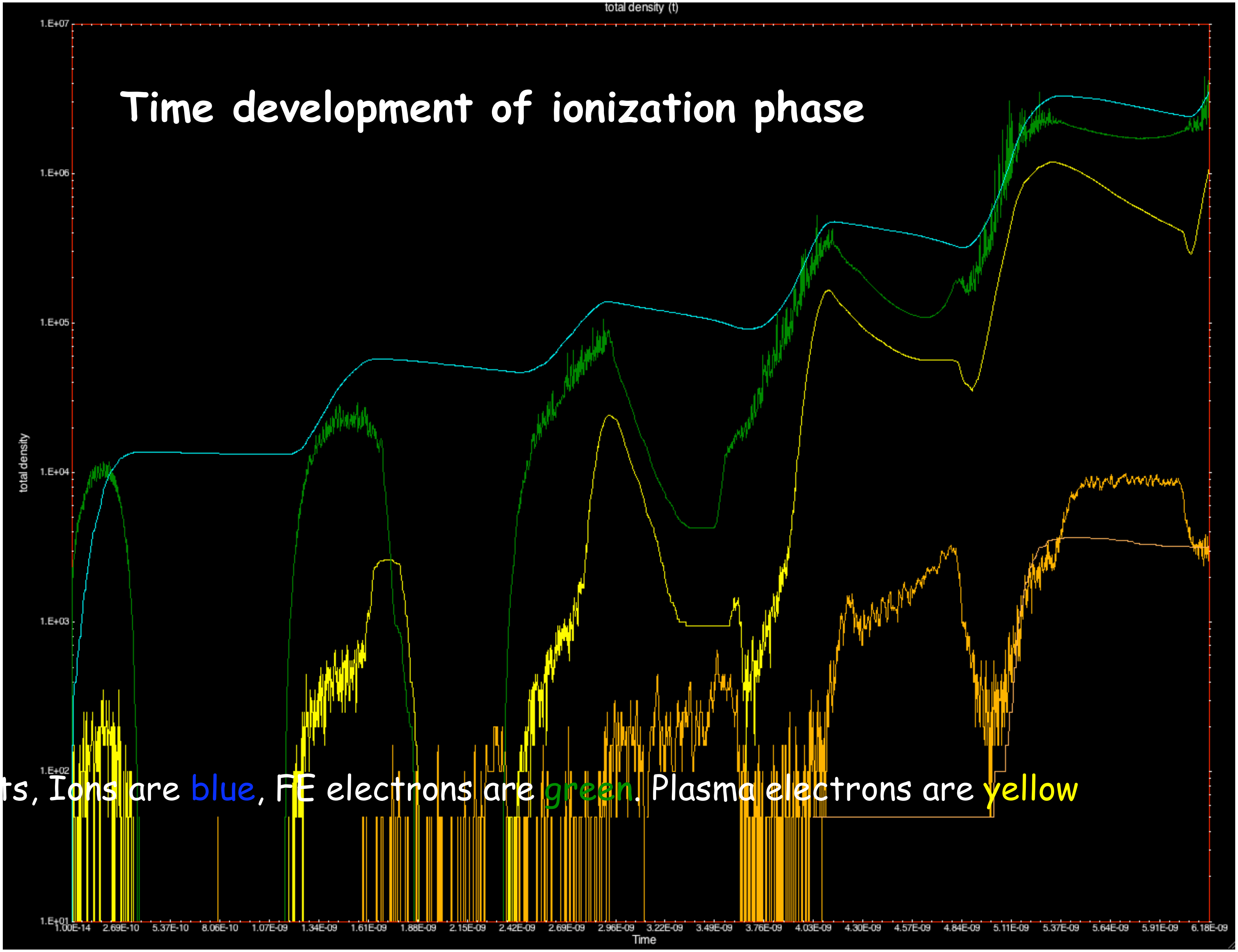


More details (mere details).





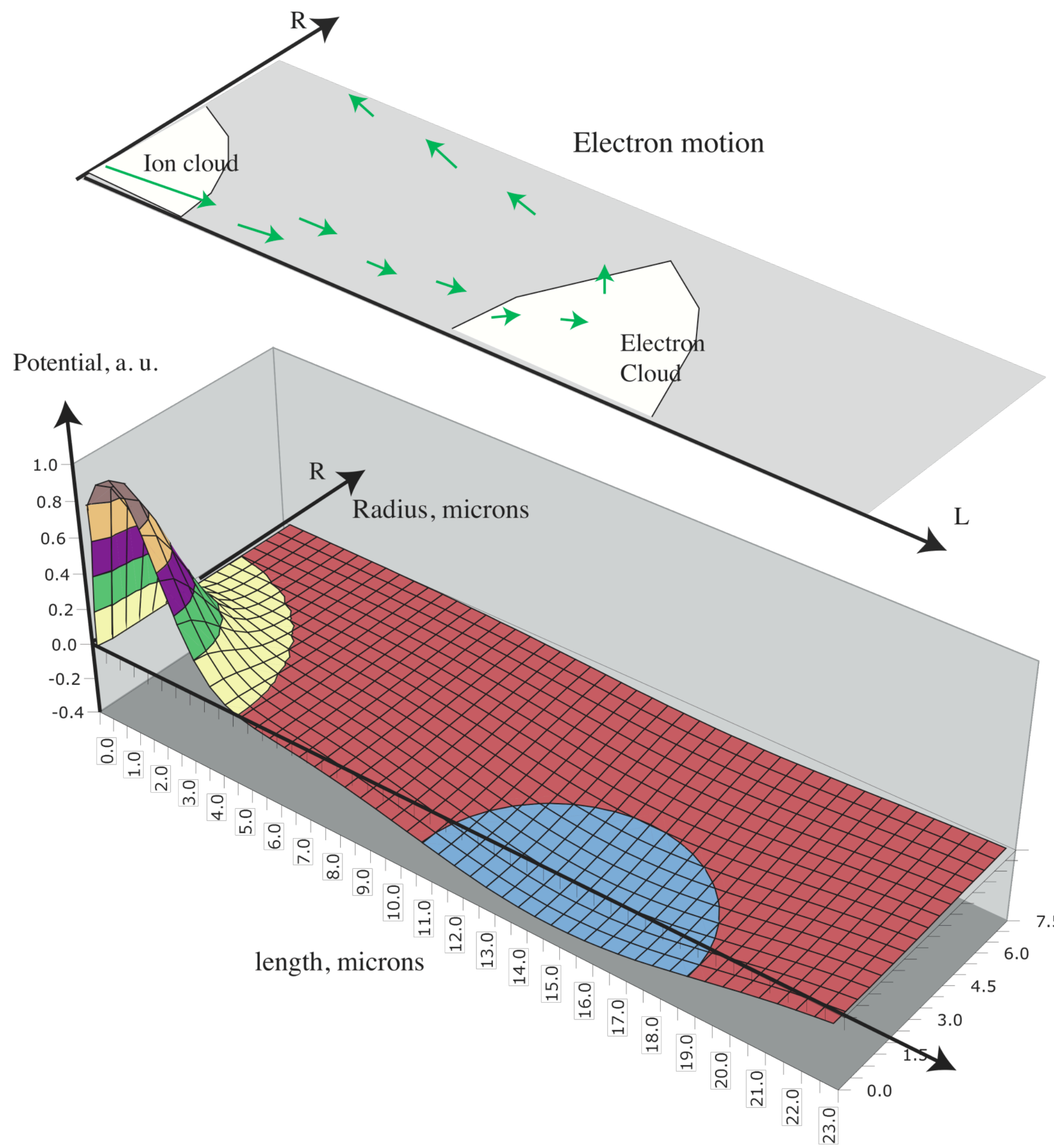
OOPIC Pro modeling shows us how the arc starts.



In plots, Ions are blue, FE electrons are green, Plasma electrons are yellow

What is a Unipolar Arc?

- A unipolar arc is an inertially confined plasma on an equipotential surface.
- The literature is not very descriptive, neither is the name. It is very bipolar.
- Unipolar arc parameters:
  - The arc is dense.
  - Electrons diffuse away
  - The plasma is charged to ~50 V.
  - FE electrons maintain the plasma.
  - Ions heat the surface.
  - FE, ion currents can be large.
  - MG Magnetic fields possible.
  - Arc energy goes into craters.
- In our case:
  - Things are very bipolar.
  - Electrons return elsewhere.
  - Arc energy goes into craters.



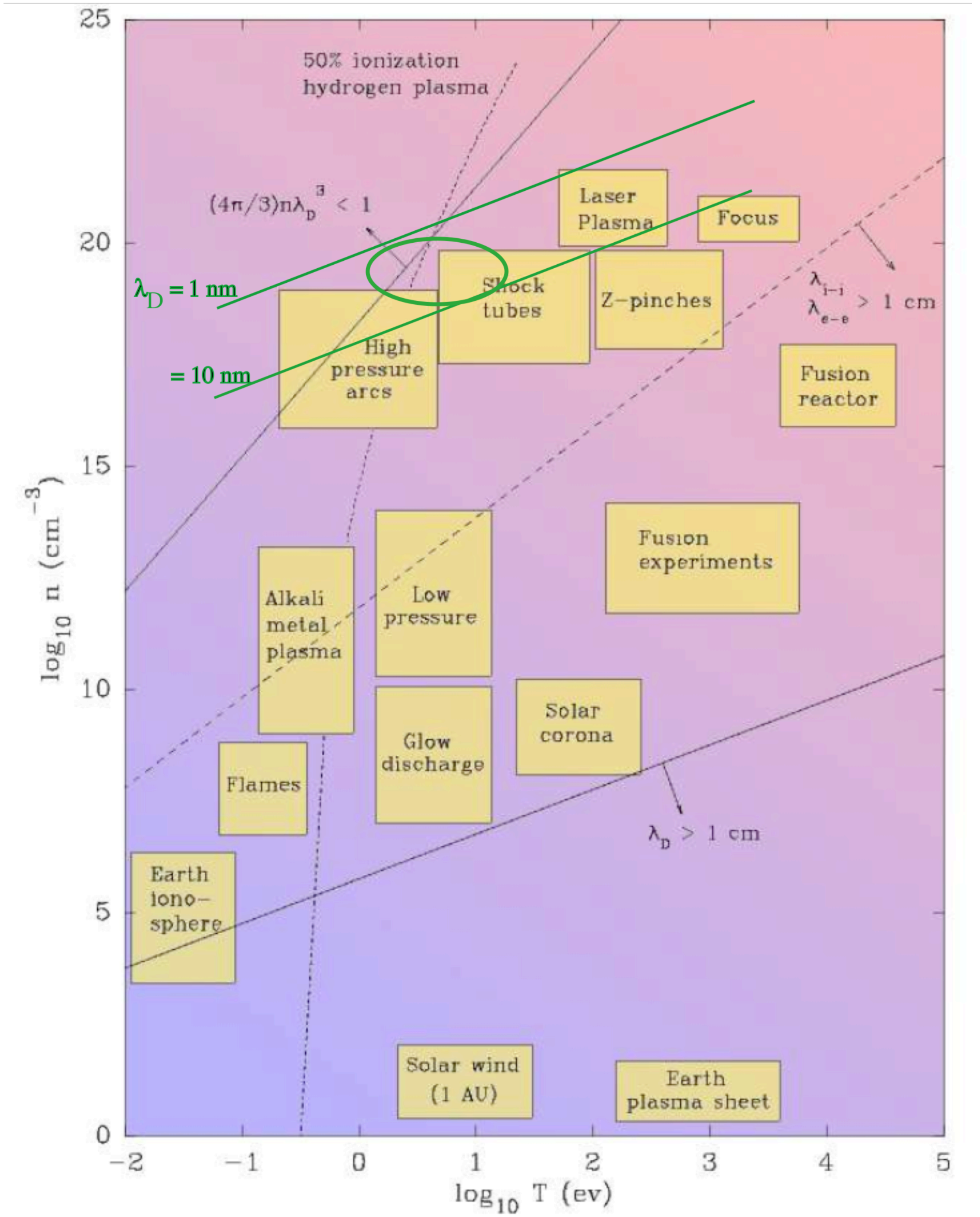
Where does the unipolar arc fit in plasma physics?

- The unipolar arc is <u>not</u> a “plasma”.
- “Plasmas” are defined by:

✔ $\lambda_D < L$ (size)
✖ $N_D >>> 1$ (screening)
✔ $\omega\tau > 1$ (collisionality)

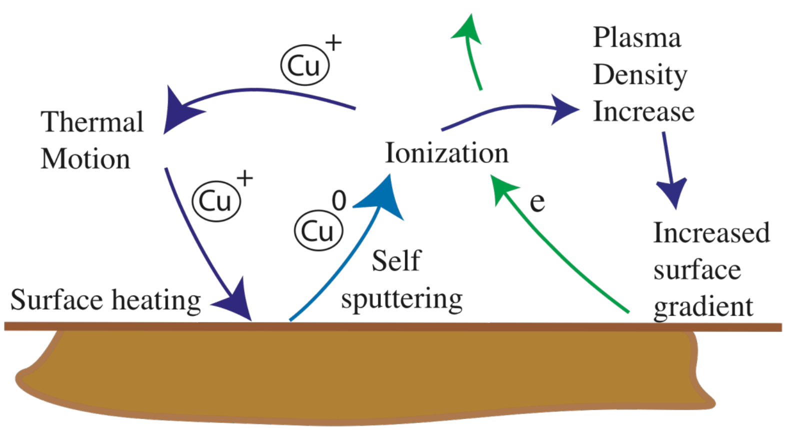
- The Debye length is too short
  screening is marginal (! ?)

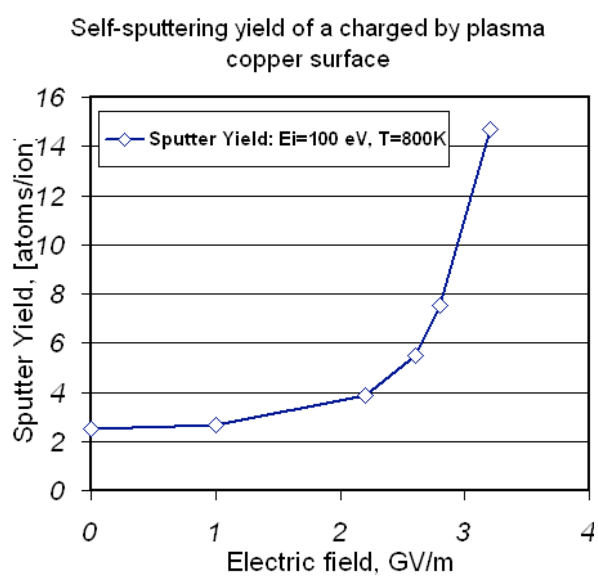
✖ Traditional plasma methods
✔ Numerical & atomistic methods

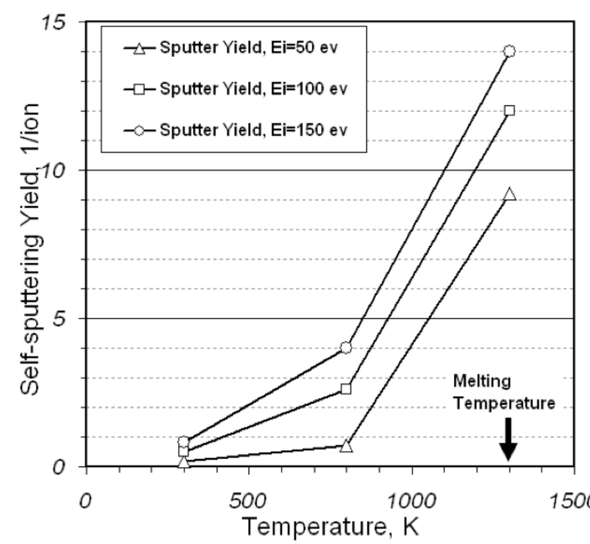


Unipolar arcs attack surfaces,

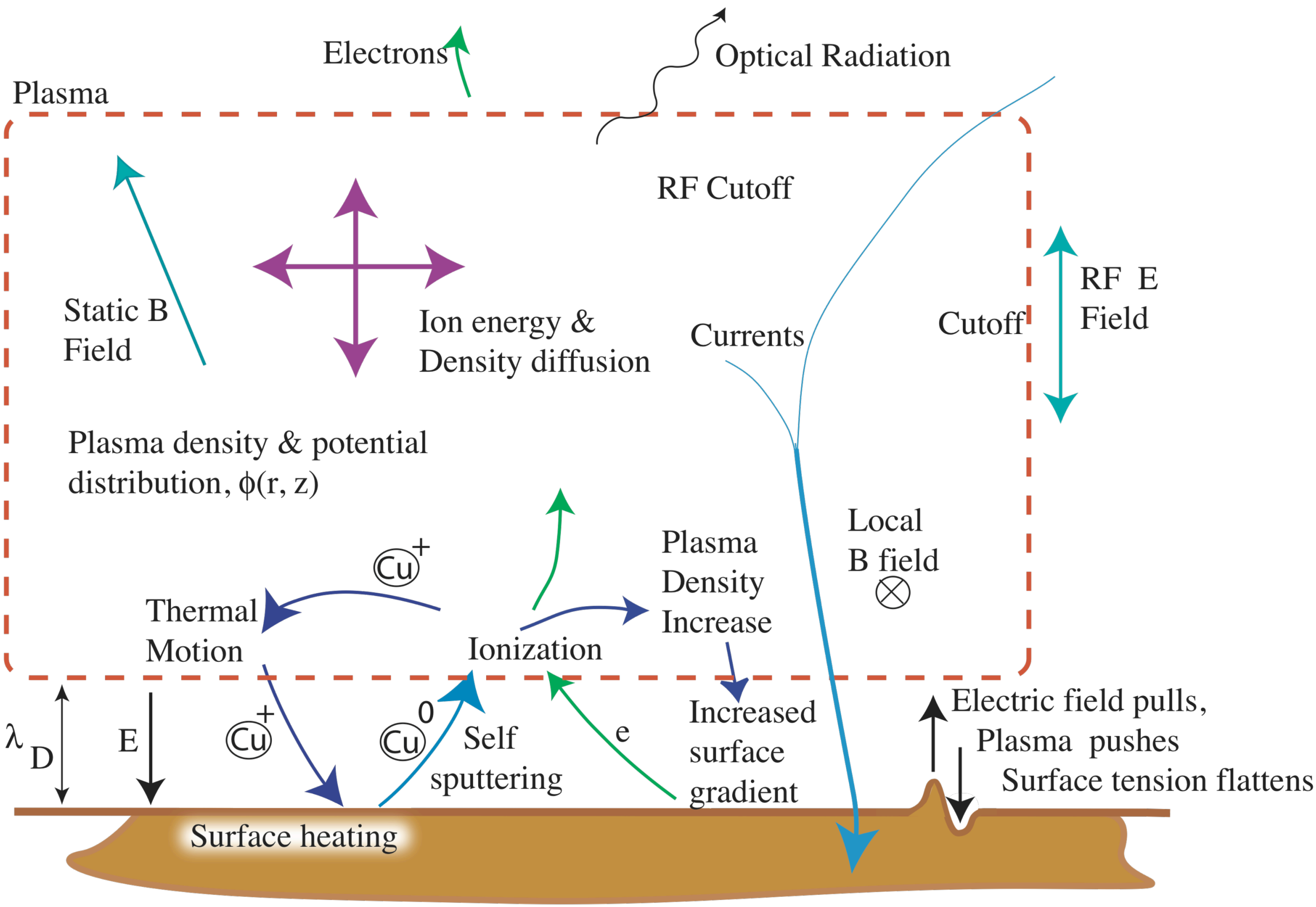
- . . . and they do it very efficiently.
- The interactions of high density, low temperature plasmas with materials was studied actively in the fusion community until about 1990.
- Numerical modeling of self-sputtering at high fields and high temperatures shows high secondary atom yields, but codes give surface temperatures of ~10000 degC so the surface could not survive.
- Erosion rates on the order of, $r = n_I\ v_I\ Y(\lambda_D,\ \phi,\ T_{surf})\ /\ V_A$ are ~ 1 m/s.







The unipolar arc is complex.



Much of the arc is experimentally accessible.

We are continuing to model the arc with OOPIC Pro and VORPAL.

Trigger

We can measure E_{local}, emitter size, and density of breakdown sites,

$n(\beta)$, $n(r)$, $n(E_{local})$ of sites

What is the material and magnetic field dependence ?

Ionization

Optical radiation(t) describes the arc (core or edge?), degree of ionization?

X rays give time development, power.

Unipolar arc

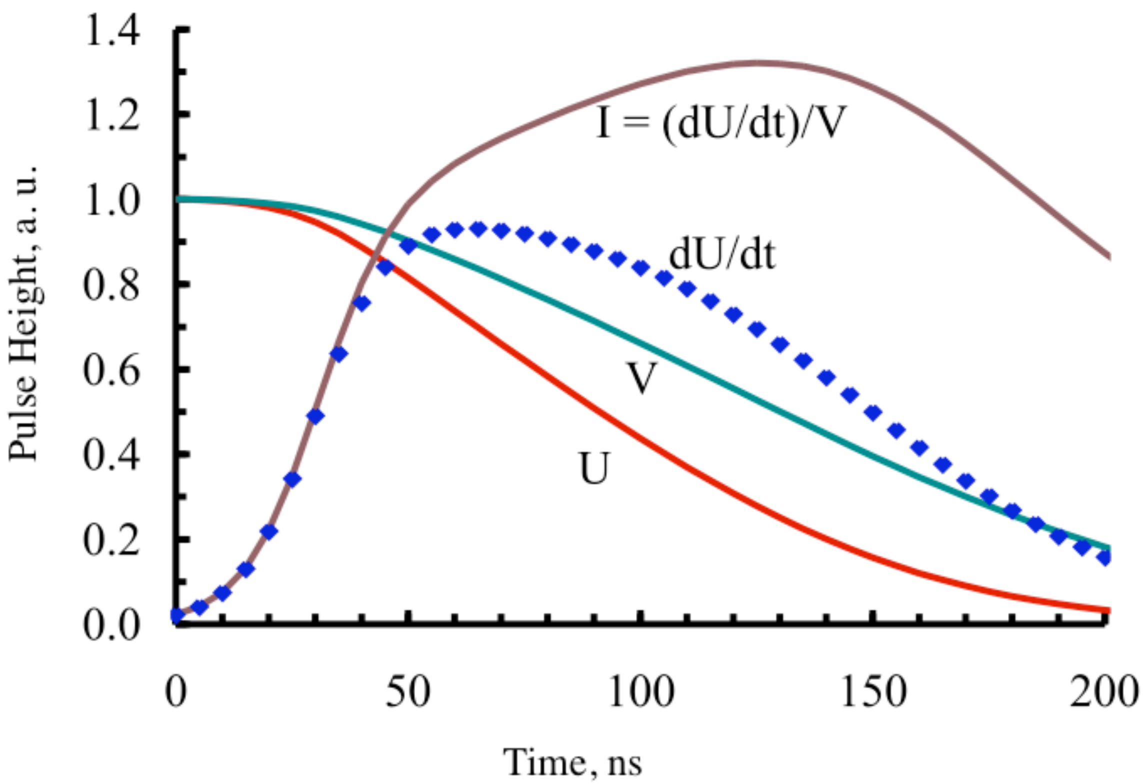
Basic dimensions and parameters could be measured better.

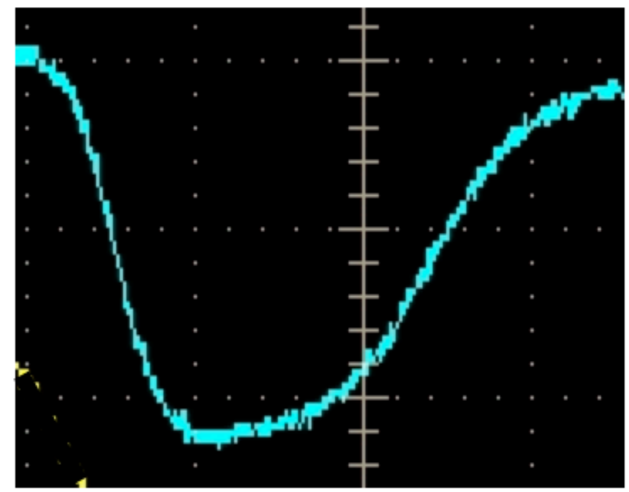
$E_{surface}$

Dependence of damage parameters on power (or anything else)

What happens to the cavity energy?

- X ray data show how energy leaves the cavity. Relativistic electrons take it.





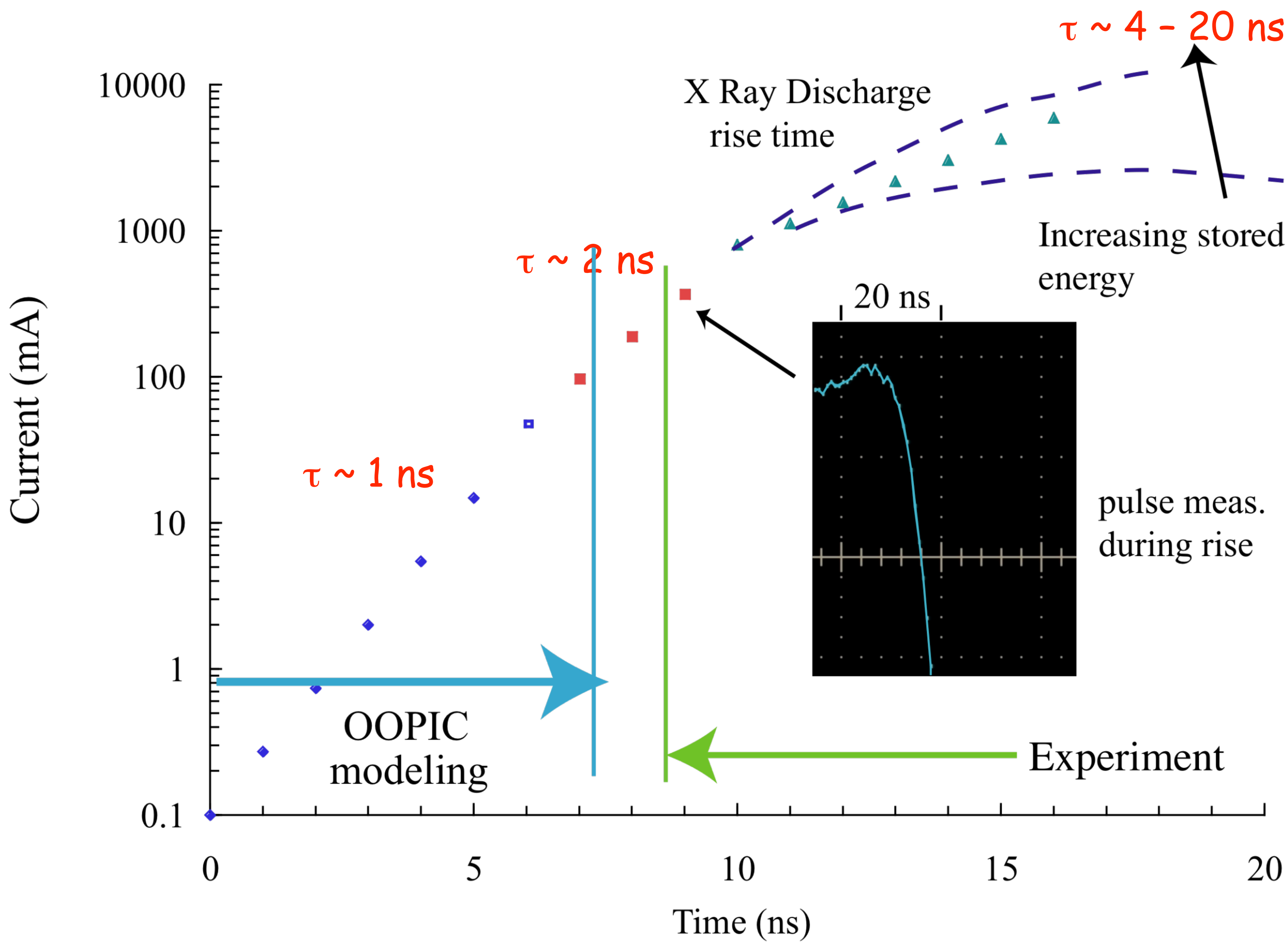
At the MTA our 805 MHz pillbox has:

- An easily measured risetime ~ 4 – 20 ns
- Stored Energy ~ 1 J
- Electron energy ~ 4 MeV
- Electron current ~ 4 A, (40,000 (?!) times the field emitted currents)

We can compare measured and predicted rise times.

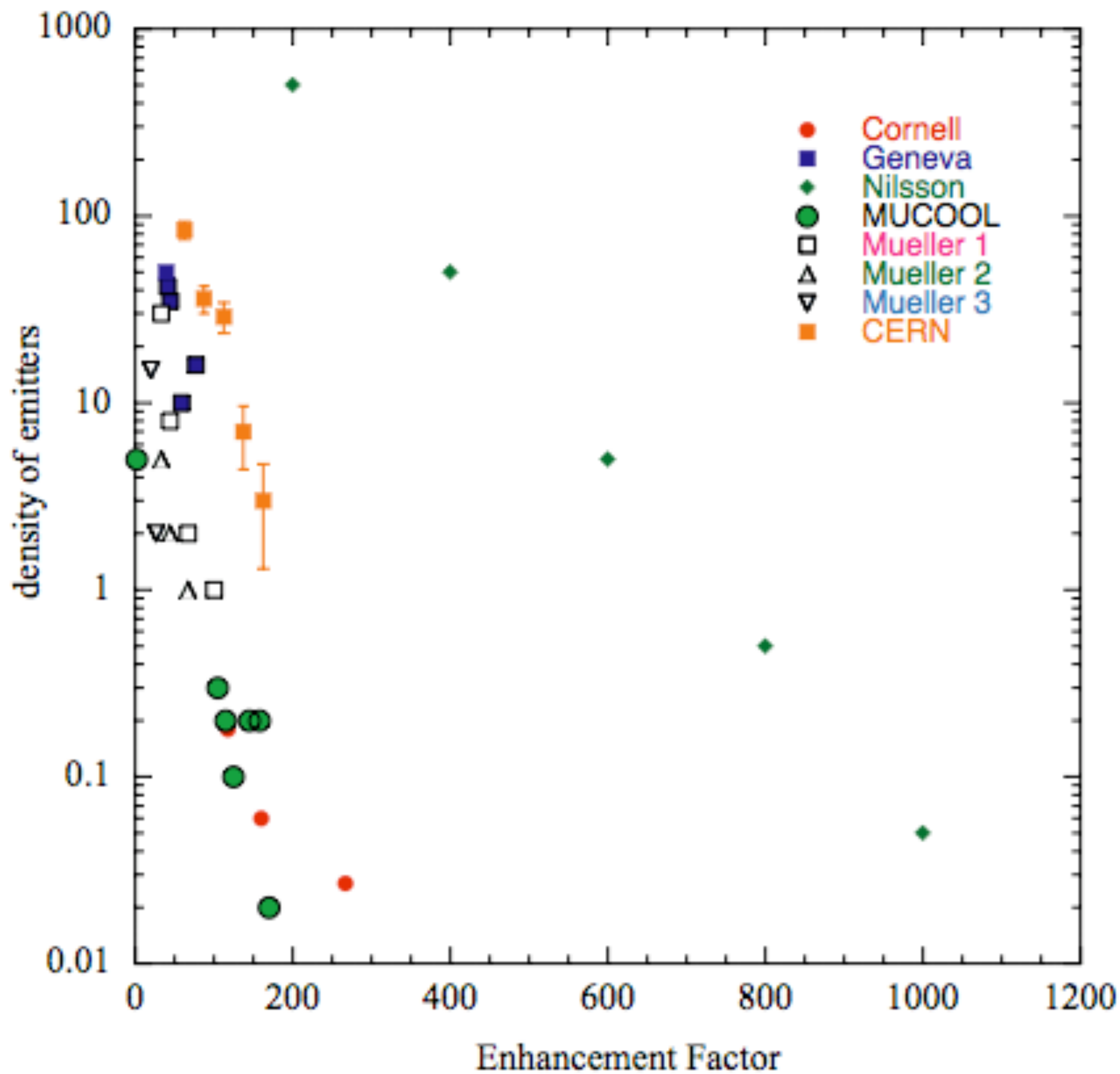
We can look at rise times of the shorting current pulse.

- The initial few ns have been modeled in detail in OOPIC Pro.
- The end of the breakdown event was measured with x rays.



There is a spectrum of enhancement factors.

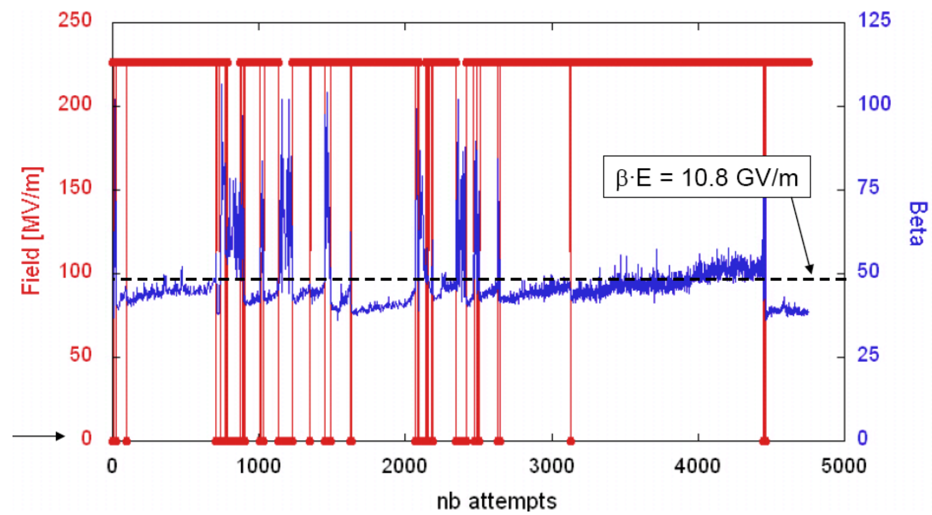
- Everyone sees roughly the same thing.

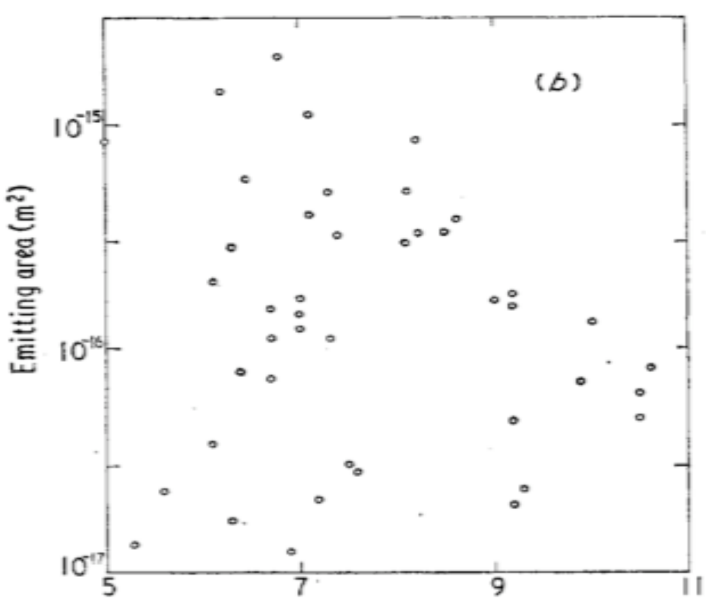


The properties of breakdown sites have been measured.

	E_{local} V/m	radius, m	
Lord Kelvin, ('04)	9.6E9		theory
Alpert et al, JVST ('64)	8e9	3E-8 to 8E-8	exp
KEK ('09)	8E9		"
CERN ('09)	10.8E9	2E-8 to 4E-8	"
Us ('03)	8E9	~5E-8	"
Cox ('74)	~7E9	< 5E-8	"

CERN data seems to show deformation of emitter tips at high fields ('09).





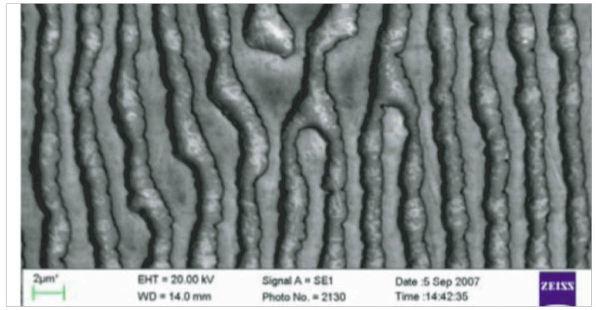
E, GV/m

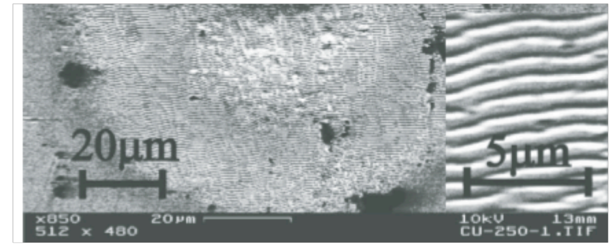
Cox ('74) measured emitter area vs E_{local}.

What is the surface field in the unipolar arc?

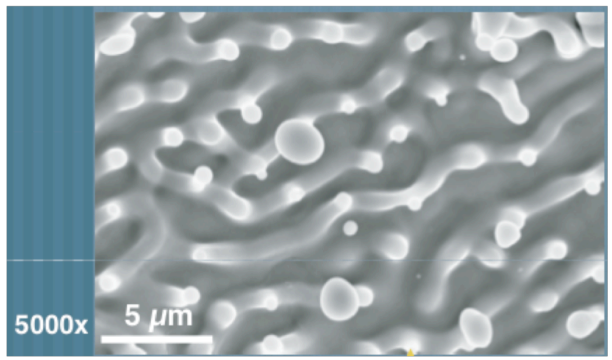
- Electrohydrodynamic spinodal decomposition gives a reasonable result.
- E_{surf} ~ 1 GV/m
- Wavelength ~ 2 μ.
- Enhancements seem to come from fracture, if dimensions ~ 10 nm.

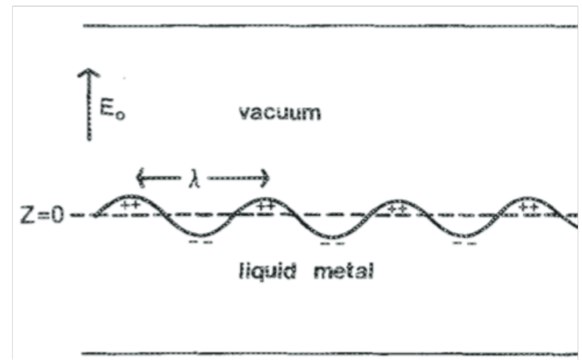
Laser material interiactions by Getvilas. et al. (2009) and J. Wang and Guo (2005)

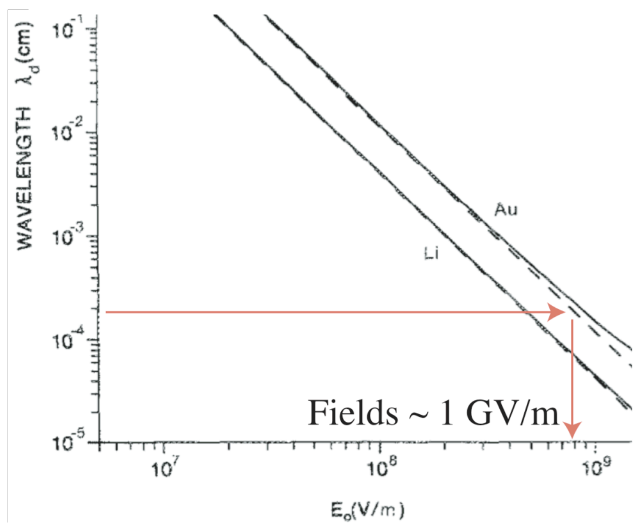


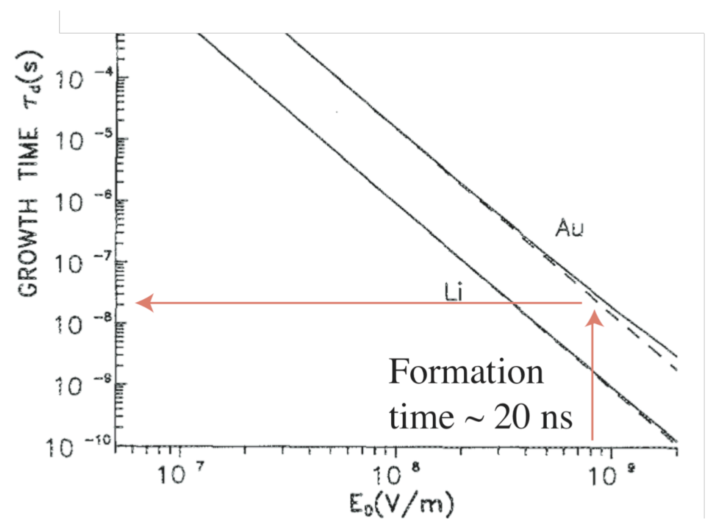


and surface waves in CLIC prototype Cu cavities (Izquierdo, 2008) . . . . .



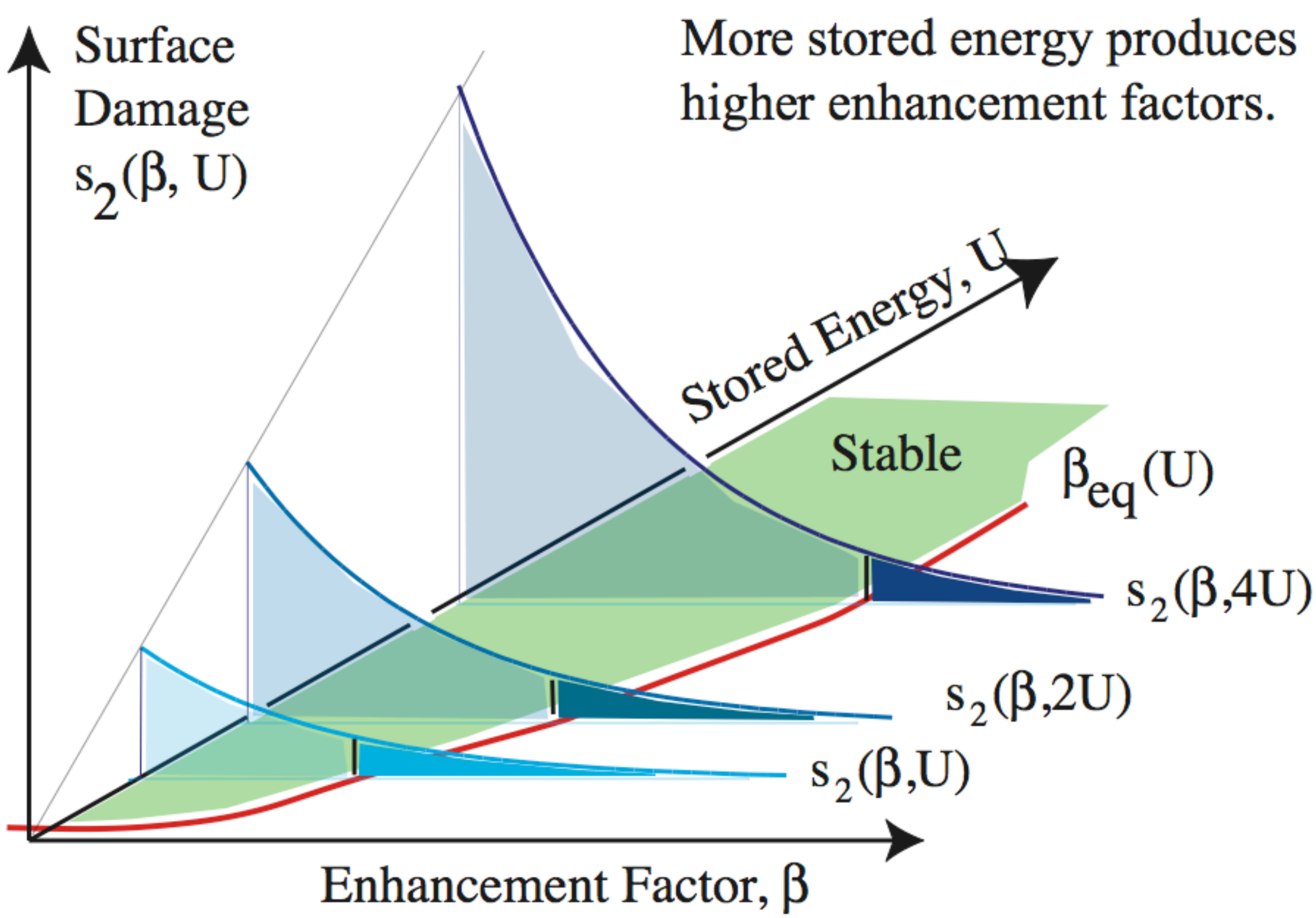






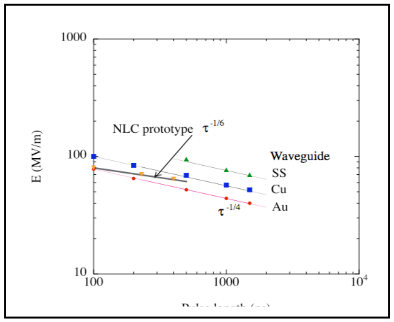
Breakdown events damage the surface

- More energy => more damage
- More damage => Higher enhancement factors => Lower operating fields
- Exponential damage spectrum => logarithmic dependence of operating field.

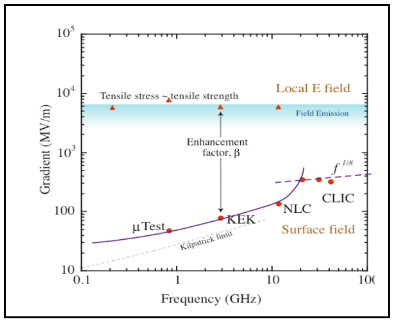


We can calculate all aspects normal rf operation.

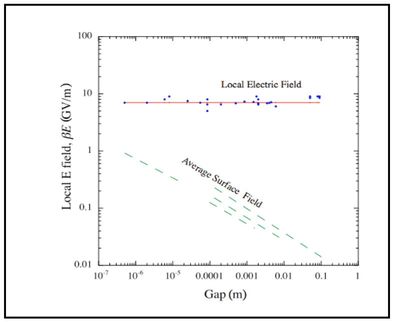
- Emax vs. Pulse Len.



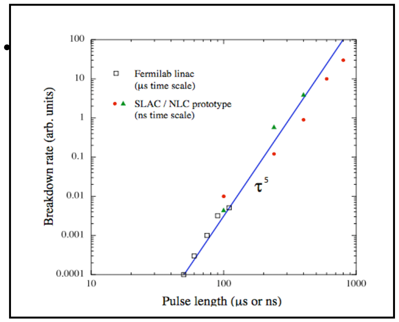
- Emax vs. f



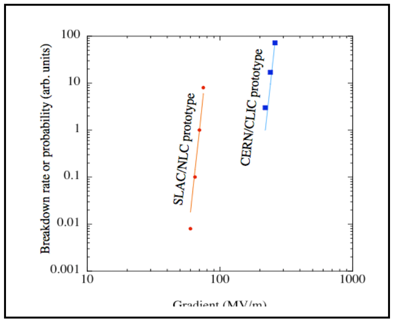
- DC breakdown



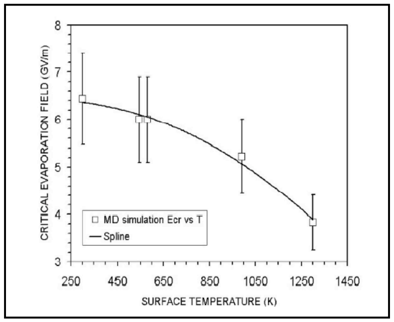
- BD rate vs. Pulse len.



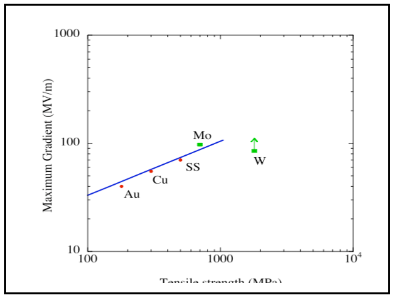
- BD rate vs. E



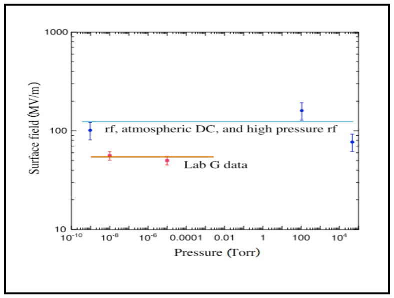
- Emax vs. T



- Material dep.



- E_{max} vs. pressure



Summary

- We can calculate all aspects of arcing.
- Unipolar arcs seem to be the key.
- All data is relevant and explainable.
- There are many applications:
  Tokamaks, SRF, small gap, laser ablation, micrometeorites, e-beam welding, . .
- Our immediate interest is understanding effects of B fields.

We have a movie you can look at through the CLIC 09 website.
We are planning a meeting on Unipolar arcs at Argonne in January