The Problem of RF Gradient Limits

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Defining terms;

Breakdown, [ˈbrāk-doun]

noun

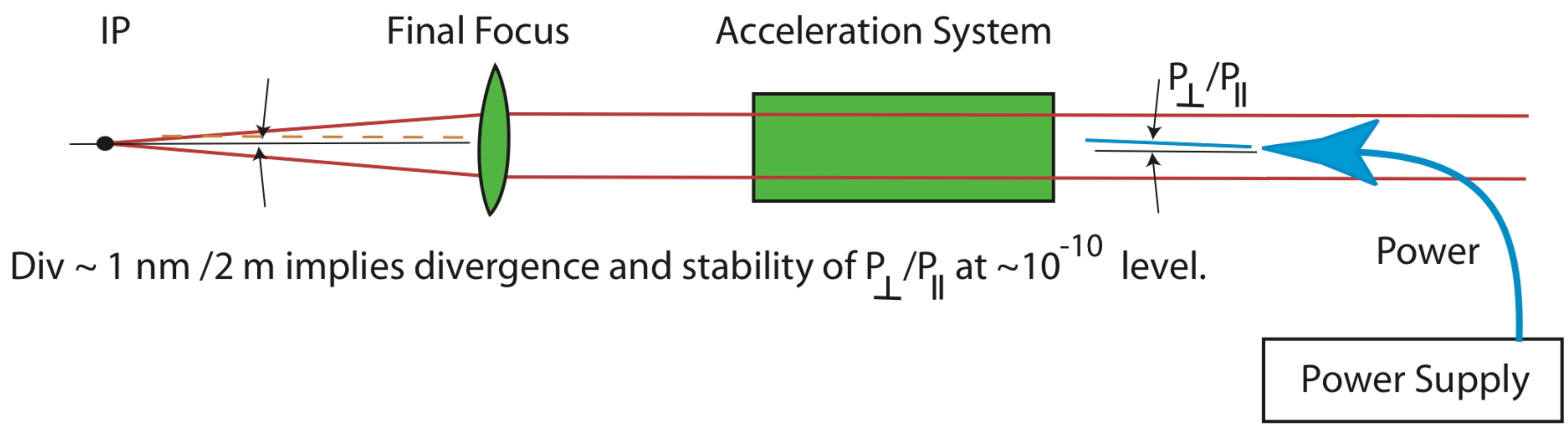
1 Mechanical failure,
Accelerator cavities experience breakdown events.

2 A failure of communication,
Is 100 years, with little agreement, a breakdown of the scientific method?

3 A musical form that features a series of breaks, each played by a different instrument,
Examples of the form are "Bluegrass Breakdown" by Bill Monroe as well as "Earl's Breakdown" and "Foggy Mountain Breakdown", both of which were written by Earl Scruggs.

Linear colliders require metal cavities - and their limitations.

- Collider requirements are very severe.



- Plasma acceleration schemes have trouble with transverse stability.
- Long metal structures provide this naturally.
- But metal structures have gradient limitations that are not completely understood.

Gradient limits are vital to accelerator performance.

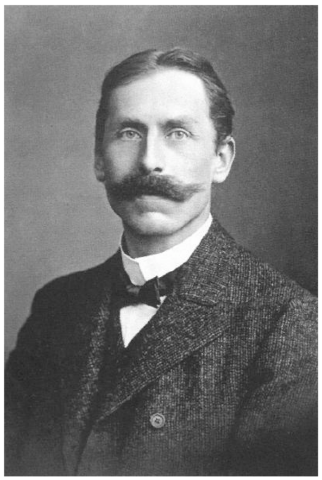
- Muon cooling might be limited by gradients.
- MICE might be limited by field emission.
- ILC had major problems with gradient.
- CLIC is uncertain about gradient.
- SNS is not reaching its design gradient.
- JPARC is intensity limited by gradient in its RFQ.
- ERLs are gradient limited by power consumption.

The breakdown problem is very old.

So is the slide.

Many have contributed - very early:

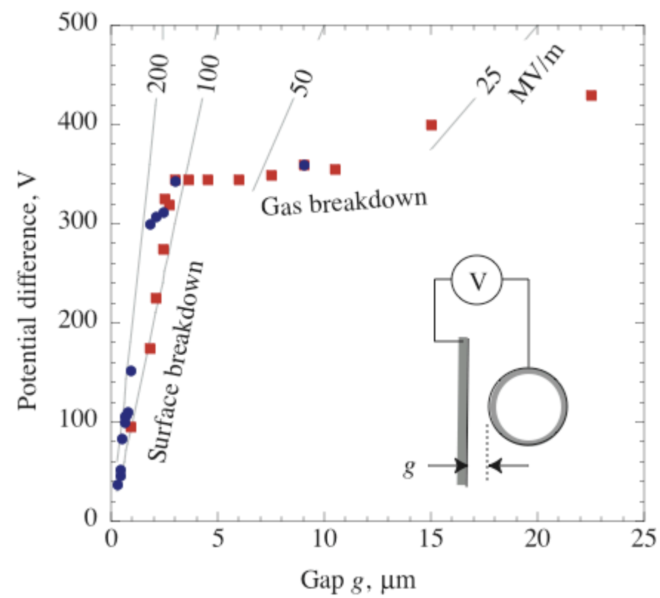
Paschen, Millikan Michelson, Lord Kelvin



In 1904, Lord Kelvin argued that:

- Field emission is electrons (electrions),
- Electron emission may imply ion emission (damage),
- Local fields of ~ 9.6 GV/m would do this,
- Tensile strength is an important parameter,
- Better experiments are needed.

We agree.



But, the field has not yet converged on a picture of arcs !!!

(even after 110 years)

Many groups

- Fusion / Plasma physics (Plasma contamination)
- Power switching (Arc dynamics)
- Coating industry (Ion production)
- Accelerators (Gradient limits)

Recent Books

- Mesyats
- Boxman, Haber, Martin
- Anders
- Latham
- Jüttner, Vasenin

Conferences / Workshops / Groups

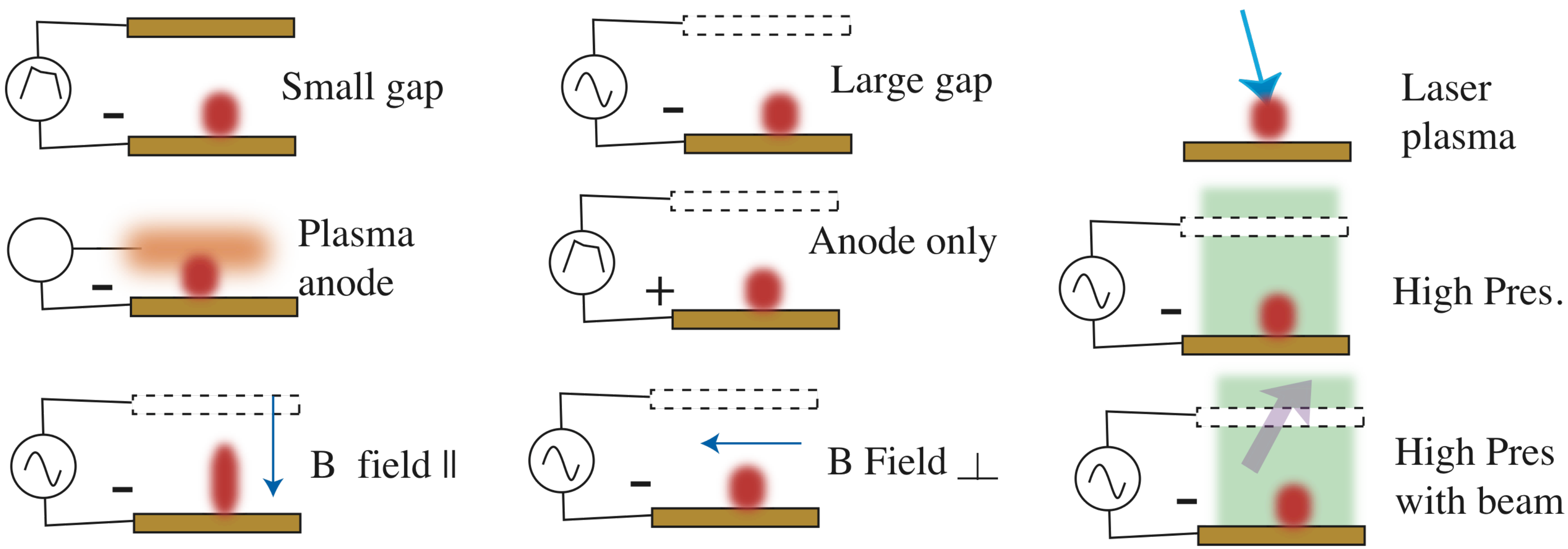
- Int. Soc. Disch. Electr. Ins. Vacuum
- US High Gradient
- CERN

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

There are many ways to look at this problem.

- Many configurations, a few basic mechanisms ?

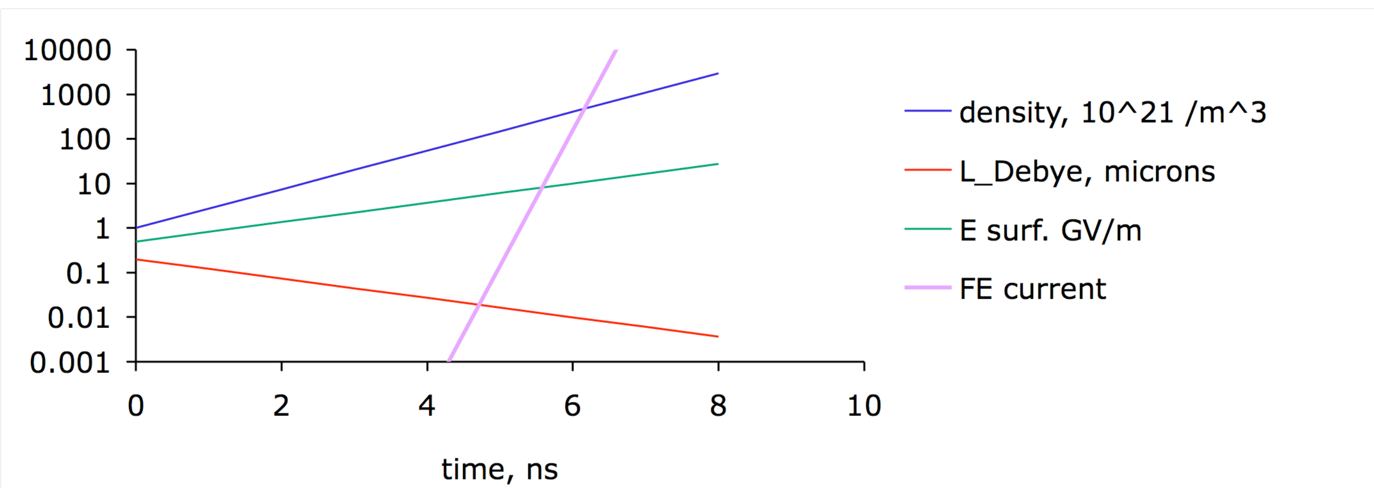


- Our rf program significantly stretches the arcing phase space.

- We want simple arguments.

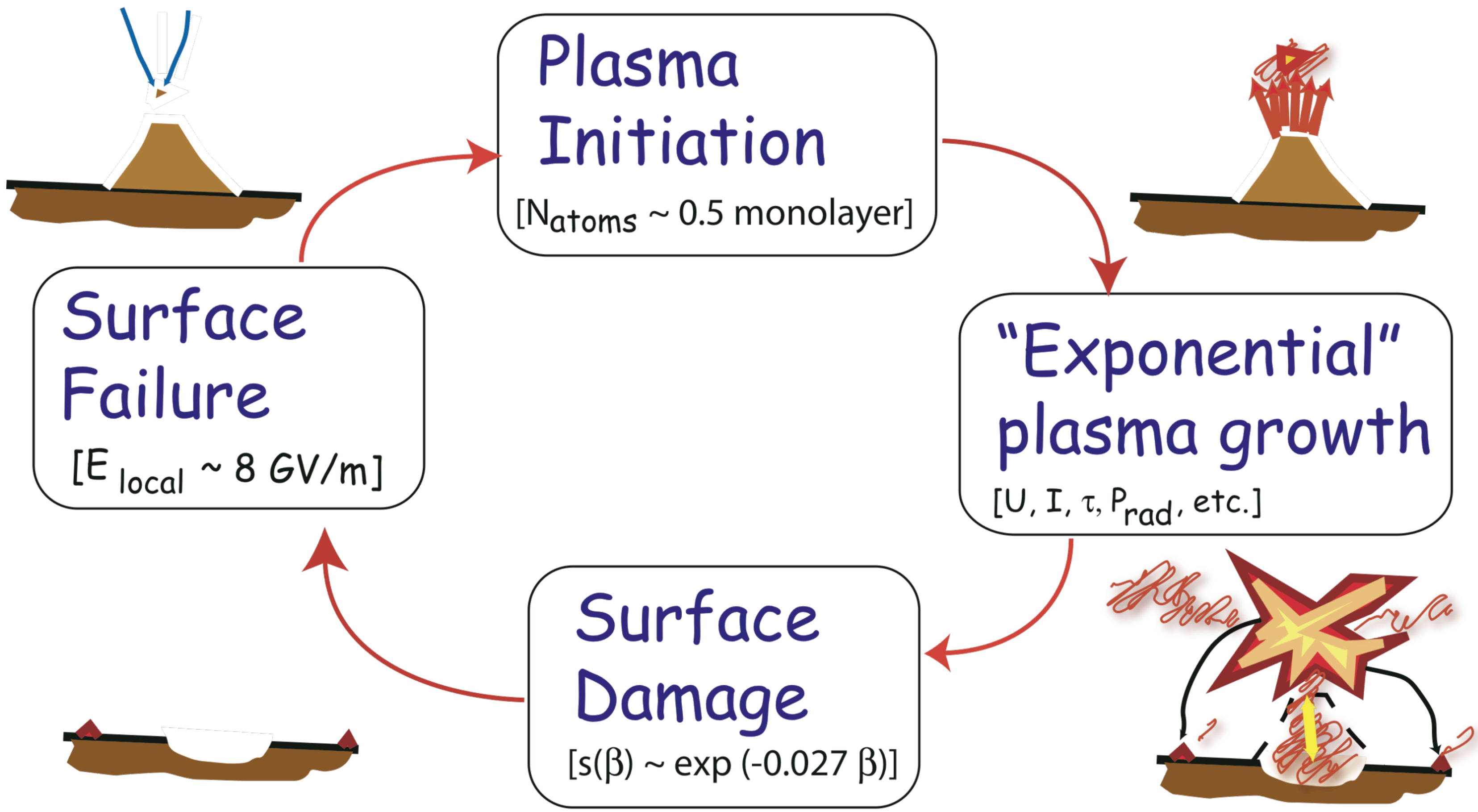
We think a few ideas may explain ALL the data.

- Breakdown is triggered by Coulomb Explosions.
- 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, $\lambda_D = \sqrt{\frac{\epsilon_0 KT}{n_e q_e^2}} = \sim\mathrm{nm}$, produce fields $E = \phi/\lambda_D \sim$ GV/m.
- High electric fields produce micron-sized unipolar arc like discharges.
- Unipolar arc energy goes into producing craters.



The big picture

- The maximum field is a result of many interactions., some uncontrollable.

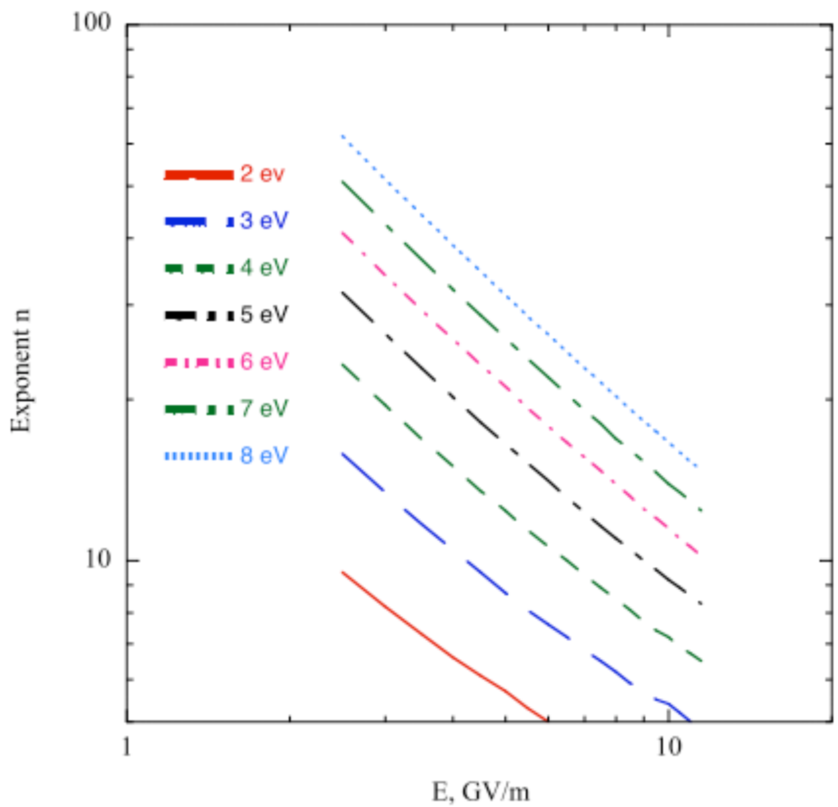


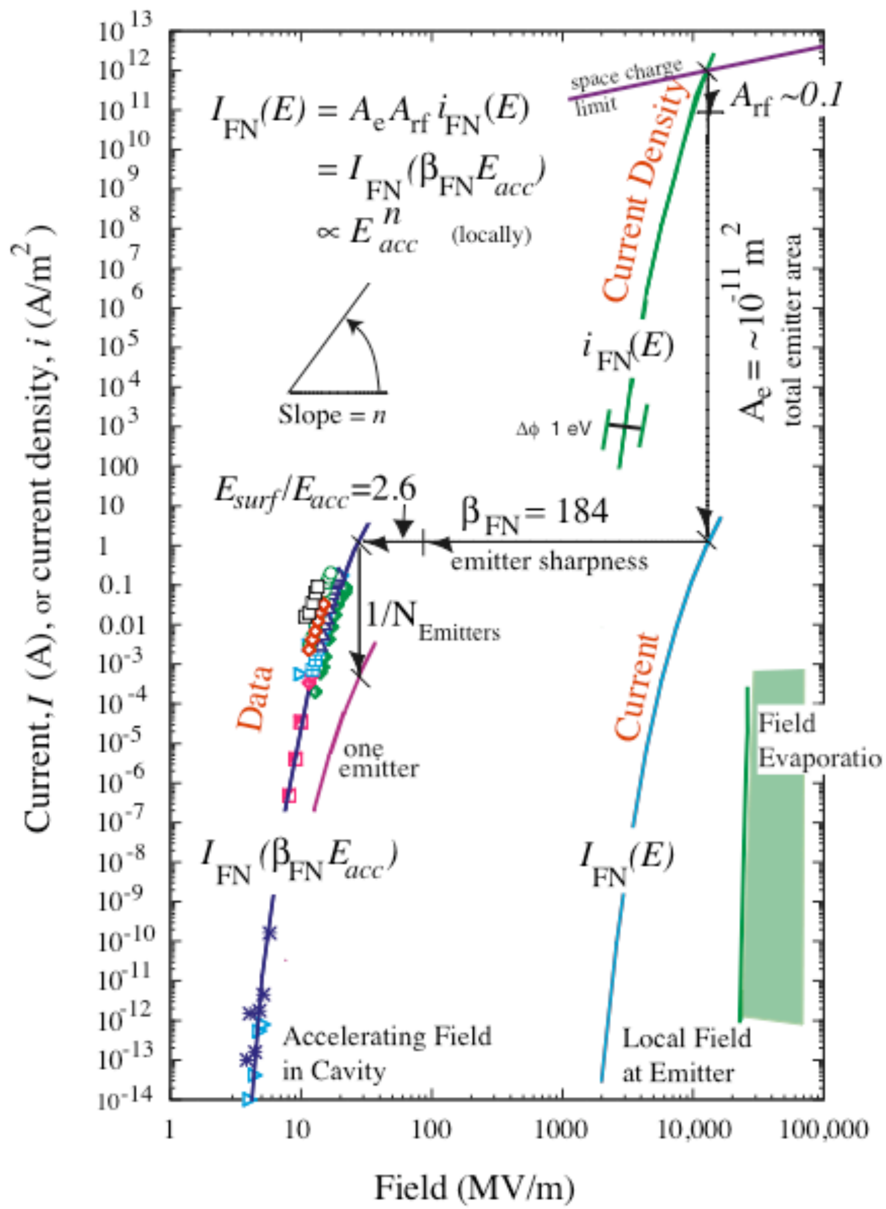
- Real constraints only come from modeling the compete cycle.

We measured the initial conditions with x rays in 2001.

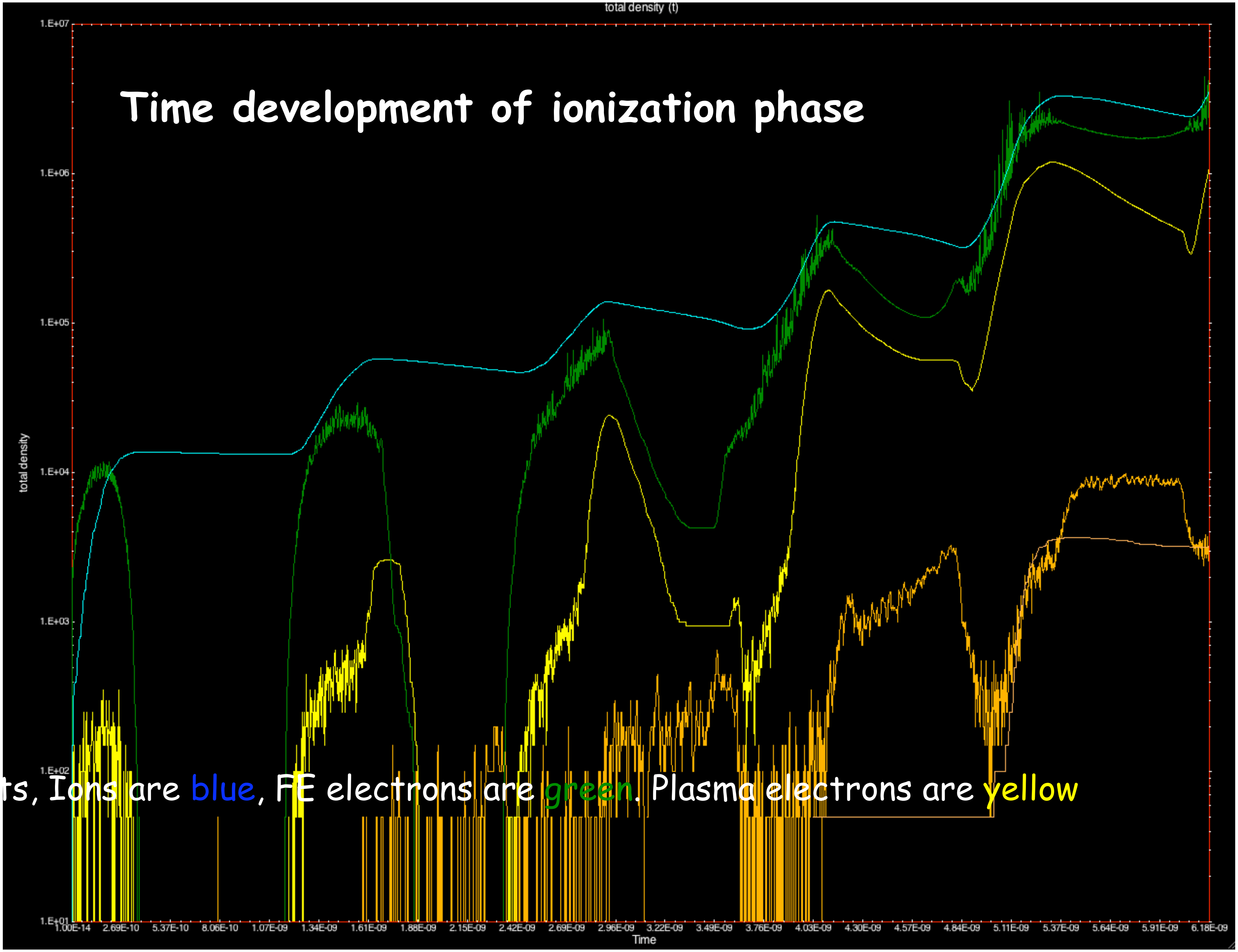
- FN can be approximated by $I = E^n$, for everybody.
- The local surface field = f(n, ϕ).~7 GV/m

- Tensile stress / fatigue explains surface failure in the most direct way, but other models exist.



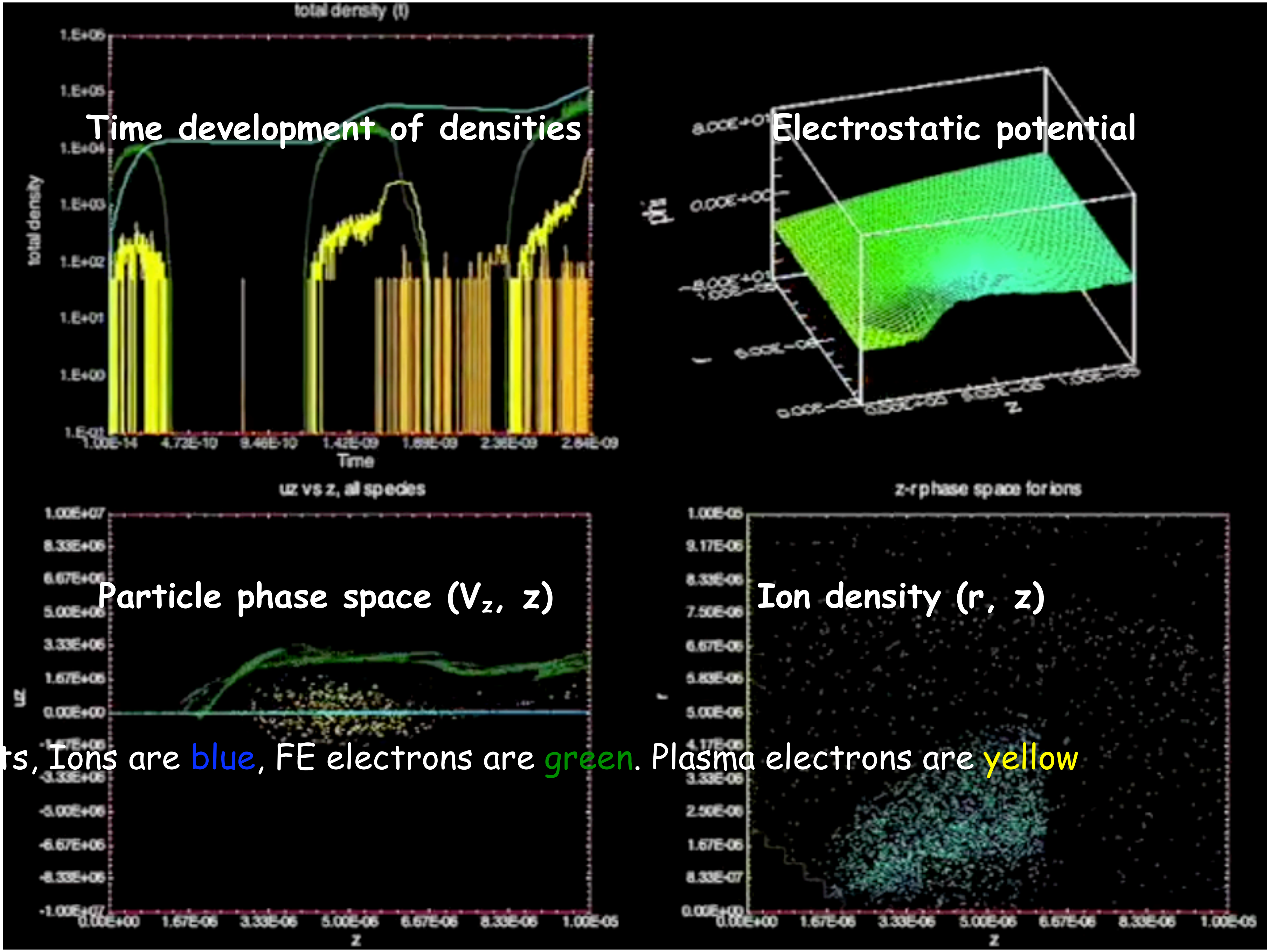


OOPIC Pro shows us how the arc starts.



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

We have a movie shows how what happens in the first few ns.

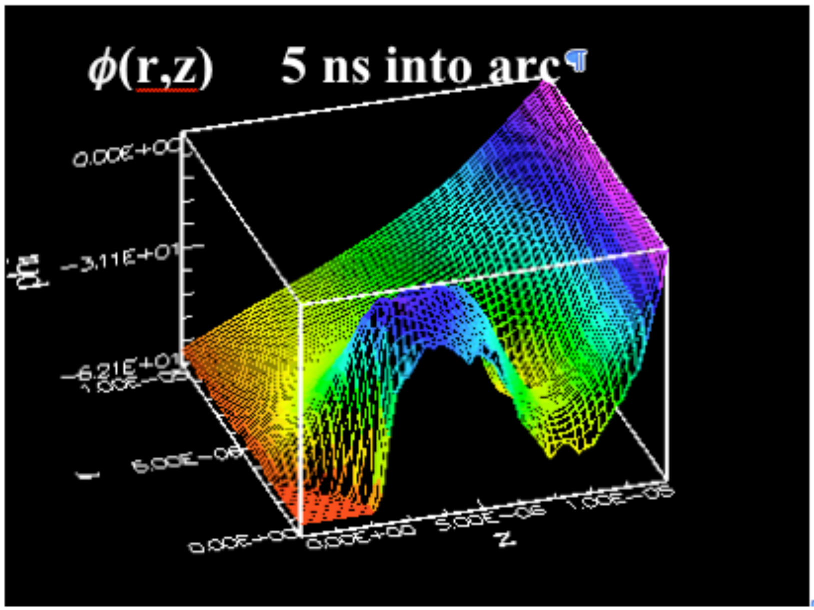


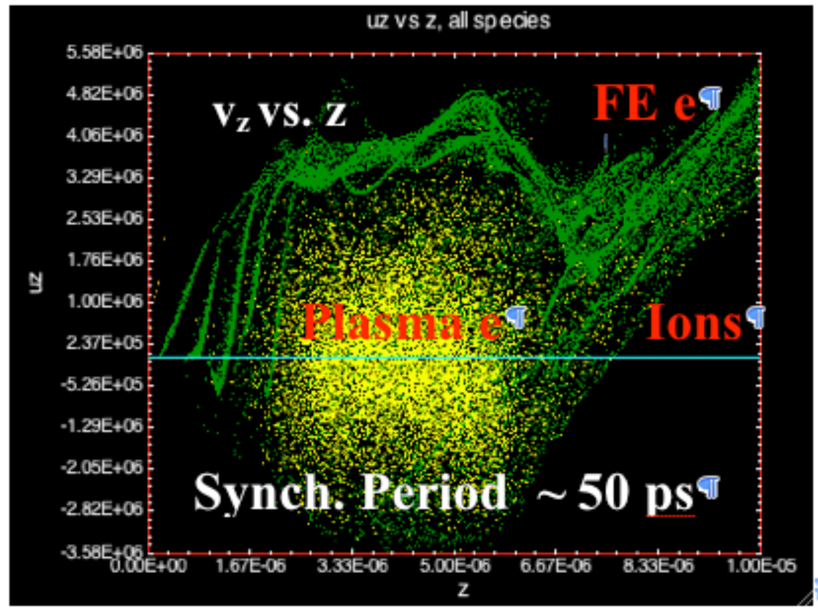
In plots, Ions are blue, FE electrons are green. Plasma electrons are yellow

FE electrons are not the only source of ionization.

- These arcs are high beta, inhomogeneous, non – equilibrium, cold, weakly ionized, non-neutral, collisional, inertially confined plasmas with two weakly interacting electron populations - different from laboratory / fusion plasma experience.

- The space potential is produced by inertially confined ions whose electrons have gone to the far wall. The potential traps electrons, and the “sheath” is a function of the proximity of the ion cloud to the ionization source.

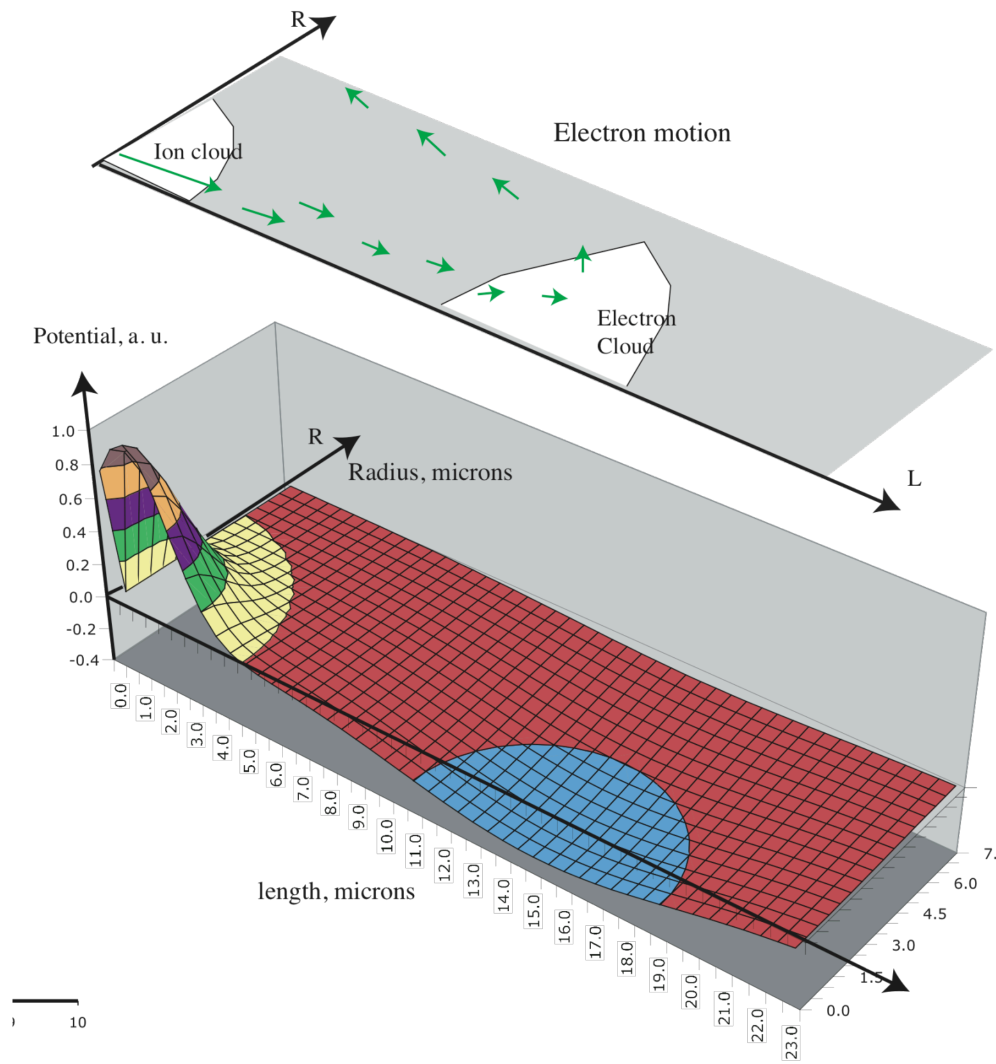




- The net result is that field emitted currents are: 1) enhanced and, 2) extend over a larger range of rf phase. The electrons execute synchrotron motion.

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.

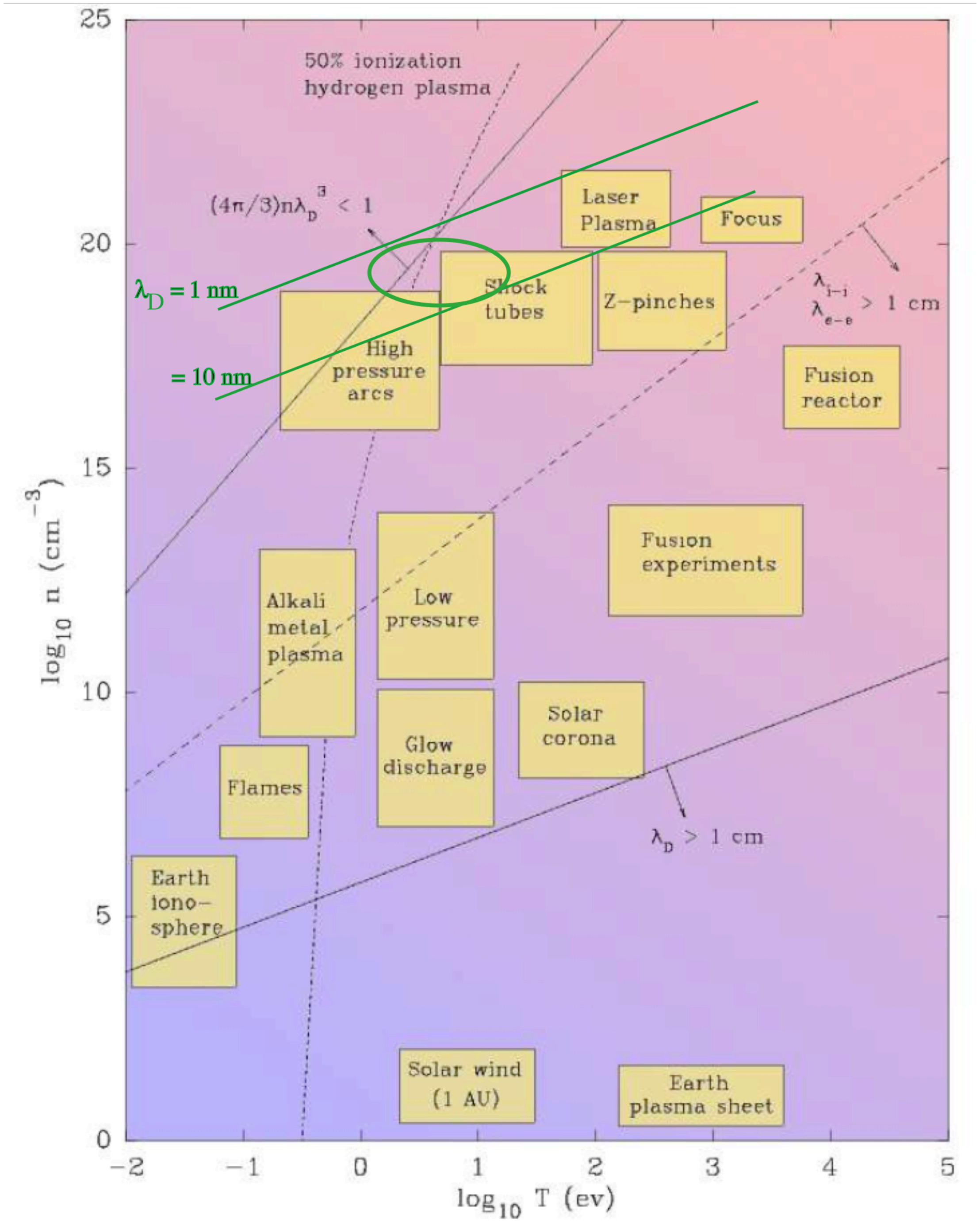


Where does this fit in plasma physics?

- The unipolar arc is not a "Plasma".
- "Plasmas" are defined by:

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

- Our Debye length is too short
  screening becomes impossible ! ?
- Some plasma techniques apply.
- Numerical methods still work.

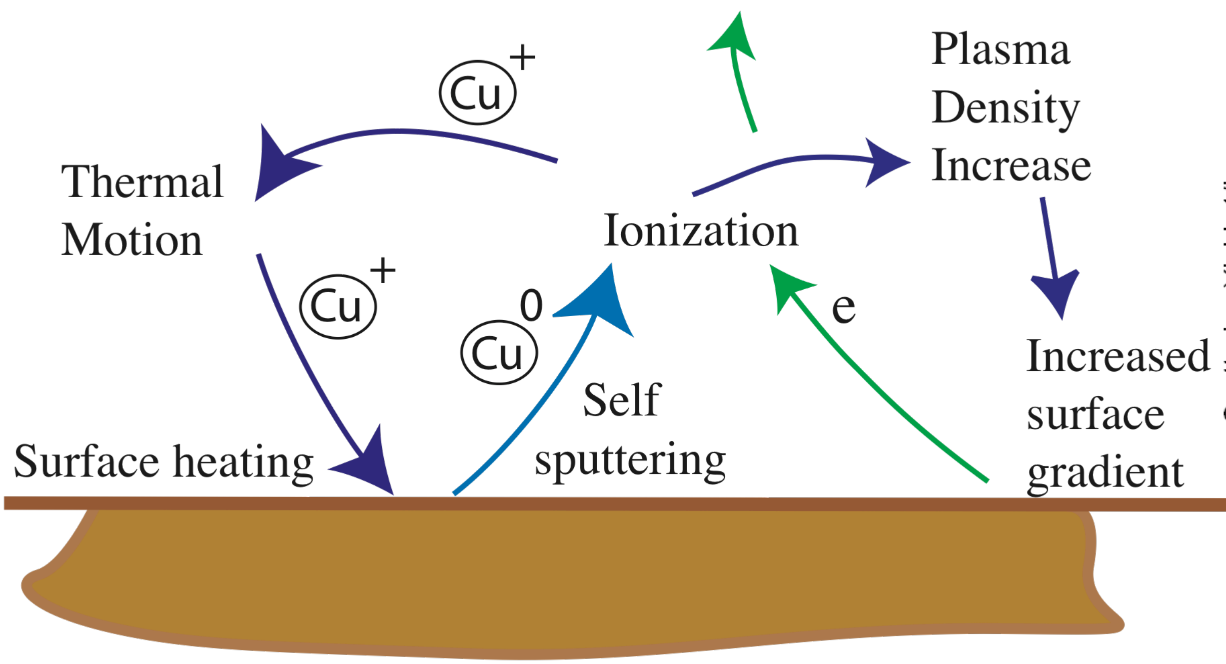


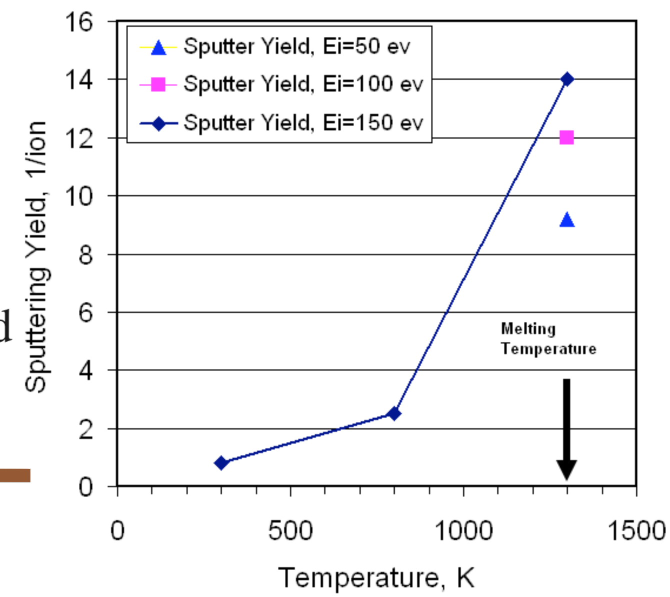
Unipolar arcs attack surfaces.

- The interactions of high density, low temperature plasmas with materials was studied actively in the fusion community until about 1990.

- There are many different mechanisms. Numerical modeling of basic processes can be done..

- Erosion rates on the order of, $r = n_I\ v_I\ Y(\lambda_D,\ \phi,\ T_{surf})\ /\ V_A \sim 1$ m/s.

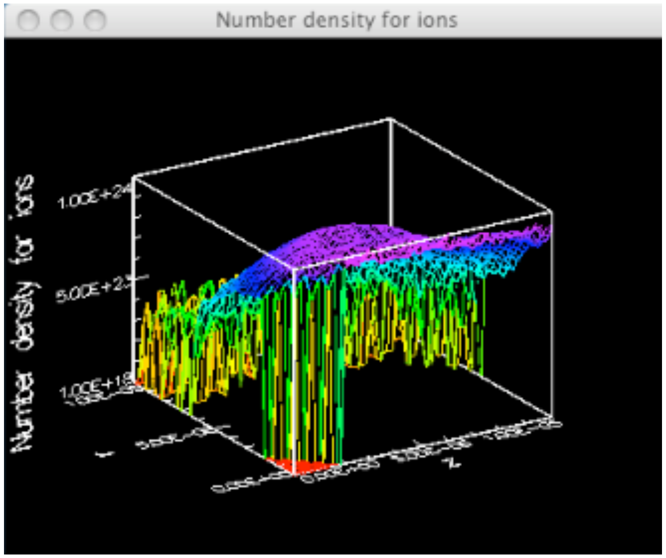


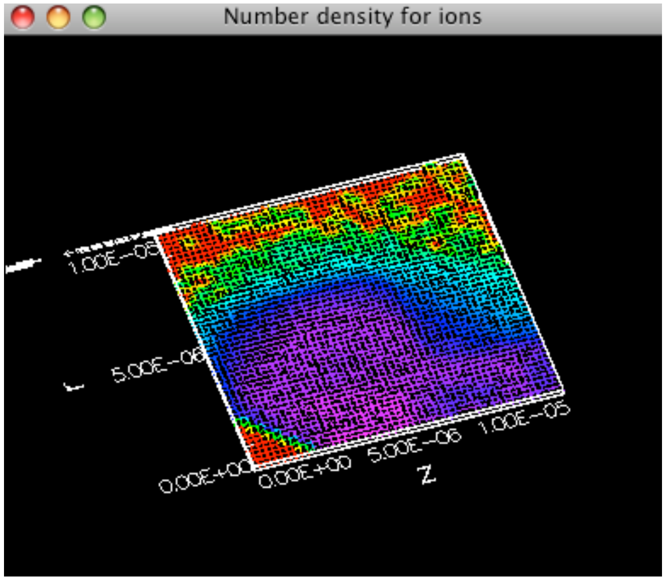


The magnetic field changes the arc, and the surface damage.

- The Larmor radius is comparable to the arc dimensions.

- Field emission electrons are focused, extending arcs in the z dimension.





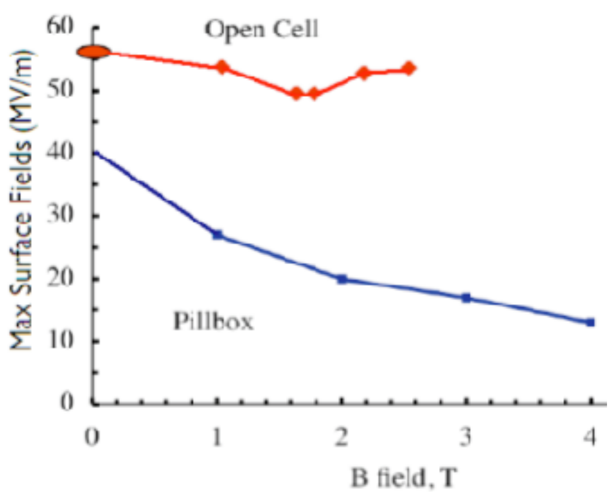
- Higher power density in the center if the arc implies more surface damage

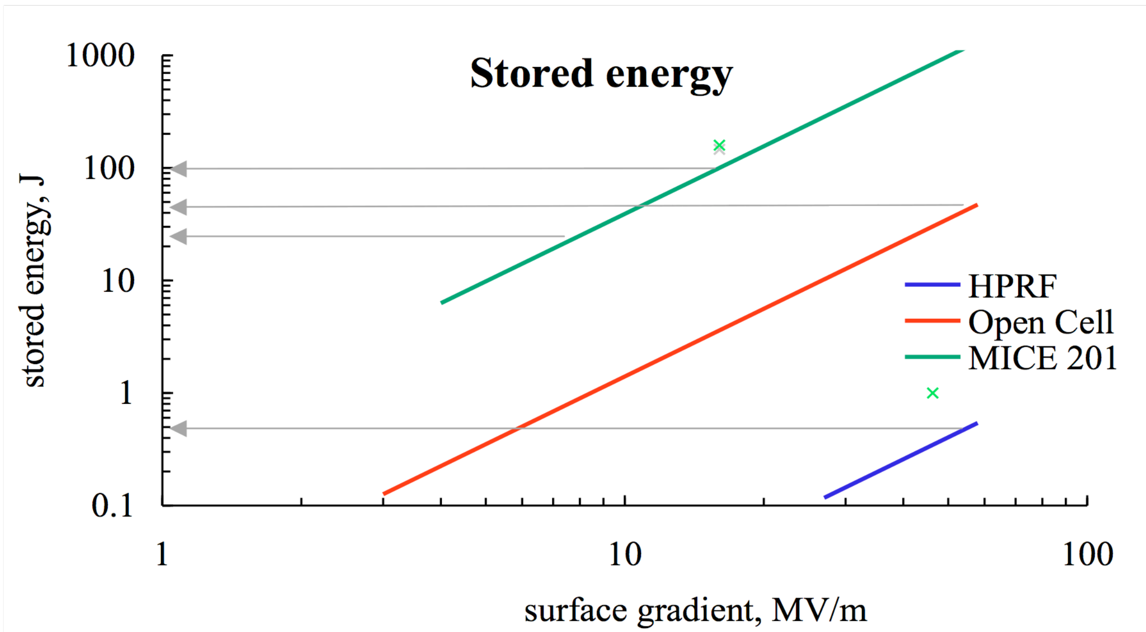
- We are proceeding with more precise calculations.

- Spark gap experiments with B field are being planned at CERN.

Curing Field Emission and Breakdown requires elimination of sites.

- A single breakdown event will produce emitters and more breakdown sites.
- Field emission beams are about 0.1 mA.
- Breakdown currents are of order 10 A in the pillbox.
- Stored energy problems get worse at 201 MHz, where the pulse length is longer.
- Note that the open cell worked best.





Questions

Why did the open cell work so well?
Can we cure rf problems?

Experimental

- What are the effects of the
  - Area to be conditioned
  - Angle between E and B
  - Stored energy
  - Materials – do they matter?
- Can you turn off breakdown and field emission sites?
  - Any other options besides ALD?
  - Laser melting?

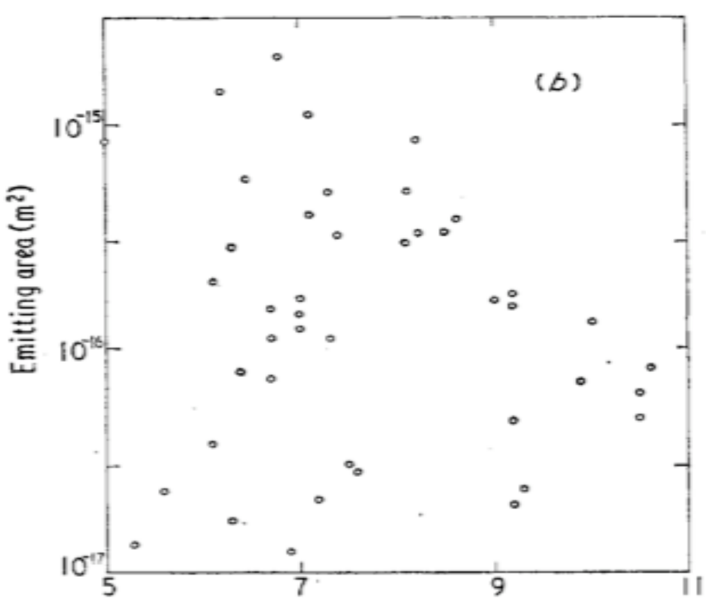
Modeling

- Predictions of experimental results
- Better understanding of materials problems

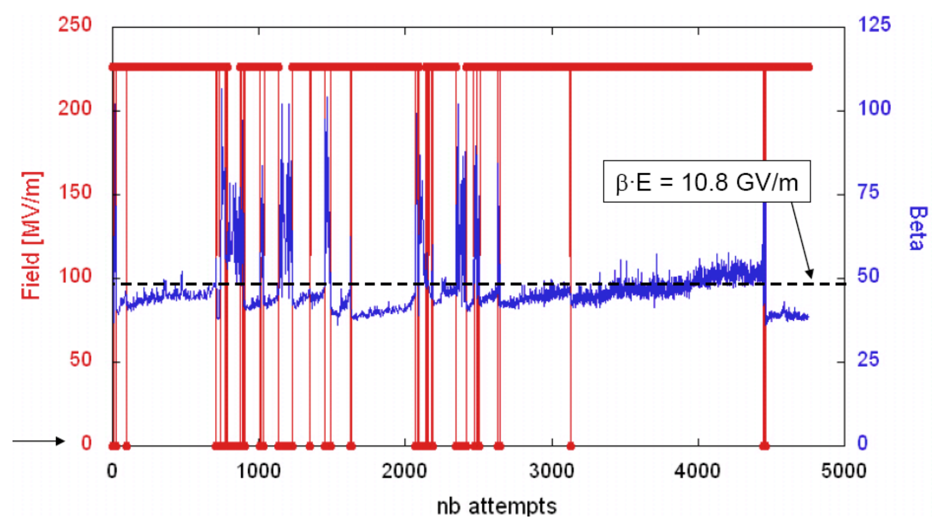
The properties of breakdown sites have been measured.

	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)	~7E-8	< 5E-8	"

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



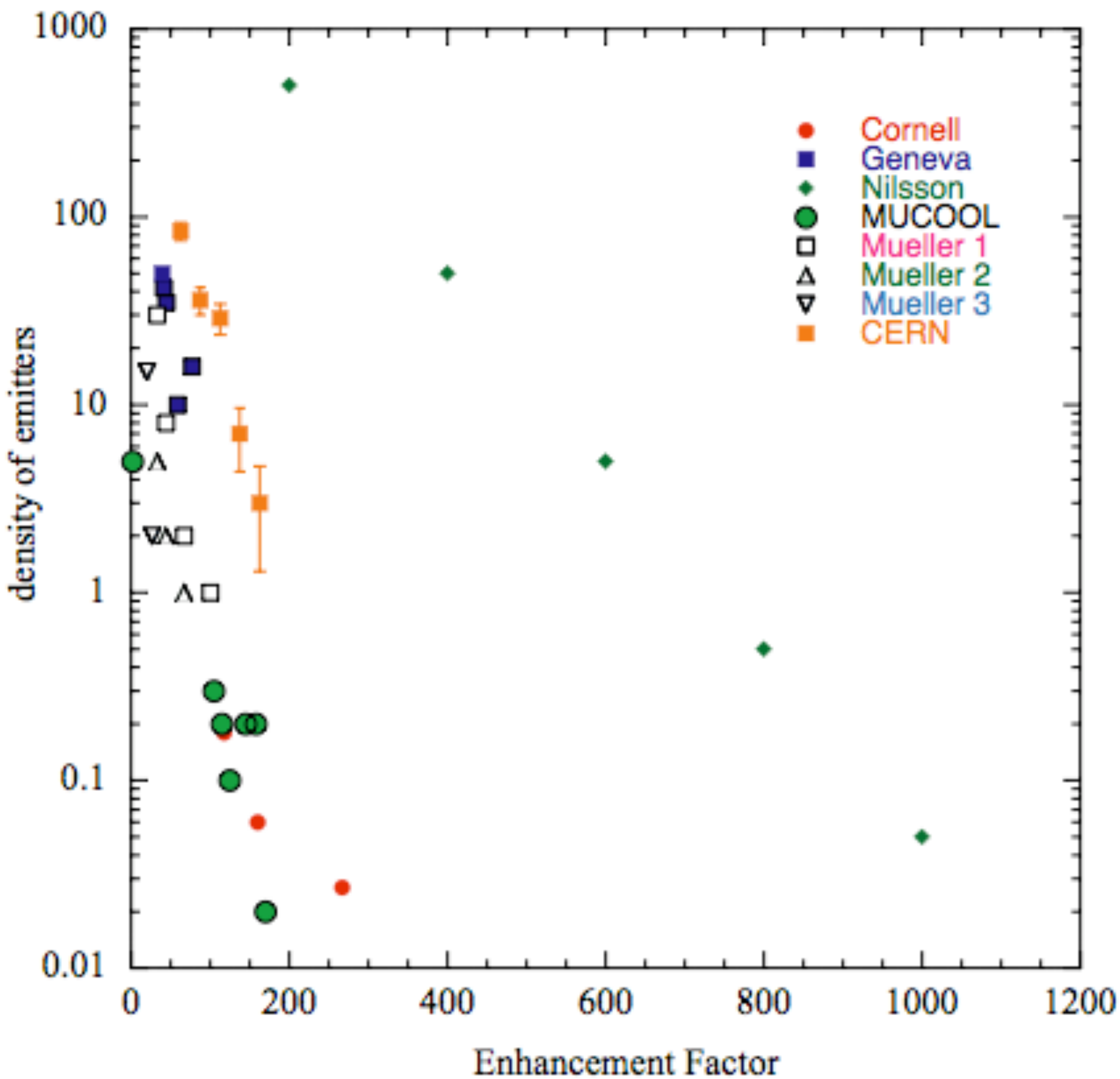
E, GV/m



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

There is a spectrum of enhancement factors.

- Everyone sees roughly the same thing.

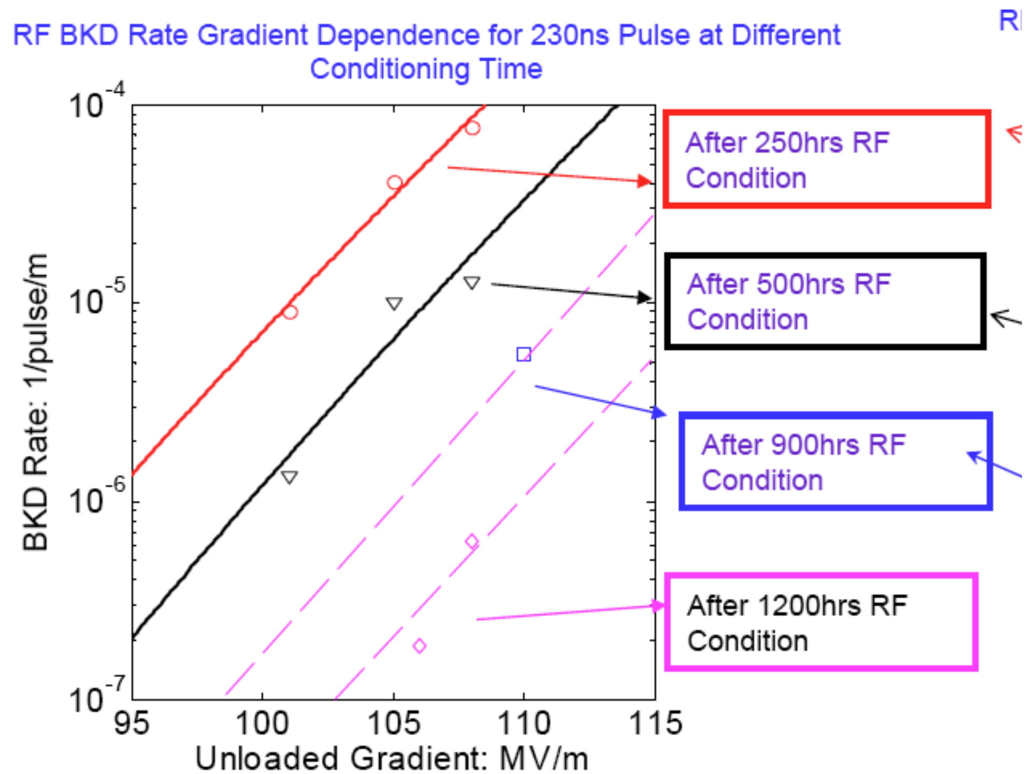


Making breakdown sites duller should improve FE and BD.

Everything goes like a very high power of the local electric field, (E ~ 1/r).

- Field emission goes like E^{14}.

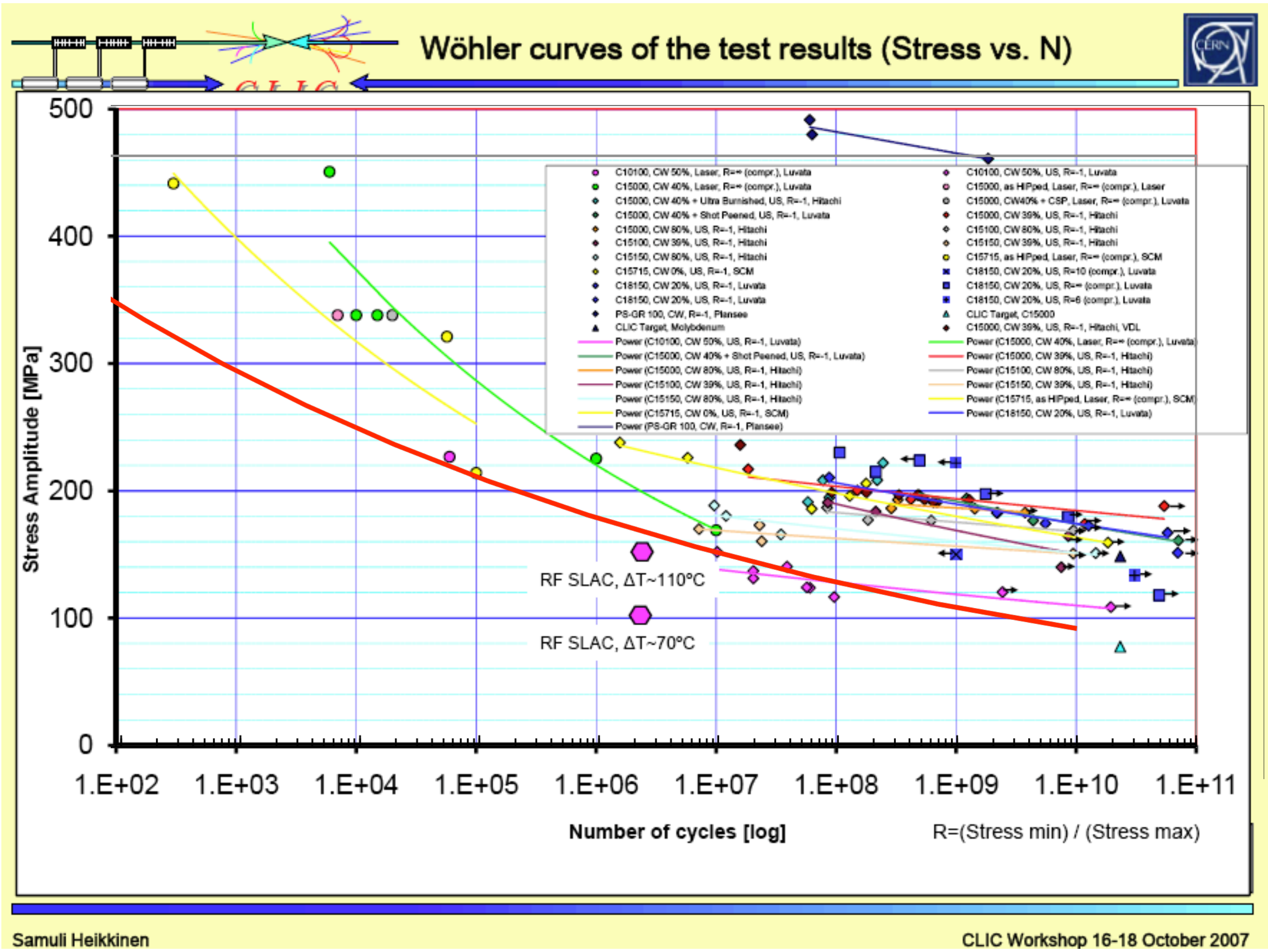
- SLAC BD rate data => r ~E^n, n ~ 35



- In Joule heating model, if j ~ E^{14}, P ~ j^2, then Joule heating power P ~ r^{-28}

CERN fatigue data give roughly the same exponent.

- In <u>Tensile stress / Fatigue</u> model, stress ~ E^2, if MTBF ~ E^{28} => red curve



Can we totally eliminate breakdown and field emission?

The technique would be:

- Condition the cavity normally up to some level, presumably making a number of field emission / breakdown sites with dimensions of ~50 nm.

- Apply conformal coatings with a thickness greater than 50 nm.

- Apply power.

We have made a lot of progress with ALD.

- We have coated three cavities, increasing the Q in all three, and the gradient in one.
- We have shown that strange oxides can be highly lossy for supercurrents.
- Coupon tests have shown that we can eliminate these oxides.

These, and other data will be reported by Thomas Proslier tomorrow

ALD can produce conformal coatings, but in-situ is best.

We have experience with superconducting structures, which seem to require High pressure water rinsing after every coating.

Our cavities are large, may eventually require recoating, are hard to move around easily, have thin Be windows and don't have drain holes, so they don't seem good candidates for high pressure water rinsing.

In situ coating avoids these problems, but have some others.

- We want to coat the high field regions of the cavity.
- We don't want to coat the rf windows / insulators.

There are solutions to these problems we are exploring (special valves, differential heating, etc.)

Arc physics is not very "scientific".

NFMCC / MCTF

Our work is published and discussed at meetings.

CLIC

The CLIC Program has operated a spark gap for many years that has produced useful data on arc triggers, different materials. Most data not published.

The fusion and arc communities (two separate groups)

Breakdown was a significant problem in the fusion community until they decided to abandon limiter designs and use divertors. There has been little effort since the 1980's.

There is also an active arc community who hold meetings (ISDEIV Symposia), but effort is primarily 1) breaking currents and 2) coating technologies.

The US High Gradient Collaboration

This group is primarily measuring different 11.4 GHz geometries, conditioning and pulse heating effects, which don't apply to us.

Who is doing what.

• CERN thermal triggers:	Do whiskers exist? Does heating work without them?
• SLAC Pulse heating:	Does it cause breakdown?
• BNL electron optics:	Do electrons matter?
• High Pressure	Are high and low pressure limits different?
• Us:	Finish complete model. Funding for ZI

Summary

- Zeke and I believe we can now understand the surface damage mechanism.

- We need data on the dependence of E_{max} on:
  - Cavity energy
  - Angle between E and B
  - Materials (lots of data around)
  - The area to be conditioned

- It should be possible to significantly improve normal cavity technology with conformal metal coating.