Open Issues in a Self-Consistent RF Vacuum Arc Model

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Outline

- Plasma physics is used to describe arcs in the many environments in which they appear, however vacuum arcs seem to be sufficiently complex that the limited range of experimental data does not produce an unambiguous, general picture that can be used to model them.

- Assuming that **unipolar arc** models are relevant to the breakdown process produces some simplifications and generalizations that make modeling easier.

- We consider some theoretical and experimental issues that could further clarify the picture of these arcs.

All references are listed in: https://www.nature.com/articles/s41598-021-81947-5
and Schwirzke, F. R., IEEE Trans. Plasma Sci. **19**(5), 690 (1991)

Vacuum Arcs have been studied for a long time,

- Vacuum Arcs seem to have been first isolated by Michelson in 1901.
- The first explanation came from Lord Kelvin in 1905.
- Field emission was understood in 1929 by Fowler and Nordheim.
- The modern approach followed experiments done mostly after 1950.
- There is a wide range of applications of this theory.
  - Corona on HV transmission lines
  - Gradient limits in accelerators
  - Performance limits in Tokamaks
  - Micrometeorite impacts on satellites
  - Integrated circuits are limited by some of the same effects

. . but the field still seems unsettled.

- Berkhard Jüttner said exactly this in 2000.
- Anders commented on “a number of more-or-less convincing explanations” for retrograde motion of arcs in 2008.
- Beilis divided “numerous hypotheses” for this motion into three groups:
  a) “…thermomagnetic and galvanomagnetic forces produced due to negative Righi-Leduc effect and by Ettinghausen effect due to the heat flux…
  b) positive space charge relative to negative space charge at the cathode…
  c) … asymmetry of the resultant magnetic field due to superposition of self magnetic field and applied field…..
- Even the mechanisms for breakdown itself are unclear. While whiskers can get hot and explode, there is little experimental evidence for these whiskers.

Local geometry makes a big difference in breakdown.

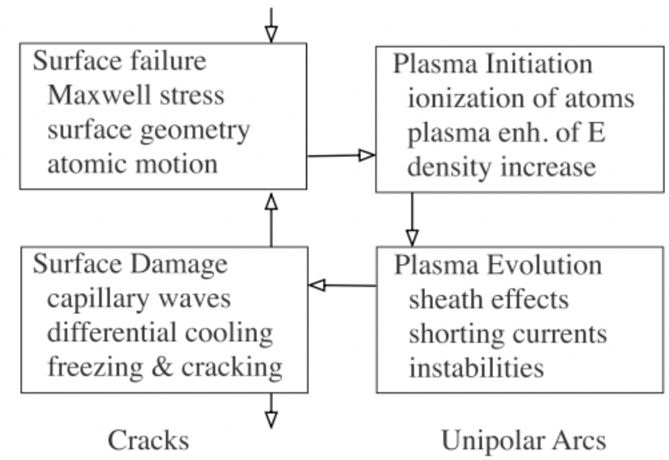
- Breakdown on **needle tips**
  Fields on needles are ~L/D times the average field.
  Field emission current densities & fields are both high
  Thermal effects dominant

- Breakdown on "**flat**" **surfaces**
  Harder to break down surfaces without obvious field enhancements
  Maxwell stress seems to be the trigger
  Thermal effects minimal

Breakdown on needles is well studied and well understood, however, in the real world the interesting problems always seem to occur on macroscopically "flat" surfaces, where there is much less experimental and modeling effort.

Four stages seem to be required.

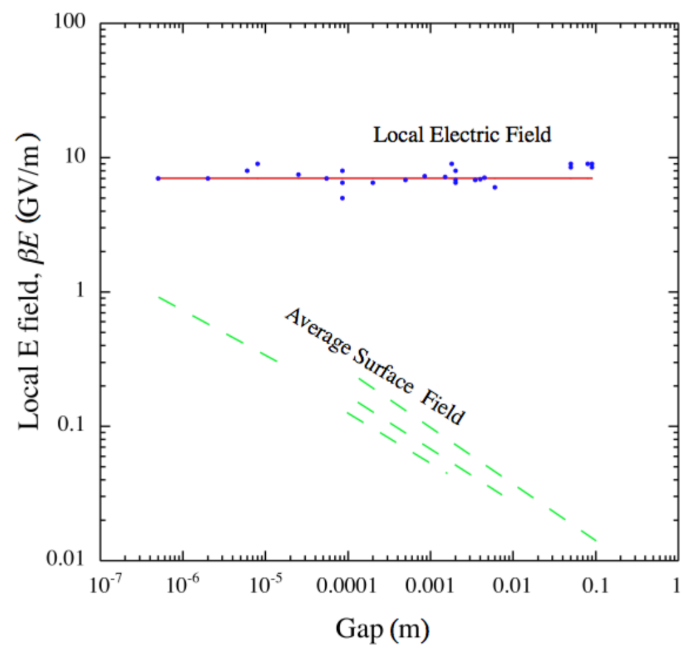
Questions



- Trigger
  - Does electromigration sharpen peaks?
  - Tensile stress or explosive emission?
- Ionization
  - Effect of ambient gas?
- Plasma Evolution
  - What are the important parameters of arcs?
  - Are image charges important?
  - How does the plasma spot work?
- Surface damage
  - Is damage determined by thermal and surface tension only?

Breakdown involves local surface fields of ~ 10 GV/m.

- Alpert data shows E_{local} ~10 GV/m.



- At this field many complicating mechanisms become active.

Field emission	~ E^{13} ~ j
Tensile strength limit	~ E^2
Field Evaporation	~ $E^{2.}$ (as in Atom Probe Tomography)
Electromigration	~ E^2
Explosive Electron Emission	~ E^{26} ~ j^2
Space charge limit	

Our approach to arcing comes from our experience.

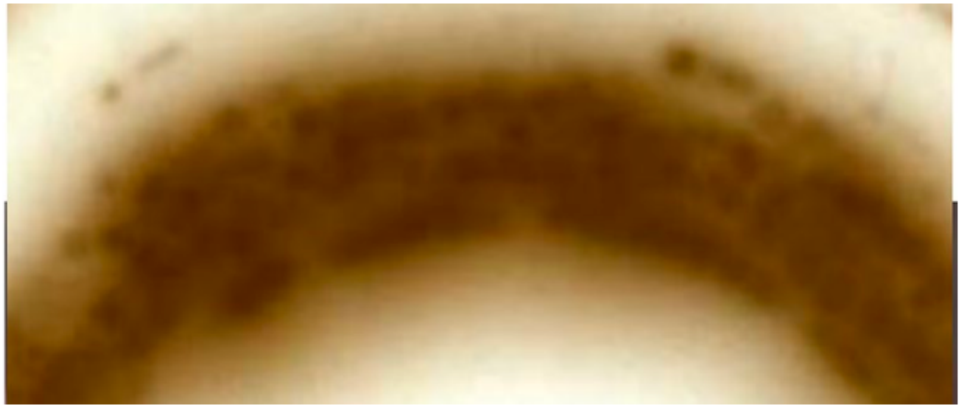
- My introduction to arcs as a problem came in connection with a tokamak we were constructing at ANL under the guidance of Bob Taylor at UCLA, who was worried about unipolar arcing, with Fred Schwirzke. My experimental work was with RF arcs in accelerators.

- Insepov and Hassanein have had years of experience with experiments and modeling ITER environments as well as a variety of other problems.

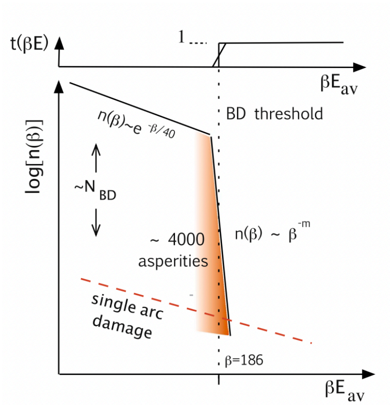
- We also consider recent work, as summarized in books by Anders and Beilis.

Our Basic Assumptions

- The most efficient operating mode of any high gradient system will be at a surface field **just below** where the system breaks down.
- Near this field we expect about 4000 small asperities to be **under stress**, and subject to field emission (~ E^{13} !), tensile stresses, evaporation, heating, electromigration and microroughness.
- If field emitters ionize adsorbed gas, residual gas, evaporated atoms etc., these ions can collect above the emitters and **increase the local field**. This process can avalanche, ultimately into breakdown.



Field emission with colinear B field.

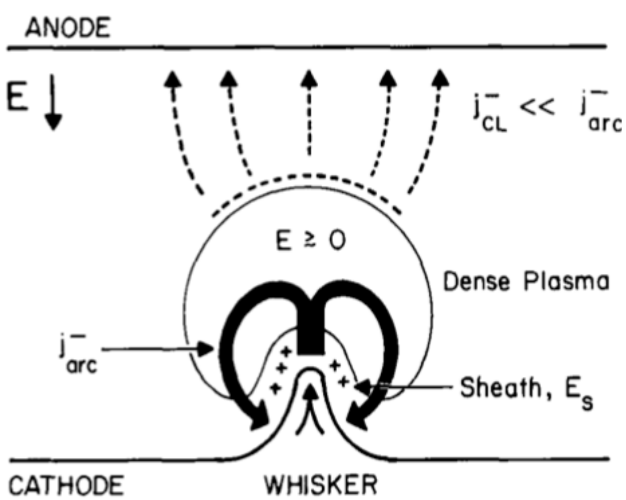


Spectrum of βs

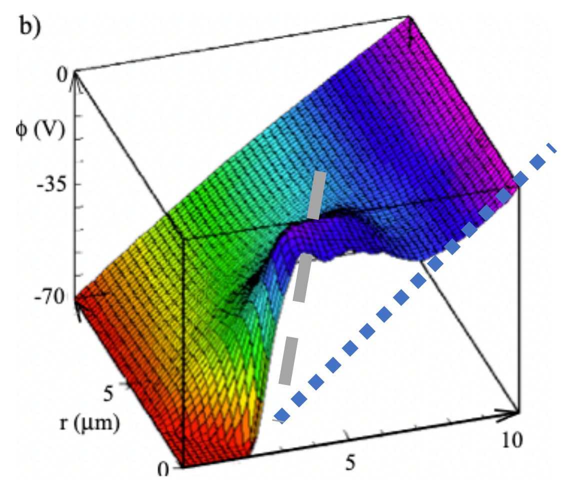
The Unipolar Arc model of Schwirzke seems useful.

- A field emitter will produce high currents in the presence of a charged plasma, which neutralizes the space charge and increases the surface field.

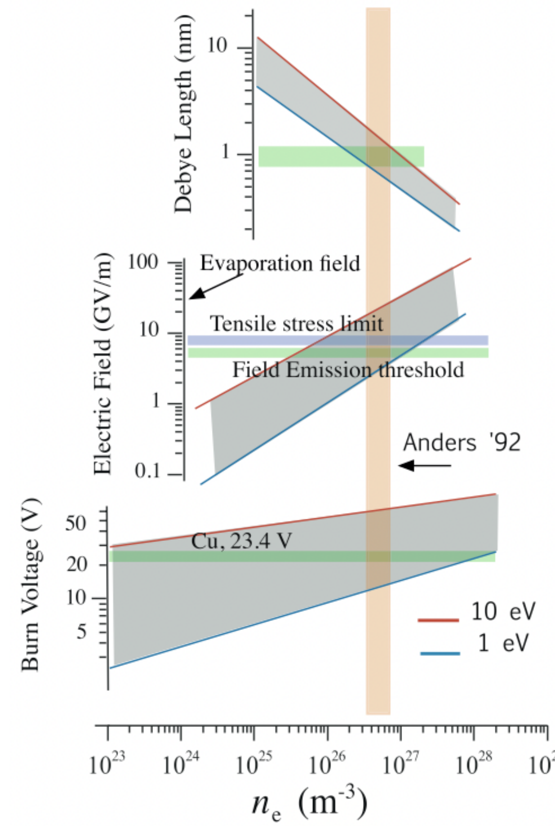
- Our calculations show E_{surf} ~ 8 GV/m, and are consistent with both PIC and MD calculations.



Schwirzke



PIC

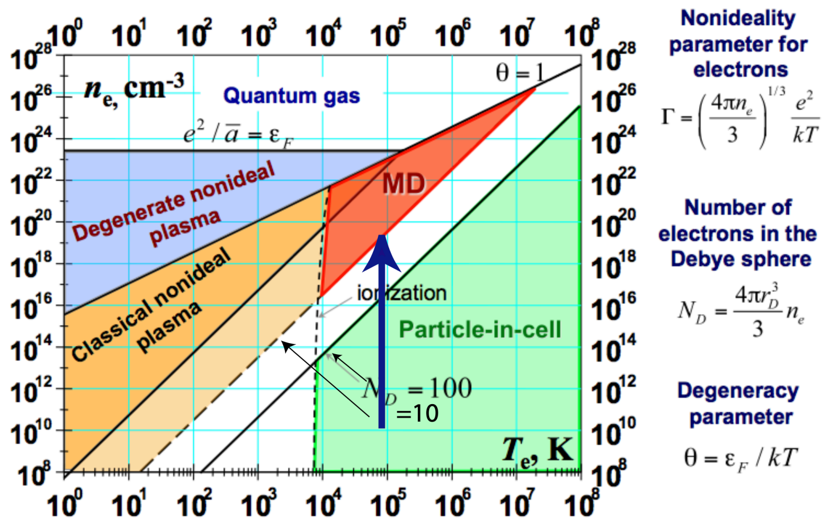


MD

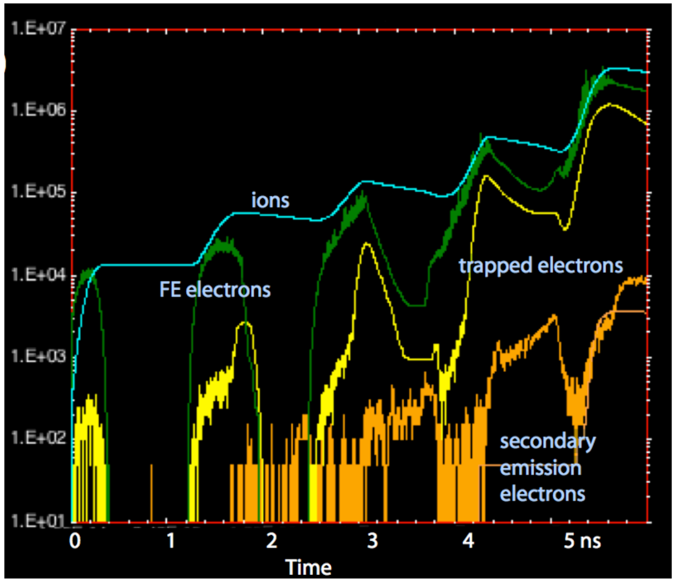
Modeling unipolar arcs is somewhat straightforward.

- Numerical models of unipolar arcs start with field emission and show how a local ion cloud is created that enhances the field and the electron currents. The formation of the arc is modeled with PIC codes where they are applicable. The far wall is a negligible perturbation.

- The currents produced with dense plasmas seem to predict retrograde spot motion.



PIC Results



Applications differ primarily in the timescales involved.

- We assume that similar physical mechanisms are at work in other applications of arcing.

- Cathodic arcs should be somewhat similar in local power dissipation, so that the primary thermal effects are due to pulse length, which can vary by many (~9) orders of magnitude.

- Approximate burn times

X band RF	100 ns
L band RF	25 μs
HV Corona	8 ms
ITER	1 min

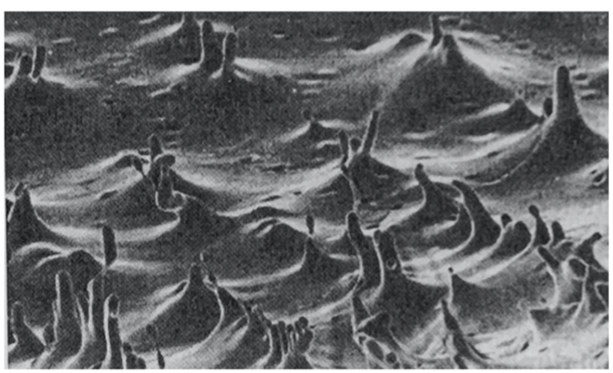
Productive directions for new work.

Although the field has been under active study for over 120 years, there are still many loose ends and confusing issues.

We think his work would be advanced by better data and modeling. We identify some issues relevant to these arcs and their application, in no particular order.

How are microparticles produced?

- We detected splashes from liquid droplets from our 805 MHz cavity operation. We also saw copper dust in the cavities.
- In tokamaks, macroparticles produced near the wall could contaminate the plasma.
- Jütter proposed a generation mechanism based on plasma pressure.
- Can surface tension snip off liquid tips caused by Maxwell stress producing a moving macroparticle?



Anders, Fig 3.15

What is the spectrum of enhancement factors?

- In principle there should be two spectra,
  one caused by the initial manufacturing process
  the other caused by arc induced damage

- When a system is first turned on, manufacturing defects dominate the spectrum of large field enhancements. After conditioning, one would expect that the field enhancements seen would be dominated by surface damage caused by the arcs.

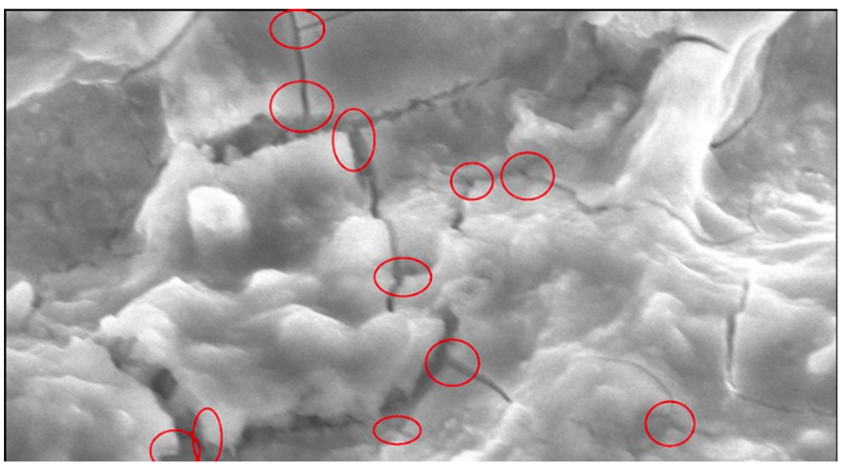
- The superconducting community measure and control manufacturing and minimize high field enhancements.

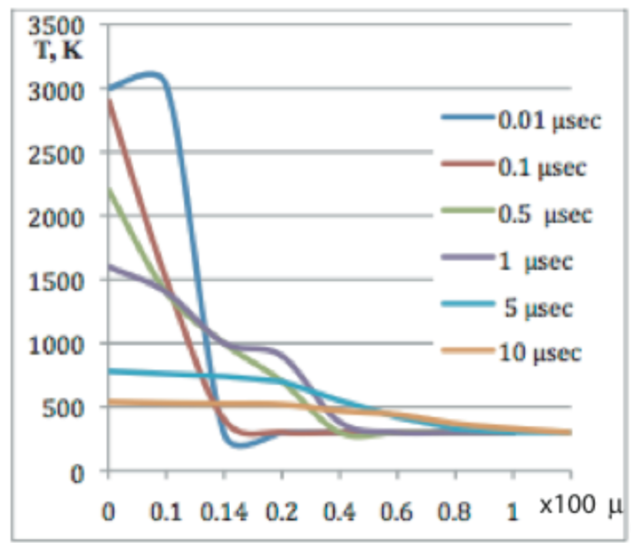
- There seems to be little data on the spectrum of field enhancements caused by arcing. Each application may be different.

Is differential cooling the dominant cause of surface damage?

- We assume that surface damage from arcs is due to differential cooling between the liquid surface under the arc. Surface tension and capillary waves tend to smooth the surface.

- Our data shows cracks and crack junctions that could produce atomically sharp corners, producing high βs. We see this with and without colinear B fields.





Are shorting currents carried by plasmas or free electrons?

- In RF systems, ions are not accelerated, and neutral atoms require time to be ionized, so we might expect that any plasma density in an RF cavity would be quite low, implying that the shorting currents would be carried by ballistic electrons, particularly with short RF pulses.
- There seems to be little experimental data on this issue.

How important is electromigration?

- After a meeting on arcing, Claire Antoine suggested that electromigration might be an important cause of failure in RF systems.

- Electromigration is very well understood since it can be responsible for failures in semiconductors. These failures have been reduced essentially to zero in modern iphones and other systems.

- We see considerable field emission in our cavities, but have not seen significant changes in field enhancements that could be produced by electromigration.

What limits the plasma density?

- The mechanisms that describe arcs all seem to increase the density of the plasma involved. Measurements of arc spots show, however, that the arc densities seem to have an upper limit. What causes this limit?

Are unipolar arcs a general phenomenon or special case?

- While unipolar arcs have been called "ubiquitous", Beilis seems to consider them only in the context of tokamaks and fusion devices, and Schwirzke primarily considers applications in laser damage..

- If they are a *general* phenomenon, the literature on them is anomalously limited.

- We believe they are a *general* phenomenon and a logical starting point for studies of all breakdown arcs.

Summary

- The physics of vacuum arcs has many applications and may be critical to many technologies

- While experiments are not particularly complicated and theory is comparatively straightforward, there are many competing mechanisms, and isolating particular processes is experimentally difficult.

- We believe that assuming **unipolar arcs** simplifies modeling.

- There are also other interesting details to study.

Conclusion

- Unipolar arcs may be the key to understanding arcing.