Vacuum Arcs are Important But Not Well Understood

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Outline

Vacuum arcs are important in many fields.

Vacuum arcs are poorly understood.

Vacuum arcs are complicated.

Vacuum arc physics is multi-disciplinary - tough to model.

A model useful for many applications seems possible and desirable.

Plasma physics, materials science & good communication required.

Vacuum arcs are important in many fields

It is desirable to have an accurate and general model of breakdown because arcing limits many technologies.

Accelerators, particularly linacs, are limited by the maximum gradients available, which affects their size and cost.

Large tokamaks, such as ITER, are vulnerable to a number of problems caused by arcing near the plasma edges, which can cause instabilities, plasma contamination and inefficient operation.

The power grid is limited by coronal losses.

Micrometeorites cause arcing when they hit satellites,

Vacuum arcs are poorly understood.

Following the discovery of the electron (1897) and gas breakdown modeling (1897):

People wondered: Are higher gradients possible in vacuum?

Answer: Breakdown also occurs on surfaces in vacuum. (Michelson, 1900).

But 100 years later Burkhard Jüttner wrote:

> The discussion on <u>the physical nature and parameters of cathode spots is not yet settled</u>. In the literature the theoretical treatment prevails, but many theories are built on unsafe experimental ground. . . . <u>The reason is the complexity of the spot and the extreme physical conditions (temperature, pressure, non-stationarity)</u>. . . . Therefore, at present <u>no model is generally accepted,</u> and this review cannot avoid a personal view. (J. Phys D Apl. Phys., 2001)

The complexity and wide applicability of this physics has thus far prevented the development of a single, comprehensive model of arcing at surfaces.

Vacuum arcs are complicated.

We arbitrarily define Four Stages

Trigger, Ionization, Plasma evolution, Damage

Many Mechanisms seem to be involved in each stage, including:

Field emission: Space charge, Nearby plasmas, Duty Cycle, Field Enhancements
Surface failure: electromigration/diffus., EEE/expl. wire, Coulomb expl. Field Emission
Ionization: 10 ns delay - atoms to Amps, image charges, geometries
Plasma/surface interactions: sheath evolution, equilibrium plasma parameters, instabilities, sputtering from liquids, surface tension, capillary waves, Maxwell stress, plasma pressure, macroparticle production & acceleration, differential cooling & cracking

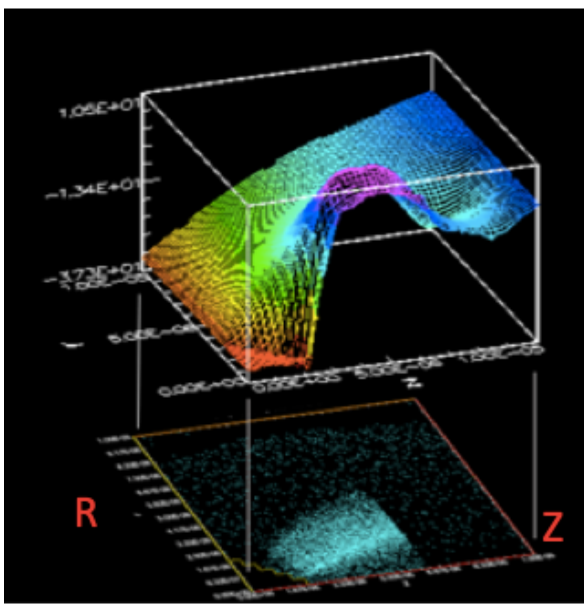
The general problem involves a wide range of timescales, densities, geometries and materials; however the same mechanisms seem to be involved in all applications.

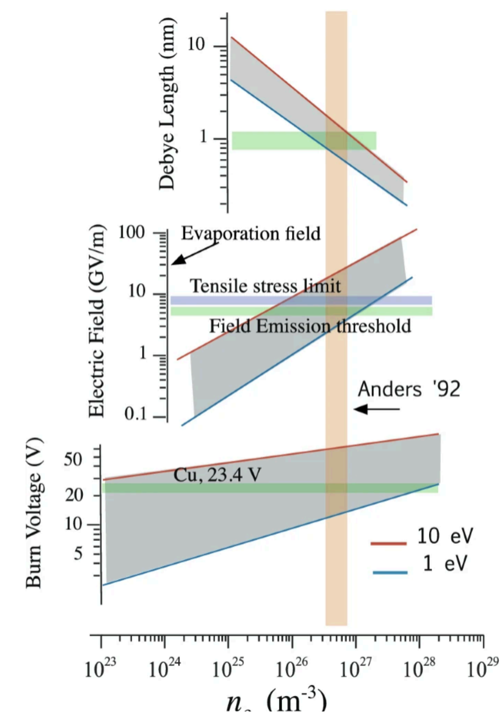
Vacuum arc physics is multi-disciplinary - tough to model.

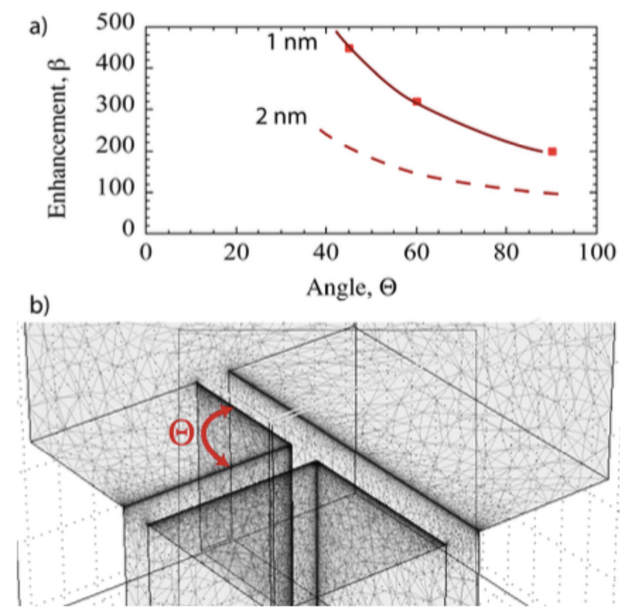
Different problems seem to require incompatible software,

We used PIC codes, Molecular Dynamics, and MATLAB to look at details.

PIC codes	MD	MATLAB
Few ns	< 10^{-13} s	variable
Few μ	< 1 μ	variable
Tech - X	Morozov	







A model useful for many applications seems possible.

A number of problems need to be addressed:

Data taken over different timescales has been difficult to compare.

Inflexibility of power systems limits experimental range.

Modeling is not regarded as essential when experimental options are limited.

However, modeling is useful, not expensive and ideally suited to university groups. This work must be done in close cooperation with accelerator, tokamak and other groups who are involved with experimental data, to constrain the results.

Plasma physics, materials science & good communication are required.

Modeling was traditionally done using algebraic systems, however there are too many variables and parameters change too rapidly for these to be useful. Arc triggers may be sub ns, and discharges could last minutes. Nevertheless, understanding field emission, self-sputtering and ionization in PIC codes should produce a useful first iteration of a general model.

Improvements would involve modeling the temperature and surface features of the (presumably molten) surface geometry and the time development of this surface after the plasma is terminated. These results would provide data on the spectrum of field enhancements and thus the local surface fields and field emission when fields were reapplied.

Vacuum arcs have many similarities with failure analysis in electronic systems and understanding the details of these problems can help understand these systems.

Summary

Almost all of modern science uses ideas, data and technology that was unheard of 120 years ago. The study of vacuum arcing, however, seems to be moving much slower.

Better arc models would be very widely used. The tools that are required already exist.

Arc modeling needs more attention, better integration and communication with other fields.

References

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