A GENERAL MODEL OF VACUUM ARCS IN LINACS

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Abstract

We are developing a general model of breakdown and gradient limits that applies to accelerators, along with other high field applications such as power grids and laser ablation. We have considered connections with failure modes of integrated circuits, sheath properties of dense, non-Debye plasmas and applications of capillary wave theory to rf breakdown in linacs. In contrast to much of the rf breakdown effort that considers one physical mechanism or one experimental geometry, we find an enormous volume of relevant material in the literature that helps to constrain our model and suggest experimental tests.

INTRODUCTION

Although 115 years have elapsed, and high electric fields in the presence of metals have been under continuous study, there seems to be no agreement about the mechanisms and parameters involved in vacuum arcs. This is particularly strange since arcing and associated processes are important factors in accelerator R&D goals, failure modes in high-density integrated circuits, fusion power systems, micrometeorite impacts and high energy density systems such as laser ablation, all of which are well-supported research interests.

Our effort, which started from a study of x rays from rf systems and has evolved into modeling arcs, models mechanisms involved in various stages of arc evolution using numerical methods. We believe that our model is simpler and more generally applicable than other explanations and in this paper we describe increasingly precise calculations, other possible uses and applications of the model and also comment on some other models [1-3].

OUR MODEL

Extensive measurements of x-rays and surface damage from rf systems convinced us that local fields were enhanced by surface asperities, and the fields could be measured using the parameters from Fowler Nordheim field emission. We found the magnitude of these enhanced fields was sufficient to produce Coulomb explosions and initiate breakdown. Our model, supported by a number of numerical calculations, is outlined in Fig. 1. The model describes the arcing process in four stages: 1) Coulomb explosions, aggravated in part by electro-migration, produce neutral gas near the surface. We have modeled the Coulomb explosion, both for smooth surfaces and for cubes with sharp corners, using MD. 2) The neutral gas 'fragments' are ionized by field emission of electrons, enhanced by plasma ions near the surface that increase both the surface field and field emission. PIC codes were used to show how field emission currents combined with local neutral atoms would produce an ion cloud, while increasing the local fields driving the field emission. 3) Evolution of the plasma whose density increases due to self-sputtering, is modeled. MD was used to model the detailed properties of the sheath as the density was increased above the nonlinear plasma limit, while separate MD calculations have shown how self-sputtering would produce a secondary yield above 10 for dense plasmas above molten metal surfaces insuring a rapid density increase. 4) The effects on the turbulent surface due to plasma pressure and surface field have also been modeled. After the plasma is gone, surface damage is produced during cooling and smoothing due to damped capillary waves and cracking of the thermally contracting surface. We have also shown how high field enhancements can be produced on an otherwise smooth surface by a combination of damped capillary waves and cracking [1,2].

We have found that two phenomena seem to dominate the physics of arcs: unipolar arcs, and surface cracking, and the study of these arcs seems to focus in these issues.

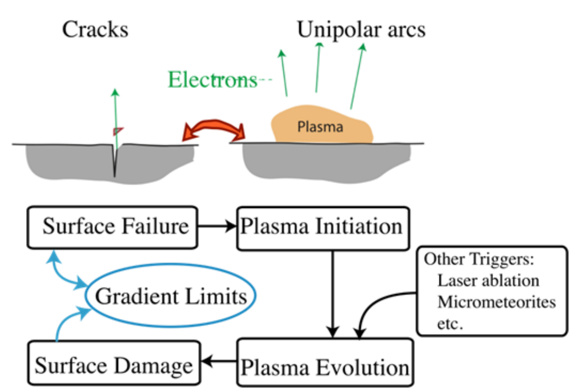

Figure 1: The four stages of a discharge describe evolution of cracks and unipolar arcs [1].

MODELING ELECTROMIGRATION

We have recently looked in more detail at electromigration as a factor in the initial surface failure. Electromigration is one of the primary causes of mass transport induced failure in electronic materials, and the effect is proportional to the local current density, j, where experimental data shows the dependence is $j^{1.6}$ [4]. We have found that current densities, both in field emission and in arcs, can be in the range of $>10^{11}$ A/m^2, and this current density is also associated with bulk transport of metal atoms in electronic systems [1,2,3,4]. We assume field emission and breakdown occurs at the corners of crack junctions and that electromigration would transport

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atoms to and beyond the field emitting tips, effectively increasing the field enhancement βs, and also enhancing the surface fracture stresses. Extensive studies done as part of the failure analysis of high-density integrated circuits have shown that electromigration can be eliminated if the current densities can be kept well below 10^{11} A/m^2, where matter transport becomes insignificant in solid systems. In the case of vacuum breakdown, since atoms are being transported to or along the surface, one would expect that the effective ion valence, Z, would be lower and surface changes would occur more easily than void formation or interpenetration in bulk materials.

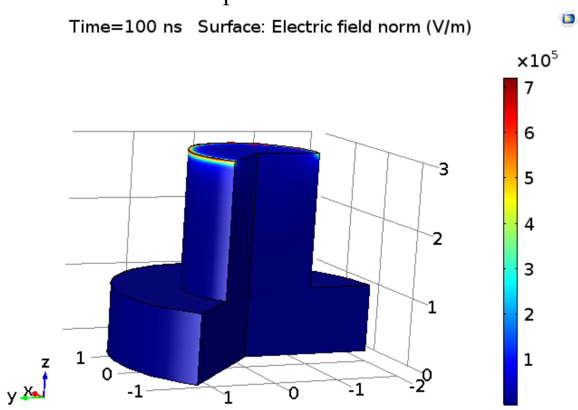

Figure 2, Modeling mass transport due to high current densities in COMSOL [5] using cylindrical coordinates.

We are continuing to study the effects of electromigration by modeling of atomic motions in a variety of geometries, see Fig. 2 [5]. We have found that high current emission brings atoms to the surface and causes growths that would increase local field enhancements.

DISCUSSION

There are a number of applications of the model from the extensive literature on environments with high local power densities. While the simplicity of this model permits comparison with data from other fields, we find that moving from one field to another, or even from DC to rf fields involves some modifications to the model.

Frequency Dependence in rf Systems

The conditions of rf systems vary widely as the frequency is changed. We find field enhancement factors $\beta \sim 200$ at L band, and $\beta \sim 10$ at X band, which is consistent with breakdown at crack junctions at low frequencies and at crack edges at higher frequencies. In CERN X-band systems, for example, pulse lengths are on the order of 200 ns, and powers can be on the order of 90 MW. L band standing wave systems have much longer pulse lengths, ~25 μs. The short heating pulse in x-band breakdown events implies shallow heating and quick cooling that should not produce crack junctions.

Shorting Currents in RF and DC Systems

Our measurements of current densities of arcs, which we assume is due to field emission from the metal surface, can be compared with historic data from laboratory plasmas [3]. In fact, they do not agree, with DC current densities in the range of ~10^{11} A/m^2, and measurements from arc spots in L band cavities giving densities on the order of 20 MA/m^2. This discrepancy seems due to the fact that unipolar arcs driven by DC fields have higher densities, and thus sheath potentials, (10 GeV/m for DC and 3 GeV/m for rf). Both of these electric fields are, however, within the normal range of measured field emission data [1].

Noise and Plasma Oscillations

In an earlier paper we showed how a equilibrium could develop around an equilibrium operating point where field emission would determine an equilibrium plasma density by regulating the sheath potential, finding experimental data that show oscillations at a frequency of 200 MHz in a 1.3 GHz rf system [2], and 350 MHz for DC systems [3]. We assume that the difference could be at least partially due to the higher density and sheath potential in the DC sheath environment.

Improving Particle Accelerator Gradients

In order to improve particle accelerator gradient limits it seems necessary to understand where these limits come from. These limits are not understood however, so a wider variety of options must be covered.

High Power Pulsed Laser Ablation of Surfaces

High power laser ablation of materials is useful for many applications, including drilling and machining hard materials rapidly and precisely. The process involves surface absorption of laser power until plasma is produced, and the process is efficient because the surface absorbs the power rather than the bulk material. The plasma formation physics is complex and depends on the properties of the laser pulse and material. On the other hand, the existence of a slow, unipolar arc phase of the arc, which could produce plasma secondaries, and would be responsible for the structure of the crater, may be comparatively independent on the details of the initiation.

Tokamak Plasma Edges

Designs for tokamak power reactors require minimal plasma contamination from the first wall materials due to arcing, although the process does exist at some level. Metal ions in the plasma can cool and pinch the discharge, increasing radiative losses and instabilities [6]. A better understanding of this environment would improve optimization of these designs.

Failure Mechanisms in Electronic Systems

During the 1970's, an extensive effort was undertaken to understand failure mechanisms in semiconductor systems, with the results available in many textbooks. The high current densities now reached in integrated circuits are well understood and directly applicable to vacuum breakdown [4].

Coronal Losses in Power Grids

The power produced at generating stations and consumed by users cannot be exactly equal, and the majority of the difference (~100 B$/y worldwide) is dissipated in by coronal losses during transmission over high voltage lines. The subject has been understood for many years and many of the definitive articles were written in the 1930's and earlier. While utilities see considerable economies possible in more closely matching the generated power with the consumed power, a more precise understanding of this loss should also be useful. Coronal losses follow the same E^{14} power law as dark current in cavities, presumably because they are both produced by Fowler Nordheim field emission [7]. Better understanding of the surface damage mechanisms should be able to reduce this loss.

COMPARISON WITH OTHER MODELS

While the model we describe seems simple and very general, we find that it disagrees with ideas in the literature.

Explosive Electron Emission (EEE) has been proposed as the primary trigger for vacuum breakdown, however the process occurs faster than would be consistent with bulk heating of asperities, and we find the heated volumes may be too small to provide significant melting of asperities [1].

Extensive modeling was done to show that breakdown could be done in high magnetic fields if the magnetic and electric fields were both perpendicular to the surfaces and the system was allowed to proceed for many pulses to allow pulse heating to produce surface fatigue from incident field emitted beams, (days or weeks). However the model does not explain how similar experimental data is seen when the direction of the magnetic field is oriented parallel to the surfaces or why all breakdown damage is produced in mirror images at opposite ends of the discharge [8].

The idea of pulse heating is based on surface heating by skin currents that occur far from the cavity irises where breakdown actually takes place, thus making this process an unlikely trigger [9].

RF experiments have many more variables than measured parameters and are insufficiently constrained, a problem that is generally true in arc physics

CONCLUSIONS

We have developed a model of vacuum breakdown that seems to be applicable not only to rf linacs, but many other extreme environments that limit many aspects of technology. We are refining our model and extending its domain of applicability to semiconductors, power grids tokamaks and other applications.

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