NUMERICAL MODELING OF ARCS IN ACCELERATORS*

Jim Norem, Zeke Insepov, Thomas Proslier, ANL, Argonne, IL 60439, U.S.A.
Sudhakar Mahalingam, Seth Veitzer, Tech-X, Boulder, Colorado U.S.A.

Abstract

We are developing a model of arcing to explain breakdown phenomena in high-gradient rf systems used for particle accelerators. This model assumes that arcs develop as a result of mechanical failure of the surface due to electric tensile stress, ionization of fragments by field emission, and the development of a small, dense plasma that interacts with the surface primarily through self sputtering and terminates as a unipolar arc capable of producing field emitters with high enhancement factors. We are modeling these mechanisms using Molecular Dynamics (mechanical failure, Coulomb explosions, self sputtering), Particle-In-Cell (PIC) codes (plasma evolution), mesoscale surface thermodynamics (surface evolution), and finite element electrostatic modeling (field enhancements). We believe this model may be more widely applicable and we are trying to constrain the physical mechanisms using data from tokamak edge plasmas.

INTRODUCTION

This paper describes a model of vacuum arcs, the primary mechanism that limits gradients in warm linacs.

THE MODEL

We have developed a model of vacuum arcs that is applicable to accelerator systems. This model considers a number of stages in the development of arcs [1,2],

- Coulomb explosions trigger breakdown - fatigue (creep) helps.
- Breakdown arcs are initiated when field emission electrons ionize fracture fragments.
- The arcs produced are small, very dense, cold, and charged to a potential of ϕ = ~75 V.
- Increasing surface fields increase density, which further increases surface fields..
- Small Debye lengths, give, $E \sim \phi/\lambda_D \sim$ GV/m.
- Unipolar arc behavior produces craters and cracks with high field enhancements.

We have modelled the mechanisms responsible for the development of these arcs using a variety of techniques. We use Molecular Dynamics {MD) for studying the initial fracture of the material and for self-sputtering, We use Particle In Cell (PIC) codes for study of the initial plasma development, up to the maximum density for these codes. We use mesoscale surface thermodynamics to look at the response of liquid surfaces to the plasma, and we use finite element calculations to determine how surface morphology affects the local field by calculating an enhancement factor, β. The results of the model have been compared primarily with results from the MuCool Test Area at Fermilab, but also with results from other accelerator labs, tokamaks and a variety of lab experiments.

The main details of this work have been published elsewhere. In this paper we highlight recent results.

SURFACE FIELD MODELING

Our modelling shows that when field emitted beams hit a gas target, the density of plasma rises essentially exponentially. An explanation for this phenomenon is that as the gas is ionized, the Debye length, λ_D, decreases and eventually becomes unphysically small.

$$\lambda_D = \sqrt{\frac{\epsilon_0 KT}{n_e q_e^2}} = \sim\text{nm}$$

As the Debye length decreases, there is a corresponding increase in the surface field, $E = \phi/\lambda_D$, in turn increasing the intensity of field emitted beams. At densities on the order of 10^{24} /m^3 with sheath potentials of around 75 volts, the average surface field would be expected to be a few GV/m for a few ns. These fields could produce field emission over large areas.

SURFACE FIELD MEASUREMENTS

If we assume that the surface beneath the arc is liquid, affected by the surface electric field, surface tension and viscosity, one can equate the surface tension force around a hemispherical bubble with the electrostatic tension force from the electric field and determine the relation between the lateral dimensions of the structure seen in arc pits and the average surface field beneath the arc. This relation is $r = 2\gamma / (0.5\varepsilon_0 E^2)$, where γ is the surface tension of liquid copper (roughly 1 N/m). A variety of measurements from different rf structures show structure at the level of 1 micron, consistent with surface fields ~1 GV/m. Because the structures seen in cold samples have cooled, and finer features may have been lost, this field is assumed to be a lower bound.

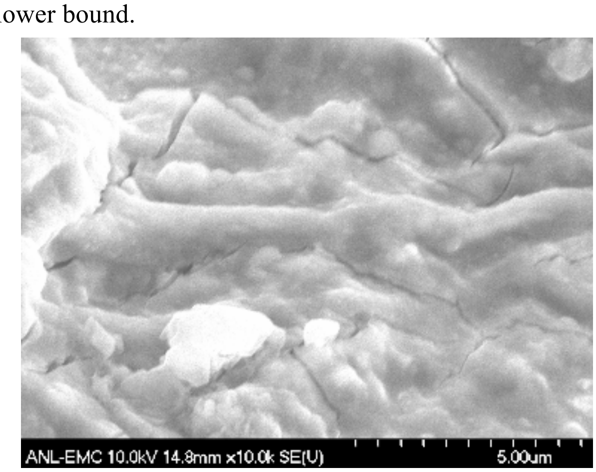

Figure 1: SEM image with cracks and ripples in arc pits.

NON-DEBYE PLASMAS

While these plasma simulations are done with particle-in-cell codes, these codes become less reliable for high densities and low temperature plasmas, because they assume well defined plasmas and 2 body collisions. For these dense plasmas Debye lengths approach atomic dimensions, plasma densities can become comparable to solid or liquid densities, and the number of particles in a Debye sphere is less than one, indicating that these plasma models are inappropriate. This is shown in Fig. 2.

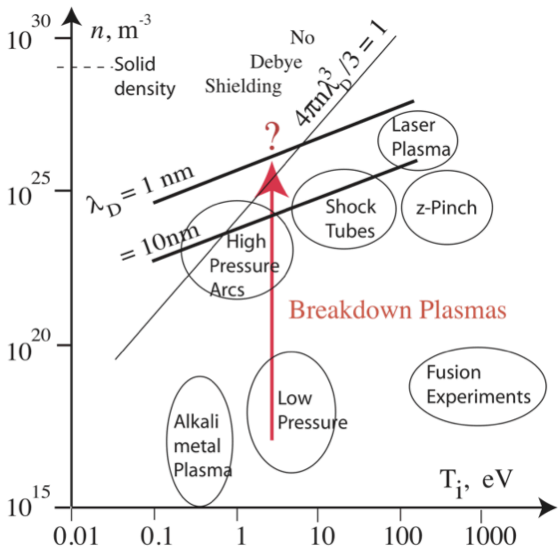

Figure 2: Plasma breakdown parameters compared with other plasma parameters.

UNIPOLAR ARCS

Since it is difficult to numerically model the behaviour of the dense plasma stage we believe we are seeing, we have assumed that the mechanism of unipolar arcs produce the surface damage from observed from dense plasmas [3]. Unipolar arcs have been studied for many years, primarily in the context of laser and tokamak plasma / surface interactions. This work is summarized in a recent Workshop on Unipolar Arcs, at Argonne on Jan. 29, 2010 [5].

Unipolar arcs seem to appear whenever dense plasmas are in contact with metallic surfaces. In the presence of magnetic fields they leave a characteristic "chicken track" trail of arc pits superficially similar to pits in rf systems.

ENHANCEMENT FACTORS

While it is frequently assumed that vacuum breakdown is due to Ohmic heating of whiskers (exploding wires), following a number of careful experiments by Dyke et. al. in the '50s, these whiskers have not been seen. On the other hand, the surfaces of arc-damaged materials are commonly covered with small cracks. We find that the enhancements factors, β, at the corners of crack junctions can be on the order of 100 – 200, compatible with the measurements in rf and DC arcing systems. The emitting areas of these crack junctions are very small, but their number is usually very large and can be compatible with measurements.

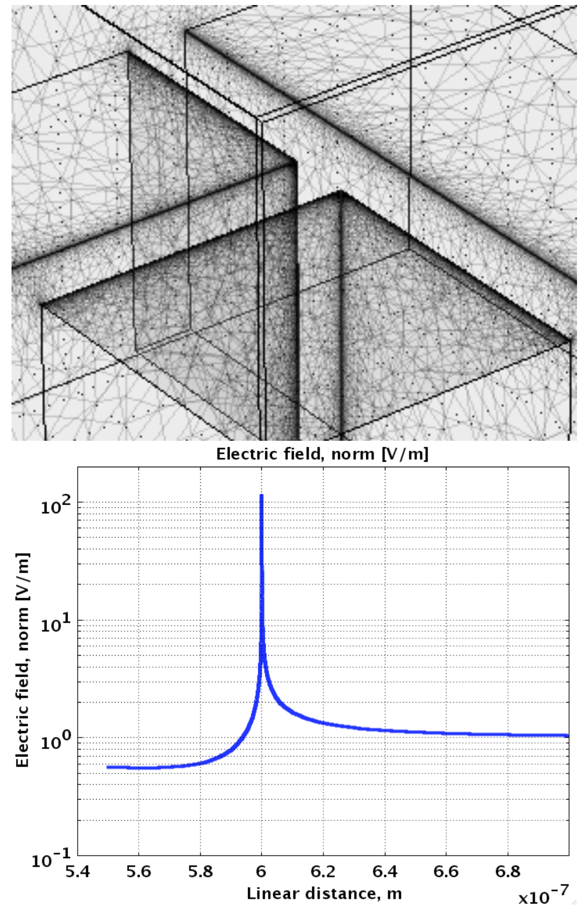

Figure 3: Triple crack junctions produce high enhancement factors

SURFACE HEATING

Surface heating in the arc is due to ion bombardment from the plasma and Ohmic heating due to field emission. We have modelled the heating in the case that the field emitters are the corners of cracks, and find that right angle corners are very difficult to heat resistivity, since the volume that is heated is quite small, and the heat diffuses into a much larger volume whose dimensions are determined by the thermal diffusion constant.

COMSOL is being used to generate thermal models for crack junctions heated by field emission and pasma ion heating. Preliminary results show that for 1 GHz structures, emission from the corners of small cracks produces negligible heating. In the case of these crack junctions, the volume that is Ohmically heated is just a few nm^3 while the thermal mass at equilibrium over ns timescales is on the order of (300 nm)^3, thus the temperature excursions for a single rf pulse are less than a milli-degree.

SELF SPUTTERING

Sputtering and self-sputtering are well-understood phenomena for cool surfaces in a laboratory environment. When the surfaces are hot (or melted) and highly charged, as we expect they would be in the interior of an arc, there is much less experimental information. We have used Molecular Dynamics (MD) to estimate the self-sputtering yields for copper atoms hitting a melted copper surface, in an electric field on the order of a GV/m, which we would expect to find in the arc. These yields, for both molten copper and GV/m gradients are above 10, providing a mechanism for surface erosion and plasma fueling.

STATIC MAGNETIC FIELDS

We have some preliminary results from VORPAL that show that static magnetic fields directly affect the plasma parameters, by focusing and confining the low energy plasma electrons. Experimental data from the Fermilab MuCool Test Area (MTA) can test these models.

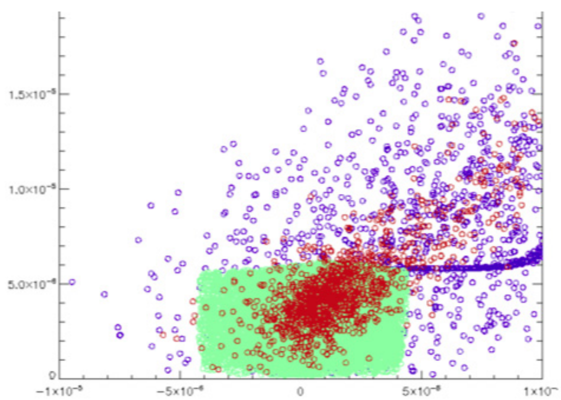

Figure 4: The effects of a 3 T field aligned at 45 degrees on the development of a plasma arc.

BDR ~ E^{30}

Breakdown rates have been found experimentally to be roughly proportional to E^{30}. While one would expect that this extreme dependence would tightly constrain the physical process, there seem to be at least three mechanisms that can produce this dependence: Ohmic heating, since $I^2R \sim (E^{14})^2 \sim E^{28}$, electromigration [4], which also is proportional to I^2, and fatigue (creep), which has a variety of dependences, depending on the failure rate, and an exponent of 30 is consistent with experimental data for low breakdown rates.

PREDICTIONS

The mechanisms we are describing seem to constrain all aspects of the arcing phenomenon, thus we are, in principle, beginning to be able to produce explanations and predictions for arcing phenomena. This model describes arcing as a single surface phenomenon, where the sensitivity to static magnetic fields would be determined from the parameters of the plasma. Hotter and more damaging arcs, for example, would result if a magnetic field prevented discharge of the cavity energy into the far wall.

OTHER ARCING ENVIRONMENTS

We argue that the mechanisms presented here are quite general, and should be active whenever high density plasmas contact surfaces. Thus this model should be relevant both to rf and DC plasmas, high and low frequencies as well as plasma surface interactions in tokamaks, impacts of micrometeorites with satellites, laser surface interactions and vacuum arcs in general.

SUMMARY

While the maximum acceleration gradient is an important parameter for an acceleration system there is no general agreement on the physics of vacuum arcs or accelerator gradient limits. The work presented here is a result of trying to produce a model specifically designed for rf breakdown and gradient limits, that is relevant to many general applications.

ACKNOWLEDGEMENTS

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