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The Problem of RF Gradient Limits

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Abstract. We describe breakdown in rf accelerator cavities in terms of a number of mechanisms. We divide the breakdown process into three stages: 1) we model surface failure using molecular dynamics of fracture caused by electrostatic tensile stress, 2) the ionization and plasma growth is modeled using a particle in cell code, 3) we model surface damage by assuming unipolar arcing. Although unipolar arcs are strictly defined with equipotential boundaries, we find that the cold, dense plasma in contact with the surface produces very small Debye lengths and very high electric fields over a large area, and these high fields produce strong erosion mechanisms, primarily self sputtering, compatible with crater formation. We compare this model with arcs in tokamaks, plasma ablation, electron beam welding, micrometeorite impacts, and other examples.

Keywords: gradient limits, rf breakdown, arcs, unipolar arcs
PACS: 52.50.Nr, 52.80.Pi, 87.56.bd

INTRODUCTION

Although the mechanisms of arcing have been under study for over 100 years, and are vital to the performance of high gradient accelerators and may other applications, the field of arcing and gradient limits is not well understood and the basic mechanisms are still debated [1, 2, 3].

Linear colliders and other energy frontier colliders require a level of stability and emittance growth that seem to be provided only by weak focusing accelerator systems using focusing produced by iron quadrupole yokes. This argument seems to require metal accelerator structures and their limitations [4].

In general, gradient limits are set by a number of factors. Metal structures can be limited by multipactor, but are primarily limited by arcing. Superconducting systems are limited by multipactor and arcing, but, because of the delicate quantum mechanical nature of superconductivity, many more factors such as quenching, external noise, imperfections in the surface, magnetic oxides and other effects can also produce gradient limits. This paper is concerned only with arcing in copper structures.

We find that our breakdown model is quite general and should also apply to other types of arcs, for example, arcing between the plasma and wall in tokamaks, laser ablation, micrometeorite impacts, electron beam welding and small gap arcs.

THE BREAKDOWN MODEL

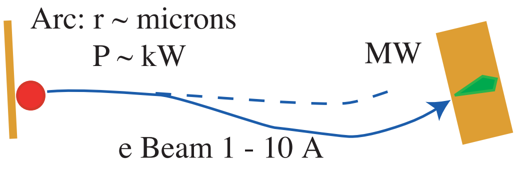

FIGURE 1. The components of the arc in cavities.

We work with a model that assumes that arcing in accelerators and most other systems consists of three stages: a) the trigger of the arc is a failure of the surface that may be due to a number of causes, b) field emission (FE) ionization of the fragments produced by the failure of the surface, and c) formation of a unipolar arc that damages the surface [5]. We find that the arcing phenomenon is similar in a very wide range of contexts, and may not depend strongly on surface polarity, frequency (DC or rf), geometry, etc. If a common arc mechanism is assumed, modeling is more highly constrained.

In rf cavities arcs the pre-breakdown state can be understood by looking at dark currents, which can easily be detected using x ray fluxes if the dark currents cannot be measured directly. We have found that all cavities in which the measurement has been done show an E^{14} behavior indicative of local surface fields at emitters on the order of 10 GV/m.

We assume that breakdown arc, Fig. 1, consists of the following mechanisms:

- Breakdown is triggered by Coulomb explosions, most probably aided by fatigue (creep at the atomic scale) and Ohmic heating due to field emitted electrons. Mechanical failure of the surface occurs at local surface fields of ~ 10 GV/m [6].
- Breakdown arcs are initiated by FE ionization of

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fracture fragments. The field emitters will continue to operate, and ionize the material that has been propelled off the surface during surface failure.

- The plasma density rises exponentially, the arc becoming small, very dense, cold, and charged ϕ = (50-100) V to surface. The ions are confined inertially and electrons tend to diffuse away. The growth phase of these arcs have been extensively modeled using OOPIC and the exponential increase in the ion and electron densities is well understood.
- The small Debye lengths produced by these dense plasmas,

$$\lambda_D = \sqrt{\frac{\varepsilon_0 KT}{n_e q_e^2}} \sim few\ nm$$

yield very high surface fields E = $\phi/\lambda_D \sim$ GV/m. At these surface fields, field emission could occur over large areas and ion bombardment would occur with an ion energy equal to the sheath potential, further heating both the plasma and the surface.

- High electric fields produce micron-sized unipolar arc discharges [7, 8]. The plasma requirements for producing a unipolar arc are not known precisely, however there seems to be a minimum surface field and plasma density.
- Unipolar arcs seem to be very efficient in converting arc energy into surface damage (craters).

The unipolar arc would continue to burn as long as the plasma could be maintained by the cavity fields. We believe these unipolar arcs are similar to arcs produced in tokamaks, laser ablation, small gap arcs, and perhaps other examples.

We have previously published papers on modeling the trigger using Molecular Dynamics and calculating gradient limits assuming a spectrum of enhancement factors produced by arc damage [6]. This paper considers plasma calculations and the physics of the unipolar arc.

Molecular Dynamics

We have modeled the initiation phase of the discharge assuming only the electrostatic tensile stress is needed to fracture the material [6]. We assume that fatigue (creep at the atomic scale) and Ohmic heating would also contribute to the mechanical failure of the surface. Molecular Dynamics is also used to calculate the self sputtering that seems to control the unipolar arc parameters.

It is difficult to directly couple Molecular Dynamics and plasma codes together because they operate over different ranges of time and space and particle density, thus coupling the calculations must be done carefully. These calculations are used to evaluate specific processes such as Coulomb explosions of surfaces and free particles, and surface processes like self sputtering.

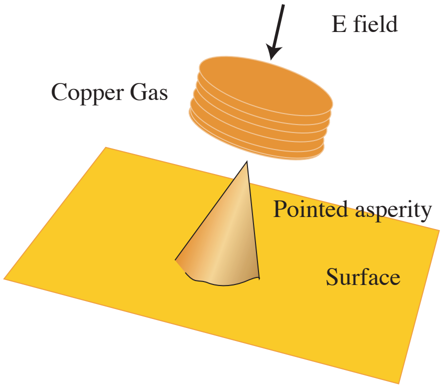

FIGURE 2. The geometry used in OOPIC Pro plasma calculations of ionization (the cone is stepped).

OOPIC Pro Modeling

The formation of the plasma has been modeled using the 2.5D (cylindrical symmetric) OOPIC Pro [9]. The geometry used in the model is shown in Fig. 2, where we assume a generic field emitter is located below a cylinder of neutral copper gas, and the plasma code models the development of the plasma produced as the field emitted electrons ionize the gas over a number of rf cycles.

The development of the plasma in OOPIC Pro can be used to understand such mechanisms as how the pulsed nature of the field emitted beam affects the initial properties of the arc, and the minimum density of material required to produce an arc.

Figures 3 and 4 show output from the OOPIC Pro code, giving the dependence of the the arc density on the initial gas density (Fig. 3) and the overall numbers of field emitted electrons ad ion simulated, the ion temperature in the arc, and the density of line radiation produced in the center of the arc (Figs. 4a, 4b, and 4c). The pressure of neutral gas is on the order of 30 mTorr when successful arcs are modeled, corresponding to approximately one half of a monolayer of material injected into the region above the field emitter. This is consistent with the dimensions of the gas being larger than the ionization length for 100 eV electrons, $x_i = 1/n_i\sigma_i$, where x_i, n_i, and σ_i are the ionization length, ion density and ionization cross section.

The evolution of the plasma over the first 7 ns is shown in Fig. 4a, where the density of field emitted electrons, ion density, plasma electrons, are, respectively, green,

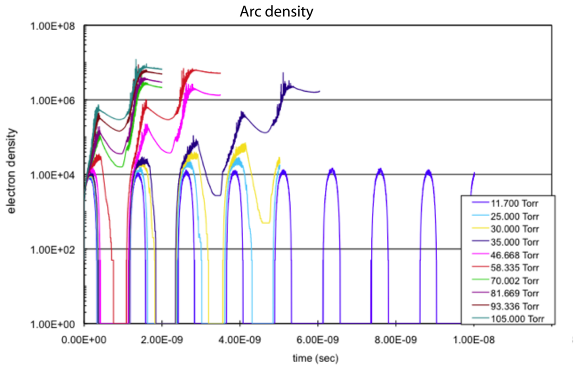

FIGURE 3. The dependence of arc density on the initial pressure of neutral gas.

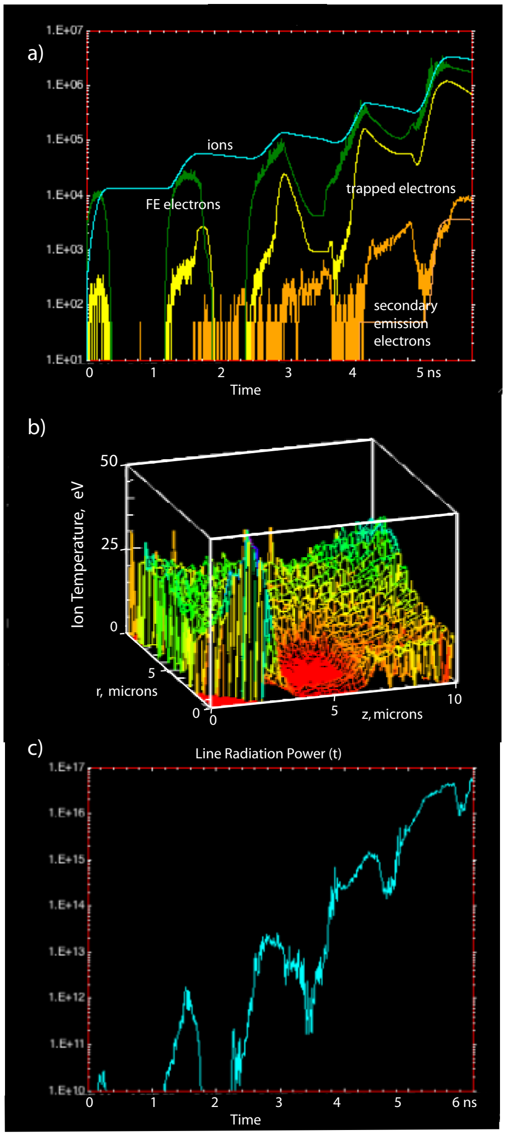

FIGURE 4. OOPIC Pro calculations of the initial 7 ns of the plasma arc, showing a) particle numbers simulated, b) ion temperature and, c) optical radiation.

blue and yellow. The Ion temperature, shown in Fig 4b, is consistent with the very low temperature plasma one would expect from recently ionized neutral gas in a partially ionized environment. Because of the space potential of the plasma, ions are accelerated as they, comparatively slowly, move away from the region where they were ionized, and reach energies comparable to the plasma potential when they hit the wall.

The optical radiation produced by the plasma is primarily line radiation from the single and doubly ionized atomic states, and is produced primarily in the visible and near UV region. The rate of growth of this radiation is essentially proportional to the density squared.

Figure 5 shows the plasma potential in the early stage of the discharge. The surface electric field is defined by the relation $E \sim \phi/\lambda_D$, where ϕ is the plasma potential. As the density of the arc increases, the Debye length decreases, continually increasing the surface electric field. OOPIC Pro implies that the plasma density can reach $10^{24} - 10^{25}$ / m^3, where the Debye length is a few nm and the surface electric field is a few GV/m, over the entire region covered by the arc. Under these conditions the plasma is continually heating the surface (OOPIC Pro estimates temperatures of 10^4 deg C), and both field emission and ion bombardment contribute to a very large local current. We believe that this environment, primarily defined by the plasma density, is the trigger for the the unipolar arc formation.

UNIPOLAR ARC PHYSICS

“The unipolar arc may be expected whenever a plasma of sufficient density and electron temperature is in contact with a metal surface of sufficient area” [8]. Although it seems to be the primary mechanism by which arcs can damage surfaces, there has been little study of this mechanism, theoretical or experimental, in the last 15 years. Unipolar arcs were first proposed by Robson and Thonemann, but more thoroughly described by Schwirzke (Fig. 6) in the context of laser ablation and tokamak plasmas arcing to the wall, where they left characteristic “chicken tracks” of arc pits [7].

Unipolar arcs are driven by the sheath potential and surface electric field between the plasma and the surface and simulations imply that the field can be very high, producing very high self-sputtering rates and potentially large field emitted currents. Sheath potentials of 70 V, combined with Debye lengths of 7 nm, give surface elec-

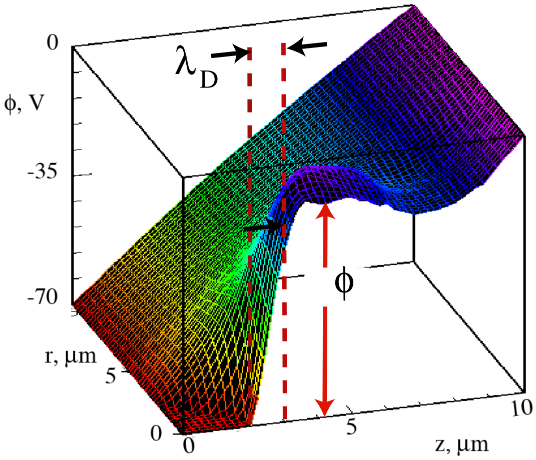

FIGURE 5. Plasma potential calculated by OOPIC Pro in the first ns of the arc, the surface electric field is $E \sim \phi/\lambda_D$.

tric fields of 10 GV/m, combined with surface temperature above the melting point of copper produce an environment in which no surface can survive. The environment is extreme, capable of producing MG magnetic fields circulating around the the central ion and electron currents. At these parameters, the Debye length is no longer thick enough to shield the sheath potential.

We have calculated the self sputtering yields of copper for high temperature surfaces and high electric gradients using Molecular Dynamics, and found that above the melting point the self sputtering coefficient may be greater than 10 (Fig. 7). We also find that at local surface fields above $E = 3$ GV/m, the self sputtering coefficients can be equally high. This, combined with the high flux of ions hitting the surface, producing exponentially rising temperatures, also produces both high surface erosion and a continuing source of atoms and ionization for further plasma heating and density increases. The result is that once a plasma has been produced near a surface, all processes are strongly exothermic and likely to move forward as fast as ion motions and processes like ionization permit. Once a given level of ionization is reached, arcing must proceed.

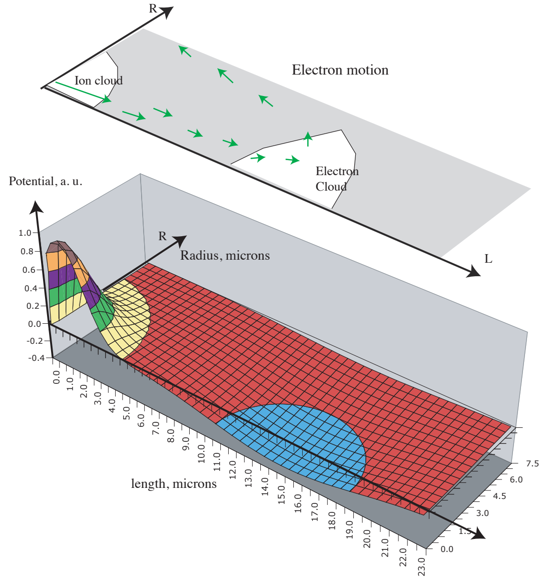

FIGURE 6. Potentials and electron motion in the classic unipolar arc as described by Schwirzke.

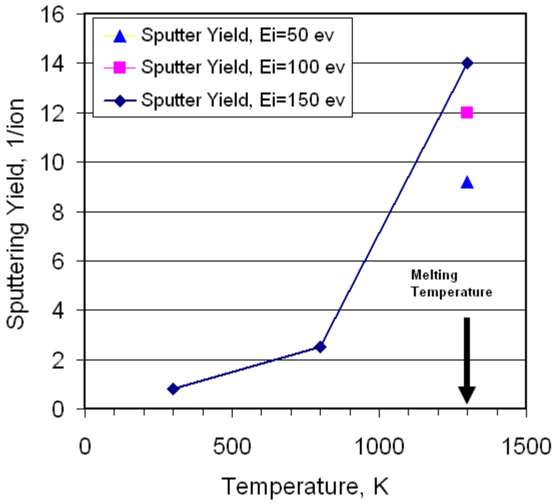

FIGURE 7. Molecular Dynamics estimates of self sputtering for melted copper.

DIFFERENT ARCING ENVIRONMENTS

Because they are rare, unpredictable, and difficult to measure, there is limited systematic data on arcs in rf structures, and it seems desirable to look at arcs in other contexts, Unipolar arcs have been identified with arcs from in a large number of environments: small gaps, large gaps, RF - DC, laser ablation, e beam welding, varying polarities, between a plasma and the wall of a tokamak, lightswitches, micrometeorites, etc.. All these arcs seem to have much in common, in particular, it seems likely that the primary mechanism for damage is unipolar arcing, and differences between arcs may be primarily differences between pathways leading to the unipolar arc. There are a number of papers exploring the parameters of these arcs in different contexts [7, 8, 10, 11, 12].

We believe that the behavior of unipolar arcs is central to the study of arcs wherever they occur, and find the lack of interest in this mechanism somewhat incompatible with their importance. Because the Debye lengths are so short, (a few nm) the number of particles in a Debye length can be less than or equal to one, violating one of the defining properties of "plasmas", however the methods of plasma physics, numerical methods and atomistic simulations in particular, remain valid and useful.

GRADIENT LIMITS

We assume that the maximum operating gradient of a particular structure is due to an equilibrium that develops between the cavity damage and the arc parameters in that structure. An earlier paper has shown that all structures seem to break down at a fixed value of E_{local} and any variation in the gradient limits must be due to the maximum enhancement factors in specific structures [14]. As the basic processes in all rf arcs follow similar mechanisms, and the primary difference between the particular structures is due to the energy of the arc.

Other work has shown that the surface density of asperities with a given enhancement factor, $n(\beta)$, seem to follow an $n(\beta) \sim e^{-c\beta}$ distribution, where β and c are the enhancement factor and a constant, which seems to be roughly 0.03 [13]. If it is assumed that $n(\beta)$ is proportional to the energy in the arc, and the maximum enhancement factor is determined by the constraint that the total number of asperities above this energy is constant, this gives the relation that β_{max} (and thus the maximum gradient) depends logarithmically on the energy in the arc. A more detailed analysis of gradient limits using this model has been published in Ref. [14].

SUMMARY

Breakdown and the gradient limits that result from this process seem to be due to high local fields at small asperities on the surface which mechanically fail, ionize and, within a short time, become dense plasmas in contact with the wall. We assume that these plasmas eventually become unipolar arcs and cause surface damage by melting and eroding the surface of the structure. This mechanism may be similar to the formation of arcs in many other environments. The damage produced limits the maximum gradient that can be maintained in the structure.

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