MODELING VACUUM ARCS IN LINAC STRUCTURES*

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Abstract

We describe our vacuum arc model, which divides breakdown into four stages: trigger, plasma formation, plasma evolution and surface damage. We have modeled all four stages numerically and find that the properties of surface cracks and unipolar arcs can explain essentially all the experimental data we have seen. In addition to linac breakdown, the model should apply to arcs in a wide variety of applications, such as laser ablation, tokamak edge plasmas and micrometeorite impacts. We also outline differences with other work.

THE MODEL

This effort began as an attempt to understand gradient limits in 805 MHz cavities used for muon cooling. We have described the overall picture of the model and some of the details in a number of papers in the context of accelerator breakdown [1-7].

Recent work has shown that the development of the arc can be explained by two mechanisms: 1) mechanical failure of the solid surface due to Coulomb explosions caused by high surface fields at crack junctions (see ref [5]) and, 2) the development of unipolar arcs that can act as virtual cathodes and produce currents that short the driving potential [3]. Once an arc starts, the surface electric field and field emission increase, increasing ionization of neutrals, increasing in the plasma density [4]. The density increase then reduces the Debye length that increases the surface electric field, thus both the electric field and the density increase approximately exponentially with time. PIC simulations of the unipolar arc model for vacuum arcs relevant to rf cavity breakdown show that the density of plasma formed above the field emitting asperities can be as high as 10^{26} m^{-3} [6]. The temperature of such plasma is low, in the range of 1-10 eV. These high densities can make the Debye screening length, λ_D, become smaller than the mean inter-particle distance or the number of particles in the Debye sphere, to become less that unity. This implies the failure of the ideal plasma approximation, as well as most of the assumptions used in simple calculations. Processes in such a dense plasma can be affected by three body particle collisions so that the Particle In Cell (PIC) method which relies on a simple collisional model, with two body collisions, becomes inappropriate and different methods, such as Molecular Dynamics (MD) must be used

Arrays of cracks are seen in many SEM images of arc damage. We believe these cracks are the result of the cooling of the melted surface that takes place in two stages; first cooling from high temperatures to the solidification point of the metal, followed by cooling from the freezing temperature to room temperature, where the solid contracts by an amount $\Delta x/x = \alpha\,\Delta T \sim 2$ %, where ΔT is the temperature change, x represents the dimension of the damage and α is the coefficient of linear expansion. The model is diagrammed in Fig. 1.

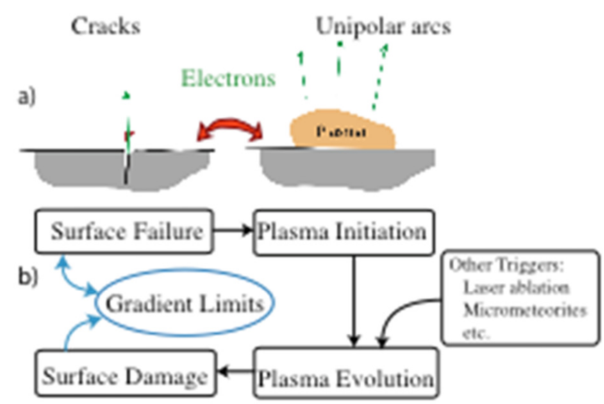

Figure 1: Breakdown proceeds through surface failure, plasma initiation, plasma evolution and surface damage. Part a) shows the physical picture, part b) shows active mechanisms.

The model provides a framework for prediction and experimental study of all aspects of the breakdown process in a variety of environments.

USING THE MODEL

In order to explore the reach of the model we consider the following issues:

Multipactor

We have reported surface damage in coupling cells where the scale of the structure was on the order of 10 nm, rather then the 1 μm commonly seen in 805 MHz Breakdown events. These are consistent with unipolar arcs caused by multipactor, and evidently are not associated with significant shorting currents. These occur at lower gradients and do not seem to be gradient limiting.

Magnetic Field Effects

The geometries of crack junctions can explain magnetic field effects. Data show similar breakdown thresholds with magnetic fields parallel and perpendicular to the surface, arguing for single surface breakdown. With B=0, melted areas are irregularly shaped, and cool so that

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primary cracks remove strain in one direction and secondary cracks form perpendicular to the primary cracks. Thus, crack junctions occur at right angles. From previous work, this geometry would produce a narrow range of enhancement factors. In a magnetic field, however, symmetric heating from shorting currents pinned to magnetic field lines results in radial strain and circumferential cracking. These cracks occur at variety of acute angles, producing higher enhancements, a wider range of enhancement factors and lower and wider range of breakdown fields [1].

Sheath Parameters

Numerical analysis of plasma sheath properties using MD has produced simple dependence on plasma densities, shown in Figure 2.

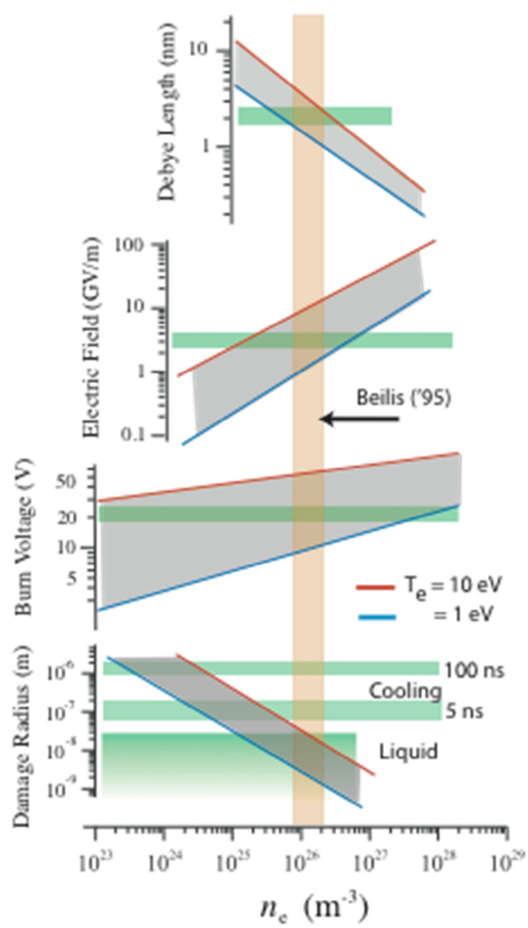

Figure 2: the dependence of experimental parameters on the density of the unipolar arc. More details are presented in Refs. [1] and [2].

If we assume that the plasma density rises until field emission currents short out the sheath, this process 1) sets a limit on the maximum plasma density, 2) determines the dimensions of the unipolar arc, and 3) seems to be compatible with unstable modes (oscillations) in plasma properties. The model can predict plasma dimensions, oscillation frequencies, thermal behavior, burn voltages, shorting currents, time evolution, frequency dependence and the nature of the surface damage produced. All these phenomena are consistent with experimental data [1-2].

Beam Deflection

The immediate results of a breakdown event in an accelerating cavity is a deflection of the beam by the shorting current and the loss of acceleration in the parts of the cavity that are no longer powered. This model assumes that shorting currents, flowing from unipolar arcs functioning as virtual cathodes, on consecutive irises will steer the beam by an angle $\theta = Bl/B\rho$, where θ is the bend angle, B is the magnetic field, l is the cell length and $B\rho$ is the rigidity of the beam. The magnetic field B can be calculated in a straightforward way from the shorting current, however it is unclear if the shorting current is operates on one or both phases of the rf, and how the time structure of the current depends on the electric field, so measurements are useful.

Surface Damage

During the liquid cooling phase, surface tension would smooth the surface, and the relation between the cooling time and the scale of surface irregularities seen in SEM images can be estimated from the dispersion relation,

$$\omega^2 = \sigma |k|^3 / \rho$$

where ω, σ and ρ are the frequency, surface tension constant and density of the liquid metal, and k is the wave number. This smoothing flattens the surface on the scale of microns and eliminates a class of possible field enhancement sites. In accelerator cavities, arcs last for on the order of 100 ns, which is not long enough to heat up the bulk copper, so thin heated surface volumes sit on essentially cold heat sinks and thermal contraction is approximately 2 % of the dimensions of the melted area. We calculate that the typical cooling time constants are in the range of a few hundred ns for accelerator cavities and the structures seen in SEM images of rf cavity damage have radial dimensions on the order of a few microns, see Fig 3. These cooling times are consistent with estimates in Ref [1]. The two stage cooling process seems to result in SEM surfaces that are somewhat smooth at the 1 micron level, but contain cracks with sharp edges at the 1 - 10 nm level that cover 2 % of any large solidified area of copper.

Frequency Scaling, Cooling and βs

Experimental data shows that 805 MHz rf cavities breakdown when the maximum local surface fields reach 10 GV/m, the same breakdown field assumed by Lord Kelvin to explain experimental results in 1904 [7]. We argue that there is minimal frequency scaling if the local field is the primary variable. Different geometries, power sources, frequencies and materials do, however, produce cavities with different maximum surface fields. This can be explained from differences in cooling and field enhancement factors, β. Assuming the plasma properties are similar, size and time history can produce quite different damage. Tiny hot spots cool rapidly and large surface areas will cool more slowly. Above the melting point surface tension will reduce surface fine structure, and below the melting point, some annealing may also produce significant smoothing,

We have produced estimates of cooling profiles dut to thermal diffusion for a variety of geometries using COMSOL [8], to show how the cooling depends on the nature of the arc parameters. We find three classes of heated surfaces that can be numerically evaluated: 1) tiny (~ micron) melted areas that cool very quickly, 2) large, more or less homogeneous areas with dimensions on the order of a few mm and, 3) intermediate sized regions (10 μm – mm), which are the dimensions seen in 805 MHz cavity damage.

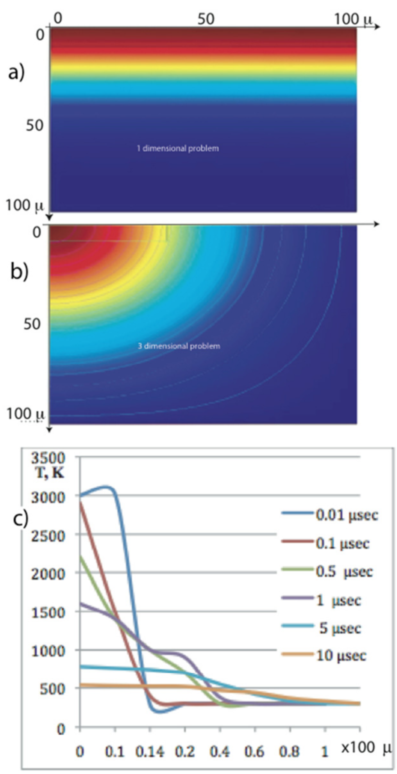

Figure 3: Extreme geometries modeled in COMSOL [8], a) planar, b)point, with c) the cooling profiles produced the case a).

COMPARISON WITH OTHER WORK

The field of vacuum breakdown is quite old, and ideas and methods have been around for a long time. We believe the model we are describing is conceptually simple and the range of applicability is large. We find, however, that this model and the conventional wisdom, do not always agree. We also question models that claim to predict frequency or magnetic field dependence without making any assumptions on the nature of the breakdown process or the damage it produces.

The conventional wisdom of breakdown is that structures producing field enhancements should look like polished fenceposts with hemispherical caps, their properties can be evaluated using a Fowler-Nordheim plot, breakdown is caused by high densities of Joule heating caused by field emission current densities, and these Joule heating events continue during the burn phase of the arc in the form of micro-explosions. While we do not specifically argue against these ideas, we find that more prosaic mechanisms alternatives seem to fit the existing data more easily. Fencepost geometries for field emitters are not seen in SEM images of arc damage, but surfaces are covered with submicron cracks. The efficiency of Joule heating depends very strongly on the geometry and the dimensions of suspected field emitters, and implies that Joule heating must be much less than heat loss to the copper bulk, making significant temperatures very hard to achieve in very small structures. Likewise, if the Debye length of the plasma sheath is on the order of a few nm, it seems hard to understand how localized current densities could produce micro-explosions phenomena due to Joule heating, and, if they could short the sheath, how these current densities could exist at all.

CONCLUSIONS

We have outlined the general principles and some details of our model of breakdown and gradient limits. We feel that this model provides a simpler and yet more general model of breakdown than other alternatives and we are continuing to develop details relevant to other applications. This model seems compatible with a wide variety of experimental data, but disagrees with some conventional wisdom.

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