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Can surface cracks and unipolar arcs explain breakdown and gradient limits?

Zeke Insepov and Jim Norem[a)]
Argonne National Laboratory, Argonne, Illinois 60439

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The authors argue that the physics of unipolar arcs and surface cracks can help understand rf breakdown and vacuum arc data. They outline a model of the basic mechanisms involved in breakdown and explore how the physics of unipolar arcs and cracks can simplify the picture of breakdown and gradient limits in accelerators, tokamaks as well as laser ablation, micrometeorites, and other applications. Cracks are commonly seen in SEM images of arc damage and they are produced as the liquid metal cools. They can produce the required field enhancements to explain field emission data and can produce mechanical failure of the surface that would trigger breakdown events. Unipolar arcs can produce currents sufficient to short out rf structures, and can cause the sort of damage seen in SEM images. They should be unstable, and possibly self-quenching, as seen in optical fluctuations and surface damage. The authors describe some details and consider the predictions of this simple model. © *2013 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4766929]

I. INTRODUCTION

While arcing and gradient limits are significant constraints on many aspects of modern technology, and the problem has been extensively studied, there is no simple picture of this process in common use. Questions like What triggers breakdown? How do arcs work? What do breakdown sites look like? What parameters and mechanisms determine gradient limits? seem to have no simple answers. We believe there is a need to develop a "simple" picture of this process that can be used to guide work in this field. The situation is somewhat complicated because the field is so wide and some of the "conventional wisdom" on this subject may have limited applicability.

In this paper, we explore how well arcing can be explained by the properties of surface cracks and unipolar arcs. The question of explaining breakdown, arcing and gradient limits presents a unique problem, since there are over 100 years of reliable published data on an enormous variety of phenomena that seem related, but no simple explanation has been adopted that can easily be applied to clarify or predict the overall physics.[1–9] While it is always possible to introduce mechanisms that can be narrowly applied to specific results, these may not be useful to explain or predict a more general class of data. We find that unipolar arc physics, combined with surface cracking, can explain a significant fraction of the data; however, these ideas are not mentioned in most of the literature on arcing. Although most of our examples are from rf breakdown, specifically the operation of fully conditioned systems where there is an equilibrium between electromagnetic gradient limits and surface damage, the conclusions should have wider applicability. The ultimate test of a model is whether the mechanisms are simple, complete, and general enough to be useful. This paper is an outline of these mechanisms.

Our picture of arcs is summarized in Fig. 1.[9,10] We argue that two processes seem to control arcing: (1) the formation and fracture of cracks and small structures and (2) the evolution and properties of unipolar arcs. Theoretically, we divide the arcing process itself into four elements as shown in Fig. 1(b): (1) mechanical failure of the surface, producing fragments, (2) initial ionization of these fragments by field emission (FE) currents, (3) evolution of the plasma, controlled by the plasma sheath and material properties, seems to involve exponential density growth of the unipolar arc to some equilibrium state, and (4) surface damage produced by the arc. The unipolar arcs act as virtual cathodes and produce currents that short the rf cavity or other high gradient structure.

The study of arcing phenomena has been complicated by the speed and unpredictability of the arcs, as well as the large dynamic range of the experimental parameters and the numerical complications involved in simulations, where the densities involved seem to exceed the applicability of the particle-in-cell (PIC) codes used for most plasma calculations. The difficulties involved in accurately modeling plasma/surface interactions for very dense plasmas have also been a significant limitation on modeling.[9]

Numerical modeling of the initiation of the arc using a PIC has been described in a number of papers.[9,10] Once an arc starts, the surface electric field and field emission increase, increasing ionization of neutrals, causing an increase in the plasma density. This density increase decreases the Debye length and causes an increase in the surface electric field, ultimately producing an exponential increase in both the electric field and density, with time. PIC simulations of the plasma evolution during rf cavity breakdown show that the density of plasma formed above the field emitting asperities can be as high as $10^{26}\,m^{-3}$, although the temperature of such plasma is low, in the range of 1–10 eV.

While we find that the basic mechanisms can be described simply and some results can be evaluated easily, obtaining more precise results using numerical modeling can be complicated by the multidisciplinary nature of the problems and

[a)]Electronic mail: norem@anl.gov

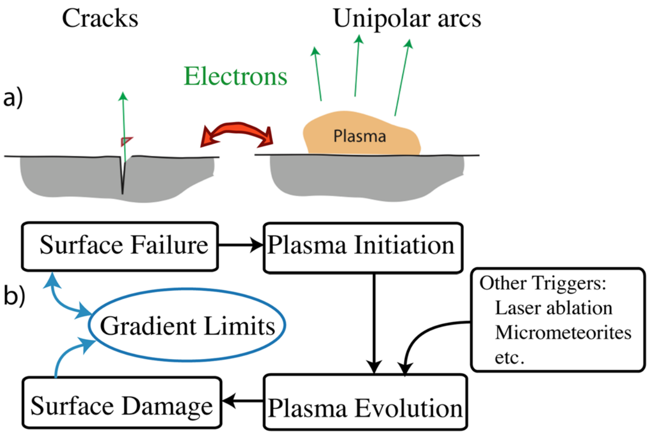

FIG. 1. (Color online) Arc process is controlled by fracture of high field areas at crack junctions and the evolution of the unipolar arc driven by sheath parameters. (a) sketches the cracks and unipolar arcs and (b) shows the general mechanisms we describe. Surface failure, plasma initiation, plasma evolution, and surface damage mechanisms can explain and predict details of arcing behavior, as described in the text.

is often not simple. We will describe some of the basic mechanisms, simple results, and more difficult calculations. We show how these arguments apply to questions about field emission, breakdown, nonideal plasmas, plasma instabilities and quenching, arc suppression, gradient limits, frequency dependence, magnetic field effects, etc.

II. ELEMENTS

Since the literature on both surface cracking and unipolar arcs in this context is somewhat limited, we briefly review the relevant physics of these phenomena as shown in Fig. 1(b). Surface failure due to Maxwell stresses has been modeled by means of molecular dynamics (MD)[11] and the plasma initiation stage and later plasma evolution by means of a PIC code.[9] The validity of the results of the PIC code is limited in the case of high density, nonideal plasmas, but calculations of nonideal sheath plasmas have been done with MD codes.[25] We assume the limiting gradient for any system will be determined by a combination of surface damage, which determines the local field enhancements, and the surface failure mechanism. Other mechanisms can produce dense plasmas on surfaces, and we also consider these cases.

A. Surface failure

It has been known for some time that breakdown occurs at local fields near $E_{local} = 10\,\mathrm{GV/m}$,[2,3] where

$$E_{local} = \beta E_{average},$$

and the enhancement factor β multiplies the average surface field $E_{surface}$. These local fields would cause pulsed mechanical stresses on the order of

$$\sigma = \epsilon_0 E^2/2 = 4.4 \times 10^8\,\mathrm{MPa},$$

where ϵ_0 and E are the permittivity factor and the electric field, respectively. These values are higher than the tensile strength of copper, and the surfaces would be subject to fatigue, accompanied by high field emission current densities, and perhaps local heating. Mechanical failure would be expected under these conditions; however, electrostatic fracture, Ohmic heating, electromigration, fatigue, and creep can all explain the mechanical failures that could trigger breakdown. The breakdown rate is proportional to $\sim E^{30}$ seen in some experiments,[12] but both Ohmic heating and electromigration are proportional to the current density squared, since field emission produces current densities in the range $j \sim E^{14}$. Electrostatic fracture is similar to field evaporation, which is governed by processes that produce field scaling from $rate \sim E^{30-150}$; thus all mechanisms seem compatible with the data, although the effects of creep and fatigue are not well understood. A more difficult problem is to describe a mechanism that is compatible with the damage seen in SEM images.

Although we favor the model of electrical stress and fatigue as a trigger for breakdown, we find that the breakdown mechanism itself is less interesting than a description of the environments that are highly stressed in many different parameters. It is important to understand nature of asperities and their geometry to understand if it is possible to suppress breakdown.

B. Plasma initiation

We have described how arc evolution can take place in rf structures and other environments using PIC codes, see Fig. 2.[9] Recent work has shown that the initiation of the arc can be explained by two mechanisms: (a) mechanical failure of the solid surface due to Coulomb explosions caused by high surface fields and (b) the development of unipolar arcs[13] that can act as virtual cathodes and produce currents that can short the driving potential. Once a plasma exists, the surface electric field and field emission increase, increasing

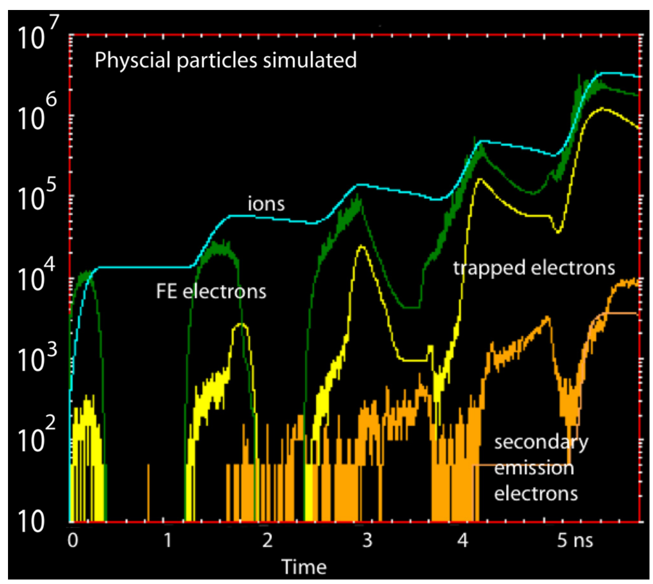

FIG. 2. (Color online) PIC code modeling of the initial 5 ns of a breakdown event in an 805 MHz rf cavity, showing the contributions of field emission, ionization, trapped electrons, and secondary electrons (Ref. 9).

ionization of neutrals, causing an increase in the plasma density. The ion density is maintained and increased by self-sputtering, which becomes more effective at high surface fields and temperatures.[9] The density increase decreases the Debye length and causes an increase in the surface electric field, thus both the electric field and the density increase exponentially with time, shown in Fig. 2, and the arrow in Fig. 2.[9] PIC simulations of the unipolar arc model for vacuum arcs relevant to rf cavity breakdown show that the density of plasma produced above the field emitting asperities can be about $10^{26}\,\mathrm{m}^{-3}$. According to PIC code results, the temperature of such plasma should be low, in the range of 1–10 eV. In the absence of electric fields, a dense plasma can be created on the surface, by micrometeorites or laser ablation, for example, and the further evolution of this plasma should be expected to be similar to that of an rf plasma.

C. Plasma evolution

Unipolar arcs were first described by Robson and Thonemann in 1959 as an explanation for the existence of isolated cathode spots on metal surfaces immersed in the plasma of a gas discharge.[13] Unipolar arc phenomena received extensive study and analysis in the 1970s and 1980s as the primary mechanism that determined the impurity content of limiter tokamaks. Schwirzke described both experimental and theoretical work with these arcs.[14] As more tokamaks were built with divertors, this mechanism seemed to become less relevant, although that may be changing as the physics of the international thermonuclear experimental reactor tokamak is better understood.[15] The most recent and thorough study of unipolar arcs is being done by Kajita, who uses laser ablation to produce a plasma on a metallic surface that starts the unipolar arc phenomenon.[16]

The evolution of the plasma is controlled by the plasma sheath parameters and the surface, which we assume will initially be solid, but eventually liquid. Heat is transferred to the plasma primarily by electrons falling through the sheath, and the surface is heated by the ion current hitting the wall. Sputtering, from singly and multiply charged ions, will be a source of ions for the plasma.[17]

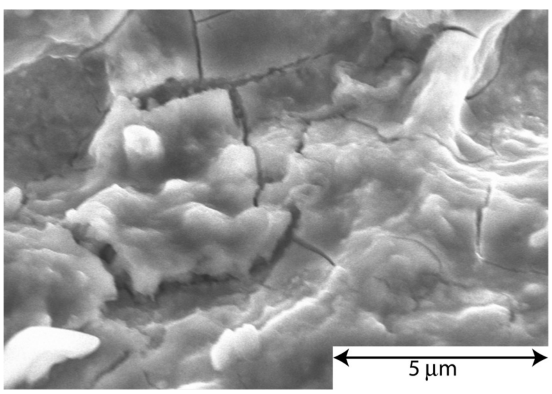

FIG. 3. SEM image of the center of an arc damage crater. The image shows both cracks, with many crack junctions and smooth structures characteristic of a chaotic surface smoothed over by surface tension. There is a wide variety of structures seen in arc damage, and this image is selected to show both cracks and evidence of turbulent structures that have been smoothed by surface tension. This image should not be considered typical.

Unipolar arcs can then travel freely on the surface or be guided by a magnetic field in the characteristic retrograde motion that has been identified in many experiments. The high plasma densities are associated with a large plasma pressure which should be responsible for particulate production. The interface between the plasma and the liquid surface is affected by high electric fields, high plasma pressures, and high surface tension forces, on the order of 100 MPa, and these pressures could produce a turbulent surface in a dense arc, where the scale of the turbulence is a function of the plasma and electrostatic pressures. Some of the parameters of the unipolar arc plasma can be experimentally estimated from the dimensions of the damage produced and measurements from SEM images imply the density is very high.

D. Surface damage

Many types of surface damage are seen in SEM images of arc damage, see Fig. 3. These images show that the surface has been melted and subjected to high local pressures. The melted surface is affected by strong plasma pressures, p_p, that push ($p_p = nKT$ where n is the plasma density, K is the Boltzmann constant, and T is the plasma temperature), electric fields that pull ($p_E = -\epsilon_0 E^2/2$), and surface tension, ($p_s = \gamma/r$, where γ and r are the surface tension constant and local radius), which tries to flatten the surface. While most of the damage is confined to areas that were underneath the arc, arcs generate particulates that can travel distances on the order of meters. These particulates are produced when the plasma pressure splatters liquid droplets away from the arc and they seem to have a role in diffusing arcing sites around a surface.[4] Particulates are difficult to quantify; however, we intend to first address the effects of cracks, which can be more precisely measured.

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 T is the temperature, x represents the dimensions of the damage, and α is the coefficient of linear expansion.

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.[18,19] This smoothing flattens the surface on the scale of micrometers 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 must 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 nanoseconds 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. 4. These cooling times are consistent with estimates in Ref. 8. The two stage cooling process seems to result in SEM surfaces that are somewhat smooth at the 1 μm level but contain cracks with sharp edges at the 1–10 nm level that cover $\sim$2% of any large solidified area of copper.

III. DETAILS

There are many details of this model that help to understand and predict experimental data.

A. Field emission

The process of vacuum breakdown was identified by students of Michaelson and Millikan almost 110 years ago and field emission was of the first mechanisms to be described using quantum mechanics by Fowler and Nordheim in the 1920s.

It is not clear if field emission currents are directly involved in breakdown; however, breakdown should occur where the electric field is high, and these sites will produce field emission currents, so field emission helps to describe the geometry of breakdown sites. Field emission currents are proportional to the applied electric field raised to a high power, $i \sim E^n$, with n around 14 at high surface fields.[1,20,21] We find that the standard method of analysis using Fowler–Nordheim (FN) plots to estimate the field enhancement factor can be unnecessarily abstract and yields a number (the enhancement factor β) that has little fundamental importance. We prefer to plot both the experimental data (currents, radiation levels, etc.) against electric field on a log–log plot along with the FN predictions, although the space charge limit and other experimental parameters can also be displayed see Fig. 5. Using this method, the two lines are offset by factors that can measure the total emitter area, duty cycle, enhancement factor, and corrections due to the cavity geometry. Because field emission currents depend on the electric field raised to a very high power, and enhancement factors are somewhat difficult to measure experimentally, few measurements of the area of field emitters are in the literature.

Following an early work by Dyke and Trolan showing that Ohmic heating of tungsten needles could produce breakdown, combined with considerable evidence that the required field enhancements and current densities could be produced with cylindrical asperities with rounded ends, Ohmic heating was widely accepted as an explanation for breakdown, although asperities of the expected dimensions were not found.[22,23] We have shown that cracks, more specifically crack junctions, can provide the required field enhancements and emitter areas (when many of them are added together) to explain field emission data.

Field emission measurements in rf cavities and high gradient structures have been made and reported in a number of references.[21] These measurements assume that the number of emitters is known and understood; however, measurements of emitter numbers and areas are never precise, because the $I \sim E^{14}$ behavior of field emission produces large uncertainties in the measured current density. A large number of much smaller, localized emitters at crack junctions can contribute as one emitter, see Figs. 3 and 5.

B. Enhancement factors

Although the most common model of surface field enhancements are cylinders with hemispherical ends (whiskers,

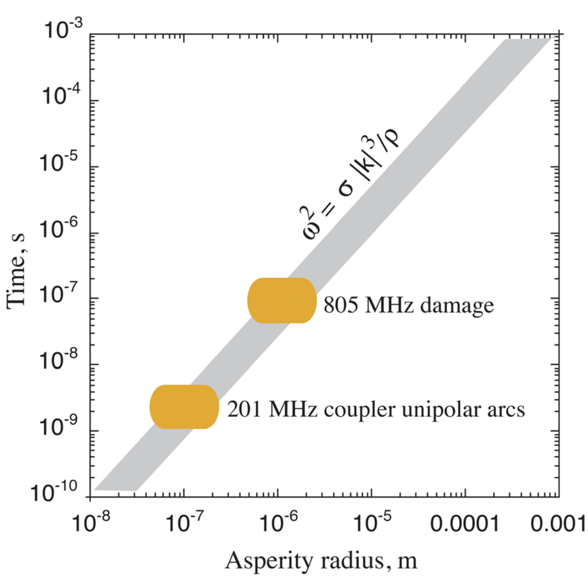

FIG. 4. (Color online) Relation between the cooling time and structure radius for liquid metals compared with data from 805 MHz cavity arcs and estimates of cooling times of unipolar arcs in coaxial lines.

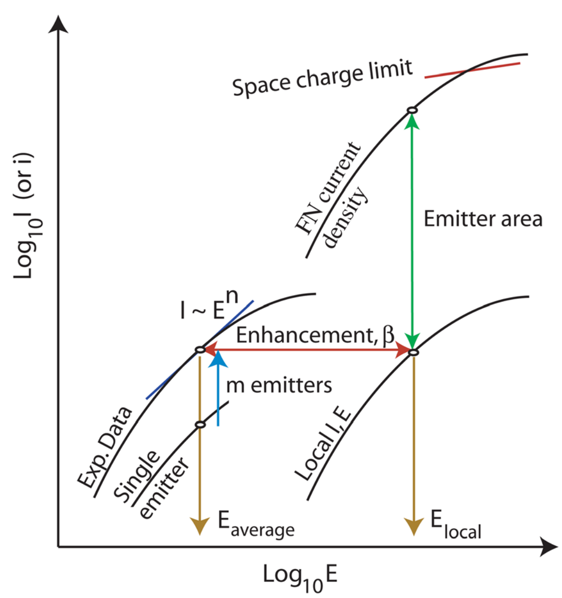

FIG. 5. (Color online) Field emission can be plotted to display the variables associated with its measurement. The horizontal and vertical offset of the data and theory curves are essentially the enhancement factor and emitter area but the effects of thermal emission, different work functions, duty cycle, structure geometry, etc., as well as systematic and statistical errors in measurement can also be displayed graphically. We also show how m small emitters could combine to produce larger currents, not to scale (Ref. 21).

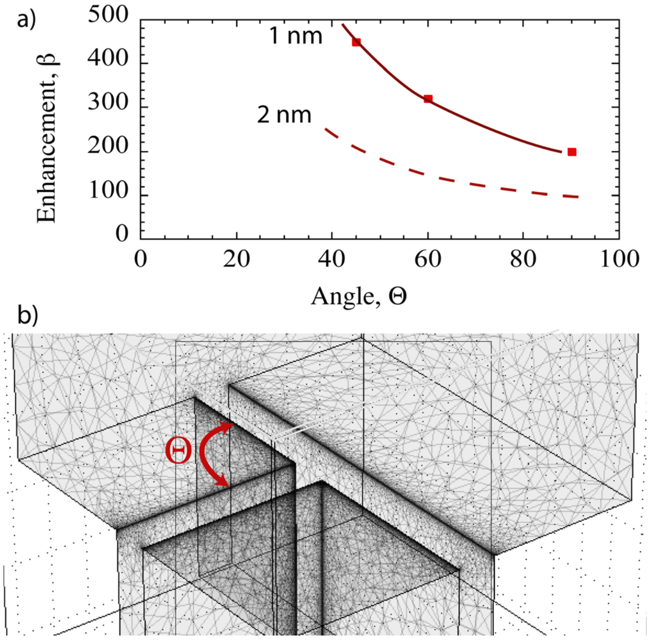

FIG. 6. (Color online) Crack junctions produce high field enhancements. These calculations, produced with COMSOL, show field enhancements as a function of crack junction angle for cracks on the order of 0.1 μm width, assuming a corner radius of 1 nm. (a) shows the results of the calculation, and (b) shows the mesh used for the 100 nm crack widths. Crack junctions are electrostatically equivalent to conical asperities on the surface, with enhancement factors that depend on crack width and the radius of the tip.

fenceposts, etc.) these objects are not seen in SEM images of arc damage. While that geometry is comparatively easy to evaluate numerically, the relevance may be limited.

If, following Feynman, we describe the surface field of a conductor as a function of the local curvature of the surface, comparing the fields at any two points a and b will give the relation $E_a/E_b = r_b/r_a$, where r is the three dimensional radius.[24] Small radii give high fields. We find these small radii at crack junctions, where the radii are too small to be resolved by SEM optics. Numerical analysis has shown that these crack junctions can produce enhancement factors in the range of $\beta \sim 200$, depending on the local radii at the tip of the crack junction and the angle at which the cracks intersect, see Fig. 6. The crack junctions produce field enhancements similar to those of conical asperities, if the radii of the tips are comparable and the width of the cracks is much larger than the tip radius.

In another example of field enhancements, one can describe the sheath potential of a tenuous plasma as an enhancement of an applied field that would add the field in the sheath to the externally applied field. As the plasma density increases, this picture becomes less appropriate.

C. Parameters of nonideal plasmas

Simulations with PIC codes have shown that field emission, significant sheath potentials, high densities of neutrals, along with self-sputtering can produce an environment where the density rises essentially exponentially while the electron and ion temperatures remain relatively low.[9,10] This increasing density is associated with a decreasing Debye length

$$\lambda_D = \sqrt{\epsilon_0 k_B T / n_e e^2},$$

so the number of particles in the Debye sphere eventually becomes less than one and the nonlinearity parameter, Θ_n, which measures the ratio of the electrostatic potential energy divided by the kinetic energy of the plasma, becomes large.[25]

Recent numerical analysis of high density, nonideal plasma sheaths has shown that for high density plasmas the properties of the plasma can be estimated using molecular dynamics. The corrections to simple estimates of sheath potential, Debye length, and surface electric field required by the nonideality condition due to the high densities involved are not large. Plasma densities were estimated from the scale of damage, where turbulence of produced by the plasma pressure is balanced against the smoothing produced by the surface tension. Since it is difficult to know the cooling time with much precision, these measurements function as an upper limit on the scale of turbulence and a lower limit on the plasma density. This procedure produces estimates of the surface plasma density $n \sim 10^{25}\,\mathrm{m}^{-3}$, surface electric fields $E \sim 2 \times 10^9\,\mathrm{GV/m}$, for electron temperatures of $10\,\mathrm{eV}$.[25]

Although the detailed plasma parameters of unipolar arcs have not been studied experimentally, we assume that the high density plasma sheath parameters described in Ref. 25 describe the plasma/surface environment in a unipolar arc and would determine the evolution of the arc itself. These issues are discussed further in Sec. V.

D. Space charge oscillations

PIC codes have shown that when field emitters can ionize dense gas near the surface, a positively charged plasma is produced, and the sheath potential of the plasma that is created increases the field on the field emitters until they become space charge limited.

The space charge limit for continuous currents between two plates is expressed using the Child-Langmuir law

$$I = \frac{4\epsilon_0}{9}\sqrt{2e/m_e}\frac{SV^{3/2}}{d^2},$$

where I is the anode current, and S the anode surface inner area.[26] While the Child-Langmuir law applies to thermionic emission, the application of this idea to field emission is not entirely straightforward. Thermionic emission of electrons is essentially constant, with fluctuations governed by variations in the temperature of the emitter. With field emission, however, the current density is proportional to the electric field to some high power ($i \sim E^{14}$); thus, fluctuations in the electric field will instantly alter the emitted current density, and fluctuations in the density of emitted electrons will immediately alter the electric field. These processes can produce fluctuations.

PIC code results show that the space charge limited current is not continuous on a microscopic scale. Electrons are emitted from the surface in bunches; they move a few microns away from the cathode where they produce a negatively charged

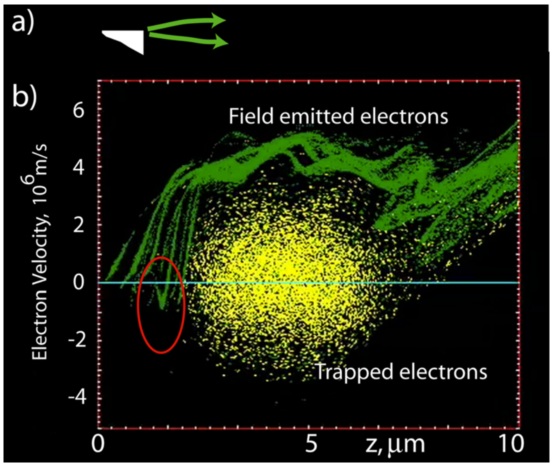

FIG. 7. (Color online) Phase space plots of the velocity of field emitted and trapped electrons against distance from the surface. Space charge causes electrons to collect near the field emitter, and return to the surface (oval). (a) Gives the geometry of the emitter, showing electrons emitted from an edge, and (b) shows the electron motion away from and toward the source, see Refs. 9 and 27.

electron cloud that erodes due to electrons moving both toward and away from the cathode, see Fig. 7. This repetitive behavior produces an oscillation in the field emitted current at a frequency of about 1 THz.[27] We are not aware of experimental observation of this phenomenon.

E. Plasma fluctuations and quenching

Vacuum arcs can be unstable. Fluctuations in the optical emission of arcs have been recorded in streak camera experiments and one of the defining properties of unipolar arcs is their random, discontinuous, trail of surface damage.[6,16] Optical fluctuations occur at frequencies up to a few hundred MHz. We describe the fluctuations seen in unipolar arcs as a similar mechanism to the fluctuations in the space charge limited field emission described above in Sec. III A. Short term fluctuations in the electric field will cause much larger variations in the field emitted current, and these field emitted currents, $i_s = \epsilon_0 E/\Delta t$, can be sufficiently large to short out the sheath in a time Δt.

Although over long time scales the plasma should maintain quasineutrality, the mechanisms controlling the electron and ion densities are quite different and have different timescales. Since the field emitted current density will be proportional to the surface electric field, $i_{FE} \sim E^{16}$, the field emission current will respond instantly and nonlinearly to changes in the surface field, and the electrons can be rapidly thermalized in a dense plasma.

We assume that the fundamental ion density increase is governed by self-sustained self-sputtering

$$\alpha\beta\gamma > 1,$$

where α is the probability that a sputtered cathode atom becomes ionized, β is the probability that the ionized atom returns to the cathode, and γ is the sputtering yield.[4,9] The ion density, n_i, should respond slowly, since the time constant for density changes would depend on collisional diffusion[28] in the arc

$$\partial n_i/\partial t = D\,\nabla^2 n_i,$$

which is a function of the density, n_i, since the diffusion constant is inversely proportional to the plasma density

$$D = v_{th}/3\nu \sim 1/n_i.$$

As the arc evolves and the density increases, the large, dense arcs should become more stable to ion density fluctuations, with time constants proportional to, $\tau_i \sim n_i$, the time constant for field emission, however, should not change and the electron thermalization time should become shorter as the density increases like, $\tau_e \sim 1/n_i$. This difference between the ion and electron density stability could complicate the ability of the plasma to maintain quasineutrality under rapid high current field emission.

As the arc evolves, surface fields created by the sheath potential become large enough to produce field emission currents that can short out the sheath potential and locally quench the arc before quasineutrality can be established. As shown in Ref. 25, the required current would be $\sim 30\,\mathrm{MA/m^2}$, which could be produced by a field of $\sim 3\,\mathrm{GV/m}$ for times, $\Delta t = 1$ ns, which is compatible with simulations produced by both PIC and MD codes. The remaining dense plasma is then either able to restart the arc nearby, or, after a time required to equilibrate the locally dense plasma, restart in the same location. These densities are compatible with data taken with 805 MHz rf structures, which have arc damage diameter of 0.5 mm and shorting currents on the order of 10 A. This argument seems to preclude surface current densities larger than $30\,\mathrm{MA/m^2}$ and plasma/surface fields significantly larger than roughly 3 GV/m, although the exact field is somewhat dependent on the surface work function.

The comparatively low current density of $30\,\mathrm{MA/m^2}$ is not large enough to produce significant Ohmic heating of the surface. This seems to conflict with the current densities required by the ecton model of Mesyats.[7] In that model, current densities of $\sim 10^{13}\,\mathrm{A/m^2}$ are required to produce a local Ohmic heating explosion of the liquid metal that maintains the arc.

F. Burn voltages

The burn voltage of an arc is primarily due to the sheath potential[4] with some corrections due to ballistic motion of electrons and small anode effects. Since the arcs are so dense, calculations of these sheath potentials seem to require more precise modeling methods than those available from PIC codes; however, the recent estimates produced by Morozov *et al.*[25] show that simple estimates of sheath potentials do provide reasonable rough estimates. We believe that the burn voltages may be one of the best ways of addressing the arcing properties of different materials.

G. Frequency dependence of gradient limits

The maximum operating gradient of a given rf or direct current (DC) system could operate should be a function of two variables: (1) the maximum local field at which the surface would fail due to tensile stresses, heating, electromigration, fatigue, or some other effect and (2) the overall design of the system itself, which determines the stored energy deposited through the arc, the way power is applied, discharge length, the way the power to the arc is turned off (suddenly or slowly) which all seem capable of affecting the surface damage, and ultimately the field enhancements seen by the surface.[29]

A large body of data showed very early that DC breakdown occurred when local fields reached 7–10 GV/m over many orders of magnitude variations in the gap length.[3] Although there are not many rf measurements, data also show that this threshold also seems to apply to systems around 1 GHz.[21] These results imply that there is no frequency dependence to high gradient breakdown as a function of the local electric field, E_{local}. On the other hand, there is an extensive literature that show that higher frequencies achieve higher gradients.

One problem with many models is why the threshold for breakdown is so tightly constrained from pulse to pulse, in spite of the fact that the breakdown process must start at a variety of sites. There seems to be very little randomness in breakdown sites as one might expect from chaotic processes. Since breakdown triggers seem to be a function of $E_{local} = \beta E_{average}$, this seems to imply that both the local fracture mechanism and the range of βs produced by the structure are remarkably independent of position and history. The model presented here would explain the narrow range of enhancement factors on the insensitivity of beta to fluctuations in the angles at crack junctions (see Fig. 6, where $d\beta/d\Theta = 0$ at $\Theta = 90°$) and the uniformity of the cracks themselves. A variety of experiments have shown that the dependence of breakdown thresholds on the local field is quite narrow.[3]

While estimates of field enhancement factors and structure geometry can give approximate breakdown parameters, detailed knowledge of scaling laws may be a more difficult problem. If the frequency dependence of gradient limits is due to the surface damage and the exact parameters are determined by the way this damage cools, the problem of generating scaling limits is difficult. The dimensions of arcs are primarily determined by quenching due to field emission, and their dimensions and cooling parameters can be nonintuitive. Some calculations, which one might expect to be fairly straightforward, turn out to be very difficult. For example, shorting currents can extract more energy from longer cavities because the energy of the electrons are higher, thus, to remove the same energy, more current is required. If the current surface density is the limiting constraint, than the arc size must change, the heating and cooling of the arc would be different and these would change the surface damage and presumably the maximum gradient. For example, arcs at 11 GHz can be 100 times the area of 1 GHz arcs, depending on cavity and power supply parameters.[30] Modeling thus becomes more difficult and less precise.

H. Magnetic fields

It has been shown that under some conditions, the maximum rf electric field that can be maintained in the presence of an externally applied electric field is reduced from that seen without the external magnetic field.[31]

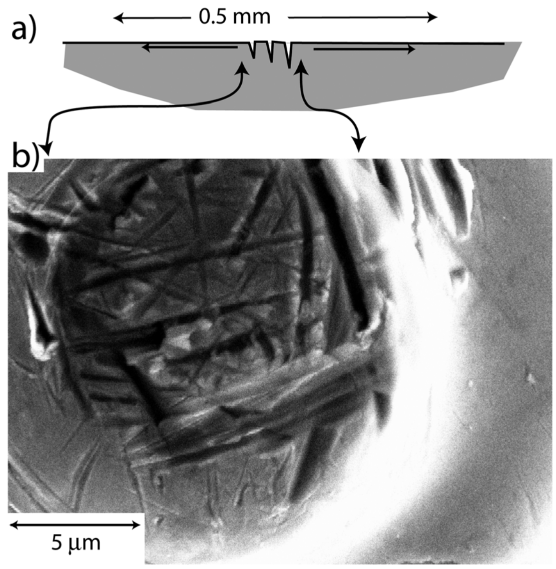

FIG. 8. Surface damage in cavities exposed to 3 T magnetic fields: (a) possible cooling mode, (b) cracking at the center of the melted area. As the 500 μm diameter molten surface freezes from the outside, thermal contraction is concentrated at the center.

The beam optics of field emitted beams in magnetic fields have been studied experimentally. The beams were actually found to be hollow, with a radius that was directly proportional to the applied electric field and inversely proportional to the square of the static magnetic field. This is consistent with a picture of field emission from a foil-less diode, where the electric and magnetic fields were not parallel.[21] At high fields, the shorting currents are tightly confined enough to melt the opposing surface. It is reasonable to expect, though not experimentally verified, that symmetric pairs of unipolar arcs triggered by shorting currents could develop at high fields, on two surfaces that faced each other.

SEM images of arc damage in copper with a magnetic field shows that surface cracking is confined to a very small area (10–20) μm in diameter surrounded by a much larger area that shows signs of being melted, see Fig. 8. We assume that the radial growth of the arcs was confined by the magnetic field, and when the arcs cooled, they cooled from the outside in, leaving the last metal to solidify to absorb all the thermal contraction. These central damaged areas have a much higher crack density that we associate with the lower electric fields that could be maintained on the surface.

The problem of current induced $\mathbf{J} \times \mathbf{B}$ forces has been discussed in Ref. 31. Large forces causing material to circulate around the axis of the arc can exist during the arc itself, but these forces should disperse once the shorting current disappears. It is not clear how these forces would affect the surface damage mechanisms that operate during the cooling of the surface.

I. Other environments

Although we consider vacuum arcing primarily in the context of rf linacs, it is useful to see how widely these arguments apply to other environments, such as tokamak rf antennas and first walls,[15] laser ablation,[16] micrometeorite impacts,[32,33] and possibly such examples as electron beam welding. SEM images of arc damage in laser ablation, tokamak first walls, and micrometeorite impacts seem qualitatively similar, but published images may tend to be selected as much for artistic as scientific merit, and this comparison should be done carefully.

The study of unipolar arcs is not an active field. Although vacuum arcing phenomena are seen in many environments, there is little contact and little coordination between different approaches used in these fields. The lack of a model or a common approach to understanding the basic mechanisms at work in unipolar arcs has further slowed progress.

IV. USEFUL EXPERIMENTS

There have been 110 years of experimentation on vacuum arcs, most of them guided, to some extent, by modeling and theory, nevertheless there is still disagreement about the nature of these arcs and the mechanisms that drive them. We believe the reason for this situation is that the arcs are small and unpredictable, and many parameters (which are individually hard to measure) evolve very rapidly over a many orders of magnitude. While models exist, theory and modeling are complicated by the large number of mechanisms that seem to be involved in arc evolution and high density plasmas that require a complicated, non-Debye analysis of even basic properties.

There are a number experimental directions that could prove promising. Space charge oscillations have not been seen as far as the authors are aware, although they would be somewhat difficult to detect because of the high frequency involved. Likewise, quenches of unipolar arcs have never been studied in any detail, as it is difficult to access the surface underneath the plasma. It would be useful to have more systematic data on the damage mechanism in normal arcs. While this field has produced considerable data, the problem is that little of it was systematically selected and documented. Likewise, it would be interesting to operate arcs close to the melting point of the metal to see if a crack-free surface would behave differently from surfaces at room temperature.

V. DISCUSSION

Arcs occur in a wide variety of environments, and parameter ranges. They can discharge huge amounts of stored energy or exist parasitically at the boundaries of tenuous plasma. Under these circumstances, it is reasonable to expect that a wide variety of mechanisms are applicable. The theoretical problem is to determine how much complexity is required in a general explanation of these phenomena. Since arc behavior seems to some extent to be independent of the vacuum gap involved, we have tried to apply the physics of dense unipolar arcs, and as the most easily quantified form of damage, we also addressed cracks and crack junctions.

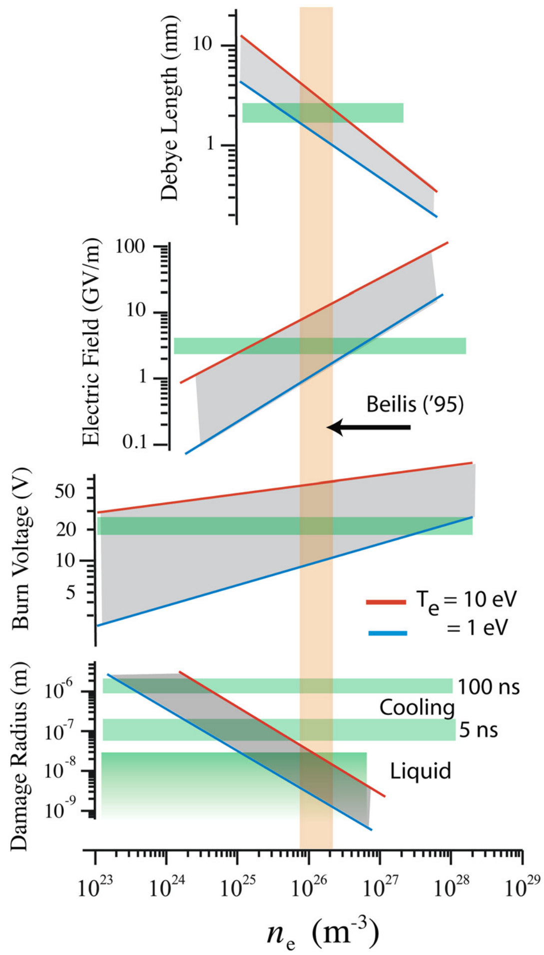

FIG. 9. (Color online) Dependence of Debye length, surface electric field, burn voltage (sheath potential), and scale length of damage on the plasma density and plasma electron temperature. There have been a number of estimates of the plasma density, and we plot those of Beilis (Ref. 8). The plot shows a consistent set of parameters, Debye length, surface electric field, burn voltage (sheath potential), damage radius (after cooling times), and plasma density obtained from studies of nonideal plasmas (Ref. 25).

From estimates of density,[25] it is possible to evaluate the most important parameters of a dense plasma/surface environment, see Fig. 9. We find that Debye lengths are very small, plasma pressures are very large, and the scale of structure on the surface of the material is comparable. While it is difficult to draw simple conclusions about the geometry of the liquid surface, once the plasma is removed, surface tension should rapidly begin to smooth the surface on the nanoscale. This cooling should proceed until the surface freezes, and subsequent cooling should produce cracks that will function as further field emission and breakdown sites. Thus, the mechanisms of cracks and unipolar arc parameters are closely related.

Qualitatively these two mechanisms can provide a clear picture of how breakdown can occur at the microscopic level, the parameters of arc, the sheath and edge plasma parameters, and the expected types and level of damage. Further studies of field emission in the dense plasma surface environment predict space charge current oscillations as well as plasma oscillations and quenching that seem to be consistent with experimental data. The problem of arcing seems to require successive iterations of a complete model, where each step considers all aspects of the problem as much as possible, since surface failure, plasma initiation, plasma evolution, and plasma damage all, to some extent affect each other as the system evolves to some equilibrium compatible with external drivers (applied fields, available energy, power levels, etc.). Historically, this has not been the common approach, but it seems possible in the near future.

A. Questioning the conventional wisdom

The conventional wisdom of breakdown is that structures producing field enhancements should look like fenceposts, and 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 "ectons."[7] 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.[9] Likewise, if the Debye length of the plasma sheath is on the order of a few nanometers, it seems hard to understand how localized current densities could produce ecton phenomena such as Joule heating microexplosions, and if they could short the sheath, how these current densities could exist at all.

On the other hand, there are possible incompatibilities of the model presented here with data. Perhaps the most obvious are data showing that current densities above the $30\,\mathrm{MA/m^2}$ can exist.[4] These may constitute an additional class of events or an environment where field emitted beams have "punched through" the arc plasma.

VI. CONCLUSIONS

We have demonstrated that the physics of unipolar arcs and surface cracking seems highly relevant to the phenomenon of arcing. Crack junctions can provide the high field enhancements seen in experimental studies of field emission and breakdown; they are formed naturally as arc damage cools and they are capable of triggering breakdown events when they fracture. Likewise, unipolar arcs are the prototypes of single sided arcs that can function as cathode spots. We find that the physics of these objects, which has not received much specific attention, is relevant to many fields.

Although unipolar arcs have been called ubiquitous, the literature on this phenomenon, both experimental and theoretical, is not extensive. We believe one reason for this is that the dense plasmas and plasma/surface interactions require very specific techniques to cope with the nonideal (non-Debye) plasmas that are not well advanced.

We have shown that cracks are commonly seen in SEM images of arc damage and described how they are produced as the liquid metal cools below the melting point to room temperature. We have shown that cracks can produce the required field enhancements to explain field emission data and can produce fractures that would trigger breakdown events. Although unipolar arcs and the interactions of nonideal plasmas with surfaces are not well understood, we have shown that field emission of electrons produced in the plasma sheath can produce currents sufficient to short out rf structures, and can cause the sort of damage seen in SEM images. These plasmas should be unstable and possibly self-quenching as seen in optical fluctuations and surface damage in a variety of experiments.

Although the internal structure and evolution of arcs and arcing have not evolved to any unanimity in the field, we find that the physics of cracks and unipolar arcs seem highly relevant and perhaps fundamental to these phenomena.

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