MODELING RF BREAKDOWN ARCS*

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Abstract

We describe modelling of an arc plasma using OOPIC, a particle-in-cell (PIC) plasma code and molecular dynamics MD), software to consider the interactions of high fields and high power fluxes of various types on materials. The effort, part of the study of low frequency rf structures for muon cooling, aims to completely describe all aspects of the arc to facilitate the design of experiments and expedite more precise modelling.

INTRODUCTION

Although the process of vacuum breakdown is experimentally accessible at voltages of a hundred volts, even in air, and has been productively studied both theoretically and experimentally for over 100 years, there are still many uncertainties about the trigger, the overall parameters of the rf arc, and practical ways to mitigate the process [1.3]. One problem is that experimental data is sparse, in the sense that different cavities are difficult to compare, and clustered, in the sense that most measurements are made over a very limited range of parameters. All measurements of arcs between copper surfaces, where the local field has been calculated, show the fields on asperities on the order of 8 – 10 GV/m, essentially one third of the field at which copper atoms will be pulled off the surface and the material will essentially dissolve [4].

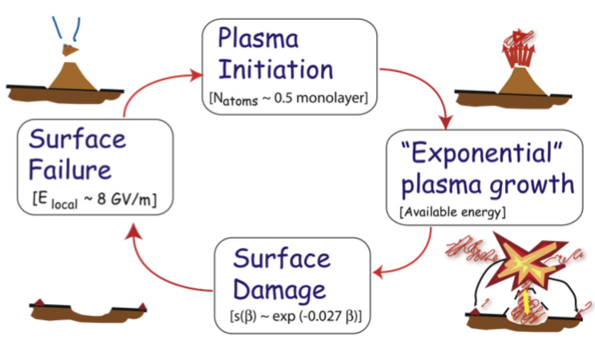

Figure 1: The overall picture of the breakdown cycle.

This paper presents the first iteration of a model of all parts of the breakdown process. We describe the arc in terms of four stages (Fig. 1) each of which can be roughly summarized with a single parameter. We assume that each breakdown event can cause damage that can trigger future events, and the overall gradient limits of any structure are caused by the equilibrium of surface damage and electromagnetic stresses on surface elements. Previous papers have discussed trigger mechanisms and surface damage[5,6].

The overall picture of the breakdown process we model is shown in Fig. 2. A small inertially confined plasma arc, with dimensions of a few microns, is located essentially in contact with the surface on one side, and the plasma functions as a cathode, producing electrons that stream to the opposite wall of the structure, effectively shorting the cavity. The majority of the energy in the structure is thus deposited in the wall by high energy electrons, usually producing significant x-ray fluxes.

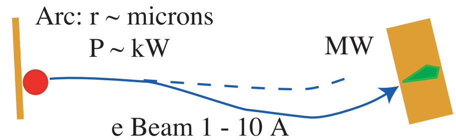

Figure 2: The arc.

METHOD

We describe the evolution of the plasma arc and the surface environment in contact with that arc using plasma and molecular dynamics, looking primarily at the plasma initiation phase of the arc, contributions of line and continuum radiation to the overall power balance, and evolution the later stages of the arc to compare with optical and x-ray measurements. We use OOPIC Pro, a 2 ½ D (with axial symmetry) that uses 3D EM fields to evaluate the first stages of the arc. The geometry used is shown in Fig. 3 [7]. We assume that the arc is produced by neutral material with a radius and thickness of 2 µm that has been projected above a field emitter, where it is subject to ionization by the field-emitted beams. The model assumes a conical asperity with a radius and length of 3 µm, projecting into an 80 MV/m field, and considers a volume with a radius and length of 10 μm..

We use Molecular Dynamics, (MD), which can calculate material properties starting from the interatomic potentials between two atoms, and surface thermodynamic modelling to understand the behavior of materials interactions (sputtering, erosion, Coulomb explosions, surface stability, etc.).. Previous papers used this technique to show how tensile stresses can fracture materials at high surface fields. Modeling results can be influenced by artefacts of the initial conditions, just as data can influenced by experimental design, we try to identify and eliminate both biases.

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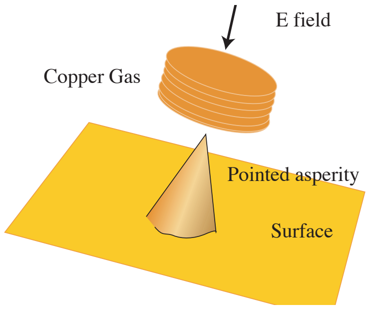

Figure 3: The geometry.

PLASMA INITIATION

We assume that the neutral gas was produced by fracture of a field emitter, whose fragments may or may not be gaseous. If solid fragments are produced, we model how they will be quickly disassociated by Coulomb explosions by field-emitted currents from the nearby asperity. The process of plasma initiation has been described before, however not to our knowledge, for an rf plasma in sufficient detail to show the development of the arc from a neutral state, optical radiation levels, the dependence of the arc on the surface material, the dependence on strong magnetic fields and other variables that can affect the trigger. The literature on arcs shows a range of experimental measurements and models [3].

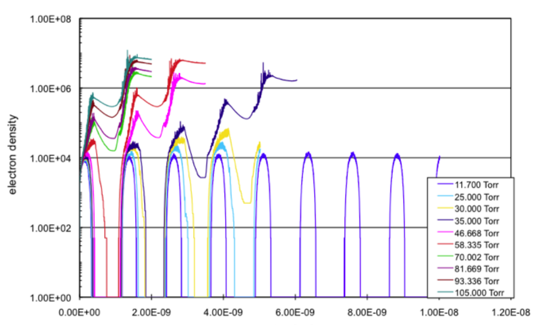

Figure 4: The dependence on gas density.

Results of the initial stage of our modeling are shown in Fig. 4, 5 and 6. Field emitted beams produce an inertially confined, low temperature ion cloud close to the surface that enhances the local electric field on the surface, enhancing the field emission and further ionization. The electric potential produced by the ion cloud also traps electrons that oscillate inside this potential, producing an additional source of ionization. While the electrostatic potential remains roughly constant during the development of the arc, the densities of field emitted electrons, ions and trapped electrons increase roughly exponentially during the arc.

The development of the plasma, as a function of the initial gas pressure confined above the emitter, is shown in Fig 4, shows as sharp threshold at a about 30 Torr, below this level a stable plasma does not develop, and above this level the plasma develops with an accelerated growth time. Since we consider cases where breakdown events are rare, we assume that the arcs we see are only slightly above this threshold. This pressure, in a 2 μm layer, corresponds to about 1/2 monolayer of material.

Our model shows that a high density of energetic trapped electrons inside the ion cloud can be the dominant source of ionization in the early stages of the plasma growth. These electrons oscillate in the ion potential with a period on the order of 10 ps. Fig. 5, which shows the phase space of the electron populations plots longitudinal velocity of electrons against the distance from the surface, shows the population of field emitted electrons (green) and the trapped ionization electrons (yellow).

EXPONENTIAL PLASMA GROWTH

We have modelled cases with and without magnetic 10 T axial field, both are characterized by exponential growth times on the order of 1 ns. We measured the growth time at the end of the breakdown event by recording the shape of the leading edge of the x ray pulse. The growth times we model are consistent with experimental measurements of 5 – 20 ns as the arc begins to reduce the cavity fields. Higher stored energies in the cavity lead to shorter growth times.

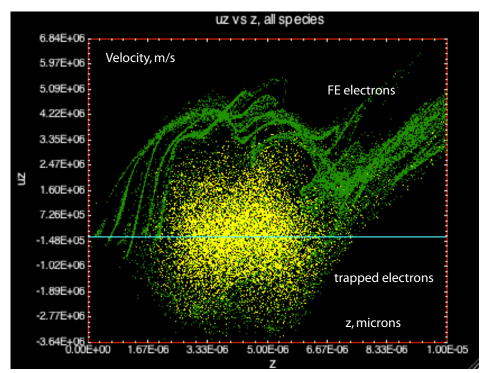

Figure 5: The phase space of field emitted (green) and trapped plasma electrons (yellow).

As the plasma density develops, the combination of the positive plasma potential augmented by increased ion density (which is partially neutralized by the ionization produced by trapped electrons) cancels the Child Langmuir limit and results in a large increase in field emission and an increase in the range of rf phase over which these currents are produced, thus the field emission increases both the duty cycle and intensity.

Fig. 6 shows results from the plasma code. The time development (Fig. 6a) of the plasma is approximately exponential, as the ion density (blue), field emitted electron current (green) and ionization electrons (yellow) all rise together. The ion temperature as a function of radius and distance from the asperity are shown in Fig 6b.

The plasma produced is dense and cold, containing two populations of electrons, the ion temperature at the center of the arc is roughly 1 eV, and ion energies are only significant at the arc boundaries, after acceleration by the plasma potential. The ion density rises to $10^{24} – 10^{25}$ m^{-3} as the arc develops. The time development of the line radiation flux is shown in Fig.6c. Optical radiation is dominated by line radiation from cold atoms, and the flux of this radiation rises with a time constant of ~0.5 ns to ~10^{18} Wm^{-3}. Continuum radiation is negligible.

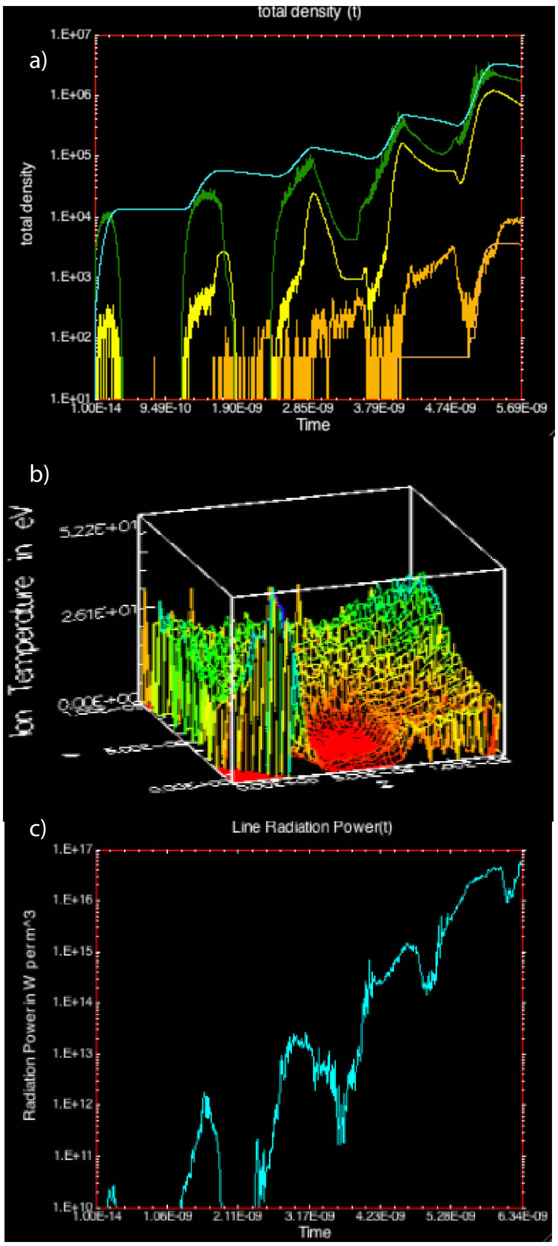

Figure 6: Examples of OOPIC Pro output showing, a) Plasma evolution in the first 7 ns (colors as in Fig. 5),
b) ion energy at 7.4 ns into the arc and,
c) growth of line radiation power. Vertical scales on a) and c0 are logarithmic.

SURFACE DAMAGE

The overall picture we develop is quite similar to the unipolar arc model of plasmas, as described by Schwirzke and others, however rf arcs exist in a oscillating potential, with the rf electric fields always sufficient to sweep electrons away from any connection to the arc in a few ps [8]. Unipolar plasmas (μm dimensions) are produced in a number of environments (laser/surface interactions, tokamaks, welding, etc.), have a high energy density. They can be produced in an electrically neutral environment, yet contain magnetic fields on the order of 1000 T. The unipolar arc model is interesting for two reasons: 1) after the cavity energy is discharged, the breakdown arc would essentially become a unipolar arc and burn until the stored energy was dissipated and, 2) unipolar arcs are understood to be the primary method for surface damage and wall ablation in a wide variety of plasma environments, and almost entirely through the production of craters, which can be on the order of 50 μm diameter. Considerable structure on a micron and submicron scale is also produced. These arcs would produce surface damage proportional to the stored energy available to the arc, and dependent on the structure of an external magnetic field..

SUMMARY

The aim of this work is to understand, and eventually improve the ultimate limits of rf structures. We have begun to simulate an rf breakdown model that considers all stages of the breakdown process, from the trigger to the final surface damage, using plasma, molecular dynamics and surface thermodynamics. The model is triggered by fracture of a field emitter at 10 GV/m, and considers the evolution of fragments, gas and plasma until high energy electron beams from the plasma “cathode” discharge all the cavity energy into the wall. Unipolar arcs may be the primary source of the microscopic (10 – 50 nm) damage that can trigger breakdown.

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