VACUUM ARCS AND GRADIENT LIMITS*

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Abstract

We have been extending and refining our model of vacuum breakdown and gradient limits and describe recent developments. The model considers a large number of mechanisms, but finds that vacuum arcs can be described fairly simply and self-consistently, however simulations of individual mechanisms can be involved, in some cases. Although based on accelerator rf data, we believe our model of vacuum arcs should have general applicability. The paper explores breakdown in plasmas, and self-sputtering and damage by parasitic arcs.

OUTLINE OF THE MODEL

The model we are describing assumes that breakdown events are triggered by electric fields on the order of 10 GV/m mechanically tearing asperities. Fragments from this event are then ionized by field-emitted beams, producing a plasma. As the plasma density builds up, the Debye length becomes smaller, causing increased surface field under the plasma, increasing the field emission and plasma energy and density. The plasma produces electrons that are driven away by the driving field, leaving ions that rapidly stream away from where they were created. These ions stream in all directions, producing high local heat fluxes that melt the surface and produce a variety of surface damage .A general summary of the model with some details has been presented in LINAC10 [1].

This paper will cover extending this model to some aspects of superconducting rf, and a variety of surface damage mechanisms not previously considered.

E-BEAM WELDING PITS

The origin of small circular pits in the Heat Affected Zone (HAZ) of full penetration e beam welds has not been identified, although these pits can be a gradient limit in Superconducting RF (SRF) systems. We consider the possibility that these pits are caused by unipolar arcs that develop during the full penetration weld around the equator of the rf structure.

As shown by Schwirzke and Taylor [2], laser induced plasmas on the surface of a metal can locally produce small pits in the surface far away from the initial point of plasma production. We have shown that the early evolution of a vacuum arc seems to involve small, dense plasmas whose sheath potential is determined by particle kinematics, and whose Debye length decreases to very small values [1]. The combination of a roughly constant sheath potential and a decreasing Debye length requires that the surface electric field under the plasma increases to very high values. We believe that the environment around full penetration ebeam welding, with a high flux of electrons leaving the surface, dense plasma and gas near the surface and high surface roughness due to particulates, could also produce spontaneous unipolar arcs that would rapidly increase in density and plasma pressure until they were able to produce the pits seen in SRF structures.

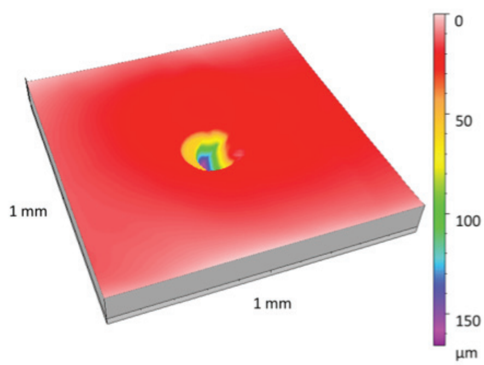

Figure 1: Pits in the heat affected zone of a full penetration weld of niobium plate, from [3]. False color shows depth.

The threshold for initiation of a self sustaining unipolar arc driven by field emission currents can be derived from the condition for vacuum breakdown, E_{local} 10 GV/m, in this case giving an expression for the required enhancement factor, $\beta \sim$ 10 GV/m / $(\phi/\lambda_D(n))$, in terms of the sheath potential, ϕ, and Debye length, λ_D, and ion density, n. Assuming $\phi \sim 75$ V, and the dependence of the Debye length as a function of plasma density, gives a relation between the plasma density and local enhancement factors, $\beta^2 n \sim 2 \times 10^{24}$ m^{-3}, that would produce a self sustaining unipolar arc driven by field emission.

The evolution of these arcs would closely follow that of normal vacuum arcs, with increasing density and surface electric field until the surface melted and began to be released as particulates [1]. The plasma pressure one would expect from these cold, dense plasmas is given by. $p = nkT$, where p, n, k and T are the pressure in Pa, density in m^{-3}, Boltzmanns constant, and the temperature in degrees K. For sheath potentials on the order of 100 eV and densities from 10^{24} m^{-3} this would produce pressures in the range 10 MPa or larger, enough to produce craters of the required size in liquid metals.

We plan to continue a modest experimental study of

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these arcs.

SELF-SPUTTERING: DEPENDENCE ON GRAIN ORIENTATION

In order to understand the plasma material interaction it is necessary to understand the mechanisms of sputtering and melting at the atomic level. Since the sputtering yield coefficients are the atomistic characteristics of the plasma ion interaction with the surface, they can be calculated directly by either Monte Carlo or molecular dynamics methods. Experimental measurements show distinctly different sputtering yields for Cu surfaces with different crystallographic planes, when bombarded by Ar+ ions. This difference cannot be explained by simply referring to different binding energies of the crystal planes since the binding energy (and the density) of (100) is higher that that of a (110) plane, and the latter is higher than the energy of a Cu (111) plane.

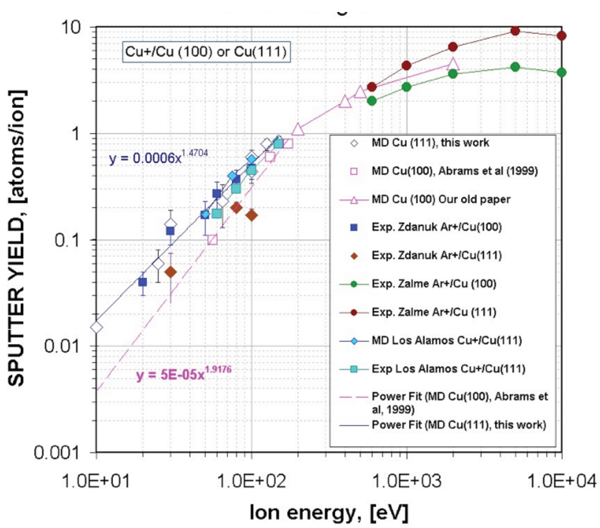

Figure 2: self-sputtering yield of copper low-index faces at low energies.

The sheath potential in unipolar arcs is on the order of 10s of eV, depending on the geometry and other parameters. In order to determine the dependence low energy sputtering on crystal orientation, we have modeled the sputtering process on copper for a variety of grain orientations with molecular dynamics (MD). The evolution of the atomic system was determined by the solution of the set of the classical equations of motion for all the atoms in the system. The copper target was represented by crystalline (100), or other, substrates.

Our MD simulation results, shown in Fig. 2 and 3, show the scale of the dependence on grain orientation. We believe that self sputtering could be a significant component of surface damage away from the immediate center of the arc, where damage sometimes appears to be dependent on individual grain properties. A variety of data seems to show

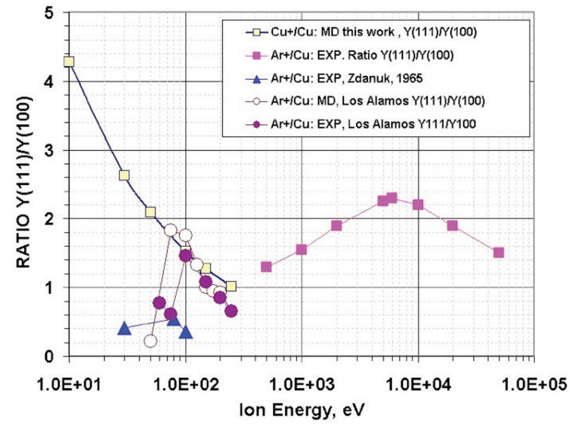

Figure 3: Ratio of self-sputtering yields for Cu bombarded with Ar and Cu ions.

structures consistent with significant mass removal due to sputtering [4].

TEMPERATURE OF BREAKDOWN SITES

The geometrical origin of field enhancements has been debated for many years. As described in an earlier paper [1], we find that sharp corners associated with crack junctions, and cone shaped asperities can produce the high enhancement factors seen in experimental measurements. Field emission would thus be produced only a very small sources. Since the heated volume would be small (nm^3) and the volume of metal heat sinked, in a ns, to the emitter is on the order of 0.1 μm^3, the time constant for cooling of the emitter would be on the order of a few 10 fs. Thus, these emitters would be difficult to heat.

TYPES OF ARC DAMAGE

Arcs are produced in a large number of environments and a wide variety of arc damage has always been seen, complicating the understanding the mechanisms that are responsible. In rf systems we find that arc behavior falls between two extremes which we call, a) killer arcs, that are able to quickly short out the cavity energy and eliminate the fields that drive them and, b) parasitic arcs, that exist in low field regions of the structure and are able to operate for long periods of time with minimal (perhaps undetectable) interactions with cavity operation. Examples of killer arcs would include the small pits seen in the iris region of X band structures [ ] and parasitic arcs, which can operate for a longer time can have the chicken track appearance of classic unipolar arcs commonly seen in tokamaks [2] We find that rf structures can produce killer arcs in an environment with no magnetic field or with parallel E and B fields, but if the electric and magnetic field are perpendicular, the arcs are qualitatively different, producing much more visible light and lasting for a longer time.

We have also been able to identify what we believe to be damage due to entirely parasitic arcs in the coupling unit

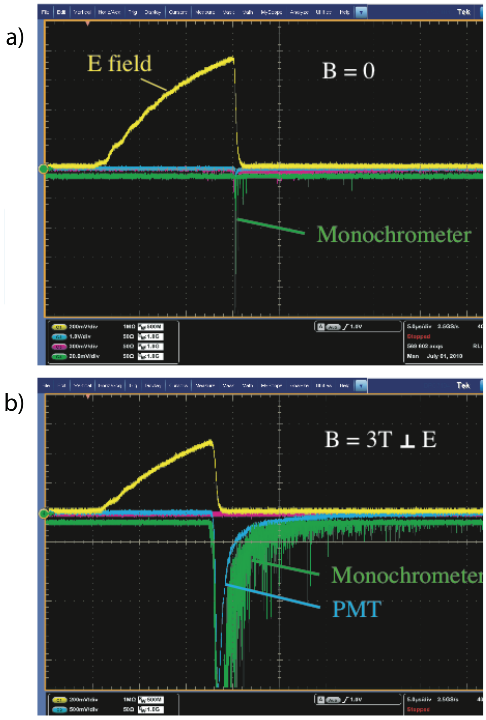

Figure 4: Plots of visible light emitted during a breakdown event, a) with no magnetic field, and b) with a magnetic field perpendicular to the electric field. The perpendicular magnetic field prevents the arc from discharging the cavity.

for the 201 MHz rf cavity. This cavity operates with a pulse length on the order of 300 μs. These tracks, which were produced in a weak (0.3 T) magnetic field, are very similar to classic unipolar arc tracks in tokamaks, produced with higher fields and longer pulses.

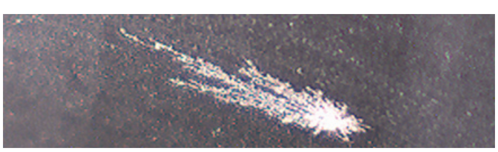

Figure 5: Tracks of arc damage, far from the high field region of the cavity. These tracks are 1 - 2 cm long.

Examining this damage at high magnifications Secondary Emission Microscope (SEM) shows considerable structure at high magnification, however at low magnifications there seemed to be little visible structure or contrast. The arc damage was, in fact, more visible by naked eye then in low power SEM images.

CONCLUSIONS

We continue to extend our model of breakdown and gradient limits to other damage mechanisms and types of arcs. We find that unipolar arcs can be produced by electron beams in the absence of any external electric field. We are

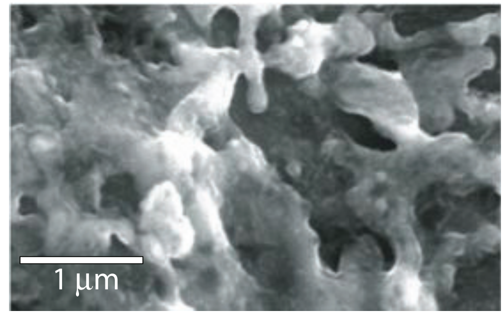

Figure 6: SEM images of arc damage (enlargement of Fig. 5). The surface was dominated by structure on the scale of a few hundred nm, and at lower magnifications showed comparatively little structure or contrast.

exploring sputtering as an explanation for many of the damage types in rf structures. We can identify a range of arcs from killer arcs, that short out their driving fields, to parasitic arcs, that burn without affecting the overall system. We describe the damage seen in these parasitic arcs.

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