TRIGGERS FOR RF BREAKDOWN*

J. Norem#, Z. Insepov, Argonne National Laboratory, Argonne IL 60439

Abstract

We outline a model of rf breakdown. Breakdown can be triggered by two mechanisms, one is fracture of the surface due to the tensile stress produced by the electric field, the second is Ohmic heating at grain boundaries and defects at very high current densities. We show how this model follows from measurements of local electric fields using electron field emission, and show how the model applies to the operating conditions of a variety of rf structures. This model may have some relevance to superconducting rf and DC structures.

INTRODUCTION

Breakdown in rf and DC systems has been studied for many years without any general agreement on what triggers this phenomenon [1,2]. We have found two mechanisms which seem to be able to produce these triggers. This paper outlines the elements of this model, shows how it is consistent with data, and outlines incompatibilities of other models with data.

Recent studies of dark currents and field emission have for the Muon Collaboration have shown that field emitters in cavities operate at electric fields on the order of 5-10 GV/m, which are associated with high tensile stresses on the emitter surfaces [3]. At these high fields, materials can emit single ions, clusters and fragments. We have shown that while single ions and electrons are unlikely to interact with each other, field emitted electrons can deposit very high power densities both in fragments and on the surface of the material. This seems a likely trigger for the breakdown phenomenon [4]. We also present data showing that high local power densities can be produced at grain boundaries and defects by Ohmic heating due to surface currents. This work is continuing.

BREAKDOWN MODEL

Field emitted electrons can measure the environment on the surface of the field emitters that seem to trigger breakdown. Electrons are not emitted unless the surface fields are very high. The surface field can be found as a function of the exponent, *n,* in the relation $I = E^n$, where I is the field emitted dark current and E is the local electric field on the surface of the field emitter. This is shown in Fig. 1, from Ref 3

Field emission describes the surface

For all rf cavities emitting x rays, the indirectly measured values of electric field seem to be in the range of 3 – 10 GV/m, which corresponds to local tensile stresses, $\tau = \varepsilon_0 E^2/2$, equal to the tensile strength of copper. The dimensions of the field emitters can be found by fitting the field emitted current with the predicted Fowler Nordheim current density [3]. The dimensions found in this way are ~ 0.1 μm, for one emitter, i.e. ~$(10^{-11}\text{m}^2/1000)^{1/2}$. The current per emitter had a maximum of about 1 mA at a surface field of about 10 GV/m. From the measured surface field one can calculate the surface charge/atom from Gauss's Law, which gives roughly 1 charge per 20 atoms, at 10 GV/m.

Two cavities were used in the Muon Collaboration tests, an open cell cavity that was conditioned aggressively for months at high electric fields, and a pillbox cavity that was not conditioned to the same surface field. A solenoidal magnetic field made it possible to image the emitters,

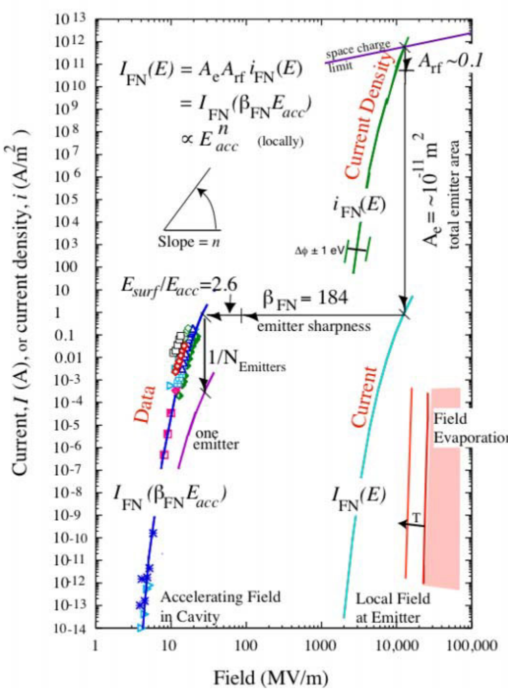

Fig. 1 The field emitter environment, N~10^3 [1,3].

showing that the fully conditioned cavity had many emitters of approximately equal intensity, but the incompletely conditioned cavity had a wide variation in emitter intensities.

Tensile stresses can pull the surface apart

At surface fields of 10 – 30 GV/m, fracture and field evaporation of surface atoms can take place. The dependence of tensile stress and exponent for field emission is shown in Fig. 2. Field evaporation generally involves single atoms, however clusters and fragments are also emitted. We have begun to model this mechanism using a Molecular Dynamics (MD) code. An example of these calculations is shown in Fig. 3, which shows charged ions being pulled of a surface by a perpendicular electric field.

* Supported by USDOE
# norem@anl.gov

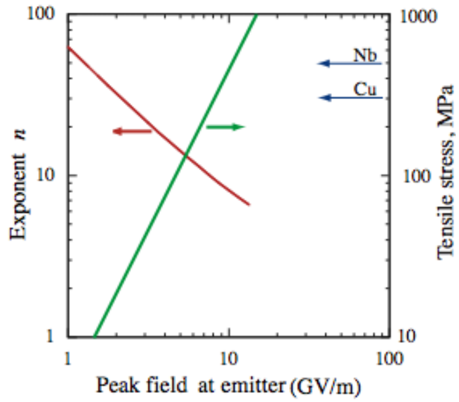

Fig. 2, The tensile stress and field dependence of field emission, $I \sim E^n$, on local electric field. The tensile strength of Cu and cold Nb are shown.

Recent results include an estimate of the thermal dependence of the production rate for clusters as a function of electric field [5].

Fragments and clusters are produced

The environment of a field emitter in an rf cavity is similar to that of a sample in a field ion microscope (FIM). Users of these devices are familiar with "sample failures", which occur when tips sharpened to 100 nm dimensions and subjected to 10 – 30 GV/m fields and the tips rupture or fail. Although the failure mode is common, there is little data in the literature on sample failures, since good condensed matter data comes only from samples that remained intact [6].

Fragments are heated by field emitted electrons

The local *E* field decreases with distance from the asperity like $1/r^2$, down to the average field. Thus the energy of electrons leaving an asperity is roughly Ed = (10 GV/m)(0.1 μm), near the surface, where *d* is the dimension of the emitter. This gives these electrons an energy on the order of 1 kV before they leave the region of the asperity. Since the electron current from a field emitter is on the order of 1 mA, the power in these electrons can be 1 W. The range of kV electrons in copper is given by,

$$r_{[m]} = 10^{-6}[(0.043E_{[keV]} + 0.37) - 0.007]^{1.77} / \rho,$$

where ρ is the density and *r* is about 7 nm[6]. Thus the deposited power density can be on the order of 10^{13} W/cm^3. As the distance from the emitter increases, the electron energy increases, and the ionization and scattering cross sections for electrons decrease. Single ions and electrons can pass quickly out of the region of the emitter surface, primarily due their initial velocity, however heavy fragments and clusters move much slower and remain near the surface for a much longer time.

Kinematics of the emission of single ions and electrons show that these particles traverse the length of an rf cavity and deposit little kinetic energy on the surface [4]. While field emitted beams do interact with single ions, the cross sections are low and decrease with the distance from the

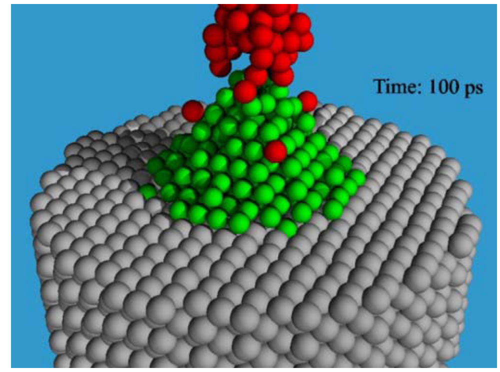

Fig 3, A molecular dynamics calculation of cluster emission at 10 GV/m

wall (electron energy) until the ions are out of range of the wall. On the other hand, clusters move slowly and are subject to very high fluxes of field emission electron current while still very close to the surface.

Currents at grain boundaries and defects

Very high surface current densities can exist in rf cavities, both near sharp corners of input couplers and over the length of high frequency cavities. These high currents can lead to distortions of the surface structure, which can, in turn, generate very high local fields and Ohmic power densities [4,7,8].

Triggers discharge stored energy

Once a certain level of local electron and ion density is reached a discharge event can proceed following of models developed at Cornell and SLAC[9,10]. A significant fraction of the stored energy of the cavity can then be deposited on the surface of the cavity, resulting in an x ray burst, vaporization of wall material, production of molten metal and the creation of craters. The dimensions and properties of the craters seem to be fairly independent of the type or cause of discharge.

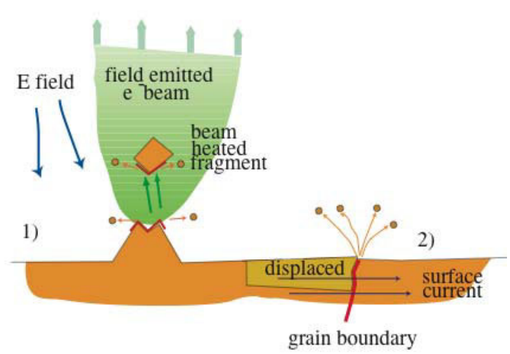

Fig. 4, Two mechanisms.

COMPARISON WITH OTHER DATA

This model predicts that surfaces will break up and arc when a tensile stress limit is reached. There is an initial distribution of field emitters of various surface fields and conditioning is required to remove the sharpest of these. A number of consequences of this model are:

- A very sharp threshold in local electric field. Breakdown rates go like E^m, with m in the range of 10 – 20. Cavities don't operate with tensile stresses greater than the tensile strength of the metal, (i.e. with exponents $n < 8$) [3].
- Little dependence on gas pressure. The high measured local fields are incompatible with weakly bound adsorbed gas [3].
- Weak dependence on material temperature. Recent data shows no significant dependence [11].
- Strong dependence on surface current density. Local ohmic temperature rises of >100 ^{O}C can trigger breakdown events [12].
- Strong dependence on material composition [11].
- Strong dependence on surface topography and cleanliness. This is seen everywhere.
- Breakdown due to high fields in field ion microscopes at comparable fields [5,6].
- Little dependence on frequency. DC and rf systems all fail at local fields of about 7 – 10 GV/m [1,3,11].

OTHER MODELS

Many models have been applied to the breakdown phenomenon. The dominant mechanism has been assumed to be particles traversing the cavity, melting of emitters, gas desorption at the surface, plasma spots, whiskers, explosive electron emission, multipactor, etc. We are looking at how other effects may contribute to these effects.

Melting

Many emitters operate at 10 GV/m fields with tensile tensile stresses incompatible with any thermal softening. While heating obviously occurs as material is ionized, slow melting of asperities does not seem to be a necessary component of the trigger mechanism. No significant dependence on the initial temperature of the material was seen in recent CERN/CLIC experiments [11].

Gas desorption

It was found in Ref 3, and elsewhere, that there is little dependence on the breakdown properties of a cavity as a function of the gas pressure. As long as the pressure in the cavity was below 10^{-5} Torr, roughly 10,000 times the base pressure of the operating cavity, the breakdown thresholds and breakdown properties were unchanged. This argues that the adsorbed gas on the surface is not a significant component to the breakdown trigger. Operation with tensile stresses of 300 MPa also argues that weakly adsorbed surface gas is not a significant component.

Plasma Spots

Localized plasmas are seen in high field environments. Field emission at asperities will ionize gas in the plasma producing bright spots. These can exist stably in cavities for long periods, i.e. weeks [9].

Explosive Electron Emission

While the mechanism driving this process is not well described, the high power densities produced in fragmentation will result in very rapid electron emission [13].

CONCLUSIONS

We have outlined a model that explains the triggers of rf breakdown in cavities in terms of tensile stress exerted by the electric field and Ohmic power densities driven by high current densities and local resistive anomalies. This model may provide a connection between measurements made with DC systems, normal and superconducting rf. This could make laboratory experiments looking at a variety of surface treatments and materials in exotic environments relevant to rf problems.

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy under contract W-31-109-ENG-38, and by the directors Competitive Grant from Argonne National Laboratory.

REFERENCES

[1] D. Alpert, D. A. Lee, E. M. Lyman, H. E. Tomaschke, J. Vac. Sci. Technol. 1, 35, (1964).
[2] W. W. Dolan, Phys. Rev. 91, 510, (1953)
[3] J. Norem, V. Wu, A. Moretti, M. Popovic, Z. Qian, L. Ducas, Y. Torun and N. Solomey, Phys. Rev. STAB, 6, 072001, (2003)
[4] J. Norem, Z. Insepov, I. Konkashbaev, Submitted to Nuc. Instr. & Meth Jan 2004.
[5] Z. Insepov, J. Norem and A. Hassanein, submitted to Phys. Rev. Lett. (2004).
[6] M. K. Miller, Atom Probe Tomography, Analysis at the Atomic Level, Kluwer Academic/Plenum Publishers, New York (2000)
[6] A. Cole, Rad. Res, 38, 7, (1969)
[7] D. Pritzkau and R. H. Siemann, Phys Rev. STAB, 5, 112002, (2002)
[8] B. G. Briner, R. M. Feenstra, T. P. Chin. J. M. Woodall, Phys. Rev. B, 54, 5283, (1996)
[9] P. Wilson, Proceedings of the PAC03 Conference, Portland OR, (2003)
[10] G. Werner, Workshop on High gradient rf, Argonne, Oct, 7-9 (2003), http://www.hep.anl.gov/rf/
[11] H. H. Braun, S. Dobert, I. Wilson, W. Wuensch, Phys. Rev. Lett. 90, 224801, (2003)
[12] V. Dolgashev, Workshop on High gradient rf, Argonne, Oct, 7-9 (2003), http://www.hep.anl.gov/rf/
[13] G. A. Mesyats D. I. Proskurovsky, Pulsed Electrical Discharge in Vacuum, Sspringer –Verlag, Berlin, (1989)