HIGH SURFACE FIELDS IN SUPERCONDUCTING RF CAVITIES*

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Abstract

Field emission in cavities requires electric fields that can be high enough to damage materials. We outline a model of breakdown and field emission from local asperities, and show how electric field effects, and field emission of electrons, field evaporation of ions, ultimately fracture, can limit accelerating fields. Although based on data from copper cavities and preliminary results from atom probe tomography experiments, the model seems to be generally valid for DC to 30 GHz, 10^{-11} to 10^{5} Torr, different materials, temperatures, conditioning status, secondary emitters, strong magnetic fields, atom probe data, and the variety of surfaces encountered during copper cavity conditioning. We believe studies of normal materials can help to understand mechanisms operating in SCRF, such as fracture, field emission and evaporation effects, control of the surface, and surface metallurgy.

INTRODUCTION

A linear collider with 1 TeV in the center-of-mass, operating with a 30 – 45 MeV/m accelerating gradient and a ratio of E_{surf}/E_{acc} of 2.5 – 3, will have roughly 10^4 m^2 of surface exposed to average surface fields of roughly 100 MV/m, and must be expected to have an operating lifetime of greater than 25 years [1]. These parameters are beyond the proven capability of normal conducting structures, although the gradient has been achieved in small superconducting structures. With the added constraint that it is desirable to optimize the procedures before beginning construction, it seems desirable to carefully examine the mechanisms at work in the surface environment on an aggressive timescale.

We find, in normal conducting rf, any measurable x-ray flux is associated with local fields at asperities that can be high enough to damage surfaces, and local fields of 6 – 7 GV/m seem to define the maximum operating field of copper cavities [2]. We have been accumulating data on damage mechanisms with a variety of techniques. We argue, however, that the physics of how fields interact with surfaces is not well understood.

This paper reviews recent data on breakdown and high gradient phenomena in normal rf and material science environments and applies to the mechanisms that may be operating in superconducting rf systems. Figure 1 shows how data from high gradient rf cavities compares with data from atom probe tomography (APT) systems.

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HIGH GRADIENT PHENOMENA

Measurements on 805 MHz cavities for the Muon Ionization Cooling Experiment (MICE) [3] and MuCool experiments [4] have shown that x-ray measurements are consistent with an interior cavity surface that has asperities that produce dark currents, and these dark currents must be produced at local field levels of 5 – 10 GV/m. At these fields, tensile stresses, $\sigma = -0.5\ \varepsilon_0 E^2$, are produced which are comparable with the tensile strength of copper. Generalizing the mechanism of failure when local mechanical stresses reach mechanical limits seems to explain most breakdown data. We have looked at the effects of gas pressure, frequency, temperature, conditioning status, magnetic field, pulse length, material, and material properties. We found this argument to be qualitatively useful, and we are trying to accumulate data to make more accurate predictions, based on more accurate data.

Failure modes at high fields

Our model of breakdown in copper cavities implies that tensile stresses fracture asperities, and the fragments or clusters produced are heated by field emission currents until they form lossy, plasmas that short cavities [5]. With superconducting cavities, the common failure mode seems to be electron field emission, at slightly lower fields than would cause fracture, which produce local heating and increasing losses that can cause inefficient operation or drive the cavity normal [6]. (There are also constraints imposed by magnetic fields in contact with the walls superconductor that are not considered here.) The field emission sources are thought to be primarily contamination. Atom probe tomography (APT) samples, small needles exposed to very high electric fields, have been shown to fail due to tensile stresses, this phenomenon has been under study at least since the early 1970's. Data from rf cavities and apt's displayed in Fig. 1, both show discontinuous behavior around 6 GV/m, however apt data shows that stable operating conditions exist at about 30 GV/m.

Tensile strength

Tensile strength, as measured in macroscopic samples, is a well-studied property of metals. Small samples, however, can be much stronger than the macroscopic values would predict [7]. The theoretical tensile strength of materials should be on the order of $Y/4\pi$, where Y is Young's modulus. Ultimately there seem to be three relevant cases: 1) large samples under uniform tensile

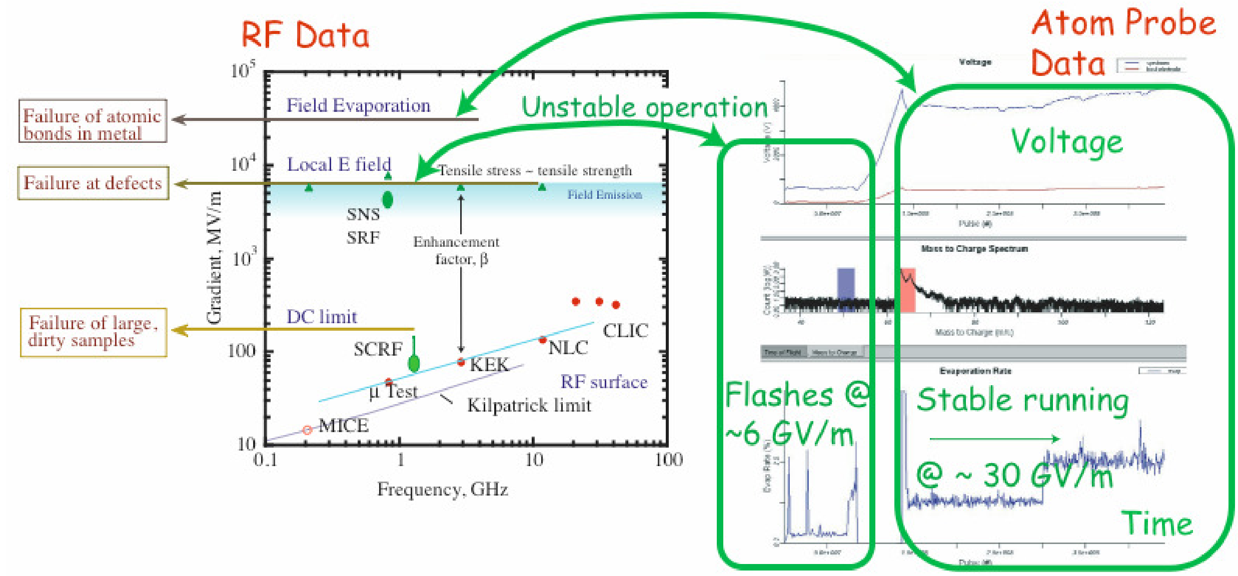

Figure 1, A comparison of rf and atom probe tomography (APT) data for copper. The rf data shows a compilation of local and surface gradients for various structures. The apt data shows anomalous behavior at estimated average local fields of 6 GV/m. We demonstrate, in fact, the surface fields during "flashes" can be much higher.

stresses, 2) microscopic samples under uniform tensile stresses, and, 3) small samples under highly localized tensile stresses. The first case is the one generally considered in mechanical engineering, the second applies to distributed tensile stresses on whiskers or perfect crystals, and the third is appropriate for electrostatic stresses as they apply to rf cavities or atom probe samples. In general, the numbers are quite different. Macroscopic values of the tensile strength for copper (1) are in the range 0.3 Gpa (~6 GV/m), microscopic values, (2), are about 20 Gpa (~120 GV/m), and small samples under localized stresses, (3), are perhaps 4 GPa (~30 GV/m). Thus, small samples can withstand very high stresses, and high fields but defects, dislocations fatigue or other effects can reduce this ability.

Local electric fields in rf cavities

The local field at asperities can be measured easily from the slope of the dependence of $I = E^n$, where I is the dark current, E, the local electric field and n is the exponent. The Fowler-Nordheim picture of field emission shows how the value of the parameter n depends on the local electric field and the work function, ϕ, of the material [8]. The relation shown in Figure 2, was used to obtain the local fields shown in Figure 1. The value of ϕ is not easily measured and is readily altered by surface contamination, crystal orientation, or other effects, which limits the accuracy of the method.

These measurements seems to show, however, that all cavities, including superconducting, that produce x rays operate at E_{local} = 6 - 7 GV/m. At these fields the tensile stresses can be equal to the macroscopic tensile strength of pure metals.

Local electric fields in atom probe microscopes

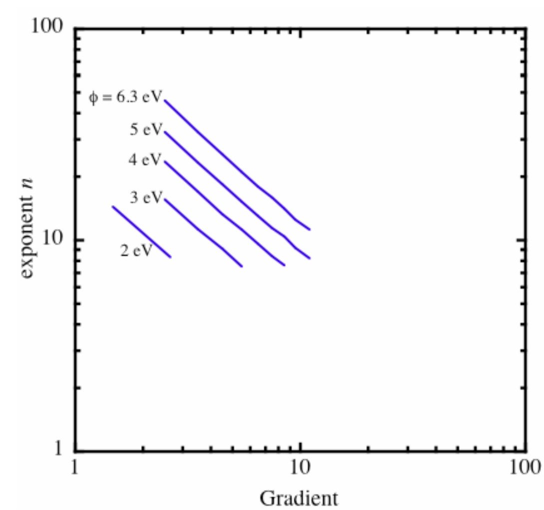

Figure 2, Estimating local fields from n and ϕ.

Atom probe samples are produced by etching wires to a diameter of ca 100 nm, which should leave a fairly smooth end surface, followed by pulse field evaporation to micropolish and produce an approximately hemispherical endform. The process seems to work because the rate of field evaporation is proportional to a very high power of the electric field, perhaps E^{80-140}, and this preferentially erodes asperities on the surface. Information from the initial stages of pulse polishing can thus produce information on the microsurface produced from different etching and polishing processes at the nm level.

The rate of field evaporation is determined by the geometry, field and material. The local electric field is given by the relation,

$$E = V/fr, \tag{1}$$

where V is the applied voltage, f is a form factor (roughly 5) and r is the radius. The field, $E_{\text{evaporation}}$, required to evaporate an n-fold charged ion at some canonical rate is given by the expression,

$$E_{evaporation} = \left(\Lambda + \sum_{i=1}^{n} I_i - n\phi\right)^2 \Big/ n^3 e^3, \tag{2}$$

where Λ is the cohesive energy, I_i is the energy necessary to ionize an atom to the n-th charge state, ϕ is the work function, and e is the charge on an electron. We find that the evaporation fields required to evaporate Cu^{+} Cu^{++}, Cu^{+++} and Cu^{++++} ions are, respectively 30, 43, 78, and 117 GV/m.

Using this model to examine the behavior of chemically polished samples of copper at room temperature, we can estimate the parameters of the surface during pulse field evaporation that ultimately results in a smooth sample. Replotting, in Figure 3, the atom probe data of Figure 1, we observe that the mass/charge ratio is dominated by the Cu^{++++} peak in the initial stages of pulse field evaporation. In this plot, a precision mass recalibration was not done for the early data thus the mass measurements were not as accurate.

It is thus possible to estimate the local radius of the evaporating surface using equation 1. The radius of the evaporating surface with the applied voltage of the sample gives values of 1.4 nm, 4 nm or 30 nm. This seems to imply that the process of pulse field evaporation is consistent with the picture in Fig 4.

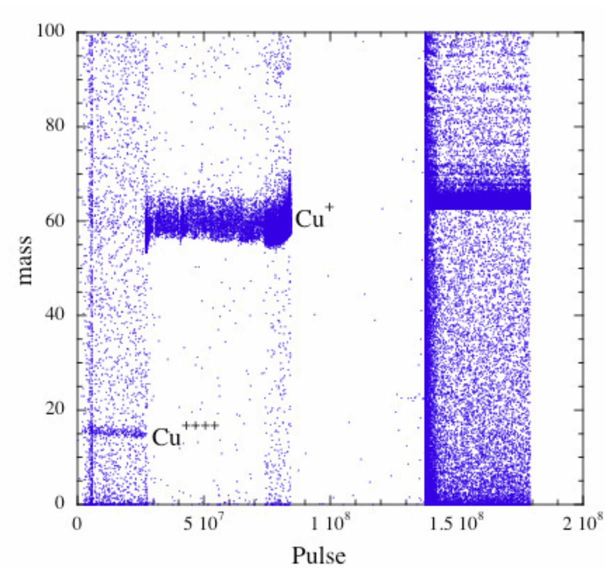

Figure 3, Mass as a function of pulse event number for data in Fig 1.

OPEN QUESTIONS

The superconducting structures of the International Linear Collider (ILC) will be a significant contribution to the construction time, cost, reliability and its ultimate performance. There are a number of open questions that may be accessible with the technology of atom probe tomography, among these are:

- What mechanical mechanisms are involved at high electric fields: whisker growth, stress, strain, differential surface expansion, fatigue, etc.
- What chemical/metallurgical mechanisms govern the behavior of surfaces: oxidation, diffusion, segregation, grain boundaries etc.
- Are any of these effects likely to have an undesirable (i.e. years) timescale?
- What improvements are possible in fabrication or repair techniques? Can dirty cavities be cleaned and fabrication tolerances relaxed?

While these questions can, in principle be studied with full sized cavity prototypes, the prototypes are expensive, the effects can be hard to isolate, the analysis can be difficult, and the cost of fabrication and testing can be high. A fundamental problem with this approach is that it may not produce the basic knowledge of fundamental mechanisms that could provide new insights or ideas for fabrication improvements or cost saving.

Attacking these problems with the smallest relevant sample size may be a practical alternative, however there are also experimental issues:

- How can surface analysis in an atom probe system be optimized?
- What effects limit the applicability of this method?

We have begun to look at these questions.

CONCLUSIONS

Surface field can be much higher than average fields or surface fields. Production of x rays implies local fields of 5 GV/m, and these fields may be high enough to cause surface damage. While most x-rays in superconducing structures may come from contamination, it is not clear what is the most efficient way to eliminate this problem. We are beginning to use atom robe tomography to study the mechanisms at with which high fields interact with materials. Atom probe tomography can produce data with incredible resolution, sensitivity, data rate and statistics, however there is limited experience understanding surface phenomena using this technique.

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