GRADIENT LIMITS AND SCRF PERFORMANCE*

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Abstract

Superconducting rf gradients are limited by a number of mechanisms, among them are field emission, multipactor, Lorentz detuning, global and local heating, quench fields, Q-Slope, assembly defects, and overall power use. We describe how each of these mechanisms interacts with the cavity fields and show how significant improvements may be possible assuming improvements in control over the cavity surface. New techniques such as Atomic Layer Deposition (ALD), the use of layered composites, Gas Cluster Ion Beam (GCIB) smoothing and Dry Ice Cleaning (DIC) have been proposed as ways to control the surface.

INTRODUCTION

Although superconducting rf technology has been adopted throughout the world for large linac facilities, it has frequently been difficult to reach the predicted performance in these structures due to a number of factors. A large number of mechanisms are involved, and the performance of any structure will be limited by whatever mechanism produces the lowest gradient limit applicable to the specific operational conditions. Although these structures are primarily limited by field emission, quench fields, when circumferential magnetic fields reach ~ 0.2 T, have been thought to be an ultimate limit.

The recent development of the idea of layered superconductors, by Gurevich, has introduced the possibility that the 0.2 T field limit may not, in fact, determine an arbitrary limiting gradient in a cavity, if it is possible to use layers of insulators and high field superconductors to shield the primary current carrying element from the quench fields. Under these circumstances it seems desirable to examine and catalogue the all the field limiting mechanisms that may apply to these structures and determine how these mechanisms operate, how they depend on accelerating field and what techniques might be required to mitigate them.

In this paper, we present a list of gradient limiting mechanisms, describe how these depend on accelerating field and identify mitigation mechanisms. It is important to note that mitigation of individual mechanisms is not likely to raise the structure performance unless all applicable gradient limiting mechanisms are mitigated, and this is a significant constraint on the range of productive approaches to this problem. Thus a complete list of these modes, combined with their dependence on electric field is useful.

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GRADIENT LIMITING MECHANISMS

Although field emission seems to be the primary limiting mechanism in most operational systems and test assemblies, quench fields also produce a hard limit to the performance of these systems.

In addition to these mechanisms are multipactor, resonant multiplication of parasitic electron beams in cavities, cavity breakdown, which seems to occur in high pulsed power tests, Lorentz detuning, where the electromagnetic forces induce pressures which distort the cavity and change its resonant frequency, excessive cryogenic losses, which limit the cavity to a gradient determined by the cryogenic capacity of the system, high field Q slope, an effect where the chemistry of the surface seems to be able to produce losses at high gradients, local hot spots, where the cavity seems to fail due to local defects, and assembly defects, where the process of assembly seems to produce defects (principally field emission sites) that can limit gradients.

Since some of these mechanisms dominate structure tests, it is useful to look in somewhat more detail at a few of them.

This list is intended to inclusively cover all the appropriate effects and mechanisms that have been seen, and we do not expect this list to be unique, definitive or to consist of orthogonal failure eigenmodes.

Field emission

Field emission is a problem in both superconducting and normal cavities and has been studied in both. This process is produced when electric fields converge on local asperities and develop high local fields. The local fields at which field emission causes quenches in superconductors can be found from fitting the shape of the field emission current, I, or radiation, R, (I or $R \sim E^n$) as a function of electric field, E [1,2]. Using a simplified version of this method seems to give local surface fields in the range of $E_{local} \sim 4$ GV/m.

Measurements of field emitting surfaces have been made both in operating cavities and sample surfaces, both normal and superconducting, and all these seem to be roughly consistent with a parameterization of the density of these enhancement factors, β, of the form $s(\beta)= A \exp(-C\beta)$, where $s(\beta)$ is in units of number per unit area, and A and C are constants that can vary depending on the material and its history [3]. Experimental data from a variety of samples seem to show C values around 0.027. A number of useful results can come from this parameterization, for example, it is possible to estimate the relative number of active emitters as a function of gradient and active area (frequency, number of cells, etc.).

One consequence of this parameterization is the possibility of estimating how the field emission problem will depend on improvements in operating fields. Since the local field at a field emitter is proportional to βE_{surf}, the density of emitters would rise faster than an exponential, and the maximum gradient would be roughly proportional to the logarithm of the particle density.

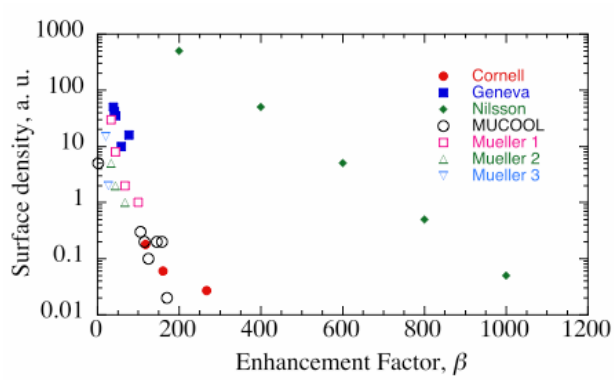

Fig 1, The spectrum of enhancements, $s(\beta) = A\exp(-C\beta)$

Breakdown

Cavity breakdown, of the sort seen in copper structures, is relatively uncommon in superconducting systems because it seems to require local surface fields on asperities greater than the 4 GV/m that can cause field emission induced quenches. Nevertheless, the process of "high pulsed power cleaning" seems to be essentially identical to the breakdown/conditioning process seen in warm copper structures. Hot field emitters seem to be permanently destroyed and radiation levels are reduced.

The tensile stress model of breakdown argues that breakdown will occur when the tensile stress exerted by the electric field is equal to the tensile strength of the material. Since niobium is a body centered cubic structure, the tensile strength of this material increases as the temperature is lowered, and has been measured at ~ 800 MPa, corresponding to about 13 GV/m. With the complex oxide structure of niobium and particulate contamination that could be the source of breakdown sites, it is more difficult to estimate the local breakdown fields than in copper.

The field enhancement spectrum for field emitters, $s(\beta)= A\ \exp(-B\beta)$, should be applicable for breakdown sites, requiring the density of breakdown sites should also rise exponentially with accelerating field with field emission sites.

Assembly defects

It has been found that many defects can be introduced into high gradient structures during assembly, and this has been attributed to the generation and transport of particulates around the inside of the structures caused by mechanical motion. While the ultimate failure mode seems to generally be field emission, but we assume that the mechanism responsible was generation of small particulates caused buy metal to metal contact during assembly, and the transport of these particles to areas of the structure that are exposed to high gradients. We assume a field enhancement spectrum and E dependence similar to those of field emission and breakdown.

Quench fields

One of the unambiguous predictions of superconducting theory is that vortexes will form in the material above the lower critical field H_{c1}, which, for niobium, is approximately 0.2 T. These vortexes will produce losses in rf systems. Recently, Gurevich has proposed that thin layers of superconductor can be used in rf systems, since sheets of superconductor which are thinner than the dimensions of a vortex cannot support vortex formation and have low rf losses [4]. This raises the effective quench field of the composite as a whole.

The ratio between the maximum magnetic field and accelerating field is a function of the cavity shape

Power and cryogenic load

Although superconductor is lossless for DC fields, the normal electrons in the metals see rf fields and produce resistive losses in superconducting systems. In addition to the power required to fill the structure, Ohmic losses rise with stored energy. These losses depend somewhat on the cavity shape, and superconductor. While the costs of the linac decrease with increasing gradient, the cost of the cryogenic system required to cool it will increase with gradient like E^2. In large facilities at high gradients or CW systems, these losses will dominate the facility cost and determine the operating gradient.

It has recently been shown by Gurevich that the cryogenic loads of superconducting structures should decrease in layered systems by as much as a factor of three [4].

Multipactor

Multipactor is the resonant amplification of parasitic electron beams, within a cavity, caused by production of secondary electrons when these beams hit a surface. A number of methods can mitigate this process including cavity shapes that complicate resonant motion, surface treatments that inhibit secondary electron production and higher power inputs that shorten the times periods over which the resonant conditions exist. This process seems to take place only at specific gradient values.

Q Slope

At high gradients, it has been found that many structures show anomalous losses that look similar to field emission, but without any x-rays, implying that some other mechanism is involved. The cause of these losses has not been definitively identified. An effective solution to this problem seems to be low temperature bake (24 hours at 130 ^{O}C), which seems to be a long-term cure. The low temperature seems to imply that the ultimate cause of this mechanism may be chemical, because many other mechanisms (structural defects, etc.,) would not respond to such a mild baking. The dependence of Q slope problems on gradient is not known.

Local heating

Many experimental measurements have shown that the temperature distribution around the surface of a superconducting resonator is very uneven, due to the effects of local hot spots. The causes of these hot spots is not completely understood, however many types of defects could cause these problems. Assuming these defects interact ohmically, one would expect that this mechanism would increase with gradient like E^2.

Lorentz Detuning and Microphonics

The electromagnetic fields and acoustic noise present in the cavity structure exert significant pressures on the walls, and these can mechanically deform the structure. The electric fields produce a tensile stress that causes the adjoining irises to attract each other, and the circumferential magnetic field produces tends to expand the cavity radially near the equator. The pressures involved are large both the electric pressure $P_E=\varepsilon_0 E^2/2$ and the magnetic pressure $P_B = B^2/2\mu_0$ are comparable to atmospheric pressures in the field range it would be desirable to operate.

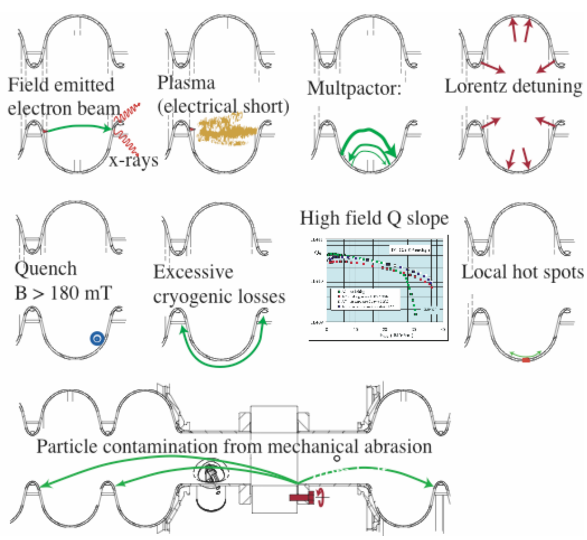

Fig. 2, Summary of failure modes.

DESIRABLE SURFACE PROPERTIES

Assuming field emission thresholds could be raised significantly by coating or polishing asperities, and quench fields could be cured by layered composities, as advocated by Gurevich, what surface properties would be required to significantly increase gradients? From the previous discussion it seems necessary that the interior surface should be: 1) nano-smooth on the scale of 10 – 100 nm, 2) with well understood and well controlled chemistry, 3) part of a rigid structure able to resist Lorentz force loading, 4) capable of insertion or repair in-situ, and 5) layered so the upper layers filter out the quench fields from the substrate, as specified by Gurevich.

NON STANDARD TREATMENTS

During the last 20 years one method of producing high gradient superconducting structures has evolved into forming a structure from niobium sheet, electropolishing the inside, rinsing with high pressure water, and installing in a cryostat, with all operations done in a clean environment. At present, these techniques seem to produce 9 cell 1.3 GHz structures with a maximum field of around 30 MV/m. There are a number of other techniques which are less well understood which might be useful in producing desirable surfaces. These include gas cluster ion beam (GCIB) smoothing, Dry Ice Cleaning (DIC), a varity of coating methods including Electron Cyclotron Resonance (ECR) plasmas, and Atomic Layer Deposition (ALD) of surface materials.

COPPER GRADIENT LIMITS

Warm structures, generally made from high purity copper, are much more tolerant of error conditions, and seem to be subject to only two if the SCRF failure modes, breakdown and surface heating. Previous work has shown that breakdown in low frequency copper structures can be explained by electrostatic tensile stresses (at E_{local} ~ 8 GV/m) tearing apart asperities on the wall, a process we also assume occurs in SCRF. At high frequencies, wall currents can heat the top few microns of the cavity surface and potentially produce stresses that would distort the material, perhaps ultimately producing deformations and asperities which would cause breakdown.

SUMMARY

The primary failure mode of superconducting structures seems to be field emission, a problem we expect would increase exponentially with increasing gradients. Many other failure mechanisms seem to apply, however, and it seems desirable to develop mechanisms that can simultaneously mitigate as many failure modes as possible.

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