SIMULATION OF NON-LINEAR RF LOSSES DERIVED FROM CHARACTERISTIC Nb TOPOGRAPHY*

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Abstract

A simplified model has been developed to simulate non-linear RF losses on Nb surfaces exclusively due to topographical enhancement of surface magnetic fields. If local sharp edges are small enough, at locations where local surface fields exceed H_c, small volumes of material may become normal conducting without thermal instability leading to quench. These small volumes of normal material yield increases in the effective surface resistance of the Nb. Using topographic data from typical BCP'd and EP'd fine grain niobium surfaces, we have simulated field-dependent losses and found that when extrapolated to resulting cavity performance, these losses correspond well to characteristic BCP/EP high field Q_0 performance differences for fine grain Nb. We describe the structure of the model, its limitations, and the effects of this type of non-linear loss contribution on SRF cavities.

INTRODUCTION

It is generally understood that surface roughness can play a role in non-linear loss mechanisms in niobium-based superconducting radio frequency (SRF) resonators. [1] The Q decrease phenomenon is a reflection of increasing average surface resistance. Several models attempt to explain various contributions to the Q slope/drop. Agreement of these models and experiments is mixed.

Typically, Buffered Chemical Polish etch (BCP) treated fine grain Nb cavity may show significant Q slope starting from 16 MV/m to 22 MV/m even after a post-chemistry bake. In extreme cases, a cavity may exhibit such non-linear losses at even lower fields, < 15 MV/m, without any associated radiation signature from electron loading phenomena. After electropolishing treatment (EP), even in such cases this dramatic loss mechanism is removed to at least much higher fields. This frequently encountered phenomenon is illustrated in Figure 1 by the performance of cavity HG006, a 7-cell 1.5 GHz CEBAF prototype cavity, before and after electropolishing. [2]

Such test results suggest that controlling topography evolution may play an important role in maximizing useful cavity gradient with minimum RF losses. In our analysis we provide a model to calculate non-linear RF loss from specific microscopic surface topographical features. An averaged surface resistance as a function of H field is derived from representative topography for comparison with cavity cold testing experiments.

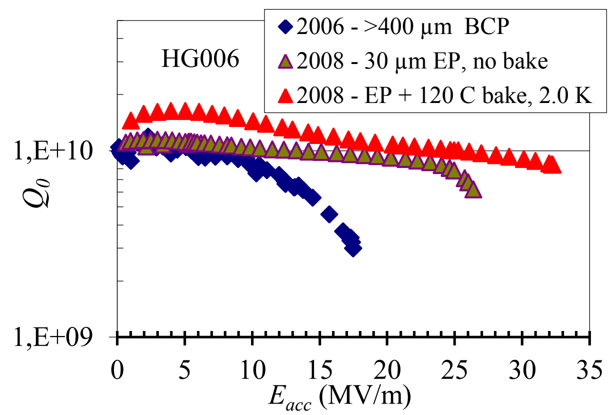

Figure 1: RF loss performance of Nb cavity HG006 after very heavy (>400 micron) etching (BCP) and subsequent light electropolish (EP). [2]

TOPOGRAPHY'S LINK TO RF LOSSES

The challenge remains to discern quantitatively what specific topographical character directly affects cavity performance. Practically, BCP-treated fine grain Nb surfaces, compared to EP-treated surfaces, yield more fluctuations in height and a greater density of sharp features on the scale of the grain size. [3] Those high and sharp features enhance the local magnetic field and may thus, even at intermediate applied field, locally exceed H_c. As a result, local superconducting transition is initiated. For simplicity in the analysis, we will consider H_c to be H_{sh}, the superheating critical field.

If the local magnetic field is greater than the local H_c, flux will enter the surface. As the field decays with depth into the surface, a location near the surface where the field is less than H_c must occur. Depending on the thermal conditions, there may be a stable interface of normal and superconducting material at this depth. This interface is moving inward and outward with the RF frequency. In this "equilibrium" condition, there will be additional RF loss due to these small normal nucleation sites on the surface. Surface temperature must increase and the local $H_c(T)$ accordingly reduces. Careful modelling is needed to evaluate the local heat generation, which in turn determines the local region's effective surface resistance.[4] Thermal feedback will increase normal zone volume, so an iteration is used to approach a stable solution. [5]

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MODEL ASSUMPTIONS

Our approach to the small-scale simulation has been presented previously. [5] We work with surface topography as measured from Nb samples by AFM. Due to the large difference in material resistivity and to simplify the analysis, we neglect all losses in the superconducting state, and attribute normal resistivity to all material where $H > H_c$.

NON-LINEAR RESPONSE FROM SURFACE FEATURES

Fig. 2 represents results of the calculation of the NC/SC phase front's deepest penetration at applied *H*-field from 100 to 180 mT. The blue lines are the deepest penetration that the normal zone can reach in each RF cycle.

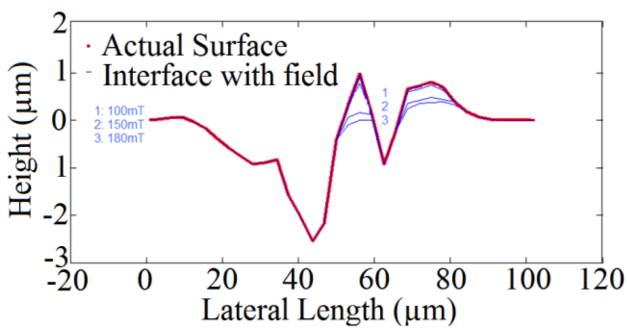

Figure. 2: Normal conducting phase fronts as calculated from different excited fields.

At low field there is no normal zone because the local field is weaker than H_c everywhere on the surface. When, for example, the highest local topographically induced field enhancement factor is 1.8 and H_c is 190mT, the normal zone is expected to nucleate at background *H* near 106 mT.

To model the thermal effects that would result from this dynamic interface, we constructed a model that isolates this surface contour segment in the center of an otherwise ideally flat sheet of Nb material, and seek to model the temperature effects influenced by typical Nb heat conduction properties to a 2.0 K bath. In this simulation, the material thickness in "height" direction is 3.3 mm. If the lateral boundaries are set too small, the simulation leads to temperature calculation error because the side boundaries are set with an isolation condition. However, setting the lateral zone too large costs computation inefficiency. To confidently model the thermal effects from a single small area, the lateral scale in the model needs to be comparable to the material thickness. We take a lateral length of 6.6 mm in our simulation. Geometry adaptive meshing is used to adapt to such a high ratio between the thermally simulated area and the scale of surface roughness features. Figure 3 shows the model results with an applied surface field of 120 mT. The surface temperature locally peaks at 2.25 K. The Matlab™ program used for the modelling outputs a simulation of the temperature map with variations within an RF cycle.

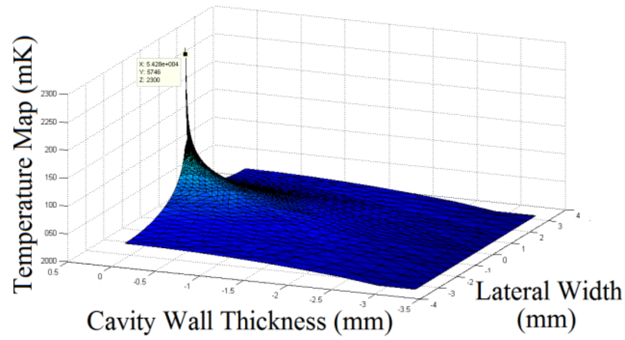

Figure 3: Temperature map calculated with applied magnetic field of 120 mT, with an isolated 100 µm rough strip as in Fig. 2.

POWER DEPOSITION ON BCP AND EP Nb SURFACES

Using the above methodology, the analysis was extended to simulate the topography-induced RF losses on specific extended surfaces of niobium. We use two representative surfaces characterized by AFM. As in Figure 4, the AFM characterization area covers 100 × 100 µm. The effective raster strip width depends on the sampling rate which, in our case, is 512 × 512. Limited by computational capacity, we reduce the matrix into 32 × 32. Thus, each strip column represents a width of 3.125µm as in Fig. 2. In this analysis, RF losses are then integrated from the normal zones in each 100 µm × 3.125 µm strip, and the effective surface resistance is calculated. The black line in Fig 4A locates one such typical strip on a BCP-treated Nb sample. A more precise analysis would need to reduce this strip width.

The indicated increasing RF loss with field is only contributed from the normal conducting zone expansion while ignoring the loss in the superconducting zone, so would represent a lower bound on actual losses. Fig. 5 gives the relation between RF loss and external field for each of the 32 sample strips which together represent one 100 µm × 100 µm area of a BCP-treated fine grain Nb sample, and the resulting average loss as a function of peak field. Fig 6 shows that average loss together with the same analysis applied to data from a 100 µm × 100 µm AFM scan of an electropolished niobium surface.

IMPLICATIONS FOR Nb CAVITIES

We would like to understand the implications of such non-linear loss mechanisms on the performance of SRF cavities. Detailed analysis within a cavity is challenging because the effective R_s is a function of local H_{pk}, not the global H_{pk}. Taking the simplifying approximation that the amplitude of surface *H* field is zero in the regions near irises and maximum along in the cells of a representative elliptical β=1 accelerating cavity, we are able to derive the expected effects on a typical cavity *Q* were the whole surface to be similar in topography to the samples modelled here.

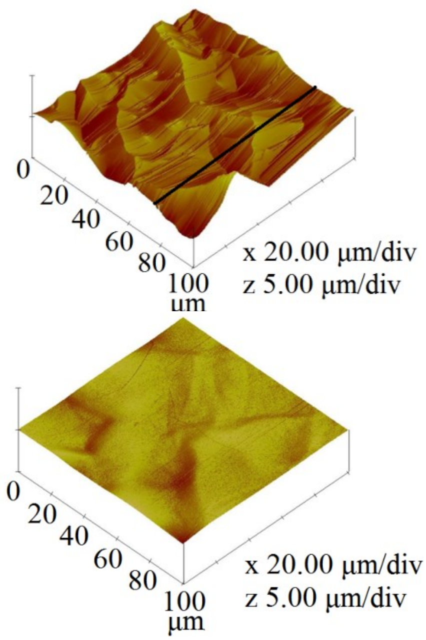

Figure 4: AFM images from a fine grain niobium sample with a) ~ 100µm removal by BCP, b) after 48 µm removal by electropolish at 30°C. Horizontal scale is 20 µm per division and vertical scale is 5 µm per division.[6]

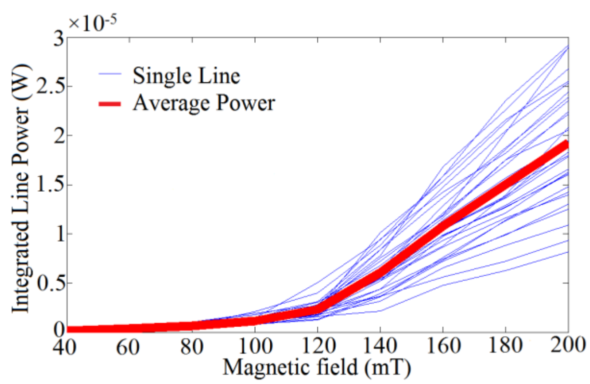

Figure 5: Calculated RF power dissipation on each 3.125 µm wide strip as a function of peak macro surface H field for a 100 µm × 100 µm BCP treated fine grain Nb surface.

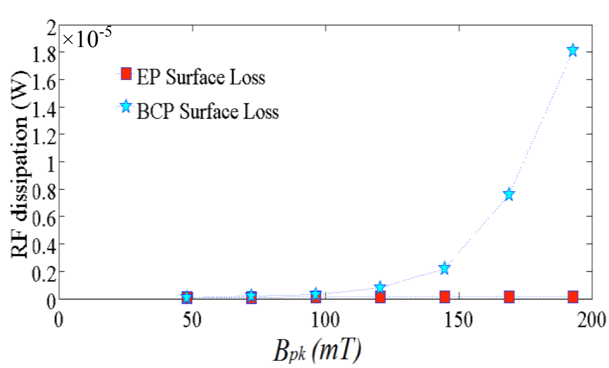

Figure 6: Average power dissipation on representative 3.125µm × 100 µm strip with BCP and EP induced surface topography as a function of peak macro H field. Superconducting state losses are ignored.

For 1st-order simplicity, the BCS surface resistance is presumed to have no field-dependence. At 1.5 GHz, R_{BCS} is ~13 nΩ at 2 K. Consequently, Q_0 is dominated by BCS resistance at low field. Figure 7 shows the results of this simplified calculation of cavity Q dependence on surface field of the two surfaces topographies considered. Above 80 mT, non-linear losses become significant. Above ~110 mT the results are overly optimistic, since the temperature dependence of the BCS component has been neglected in this simple model. As the normal zones grow, some of the simplifying assumptions break down, the superconducting material losses become non-negligible, and the Q drops faster than is modelled here.

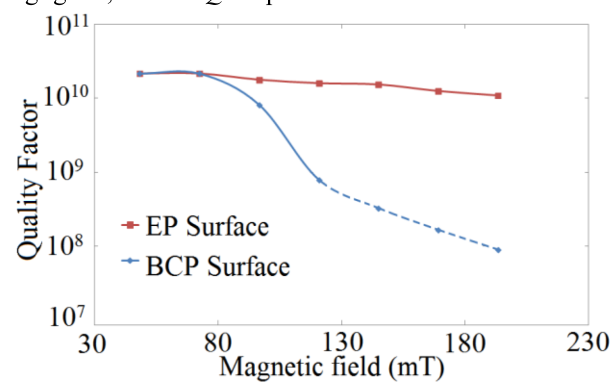

Figure 7: Simulated topography-limited Q for BCP and EP fine-grain Nb surfaces.

SUMMARY

Simplified electromagnetic and thermal simulations have been developed to analyze the microscopic scale geometric surface field enhancement and the normal/superconducting material interface when the local field exceeds H_c. The normal zone areas contribute significantly to the RF power loss. The volume of the normal zones on the surface expand nonlinearly with increasing external magnetic field. Such nonlinearity in dissipative RF power is represented by an effective non-linear surface resistance. Initial results of this analysis using representative topographic profile data from typical BCP etched and electropolished fine grain niobium surfaces yield a nonlinear loss character and Q dependence with field which are quite similar to that typically observed with L- band SRF accelerating cavities with the corresponding surface treatments.

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