SURFACE ROUGHNESS EFFECT ON THE PERFORMANCE OF Nb_3Sn CAVITIES*

R. Porter†, D. L. Hall, M. Liepe, J. T. Maniscalco
Cornell Laboratory for Accelerator-Based Sciences and Education (CLASSE),
Ithaca, NY 14853, USA

Abstract

Surface roughness of current Niobium-3 Tin (Nb_3Sn) superconducting radio-frequency (SRF) accelerator cavities can cause enhancement of the surface magnetic field. This enhancement can push the surface magnetic field beyond the critical field, which, if it occurs over a large enough area, can cause the cavity to quench. This paper presents simulations of the surface magnetic field enhancements in SRF cavities caused by the surface roughness of current Cornell Nb_3Sn cavities, which have achieved record efficiency. Simple, smooth cavity geometry is defined and surface magnetic fields calculated using SLANS2. The cavity geometry is modified with a small rough region for which the geometry is determined from AFM scans of a Nb_3Sn coated sample and the surface fields are calculated again. The calculated surface fields of the smooth and rough cavities are compared to determine the extent of the field enhancement, the area over which the enhancement is significant, and which surface features cause large field enhancement. We find that 1% of the surface analyzed has fields enhance by more than 45%. On average the Q-factor is increased by (3.8 ± 1.0)%.

INTRODUCTION

Nb_3Sn cavities produced at Cornell University [1–3] have rougher surfaces than conventional Niobium cavities. Previous simulations and calculations have shown that both bumps and pits in the surface of a cavity can cause local enhancement of the surface magnetic field [4,5]. If the magnetic field is sufficiently enhanced over a large enough area it could lower the quench accelerating field of the cavity. The increased surface area and changes in local magnetic surface field could also impact the quality (Q) factor of the cavities. When analyzing experimental data the average surface resistance is usually derived from the measured quality factor assuming a smooth cavity surface, so any significant difference could impact previous analysis of Nb_3Sn cavities.

Here we present electromagnetic simulations of the impact of the observed surface roughness of Nb_3Sn cavities on the enhancement of surface magnetic fields and Q-factors. We define the H-field enhancement, β, as $\beta = H_{rough}/H_{smooth}$, where H_{rough} is the surface H-field along the rough surface and H_{smooth} is the surface H-field along the smooth surface. The Q-factor enhancement is defined as Q_{rough}/Q_{smooth}, where Q_{rough} is the Q-factor of the rough cavity and Q_{smooth} is the Q-factor of the smooth cavity.

* Work supported by U.S. DOE award DE-SC0008431

† rdp98@cornell.edu

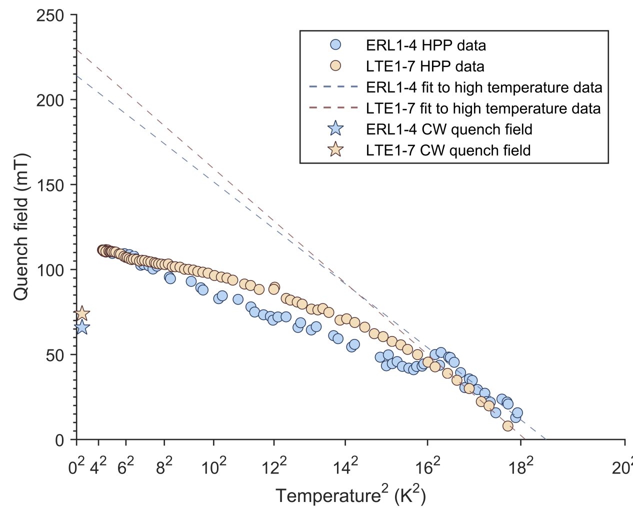

Figure 1: Plot of quench field (calculated from stored energy) versus T^2 from klystron high pulsed power measurements of Cornell Nb_3Sn cavities [6]

THE SUPERHEATING FIELD

Klystron high pulsed power measurements near Tc (see Fig. 1) suggest the superheating field in our Nb_3Sn cavities is ≈230 mT (extrapolated 0 K) [6]. This is significantly lower than theoretical calculations that predict superheating fields of ≈400 mT (at 0 K) [7]. In these results the surface quench field is calculated based on the energy within the cavity, assuming a completely smooth geometry. If the cavity is quenching at locations where the surface H-field is enhanced then the actual H-field causing the quench is higher than what is calculated. Not including field enhancement from surface roughness effects is likely the cause of the lower experiment results.

METHOD

The surface height data was taken from Atomic Force Microscope (AFM) scans of Nb_3Sn samples that were coated at Cornell University (see Fig. 2). The calculation of the surface magnetic was done using the 2D finite element code SUPERLANS2 (SLANS2) [8]. This code calculates non-azimuthally symmetric modes in azimuthally symmetric cavities.

The method of calculation used was based on the work of V. Shemelin [4], in which the surface magnetic fields of pits and bumps were calculated using SLANS2. This was done by creating a model with an elliptical bump or rounded pit in the center of the flat end of an otherwise

ISBN 978-3-95450-169-4

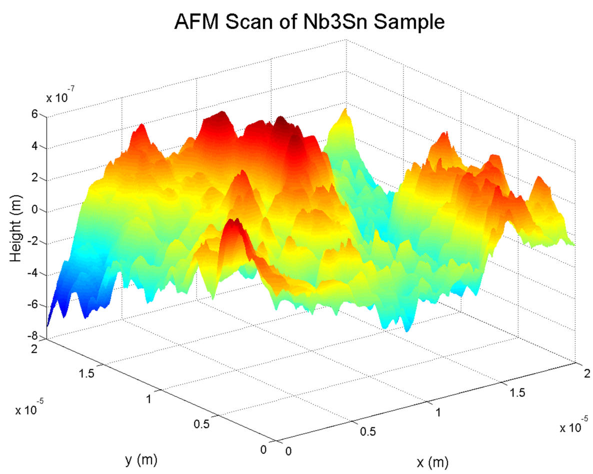

Figure 2: A surface plot of an AFM scan of a Nb_3Sn surface.

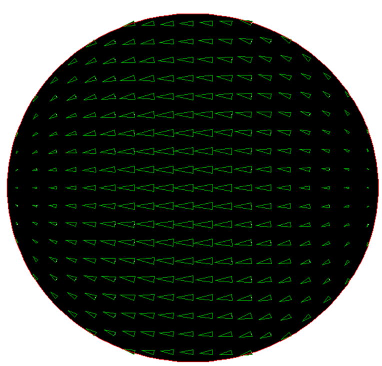

Figure 3: Vector field plot of the surface H-field at the flat end if a cylindrical pillbox cavity operated in the TE-111 mode.

cylindrical cavity, then solving for the magnetic fields in the TE-111 mode. The TE-111 mode in a cylindrical cavity has an approximately constant, uniform surface magnetic field at the flat ends of the cavity (see Fig. 3), making this location ideal for calculating the magnetic field enhancement in a uniform field.

3D height maps could not be used because SLANS2 is limited to azimuthally symmetric geometry. Instead, line segments were taken through the 3D height data to create segments such as the one shown in Fig. 4. This 2D data is given to SLANS2, which solves for the electromagnetic field assuming this height map data is rotated 360° to create the 3D geometry.

The magnetic fields are not truly constant inside the cavity. In this mode, the magnetic field decreases when moving transversely towards the center of the cavity and when moving radially away from the center. When setting up the models it was important to ensure the rough geometry remained where the field is approximately constant (without roughness). Shemelin and Padamsee [4] adjusted the size of the ellipsoidal bumps while keeping the geometric ratios (height to width) constant. When the bump penetrated more than $1/80^{th}$ of the way into the cavity (end to end), the H-field enhancement factor dropped by 0.01, as such, our rough patch geometry was scaled[1] so that it did not penetrate this far into the cavity. Radially, it was noticed that for a smooth cavity the H-field dropped by 5% when moving out $1/10^{th}$ of the way from the center of the cavity, as such, the geometry was scaled so that it did not exceed this. In addition, the rough patch could not significantly change the electromagnetic fields elsewhere in the cavity. For all geometries tested with the above conditions, the frequency of the mode only changed by 0.1% and the fields were equal far from the rough patch.

The height map data could not be directly input into the SLANS2 geometry. Doing so would command SLANS2 to linearly interpolate the points, creating a geometry with sharp spikes. Instead, smooth curves are needed. The only curve available in SLANS2 is an elliptical arc. In order to input the geometry an algorithm was written to interpolate the height map data using non-rotated ellipses. This algorithm was written so that the interpolated line appeared to be a reasonable estimate of geometry (no wild oscillations between data points), but the algorithm did not minimize the curvature. This could bias the results since the H-field enhancement is dependent on the curvature of the geometry.

The mesh density was optimized by increasing the mesh density until the improvement was not considered worth the increased computation time. Densities of 1, 2, 4 and 6 mesh cells per data point were tested. In general, the field enhancement increased everywhere, and the quality factor decreased, with increasing mesh density. Going from 4 to 6 increased the field enhancement by approximately 0.01 and decreased the quality factor by approximately 1%. Increasing to 6 mesh cells would reduce the maximum length of sample that could be simulated, so 4 mesh cells was chosen.

To choose the samples studied, a procedure was established to pick segments: A cross section was taken through an AFM map; a flat spot near the average height of the sample was chosen as the starting point; another flat point was chosen that 1.5 to 3 µm away (the furthest point was chosen if available). This was done to try to keep the samples as randomized as possible within the restraints of the computation. The ≈3 µm upper limit was chosen because longer segments often failed to compute in SLANS2. 20 samples were chosen this way. The average length of a sample was 2.24 µm.

RESULTS AND DISCUSSION

The magnetic field enhancement was computed by taking the ratio of surface magnetic fields at the same radial component, r (e.i. $\beta(r) = H_{rough}(r, h(r))/H_{smooth}(r, 0)$, where h(r) is the height at r of the rough surface). This ratio was taken along the surface H-field line through r = 0. The result is shown in Fig. 4 for one rough patch.

[1] The surface H-field enhancement factor in an initially uniform H-field is independent of the scale of the feature and only depends on the relative geometry [5]

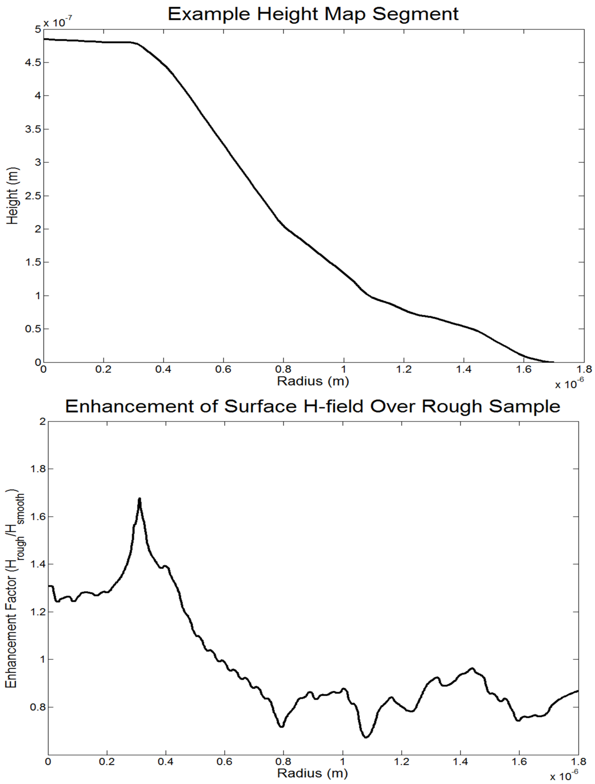

Figure 4: Top: A 1D AFM height map used for simulating surface H-field. Bottom: The field enhancement found for the height map shown above.

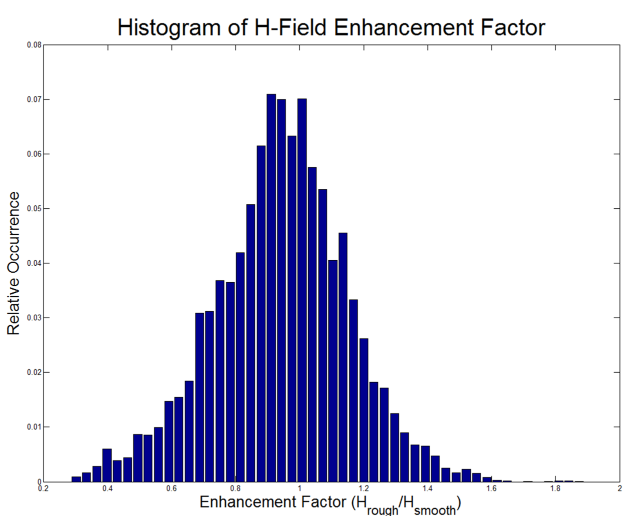

Figure 5: Histogram of relative area with a certain H-field enhancement factor.

The H-field enhancement factor of all mesh cells in the rough patch of all 20 samples is histogrammed in Fig. 5. This histogram is weighted for the arc length of the mesh cell. The mean of the distribution is $(0.958 \pm 0.011(stat))$. 10% of the points are over 1.2, 5% of the points are above 1.29 and 1% of the points are above 1.45.

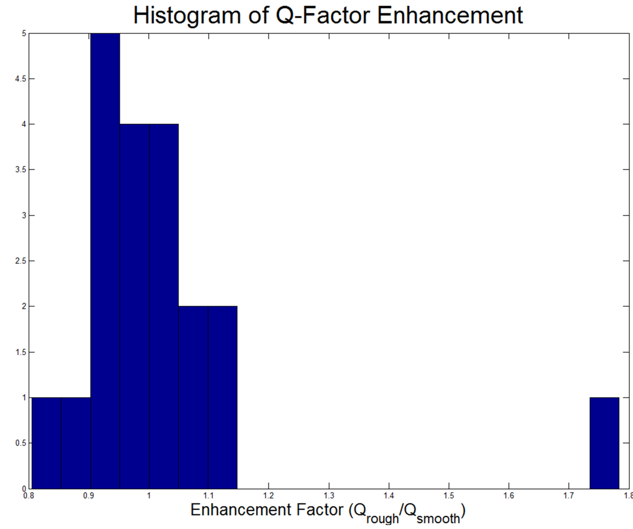

Figure 6: Histogram of quality factor enhancement of the samples simulated. The weighted (by length) mean of the distribution is $(1.038 \pm 0.010(stat))$.

To calculate the enhancement of the quality factor $\sum H^2\, ds$ (where ds is the arc length) was computed over the rough region (or equivalent region on the smooth geometry) for the rough and smooth geometries and the ratio of the two was taken. This assumes that no location surpasses the critical field and becomes normal-conducting or anything else changes the surface resistance (R_s independent of H).

Figure 6 shows an (unweighted) histogram of the Q-factor enhancements for all 20 samples. The weighted (by length) mean of the distribution is $(1.038 \pm 0.010(stat))$.

CONCLUSION

Field enhancement due to surface roughness must be accounted for when determining the superheating field from high pulsed power measurements. Assuming (roughly) that 1% of the cavity becoming normal conducting is enough to cause a quench, Cornell University klystron pulsed power experiments suggest a superheating field of 1.45×230 mT = 330 mT. This brings measurements much closer to the theoretical prediction of 400 mT.

It is not, however, important to consider surface roughness when calculating average surface resistance from experimental Q data, as the roughness causes almost no change in Q-factor. This assumes that no fields are high enough to drive parts of the surface normal conducting. As discussed by Kbobloch et al. for Niobium cavities [9], if fields are high enough that some enhanced regions start to go normal-conducting then the quality factor will begin to drop, making roughness effects important.

REFERENCES

[1] S. Posen and M. Liepe, "Stoichiometric Nb3Sn in First Samples Coated at Cornell," in *Proceedings of SRF 2011*, Chicago, Illinois, July 2011.

ISBN 978-3-95450-169-4

[2] S. Posen, M. Liepe, and Y. Xie, “Cornell SRF New Materials Program,” in *Proceedings of IPAC 2011*, San Sebastian, Sept. 2011.

[3] S. Posen, G. Hoffstaetter, M. Liepe, and Y. Xie, “Recent Developments in Cornell Nb3Sn Initiative,” in *Proceedings of IPAC 2012*, New Orleans, Louisiana, May 2012.

[4] V. Shemelin, and H. Padamsee, “Magnetic field enhancement at pits and bumps on the surface of superconducting cavities,” Cornell University, Ithaca, New York, SRF Report 080903-04, July 2008.

[5] arXiv, `https://arxiv.org/pdf/1407.0767.pdf`

[6] D. L. Hall, J. J. Kaufman, M. Liepe, J. T. Maniscalco, and R. Porter, “High Performance Next-Generation Nb_3Sn Cavities for Future High Efficiency SRF LINACs,” presented at *Proceedings of LINAC 2016*, East Lansing, Michigan, Sept. 2016.

[7] S. Posen, “Understanding and Overcoming Limitation Mechanisms in NB3SN Superconducting RF Cavities” Ph.D. thesis, Phys. Dept., Cornell University, Ithaca, New York, 2014.

[8] D. G. Myakishev and V. P. Yakovlev, “The new possibilities of SuperLANS code for evaluation of axisymmetric cavities,” in *Proc. of 1995 PAC and Int. Conf. on High-Energy Accel.*, Texas, May 1995

[9] J. Knobloch, R. L. Geng, M. Liepe, and H. Padamsee, “High-Field Q Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries,” in *Proceedings of 9th International workshop on RD Superconductivity*, Sante Fe, New Mexico, 1999.