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PROGRESS IN Nb_3Sn SRF CAVITIES AT CORNELL UNIVERSITY*

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Abstract

Niobium-3 Tin (Nb_3Sn) is the most promising alternative material for next-generation SRF cavities. The material can obtain high quality factors (> 10^{10}) at 4.2 K and could theoretically support ≈ 96 MV/m operation of a TESLA elliptical style cavity. Current Nb_3Sn cavities made at Cornell University achieve high quality factors but are limited to about 17 MV/m in CW operation due to the presence of a surface defect. Here we examine recent results on studying the quench mechanism and propose that surface roughness is a major limiter for accelerating gradients. Furthermore, we discuss recent work on reducing the surface roughness including chemical polishing, modification of material growth, and tin electroplating.

INTRODUCTION

Niobium-3 tin (Nb_3Sn) is the most promising alternative material to niobium (Nb) for superconducting radio frequency (SRF) accelerator cavities. This material has nearly twice the critical temperature (T_c = 18 K *vs.* 9.2 K [1]) compared to Nb and nearly twice the superheating magnetic field (≈ 425 mT *vs.* ≈ 220 mT [2]). The high T_c allows for higher quality factors (Q) and for 4.2 K operation where complex cryogenic equipment can be removed from the accelerator or cryocoolers can be used for small scale accelerators. The increased superheating field allows for larger accelerating gradients (E_{acc}), with the potential to reach ≈ 96 MV/m in a TESLA style elliptical cavity.

Cornell University has a strong program to create Nb_3Sn accelerator cavities [3–7]. Due to the material being brittle it cannot be shaped after it is created. Instead, a niobium cavity is formed and then coated in Nb_3Sn. This is done by vaporizing Sn in a higher temperature vacuum furnace and allowing it to absorb into the Nb.

Figure 1 shows a temperature profile of the coating process [8]. The first stage is a nucleation step where Sn_2Cl is vaporized at 500 C for 5 hrs. This material has a much higher vapor pressure at 500 C then Sn and decomposes on the surface of the cavity to leave Sn nucleation sites. After the nucleation phase the temperature of the cavity is raised to ≈ 1120 C for a coating step. Simultaneously a crucible of Sn is raised to 1400 C to increase the flux of Sn vapor reaching the cavity. Coating occurs for 1.5 hrs and then the Sn crucible heater in turned off and the temperature drops to 1120 C where the Sn vapor pressure is much lower. The cavity is held at this temperature for 1 hr as an annealing step to allow excess Sn to absorb into the cavity. After the process is complete the cavity is covered in 2–3 µm of Nb_3Sn.

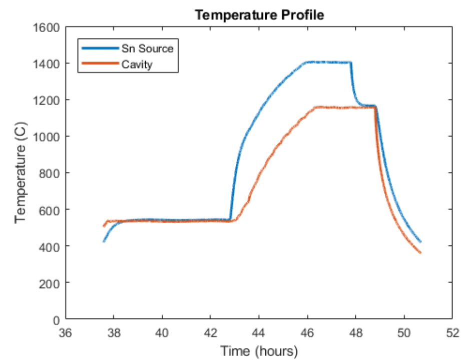

Figure 1: Temperature profile from the coating of a Nb_3Sn cavity. Both the temperature of the cavity and the Sn source are shown.

Current state-of-the art Nb_3Sn cavities at Cornell university achieve a 4.2 K quality factor of $2 \cdot 10^{10}$ and a maximum accelerating gradient of 15–18 MV/m at 1.3 GHz. Figure 2 shows an example Q *vs.* E_{acc} plot. The accelerating gradient achieves a usable field level but is much below the theoretical limit. Increasing the quench field is active area of research [9].

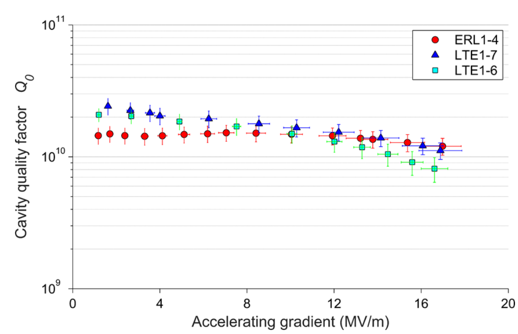

Figure 2: Q *vs.* E at 4.2 K of several 1.3 GHz TESLA elliptical cavities made at Cornell University.

Recent progress at Cornell University has focused on increasing the frequency [10, 11] and accelerating gradients of these cavities. In this paper we discuss recent progress in understanding the quench field. We propose that reducing the surface roughness of Nb_3Sn cavities should increase the achievable accelerating gradient. Finally, we discuss recent results in creating smoother Nb_3Sn.

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QUENCH MECHANISM

Previous work has shown that the quench starts at a localized region, caused by thermal runaway on the location [4, 12]. Figure 3 shows a quench map of a Nb_3Sn cavity. This quench map is produced by measuring the temperature on the exterior of the cavity. The temperature is integrated on each sensor as the cavity continually goes through quench, leading to a higher average temperature at the origin of the quench. This measurement reveals the localized aspect of the quench and the location where it occurs (within ≈ 1 cm).

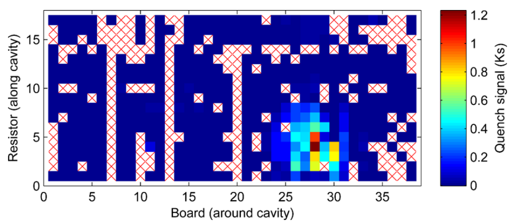

Figure 3: A quench map of a Nb_3Sn cavity showing localized heating into the bottom right sector. This demonstrates to localized area of the quench. Note: red x's show thermometers that failed during the test.

Further work has been done on the time evolution of temperature occurring at the quench site that shown sudden temperature jumps at the quench [4, 12]. This has been done by measuring solely the thermometer at the quench site at a 25 kHz rate while the RF field rises and falls in the cavity. The RF field nears the quench field but not does reach it. Figure 4 shows a key result from this study. The cycle starts with linear heating (with respect to B^2), indicative of Ohmic heating, but then then sudden jumps are seen in the temperature when near the quench field. When the RF field falls there are similar jumps down in temperature but there is a hysteresis. Further investigation and analysis found the larger temperature jumps to be integer multiple of the smallest jump [4, 12].

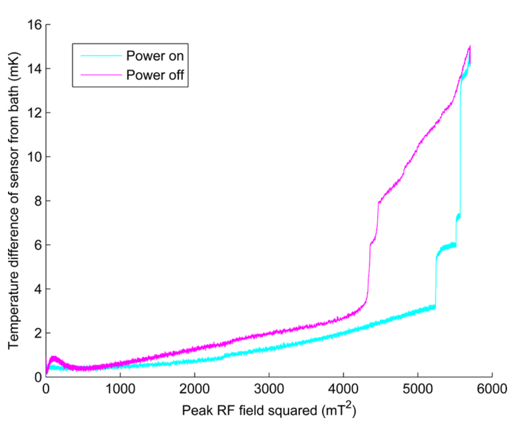

Figure 4: Measuring the temperature rise at the quench site (outside surface) with respect to time as the RF field rises (cyan) and then falls (magenta) in the cavity. The cavity does not quench during the cycle. Temperature jumps are present at higher RF field levels (near quench).

The apparently quantized nature of the temperature jumps and the hysteresis could indicate that magnetic vortices are entering the material. The quench in these cavities occurs well above H_{c1} of Nb_3Sn, meaning that the cavities are operating in a meta-stable Meissner state during the temperature jumps and magnetic vortices are energetically favorable in the material. At the moment magnetic vortex entry remains our primary candidate for the quench mechanism.

Microscopy at the quench site has not revealed an obvious defect in the coating. Figure 5 shows an SEM scan in the area where the quench location is likely located. There is no obvious culprit found with this microscopy. The small superconducting coherence length (4.2 nm [1]) of Nb_3Sn and the low resolution of the temperature map (≈ 1 cm between sensors) makes locating the defect using microscopy challenging. Only general characteristics of the film can be learned through microscopy; in particular, we find that the Nb_3Sn film is considerably rougher compared to standard electropolished Nb [13].

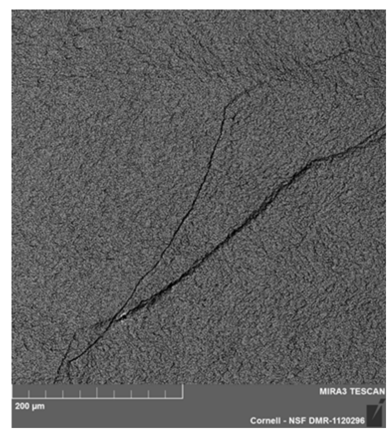

Figure 5: SEM scan of a quench site cut out from a cavity. The black lines are likely Nb substrate grain boundaries.

QUENCH MECHANISM THEORY

The rough Nb_3Sn surface could be severely limiting the maximum accelerating gradient. The surface has 1 µm peak-to-peak (over 20 µm^2 area) surface roughness [13]. This can cause deleterious effects in (at least) two ways: by causing magnetic field enhancement; and by creating geometry that allows for easier entry of magnetic vortices.

Sharp surface features from the surface roughness pinch up the magnetic field and create a region of increased magnetic field on the tip of the feature. Previous work has simulated the impact of the rough Nb_3Sn surface on the surface magnetic field of the cavity [13] and a histogram of the field enhancement is shown in Fig. 6. We are far enough below the quench field and the enhancement distribution is narrow enough that it seems unlikely that any suitably large enough site reaches the superheating field. However, whatever the quench mechanism is, there are likely a multitude of them and the first one to activate and cause quench is likely sitting on a field enhanced region. Thus, reducing the surface

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roughness could increase the quench field by reducing the field enhancement this defect sees.

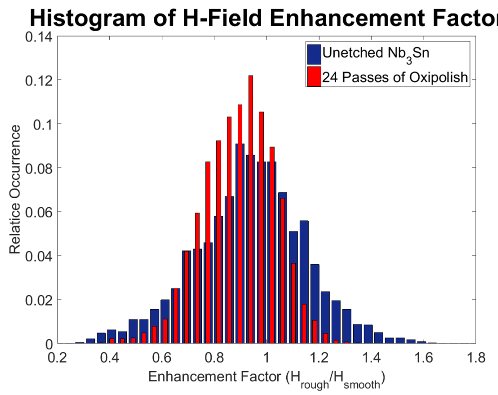

Figure 6: Histogram of magnetic field enhancement of Nb_3Sn and oxypolished Nb_3Sn [14]. The y-axis shown the relative fraction of surface at a field enhancement value.

A. Pack et. al. have been conducting time-dependent Ginsburg-Landau simulation of magnetic vortex entry at grain boundaries in Nb_3Sn [15]. The work finds that both bad chemical composition and steep grain boundary geometries can lead to early vortex entry. In addition, it is found that a small number of magnetic vortices can be nucleated into the Nb_3Sn grain boundary, without entering the bulk or causing an avalanche of magnetic vortices. At a higher field (below the superheating field) vortices are then able to enter the bulk. This was only shown when grain boundaries had suppressed T_c. This is not commonly seen in Cornell Nb_3Sn coatings, but some poor grain boundaries may exist, or T_c suppression may not be required for this phenomenon. These simulations are similar to the experimental observations that suggest magnetic flux entry.

Though there are other possible explanations of the quench mechanism and observed temperature rise [16], these mechanisms suggest that reducing the surface roughness may increase the achievable accelerating gradients in Nb_3Sn cavities. Furthermore, decreasing surface roughness is both achievable and a direct test that could be used to (at least) disprove the hypothesis. This leads us to pursue decreasing surface roughness as a next step to improving Nb_3Sn cavity accelerating gradients.

DECREASING SURFACE ROUGHNESS

Decreasing the surface roughness of the Nb_3Sn has two obvious paths: chemically polishing the Nb_3Sn surface or preventing the film from becoming rough. Cornell University has been investigating both routes in pursuit of reducing the surface roughness.

We have conducted preliminary investigations of standard chemical polishing techniques used on Nb cavities. The usage of these techniques is difficult as we only have a 2-3 µm film. The preliminary studies found that oxypolshing [14] (see Fig. 6) could half surface roughness and field enhancement with ≈ 1 µm of material removal. However, careful chemical analysis must still be conducted to ensure film quality has not been compromised. Initial studies of electropolishing have found similar reductions in surface roughness, but etching was non-uniform and chemical composition may have been compromised [17]. These early results are promising but further development is needed before these techniques can be applied to a cavity.

Another route is to change the coating process to create smoother surface. We have been studying the growth of Nb_3Sn in our high temperature vacuum furnace to understand the formation of surface roughness and other material defects [18–21]. One result has been that the nucleation step is key to determining the final surface roughness. We believe if we can achieve more, evenly spread nucleation sites we can reduce the surface roughness. Work is ongoing to change the nucleation step to do this.

A very promising Sn plating technique has been developed by Z. Sun *et al.* at Cornell University that improves final surface roughness [22]. Z. Sun developed a process to electroplate Sn onto Nb. This allows nucleation to be replaced by electroplating a smooth Sn layer onto the Nb substrate (sample). After the plating we baked the sample in our high temperature vacuum furnace, following our regular coating procedure (without Sn_2Cl present) to produce Nb_3Sn.

The final Nb_3Sn layer was much smoother than our regular Nb_3Sn production process. This reduced the surface from $R_a \approx 300\,\text{nm}$ to $R_a \approx 60\,\text{nm}$, a five times reduction is surface roughness. This gives us a new technique to produce smooth Nb_3Sn.

CONCLUSION

Reducing the surface roughness of Nb_3Sn is a promising avenue to increasing accelerating gradients in Nb_3Sn SRF accelerators cavities. Estimating the amount of increase expected is difficult. There are several promising results to creating smooth Nb_3Sn including chemical polishing, modifying nucleation steps, and applying Sn using electroplating instead of vapor deposition. In particular, the Sn electroplating technique has already shown a 5 times reduction in surface roughness in sample studies. Further work will be conducted on improving surface polishing and Sn nucleation, and we extend Sn plating technique to work on cavity geometries. We plan to test a smooth Nb_3Sn cavity soon in order to verify the hypothesis.

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