NEXT GENERATION Nb₃Sn CAVITIES FOR LINEAR ACCELERATORS*

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Abstract

Niobium-3 Tin (Nb₃Sn) is a very promising alternative material for SRF accelerator cavities. The material can achieve higher quality factors, higher temperature operation and potentially higher accelerating gradients ($E_{acc} \approx$ 96 MV/m) compared to conventional niobium. This material is formed by vaporizing Sn in a high temperature vacuum furnace and letting the Sn absorb into a Nb substrate to form a 2-3 µm Nb₃Sn layer. Current Nb₃Sn cavities produced at Cornell achieve $Q \approx 2 \cdot 10^{10}$ at 4.2 K and $E_{acc} = 17$ MV/m. Here we present a summary of the current performance of Nb₃Sn cavities at Cornell and recent progress in improving E_{acc}.

INTRODUCTION

Nb₃Sn possesses a high critical temperature (18 K [1]) and superheating field (425 mT [2]) giving it the potential for higher quality factors than Nb, 4.2 K operation, and for accelerating gradients of ≈ 96 MV/m. Cornell has a leading program in developing Nb₃Sn accelerator cavities [3–7]. Here we present the current status of the material and review recent progress. In particular we discuss the cause of the low (relative to the maximum possible for this material) quench fields and progress towards raising them.

Nb₃Sn GROWTH PROCESS

Nb₃Sn accelerator cavities cannot be pressed out of a Nb₃Sn sheet as can conventional Nb cavities due to the difficulty of making Nb₃Sn and its brittle nature. Instead, current Nb₃Sn cavity programs use Sn vapor deposition to grow Nb₃Sn on a Nb substrate that is already in the shape of a cavity [8]. In this process an Nb cavity is placed in a high temperature vacuum furnace with a crucible full of Sn and bowl of SnCl₂. After a $24 - 48$ hr degas step at 180 °C, the temperature is ramped to 530 °C, and held for 5 hrs while the nucleation agent, SnCl₂ vaporizes and decomposes on the Nb leaving behind Sn. The temperature is then raised to ≈ 1150 °C for coating where there is an appreciable Sn vapor pressure. Sn vapor lands on the surface of the cavity where it forms Nb₃Sn. To further increase the Sn vapor pressure the Sn crucible is heated to an even higher temperature. After 1.5 hrs at this temperature the crucible heating is turned off and the surface is allowed to anneal for 1 hr. This process forms a $2-3$ µm Nb₃Sn layer. Figure 1 shows the temperature profile for a Nb₃Sn coating run.
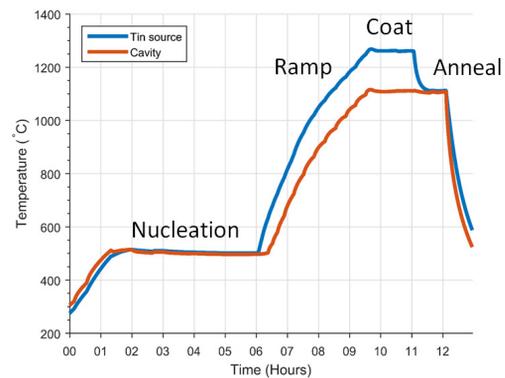
Figure 1: Temperature during Nb₃Sn coating showing both the cavity and the tin source temperatures.

CURRENT PERFORMANCE

Current performance offers transformational quality factors of $2 \cdot 10^{10}$ at 4.2 K and 1.3 GHz (see Fig. 2). This is more than a 20 times improvement in Q over Nb at 4.2 K, allowing 4.2 K operation. In CW operation our Nb₃Sn cavities currently quench around 17 MV/m, capable of meeting accelerator gradient requirement of some current CW LINACs. Pulsed operation (see Fig. 3) sees greater accelerating gradients of up to 26 MV/m [9]. These are usable accelerating gradients, but far below the theoretical maximum of 96 MV/m, giving Nb₃Sn a lot of room for improvement.
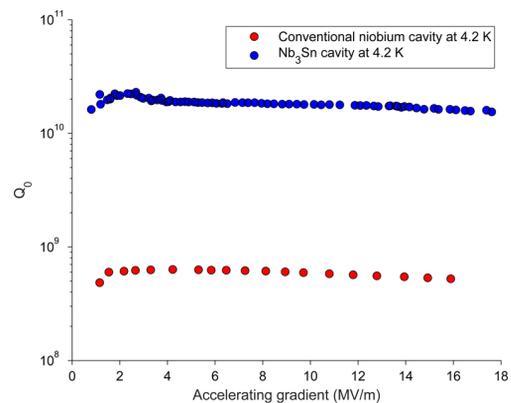

Figure 2: Q versus E performance of a Nb₃Sn cavity versus a Nb cavity at 4.2 K and 1.3 GHz.

THERMOMETRY OF DEFECT

Thermometry (temperature maps) reveal that quench are being caused by heating at some localized defect [10]. The key to raising the quench fields is removing the defect. This requires a firm understanding of what the defect is. To that end Cornell used time resolved thermometry of the quench
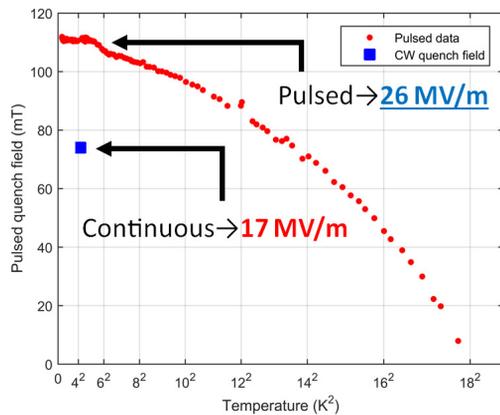
Figure 3: Pulsed quench field versus temperature squared with CW quench field at 4.2 K also shown. At 4.2 K the pulsed quench field reaches 26 MV/m.

site [11]. This revealed an interesting feature of the defect (see Fig. 4): at first when raising the electromagnetic field strength in the cavity the temperature increases with the field squared, as expected from Ohmic heating, but near the quench field there appear sudden jumps in temperature. These jumps appear to be quantized (multiples of the smallest jump). When the field is lowered again there are jumps back down but they occur at a lower field.
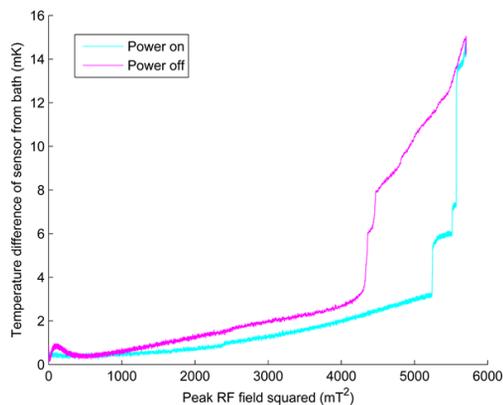

Figure 4: A plot showing the temperature rise of the defect (on the outside of the cavity) while the RF power is cycled and the maximum field is close to, but below, the quench field. Note the sudden jumps in temperature and the hysteresis between the rise and fall of the RF power.

The quantization, hysteresis, and some additional observations discussed in [4, 11] lead us to believe this is magnetic flux entry at a defect. A potential was proposed by Ahmad Sheikhzada and Alex Gurevich [12]. In this model a bad grain boundary could act like a Josephson junction and at critical fields permit quantized flux entry. It replicates many of the observed phenomena and we will be conducting further studies into the thermal properties of the defect to determine if it matches the theory.

Technology

Superconducting RF

SURFACE DEFECTS

In addition to thermal studies we have been using microscopy to look for surface defects that degrade performance or could cause quench. Two discovered defects are Sn depleted regions [10] and thin film regions [13].

Sn depleted Nb_3Sn has the correct crystal structure but with a lower atomic percentage of Sn (see Fig. 5). Sn depletion can heavily lower the critical temperature and possibly the superheating field (maximum possible quench field). These Sn depleted regions occur both on the surface and in the layer and seem to have different formation mechanisms. The surface Sn depleted regions seem to form when Nb_3Sn is annealed for too long. After all the free surface Sn is gone the layer will continue growing by stealing Sn from already formed Nb_3Sn, creating Sn depleted sites on the surface. So far, no surface sufficiently Sn depleted regions on the surface have been observed that could explain the current quench fields, but this may be because we can only look at a small fraction of the cavity surface and may not have seen particularly bad regions in the small sample. Sn depleted regions within the layer tend to have worse Sn depletion, but so far none have been observed near enough to the surface to impact performance. However, some may be closer to the surface and any chemical treatments to remove surface defects may expose this defect, necessitating removal/prevention. In the next section we will discuss a proposed method to prevent this defect.
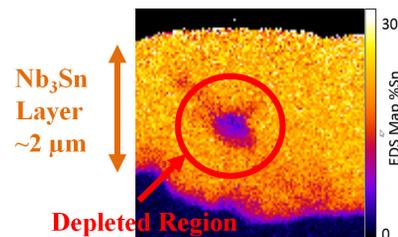

Figure 5: An EDS cross-section of a Nb_3Sn layer showing a tin depleted region within the Nb_3Sn layer.

In addition to Sn depletion, thin regions have been observed in the Nb_3Sn layer. These regions are a single crystal grain only a few hundred nm thick and large compared to the standard grain size. Figure 6 shows an EDS map of an Nb_3Sn surface where the thin regions are shown in red. This may not be thick enough to fully shield the RF field from the possibly highly lossy Nb-Nb_3Sn interface, decreasing Q. Great progress has been made on preventing this type of defect. It was found that growing a thick oxide on the surface (anodization) of the Nb substrate before coating could completely suppress this defect [13]. Studies into why anodization is effective are still on going.

LAYER GROWTH STUDIES AND GROWTH DYNAMICS

Once a defect is identified it must be removed or we must find a way to prevent the defect from forming to be-
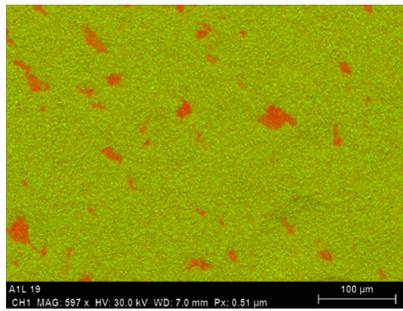
Figure 6: An EDS map of a Nb$_3$Sn surface. The regions in red are where the Nb$_3$Sn layer is thin and unable to shield the Nb from the RF field.

gin with. To prevent defects from forming we need a good understanding of how the Nb$_3$Sn grows. To accomplish this we have been conducting layer growth studies where the coating process is stopped at different points in the process (primarily while ramping up to the coating temperature of 1150 °C) [13]. These samples are then analyzed with microscopy.

False colored SEM scans are shown in Fig. 7 for various stopping temperatures and for substrates that were both anodized and with only the native oxide layer. After nucleation we can already see the difference between the two preparations, with the anodized surface having large droplets of Sn (red). At 800 °C we can see chunks of a Sn rich Nb-Sn compound of the surface (purple) surrounded by a thin layer of Nb$_3$Sn (green). These large Nb-Sn compounds undergo a phase transition to Nb$_3$Sn at 875 °C where purple is thick Nb$_3$Sn and green is thinner Nb$_3$Sn. Finally by 1120 °C we see more uniform Nb$_3$Sn, but the native oxide sample has formed a thin region highlighted in green.

The layer growth studies inform theoretical models based on Density Functional Theory that are being developed in collaboration with the Center for Bright Beams (CBB). Recently these models suggested a way to modify the growth process to prevent Sn depleted regions from forming in the layer [14]. In this model the Sn depleted regions form during a Sn-starved phase of the process when all the free Sn from nucleation is used before Sn the crucible gets hot enough to supply more (during the temperature ramp to the coating temperature). These sites can then get buried beneath enough Nb$_3$Sn that they can't get filled in once more Sn is available (Sn diffusion though Nb$_3$Sn is slow though bulk but fast through grain boundaries). A change was suggested of adding more SnCl$_2$ to prevent this from happening and is in the process of being tested.

CONCLUSION

Nb$_3$Sn is a promising material for future LINACs due to the high Q, 4.2 K operation, and high accelerating gradient limit. It currently offers high Q at 4.2 K and usable gradients. Great progress has been made in identifying and removing defects that limit E_{acc}. Many defect types have been identified such as thin film regions and Sn depleted
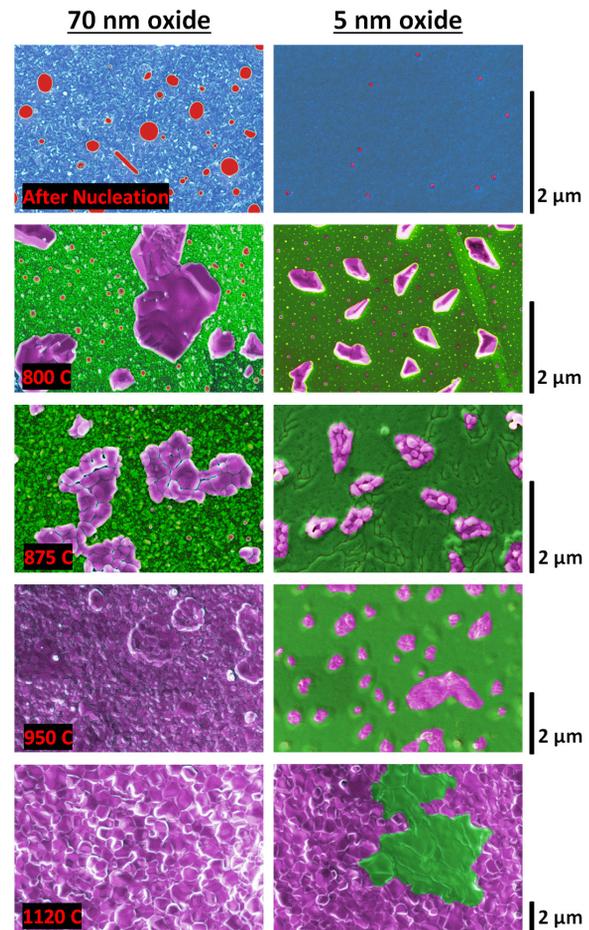
70 nm oxide **5 nm oxide**

Figure 7: False colored SEM images of layer growth samples of Nb$_3$Sn terminated at various temperatures in the growth process (see Fig. 1). Two different preparations are shown: one with a 70 nm oxide (anodized) and one with the native oxide layer. The images have been false colored to highlight regions with different morphology. Not false colored SEM images published in [13].

regions. Collaboration in the Center for Bright Beams with microscopists and theorists, combined with layer growth samples has led to an increased understanding of our growth process and has already led to suggestions on how to prevent Sn depleted regions. Flux entry at grain boundaries has been identified as a key quench mechanism. Further work will be conducted to understand this defect and mitigate its effects on performance.

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