FIRST RESULTS FROM NEW SINGLE-CELL Nb_3Sn CAVITIES COATED AT CORNELL UNIVERSITY*

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Abstract

Cavities coated with Nb_3Sn at Cornell University demonstrate quality factors of $>10^{10}$ at 4.2 K, outperforming equivalent niobium cavities by a factor of >30 at these bath temperatures. These quality factors have been maintained up to fields of 17-18 MV/m without significant Q-slope. Recently, new single-cell cavities have been added to the Cornell Nb_3Sn programme in an effort to improve statistics and allow further exploration of the available parameter space. In this paper we report on the first results of these new cavities, as well as the latest performance from other cavities already in use on the programme. Furthermore, continuing work to optimise the coating procedure is reported on, and the latest understanding of the ideal coating profile is discussed.

INTRODUCTION

The A15 superconductor Nb_3Sn has proved itself to be a promising next-generation alternative to niobium in SRF accelerator cavity applications [1–5]. In particular, 1.3 GHz single-cell niobium cavities coated with a thin layer of Nb_3Sn at Cornell University using the vapour diffusion method have demonstrated quality factors of $Q_0 > 10^{10}$ at 4.2 K at fields of 14-17 MV/m, although they require a slow cooldown through the transition temperature to do so [6]. With a superheating field of 400 mT [7], however, the theoretical limitation on Nb_3Sn is far higher, approaching 90 MV/m in ILC-style cavities. As the limits of niobium are achieved – and, at time of writing, this is understood to have occurred, at least in R&D cavities – Nb_3Sn offers the opportunity of a next-generation replacement for the decades following.

The Nb_3Sn programme at Cornell, originally limited to the use of two ERL-style single-cell cavities, has previously been expanded to include two ILC-style single-cells [8], with two more having recently been added to the programme. In this paper we report on the latest results from these cavities as they are used to explore the coating parameter space and build statistics to drive the optimisation and development of the coating process.

COATING PROCEDURE

The coating procedure for Nb_3Sn is well described in Ref. [8], but will be briefly summarised here. A specially adapted ultra-high vacuum coating furnace, containing an internal coating chamber that can be isolated from the main heater filament vacuum space, is used to house the niobium substrate – cavity or sample – that will be coated. At the base of the coating chamber is a cylinder housing a crucible filled with high purity tin. Surrounding the cylinder is a secondary heating element, which allows the tin crucible – referred to as the *source* – to be held at a higher temperature than the coating chamber. This crucial feature allows careful control of the rate of evaporation of tin from the source versus the growth rate of the Nb_3Sn in the chamber. An annotated diagram of the coating setup is seen in Fig. 1.

The coating recipe used in the furnace consists of a number of common elements: 1) a 24+ hour degas at 180°C; 2) a 5 hour nucleation stage at 500°C during which time the $SnCl_2$ agent is allowed to decompose onto the substrate to form tin nucleation sites, aiding layer uniformity; 3) a ramp to coating temperatures, during which time a temperature gradient of > 100°C is maintained between the source and the chamber; 4) a coating stage, during which the source is held at a higher temperature than the chamber; 5) and an annealing stage, at which point the source heater is turned off, allowing the source to cool to the temperature of the chamber. A the end of the annealing step, the furnace is turned off and allowed to cool naturally.

Given in Table 1 are the specific coating parameters for the cavities whose performances are reported in this paper. The two types of cavities, bearing designation ERL – for Cornell's Energy Recovery Linac design – and LTE – an ILC-style design – are 1.3 GHz single-cells, similar enough

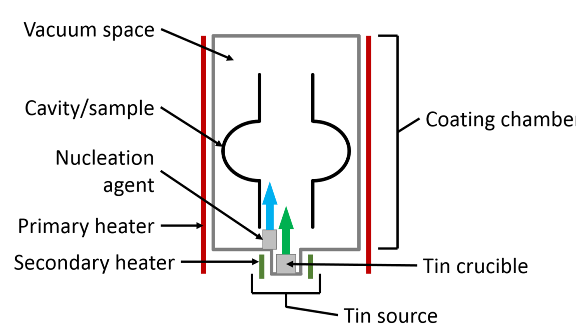

Figure 1: A simplified diagram of the Nb_3Sn coating furnace.

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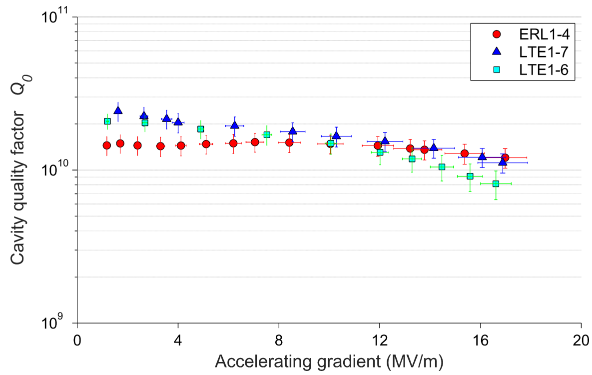

Figure 2: Quality factor vs. Accelerating field at 4.2 K bath temperature for three of the best cavity performances on the Nb_3Sn program.

in terms of operational parameters that comparisons between the two styles remain relevant.

RESULTS

The results from some of the best performing recipes, coated on ERL1-4, LTE1-6, and LTE1-7, are shown in Fig. 2. All three of these cavities achieve Q's approaching or exceeding 10^{10} at 4.2 K and 15-16 MV/m. Although all three had different coating recipes (albeit more similar to one another than other attempted recipes), they show remarkably similar performance, both in terms of highest Q_0, the amount of Q-slope, and the ultimate quench field.

Sample studies contemporary to these coatings revealed the presence of thin-film regions on the Nb_3Sn surface of many samples [9–11]. These regions, where the Nb_3Sn layer is thinner than 500 nm and therefore of insufficient thickness to screen the niobium substrate from the RF field. When the percent of surface area covered by these regions is large – exceeding 50% – the losses incurred from their presence are substantial, severely degrading the performance of the cavity. However, the presence of thin film regions has also been

Table 1: Specific Coating Parameters for Recent Cavities on the Cornell Nb_3Sn Program

Cavity	Recipe
ERL1-4	3 hrs at 1120°C with 1200°C source 30 mins annealing at 1120°C
LTE1-7	1.5 hrs at 1120°C with 1250°C source 1 hr annealing at 1120°C
LTE1-6 1st coating	1.5 hrs at 1120°C with 1250°C source 1 hr annealing at 1120°C
LTE1-6 2nd coating	Anodisation to 30 V 1.5 hrs at 1120°C with 1250°C source 1 hr annealing at 1120°C
LTE1-9	3 hrs at 1120°C with 1250°C source No annealing step
LTE1-10	4 hrs at 1050°C with 1200°C source No annealing step

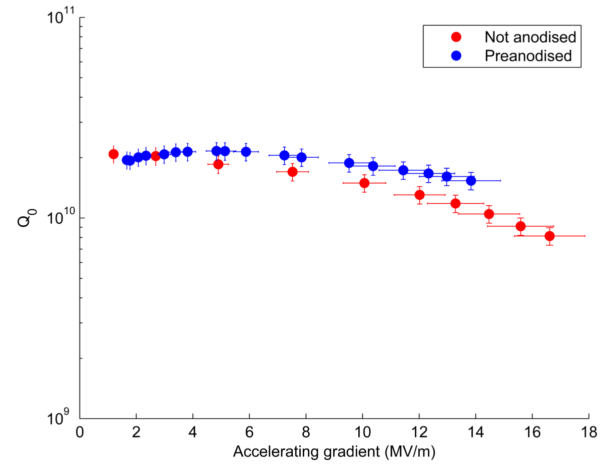

Figure 3: Quality factor vs. Accelerating gradient at 4.2 K bath temperature for a cavity having no anodisation before coating (red) and with pre-anodisation to 30 V before coating.

detected [10], albeit in smaller amounts of 2-7%, in samples manufactured from the same material use to produce the well-performing cavities seen in Fig. 2.

It has been shown that growing the oxide layer of the niobium substrate prior to coating using electrolytic anodisation will strongly suppress the formation of these layers, to the point in which their area coverage falls significantly below 1%, the detection limit of the method used to find them [3].

To determine whether the efficiency of a well-performing cavity could be further improved through the uee of pre-anodisation, the cavity LTE1-6 was stripped and pre-anodised to a voltage of 30 V, equivalent of growing an oxide of 70 nm thickness. The resulting substrate turned a pleasant sky blue colour. After pre-anodisation, the cavity was coated using the same recipe used for its first coating, as given in Table 1. The performance of the cavity relative to its original coating is shown in Fig. 3.

As can be seen, the cavity performance is improved, although the quench field was somewhat lower – although still within the limits most often seen in Nb_3Sn cavities, which leads us to believe that the lower quench field was not necessarily instigated by the use of pre-anodisation.

More recent studies into the quench field of the cavities has pointed to the presence of flux entry at fields approaching the quench field [12]. Calculations of the flux entry field from Ginsburg-Landau theory suggest that tin-depleted regions at the surface could significantly lower the field of flux entry. Such features, such as tin-depleted grains on the surface, have been seen in recent surface studies of sample coupons. Simulations done using Joint Density Functional Theory suggest the annealing step may be culpable for draining the surface, as, once the source is turned off, tin at surface features is carried by grain boundaries into the bulk.

To investigate this, the two new cavities on the program, LTE1-9 and LTE1-10, were coated without annealing step. Pre-anodisation was not used in these cavities. LTE1-9 re-

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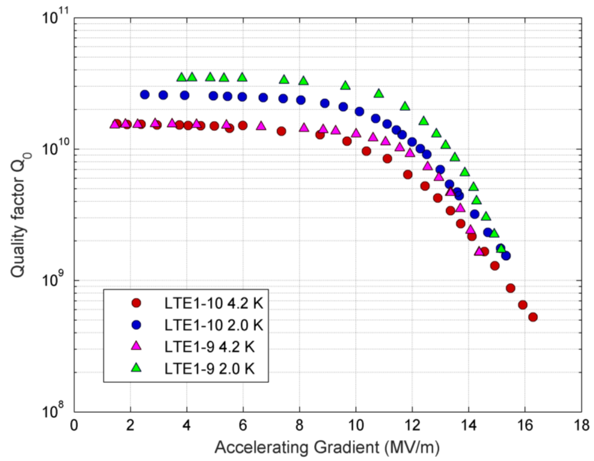

Figure 4: Quality factor vs. Accelerating field at 2.0 K and 4.2 K bath temperature for two cavities that received coating recipes that omitted the annealing stage.

ceived an identical coating to LTE1-7 barring the absence of the annealing step, whilst LTE1-10 was coated with the cavity at a lower chamber temperature of 1050°C. This was done because JDFT simulations [9] state that whilst both tin-depletion and the repair of tin-depleted regions is energetically favourable, with the latter being more so than the former, the balance may shift even more so towards depletion repair at lower temperatures.

The performance of LTE1-9 and LTE1-10 is given in Fig. 4. As can be seen, both suffer from onset of Q-slope, although, their low field quality factor is similar to the cavities seen in Fig. 2. Both quench at fields similar to those seen previously; LTE1-9 quenched at around 15 MV/m and LTE1-10 quench just above 16 MV/m.

The onset of Q-slope in both cavities does not appear to be of the same nature as that seen in previous Nb_3Sn cavities, but instead bears more semblance to losses from thermal feedback. Interestingly, sample coupons coated in a manner identical to TE1-9 showed an accumulation of un-alloyed tin on the surface of the thin film regions, but not on the thicker regions. This is likely due to the absence of grain boundaries in these thin film regions significantly slowing the uptake of tin, allowing it to accumulate in the absence of annealing step. It is possible that pre-anodisation could produce an un-annealed cavity free of Q-slope. Also being attempted is the use of a post-anodisation, in which the cavity is anodised to convert the un-alloyed tin into dielectric SnO_2, which will present lower losses and could remove the Q-slope. However, even in the absence of Q-slope, the insignificant change in the quench field seems to indicate that merely removing the annealing step did not mitigate the tin depletion at the surface. This is confirmed by contemporary sample studies, in which tin-depleted grains have been found in un-annealed samples.

CONCLUSION

Niobium cavities coated with Nb_3Sn repeatedly demonstrate quality factors of $> 10^{10}$ at 4.2 K, although are limited by a defect-based quench at fields of 14-17 MV/m. Substantial changes in the coating procedure have had no discernible impact on the value of the quench field, which is in agreement with previous results seen in 10 GHz cavities. The choice of recipe and preparation does, however, have a significant control on the onset of Q-slope. The removal of the annealing stage, with the intent of suppressing the presence of tin-depleted phases at the surface, results in the onset of Q-slope at and above 10 MV/m, although the quench field remains largely unchanged. Contemporary studies show that thin film regions accumulate un-alloyed tin in the absence of an annealing step, which create a thermal feedback mechanism that explains the Q-slope. The use of pre-anodisation before the cavity coating improves the quality factor via the removal of these thin regions, as has been shown previously in sample studies.

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