HIGH PERFORMANCE NEXT-GENERATION Nb_3Sn CAVITIES FOR FUTURE HIGH EFFICIENCY SRF LINACS*

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Abstract

A 1.3 GHz ILC-shape single-cell Nb_3Sn cavity fabricated at Cornell has shown record performance, exceeding the cryogenic efficiency of niobium cavities at the gradients and quality factors demanded by some contemporary accelerator designs. An optimisation of the coating process has resulted in more cavities of the same design that achieve similar performance, proving the reproducibility of the method. In this paper, we discuss the current limitations on the peak accelerating gradients achieved by these cavities. In particular, high-pulsed-power RF testing, and thermometry mapping of the cavity during CW operation, are used to draw conclusions regarding the nature of the quench limitation. In light of these promising results, the feasibility and utility of applying the current state of the technology to a real-life application is discussed.

INTRODUCTION

The A15 superconductor Nb_3Sn is a promising alternative for niobium in superconducting RF cavities. With a transition temperature of 18 K and a superheating field of approximately 400 mT [1, 2], the material has the potential for both greater efficiency at 2.0 and 4.2 K operation as well as higher operating gradients. The Cornell Nb_3Sn program began in 2009 [3–5], coating bulk niobium cavities with tin to form a thin Nb_3Sn layer using the vapour diffusion method [6].

In this paper we present the the latest performance results from the 1.3 GHz single-cell cavities in use at Cornell. We also discuss the limitation in accelerating gradient, currently understood to be due to a localised surface defect. Surface analysis of samples has revealed a number of features that could potentially lead to cavity quench, examples of which are given here. We conclude with a discussion on the next steps that will be taken to identify the current cause of quench in the single-cell cavities shown here.

SINGLE-CELL CAVITY PERFORMANCE

There are currently three 1.3 GHz single-cell cavities in use on the Cornell Nb_3Sn program. Of these, one, designated ERL1-4, is of Cornell ERL design, with the other two, LTE1-6 and LTE1-7, are of ILC design. Two more ILC single-cell cavities have recently been completed and are currently undergoing baseline testing in preparation for coating with tin.

The coating apparatus used at Cornell University is described in detail in Ref. [7], but will be surmised here: a niobium coating chamber, containing the cavity/sample to be coated, sits within an ultra-high vacuum (UHV) furnace. At the base of the coating chamber is a recessed area containing a crucible filled with tin. The recessed area is surrounded by a secondary heating element that allows the tin crucible, referred to as the source, to be held at a temperature higher than that of the furnace and coating chamber. The generation of a temperature gradient between source and chamber alters the ratio of the rate of arrival of tin at the surface of the niobium being coated and the rate of growth of the Nb_3Sn layer.

An optimisation of the coating cycle [8] has resulted in all three of the single cell cavities achieving accelerating gradients of greater than 16 MV/m with high efficiency at 4.2 K. The continuous wave (CW) performance of these cavities can be seen in Fig. 1. All three cavities quench at approximately the same accelerating gradient of 17-18 MV/m. Processing of the cavity by continuously quenching over an extended period of time does not result in an increase in the quench field.

In high pulsed power (HPP) testing, the cavity is filled with energy as quickly as possible in an attempt to overcome thermal limitations [9]. During HPP tests, ERL1-4 [10] and LTE1-7 achieved fields higher than those achieved during CW testing, with both achieving fields of approx. 110 mT at 4.2 K, corresponding to an accelerating gradient of 25 MV/m in an ILC cavity. At higher temperatures close to the transi-

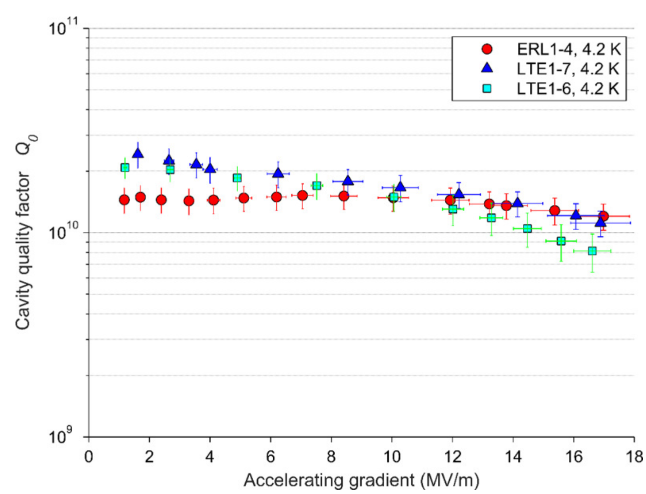

Figure 1: Quality factor vs. accelerating gradient at 4.2 K bath temperature for the three single-cell 1.3 GHz cavities on the Cornell program.

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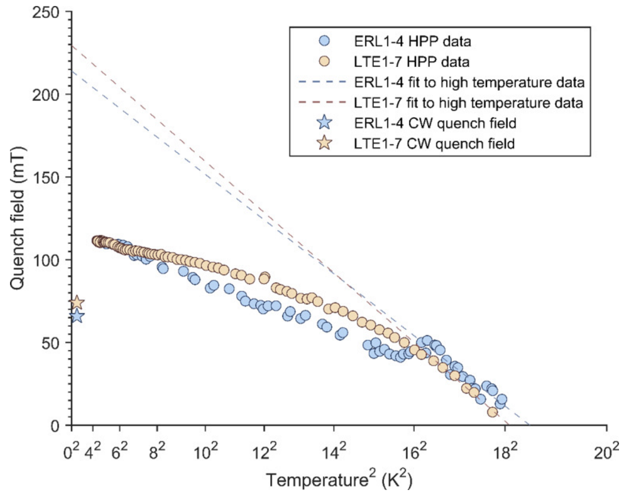

Figure 2: Cavity quench field vs. temperature (as T^2) during pulsed power testing for ERL1-4 and LTE1-7. During pulsed testing, the cavities exceed their CW quench field, also shown, by quite some margin. A fit to the data near T_c is shown extrapolating the ultimate flux entry field down to 0 K.

tion temperature, the extrapolated ultimate flux entry field (which ideally should converge to the superheating field) for both cavities is approximately 230 mT. The HPP performance of LTE1-7 and ERL1-4 is shown in Fig. 2.

POTENTIAL QUENCH MECHANISMS

Even in HPP testing, the ultimate flux entry field is still almost a factor of 2 lower than that expected of Nb_3Sn. However, atomic force microscopy of Nb_3Sn samples [11] show that the as-coated layer is quite rough, on the order of 1 micron grit. The sharp edges of the surface are resulting in local field enhancement. Recent studies, published in these proceedings [12], have used field simulations to quantify the level of field enhancement expected from the surface roughness. Results of this study have indicated a field enhancement factor of 1.4-1.6 in some small percentage area of the surface. This would rescale ultimate flux entry field seen in Fig. 2 to 330-375 mT, much closer to the expected superheating field. Previous studies on Nb_3Sn at Simemens AG [13] found that oxipolishing the surface of 10 GHz TE-mode cavities resulted in CW quench fields of 100-105 mT, which is in line with the reasoning that reducing the surface roughness is critical to achieving higher cavity gradients.

However, it is unlikely that surface roughness alone is responsible for the cavity quench at lower temperatures. The shape of the curves shown in Fig. 2 is indicative of a thermal limitation at temperatures below 16 K that the pulsed power is unable to overcome due to an insufficiently short, powerful pulse. To investigate this quench, cavity temperature mapping was used to monitor the surface temperature of the cavity during quench. Quench maps of LTE1-7, taken during three separate tests, are shown in Fig. 3. The quench location is unchanged between cooldowns, and is isolated to an area on the upper half-cell of the cavity. This would imply a localised defect inherent to the coated layer in that region.

During sample studies, two separate surface defect types have been discovered so far. The first of these is tin-depleted regions within the Nb_3Sn layer. Energy dispersive X-ray spectroscopy (EDS) maps of cross-sections of the Nb_3Sn layer [14] show regions of tin-depletion roughly 200 nm in size, some within a distance on the order of the RF penetration depth from the RF surface, and thus within the influence of the RF field. An example of such a region is shown in Fig. 4. Tin-depleted Nb_3Sn has a significantly lower transition temperature of 6 K [15]. The lower transition temperature results in an increased BCS resistance. It is expected that these regions will be far more susceptible to thermal runaway, an effect exacerbated by poor thermal conductivity of Nb_3Sn. However, further alterations to the coating recipe may suppress the formation of these regions.

The second surface defect type found are regions of anomalously thin film, in which the Nb_3Sn layer is only 200-400 nm thick [16]. These regions are revealed by taking an EDS map in a scanning electron microscope using a high beam voltage, resulting in regions that show a severe excess in the niobium signal due to the beam penetrating

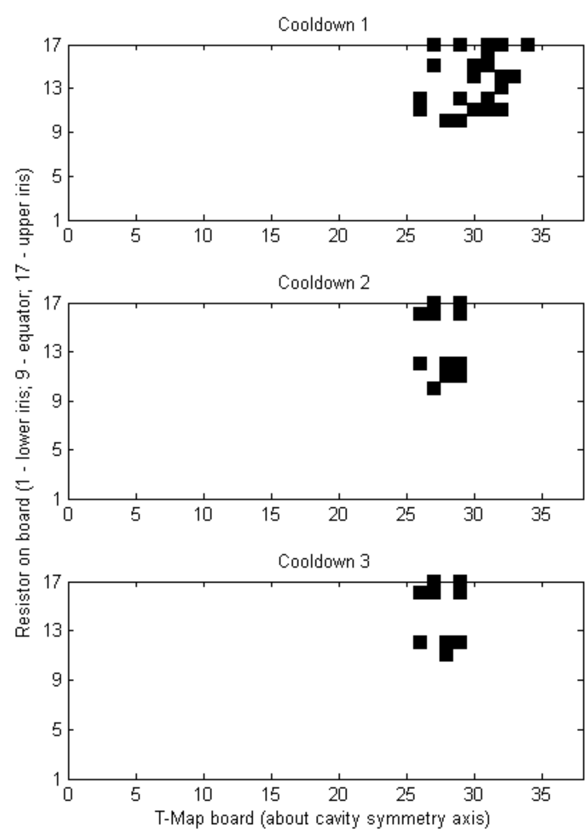

Figure 3: Quench map of LTE1-7 during three separate cooldowns. The temperature maps are read with the horizontal axis going about the cavity symmetry axis, and the vertical axis going from the cavity lower iris to the upper iris. Dark squares indicate regions in which surface heating was detected during a quench.

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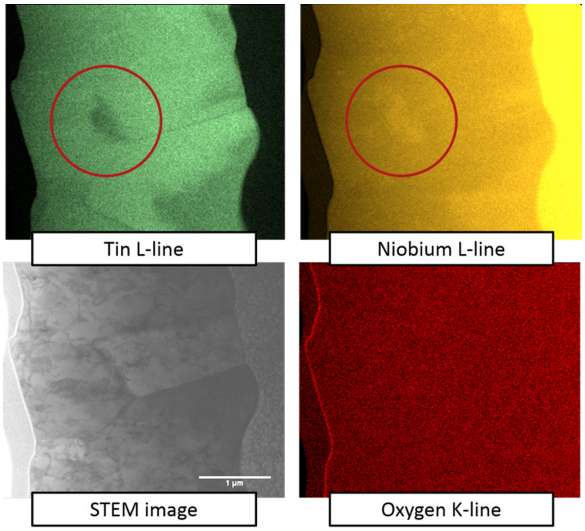

Figure 4: A cross-section EDS map of a sample of Nb_3Sn coated at Cornell. Shown top left and top right are the tin and niobium X-ray intensities, respectively. Bottom left is the STEM image, with the RF surface (coated with a protective layer of Pt) on the left and the niobium substrate on the right. The sharp interface between the niobium bulk and the Nb_3Sn layer is clearly visible. A region of tin-depletion is highlighted in the top two images. These images are courtesy of T. Proslier, Argonne National Laboratory, USA.

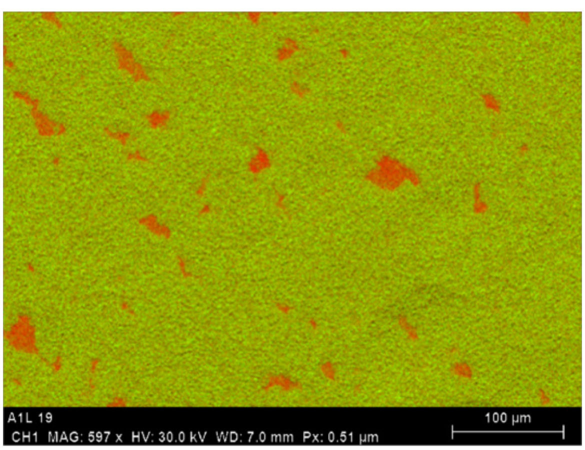

Figure 5: An SEM-EDS map of the surface of a sample coated with Nb_3Sn at Cornell. Regions in green are of sufficient thickness to screen the bulk from the RF field, i.e. 1 micron or greater. Regions in red, conversely, are too thin to do so, being of a thickness on the order of 100-300 nm.

beyond the Nb_3Sn layer in these regions to probe the niobium bulk beneath it. An example of one such EDS map showing these thin film regions is shown in Fig. 5. These regions, of insufficient thickness to effectively screen the bulk from the RF field, are known to result in increased losses [16], and may be susceptible to thermal runaway in the same manner that is expected of the tin-depleted regions mentioned previously. However, pre-anodisation of the sample to be coated has shown to be capable of, to the limits of detection, suppressing the formation of these regions during coating [17, 18].

CONCLUSION

Following an optimisation of the Nb_3Sn coating recipe used at Cornell, all three single-cell cavities in use on the program reach accelerating gradients of >16 MV/m. Temperature mapping of the quench region suggests that the quenches are the result of a localised surface defect. Samples studies carried out over the last year have identified two features of the film that may result in cavity quench. The effect is exacerbated by the surface roughness, which will result in local field enhancement that further lowers the accelerating gradient at which the cavity quenches. An upgrade to the temperature mapping system in use at Cornell is currently underway to improve the resolution of the quench map of LTE1-7, so that the centre of the quench can be pinpointed with an accuracy better than 1 cm^2. The region will then be cut out and investigated using an array of surface analysis methods to identify the cause of quench.

Even with the current achievable quench fields being limited to 18 MV/m, Nb_3Sn already shows promise for use in contemporary accelerator designs. The Q at 4.2 K lends these cavities an efficiency that enables operation in a cryomodule at 4.2 K, offering a significant decrease in power consumption when compared to niobium at 2.0 K [8]. Furthermore, it has already been seen in the past that 10 GHz Nb_3Sn cavities are capable of achieving CW fields of 106 mT [13], corresponding to approx. 25 MV/m in these single-cell 1.3 GHz cavities. Many contemporary CW designs for light sources and energy recovery LINACs favour efficiency over high gradients, and as such these Nb_3Sn cavities already meet and exceed these specifications. As development continues, we expect to see these cavities achieve both higher gradients and quality factors, enabling the creation of a new generation of high-efficiency, high-gradient accelerators operating at 4.2 K.

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