RF MEASUREMENTS ON HIGH PERFORMANCE Nb_3Sn CAVITIES*

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Abstract

A single-cell 1.3 GHz ILC-shape thin-film Nb_3Sn-on-Nb cavity recently achieved accelerating gradients of >16 MV/m with a record Q_0 of approx. 2×10^{10} at 4.2 K, exceeding the power efficiency seen in the current most efficient niobium cavities. A concurrent study of the coating process has resulted in a coating procedure that is capable of replicating this performance in other single-cell cavities. In this paper we demonstrate the RF performance and behaviour of these next generation SRF cavities, with an emphasis on both the impact from both external magnetic fields and the cavity cool down procedure on cavity performance.

INTRODUCTION

The A15 superconductor Nb_3Sn shows particular promise for replacing niobium as the material of choice for superconducting radio-frequency cavities, with it's comparatively high superconducting transition temperature T_c = 18 K [1] and superheating field H_{sh} = 400 mT [2, 3]. Previous work has produced cavities capable of achieving peak surface fields of up to 100 mT, although always plagued by a medium field Q-slope that greatly reduced the cryogenic efficiency of the cavity at useable gradients [4, 5]. However, cavities produced as part of the Nb_3Sn program at Cornell University between 2014 and the present day have not shown the same aggressive Q-slope [6–8], with one cavity in particular achieving gradients of 16 MV/m with a Q_0 at 4.2 K greater than 1×10^{10}.

In this paper we present the results of an optimisation of the coating process aimed at replicating the performance of this cavity in the other single-cell 1.3 GHz ILC-style cavities in use in Cornell's Nb_3Sn program. We begin with a brief summary of the fabrication process, followed by the results of the optimisation process and the design of an optimised coating procedure based on these results. We then present the results of two different Nb_3Sn cavities that are the result of this optimisation. Finally, we will briefly discuss the impact of environmental factors with regards to the RF performance of the cavity, in particular the environmental magnetic fields and the cooldown procedure.

OPTIMISATION OF THE COATING PROCEDURE

The exact procedure for the fabrication of Nb_3Sn cavities at Cornell is given more completely in Ref. [9], but will be summarised here: a bulk niobium cavity, whose surface is cleaned and prepared using a buffered chemical polish, is coated with tin in an ultra-high vacuum (UHV) furnace, at temperatures that result in the growth of a Nb_3Sn layer across the entire surface of the cavity. The UHV furnace is specially designed for this process: beneath the cavity, which sits within a coating chamber inside the furnace, is a secondary heater, inside which is a tungsten crucible filled with tin. Operation of this second heater allows the tin source to be held at a higher temperature than the cavity, which in turn allows control of the rate of the tin arriving at the cavity surface versus the rate of formation of Nb_3Sn. Control of these rates is necessary to ensure a uniform, stoichiometric layer suitable for the purposes of SRF.

The coating process consists of four stages: 1) a degas stage, in which the entire furnace is taken to a temperature of approx. 160 °C for 24 hours, 2) a ramp to 500 °, at which temperature the cavity is held for 5 hours while the nucleation agent ($SnCl_2$) deposits tin nucleation sites on the surface, 3) a ramp up to coating temperatures, at the start of which a temperature gradient is developed between the cavity and the source, 4) a coating step, during which time the temperatures are held constant with the temperature gradient developed during the ramp up, and 5) an annealing step, during which time the secondary heater is turned off and the source temperature is allowed to equilibrate with the cavity temperature. After the annealing step, the furnace is powered down and allowed to cool by thermal radiation before removing the cavity for testing.

The original coating procedure used at Cornell (primarily used in Ref. [9]) consists of a 5 hour nucleation step, a 3 hour coating step with the cavity at 1100 °C and the source

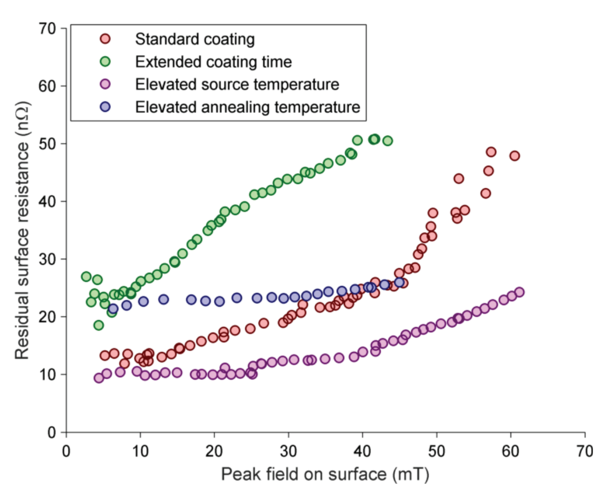

Figure 1: Surface resistance versus peak surface magnetic field at 2.0 K for the four different coatings of LTE1-7. The differences between the coatings are described in the text.

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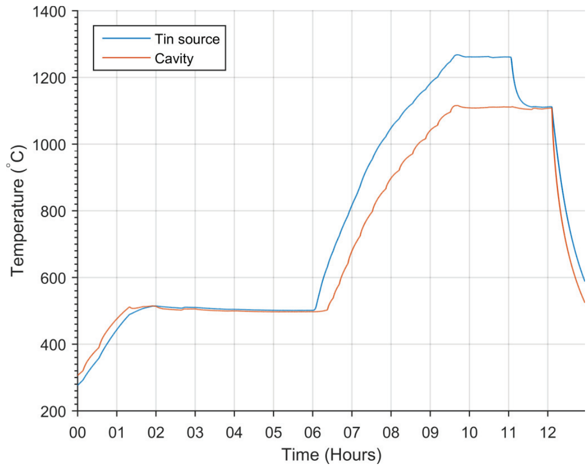

Figure 2: Temperature profile of the coating cycle used for LTE1-7 and LTE1-6, although the latter omitted the 5 hour nucleation step at the beginning.

at 1200 °C, followed by a 6 hour anneal. However, the best performance found in Ref. [9] was obtained using a recipe similar to that originally found in Ref. [10], in which the annealing period only last 30 minutes.

To perform the optimisation, a 1.3 GHz single-cell cavity was coated 4 times, each time varying the coating procedure:

1. **No change** A cavity coated using the standard coating recipe found in Ref. [9].
2. **Extended coating** The coating step was extended to last 6 hours.
3. **Elevated source temperature** The temperature gradient between the source and the cavity was increased.
4. **Elevated annealing temperature** The temperature of the cavity was increased during the annealing step.

Following each coating, the surface resistance vs. accelerating gradient at 2 K was measured to determine the quench field and residual resistance. The results of these 4 tests can be seen in Fig. 1. From these results, the coating profile shown in Fig. 2 was developed. The reasoning surrounding this coating profile is as follows: the source temperature was increased to increase the tin transfer rate and reduce the mean free path of the tin gas, simultaneously raising the rate of arrival of tin at the surface and the uniformity of the layer. Conversely, the length of the coating step was decreased to 1.5 hours to avoid transferring excessive amounts of tin. Expecting that the balance has not shifted by much compared to the recipe found in Ref. [10], the annealing time was kept short (1 hour), as excessive annealing times and temperatures have been shown to increase the residual resistance and lower the quench field.

Using this procedure, two 1.3 GHz single-cell ILC-style cavities were coated. The first, designated LTE1-7, received the coating profile shown in Fig. 2. The second, designation LTE1-6, received the same coating, but omitting the 5 hour nucleation step, proceeding instead directly to the development of the temperature gradient and the ramp to coating temperatures. This choice was made due to the recipe in Ref. [10] having likewise omitted a 5 hour nucleation step, in contradistinction to Cornell's coating recipe. The cavities were then tested; the results are given in the next section.

RESULTS

The performance of the two cavities coated using the optimised coating recipe at 4.2 K and 2.0 K is given in Fig. 3. The cavities show strikingly similar performance to the best cavity performance seen in Ref. [6]; that of cavity designated ERL1-4. These results demonstrate that not only is the latter result reproducible, but that the coating parameters can be altered to create two different cavities of matching performance. Given the accelerating gradient achieved, and the quality factor at 4.2 K, these are the first series of Nb_3Sn cavities that could be seriously considered for use in a contemporary accelerator.

To achieve the best performance, it is necessary that the cavity be cooled slowly, in as small a spatial temperature gradient as possible, to minimise impact from the magnetic field generated by thermal currents developed between the Nb_3Sn film and the niobium substrate. For reference, the cooldown parameters for the tests shown in Fig. 3 are given in Table 1. For similar reasons, quenching the cavity will result in a severe degradation in cavity quality factor (but not quench field) that can only be solved by a slow thermal cycle through 18 K.

The susceptibility of the cavities to trapped external magnetic flux appears to be similar to that of bulk niobium that has received a 120°C bake. Flux trapping measurements for the cavities ERL1-4 and LTE1-6 are shown in Fig. 4, giving a susceptibility to trapped flux of (0.66 ± 0.07) nΩ/mG. Due to the requirement that these cavities be cooled slowly

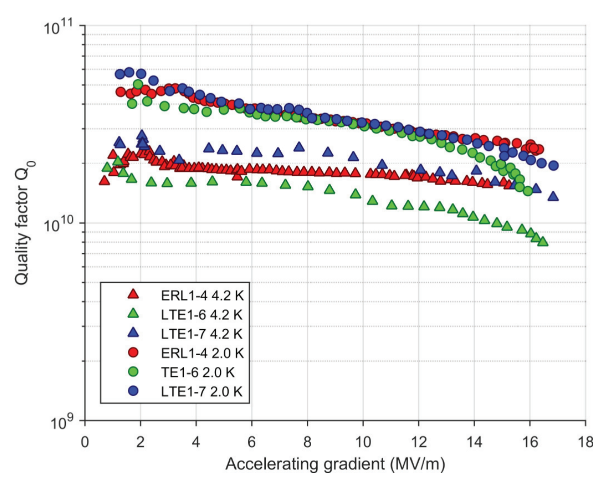

Figure 3: Quality factor vs. accelerating field at 4.2 K and 2.0 K for the three single-cell 1.3 GHz ILC-style Nb_3Sn cavities coated at Cornell. Error bars are omitted for visual clarity, and are 10% on Q_0 and 7.5% on accelerating gradient.

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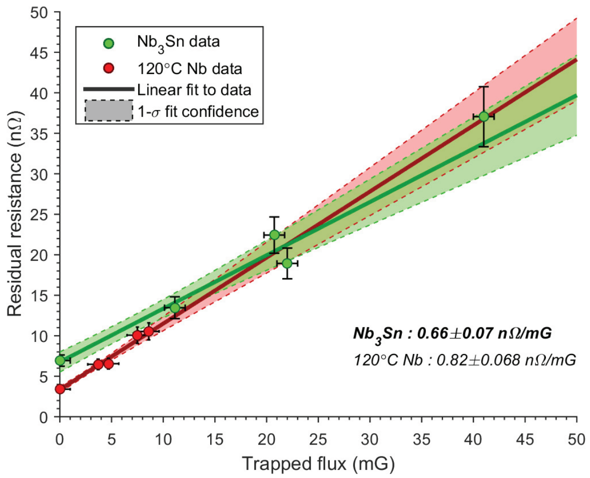

Figure 4: Susceptibility with trapped flux – measured in nΩ/mG – for Nb_3Sn cavities coated at Cornell. A more conventional 120°C-baked niobium cavity (data from Ref. [11]) is shown for reference.

Table 1: Cooldown Data for the Test Results Shown in Figure 3.

Test	ΔT (mK)	dt/dT (min/K)
ERL1-4 2.0 K	≤ 30	14.6 ± 1.5
ERL1-4 4.2 K	≤ 30	14.6 ± 1.5
LTE1-6 2.0 K	≤ 30	13.8 ± 1.4
LTE1-6 4.2 K	≤ 50	17.1 ± 1.7
LTE1-7 2.0 K	≤ 50	8.3 ± 0.8
LTE1-7 4.2 K	≤ 30	18.8 ± 1.9

(and that therefore practically all environmental flux will be trapped), this comparatively small susceptibility is a relieving result.

CONCLUSION

An optimisation of the coating process used at Cornell University has produced multiple cavities capable of achieving Q's of $\approx 10^{10}$ at 4.2 K at their quench fields of 16 MV/m, are the first that might be considered for practical contemporary use. Although the cavities require that they be cooled through 18 K in a small spatial gradient, such a cooldown has already been successfully performed in a standard cryomodule equipped with a 7-cell 1.3 GHz niobium cavity [12] as part of Cornell's ERL program. Furthermore, the comparatively low susceptibility to trapped magnetic flux suggests that the shielding already used for niobium cryomodules is sufficient for good performance.

Future studies will focus on understanding the nature of the quench, which is strikingly similar for the three cavities and is therefore likely a result of the same mechanism. Once the reason for the quench is determined, this information will be used to further optimise the coating process for increased performance, both in terms of cryogenic efficiency and maximum achievable gradient.

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