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NB$_3$SN TECHNOLOGY FOR LOW-BETA LINACS*

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Abstract

Nb_3Sn is the most advanced potential successor for niobium in superconducting RF accelerator cavities. Nb_3Sn has a significantly higher critical temperature (18.3 K) compared to that of niobium (9.2 K). This has a large effect on the BCS surface resistance, and therefore, on the dynamic RF losses at 4.5 K. The higher critical temperature allows two important changes for cavity and cryomodule design. First, the lower BCS losses allow the designer to use a higher frequency, translating to physically smaller cavities and cryomodules. Second, the low dynamic losses allow the use of stand-alone cryocoolers instead of complex helium refrigerators and distribution systems. Fabrication of a prototype 218 MHz cavity, test results, and continuing challenges are discussed.

INTRODUCTION

Heavy-ion linear accelerator resonators based on niobium are necessarily designed around for relatively low frequencies to keep the BCS resistance manageable for operation. This BCS resistance is the main source of surface resistance for niobium cavities and is strongly dependent on frequency and operating temperature. Figure 1 gives a comparison of calculated BCS resistance for niobium (at two frequencies, 72 MHz and 218 MHz) and for Nb_3Sn (at 218 MHz). At the operating temperature of 4.5 K the advantage of lower frequencies for bare niobium is clear. However, Nb_3Sn, even at the higher frequency, offer the possibility of an order of magnitude lower BCS resistance. The higher frequency translates to physically smaller cavities (reducing raw material costs as well as cryomodule fabrication size and cost) and a much lower dynamic RF load allowing the utilization of cryocoolers.

With the substantially higher Tc, Nb_3Sn could allow low-beta cavity operation at frequencies up near 1 GHz with a few nΩ of surface resistance [1].

PROTOTYPE FABRICATION

A prototype quarter wave cavity was constructed with high purity (RRR>250) niobium (and reactor grade for all non-RF surfaces) to serve as a base for the thin Nb_3Sn coating. The frequency chosen was 218 MHz, a harmonic of the ATLAS clock, and substantially higher than typical quarter wave cavities. Subassemblies were hydroformed at a local shop, Stuecklen Inc. The complex center conductor tip and gussets were machined by our collaborators at RadiaBeam. All welds were performed by electron beam welding at Sciaky Inc. The finished cavity was electropolished (125 µm) before cold testing without low temperature baking (Fig. 2).

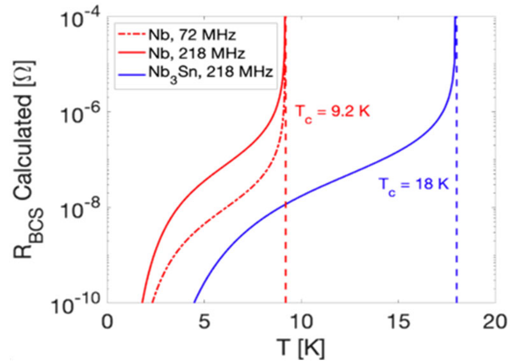

Figure 1: SRIMP calculated BCS surface resistance of Nb (at 72 MHz and 218 MHz) and Nb_3Sn (at 218 MHz) vs operating temperature.

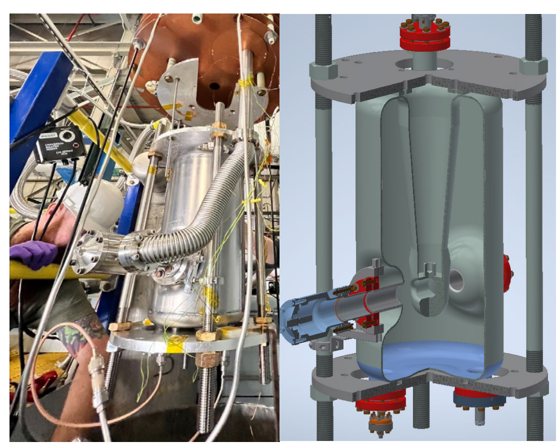

Figure 2: Cavity being inserted into 24” dewar (left) and section view of the cavity test assembly (right).

Following fabrication, the bare niobium cavity was cold tested to verify a good substrate for the thin film coating. The intent was to identify any possible defects that could cause early quench in the coated cavity testing. The cavity had a low Q of 8×10^8, but this was expected as the cavity was not de-gassed and showed classic symptoms of Q-disease. However, the cavity met the design goal of 60 mT peak magnetic field, no defect initiated quench.

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Nb_3Sn COATING

This cavity was coated at Fermilab in a high vacuum furnace modified for the Nb_3Sn coating process. The entire cavity is heated to 1100 C while a crucible holding tin (and tin-chloride) is heated an additional 100-200 ºC via wire heaters attached to two cavity ports.

COATED CAVITY COLD TESTING

After coating, the cavity received a high-pressure rinse before clean assembly with test hardware. Mechanical handling of the cavity post-coating was found to be of utmost importance, as the high temperature had softened the niobium significantly. Previous testing had shown no plastic deformation upon pumping out the cavity, but large mechanical deformation was seen after pumping on the coated cavity. This deformation is a suspected reason for limited performance in the first coating test, which performed well at low field ($Q_0=6\times10^9$) but exhibited steep Q-slope around 3-4 MV/m. This lessons-learned led to adding a gusset and stiffening rod during the second coating.

The first coating showed good performance at low field, around 3-4× higher Q than expected for a bare niobium cavity at this frequency. The steep Q-slope showed no x-ray radiation, and the testing was limited by RF power and cryogenic capacity.

Suspected mechanical damage to the thin film coating led us to strip the cavity and re-coat. The second coating process was the same except for swapping the heaters to the dome side of the cavity (during the first coating these were mounted on the toroid side). The cavity was re-assembled with additional support and cold tested again.

The second coating showed significantly lower performance in terms of Q, with a very steep drop in Q at very low field. However, the cavity was easily achieved high gradient than the previous coating, reaching out to 10 MV/m. Curiously the cavity exhibits a sort of anti-Q slope in the 1-5 MV/m region. Figure 3 shows the results of both coatings.

Significant multipacting occurred in early tests, with some barriers being seen in all cases. This may present an operational barrier, and conditioning with HOMs seemed to be moderately effective.

In both tests the cavity was cooled as slowly and as uniformly as possible to avoid thermocurrents which lower the overall residual resistance due to trapped magnetic flux. In recent testing a thermometer was added inside the center conductor tip, to ensure no large temperature gradients existed, but found all thermometers tracked within 0.2-0.3 K during slow cooldown and most of that temperature difference is suspected to be thermometer calibration error.

HCL RINSE

A primary suspected cause of poor performance in the second coating is excess tin left on the RF surface. Internally the coating is visually uniform, but the ports where the heaters were mounted showed macroscopic droplets seen in Fig. 4.

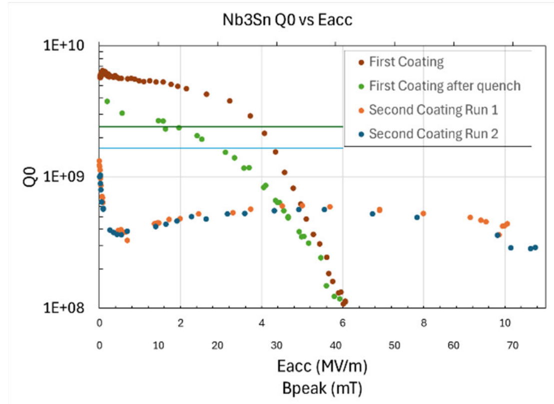

Figure 3: Comparison of two coating results. Solid lines represent two calculated values of maximum Q_0 for bare niobium.

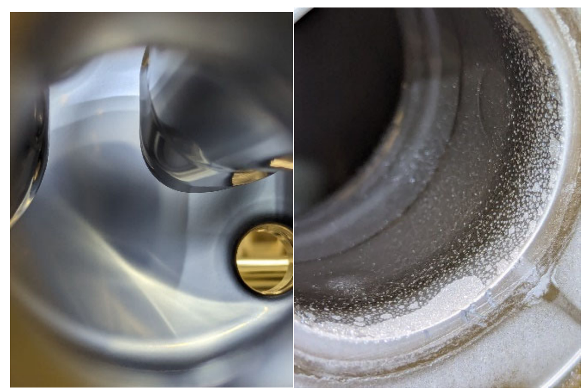

Figure 4: Uniform internal coating (left) and droplets of excess material, suspected tin (right).

Following poor test results with the second coating, it was decided to attempt light chemistry to remove excess tin droplets that may have formed on the RF surface while coating. Discussion with experts in the field led toward identifying the sharp low field drop as most likely being the superconducting proximity effect, with excess tin as the non-superconductor. Visual evidence near the heaters (Fig. 4) seem to support this hypothesis of excess tin on the cavity surface. Post-coating treatment options discussed were a dilute HCl rinse [2], a fast HF rinse [3], or annealing in a vacuum furnace [4].

The cavity was first rinsed in a dilute (5%) HCl solution for 5 minutes (in two orientations). No visual indication was seen of any change, so the cavity was rinsed for a longer period of time (1 hour on each side). Though most of the tin remained, discoloration on a flange with excess material provided indication of some chemical action, so the cavity was cleaned and assembled for testing.

However, cavity performance tracked previous measurements closely, with the same sharp low field Q drop. Unexpectedly, the cavity had little multipacting in comparison to previous tests.

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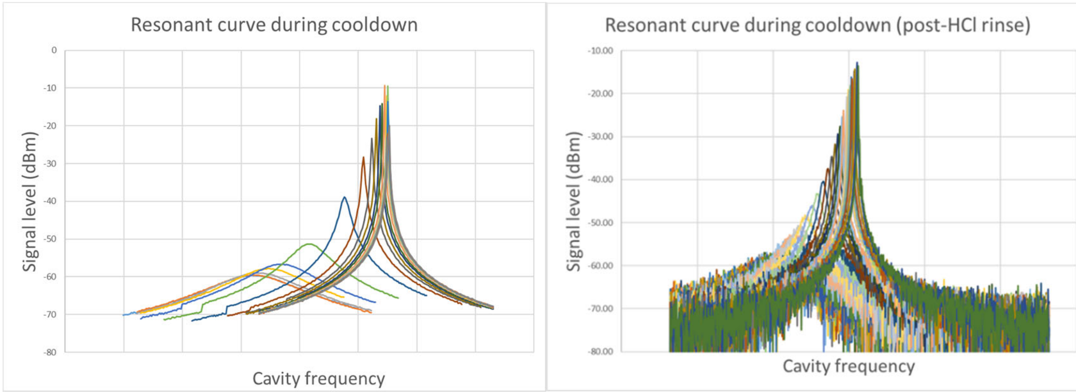

Figure 5: Resonant curves measured during cooldown.

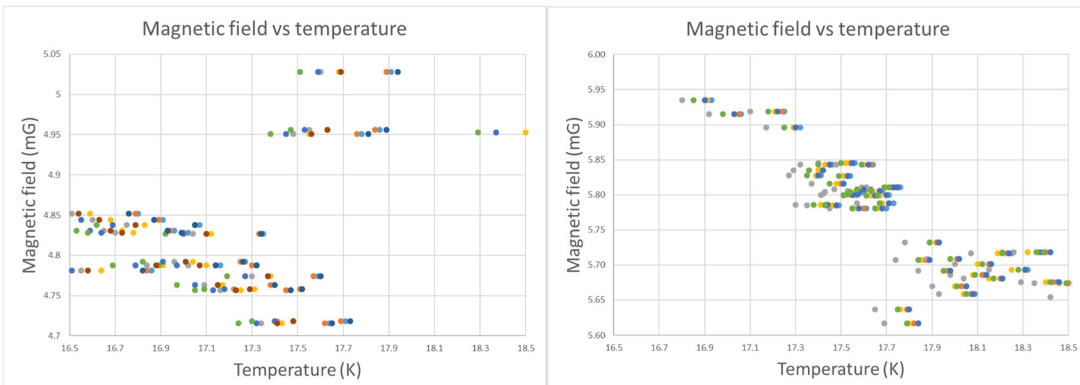

Figure 6: Magnetic field monitored near toroid during cooldown.

LOW TEMPERATURE BAKE

Multipacting observed with both coatings, along with simulations showing bands and their locations within the cavity, indicated multipacting may contributed to reduced Q. To test this the evacuated cavity was heated to 50 ºC for several days to reduce adsorbed water and perhaps reduce multipacting impacts on Q. Results post-bake showed the same Q and same qualitative Q curve features, with no significant improvement. If multipacting is affecting the measured Q, conditioning or baking the cavity appears to offer no benefit. This seems unlikely. Therefore, multipacting is likely not a main cause of Q drop does and excess tin remains the suspected cause.

MEASUREMENTS NEAR T_C

Recently, detailed data were taken during the superconducting transition. Cavity thermometry, magnetic field sensors, and cavity frequency and Q were all monitored during the transition. Cavity Q and frequency were logged on a network analyzer, showing the transition from normal conducting to superconducting (though not used to measure Q below Tc due to bandwidth limits).

Flux expulsion, small when cooling slowly, and frequency/Q shifts were used to identify the temperature range over which the cavity transitioned. This provides a useful comparison to the ideal 18.3 K transition temperature for Nb_3Sn and may provide insight into stoichiometry issues or helpt identify if post-coating chemistry leads to an increase in T_C.

Figures 5 and 6 are for the 2nd round of coating before and after HCl rinsing. These were collected simultaneously with temperature data and T_c was estimated to be 17.5 K, notably lower than 18.3 K. Measurements after the HCl rinsing and low-temperature baking showed a similar value.

FUTURE WORK

The initial prototype cavity will receive additional chemistry and eventually likely a third coating. A similar 145 MHz cavity is nearly complete and will be coated and a proof-of-concept 1 GHz quarter wave cavity has been fabricated, coated and will be tested soon.

CONCLUSION

Initial coating and testing of a Nb_3Sn quarter wave cavity has been challenging, however, considerable progress has been made and with important lessons learned for low-beta cavities.

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