

# Nb<sub>3</sub>Sn FOR SRF APPLICATION\*

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## Abstract

The superconductor Nb<sub>3</sub>Sn is a promising alternative to standard niobium for SRF applications for two reasons: Its larger superconducting energy gap results in significantly lower BCS surface resistance at typical SRF operating temperatures. Additionally, theoretical predictions suggest that the maximum operating field of Nb<sub>3</sub>Sn cavities could be twice that of niobium cavities. Early work on a small number of Nb<sub>3</sub>Sn coated cavities indeed showed 2K to 4.2K quality factors well above what is achievable with niobium, though at accelerating fields below  $\approx 10$  MV/m only. After many years of worldwide inactivity, Cornell has taken the lead and initiated a new R&D program on Nb<sub>3</sub>Sn to explore its full potential for SRF applications. New facilities for coating cavities with Nb<sub>3</sub>Sn have been set up at Cornell, and 1.3 GHz single cell cavities have been coated and tested. This paper presents a summary of Cornell's Nb<sub>3</sub>Sn program, discusses first promising results obtained, and also gives an overview of other Nb<sub>3</sub>Sn SRF work worldwide.

## INTRODUCTION

Niobium is the current material of choice for SRF applications. After many years of worldwide R&D, niobium cavities are now approaching their fundamental limits, both in terms of maximum field as well as in terms of surface resistance at typical operating temperatures. For the future of our field and for the further of SRF driven accelerators it is therefore of utmost importance to look into materials offering SRF performances beyond niobium. Nb<sub>3</sub>Sn is such a material.

## POTENTIAL AND CHALLENGES

Nb<sub>3</sub>Sn is a material with tremendous potential for SRF applications. It has extremely small surface resistance  $R_s$ , as a result of its small normal resistivity  $\rho_n$  and large critical temperature  $T_c \sim 18$  K (twice as high as niobium). It also is an excellent candidate for achieving large  $E_{acc}$ , with very large predicted superheating field  $B_{sh} \sim 400$  mT (again twice as high as niobium). Furthermore, it can be coated onto niobium substrates, allowing existing niobium cavities to be upgraded. It is non-reactive with water, and it adheres strongly to niobium when coated onto it, so that Nb<sub>3</sub>Sn cavities can be cleaned using the high-pressure-water-rinsing methods developed for niobium.

Nb<sub>3</sub>Sn is brittle, and it has low thermal conductivity, so it has to be used in film form. Therefore it faces challenges associated with using SRF films: (1) achieving uniform

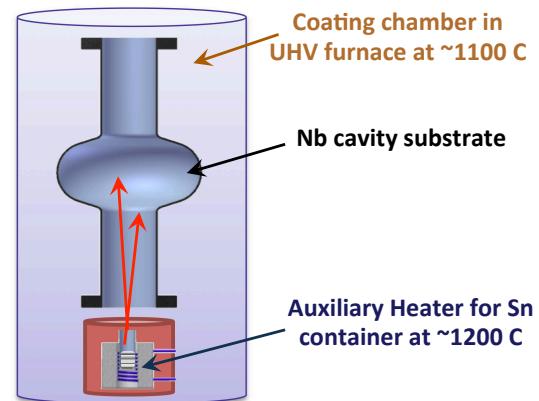


Figure 1: Principle of coating Nb<sub>3</sub>Sn cavities via vapor diffusion.

coating of the entire cavity surface; (2) only light chemistry is available to clean the surface due to the small thickness of the film; (3) thermal gradients can cause thermocurrents due to the interface between the film and the substrate, which in turn can trap flux that causes excess  $R_{res}$ . Finally, with 3-4 nm, the coherence length  $\xi$  of Nb<sub>3</sub>Sn is significantly smaller than that of niobium. There is an energy barrier to vortex penetration, which for an ideal surface prevents vortex entry and resulting strong vortex dissipation up to the superheating field  $B_{sh}$  [1], but small defects with size on the order of the coherence length can decrease it. This risk of all alternative superconductors for SRF applications has been one of the major concerns in the past, and might limit these materials the field below the lower critical field  $H_{c1}$ , which is small for all type II alternative superconductors. However, as summarized below and discussed in greater detail in [2], recent results at Cornell on Nb<sub>3</sub>Sn give great hope that all of these challenges of Nb<sub>3</sub>Sn can be overcome.

## PREPARATION METHODS

The Nb<sub>3</sub>Sn fabrication method that has produced the most encouraging SRF results so far is vapor diffusion. The technique was developed at Siemens AG [3] and University of Wuppertal [4], and it is now being employed by researchers at Cornell University and Jefferson Lab. A niobium cavity is placed in an ultra-high-vacuum furnace with a small amount of tin, see Fig. 1. The temperatures of both are raised to above 1000°C, so that the tin has a high enough vapor pressure to reach the cavity, and once it reaches the surface, the temperature is high enough to encourage diffusion and alloying. As shown in Fig. 2, Nb<sub>3</sub>Sn layers produced via vapor diffusion have to typical thick-

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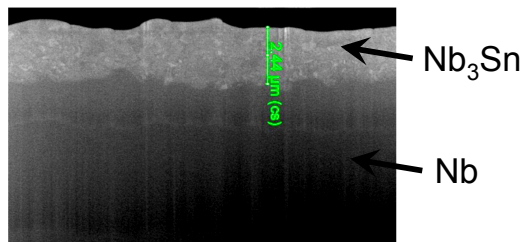


Figure 2: SEM picture of a cross section cut out showing a  $\approx 2\mu\text{m}$  thick Nb<sub>3</sub>Sn layer on top of Nb. The cross section was cut out with a gallium focused ion beam at Cornell.

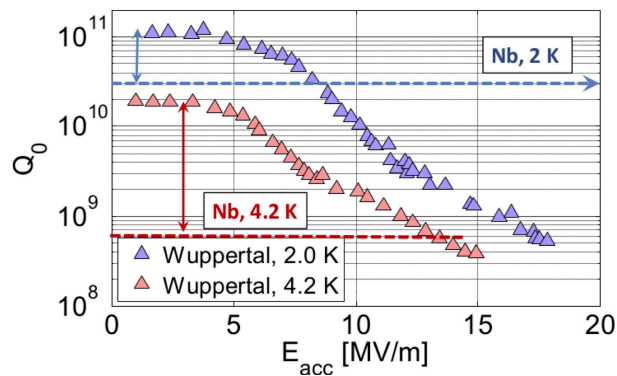


Figure 3: Q vs E curves at 2K and 4.2K for one of the best Nb<sub>3</sub>Sn cavities produced by U. Wuppertal [4]. The approximate values for a Nb cavity are shown for comparison.

ness of  $\approx 2\mu\text{m}$ . The  $Q_0$  vs  $E_{acc}$  curve of one of the best cavities produced by University of Wuppertal and tested at JLab is shown in Fig. 3. As can be seen, the cavity achieved very small surface resistance at low fields, but all the Wuppertal cavities showed a strong increase in surface resistance with increasing field above  $\approx 5$  MV/m. Various causes for the Q-slope were suggested, such as inter-grain losses, imperfect stoichiometry, and dissipation due to vortex penetration beginning at the lower critical field  $B_{c1}$  [5]. As a result, it has been unclear whether or not this Q-slope behavior is fundamental to Nb<sub>3</sub>Sn.

Researchers at several institutions have recently attempted to fabricate Nb<sub>3</sub>Sn using novel methods; refer to Fig. 4. Dipping of a niobium cavity into liquid tin with subsequent annealing was explored at INFN [6], but showed problems with tin droplets on the cavity surface and spurious tin-rich phases. Pulsed laser deposition studies have started at KEK [7]. Multilayer sputtering was investigated at INFN [8], in which alternate layers of Nb and Sn are deposited and then annealed to form Nb<sub>3</sub>Sn. However, no encouraging RF results have been achieved so far with this method. Cathodic arc deposition was done at Alameda Applied Sciences Corp. [9], but the coatings obtained only low critical temperatures.

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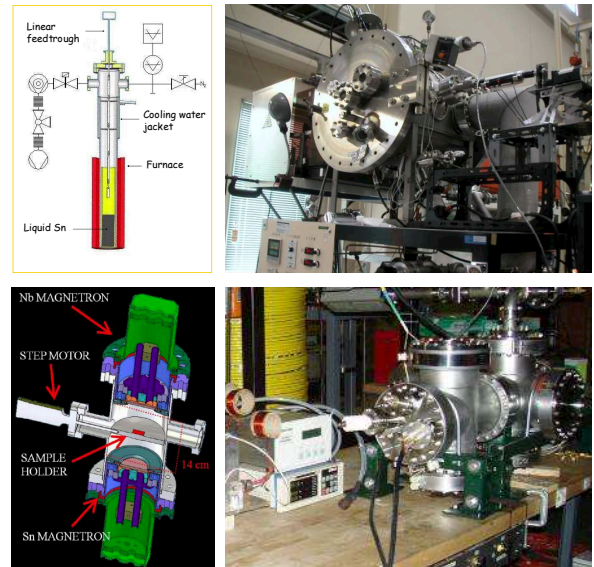


Figure 4: Alternative Nb<sub>3</sub>Sn fabrication methods. Top left: Liquid Tin Dipping at INFN [6]. Top right: Pulsed Laser Deposition at KEK [7]. Bottom left: Multilayer Sputtering at INFN [8]. Bottom right: Cathodic Arc Deposition at Alameda Applied Sciences [9].

## CURRENT STATUS

Current research on Nb<sub>3</sub>Sn development at Cornell University and Jefferson Lab uses the vapor diffusion method. In 2009, Nb<sub>3</sub>Sn development began at Cornell, and Cornell is now the leader on new Nb<sub>3</sub>Sn R&D efforts on SRF cavities [2, 10]. Following the encouraging first results from Cornell, Jefferson Lab has started the development of a Nb<sub>3</sub>Sn vapor diffusion deposition system within an R&D development program towards compact light sources [11]. Recently, JLab has coated several samples (flat plates for material characterization and a coaxial sample for penetration depth measurements) in an all niobium reaction chamber. All samples exhibited complete surface coating with Nb<sub>3</sub>Sn, however two of the samples, had Sn droplets on the surface. The coaxial sample was placed into an existing JLab sample measurement system, and the critical temperature  $T_c$  was measured via resonant frequency change, which is proportional to the field penetration change. As shown in Fig. 5, the mid-point transition temperature of coated Nb<sub>3</sub>Sn was measured to be 17.85 K. A 1.3 GHz 1-cell cavity insert has been built and a test run without Sn was completed in an existing horizontal furnace. The insert design as well as the as-built insert are shown in Fig. 6. Concurrently with the insert testing, a new vertical furnace for Nb<sub>3</sub>Sn coating development has been procured and is now being commissioned at Jefferson. Refer to [11] for details on the JLab Nb<sub>3</sub>Sn program.

Nb<sub>3</sub>Sn development at Cornell began with the design, fabrication, and commissioning of a small coating chamber for samples. After establishing the capability to repeatedly produce Nb<sub>3</sub>Sn films of high quality [10], Cornell began

### 09 Cavity preparation and production

#### I. Basic R&D New materials - Deposition techniques

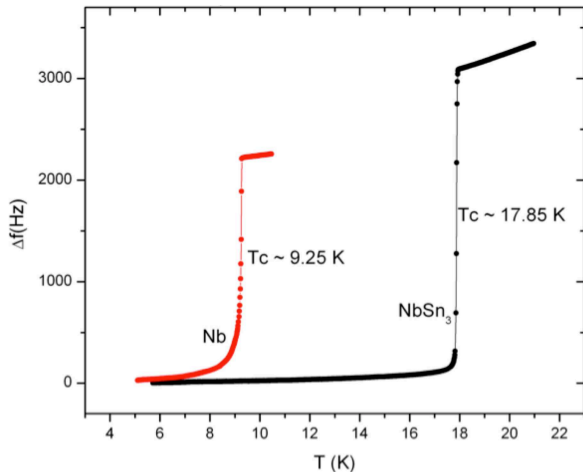


Figure 5: Critical temperature  $T_c$  results on the coaxial  $Nb_3Sn$  coated sample at JLab. The data shows a transition temperature of 17.85 K.

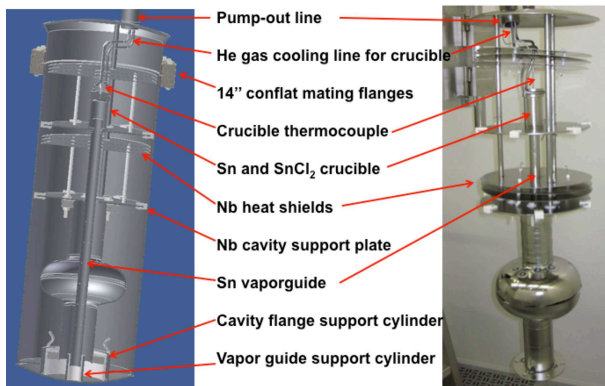


Figure 6: JLab insert design (left) and as-built insert (right).

work on a large coating chamber for single cell 1.3 GHz cavities, shown in Fig. 7. A 1.3 GHz single cell cavity was coated with  $Nb_3Sn$  via thermal vapor diffusion. The cavity, before and after coating, is shown in Fig. 8. After the coating process it was treated with only a high pressure rinse (HPR) before mounting to a vertical test stand for cryogenic performance test. The  $Q$  vs  $E$  curve of the Cornell  $Nb_3Sn$  cavity is shown in Fig. 9, along with that of the Wuppertal cavity from Fig. 1 for comparison. Overall, the performance is excellent. Unlike the cavities produced by Wuppertal, it does not show a strong reduction in  $Q_0$  above 5 MV/m. At 4.2 K, at medium fields the  $Q_0$  is up to approximately 10 times higher than that of the Wuppertal cavity, and approximately 20 times higher than a niobium cavity. Quench occurred at approximately 13 MV/m. Temperature mapping revealed that the quench is caused by a small, localized defect on the surface, and is not an indication of a global problem with the  $Nb_3Sn$  coating. Details measurements of the material properties of the coating show a high critical temperature  $T_c$  of about 18 K, and an estimate of the lower critical field of  $B_{c1} = 27 \pm 5$  mT [2]. This value

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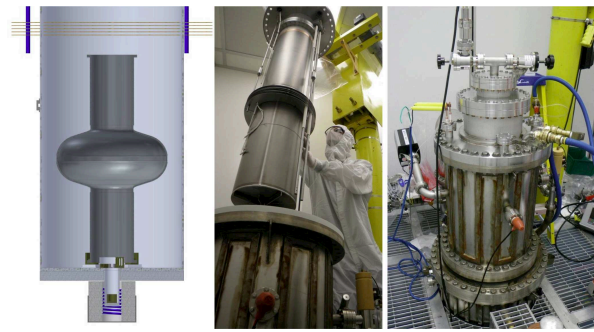


Figure 7: Cross-section of coating chamber (left), coating chamber being lowered into furnace (center), and UHV furnace with chamber inside (right).



Figure 8: Coated cavity (left); view looking down into cavity before (top right) and after coating (bottom right).

agrees well with a  $B_{c1}$  measurement performed with  $\mu$ -SR by A. Grassellino et al. [12] on a  $Nb_3Sn$  witness sample produced by Cornell. These first results indicate that maximum magnetic surface fields well above the lower critical field were achieved in the coated cavity without a significant increase in surface resistance. This is important, as it shows that  $Nb_3Sn$  bulk films can be produced with sufficient high quality to prevent vortex penetration at  $B_{c1}$ , even for superconductors with small coherence length. The energy barrier keeps the Meissner state metastable above  $B_{c1}$ . The Q-slope seen in the Wuppertal cavities therefore does not represent a fundamental problem for alternative SRF materials. Refer to [2] for details on the Cornell  $Nb_3Sn$  program.

CONCLUSIONS

With its high critical temperature and superheating field,  $Nb_3Sn$  is a material with tremendous potential for SRF applications. Currently, the most promising RF results have been achieved with  $Nb_3Sn$  cavities coated via vapor diffusions of tin into niobium substrate. A  $Nb_3Sn$  cavity pro-

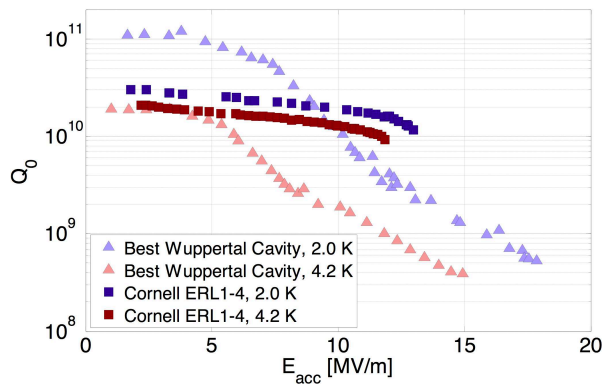


Figure 9:  $Q$  vs  $E$  curve from the new Cornell Nb<sub>3</sub>Sn cavity, showing a small residual resistance at low fields and a large improvement in  $Q_0$  at usable gradients over one of the best U. Wuppertal cavities. Uncertainty in  $Q$  and  $E$  is approximately 10%.

duced at Cornell achieved a outstanding performance: at 4.2 K and  $\approx 12$  MV/m, it had a  $Q_0$  of  $10^{10}$ , 20 times higher than Nb, making it the first alternative material accelerator cavity to far outperform niobium at useful gradients and temperatures. Importantly, the peak surface magnetic field in this cavity significantly exceeded the lower critical magnetic field  $B_{c1}$ , disproving speculation that the Q-slope observed in previous Nb<sub>3</sub>Sn cavities was an inevitable result of exceeding  $B_{c1}$ .

Already with its current performance, Nb<sub>3</sub>Sn has now become an alternative material for certain future accelerators. Encouraged by the new Cornell results, several labs are now starting Nb<sub>3</sub>Sn research programs, and future research on improved Nb<sub>3</sub>Sn preparation methods can be expected to overcome non-fundamental limitations with time as they have in niobium.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).
- [2] S. Posen and M.Liepe, TUP087, Proceedings of SRF13, Paris, France, (2013).
- [3] B. Hillenbrand et al., IEEE Trans. Mag. 13, 481 (1997).
- [4] G. Mueller et al. EPAC 1996. p. 2085 (1996).
- [5] A. Gurevich, App. Phys. Lett. 88, 012511 (2006).
- [6] S. Deambrosis, Ph.D. Thesis, University of Padua (2008).
- [7] S. Mitsunobu, Presented at the TFSRF Workshop, Padua, Italy (2010).
- [8] A. Rossi et al. (2009).
- [9] M. Krishnan, C. James and B. Bures, Presented at the TF-SRF Workshop, Newport News, USA (2012).
- [10] S. Posen, M. Liepe, PAC 2011, New York, USA (2011).
- [11] G. Ereemeev, Proceedings of SRF13, Paris, France, (2013).
- [12] A. Grassellino et al., TUP029, Proceedings of SRF13, Paris, France, (2013).