Simulating Nb_3Sn Coating Process Inside SRF Cavities

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1. Introduction

A thin layer, approximately 2 – 3 µm thick, of Nb_3Sn formation on the inner surfaces of a niobium superconducting radiofrequency (SRF) cavity has been shown to improve cryogenic efficiency a substantial amount compared to an uncoated, standard, niobium cavity. The key reason for this result is that the critical temperature at which Nb_3Sn becomes superconducting is twice that of Nb alone. Additionally, there is a predicted benefit that the coated cavity will have an increased electric field for charged particles to accelerate through. The process of coating a niobium SRF cavity involves vapor diffusion in which a tin source is liquefied evaporating into the volume of the niobium cavity and onto the inner surfaces while inside an ultra-high vacuum oven at high temperatures. The following overview will focus on using COMSOL, a physics simulation software, to predict via simulation the locations inside the cavity where the tin will eventually arrive. The importance of knowing the distribution of tin inside the cavity in the early stages of the vapor diffusion process is so that the degree of uniformity can be determined and optimized allowing for a more efficient nucleation process.

2. Goals

The goal of doing such research is to determine a parameter defined as the "Sticking Coefficient". This parameter is the probability of a single tin molecule sticking to the niobium surface instead of reflecting off the niobium substrate and the value of this coefficient is still yet to be determined. Simulations using varying values for the sticking coefficient from 0.1 to 0.9 are used to give a range of what could be experimentally expected. These sets of simulations provide the foundation to be used later once the sticking coefficient is accurately determined. They also give insight on different design options that may have to be explored. The overall goal is to synthesize experimental data with theoretical simulation data to gain a better understanding of how uniform the tin distribution is and to use this knowledge to design and optimize the procedures in Nb_3Sn formation in SRF cavities.

3. Benefits

The critical temperature for Nb is about 9K allowing Nb SRF cavities to operate at about 2K. The critical temperature for Nb_3Sn is about 18K allowing for cavities to theoretically operate at about 4K. Increasing operational temperature of cryomodules housing SRF cavities from about 2K to 4K will have the potential to save millions of dollars. Also, the use of Nb_3Sn will increase the efficiency of the SRF cavity as it will have a lower dissipation of power input. With this more efficient operating SRF cavity there is potential to have a higher maximum field strength allow for more acceleration of charged particles over the same distances.

4. Brief Coating Process Overview

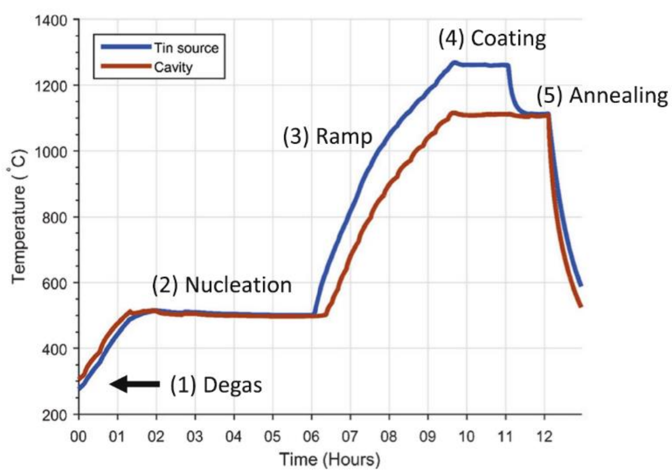

Figure 1. Temperature profile of the coating furnace used at Cornell University since February 2016. The temperature of the cavity and the tin source are given separately, reflecting the presence of the second hot zone. The steps indicated on the temperature profile are explained in the text. [1]

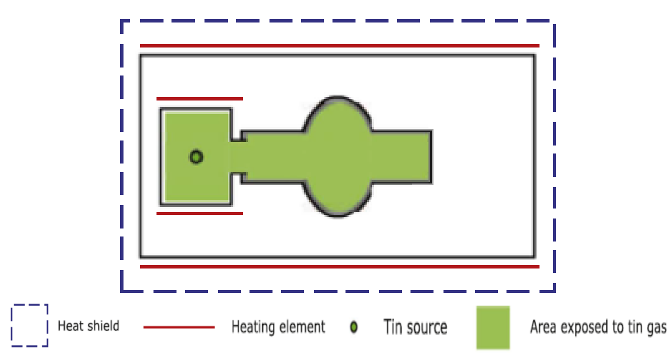

Figure 2. Ultra-high vacuum oven vapor diffusion set up used at Fermilab. [1]

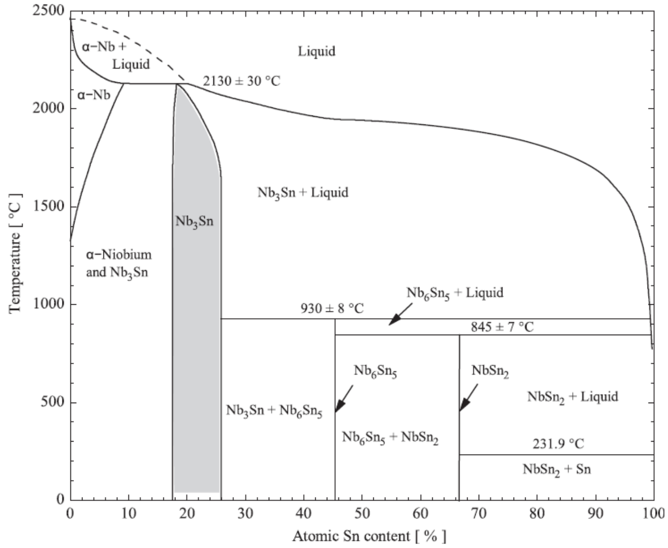

Figure 3. Phase diagram of the niobium–tin system. [2]

Using an ultra-high vacuum oven at the temperatures and times from figure 1, the process of diffusing tin into the inner surface of a niobium SRF cavity can be accomplished. The research into the chemistry of Nb and Sn bonding is well established leaving us with the main challenge of achieving the most uniform distribution of tin molecules inside the cavity that will result in a consistent formation of Nb_3Sn at a thickness of approximately 2 to 3 microns. Figure 2 shows the current set up being used where the entire system is heated to approximately 1100C and the tin source is being heated separately but still inside the UHV oven at temperature of at least 1200C. Figure 3 shows the phase diagram of niobium and tin and the shaded region is the target area for the formation of Nb_3Sn. Notice however even with a higher tin content at the previously discussed temperatures it will only still result in Nb_3Sn plus liquid tin which is can be removed.

5. COMSOL Simulations

The goal of these simulations is to gain insight on the tin distribution inside the niobium cavity. Before choosing a physics module in the COMSOL software its vital to know the type of flow that can be expected from the tin source. Flow types can be determined from the following dimensionless parameter:

$$Kn = \frac{\lambda}{d}$$

In this equation, Kn is the Knudsen number, λ is the mean free path of tin and d is the characteristic diameter.

The following table provides values for λ at increasing temperatures:

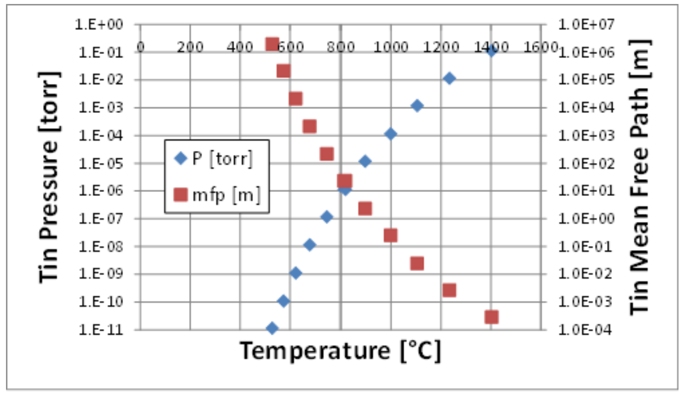

Figure 4. Mean free path and pressure of tin at increasing temperatures.

At the temperatures of tin in the system, λ can be safely assumed to range from 1.0E-02 meters to 1.0E-03 meters. The value d is approximately 7 cm. The resulting Knudsen numbers from these values are from approximately 0.014 to 0.14. Using these Knudsen values the flow type can be determined from the following:

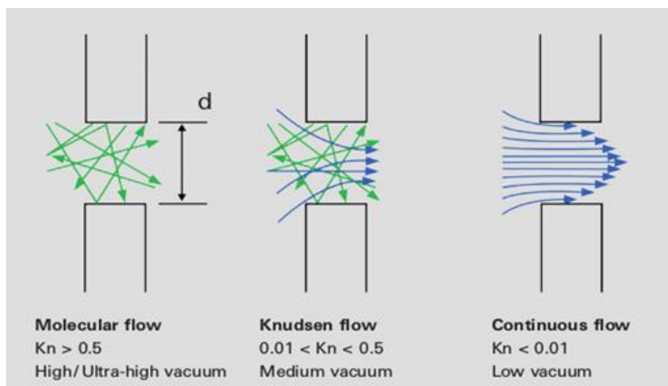

Figure 5. Flow types specified by Knudsen number. [3]

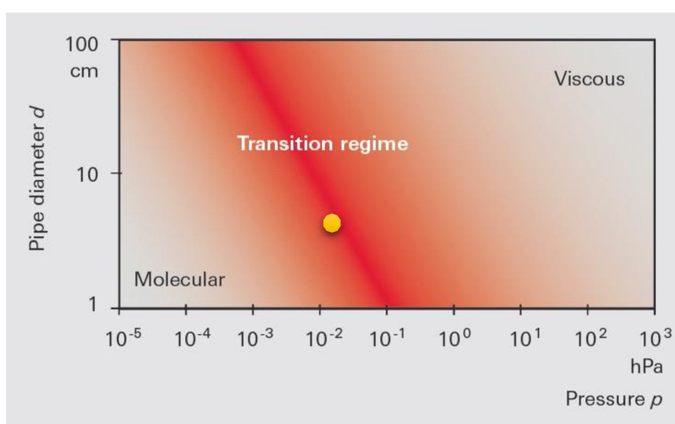

Figure 6. Region of fluid in terms of pressure at various pipe diameters from 1 to 100 cm. [3]

Using figure 5 and calculated Knudsen number, the tin vapor is located in the transitional region. Unfortunately, that region is very difficult to simulate accurately because the COMSOL software's ability to simulate that region is still in its infancy. To reach the region of viscous/continuous flow, for which the ability to simulate has been well established, the tin vapor would have to reach temperatures of approximately 1400C which would result in a mean free path of about 0.5E-3 meters and a Knudsen number of about 0.07. The simulations will have to be done using COMSOL's free molecular flow module which is for tin in the viscous flow region. At this point in time it is unknown whether transitional flow or viscous flow is more beneficial to uniformity or if the difference in flow types are negligible.

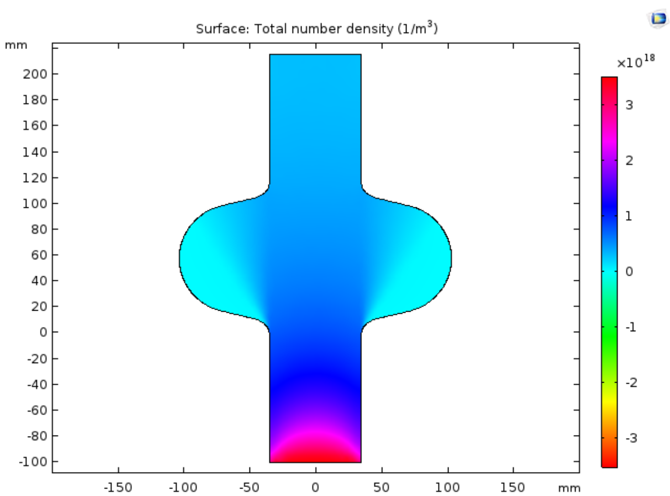

Figure 7. Number density of tin from COMSOL simulation using the free molecular flow module.

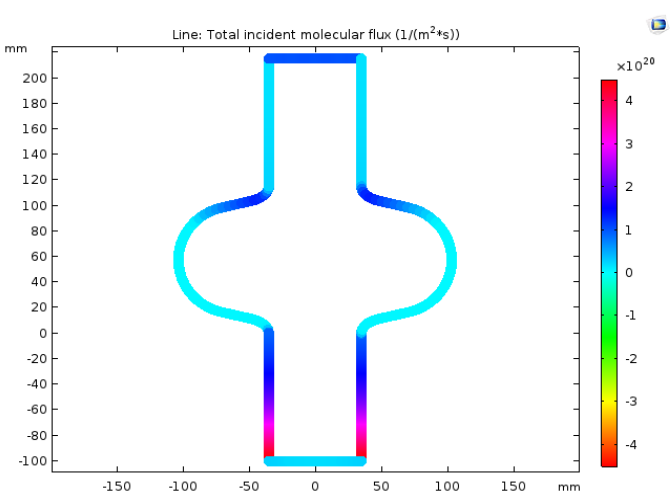

Figure 8. Total incident flux on niobium surface from COMSOL simulation using free molecular flow module.

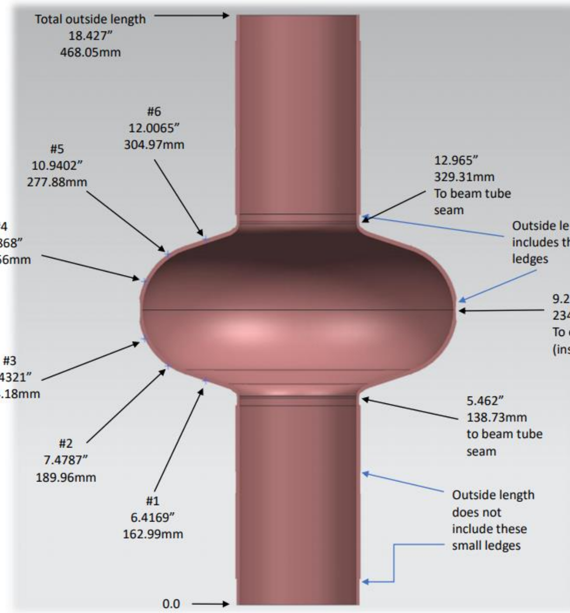

Figure 9. Physical sample locations on cavity to be analyzed and compared to the simulations.

As seen in figure 7 and figure 8, the difficulty in solving this problem is the geometry of the cavity. It is important to note that a second source on the other end of the cavity may seem like an easy solution but the final goal is coat a 9-cell cavity approximately 1 meter long seen below.

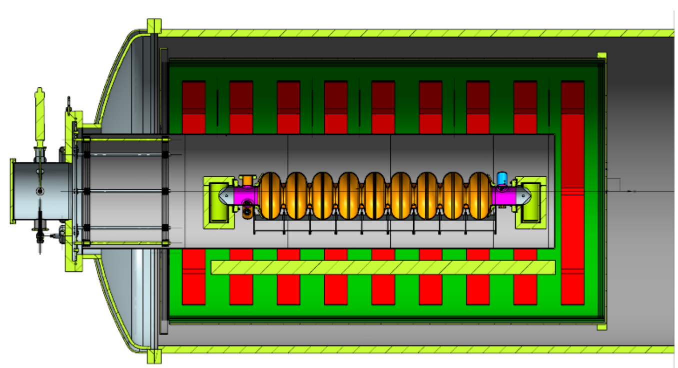

Figure 10. Visual representation of a 9-cell cavity vapor diffusion procedure inside an UHV oven. [1]

From figure 10, it can be determined that one source is responsible for coating four and half of the cavity's cells. Therefore, coating a single cell with one source must be proven to work efficiently before moving on to the final overall objective of coating a 9-cell SRF cavity.

Figure 11. Ration of the sample 1 over sample 6 vs increasing values of sticking coefficient.

Data from figure 11 was extracted from multiple COMSOL simulations where the only parameter changed for each iteration was the sticking coefficient. The ratio of S1/S6 was chosen because S1 is the lowest incident flux location and S6 was the highest incident flux location. These sample sites can be found on the cavity by referencing figure 9. This graph shows a strong correlation that as the sticking coefficient increases the ratio of the lowest to highest incident flux locations decreases. Using this information and future analysis of physical samples, the sticking coefficient can be accurately determined thereby allowing the simulation to become more accurate so 9 cell simulations may be performed with increased accuracy.

6. Conclusion

Gaining knowledge of the sticking coefficient is imperative to a successful vapor diffusion process. This value will allow for an accurate depiction of what can be expected from coating a 9-cell cavity. It can be hypothesized that continuous/viscous flow may be most beneficial to coating larger 9-cell surfaces so it may be the case that the tin source needs to be heated to at minimum 1300C and possibly even 1400C if the equipment allows for it. This increase temperature would provide a greater value for tin vapor pressure allowing the tin to flow into the hard to reach locations of a 9-cell geometry. It is also important to note that keeping the tin temperature at such a high value would greatly increase the mass flow rate of the tin which may not be desirable. Perhaps, too much tin over a certain period of time would cause unforeseen issues. It may be the case that the most optimal solution would be to start the tin temperature as high as possible early on allowing for a full coating of the geometry and then slowly ramping the tin temperature down to a more suitable mass flow rate that would not leave the niobium surface over saturated after completion of the vapor diffusion process. Unfortunately, the physical data has yet to be completed at the time of this report but these COMSOL simulations have provided a foundation for future research to build on. The fact that Nb_3Sn shows greater superconducting properties at twice the critical temperature of Nb alone and has shown the ability to be created at the necessary thicknesses inside SRF cavities to be functional is very promising. The potential achievement of optimizing this process will save substantial amounts of energy it takes to cool down cryomodules to superconducting temperatures.

References

[1] S. Posen and D. L. Hall, "Nb3Sn superconducting radiofrequency cavitities: fabrication, results, properties, and prospects," *Superconductor Science and Technology*, 2017.

[2] A. Godeke, "A review of the properties of Nb3Sn and their variation with A15 composition, morphology and and strain state," *Superconductor Science and Technology*, 2006.

[3] Pfeiffer Vacuum, "1.2.6 Types of Flow," 2017. [Online]. Available: https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/. [Accessed 16 August 2017].