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# DEVELOPMENT OF $Nb_3Sn$ CAVITY COATING AT IMP*

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*Abstract*

In this paper, the progress in the development of $Nb_3Sn$ cavity coating by vapour diffusion method at IMP was reported. Three 1.3 GHz single cell cavities were coated and one of them was vertically tested both at 4K and 2K. Effect of low temperature baking ($100^0$C for 48 hs) on the RF performance of $Nb_3Sn$ cavity was studied. After baking, the Q drop in the low field region was eliminated and the Q value in the intermediate field region was increased ~8 times. The Q value of the $Nb_3Sn$ cavity coated at IMP was 12 times larger than that of the Nb cavity at 4.2K even in the case of the ambient field larger than 20 mGs and with the slow cooling down absent. This study shows that the low temperature baking is an effective enrichment to the post treatment of the $Nb_3Sn$ cavity.

## INTRODUCTION

The radio-frequency (RF) superconducting accelerator can operate in long-pulse mode or even continuous wave (CW) mode due to its extremely low surface resistance. Most advanced accelerator projects both in construction and future planning, including synchrotron radiation source, high energy experimental project, free electron laser, proton and heavy ion accelerator, have chosen to use RF superconducting (SRF) technology. After many years of worldwide R&D, niobium cavities are now approaching their fundamental limits, both in terms of maximum field [1] as well as in terms of surface resistance [2,3] 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. Among which, the A15 superconductor $Nb_3Sn$ is the most promising alternative materials to standard niobium for SRF applications. Therefore, the development and testing of the Nb-substrate $Nb_3Sn$ thin film SRF cavity by vapour diffusion method was carried out at IMP.

## COATING OF THE $NB_3SN$ CAVITY

The cavity deposition and processing facility was shutdown because of the environmental concerns from the local government until to the end of April 2018. About four months was spent to find limitations, make improvement plans, and complete debugging of the furnace for $Nb_3Sn$ cavity coating. The furnace includes two heating zones. This allowed for separate temperature control of the niobium cavity and the tin source. However, there is no separate all Nb coating camber. So the $Nb_3Sn$ samples have to be prepared together with the cavity.

### *Separate Temperature Control Route*

The first $Nb_3Sn$ cavity was coated using a recipe based on the temperatures and times specified by Cornell University [4] with the cavity at $1100^0$C and the tin source at $1200^0$C, which was shown in Fig. 1. Material measurements (Fig. 2, Fig. 3 and Fig. 4) showed that the structure and composition of the $Nb_3Sn$ samples was good. However, the cavity showed the expected grey appearance in the downside half-cell, the upside half-cell showed the visually non-uniform shiny appearance. As a result, the first $Nb_3Sn$ cavity was not vertically tested.

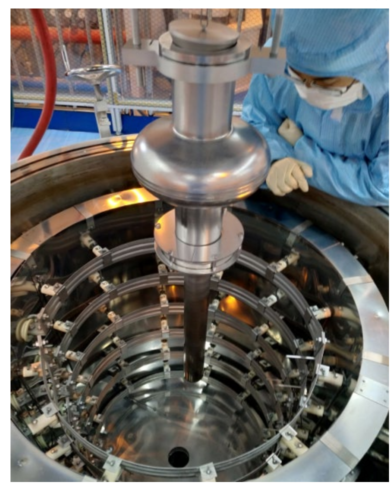

Figure 1: The Nb cavity was lowered into the furnace.

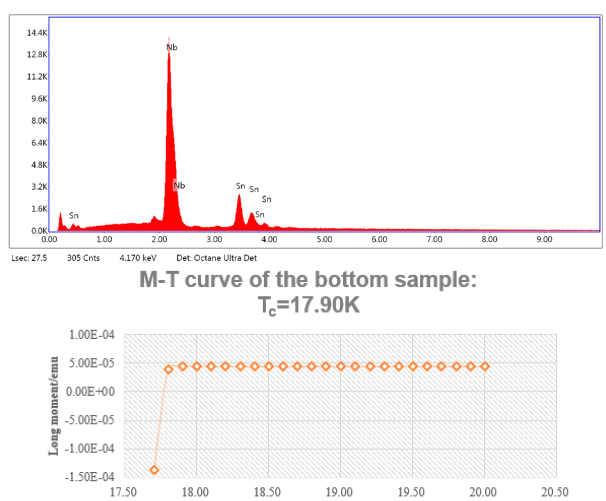


Figure 2: EDS spectrum of the first batch $Nb_3Sn$ samples indicates composition 24.49 At. % Sn (top); $T_c$ of the first batch $Nb_3Sn$ samples reached ~17.9K

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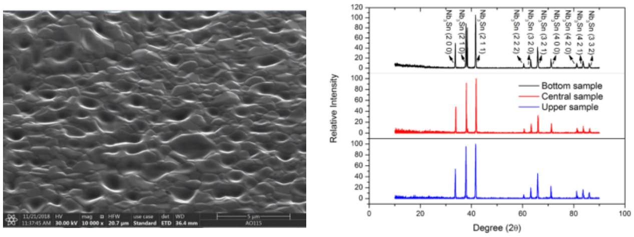
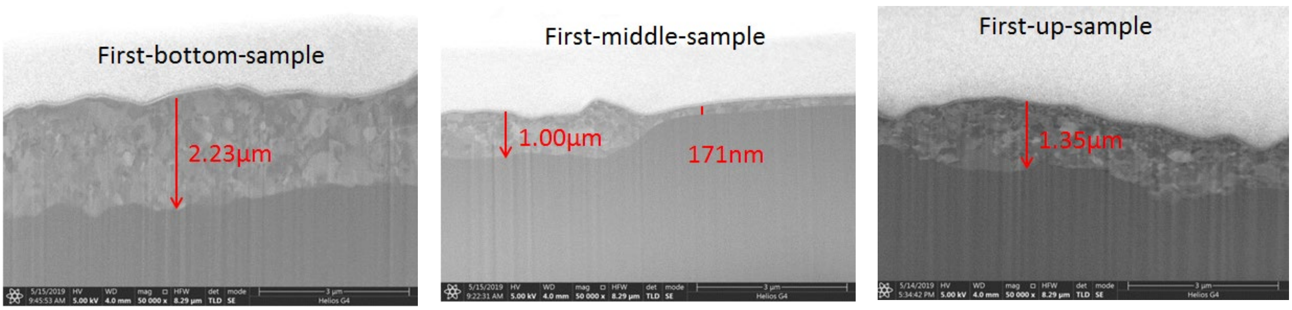



Figure 3: SEM images of the first batch samples tilted at $55^0$ to show three-dimensional features (left); XRD results showed no undesired low-$T_c$ phases were detected (right).

Figure 4: Grey appearance in the downside half-cell; visually non-uniform shiny appearance in the upside cell.




(a) (b) (c)

Figure 5: Profiles of layers made visible by ion beam of the bottom sample (a), the central sample (b) and the upper sample (c).

FIB-SEM measurements in Fig. 5 showed directly that the thickness of the bottom sample is obviously thicker than that of the central and upper samples. The reason that caused the non-uniform $Nb_3Sn$ coverage between the downside and upside half-cell is the unreasonable design of the furnace. The distance between the hot zone of Sn source and Nb cavity is too far, resulting in an obvious decrease of Sn pressure in the upside cell.

### *Isothermal Route*

In view of the inherent defects involved in the furnace, we chose to change the coating process and adopted that from JLab temperatures and times [5]. The 2nd and 3rd $Nb_3Sn$ cavity was coated by maintaining both the Sn source and Nb cavity at $1200^0$C for 3 hours with the Sn placed at the bottom flange of the cavity. With the modified coating process, both the downside and the upside half-cell of the cavity was covered with uniform $Nb_3Sn$ film, which was shown in Fig. 6.

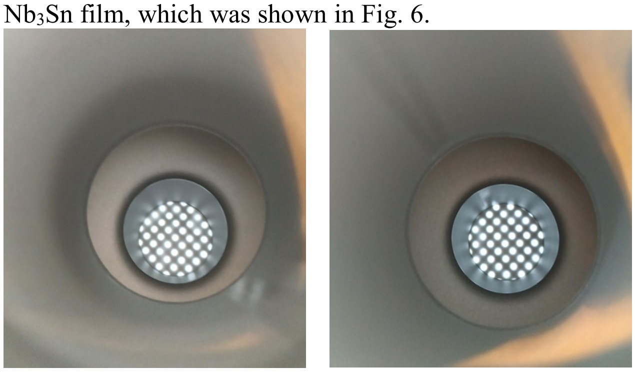


Figure 6: Typical matte grey $Nb_3Sn$ surface from top view (left) and bottom view (right) indicating uniform $Nb_3Sn$ coverage.

FIB-SEM measurements in Fig. 7 showed that the thickness of the $Nb_3Sn$ film was almost the same.

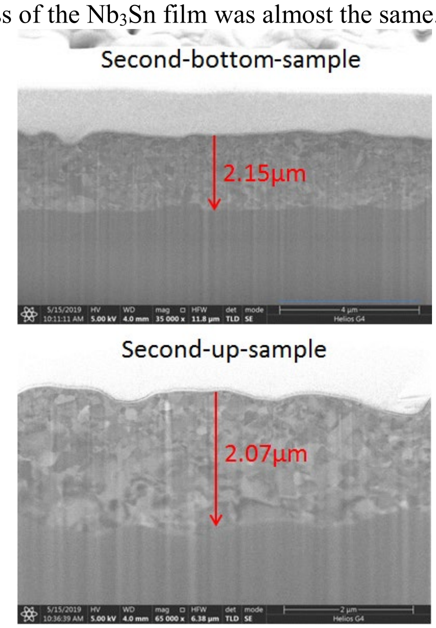



Figure 7: With the modified coating process that kept the Sn source and the cavity at $1200^0$C for 3 hours, the thickness of the bottom sample and the upper sample is almost the same.

## VERTICAL TEST OF THE $NB_3SN$ CAVITY

Due to the limited SRF conditions in China, only one $Nb_3Sn$ cavity was vertical tested. At first, the cavity was tested at Peking University. Before the test, the cavity was treated with high pressure water rinse to clean the surface. No other treatment was performed to the cavity. Figu-

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re 8 showed the magnetic field was effectively shielded and the ambient field was below 5 mGs. A slow cooldown of about ~5 min/K was achieved from 25K to 15K as shown in Fig. 8. However, the vertical test results in Fig. 9 showed the $Q_0$ was only ~2.7e9 at 4.2K and 4.6e9 at 2K in the low field region. What's more, the $Q_0$ dropped seriously at the low field region below $E_{acc}$<4MV/m both at 4.2K and 2K. The maximum accelerating field $E_{acc,max}$ was 8 MV/m. Then the $Nb_3Sn$ cavity was taken back to IMP and re-tested at 4.2K without a slow cooldown process. Before the test, the cavity was treated with HPR again. Also, the ambient field was as high as 22 mGs. No accident, the result is worse. The $Q_0$ was degraded to ~1.3e9 at low field. But the $E_{acc,max}$ reached 10.4 MV/m. However, the low field Q-slope existed in the IMP test again. Based on our previous testing experience, the low field Q-slope may be caused by insufficient degassing. So the cavity was warmed up and baked at 100$^0$C for 48 hours. After that the cavity was cooled down and tested again. Surprisingly, the $Q_0$ at low field was increased to the value of 2K at Peking University. What's more, the low field Q-slope was eliminated and the Q value in the intermediate field region was increased ~8 times. A 1.3 GHz single cell Nb cavity with the standard treatment was tested at IMP with the same cooldown rate and ambient field. The Q value of the $Nb_3Sn$ cavity coated at IMP was 12 times larger than that of the Nb cavity at 4.2K even in the case of the ambient field larger than 20mGs and with the slow cooling down absent. This study shows that the low temperature baking is an effective enrichment to the post treatment of the $Nb_3Sn$ cavity.

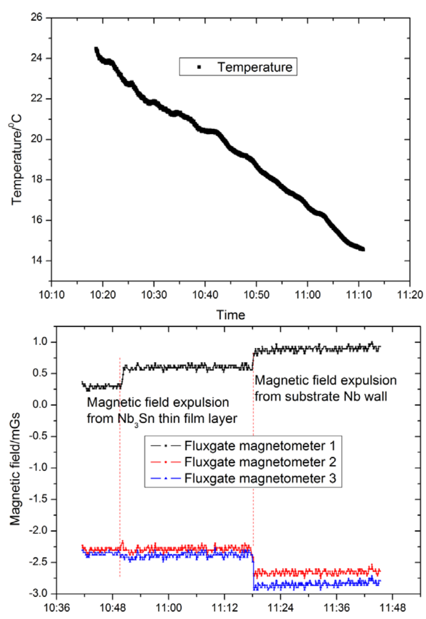


Figure 8: (Top) A slow cooldown of ~5.23min/K was achieved at Peking University; (Down) Magnetic field expulsion was observed during the cooldown at Peking University.

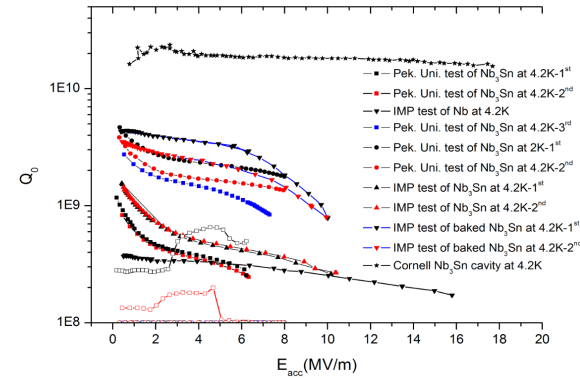


Figure 9: Vertical test results of the $Nb_3Sn$ cavity coated at Peking University and IMP.

To be honest, even after baking, the results of the $Nb_3Sn$ cavity are still far from Cornell University and JLab. The $Nb_3Sn$ samples coated together with the cavity was analyzed. In summary, the reasons for the slightly worse performance may be mainly due to two aspects. The first reason is the pollution from the furnace during the coating process. Because there is no pure Nb chamber to isolate the Nb cavity from the furnace, the inner surface of the furnace was carefully cleaned before each coating. However, it can be seen from Fig. 10 that the inner surface of the furnace was badly polluted after each coating.

Figure 10: The inner surface of the furnace was badly polluted after each coating.

The second reason maybe arises from the inappropriate coating parameter. EDS measurements indicates composition of only 22% At. % Sn. Correspondingly, the $T_c$ of the $Nb_3Sn$ samples coated with the 2$^{nd}$ and 3$^{rd}$ cavity is about 17.6K in Fig. 11.

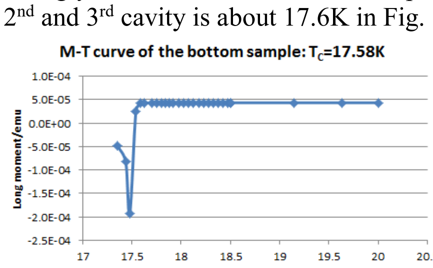


Figure 11: $T_c$ of the $Nb_3Sn$ samples coated with the 2$^{nd}$ and 3$^{rd}$ cavity is about 17.6K.

The surface morphology of the samples coated with the 2$^{nd}$ and the 3$^{rd}$ $Nb_3Sn$ cavity in Fig. 12 directly showed more voids compared with the $Nb_3Sn$ samples coated with the cavity at 1100$^0$C and the Sn source at 1200$^0$C.

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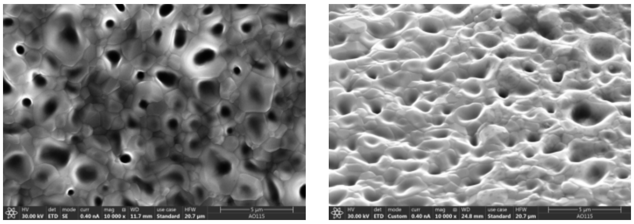
Together with the EDS spectrum and the Tc measurements, it may indicate that the coating parameters of the 2nd and the 3rd cavity is inappropriate and need further optimization.



(a) (b)

Figure 12: SEM pictures obviously showed many voids on the surfaces of the 2nd and 3rd batch samples.

## CONCLUSION

To summarize, the first $Nb_3Sn$ cavity has been coated and tested successfully at IMP and showed obvious advantage of high Q value. Although there is still a gap in performance compared with Cornell University, JLab and FNAL [6], the study of Sn nucleation on Nb samples [7] and the finding of low temperature baking effect to the $Nb_3Sn$ cavity point out the direction for the follow-up upgrade of the furnace, the further optimization of the coating parameters and the exploration of post treatments of $Nb_3Sn$ cavities at IMP. It may also be beneficial to the further improvement and breakthrough of the RF performance and even practical application of the $Nb_3Sn$ cavities.

## ACKNOWLEDGEMENTS

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