Nb_3Sn PROGRAM FOR SUPERCONDUCTING CAVITIES

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This paper discusses the work done with Nb_3Sn in the studies of superconducting radio frequency (SRF) cavities. ERL1-4, a cavity tested in July 2013, performed better than previous cavities of its type and marked a breakthrough in this field of research. Not only did it maintain a remarkable quality factor, but it also revealed that the onset of the Q_0-slope is not fundamental, as it had been considered throughout previous research. Further MATLAB analysis was used to investigate one hypothesis on the possible reasoning behind the Q_0-slope.

INTRODUCTION

Niobium cavities are critical to Cornell's Energy Recovery Linear–accelerator (ERL) as well as accelerators everywhere. Niobium is effective in the sense that it has a high critical temperature and a very low surface resistance; therefore, it makes for a useful superconductor at low temperatures. Labs throughout the world are currently using niobium cavities successfully.

Nb_3Sn is an alternative SRF material that has not been developed extensively. It has a higher critical temperature than niobium (which has a T_c of 9.2 K), so when it is cooled to 4 K from its T_c of 18 K, it's surface resistance is extremely low. Its rate of energy loss throughout the system as a whole was lesser than that of niobium, meaning the quality factor (Q_0) is higher. Nb_3Sn also, in theory, has a higher superheating field, which allows for a higher accelerating gradient. Past research involving Nb_3Sn includes a cavity at Wuppertal, dating back to the 1980s. It had been the best performance seen within a Nb_3Sn cavity up until this point, and it exhibited a distinct Q_0-slope, which became the expected result in the research to come [1].

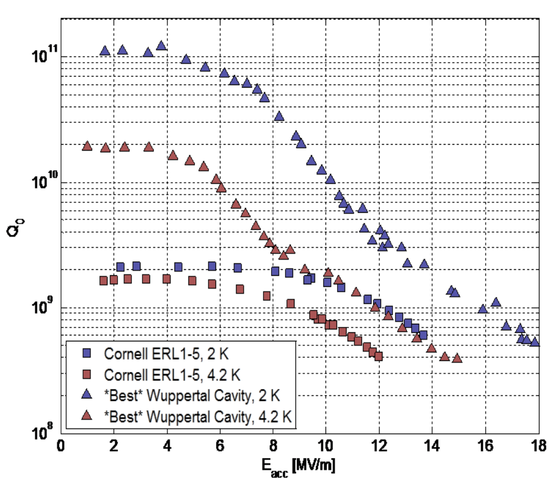

Figure 1. Wuppertal cavity and its Q_0-slope compared to Cornell's ERL1-5.

ERL1-5 and ERL1-4 are Nb_3Sn cavities from Cornell tested to better understand the overall RF performance of Nb_3Sn. They were also compared in performance to that of Wuppertal.

CAVITY PREPARATION AND TESTING

I. Coating the Cavity

A standard niobium cavity is used for this process. It is brought within the clean room to be ideally particle-free on its surface before it is coated. By rinsing it for a few consecutive hours with high-pressured deionized water, it is expected that the cavity's interior is strictly niobium—no excess particles.

Tin is then carefully weighed, as well as a tin chloride. The tin chloride is there to assist the coating process, whereas if it were all purely tin, the nucleation during the bonding of the tin and the cavity wall may not work as planned and ultimately pose a problem within the test. Once weighed, the portions are placed in slots at the bottom of the furnace, as well as two witness samples of niobium, followed by the cavity itself. Heating shields are then placed over the entire apparatus within the furnace to assist the heating process. The furnace is then bolted shut and placed under vacuum, and is heated up to about 1300 ºC over the course of about 6 hours.

II. Applying the Temperature-Mapping Boards & Placing in the Dewar

Once the cavity is fully prepared within the clean room, it is wrapped with an array of thermometers. They provide a full temperature profile of the cavity during operation. There are thirty eight temperature-mapping boards in total, each holding seventeen resistors. Six cernox sensors are then put in position.

Three cernox sensors are placed on the cavity at locations that are approximately equidistant from one another. Their purpose is to measure the temperature of the cavity during the slow cool. The other three are used for the actual t-mapping, and record the temperature of the helium bath during operation.

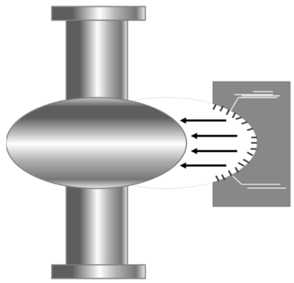

Figure 2. The cavity and a temperature-mapping board.

Once the temperature-mapping boards are in place, the insert to which the cavity is attached is lowered into the cryogenic test pit and bolted down. The air is then pumped out of the system and leak checks are done to make sure that the dewar is vacuum sealed. Once secure, the outer shell of the dewar is filled with liquid nitrogen until it reaches about 100 K, so that it may act as a shielding layer. Liquid helium is then pumped into the inner dewar until it reaches about 4 K (its boiling point at atmospheric pressure).

III. Testing

Once cooled to 4 K, the cavity is now superconducting. A field is put in the cavity and the resistors pick up the subtle changes in temperature compared to the temperature of the helium bath recorded by the cernox sensors. The quality factor as a function of the accelerating field is then plotted using a graphical user interface (GUI). This process continues until cavity's performance is characterized.

RESULTS

ERL1-4 (tested July 2013) outperformed other cavities of its type to date. Not only did it have a remarkable quality factor (10^{10} at 4.2 K at an E_{acc} of 12 MV/m), but it surpassed the performance of the Wuppertal cavity, making this a truly groundbreaking test. In fact, it had a Q_0 ten times higher than that of the Wuppertal cavity at 12 MV/m.

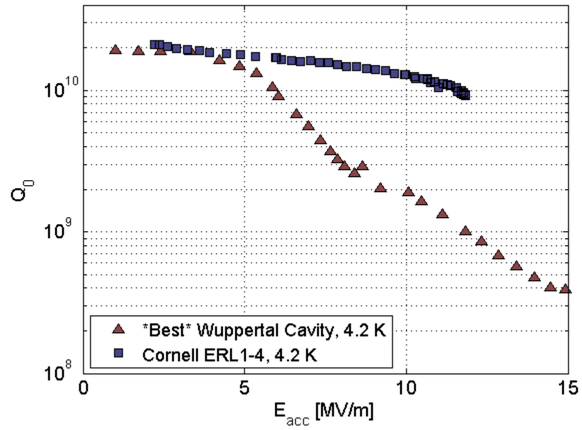

Figure 3. ERL1-4 compared to the 'Best' Wuppertal Cavity at 4.2 K.

In the case of Wuppertal's cavity, it had been suggested that the reason for the Q_0-slope was strictly a fundamental occurrence. This breakthrough test shows that the reason for the degradation is in fact *not* fundamental.

EXTERNAL DATA ANALYSIS

ERL1-5, manufactured at Cornell and tested in May 2013, also showed a similar result to Wuppertal. In an attempt to try and further understand the Q_0-slope, the data regarding temperature change was examined.

Finding the onset of the Q_0-slope was the first necessity. Looking at the quality factor as a function of the accelerating field provided an approximation of when exactly the degradation began.

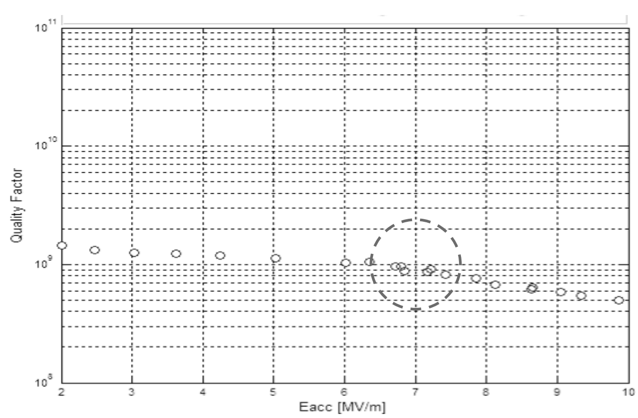

Figure 4. Q_0 vs. E_{acc}. The Q_0-slope onset is circled; approximately 7 MV/m.

As shown in Figure 4, the Q_0-slope began at approximately 7 MV/m, the corresponding value of transmitted power (Pt) was looked up, and found to be about 5.8 μW.

Once that was known, MATLAB was used for the calculations that follow. One hypothesis of the reasoning for the Q_0-slope was that it could be affected by the areas of the cavity that experience the maximum heating. More heating could imply surface defects, which could be a reason for the sudden onset of the degradation. To investigate this further, the change in temperature as a function of transmitted power was plotted for all six hundred and forty-six resistors.

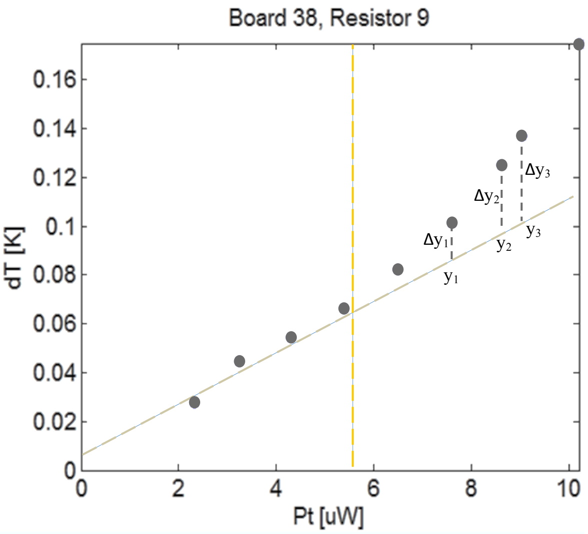

Figure 5. dT vs. Pt for board 38, resistor 9. Approximate onset of Q0-slope represented by the orange line. The gray line represents the trend of the data that came before the degradation.

The data before the onset was fit to a common trend line. The data during the Q_0-slope was then measured for its deviation from said trend line, providing the normalized residual.

$$\mathrm{NR} = \frac{\Delta y_1}{\mathrm{y}_1} + \frac{\Delta y_2}{\mathrm{y}_2} + \frac{\Delta y_3}{\mathrm{y}_3} + \cdots + \frac{\Delta y_n}{\mathrm{y}_\mathrm{n}} \quad (1)$$

Once this value was found, the maximum heating of each individual resistor was plotted as a function of the normalized residual. Any negative NR values could be omitted because they were either poor readings or bad resistors. The resulting graph was as follows.

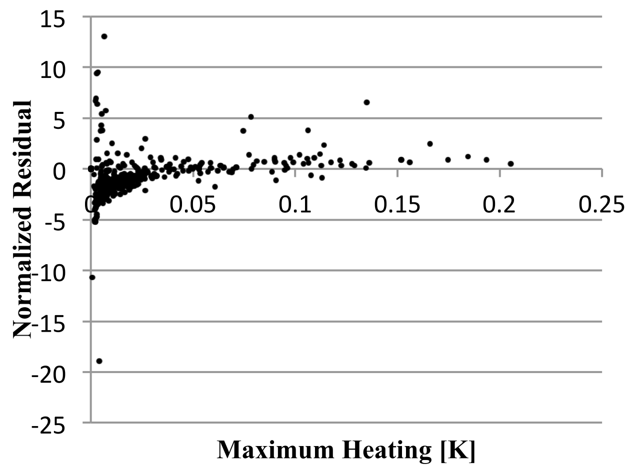

Figure 6. Normalized residual vs. maximum heating for all resistors. Negative NR values can be disregarded.

A majority of the data points to the left of 0.05 K can be considered noise. Most valid results lie between a NR value of 0 and 2 with no increase with the rise of maximum heating. That's a preliminary indication that the Q_0-slope may not be affected simply by the areas with the most heating, but is happening throughout the entire cavity.

CONCLUSION

The research and development of Nb_3Sn has made breakthrough progress. ERL1-4 not only had a high quality factor, but it also showed that the Q_0-slope was not something fundamentally occurring. Data analysis indicated that areas with higher heating are not the cause of the Q_0-slope. Further investigations for the possible reason are ongoing.

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REFERENCES

[1] H. Padamsee, RF Superconductivity for Accelerators, Wiley-VCH Verlag GmbH & Co. KGaA, Weinham (2008)