Summary Report on SRF 13 - Hot Topic Session:

What is the best surface treatment for high Q and medium gradient?

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Session Slides on SRF 13 Web Site

Introduction

The SRF community has made a lot of progress on high gradients for pulsed applications. But for CW applications the gradient becomes cost limited by the dynamic heat load. The cost of refrigeration for a several GeV CW accelerator becomes substantial, so that the optimum gradient for lowest cost is likely to be in the 15 – 20 MV/m range. Higher Q's will likely drive the optimum gradient higher and the cost lower. Hence the goal of the discussion is to help identify the best treatment that will give the highest Q at medium gradients. We restricted the discussion to 1.3 GHz cavities, although the topic is also very interesting and germane for low frequency, low beta cavities for a future discussion.

Panelists

The panel members who presented data and discussions were Alexander Romanenko (Fermilab), Anna Grasselino (Fermilab), Mathias Liepe (Cornell), Pashupati Dhakal (Jlab) , Detlef Reschke (DESY) and Julia Vogt (BESSY).

Overall Summary

There have been remarkable strides on the Q-frontier in the last year. A variety of improved paths have been found to raise the Q so that at medium fields (15 - 20 MV/m), Q values of $3x10^{10}$ can be expected at 2 K and $4 x10^{10}$ at 1.8 K. Many exciting new paths are under exploration to reach even higher Q's. Exceptional numbers of $6 – 8 x 10^{10}$ at 1.8 K were reported. These numbers should be compared to typically reported Q values (in vertical tests) at T= 2K in the range $1.5x 10^{10}$ to $2x10^{10}$, and $2x10^{10}$ to $3x10^{10}$ at 1.8K. Ways have also been found to help preserve high Q's in cryomodules. Many of the new paths need more tests to confirm reliability, and to understand the responsible mechanisms.

BCP vs. EP, 120 C Bake and HF Rinse

In the first set, we addressed questions related to: What is the best *Surface Treatment* for highest Q? Is BCP or EP the superior treatment? Does 120 C bake have an influence on the choice of BCP vs. EP? What is the benefit of HF rinsing after 120 C for both treatments?

The bottom line is that at low fields BCP and EP treatments give similar Q (about $1.3x10^{10}$ at 2 K). But at higher fields, BCP shows a slightly stronger field dependence of Q, due mostly to changes of the residual resistance. Hence at 20 MV/m the BCP Q falls to about $1 x 10^{10}$, whereas the EP Q remains at $1.1 x10^{10}$.

There is a lot of experience with baking cavities at 120C, a simple procedure which arose to eliminate of the high field Q-slope of EP cavities. As expected from the BCS theory, 120 C bake shortens the electron mean free path and so lowers the BCS resistance by about a factor of two for both BCP and EP treatments. But the residual resistance rises a few nΩ, presumably due to the "spoiling" of the pentoxide layer. HF rinsing removes the bad oxide and re-grows a good oxide to lower the resistance by a few nΩ. The effect is similar for EP and BCP, but may give slightly higher Q's for EP due its weaker Medium Field Q-Slope (MFQ slope). Cornell has achieved Q values of $3x10^{10}$ at 1.8 K with several 7-cell ERL cavities by applying BCP/120C bake/HF rinse. Even higher Q values have been obtained for one of these cavities in a horizontal cryostat (see below).

Hence 120 C bake followed by HF rinsing is a simple recipe to achieve Q values $3x10^{10}$ and higher at 1.8 K.

To better understand the field dependence of Q, Alexander presented data from the new "deconvolution" analysis of the two components of "temperature independent" and "temperature dependent" of surface resistances. For convenience he calls the temperature independent part "residual" and the temperature dependent part "BCS". The decomposition analysis shows that BCP and EP treatments give similar values of BCS resistance, and similar field dependence to 20 MV/m. But after baking at 120 C, the MFQ slope is stronger for BCP due to the stronger field dependence of the residual component.

Tumbling

Does tumbling help to reach higher Q's (above the statistical spreads)? Does a mirror smooth surface contribute to higher Q?

Anna presented Fermilab data on single and nine-cell cavities, comparing tumbled with non-tumbled cavities. At best one can say that the tumbled cavities offer a 10% higher Q, but the spreads in Q values are usually much larger. The slightly higher Q value of tumbled cavities may also arise from the addition baking at 800 C necessary to remove the excess H incorporated by tumbling. Finally, a tumbled cavity with a mirror smooth surface was successfully measured *without* any post-chemistry. It showed the same Q as after post chemistry (EP) when the surface assumed the typical roughness for an EP process. Hence mirror smooth does not lead to higher Q's.

Large Grain vs Fine Grain

Does large grain material give higher Q's (above the statistical spreads)?

Detlef from DESY presented extensive data on 11 LG and 18 FG 9-cell cavities **at 2 K**. Although at low fields the Q of LG cavities (e.g. 2.5 -3.5 $x10^{10}$) is *slightly* above the FG cavities (e.g. 2 - 3 x 10^{10}), the spreads are large. The difference shrinks at medium fields so that LG is (1.8 – 2.3) x 10^{10} and FG is (1.5 – 2) x 10^{10}
At 1.8 K and 20 MV/m, DESY reported 3 – 5 $x10^{10}$ with several 9-cell cavities. JLAB has single cell LG results that reach 3 – 3.5 $x10^{10}$ at 20 MV/m.

There may be a simple explanation why there is a (small) difference between LG and FG. The magnetic flux trapping tendency (discussed below) for large grains is less than for fine grains. Results are presented below to show there are ways to reduce the trapped flux, by better shielding and slower cool-down, which could also eliminate the small Q difference between LG and FG, and so provide a future path to further improve Q values.

800 C Treatment and High Q

Does higher temperature (800 C and above) annealing raise Q?

Most labs perform a light, final chemistry after 800 C bake because there is a real possibility of furnace contamination, which can cause Q-drop or field emission. Recent results from Fermilab with single cells show that these problems can be avoided if the 800C annealing is performed with Nb end caps, so contamination does not enter. Whether this technique can be applied successfully to multi-cells and whether it can reliably avoid field emission needs many more tests. However the single cell results are very encouraging. 800 C bake without final chemistry showed at 2 K a Q improvement to 3 $x10^{10}$, compared to baseline test result of 2 $x10^{10}$. This improvement held up to 25 MV/m. Another interesting result was that the Q was comparable to cavities with 120 C bake, so it is likely the mean free path in the rf layer is also shortened by the 800 C bake. If this procedure can become reliable it eliminates two processing steps (post chemistry and 120C bake) and their associated costs. It also reduces the risk of some H re-admission during the final chemistry.

Temperatures Higher than 800 C

What about higher temperatures than 800 C?

Mathias reported that at Cornell a single cell was heated to 1000 C for 5 days, then tested without and with chemistry. Without chemistry the low field Q was very high, nearly 3 $x10^{11}$ at 1.4 K. However the Q fell to 10^{10} at 10 MV/m. Even after 80 microns of material removal the Q drop could not be removed. But after 280 micron BCP, the Q was $7x10^{10}$ at 20 MV/m and 1.6 K. Pahsupati reported that Jlab also has incidents of very high Q with 800 – 1600 C treatment. More tests are needed to determine the reliability and the mechanisms of the very high temperature effects, and to understand the need for significant material removal. Also, the drop in yield strength after 1000+ C treatment could be a problem for practice, unless thicker material is used.

New Treatments

An exciting new result at Fermilab has been Q enhancements via N and Ar doping (10^{-2} torr for 10 minutes) at 800 C, followed by a light EP of about 10 microns. The best time and temperature for doping as well as post material removal is still under exploration. Q values of $4x10^{10}$ at 2 K and 8 $x10^{10}$ at 1.8 K were obtained. Their results also show an “anti-Q-slope” in the medium field region, so eliminating the MFQS. Deconvolution studies suggest that the anti-Q-slope comes from the BCS component, the cause of which needs to be understood. The parameters of time/temperature/Npressure/post-chemistry need to be further explored and optimized to obtain some of the highest Q's so far demonstrated.

The other area for promising new results come from Nb_3Sn work at Cornell. A single cell at 4.2K reached 10^{10} at 12 MV/m. This is a very promising result for the future, especially if higher gradients than Nb can also be demonstrated. Parameters for making the best Nb_3Sn need to be optimized and demonstrated with multi-cells.

<u>High Q's in Cryomodules</u>

What are the precautions/procedures to maintain higher Q's from vertical test to cryomodule?

Generally cavity-to-coupler and cavity-string assembly procedures can lead to lower Q's due to contaminants that enter. But Detlef showed DESY reached Q values of 2.5 – 3.5 $\times 10^{10}$ at 2 K for a full CM with eight 9-cell cavities by careful assembly and good magnetic shielding. Cornell showed a 7-cell cavity in a CM with a Q of 3.5×10^{10} at 2 K by slow cool down to avoid flux trapping from thermo-currents. The same cavity showed Q increase to 6×10^{10} at 1.8 K and 10^{11} at 1.6 K. Hence significant gains in final CM Q values are possible but call for stringent cleanliness in string assembly, excellent magnetic shielding and controlled slow cool down.

Julia from BESSY presented thermocurrent/flux trapping studies from a closed loop between Nb and Ti, similar to the conditions for Nb cavities with Ti He-vessels. The studies showed that slow cool down with reduced thermal gradients will generate less trapped flux and so yield higher Q values. Cornell benefitted from such procedure to reach the high Q's discussed above. Another important study at CERN (by Sarah Aull) showed that the amount of flux trapped by Nb (when cooled in an external magnetic field) is between 80 – 100% for FG Nb, but only 40 - 70% for single crystal Nb. Presumably LG Nb also traps similarly smaller amounts of flux. This provides a mechanism for why LG cavities may show higher Q's. This could be a clue that better magnetic shield will yield comparable results between LG and FG cavities. BESSY also showed that it is possible to release some of the trapped flux by cooling slowly through the transition temperature.