HIGH Q_0 IN SUPERCONDUCTING NIOBIUM CAVITIES: PROGRESS AT FNAL AND FUTURE PLANS*

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Abstract

Consistent improvement in the quality factors of SRF cavities at medium surface fields represents a direct cost savings factor for the proposed Project X linac and other SRF accelerator projects based on CW operation such as NGLS at LBNL and Cornell ERL. Current state-of-the-art in SRF does not provide processing recipes to maximize the Q_0 at medium fields since a complete understanding of the mechanisms affecting the quality factor is not yet developed. In this contribution we discuss recent FNAL effort in both scientific understanding and practical improvements and outline directions we are pursuing for future research.

INTRODUCTION

Recent developments in the field of particle accelerators brought the shift of focus from the high energy frontier to the intensity frontier. This shift brought about the requirements of CW or high duty factor operation for many of the proposed machines, such as for example Project X, Cornell ERL, and NGLS at LBNL.

The quality factor of superconducting niobium cavities is defined by the following equation:

$$Q_0 = \frac{\omega U}{P_{diss}} \approx \frac{G}{R_s},$$

where $\omega = 2\pi\nu$, ν is the resonant frequency of the cavity, U is the stored energy, P_{diss} is a dissipated power, G is a cavity geometry factor, and the last equality holds only if R_s is not strongly dependent on the field. The microwave surface resistance R_s can be represented as a sum of the temperature-dependent BCS and temperature-independent residual resistances:

$$R_s(T) = R_{BCS}(T) + R_{res}.$$

Furthermore, three different Q-slopes are typically distinguished – low, medium, and high field – which affect the Q_0 of the cavity (see [1] for review). All three Q-slopes remain poorly understood and are an active area of research. For the purpose of the maximization of Q_0, and specifically in the field range around 70 mT for Project X, the most important is the medium field Q-slope and values of the residual and BCS resistances at low fields, which are affected by different treatments. Recent achievement of high quality factors at FNAL by minimizing the low field surface resistance by combination of 120^{0}C baking and HF rinsing [2] makes understanding and minimization of the medium field Q-slope extremely promising.

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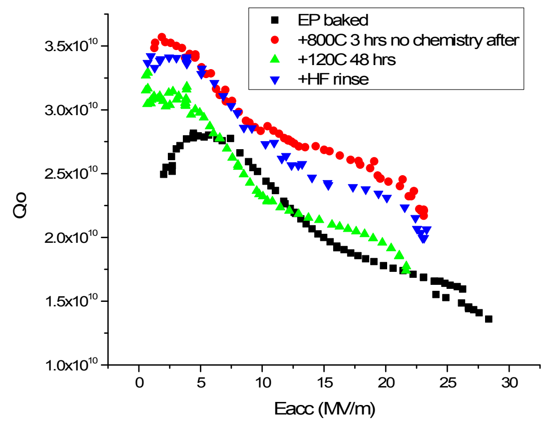

Figure 1: $Q_0(E_{acc})$ curves at T = 2 K for the large grain cavity (grain size ~10 cm). Notice the linear scale.

We have selected to pursue both heat and chemical treatments followed by RF testing coupled with temperature mapping to understand physics behind and achieve the maximum Q_0 in 1.3 GHz single cell cavities.

RESULTS

Recent findings pointing towards the hydrogen-related defects as a source of the medium and high field Q-slopes [2] motivated us to try to minimize the amount of such defects by performing vacuum heat treatments.

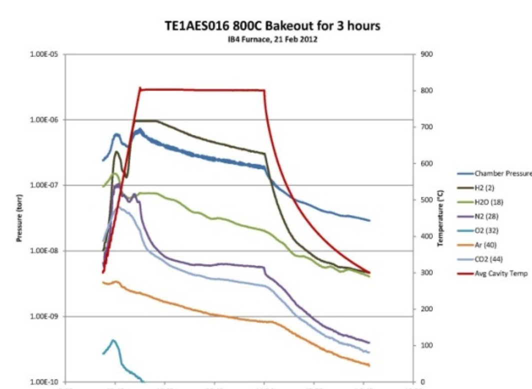

Figure 2: RGA data during the 800^{0}C treatment of the large grain cavity.

Typically such treatments are followed by a light electropolishing (EP) or buffered chemical polishing (BCP). But such chemical treatments reintroduce hydrogen into niobium as found out by previous studies [4]. Some preliminary heat studies [5] without chemistry afterwards showed increased Q_0 values further motivating our approach. We have started the exploration by applying no chemistry after 800^{0}C 3 hours vacuum furnace treatment on a large grain (~10 cm) and several fine grain (~50 um) single cell 1.3 GHz cavities.

The large grain cavity results are shown in Fig. 1 with the corresponding RGA data in Fig. 2. After the 800^{0}C treatment followed by ultrasonic cleaning and HPR only, the Q_0 of the cavity increased significantly at all field levels.

Subsequent 120^{0}C 48 hours baking decreased the Q_0, presumably due to the increase in the residual resistance. A hydrofluoric acid (HF) rinse for 5 minutes applied after 120^{0}C treatment restored the Q_0 to practically the same level as before, which is consistent with the other studies reported in [2]. Temperature mapping of the RF losses was used in the last RF test (blue triangles) and a temperature map at E_{acc} = 22 M/m is shown in Fig. 3. The losses causing the medium field Q-slope are concentrated in the region of a high magnetic field around cavity equator in line with findings in [2] as well. The resulting improvement in Q_0 is about 25-30% at all field levels.

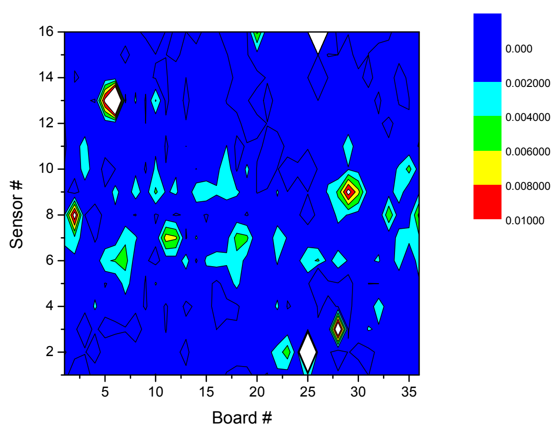

Figure 3: Contour plot of the temperature map at E_{acc} = 22 MV/m for the large grain EP cavity (blue curve in Fig. 1). Color scale is in Kelvin.

Contrary to the successful large grain result, all five fine grain cavities we investigated exhibited the same behaviour after 800^{0}C furnace treatment followed by no chemistry. A severe Q-disease appeared in the Q_0(Eacc) curve as shown in Fig. 4.

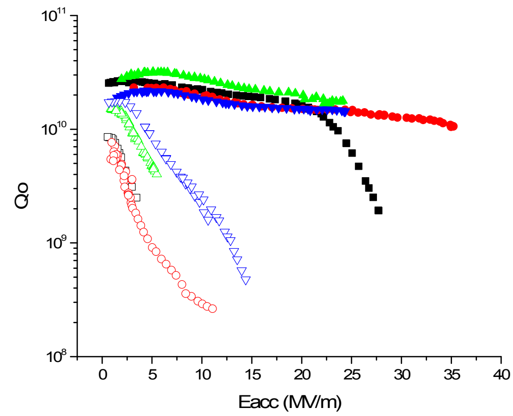

Figure 4: Q-disease in fine grain cavities after 800^{0}C 3 hours furnace treatment with no chemistry afterwards. Solid points are before and open ones of the same color are after the treatment for the same cavity.

This is a surprising result since all cavities previously treated in the same furnace with 10-20 um of EP afterwards exhibited no Q-disease. In order to investigate the origin of the Q-disease we have performed 10 HF rinse cycles on one of the cavities. Such treatment removes of the order of 20 nanometers of the niobium surface. The cavity did not recover and the Q-disease was still present with some slight change as shown in Fig. 5. Temperature maps obtained for this RF test have shown heating over the whole cavity surface as shown in Fig. 6. Furthermore, we have performed a 100 K hold of this cavity for about 7 hours. This is a typical test used for the presence of large amounts of hydrogen. The result was a severe deterioration of the cavity Q_0 from ~8*10^9 down to 3*10^7, which strongly suggests the presence of large amounts of hydrogen.

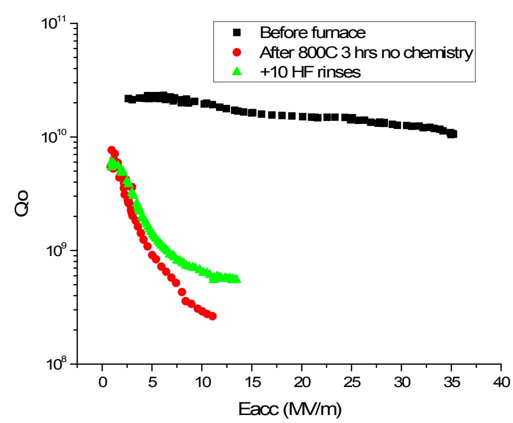

Figure 5: Non-recovery of the Q-diseased cavity by 10 HF rinses.

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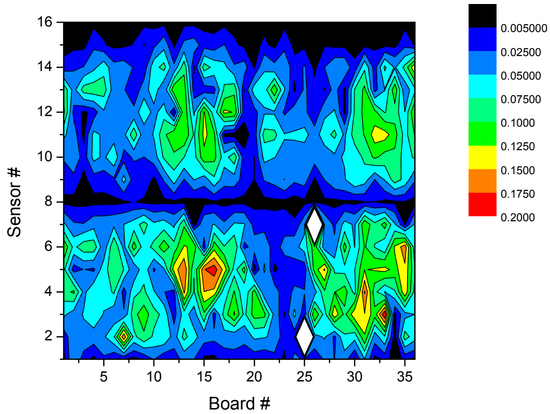

Figure 6: Strong heating of the most of the cavity surface into the Q-disease. Color scale is in Kelvin.

On the other cavity inflicted with the Q-disease we have performed a light EP of 20 um and the performance of the cavity recovered as shown in Fig. 7.

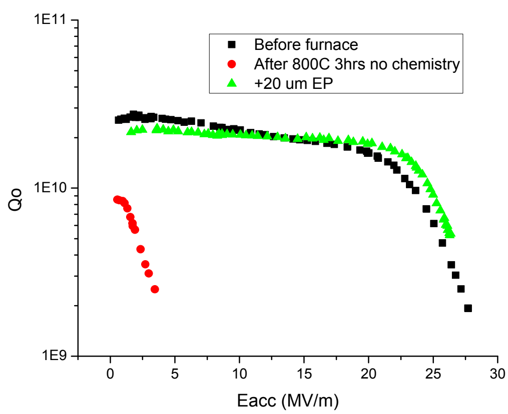

Figure 7: Light electropolishing (20 um) recovers the furnace-induced Q-disease.

In summary, our preliminary results indicate that a significant improvement in Q_0 can be achieved on large grain cavities by performing no chemistry after a typical 800^0C furnace treatment. Fine grain cavities gain a Q-disease upon such treatment, the reason for which is not yet clear.

FUTURE PLANS

Eliminating chemistry after $T>600^0$C furnace treatments typically used for preventing hydrogen Q-disease represents the first step toward minimizing the amount of near-surface hydrogen and hydrogen-induced defects, which we believe may be causing the medium field degradation. One of the objectives is to prevent reabsorption of hydrogen during the exposure to atmospheric air and/or during the cooldown from high temperatures after annealing. We intend to explore several strategies following [3,4]: 1) introduce a small partial pressure of pure oxygen into the furnace at room temperature following the cooldown; 2) introduce O_2 or N_2 in small amounts at elevated temperatures.

CONCLUSION

An active program targeted on increasing the quality factors Q_0 of superconducting niobium cavities is underway at Fermilab. Preliminary results indicate that even just eliminating chemistry after hydrogen degassing may already improve Q_0 by about 30% in large grain cavities.

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