OBSERVATION OF HIGH FIELD Q-SLOPE IN 3 GHz Nb CAVITIES*

G. Eremeev†, F. Hannon
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.

Abstract

A degradation of the unloaded quality factor is commonly observed above about 100 mT in elliptical niobium cavities. The cause of this degradation has not been fully understood yet, but the empirically found solution of heating to about 100-120 °C for 24-48 hrs. eliminates the degradation in electropolished fine grain or large grain niobium cavities. While numerous experiments related to this phenomenon have been done at 1.3 GHz and 1.5 GHz, little data exists at other frequencies, and the frequency dependence of this degradation is not clear. We have measured the unloaded quality factor of 3 GHz fine grain niobium cavities, which were chemically polished as the final treatment before RF tests in a vertical Dewar and observed the characteristic degradation in two cavities. The measurement of the quality factor degradation at different bath temperatures points to a field-dependent rather than a temperature-related effect.

INTRODUCTION

As a part of new material development, several 3 GHz single cell cavities were built out of niobium to serve as a substrate for future new material coatings. The cavities received the standard modern cavity processing and were measured at T_{bath} = 2.0 K to confirm their suitability as a substrate. Two of the cavities reached fields significantly higher than we anticipated and were limited by a Q-slope reminiscent of the high field Q-slope.

The high field Q-slope was identified in the 1990s [1], when advances with high pressure rinsing allowed for a field emission free cavities reaching to above B_{peak} = 100 mT. At this field a strong degradation in the quality factor was consistently observed in many cavities. Further experiments with temperature mapping indicated broad heating in the high magnetic field regions. Significant effort has been spent in the 2000s to understand the phenomenon and several dissertation were written on the topic [2, 3, 4, 5, 6]. Also, in the late 1990s - early 2000s an empirical solution was found to avoid the degradation: electropolishing followed by 120 °C baking for 48 hours [7, 8]. The solution allowed for high gradient niobium cavities and is used today as a standard treatment.

The 2000s were dominated by oxygen pollution hypothesis as the explanation for the high field Q-slope [9, 10]. Oxygen pollution layer in the RF penetration layer was postulated, and interstitial oxygen was known to degrade superconducting properties of niobium [11]. While the presence and the role of oxygen at the interface is still not completely elucidated, ample evidence eliminate the oxygen pollution layer as a sole culprit behind the Q-drop. With oxygen out of the picture, hydrogen filled the void.

High concentration hydrogen has been known to degrade the quality factor of superconducting cavities due to formation of Nb-H at low temperature [12]. Due to high mobility of hydrogen, it was assumed that hydrogen cannot be involved with mild baking effect, but present models involving hydrogen-crystal defects speculate that Nb-H systems are the cause of the high field Q-slope [13, 14]. Recently, material surface studies have provided some support for the hypothesis [15], but most questions regarding the phenomenon remain standing: why the difference between electropolishing and buffered chemical polishing, why anodizing removes benefit, why the grain size matters, etc.

One of the questions is the frequency dependance of the degradation. Since most of the data related to the degradation were collected at 1.3 or 1.5 GHz, models are required to predict what happens when one goes up or down in frequency. A couple of papers addressed the topic using the data sets available at the time [16, 17]. Our measurements reported here contribute to the data set on the frequency dependence of the high field Q-slope.

RF RESULTS

The half cells were stamped from 3mm RRR niobium sheet, mechanically polished, and electron beam welded together to form 3 GHz cavity. The cavity received 80 μm of bench chemical polishing BCP(1:1:1). After bulk chemistry the cavities were annealed in a vacuum furnace at 600 °C for 10 hours. After annealing, the cavities were chemically polished with BCP (1:1:1) solution for 10 μm, high pressure rinsed, assembled for cold RF test, and tested in the dewar. All three cavities were tested at 2.0 K to check their suitability for subsequent new material development. FH3C was also tested at 1.8 and 1.6 K while still in the dewar. FH3D was removed from the dewar after 2.0 K, baked "in-situ" at 120 °C for 48 hours, and tested again at 2.0 K.

FH3A had a low field $Q_0 = 6\cdot10^9$ and was limited by quench at about 13 MV/m. The cavity Q_0 curve also exhibits a strong slope starting from very low gradient, Fig. 1.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

† grigory@jlab.org

The beam tube of these cavities is too small for the viewing tubes of our existing optical inspection systems, but the cavity internal surface was inspected with a boroscope. Several features were found in the heat affected zone near

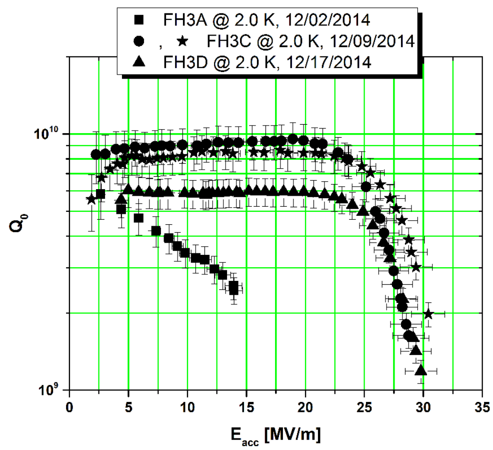

Figure 1: Baseline test results for FH3A[squares], FH3C[circles], and FH3D[triangles] at T_{bath} = 2.0 K. FH3A was limited by quench at the highest field. FH3C and FH3D were limited by the available power.

the equator. We suspect that one of the features caused the quench, but the cause of strong Q-slope in this cavity is not clear at the moment.

FH3C had a low field quality factor of about $8{\cdot}10^9$, which improved by about 20 % with field up to about E_{acc} = 20 MV/m. At this field a strong degradation of the quality factor set in. The cavity was limited to E_{acc} of about 30 MV/m, where the quality factor degraded to about $1{\cdot}10^9$ and we were limited by the 60 Watt available RF input power, Fig. 1. With the cavity still in the dewar, the dewar was topped off with liquid helium the next day and the

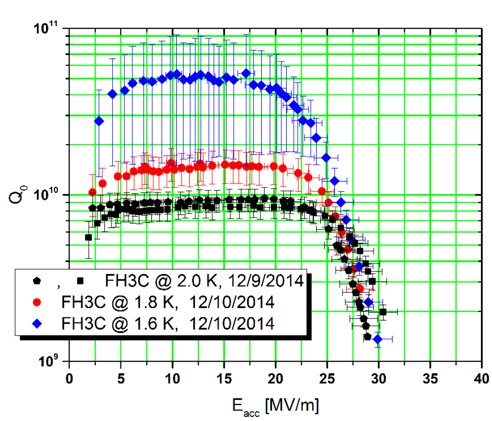

Figure 2: FH3C test results for three different helium bath temperatures, 2.0, 1.8, 1.6 K. Note the increase in the low field quality factor as expected, but similar high field Q-slopes.

cavity was tested at T_{bath} = 1.8 K and T_{bath} = 1.6 K. The low field quality factor has improved as we expected with the bath temperature reaching $1.5{\cdot}10^{10}$ at T_{bath} = 1.8 K and $5.3{\cdot}10^{10}$ at T_{bath} = 1.6 K. However, the high field Q-slope did not change and the cavity was still limited by the high field Q-slope to $E_{acc} \cong$ 30 MV/m. No radiation was observed during the measurements.

FH3D had a low field quality factor of about $6{\cdot}10^9$, which stayed constant with field up to E_{acc} = 20 MV/m. Above E_{acc} = 20 MV/m, a strong Q_0 degradation was observed, and the cavity was limited by the available power at $E_{acc} \cong$ 30 MV/m, Fig. 1. After the baseline test, the cavity

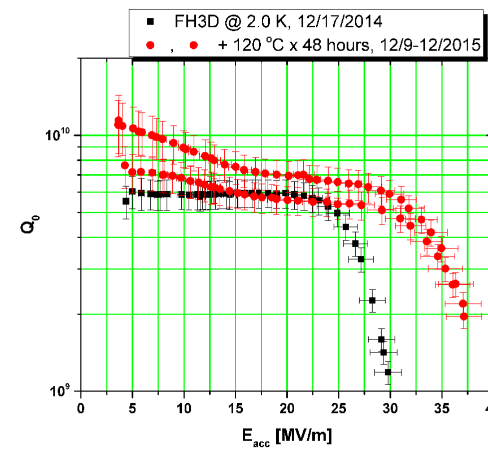

Figure 3: FH3D test results at T_{bath} = 2.0 K before and after 120 °C x 48 hours baking.

was removed from the dewar and baked at 120 °C for 48 hours. The cavity was then put back in the dewar, tested at 2.0 K, and then tested again at 2.0 K two days later. The low field quality factor improved to about $7\text{-}10{\cdot}10^9$, but degraded with field to about $6\text{-}7{\cdot}10^9$ at E_{acc} = 20 MV/m. The cavity was limited by a high field Q-slope to about E_{acc} = 37 MV/m, Fig. 3. No radiation was observed during the measurements.

DISCUSSION

The quality factor degradation observed in FH3C and FH3D has many characteristics of the high field Q-slope commonly observed in 1.3 and 1.5 GHz SRF cavities. The high field Q-slope is the degradation of the quality factor without X-rays, which we also did not seen in these experiments. It may be argued that due to a small accelerating gap of these cavities, of just 5 cm, the same field emission sites may not induce enough radiation to be detected with the standard instrumentation. The standard check in this case would be to test the cavity with a thermometry setup, but it is not available to us at present. However, the consistency between the degradation in FH3C and FH3D would be surprising to be caused by such a random effect as field emission. Further, in Fig. 4 earlier data on 3 GHz reproduced from [18] is shown along with our results. The Q-

ISBN 978-3-95450-178-6

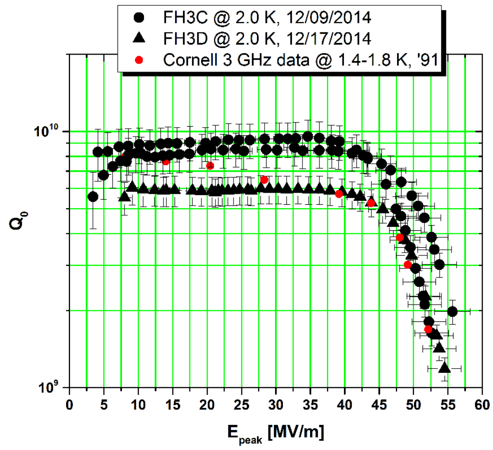

Figure 4: FH3C and FH3D at T_{bath} = 2.0 K are plotted here along with old Cornell data reproduced from [18]. E_{peak}/E_{acc} = 1.83 was used for 3 GHz cavities (ANL 3 GHz). Note that old Cornell cryogenic system was a constant pumping speed system, so the temperature of the helium bath increases from about 1.4 to about 1.8 K with RF dissipated power for Cornell test.

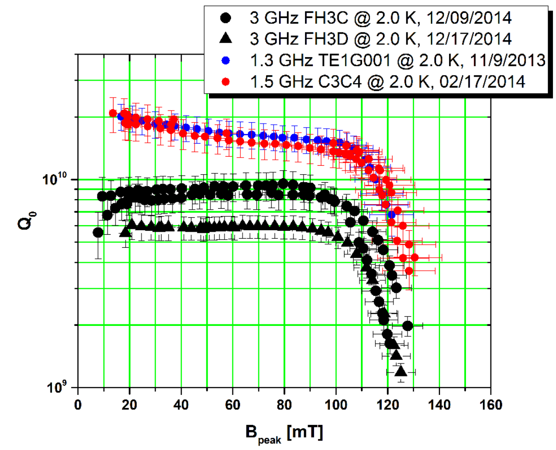

Figure 5: FH3C, FH3D results are plotted here along with test results for a 1.3 GHz and a 1.5 GHz single-cell cavities. B_{peak}/E_{acc} = 4.2 mT/(MV/m) was used for 1.3 GHz (TESLA end cell) and 3 GHz (ANL 3 GHz); B_{peak}/E_{acc} = 4.5 mT/(MV/m) was used for 1.5 GHz (OC center cell). All data is measured at T_{bath} = 2.0 K. No field emission was observed in any test.

slope in the older data has been reported to be common and the thermometry results on those cavities indicated broad areas of heating, which indicates that field emitter was not the limiting cause in those test. The field emission also does not improve after the mild baking [19], which was the case with FH3D, Fig. 3. Hence, we conclude that the slope in our cavities was not caused by field emission.

Thermal feedback was suggested as the cause of degradation in the past. Since at that time the helium bath temperature was not constant during the RF test, models accounted well for the degradation at this frequency. Our VTA facility has a feedback loop that ensures a constant bath temperature throughout the test. The RF test of FH3D at three different bath temperature shows that the slope is not sensitive to such bath temperature variation. Since thermal feedback models indicate that the onset of the degradation shifts with the helium bath temperature [20], we argue that the observed slope is a field effect.

In Fig. 5, we plot our results along with the representative results for 1.3 and 1.5 GHz single-cell cavities for comparison. In this plot we show 1.5 GHz 1-cell cavity C3C4, which received 20 μm BCP (1:1:2) as the final treatment and 1.3 GHz 1-cell cavity TE1G001, which received 25 μm EP as the final treatment. No x-rays were detected in any of the tests. The low field quality factor of the lower frequency cavities is higher as expected from the temperature dependence of the BCS part of the surface resistance. At high fields all cavities are limited to about B_{peak} = 120-130 mT, but the onset of the high field Q-slope seems to be decreasing with frequency. If we compare the field at which quality factor reaches $4{\cdot}10^9$, we find that for 1.3 GHz cavity it was reached at B_{peak} = (128 $\pm$ 8) mT and for 3 GHz cavities it was reached at B_{peak} = (114 $\pm$ 5) mT.

CONCLUSION

A degradation of the unloaded quality factor is commonly observed above about 100 mT in elliptical niobium cavities. We have measured the unloaded quality factor of 3 GHz fine grain niobium cavities, which were chemically polished as the final treatment before RF tests in a vertical Dewar and observed the characteristic degradation in two of the cavities. The onset of degradation in the tested 3 GHz cavities is also close 100 mT, but seem to be slightly lower than in the lower frequency cavities.

ACKNOWLEDGMENTS

We would like to thank Jefferson Lab technical staff for technical assistance.

REFERENCES

[1] B. Bonin and M. Juillard, Proc. EPAC'94, 2045:2047 (1994).

[2] L. Lilje, Ph.D. dissertation, Universitaet Hamburg, (2001).

[3] G. Ciovati, Ph.D. dissertation, Old Dominion University, (2005).

[4] H.Tian, Ph.D. dissertation, The College of William and Mary, (2008).

[5] G. Eremeev, Ph.D. dissertation, Cornell University, (2008).

[6] A. Romanenko, Ph.D. dissertation, Cornell University, (2009).

[7] J.P. Charrier, B. Coadou, and B. Visentin, Proc. EPAC'98, Stockholm, Sweden, 1885-1887 (1998).

[8] K. Saito, H, Inoue, E. Kako, T. Fujino, S. Noguchi, M. Ono and T. Shishido, Part. Acc., 60:193-217 (1998).

[9] H. Safa, Proc. SRF'01, Tsukuba, Japan (2001).

[10] J. Knobloch, R. L. Geng, M. Liepe and H. Padamsee, Proc. SRF'99, Santa Fe, U.S.A.

[11] W. DeSorbo, Phys. Rev. 132, 107 (1963).

[12] B. Bonin and R.W. Roeth, Proc. SRF'91, Humburg, Germany (1991).

[13] A. Romanenko, A. Grassellino, F. Barkov, A. Suter, Z. Salman and T. Prokscha, Appl. Phys. Lett. 104, 072601 (2014).

[14] G. Ciovati, G. Myneni, F. Stevie, P. Maheshwari and D. Griffis, PRST-AB 13, 022002 (2010).

[15] Y. Trenikhina, A. Romanenko, J. Kwon, J.-M. Zuo and J. F. Zasadzinski, J. Appl. Phys. 117, 154507 (2015).

[16] P. Bauer, G. Ciovati, H. Edwards, J. Halbritter, H. Padamsee, K. Saito, B.Visentin, Fermilab technical note, TD-05-56 (2006).

[17] H. Weingarten, PRST-AB 14, 101002 (2011).

[18] H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators, Wiley, New York (2008).

[19] A. Navitski, S. Lagotzky, D. Reschke, X. Singer, and G. Mueller, Phys. Rev STAB 16, 112001 (2013).

[20] J. Vines, Y. Xie, H. Padamsee, Proc. SRF'07, Beijing, China (2007).

ISBN 978-3-95450-178-6