# PERFORMANCE OF A FNAL NITROGEN TREATED SUPERCONDUCTING NIOBIUM CAVITY AT CORNELL*

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*Abstract*

In many tests of superconducting cavities, the performance of the cavity in the medium field region will be limited by medium field Q slope. For projects such as the proposed Cornell Energy Recovery Linac, high intrinsic $Q_0$ operation at medium fields is necessary to meet specifications for efficient CW cavity operation. A single cell niobium cavity was prepared by Fermilab by electropolishing it and baking it at 1000°C with $1\times10^{-2}$ Torr of Nitrogen, and subsequently tested at Cornell. The cavity displayed an increase in $Q_0$ at medium fields between 5 and 20 MV/m at 2.0 K, opposite of the usual medium field Q slope. The material properties of this cavity were studied and correlated with performance. This analysis gives first insight into the anti-Q slope mechanism and suggests that a field dependent energy gap may be the cause of the anti-slope.

## INTRODUCTION

Future particle accelerators operating SRF linacs in CW mode will require high intrinsic quality factors at medium field. In the case of the Cornell Energy Recovery Linac (ERL) cavities must meet a specification of $2\times10^{10}$ at 1.8 K at an accelerating field of 16 MV/m. In order to more consistently produce high $Q_0$ cavities in the medium field region, there is much interest in the development of methods to reduce or eliminate the medium field Q slope (reduction of intrinsic quality factor between 5 and 20 MV/m) that typically plagues SRF cavities.

Recently, FNAL has explored the idea of high temperature baking of niobium cavities in a low pressure atmosphere of nitrogen. Not only have they seen a complete elimination of the medium field Q slope at temperatures below 2 K, the $Q_0$ increases with field up to 17 MV/m [1]. In order to confirm their results and shed new insight onto the underlying mechanism, a cavity prepared at FNAL was sent to Cornell for testing. This paper discusses the results of this test at Cornell.

## CAVITY PREPARATION AND TESTING

A 1.3 GHz single-cell fine grain niobium ILC shaped cavity was prepared with electropolising. It was then heat treated at 1000°C for 1 hour in $1\times10^{-2}$ Torr of Nitrogen and then given a final EP of 80 $\mu m$. This preparation was done at FNAL [2]. At Cornell, the $Q_0$ vs $E_{acc}$ performance was measured at eight temperatures between 1.6 and 4.2 K. $Q_0$ vs T was also measured at low fields as was the resonance frequency vs temperature to measure $T_c$. The $Q_0$ vs $E_{acc}$ performance at 1.6, 1.8, 1.9, 2.0, and 2.5 K is shown in Fig. 1. The $Q_0$ at 1.6 K was very high, on the order of $9\times10^{10}$. Below 1.9 K, the medium field Q slope that is usually seen in SRF cavities is not present at all. At 1.9 and 2.0 K, the $Q_0$ increases between 5 and 20 MV/m.

## MATERIAL PROPERTIES AND FIELD DEPENDENCE

Average low-field (3-5 MV/m) material properties of the surface RF layer were extracted from the $Q_0$ vs temperature and resonance frequency vs temperature data. Using the method described in [3], $T_c$ and mean free path were extracted from the frequency (converted to change in penetration depth) vs temperature data as shown in Fig. 2. Residual resistance and energy gap ($\Delta/k_BT_C$) were extracted from the $Q_0$ (converted to surface resistance) vs T data using SRIMP [4] as shown in Fig. 3. All material properties are summarized in table 1. The Ginzburg-Landau constant $\kappa_{GL}$ was calculated and found to be $15\pm3$ and the critical magnetic field was found to be $28\pm18\,\mathrm{mT}$. As can be seen from the $Q_0$ vs $E_{acc}$ plots in Fig. 1, the cavity far exceeds $B_{C1}$ without any degradation to $Q_0$ (Q slope begins at 20 MV/m or 84 mT in units of maximum magnetic field).

From the low-field material properties obtained from the SRIMP fitting shown in table 1, it can be seen that $T_c$ and energy gap show standard values for a typical niobium cav-

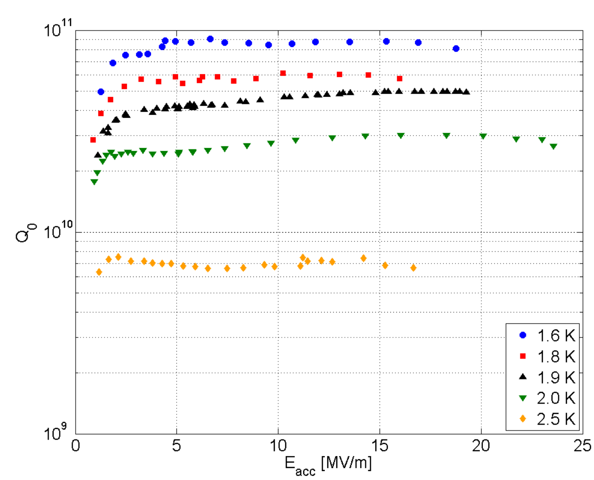


Figure 1: $Q_0$ vs $E_{acc}$ performance at 1.6, 1.8, 1.9, 2.0, 2.5 K. The error on $Q_0$ is 20% and 10% on $E_{acc}$.

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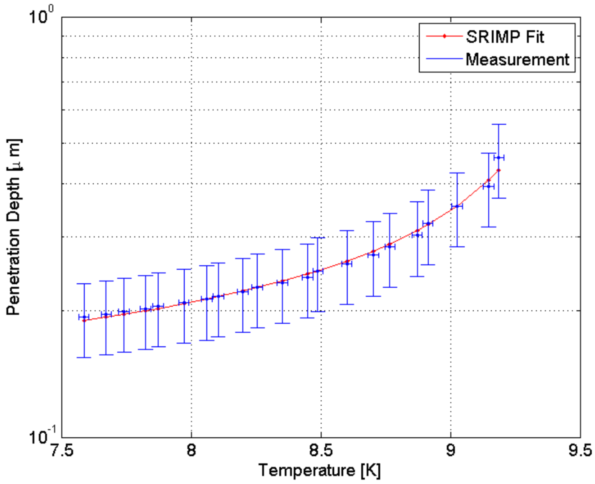


Figure 2: Fit of penetration depth vs Temperature using SRIMP to extract $T_c$ and mean free path.

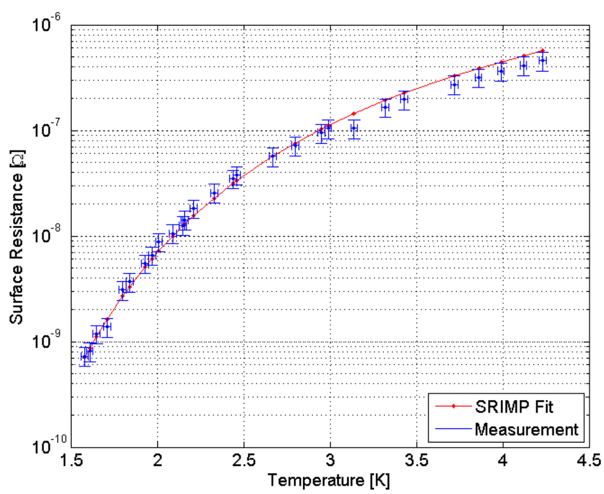


Figure 3: Fit of $R_s$ vs Temperature using SRIMP to extract $R_0$ and energy gap.

ity. The residual resistance is very low ($3 \pm 0.7\,\text{n}\Omega$) which is consistent with a very high $Q_0$ at low temperatures. The mean free path is very low, $3.1 \pm 0.3\,\text{nm}$. This measurement of a very low mean free path is consistent with other measurements with similar methods also done at Cornell in which very high $Q_0$ was found in a cavity with low mean free path [3]. It is not immediately clear if the performance is caused by just the baking process, the nitrogen treatment, or a combination of both. Future studies, such as those done in [5] can shed additional insight on this process.

### *Field Dependence of Material Properties*

While the low-field material properties and quality factor of this cavity are similar to standard niobium cavities, the unique $Q_0$ performance of nitrogen treated cavities appears at higher fields with maximum $Q_0$ between 15 and

Table 1: Extracted Material Properties at Low Fields

| Property | Value |
|---|---|
| $T_c$ [K] | $9.5 \pm 0.9$ |
| $\Delta/k_B T_C$ | $1.96 \pm 0.03$ |
| Mean Free Path [nm] | $3.6 \pm 0.3$ |
| $R_{res}$ [n$\Omega$] | $3.4 \pm 0.8$ |
| $\kappa_{GL}$ | $15 \pm 3$ |
| $B_{C1}$ [mT] | $28 \pm 18$ |

20 MV/m. It is therefore instructive to analyze the field dependence of the BCS parameters in order to determine the underlying mechanism of the anti-Q slope. The extensive $Q_0$ vs $E_{acc}$ data obtained was used to extract residual resistance, energy gap, and mean free path as a function of field. This was obtained by fitting $Q_0$ vs T at different field levels using only data below the lambda point in order to avoid non-uniform heating in the normal-fluid helium bath. Using the data from different temperatures, we were able to fit a $Q_0$ vs T at 1 MV/m intervals up to approximately 18 MV/m. For this analysis, the surface resistance was separated into a temperature-independent residual resistance and a temperature-dependent BCS resistance using

$$R_S = R_{res} + R_{BCS}. \tag{1}$$

BCS resistance as a function of field is shown in Fig. 4. Notice that the BCS resistance shows a clear reduction with increasing accelerating field at 1.9 and 2.0 K. Residual resistance vs field is shown in Fig. 5, energy gap vs field is shown in Fig. 6, and mean free path vs field is shown in Fig. 7.

From Fig. 5 it can be seen that the cavity's residual resistance does show some variation with field. The point at the lowest field has a significantly higher $R_{res}$ causing the reduction in $Q_0$ at very low fields. Accordingly, this low field $Q_0$ slope is caused by residual resistance decreasing with increasing field, consistent with measurements conducted in [3]. At high fields, there appears to be a small increase in residual resistance.

Within the error bars, the mean free path is constant with field. However, the field dependence of the BCS resistance below 2.1 K can be well described by an energy gap increasing with field in the Q anti-slope field region. We can therefore theorize that the nitrogen treatment causes a field dependent energy gap which in turn causes the field dependent BCS resistance, though the exact mechanism is unknown.

## CONCLUSION

A single-cell SRF cavity was prepared at FNAL by electropolishing and heat treatment at 1000°C with $1{\times}10^{-2}$ Torr of Nitrogen. The cavity was then tested at Cornell for further analysis. The usual medium field Q slope was non-existent at temperatures below 1.9 K. An anti-Q slope was observed at 1.9 and 2.0 K, while at other temperatures,

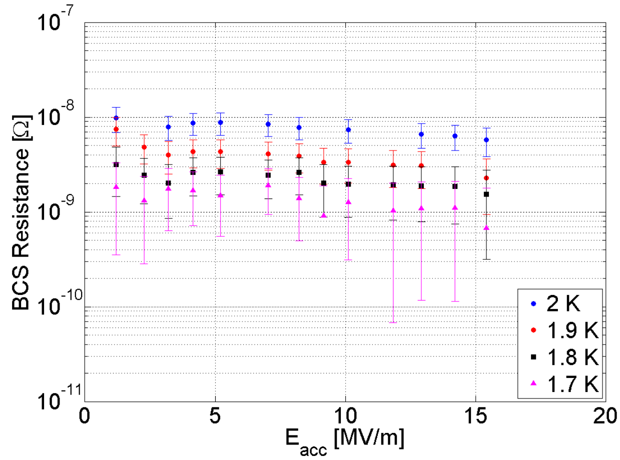


Figure 4: BCS Resistance vs $E_{acc}$.

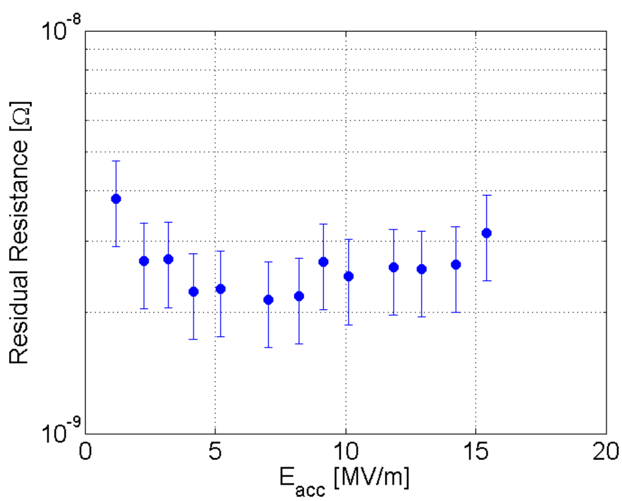


Figure 5: Residual Resistance vs $E_{acc}$.

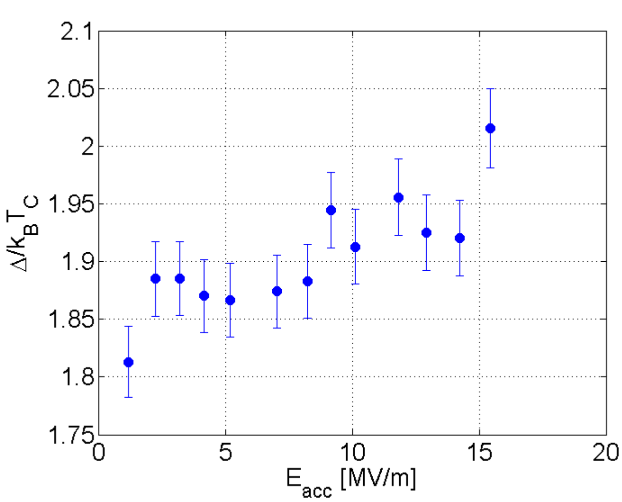


Figure 6: Energy Gap vs $E_{acc}$.

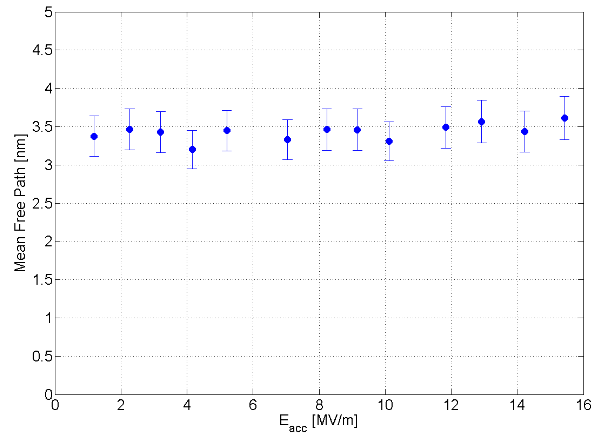


Figure 7: Mean Free Path vs $E_{acc}$.

the $Q_0$ remained unchanged up to 20 MV/m. Detailed $Q_0$ vs T data was measured to extract field dependent material properties of the surface RF layer. It was found that the mean free path of the material is field independent. However, the field dependence of the BCS resistance below 2.1 K can be well described by the energy gap increasing with field. This preliminary analysis suggests that the anti-Q slope observed in nitrogen treated cavities is caused by a field dependent energy gap.

Future work is needed to further explore the effects of baking in a gaseous atmosphere. Cavities are being prepared both at FNAL and Cornell to investigate this effect more.

## ACKNOWLEDGMENTS

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