HIGH Q_0 STUDIES AT CORNELL*

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Abstract

The construction and preparation of superconducting RF cavities with very high quality factors is very advantageous for future particle accelerators operating in CW mode. A Cornell ERL single-center-cell cavity was prepared with BCP and a five day heat treatment at 1000°C. Following this treatment, the cavity was tested and achieved a record high intrinsic quality factor of 2.9×10^{11} at 1.4 K, corresponding to a very small residual resistance of (0.36±0.08) nOhm. This cavity was then given a series of BCPs of 80 and 200 μm and retested. The cavity was finally baked for 48 hours at 120° C and retested. Material properties were extracted from the data hinting at a very low mean free path of the niobium. In this paper we discuss the unusual material properties of the surface layer of the cavity and their implication for the RF performance of the cavity. We find that a surface field far above the lower critical field B_{c1} can be achieved without a significant increase in surface resistance. This clearly demonstrates that the lower critical field is not a fundamental limit and that an surface energy barrier prevents flux penetration above B_{c1}. Our data also confirms that the 120°C bake increases the energy gap of superconducting niobium.

INTRODUCTION

Superconducting RF cavities are one of the main driving forces for modern particle accelerators. The development of cavities with consistently high intrinsic quality factors is especially important for new CW machines such as the proposed Cornell Energy Recovery Linac (ERL). Single-cell cavities have been able to achieve quality factors as high as 1×10^{11}, however this has not been achieved routinely. A large effort has been undertaken at Cornell to investigate how high quality factors of this order can be achieved consistently [1] [2] [3]. As part of this effort we have heat treated a single-cell niobium cavity at 1000°C for five days and tested it repeatedly after additional surface treatments. In this paper we report on the unique performance of this cavity which provides important new insights into RF superconductivity.

CAVITY PREPARATION AND TESTING

A 1.3 GHz Cornell ERL center-single-cell cavity was fabricated from fine grain niobium with a RRR of 300 and then prepared by bulk 100 μm BCP followed by a heat treatment at 1000°C for five days in a UHV furnace. It was immediately tested and Q_0 vs E_{acc} at different temperatures, Q_0 vs T at low fields, and resonance frequency

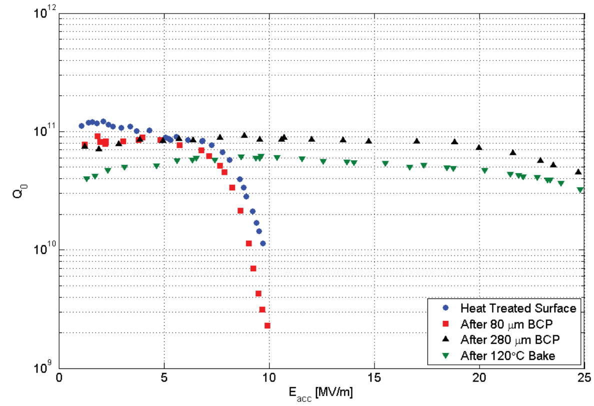

Figure 1: Q_0 vs E_{acc} at 1.6 K for different amounts of material removal. Error bars on Q_0 are 20% while error bars on E_{acc} are 10%.

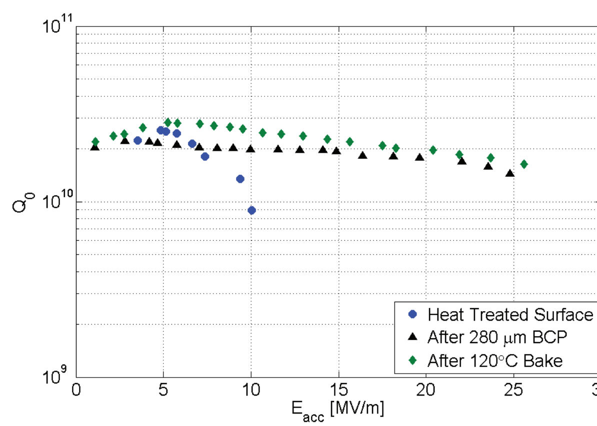

Figure 2: Q_0 vs E_{acc} at 2.0 K for different amounts of material removal. Error bars on Q_0 are 20% while error bars on E_{acc} are 10%.

vs T was measured. The cavity was then given a series of BCPs (80μm and 200μm additional surface removal) and retested. Finally, the cavity was given a 48 hour 120°C bake and the performance before and after bake was compared. Material properties were extracted from the data sets after each preparation step. The 1.6 K Q_0 vs E_{acc} performances at each step are shown for comparison in Fig. 1. The 2.0 K performance is shown in Fig. 2.

Additionally, samples heat treated with the cavity were tested using SIMS and XPS. Specifically nitrogen, oxygen, molybdenum, and titanium were looked for in the samples.

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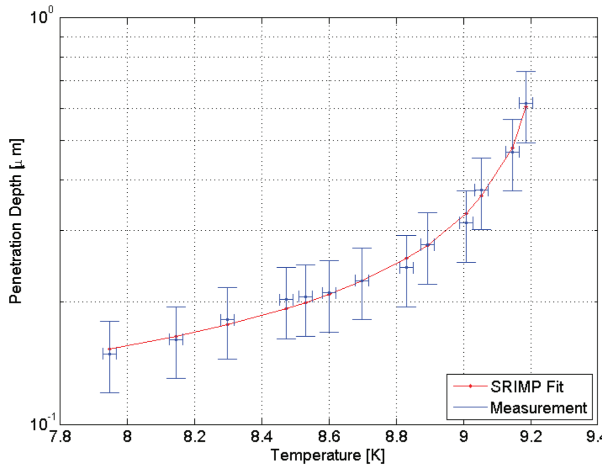

Figure 3: Fit of the penetration depth vs temperature using SRIMP to extract T_c and mean free path for the 1000°C heat treated surface.

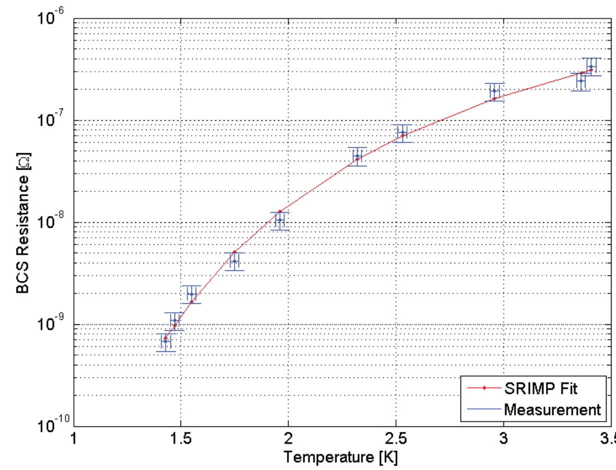

Figure 4: Fit of the BCS resistance vs temperature of the heat treated cavity using SRIMP to extract residual resistance and energy gap, using the values obtained from figure 3 for T_c and mean free path.

MATERIAL PROPERTIES

The material properties of the RF penetration layer can be extracted from the resonance frequency vs temperature and Q_0 vs temperature data measured. Change in resonance frequency was converted to change in penetration depth using

$$\lambda = \lambda_0 - \frac{1}{\beta}\left(f - f_0\right), \tag{1}$$

where λ is the penetration depth, f is the resonant frequency, β is a constant equal to $12.4\,\mathrm{kHz}/\mu\mathrm{m}$ and λ_0 and f_0 are the penetration depth and resonant frequency at a reference point[4]. The SRIMP algorithm which solves BCS theory can be used to fit the data to extract T_C and mean free path [5]. A London penetration depth of 390 Å and a coherence length of 380 Å for clean niobium was used. An example of the fit is shown in Fig. 3 for the heat treated surface. Using the values obtained for T_C and mean free path, the Q_0 vs temperature data can again be fitted with SRIMP to extract energy gap ($\Delta/k_B T_C$) and residual resistance (R_{res}). An example of the fit for surface resistance versus temperature is shown in Fig. 4 for the heat treated surface. We can separate the surface resistance into two terms using

$$R_S = R_{res} + R_{BCS}, \tag{2}$$

where R_{res} is temperature independent and R_{BCS} is the temperature dependent BCS surface resistance.

Extracting material properties using both Q_0 vs T and f vs T allows for more accurate results than using just one or the other. The penetration depth is highly sensitive to the mean free path and T_C while Q_0 vs T strongly depends on $\Delta/k_B T_C$. The mean free path obtained from SRIMP fitting can be used to calculate the Ginzburg-Landau constant, κ_{GL} [6]. This in turn can be used to calculate the lower critical field of the superconductor B_{c1} [7]. B_{c1} can be compared to Q_0 behavior to see if any correlation can

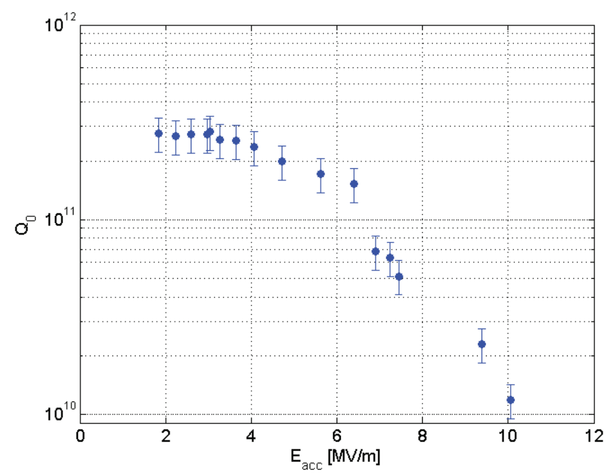

Figure 5: Q_0 vs E_{acc} of the 1000°C heat treated surface at 1.42 K. The cavity obtained a record high Q_0 of 2.8×10^{11} at $3\,\mathrm{MV/m}$.

be found between quench and/or Q slope and B_{c1}. All material parameters determined are summarized in table 1.

RESULTS AND DISCUSSION

Field Dependence of the Surface Resistance

Immediately following the 1000°C heat treatment for 5 days, the cavity obtained a record high Q_0 of 2.8×10^{11} at an accelerating field of $3\,\mathrm{MV/m}$ at 1.42 K. The entire curve is shown in Fig. 5. The cavity showed a very large Q drop above 5 MV/m, quenching just above 10 MV/m. This field proved to be the hard limit and couldn't be pushed higher.

After 80 μm removal, the performance was similar, with

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Table 1: Summary of Extracted Material Properties

Property	1000°C Surface	After 80 μm BCP	After 280 μm Total BCP	After 120°C Bake
T_c [K]	9.3 ± 0.9	9.3 ± 0.9	9.3 ± 0.9	9.5 ± 0.9
$\Delta/k_B T_C$	1.78 ± 0.02	1.78 ± 0.02	1.79 ± 0.01	1.96 ± 0.02
Mean Free Path [nm]	8 ± 2	8 ± 2	7 ± 2	6 ± 2
R_{res} [nΩ]	0.36 ± 0.08	1.23 ± 0.03	1.34 ± 0.03	5 ± 1.2
κ_{GL}	7 ± 1	8 ± 1	8 ± 1	10 ± 2
B_{c1} [mT]	45 ± 14	44 ± 14	42 ± 15	37 ± 16
Onset of Q Slope [MV/m]	6.8	7.6	18.8	20.2
Quench Field [MV/m]	10	10	25	25

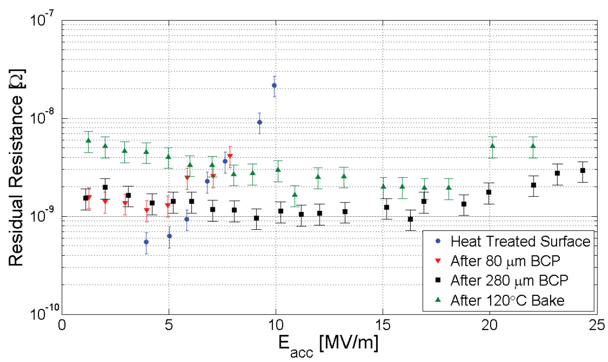

Figure 6: Residual resistance as a function of accelerating field for different amounts of material removal.

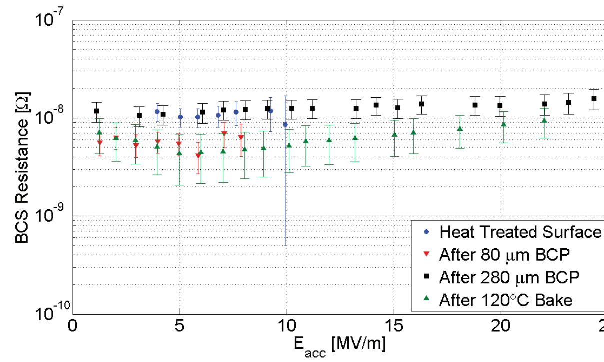

Figure 7: BCS Resistance as a function of accelerating field for different amounts of material removal. All tests were for 2.0 K except the 80μm removal which is at 1.8 K.

a high Q at low fields and a large Q drop up to a quench at 10 MV/m. However, after a total of 280 μm removal, the performance drastically changed to a more typical cavity performance, still with a very high Q but with very small medium field Q slope. Following the 120°C bake, the performance was similar but with a lower Q. This data can be seen in Fig. 1.

The residual resistance as a function of accelerating field is shown in Fig. 6. From this, it can be seen that there is a very similar slope in R_{res} as there is in Q_0 for the heat treated surface and after 80μm removal. Fig. 7 displays the BCS resistance for each test, showing that the BCS resistance is constant with field, unlike the residual resistance. This implies that the Q slope of the heat treated surface and up to at least 80 μm removal is caused by the residual resistance increasing with the accelerating field. The heat treatment modified the surface layer at two different length scales; down at least 80 μm but less than 280 μm a mechanism causing the large Q slope was introduced. Additionally, the mean free path was significantly lowered at least 280 μm into the surface.

Material Properties vs. Surface Removal and Sample Analysis

The mean free path and energy gap as a function of material preparation are shown in Fig. 8. From the mean free path, κ_{GL} was calculated. A plot of κ_{GL} vs material removal is shown in Fig. 9. The material's mean free path is very low, as for a dirty superconductor. However, sample analysis indicates the small mean free path is not caused by impurities. SIMS and XPS were used to analyze samples heat treated at 1000°C with the cavity, and it was found that concentrations of nitrogen, oxygen, molybdenum, and titanium were below the observable threshold. This suggests that contamination from impurities was not causing the small mean free path. We will further investigate crystal dislocations and lattice defects in ours samples, as these might be the cause of the low mean free path.

Lower Critical Field and Cavity Performance

A plot of B_{c1} and the onset of the Q slope vs material removal is shown in Fig. 10. From this, it is obvious that the onset of the Q slope and B_{c1} are not correlated. In fact, the onset of the Q slope increased with material removal while B_{c1} decreased. Making note of the Q vs E performance shown in Fig. 1, it can be clearly seen that the cavity far exceeds B_{c1} without any degradation to Q. The quench field also is not correlated to B_{c1} as is evident from table 1 and Fig. 10. This result proves that metastable fields significantly above B_{c1} can be reached without vortex penetration and the resulting large heating of the cavity surface by oscillating vortices. Accordingly, the lower critical field, B_{c1}, is not a fundamental limit for the maximum

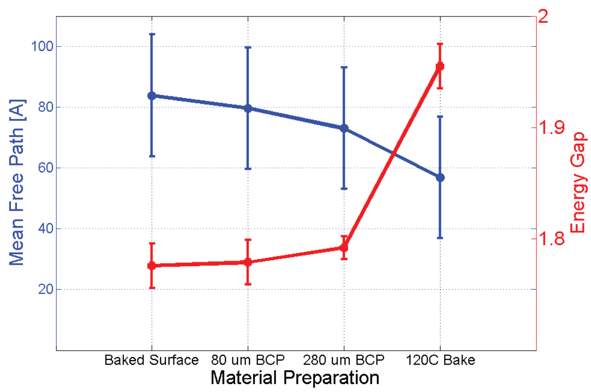

Figure 8: Mean free path and energy gap as a function of material removal.

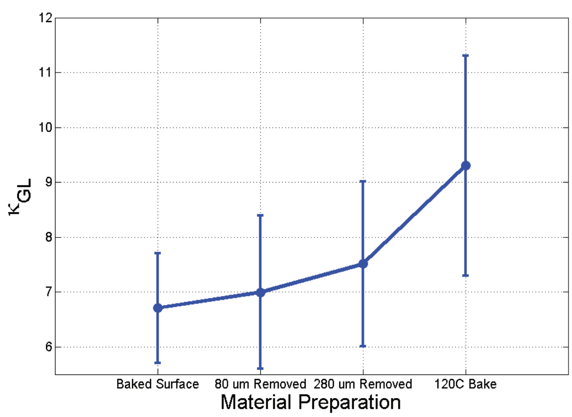

Figure 9: κ_{GL} as a function of material removal.

gradient achievable in SRF cavities.

120°C Bake and Material Properties

It can be seen from table 1 and Fig. 8 that the 120°C bake has a strong effect on the material properties of the cavity. Specifically, we have confirmed that the residual resistance increases after 120°C bake and the BCS resistance decreases due to a significant increase in the energy gap.

CONCLUSION AND FUTURE WORK

A single-cell niobium cavity was prepared with bulk BCP and then heat treated at 1000°C for 5 days, tested, and re-tested after additional preparation steps. Material properties extracted show a very low mean free path at least 280 μm into the surface due to the heat treatment. Immediately following bake, the cavity achieved a record high intrinsic quality factor of 2.8×10^{11} with a residual resistance of $(0.36 \pm 0.08)n\Omega$. After 280 μm removal, the cavity reached an accelerating field of more than 25 MV/m with a very high Q_0 on the order of 9×10^{10} at 1.6 K and with an unusually flat Q up to about 20 MV/m. Therefore our experiment demonstrates that high temperature baking can

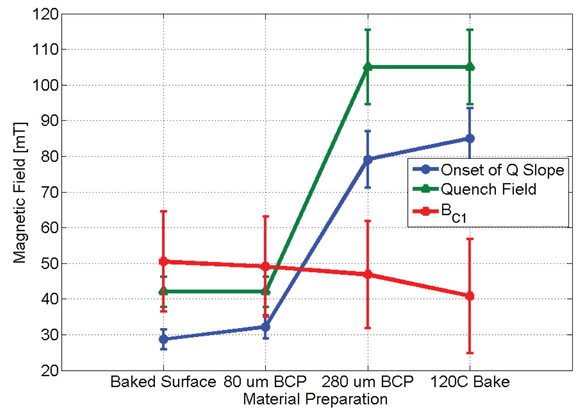

Figure 10: B_{c1}, onset of Q slope, and quench field (in units of maximum magnetic field) as a function of material removal.

be beneficial for high Q SRF applications by optimizing the BCS parameters such as lowering the mean free path.

The lower critical field B_{c1} was extracted from the mean free path and found to be significantly lower than the quench field. Additionally, it was shown that fields far exceeding B_{c1} can be achieved without significant increase in surface resistance. This proves that B_{c1} is not a fundamental limit for SRF applications and that metastable fields indeed can be used reliably.

We have confirmed that the 48 hour 120°C bake raises the residual resistance and lowers the BCS resistance by increasing the energy gap.

Our next step will be to give the cavity a brief HF rinse to lower the residual resistance, while keeping the BCS resistance low. More high temperature heat treatment studies will also be conducted in order to further investigate the effects of high temperature baking and to develop an optimum algorithm for high Q cavities. We will further analyze our witness samples to explore other possible mechanisms for causing the Q drop behavior we have observed. Specifically we will look at crystal dislocations and lattice defects next.

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