TEMPERATURE DEPENDENCE OF THE SUPERHEATING FIELD: DC AND RF CRITICAL FIELDS*

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Abstract

The superheating field is a metastable state wherein the Meissner state persists at fields higher than would be predicted from steady-state energy considerations. Previous work demonstrated that the phenomenological prediction of the superheating field can also be consistent with low temperature results. This work expands upon the RF results, comparing scaling of H_{sh} for the same material prepared in two different methods, and presents a method to measure the DC superheating field.

INTRODUCTION

The magnetic superheating field, H_{sh}, is a fundamental property of superconductors. This state, wherein the material remains metastably within the Meissner state at magnetic fields larger than would be measured in steady-state conditions, has proved both difficult to calculate theoretically and to measure experimentally. Niobium was used to experimentally probe this limiting field, and the effect of different material preparations on H_{sh} are discussed.

Measuring the superheating field is important on several counts. First, superheating field measurements prior to our work were limited to near the critical temperature[1], leaving the temperature dependence an open question. Secondly, the regions in which empirical models accurately describe the field tend to be in limiting cases, such as in the high-κ limit[2], which means that new measurements can guide the development of better theoretical models. Finally, the accurate determination of the superheating field is of particular interest in applications. While theory and experiment agree near T_c, niobium microwave cavities for particle accelerators operate at temperatures $T < T_c/4$, where theory and experiment are incomplete, so measurements over the full temperature range can set limits on what is achievable with Nb superconducting cavities.

THE SUPERHEATING FIELD

If a superconductor in a low enough constant magnetic field is cooled below its critical temperature the magnetic field will be expelled from the bulk of the superconductor. Magnetic field penetrates the superconductor only in a small region close to the surface, characterized by a penetration depth λ_L, which is the region in which supercurrents flow. Increasing the magnetic field above a certain value will cause flux to enter the bulk of the material and initiate a transition into the normal conducting state. Investigating this transition is the focus of this work

An important length scale in superconductors is the coherence length, ξ_0 which is related to the spatial variation of the superconducting electron density. The ratio of the penetration depth the coherence length yields a phenomenological parameter, $\kappa \equiv \lambda_L/\xi_0$.

This parameter, κ, separates superconductors into two broad categories; Type-I with $\kappa < 1/\sqrt{2}$ and Type-II with $\kappa > 1/\sqrt{2}$. Here we reference the fact that κ depends on material properties including the electron's mean free path, ℓ such that $\kappa(\ell) \propto [(\xi_0 + \ell)/\ell]^{3/2}$.[3]

Before a transition from the Meissner state to the normal conducting state occurs, there is an energy cost to nucleate a fluxoid, leaving open the possibility of a metastable state in which the energetically favorable transition has not occurred due to the activation energy barrier. This barrier vanishes at the superheating field, H_{sh}.

Both Type-I and Type-II superconductors can persist in the Meissner state above their lower critical magnetic fields. The precise relationship between H_{sh} and H_c is still a field of active experimental and theoretical research, but a phenomenological result shows that near T_c the superheating field has the dependence:

$$H_{sh} = c(\kappa) H_c \left[1 - \left(\frac{T}{T_c}\right)^2\right], \tag{1}$$

where $c(\kappa)$ is the ratio of the superheating field and the thermodynamic critical field at 0 K.[4]

EXPERIMENTAL METHOD

A 1.3 GHz re-entrant shaped[5] Nb cavity, LR1-3, was used to probe the temperature dependence of the superheating field for two different values of κ. Preparation A consisted of out-gassing the cavity at 800°C for two hours, vertically electropolishing the cavity, high pressure rinsing it for two hours, and then cleanly assembling it on a waveguide test stand. Finally it was evacuated, and baked at 120°C for 48 hours, a process known to mitigate the effects of high field Q-slope[6]. Preparation B (of the same cavity) consisted of out-gassing the cavity at 800°C for two hours, performing a 15 μm electropolish, high pressure rinsing the cavity for two hours then cleanly assembling the cavity. Preparation B did not include a 120°C bake. The

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cavity, prepared in these two ways, was tested with continuous wave RF to determine material properties, then tested with high pulsed power to measure the superheating field.

The RF superheating field of niobium was measured by using high power (up to 1.5 MW) RF pulses (50-500 μs) to drive the cavity on resonance and noting the field level that causes a superconducting to normal conducting transition.[7]. The location of the quench origin can be determined by using oscillating superleak detectors.[8] If the quench is found to be global, then the limiting field is a fundamental property of the material, not simply caused by a localized defect, and suggest that the superheating field was reached. Thermometry on the outer cavity wall allows the temperature of the inner RF surface to be inferred.

By measuring the cavity's quality factor during the pulse, one can pinpoint the time the cavity transitioned into the normal conducting state by the sudden decrease in intrinsic quality factor of the resonator. The surface magnetic fields at the transition time yield the superheating field, the calculation of which has been discussed elsewhere at length.[3]

EXPERIMENTAL RESULTS

The cavities were first tested in continuous wave (CW) mode to measure material properties. Their intrinsic quality factors as a function of accelerating gradient is shown in Fig. 1. Both measurements demonstrate a strong decrease in Q_0 (i.e. increase in surface resistance) at high fields, though the cavity with preparation A has a significantly higher quality factor above 30 MV/m. The maximum field in neither measurement was quench limited, but limited by the RF amplifier power driving the cavity.

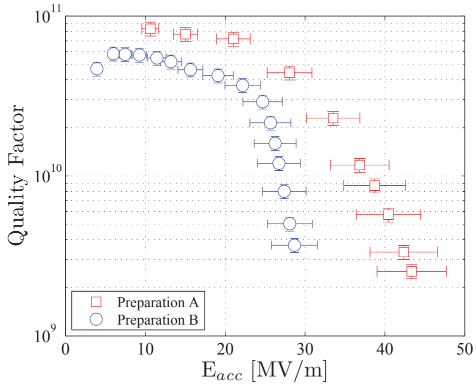

Figure 1: Quality factor versus accelerating gradient for different surface preparation methods, taken at $(1.65 \pm 0.05)K$. The 120°C treatment has the effect of increasing the quality factor at high gradients compared to the case without the 48 hour bake.

The measurement of the quality factor vs temperature allowed for surface material characterization via curve fitting with SRIMP.[9] The inferred material properties obtained from the curve fit can be used to estimate κ. For a given value of κ, the phenomenological result then relates H_{sh} and H_c near T_c. These results are presented in the top section of Table 1

Table 1: Top: Material properties determined from the BCS resistance versus temperature data. SRIMP uses the "clean" values for coherence length at zero temperature of ξ_0=28 nm,[10] and London penetration depth of λ_L=36 nm[11, Chap. 8]. The energy gap is defined as $\Delta(0)/k_B$. The values of ξ and λ in the table take into account variable electron mean free-paths due to scattering sites. Bottom: Superheating field measurement results. Top value of $c(\kappa)$ is calculated from Eilenberger theory from the value of κ obtained from material properties.[12] Bottom value of $c(\kappa)$ is from the slope measurement of the H_{sh} data.

Parameter	Prep. A	Prep. B	Unit
Material Properties from BCS Resistance			
Frequency	1294.5	1294.1	MHz
Energy Gap	19.3±0.5	18.4 ± 0.8	K
Mean Free Path	26.9±1.2	167 ± 53	nm
Resid. Resistance	1.2 ± 0.2	3.9 ± 0.3	nΩ
Critical Temp.	9.15 ± 0.20	9.15 ± 0.20	K
ξ	15.9 ± 0.5	27.5 ± 2.6	nm
λ	56.3 ± 0.9	36.3 ± 1.7	nm
κ	3.53 ± 0.10	1.31 ± 0.05	—
$c(\kappa)$	1.04 ± 0.01	1.21 ± 0.03	—
Superheating Field Measurements			
Critical Temp.	8.86 ± 0.20	9.22 ± 0.20	K
$c(\kappa)$	0.99 ± 0.05	1.23 ± 0.15	—

The curve fits of the BCS resistance vs temperature data demonstrate that the properties of superconducting surface varies with the material preparation. Preparation A yielded a surface with larger κ (more strongly Type-II). Preparation B, however resulted in a surface with smaller κ, and the Niobium is very nearly Type-I in this case.

A few comments about these results should be mentioned: The reduction in mean free path in Preparation A is due to an increase in impurity content in the surface RF layer by the 120°C bake.[13] The energy gap, $\Delta(0)/k_B$, of the niobium is larger than the reported value of 18.1 K for pure niobium.[11]. The surface preparation, in this case the 120°C bake, has been shown to effect the energy gap[13], which could explain the difference in energy gap, but this should be investigated further.

Preparation B resulted in material properties consistent with higher purity Niobium than in Preparation A. This suggests that there is not significant oxygen contamination, in agreement with the larger electron mean free path.

After continuous wave measurements, the cavity was pulsed to perform superheating field measurements. The results of these measurements are presented in Fig. 2

The high quality factor of the cavity with Preparation A allows the superheating field to be reached over the full measured temperature range at high fields. Preparation B shows strong quality factor degradation at high gradients. This leads to heating of the niobium inner surface at high accelerating field gradients, even with pulse lengths of a few $100's$ of microseconds. The temperature increase at the inner wall is mostly undetected by the thermometry mounted on the outside wall. For this reason, for Preparation B, only points near T_c where the fields are relatively low and thus do not strongly heat the surface prior to quench are taken as accurate measurements of the superheating field.

Fitting the obtained H_{sh} data sets yields two key parameters: First, since the superheating field vanishes at the material's critical temperature, the horizontal intercept measures T_c. Second, near T_c, where the phenomenological model applies, the slope of the graph yields $c(\kappa)$.

For Preparation A, a fit of the data over the entire temperature range yields values for $c(\kappa)$ and T_c that are presented in the bottom half of Table. 1. Note that for Preparation A, Eq. 1 describes H_{sh} to below $T_c/4$ which is the entire measured region (See Fig. 2). For Preparation B, a fit of the points in the temperature range $7.4K < T < 9.2K$ yields the parameters in Table 1. Both results use the accepted value H_c = 200 mT for niobium. Note that in both cases the coefficients $c(\kappa)$ from the superheating field measurements are in agreement the phenomenological $c(\kappa)$ results using material properties.

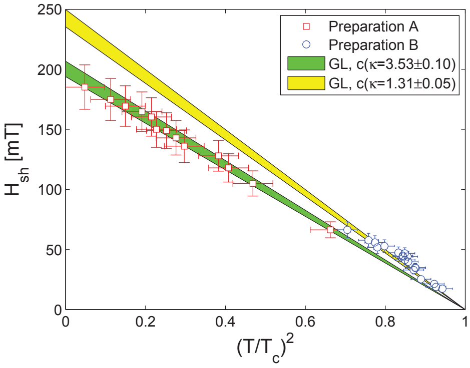

Figure 2: Superheating field measurements for both cavity treatments. The solid regions denote the phenomenological result, including uncertainty in κ. The preparation methods succeeded in changing the Nb from a strongly Type-II material to one that is closer to Type-I.

CONCLUSIONS

The work presented here demonstrates that the Meissner state can exist metastably above H_{c1} over the full temperature range. We have measured the temperature dependence of the superheating field and shown that it can be changed via surface treatments. The results show that while the phenomenological model is not a complete description of the superheating field mechanism at low temperatures, it can be an accurate description over the full temperature range. This suggests that the Meissner state may metastably persist to between 200–250 mT in Nb at low temperatures, if heating issues can be mitigated.

Furthermore, these results show that surfaces treated by the standard high gradient cavity preparation treatments significantly reduces the superheating field via increasing impurities in the RF layer via the 120°C baking process. This makes Nb more strongly Type-II and thereby reduces H_{sh} since $c(\kappa)$ decreases as κ increases. This leads naturally to ask if an alternative to the 120°C bake that eliminates high field Q-slope while not reducing the material's mean free path can be developed.

Though theoretical predictions with the Eilenberger equations are progressing, there is still a significant effort that needs to be done before they converge for low temperatures. The work here provides experimental data to help guide the further development of theory.

Future work will compare RF measurements with DC measurements using a solenoid to apply a strong magnetic field (up to 300 mT) to the outside of the cavity, while a small RF field on the inside is used as a probe of the persistence of the Meissner state. Energy considerations give

$$\frac{dU}{dt} = -\frac{U}{2\pi f}\left[\frac{1}{Q_{ext}} + \frac{1}{Q_0(t)}\right]^{-1}, \qquad (2)$$

where U is the energy stored inside the cavity, t is time, f is the cavity resonant frequency, Q_{ext} and Q_0 are the external and intrinsic quality factors of the cavity. By measuring the time dependence of the stored energy as a DC magnetic field is increased, $Q_0(t)$ can be determined, and the DC critical field can be measured.

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