EXPLORING THE MAXIMUM SUPERHEATING MAGNETIC FIELDS OF NIOBIUM*

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Abstract

The RF superheating magnetic field of superconducting niobium was measured with a 1.3 GHz re-entrant cavity at several points in the temperature range from 1.9K to 4.2K. This experimental data is used to discriminate between two competing theories for the temperature dependent behavior of the RF superheating field. Measurements were made with <250 μs high power pulses (HPP, ∼1MW). Our test incorporated oscillating superleak transducers to determine the cavity quench locations and characterize changes and the migrations of the quench locations during processing. Using a vertically electropolished cavity, the temperature dependence of the superheating field was found to agree with Ginzburg-Landau predictions to within 10% down to a temperature of 4.2K; whereas prior to this experiment, theory and experiment only agreed at temperatures greater than 6.2K.

INTRODUCTION

Over the past 30 years accelerating gradients in superconducting cavities have been increased from 5 MV/m to over 50 MV/m[1]. To determine how much higher these gradients can be pushed, we must understand the fundamental limit, the critical RF magnetic field, H_c^{RF}. Finding the limit of this field is the purpose of this work.

The critical field is postulated to be the same as the superheating field [2], the field level above which a superconductor undergoes a phase transition to the normal conducting state. Previous measurements, using a buffer chemical polishing (BCP) process, found 10% agreement with theory down to a temperature of 6.2K [3]. Experiments reported here, with an an electropolished (EP) cavity allows us to set a lower bound on the superheating field that has 10% agreement with theory down to a temperature of 4.2 K, and allows discrimination between competing models characterizing the superheating field.

To ensure measurement of a fundamental quantity, instead of the result of a cavity defect, short, high power pulses were used to minimize heating. To further identify the nature of the quenches oscillating superleak transducers (OST) were used to determine the cavity's quench locations [4].

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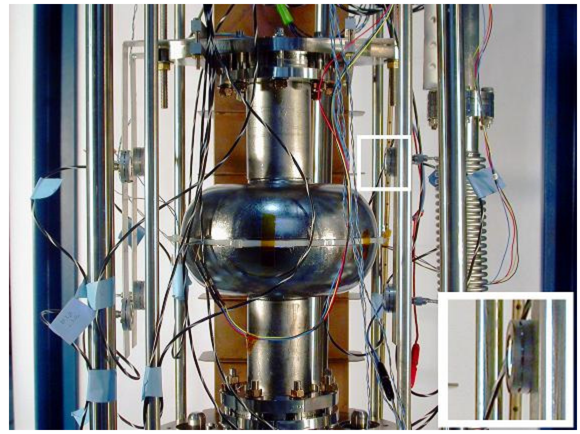

Figure 1: Experimental setup showing 1.3 GHz re-entrant cavity mounted on a test stand. The copper waveguide behind the cavity connects to the klystron and supplies the HPP. Eight OSTs are mounted at corners of a cube around the cavity and are used to detect quench locations. An enlargement of an OST is shown in the lower right corner.

EXPERIMENT

This experiments discussed here used a 1.3 GHz reentrant design cavity that was previously tested to have a maximum accelerating gradient of over 50 MV/m and made of Niobium with a RRR of 500. The cavity, LR1-3, was produced by Cornell University. It was shipped to KEK, for a 6 hour high temperature bake, 300 μm centrifugal barrel polish and a 110 μm EP and finally shipped back to Cornell [1].

Prior to testing at Cornell, the cavity received a vertical EP, removing $\sim 10\mu$m of material, underwent an ultrasonic degreasing in a 1% alconox solution, was high pressure rinsed, and baked for 48 hours at 110 °C, a process which is known to reduce the high field Q-slope [5].

To minimize heating caused by thermal defects, the cavity was driven by a klystron at 1 Hz with high power pulses of up to 1.5 MW with pulse length <250 μs. The goal of using short pulses is to raise the fields in the cavity before any defects can heat the cavity, so in general, the shorter the pulse length the better. The klystron power was coupled to the cavity such that the external quality factor could be adjusted between 10^5 and 10^6. Coupling in this range allows a fair balance between quickly ramping up fields and being able to measure Q_0 accurately to determine when the normal conducting transition takes place.

Central to this experiment is arriving at an accurate value of the intrinsic quality factor of the cavity as a function of time. Determining this value is dealt throughly in Hays' papers [3, 6], but will be briefly summarized here.

When power is applied to the cavity, we can write down an equation for the conservation of energy and an expression for the reflected power as

$$P_f = P_{diss} + P_r + \frac{dU}{dt} \quad (1)$$

$$P_r = \left(\sqrt{P_f} - \sqrt{\omega U/Q_{ext}}\right)^2 \quad (2)$$

where P_f, P_{diss} and P_r are forward, dissipated and reflected power, respectively, Q_{ext} is the "external" Q of the cavity, and U is the energy stored in the cavity. Substituting the second equation into the first yields

$$\frac{1}{Q_0} = \frac{2\left(\sqrt{\frac{dP_f\omega}{dQ_{ext}}} - \frac{d\sqrt{U}}{dt}\right)}{\omega\sqrt{U}} - \frac{1}{Q_{ext}}. \quad (3)$$

where ω is the angular radio frequency and t is time. Equation 3 allows for the determination of the precise time the cavity becomes normal conducting, giving a value for H_c^{RF}.

Eight OSTs were placed around the cavity; a picture illustrating their placement is shown in Fig. 1. By measuring the arrival time of the second sound waves at different OSTs the quench location can be determined in 3D [4]. The speed of the second sound wave is highly temperature dependent, so resistive temperature detectors were used to accurately measure the bath temperature to ensure accurate calculation of quench locations.

MEASUREMENTS AND ANALYSIS

High pulsed power measurements were taken between 1.9 and 4.2 K and are plotted in Fig. 2. The peak magnetic field of the cavity is the field obtained where the cavity transitions from its superconducting to its normal conducting phase. Hays demonstrated that quality factors exceding 2×10^6 correspond to at least 90% of the cavity remaining in the superconducting state [6]. Thus, the magnetic field at $Q_0 = 2 \times 10^6$ are used as the lower bounds for H_c^{RF}. An example trace is shown in Fig. 3 illustrating how the peak magnetic field was determined.

The experimental data agree with Ginzburg-Landau (GL) theory to 10% at temperatures as low as 4.2 K. This theory predicts that near T_c, the superheating field goes as $H_c^{RF} = c_{sh}(T)H(0)[1 - (T/T_c)^2]$, where for Nb $c_{sh}(T_c) \approx 1.2$ [8]. It is notable that taking a constant value for c_{sh} agrees with experiment for temperatures as low as $T/T_c \approx 0.5$, even though the theory is only valid near T_c.

This is to be contrasted with previous BCP cavity results which found a 10% departure from the ideal curve at 6.2 K. Because the EP result shows increasing field at decreasing temperatures down to 2K, up to a field of 1990 Oe measured at 1.9K, it is in disagreement with the Vortex Line Nucleation Model, which predicts that the superheating field plateaus below a certain temperature, and Nb can only reach H_c^{RF} of 1800 Oe [7].

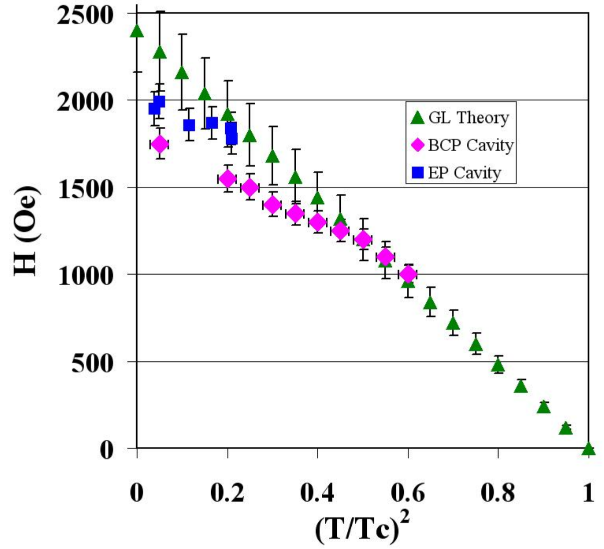

Figure 2: Graph of H_{sh} vs $(T/T_c)^2$, where T is the bath temperature. The green triangles are the GL prediction $H_c^{RF}(T) = 1.2H(0)[1 - (T/T_c)^2]$, with $H(0) = 2000$ [2]; error bars of 10% have been included to correspond with the uncertainty in c_{sh}. The pink diamonds are the BCP cavity results [3]. The blue squares are the most recent EP cavity results. Error bars of $\pm 5\%$ have been included corresponding to calibration uncertainty.

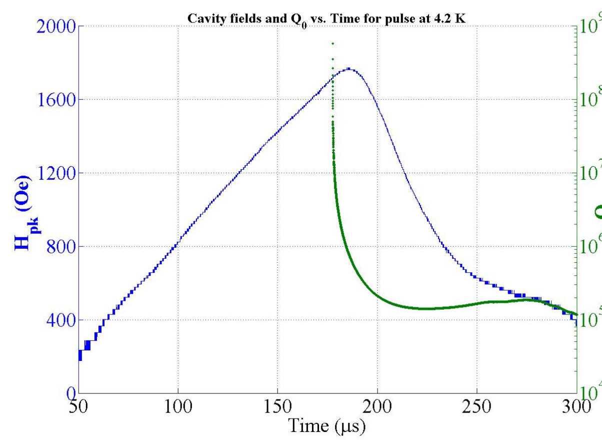

Figure 3: Plot of H_{pk} (blue line) vs. time and Q_0 (green dots) vs time at 4.2 K. The RF power pulse lasted from 25 - 275 μs on the trace. The cavity becomes normal conducting at a peak field of 1760 Oe. Prior to this time, the Q_0 of the cavity is too high to be measured by methods used in pulsed operation.

No observed quenches were found to be due to cavity defects. The OST array measured second sound waves arriving simultaneously at all detectors, shown in Fig. 4. The second sound wave arrival times demonstrate that the waves emanate from points on the cavity nearest each detector. This region, extending 1.5 cm on either side of the equator weld, is the high magnetic field region of the cav-

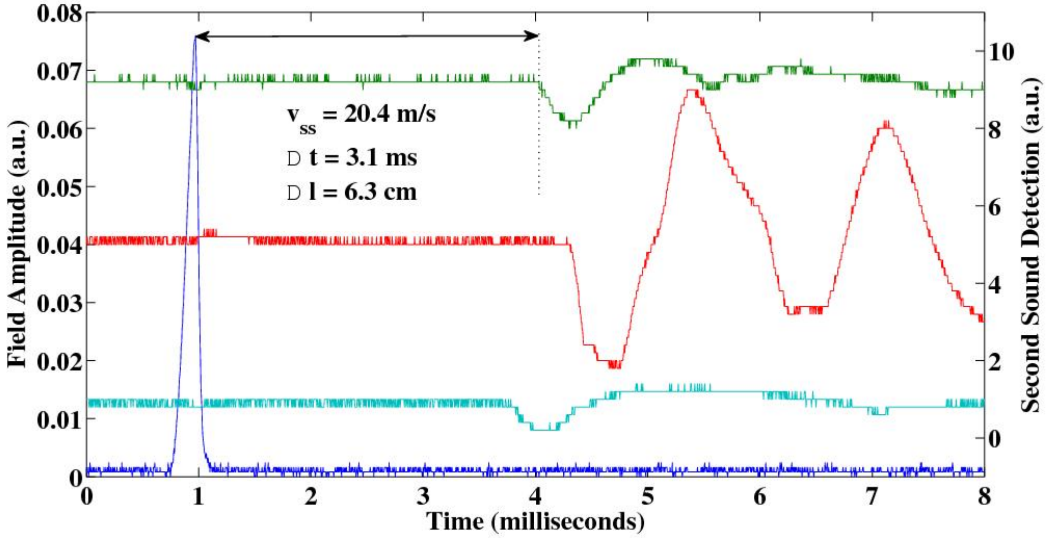

Figure 4: OST data for a single quench event. The lower trace is cavity field amplitudes, and the three upper traces are OST signals. The small time discrepancy between measured arrival times correspond to different OST positions. The OSTs all found the cavity quench to be a global event.

ity. The simultaneity of OST detections demonstrate that this entire region under goes a phase change from the superconducting state to the normal conducting state. The phase change occurs in less than 5 μs. All of this is consistent with observing a fundamental physical limit.

Preliminary finite element simulations suggest that there may be as much as 1K of heating in the wall during field ramp up, which could increase the correspondence between experimental results and GL theory.

CONCLUSIONS

We were able to successfully determine the Q_0 of the cavity in pulsed mode, and use that information to determine the critical RF magnetic field. We demonstrated that the peak fields measured are a fundamental limiting values because the entire high magnetic field region of the cavity changed from superconducting to normal conducting. The transition occured in a span of a few microseconds, a time scale inconsistent with thermal break down or field emission. Furthermore, the OSTs show that the quench is not due to a local defect or field emission heating, adding further credence to the transitions occurring at a fundamental limit, the superheating field.

Our results demonstrate that a vertical EP followed by a low temperature bake allows one to obtain higher peak magnetic fields than with a BCP and bake. The EP surface preparation allowed increasing the lower bound on H_c^{RF} to 1990 Oe at 1.9K, 13% higher than previously measured with BCP cavities.

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