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Determining H_c^{RF} for Nb and Nb_3Sn through HPP and Transient Q Analysis*

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Abstract

A technique to find the transient cavity Q from transmitted power is applied to superconducting cavities to explore the maximum rf surface magnetic field, H_c^{RF}, that can be supported in the superconducting state. With high power pulses (HPP), in short time scales, the fields in a superconducting cavity can be driven well past the CW breakdown limit. With knowledge of the Q during breakdown, one can show that a large fraction of the surface was still superconducting as the cavity reached high fields. Short, high peak power pulses are applied to a 1.3 GHz Nb cavity and a 3 GHz Nb_3Sn on Nb cavity to measure lower limits to the critical rf magnetic field despite the presence of thermal defects. Measurements are made over a range of temperatures below the superconducting transition temperature using liquid and gaseous helium cooling. The results for Nb are consistent with the theorized superheating critical field, but the measurements for Nb_3Sn fall far short of theory.

Introduction

As the techniques of cavity fabrication and surface preparation mature, the achievable accelerating gradients continue to rise. These techniques and *in situ* processing of field emission have already advanced practical accelerating gradients above the 25 MV/m level.[1] How much higher can Nb go? Eventually we will hit the ultimate barrier of the critical RF magnetic field, H_c^{RF}.

To go higher, attention must turn to other superconductors such as Nb_3Sn that have higher DC critical fields. We must then ask, is the H_c^{RF} of Nb_3Sn films significantly higher than bulk Nb?

The presence of thermal defects in real cavities complicates the measurement of H_c^{RF}. These defects cause thermal breakdown of the cavity to occur at a CW field level much lower than H_c^{RF}. A normal conducting region grows from the defect and eventally encompasses the cavity. But this growth takes a finite amount of time.

With high peak power pulsing, the cavity fields can be quickly raised well above the CW quench field while the normal region is still growing. To determine H_c^{RF}, one must be sure that the cavity is still superconducting at the relevant high field region. This is accomplished by using a technique that allows calculation of the instantaneous cavity Q_0 any time during the filling or decay. By knowing Q_0, one can estimate the size of the normal region and ensure that H_c^{RF} is measured at a superconducting surface. In the present work, we use this technique to measure a lower bound of H_c^{RF} for a 1.3 GHz Nb cavity for temperatures from 2.1 K up to 8.3 K. We also measure a lower bound of H_c^{RF} for a 3 GHz Nb_3Sn coated cavity from 6.9 K to 18 K.

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Finding Transient Q

We outline here the derivation of the Q_0 extraction technique. A more complete description is presented elsewhere.[2] Consider a cavity driven on resonance with one coupler. By conservation of energy we can write

$$P_f = P_{diss} + P_r + \frac{dU}{dt}. \tag{1}$$

where

$$\begin{aligned} P_f &= \text{forward (incident) power} \\ P_{diss} &= \text{cavity dissipated power} = \omega U/Q_0 \\ P_r &= \text{reverse power} \\ U &= \text{stored energy (inside the cavity)} \\ t &= \text{time.} \end{aligned}$$

Note that the reverse power satisfies

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

where Q_{ext} is the "external" Q of the coupler. This expresses that the net reverse wave results from a superposition of a wave reflected off the input coupler and a wave being emitted from the cavity.

Substituting (2) into (1) and solving for Q_0, one obtains

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

From (3) one can determine Q_0 at any instant that the cavity has stored energy.

Cavities

The niobium measurements are made on a 1.3 GHz single cell cavity. Formed from Russian Nb sheets with a starting RRR of 460 ± 150, this cavity has been purified by heat treating. Witness samples indicated that the final RRR was greater than 1500.

The Nb_3Sn measuremens are made on a 3 GHz single cell Nb cavity that has an inside layer of Nb_3Sn. The Nb_3Sn coating was done at Wuppertal. An inside etch was subsequently performed at Cornell. Recent results presented at this conference suggest that better results would have been obtained if the last chemistry was omitted.[3]

Pulsing to Reach H_c^{RF}

It is thought that $H_c^{RF}$is equal to the superheating critical field, H_{sh}, a metastable state above the thermodynamic critical field, H_c.[4] H_{sh} can be achieved in RF because the nucleation time for flux penetration is much longer than an RF period.[5] The race to beat the growth of the normal conducting region requires that the cavity fields be ramped up to H_c^{RF}in less than 100 μs, the faster the better.

For Nb, as long as Q_0 is greater than 2×10^6 then at least 90% of the cavity is superconducting. Since the 10% normal region occupies the area around the defect, it is then assured some part of the high field equatorial region of the cavity is superconducting. For Nb_3Sn the Q_0 needs to be greater than 7×10^4.

In these measurements, for the Niobium cavity, a very strong input coupling ($Q_{ext} \simeq 10^6$) is used. Higher couplings could ramp the fields faster but that would result in too much of a sacrifice in the measurable range of Q_0. The ideal Q_{ext} is the target Q_0 at 90% superconducting. For the Nb_3Sn cavity, the Q_{ext} in the experiment wasn't at the optimum value, but was an order of magnitude higher.

To gain confidence in the warmer measurements, the Nb cavity was cooled with flowing gaseous helium at 4.2 K and the fast pulsed breakdown behavior was found to be similar to that of liquid cooling. There was the worry that the cavity would have a different thermal breakdown behavior due to the inferior cooling power of the gas, but the time scales are so short that the cold reservoir oustside the cavity doesn't have time to play a large role in the heat transfer.

Bathed by flowing helium gas, the cavities were slowly warmed up to their transition temperature (9.25 K for Nb and 18 K for Nb_3Sn). As each cavity warmed, high peak power pulsed measurements were made. Two such pulses on the Nb cavity and the extracted Q_0 are presented in Figure 1. At the beginning of each pulse, Q_0 is too high to measure, but as the normal region grows, Q_0 plummets until it reaches the value of a completely normal cavity. As the temperature is raised from Figure 1 a) to 1 b), the breakdown field is lower, and Q_0 drops earlier. Note that because of the strong coupling and high inci-

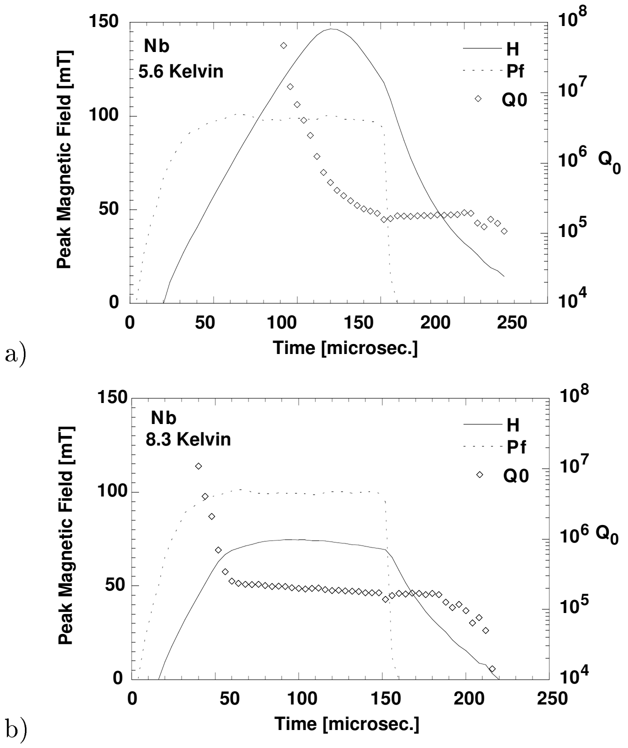


Figure 1: Pulses to the Nb cavity causing thermal breakdown at a) 5.6 K and b) 8.3 K. Since the Nb cavity is almost completely normal conducting at its peak field, it is vital to extract Q_0 while the fields are rising to be assured that most of the cavity is superconducting. Forward power is shown with arbitrary units.

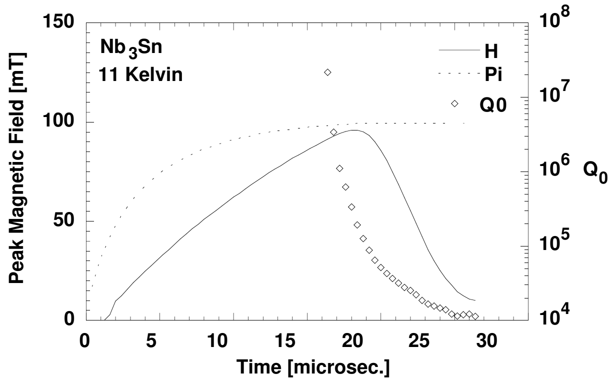


Figure 2: Example pulse causing thermal breakdown in the Nb_3Sn cavity at 11 K. The Nb_3Sn pulses are easier to analyze than the Nb ones because the cavity is over 90% superconducting at its peak field.

dent power, the cavity fields continue to rise despite the plumetting Q_0. Since the cavity is almost completely normal conducting at its peak field, it is vital to extract Q_0 while the fields are rising to be able to measure a lower bound to H_c^{RF} with confidence.

For the Nb_3Sn cavity, the combination of normal conducting Q_0, Q_{ext}, and available rf power didn't permit the cavity to be driven fully normal conducting. Instead, as the cavity began to grow a normal region, the stored energy rapidly dissipated as shown in Figure 2. The result is that the peak field reached in the 3 GHz Nb_3Sn cavity occurs when the cavity is over 90% superconducting. Although this makes data analysis easier, it suggests that with a better optimized test, one could push this Nb_3Sn cavity to higher fields.

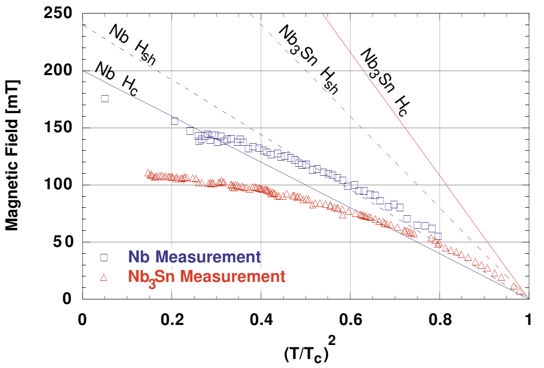
The results from analyzing the pulses to the cavities are consolodated in Figure 3. The two lowest temperature Nb data points were acquired using liquid helium cooling at 2.1 K and 4.2 K with higher peak power and greater input coupling.

For comparison, criticial magnetic field curves are also shown in Figure 3. The curve for H_{sh} is obtained from the assumption that $H_{sh}(0) = c_{sh}H_c$ with $c_{sh} = 1.2$ for Nb and $c_{sh} = .75$ for Nb_3Sn.[6] Measurements for both Nb and Nb_3Sn drop well below the theoretical H_c^{RF} at low temperatures. This may be due to the difficulty reaching the higher fields required at low temperature in the presence of a thermal defect.

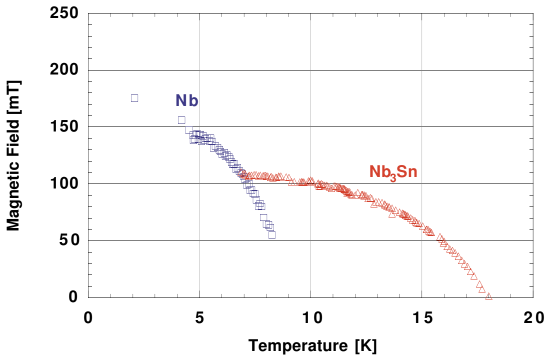
Conclusions

The Q_0 extraction technique was successful in exploring high magnetic fields in a superconducting cavities despite the presence of thermal defects. Measurements on Nb up to 8.3 K are consistent with the idea that H_c^{RF} is the superheating critical field.

Measurements on Nb_3Sn were made but the peak magnetic field during this experiment fell far short of



a)



b)

Figure 3: (a) This graph shows the net results of acquiring and analyzing the types of pulses shown in Figures 2 and 3. The relevant critical fields for the two superconductors are shown. H_c is the thermodynamic critical field. $H_{\rm sh}$ is an estimate of the superheating critical field. (b) The same results as in (a) are replotted on an absolute temperature scale. The higher T_c of Nb_3Sn gives an advantage above 7 K.

the theoretical critical field. The measurements were severly limited by a thermal defect.

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