Measuring the RF Critical Field of Pb, Nb, and Nb_3Sn*

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Abstract

High peak pulsed power is used to raise the cavity fields well above the cw limits. By raising the fields fast enough, high magnetic fields are reached at the superconducting surface before local defects create large normal conducting regions. In this way the fundamental rf critical magnetic field is measured. By measuring the Q_0 of the cavity during the pulse, one is sure that the cavity is still superconducting at a given rf field level. The rf critical magnetic field is measured as a function of temperature up to T_c for 1.3 GHz cavities of lead on copper, niobium, and Nb_3Sn on niobium. A 3 GHz measurement of Nb_3Sn on niobium is also presented. Niobium and lead measurements were consistent with the superheating critical field model whereas the Nb_3Sn results fall short of that prediction.

1 Introduction

Presently the achievable accelerating gradients reached in superconducting cavities are limited either by electron field emission or thermal breakdown. As these barriers are rapidly being pushed back through improved cavity production and assembly techniques, a more fundamental limit will be realized — the rf critical magnetic field, H_c^{rf}. This fact suggests two questions. What is H_c^{rf} for Pb and Nb, the popular superconductors used for accelerators? As we approach this limit in cw operation, what alternate materials (with higher H_c^{rf}) could be used in the future to push back this H_c^{rf} barrier?

The measurements presented here attempt to answer these two questions. H_c^{rf} for Nb and Pb are measured to determine the present limits. H_c^{rf} for Nb_3Sn is measured to see if that material presents itself as an alternate material for very high gradient accelerators of the future.

2 Superheating critical field

For Type I superconductors, H_c is the magnetic field above which superconductivity will stop because it is energetically more favorable for the fields to penetrate the superconductor (and quench the superconductivity) than to perisist in the Meissner state excluding the field. According to the theory of the superheating critical field, the Meissner state is metastable above H_c. Like a supersaturated solution or a superheated liquid, the superconductor might stay in the Meissner state if no nucleation of the normal conducting region occurs. The field above which this metastability dissapears is called the superheating critical field, H_{sh}. For strong Type II superconductors, H_{sh} is lower than H_c. The following relations [1, 2] are predictions for H_{sh} made by solving the one dimensional Ginzburg-Landau equation.

$$\begin{aligned} H_{sh} &\approx \frac{0.89}{\sqrt{\kappa_{GL}}} H_c \quad \text{for} \quad \kappa \ll 1, \\ H_{sh} &\approx 1.2 H_c \quad \text{for} \quad \kappa \approx 1, \\ H_{sh} &\approx 0.75 H_c \quad \text{for} \quad \kappa \gg 1. \end{aligned} \tag{1}$$

Here κ is the Ginzburg-Landau parameter. More thorough discussions of the superheating critical field and its relationship to rf fields can be found in Müller [3] and Padamsee et al. [4].

Reaching the superheating critical field in dc is possible but very difficult since it requires the absence of nucleation sites. If the nucleation of flux penetration sites takes much longer than an rf cycle, the superheating critical field should be easy to achieve in rf.

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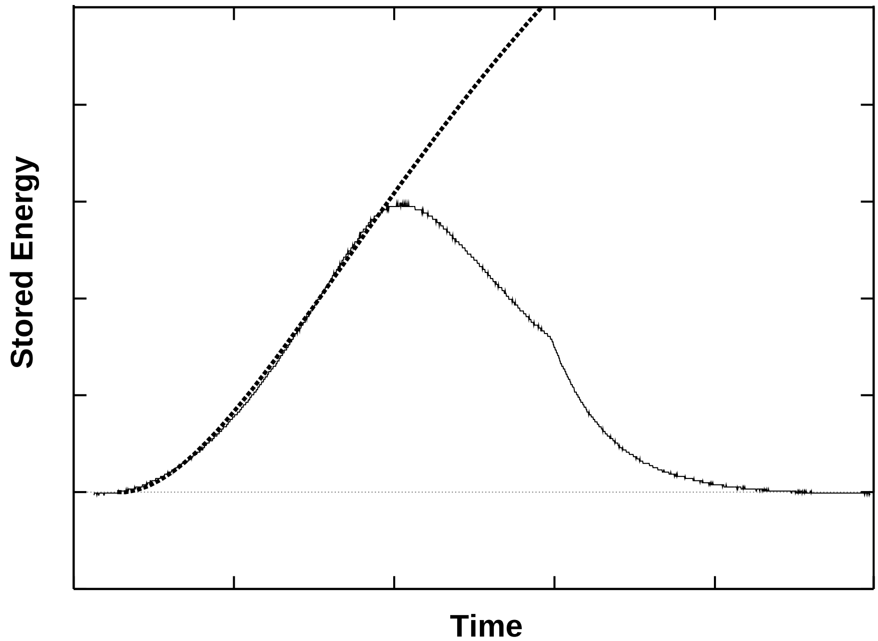

Figure 1: Comparing the behavior of a cavity that quenches with an idealized cavity with no quench. The point where the two diverge is the H_c^{rf}.

3 Measuring H_c^{rf}

If one is working with a thermal-defect-free and field-emission-free cavity, measuring H_c^{rf} can be as easy as turning up the incident power and observing the field at which the superconducting cavity quenches. Depending upon the surface resistance of the cavity and the heat conduction path away from the rf surface, the temperature of the rf surface may be elevated much above the cooling bath temperature. The observed quench field would then be an indirect measure of the temperature dependent rf critical magnetic field.

To circumvent the problem of localized defects, H_c^{rf} is measured in a pulsed mode instead of continuous wave. By coupling in power very strongly, the surface fields in the cavity are raised much faster than the characteristic timescales of heat propagation. A growing normal conducting region in the vicinity of a defect doesn't have time to envelop the cavity. The cavity quenches due to its intrinsic H_c^{rf} while the normal zone is still small. The size of the normal zone is estimated by measuring the Q_0 of the cavity.

There have been three general methods used to pulse superconducting cavities to measure H_c^{rf}. These differ in the way that they measure the cavity Q_0.

3.1 Method #1: Estimating Q_0 after the pulse

To have the best chance of beating the growth of the normal region, Campisi [5] used a very short ($\approx$2 μs) pulse of high power rf. To evaluate whether the cavity quenched during the pulse, they turned up the incident power on successive pulses and observed when the cavity deviated from being perfectly superconducting. At the end of the pulse, the power emitted from the cavity was integrated to measure the cavity's maximum stored energy. When the stored energy deviated from that expected for the incident power level, the peak surface field had exceeded H_c^{rf}.

Figure 1 illustrates conceptually what was being measured. The stored energy as a function of time for a cavity experiencing a quench deviates from the expected value. The point at which the cavity deviates is the value taken as H_c^{rf} in this method.

3.2 Method #2: Estimating Q_0 during the pulse

Yogi [2] measured H_c^{rf} with a longer pulse length and a lower power level than used in Method #1. During the incident power pulse, the reflected power (P_r), incident power (P_i), and cavity stored energy (U) were measured

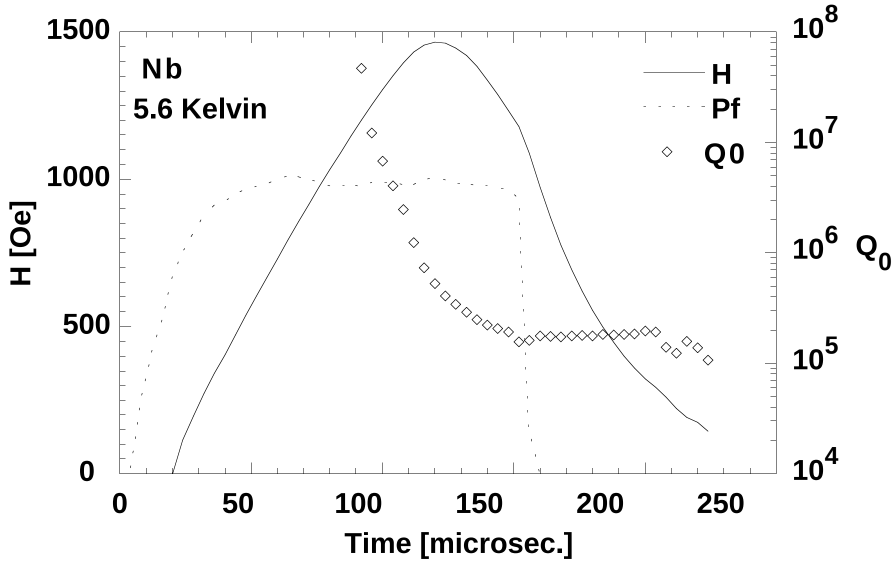

Figure 2: An example pulse illustrating the use of the Q_0 extraction technique to interpret cavity behavior during a quench.

as a function of time. By conservation of energy,

$$P_c = P_i - P_r - dU/dt, \tag{2}$$

the power dissipated in the cavity's walls, P_c, is measured. The Q_0 of the cavity as a function of time can then be found from

$$Q_0(t) = \frac{\omega U(t)}{P_c(t)}. \tag{3}$$

One difficulty of this method is that it requires the simultaneous precision measurement of three time dependent signals.

3.3 Method #3: Estimating Q_0 during the pulse

In this work, we measure Q_0 during the pulse by a technique similar to Yogi. For a high Q resonator, the reflected power can be predicted from incident power and the cavity's stored energy by the relation

$$P_r = \left(\sqrt{P_i} - \sqrt{\omega U/Q_e}\right)^2 \tag{4}$$

where Q_e is the "external" Q of the input coupler. This expression substituted into (2) allows one to solve for the cavity's Q_0:

$$\frac{1}{Q_0} = \frac{2\left(\sqrt{\frac{P_i\omega}{Q_e}} - \frac{d\sqrt{U}}{dt}\right)}{\omega\sqrt{U}} - \frac{1}{Q_e}. \tag{5}$$

The advantage of this method over Method #2 is that it requires only two simultaneous precision measurements of time dependent signals instead of three.

An example of using this technique is shown in Figure 2. A 1 MW peak power pulse was used to drive the cavity. The Q_0 can be observed to drop until it reaches the normal conducting value of 2×10^5. The peak magnetic field during the pulse occurred when the cavity was almost completely normal. By extracting the Q_0, a magnetic field can be selected when 90% of the cavity is still superconducting, i.e., when the $Q_0 = 2 \times 10^6$.

If all of the signals were measured with arbitrary precision, one could obtain a Q_0 versus E curve from one of these pulses. The Q_0 would be measured as the cavity is filling to avoid the additional losses due to the quench. Unfortunately, with the strong external coupling needed to ramp the cavity fields in these short time scales, the cavity Q_0 is not measurable until it drops closer toward Q_e.

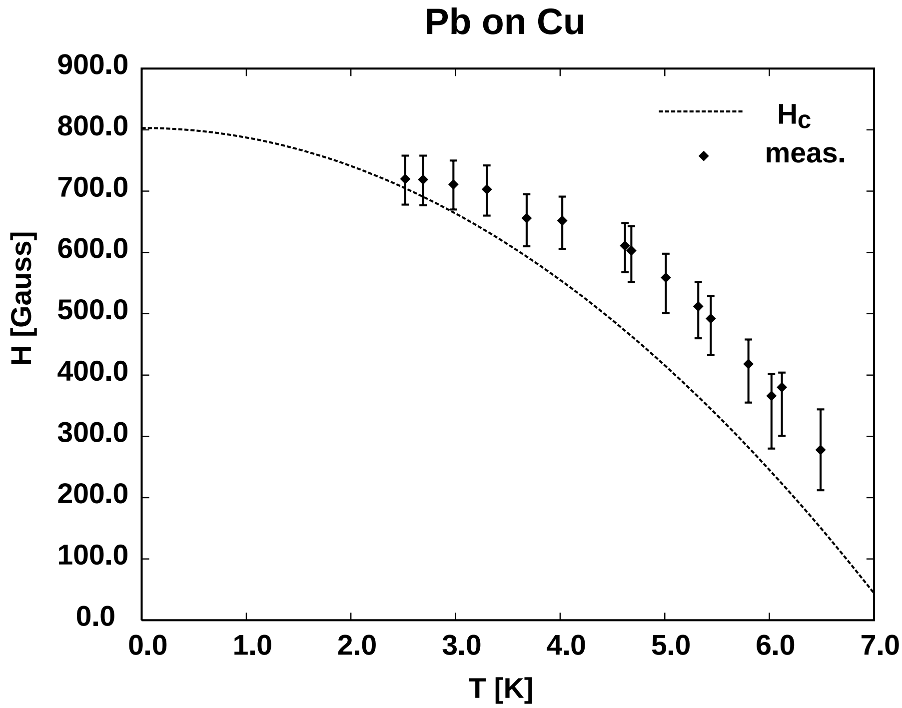

Figure 3: Measuring the H_c^{rf} of lead by pulsing a lead coated copper 1.3 GHz cavity.

4 Apparatus

Most of the measurements were made using a 1.3 GHz klystron capable of producing a peak power of 2 MW for 300 μs. For one sample a 3 GHz klystron was used to provide a peak power of 150 kW.

A uniform cavity temperature was achieved either by immersing the cavity in liquid helium or flowing helium gas past the cavity depending upon the temperature range desired. To show that gas cooling is adequate for this type of pulsed measurement, it was verified that liquid cooling at 4.2 K and gas cooling at 4.2 K yield the same results.

Thermometers were located above and below the cavity to record any temperature gradients. Usually the gradient was kept well below 0.1 K.

5 Measurements

Method #3 described above was used to measure the rf critical field for three superconductors: niobium, Nb_3Sn on niobium, and lead on copper. The lead on copper cavity started out as a 1.3 GHz copper single-cell cavity made at Cornell. A pure lead coating (nominally 2 μm) was electroplated onto the cavity by John Noé's group at Stony Brook. Measurements of the rf critical magnetic field are shown in Figure 3. For this Type I superconductor, H_c is clearly exceeded. Like those of Yogi [2], these measurements are not quite as high as the superheating critical field would suggest.

The bulk niobium 1.3 GHz cavity was made at Cornell from Russian high-RRR material and post-purified by solid state gettering to 1000 RRR. The results from this measurement are presented in Figure 4. On the same plot is shown the theoretical value for H_{sh} from (2). These measurements show that H_c is exceeded and are consistent with the existence of a superheating critical field.

There were two Nb_3Sn on niobium single-cell cavities made and tested, one at 3 GHz and one at 1.3 GHz. The cavities were made at Cornell and the Nb_3Sn coating was done by Cryoelectra. Figure 5 summarizes all the measurements made on these two cavities. The 1.3 GHz cavity was tested three times. The first two times, the cavity received no surface treatment except for high pressure water rinsing after the Nb_3Sn coating process. Measurements were made at different external Q values to see if the cavity fill rate had a large effect on the measured H_c^{rf}. It turned out that a lower Q_e yielded a slightly higher H_c^{rf}. The test on the 3 GHz cavity and the final test of the 1.3 GHz cavity were made after removing 0.1 μm from the surface through annodization followed by a dip in HF. This removal appeared to have no significant effect on the H_c^{rf}.

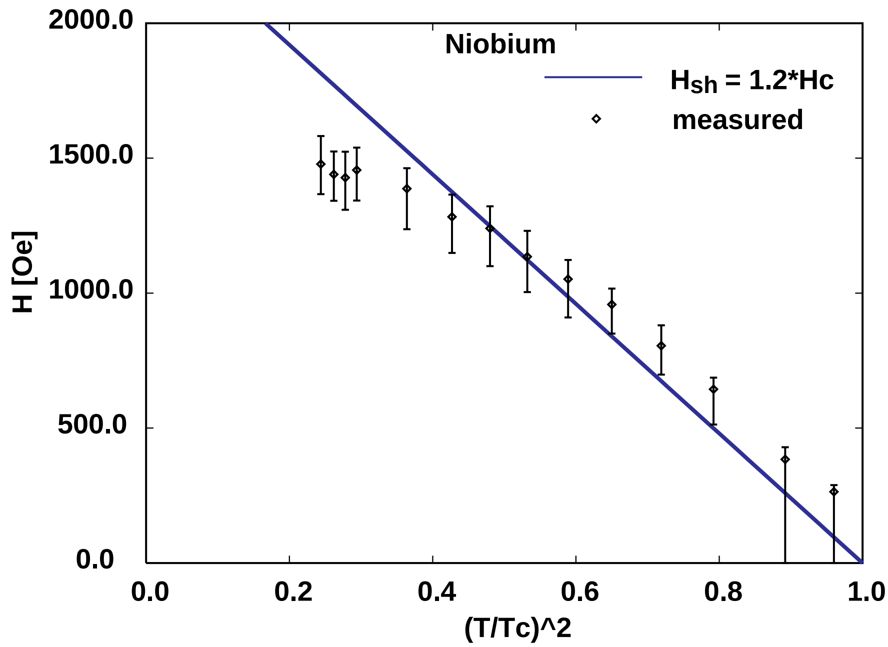

Figure 4: Measuring the $H_c^{rf}$of niobium by pulsing a 1.3 GHz bulk niobium cavity of high RRR.

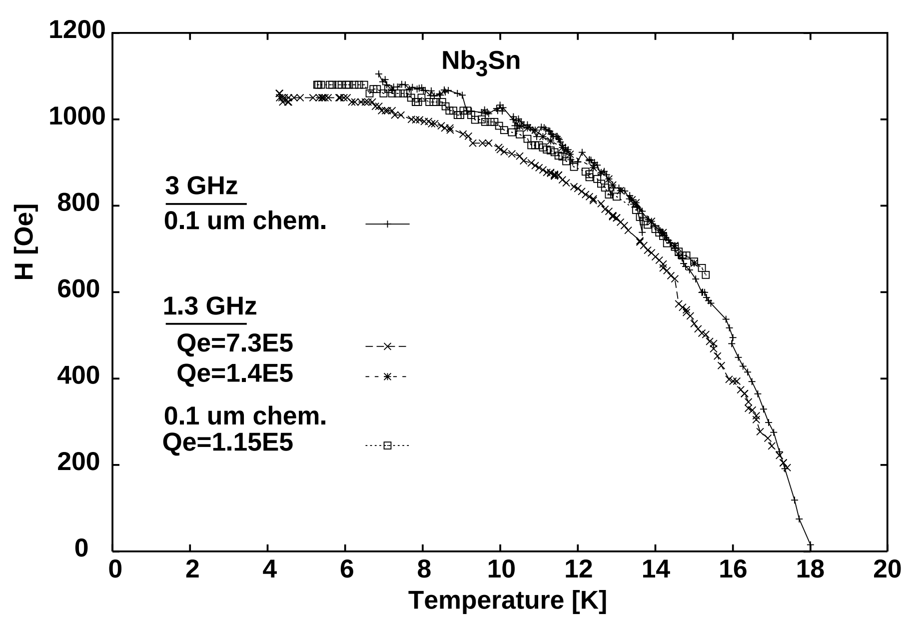

Figure 5: Measuring the H_c^{rf} of Nb_3Sn by pulsing a Nb_3Sn coated niobium 1.3 GHz cavity and a Nb_3Sn coated niobium 3 GHz cavity. Multiple measurements were made on the 1.3 GHz cavity with different couplings and surface treatment.

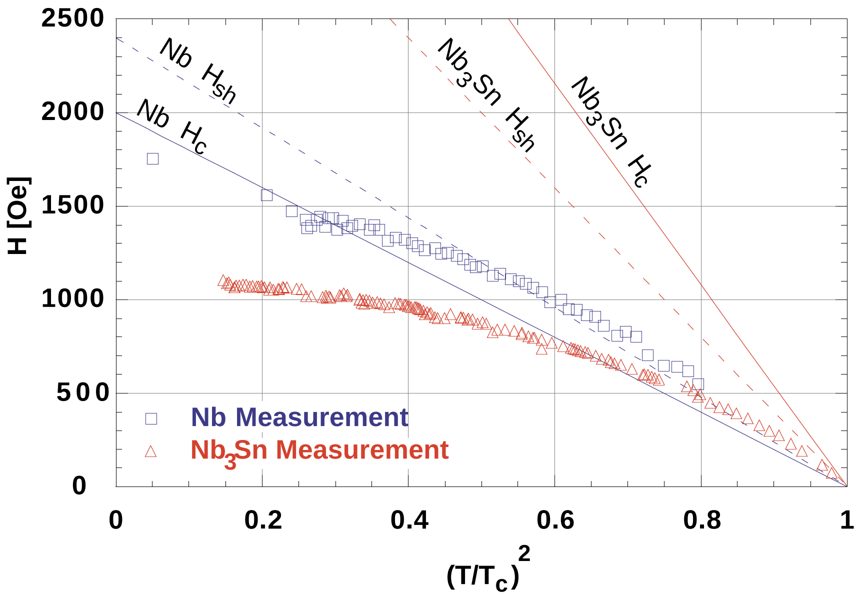

Figure 6: Comparing the niobium and Nb_3Sn measurements against the superheating critical field predictions.

Figure 6 shows where the measurements of niobium and Nb_3Sn fall in relation to the theoretical predictions of (2). Niobium shows itself to be close to the theoretical values but Nb_3Sn is considerably lower. Measurements by Campisi [5] were slightly higher than those presented here but were still considerably lower than H_{sh}.

Why is niobium close to the theoretical H_{sh} and Nb_3Sn so far away? The Nb_3Sn tested here differs from niobium in three significant ways. First, it has 20 times the κ of niobium. Are the superheating critical field calculations we are using valid for such strong Type II materials? Second, the Nb_3Sn is highly granular. Third, it is a thin film instead of a bulk superconductor. It remains to be seen if any or all of these factors are playing a significant role in explaining the low H_{sh} values measured for Nb_3Sn.

6 Acknowlegements

We are grateful to John Noé and his team for all their hard work in preparing the lead coating on the copper cavity.

References

[1] J. Matricon and D. Saint-James, *Phys. Lett. A*, **24**:241 (1967).

[2] T. Yogi, *Radio Frequency Studies of Surface Resistance and Critical Magnetic Field of Type I and Type II Superconductors*, PhD thesis, California Institute of Technology, 1977.

[3] G. Müller, in *Proceedings of the Third Workshop on RF Superconductivity* (1987).

[4] H. S. Padamsee et al., *RF Superconductivity for Accelerators*, Wiley and Sons, Inc. (1998). To be published.

[5] I. E. Campisi. On The Limiting RF Fields in Superconducting Accelerator Cavities. Technical Report SLAC/AP-58, Stanford Linear Accelerator Center, 1987.