Presented at the 1995 Particle Accelerator Conference, Dallas, TX SRF 950508-10

Response of Superconducting Cavities to High Peak Power*

T. Hays, H. Padamsee, Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853 USA

Abstract

A technique to find the transient cavity Q from transmitted power is presented. This technique can facilitate finding the Q as a function of accelerating electric field for low power pulsed measurements, but it has a special application to analyze the thermal breakdown behavior during high peak power pulsing. With high power, 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. A lower bound to the critical RF magnetic field can then be determined.

Results of pulsing a 1.3 GHz Nb cavity with 340 kW for 150μs are presented. The Q extraction technique is used to measure a lower limit of H_c^{RF} over the range of 2 K to 8.3 K despite the presence of a thermal defect.

I. INTRODUCTION

As we continue to push the achievable accelerating gradients in Nb cavities, the critical RF magnetic field, H_c^{RF}, will eventually show up as a hard limit. Improvements in Nb purity and processing of field emission have already advanced practical accelerating gradients above the 25 MV/m level.[1] How much farther can Nb be pushed? When is it time to abandon Nb in favor of other superconductors such as Nb_3Sn that have higher DC critical fields? Is the H_c^{RF} of Nb_3Sn films significantly higher than bulk Nb?

The difficulty in answering these questions is largely due to the presence thermal defects that quench the superconductivity and prematurely limit the sustainable surface magnetic field. In CW operation, in addition to the defect's particular characteristics, the quench field is dependent upon the specifics of the steady state heat transfer. Thus improving the thermal conductivity of Nb serves to raise the quench field. A small normal conducting "hot spot" can be sufficiently cooled and contained to avoid thermal runaway. If the cavity fields are raised above this CW quench field, the normal region grows to eventually encompass 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 growing. To determine H_c^{RF} from this, one must be sure that the cavity is still superconducting at the relevant high field region. A new technique is presented that allows calculation of the instantaneous cavity Q any time during the filling or decay. By knowing Q, 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 H_c^{RF} of a 1.3 GHz Nb cavity for temperatures from 2.1 K up to 8.3K.

In addition, since the accelerating field is known at every instant, this Q extraction technique can be used to quickly determine Q vs E_{acc}. Application in this manner is the subject for further work.

II. FINDING INSTANTANEOUS CAVITY Q

In what follows, the differential equation of the cavity state is derived and solved for Q_0. 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

P_f = forward power (toward the input coupler)
P_{diss} = cavity dissipated power
P_r = reverse power
U = stored energy (inside the cavity)
t = time.

The only tricky part about this expression is the reverse power which satisfies

$$P_r = \left(\sqrt{P_f} - \sqrt{P_e}\right)^2 \tag{2}$$

where

$$P_e = \omega U / Q_{ext}. \tag{3}$$

Q_{ext} is the "external" Q of the coupler.

Equation (2) indicates 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 using

$$P_{diss} = \frac{\omega U}{Q_0} \tag{4}$$

for the cavity losses and

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{5}$$

for the "loaded Q" as well as (3) we arrive at a differential equation for stored energy:

$$\frac{dU}{dt} = 2\sqrt{\frac{P_f \omega U}{Q_{ext}}} - \frac{\omega U}{Q_L}. \tag{6}$$

A clearer form results when written in terms of the fields ($\propto \sqrt{U}$).

$$\frac{d\sqrt{U}}{dt} = \frac{1}{2\tau_L}\left(\sqrt{U_0} - \sqrt{U}\right) \tag{7}$$

where $\tau_L \equiv \frac{Q_L}{\omega}$ and

$$U_0 \equiv \frac{4{\tau_L}^2 \omega P_f}{Q_{ext}} \tag{8}$$

is the steady state stored energy.

Equation (7) shows that the cavity has a natural time constant τ_L for response and that the field changes at a rate proportional to the displacement from its equilibrium value.

*Work supported by the NSF with supplementary support from the U.S.-Japan Cooperative Agreement

If the cavity-coupler system had more than one coupler, (1) would have an additional term with the form of (3) for the emitted power of each coupler. The only effect this has on the subsequent equations is to require that the definition of "loaded Q" in (5) have an additional $1/Q_{ext,k}$ term for each of the k new couplers.

From (7) and (2) the time dependent cavity behavior can be determined analytically or numerically.

The above treatment gives $U(t)$ from Q_0 (and other variables) but to go the other way, one has only to solve for Q_0 in (7) to get

$$\frac{1}{Q_0} = \frac{2\left(\sqrt{\frac{P_f \omega}{Q_{ext}}} - \frac{d\sqrt{U}}{dt}\right)}{\omega\sqrt{U}} - \frac{1}{Q_{ext}}. \qquad (9)$$

Again, if there are k additional couplers, they would show up as further $1/Q_{ext,k}$ terms subtracted from the right side of (9).

Equation (9) is useful for extracting the $Q(t)$ or the $Q(E)$ behavior of a cavity during pulsed operation. And unlike previous methods of getting $Q_0(E)$ from a pulse that examined only the cavity decay[2], this technique can be used any time the cavity has energy. This method also improves over past methods in that it requires only the instantaneous values of U, $d\sqrt{U}/dt$, and P_f. The cavity's history (or future) need not be considered, and no functional fits are needed.

If the cavity is grossly overcoupled ($Q_{ext} \ll Q_0$) then Q_0 plays little role in determining the shape of $U(t)$. For the overcoupled case, in order to extract Q_0, $U(t)$ must be known to first order within a fractional error of Q_{ext}/Q_0. When Q_0 does have a negligible contribution, one can take advantage of this to extract Q_{ext}. When ($Q_{ext} \ll Q_0$), Q_{ext} can be found by

$$\frac{1}{\sqrt{Q_{ext}}} = \frac{\sqrt{P_i} \mp \sqrt{P_i - \frac{dU}{dt}}}{\sqrt{\omega U}} \qquad (10)$$

where the negative sign is used when d^2U/dt^2 is positive and vice versa.

III. EXPERIMENTAL APPARATUS

Cavities of the DESY shape (1.3 GHz) are tested using a high power klystron and modulator system[3] capable of providing 1.5 MW for 270 μsec. Currently input coupler limitations allow the full 1.5 MW to be used only when the pulse length is reduced to $\sim$150 μsec.

Results presented here are for a single cell cavity made from Russian Nb sheets with a starting RRR of 460$\pm$150. Subsequent solid state gettering with Ti resulted in a RRR of 1825 $\pm$ 700[1]. Because the cavity's resonance was not at the center frequency of the klystron, the experimental results presented here were limited to a peak power of 1 MW.

Germanium thermometers were mounted on each beam tube to monitor the cavity temperature and any thermal gradient. Three Allen-Bradley resistor thermometers were mounted on the cavity equator to observe fast temperature changes as a result of pulsing. Measurements of incident and transmitted power during pulsing are made by crystal detectors monitored by an 8-bit digital storage oscilloscope (Tektronix 2212). The oscilloscope traces are acquired and processed by a Macintosh computer running LabVIEW software.

IV. 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. To do this 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 Q_0.

Oscilloscope traces of up to 1 MW peak power pulses to the liquid helium cooled Nb cavity were acquired at 2.1 K and 4.2 K. By warming the cavity we hoped to be able to lower H_c^{RF} enough to come close to it even with the thermal breakdown. To prepare for warmer measurements, the 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 outside the cavity doesn't have time to play a large role in the heat transfer.

Bathed by flowing helium gas, the cavity was slowly warmed up to its transition temperature 9.25 K while high peak power pulsed measurements were made (with $Q_{ext} = 9 \times 10^6$ and $P_f = 340$ kW). Two such pulses and the extracted Q_0 are presented in Figure 1. At the beginning of the 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 incident 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.

At the beginning of the pulses in Figure 1, Q_{ext} was sucessfully extracted using Equation (10). The value thus obtained agreed well with independent measurements of Q_{ext}.

The 8-bit amplitude resolution on the oscilloscope was the most serious limitation to the data. Averaging was required get rid of a little noise and to remove the "steps" caused by this resolution limit.

To be positive that there is a superconducting surface reaching the peak field, we claim the cavity must be at least 90% superconducting. Since the 10% normal region occupies the area around the local defect, it is assured some part of the high field equatorial region of the cavity is superconducting.

A conservative calculation then dictates that Q_0 must be at least 2 $\times$ 10^6. Applying this criterion to the pulses measured yields the data in Figure 2. The two lowest temperature data points were acquired using liquid helium cooling at 2.1 K and 4.2 K with higher peak power and greater input coupling. Be-

[1]The RRR measurements were done on small witness samples.

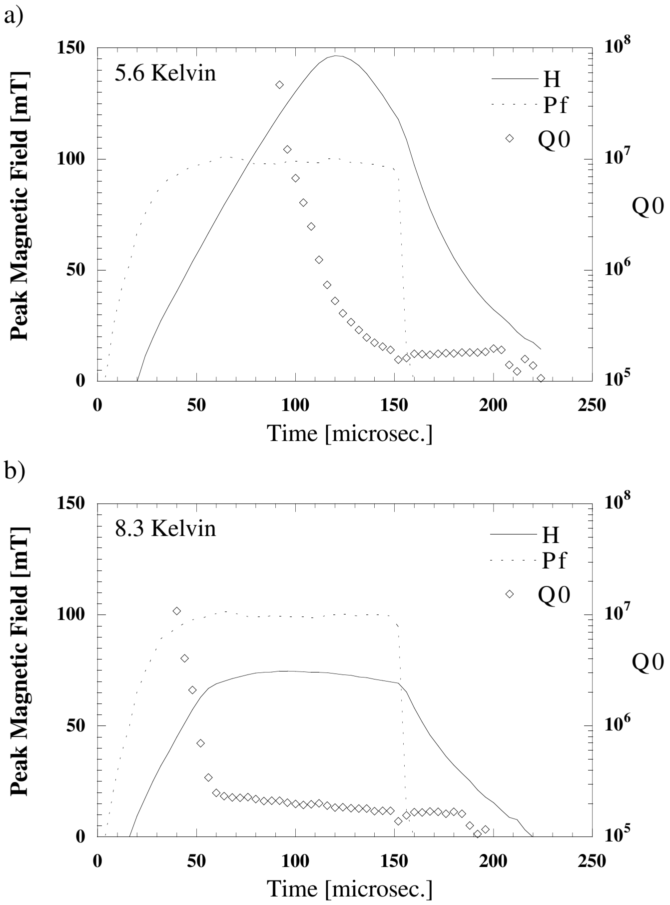

Figure 1. Pulses to the cavity causing thermal breakdown at a) 5.6 K and b) 8.3 K. Peak forward power was 340 kW for both pulses. Forward power is shown with arbitrary units.

cause the breakdown occurred so early in the pulse, testing the cavity much above 8.3 K gave inconclusive results.

For comparison, criticial magnetic field curves for Nb are also shown in Figure 2. The curve for H_{sh} is obtained from the simplistic assumption that $H_{sh}(0) = c_{sh} H_c$ with $c_{sh} = 1.2$ throughout the temperature range. The exact values are not easily predicted, but because of the temperature dependence of the Ginsburg-Landau parameter it is expected that c_{sh} is lower for lower temperatures and higher closer to T_c. One might think that it is suggestive that the experimental data in Figure 2 also follows this trend, but the stronger influence of the thermal defect on the lower temperature points is probably dominating the shape.

Note that these first experimental measurements are tentative. Improvements in the reliability of power measurements and better data resolution are in progress.

V. CONCLUSIONS

The new Q_0 extraction technique was successful in exploring high magnetic fields in a superconducting cavity despite the presence of a thermal defect. Measurements on Nb up to 8.3 K are consistent with the idea that H_c^{RF} is the superheating critical field. These measurements suggest that high magnetic field studies of Nb_3Sn are feasible using this Q_0 extraction tool.

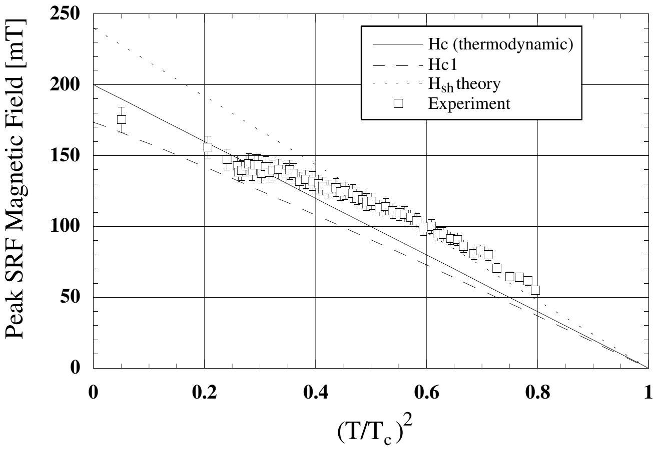

Figure 2. Measured surface magnetic fields on the superconducting Nb surface compared with DC critical fields[6] and a reasonable guess at H_{sh}.

VI. ACKNOWLEDGMENTS

We wish to thank our colleagues W. Hartung for helpful criticism on the theory, J. Sears for assistance in cavity purification, and E. Chojnacki for help with the klystron. Thanks go to K. Hosoyama from KEK for assistance with the helium gas cooling. We are also grateful to the many members of the international TESLA Collaboration that aided in setting up the 1.3 GHz cavity test facility at Cornell.

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