STUDY OF THE TEMPERATURE INTERFACE BETWEEN NIOBIUM AND SUPERFLUID HELIUM. TEMPERATURE WAVES MEASUREMENTS FROM HEAT SOURCES

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Abstract

One of the most important properties of Superconducting Radio Frequency (SRF) cavities is their ability to disperse generated heat from the internal cavity wall to the external super fluid helium bath. If the generated heat is not removed fast enough, an effect known as thermal feedback dominates, resulting in medium field Q-slope and a cavity quench. This generated medium field Q-slope has the ability to negatively impact the Q factor should it become strong enough. To determine what physical factors affect the creation of the medium field Q-slope we will be computationally modelling the medium field Q-slope with varying parameters, such as thermal boundary resistance, called Kapitza resistance [1], wall thickness, RF frequency, bath temperature, residual resistivity ratio, residual resistance, and phonon mean path. For already prepared cavities, the Kapitza resistance and wall thickness near quenching area are the only parameters that can be modified.

Our results show that the medium-field Q slope is highly dependent on the Kapitza conductivity and that by increasing the Kapitza conductivity the medium field Q-slope reduces significantly. Understanding and controlling the medium field Q-slope will benefit future continuous wave (CW) applications such as the Energy Recovery Linacs (ERL) where cryogenics costs dominate due to CW operation at medium fields (< 20 MV/m).

INTRODUCTION

For successful operation of various linear accelerators SRF cavities must attain high Q and accelerating field specification. Chemical treatment such as buffered chemical polishing and/or electro-polishing for cavity quenching at field >25MV/m may not always lead to the improvement of the cavity performance but instead cause the development of new surface defects and reduced quenching field.

Also, it is extremely time consuming to do internal treatment for large arrays of cavities, such as the 16,000 needed for the International Linear Collider. In this case we would like to consider outside cavity treatment by improving the temperature boundary resistance between cavity and superfluid helium and by reducing the wall thickness where heating from surface defects occurs.

A superconducting radio-frequency (SRF) cavity's most influential limiting factor is its ability to effectively remove the heat created within the cavity. A cavity that cannot sufficiently do this will heat up, causing thermal feedback and cause a cavity quench. In order to summarize the relationship between the heat produced and the RF field, the Q factor is discussed. The Q factor quantitatively calculates the number of RF cycles in order to dissipate the energy stored within the cavity. The medium field Q slope is also commonly used as measure of the dependence of the Q factor on the RF field strength.

There are many physical factors and variables that are used when calculating the Q factor and medium field Q slope, but most of them are either material properties of the metal or arise from the geometry of the cavity, meaning that they cannot be easily modified. Out of all the variables that make up the Q factor/medium field Q slope, the only one that can be readily modified is the Kapitza resistance. The Kapitza resistance is a type of thermal resistance that occurs between a metal and a liquid helium bath. The heat transfer between the walls of the cavity and the helium bath occur via phonons. The phonons in the helium bath have a much lower velocity than those in the metal, and this mismatch of velocity means that only at certain angles are the phonons actually able to enter the metal walls. The critical angle of incidence is calculated using Snell's Law.

$$\alpha_{crit} = \arcsin\left(\frac{v_h}{v_s}\right) \approx 3^{\circ} \tag{1}$$

The velocity of the phonons in helium is v_h and v_s is the velocity of the phonons in the metal. Of all the phonon that try to move from the helium bath to the cavity walls, only a fraction of the phonons from the helium bath hit the cavity wall within the critical angle.

$$f = \frac{\pi \sin^2(\alpha_{crit})}{2\pi} \approx 2\times10^{-3} \tag{2}$$

Not all of those phonons have the ability to penetrate into the cavity wall due to acoustic impedance. Only a fraction of the above fraction makes it into the cavity's walls.

$$ft = \frac{2\rho_h v_h^3}{\rho_s v_s^3} < 10^{-5} \tag{3}$$

The number of phonons that are able to penetrate from the metal to the helium and allow heat transfer is quite small, which is the cause for the Kapitza resistance.

$$R_k = \frac{15\hbar^3 \rho_s v_s^3}{2\pi^2 k_B^2 T^3 A \rho_h v_h} \tag{4}$$

All of the variables are held constant except for the surface area, which can be easily altered.

$$R \approx A^{-1} \tag{5}$$

This proportion tells us that ideally, by increasing the surface area the Kapitza resistance will be lowered therefore allowing the heat to be dispersed more rapidly. Even cavities made with the best materials and treatment still do heat up, most commonly due to defects that cause hot spots in the cavity's walls. Until recently there was only one reliable technique to find possible defects responsible for the quench -- temperature mapping. A powerful alternative technique to resistance tthermometry is the use of 2nd sound in superfluid helium to image the heat transfer from the resonator to the superfluid helium bath [2]. By testing a superconducting resonator in a superfluid helium bath it is possible to observe the second-sound temperature and entropy waves driven by the conversion of stored RF energy to thermal energy at a defect. By measuring the time-of-arrival of the second sound wave at three or more detectors which form a basis for the resonator's three dimensional coordinate system, the defect location can be unambiguously determined. For our research we used the unique property of superfluid helium and its ability to support propagation of temperature or entropy waves, called second sound. The velocity of the second sound is an order of magnitude less than the velocity of the "traditional" density waves and near the cavity operational temperature at 2K is 16m/s.

In this paper we will discuss a common theoretical model for the flow of heat through a sheet of metal. Using this program we will model how various physical parameters affect the Q factor, most importantly how the Kapitza resistance affects it. We will also experimental determine how second sound waves penetrate through a metal plate and are detected by OST's.

THEORETICAL MODEL

Calculating the Medium Field Q Slope and Q Factor

The theoretical model used is the 1D Heat program written in C++ and Matlab. The program models how heat is dispersed through a sheet of metal and calculates the conductivity between each of the layers for an ideal case without defects. The model estimates the medium field Q slope and the Q factor and has the ability to determine what physical factors affect them.

The medium field Q slope is calculated using an approximation proposed by Halbritter [3].

$$\gamma = \frac{B_c^2}{2\mu_0^2} \frac{\Delta}{k_B T_b^2} R_{BCS}(T_b)\left(\frac{d}{k} + \frac{1}{H_k}\right) \tag{6}$$

Where k is termal conductivity and d is thickness of niobium, T_b – temperature of helium bath. The standard BCS resistance used to calculate the medium field Q slope uses a Pippard approximation. [4]

$$\begin{aligned} R_{BCS}(T) &= (2.78\times10^{-5}\Omega)\frac{v^2}{t}\ln\left(\frac{148t}{v}\right)\exp\left[-\frac{1.81g(t)}{t}\right] \\ t &= \frac{T}{T_c} \\ v &= \frac{f}{2.86GHz} \\ g(t) &= \left[\cos\left(\frac{\pi t^2}{2}\right)\right]^{1/2} \end{aligned} \tag{7}$$

Kapitza conductivity of annealed niobium uses the following equations which have been fit to experimental data sets [5].

$$H_\kappa(T_d, T_b) = \left(200\frac{W}{m^2K}\right)\left(\frac{T_b}{1K}\right)^{4.65} f(t) \tag{8}$$

In our case the temperature is the temperature of the helium bath, which is held constant; therefore, the only factor that is changing is the RF frequency (f). In the code there are two options when using the BCS resistance function. There is a choice for when the RF field is 1.3GHz and one for when it is at any other frequency. When the RF field is 1.3GHz the standard BCS resistance is held at a constant value otherwise the above equation is used to calculate the BCS resistance.

The Q factor is written as a function of the magnetic field and the medium field Q slope.

$$Q(B) = \frac{G}{R_{s0}}[1-\gamma(\frac{B}{B_c})^2 + O(B)^4] \tag{9}$$

The higher-order function, O(B), is assumed to be insignificant and therefore ignored in the program.

RRR is a measured quantity of the purity of a sample of niobium and cannot be modified. Fig. 1 and 2 demonstrate that even if the sample of niobium is not very pure, by increasing the

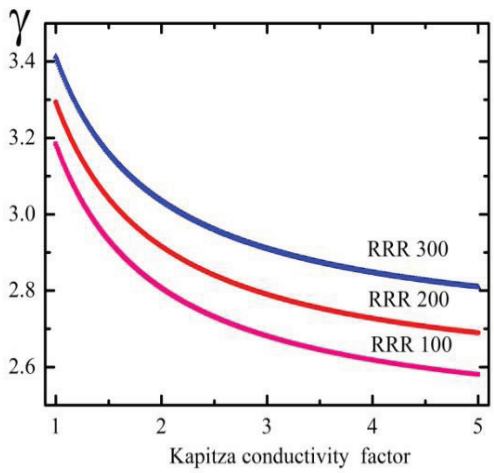

Figure 1: Medium Field Q Slope (B = 0.1T, f = 3GHz, phonon mean free path = 0.0001m, d = 0.003m) for increasing Kapitza conductivity.

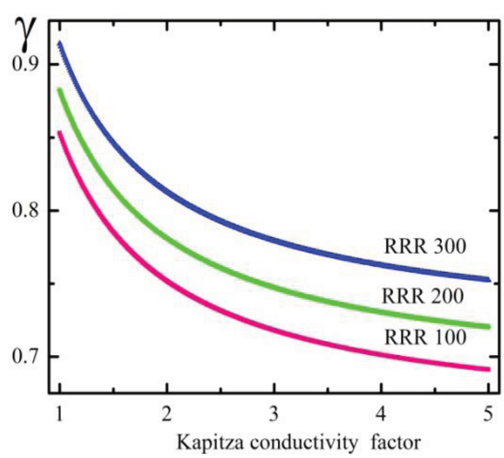

Figure 2: Medium Field Q Slope (B = 0.1T, f = 1.3GHz, phonon mean free path = 0.0001m, d = 0.003m) for increasing Kapitza conductivity.

Kapitza conductivity we can compensate for that and still have a good cavity. The Q factor was also computed at various Kapitza conductivity values.

In both cases as the Kapitza conductivity is increased so is the Q factor. It does appear to reach a limit after the Kapitza conductivity is multiplied by a factor of 10.

As we can see from Fig. 3, if we improve Kapitza conductivity even up to 10 times, at magnetic field 0.07mT for 3GHz cavity, Q factor can be improved by 20%. For 1.3GHz cavities near 0.1mT range Q-factor can be increased by ~ 12%.

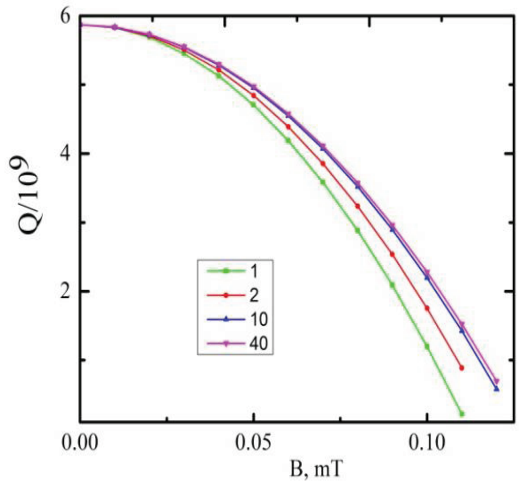

Figure 3: Q factor computed at f= 3GHz at various Kapitza conductivities.

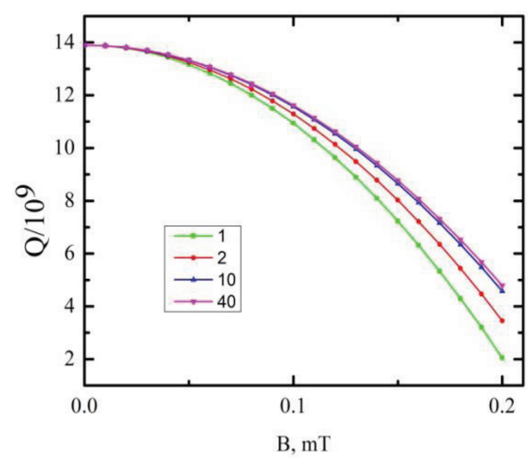

Figure 4: Q factor computed at f 1.3GHz at various Kapitza conductivities.

In the case of point-like defect on the vacuum side the temperature can reach several Kelvin [6] and change niobium into its normal conducting state leading to a cavity quench. The quench location can be detected using a method developed at Cornell, by using the properties of second sound waves propagation. Once the defect location is found, local wall thinning with surface area development (decreasing Kapitza resistance) can be an efficient tool for the improvement of heat transport from the RF side to superfluid helium bath.

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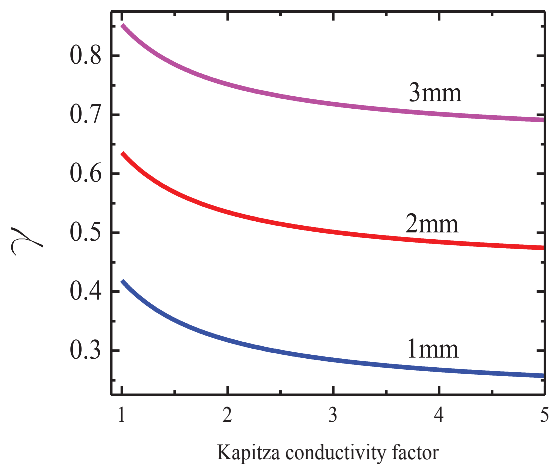

Figure 5: illustrates medium field Q slope with Kapitza conductivity improvement and with reducing niobium wall thickness from 3 mm down to 1 mm for 1.3GHz cavity.

EXPERIMENTAL SECTION

For understanding the propagation of second sound waves in restricted geometry where number of obstacles play role we made modelling experiments in a small Dewar. Experimental set up is presented on the Fig. 5. Three 50-ohm heaters have been glued to a G-10 non-conductive post separated by a few mm from an aluminum plate 0.5mm thick. Holes were drilled through the plate adjacent to each heater, 3mm diameter for the upper two heaters, 6mm for the lowest. On the other side of the plate three OST's were anchored to the top plate keeping the geometry 'heater -- drilled hole – OST detector' on same sight-line. One more heater was directly attached to the middle of the metal plate.

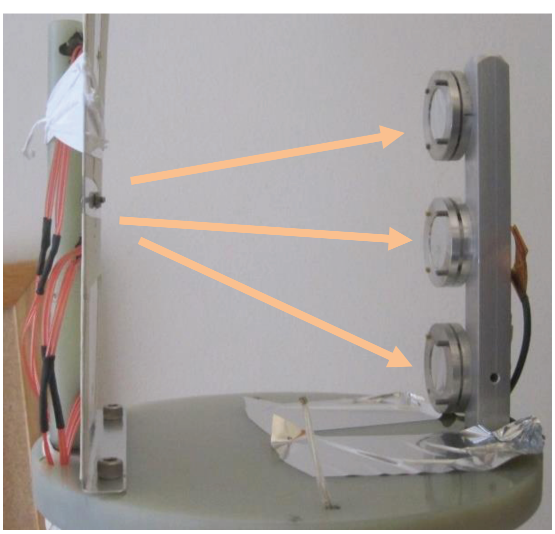

Figure 5: Experimental setup.

In Fig. 6 we see the propagation of the temperature wave launched by heater 1 through the 3 mm open hole and detected by OST-1 for two different pulse drives, top 50V and bottom 450V, pulse duration was 0.1msec for both cases.

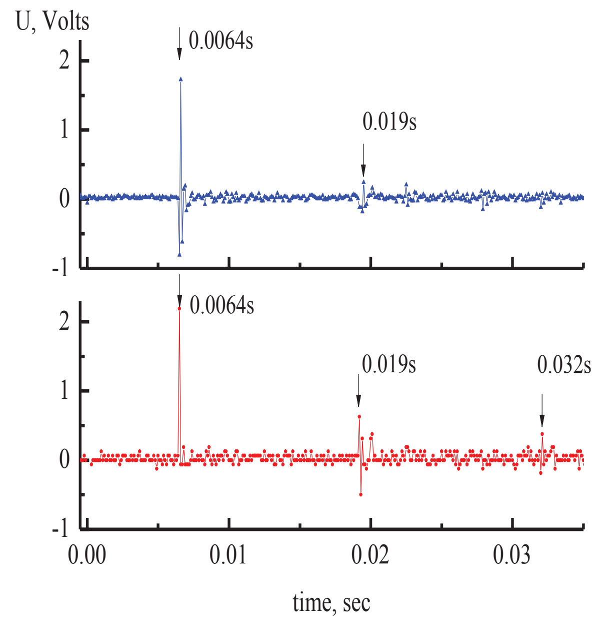

Figure 6: Propagation of second sound through a 3mm hole, excited by a square pulse in a 50-ohm heater with 0.1ms duration, 50V (top), and 450V (bottom) trace.

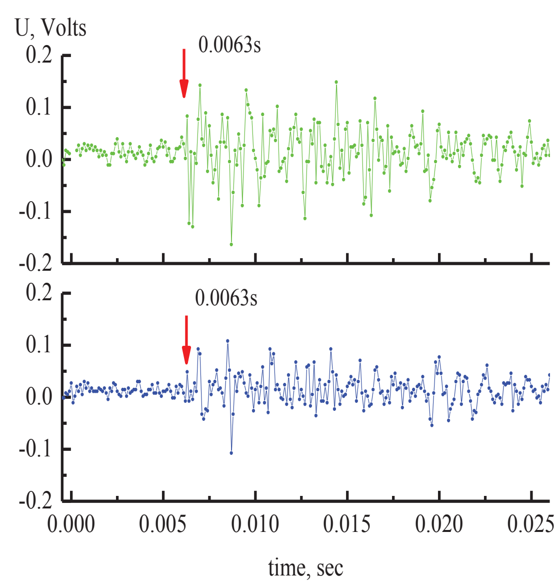

Figure 7: Propagation of second sound through 0.5mm aluminium plate at 450V drive top trace and 50V bottom trace.

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Time propagation of the first peak at 6.4 msec exactly corresponds to the geometrically shortest path (~ 12mm) from heater to OST, where the velocity of second sound at 1.65K is 20.36 m/sec.

We observed a number of reflections from walls of the Dewar and metal plate that roughly doubles the propagation path length, and could only the first reflection for 50V found and first and third for 450V.

Fig. 7 demonstrates the pattern of second sound waves detected from the heater mounted on the metal plate, where the heat must pass through the plate, changed drastically. The signal is significantly attenuated by the metal plate and becomes ten times smaller compared with the open geometry test. Another remarkable observation is the development of the shock wave front (indicated by red arrow) with the increasing of drive. At 50V the onset time is on the level of noise and the second pick could be identified as an arrival time. Currently, the research is under progress where a more comprehensive paper will be published elsewhere.

IMPROVEMENT OF KAPITZA CONDUCTIVITY

In order to increase the Kapitza conductivity, the surface area needs to be increased. There are several ways we propose that this can be done.

The most common way to increase surface area in low temperature physics is silver sinter. Powder sinters have large surface areas, in the range of couple square meters per gram, and are typically good candidates for efficient heat transfer improvement. The sound velocity in silver is also small compared to other metals: silver powders have a low sintering temperature ~ 250C.

In order to avoid any risk of bringing nanoparticles into the clean room environment we considered another way to increase the surface area, which appears more suitable for SRF research, by coating the outside of the cavity by nanoporous gold. Hieda et al [7], found that they could increase the surface area by around a factor of 40 of an object by coating it in a micrometer layer thick of nanoporous gold [7]. Using this same method, coating the outside of the SRF cavity with nanoporous gold could increase the surface area by a factor of 40 thereby improving the Q factor.

CONCLUSIONS

Following the Vines et.al. paper on the "Systematic Trends for the Medium Field Q-Slope" [8], the Kapitza conductivity plays a role in improving the Q factor when other physical parameters in an already prepared cavity - such as wall thickness, RF frequency, residual resistivity ratio, residual resistance, and phonon mean path cannot be changed. The Kapitza conductivity is directly proportional to surface area, so by increasing the surface area the cavity will be more able to remove heat from its walls into the helium bath. One way that looks feasible to increase the cavity's surface area by a factor of 40 is to coat the outside of the cavity with a layer of nanoporous gold which is harmless treatment for the cavity performance improvement. It should be even more important for single crystal niobium (111) where Kapitza resistance play dominating role in heat transport to helium bath [9]. Based on the experimental results, there is a need of future tests in order to better understand how second sound is reflected. In order to better model a hot spot in a cavity, an experiment with the heater inside a vacuum sealed cell and with both pure niobium and niobium covered by nanoporous gold is planned.

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