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TEMPERATURE DEPENDENT EFFECTS ON RF SURFACE RESISTIVITY

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Abstract

A promising future for linear accelerators such as compact free electron lasers and electron positron colliders is higher gradient RF cavities enabled by cryogenic temperature operation. Breakdown rates have been shown empirically to be significantly reduced at low temperatures allowing for higher gradient. The surface physics associated with this observation is complicated and there many remain questions as to the exact phenomena responsible. One major figure of merit that can better inform the theory of breakdown is the RF surface resistivity which can be used to compute for example the RF pulse heating during operation. We then use techniques developed for previous X-band and S-band low power surface resistivity measurement by way of temperature dependent quality factor measurements to study C-band cavities. We first present a review of low temperature effects that may be responsible for the change in surface resistivity at low temperature. We then explain some of the initial measurements of these low power RF quality factor tests and compare them to a review some of the physical phenomena that could determine the low temperature surface effects.

INTRODUCTION

We are entering a new regime of cryogenic radiofrequency (RF) cavity operation especially for the future UC-XFEL and cool copper collider concepts [1, 2]. It is thus in our best interest to review the potential effects of temperature dependence on certain RF properties. The main figure of merit which we use is the RF surface resistivity. It is often calculated as the real component of the complex impedance of a cavity with respect to the RF field. In the classic sense this becomes the following in the normal skin effect regime.

$$R_s = Re(Z_s) = \sqrt{\frac{\omega\mu_0\rho}{2}} \tag{1}$$

Anomalous Skin Effect

Divergence from this occurs at low temperatures where surface resistivity is significantly higher than would classically be expected. The most cited theory used to explain this anomalous skin effect regime was originally derived by Reuter and Sondheimer in the 1950s [3]. Since then a number of different forms have been used to calculate the effects [4, 5]. Limits are usually taken to extreme high temperature and extreme low temperature and then patched together to generate a useful piecewise form [6]. We can thus see that the Reuter and Sondheimer explanation for ASE is independent of the bulk resistivity in the low temperature limit and only a function of frequency of resonance at low temperature.

In order to obtain the full temperature dependence of the Reuter and Sondhiemer prediction we can use the simplest model for a temperature dependent resistivity: the Bloch-Gruneisen formulation given in integral form in Eq. 2. The simplest form uses $n = 5$ for a simple metal and a Debye temperature Θ_R that is independent of temperature.

$$\rho(T) = A\left(\frac{T}{\Theta_R}\right)^n \int_0^{\Theta_R/T} \frac{t^n}{(e^t-1)(1-e^{-t})} dt + C. \tag{2}$$

Putting this information all together we can calculate the surface resistivity by either rigorously computing the integrals in the initial Reuter and Sondheimer form or using the patching functions. To emulate a non ideal metal, a constant can be added to Eq. 2 to match experimental measurements in order to denote the nonzero residual resistivity ratio (RRR) found at low temperatures. We can can plot these calculations in Figure 1.

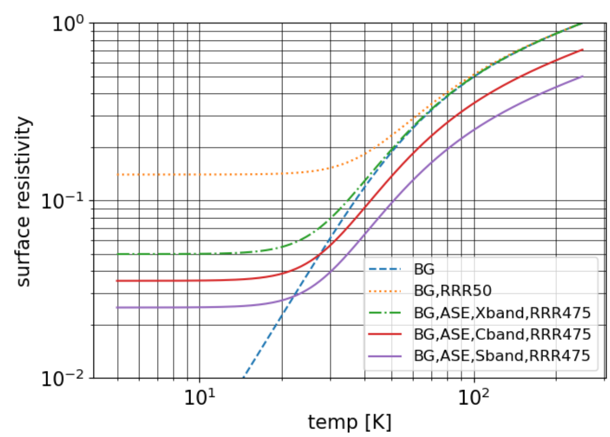

Figure 1: Chou formulation [6] of equation patching used to calculate surface resistivity from Reuter and Sondheimer using Bloch-Gruneisen temperature dependent bulk resistivity.

We can note several features of this formulation of ASE, in particular the main deficiency is that it does not replicate the local minimum empirically observed in certain surface resistivity measurements [7, 8].

BULK RESISTIVITY IMPROVEMENTS

In order to more fully understand the low temperature regime we first consider modifications and or improvements to the bulk resistivity. With respect to the forms often used there are some modifications that can be made.

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In addition to the simplest model of bulk resistivity we can use possible alternatives to a usual Bloch-Gruneisen understanding. The first and most notable is that the numerical factor n is limited to 5 for simple metals. We note that for transition metals such as copper and for the thin films the value is more correctly $n = 4$ [9]. This is especially relevant for our modifications to Reuter & Sondheimer theory as detailed in the next section.

In Fig. 2, instead of using Bloch-Gruneisen, we plot the bulk resistivity using the NIST monogram data [10]. In addition, we plot the electrical conductivity obtained from using Wiedemann–Franz law law scaling of thermal conductivity measurements. We can see that in the case of NIST published monograms, minimal change is seen with respect to our initial ASE calculations. The intermediate temperature deviation in the Wiedemann–Franz law calculations appears due to the scaling laws breakdown at intermediate temperatures. Both modifications fail to predict the minimum surface resistivity.

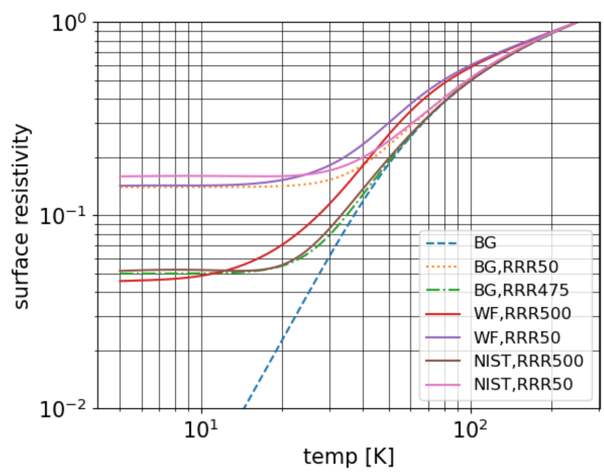

Figure 2: Calculations of surface resistivity using Reuter & Sondheimer theory with Bloch-Gruneisen resistivity for multiple RRR values and frequencies, normalized to room temperature X-band.

Kondo Effect

There are additional magnetic effects that can considered as well, namely the Kondo effect. We are however satisfied to ignore these effects at least temporarily as the previous experimental setups used cavities with minimal magnetic fields so we do not expect to see these effects.

BEYOND REUTER & SONDHEIMER

Moving on from modifications to bulk resistivity modifications we instead consider a more nuanced application of RF resistivity using the skin depth found as

$$\delta = \sqrt{\frac{2\rho}{\mu_0\omega}}. \tag{3}$$

Thin Film Explanation

In many cases, it is justifiable to consider one skin depth to function effectively as a thin film of equivalent depth [11]. As a result, we can calculate a bulk resistivity modification similar to that derived by the later Fuchs and Sondheimer [12]. We thus obtain a stronger bulk resistivity dependence in the surface resistivity through the dependence on skin depth. Here we consider several such modified for the thin film case. Similar considerations have been made elsewhere [13, 14].

Our insight here becomes using the thin film resistivity in place of the bulk resistivity used in earlier Reuter and Sondheimer style calculations. In Eq. 5, we have generated an expression of the same form as Fuchs and Sondheimer. The parameter p_s is of order unity and is a measurement of the amount of specular surface scattering.

$$\rho = \rho_b \left[1 - \frac{3}{2k}(1-p)\int_1^\infty \left(\frac{1}{t^3} - \frac{1}{t^5}\right)\frac{1-e^{-kt}}{1-pe^{-kt}}dt\right]^{-1} \tag{4}$$

where $k = \frac{\delta}{\ell}$. Taking a number of simplification we can write this as the following

$$\rho_{film} = \rho_{bulk}\left[1 + \frac{3}{8}(1-p_s)\frac{\ell_{bulk}}{\delta}\right]. \tag{5}$$

Which gives

$$\rho = \rho_b\left[1 - \frac{3\ell}{2\delta}\right]^{-1}. \tag{6}$$

We treat the RF skin depth as our thin width and obtain an effective thin film resistance which can be written in terms of a temperature dependent bulk Bloch Gruneisen resistance as follows

$$\rho \to \rho_b\left[1 - \frac{3\ell}{2}\sqrt{\frac{\mu_0\omega}{2\rho}}\right]^{-1}. \tag{7}$$

We note that the resistivity is unchanged in the limit

$$\delta \gg \ell.$$

We can use mean free path lengths calculated simply from room temperature and skin depths from the value scaled to temperature to obtain the calculations shown in Figure 3.

There are certain features which we can note here. First, using a realistic room temperature mean free path length for electrons in metal of 39 nm we can see how increasing the RRR value monotonically lowers the cryogenic surface resistivity up until the mean free path length is allowed to be larger than the skin depth leading to the formation of a minimum around 30 K, consistent with previous empirical data. In addition, we can see that artificially shrinking the mean free path length of high purity copper at room temperature to 10 nm means that skin depth remains larger than the mean free path length down to low temperatures and we recover our ASE results.

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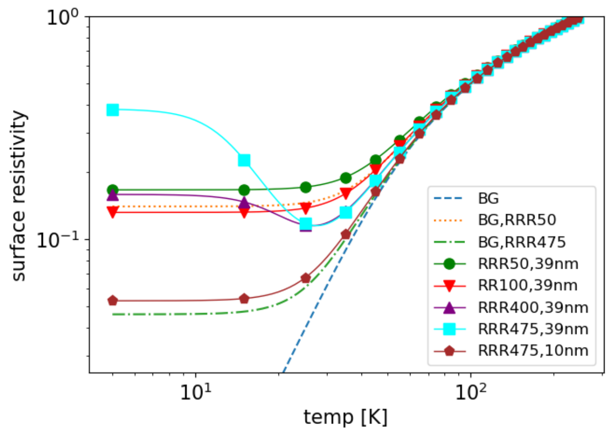

Figure 3: Comparison between calculations of new thin film surface resistivity theory with calculations using Reuter & Sondheimer with Bloch-Gruneisen resistivity. Note the minimum which appears for high purity, RRR, copper.

Viscous Electron Flow

Viewing the problem of the surface resistivity as a thin film problem with the skin depth acting as an effective sample width means that we can start to consider RF cavities at cryogenic temperatures as a potentially a novel test bed for observation of one dimensional surface physics. Specifically, here we are motivated by the possibility that we are observing viscous electron flow. Indeed, Gurzhi theory predicts a minimum in surface resistivity and has worked out the skin depth problem as a thin film using hydrodynamic methods [11, 15].

EXPERIMENTAL REALIZATION

We are currently midway through an extensive study of low level RF tests using pillbox cavities [16]. However, since we predict the surface resistivity to be dependent on the bulk resistivity even in the cryogenic limit, we can also propose a different method to measure the anomalous increase. We intend to do this by measuring the balancing of average RF heating of a new 1/2-cell test cavity we have produced. We should be able to measure the changes in cavity gradient from Reuter and Sondheimer theory as shown in the simulations in Figure 4. We also refer to a number of simulation workflows developed for RF heating [8, 17].

CONCLUSION & FUTURE DIRECTIONS

We have reviewed relevant possible explanations and alternative resistivity explanations. Our goal to identify the reason for an empirical local minimum in surface resistivity has led us to consider treating cryogenic normal conducting RF cavities as thin films. We also find an implied optimum working point that is advantageously at a more manageable temperature than previous working points of 27 K. Instead, this new point would be around 35 K. We further have proposed an experimental realization of the phenomena as a working point in our phased development of a cryogenic

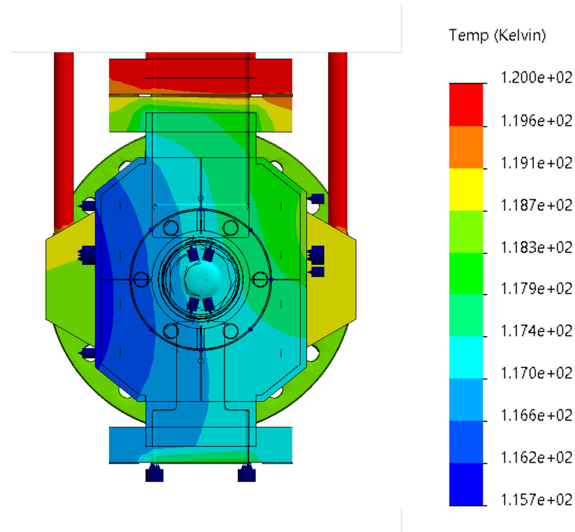

Figure 4: Averaged heating from RF pulsing of new $\frac{1}{2}$ cell photogun. Based on expected dependence of bulk resistivity we expect to be able to observe the resistivity minimum.

photocathode test bed at UCLA [18]. We can thus conceive of normal conducting RF cavities as possible novel test beds for observation of viscous electron flow. Future directions will also compare the thin film calculations more quantitatively with Gurzhi theory and also modify the BG resistivity predictions to account for the reality of observed thermophysical behavior.

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