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A PARAMETRIC STUDY OF BCS RF SURFACE IMPEDANCE WITH MAGNETIC FIELD USING THE XIAO CODE *

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Abstract

A recent new analysis of field-dependent BCS rf surface impedance based on moving Cooper pairs has been presented.[1] Using this analysis coded in Mathematica™, survey calculations have been completed which examine the sensitivities of this surface impedance to variation of the BCS material parameters and temperature. The results present a refined description of the "best theoretical" performance available to potential applications with corresponding materials.

INTRODUCTION

The radiofrequency (RF) surface impedance of a superconductor may be considered a consequence of the inertia of the Cooper pairs in the superconductor. The resulting incomplete shielding of RF field allows the superconductor to store RF energy inside its surface, which may be described as surface reactance. The RF field that enters the superconductor interacts with quasi-particles, causing power dissipation, represented by surface resistance. Based on the BCS theory [2] and anomalous skin effect theory [3], a derivation of a superconductor's surface impedance was developed by Mattis and Bardeen [3, 4]. Mattis-Bardeen theory, however, does not consider the field dependence of surface impedance. In particular, its real part, surface resistance, which is of great interest in superconducting radiofrequency (SRF) applications, is unaddressed. Several models have been previously proposed to address this issue. [5, 6]

Recently a new model has been put forward by Xiao *et al*., [1]starting from the BCS theory with a net current in a superconductor, the electron states distribution at 0 K were calculated, together with the probability of electron occupation with finite temperature and applied to anomalous skin effect theory, to obtain a new form of RF field dependence of the surface impedance of a superconductor. A Mathematica™ program has been developed by Xiao to accomplish the calculation of the resulting challenging quadruple integral. It is applicable to any standard superconductor described by BCS theory. The code reproduces the standard Mattis-Bardeen theory result at zero field as calculated, for example, by the commonly used Halbritter code, SRIMP. [7]

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A rather surprising result of the calculation with potential importance to SRF applications is the prediction of non-linear, *decreasing* surface resistance in an RF field regime that is prime domain for accelerator applications. The corresponding prediction of *increasing* Q_0 with field matches remarkably well recent reports of record-breaking low losses [8, 9] and raises the prospect that the common expectation of "best theoretical" cryogenic performance from Nb, and in principle other BCS superconductors, may be dramatically revised for the better.

We have used this code to perform a parametric sensitivity survey with each the characteristic BCS material parameters of the field-dependent RF surface impedance in hopes of supporting increased insight into a performance optimization strategy.

STANDARD CONDITIONS

The present analysis focused on niobium, using the following characteristic parameters as standard conditions: $\Delta_0/kT_c(0) = 1.85$, $T_c(0) = 9.25$ K, $\xi_0 = 40$ nm, $\lambda_L(0) = 32$ nm, and mean free path $\imath$ = 50 nm [10] exploring the predicted surface impedance with departures from these values.

The calculated standard condition surface impedance of niobium at 1.5 GHz and 2.0 K is shown as a function of Cooper pair velocity in Figure 1.

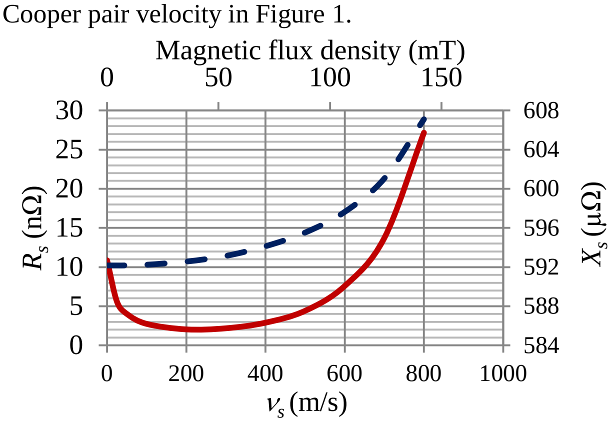

FIG. 1. Surface resistance, R_s, (red line) and reactance, X_s, (blue dashed line) versus Cooper pair velocity for Nb at 2 K and 1.5 GHz.

The surface resistance R_s, with a value of 10.9 nΩ at 0 m/s cooper pair velocity v_s, first decreases with increasing v_s, then increases with increasing v_s, with a minimum R_s of 2.0 nΩ at 230 m/s v_s. Since the supercurrent density varies both with depth into the surface and time, the local surface impedance does as well, so calculation of effective surface impedance must integrate over material depth and RF cycle. See reference [1] for discussion of simplifying assumptions that are made in the analysis.

The resulting effective surface impedance under the standard conditions is shown in Figure 2, together with the result of similar calculations at 0.7 and 1.3 GHz.

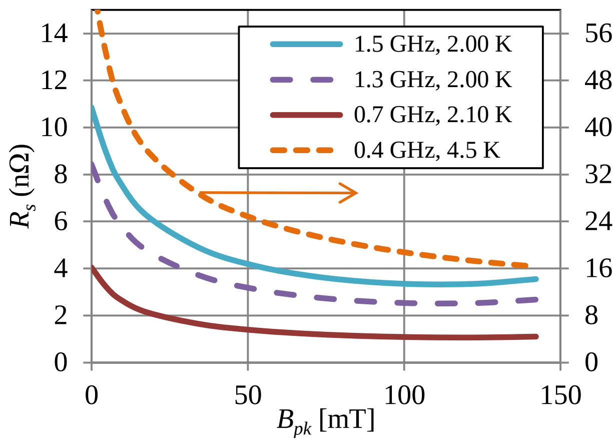

FIG. 2. Calculated effective surface resistance under "standard conditions" for Nb versus peak RF magnetic field for 1.5 and 1.3 GHz at 2.0 K, 0.7 GHz at 2.1 K, and 0.4 GHz at 4.5 K.

PARAMETER SURVEY

In order to potentially use the field dependence of the surface resistance to gain insight into potential changes of the superconducting material parameters, we have undertaken a calculation parametric survey to assess the sensitivity of the derived effective RF R_s to variation from our "standard parameter" set. For all conditions considered here, T_c is treated as fixed at 9.25 K.

Calculated R_s for Nb vs. peak rf magnetic field for several temperatures between 1.5 and 2.3 K are presented in Figure 3.

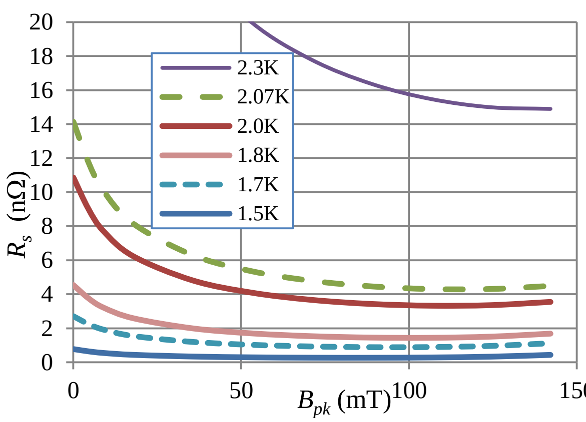

FIG. 3. Effective 1.5 GHz surface resistance of standard Nb material parameters at various temperatures of interest.

The derived field dependence of R_s at 2.0K with variations around coherence length and London penetration depth values of ξ_0 = 40 nm and $\lambda_L(0)$ = 32 nm are presented in FIG. 4 and FIG. 5, respectively. Note that R_s decreases slightly more quickly with higher ξ_0, but rather is insensitive to ξ_0 in the B_{pk} = 100–120 mT range, while monotonically decreasing with lower λ_L.

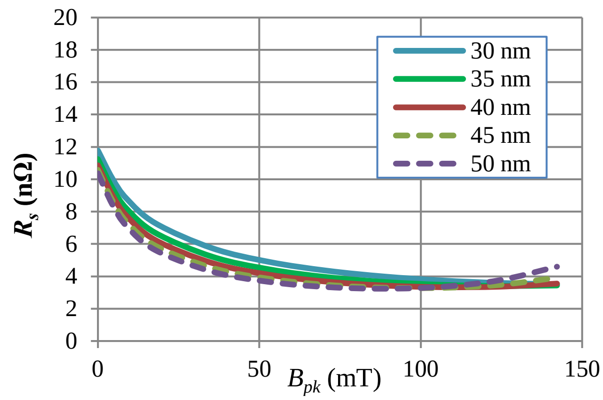

FIG. 4. Effective 1.5 GHz surface resistance of Nb at 2.0 K with variations of coherence length ξ_0.

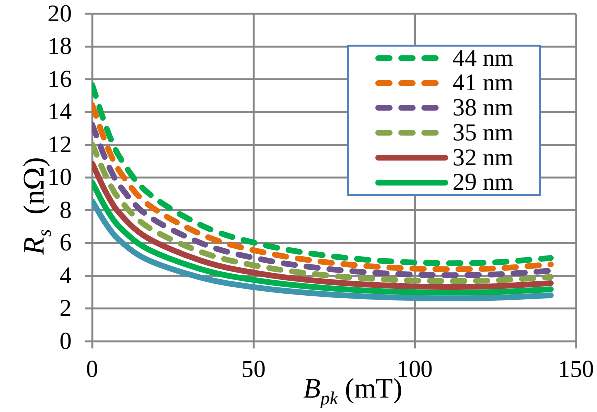

FIG. 5. Effective 1.5 GHz surface resistance of Nb at 2.0 K with variations of London penetration depth λ_L.

Sensitivity of R_s field dependence with electron mean free path, ι, is more complex, with a clear minimum of both absolute and field-dependent components observed between 25 and 50 nm, where ι is comparable to ξ_0, as may be observed from Figure 6. This is consistent with data reported from previous experimental studies.[11]

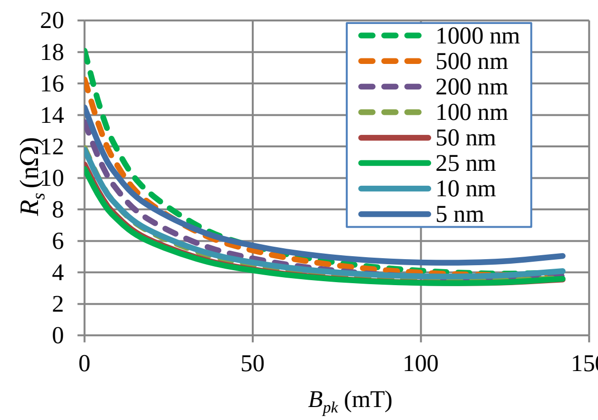

FIG. 6. Effective 1.5 GHz surface resistance of Nb at 2.0 K with variations of electron mean free path.

Variation of the BCS gap energy, as illustrated in Figure 7, yields a decrease in R_s with increasing gap, as expected, but fractional R_s change with field shows no additional structure.

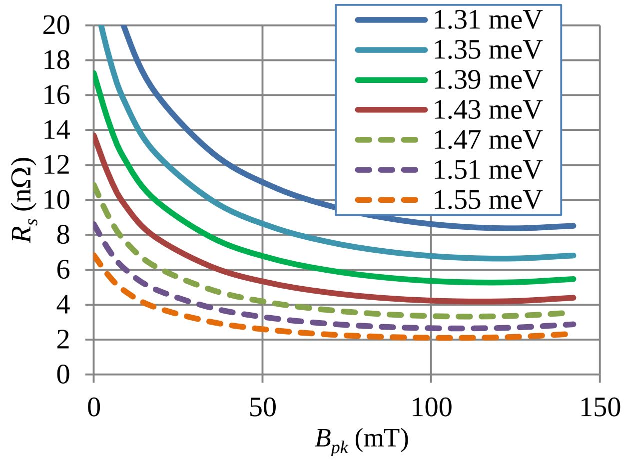

FIG. 7. Effective 1.5 GHz surface resistance of Nb at 2.0 K with variations of the BCS energy gap, Δ_0.

COMPARISON WITH RECENT DATA

Recent investigations into Nb material treatment processes which yield higher Q_0 of SRF accelerating cavities have begun to produce results which show increasing Q with field well beyond the range of the familiar, but enigmatic, "low-field Q slope."[8, 9] Seeking to evaluate the relevance of the present theory to this experimental phenomenon, we plot in Figure 8 the standard parameter calculation from Figure 2 together with the published data for three cavities, one large-grain and two fine-grain niobium, after subtracting a field-independent 1.7 nOhm from the LG cavity and 3.0 nOhm from the FG experimental data.

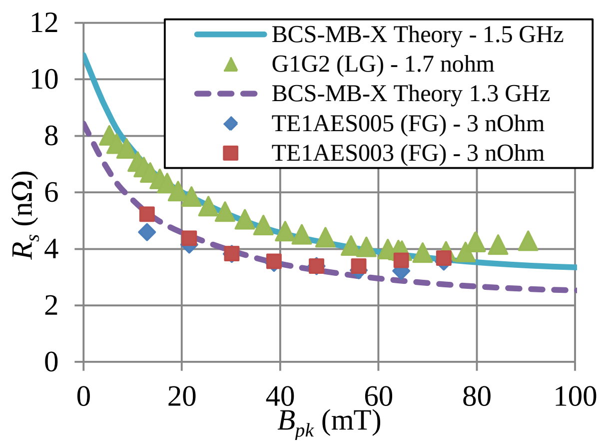

FIG. 8. Field-dependent BCS surface resistance at 2.0 K, calculated by Xiao's code and recent very low loss cavity test data from JLab at 1.5 GHz [8]and FNAL at 1.3 GHz [9] prepared by different methods.

DISCUSSION

The correspondence of the RF amplitude dependence of recent "high Q" cavity data to the predictions of the Xiao extension of Mattis-Bardeen theory of SRF surface impedance is striking. Significant further study is needed to examine experimentally the temperature dependence of the loss mechanisms present to further test the theoretical predictions. That agreement is obtained with subtraction of only small field-independent, and perhaps residual, resistance suggests that the unusual performance is due to the inhibition of common parasitic loss mechanisms rather than the creation of unusual enhancements. The basic phenomenology appears with both fine-grain and large-grain niobium.

Since the theory, albeit with its approximations, is a treatment of an "ideal" BCS superconductor, one may perhaps interpret the observed increasing Q as the way "good" niobium should be expected to perform absent any parasitic effects. If this is the case, then the implication is that the "normal" niobium to which the community is presently accustomed is actually "polluted" in some way, at least within the RF penetration depth, in a way which contributes very common, but modest, additional losses.

Clarification of such a mechanism and the engineering of processes to avoid it would seem to be quite worthy undertakings. Success at this would enable very significant improvements in the economy of SRF-based accelerator construction and operation. The cost optimization of cryoplant capital and operating expenses together with accelerator systems might change considerably if these theoretical predictions and recent low loss data can be generalized.

Further ahead, since the theory is general to BCS superconductors, one might look for further cryogenic cost benefits from the use of higher-T_c materials.

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