Study on the Superconducting Radio-frequency Performance of the Copper-Niobium Composite Cavities Based on a Heat Transfer Computational Model

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Abstract

Thermal stability is a significant indicator for evaluating the long-term operational reliability of superconducting radio-frequency (SRF) cavities. Theoretically, the copper-niobium (Cu-Nb) composite cavity has the potential for high mechanical and thermal stability by combining the exceptional mechanical rigidity and thermal conductivity of the thick Cu layer with the excellent SRF performance of the Nb layer. However, the existence of the Cu-Nb bimetal structure as the cavity wall complicates the heat transfer process compared to that of bulk niobium cavities. Further understanding of the influence of physical property parameters on the thermal transfer efficiency is essential for high-quality application of the Cu-Nb composite cavity. In this paper, we proposed a comprehensive heat transfer computational model for analyzing the RF performance of the Cu-Nb composite cavities, incorporating key parameters including the measured copper-niobium thermal boundary resistance (2-4$\times10^{-5}$ $m^2 \cdot K/W$). The model was applied to three types of cavities to investigate the effect of the material layer thickness, the thermal conductivity of Cu, and the hot island diameter on the RF performance of the Cu-Nb composite cavities at 4.2 K and 2 K. Moreover, the model was used to analyze the RF test data of a Cu-Nb composite half-wave resonator with an optimal β value of 0.3 (labeled as the HWR030 Cu-Nb composite cavity) at 4.2 K and 2 K. The simulation results indicate that the defects may be the primary cause of performance degradation of the HWR030 cavity. Finally, the dynamic process simulations of hot island on the RF surface of the cavity were conducted, revealing the expansion behavior and the size limit of the hot island, providing insights into performance degradation of the SRF cavities compared to their theoretical performance limit. The proposed heat transfer model can guide the design of the Cu-Nb composite cavities and help to understand the underlying mechanism of cavity performance degradation.

Full Text

Preamble

Study on the superconducting radio-frequency performance of the copper-niobium composite cavities based on a heat transfer computational model∗

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Thermal stability represents a critical indicator for evaluating the long-term operational reliability of superconducting radio-frequency (SRF) cavities. Theoretically, copper-niobium (Cu-Nb) composite cavities offer enhanced mechanical and thermal stability by combining the exceptional mechanical rigidity and thermal conductivity of a thick copper layer with the excellent SRF performance of a niobium layer. However, the bimetallic cavity wall structure complicates heat transfer compared to bulk niobium cavities. A deeper understanding of how physical property parameters influence thermal transfer efficiency is essential for high-quality application of Cu-Nb composite cavities. This paper proposes a comprehensive heat transfer computational model for analyzing the RF performance of Cu-Nb composite cavities, incorporating key parameters including the measured copper-niobium thermal boundary resistance ($2-4\times10^{-5}$ $m^2\cdot K/W$). The model was applied to three cavity types to investigate the effects of material layer thickness, copper thermal conductivity, and hot island diameter on RF performance at 4.2 K and 2 K. Additionally, the model was used to analyze RF test data from a Cu-Nb composite half-wave resonator with an optimal β value of 0.3 (designated as the HWR030 Cu-Nb composite cavity) at both temperatures. Simulation results indicate that defects may be the primary cause of performance degradation in the HWR030 cavity. Finally, dynamic process simulations of hot islands on the cavity RF surface were conducted, revealing expansion behavior and size limits that provide insights into performance degradation relative to theoretical limits. The proposed heat transfer model can guide Cu-Nb composite cavity design and help understand the underlying mechanisms of cavity performance degradation.

Keywords: Superconducting radio-frequency cavities, copper-niobium composite, heat transfer analysis, hot island

INTRODUCTION

Superconducting radio-frequency (SRF) cavities operating at 4.2 K or 2 K are widely used in modern particle accelerators due to their low RF loss and larger beam aperture compared to normal-conducting RF cavities [?]. Cavity performance is primarily characterized by the maximum accelerating field, E_{acc}, the unloaded quality factor, $Q_0 = \omega U / P_{loss}$, and operational stability, where U represents the stored energy of the cavity and P_{loss}/ω denotes the power dissipation per RF cycle on the cavity’ s inner wall [?]. Currently, SRF cavities are mainly fabricated from bulk Nb, but their performance is often limited by thermal breakdown at high fields \cite{2-5}. Consequently, alternatives such as copper-niobium (Cu-Nb) structures have been explored for enhanced heat dissipation. Theoretically, Cu-Nb cavities improve thermal and mechanical stability by combining the excellent SRF performance of the Nb layer with the thick Cu layer’ s high mechanical rigidity and thermal conductivity. Cu-Nb cavities are primarily classified into Nb thin-film coated Cu cavities and Cu-Nb composite cavities. The thin-film coated variety, produced by sputtering technology in several laboratories \cite{6-8}, can exhibit much higher Q_0 values than bulk Nb cavities due to lower Bardeen-Cooper-Schrieffer (BCS) surface resistance and reduced sensitivity to residual magnetic fields [?]. However, prepared Nb films typically contain more defects than bulk Nb, and most cavities suffer from poor heat transfer performance due to inadequate Cu-Nb bonding at high fields [?]. Consequently, Nb thin-film coated Cu cavities produced with current technology still exhibit a considerable RF performance gap compared to bulk Nb cavities. By replacing the niobium film with a bulk niobium layer in Cu-Nb composite cavities, surface defect issues inherent to films can be avoided while enabling application of advanced surface treatment techniques originally developed for pure niobium cavities. Although Cu-Nb composite cavities have been investigated in several laboratories \cite{11-14}, no comprehensive analysis or understanding of the heat transfer mechanism currently exists.

The presence of a Cu layer in Cu-Nb cavities complicates heat transfer between the RF surface and liquid helium (LHe). In addition to the thermal resistance of the Cu layer, extra thermal resistance arises at the Cu-Nb interface due to phonon mismatch originating from differences in phonon mean free paths between Nb and Cu. Therefore, the complex heat transfer system in Cu-Nb composite cavities involves Nb, the Nb-Cu interface, Cu, and He, rather than the simpler Nb-He system of bulk Nb cavities. The Q-slope observed in Nb thin-film coated Cu cavities has been explained by heat accumulation with increasing field due to Cu-Nb thermal boundary resistance [?], though this explanation may be insufficient given effective bonding between Cu and Nb achieved through new techniques [?]. In our previous work, we proposed a Cu-Nb composite scheme based on electroplating technology (Nb-intermediate layer-electroplated thick Cu), where an Ag interlayer was placed between Nb and Cu and then annealed to enable mutual diffusion and effective bonding at the Cu-Ag-Nb interfaces [**?**]. Using this approach, we successfully fabricated a Cu-Nb composite half-wave resonator with an optimal β of 0.3 (designated as the HWR030 Cu-Nb composite cavity). Cryogenic tests were performed, and the cavities finally quenched without field emission—a phenomenon requiring further theoretical analysis to better understand the underlying quench mechanisms.

II. THEORY AND METHODS

A. RF Loss Mechanism and Heat Transfer in Cu-Nb Composite Cavities

The RF loss of a Cu-Nb composite cavity can be derived from Maxwell' s equations as follows [**?**]:

$$P_{loss} = \int_S |H_{RF}|^2 R_s \, ds$$

where H_{RF} is the magnetic field intensity on the cavity' s inner surface and R_s is the average surface resistance [**?**]. In this paper, we established a comprehensive heat transfer computational model utilizing the Finite Element Analysis (FEA) method. This model considers the temperature response of the material's critical magnetic field, the thermal feedback mechanism of the cavity wall, and hot islands distributed on the cavity' s inner surface. The computational model was applied to three cavity types to investigate the impact of material layer thickness, copper thermal conductivity, and hot island size on the RF performance of Cu-Nb composite cavities.

Through systematic analysis of these parameters, we further investigated the performance degradation of the HWR030 Cu-Nb cavity, indicating that defects may play a significant role. Finally, the model successfully explained the performance degradation process through hot island area expansion. It was found that a hot island region reduces the critical magnetic field of the surrounding superconducting region, causing the surrounding area to transition to a normal-conducting state. The hot island region then incorporates this newly formed normal-conducting zone, creating an expanded hot island region and ultimately degrading the cavity' s RF performance.

The total RF loss during operation arises not solely from the intrinsic surface resistance (R_{so}) but also from three dominant contributions: (1) intrinsic surface resistance without RF field effects (R_{so}), (2) defect-induced RF loss, and (3) field emission (FE) associated dissipation. The intrinsic surface resistance can be decomposed into BCS resistance and residual resistance. The BCS resistance is primarily generated by the interaction between the RF field and thermally activated electrons in a superconductor [**?**]. When $T \ll T_c$, the BCS resistance simplifies to:

$$R_{BCS}(T,f) = 4\pi^2 A f^2 \left(\frac{\Delta}{k_B T}\right)^2 \exp\left(-\frac{\Delta}{k_B T}\right)$$

where Δ represents the energy gap, $\omega = 2\pi f$ denotes the angular frequency of the cavity, k_B stands for the Boltzmann constant, T indicates the temperature of the cavity' s inner surface, R_{res} signifies the residual resistance, and A is a constant that depends on f, Δ, the penetration depth λ, and the coherence length ξ. Therefore, the RF surface intrinsic resistance can be expressed as:

$$R_{so}(T,f) = 4\pi^2 A f^2 \left(\frac{\Delta}{k_B T}\right)^2 \exp\left(-\frac{\Delta}{k_B T}\right) + R_{res}$$

Calculations can generally be performed using the empirical formula:

$$R_{so}(T,f) = 2 \times 10^{-4} \left(\frac{f}{1.5}\right)^2 \left(\frac{\Delta}{k_B T}\right)^2 \exp\left(-\frac{\Delta}{k_B T}\right) + R_{res}$$

Defects and field emission, originating from material impurities and localized geometry variations on the cavity' s inner surface (pits or bumps), generate much higher RF loss density compared to the surrounding surface, forming hot islands (or hot spots) [?, ?]. In general, the total RF loss of the Cu-Nb cavity can be expressed as:

$$P_{loss} = \int_S R_{so} H_{RF}^2 \, ds + P_{Defect} + P_{FE}$$

This total RF loss constitutes the fundamental heat source at the inner surface, with the deposited energy subsequently participating in the cryogenic heat transfer process.

Three factors affect cavity heat transfer: (1) thermal conductivity of the cavity material, (2) thickness of the cavity material, and (3) thermal resistance at interfaces between different materials. Remarkably, the thermal feedback mechanism plays a significant role in this process. Thermal feedback is the dynamic process by which the temperature distribution within the cavity wall continuously adjusts as it moves toward thermal equilibrium, affecting important elements of the heat transfer process (such as material thermal conductivity) and influencing overall results.

Material thermal conductivity is particularly crucial when thermal feedback is present. As shown in [Figure 2: see original paper], the thermal conductivity of high-purity Nb (residual resistivity ratio RRR 300) increases by about six times from 2 to 4.2 K (from 10 W/(m · K) to 60 W/(m · K)) [?], while the thermal conductivity of Cu (electroplated Cu) increases by about 1.5 times (from 200 W/(m · K) to 300 W/(m · K)) [?]. Therefore, simulations that fail to account for the thermal feedback mechanism are inaccurate, as heat transfer capability is enhanced by increased thermal conductivity.

The problem becomes more complex regarding thermal resistance at material interfaces, referred to as thermal boundary resistance. The Cu-Nb cavity contains an Nb-Cu-He heat transfer system, while the Nb cavity only has an Nb-He system. Partial substitution of Nb with Cu theoretically improves cavity heat transfer performance due to copper's high thermal conductivity, but it generates thermal boundary resistance between Nb and Cu that correlates with bonding quality [?]. Additionally, the cavity' s outer surface immersed in LHe exhibits Cu-He thermal boundary resistance that depends on the LHe state. At 4.2 K, LHe is in the He-I state. [Figure 3: see original paper] illustrates the three states through which LHe on the cavity' s outer surface passes as temperature increases: convection cooling, nucleate boiling, and film boiling [?]. The cavity' s outer surface temperature significantly influences Cu-He thermal boundary resistance depending on the LHe state. At 2 K, LHe transitions from He-I to He-II, entering the superfluid state, which greatly enhances LHe heat transfer capability. The Cu-He thermal boundary resistance remains approximately constant at 2–4 × 10^{-4} $m^2 \cdot K/W$ \cite{27-29}. In summary, cavity performance is influenced by a closed-loop electro-thermal feedback mechanism.

B. Establishment of the Heat Transfer Computational Model

Based on the heat transfer mechanism of Cu-Nb cavities, we proposed a dual-component computational model: (i) a two-dimensional (2D) plate model for maximum peak magnetic flux density ($B_{peak,max}$) prediction, and (ii) a three-dimensional (3D) cavity model for evaluation of the unloaded quality factor Q_0. The 2D model uses a 100 mm × 100 mm × h mm plate (where h denotes cavity wall thickness), reducing computational costs and minimizing boundary effects. The upper surface represents the equivalent LHe (or cold head) boundary, and the lower surface corresponds to the RF surface. A 100 µm diameter circular zone at the center of the lower surface investigates hot island effects. Due to the highly non-uniform surface magnetic field in low-β cavities and the need to calculate Q_0, a uniform input magnetic field intensity is applied as a boundary heat source. This approach focuses on calculating the maximum magnetic field (or accelerating gradient) while considering limiting cases (such as worst-case thermal load scenarios). Computational efficiency is improved by using uniform input magnetic field intensity without sacrificing accuracy due to the small model size.

Under these conditions, the steady-state heat conduction equation can be expressed as:

$$\nabla \cdot (\kappa \nabla T) + R_s(T(x,y), f) H_{peak}^2 \, ds = 0$$

where T is temperature and κ is the effective thermal conductivity combining Cu and Nb conductivities, Cu-Nb thermal boundary resistance, and Cu-He thermal boundary resistance:

$$\kappa_{eff} = \frac{d_{total}}{\frac{d_{Cu}}{\kappa_{Cu}} + R_{Cu/Nb} + \frac{d_{Nb}}{\kappa_{Nb}} + R_{Cu/He}}$$

where d_{total}, d_{Nb}, and d_{Cu} denote total wall thickness, Nb layer thickness, and Cu layer thickness, respectively. The surface resistance $R_s(T(x,y),f)$ exhibits spatial dependence and is modulated by the temperature-dependent superheating field ($B_{sh}(T=0\,\mathrm{K}) = 240$ mT [?]), governing the critical magnetic flux density as:

$$B_{lim}(T) = B_{sh}(T=0\,\mathrm{K})\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

Consequently, the surface resistance can be expressed as:

$$R_s = R_s(T(x,y),f) = \begin{cases} 2\times 10^{-4}\left(\frac{f}{1.5}\right)^2\left(\frac{\Delta}{k_B T(x,y)}\right)^2 \exp\left(-\frac{\Delta}{k_B T(x,y)}\right) + R_{res}, & B_{RF} \le B_{lim}(T) \\ \infty, & B_{RF} > B_{lim}(T) \end{cases}$$

The temperature distribution is iteratively fed back into the surface resistance $R_s(T(x,y),f)$ and critical magnetic flux density $B_{lim}(T)$ before reaching thermal equilibrium (with relative convergence tolerance ≤ 0.001), yielding a stable solution. Since B_{peak}/E_{acc} remains constant in Cu-Nb cavities, the input magnetic flux density can be adjusted to solve for steady-state temperature distribution under different accelerating gradients [?]:

$$B_{peak} = \lambda_{acc}E_{acc}$$

In the 3D cavity model, we first compute eigenmodes using the electromagnetic module, where electromagnetic field equations can be expressed as:

$$\nabla\times\mu^{-1}(\nabla\times E) - k_0^2\epsilon E = 0$$

where $E = E(x,y,z)e^{i\omega t}$ represents electric field intensity, μ and ϵ denote relative permeability and permittivity, respectively, and $k_0 = \omega/c$ corresponds to the free-space wavenumber. The boundary condition at the cavity' s inner surface accounts for RF loss:

$$\mathbf{n}\times E = (R_s + i\mu_0\omega\lambda_L)H_{tan}$$

where $\mathbf{n}$ is the unit normal vector, R_s denotes surface resistance, λ_L (40 nm) represents the London penetration depth, and H_{tan} is the tangential magnetic field intensity. The RF loss power density distribution $P_s = \frac{1}{2}R_s|H|^2$ on the inner surface is derived from the electromagnetic field distribution and introduced as a heat source in the heat transfer module. As in the 2D model, surface resistance depends on spatial position and is influenced by the superconductor' s critical magnetic field:

$$R_s = R_s(T(x,y,z),f) = \begin{cases} 2\times 10^{-4}\left(\frac{f}{1.5}\right)^2\left(\frac{\Delta}{k_B T(x,y,z)}\right)^2\exp\left(-\frac{\Delta}{k_B T(x,y,z)}\right) + R_{res}, & B_{RF} \leq B_{lim}(T) \\ \infty, & B_{RF} > B_{lim}(T) \end{cases}$$

Under these conditions, the steady-state heat conduction equation becomes:

$$\nabla\cdot(\kappa\nabla T) + R_s(T(x,y,z),f)|H_{RF}|^2\,dV = 0$$

Consistent with the 2D plate model, the obtained temperature distribution is iteratively fed back into $R_s(T(x,y,z),f)$ and $B_{lim}(T)$ until thermal equilibrium is achieved (relative convergence tolerance ≤ 0.001). To compute steady-state temperature distribution under different fields, a proportional factor is introduced:

$$U_{tar} = \alpha U_{ini}$$

where U_{tar} and U_{ini} denote stored energy of the target field and initial field, respectively. The initial stored energy U_{ini} is computed from the cavity model. Since stored energy U relates to accelerating gradient E_{acc} by $E_{acc} = \gamma_{acc}\sqrt{U_{tar}}$, the target stored energy can be calculated accordingly [?].

In computational setup for hot islands, these regions are treated as normal-conducting domains using the formulations specified above. Since cavity wall thickness influences RF performance, we varied wall thickness while refining the mesh to maintain at least five elements along the normal direction for each configuration. The hot island region mesh was further refined to ensure at least 20 elements for improved resolution.

2. Parameters Setup

The parameters considered include material thermal conductivity (for Cu, κ_{Cu}, and Nb, κ_{Nb}), Cu-Nb thermal boundary resistance ($R_{Nb/Cu}$), Cu-He thermal boundary resistance ($R_{Cu/He}$), and hot island diameter (D_{hot}). For Nb thermal conductivity, we adopted parameters for high-purity Nb with RRR = 300, which exhibits significant temperature dependence as shown in [Figure 2: see original paper] and is therefore treated as a temperature-dependent variable. In contrast, Cu thermal conductivity shows negligible temperature variation ([Figure 2: see original paper]) and is held constant.

Regarding Cu-Nb interface thermal boundary resistance, reported values range from 0.03 to 110 $cm^2 \cdot K/W$, but these data were obtained from Nb thin-film coated Cu cavities and may not apply to Cu-Nb composite cavities. We directly measured the thermal boundary resistance using the experimental setup and principle illustrated in Figure 5: see original paper. By characterizing thermal conductivity of the Nb layer, Cu layer, and selected regions, we derived corresponding thermal resistances and ultimately calculated the Cu-Nb thermal boundary resistance. The results (Figure 5: see original paper) indicated values within 2–4 × 10^{-5} $m^2 \cdot K/W$, demonstrating excellent interface bonding quality. A fixed value of 3 × 10^{-5} $m^2 \cdot K/W$ was adopted for simulations.

We also accounted for LHe temperature effects. The LHe thermal boundary resistance is 2 × 10^{-4} $m^2 \cdot K/W$ at 2 K and temperature-independent. As LHe temperature increases to 4.2 K, the thermal boundary resistance passes through three states depicted in [Figure 3: see original paper] as outer surface temperature increases. Initial parameters for the heat transfer computational model are listed in .

3. Performance Calculation

$E_{acc,max}$ is determined via the 2D sheet model, with limits defined by thermal imbalance identified through two criteria: (1) numerical non-convergence with relative tolerance exceeding 1 × 10^{-3}, and (2) abrupt temperature increase on the RF surface (>10 K) as E_{acc} increases. Q_0 is computed using the 3D cavity model derived from key parameters:

$$Q_0 = \frac{2\pi f U}{P_{loss}}$$

where $P_{loss} = \int_V R_s(T(x,y,z), f)|H|^2\, dV$ is the RF power density. The Q_0 value is determined by simultaneously computing RF loss in both superconducting and normal-conducting regions.

III. RESULTS AND DISCUSSION

A. Analysis of Key Parameters Affecting Performance

To investigate key parameters affecting Cu-Nb composite cavity performance, simulations were conducted using our developed heat transfer computational model. The influence of material layer thickness, Cu thermal conductivity, and hot island diameter was studied by applying this model to three cavities of different geometries: a 1.3 GHz single-cell elliptical cavity, an HWR010 cavity (half-wave resonator with optimal $\beta = 0.10$), and an HWR030 cavity (half-wave resonator with optimal $\beta = 0.30$). RF parameters for these cavity types are summarized in .

1. Material Layer Thickness RF performance for cavities with different Nb and Cu layer thicknesses is evaluated in [Figure 6: see original paper] and [Figure 7: see original paper]. Performance degrades more significantly when Nb layer thickness increases compared to Cu layer thickness in the 1.3 GHz single-cell elliptical cavity. For instance, maximum magnetic flux density $B_{peak,max}$ decreases from 226 mT (1 mm Nb) to 204 mT (4 mm Nb) at 2 K—a reduction of approximately 11.3%—while thickening the Cu layer has negligible influence on $B_{peak,max}$ and Q_0. This occurs because the Nb layer contributes more significantly to total thermal resistance (accounting for ~55.8% when $d_{Nb} = 3$ mm and $d_{Cu} = 3$ mm at 2 K), where increased thickness directly impairs heat transfer performance. In contrast, the Cu layer' s thermal resistance contribution is minor (~1.4% under identical conditions). However, the impact of material layer thickness (from 1 mm to 4 mm) is insignificant in HWR010 and HWR030 Cu-Nb cavities because their surface resistance is substantially lower than that of the 1.3 GHz single-cell elliptical cavity (by 96.7% at 4.2 K and 44.4% at 2 K). Consequently, heat generation is substantially reduced, making degradation from Nb layer thickening insignificant for low-β cavities.

2. Cu Thermal Conductivity Simulation results for Cu-Nb cavity performance at different Cu thermal conductivities are shown in [Figure 8: see original paper]. The 1.3 GHz single-cell elliptical cavity shows no significant performance variation with improved Cu thermal conductivity, exhibiting only slight improvement at 2 K when conductivity is between 50 and 150 W/(m·K). The effect steadily decreases as conductivity increases further. The Cu layer' s contribution to overall thermal resistance is 15.4% at 50 W/(m·K) and only 4.3% at 200 W/(m·K), consistent with previous findings. Consequently, the heat transfer process is less affected, decreasing its impact on RF performance. Low-β cavities operate steadily despite Cu thermal conductivity changes, aligning with earlier analysis.

3. Hot Island Diameter [Figure 9: see original paper] illustrates drastic cavity RF performance decline as hot island diameter increases. Maximum peak magnetic flux density $B_{peak,max}$ drops from 145 mT at 5 µm to 77 mT at 50 µm (a deterioration of ~47.1%) for the 1.3 GHz single-cell elliptical cavity at 2 K. This behavior occurs because hot islands increase local heat flux density relative to the surrounding superconductor, raising temperatures in affected areas. Early quench occurs in regions outside the initial hot island as neighboring superconducting material' s critical magnetic field diminishes. As the normal-conducting zone expands, it eventually leads to full cavity quench.

B. Quench Mechanisms in the HWR030 Cu-Nb SRF Cavity

Parametric analysis in Section III.A showed that the simulated maximum accelerating gradient of the HWR030 Cu-Nb composite cavity at 2 K (~33 MV/m) under hot-island-free conditions exhibits a 57% overestimation compared to experimental measurements (~21 MV/m). This suggests that reported cavity performance decline cannot be fully explained by thermal feedback mechanisms alone. The observed quench without field emission in the HWR030 Cu-Nb composite cavity indicates that hot islands on the inner surface are the primary cause. Computations were conducted using parameters listed in to study the quench mechanism.

An equivalent circular hot island was positioned at the B_{peak} location on the RF surface with diameter $\phi = 30$ µm. Simulations accurately predicted quench at 2 K ([Figure 10: see original paper]), with a simulated maximum accelerating gradient of approximately $E_{acc,max} = 21$ MV/m (corresponding to $B_{peak} = 144.9$ mT), aligning well with experimental data. This decrease can be attributed to increased RF loss in hot island regions, which reduces the critical field B_{lim} and causes magnetic quench of Nb. Simulation results at 4.2 K also showed excellent agreement with experimental observations, indicating a quench field of approximately $E_{acc,max} = 15$ MV/m (corresponding to $B_{peak} = 103.5$ mT). However, quench at this temperature was affected by high LHe thermal boundary resistance rather than the hot island itself. The defect influenced temperature distribution in the surrounding superconductor, reducing the critical magnetic field of the localized region. This region transitioned from superconducting to normal-conducting state, increasing RF loss. Finally, $E_{acc,max}$ and Q_0 degradation were analyzed, suggesting that hot islands—potentially initiated by RF surface defects—were the primary contributor to the HWR030 Cu-Nb composite cavity' s pre-threshold quench.

C. Discussion

Based on simulation data, hot islands significantly impact Cu-Nb cavity RF performance through the following mechanism: when RF magnetic field intensity is sufficiently high, temperature at specific hot islands (such as defects) increases substantially compared to surrounding superconducting regions. This temperature rise decreases the critical magnetic field in these areas, leading to localized quench near hot islands. Dynamic expansion of hot islands under increasing RF fields is revealed by computing the HWR030 Cu-Nb cavity behavior ([Figure 11: see original paper]). A 21 mT increase in peak field (from 124 to 145 mT) causes approximately 8 µm radial growth of the normal-conducting zone along with heat accumulation.

If heat transfer within these hot islands is controllable, only a small area transitions to normal-conducting state while the majority of the cavity remains superconducting. During this phase, RF loss in the hot island increases dramatically—by approximately 10^6 times, since Nb resistance in the normal state is about 10^6 times higher than in the superconducting state. As the RF field intensifies, the normal-conducting region initially expands but eventually reaches a stable size. Even with a localized normal-conducting region present, complete quench does not occur across the entire cavity. The rapid rise in RF loss and gradual decrease in Q_0 contribute to the Q-slope phenomenon. However, if these regions expand uncontrollably and the RF field continues to increase, normal-conducting regions will grow beyond the limit, leading to more extensive quench. This expansion can eventually result in sudden, complete quench at a certain acceleration gradient. We define the "breakdown boundary" as the maximum borderline of the normal-conducting region, with the underlying principle illustrated in [Figure 12: see original paper].

IV. CONCLUSION

Theoretically, Cu-Nb composite cavities offer greater potential than bulk Nb cavities in terms of mechanical and thermal stability, combining the exceptional mechanical rigidity and thermal conductivity of thick Cu layers with the excellent SRF properties of thin Nb layers. However, the Cu-Nb cavity structure complicates heat transfer from the inner surface to the cooling medium (LHe). To analyze and investigate RF loss behavior from a heat transfer perspective, we developed a comprehensive computational model using measured Cu-Nb thermal boundary resistance of 2-4 $\times 10^{-5}$ $m^2 \cdot K/W$ from our electroplated samples as input parameters.

Utilizing this model, we investigated the influence of key physical property parameters (material layer thickness, Cu thermal conductivity, and hot island diameter) on Cu-Nb composite cavity RF performance. Results indicated that both increased hot island diameter and Nb layer thickness significantly degrade cavity performance. Additionally, increasing Cu thermal conductivity improves RF performance when below 150 $W/m \cdot K$, but further enhancement yields only slight improvement beyond this threshold. Furthermore, we studied RF performance degradation of the HWR030 Cu-Nb composite cavity relative to its theoretical limit, suggesting that defects may be the primary performance limiter, reducing the theoretical peak magnetic field from 228 to 145 mT (36% degradation) at 2 K. At 4.2 K, performance degradation mainly stems from insufficient heat transfer efficiency at the Cu-He interface. Based on these simulations, we further studied hot island behavior, revealing two different expansion paths as field increases. If thermal balance can be maintained, the hot island region stabilizes after certain expansion, causing the obvious Q-slope phenomenon. Conversely, uncontrollable hot islands continue expanding, eventually leading to thermal imbalance and cavity quench.

This work identifies key factors influencing Cu-Nb composite cavity RF performance and the dynamic hot island expansion process, thereby guiding Cu-Nb composite cavity design and helping to understand the underlying mechanisms of SRF cavity performance degradation.

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Note: Figure translations are in progress. See original paper for figures.