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$×10^{-5}$ m^{2} · 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 Copper-Niobium Composite Cavities Based on a Heat Transfer Computational Model

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Thermal stability is a critical indicator for evaluating the long-term operational reliability of superconducting radio-frequency (SRF) cavities. Theoretically, copper-niobium (Cu-Nb) composite cavities offer promising potential for achieving high 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 Cu-Nb structure of the cavity wall introduces complexity to the heat transfer process compared to bulk niobium cavities. A deeper understanding of how physical property parameters influence thermal transfer efficiency is essential for the high-quality application of Cu-Nb composite cavities. In this paper, we propose a comprehensive heat transfer computational model to analyze the RF performance of Cu-Nb composite cavities, incorporating key parameters including the measured Cu-Nb thermal boundary resistance (2–4 $\times$ 10^{-5} $\mathrm{m}^2 \cdot \mathrm{K/W}$). The model was applied to three types of cavities to investigate the effects of material layer thickness, copper thermal conductivity, and hot island diameter on the RF performance of Cu-Nb composite cavities at 4.2 K and 2 K. Furthermore, 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 4.2 K and 2 K. 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' s RF surface were conducted, revealing the expansion behavior and size limits of hot islands and providing insights into performance degradation relative to theoretical limits. The proposed heat transfer model can guide the design of Cu-Nb composite cavities and help elucidate 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 employed in modern particle accelerators due to their low RF losses and larger beam apertures compared to normal-conducting RF cavities [**?**]. The performance of an SRF cavity is primarily characterized by the maximum accelerating field, E_{acc}, and the unloaded quality factor, $Q_0 = \omega U / P_{loss}$. Here, 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, niobium (Nb) is the primary material for SRF cavities owing to its highest superconducting transition critical temperature and highest lower critical magnetic field among elemental superconductors [**?**]. Extensive research has been conducted to improve the RF performance of Nb cavities, including the development of advanced surface processing techniques (e.g., mid-temperature baking \cite{4-6}, nitrogen doping [**?**, **?**], nitrogen infusion [**?**], and plasma cleaning \cite{10-12}) and the exploration of alternative materials beyond Nb (e.g., Nb_3Sn \cite{13-15}, NbN [**?**, **?**], and MgB_2 [**?**, **?**]).

At present, bulk Nb cavities exhibit the best overall Q_0 and E_{acc} among reported SRF cavities. However, their RF performance is often limited by thermal breakdown at high fields \cite{2, 19-21}. Consequently, alternatives such as copper-niobium (Cu-Nb) structures have been explored to enhance heat dissipation. Theoretically, compared to bulk Nb cavities, Cu-Nb cavities improve thermal and mechanical stability by leveraging the excellent SRF performance of the Nb layer along with the high mechanical rigidity and thermal conductivity of a thick Cu layer. Cu-Nb cavities are primarily classified into Nb thin-film coated Cu cavities and Cu-Nb composite cavities. Nb thin-film coated Cu cavities are mainly produced via sputtering technology in several laboratories \cite{22-26}. However, the 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, particularly at high fields [**?**]. Consequently, Nb thin-film coated Cu cavities currently exhibit a considerable RF performance gap compared to bulk Nb cavities.

By replacing the Nb film with bulk Nb in Cu-Nb composite cavities, surface defect issues inherent to thin films can be avoided while enabling the application of advanced surface treatment techniques originally developed for pure niobium cavities. Although Cu-Nb composite cavities have been investigated in several laboratories \cite{28-31}, no comprehensive analysis or understanding of the heat transfer mechanism exists. The presence of a Cu layer in Cu-Nb cavities complicates the heat transfer process between the RF surface and liquid helium (LHe). In addition to the thermal resistance of the Cu layer, an extra thermal resistance arises at the Cu-Nb interface due to phonon mismatch, originating from differences in the phonon mean free path 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 [**?**]. However, this explanation may be insufficient given the 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 ultimately quenched without field emission—a phenomenon requiring further theoretical analysis to better understand the underlying quench mechanisms.

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 types of cavities (a 1.3 GHz single-cell elliptical cavity and two half-wave resonators) to investigate the impact of thermal conductivity of Cu, material layer thickness (Cu and Nb), and the size of the hot island region on the RF performance of the Cu-Nb cavity.

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 in the performance degradation. Finally, the model successfully explained the performance degradation process of the cavity by the hot island area. It was found that a hot island region reduces the critical magnetic field of the surrounding superconducting region, turning the surrounding region into a normal-conducting region. 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.

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 is implemented using a 100 mm × 100 mm × h mm plate (where h denotes the cavity wall thickness), which reduces computational costs and minimizes boundary effects. The upper surface represents the equivalent LHe (or cold head) boundary, and the lower surface corresponds to the RF surface. Moreover, a 100 µm diameter circular zone is introduced at the center of the lower surface to investigate hot island effects. Due to the highly non-uniform surface magnetic field in low-β cavities and the significant dependence of Q_0 calculations on the surface electromagnetic field distribution, the 2D plate model is unsuitable for calculating Q_0 of low-β cavities. Our 3D cavity model enables Q_0 calculation by first computing the electromagnetic field distribution based on cavity geometry, then deriving the surface RF loss distribution.

In the 2D plate model, the magnetic field intensity is set to the peak surface magnetic field (H_{peak}) as the input value, with the RF loss power density ($p_s = \frac{1}{2}R_s H_{peak}^2$) applied as a boundary heat source. This approach is adopted because the model focuses on calculating the maximum magnetic field (or accelerating gradient), requiring consideration of limiting cases (such as worst-case thermal load scenarios). Additionally, 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:

$$\nabla \cdot (\kappa \nabla T) + \frac{1}{2d} R_s(T(s), f) H_{peak}^2 = 0$$

where T is the temperature, d is the cavity wall thickness, and κ is the effective thermal conductivity that combines the conductivities of Cu and Nb, the Cu-Nb thermal boundary resistance, and the Cu-He thermal boundary resistance:

$$\kappa = \frac{d_t}{\frac{d_{Cu}}{\kappa_{Cu}} + R_{Cu/Nb} + \frac{d_{Nb}}{\kappa_{Nb}}}$$

where d_t, d_{Nb}, and d_{Cu} denote the total wall thickness, Nb layer thickness, and Cu layer thickness, respectively.

The surface resistance $R_s(T(s), f)$ in Eq. (7) exhibits spatial dependence and is modulated by the temperature-dependent superheating field ($B_{sh}(T = 0\,\mathrm{K}) =$ 240 mT [**?**]), thereby governing the critical magnetic field (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 [**?**]:

$$R_s = R_s(T(s), f) = \begin{cases} 2 \times 10^{-4}\sqrt{\frac{\omega\mu_0}{2}}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{\Delta}{k_B T(s)}\right) + R_{res}, & B_{RF} \le B_{lim}(T(s)) \\ R_n, & B_{RF} > B_{lim}(T(s)) \end{cases}$$

The temperature distribution is iteratively fed back into the surface resistance $R_s(T(s), f)$ and the critical magnetic flux density $B_{lim}(T(s))$ before reaching thermal equilibrium (with a relative convergence tolerance $\le$ 0.001), yielding a stable solution. Given that B_{peak}/E_{acc} remains constant in Cu-Nb cavities, the input magnetic flux density can be adjusted using Eq. (12) to solve for the steady-state temperature distribution under different accelerating gradients E_{acc} [**?**]:

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

In the 3D cavity model, we first compute the eigenmodes using the electromagnetic module, where the 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 the electric field intensity, μ and ϵ denote the relative permeability and relative permittivity, respectively, and $k_0 = \omega/c$ corresponds to the free-space wavenumber. Additionally, the boundary condition at the cavity' s inner surface was implemented to account for RF loss:

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

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

$$R_s = R_s(T(s), f) = \begin{cases} 2 \times 10^{-4} \sqrt{\frac{\omega \mu_0}{2}} \left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{\Delta}{k_B T(s)}\right) + R_{res}, & B(s) \leq B_{lim}(T(s)) \\ R_n, & B(s) > B_{lim}(T(s)) \end{cases}$$

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

$$\nabla \cdot (\kappa \nabla T) + \frac{1}{2d} R_s(T(s), f) |H|^2 = 0$$

Consistent with the 2D plate model, the obtained temperature distribution is iteratively fed back into the surface resistance $R_s(T(s), f)$ and the critical magnetic field $B_{lim}(T(s))$ until thermal equilibrium is achieved, yielding a stable solution (with a relative convergence tolerance ≤ 0.001). To compute the steady-state temperature distribution under different fields, a proportional factor is introduced as in Eq. (16):

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

where U_{tar} and U_{ini} denote the stored energy of the target field and initial field, respectively. The initial stored energy U_{ini} can be computed from the cavity model, and the stored energy U_{tar} is derived from E_{acc} [**?**]:

$$E_{acc} = \gamma_{acc} \sqrt{U_{tar}}$$

where γ_{acc} is determined by numerical eigenmode simulations.

In the computational setup for hot islands, these regions are treated as normal-conducting domains using the formulations specified in Eq. (11) and Eq. (15). Furthermore, since the influence of cavity wall thickness on RF performance was studied, we varied the wall thickness while ensuring computational accuracy by refining the mesh to maintain at least five elements along the normal direction for each thickness configuration. The hot island region mesh was further refined, ensuring at least 20 elements for improved resolution. A mesh convergence study was conducted using progressively refined meshes: coarse (10,000 elements), medium (200,000 elements), and fine (600,000 elements). Results indicate that the maximum temperature stabilizes with the fine mesh, exhibiting variations below 0.5%, confirming its adequacy for computational accuracy requirements. Consequently, all subsequent simulations employed this fine mesh setting.

2. Parameters Setup

The parameters considered in this study include the thermal conductivity of materials (for Cu, κ_{Cu} and Nb, κ_{Nb}), the Cu-Nb thermal boundary resistance ($R_{Nb/Cu}$), the Cu-He thermal boundary resistance ($R_{Cu/He}$), and the hot island diameter (D_{hot}). For Nb thermal conductivity, we adopt the parameters of high-purity Nb with a residual resistivity ratio (RRR) of 300. As shown in Figure 2, the thermal conductivity of Nb exhibits significant temperature dependence and is therefore treated as a temperature-dependent variable in the computation. In contrast, the thermal conductivity of Cu shows negligible changes with temperature (Figure 2) and is held constant.

Regarding the thermal boundary resistance at the Cu-Nb interface, values ranging from 0.03 to 110 $\text{cm}^2 \cdot \text{K/W}$ have been reported [**?**, **?**]. However, these data were obtained from Nb thin-film coated Cu cavities and may not be fully applicable to Cu-Nb composite cavities. To determine the Cu-Nb thermal boundary resistance, we directly measured it using a prepared Cu-Nb composite sample. The sample was cut into an initial piece measuring 1 × 1 × 10 mm, mechanically polished, and ultrasonically cleaned with deionized water. The thermal conductivity of different sample components (copper, niobium, and total equivalent thermal conductivity) were then measured using the Physical Property Measurement System (PPMS). The experimental setup and measurement principle are illustrated in Fig. 5(a). By characterizing the thermal conductivity of the Nb layer, Cu layer, and selected regions, we derived the corresponding thermal resistances and ultimately calculated the Cu-Nb thermal boundary resistance. The results (Fig. 5(b)) indicated a Cu-Nb thermal boundary resistance within the range of 2–4 $\times 10^{-5}$ $\text{m}^2 \cdot \text{K/W}$, demonstrating excellent bonding quality at the interface. A fixed Cu-Nb thermal boundary resistance value of 3×10^{-5} $\text{m}^2 \cdot \text{K/W}$ was adopted for the simulations.

We also accounted for the influence of LHe temperature in our model. The LHe thermal boundary resistance is 2×10^{-4} $\text{m}^2 \cdot \text{K/W}$ at 2 K and is temperature-independent. As the LHe temperature increases to 4.2 K, the LHe thermal boundary resistance passes through three states depicted in Fig. 3 as the outer surface temperature increases. Some initial parameters of the heat transfer computational model are listed in Table 1 .

3. Performance Calculation

$E_{acc,max}$ can be determined via the 2D plate model, where the limit is defined by thermal imbalance identified by two criteria: (1) numerical non-convergence with a relative tolerance exceeding 1×10^{-3}, and (2) abrupt temperature increase in the RF surface (>10 K) as E_{acc} increases.

Q_0 is computed using the 3D cavity model, where its value is derived from the following key parameters [**?**]:

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

where $P_{loss} = \frac{1}{2} \int_S R_s(T(s), f)|H|^2\, ds$ is the power density substituted into Eq. (19) to derive Q_0:

$$Q_0 = \frac{2\pi f \int_V |H|^2\, dV}{\int_S R_s(T(s), f)|H|^2\, ds}$$

The Q_0 value of the cavity 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 β of 0.10), and an HWR030 cavity (half-wave resonator with optimal β of 0.30). The RF parameters of these cavity types are summarized in Table 2 .

1. Material Layer Thickness The RF performance of cavities with different Nb and Cu layer thicknesses is evaluated in Figs. 6 and 7. Performance degrades more significantly when the Nb layer thickness increases compared to the Cu layer in the 1.3 GHz single-cell elliptical cavity. For instance, the 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 11.3%—with negligible influence on $B_{peak,max}$ and Q_0 from thickening the Cu layer. This is explained by the larger contribution of the Nb layer to the 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 the cavity' s heat transfer performance. In contrast, the heat transfer ability of the Cu-Nb cavity is not significantly influenced by the Cu layer thermal resistance (accounting for 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 (for HWR010 by 96.7% at 4.2 K and by 44.4% at 2 K compared to the 1.3 GHz single-cell elliptical cavity). Consequently, heat generation is substantially reduced, making the degradation of heat transfer efficiency due to 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 Fig. 8 [Figure 8: see original paper]. The RF performance of the 1.3 GHz single-cell elliptical cavity shows no significant variation with improved Cu thermal conductivity. A small improvement is observed at 2 K when Cu thermal conductivity is between 50 and 150 W/(m · K). However, the effect of thermal conductivity on cavity performance steadily saturates as Cu thermal conductivity increases further. The contribution of the Cu layer to the overall thermal resistance is 15.4% at 50 W/(m · K) and only 4.3% at 200 W/(m · K), consistent with previous findings. As a result, the heat transfer process is less affected, decreasing its impact on the cavity' s RF performance. The RF performance of low-β cavities is unaffected by Cu thermal conductivity (from 50 to 1000 W/(m · K)). The lower heat generation has no apparent impact on heat transfer efficiency and thus no effect on cavity performance, similar to the analysis of material layer thickness.

3. Hot Island Diameter Figure 9 [Figure 9: see original paper] illustrates a drastic decline in cavity RF performance as hot island diameter increases. The 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. The main reason for this behavior is that hot islands increase the local heat flux density relative to the surrounding superconductor, raising the temperature in the impacted area. Early quench occurs in regions outside the initial hot island as the 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

As the parametric analysis in Section III.A showed, 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 the reported cavity performance decline cannot be fully explained solely by the thermal feedback mechanism. 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 therefore conducted using the parameters listed in Table 3 to study the quench mechanism.

An equivalent circular hot island was positioned at the B_{peak} location on the RF surface with a diameter of $\phi = 30$ µm. The simulations accurately predict the quench at 2 K (Fig. 11 [Figure 11: see original paper]), with a simulated maximum accelerating gradient of approximately $E_{acc,max} = 21$ MV/m (corresponding to $B_{peak} = 144.9$ mT), which aligns well with experimental data. This decrease can be attributed to increased RF loss in the 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, the quench at 4.2 K was affected by high LHe thermal boundary resistance rather than the hot island. Moreover, the defect influenced the temperature distribution of the surrounding superconductor in our model, reducing the critical magnetic field of the localized region. This region transitioned from superconducting to normal-conducting state, increasing RF loss. Finally, the $E_{acc,max}$ and Q_0 degradation of the cavity was analyzed, suggesting that hot islands—potentially initiated by RF surface defects—were the primary contributor behind the HWR030 Cu-Nb composite cavity' s pre-threshold quench.

C. Discussion

Based on the simulation data, hot islands significantly impact the RF performance of Cu-Nb cavities through the following mechanism: when the RF magnetic field intensity is sufficiently high, the temperature at specific hot islands (such as defects) increases significantly compared to surrounding superconducting regions. This temperature rise decreases the critical magnetic field in these areas, leading to localized quench near the hot islands. Dynamic expansion of hot islands under increasing RF fields was revealed by computing the HWR030 Cu-Nb cavity. Figure 11 depicts the derived temperature distribution (based on B_{lim} screening), revealing a central hotspot region surrounded by concentric rings (1 µm spacing) to monitor its expansion, with the expansion magnitude annotated above the image: a 21 mT increase in the peak field (from 124 to 145 mT) causes 7 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 a 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 the resistance of Nb 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, it does not cause complete quench 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, the normal-conducting regions will grow and exceed the limit, leading to more extensive quench. This expansion can eventually result in sudden, complete quench at a certain accelerating gradient, E_{acc}. We define the "breakdown boundary" as the maximum borderline of the normal-conducting region. The underlying principle is illustrated in Fig. 12 [Figure 12: see original paper].

IV. Conclusion

Theoretically, Cu-Nb composite cavities have greater potential than bulk Nb cavities in terms of high mechanical and thermal stability, combining the exceptional mechanical rigidity and thermal conductivity of a thick Cu layer with the excellent SRF properties of a thin Nb layer. However, the Cu-Nb structure complicates the heat transfer process from the cavity’ s inner surface to the cooling medium (i.e., LHe).

To analyze and investigate RF loss behavior from a heat transfer perspective, a comprehensive heat transfer computational model was developed. The measured Cu-Nb thermal boundary resistance of our electroplated Cu-Nb samples (2–4 $\times 10^{-5}$ $\mathrm{m}^2 \cdot \mathrm{K/W}$) was used as an input parameter in the proposed model. Utilizing this model, the influence of key physical property parameters (e.g., material layer thickness, Cu thermal conductivity, and hot island diameter) on the RF performance of Cu-Nb composite cavities was investigated. 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 $\mathrm{W/m \cdot K}$, but further enhancement beyond 150 $\mathrm{W/m \cdot K}$ has only slight effects. Furthermore, the RF performance degradation of the HWR030 Cu-Nb composite cavity compared to its theoretical limit was studied. It is suggested that the primary performance limiter may be attributed to defects, reducing the cavity’ s 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. Results showed two different expansion paths for hot islands as field increases. If thermal balance can be maintained as the field increases, the hot island region remains stable after certain expansion, causing the Q-slope phenomenon. Conversely, uncontrollable hot islands continue to expand, eventually leading to thermal imbalance and cavity quench.

This work identifies key factors influencing the RF performance of Cu-Nb composite cavities and the dynamic process of hot island expansion with increasing field, thereby guiding the design of Cu-Nb composite cavities (such as adjusting cooling structures to mitigate hot island impacts) 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.