

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 ($2\text{--}4 \times 10^{-5} \text{ m}^2 \cdot \text{K}/\text{W}$). 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 degra-

dation 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 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 propose 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 ($2-4 \times 10^{-5} \text{ m}^2 \cdot \text{K/W}$). The model is 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 is 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 defects may be the primary cause of

performance degradation of the HWR030 cavity. Finally, dynamic process simulations of hot islands on the RF surface of the cavity are 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.

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 [?]. 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 [?]. At present, niobium (Nb) is the primary material for SRF cavities owing to its highest superconducting transition critical temperature and highest lower critical magnetic field among the elementary 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 [4-6], nitrogen doping [?, ?], nitrogen infusion [?], and plasma cleaning [10-12]) and the exploration of alternative materials other than Nb (e.g., Nb₃Sn [13-15], NbN [?, ?], and MgB₂ [?, ?]).

Currently, bulk Nb cavities exhibit the overall best Q_0 and E_{acc} among the reported SRF cavities. However, their RF performance is often limited by thermal breakdown at high fields [2,19-21]. Thus, alternatives like copper-niobium (Cu-Nb) structures were explored for enhanced heat dissipation. Theoretically, compared to bulk Nb cavities, Cu-Nb cavities improve the thermal and mechanical stability of the cavity by utilizing the excellent SRF performance of the Nb layer along with the thick Cu layer's high mechanical rigidity and thermal conductivity. The Cu-Nb cavities are primarily classified into Nb thin-film coated Cu cavities and Cu-Nb composite cavities. The Nb thin-film coated Cu cavities are mainly produced by sputtering technology in several laboratories [22-26]. However, the prepared Nb film usually has more defects than bulk Nb. Moreover, the majority of cavities suffer from poor heat transfer performance due to inadequate Cu-Nb bonding, especially at high field [?]. Consequently, Nb thin-film coated Cu cavities produced under current technology still exhibit a considerable RF performance gap compared to bulk Nb cavities.

By replacing Nb film with bulk Nb in Cu-Nb composite cavities, surface defect issues inherent to these films can be avoided, while enabling the application of

advanced surface treatment techniques—originally developed for pure niobium cavities—to Cu-Nb composite cavities. Although Cu-Nb composite cavities have been investigated in several laboratories \cite{28-31}, there is no comprehensive analysis or understanding of the heat transfer mechanism. The existence 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 the difference in the mean free path of phonons between Nb and Cu. Therefore, the complex heat transfer system in Cu-Nb composite cavities involves Nb, the Nb-Cu interface, Cu, and He, instead of the simpler Nb-He system of bulk Nb cavities.

The Q-slope observed in Nb thin-film coated Cu cavities is explained by heat accumulation with increasing field due to the Cu-Nb thermal boundary resistance [?]. However, this explanation may not be sufficient due to 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 (labeled as the HWR030 Cu-Nb composite cavity). Cryogenic tests were performed, and the cavities finally quenched without field emission—a phenomenon that requires further theoretical analysis to better understand the underlying quench mechanisms.

In this paper, we establish a comprehensive heat transfer computational model to analyze the RF performance of Cu-Nb composite cavities. The model incorporates the measured Cu-Nb thermal boundary resistance and investigates the influence of 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 investigate 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 explains 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.

II. Theory and Methods

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

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

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

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 establish 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' s wall, and hot islands distributed on the cavity' s inner surface. The computational model is applied to three types of cavities (a 1.3 GHz single-cell elliptical cavity and two half-wave resonators) to investigate the impact of the thermal conductivity of Cu, material layer thickness, and hot island diameter.

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 the effect of RF field (R_{so}), (2) defect-induced RF loss, and (3) field emission (FE) associated dissipation. The intrinsic surface resistance can be decomposed into two parts: 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 $T < T_c/2$, the BCS resistance is simplified to:

$$R_{BCS}(T, f) = 4\pi^2 A f^2 ()$$

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 obtained as:

$$R_{so}(T, f) = 4\pi^2 A f^2 () + R_{res}$$

Calculations can generally be performed using the empirical formula:

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

Defects and FE originate from material impurities and localized area geometry of the cavity' s inner surface (pits or bumps) and generate a much higher heat flux compared to the RF surface resistance \cite{36-39}, known as hot islands (or hot spots) [?, ?]. In general, the total RF loss of the Cu-Nb cavity can be expressed as:

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

The total RF loss constitutes the fundamental heat source at the inner surface of cavities, where this deposited energy subsequently participates in the cryogenic heat transfer process.

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

The thermal conductivity of materials is crucial, particularly when a thermal feedback mechanism is present. As shown in Fig. 2 [Figure 2: see original paper], the thermal conductivity of high-purity Nb (residual resistivity ratio, RRR of 300) increases by about 6 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 neglecting the thermal feedback mechanism are inaccurate, as the heat transfer ability is enhanced due to increased thermal conductivity.

The problem becomes more complex when considering the thermal resistance of the interface between different materials, which is referred to as thermal boundary resistance. The Cu-Nb cavity contains a Nb-Cu-He heat transfer system, while the Nb cavity only has the Nb-He heat transfer system. The partial substitution of Nb with Cu theoretically improves the heat transfer performance of the cavity due to the high thermal conductivity of Cu, but it generates thermal boundary resistance between Nb and Cu that is correlated with the quality of bonding [?]. In addition, the outer surface of the cavity immersed in LHe exhibits a Cu-He thermal boundary resistance, which depends on the state of LHe. The LHe is in the He-I state at 4.2 K. Figure 3 [Figure 3: see original paper] illustrates the three states through which the LHe on the cavity' s outer surface passes as the temperature increases: convection cooling, nucleate boiling, and film boiling [?]. The temperature of the cavity' s outer surface significantly influences the Cu-He thermal boundary resistance, depending on the state of LHe on the outer surface of the cavity. The heat transfer ability of LHe is

greatly enhanced at 2 K due to the transfer of LHe from the He-I state to the He-II state, where the LHe enters the superfluid state. Also, the Cu-He thermal boundary resistance remains at a constant value of approximately $2\text{--}4 \times 10^{-4} \text{ m}^2 \cdot \text{K}/\text{W}$ [cite{47-49}]. In summary, the cavity's performance is influenced by a closed-loop electro-thermal feedback mechanism, as illustrated in Figure 4 [Figure 4: see original paper].

B. Establishment of the Heat Transfer Computational Model

Based on the heat transfer mechanism of the Cu-Nb cavities, we propose a dual-component computational model: (i) a two-dimensional (2D) plate model for the maximum peak magnetic flux density ($B_{peak,max}$) prediction, and (ii) a three-dimensional (3D) cavity model for the evaluation of the unloaded quality factor Q_0 . The 2D model is implemented using a $100 \text{ mm} \times 100 \text{ mm} \times h \text{ mm}$ plate (h denotes the thickness of the cavity wall), 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 $100 \text{ }\mu\text{m}$ diameter circular zone is introduced at the center of the lower surface to investigate the effect of hot islands. Due to the highly non-uniform surface magnetic field in low- β cavities and the fact that calculation of Q_0 significantly depends 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 the calculation of Q_0 by first computing the electromagnetic field distribution based on the cavity geometry, and 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 the limiting case (such as the worst-case thermal load scenario). 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:

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

where T is the temperature, 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:

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

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

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

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

Consequently, the surface resistance can be expressed as [?]:

$$R_s = R_s(T(s), f) = \begin{cases} 2 \times 10^{-4} \frac{1}{T(s)} \sqrt{\frac{\omega \mu_0}{2}} \left(\frac{f}{1.5} \right)^2 \exp\left(-\frac{\Delta}{k_B T(s)}\right) + R_{res}, & B_{RF} \leq B_{lim}(T(s)) \\ \infty, & B_{RF} > B_{lim}(T(s)) \end{cases}$$

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 ≤ 0.001), yielding a stable solution. Given that B_{peak}/E_{acc} remains constant in the 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 intensity of the electric field, μ and ϵ denote the relative permeability and relative permittivity, respectively, and $k_0 = \omega/c$ corresponds to the free-space wavenumber. The boundary condition at the cavity' s inner surface accounts for the RF loss:

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

where \mathbf{n} is the unit normal vector at the inner surface boundary, R_s denotes the surface resistance, λ_L (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 depends on spatial position and is influenced by the superconductor' s critical magnetic field:

$$R_s = R_s(T(s), f) = \begin{cases} 2 \times 10^{-4} \frac{1}{T(s)} \sqrt{\frac{\omega\mu_0}{2}} \left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{\Delta}{k_B T(s)}\right) + R_{res}, & B(s) \leq B_{lim}(T(s)) \\ \infty, & B(s) > B_{lim}(T(s)) \end{cases}$$

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

$$\nabla \cdot (\kappa \nabla T) + R_s(T(s), f) |H|^2 = 0$$

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:

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

where U_{tar} and U_{ini} denote the stored energy of the target field and the 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 corresponding 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 employing 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 an RRR of 300. As shown in Figure 2 [Figure 2: see original paper], the thermal conductivity of Nb exhibits significant temperature dependence and is therefore treated as a temperature-dependent variable. 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 in the range from 0.03 to 110 $\text{cm}^2 \cdot \text{K}/\text{W}$ were 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 this parameter. To acquire the test sample, we first cut the prepared Cu-Nb composite into an initial sample of $1 \times 1 \times 10$ mm. After mechanical polishing and ultrasonic cleaning with deionized water, the thermal conductivity of different sample components (copper, niobium, and total equivalent thermal conductivity) was measured employing the Physical Property Measurement System (PPMS). The experimental setup and measurement principle are illustrated in Fig. 5 Figure 5: see original paper. 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 Figure 5: see original paper) indicated the Cu-Nb thermal boundary resistance within the range of $2\text{--}4 \times 10^{-5} \text{ m}^2 \cdot \text{K}/\text{W}$, demonstrating excellent bonding quality at the interface. Finally, a fixed Cu-Nb thermal boundary resistance value of $3 \times 10^{-5} \text{ m}^2 \cdot \text{K}/\text{W}$ was adopted.

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

Table 1. Initial parameters of the heat transfer computational model.

Parameters	Value
Cu Thermal Conductivity κ_{Cu} ($\text{W}/\text{m} \cdot \text{K}$)	300
He Bath Temperature (K)	4.2 / 2
Nb Layer Thickness d_{Nb} (mm)	3
Cu Layer Thickness d_{Cu} (mm)	3
Cu-Nb Thermal Boundary Resistance $R_{Cu/Nb}$ ($\text{m}^2 \cdot \text{K}/\text{W}$)	3×10^{-5}

Parameters	Value
Equivalent Hot Island Diameter ϕ (μm)	100

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 the RF power loss density $P_{loss} = \int R_s(T(s), f) |H|^2 ds$ and the stored energy $U = \int \mu |H|^2 dV$. Substituting these into Eq. (19) yields:

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

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 based on our developed heat transfer computational model were conducted. The influence of material layer thickness, Cu thermal conductivity, and hot island diameter was studied by applying this model to three cavities of different shapes—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). RF parameters of these cavity types are summarized in Table 2.

Table 2. RF parameters of three types of cavities.

Parameters	1.3 GHz Single-cell Elliptical Cavity	HWR010 Cavity	HWR030 Cavity
Frequency (MHz)	1300	162.5	162.5
$\beta = v/c$	1.0	0.10	0.30

Parameters	1.3 GHz Single-cell Elliptical Cavity	HWR010 Cavity	HWR030 Cavity
E_{peak}/E_{acc}	2.0	6.5	4.8
B_{peak}/E_{acc} (mT · MV ⁻¹ · m ⁻¹)	4.2	10.0	6.9
R/Q (Ω)	1000	120	200
G (Ω)	270	15	30
R_{res} (nΩ)	10	5	5
γ_{acc} (MV · m ⁻¹ · J ^{-1/2})	1.5	0.8	1.2

1. Material Layer Thickness The RF performance of cavities with different Nb and Cu layer thicknesses is evaluated as shown in Figs. 6 and 7 [FIGURE:6, FIGURE:7]. Performance degrades more when the thickness of the Nb layer 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 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 improving Cu thermal conductivity. Performance exhibits a small improvement 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 grows further. The contribution of the Cu layer 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. As a result, the heat transfer process is less affected, which decreases its impact

on cavity RF performance. However, the RF performance of low- β cavities is not affected 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 has 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 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 quench of the full cavity.

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 occurrence of 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 the parameters listed in Table 3 to study the quench mechanism.

Table 3. Parameters of the heat transfer computational model based on the HWR030 Cu-Nb cavity.

Parameters	Value
R_{res} (n Ω)	5
T_{Bath} (K)	4.2 / 2
κ_{Cu} (W/(m · K))	300
d_{Nb} (mm)	3
d_{Cu} (mm)	3
$R_{Cu/Nb}$ (m ² · K/W)	3×10^{-5}
ϕ (μm)	30

An equivalent circular hot island was positioned at the B_{peak} location on the RF surface with a diameter of $\phi = 30 \mu\text{m}$. The simulations match the quench at 2 K (Fig. 10 [Figure 10: see original paper]), with a simulated maximum accelerating gradient of approximately $E_{acc,max} = 21 \text{ MV/m}$ (corresponding to

$B_{peak} = 144.9$ mT), which aligns well with experimental data. This decrease can be attributed to increased RF loss in hot island regions, which reduces the critical field B_{lim} and causes magnetic quench of Nb. In addition, 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 instead of the hot island. Moreover, defects influenced the temperature distribution of the surrounding superconductor in our model, reducing the critical magnetic field of the localized region. This region was thus transferred from the superconducting state to the normal-conducting state, raising RF loss. Finally, $E_{acc,max}$ and Q_0 degradation of the cavity were 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.

Figure 11 [Figure 11: see original paper] depicts the expansion of normal-conducting zones (circular region) with increasing peak magnetic field (B_{peak}).

C. Discussion

Based on simulation data, hot islands significantly impact the RF performance of Cu-Nb cavities via the following mechanism: when RF magnetic field intensity is sufficiently high, the temperature at specific hot islands (such as defects) significantly increases 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 is 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 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 will transition 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 though a localized normal-conducting region is 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 and complete quench at a certain acceleration gradient E_{acc} . We define the “break-down 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. They can combine 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 of the cavity complicates the heat transfer process from the inner surface of the cavity to the cooling medium (i.e., LHe).

To analyze and investigate RF loss behavior from the perspective of heat transfer, a comprehensive heat transfer computational model was developed. The measured Cu-Nb thermal boundary resistance of our electroplated Cu-Nb samples in the range of $2\text{--}4 \times 10^{-5} \text{ m}^2 \cdot \text{K}/\text{W}$ 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 the thermal conductivity of Cu improves RF performance of Cu-Nb composite cavities when its thermal conductivity is below $150 \text{ W}/(\text{m} \cdot \text{K})$, but further enhancement affects RF performance only slightly as the value exceeds $150 \text{ W}/(\text{m} \cdot \text{K})$. Furthermore, RF performance degradation of the HWR030 Cu-Nb composite cavity compared to its theoretical performance 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 behaviors. Results showed two different paths for hot island expansion 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, thereby guiding the design of Cu-Nb composite cavities (such as adjusting the cooling structure to mitigate the impact of heat islands on cavity performance) and helping to understand the underlying mechanism of performance degradation in SRF cavities.

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