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TEMPERATURE DEPENDENT EFFECTS ON QUALITY FACTOR IN C-BAND RF CAVITIES

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Abstract

Cryogenic operation and associated skin effects are promisng fields of study for increasing RF gradients within cavities and decreasing the required size for linear accelerators and their applications, such as free electron lasers [1–6]. Notably, a cavity's RF quality factor Q, the ratio of the outgoing RF signal power to the input power, is theoretically multiplied by over 4 when subjected to cryogenic temperatures [7, 8]. Precise measurements of this Q factor require defining a cryostat unit, which consists of a high vacuum chamber, a coldhead, and multi-layered insulation (MLI) shielding. We optimized the cryostat by running several cool down tests at high vacuum, incorporating different geometries of MLI shielding to achieve the lowest possible temperatures. We then performed a low power C-band test after installing a cylindrical copper RF cavity to measure the Q factor. Finally, we improved stability and amplification within the chamber by installing edge welded bellows to the coldhead to reduce vibrations. These measurements provide a basis for the development of cryogenic infrastructure to sustain a cryogenic temperature environment for future RF applications.

CRYOGENIC THEORY

Skin effects govern the atypical behavior of resonating C-band radiation within these RF cavities at cryogenic temperatures [7, 8]. Namely, the anomalous skin effect theory, developed by Reuter and Sondheimer, predicts that, as the temperature of an RF conducting cavity decreases, the electron free mean path length shrinks to the order of the skin depth of the conductor. This results in the surface conductivity scaling both to a non-zero value at cryogenic temperatures as well as inversely to the quality factor of the RF cavity: the ratio of outgoing power of RF radiation to the input signal power. We expect an increase of the quality factor on the order of 3-4.5 times at temperatures less than 40 K [6,7]. Given the radius, a, and the height, h, of a cylindrical cavity of conductivity σ, Equation 1 demonstrates how to evaluate the Q factor from geometry and material considerations alone [8]:

$$Q = \frac{\sqrt{2a\eta\sigma\chi_{01}}}{\left(1 + \frac{a}{h}\right)}, \tag{1}$$

where $\eta = \sqrt{\frac{\mu_0}{\epsilon_0}}$ and χ_{01} is a constant proportional to the resonant frequency ω_0 given by the relation:

$$\omega_0 = \chi_{01}\frac{c}{a}. \tag{2}$$

CRYOSTAT OVERVIEW

The cryostat, shown in Figure 1, is a rectangular stainless steel vacuum chamber, a 1 phase helium cooled cryocooler coldhead and necessary vacuum and cooling components to ensure a high vacuum seal and temperatures consistently below 90 K. The cavity is mounted on 80/20 aluminum rods that are insulated by polyether ether ketone (PEEK) material. MLI shielding surrounds the cavity and the coldhead to shrink the effective size of the chamber and minimize heat leaks. Edge welded bellows have been implemented to reduce vibrations from the coldhead, thereby diminishing heat transfer and chamber instability from vibrations. The coldhead is a 1 phase cryocooler with a copper plated tip that allows for a copper thermal braid to join the cavity to the coldhead in thermal contact [8].

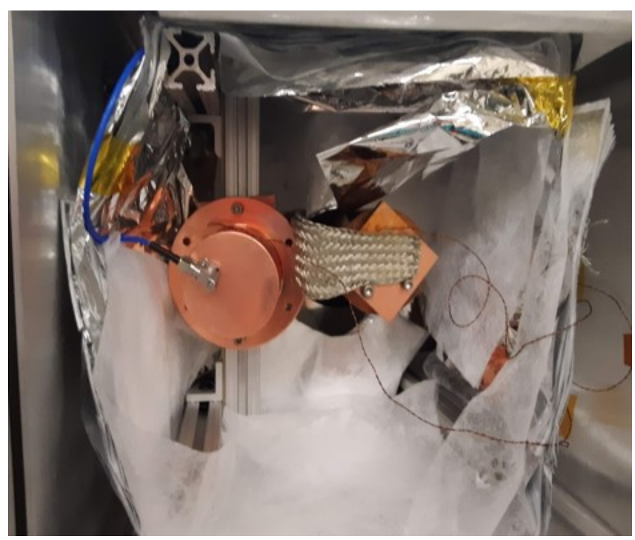

Figure 1: View of internal cryostat components, including MLI wrapping, 80/20 supports, coldhead, and thermal braid connection.

Cavities

The cavity itself is a 14.7 cm diameter cylindrical brazed copper cavity of height 7.3 cm with an RF port on top and coupling sites for thermal braid connections. It is designed to run low-level radio frequency (LLRF) room temperature and cryogenic c-band tests. A secondary cylindrical copper cavity, fabricated by Comeb, will be tested in future applications. See also Figure 2.

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Figure 2: Brazed copper cavity (top) utilized in our cooldown tests and Q factor measurements. The Comeb cavity (bottom) will be tested in the near future.

COOLDOWN AND QUALITY FACTOR TESTS

Thermal Braid and MLI Shielding Measurements

Cryogenic infrastructure tests involve cool-down tests with different configurations of MLI shielding and thermal braiding. We have collected an assortment of cool-down curves for the cryostat by testing each thermal component separately. Each test was performed at high vacuum between 10^{-4} – 10^{-6} hPa. First, we measured cooldown rates for the coldhead-cavity system in the presence and absence of a copper thermal braid. Figure 3 demonstrates that thermal coupling drastically increases cooldown rate at higher temperatures relative to the lower limit.

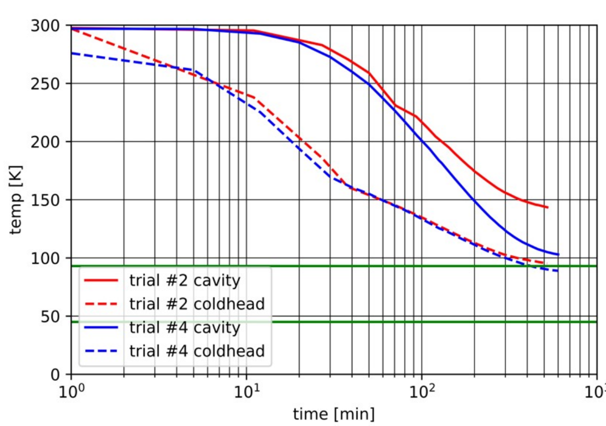

Figure 3: Copper thermal braid (dashed) cooldown efficiency compared to uncoupled coldhead-cavity system.

All MLI cooldown tests were performed unloaded to determine the lower limit on temperatures the cryostat can reach. MLI geometries are optimized to shrink the effective chamber volume to increase cooldown effectiveness to lower temperatures while minimizing heat shorts through contact with multiple instruments. "Outer" MLI refers to wrapping around the 80/20 supports and "inner" MLI is a sleeve placed on the coldhead. As shown in Figure 4, the unloaded cryostat reached a minimum temperature of 40 K under optimal conditions.

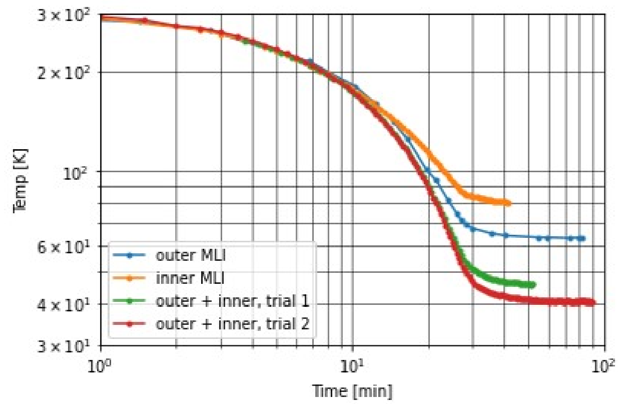

Figure 4: Cooldown tests with different MLI geometries and combinations reaching a minimum temperature of 40 K.

Q Factor Measurements

We measured the reflection coefficient versus frequency to generate a spectrum from which we take S_{11} at the minimum of the spectrum to be the resonant frequency. We have collected normalized quality factor measurements in Figure 5 from room temperature to 100 K, with intent to eventually reach 40 K.

Preliminary data shows a lower than expected Q factor, which likely suggests that the residual-resistance ratio (RRR) of the cavity is lower than expected (< 50). At lower temperatures with a better thermal coupling, we expect future Q factor measurements to align closer to theoretical values. The Comeb cavity will likely have less impurities than the brazed cavity, so future tests on the Comeb cavity should produce higher Q values.

CONCLUSION AND FUTURE DIRECTIONS

Ultimately, this experiment provided critical insight into the development of cryogenic infrastructure for cryochambers with volumes greater than 1 cubic foot. The addition of C-band measurements to the previously accumulated data generates a complete picture of the temperature dependent effects on quality factors of RF oscillators with any incident frequency radio wave. Once we establish lower temperatures, we will complete the data set with our desired values between 20-40 K. A bigger stainless steel chamber will provide more space for internal infrastructure and lead to less heat leakage due to surface contact between instruments. Replacing the 80/20 cavity mount with a better thermally insulating material will drastically decrease the temperature

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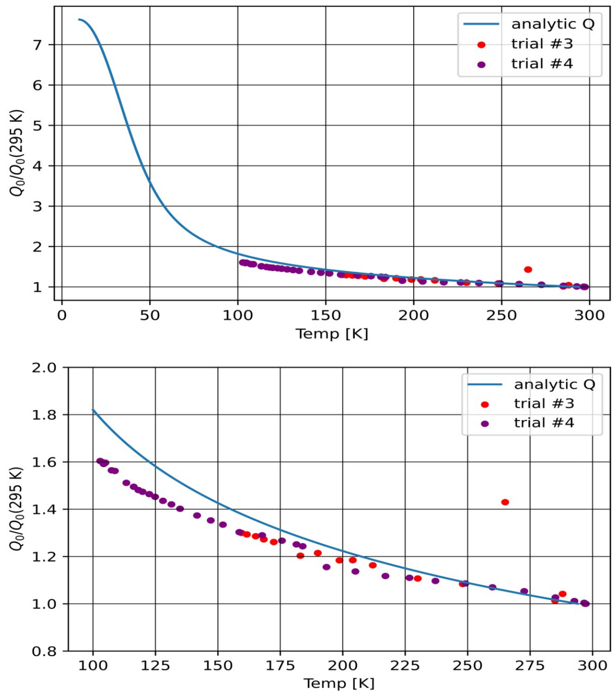

Figure 5: Normalized Q factor measurements plotted on linear scale against temperature running from 295 K to 100 K.

of the cavity, leading to more precise measurements of the enhanced quality factor. A smaller, more conductive thermal braid complete with indium foil wrappings will strengthen the thermal contact between the cavity and the coldhead. The edge-welded bellows have proven extremely useful for reducing vibrations, so they will soon be transferred to the half cell project in progress [1,5]. We will also begin testing a molybdenum insert which will stand in for future high brightness cathode plugs [5].

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