

## DIAGNOSIS, ANALYSIS, AND RESOLUTION OF THERMAL STABILITY ISSUES WITH HOM COUPLERS ON PROTOTYPE CEBAF SRF CAVITIES\*

C. E. Reece<sup>#</sup>, E. F. Daly, G. K. Davis, W. R. Hicks, T. Rothgeb, H.L. Phillips, J. Preble, H. Wang,  
and G. Wu<sup>†</sup>, Thomas Jefferson National Accelerator Facility, Newport News, VA, USA 23606

### Abstract

During initial testing of the prototype cavities incorporated into the developmental cryomodule *Renascence* severe thermal stability issues were encountered during CW operation. Additional diagnostic instrumentation was added. This enabled identification of an unanticipated thermal impedance between the HOM coupler probe feedthrough assembly and the cavity beamtube. Subsequent detailed FE analysis successfully modeled the situation and indicated the need for alternate cooling path for the couplers on those cavities. HOM damping was measured to be adequate employing only two of the four HOM couplers. The two pickup probes on the couplers at the input power coupler side of each cavity were removed, the remaining HOM probe feedthroughs were heat stationed to two-phase helium supply piping, and a novel heat sink was added to station both the inner and outer conductors of the remaining HOM rf cables. The characterization measurements, analysis, modifications, and resulting performance are presented.

### INTRODUCTION

In the design of prototype upgrade cavities for CEBAF the DESY-style HOM couplers were moved in close to the cavity cells in order to maximize the damping of dipole modes so as to increase the threshold for beam breakup (BBU) instabilities in recirculating linac applications. By design, these couplers incorporate tuned notch filters to reject outcoupling of the fundamental mode. Significant amplitude fields of the fundamental mode are present in the coupler, however. For the chosen geometry the amplitude of fundamental  $-$ mode magnetic field on the electric-field pickup probe is of order 10% of the peak field in the cells. See Figure 1.

These circumstances then require that the materials involved be superconducting. The coupling probe is the center conductor of a coaxial rf transmission line and so is supported by a dielectric spacer in the interface feedthrough. It was recognized early that for this application a custom feedthrough was required to include both a niobium coupling probe and also excellent thermal grounding of that niobium through a high thermal

conductivity dielectric in the feedthrough. Such a feedthrough was successfully developed at JLab[1] and has been adapted for use at BESSY and Daresbury, and is under consideration for use in the European XFEL.

Despite this successful development, serious performance issues arose during the testing of the *Renascence* cryomodule when these cavities and feedthroughs were first employed.[2]

A series of tests, model analyses, and adaptations were made which both clarified the debilitating thermal issues and yielded satisfactory resolution.

The magnetic fields in this region are  $\sim 10\%$  of the peak surface fields in accelerating cells.

⇒ Probe material must be superconducting

⇒ Good thermal anchoring is required

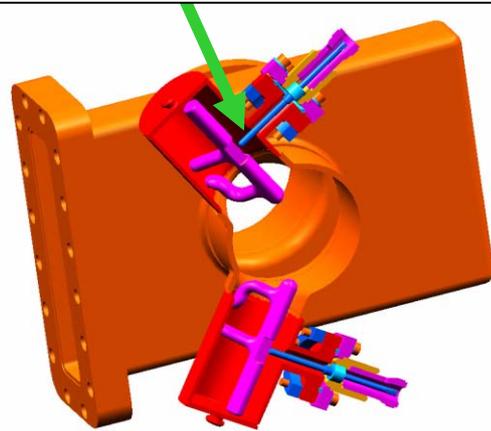


Figure 1. HOM coupler configuration in the CEBAF *Renascence* prototype cavities, locating the critical cooling situation.

### THERMAL ISSUES

#### *End group quenching*

Upon initial testing of the cavities in the *Renascence* cryomodule, we found cavity endgroup quenching occurred at low gradients (6-12 MV/m) during CW testing. Cavity response was much better in pulsed rf conditions using 10% duty cycle. The issue was thus understood as a thermal conduction problem.

Diagnostic instrumentation on a few of the HOM rf feedthroughs indicated unexpectedly high temperatures ( $\sim 6.4$  K) under static cryogenic conditions. With moderate rf operation these feedthroughs warmed through transition

\* This manuscript has been authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

<sup>#</sup>reece@jlab.org

<sup>†</sup>Currently at FNAL

of the niobium, subsequently the additional heat would cause the cavity to quench.

To thoroughly characterize the problems, the cryomodule was warmed and a set of instrumentation and thermal clamping was added *in situ*.

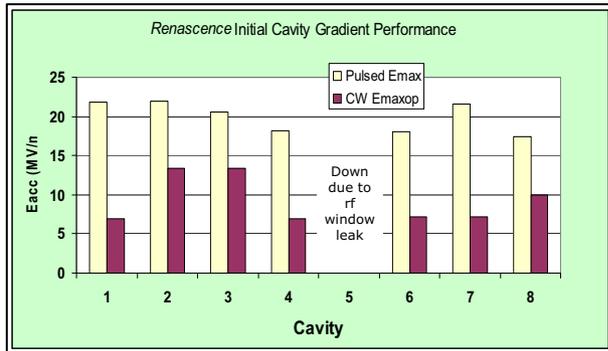


Figure 2. Maximum performance of Renaissance cavities on first test.

**Observation Summary**

- FPC endgroup temperatures (and thus those HOM couplers) were higher than expected – both static and with rf operation. Under high power operation (10.2 kW CW) the waveguide body temperature readout was 8.4 K, with several watts being conducted from the waveguide interface through the endgroup to the 2 K helium vessel around the cavity cells.
- The HOM coupler rf cable center conductors were not well cooled. Although the cable outer conductor was effectively tied to both the 50 K shield and 2 K piping, the center conductor had no thermal intercept between room temperature and the cavity feedthrough.
- Static conditions with only 20 mW conducted via the rf cable produced unacceptable temperatures to the HOM probe assembly.
- The heat conducted to the HOM couplers via the RF cable was observed to be as high as 30-45 mW, significantly higher than expected.
- The custom rf feedthroughs had been developed to provide excellent thermal conductivity to the Nb probe via a brazed single-crystal sapphire dielectric.[1] These had performed satisfactorily in separate tests.
- The Nb probe is isothermal with the Cu body of the HOM feedthrough, but not with the cavity. The thermal impedance between the HOM feedthrough and Nb cavity was thus higher than expected.
- Examining the shifts in differential temperatures in response to applied heat, we discerned that the HOM coupler port tube/flange weld on the cavity has high thermal impedance due to small cross-section ~35 mK/mW, and the impedance from the stainless steel flange on the feedthrough across the gasket/bolt assembly to the NbTi flange was ~24 mK/mW.

- With low gradient cavity operation, the HOM coupler rf feedthroughs quenched and led to subsequent cavity quench.
- Under all circumstances with rf in a cavity, when an HOM probe feedthrough temperature reached 8.2 – 8.5 K, the interior Nb probe went normal and the feedthrough temperature rose dramatically (60 – 90 K) prior to the cavity proper quenching.
- The thermal relaxation time of the waveguide system is 2.9 minutes. The thermal relaxation time of just the Nb endgroup is < 2 seconds.

The most important conclusions were obvious: independent thermal strapping of the feedthrough body was necessary, and a thorough thermal analysis was required.

**THERMAL ANALYSIS**

A detailed ANSYS model of the feedthrough, cable, and coupler port tube interface was constructed. See Figure 3. Previous models had failed to account for the small conduction cross section between the NbTi flange and the Nb port tube. The new model correctly predicted the experimental observations. Addition of thermal strapping to the copper body of the feedthrough is clearly needed.

Figure 4 shows the same model with such thermal stationing added.

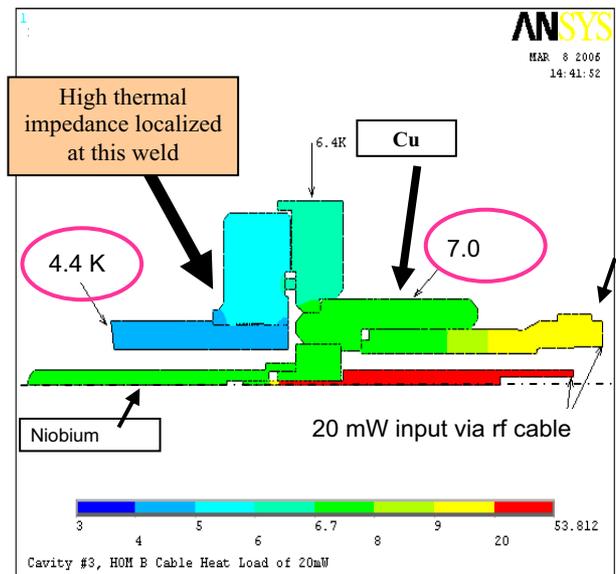


Figure 3. ANSYS thermal model of the as-built configuration of the HOM coupler/probe feedthrough assembly.

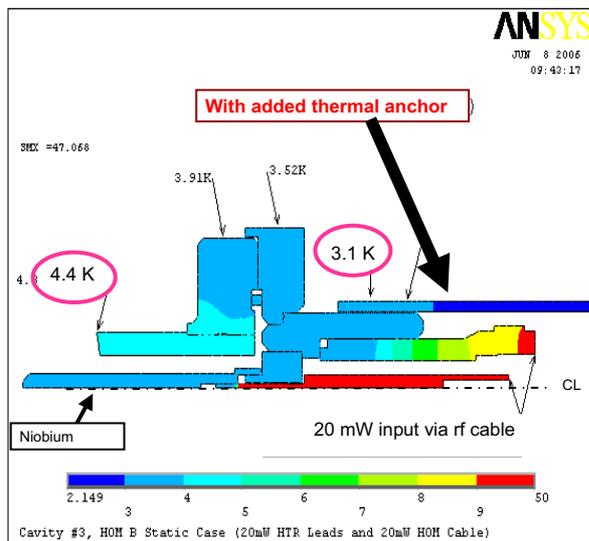


Figure 4. ANSYS thermal model of the HOM coupler/probe feedthrough assembly with added thermal anchor.

In addition, an integrated ANSYS model was constructed to better understand the thermal profile of the whole input coupler endgroup. See Figure 5. The waveguide coupler endgroup is conduction cooled to the cavity helium vessel. A copper-plated waveguide section connects the cavity to the outside.[3] A serpentine-shaped aluminum gasket forms the seal between the cavity flange and the input waveguide. This gasket provides desirable thermal impedance against conduction through the cavity endgroup.

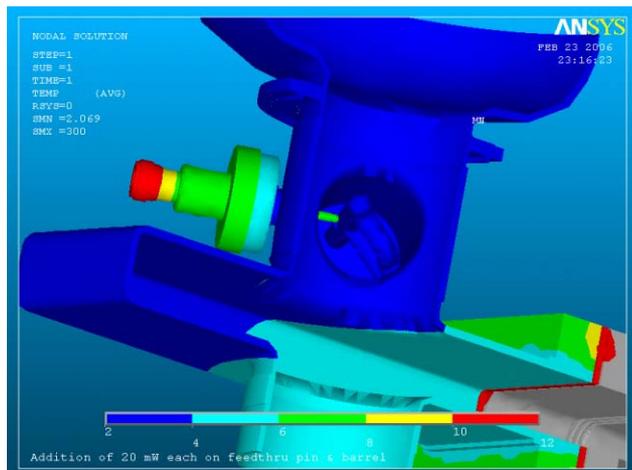


Figure 5. Integrated ANSYS model of Renascence LL cavity endgroup, input waveguide, and HOM coupler feedthrough

### Results from analysis

The measurements on Renascence and the analytical thermal models yielded a consistent picture.

### The 2 K load conducted via the waveguide coupler is acceptable for design conditions.

- There is 1 W static load from the waveguide flange to 2 K via endgroup conduction. An additional 2-3 W is expected under nominal rf operating conditions.
- The calculated temperature profile is consistent with the measurements on *Renascence*.

### The HOM feedthroughs were not thermally stabilized.

- We cannot depend on conduction cooling through the gasket and flange.
- Strap the Cu body to a 2 K supply line.

### The HOM couplers on the FPC end of the cavities were particularly problematic.

- Subject to dynamic thermal environment due to conducted waveguide heat.
- Adequate fundamental rejection was not consistently achieved.
- These problems are eliminated if these couplers can be removed.

### The HOM coupler rf cables need better thermal intercepts for the inner conductor.

- Measure cable conduction properties to enable better system engineering.
- Avoid continuous 300 K to 2 K conductor.
- A thermal shunt has been developed and subsequently used in *Renascence* and the C100 cavity Horizontal Test Bed tests.

### The fundamental $H$ fields on the HOM hook and probe are ~10% of the peak field in cells.

- This produces rf dissipation of 5-20 mW on the Nb probe at 20 MV/m operation.
- This heat source term may be reduced by optimizing the coupler orientation and location. (This was subsequently done in the C100 cavity design.)

## RESOLUTION OF ISSUES

### Coupler design modifications

To dramatically reduce the heat source term in future CEBAF upgrade cavities, the location and orientation details of the HOM couplers has been re-optimized.[4] In the new configuration the rf dissipation on the probe has decreased by a factor of 90. See Figure 6.

### Thermal intercept for rf cable

Providing thermal stationing of the outer conductor of a coaxial cable is straightforward. Such is routinely accomplished by removing the cable jacket and then sandwiching a section of the cable in a copper clamp with indium foil to establish a good thermal bond. The copper clamp is bonded to either a shield (e. g. 50K) or primary (2K) surface.

Establishing a thermal anchor for the coaxial cable center conductor is more difficult. Typically the cable dielectric is either a solid or spun fabric Teflon and has poor thermal conduction.

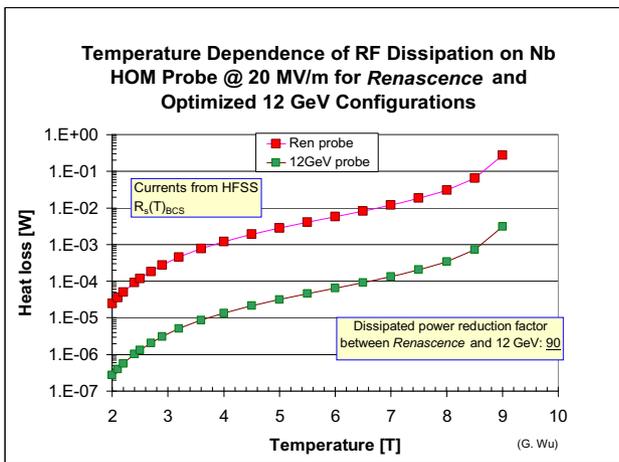


Figure 6. Calculated rf dissipation on the HOM coupler probe at 20 MV/m CW operation in the original and optimized configurations.

We developed, tested, and implemented a new rf intercept component. This device is based on an rf stripline using high purity alumina dielectric with the ground plane thermally anchored. See Figure 7. The device effectively shunts >100 mW of conducted heat from the rf cable center conductor while maintaining excellent rf transmission characteristics in the required 1-4 GHz band.

*Thermal strapping for feedthroughs*

Copper straps were added between clamps on the HOM coupler probe feedthroughs and brazed connections to the 2 K distribution header. The final configuration used in the Renascence cryomodule is indicated in Figure 8.

*Performance*

Implementing these enhancements in the Renascence cryomodule and the C100 Horizontal Test Bed test yielded quite stable performance. In both configurations, monitoring temperature diodes on the rf feedthroughs showed only 0.1 K increase from ~ 4.5 K under full CW

20 MV/m cavity operation. [2, 4] The thermal problems encountered have thus been well characterized and remedied.

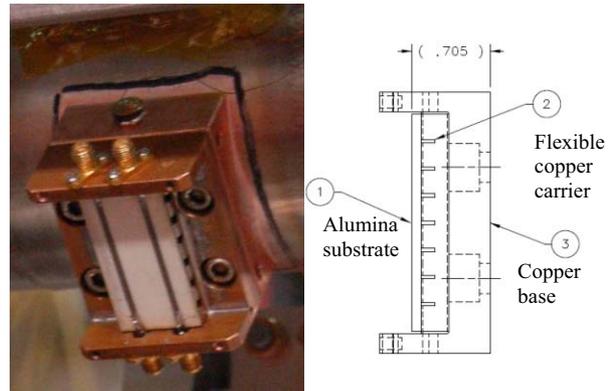


Figure 7. Thermal intercept for rf transmission from HOM coupler to room temperature.

**ACKNOWLEDGEMENTS**

The skilled and flexible hands of members of the JLab cryomodule assembly group did an amazing job implementing the “*in situ*” diagnostics that allowed us characterize the thermal conduction issues in *Renascence*.

**REFERENCES**

- [1] C. E. Reece et al., “[High Thermal Conductivity Cryogenic RF Feedthroughs for Higher Order Mode Couplers](#)” PAC05, p.4108, TPPT082.
- [2] C. E. Reece et al., “Performance of the CEBAF Prototype Cryomodule *Renascence*,” contribution WEP32 to this Workshop.
- [3] E. F. Daly et al., “[Improved Prototype Cryomodule for the CEBAF 12 GeV Upgrade](#),” PAC03, p.1377, TPAB077.
- [4] C. E. Reece et al., “Optimization of the SRF Cavity Design for the CEBAF 12 GeV Upgrade,” contribution WEP31 to this Workshop.

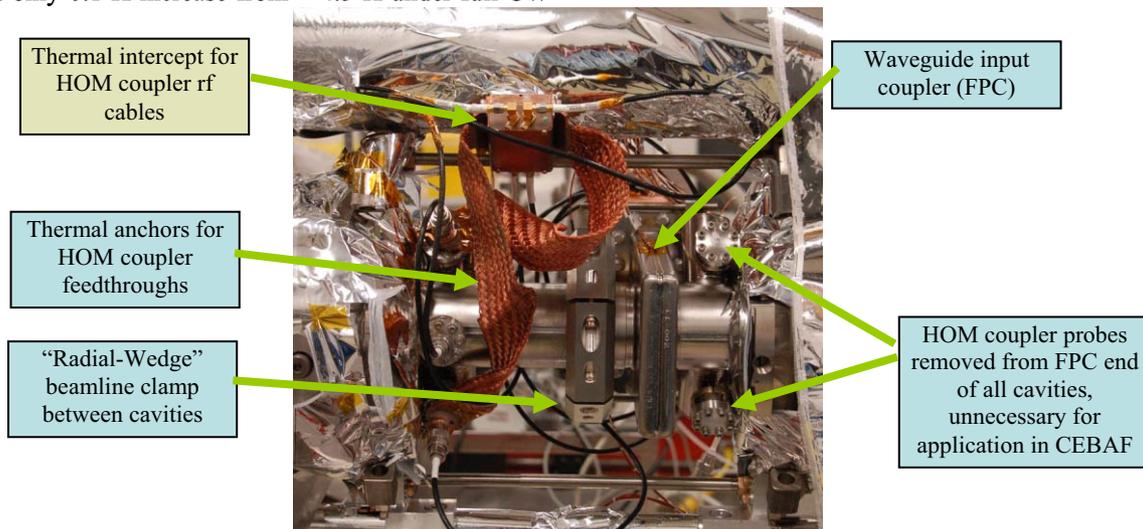


Figure 8. Photograph of HOM coupler region of the cavities with additional thermal anchoring.