RF-THERMAL COMBINED SIMULATIONS OF A SUPERCONDUCTING HOM COAXIAL COUPLER*

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Abstract

To benchmark a multi-physics code VORPAL developed by Tech-X, the High Order Mode (HOM) coaxial coupler design implemented in Jefferson Lab's 12GeV upgrade cryomodules is analyzed by use of commercial codes, such as ANSYS, HFSS and Microwave Studio. Testing data from a Horizontal Test Bench (HTB) experiment on a dual-cavity prototype are also utilized in the verification of simulation results. The work includes two stages: first, the HOM feedthrough that has a high RRR niobium probe and sapphire insulator is analyzed for the RF-thermal response when there is travelling wave passing through; second, the HTB testing condition is simulated and results from simulation are compared to thermal measurements from HTB tests. The analyses are of coupled-field nature and involve highly nonlinear temperature dependent thermal conductivities and electric resistivities for the eight types of materials used in the design. Accuracy and efficiency are the main factors in evaluation of the performance of the codes.

HOM COAXIAL COUPLER

HOM coaxial couplers are typically used for damping the higher order mode microwave filtered from accelerator cavities. For Jefferson Lab (JLAB) 12 GeV upgrade cryomodule cavity (also called C100 cavity) end group, two identical HOM couplers per cavity are installed as illustrated in Fig. 1. The portion of HOM coupler except HOM can and hook is called HOM feedthrough. During JLAB's past cryomodule development, thermal impedance of HOM coupler was found to be a cause of superconducting cavity thermal instability [1]. Various designs of HOM couplers for other cryomodules were analyzed [2] and tested [3] previously for better understanding of RF heating and thermal impedance in the coupler.

The current design incorporates a thermal anchor to the cold surface of 2K liquid helium headers via a braided copper wire thermal strap that is brazed to a copper bracket. The HOM coupler has a high RRR niobium pick-up probe with a tapered tip. Strong magnetic field occurs at the gap in between the probe tip and the hook. It is thus desirable to keep the Nb probe at superconducting state to mitigate the heat generated. At the other end of the Nb probe, it is brazed to both the pin of a type N connector and a sapphire ring. The connector connects to a coaxial RF cable through a 90° elbow adapter. The cable's inner pin and outer conductor transfers two types of heat to the HOM coupler: static load due to thermal conduction and dynamic load due to RF heating.

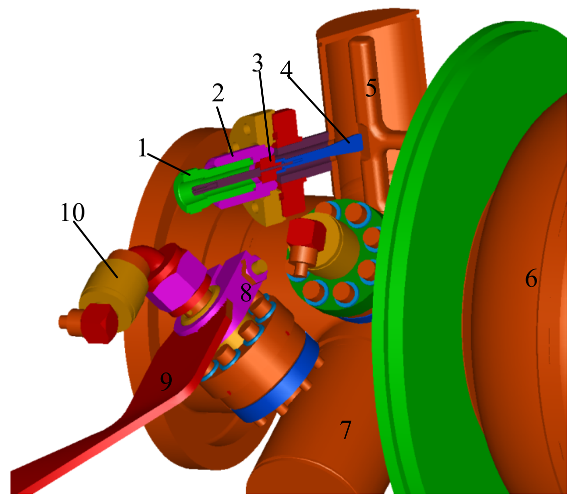

Figure 1: HOM coaxial couplers on JLAB 12 GeV upgrade cryomodule cavity end group (some components are abridged for clarity): 1. Type N connector; 2. Cu sleeve; 3. Sapphire ring; 4. Nb probe; 5. Nb hook; 6. Nb cavity; 7. HOM can; 8. Cu bracket; 9. Cu thermal strap; 10. Elbow adapter.

HTB TESTS OF HOM COUPLERS

During JLAB's HTB test of a two-cavity prototype C100 cryomodule in 2008, the temperatures of all four HOM couplers are monitored at HOM feedthrough copper sleeves. Figure 2 shows two HOM couplers on one C100 cavity in HTB prototype cryomodule. To investigate how excessive heating would affect the temperature of Nb probe, a heater is attached to the copper sleeve of the HOM feedthrough. Temperature sensor is mounted on the opposite side of the heater resistor. The assumption is that the temperature on the copper sleeve is close to that of the Nb probe tip. Up to 10 heater power levels were run for the zero RF and non-zero RF scenarios. The acceleration gradient of 19.5 MV/m, which is the specified acceleration gradient for C100 cavity operating at 1497 MHz fundamental frequency, was achieved. It is found that at 19.5 MV/m, heater power greater than 300 mW could bring the coupler body temperature above the 9.2K transition temperature of Nb. The HTB test also indicates that at the zero RF static equilibrium, the temperature at the HOM coupler and HOM can body is around 4.1K.

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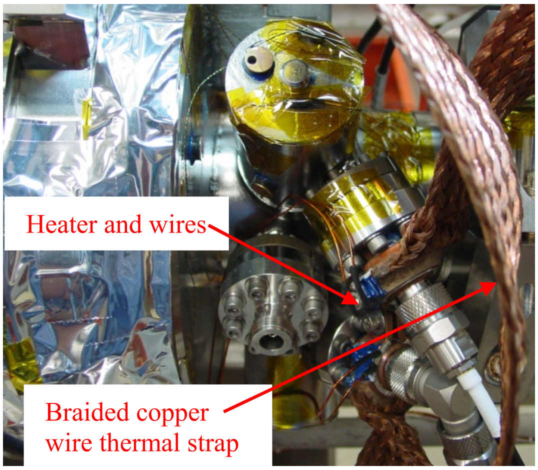

Figure 2: HOM coaxial couplers in HTB cryomodule.

RF-THERMAL MODEL AND LOADS

To simulate the steady-state performance of HOM coaxial coupler, a few RF-Thermal models with slight variations were created for analysis in multiple software packages. Figure 3 shows a simplified 10-degree wedge model of the HOM feedthrough. Since the feedthrough is separated from HOM can and elbow adaptor, appropriate boundary conditions need to be applied.

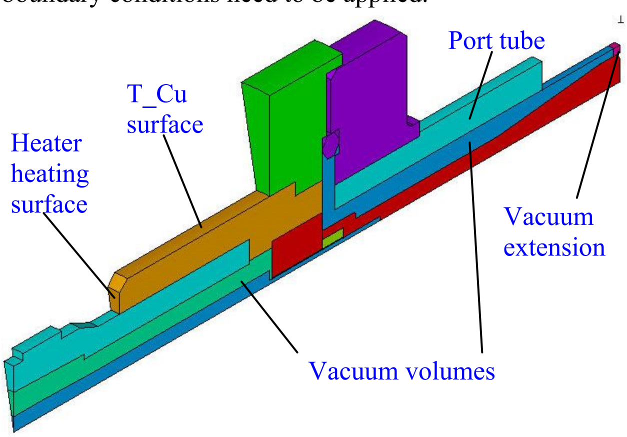

Figure 3: A wedge model of HOM feedthrough.

For the RF analysis, the pick-up/input port is located at the Nb probe tip side and the output port is at the type N connector side. Settings of input power and frequencies are relying on the scenarios to study.

The HOM coaxial coupler is subjected to static and dynamic loads as mentioned above, depending on whether the RF is on or off. The following is a list of boundary conditions and thermal loads needed:

1. Temperature at thermal strap cold end is 2.0K.
2. Temperature at port tube end face is 4.1K.
3. Static loads from coaxial RF cable to type N connector.
4. Dynamic load from coaxial RF cable to type N connector.
5. RF heat due to notch magnetic field in HOM can at Nb probe tip. A probe tip temperature vs. RF heat relationship was developed by G. Wu [2] and revised by H. Wang. Refer to Fig. 4 red curve for C100 cavity. Probe heating above 9.2K is 50~60mw.
6. RF heating in HOM feedthrough by travelling wave either due to a fundamental power leaking from the HOM can or a second harmonic power from the nearest waveguide possibly produced from the klystron.

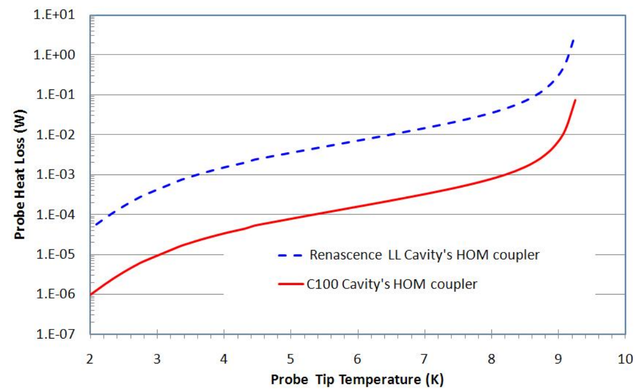

Figure 4: Niobium probe tip heat vs. Temperature at E_{acc} = 20MV/m by 3D RF code (HFSS or Omeg3P).

COMPARISON OF ELECTRIC AND MAGNETIC FIELD RESULTS

The analysis involves the evaluation of RF loss based on surface magnetic field. During the early stage of the benchmark work, a RF model that has slightly different vacuum extension from that shown in Fig. 3 is analyzed by multiple software packages: ANSYS, MWS, HFSS, and VORPAL for cross check. The incipient 1497 MHz RF microwave is continuous travelling wave having 0.5 Watts time average power. The comparisons of electric and magnetic field magnitudes along a straight line stretched across the model, from the analyses conducted by multiple codes, are presented in Figs. 5 and 6, respectively. All codes agree well on electric field solutions. Slight discrepancies are observed from the magnetic field solutions.

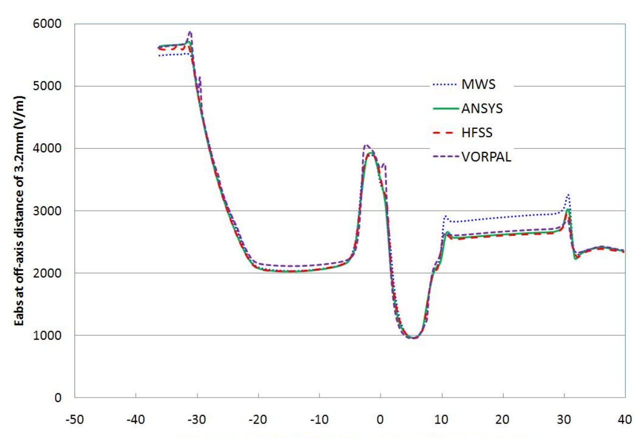

Figure 5: Electric field magnitude comparison.

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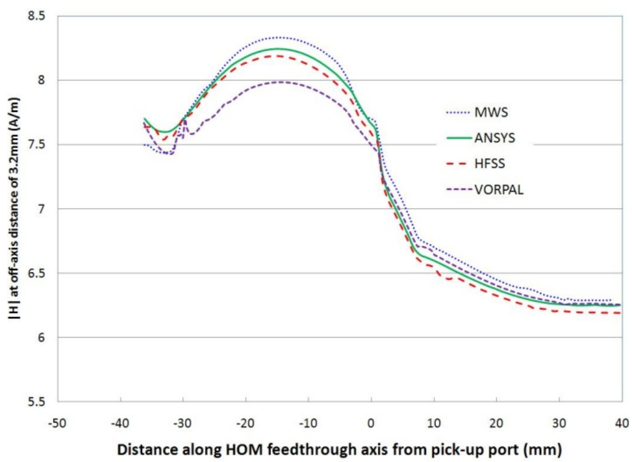

Figure 6: Magnetic field magnitude comparison.

ANALYSIS VS HTB TEST DATA

RF-thermal coupled analysis by ANSYS is conducted to simulate the HTB tests using heater power to drive the superconductors to across the transition temperature of 9.2K. The estimated static loads from RF cable are 12.0 mW and 39.13 mW and the dynamic loads are 8 mW and 2.78 mW to the inner and outer conductors, respectively. The input RF microwave is 1497MHz travelling wave with 208.4 mW time averaged power. An 1-D thermal link is used to represent the thermal strap. The RRR of thermal strap is found to be quite influential on the temperature results. Copper RRR = 60 is used in this analysis.

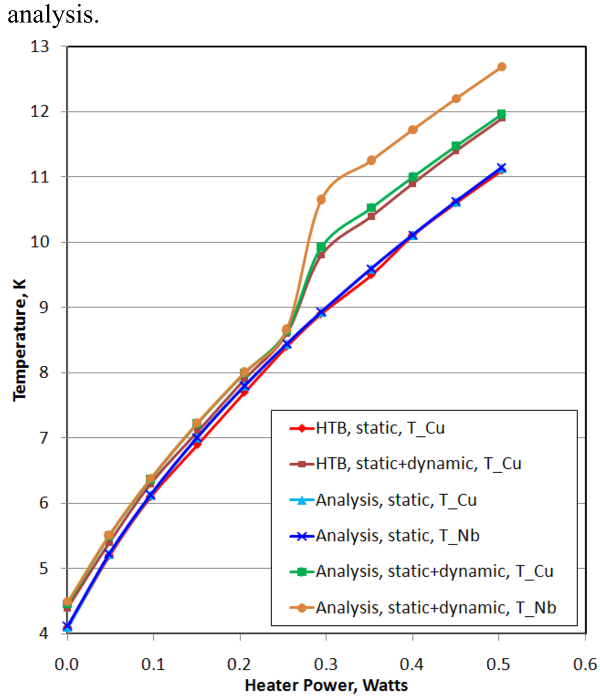

Figure 7: Temperatures from analysis and HTB tests.

Copper sleeve and Nb probe tip temperatures are compared to HTB data in Fig. 7 for the scenario of dynamic load generated from 19.5 MV/m acceleration gradient. It is seen that the ANSYS analysis agrees very well with testing results at all heater power levels. For the static load only cases, copper sleeve and Nb probe tip have almost the same temperatures. The deviation occurs when heater power is above 300 mW and Nb probe tip becomes normal conducting.

Both a 10-degree wedge model (see Fig. 3) and a 360° degree full model (see Fig. 8) are developed. The copper and Nb temperatures from both models are close. For example, at heater power of 503 mW, for the static + dynamic load case, wedge model predicts T_Cu = 11.96K and full model yields T_Cu = 11.84K. The full model does have a gap in the copper bracket volume to simulate the break in the real part.

The models, material properties, boundary conditions, etc. can be used in VORPAL or other multiphysics simulation packages for benchmarking analysis.

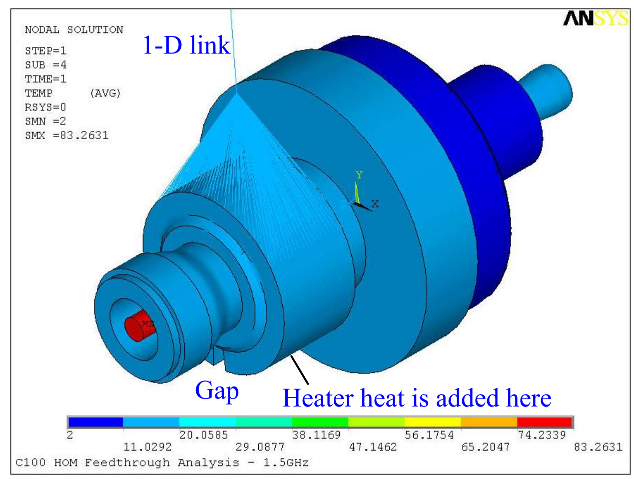

Figure 8: Temperature in a full model when the heater power is 503 mW.

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