TESTING STATUS OF THE SUPERCONDUCTING RF POWER COUPLER FOR THE APT ACCELERATOR

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Abstract

The Accelerator Production of Tritium Superconducting Radio Frequency Power Coupler has undergone preliminary testing at room-temperature conditions. To date, the window/coupler assemblies have transmitted up to 1 MW of continuous power and 850-kW standing wave at 700 MHz through a room-temperature TM_{010} cavity. This was accomplished with the first set of coupler components tested on a recently completed, room temperature test stand. Only one small range near 280 kW has shown any propensity for multipacting. Thermal data obtained from infrared (IR) camera mapping and numerous thermometers are presented as a function of power transmitted through the test stand. Calorimetry data based on coolant-flow temperatures is presented. Preliminary vacuum and RF results are also presented. The remaining thermal, RF, and mechanical testing plan is discussed, including the adaptation of the test stand to test the power coupler at cryogenic temperatures.

1 INTRODUCTION

The superconducting portion of the 1030 MeV APT accelerator will have numerous five-cell cavities. Each cavity will requires a total of 420 kW of continuous radio frequency (RF) power at a frequency of 700 MHz.

There are three major components in the APT design, consisting of the RF-window assembly, the inner conductor, and the outer conductor. The RF-window assembly was produced by EEV of England. Full-height WR-1500 waveguide goes through a T-bar to 6 in. (50 Ohm) coaxial transition, through a double ceramic window section and then to the coupler. One of the two uncoated, planar, ceramic windows serves as the vacuum barrier. The coupler starts at a 6-in. coaxial, quarter-wave stub, right-angle section. The coupler and RF window assembly join at the tee bellows, which relieves most of the stress that would normally be transferred to the window through the inner conductor. A 6-in. diameter vacuum port, located directly below the quarter-wave intersection, provides good vacuum pumping near the window. The coaxial line tapers to standard 4-in. dimensions, terminating with a bulged probe-tip end on the inner conductor. The outer conductor is constructed of

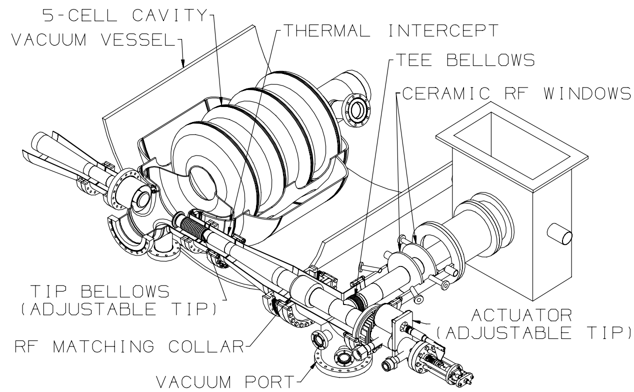

Figure 1: Power coupler, RF window, and cavity assembly

bright-acid copper-plated 304L stainless steel while the inner conductor is primarily OFE copper. The components are shown assembled in Figure 1. More design details are presented in another paper [1].

Three fixed-tip inner conductors dubbed the gamma design, eight outer conductors, and four RF-window assemblies have been fabricated. Testing with high-power RF began in July of 1999.

2 LOW POWER COUPLER TESTING

The windows and couplers have been well characterized. The double window assembly was specified to be very low loss. As can be seen in Figure 2a below, the transmission and return loss are very good, even over a large range.

The power coupler is a singly resonant, quarter-wave stub design. The vacuum port just below the tee region required the use of a substantial matching collar on the inner conductor. The coupler is not broadband in the strictest sense, but its transmission characteristic is sufficiently broadband to load the other resonant modes of the cavity. Figure 2b shows the coupler's low power test data. The resonant frequency in the test data is slightly low due to the fact that the matching collar of the dummy inner conductor (used for network analyzer measurements) was machined 1.5 mm off. Sensitivity of the position of the matching collar and of the quarter-wave short is approximately 2 MHz/mm along the axis.

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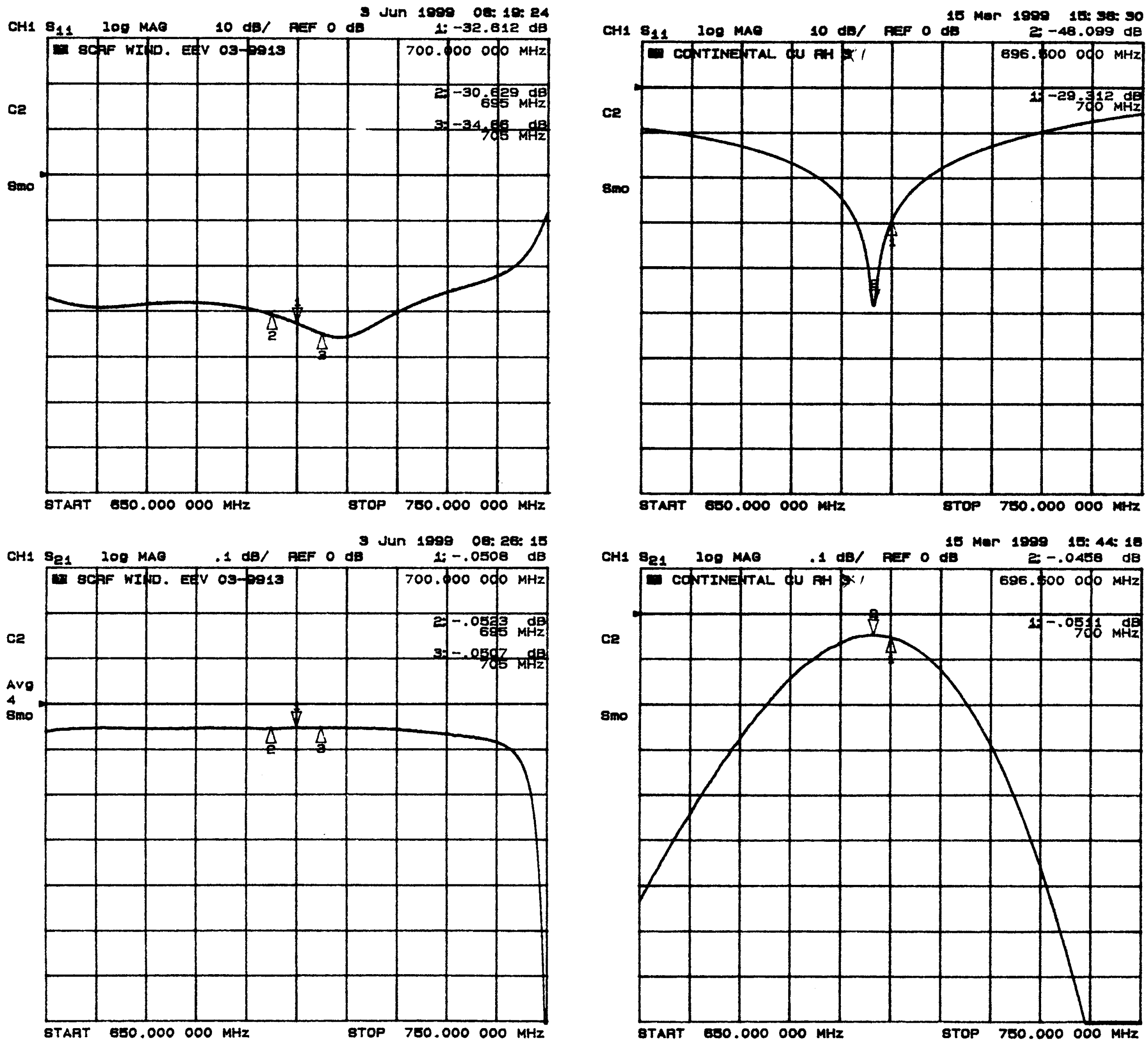

(a) (b)

Figure 2: Transmission (above) and reflection (below) coefficients obtained at low power for (a) the EEV RF-window assembly and (b) the power coupler assembly

3 HIGH POWER COUPLER TESTING

Testing of the power couplers was accomplished on a test stand dubbed the Room Temperature Test Bed (RTTB) (Figure 3) [2]. Up to 1 MW CW of RF power is available from a 700-MHz klystron. Two pairs of couplers and RF window assemblies are coupled by a pillbox cavity in the TM_{010} mode. The RTTB also serves as a means to demonstrate the vacuum and control systems for the cryomodule. Its future use will be to condition coupler/window assemblies prior to assembly on the cryomodule. The RTTB has complete data acquisition, interlock, and vacuum hardware and control systems. Labview [3] is used to run both the vacuum system and the data acquisition. The RTTB is versatile and can be easily adapted to test components at high RF power.

In the initial setup, one of the inner conductors had a leak. This component set was conditioned to 450 kW despite the leak. The remaining coupler testing, and the data presented in this paper was with the leaking inner conductor replaced. Testing has consisted of determining RF transmission characteristics at power levels up to 1 MW continuous travelling and 850 kW continuous and pulsed standing wave. Other testing was for verification of the coolant system, demonstration of the vacuum, and determining outgassing behavior of various plating and cleaning techniques.

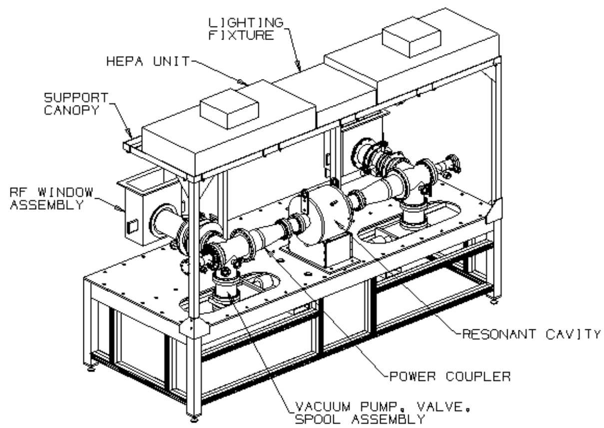

Figure 3: Room Temperature Test Bed

3.1 RTTB Coolant System

The design of the coolant system is based on finite different method calculations. Detailed results for the inner and outer conductors have been published [4]. For operation in the accelerator, calculations show the inner conductor will be adequately cooled for both travelling and standing waves by using 300 K helium at 1.2 atm, flowing at 3 g/s through the annular space formed by a stainless-steel sleeve within the copper inner conductor. Outer conductor cooling consists of a dual point thermal intercept located between itself and the Niobium cavity with 4.6 K He at 18 atm. Natural convection cools the portion of the outer conductor that is outside the vacuum vessel (Figure 4), and forced air cools the RF-window.

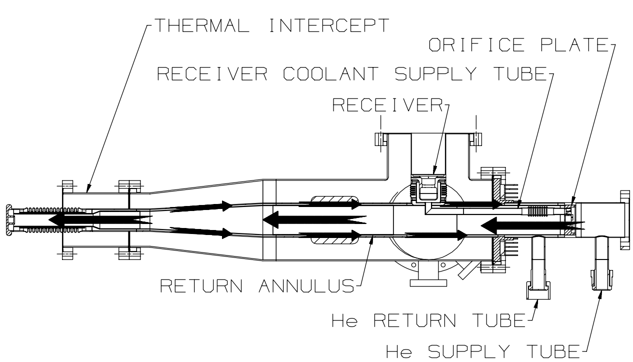

Figure 4: Coupler coolant system shown with Alpha IC

The test stand coolant system varies from this somewhat. There is no thermal intercept on the outer conductor, and two 0.25 HP blowers in series deliver a maximum of 18 ft^3/min. of air to each inner conductor for internal cooling. Each RF window assembly is cooled with two air streams. Air is blown between the ceramic windows and also enters the waveguide T-bar transition, travels down the inner conductor, across the air-side window, and exits the outer conductor near the waveguide.

Temperature was measured using thermocouples (TC) and resistive thermoelectric devices (RTD). Two TC's measure inner conductor temperature at the tip and the matching sleeve. RTD's measure all other external surface and coolant air inlet and outlet temperatures of the components. An infrared camera was used to determine locations of possible hot spots due to field enhancement or multipacting. The side port of the outer conductor was used to view the tee bellows and the vacuum side of the RF window. Temperature is measured at four exterior points at the ceramic windows.

3.2 Coolant Testing Results

Testing to date has consisted of steady state acquisition of temperature at transmitted power levels up to 450 kW. Figure 5 shows the steady state temperature of the shorting flange, tip, and outlet gas for the input inner conductor. Figure 6 is the outer conductor external temperatures. Figure 7 is the average ceramic temperature measured on the external surface and the exit air temperatures of the RF window coolant air. The non-linearity of the data points from 150 kW to 300 kW was due to data recording prior to thermal equilibrium.

Calorimetry was performed on the cavity, power coupler, and RF window assembly based on coolant temperatures and estimates of heat loss due to convection. A convection coefficient of 10 W/m^2-K was used for the outer conductor and RF window assembly. Figure 8 is a plot of the total power loss for the power coupler assembly vs. transmitted power.

3.3 Flow Testing Results

The inner conductor coolant is divided between the tip and the receiver. Flow tests were performed to determine the portion of gas entering each region of the inner conductor. About 20 % of the gas goes to the receiver with the balance travelling to the tip and out the annular region. Pressure drop was measured for several volumetric flow rates, shown in Figure 9 for air with no RF heating.

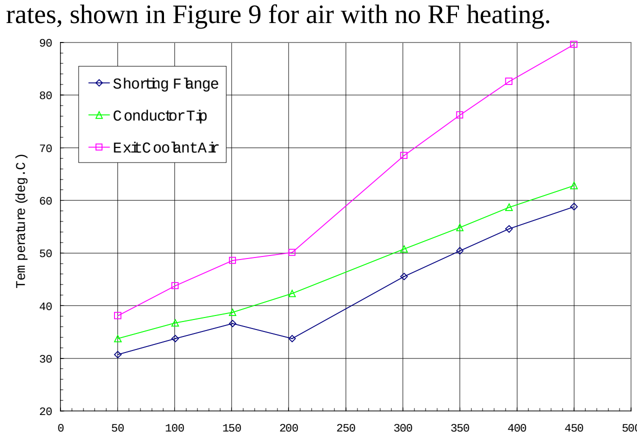

Figure 5: Equilibrium temp. for the input inner conductor

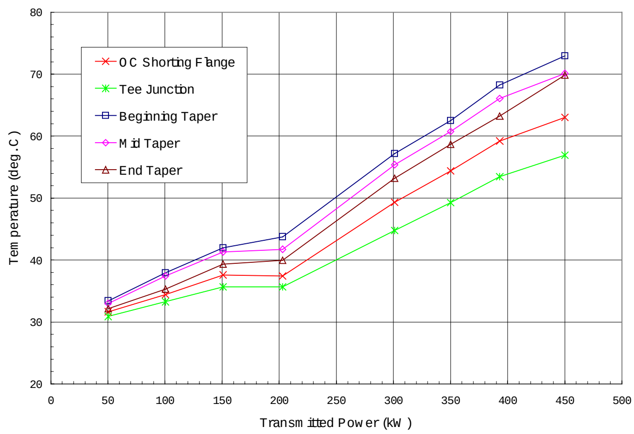

Figure 6: Steady state temperatures of the outer conductor vs. transmitted power levels

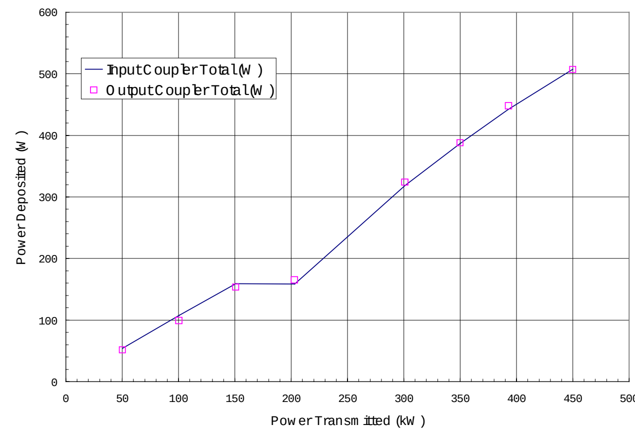

Figure 8: Power deposited in the input and output power couplers

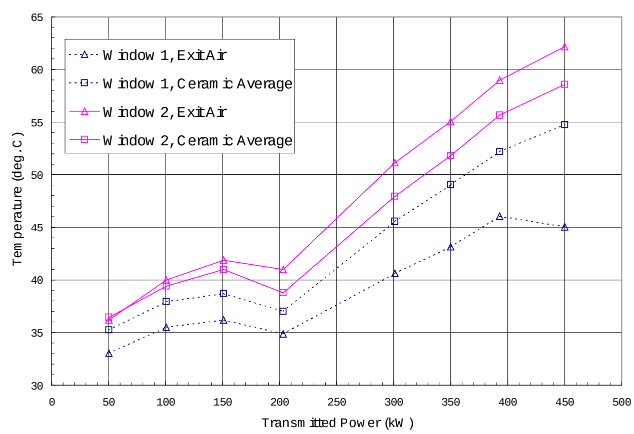

Figure 7: Steady state temperatures of the RF window external to the ceramic and the exit air temperature

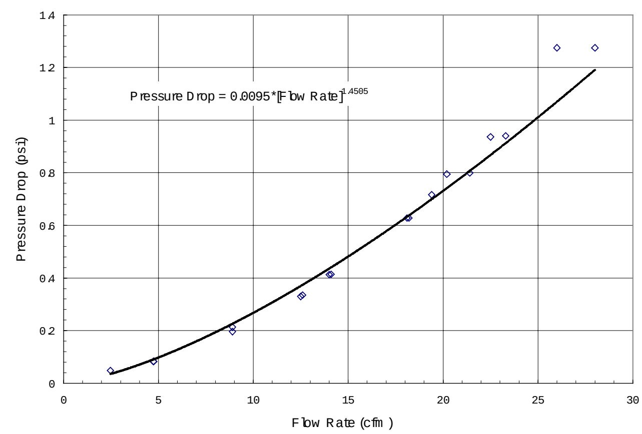

Figure 9: Pressure drop in inner conductor coolant passage versus flow rate of air with no RF applied

3.4 RF and Vacuum Performance

Coupler components were cleaned prior to assembly with low pressure deionized (DI) water, except for one of the inner conductors, which was cleaned with Citronox. The RF window assemblies and the cavity were cleaned with ethanol. Components were baked at 150 °C for two days under vacuum and then RF power was applied. It took approximately 16 hours of conditioning to reach a transmitted power level of 1 MW. Figures 10 and 11 show the conditioning history of this set of components plotted versus time. Large breaks in the data actually indicate a different day of operation.

A long, continuous run was performed at the 950 kW level. Figure 12 shows the time history of the power levels and ion gage data for the couplers and the cavity. Figure 13 depicts the data from a residual gas analyzer (RGA) for the same run. Note the rise in the hydrogen and carbon constituents at the higher power levels. Both rise more quickly than the other species. This could be an indication that there was some organic solvent left over from the cleaning, or organic material was being baked out of the plated layer. In either case, the couplers and cavity require a more thorough cleaning to determine if there can be any improvement in the conditioning time.

All throughout conditioning, there were no hard multipacting barriers encountered. There were two possible power levels that showed repeatable, although very weak indication of electron activity due to vacuum levels. Figure 14 is a plot of pressure versus time while sweeping the power level from 265-290 kW.

The braze joint at the inner conductor of the output window also glowed a bright orange hue above 400 kW. While the glow did not get better or worse with time, it may indicate a lifetime limit for this particular window assembly. The glow is shown in Figure 15 at the center of the viewport. This may be an indication that the materials and brazing techniques are not necessarily consistent, even on closely related windows. More conductive braze materials, or keeping the wall currents low near a braze joint, could be of significant benefit to future designs.

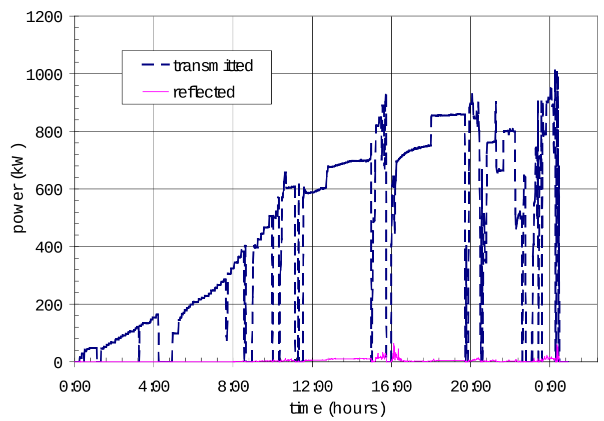

Figure 10: Transmitted and reflected power versus time during conditioning of power couplers

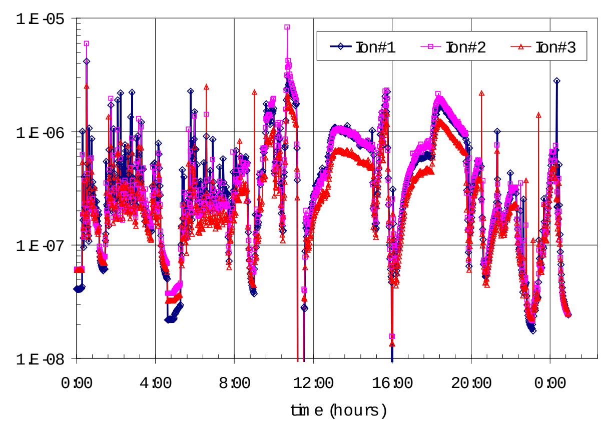

Figure 11: Pressure (torr) versus time for the same conditioning period as in Figure 10 (data is from three separate pressure measurements throughout system)

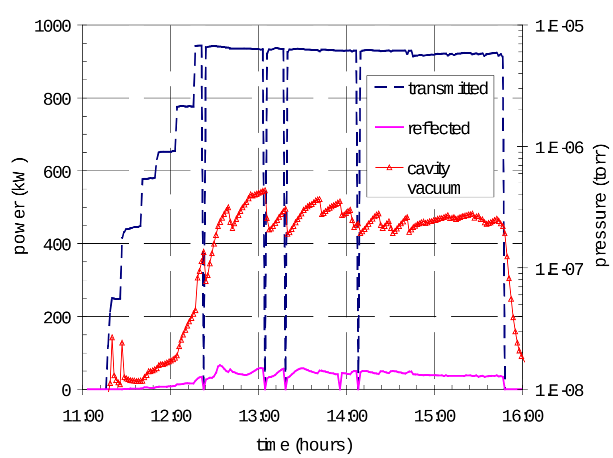

Figure 12: Transmitted power, reflected power, and pressure versus time during prolonged 950 kW test

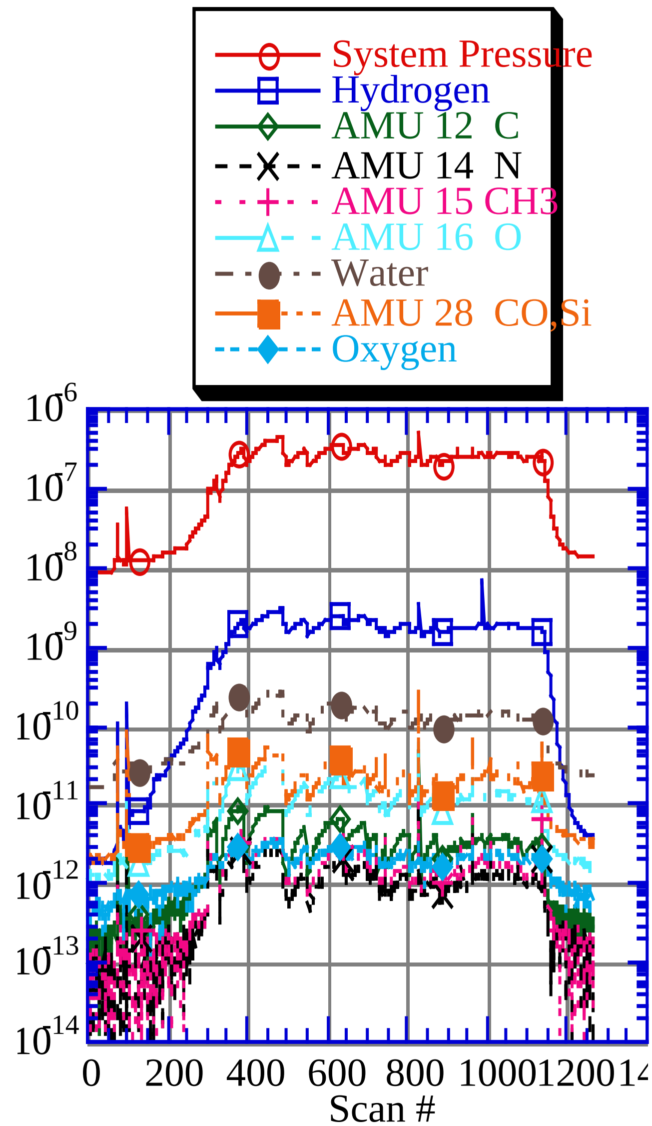

Figure 13: RGA data from the 950 kW run, vertical axis is peak intensity in amps

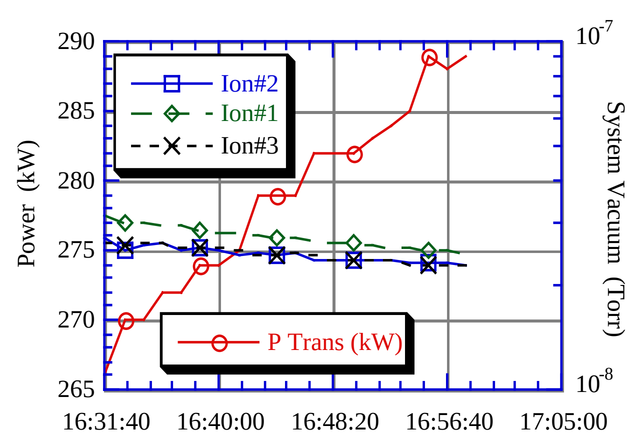

Figure 14: Vacuum activity centered around 280 kW

Figure 15: Braze joint at the output window's inner conductor at 900 kW

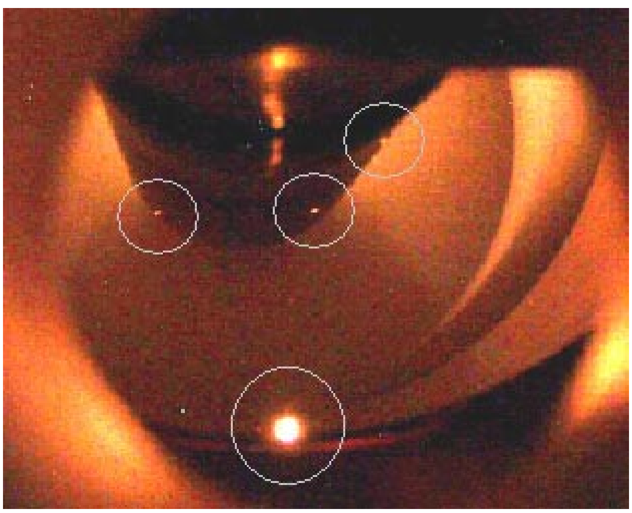

Figure 16: Glowing particles in input coupler, 900 kW

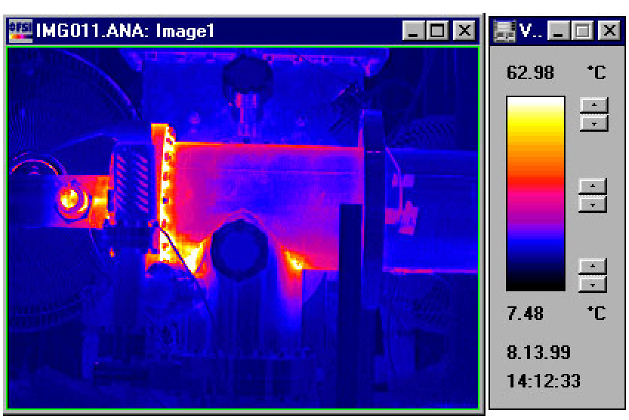

Figure 17: Thermal image of the tee section, 300 kW

During the high power run, a number of glowing specks could be seen through a viewport on the inner and outer conductor near the ceramic window. It is not yet known what these specks consist of, but most likely they are some form of carbon compound. A picture of the specks can be seen in Figure 16, highlighted by circles.

Thermal images of the outer conductor were obtained with an infrared camera at several different powers. Figures 17 and 18 images at 300 kW.

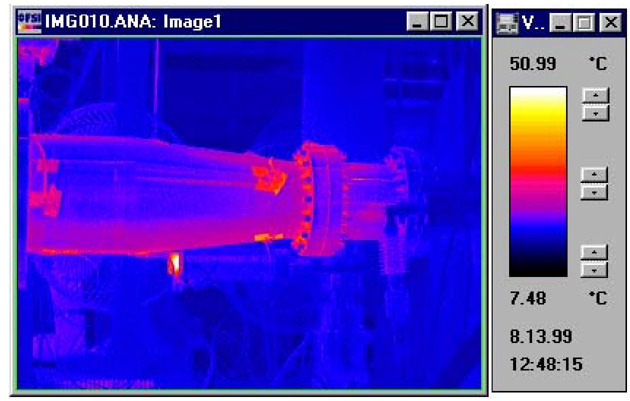

Figure 18: Thermal image of the tapered section, 300 kW

3.5 Standing Wave Testing

We have also tested the couplers with fully reflected power. At the maximum locations, the standing waves produce temperatures of four times the values reached by travelling wave operation. Therefore, simulation of up to 4 MW transmission and local heating affects may be possible.

The couplers were tested at five standing wave positions, spaced at one-eighth wavelength intervals, using a sliding short. At positions where the heating in the windows was excessive, a maximum power level of 500 kW was maintained for about a minute. At positions where the windows were lightly heating, the maximum level could be raised to 850 kW and maintained for long periods of time. In general, there was only a slight breakdown problem in the waveguide T-bar region at one sliding-short location. Window heating and light plasma glow would occur when the window was at a field maximum with the power level above 400 kW. We switched to pulsed operation with a 50 % duty factor and were able to reach 850 kW at all short locations without exceeding permissible temperatures. Multipactor bands were not searched for carefully, but none significantly affected operation at any particular power level.

4 FUTURE TESTING

4.1 Cold Testing

A cold test of the power coupler is planned on the RTTB with minimal facility requirements. The dual point thermal intercept designed for liquid helium use in the cryomodule will be used on the test stand with liquid nitrogen. Based on the analysis and typical residual gas spectrums obtained, a location 0.65 m from the shorting plate is the optimal location of the cold point to duplicate the temperature profile that the outer conductor will experience during operation on the cryomodule. Figure 19 shows the calculated temperature distribution of the outer conductor in the cryomodule and for the RTTB with its cold point. Also shown on Figure 19 is the location that residual gas species will freeze out on the inner surface of the outer conductor based on a total pressure of 1 x 10^{-7} Torr. The only species that freeze out near the end of the taper are H_2O and CO. It doesn't appear that H_2 will condense until the Niobium nipple of the cavity. Multipacting bands will be explored at all power levels under this cold operating condition.

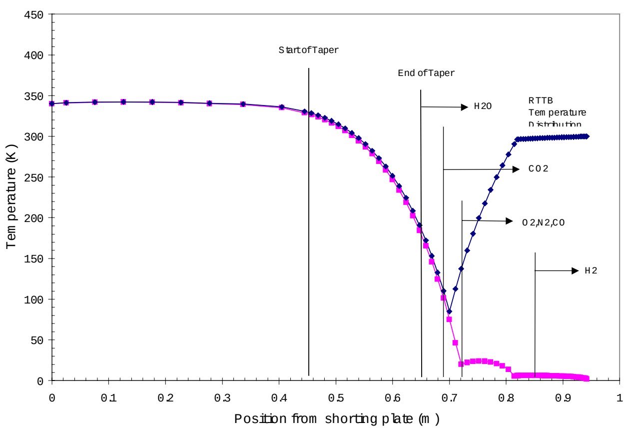

Figure 19: Calculated temperature distribution of outer conductor on cryomodule (magenta squares) and on the RTTB (blue diamonds) with cold point, 210 kW, CW, TW

4.2 Future Mechanical and Material Testing

The adjustable tip inner conductor, dubbed the alpha design is currently in fabrication with testing scheduled for January of 2000. Coupling control will be tested and the bellows concept at the tip will be demonstrated under high RF power. The RTTB will be outfitted with a full feedback control system for the actuator to demonstrate its use for the cryomodule.

Bellows development will continue. Both Be-Cu and Cu coated stainless steel bellows are being pursued. These will be cycle tested to determine if the design can handle the +/- 0.01 m travel required for the design. The adhesion of the Cu coatings will be verified by thermally shocking and cycling the coated bellows.

A second lot of outer conductors is being fabricated out of 316LN stainless steel instead of 304L. The magnetic permeability of the weld regions and the bulk material as fabricated will be measured for the two materials.

The power coupler will be analyzed dynamically, and the modes and damping coefficients will be measured. The potential for affect on the external Q and cavity fields due to mechanical vibration of the inner conductor will be determined from this analysis.

5 CONCLUSIONS

Preliminary data has been acquired for a set of power coupler components at room temperature. Due to thermally induced expansion of the coupler and frequency variations with the klystrons, it will be necessary to have an adjustable tip coupler during any cryomodule tests involving a fully loaded cavity. Testing will continue next year to increase the database with both the fixed-tip and adjustable power couplers.

Inspection of the first inner conductor did not reveal any thermal affects on the inner conductor. Hot regions on the outer conductor coincide with what was expected for the geometry. The power coupler thermal design was adequate for room temperature operation up to 500 kW, CW. Power levels beyond this will require enhanced heat transfer mechanisms.

The coupler RF design has proven to be quite robust, to date. There were no hard multipacting barriers present in the room-temperature operation. Inspection of the first inner conductor did indicate some electron activity on the surface. The coupler has excellent vacuum pumping very near the window, which may help suppress multipactor problems. The quarter-wave stub section may help to filter unwanted modes from the klystron or from the cavity. However, the true performance of the coupler can only be evaluated after cold testing. This is planned as the next step in verifying the design prior to a full cryogenic test in a cryomodule.

6 REFERENCES

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