High Power Co-Axial Coupler Phase II

Final Report for STTR Project Starting 7/20/2009, ending 8/14/2013

Small Business: Muons, Inc.
552 N. Batavia Ave.
Batavia, IL 60510

Muons, Inc. PI**:** Michael Neubauer

Research Institution: Thomas Jefferson National Accelerator Facility
12000 Jefferson Ave.
Newport News, VA 23606

Research Inst. PI: Dr. Robert Rimmer, under CRADA JSA-2011S009

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ABSTRACT

A superconducting RF (SRF) power coupler capable of handling 500 kW CW RF power at 750 MHz is required for present and future storage rings and linacs. There are over 35 coupler designs for SRF cavities ranging in frequency from 325 to 1500 MHz. Coupler windows vary from cylinders to cones to disks and RF power couplers will always be limited by the ability of ceramic windows and their matching systems to withstand the stresses due to non-uniform heating from dielectric and wall losses, multipactor, and mechanical flexure.

In the Phase II project, we built a double window coaxial system with materials that would not otherwise be useable due to individual VSWRs. Double window systems can be operated such that one is cold (LN2) and one is warm. They can have different materials and still have a good match without using matching elements that create problematic multipactor bands. The match of the two windows will always result from the cancellation of the two window's reflections when they are located approximately a quarter wavelength apart or multiples of a quarter wavelength. The window assemblies were carefully constructed to put the window material and its braze joint in compression at all times. This was done using explosion bonding techniques which allow for inexpensive fabrication of the vacuum / compression ring out of stainless steel with copper plating applied to the inner surface.

The EIA 3-1/8" double window assembly was then successfully baked out and tested to 12 kW in a 3-1/8" co-axial system. The thermal gradient across the window was measured to be 90C which represents about 15 ksi tensile stress in an uncompressed window. In our design the compression was calculated to be about 25 ksi, so the net compressive force was 5 ksi at full power.

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Project Summary Phase II SBIR 2012-2014:

A superconducting RF (SRF) power coupler capable of handling 500 kW CW RF power at 750 MHz is required for present and future storage rings and linacs. There are over 35 coupler designs for SRF cavities ranging in frequency from 325 to 1500 MHz. Coupler windows vary from cylinders to cones to disks and RF power couplers will always be limited by the ability of ceramic windows and their matching systems to withstand the stresses due to non-uniform heating from dielectric and wall losses, multipactor, and mechanical flexure.

In the Phase II project, we built a double window coaxial system with materials that would not otherwise be useable due to individual VSWRs. Double window systems can be operated such that one is cold (LN2) and one is warm. They can have different materials and still have a good match without using matching elements that create problematic multipactor bands. The match of the two windows will always result from the cancellation of the two window's reflections when they are located approximately a quarter wavelength apart. The window assemblies were carefully constructed to put the window material and its braze joint in compression at all times. This was done using explosion bonding techniques which allow for inexpensive fabrication of the vacuum / compression ring out of stainless steel with copper plating applied to the inner surface.

Double windows were utilized for two reasons. Double windows provide improved vacuum protection between the RF source side and the accelerator / ring side. Also, utilizing two windows allows for a significantly better "match", as the two windows can be spaced so that the reflections from the window surfaces are cancelled by reflections from the other window's surfaces. i.e. "roughly" ¼ wavelength. Additional advantages, as mentioned above, are that the windows may be of differing materials (and thus dielectric constants), and if a vacuum is present between the windows, one window may be room temperature, while the one closest to the accelerator can be at LN2 temperatures.

These windows were fabricated such as to remain constantly "under compression". Thus, thermal effects due to heating do not stress the joint between the ceramic and the sleeve. This also allows for a good thermal path from the outer window diameter to the outside of the system for cooling.

Major Components of the SRF Coaxial Coupler Assembly

The Dual Window SRF Coaxial Coupler was intended to couple RF power into an accelerator cavity. As such, it needed to consist of more than just the dual RF windows in a vacuum shell. **Figure 1** shows a concept for the entire JLAB Dual Window SRF Coaxial Coupler assembly.

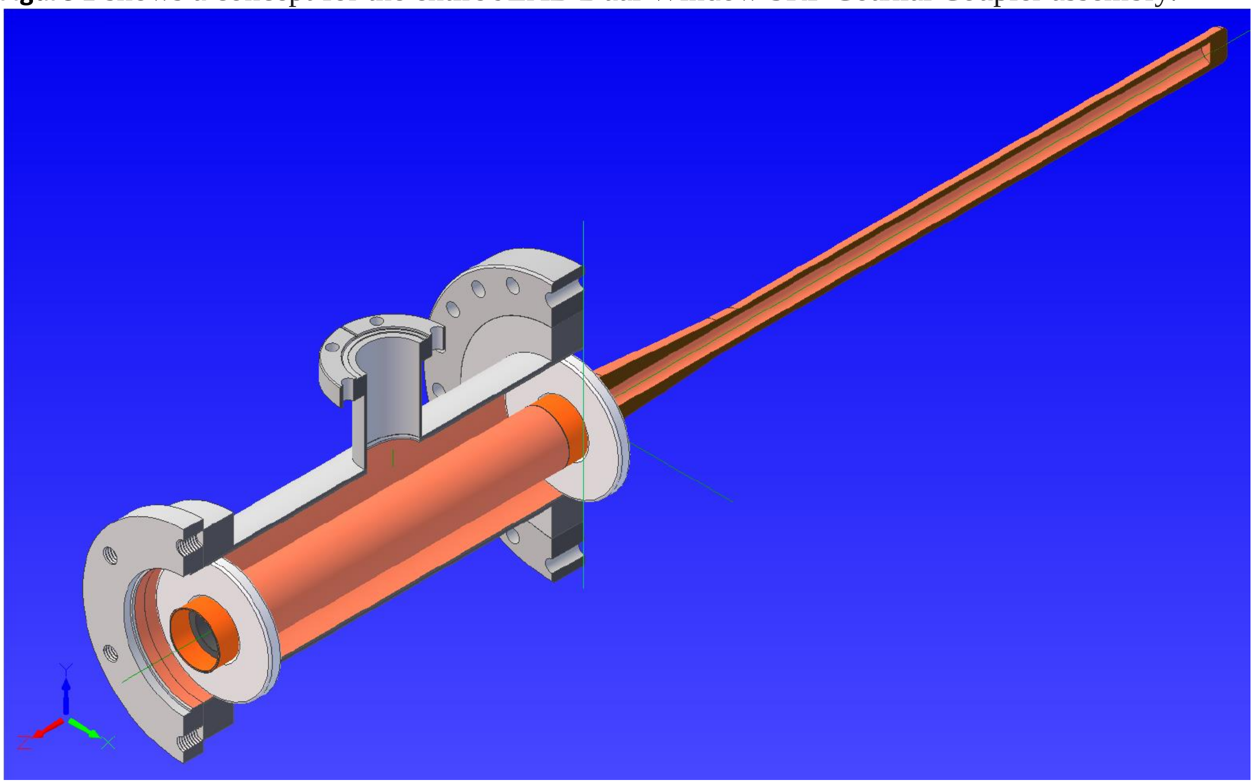

Figure 1: Shown is a cut-away view of the complete Coupler assembly.

Figure 1 shows the major features of the complete coupler assembly designed to couple RF power between the RF source and the SRF cavity. These major features consist of:

- A EIA 3-1/8" flange
- A 2-¾" Conflat style flange
- A 6-¾" Conflat style non-rotatable flange
- A machined explosion bonded (copper on 316L stainless steel) vacuum wall.
- Toroidal Backing Rings and a hollow Inner Conductor.
- Properly spaced Alumina coaxial ceramic windows.

The EIA 3-1/8" flange was designed to mate with the EIA transmission line of the RF system. The 2-¾" Conflat style flange was designed as the pump-out port connection for the vacuum between the dual RF coaxial windows. On the output (accelerator) side a 6-¾" non-rotatable Conflat style flange was intended to mate with the matching flange on the cavity.

As partially shown in **Figure 1**, the Backing Rings are toroidal in shape rather than the solid disks of earlier in the design. The opening in the Backing Rings allows for water cooling lines, intended for cooling the antenna, to be run through the Coupler. No design for these water cooling lines was performed during the Phase II project.

Stress and Deformation calculations

Since the basis of the design involves compression of the Coaxial RF Windows, significant effort was spent on the analysis of the stresses on the various components due to the various assembly processes and subsequent brazing operations. These analyses were performed using ANSYS.

Figure 2 shows the basic components of a RF window assembly made with compression technology, and shows the basic configuration which was analyzed using ANSYS. The left edge of the pictured drawing is the center-line of the assembly. The Moly Keeper Ring is utilized during subsequent brazing operations to provide a compressive force opposing the thermal expansion of the Compression Ring. The Backing Ring provides a similar function limiting the inward expansion of the ceramic window against the copper inner conductor. In some of the calculations, the backing ring was a disk. In the final assembly the backing ring is a cylinder. ANSYS was used to determine various stresses and the amount of deformation at various places throughout the assembly, and to adjust the design accordingly.

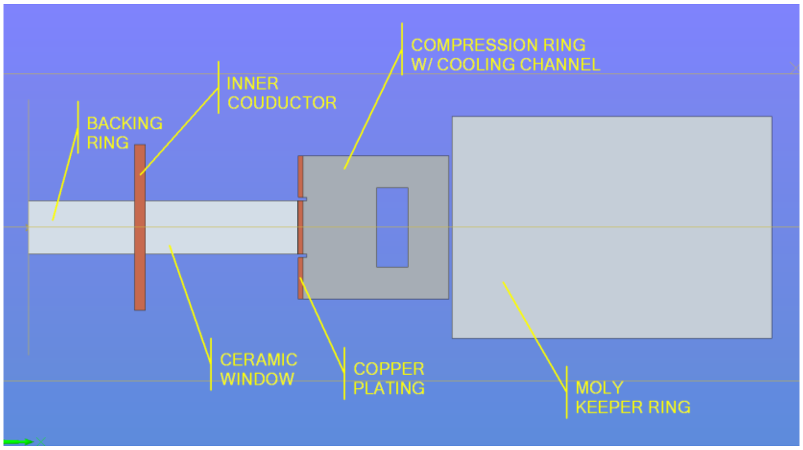

Figure 2: Shown are the fundamental components of a ceramic RF Window assembly in a Conpression Ring and Backing Ring. (The moly keeper ring is only used during brazing.)

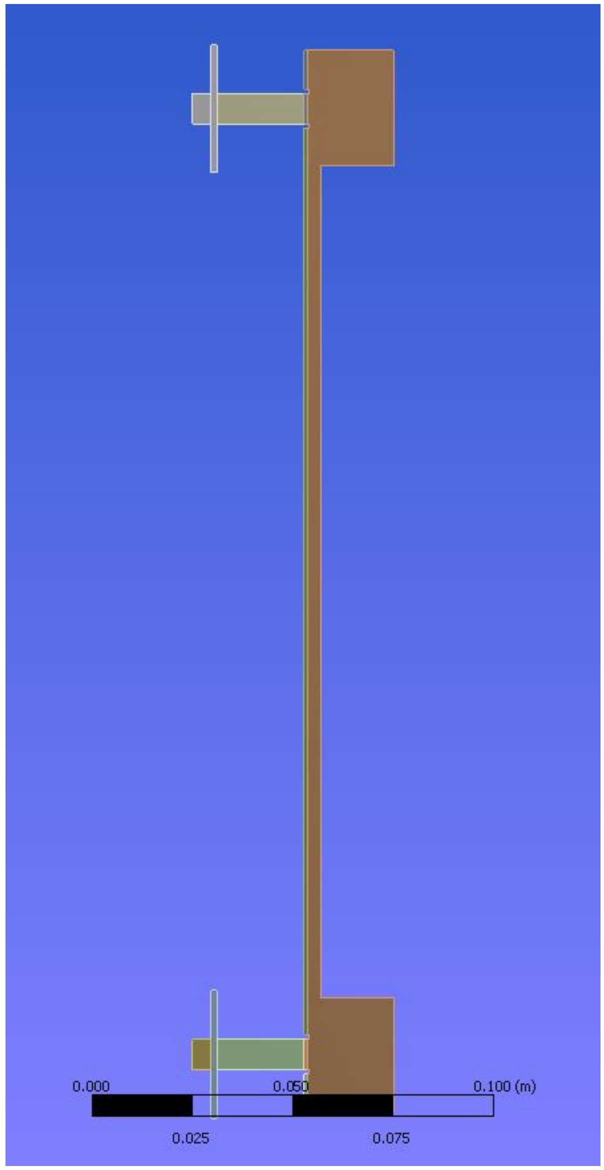

Figure 3: Shown is the model for a dual window and vacuum envelope braze assembly.

In order to create an assembly with "dual" RF windows it was decided to braze the entire assembly simultaneously. i.e. both RF windows, the center conductor, and the outer conductor / vacuum shell. Figure 3 shows the simulated model. In this model the backing rings are "rings" rather than "solid "disks" as in the single window model. Thus, the center-line of the model is a bit to the left of the edge of the Backing Rings shown in Figure 3.

As in the single window ANSYS runs, the stresses and displacements were analyzed for this complete braze assembly. The model was run for a thermal cool down cycle from 1050°C back to room temperature over a number of hours.

A great deal of information was determined via ANSYS simulations of the assembly. This information allowed for design changes to prevent the various components from possible failure in the application. For example stress relieving cuts above and below the window in the compression ring were added as a result of this type of analysis. Results determining stress in the Backing Ring provided information which determined how thick the Backing Ring needed to be, etc. These ANSYS analyses provided critical design information which led to a successful design and test result.

Copper clad stainless steel

The vacuum envelope and the outer conductor of the Coupler are one and the same. The design and fabrication of this part was one of the novel / inventive parts of this design. Rather than "plating" the copper to form the outer conductor of the coax) to the inner surface of the 316L stainless steel tubing (which provides the vacuum envelope) the copper was explosion bonded to the inner surface of the SS tubing. This was "experimental" in nature as far as the prototype Coupler was concerned, but if more Couplers were to be produced, would yield a cost savings. In addition, the thickness of the copper layer was much thicker than would be achievable via the plating process. This made the outer conductor surface more resistant to damage, scraping, etc. And, allowed for better electrical connection between this surface and the copper outer conductor surface in the region of the RF window. To make the some of the test window assemblies some of the explosion bonded material was utilized. As can be seen in Figure 4, the outer conductor material from the explosion bonding is much thicker than would be obtainable by plating. This easily produces the substantial "buffer" layer of copper which is the necessary "cushion" for the brazing operation described later. Brazing a "thick" tube of copper to the ID of the SS would be difficult and costly, and would likely lead to problems due to differing CTEs during the braze cycle.

Figure 4: A coaxial window assembly made with an explosion bonded Compression Ring. For scale, the window ceramic OD is approximately 3 inches.

Fabrication method, manufacture, and issues

Explosion Bonding is pretty much as the name implies. Two metals are "bonded" together by the pressure wavefront of an explosion. We used High Energy Metals, Inc. (HEMI) to perform the bonding. They started with a 316L stainless steel tube 12" long × 5" OD × ~2.9" ID, and explosion bonded an inner tube of copper onto the inner surface, such that there was ~0.2" thick copper bonded to the SS afterward. Figure 5 shows the concept / method for how this is done.

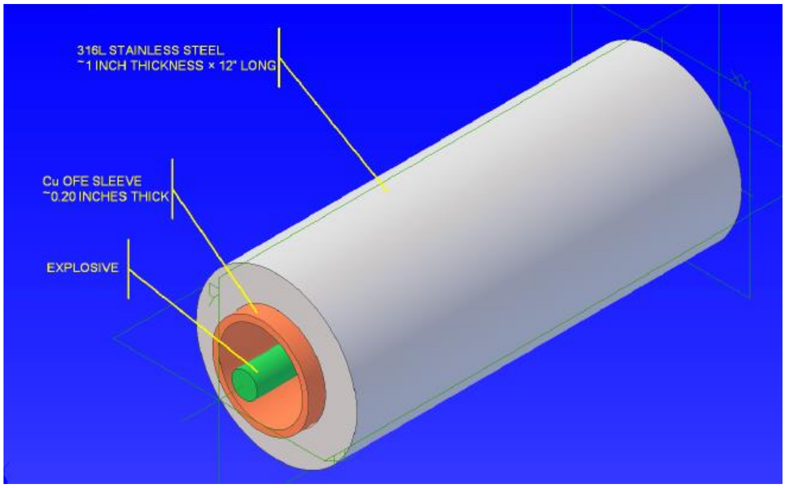

Figure 5: Method for Explosion Bonding this type of component.

As one would expect, the explosive force necessary to bond that thickness of copper onto the approximate 3" diameter inside of the SS tube is considerable. Even a 1" thick tube does not con through this explosion unscathed. Indeed, there is moderate "bulging" of the assembly after the explosion. Figure 6 shows some diameter vs. axial distance measurements for one of the explosions bonded assemblies. The graph shows a diameter measurement for the entire 12" tube length with a measurement taken approximately every 1 inch. The graph clearly shows the "bulge" due to the explosion.

The "pre EB tube ID" shows the SS tube machined ID prior to the explosion bonding process, in this case 3.0 inches. After the explosion, the "bond line" was measured ultrasonically, and is shown in the graph by the green triangles. The inner ID of the copper bonded to the tube is shown by the red squares. The dashed line indicates the diameter of the final machined ID for the assembly and matches the ID for the outer conductor of the transmission line. This machining provides a proper cylindrical surface as the outer conductor even though the thickness of copper on the wall along the length of the tube may vary. The two gray rectangles on the graph represent the portion of the tube used for the Coupler assembly. As can be seen the thickness of the copper in the Coupler wall varied from roughly 0.1" to 0.2".

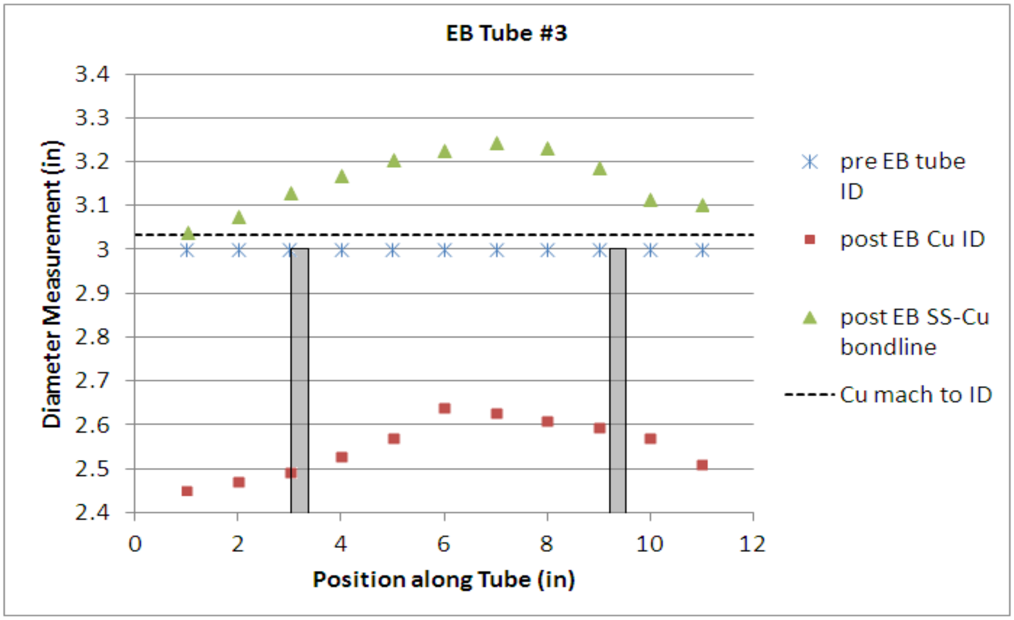

Figure 6: Shown are the relevant diameters for the third explosions bonded tube fabricated.

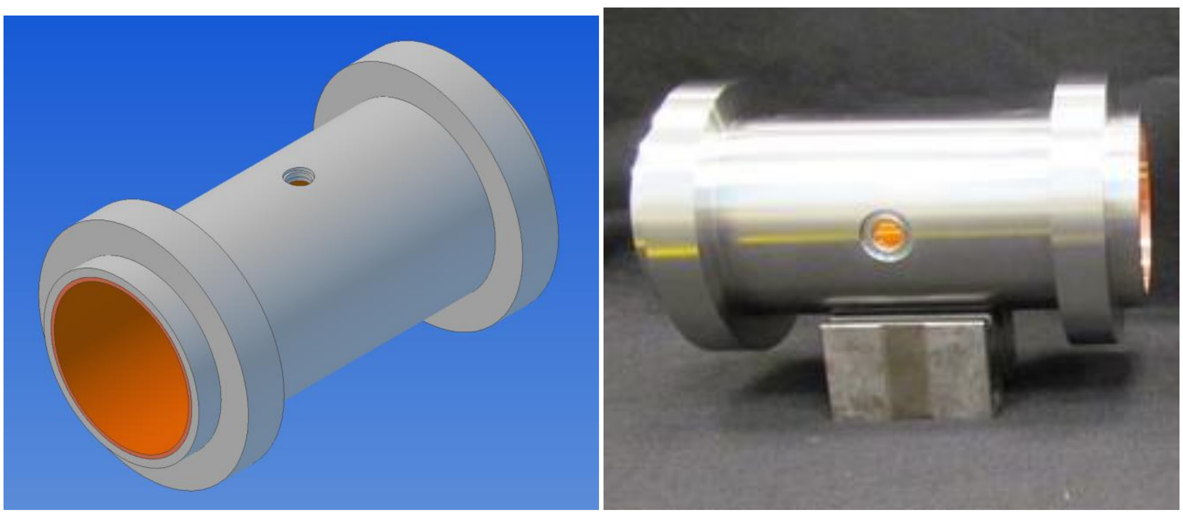

Figure 7: Shown is a graphical representation and the actual machined part of the Explosion Bonded assembly after final machining.

Figure 7 shows the part that was machined from the Explosion Bonded assembly. The outer diameter of the assembly has been machined down except in two places near the ends. These “places” served as the Compression Rings for the ceramic window assemblies discussed previously.

Assembly of The Dual Coaxial Windows

Figure 8 shows the some of the careful alignment process utilized to create the braze stack for the inner conductor assembly. This assembly was created separately and would later be assembled with the Outer Conductor / Vacuum Shell assembly to form the complete Coupler assembly. Figure 9 shows the completed Dual Window and Inner Conductor assembly (left view), and shows both the two major components of the Coupler assembly (on the right).

Figure 8: shown are some of the steps of for the Dual Window / Inner Conductor braze stack.

Figure 9: Windows and Inner Conductor sub-assembly (on the left) and both Coupler sub-assemblies (on the right).

Coupler Assembly

The complete SRF Coupler Assembly was assembled by brazing the two sub-assemblies, shown in the right-hand photo of Figure 9, in one step. To do this, it was necessary to utilize two Molybdenum Keeper Rings to keep the Compression Ring (CR) portions of the Outer Conductor / Vacuum Shell Assembly from expanding away from the ceramic coaxial windows, during the braze cycle. Rather the SS CR and its bonded copper layer expand inward toward the ceramic and to a lesser extent the ceramic expands outward to meet and embed in the copper. This type of window design has been reported on previously and is well covered in reference [1].

Calculations

Of course, in order for these two sub-assemblies to braze / bond successfully and vacuum tight, all the components must be the correct size, both at room temperature and at braze temperature. If the sizes are not correct the thermal expansion of the various materials involved will either not allow for bonding, or will produce forces between the parts which is in excess of the strength of the materials. We performed these analyses using ANSYS, and simulated various combinations of the room temperature spacing between the components. The graph of Figure 10 summarizes the results of this analysis.

The graph compares various window OD to copper sleeve spacings for various spacings between the Compressions Ring OD to the Moly Keeper Ring ID. This helped determine to what size the ID of the explosion bonded copper should be machined, and to what size the OD of the Compression Ring portion of the Outer Conductor / Vacuum Envelope should be machined (given that one of the expensive Moly Keeper rings already existed). The three different lines represent three different room temperature spacings between the Compression Ring OD and the Keeper Ring ID. The room temperature spacings between the ceramic window OD and the bonded copper sleeve ID is represented on the x-axis, and the resultant hot temperature spacings are represented on the y-axis.

Using the graph it is rather easy to select either the room temperature window OD to sleeve gap and/or the Compression Ring to Keeper Ring gap based on how much "compression" is desired at the hot brazing temperature. For example, if the Compression Ring OD to Keeper Ring ID gap is 0.0069" then it is simple to create Table 1. Additional discussion may be found in Appendix 1.

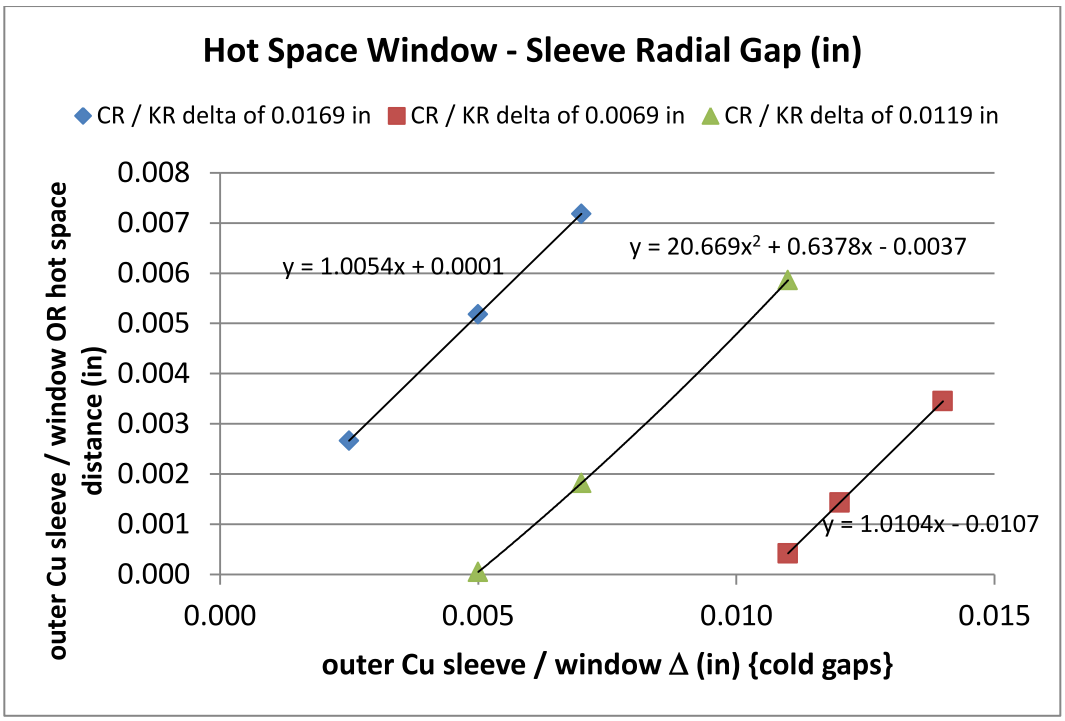

Figure 10: A graph of the ANSYS simulation results parameterizing the window OD / outer sleeve distance for room temperature vs. braze (hot) temperature.

Table 1: Cold to Hot gap spacings for the ceramic window OD to Compression Ring sleeve ID, for a Compression Ring OD to Keeper Ring ID of 0.0069"

window / CR cold gap	window / CR hot gap
0.010	0.0047
0.009	0.0037
0.008	0.0027
0.007	0.0018
0.006	0.0009
0.005	0.0000
0.004	-0.0008
0.003	-0.0016
0.002	-0.0023
0.001	-0.0030

Figure 11 shows the complete Coupler Assembly after fabrication and hot testing. The Compression Rings show oxidation from heating as this prototype did not contain the water cooling channels. Further testing results will be presented in a later section of this report.

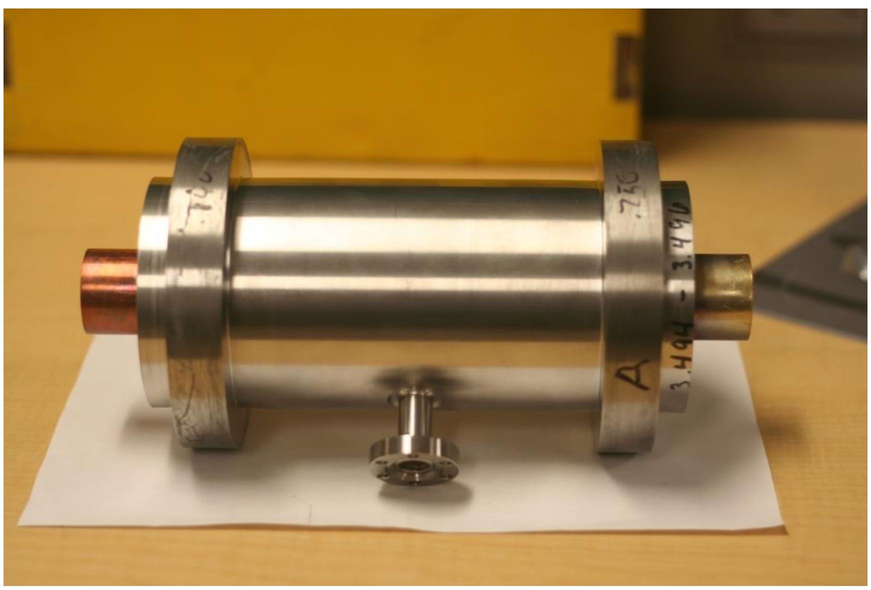

Figure 11: Shown is the complete Coupler Assembly after fabrication and hot testing.

Matching the Dual Windows

Cold Test measurements of the Coupler sub-assemblies performed at JLAB are shown in Figure 12. The windows after brazing showed that some additional matching would be required to operate the Coupler at 1500 MHz. The discrepancy between 1500 MHz and 1231 MHz represents the spacing errors that were caused by the brazing fixturing. This error will need to be fixed for commercialization of this assembly technique. For our purposes in full power tests additional iris' were designed. This is shown in Figure 13 to Figure 16.

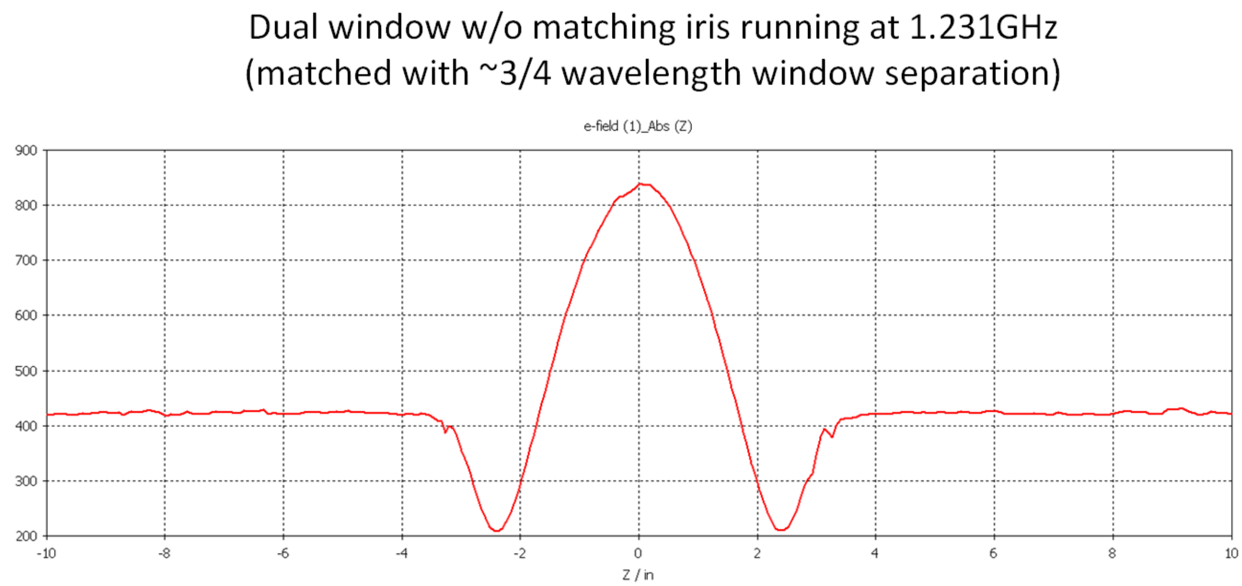

Figure 12: Cold Test measurements of the Coupler as fabricated.

A matching iris design as shown in Figure 13 was determined at JLAB to match the Coupler for 1500 MHz operation, and Figure 14 shows the Cold Test result with the matching irises. Figure 15 shows the Comsol model used to simulate the E-fields in the design with the irises, and Figure 16 shows the Comsol result.

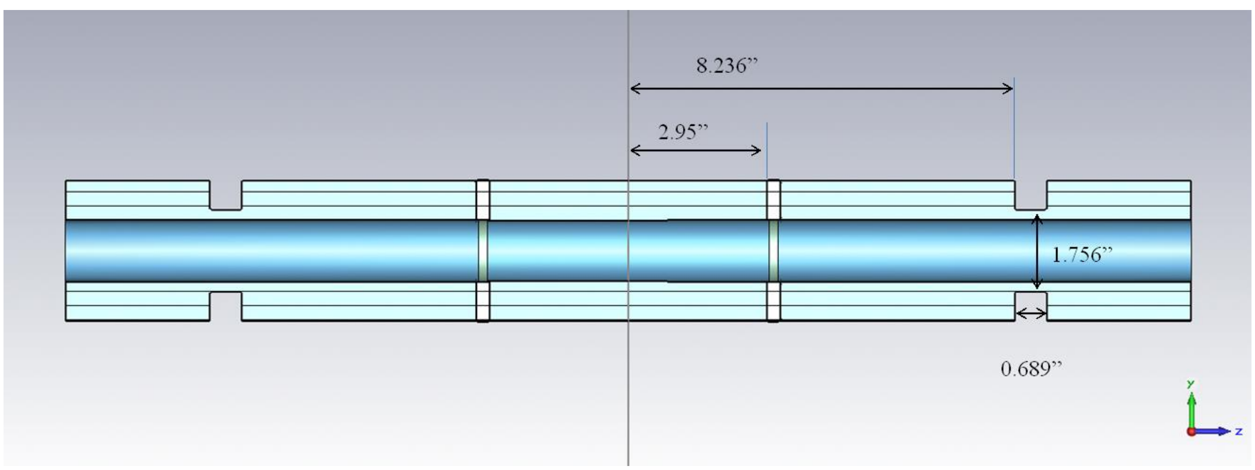

Figure 13: Graphic showing size and locations for matching

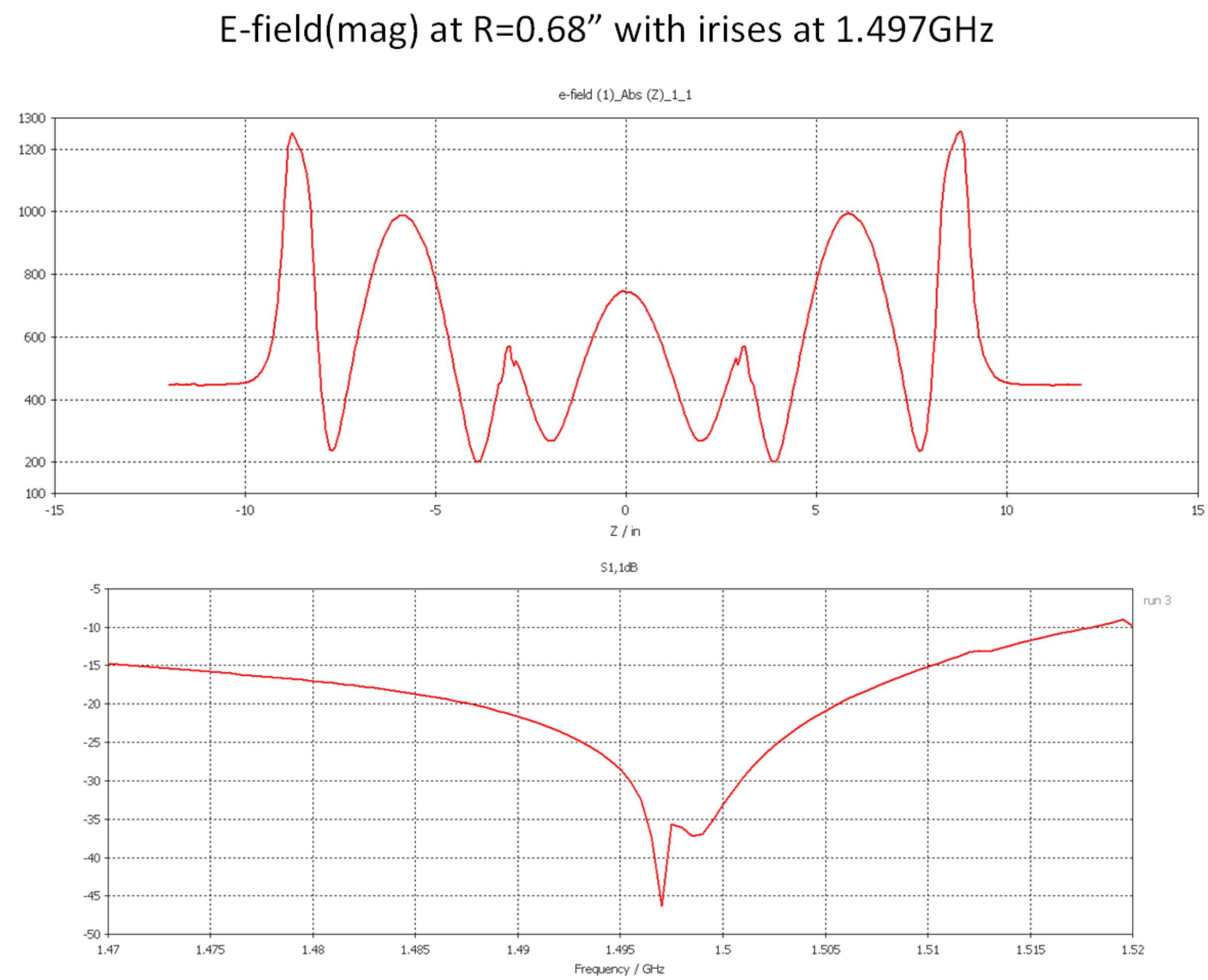

Figure 14: Cold Test results of the Coupler with matching irises.

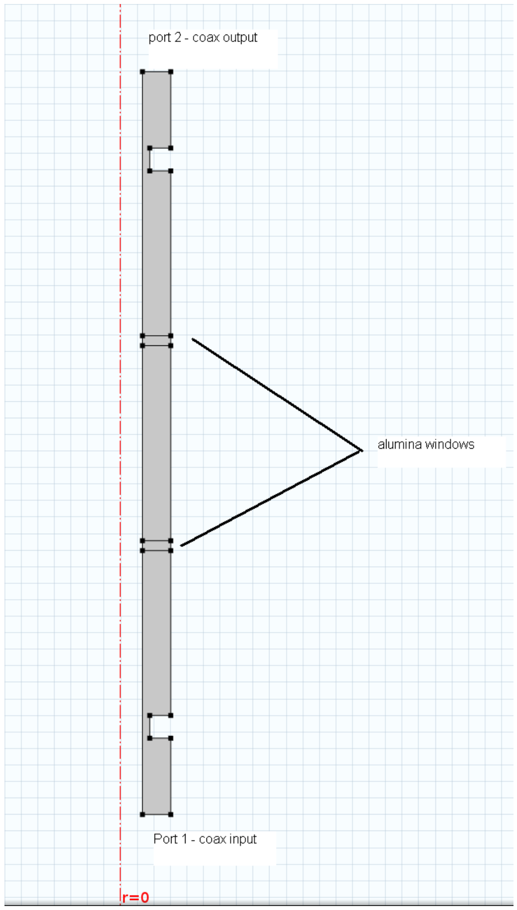

Figure 15: Comsol model for Coupler with matching irises.

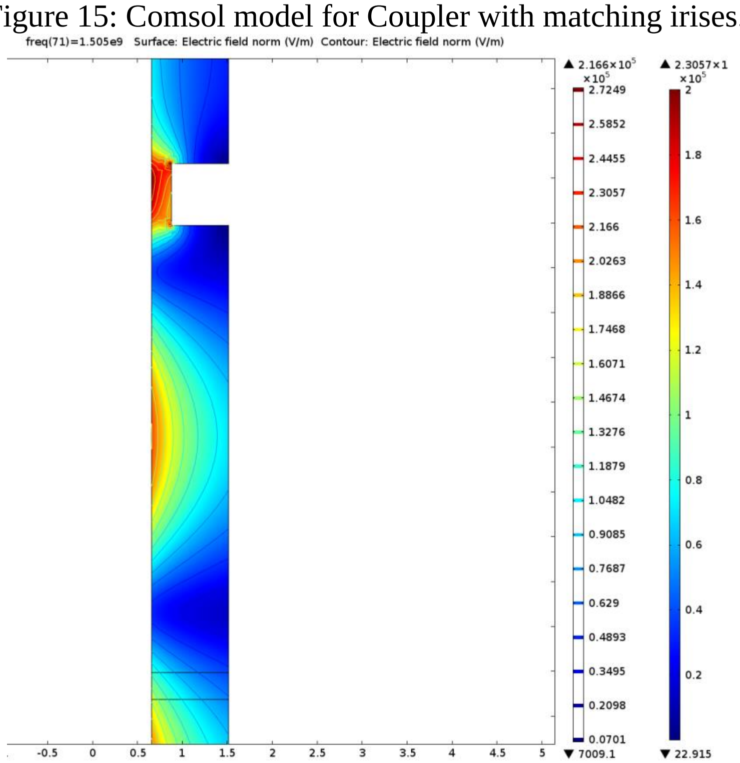

Figure 16: Comsol result showing E-field strength in the region of the iris and Coupler window.

Figure 17 shows a Comsol modeled result (for the model of Figure 13) for the effect on operating frequency due to variations in the real part of the dielectric constant of the Alumina windows.

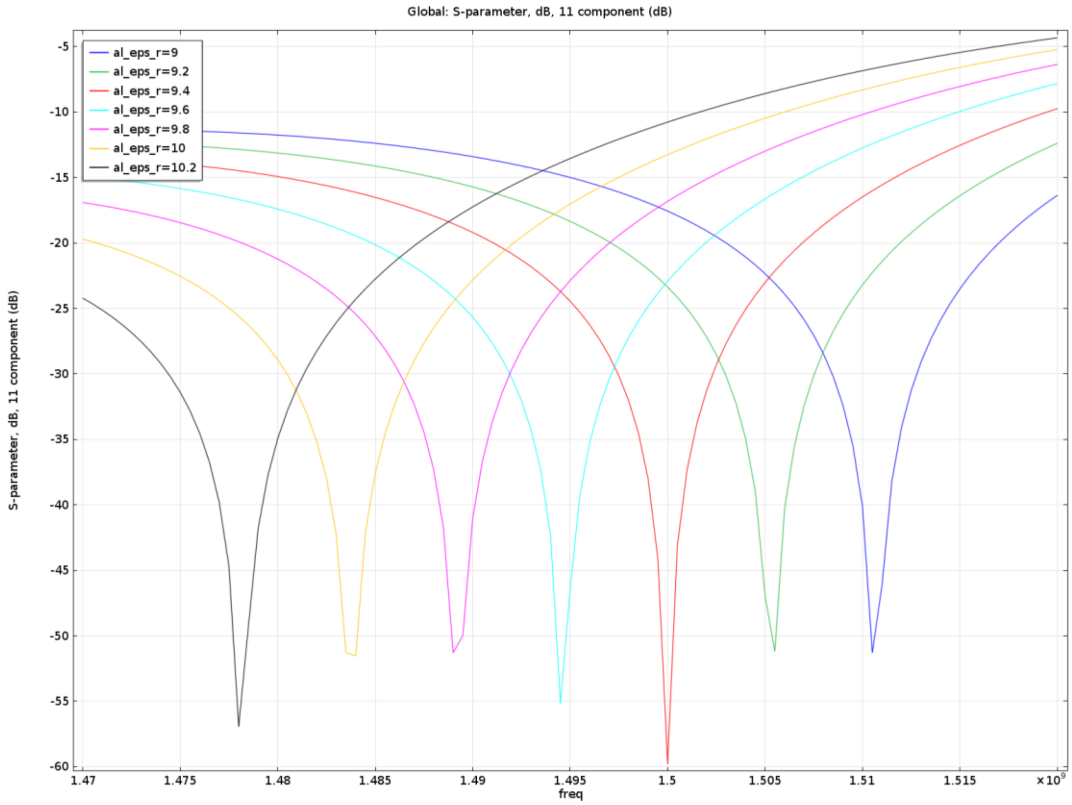

Figure 17: A Comsol analysis showing the result of varying □r for the Alumina RF windows.

Hot Testing of the Coupler Assembly

The Coupler as designed and fabricated was intended for full power testing to the JLAB operating power level of 12 kW. The design as fabricated only lacked the water cooling channels built into the Compression Rings, but nonetheless hot testing was performed into a load and as a standing wave test with the field maximum at the Coupler's RF input side window. Figures 27 and 28 show schematically the test set-ups.

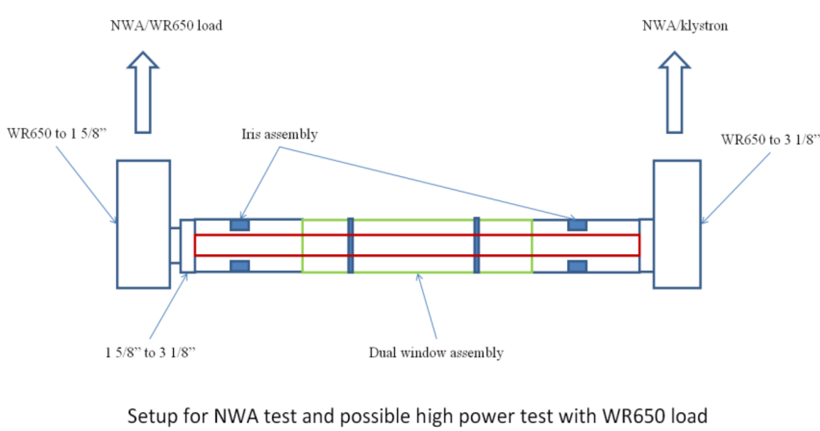

Figure 18: Hot Test set-up schematic for the Standing Wave Test.

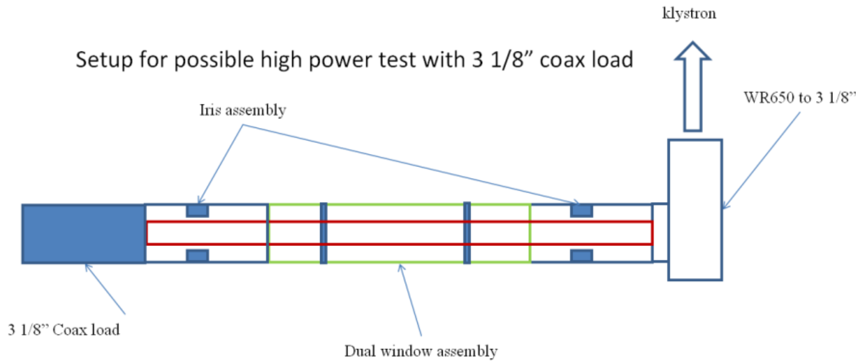

Figure 19: Hot Test set-up schematic for the Vacuum Test.

Both these experimental set-ups were used in experiments at JLAB, and the following figures are photos of those experiments.

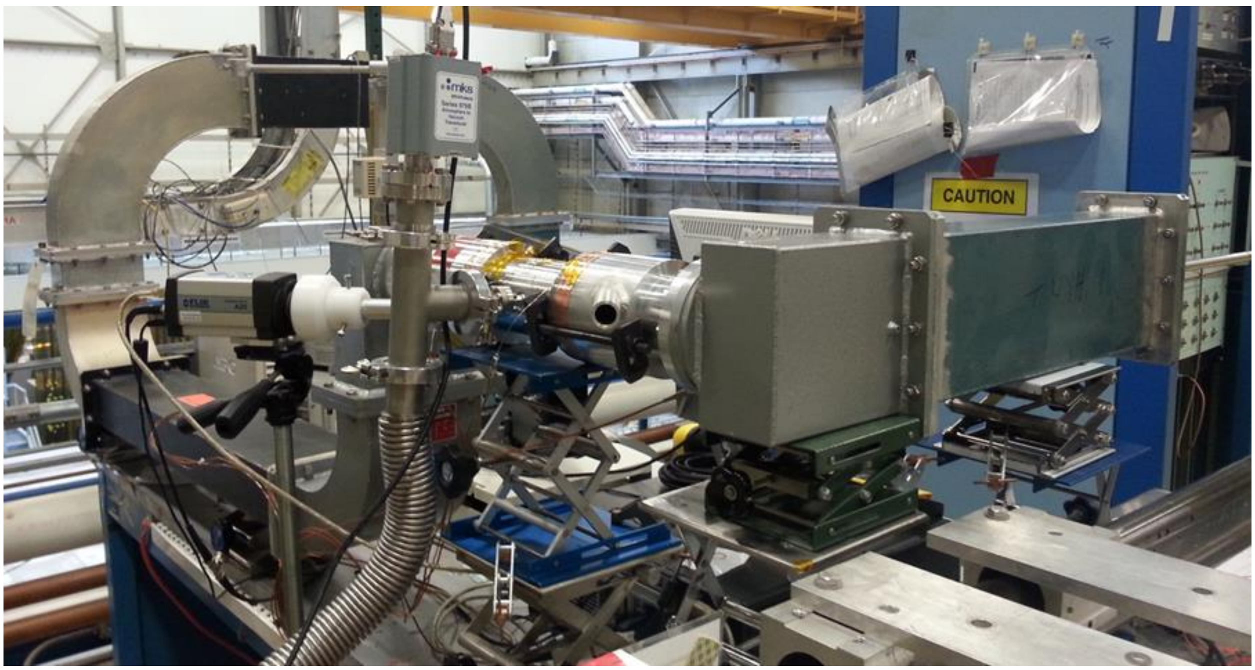

Figure 20: Photo of the experimental set-up for the Standing Wave test. Corresponds to the schematic of Figure 18.

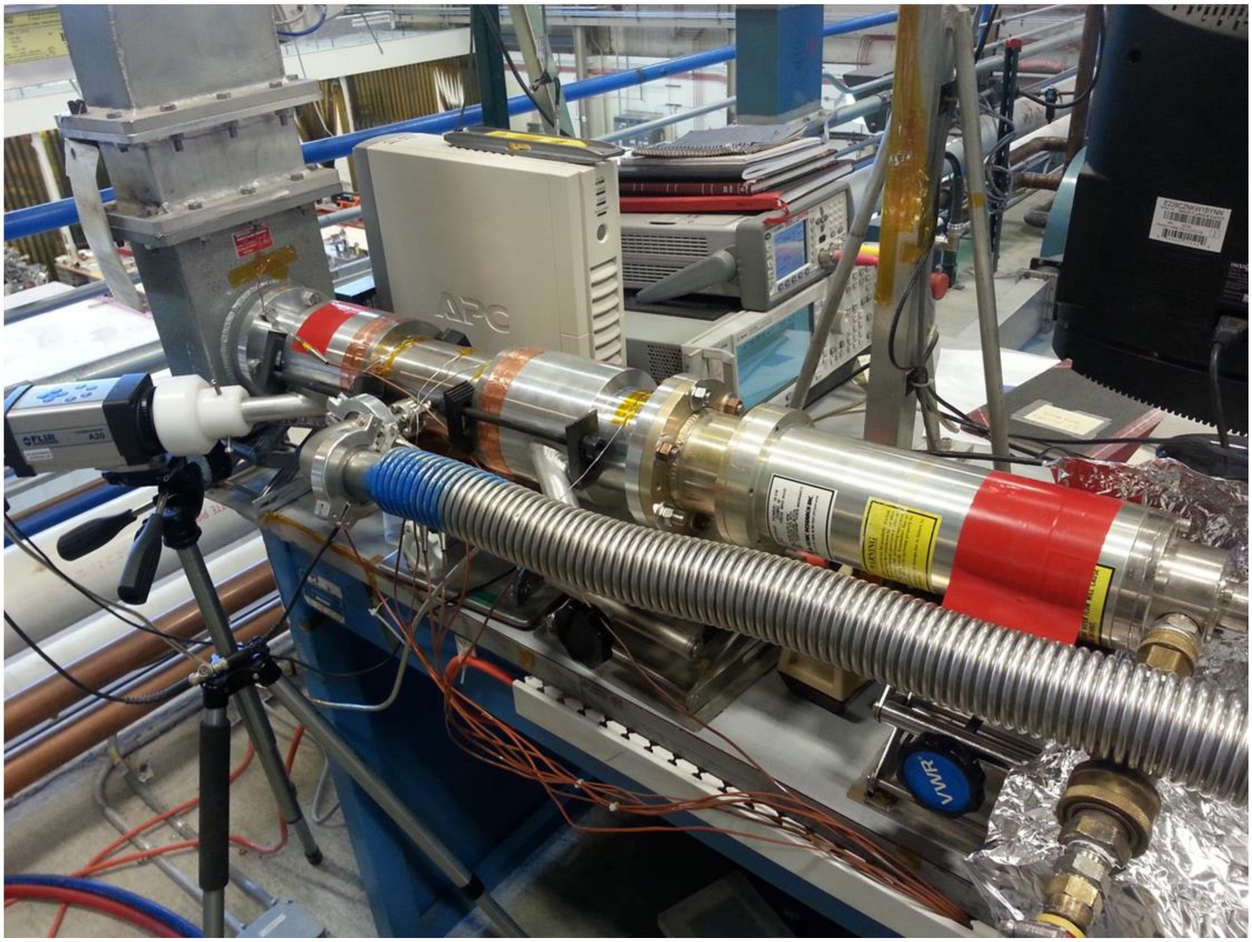

Figure 21: Photo of the experimental set-up for the Vacuum Test, which corresponds to the schematic of Figure 19.

The following hot tests and measurements were performed:

1. A window test in air. An IR camera was used to look at the up-stream window while the power was ramped from zero to 12 kW, allowed to stabilize, and then cooled down. This test was run twice.

2. A window test in air. The IR camera was looking at the down-stream window while the power was ramped from zero to 12 kW and run for ~2.5 hours.

3. A window test in vacuum, with the IR camera looking at the up-stream window. Stepped up power in 30 minute steps of 1 kW, 2 kW, 4 kW, 6 kW, and 12 kW.

4. A window test in vacuum, with the IR camera looking at the up-stream window. Stepped up power in 15 minute steps of 1 kW, 2 kW, 4 kW, 6 kW, and ran 4 hours at 12 kW.

5. Connected the High Power Sliding Short and adjusted the Short to produce a maximum standing wave at the klystron side Coupler RF window, then the power was ramped up to 12 kW.

6. A high power vacuum test was conducted using an Inficon Leak Detector to supply and monitor the Coupler vacuum while the power was ramped up to 12 kW for 4 hours.

Test Results

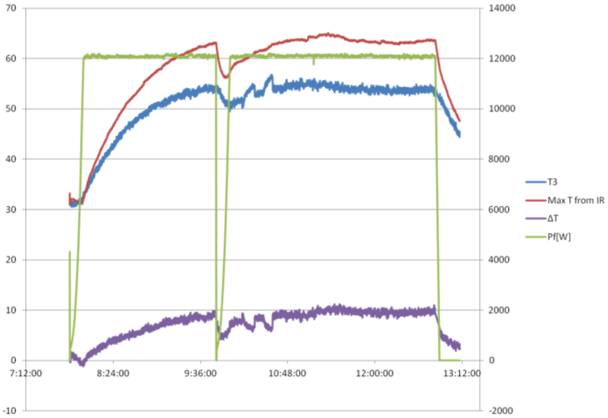

Figure 22: Up-stream RF window.

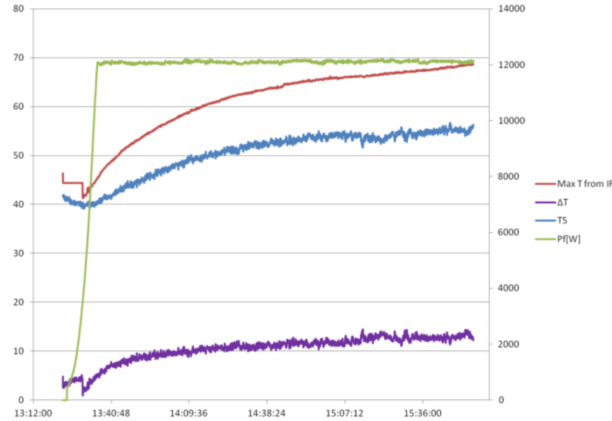

Figure 23: Down-stream RF window.

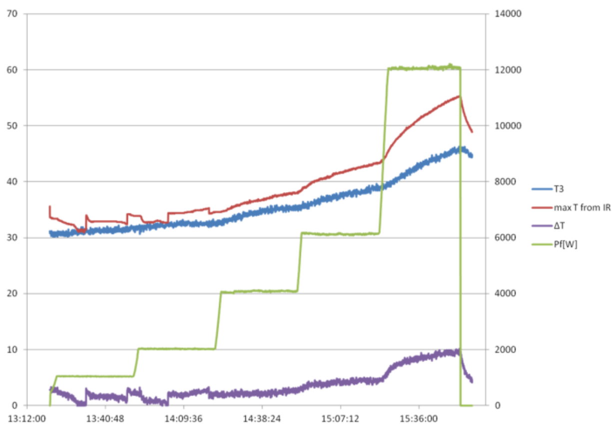

Figure 24: 30 minute power step up test.

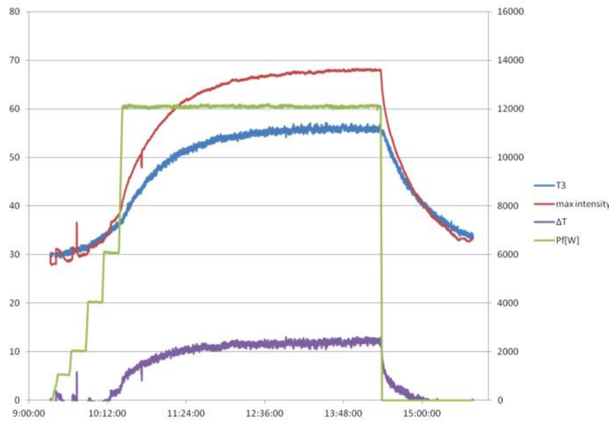

Figure 25: 15 minute power step up test.

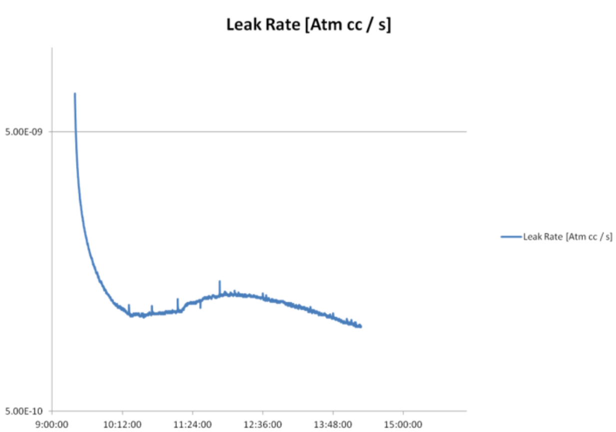

Figure 26: Vacuum Leak rate during step-up test.

Figures 31 through 35 show the test results for tests 1 through 4 listed above. As can be seen the results are quite good, with the Coupler operating to 12 kW for a number of tests and for hours at a time, while maintaining an excellent vacuum. Figures 36 through 38 show test results for the tests numbered 5 and 6 above. Even with the standing wave placed at the RF Window Figure 27 indicates that the window temperature stabilizes at 150 °C, even without the benefit of water cooling in the Compression Rings.

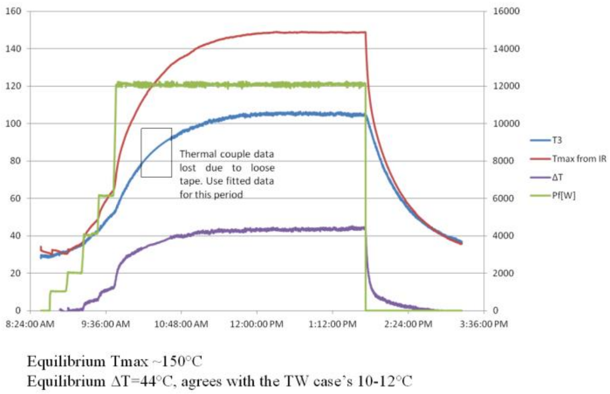

Figure 27: Up-stream RF window.

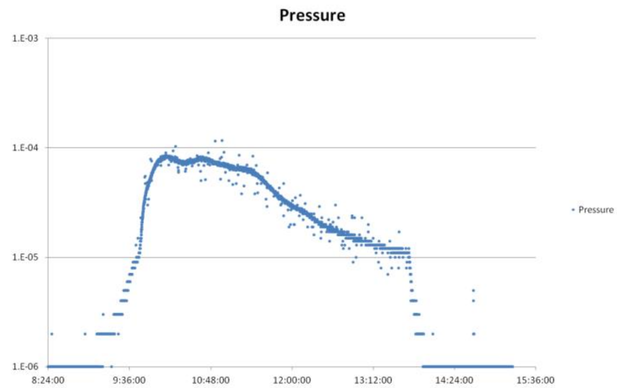

Figure 28: Pressure in Coupler during Standing Wave testing.

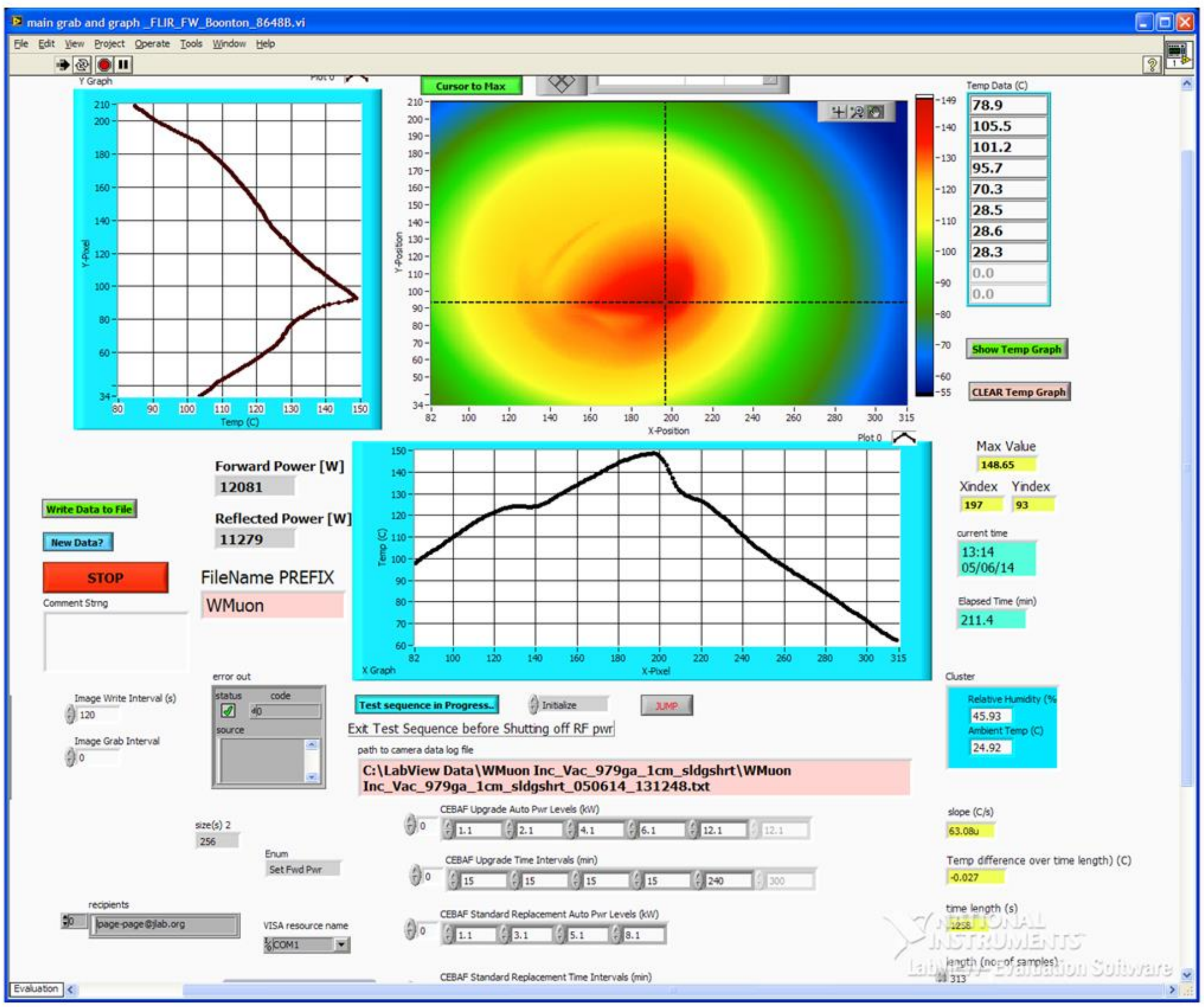

Figure 29: A LabView screen capture of the thermal profile of one of the RF Windows while the power level is at 12 kW.

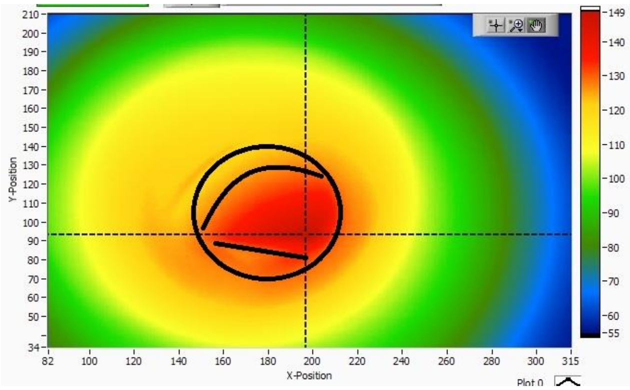

Figure 30: The FLIR from LabView marked to show the viewable area of the ceramic window.

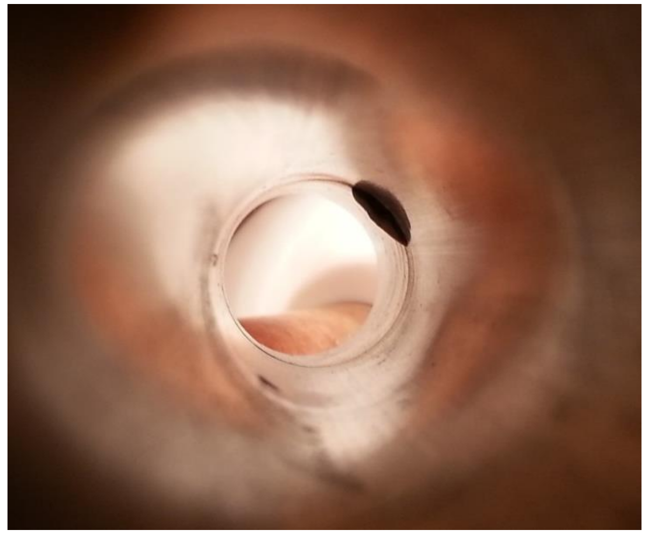

Figure 31: a visible light photo showing the view of the FLIR camera and the viewable area of the ceramic window.

Figures 39 and 40 looked at together help in understanding which portion of the IR photo is the window ceramic. The dashed lines in Figure 29 and Figure 30 are the cross-sections over which the two temperature profiles are made. The "hottest" portion of the window is seen to be near the center conductor, which makes the sense since the E-field is the greatest near the center conductor.

Summary

A Dual Coaxial RF Window Coupler was designed and fabricated by Muons, Inc. and tested up to 12 kW by JLAB. The Coupler design incorporated Muons' coaxial ceramic windows under compression technology, and the novel technology of explosion bonding the outer conductor to the stainless steel vacuum envelope. Both these innovative technologies worked well, and the Coupler was vacuum tight and remained so under hours of continuous operation at the design power level of 12 kW. Further work is required to control the spacing between the windows during brazing.

References:

[1] Neubauer, M., et. al. "High Power Coax Window", PAC 2010.

[2] Neubauer, M., et. al. "High Power Co-axial SRF Coupler", PAC 2012.