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ENGINEERING DESIGN OF 402 MHz NORMAL CONDUCTING COAXIAL WINDOW*

S. U. Thielk, R. Agustsson, S. Kutsaev†, A. Pronikov, RadiaBeam LLC, Santa Monica, CA, USA

Abstract

RadiaBeam is fabricating a novel RF vacuum window for use with the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL). The window features a coaxial ceramic window between two waveguides, brazed as a single assembly. Unlike traditional pillbox window designs, this approach allows the outer diameter of the ceramic to decrease and the added benefit of water cooling the inner diameter of the ceramic. This paper covers the engineering design including details of key features, the impact of the unique RF design on manufacturability, and mechanical simulations. A status update on the fabrication is also provided with emphasis on the ceramic TiN coating and brazing process.

INTRODUCTION

The radio-frequency (RF) window is a critical aspect of most accelerator systems since it is responsible for separating the vacuum volume of the accelerating cavity from the RF power transmission line. For rectangular waveguide, this is commonly achieved by brazing a disk of dielectric material, typically alumina, into a cylinder that is then placed into the transmission line. Dimensions of the cylinder are optimized to minimize RF reflections often resulting in a diameter for the alumina window that is larger than the waveguide. For compatibility with the Spallation Neutron Source (SNS), which operates at 300-500 kW average power and 402.5 MHz, the window transitions from WR2100 waveguide (533.4 mm x 266.7 mm) on the input side to half height WR2100 waveguide (533.4 mm x 133.4 mm) on the output, or vacuum side of the assembly. The vacuum side interfaces with the iris coupler for the SNS drift tube LINAC [1]. A traditional pillbox style window for this assembly would require a ceramic diameter of approximately 330-360 mm, creating a host of challenges ranging from ceramic sourcing to excessive thermal gradients. A review of the RF design can be found in [2].

In response to this, RadiaBeam has developed a novel design that employs a coaxial window, instead of cylindrical. This approach provides several benefits. First, the diameter of the coaxial line is defined by the RF power not frequency since it operates in Transverse Electro-Magnetic (TEM) mode. The window size can be reduced to approximately 250 mm which significantly reduces the fabrication complexity and improves structural stability. Second, water cooling can be applied to both inner diameter (ID) and outer diameter (OD), instead of just the OD of the cylindrical window. Therefore, the field distribution in the coaxial line is more uniform, which reduces dielectric losses and thermal gradients.

MECHANICAL DESIGN

The engineering design is the culminating result of the RF, thermal, and manufacturability requirements. With large internal volumes and changing cross-sectional geometries, breaking the top-level model into sub-assemblies and parts required careful consideration for machining, brazing, handling, and cost. The result is a final assembly that consists of five main sub-assemblies, as demonstrated in Fig. 1. Each sub-assembly requires multiple braze steps prior to the final braze using Gold Copper braze alloys.

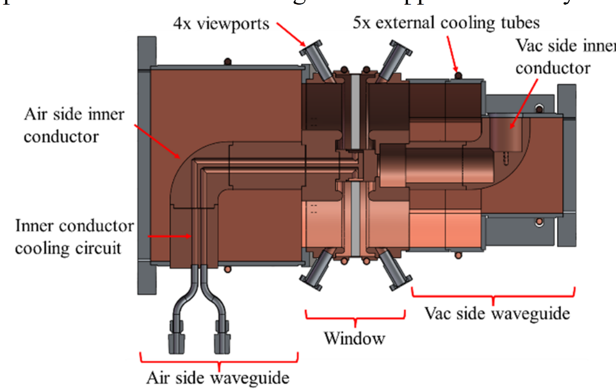

Figure 1: Cross-section view highlighting major sub-assemblies and components.

The window sub-assembly features the critical ceramic window braze. Additional details regarding the Titanium Nitride (TiN) coated Kyocera AO479U window can be found in prior publications [3, 4]. The parts brazed to the inner diameter of the ceramic form a cooling channel that places all braze joints on the air side of the assembly to eliminate risk of water to vacuum leaks. The sleeve that forms the hermetic seal with the metallized ceramic inner diameter is 1.27 mm thick. This allows the sleeve to deform during the high temperature braze to absorb the residual stress caused by the differential coefficients of thermal expansion (CTE) between copper and alumina. Additionally, the thin wall provides excellent heat transfer characteristics.

The outer diameter of the ceramic is brazed to another thin wall sleeve. During brazing, tooling constricts the thin wall to control the growth of the copper sleeve and the gap between the sleeve and the outer diameter of the ceramic at brazing temperatures. Without constrictive tooling, the differential expansion between the copper and alumina would result in a ~1.52 mm gap, far beyond the .025-.076 mm gap required for liquid braze alloy to be pulled into the joint via capillary action. Similar approaches have been demonstrated throughout literature [5-7]. Components

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† kutsaev@radiabeam.com

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with choke features, angled ports for arc detectors and cooling lines are then joined with a secondary braze.

The air side WR2100 waveguide is constructed from 304L stainless steel plates brazed together to make a box. Post braze machining is then performed for fitment to the flange and end plate, which are attached in a subsequent braze. A feedthrough aperture for the air side inner conductor, a cooling tube, and mount locations are also included.

The vacuum side half height WR2100 waveguide is more complicated as it transitions cylindrical to rectangular geometry. In addition to the box construction that the vacuum flange attaches to, an additional sub-assembly is required to create the geometry. Two cooling tubes and eight mounting locations are brazed to the exterior. To prevent excessive deflection of the walls when the interior is put under vacuum, reinforcing bars are welded to the exterior after brazing.

The inner conductor sub-assemblies are L-shaped parts that short the window inner conductor to the broad walls of their respective waveguides. The air side features internal cooling channels that complete the circuit that passes water around the ID sleeve of the window. The vacuum side parts are hollowed out to reduce weight. The interior is vented through an aperture in the half height WR2100 waveguide which also provides a method to hold the face of the inner conductor flush to the waveguide with fasteners during brazing.

All five sub-assemblies are joined together in a final braze, as shown in Fig. 2.

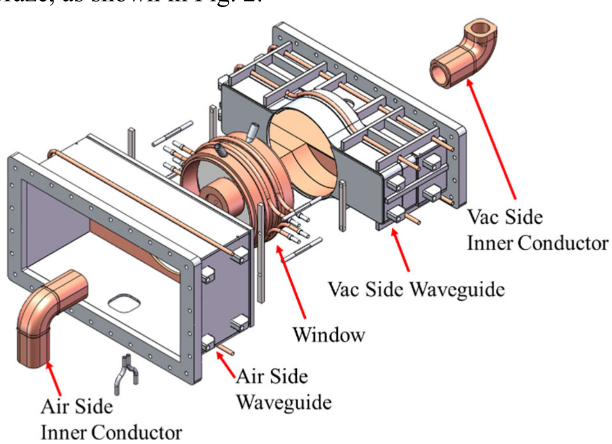

Figure 2: Exploded view of final braze assembly.

MECHANICAL SIMULATIONS

Handling of the approximately 117 kg final assembly presents risks. Of particular concern is the window sub-assembly and ceramic braze joints. To ensure safe handling and shipping, fixturing was designed to enable lifting and mechanical simulations were run to assess the viability. Simulations were performed in ANSYS Mechanical 2024 under room temperature conditions. The mesh resolution was set to 7, the highest possible value. The maximum element size was set to 4 mm and adaptive sizing was turned on. All braze and weld joints were considered fully bonded and the properties of the braze alloy itself were ignored. The model was simplified by removing details such as edge breaks, small gaps for part fitment and braze shims. The faces of the 16 mount locations on the short walls of the waveguides were fixed. The results show a maximum stress of 4.06 MPa, located at the inner diameter braze joint of the ceramic, shown in Fig. 3. This value is well below the yield strength of annealed copper (33 MPa) and therefore considered safe.

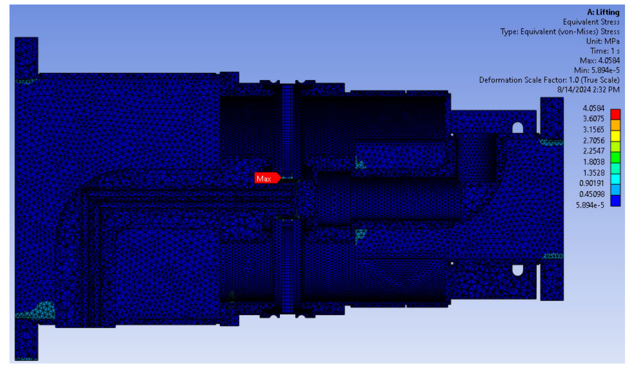

Figure 3: Cross-section view of von Mises stress plot of final assembly under lifting conditions.

Since the assembly will be installed at a 45° angle, an additional simulation was run to evaluate this orientation (Fig. 4). The same mesh and parameters were applied as for the lifting simulation, but only the two RF flange faces were fixed. A maximum stress of 3.27 MPa located at the ceramic ID braze joint was identified, validating the safety of the installation orientation.

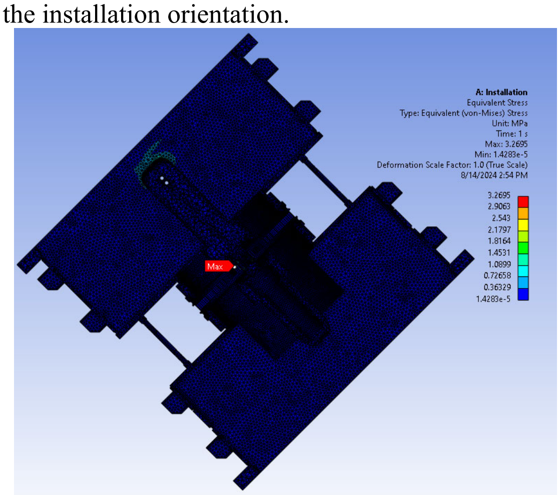

Figure 4: Cross-section view of von Mises stress plot of assembly representing installation conditions.

Considering the large surface areas of both the ceramic and the vacuum side waveguide, a simulation was executed to assess the impact of vacuum forces on the assembly. The set up was similar to the installation configuration, with both RF flange faces fixed. A 0.101 MPa force was applied to all relevant faces on the vacuum side of the assembly, including to the face of the ceramic. A maximum stress, as shown in Fig. 5, of 45.9 MPa was found at the corner of one of the mounts and considered to be an artifact of the simulation and meshing. The maximum stress on the broad walls of concern was approximately 20 MPa, providing a >8x safety factor when compared to the yield strength of

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annealed 304L stainless steel (172 MPa). The maximum deformation shown in Fig. 6 was 0.017 mm, which is less than the anticipated manufacturing tolerances and therefore considered acceptable.

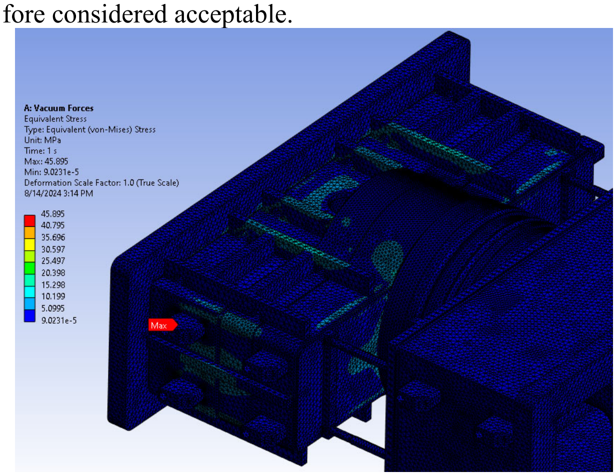

Figure 5: Von Mises stress plot of due to vacuum forces.

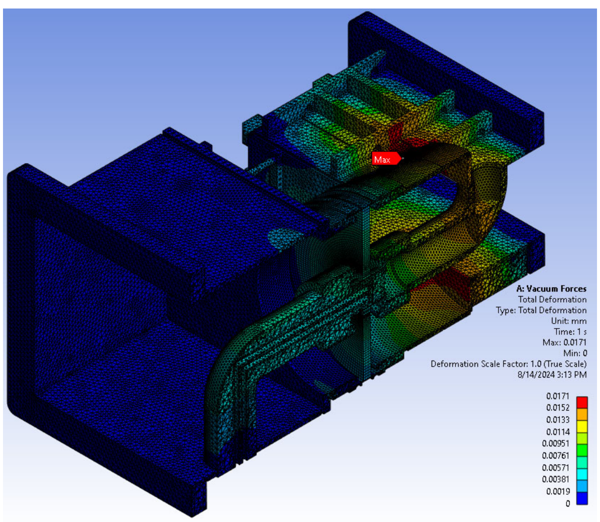

Figure 6: Total deformation plot due to vacuum forces.

CURRENT STATUS

Fabrication has begun on several key components. Namely, the metallized ceramics have been delivered by Kyocera and TiN coated (Fig. 7). Sapphire witness coupons placed in the inner diameter opening during deposition were measured with a profilometer and demonstrated conformance to the 2-4 nm thickness specification.

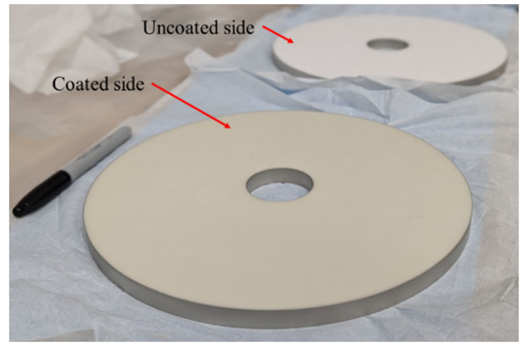

Figure 7: TiN coated windows highlighting the color change between coated and uncoated faces.

Test brazes to validate the inner conductor braze joint were conducted. The initial braze used a 0.051 mm thick braze foil inserted into the joint during assembly. The squeezing of the copper against the foil and ceramic during heating resulted in excess braze alloy flowing out of the joint. A second test braze was then conducted using a 0.025 mm thick braze foil which eliminated the excess alloy (Fig. 8). Both assemblies were leak checked with elastomer seals and found to be hermetic to $1x10^{-9}$ mbar*L/sec. Following this success, machining of the inner and outer sleeves to be brazed to the ceramic have also been completed, as shown in Fig. 9.

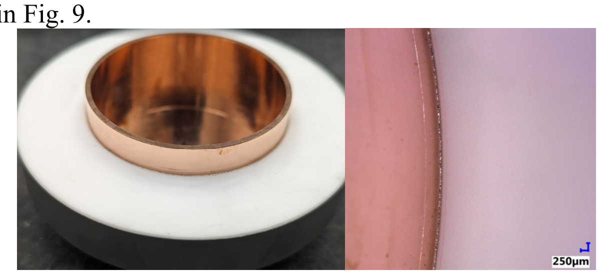

Figure 8: (Left) Second ID test braze assembly showing clean joint without excess alloy flow. (Right) close up view of braze joint.

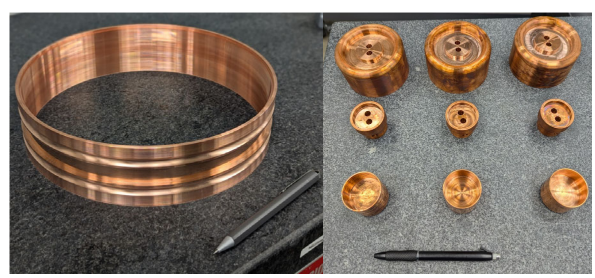

Figure 9: (Left) Outer conductor sleeve. (Right) Inner conductor sleeve and air side choke components.

CONCLUSION

A unique design for a coaxial RF window for use in rectangular waveguide has been completed. The fabrication approach consists of a series of vacuum brazed assemblies using conventionally machined components. Mechanical simulations to validate the handling, installation and vacuum forces have confirmed the design feasibility. Fabrication has begun on the ceramic sub-assembly with completion of the full assembly expected in mid-2025.

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