GA–A22648

T25 ITER ECH WINDOW DEVELOPMENT
110 GHz ECH DISTRIBUTED WINDOW DEVELOPMENT

FINAL REPORT

for the period
May 1, 1994 through December 31, 1995

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R.A. OLSTAD, C.P. MOELLER, and H.J. GRUNLOH

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Summary

Electron Cyclotron Heating (ECH) is one of the major candidates for Heating and Current Drive on ITER. ECH is extremely attractive from a reactor engineering point of view, offering compact launch structures, high injected power density, and a simple interface with the shield/blanket. Economic deployment of ECH for ITER requires MW unit microwave sources (gyrotrons). The present technology limitation is the availability of suitable low loss output windows. These are needed for the torus as well as the tube. The torus window, in particular, is a demanding application as it also serves as a tritium barrier. Several distinct window concepts are under development by the various Parties. This report summarizes the efforts to make and test a “distributed” window suitable for 1 MW cw operation at 110 GHz. A companion report (Final Report on Task 245+) describes the efforts to make a distributed window suitable for 1 MW cw operation at 170 GHz, the main frequency of interest to ITER.

General Atomics (GA) fabricated a 4 in. × 4 in. 110 GHz distributed window which was delivered in September 1995 to Communications and Power Industries (CPI). Hot tests at CPI confirmed the power handling capability of the window. Tests were conducted with a reduced beam size at 200 kW with 0.7 s pulses without any arcing or excessive window temperatures. The power density and pulse length were equivalent to that in a full size 1.2 MW CW beam with a peak-to-average power ratio of 2.7. This window was assembled using a gold braze material to bond the sapphire strips to the niobium frame. The braze was successful except for small leaks at two locations, and re-braze efforts were unsuccessful.

Subsequent work on making a 110 GHz distributed window was performed under DIII–D funding. These efforts did not result in a perfectly leak-tight window. However, based on what has been learned from the window fabrication experience, there is high confidence that a good leak-tight window could be made by starting with a new frame and by using copper, rather than gold, as the braze material. Due to funding limitations and schedule requirements for gyrotron installation at DIII–D, no further work is presently planned on the 110 GHz distributed window. In addition, the rapid development of diamond window technology promises a simpler, yet costly, alternative solution. In addition, the rapid development of diamond window technology promises a simpler, yet costly alternative solution.

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1. Objective of Task

The objective of this task was to produce a distributed window capable of transmitting 1 MW cw 110 GHz microwave power. The window was to be hot-tested and, if successful, mounted on a DIII–D gyrotron for testing and operation up to 1 MW 10 s.

2. Distributed Window Design

The design concept for the distributed window has been described in detail in Ref. 1. As shown in Fig. 1, the window consists of an array of thin sapphire slats separated by hollow tapered niobium vanes through which water coolant passes. The sapphire slats are metallized and brazed to the niobium.

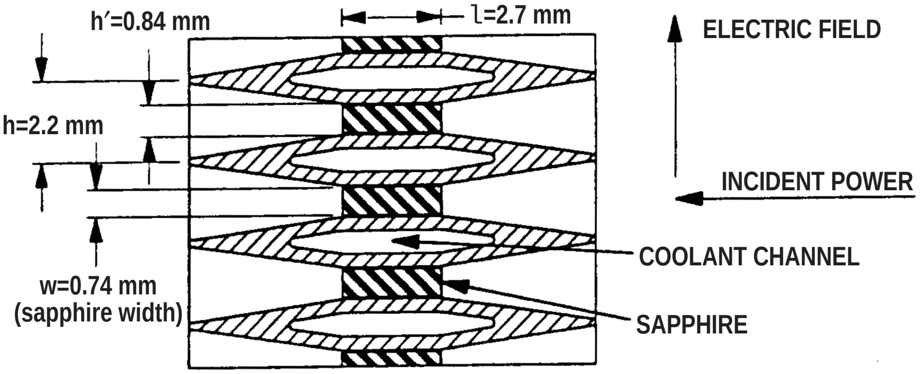

Fig. 1. Typical cross-section of 110 GHz distributed window.

The period h is dictated by the microwave wavelength and must be less than the free space wavelength to prevent propagation of higher modes. For the geometry shown in Fig. 1, the total calculated losses are less than 4% at 110 GHz, with half of this due to Ohmic losses at the metallization layer on the sapphire, and the rest from losses in the sapphire and tapers. Calculations also show that a 100 cm^2 window is capable of readily passing 1 MW in the HE_{11} mode with peak sapphire temperatures of less than 150°C.

3. Small Prototype 110 GHz Window

3.1. Window Verification

To verify the approach for fabricating a sapphire/niobium distributed window, GA fabricated, on private funds, a 2.4 in. × 2. in. (61 mm 61 mm) prototype window. The window and its test interface hardware are shown in Fig. 2. The niobium frame was fabricated from an integral plate of niobium by first drilling pilot holes at the center of each water channel, and then EDMing out the water channels. Similarly, the slots for the sapphire pieces and the tapered vanes were made using EDM techniques.

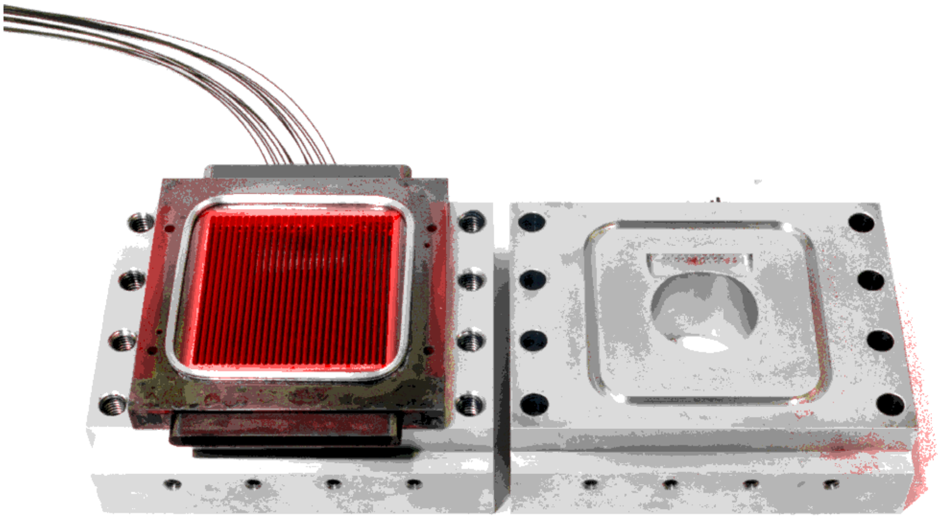

Fig. 2. 110 GHz prototype window.

3.2. Test Results

As reported in Ref. 2, the GA prototype distributed window was tested in October 1994 in a 32 mm diameter waveguide system at a power density suitable for a MW gyrotron, using the Japan Atomic Energy Research Institute (JAERI)/Toshiba 110 GHz long pulse internal converter gyrotron in the JAERI test stand.

A pulse length of 300 ms (10 times the calculated thermal equilibrium time of 30 ms) and power level of 65 kW were reached. The peak power density of 30 kW/cm^2 was that corresponding to 800 kW for a 10 cm × 10 cm window with the HE_{11} mode. It is also equivalent to the power density of a 2 MW system with a flattened profile. The presence of the distributed window had no adverse effect on the gyrotron operation.

The window passed at least 750 pulses greater than 30 ms and 343 pulses greater than 60 ms. Beyond 100 ms, the window calorimetry reached steady state, allowing the window dissipation to be measured in a single pulse. The measured loss of 4.0% agrees both with the estimated loss and with the attenuation measured at low power in the HE_{11} mode. There was no evidence of arcing in the part of the window directly illuminated by the microwaves, although there apparently had been some arcing in a recess containing an optical diagnostic which outgassed. Also, there was no failure of the metal-sapphire joints during the total operating time of 50 s consisting of pulses longer than 30 ms.

4. Full-Size 110 GHz Windows

4.1. Fabrication of 2 in. x 8 in. and 4 in. x 4 in. Windows

The initial effort to make a full-size window was to scale up the small prototype window by merely making it almost four times longer and increasing by a factor of four the number of sapphire pieces and water channels. One of the most critical early steps in fabricating the niobium frame was to insert pilot holes at the center of the coolant channels, so that the rest of the material in the channel can be removed using wire EDM. The EDM vendor had the hole-popping done by one of their vendors, and after a considerable number of months, the frame was returned and EDMed. In the process of EDMing the sapphire slots and vanes, it was apparent that the pilot holes had not all been straight since one of them pierced the sidewall of the vane. The holes had been made by hole-popping from each end of the frame such that they would intersect near the middle of the frame. Rather than make a second 2 in. × 8 in. frame, it was decided to make a 4 in. × 4 in. window which was preferred by Varian for mounting on one of their gyrotrons.

GA engineering staff worked closely with two local vendors with EDM capability to see if they could develop the capability to produce pilot holes in a 6 in. × 6 in. niobium frame used to make a 4 in. × 4 in. window. After considerable effort on both companies' parts, both independently developed such a capability. In order to reduce the vendor's risk in making a niobium frame, GA designers realized they could increase the spacing somewhat between adjacent channels without compromising the microwave performance. With 43 holes rather than the original 48 holes, both vendors accepted purchase orders to make a niobium frame for the distributed windows.

As a fall-back position in case the EDM vendors were not successful, GA pursued, in collaboration with Lawrence Livermore National Laboratory (LLNL), a technique for hot-pressing two niobium plates together, one of which had grooves machined into the face. After bonding, these grooves would be the pilot holes for subsequent EDMing. This technique was first demonstrated on a small scale under GA private funds, and the effort at LLNL was to use their hot press to bond the full-size plates together. LLNL successfully bonded two plates together. Sections at the end of the bonded plates were removed and examined. After polishing and etching, a large amount of porosity was visible at the interface. In addition, hot pressing caused some distortion of the plate which made the spacing between holes not as uniform as desired. By this time, one of the EDM vendors had succeeded in making pilot holes for a 4 in. × 4 in. window, so no further work was done on the hot-pressing technique.

After this first frame was EDMed, the window was assembled using gold foils as the braze material. After brazing, leak checking showed there were some leaks. A re-braze effort did not significantly reduce the leaks. It was decided to test the window at CPI's test stand anyway because the window would have vacuum on both sides. The results of the tests are described in Section 4.2. The delivery and testing of this window marked the completion of the milestones under Task 25.

For completeness, the additional efforts carried out on 110 GHz distributed window fabrication under DIII–D funding are summarized here because they are relevant to the potential future use of distributed windows for ITER.

Window modeling at LLNL showed that the sapphire thickness used in the previous window was slightly too large because the effective thickness of the sapphire is larger than its actual thickness because of wave scattering effects (Ref. 3). Dr. Michael Shapiro of the Massachusetts Institute of Technology subsequently confirmed this effect analytically, and in addition showed that since the dielectric constant of sapphire increases with temperature, the effective thickness of the sapphire also increases as it heats up during a microwave pulse. The consequence of having the sapphire too thick is that window reflectivity will be too high at the operating temperature. As shown in Figs. 3A and 3B, for a sapphire thickness of 2.67 mm (as for the window described above), the calculated reflectivity at 110 GHz is approximately 2% at 300 K, and increases to approximately 6% as the temperature increases to 370 K. These calculated values are in reasonable agreement with values determined experimentally at GA. As shown in Fig. 3C, Dr. Shapiro's calculations show that for an optimum thickness of 2.65 mm, the reflectivity varies from 2% at room temperature, decreases to 0.6% at 355 K, and increases back to 2% as the temperature increases to 410 K. This 2.65 mm thickness was chosen for the next window.

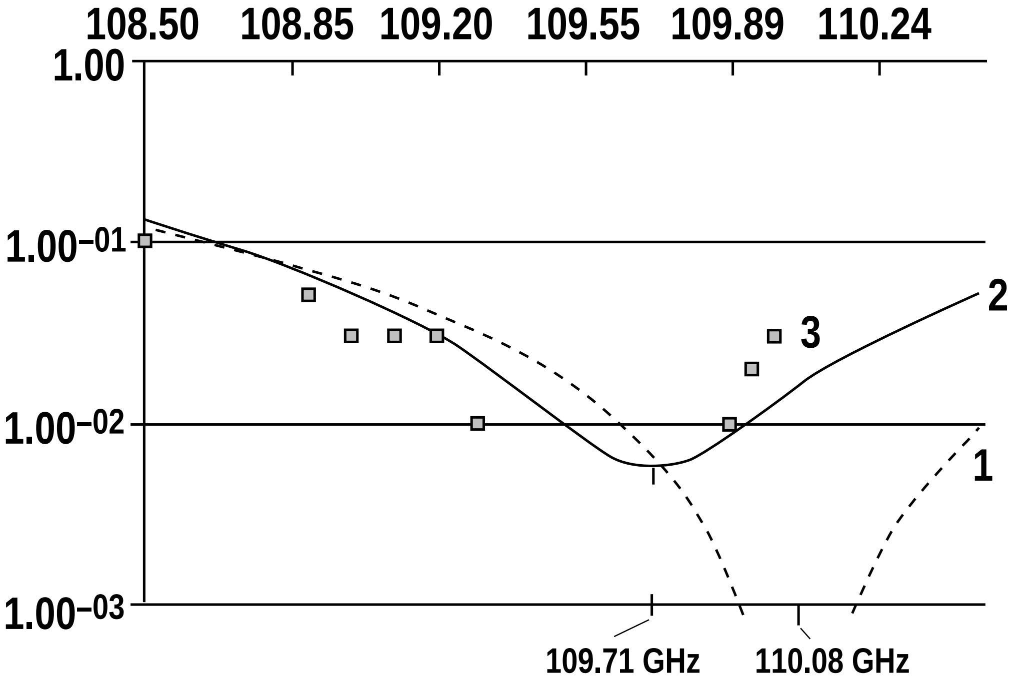

Fig. 3A. Reflectivity versus frequency for a sapphire thickness of 2.67 mm at 300 K.

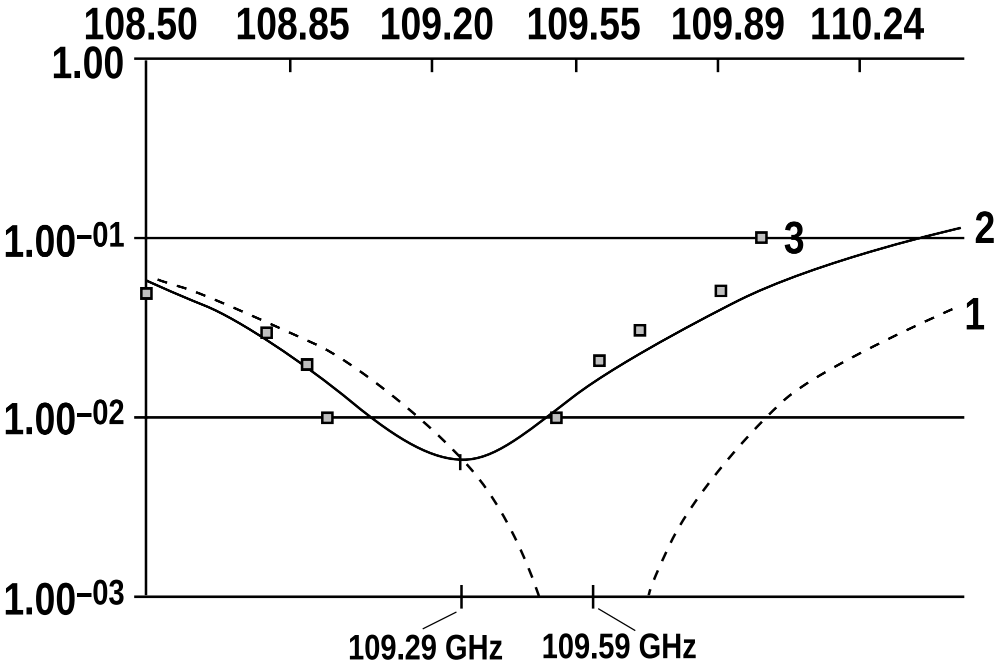

Fig. 3B Reflectivity versus frequency for a sapphire thickness of 2.67 mm at 355 K.

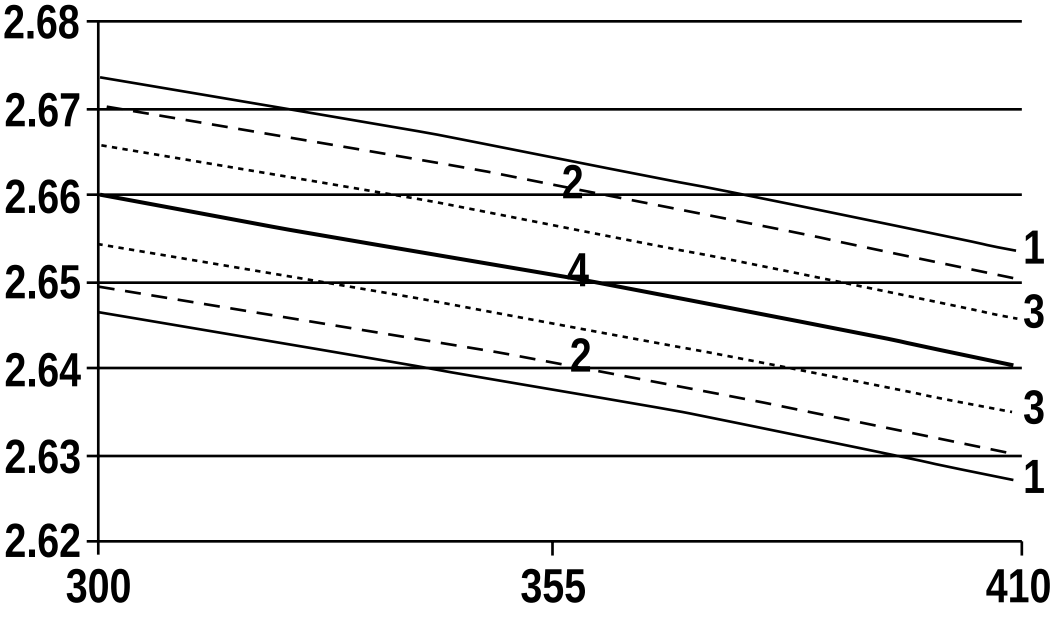

Fig. 3C Reflectivity values versus sapphire thickness and sapphire temperature.

Another window was assembled using gold braze, but was not usable because there was poor wetting of the sapphire at the ends. The sapphire was removed by dissolving the gold out of the niobium frame so that both sapphire and niobium could be used again. In the course of this activity, it was learned that the gold penetrates significantly into the niobium and that some niobium diffuses through the gold and adheres very strongly to the sapphire, as evidenced by pitting that occurred during the dissolution process. This was considered undesirable for several reasons: (a) unless the brazing is perfect the first time, the frame and sapphire may not be reusable for a reassembly and new braze, (b) re-braze efforts will result in even more diffusion and interaction of sapphire with niobium and create a brittle interface that may open up leaks during subsequent cool-down and bake-out steps, and (c) the Ohmic loss at the metallization layer will increase because of the formation of higher resistivity compounds.

For these reasons, considerable effort was given to finding a barrier layer that will prevent interdiffusion between the gold and niobium. A tungsten coating was applied to a niobium frame, but sections of the coating debonded during the braze cycle. Presumably this was partly due to the thermal expansion mismatch between niobium and tungsten. Rhenium has a better thermal expansion match with niobium, and a technique was developed to evaporatively coat rhenium onto the niobium frame. Tests showed that the niobium surface needed to be electropolished before coating with rhenium if the rhenium was to act as an effective barrier. Rhenium was coated on an electropolished frame and a window was assembled. During the assembly process it became apparent that the rhenium did not form a hard coating in the region between the vanes, most likely because of the shallow angle at which that the rhenium atoms hit the niobium surface during the coating process.

Because of the failed attempt at applying a barrier coating, alternate braze materials were investigated. Work on the 170 GHz window task (T245+) showed that copper can be a very effective braze material if the niobium surface is free of oxygen. Copper has a melting point of 1083°C, well above the 450°C–500°C gyrotron tube bakeout temperature.

A previously-used niobium frame was coated with copper and assembled with sapphire slats using copper foil braze material. The braze window had several leaks, all but one of which were repaired by inserting small pieces of active braze alloy foils with a slightly lower melting point than copper and going through a braze cycle. The braze difficulty was due to the large gaps that had to be filled with copper. These gaps were larger than the design values because the niobium/gold interaction layer from its previous use had to be removed by EDM before the frame could be used again. A photo of the completed window is shown in Fig. 4. The window was sent to CPI for testing, and the test results are described in Section 4.2.

By this time, the DIII–D schedule required that CPI proceed with completing fabrication of the gyrotron using a double disk sapphire window. With this window, the gyrotron is capable of 1 MW 0.8 s operation rather than the preferred 1 MW 10 s operation.

4.2. Test Results on 4 in. x 4 in. Windows

The first 4 in. × 4 in. window was received at CPI on September 18, 1995 and assembled in its test configuration interface hardware. (See Appendix A for a description of

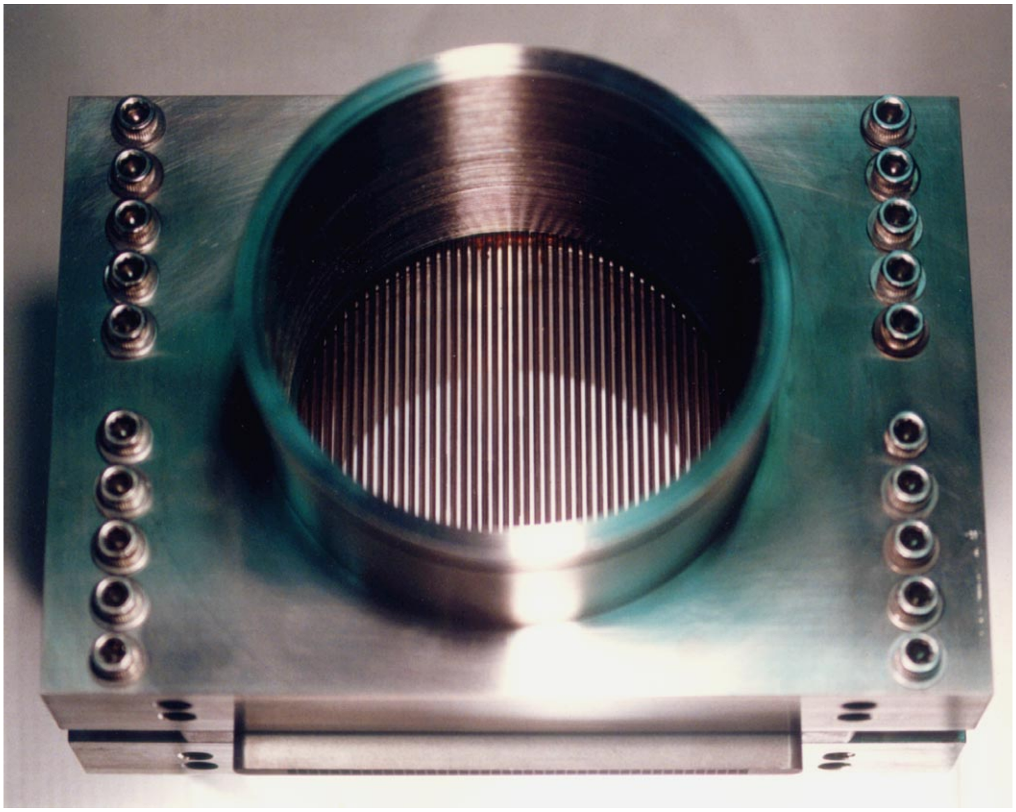

Fig. 4. Full-size 110 GHz window (copper braze version) and test configuration interface hardware.

the interface hardware.) The window was mounted between a mirror/elbow and a dummy load, with the consideration that any reflected power would not get back into the gyrotron with such a setup. After initial tests to verify that the window was oriented with the beam's E field perpendicular to the vanes, the window was operated at 250 kW at maximum pulse duration of 1.7 ms, a repetition rate of 30 pps, and a water flow rate of 7 gpm. The window absorbed 15 kW, or 5.7% of the incident power. The flow rate was increased to 12.2 gpm, the maximum pulse was increased to 1 ms, the power was held at 250 kW, and the elbow/mirror was adjusted to get the Gaussian beam centered on the window. The window losses began climbing, and the losses in the elbow and internal load also increased. The window temperatures also were getting greater than 300°C according to the IR camera. Tests were stopped and the window was removed.

Inspection of the window showed that there was some braze material that had melted and solidified onto the niobium vanes, and there was damage to the sapphire at the beam location. It was determined that the damage was due to arcing because of poor vacuum. The vacuum pressure reading at the turbopump was 5 mtorr, and was therefore even higher at the window. Also there was no arc detector to determine early on that arcing was occurring.

The window was returned to GA to remove the deposits from the sapphire surface and niobium vanes. The window was returned to CPI and additional testing began on November 14, 1995. The vacuum pressure was improved to 5×10^{-4} to 7×10^{-5} near the window, and arc detection was provided. The reduced diameter beam was shifted off-center so that it did not impinge on the damaged portion of the window. Water flow rate was increased to 22–25 gpm, and the window was tested up to 200 kW, 700 ms. The measured losses were 7% (higher than the predicted 4% with gold braze) because of the rebraze cycle and damage the window had encountered earlier. The thermal equilibrium time constant for the window is approximately 0.2 s, so the 0.7 s pulses were equivalent to steady state. The peak power density during 200 kW operation was equivalent to the level that would be experienced if the window had been mounted on the gyrotron and the output were 1.2 MW with a peak-to-average power ratio of 2.7.

The window brazed with copper was also tested at CPI. With a 25 mm diameter beam, 100 kW 350 ms pulses were applied before the measured losses and IR camera indicated a problem. The 100 kW level was equivalent to 600 kW in a gyrotron window. A vacuum leak had opened up in the load, causing the vacuum pressure to increase to 1×10^{-3} torr. Even though there was an arc detector, its sensitivity did not allow the arcing to be detected before the window was damaged. The measured losses in the window were only 4.5% before arcing caused the losses to increase. This was lower than the 5.7 and 7% values measured on the gold-brazed window, which had gone through a rebraze cycle which increased its Ohmic losses. The measurements on the copper-brazed window confirmed that copper braze gives a low metallization layer Ohmic loss, even after a rebraze cycle.

5. Conclusions

The work performed under this Task T25, the subsequent 110 GHz window fabrication work done under DIII–D funding, and the brazing technology work done under Task T245+ have confirmed the viability of the distributed window concept for use on MW-level cw gyrotrons. Even though a perfectly leak-tight window was not made before running out of time and funding, there is high confidence that a leak-tight window could be made by starting with a new niobium frame and using copper as the braze material. The high power testing of the first 4 in. × 4 in. window at CPI confirmed that the power handling capability of the window exceeds 1 MW, particularly if the beam has a flattened profile.

6. Acknowledgment

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER52153.

7. References

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2. C.P. Moeller *et al.*, GA Microwave Window Development, Milestone No. 1, GA-C21874, October 1994.
3. S.C. Nelson *et al.*, “Electromagnetic and Thermal Analysis of Distributed Cooled High Power Millimeter Wave Windows,” in Proc. 11th Topical Conference on Radio Frequency Power in Plasmas, Palm Springs, CA (1995), pp. 441–445.

Appendix A: Interface Hardware

A related effort to fabricating the distributed window itself was the design and fabrication of interface hardware for the window. Two configurations were needed: (a) configuration for hot-testing the window under vacuum some distance away from the gyrotron, and (b) the service configuration that would be used once the window is mounted on a gyrotron. A critical feature of this second configuration is that it be compatible with baking out the mounted window/gyrotron at approximately 500°C for an extended period of time as one of the final gyrotron fabrication steps. The two configurations are shown in Figs. A1 and A2. Both sets of interface hardware were fabricated.

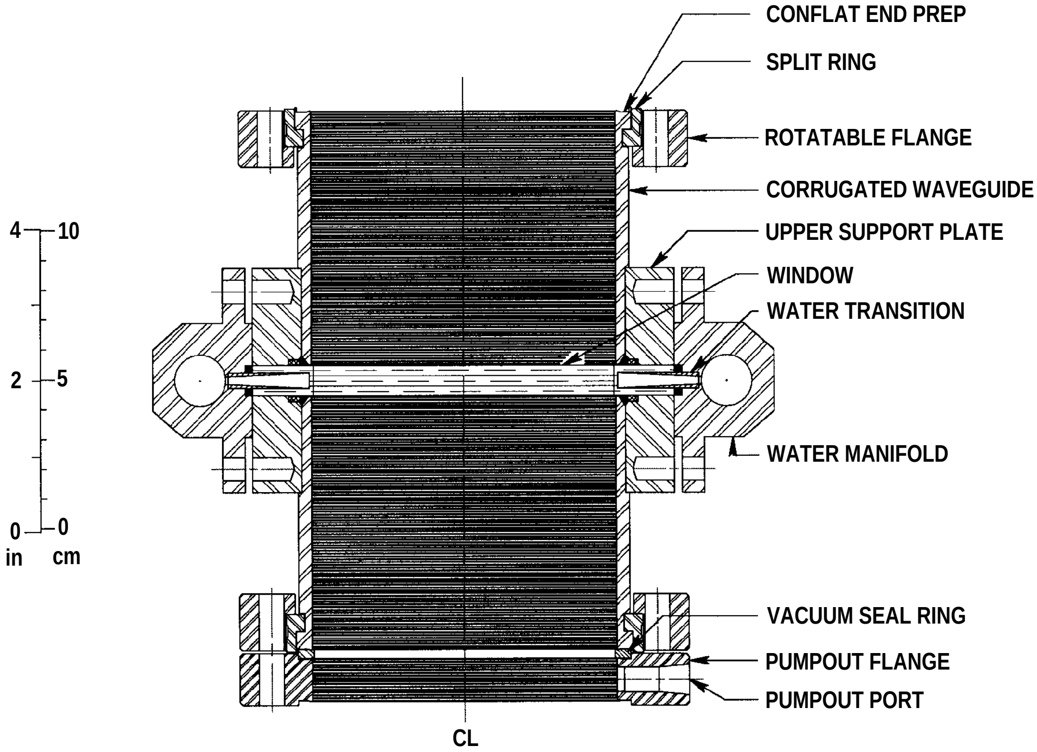

Fig. A1. Interface hardware for test configuration.

The test configuration drawing shown in Fig. A1 shows the key features of the design. The window is cooled by pumping water through water manifold pieces on each end of the window. Water is forced through water transition pieces that butt up against the cooling channels in the niobium frame. The water transition pieces have 43 holes which align precisely with the 43 coolant channel holes. Vacuum sealing is accomplished using Helicoflex seals between the upper support plate pieces and the window. The upper support plates are welded to corrugated waveguide sections to maintain the HE_{11} mode on both sides of the window.

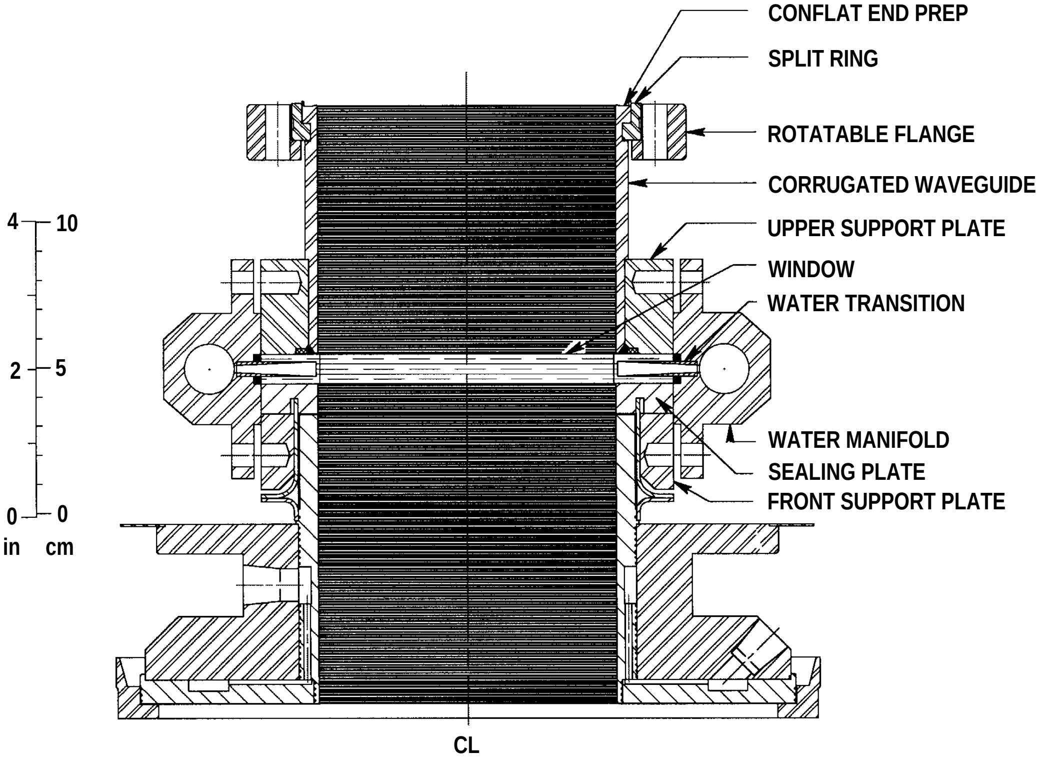

Fig. A2. Interface hardware for service configuration.

The service configuration shown in Fig. A2 uses the test configuration on the tokamak side of the window. The interface hardware on the gyrotron side is more complicated. Since the window and the gyrotron side hardware need to survive a 500°C bakeout, aluminum Helicoflex seals cannot be used. Vacuum sealing on this side is accomplished by e-beam welding a niobium sealing plate to the edge of the window. A stainless steel ring is brazed into a groove in the sealing plate, and this ring is in turn welded to a sealed mating ring. The hardware closest to the gyrotron can be water-cooled to remove heat dissipated in the waveguide from modes other than HE_{11} generated from the gyrotron.