GA–C21874

MILESTONE NO. 1
TASK ID NOS. T243 (U.S. task 3.2) and T242 (JA Task 2.1)

GA MICROWAVE WINDOW DEVELOPMENT

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C.P. MOELLER, General Atomics

A. KASUGAI, K. SAKAMOTO, and K. TAKAHASHI,
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ABSTRACT

The GA prototype distributed window was tested in a 32 mm diam. waveguide system at a power density suitable for a MW gyrotron, using the JAERI/Toshiba 110 GHz long pulse internal converter gyrotron in the JAERI test stand. The presence of the untilted distributed window had no adverse effect on the gyrotron operation.

A pulse length of 10 times the calculated thermal equilibrium time (1/e time) of 30 msec was reached, and the window passed at least 750 pulses greater than 30 msec and 343 pulses greater than 60 msec.

Beyond 100 msec, 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, on which our stress calculations are based, and with the attenuation measured at low power in the HE_{11} mode. After the end of the tests, the window was examined; no evidence of arcing or coating was found in the part of the window directly illuminated by the microwaves, although there was discoloration in a recess containing an optical diagnostic which outgassed, causing a local discharge to occur in that recess.

Finally, there was no failure of the metal-sapphire joints during a total operating time of 50 seconds consisting of pulses longer than 30 msec.

1. INTRODUCTION

This report describes the results of the first effort to test the prototype GA distributed microwave vacuum window to determine its power handling and loss properties. The tests were performed at the JAERI gyrotron test stand, which has the most successful high power source currently available, a 500 kW long pulse gyrotron built by JAERI/Toshiba, which had recently demonstrated 350 kW for 5 seconds, and which was reinstalled in the JAERI gyrotron test stand for these tests.

Since the high power tests of the gyrotron had been run using a 32 mm diam. load (purchased from) and a transmission system which uses the GA couplings, additional equipment needed would be minimized if the test was done using the same 32 mm diam. Although the GA window is 61 × 61 mm, it was easy to mask all but the central 32 mm diam. With the distributed window design, it is only necessary to demonstrate the same peak and average power density as would be used in a 1 MW window, because the cooling is distributed over the cross section by dividing the incident power among many parallel strip windows.

The heat removal and breakdown issues are therefore local, and depend only on the peak power. In this case, only 80 kW in a circular HE_{11} profile is equivalent to 1 MW in the 100 mm square window in the HE_{11} mode.

1.1. Experimental Setup and Diagnostics

The experimental setup is shown schematically in Fig. 1.

The adaptors for 32 mm diam., which sandwiched the distributed window "plate," contained two diagnostics, a set of optical fibers for visible light, and a set of IR fibers with which we hoped to get an indication of the sapphire temperature rise. With the distributed window geometry, the individual strips are well isolated optically, so a fiber is required for each of the 12 strips that are exposed by the 32 mm diam. guide. In addition, a 0.5 mm diam. sheathed exposed by the 32 mm diam. guide. In addition, a 0.5 mm diam. sheathed thermocouple was installed in the outlet water stream of the window for a measurement of the total window dissipation.

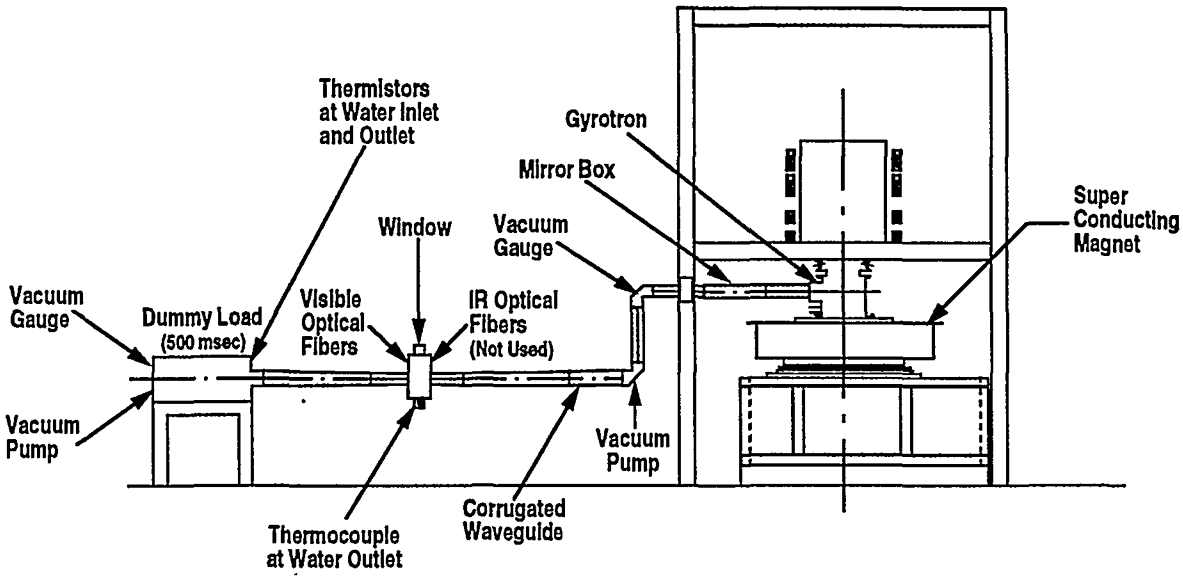

Fig. 1. Experimental setup for distributed window in the JAERI test stand.

We decided to use a Toshiba calorimeter initially, capable of 80 kW for 500 msec, because the power measurement is so much quicker with that device than with the long pulse load. The calorimeter was first used without the window (but with the tapers down to 32 mm diam. and back up to 89 mm diam.) to find parameters that would give the low power required. They found they could operate as low as 50 kW, although the magnet adjustments were rather critical.

The window was than installed and the system leak-checked on the gyrotron side of the window, which was easy since the pump (which is coupled through one of the 89 mm miter bends) is also the leak checker. There was in fact a leak at a joint in the down taper, but the pressure got down to 4–5 × 10^{-4} torr, as seen on an ion gauge on the other miter bend. The load also has pump and gauge ports, but they are only 10 mm diam. and so the pressure was not good even before the window was installed, only 5–6 × 10^{-3} torr. We decided to proceed anyway.

An effort was made to calibrate the IR fibers using JAERI's long wavelength camera (8–11 μm). It was found that although the fiber has low attenuation, the combination of reflection and collection efficiency gives an apparent temperature that is much lower than the true value, although usable if calibrated. More important, the camera scans over about 1 sec, and a consistent reading requires an accurate focus on the fiber. Therefore, we did not pursue it further. With a fixed detector, better coupling, and calibration in the same geometry in which they are to be used, the IR fibers could be made useful.

1.2. Experimental Experience

We found, after inserting the window, that with the previously determined magnet settings and beam current the power measured by the calorimeter was very close to the previous value. This is very important because it shows that stability of the gyrotron operation was not affected by the presence of the window, even with an internal launcher of only 80% efficiency. This is especially noteworthy because this window was not tilted, so any reflection would get back to the gyrotron cavity. Ultimately, after we reached 180 msec, we saw some evidence from a 1-hole coupler that there probably was a small frequency jump. I was given the impression that normally as the cavity heats up the frequency shifts smoothly. It may be that at the 110.14 to 110.16 frequency at which we operated our window is not perfectly matched.

In general, we found detectable light from the visible fibers, but only from 1 of the 12 initially, and later 2 (symmetrically placed, 3rd from center). Normally, the light just rose in milliseconds to a stable value and remained there, unless the gyrotron made a small frequency jump during long pulses, in which case there could also be a step in the light. Occasionally, especially in the beginning, if we attempted to extend pulse length too quickly, the light would rise in tens of microseconds to the trip level. We interpreted these events as arcs at the time. By going back to 1 msec pulses, this rapid rise would cease either immediately or after a few pulses, after which we could quickly get back to where we had been. Later, it became apparent that simply waiting achieved the same effect, suggesting we just had to pump some gas.

After we quit, an examination of the window showed no deposits or evidence of arcing in the region of the sapphire strips or in the 32 mm clear diameter. It was apparent, however, that there probably was a glow discharge in the vicinity of the optical fibers, which are outside the waveguide diameter, because the vane structure near these fibers was discolored. Only diffracted power can reach this region, but there must have been enough to cause the epoxy, which seals the optical fibers and which is slightly exposed, to heat up and outgas. This is consistent with the observations that we could recover by waiting and that the only evidence of a discharge was immediately in front of the fibers, outside the region of high power.

1.3. Quantitative Experimental Results

In the expectation that some conditioning would be required, we began with 0.5 msec pulses and worked out to 20 msec in 1 msec steps, then 100 msec in 5 and 10 msec steps, and finally 300 msec in 10 and 20 msec steps. This was all done at 55–65 kW. At various points, the power was measured with the calorimeter; in particular at 300 msec, it was measured to be 65 kW, corresponding to 800 kW for a 10 cm × 10 cm window with the HE_{11} mode. This lower power was settled on initially because the maximum water flow rate available through the window was 0.95 ℓ/sec, rather less then the 1.2 ℓ/sec that was assumed when window temperatures were calculated. Even this lower power density is highly relevant to a 1 MW gyrotron, however, because with a flattened profile, as is planned for the Varian and Russian gyrotrons, this 65 kW is equivalent to as much as 2 MW in a 10 cm × 10 cm window.

We also ran, in the few hours that remained for the experiment, 85 kW pulses, inspite of the somewhat low water flow. We were quickly able to obtain 40 msec pulses, but we then encountered a rapid light increase, which set us back to 1 msec pulses. Which short pulse conditioning, and later, we disconvered, just waiting, we were able to reach 30 msec again, but we were too hurried to properly condition the source of outgassing at the higher power to get beyong that pulse length. We did pass 85 kW through the window for a total of 7.5 seconds of pulses greater than 1 msec, which shoud have resulted in some damage if any real arcing were occuring.

Regarding the relevance of the pulse length we reached, the time to thermal equilibrium is approximately 30 msec (1/e time), as determined by a finite element analysis provided by Richard Temkin and Philipp Borchard at MIT. This analysis did not take the temperature dependence of the loss tangent into account during the temporal evolution, but by iteration used the correct final value in the calculation. The diffusion time is short because heat generated in the sapphire only has to diffuse 0.4 mm to the braze and 0.25 to 0.50 mm further through the niobium to the water. Therefore, by 60 msec, the window should have reached 90% of the final temperature. We took at least 750 pulses greater than 30 msec, and 343 pulses greater than 60 msec, which should have provided adequate opportunity for mechanical failure.

Regarding the window dissipation measurement, at the usual flow rate of 50 ℓ/min, it only takes 7 msec for water to pass through the cooling channel, so the water temperature should follow the temperature of the structure closely. Unfortunately, the response time of the thermocouple is unknown, while the amplifier used with the thermocouple has a 7 Hz bandwidth to limit the noise level, which means the rise time is ≥50 msec. With the 300 msec pulses, after about 100 msec the signal reaches a very obvious flat top, as can be seen in Fig. 2. The ripple is 50 Hz pickup, which is difficult to eliminate at the microvolt level. The 30 microvolt flat top corresponds to a water temperature rise of 0.75°C and dissipation of 2.6 kW. With 65 kW from the gyrotrons, that gives an efficiency of 4.0%, which is at the center of the range of estimated attenuation values, as well as the value measured at low power for the attenuation of the HE_{11} mode (4% ± 2%). This is important not only with regard to efficiency, but because the peak temperature and hence the stresses depend on the heat input, so if the measured attenuation agrees with the estimated value then the peak temperature and stresses are most likely close to the estimated values as well.

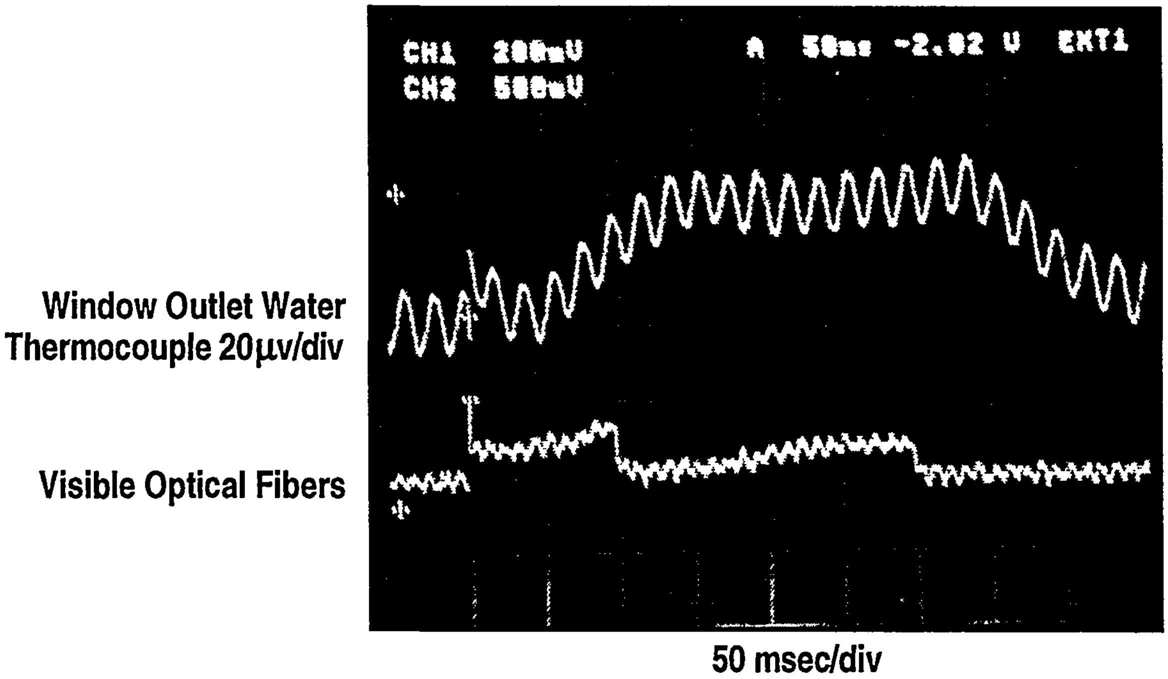

Fig. 2. 300 msec pulse, 63 kW measured at load. The 30 µv rise is equivalent to 2.6 kW dissipated, which is 4.0% of the incident power the step in the light signal is most probably due a frequency junp, since it is also seen on the rf dectector diode.

2. CONCLUSIONS

To summarize, we passed a peak power of 30 kW/cm^2 through the distributed window for pulses as long as 300 msec, 5 times the 1/e^2 equilibrium time of 60 msec, 343 pulses which were longer than 60 msec, 750 pulses which were longer than 30 msec, and an accumulated "on time" of 50 sec of pulses longer than 30 msec. The 30 kW/cm^2 is consistent with 1 MW in a 10 cm diameter with a slightly flattened profile. In addition, we reached 40 msec at 40 kW/cm^2 by the end of the experimental time and an accumulated on time of 7.5 sec, the latter power density corresponding to 1 MW in a 10 cm diameter circular HE_{11} mode. At the end of the experiment, the window was examined and no evidence of arcing or coating was found on the sapphire anywhere or on the metal vanes within the waveguide diameter, although there was a detectable coating of the vanes opposite our optical fibers, presumable from outgassing of the sealing epoxy.