# Calorimetric Measurements of the Output Power of the 2.48 GHz Commercial Magnetron

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## ABSTRACT

A 2.45 GHz magnetron from a domestic microwave oven, with a power output rating of 1.5 kW, is utilized as the microwave source in the design of a multipurpose electron cyclotron resonance plasma device in the Plasma Physics Laboratory of the National Institute of Physics. Measurements of the power output to a 2 liter water load and a dummy load were obtained using calorimetry. The experiment shows that it is possible to achieve a relatively stable maximum average power of 190 W delivered to the 2 liter water load continuously for at least 10 min. It is also shown that the magnetron can deliver a maximum power of about 2.2 kW.

## INTRODUCTION

In electron cyclotron resonance (ECR) plasmas, the electrons are heated in the inhomogeneous magnetic field by interaction with axially launched electromagnetic waves (Kawai et al., 2001). The advantage of an ECR device unlike the dc or low-frequency discharges is that the vessel walls are not bombarded by electrons that release more electrons and impurity atoms that can contaminate the plasma volume (MacDonald & Tetenbaum, 1978). The compact ECR device also reduces power consumption due to the use of permanent magnets to produce minimum-*B* structures for electron plasma confinement (Schlapp et al., 1992).

In some devices using microwave discharges, thin-film deposition and surface treatment are performed on substrates which are not heated by other means than the one delivered by the discharge itself. Thin films of silicon carbide (SiC) (Shimada et al., 1997) and silicon nitride (SiN) (Sitbon et al., 1995) have been deposited in this manner. ECR technology is also utilized in the deposition of diamond thin films (Barshilia et al., 1996) through microwave plasma enhanced chemical-vapor deposition (MPECVD). Microwave plasmas are also used as ion sources for beam-assisted surface modification and deposition (Wartski et al., 1996).

High-power microwave sources are often expensive for the assembly of the ECR device so that 2.45 GHz commercial magnetrons used in microwave ovens were also used as altenative microwave sources. Schlapp et al. (1992) and Wutte et al. (1994) constructed ECR devices using a 2.45 GHz magnetron for the production of multiply charged ions (Schlapp et al., 1992) and $Li^+$ ions (Wutte et al., 1994), respectively.

An increasing interest in the application of high-power microwaves led to the design of different methods of establishing the actual value of power delivered by the microwave source. Piotrowski (1998) mentioned that there are three methods currently utilized for microwave power measurements. The first type is based on sampling high-power microwaves via a directional coupler with precisely known directivity and using an accurrate power meter. This method is often expensive and requires special calibration. The second type is based on the calorimetric measurements of a heated flowing water load. The system consists of a glass tube filled with water, which is introduced into a waveguide at a small angle with respect to the incident radiation to reduce the reflection of microwaves. Piotrowski himself used this method for designing a low-cost calibration system for high-power microwave sources. The third type is based on the comparison of temperature increase of a heated water load from a dc-powered heater. This method requires sophisticated heating and temperature control equipment.

A dummy load is installed in the setup that would serve as a complementary load to the target load, in this experiment, a 2 L water load, and later would be the plasma in the ECR vacuum chamber. It would be used to calibrate the delivered power to the load by measuring the power delivered to it. It is therefore important to determine in this experiment the various power measurements to the load and dummy load for the different configurations of the setup.

## METHODOLOGY

The schematic diagram of the microwave source is shown in Fig. 1. The microwave source has a basic RLC circuit. The high-voltage transformer steps up the voltage source to approximately 3–4 kV that will be supplied to the magnetron.

The magnetron used in the experiment has a frequency of 2.45 GHz and an output power rating of 1.5 kW. It is enclosed by an aluminum casing with air inflow and outflow fans installed on its sides used specifically for cooling the magnetron. The diagram of the experimental setup is shown in Fig. 2. The magnetron is coupled to a circulator, which splits the path of the microwave into two parts.

The dummy load is comprised of two glass tubes where water would flow at a rate of 5.95 L/min. The top view and cross section of the dummy load is shown in Fig. 3. The water for the dummy load is supplied by a CFT-75 recirculating chiller, which also controls the water flow rate and temperature. The excess reflected power would be dumped into the dummy load to avoid damaging the magnetron.

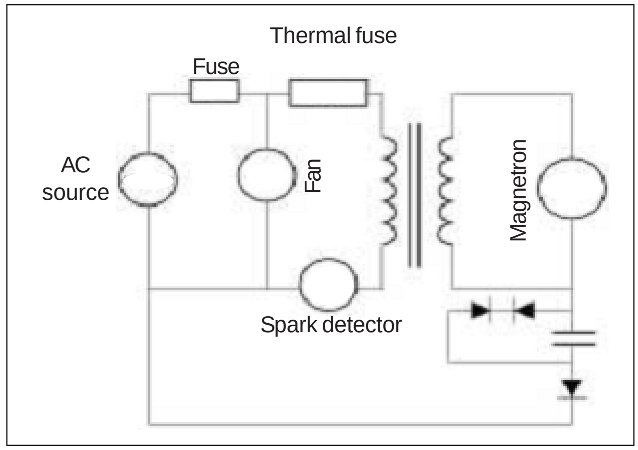


Fig. 1. Schematic diagram of the microwave source circuit.

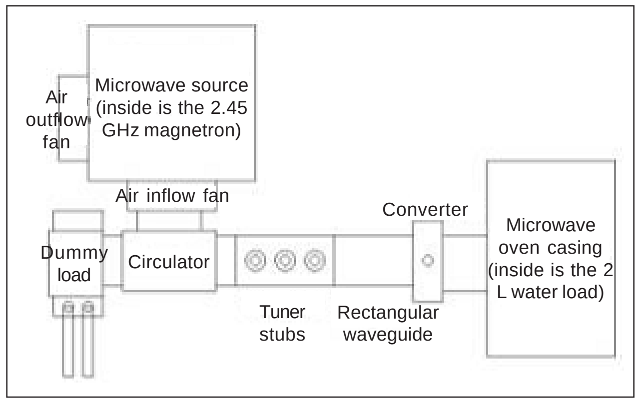


Fig. 2. Diagram of the experimental setup.

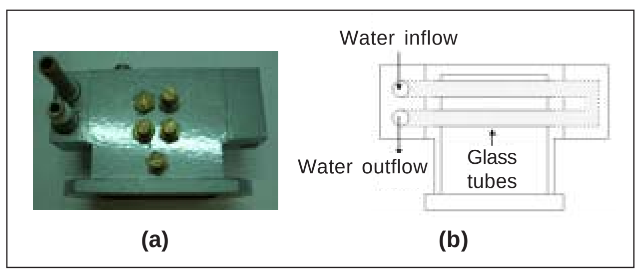


Fig. 3. Dummy load component: (a) Top view and (b) top-view cross section.

The other side of the circulator is connected to the microwave oven case through a rectangular waveguide and tuner stubs assembly. The tuner stubs are used for matching the impedance of this branch of the circulator with the microwave source. The microwaves are converted from rectangular to cylindrical volumes by adding a converter between the rectangular waveguide and the microwave oven casing. The microwave converter is shown in Fig. 4.

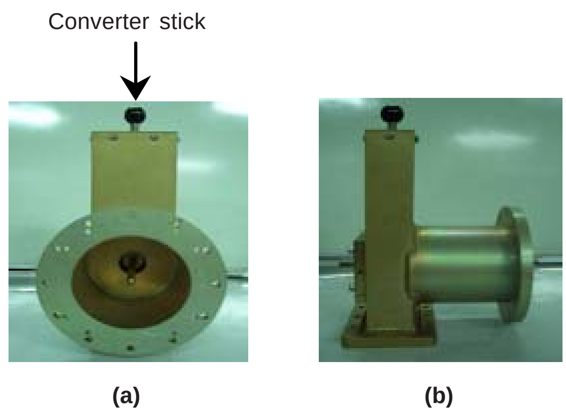


Figure 4. Microwave converter with fully depressed converter stick: (a) Front view and (b) side view.

The 2 L water load is heated for different times of operation (2, 4, 6, 8, and 10 min) with converter stick settings. The tuner stubs are all kept at a setting where all the stubs are fully withdrawn. Three runs are done for the same exposure time to the microwave radiation. The initial and final temperatures of the 2 L water load are measured using a BK toolkit 2706 as a digital thermometer within 0.01°C. The dummy load is heated for 10 min, while simultaneously measuring the temperature for 1 min intervals.

The power absorbed by the 2 L load, $P_{2\text{ L water load}}$ is calculated from the following equation:

$$P_{2\text{ L water load}} = [\,(m_w c_w + m_c c_c)(Tf - Ti) / t\,]\,, \qquad (1)$$

where $m_w$ is the mass of the water load, $c_w$ is the specific heat of water, $m_c$ is the mass of the water container, $c_c$ is the specific heat of the water container, $Tf$ and $Ti$ are the final and initial temperatures of the 2 L water load, and $t$ is the exposure time to microwave radiation.

The power absorbed by the dummy load $P_{\text{Dummy load}}$ is calculated from the following equation:

$$P_{\text{Dummy load}} = [\,f c_w (Tf - Ti)]\,, \qquad (2)$$

where $f$ is the mass flow rate per second, $c$ is the specific heat of water, $Tf$ and $Ti$ are the temperatures of the outflow and inflow water loads, respectively.

The total power absorbed by the two loads $P_{\text{Total}}$ is calculated from the following expression:

$$P_{\text{Total}} = P_{2\text{ L water load}} + P_{\text{Dummy load}} \qquad (3)$$

The heat lost from the 2 L water load to air and the heat from the conduction of the ceramic bowl to the microwave oven casing are negligible and they would be a small correction to the calculated total power.

## RESULTS AND DISCUSSION

The power absorbed by the 2 L water load and its average values for 10 min are shown in Figs. 5 and 6, respectively. The converter stick settings correspond to the percentage of the length of the converter stick that is pushed down. The 0% converter stick setting means that the converter stick is fully pulled up while the 100% means that the converter stick is fully pushed down. The estimated errors for Fig. 5 are in the 6 min exposure time.

The total power absorbed by the two loads and its average values are shown in Figs. 7 and 8, respectively. The maximum power absorbed by the 2 L water load was observed at the 50% converter stick setting while the minimum was observed at the 75% converter stick setting as seen in Figs. 6 and 8. The maximum power

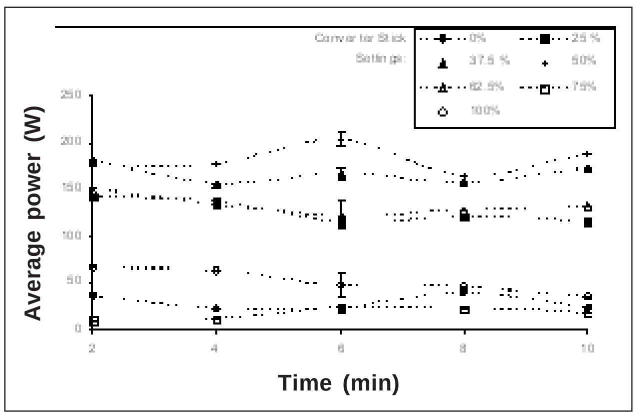


Fig. 5. The power absorbed by the 2 L water load for an exposure time of 10 min with different converter stick settings.

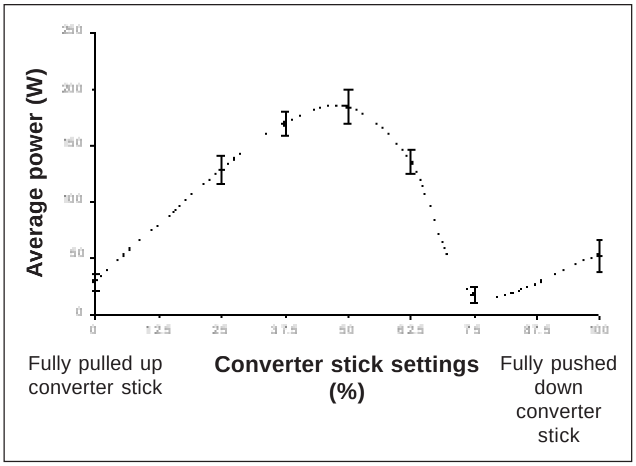


Fig. 6. Average power absorbed of the 2 L water load with with different converter stick settings.

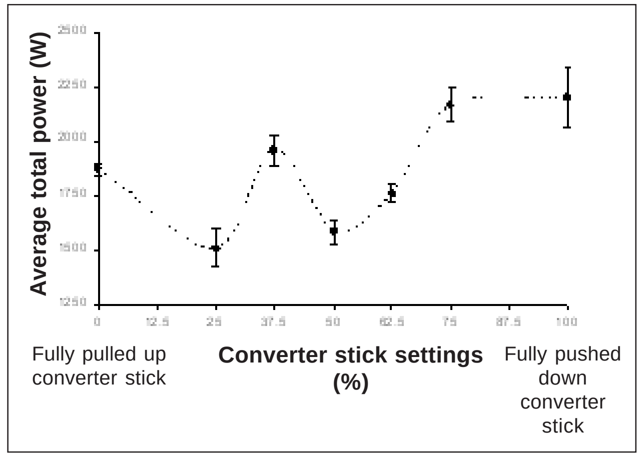


Fig. 8. Average total power absorbed from the microwave source with different converter stick settings.

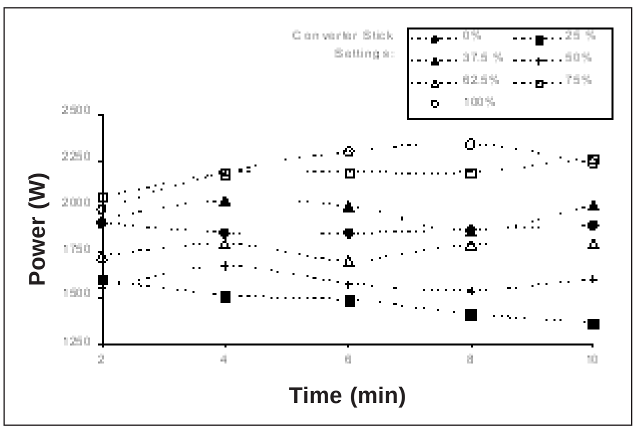


Fig. 7. The total power absorbed by the 2 L water load and the dummy load for an exposure time of 10 min with different converter stick settings.

absorbed by the 2 L water load has an average of 190 W as seen in Fig. 6. The maximum total power absorbed by the 2 L water load and the dummy load was observed at the 100% converter stick setting while the minimum was observed at the 25% converter stick setting as seen in Figs. 6 and 8. It is seen in Figs. 6 and 8 that the average power delivered by the magnetron fluctuates and depends on the converter stick settings.

## CONCLUSION

The power delivered to the load is attenuated by the rectangular to cylindrical mode converter as shown in the calculated power for the different settings of the converter stick. This result could be used to vary the power delivered to the plasma chamber of the ECR device aside by the use of tuner stubs. Even with mismatch in the geometry of the rectangular microwave case with the cylindrical waves, a relatively stable maximum power of 190 W is still delivered to the 2 L water load continuously for at least 10 min. The 190 W is enough to maintain the plasma for the generation of multiply charged ions in the ECR device.

The large difference of the measured total power of 2.2 kW for some of the data compared to the rating of 1.5 kW may have resulted from the mismatch of the load characteristics with that of the magnetron circuit. This could have easily resulted in the change of the frequency of the microwaves and the power delivered to the load. Evidently, from Fig. 8, the total power obtained around 1.5 kW is near the condition of the maximum power delivered to the 2 L water load, that is at 50% setting of the converter stick. This could be the condition for optimized impedance matching between the magnetron circuit and load.

The experiment have shown that it is possible to correlate the power delivered between the load and the dummy load. This correlation can be later used to estimate the power delivered to the plasma in the forthcoming ECR experiments without directly measuring the power delivered to it, but by monitoring the power delivered to the dummy load.

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