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An efficient plasma beam applicator has been developed that utilizes countercurrent cooling techniques to operate at atmospheric pressure and at microwave powers in excess of 5 kW. The device has been operated continuously for tens of hours and shows no signs of degradation. Argon is used as the discharge gas and once initiated, the plasma is self-sustaining. The beam or jet of plasma is highly collimated with a beam diameter of 3 mm, is in excess of 250 mm in length, and has high heat capacity. It could potentially be used to melt industrial ceramics such as silica and alumina, but the immediate intended use is for sheet steel welding applications. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1406920]

I. INTRODUCTION

Research into ultrahigh frequency discharges in gases evolved from the development of high power magnetrons used for radar purposes during the Second World War. One of the first successful attempts to create an atmospheric pressure plasma device was reported by Cobine and Wilbur.[1] The equipment used was designed at the General Electric Research Laboratory and consisted of a coaxial applicator which produced a torch-like flame at atmospheric pressure from 1 kW development magnetrons operating in the frequency range of 500–1100 MHz. The microwave energy was coupled into a cavity which was then coupled into a coaxial section terminating in the plasma torch. In 1965, Fehsenfeld *et al.*[2] utilized medical diathermy units operating at 2450 MHz and having a maximum output power of 125 W to supply continuous wave (cw) microwave power to six cavities of differing design. The principal use of these discharge cavities was as spectroscopic light sources. In each of the Fehsenfeld's cavities, microwave power was supplied coaxially whereas the cavity of Cobine and Wilbur was supplied with microwave power by direct coupling to the magnetron. Each of these methods of coupling microwave power to a cavity has both advantages as well as disadvantages. For example, the power that can be supplied by coaxial cable is limited and excitation of the desired field pattern within the cavity is critically dependant upon the coupling mechanism and the correct placement of the coupling antenna. Waveguides designed to operate in the fundamental or TE01 mode at 2450 MHz are bulky rigid structure and, depending on what they are constructed from, can heat considerably due to resistive losses in the walls. Reflective losses are also of concern when waveguide components are not aligned correctly.

To determine which microwave power delivery method to employ it is necessary to examine the requirements and functions of the resultant applicator. In this instance, an applicator that could produce a beam of plasma at atmospheric pressure with enough thermal capacity to melt sheet steel was required. To produce such a plasma the applicator would need to meet the following requirements: (i) a well collimated beam with a diameter as small as possible, (ii) a plasma beam with sufficient heat capacity to rapidly metal steel, (iii) a discharge gas flow rate low enough to ensure molten metal is not ejected from the weld pool, and (iv) the ability to shape the plasma beam. Taking these things into consideration, it was decided to concentrate on cavity designs that required waveguide delivery of microwave power. To that end, this article reports on a high power microwave plasma beam applicator that is relatively simple to construct and can achieve high average power because of the use of a countercurrent cooling jacket. Said jacket is located in the microwave field and surrounds the refractory dielectric chamber in which the plasma beam is formed.

II. EQUIPMENT

In all instances, microwave power was delivered to the applicator via a WR340 waveguide. This waveguide has internal dimensions of 43×86 mm and microwaves propagate in the fundamental or TE10 mode. Microwave power was generated using a National YJ1600 6 kW water-cooled magnetron powered by a Spellman High Voltage Corporation MG10 switched mode 10 kW magnetron power supply. A circulator was used to prevent reflected microwaves from coupling to the magnetron antenna thereby leading to magnetron failure. To enable simultaneous measurement of forward and reflected power, two model 435A Hewlett-Packard power meters, with model 8481A power sensing heads, were attached to a dual directional coupler. Load and source impedances were matched by the use of a three-stub tuner. The experimental arrangement is shown schematically in Fig. 1. The network analyzer used for low-power cavity design tests was a Hewlett-Packard model 8753C, with model 85046A S parameter test set.

III. EXPERIMENT

The water-cooled applicator, presented in Sec. III C, was the result of several design iterations. The first of these was

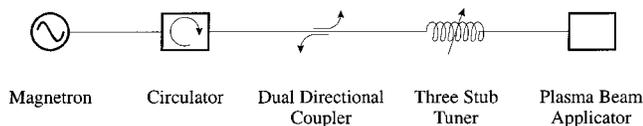[a)]Electronic mail: steveg@uow.edu.au

FIG. 1. Schematic diagram of experimental arrangement.

based on a cylindrical cavity and is given in Sec. III A. The cylindrical cavity was of a similar design to that of Asmussen[3] except that power was delivered via waveguide not coaxially. This cylindrical cavity design is one of many covered in the literature.[4–8] The waveguide applicator presented in Sec. III B does not rely on a cavity but simply on a sliding short circuit to produce a standing wave pattern. Waveguide applicators are given some coverage in the literature[9–11] but none utilize the cooling arrangement of the water-cooled applicator reported on here.

A. Cylindrical cavity design

The first cavity constructed, shown in Fig. 2, was of cylindrical design and was intended to resonate in the TM010 mode. The resonant frequency of a cylindrical resonator is determined purely by the diameter of the cylinder[12] and for an air-filled cavity resonating at 2450 MHz, this corresponds to a diameter of 93.6 mm. Note however, that this dimension only applies for an air-filled cavity. With the introduction of a ceramic plasma confinement chamber and plasma, and at a fixed driving frequency, the diameter necessary for resonance will change.

In order to determine the internal diameter that would produce the most efficient dielectric loaded cavity, the electrical properties of a cylindrical cavity/plasma system were measured while operating at high power. Specifically, the voltage standing-wave ratio (VSWR) and load impedance phase were determined for a set of operating conditions, e.g., discharge gas flow rate of 5 l/min, a microwave power of 1.5 kW, and an arbitrary fixed cavity diameter. The numerical value of VSWR is the square root of the ratio of the voltage maxima to voltage minima as measured from the standing
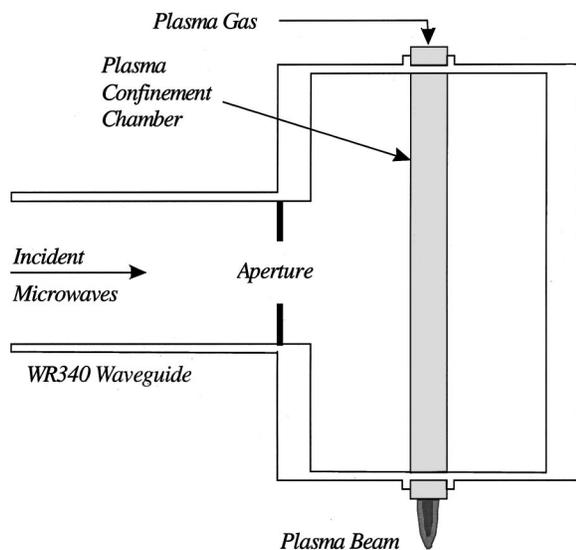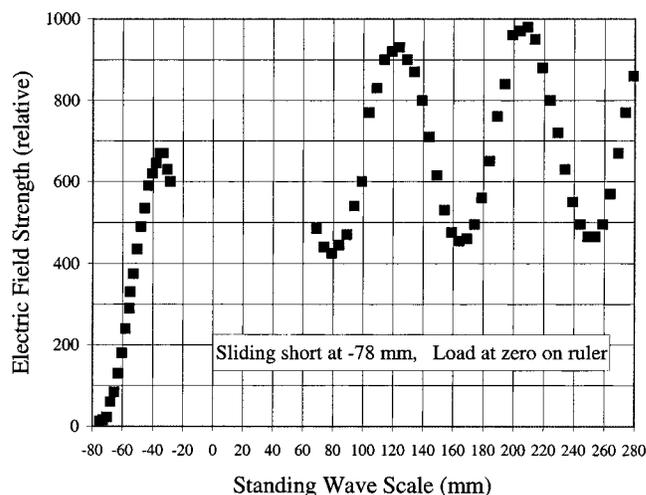

FIG. 2. TM010 cylindrical cavity used during preliminary investigations.

FIG. 3. Electric field standing wave pattern about the plasma confinement chamber for the waveguide applicator.

wave pattern of the microwaves in the waveguide. This pattern was mentioned using a slotted section of waveguide and one of the HP power meters mentioned previously.

A section of 2.5 mm diameter brass tubing was then inserted into the high power cavity and cut to such a length as to give an identical VSWR and load impedance phase when examining the S21 parameters on a network analyzer. The S21 parameter is the ratio of the amplitude of the wave leaving port 2 to the wave entering port 1. The rationale for using the brass tube to mimic the plasma during low power tests is based on the fact that the plasma behaves as a partially conducting medium since it has some degree of ionization. This is well illustrated by examining the standing wave pattern for the waveguide applicator operating at 360 W (forward microwave power) and shown in Fig. 3. Extrapolating either curve to zero on the standing wave scale gives a near minimum in the electric field strength at the position of the load (the load was positioned at zero on the scale), which is consistent with the boundary conditions of $\mathbf{E}=0$ on a conductor.

The length of brass tubing was then used to simulate the plasma in low power tests by inserting it into the plasma confinement chamber of a cavity modeled from polystyrene and aluminum tape that had an identical diameter to the cavity used for high power investigations. Ideally, when examined on the network analyzer the resonant frequency of the cavity with the dielectric and the simulated plasma (brass tubing) would be 2450 MHz. If this was not the case, a new cavity with a different inside diameter, hopefully giving the desired resonant frequency, could be quickly constructed. This method of rapid prototyping was relatively easy to using polystyrene models wrapped in aluminum tape.

Unfortunately this method of rapid prototyping, though appropriate in the first approximation, could not simulate the change in effective dielectric constant of the applicator system with the change in temperature associated with high power operation. To experimentally determine the internal diameter of a cylindrical cavity, containing a high power plasma and dielectric load resonating at 2450 MHz in the TM010 mode, a cavity was constructed from a 100 mm
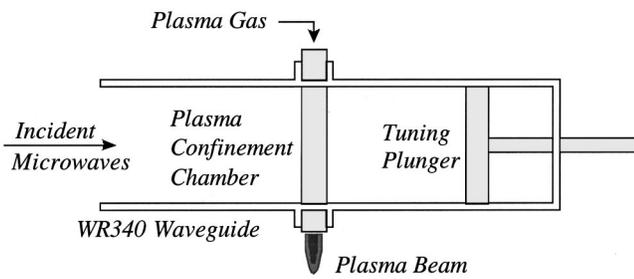
FIG. 4. Waveguide applicator.

FIG. 5. Percentage reflected power and VSWR as a function of sliding short position for the waveguide applicator.

length of aluminum bar. The outside diameter of the bar was 100 mm and the inside was reamed out to give an inside diameter (i.d.) of 60 mm. The resonant frequency of the cavity was then altered by using a lathe to increase the inside diameter in steps of 2 mm up to a maximum value of 92 mm. After each increment in the i.d. experiments were performed to determine whether or not a plasma could be generated using either quartz or boron nitride as the plasma confinement chamber when argon was used as the discharge gas. Microwaves were coupled to the cavity centrally via a waveguide with the broadwall of the waveguide aligned with the axial dimension of the cavity. Apart from the three-stub tuner situated "upstream" from the cavity, there were not tuning elements associated with the cylindrical cavity. The aperture shown in Fig. 2 represents the "window" into the cavity as viewed down the center of the waveguide.

B. Waveguide applicator design

A schematic diagram of the rectangular waveguide applicator is given in Fig. 4. As can be seen from the diagram, the applicator is a section of waveguide fitted with a sliding short circuit, or movable tuning plunger, with the plasma confinement chamber passing centrally through the broadwall of the waveguide. Microwaves enter the applicator and are reflected from the plunger at the rear where boundary conditions require the electric field to be zero. The plasma is easiest to initiate when the superposition of forward traveling and reflected waves produce a standing wave pattern with a maximum centered on the plasma confinement chamber. Once the plasma has been initiated, the plunger position is adjusted to give a minimum of reflected power. The adjustment means that the condition necessary for matching efficiently to, and maintaining, a plasma are different from those necessary to initiate one. This is consistent with theory since the resonant frequency of a cavity will change when any dielectric, such as a plasma, is added.

The data presented in Fig. 5 is for an argon discharge gas with a flow rate of 7.5 l/min and 600 W cw microwave power. The peak coupling efficiency represented here is approximately 98.5% where coupling efficiency is defined as the ratio of the absorbed power to transmitted power. It is evident from this figure just how critical the tuning plunger position (or the sliding short-load distance) is on the matching characteristics. The ability to match the load so effectively to the source for any operating condition means any form of matching aperture or iris can be dispensed with altogether. Although this applicator design proved successful
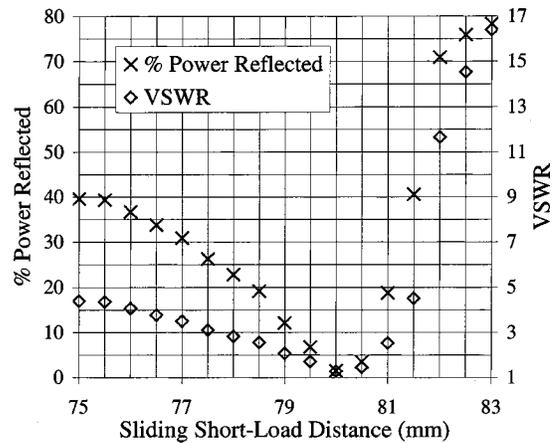
in generating and sustaining a microwave plasma, it was limited in functionality to sustained operation below 700 W of cw microwave power. This threshold could be increased to approximately 1 kW of cw power if the plasma confinement chamber was forced-air cooled. Sustained operating above these power levels led to the failure of the plasma confinement chamber due to the effects of thermal runaway and/or oxidation. Thermally runaway is a positive feedback condition whereby the ability of the ceramic plasma confinement chamber to absorb microwave energy increases with temperature. As the plasma confinement chamber heats due to contact with the plasma, it becomes more electrically conducting and absorbs more microwave energy, which increases the temperature of the chamber even further. The result is that the plasma confinement chamber eventually heats until its melting point is reached and then fails. Boron nitride is a sintered ceramic and does not melt but fails due to the effects of accelerated oxidation at high temperatures. The working temperature of boron nitride is approximately 1400 K in an air/oxidizing atmosphere.[13] This can be increased to approximately 2100 K in a reducing/inert atmosphere. The thermal ruggedness of the boron nitride plasma confinement chamber allowed experiments to be performed in excess of the working temperature in air with the realization that replacement would be necessary after a few hours due to oxidation.

C. Water cooled waveguide applicator design

To overcome the problem of thermal runaway, a more efficient mechanism for heat removal was required. The op-
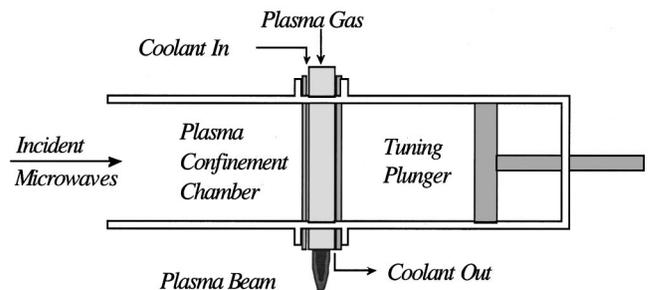

FIG. 6. Water-cooled waveguide applicator.

portunity arose[14] to discuss the cooling methods of Arata *et al.*[15] with Professor S. Miyake from the Japanese Welding Research Institute (JWRI). Though the cooling methods employed in the research of Arata were for determining the heat loss through the walls of the plasma confinement chamber using calorimetric methods, it was reasoned that a similar method could be used to remove the heat from the plasma confinement chamber thereby preventing thermal runaway. It was uncertain whether such a method could be employed since the applicator design and more importantly, the plasma confinement chamber i.d., were different from those used by Arata. A helical gas flow in the plasma confinement chamber (10 mm i.d.) of Arata produced a cold gas wall that prevented the plasma from coming into contact with the plasma confinement chamber. As the ultimate goal of this research was to produce an applicator capable of generating a fine, collimated plasma beam, the 10 mm i.d. plasma confinement chamber of Arata would be far from desirable. In addition, it would be extremely unlikely that a helical flow of gas could be created inside a plasma confinement chamber with an i.d., of only 1–3 mm and so produce the cold gas wall.

The waveguide applicator was modified to determine whether it was possible to initiate and sustain a plasma inside an annulus of water. The modifications are reflected in Fig. 6 (compare Fig. 4). For the initial experiment, cw microwave power was varied between 0.3 and 1.6 kW and the argon discharge gas flow rate set at 7.5 l/min. Pyrex was used for the plasma confinement chamber and had dimensions of 3.44×5.10 mm (i.d.×o.d.). The water-jacket tube had dimensions of 6.24×8.10 mm (i.d.×o.d.), giving an annulus of water 0.57 mm thick surrounding the plasma confinement chamber. The water flow was started and then the plasma successfully initiated. The temperature of the cooling water increased as would be expected. If the water flow was stopped and then restarted after about 5 s, the plasma confinement chamber would shatter due to thermal shock. This did not occur when the plasma confinement chamber was quartz as thermally quartz is very robust. This result, the ability of generate and sustain a plasma inside an annulus of water, is counterintuitive since water is such a good receptor

TABLE I. Experimental water-jacket thickness data.

Plasma confinement chamber		Water jacket		Annulus thickness	Plasma generation
(i.d.)	(o.d.)	(i.d.)	(o.d.)		
10.3	12.48	13.26	16.10	0.39	Yes[a]
3.44	5.10	6.24	8.10	0.57	Yes
8.04	10.06	13.26	16.10	1.60	Yes[a]
5.80	9.00	13.26	16.10	2.13	Yes[a]
5.76	8.00	13.26	16.10	2.63	Yes[a]
4.00	6.10	13.26	16.10	3.58	Yes[a,b]
3.21	5.04	13.26	16.10	4.11	Yes[a,b]

Note: All dimensions in millimeters.
[a]Microwave power 800 W.
[b]Plasma diminished in intensity.

of microwave energy and the electric field strength at the center of the plasma confinement chamber would be expected to be insufficient to sustain the plasma.[16] Indeed, the plasma is seen to diminish in intensity as the thickness of the water annulus is increased. Following the success of the initial experiment, it was repeated with differing cooling water annulus thicknesses.

Table I gives the water-jacket and plasma confinement chamber diameters along with the water annulus thicknesses. This data, except for row 2, was generated using a cw microwave power of 800 W and an argon plasma gas flow rate of 7.5 l/min. Row 2 was generated with microwave powers between 300 and 1600 W. As can be seen, it was possible to generate a plasma even when the plasmas confinement chamber was surrounded by an annulus of water 4 mm thick. This plasma, however, visually appeared to be somewhat diminished in both length and intensity when compared to the plasma generated when no coolant was present.

The final design of the water-cooled waveguide applicator was drawn from many elements of the experimental program, not the least the success of the water-cooled plasma confinement chamber, and needed to take into account the operational requirements necessary to produce a fine, collimated plasma beam. The final design, as given in Fig. 7
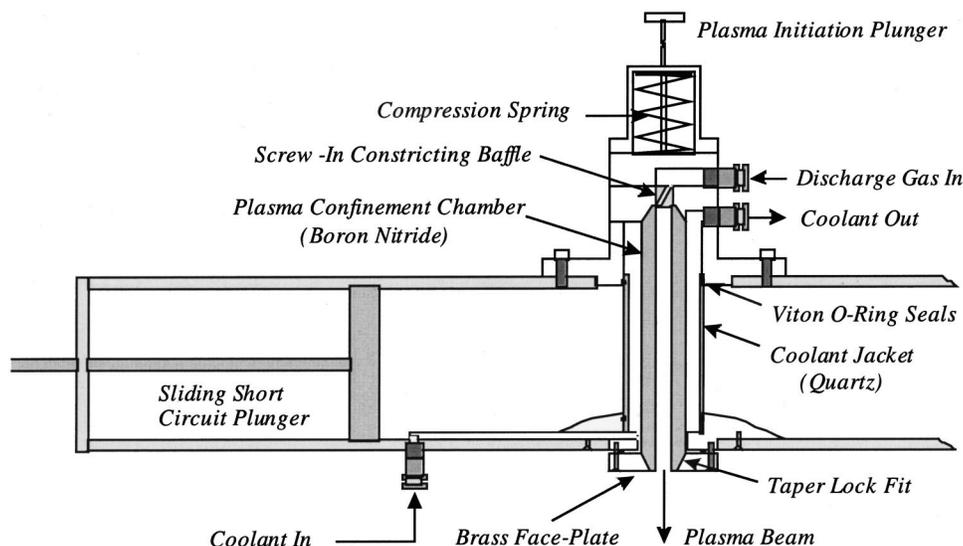

FIG. 7. Final design of the water-cooled waveguide applicator.

employs a countercurrent coolant flow in which the coolant flows past the hottest part of the plasma confinement chamber first. The coolant enters through the bottom of the waveguide and travels along a small diameter brass tube before reaching the void between the coolant jacket and the outside of the plasma confinement chamber near the plasma exit orifice. The coolant then travels along the plasma confinement chamber and exits through a quick fit connector at the top of the applicator. The other advantage of countercurrent cooling is that the water jacket fills from the bottom up, thereby minimizing possible air voids. This is especially important if th annulus thickness, the distance between the o.d. of the plasma confinement chamber and the i.d. of the coolant or water jacket, is small. The coolant is contained by Viton O-ring seals between the outside of the quartz coolant jacket and the applicator body. The coolant is prevented from leaking into the plasma region by a taper lock fit between the ends of the plasma confinement chamber and the applicator body. A compressive force is applied to the taper lock by an adjustable brass faceplate at the plasma exit orifice.

The discharge gas enters the applicator through a separate quick-fit connector and then passes through a constricting baffle before entering the plasma confinement chamber to be ionized and ejected as a plasma. The purpose of the constricting baffle is twofold. First, the gas feed hole can be angled and offset to optimize gas flow dynamics within the plasma confinement chamber. And second, the small diameter gas feed hole ensures that the plasma only flows out through the exit orifice and to back along the gas feed line. The plasma is initiated by a momentary insertion of the spring-loaded initiating plunger into the waveguide. No microwave leakage occurs during this action because the plunger is in intimate contact with the applicator body which is at earth potential.

The plasma confinement chamber in the ultimate design was fashioned from pure boron nitride and had an i.d. and o.d. of 3 and 15 mm, respectively. The coolant jacket was fashioned from quartz and had an i.d. and o.d. of 16 and 19 mm, respectively. This gave an annulus thickness of 0.5 mm which was more than adequate for a 6 kW plasma when coolant flow rates were of the order of 0.5 l/min. An attempt to use more commonly available alumina (Al_2O_3) for the plasma confinement chamber in this design was abandoned because it would shatter due to thermal shock whenever the plasma was initiated. Figure 8 gives the coupling efficiency of the water-cooled applicator as a function of input power for an argon discharge gas flow rate of 2 l per min.

IV. DISCUSSION

For the cylindrical cavity, it was possible to spontaneously generate a plasma for every value of i.d. when using boron nitride as the plasma confinement chamber. However, when using quartz as the plasma confinement chamber it was not possible for any cavity dimension. To generate a plasma it was necessary to momentarily insert an insulated tungsten wire into the plasma confinement chamber thereby creating an electron source from the resultant spark. The ability to spontaneously generate a plasma when boron nitride was the
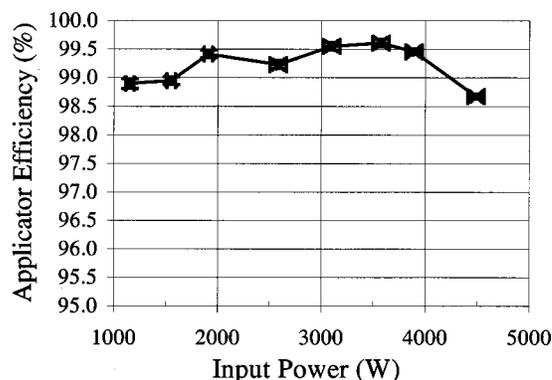

FIG. 8. Applicator coupling efficiency as a function of input power for the water-cooled waveguide applicator.

plasma confinement chamber is easily explained when the loss factors of the two dielectrics are considered. The loss factors of quartz and pure boron nitride at 3000 MHz are 0.0002 and 0.000 75, respectively.[17,18] The boron nitride used for the plasma confinement chamber was not pure and so had a higher loss factor than the pure material. The greater the loss factor of a material, the more readily it will absorb mi-
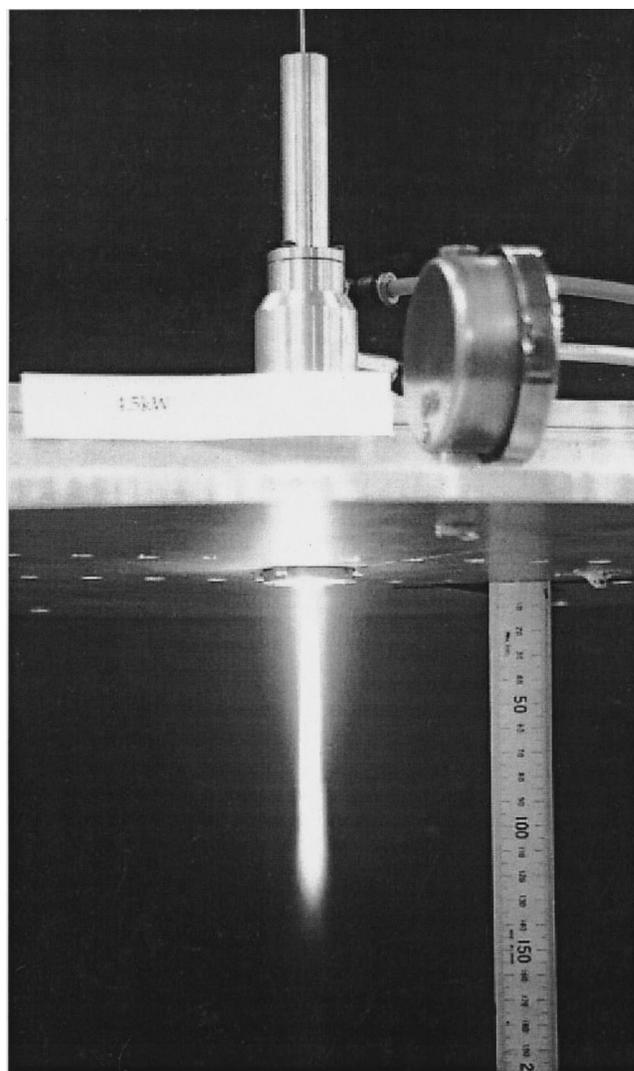

FIG. 9. Water-cooled applicator operating at 4.5 kW.

crowave energy. This higher loss factor meant the chamber heated to "red hot" through absorption of microwave energy and provided an electron source for plasma initiation. The quartz plasma confinement chamber was essentially transparent to microwaves and could not initiate a plasma since it did not heat up. The fact that a plasma could not be initiated in the quartz plasma confinement chamber suggests that, for the current arrangement, a plasma cannot be initiated purely from dielectric breakdown of the discharge gas but needs initiating through some secondary mechanism such as thermionic emission of electrons from the heated plasma confinement chamber or from the spark generated on the tip of a tungsten wire inserted into the cavity. The maximum efficiency obtained for the cylindrical cavity was 60%.

Where the cylindrical cavity fails the waveguide applicator excels. Routine efficiencies greater than 98% and extended operation at high powers makes the water-cooled waveguide applicator far superior to the cylindrical design. No other device containing a small diameter plasma confinement chamber has been capable of sustained operation at powers above 1.5 kW. The water-cooled device as described has been operated continuously for tens of hours and shows no signs of degradation. Figure 9 shows the water-cooled applicator operating at 4.5 kW and resultant welding trials have shown the applicator to produce a sheet steel weld with comparable quality to tungsten inert gas (TIG) welded samples.[19] The capital expenditure required for a microwave induced plasma beam welder is similar to that required for a TIG welding system. Advantages of the current system over TIG are the ability to weld nonconducting workpieces, the ability to shape the profile of the plasma beam, as well as the plasma being "softer." A soft plasma would be advantageous when used on workpieces that have a relatively low melting temperature such as plastics.

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