

# Direct Plasmadynamic Conversion of Plasma Thermal Power to Electricity for Microdistributed Power Applications

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## Abstract

A microwave plasma source with input power levels up to  $12.83 \text{ W/cm}^3$  that provides reproducible, stable plasmas with power densities on the order of those of chemically assisted (CA-) plasmas was used to characterize plasmadynamic power conversion (PDC) of plasma thermal power to electricity. PDC extracted electrical power approaching 2 W has been achieved as a demonstration. It is envisioned that such a system may be readily scaled to a few hundred Watts to several 10's of kW output power for microdistributed commercial applications (e.g. household, automotive, light industry, and space based power). The most important consideration in collector output performance is shown to be plasma conductivity. Increasing collector surface area in contact with the plasma, plasma charge carrier density, and plasma temperature, and reducing the fill gas pressure all increase the extracted power. Peak performance is found at 0.5 Torr fill of He at 50 sccm at  $8.55 \text{ W/cm}^3$  input power where the load match is  $250 \Omega$  and peak extracted power is 1.87 W or  $3.6 \text{ W/cm}^3$  (21.8 V, 86 mA) for a volumetric conversion efficiency of 42%.

## Introduction

A chemically assisted plasma (CA-plasma) as a novel power source using hydrogen as the fuel has been reported previously [1–3]. Since the power is in the form of a plasma, high-efficiency, low-cost direct energy conversion may be possible, thus, avoiding a heat engine such as a turbine [1,3] or a reformer-fuel-cell system.

High temperature plasmas possess a substantial inventory of energy stored in the thermal and/or kinetic components of plasma ions, electrons, and in some cases neutral gas particles in some weakly ionized plasmas. There is obvious incentive then in devising methods and technologies to efficiently extract this energy and convert it to a more useful form. A number of plasma energy conversion schemes have been previously studied including thermal steam cycle [4,5] or direct conversion of plasma charged particle kinetic to electric energy [6]. Whereas for CA-plasma cell

devices, possessing only weakly ionized and relatively cold plasmas, conversion methods more compatible with a fluid environment like MHD [7] or PDC [8] are required.

Herein, we demonstrate the plasmadynamic conversion (PDC) of plasma thermal to electrical energy using microwave plasma cells as a test bed for the conversion process. As in MHD conversion, PDC extracts stored plasma energy directly. Unlike MHD, however, PDC does not require plasma flow. Instead, power extraction by PDC exploits the potential difference established between a magnetized and an unmagnetized electrode [9] immersed in a plasma to drive current in an external load and, thereby, extract electrical power directly from the stored plasma thermal energy. For the first time, a substantial quantity of electrical power is extracted ( $\sim 2 \text{ W}$ ). Further power scale-up to commercially appropriate power levels is now realizable. The engineering relationships learned from these simulation studies can be applied to converting the thermal power from CA-plasmas to electrical power.

## Theory

Plasmadynamic conversion (PDC) of thermal plasma energy to electricity is achieved by inserting two floating conductors directly into the body of a high temperature plasma. One of these conductors is magnetized by an external electromagnet or permanent magnet, the other is unmagnetized. A complete analytic theory describing the potential difference between the two conductors (now appropriately referred to as electrodes) is described in Ref. [8] and given by the difference in unmagnetized and magnetized floating potential. Referring to this potential difference as the open circuit PDC voltage,  $V_o$ , one finds

$$V_o = \frac{kT_e}{2e} \ln(1 + \Omega^2) \quad - 1$$

As an example of a strongly magnetized plasma ( $\Omega \sim 20$ ) at 2 eV, a respectable  $V_o \sim 6 \text{ V}$  can be

generated. The  $\ln B$  dependence at large  $B$  is expected from the Boltzmann relation behavior of thermal electrons reaching the probe as it decreases as  $1/B$  for large field strength.

Shorting the PDC electrodes with the load,  $R_L$ , allows the circuit to be completed, and current and power flow in the external load. The PDC source is necessarily loaded by this action, thereby reducing the source voltage to  $V_o - iR$ , where  $R$  is the internal resistance of the source (*i.e.* plasma & PDC electrode system). Assigning the loaded PDC voltage as

$$V_{PDC} = V_o - iR$$

where  $i = V_o / (R + R_L)$ , the extracted power is found

$$P_{PDC} = \frac{R_L}{(R + R_L)^2} V_o^2$$

As expected, the impedance matching condition  $R = R_L$  determines the peak extracted power

$$P_{max} = \frac{1}{4R_L} V_o^2 \quad - 2$$

In the  $V_o \sim 6$  V example from above and with  $R_L \sim 10$  k $\Omega$ , a maximum extracted power of 0.9 mW can be obtained. Attaining 1 W of extracted power from PDC under these plasma conditions requires a source impedance matched to the load at  $R_L \sim 9 \Omega$ .

## Experimental Apparatus

The microwave plasma experimental setup is comprised of a 1.5 kW maximum output power, 2.45 GHz microwave power unit and generator with circulator and dummy load; three stub tuner; and downstream plasma applicator [8]. The device was typically operated at 200 – 1000 W cw with  $\leq 1\%$  reflected power. Tap water at  $\sim 20$  °C and 0.65 lpm was sufficient to allow continuous operation at full rated power. A mass flow controller (MKS 1179A) provided steady, regulated He gas flow in the range 0 – 100 sccm. Since the experimental results were not sensitive to gas flow rate, a flow rate of 50 sccm was used throughout as this choice proved convenient pressure adjustment of the He gas in the range of 0.2 – 10 Torr for the experiments discussed here.

PDC anode magnetization was provided by a 4 in. dia. Helmholtz type electromagnet coil. The coil consisted of 360 turns of 18 gauge magnet wire wound on an

aluminum spool yielding to  $\sim 27.9$  G/A in air. The spool was machined to allow water flow from a chiller at 4 – 20 °C and 15 lpm through the spool on the inboard side of the windings. The magnet coil was powered by an 80 V, 37 A (Sorensen DCS 80-37) DC power supply. The coil can be indefinitely operated with a steady current of 5 A. The temperature measured by an imbedded K-type thermocouple was found to be less than 100 °C under these conditions. Field uniformity was measured to be  $\pm 1.5\%$  at 10 mm from the axis along the center plane of the magnet.

Two sets of PDC electrodes were fabricated for use in the microwave system. The unmagnetized electrode was fabricated from 0.125 in. dia. SS rod extended through an alumina insulator into the plasma a length of 5 – 15 mm. The magnetized electrode was formed in the shape of a “T” so that the exposed collection area extends in the same direction as the applied magnetic field. In the first case the T-electrode was comprised of a 0.094 in. dia. SS rod with a collection area of  $1.125 \times 10^{-4}$  m<sup>2</sup>. To increase the collection area a second T-electrode was fabricated in the shape of a 0.08 in thick tungsten plate cut to a 0.855 in. dia. truncated circular disk with collection area  $5.2 \times 10^{-4}$  m<sup>2</sup>.

A single-tipped Langmuir probe was also employed to measure electron density,  $n_e$ , and temperature,  $T_e$ . The probe consisted of a 0.04 in. dia. W weld rod tip extending 5 mm beyond the end of a short section of Alumina 2-bore with 0.052 in. ID and 0.156 in. OD which was then telescoped inside a 12 in. long section of Alumina single bore, 0.188 in. ID and 0.25 in. OD. Using a separate 600 V, 2A DC power supply, the probe was biased over the current-voltage characteristic from full ion saturation to the exponential electron collection region. Probe bias was manually swept from 30 – 50 V below to several volts above the floating potential. Typical plasma parameters were found in the range 2 – 11.7 eV and  $1 - 3.2 \times 10^{12}$  cm<sup>-3</sup>.

## Results and Discussion

The expected power scaling (Eq. 2) through  $T_e$  dependence in  $V_o$  (Eq. 1) has been demonstrated previously [8]. Similarly, the power scaling with source impedance at the load match condition ( $P \sim 1/R_L \sim 1/R \sim A_p/\eta \sim A_p n_e/n_n$ ) had also been demonstrated therein (where  $n_n$  is the neutral gas density). Figure 1 shows  $V_{PDC}$  and  $i$  as functions of load resistance for 1 Torr He microwave plasma at 8.55 W/cm<sup>3</sup> input power density for the smaller collection electrode. The asymptote in  $V_{PDC}$  is the open circuit

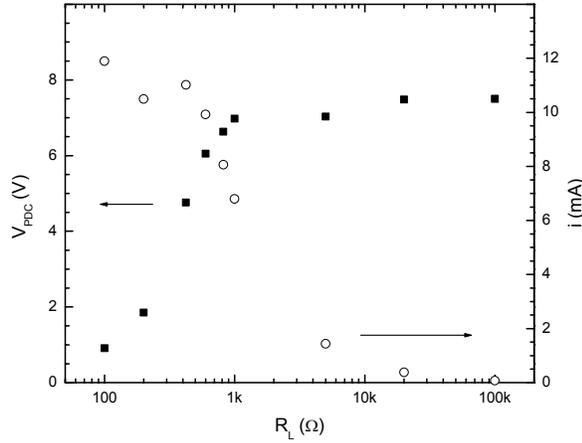


Figure 1: Small electrode PDC voltage (■) and current (○) as a function of load resistance in the microwave device at 8.55 W/cm<sup>3</sup> and 1 Torr He.

PDC extracted power as a function of  $R_L$  in the microwave discharge for this case is shown in Fig. 2. The optimal (impedance matched) condition is found to be 600  $\Omega$  where the peak PDC power was 60 mW, a factor of 136.4 over that obtained in the glow discharge

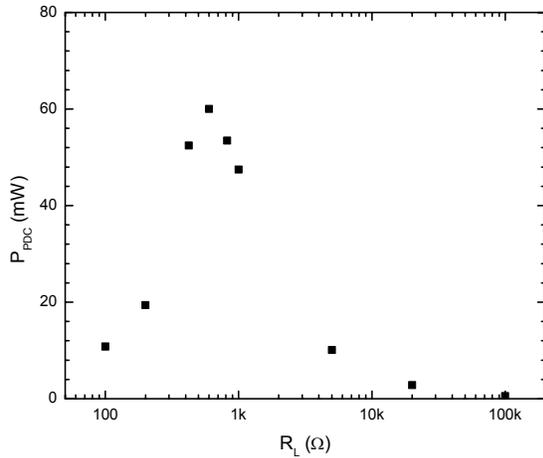


Figure 2: Small electrode PDC extracted power as a function of load resistance in the microwave device at 8.55 W/cm<sup>3</sup> and 1 Torr He.

Still further improvement has been identified by varying the operating conditions slightly to 0.75 Torr He at 50 sccm. Figure 3 shows  $P_{PDC}$  as a function of the microwave power density for 0.75 Torr fill pressure and 600  $\Omega$  load. This case demonstrated the maximum observed PDC performance for the small electrode.

The PDC power increase to  $\sim 220$  mW was consistent with a measured  $T_e$  increase to  $\sim 7$  eV over the 1 Torr case. Plasma density measured for this enhanced PDC performance case was similar to that at 1 Torr. The asymptotic behavior in the PDC power with microwave power shown in Fig. 3 is consistent with the leveling off of plasma conductivity suggested by the absence of further electron density increase with power [8].

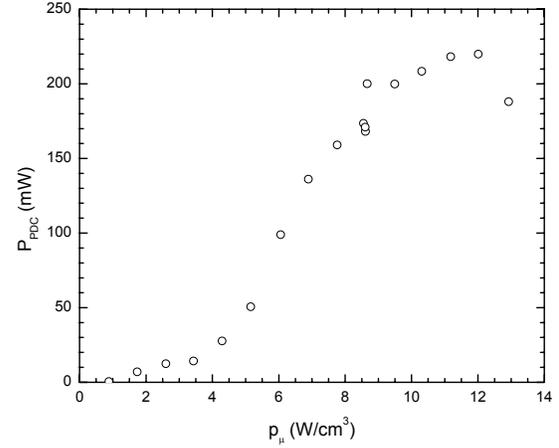


Figure 3: Small electrode PDC extracted power as a function of microwave power density for  $R_L = 600 \Omega$  and 0.75 Torr He.

An increase in electrode collection area shows a demonstrable and approximately proportional increase in extracted power [8]. The best ever to-date PDC power extraction has been achieved with the large area electrode ( $A_p \sim 5.2 \text{ cm}^2$ ) as illustrated in Fig. 4. Here  $P_{PDC}$  is shown as a function of He gas filling pressure in the microwave discharge device at 8.55 W/cm<sup>3</sup> input power density. Under these conditions the source is matched at  $R_L \sim 250 \Omega$ . This reduction from the previous 600  $\Omega$  is direct indication of increased conduction afforded by the large collection surface. The inverse dependence of  $P_{PDC}$  on He fill pressure ( $\propto n_n$ ) is direct evidence of plasma conductivity increase with  $n_n$  and as well as enhancement with  $T_e$  which also increases with  $n_n$  reduction.

The conversion efficiency,  $\epsilon$ , is determined as the ratio of conversion to input power densities in the plasma discharge device

$$\epsilon = \frac{P_{PDC}}{p} \quad - 3$$

Here  $p_{PDC} = P_{PDC}/V_{PDC}$ , where  $V_{PDC}$  represents the plasma volume accessible to PDC power extraction,

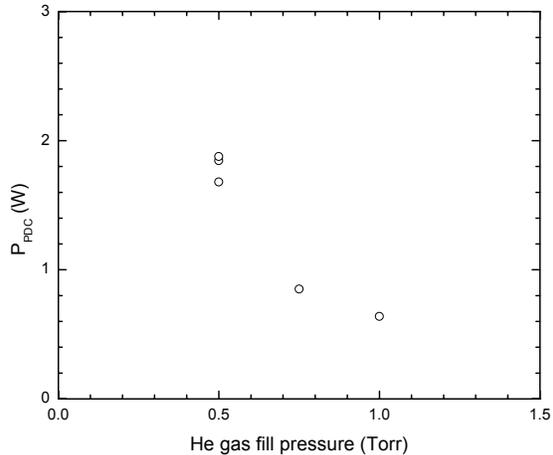


Figure 4: Large electrode PDC extracted power as a function of He gas fill pressure at microwave power density of  $8.55 \text{ W/cm}^3$  and  $R_L = 250$ .

and  $p$  is the input power density to generate and sustain the discharge. (In a CA plasma, the external power input may be reduced substantially below that required in a non-CA plasma.) As the probe's electrostatic influence does not extend beyond the pre-sheath, the relevant interaction volume is defined by the electron mean free path for collisions in this high pressure discharge. At 0.5 Torr He the PDC accessible plasma volume is  $\sim 0.52 \text{ cm}^3$ . With a collected power of  $\sim 1.87 \text{ W}$ , the collection power density is  $\sim 3.6 \text{ W/cm}^3$  and the conversion efficiency is  $\sim 42.1\%$  for this case.

Further optimization of PDC power conversion on a single electrode set is in progress as well as power scale-up with multiple electrode sets. A linear power scale-up is anticipated. It is, however, recognized that indefinite increase in electrode number and size relative to that of the discharge is not possible without interfering with plasma conditions. Discharge seeding by CA-plasma catalysts such as certain alkali and alkali-earth metals [10] to increase charge density may also be employed in an effort to increase conductivity, extracted power, and efficiency, and may also lead to increases in the CA-plasma power.

## Conclusions

A microwave plasma source that provides reproducible, stable plasmas with power densities on the order of those of CA-plasmas were used to characterize PDC. The PDC generation of electrical power was experimentally demonstrated at the  $\sim 1 - 2 \text{ W}$  level in laboratory plasma devices for the first time.

These results were demonstrated to be in agreement with a simple model describing electron current restriction to a magnetized electrode. Power-load curves identify the impedance matching condition at  $\sim 250 \Omega$  for which the peak PDC extracted power is  $\sim 1.87 \text{ W}$  and collection efficiency is  $\sim 42\%$ .

Plasmadynamic conversion may be optimized for high power and efficiency. The system is simple with projected costs on the order of 1% those of fuel cells. The implications for microdistributed power are profound. Scale-up to several to 10s of W in a small, modular array converter unit is under development.

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