Open-Ended RF SusTainEd Discharge (OERSTED)

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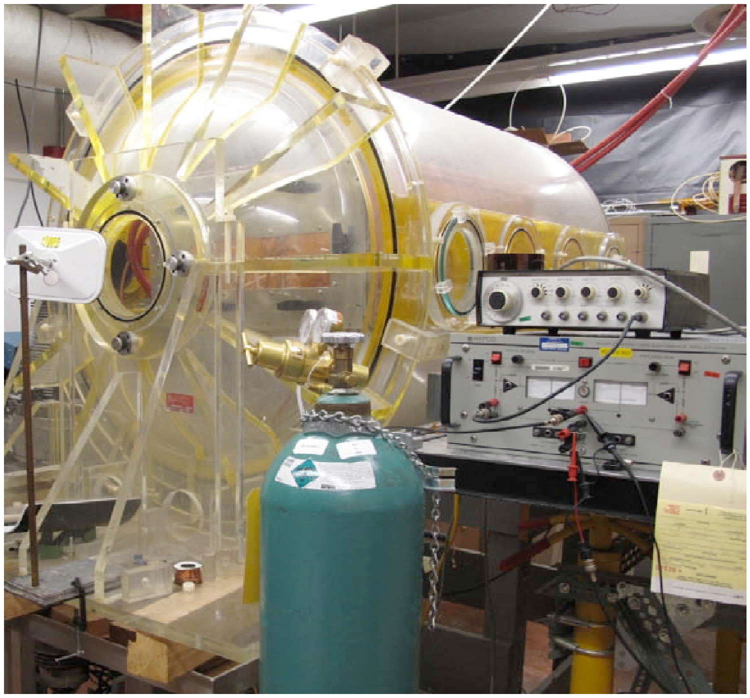


Figure 1. OERSTED vacuum chamber, CO_2 supply, and Langmuir probe circuitry.

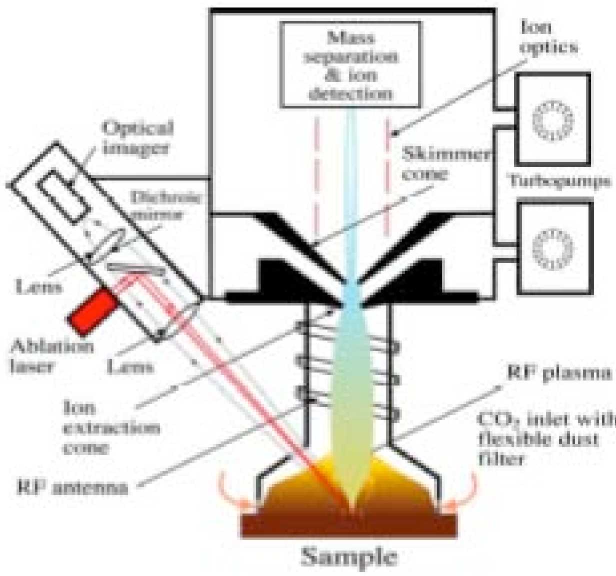
Introduction

I spent most of my time in the Electric Propulsion and Plasma Dynamics Lab (EPPDyL) working on the Open-Ended RF Sustained Discharge (OERSTED) project. OERSTED is part of an effort to develop an instrument front-end that will enable high-sensitivity, spatially-resolved, multi-element geochemical analysis on Mars, when combined with a mass spectrometer. OERSTED uses an RF discharge plasma "torch" to ablate and ionize a sample, which is then fed into a mass spectrometer for analysis. It is a simpler version of the Plasma and Laser Ablation System for Multi-Element Analysis (PLASMA), which was developed by Prof. Choueiri of EPPDyL and Dr. Jay Polk of Jet Propulsion Laboratory (JPL), among others, to submit to NASA's Planetary Instrument Definition and Development Program (PIDDP).

Background and Theory

Current concepts for mass spectrometry have limited analytical capability, which is the motivation for developing the PLASMA technology which is studied through experimentation on OERSTED. Electron beam ionization suffers from low ionization efficiency, on the order of 0.1%. Laser ablation ionization creates highly ionized, high velocity plasma plumes, which are both difficult to focus into the mass spectrometer and not always representative of the bulk sample material. In addition, the plumes can be cooled and neutralized by the ambient gas, which makes them undetectable to the mass spectrometer.

PLASMA and OERSTED both have advantages over these techniques. In both systems, the plasma used is made from 6 Torr of CO_2 – the makeup of the Martian atmosphere. Thus, no material for making the plasma needs to be transported. OERSTED allows 100% ionization of the ablated sample, and this ionization is considered "soft," meaning that molecules remain intact, which takes the guesswork out of determining what molecules exist in a sample. The OERSTED device has a very simple design – it is truly "open-ended" in that the torch can simply be applied to a sample, and then the mass spectrometer can analyze it. PLASMA is more complicated because of the laser ablation system, but this system allows high spatial resolution



of the sampling area, which increases our ability to determine the evolution of the Martian surface and interior, to understand Martian climate processes, and ultimately to investigate whether life arose on Mars. Below is a diagram of the PLASMA system:
Figure 2. PLASMA system schematic.

In 2008, PLASMA was submitted to NASA's PIDDP competition, and the proposal was deemed "selectable," but was not selected, for gaining additional NASA support. There were two elements identified that needed improvement: Measurements were needed to ensure the stability and repeatability of the RF source which creates and sustains the CO_2 plasma; and the electron temperature and electron density needed to be measured in order to better estimate the probability of ionizing an analyte sample. The probability calculation allows us to determine which elements can be ionized. Solving these two issues was the main goal of my experiments on OERSTED.

Experimentation on OERSTED in EPPDyL

The measurement tool I used was a single Langmuir probe, which we constructed ourselves, using tungsten for the probe tip. I will assume that the reader is familiar with how a Langmuir probe operates, but briefly, a Langmuir probe is a shielded wire which is inserted into the plasma and to which a sweeping voltage is applied. The probe draws current that is dependent on parameters such as electron temperature and density – the quantities we are interested in measuring.

In order to measure electron temperature, we plot the probe characteristic (measured current vs. applied voltage), and find the slope in the exponential region of the curve. The equation of a theoretical probe characteristic for a single, cylindrical Langmuir probe is:

$$I_P = i_+\left(q^{e(V-V_F)/kT_e} - 1\right) \tag{1}$$

where i_+ is the ion saturation current, q is the fundamental charge, V_F is the floating plasma potential, and T_e is the electron temperature. We can extract T_e by taking a logarithm involving equation (1):

$$\ln\left(I_P + i_+\right) = (q/kT_e)(V - V_F) + \ln(i_+) \tag{2}$$

Using equations (1) and (2) in a Mathematica program developed by Ben Jorns, a graduate student working in EPPDyL, I was able to determine the exponential region of the probe characteristic and thereby find T_e. To find n_e, the electron density, we use the following equation:

$$i_+ = 0.61 q n_e A\sqrt{\frac{Z_i k T_e}{M}} \tag{3}$$

where A is the area of the probe exposed to plasma, Z_i is the charge state, and M is the molar mass.

Because the CO_2 plasma was created inside an RF-driven coil, we experimented with using RF compensation in our probes. We employed a low-pass filter to remove the high frequency noise from our signal, but saw not major difference in the quality of the signal on an oscilloscope. We then built a new Langmuir probe using RF chokes (inductors) in series; however, we found that practically, the new probe was difficult to use because the chokes are extremely delicate. The electrical connection through the center conductor of a coax, to which the probe is attached, was easily broken. Ultimately, we determined that the oscillations due to the RF driving source were on the order of 0.1% of the signal which we wanted to record; therefore, we were able to take data without using RF compensation.

In order to measure the stability of the plasma, I measured the ion saturation current for a period of 10 seconds 3 times while the RF source was continuously operating. In order to measure the stability of the source itself, and therefore the repeatability of the OERSTED device, I measured the ion saturation current for a period of 10 seconds 3 times, and restarted the source between data runs.

Results and discussion

I will now present and discuss the data I recorded for electron temperature, electron density, plasma stability, and source stability. This data was included in Prof. Choueiri's and Dr. Polk's 2009 PLASMA proposal submitted to NASA PIDDIP.

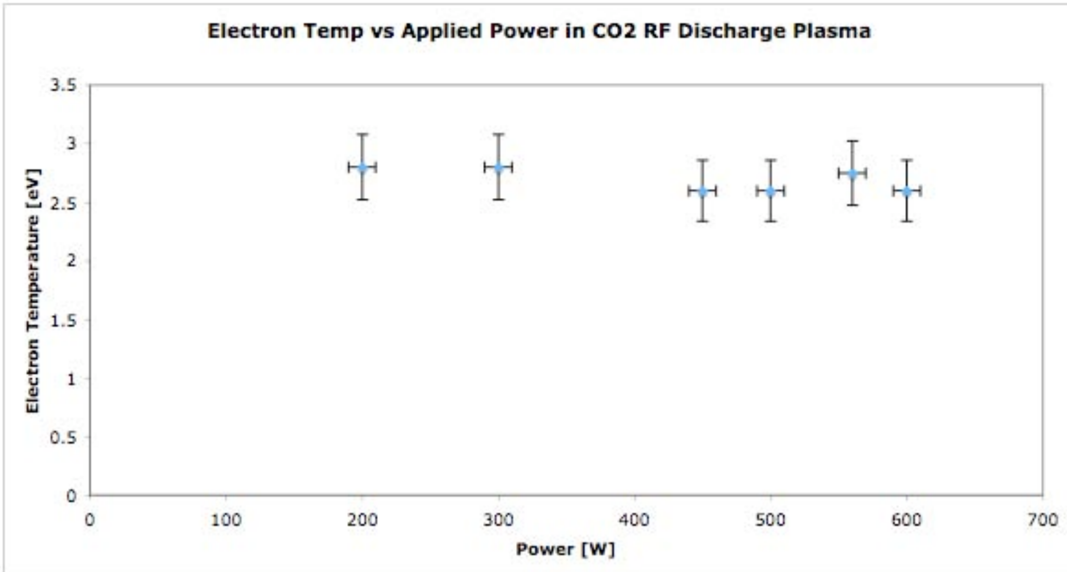


Figure 3. Electron temperature vs. applied power.

Electron temperature at the coil center shows only slight variation with applied power. Vertical error bars represent a ±10% uncertainty resulting from the experimenter's best judgment of the exponential region of the probe characteristic. Horizontal error bars represent a constant applied power for the duration of each measurement to within ±10W.

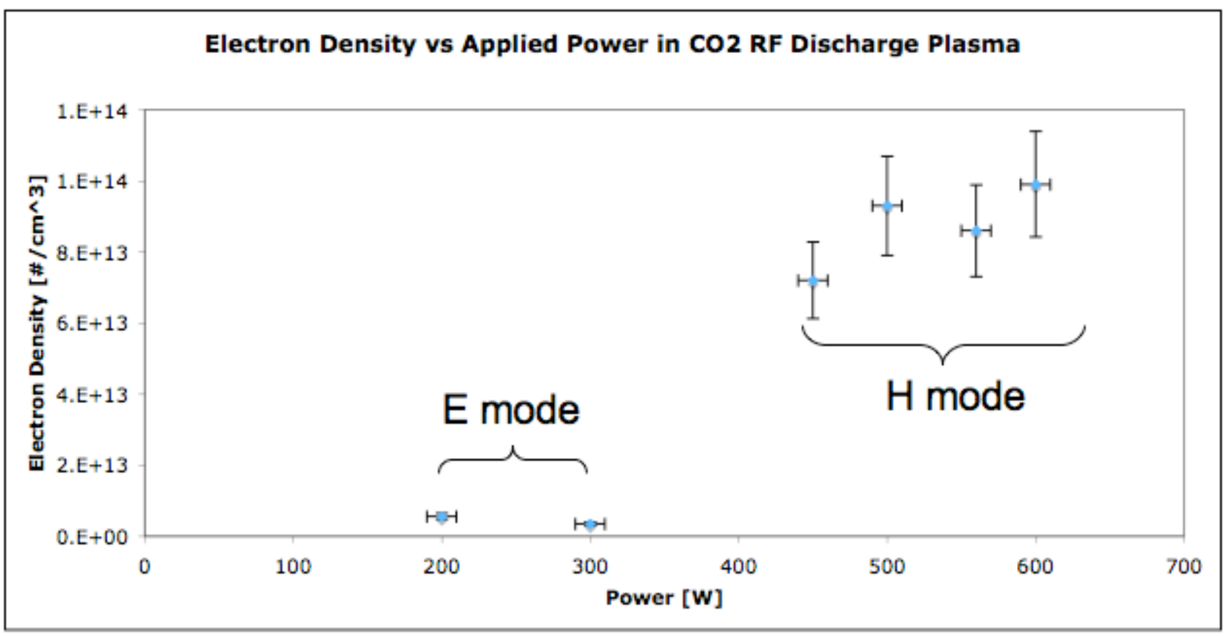


Figure 4. Electron density vs applied power.

Electron density at the coil center is plotted as a function of applied power. Two modes of excitation are evident, one at lower power (E mode) and one at power above about 425W (H mode). Miller[1] observed this phenomenon in 1986 in a 27 MHz helium inductively coupled plasma and achieved electron densities on the order of 10^{15}. His explanation for the density jump is that in the H mode, the plasma is excited by the magnetic field from the RF radiation, whereas E mode plasma is coupled only to the electric field.

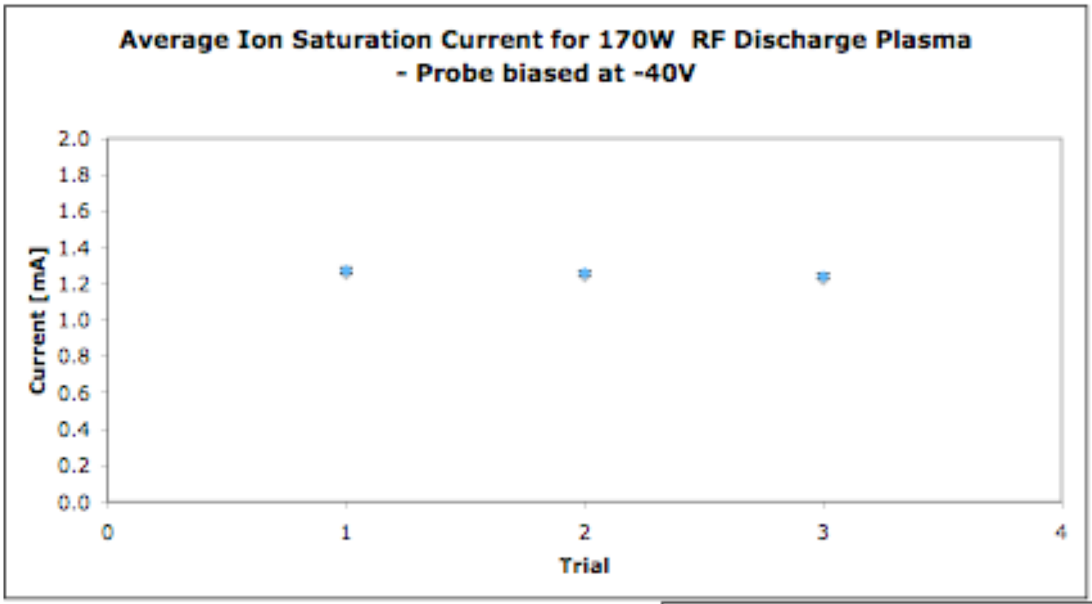


Figure 5. Average ion saturation current for 3 trials with continuous RF source operation.

Average ion saturation current for three 10-second trials is plotted. Each trial contained 10^5 samples; error bars were taken to be the standard deviation for each trial. The data shows that during continuous RF source operation, the plasma is stable in the ion saturation regime.

[1] Miller, D.C. et. al. "Fundamental Chemical Processes in a Low-Density 27 MHz Helium ICP" University of Cincinnati, Cincinnati, OH. *Applied Spectroscopy*, Volume 40, Number 5, 1986.

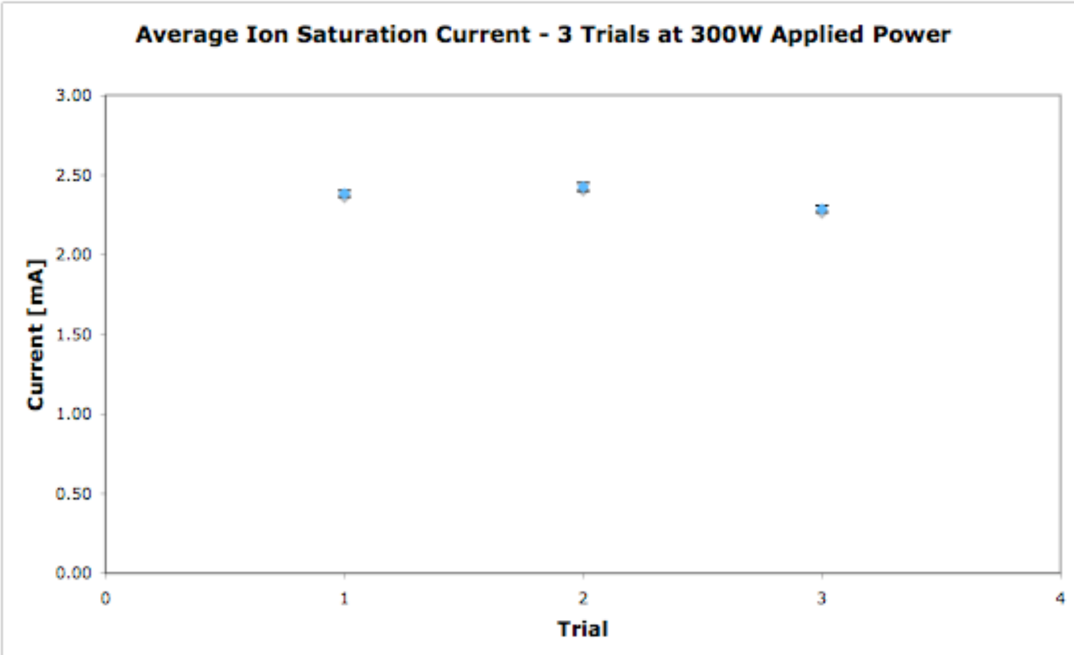


Figure 6. Average ion saturation current for 3 trials with RF source restarted between each trial.

Average ion saturation current for three 10-second trials is plotted. Again, each trial contained 10^5 samples, so standard deviation was used for error bars. The data shows that the RF source is stable and produces repeatable results in the ion saturation regime.

Additional Experimentation in Pulsed Power

If a device like OERSTED is ever to be practical for use on Mars, it is important that its power requirements are not too great. Excessive power requirements entail greater weight, which is very significant for a spacecraft on a long distance mission. Therefore, Prof. Choueiri suggested that I investigate the requirements for pulsing the RF power while still maintaining a quasi-steady state within the plasma. Below are the results of my study.

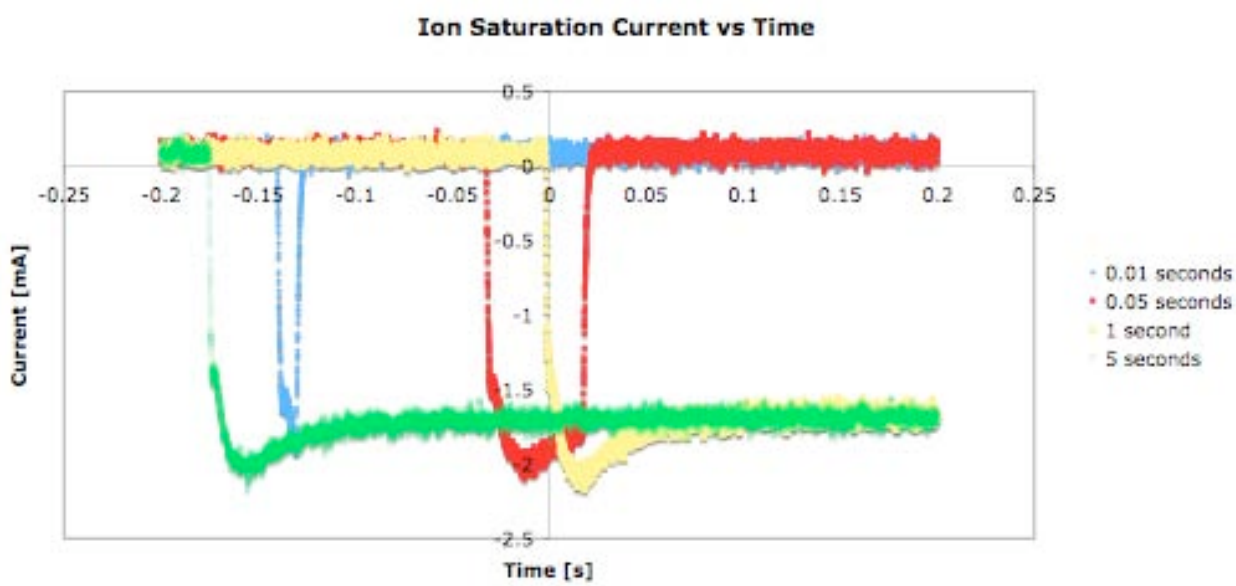


Figure 7. Ion saturation currents (5-point moving average) vs time, for different pulse durations.

The ion saturation current in the CO_2 RF discharge plasma used in OERSTED was measured. 300 W pulsed power was delivered. The Langmuir probe was biased at -40 V to be within the ion saturation regime. From the data, it appears that stable ion saturation current can be achieved at pulses of 0.05 seconds or longer. Below this threshold, a transient ion saturation current exists, but the current does not reach quasi-steady state.

Conclusions

I took and reported the measurements that were required in order to complete the proposal that was submitted to the NASA PIDDP competition. In the process, I learned a great deal about plasma diagnostics and experimentation, both by running experiments and by constructing the tools and circuitry required to take the data needed.

Acknowledgements

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