R&D status of the Pocket Rocket thruster and its role in future micro-satellites space and astronomical missions

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Abstract: The Space Plasma Power and Propulsion Laboratory is developing a suite of propulsion devices for cubesats, micro-sats and telecommunications satellites and has all the infractructure in place for carrying out development, testing and qualifications of these technologies. Our strongest candidate for use on small satellites is Pocket Rocket (PR), a low-volume, low-cost, low-weight, electro-thermal radiofrequency plasma thruster which can operate with 'green' and safe propellants. Basically, the rf generates a high density plasma with a density > 1012 cm-3 having a volume less than 1 millilitre. Ambipolar diffusion heats the neutrals via charge exchange collisions, the plasma serving as an intermediary in the power flow but not being directly involved in producing thrust.

I. Introduction

The development of increasingly smaller satellites and spacecraft has in turn developed a need for micro-thrusters that have low mass, volume and power consumption. Electric propulsion is favourable in such circumstances as the specific impulse is much higher than conventional chemical rockets [1]. Hall and gridded ion thrusters are current highly developed electric propulsion systems, however, these systems lose efficiency when scaled down [2]. Alternate options for electric micro-thrusters include resistojets and arcjets [1], hollow cathode thrusters [1,3] and radio frequency (RF) capillary discharge [4].

Another possible micro-thruster electric propulsion system consists of a capacitively coupled RF discharge (13.56MHz) within a tube with a 4.2mm inside diameter and 20mm length known as Pocket Rocket [5]. Gas, usually argon, is introduced to the system via an upstream plenum chamber with pressures around a few Torr. Electrodes placed around the Pocket Rocket tube create a cylindrical plasma discharge which is expanded into a vacuum. The discharge is weakly ionized (less that 1%) due to the higher pressures [6], therefore direct thrust from ion acceleration is negligible. However, the ions would typically reach a Bohm velocity in the order of 3000ms^{-1}, much greater than a typical thermal gas velocity of 300ms^{-1}. Charge exchange collisions between ions and neutrals may therefore result in neutral gas heating within the discharge and the thrust produced by the device will be increased over a cold gas thruster. Increased thrust from neutral gas heating makes Pocket Rocket a potentially viable micro-thruster for micro-satellites.

Previous experiments performed using a Langmuir Probe to determine the electron temperature of the Pocket Rocket discharge estimate the neutral gas temperature as 3200K at 10W and 1.5 Torr [6]. In the same paper, power coupling calculations relating the input power to discharge velocity estimated the neutral gas temperature for the same conditions much lower at 1430K.

To determine the temperature of the neutrals in the discharge, a non-invasive spectroscopy method was used where a small amount of nitrogen gas added to the discharge produces ro-vibrational spectral bands. The measured bands can be compared to simulated spectra to determine the rotational and vibrational temperature of the nitrogen molecules, from which the neutral gas temperature is inferred as the rotational temperature. This technique has been previously used to determine the temperature of similar discharges [7,8].

II. Experiment

The Pocket Rocket device, as shown in Figure 1(a) consists of a 4.2mm inside diameter, 1.3mm thick, 20mm long alumina tube. Argon gas is introduced to the system through an upstream plenum chamber with a diameter of 40mm and a length of 12mm. A 6mm wide copper electrode surrounds the tube at the midway point with two 3mm wide

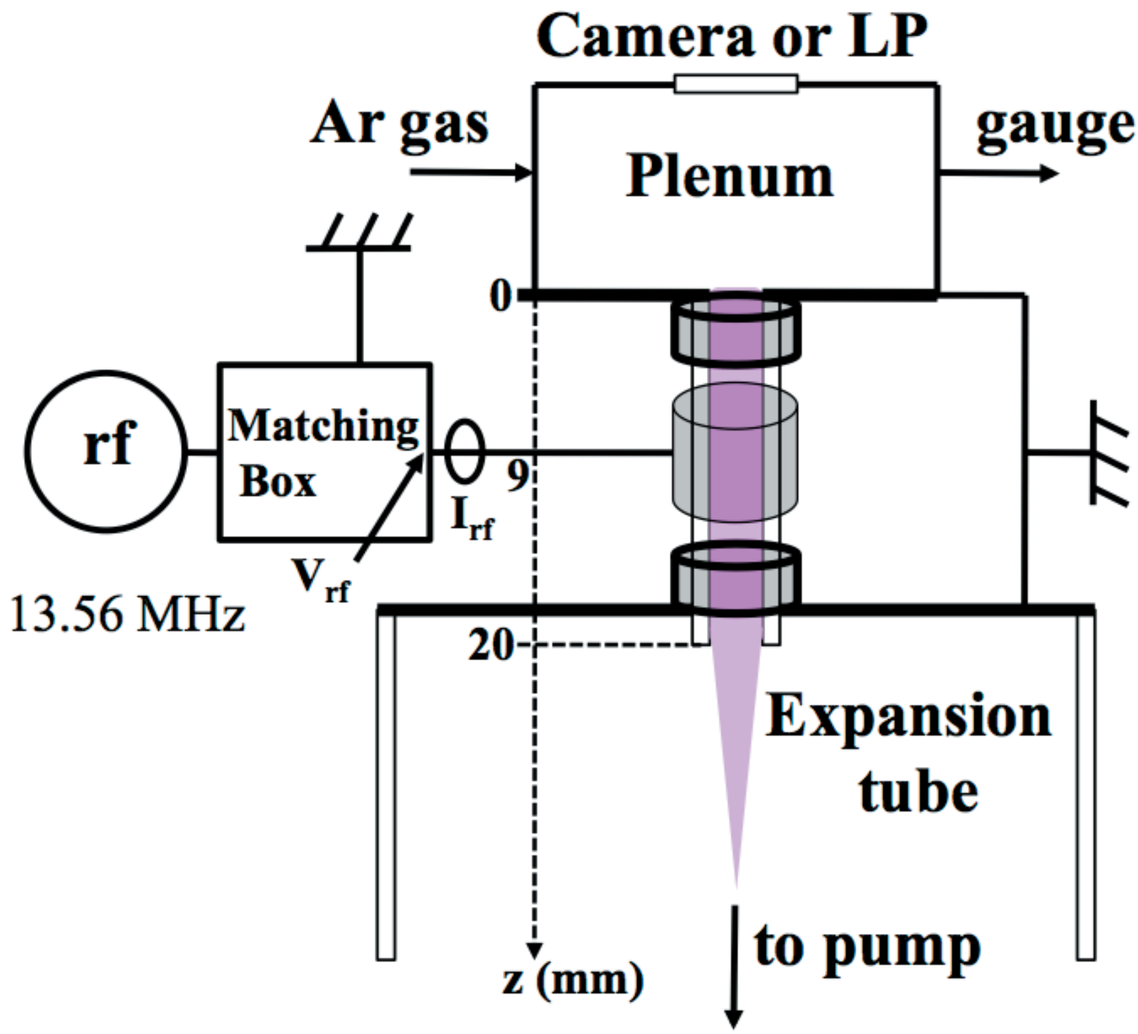

Figure 1 A cartoon of the experimental apparatus, please note the dimensions.

copper grounded electrodes placed either side at a distance of 3mm, creating a capacitively coupled discharge inside the tube. The discharge expands into a 750mm long, 50mm diameter evacuated glass tube which is itself attached to a vacuum chamber (160mm diameter, 300mm length) equipped with a primary rotary oil pump. A Convectron gauge measures the pressure in the upstream plenum, while a Baratron gauge measures the pressure in the vacuum chamber. The base pressure in Pocket Rocket is in the order of 10^{-3} Torr. Operating pressures measured in the plenum chamber ranged from 0.5 Torr to 4 Torr, resulting in vacuum chamber pressures approximately 2.2 times lower, from 0.2 to 1.8 Torr. Power from an RF generator (13.56MHz) ranging from 5-40W is coupled to the system through a pi-matching network. The current and voltage supplied to the electrode are measured using a Rogowski coil and a 1/1000 high voltage probe respectively. In addition, a Bird power meter and standing wave ratio (SWR) meter are inserted between the RF generator and the matchbox to measure the forward and reflected power.

III Results

Theoretical calculations of the performance of PR showed that even a small system weighing only a few hundred grams can be very performant: assuming a perfect gas and 100% absorption of 10 Watts rf power into an argon flow of 100 sccm results in an increase in gas temperature to 1400K. The cold gas thrust of 0.9 mNewton and Specific Impulse (ISP) of ~ 30 would then become 2 to 3 mNewton and ISP ~ 90. Spectroscopic measurements have shown rotational temperatures of about 1200K, very close to the prediction. In order to verify the basic physics and engineering, we have conducted a thorough modeling campaign using a computational fluid dynamics code with an additional plasma module. The computed results are very close to the experimental measurements and show that the rf discharge is operating in a "gamma" mode, ie. ions attracted to the ceramic walls in the source produce secondary electrons which are then accelerated into the plasma and ionize the flowing gas.

An argon plasma discharge was analysed using optical emission spectroscopy (OES) for various powers and pressures in the ranges 5 W to 40 W and 0.5 Torr to 4 Torr. Trace amounts of nitrogen were added to the discharge to estimate the temperature of the neutrals using rovibrational band matching of the 2nd positive system of nitrogen. Comparing simulated computer generated spectra of these bands to experimentally measured spectra determined preliminary results for the rotational and vibrational temperatures of the nitrogen gas, from which the temperature of the neutrals was inferred by assuming the rotational temperature was the same as the neutral gas temperature.

The raw spectral data was affected by relatively large background noise. A Matlab program was written to remove the noise using a smoothing function and subtract the baseline from the data. In addition, some argon peaks visible in the region of interest, identified by recording the spectrum of an argon only plasma to determine the wavelength and intensities of the relevant lines, were removed from the final nitrogen spectrum. The large amount of post-processing may affect the accuracy of the experimental data and reduce the accuracy of the gas temperature

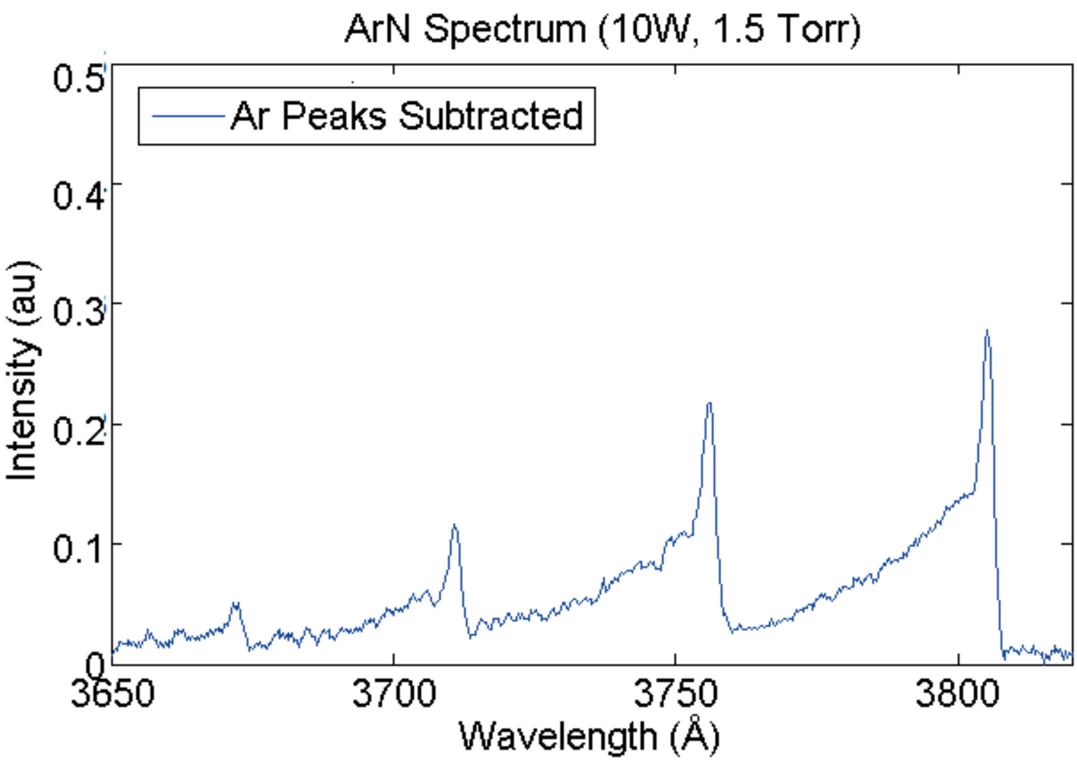

Figure 2: Measured spectrum for a 10W, 1.5 Torr argon nitrogen plasma.

determined. However, the preliminary experimental data obtain is sufficient to demonstrate the validity of matching a simulated spectrum to the experimental data for this discharge and provide preliminary results regarding the neutral gas temperature of the discharge and the related trends with pressure and power.

An example of the experimentally determined spectrum is shown in Figure 2, for a 10 W, 1.5 Torr argon-nitrogen plasma discharge. The simulated spectrum overlaid with the same measured data is shown in Figure 3. The resulting temperatures determined were $1605 \pm 15K$ for rotational and 3905K for vibrational, inferring a neutral gas temperature T_g $1605 \pm 15K$. This value is within the order of the temperature estimates from the power coupling and Langmuir probe estimates discussed in the introduction, of 1430K and 3200K respectively [6].

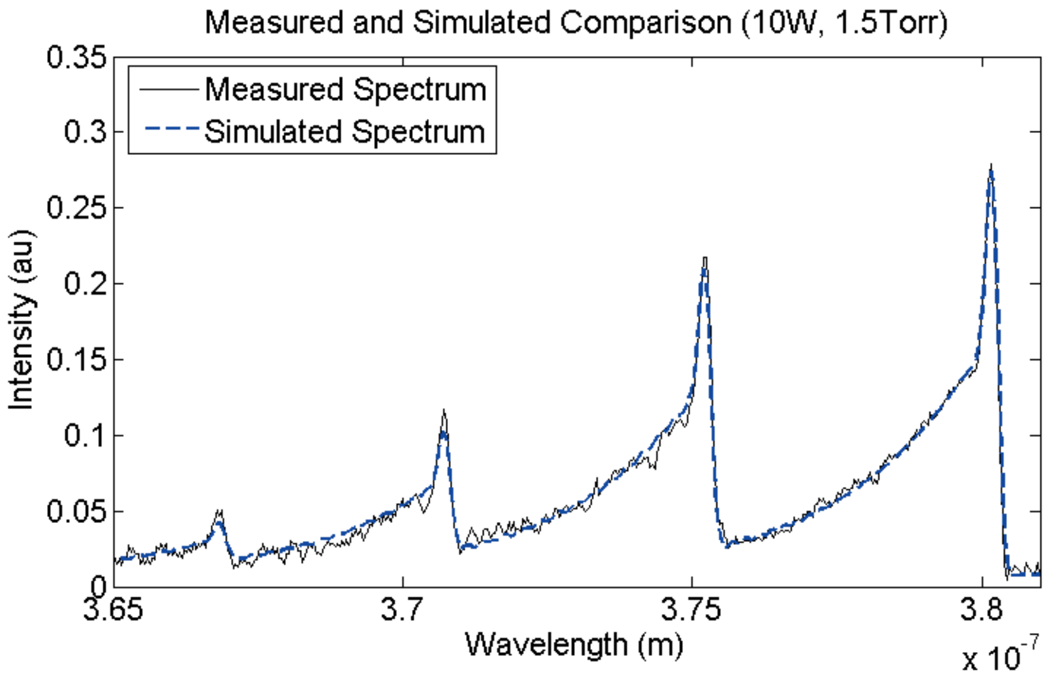

Figure 3: Measured and simulated spectrum for a 10W, 1.5 Torr argon nitrogen plasma.

Two independently developed codes were also used to check the measured and simulated spectra, one from the Open University in the United Kingdom and the other from the York Plasma Institute at the University of York. The Open University code compared the measured and simulated data over all four bands, determining temperatures of T_v $4050K$ and T_r $1570 \pm 75K$. The University of York code compared only the highest intensity band around 380nm to determine a rotational temperature of T_r $1530 \pm 25K$.

The range of temperatures determined with this simulated spectrum is completely within the range of temperatures determined using the Open University code. As these codes were developed independently, the overlap demonstrates the simulated spectrum code is producing expected values. The temperature range found by the York Plasma Institute is slightly lower. However, the York code only analysed one band of the spectrum and would therefore be expected to produce slightly different results.

Radial plasma densities were determined using digital photographs taken through the rear viewport on the Pocket Rocket plenum chamber. Images were captured with a Casio Exilim EX-F1 digital camera, used in conjunction with bandpass filters corresponding to the relative transition wavelengths used to determine the plasma density. The use of bandpass filters allowed only the light from the transition of interest to be imaged by the digital camera. Therefore, the intensity of each pixel imaged by the camera is a direct relation to the intensity of the transition at that point. A specially written MATLAB code was used to convert the digital photograph to pixel intensity measurements, then plot the result across the discharge diameter. The ArII 487.986 line corresponds to the $4p^2D^o \rightarrow 4s^2P$ transition and has a factor of n_e^2 in the coronal model where n_e is electron density. The intensity of the 488nm Ar II line for various pressures from 0.5 to 3.1 Torr is shown in Figure 4. The results show that at lower pressures, up to ~2 Torr, the intensity peaks around the central axis. At higher pressures, around 3 Torr, the discharge exhibits an annulus with a maximum intensity near the edge of the Pocket Rocket tube. As the Paschen minimum occurs at 1.5 Torr, the pressure region of interest is the lower pressures where the intensity peaks around the central axis.

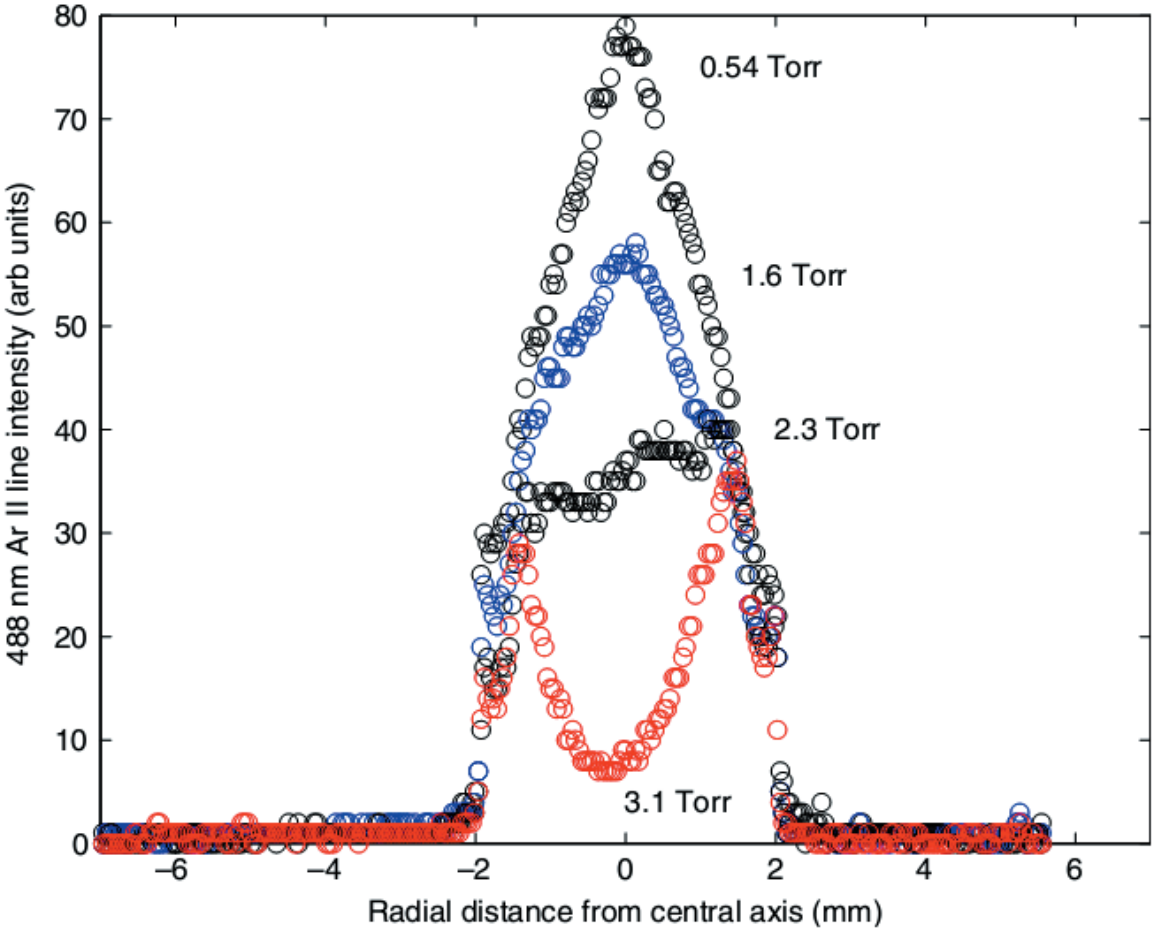

Figure 4: 488nm Ar II line intensity as a function of radial distance for upstream pressures from 0.5-3.1 Torr at 40W rf power.

For an argon discharge at 1.5 Torr, the 100sccm gas flow corresponds to approximately 3 mg/s or 4.5×10^{19} atoms per second. The mean free path for charge exchange and elastic ion-neutral collisions is 45 µm. A mean free path of 45 µm results in approximately 92 ion neutral collisions across the 4.2mm discharge diameter. About half of the ion-neutral collisions would be charge exchange collisions resulting in neutral gas heating. Assuming an exit velocity of the speed of sound (v_{ex} = 300m/s), the thrust is estimated as $T = v_{ex}\frac{dm_p}{dt} = 0.9mN$.

IV Conclusions

This thruster has now been installed on a thrust balance in a very large vacuum system and is presently being tested with calibrated flow controllers (the water bucket test) and onboard rf systems. The luminous plume of the plasma flowing afterglow can be seen in the photograph on the right.

The R&D status of Pocket Rocket will be presented. Thrust measurements and efficiencies will be presented for operation as a micro cold gas thruster compared to operation as an electrothermal thruster for different nozzles, flow volumes and rf power.

Acknowledgements

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References

[1] D.M. Goebel and I. Katz, *Fundamentals of Electric Propulsion,* (Los Angeles: JPL, 2008), 1-10.
[2] A. Smirnov et al., J. App. Phys. 92 (2002)
[3] X. Gaungqing et al., Tsinghua Sci. Technol. 14 (2009)
[4] A. Dunaevsky et al., Appl. Phys. Letters. 88 (2006)
[5] R. Boswell et al., IEEE Trans. Plasma Sci. 39 (2011)
[6] C. Charles et al., Plasma Sources Sci. Technol. 21 (2012)
[7] X. Huang et al,. Physics of Plasmas. 15 (2008)
[8] B. Bai et al,. J. App. Phys. 99 (2006)