A review of plasma thruster work at the Australian National University

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Abstract: **The Space Plasma Power and Propulsion Laboratory is conducting experimental and theoretical research into two types of plasma thruster. The first is the Helicon Double Layer Thruster (HDLT) and the second is a miniature capacitively coupled plasma thruster. Initial focus concerns the second generation Helicon thruster prototype, HDLT Gen II, an inductively/wave heated radiofrequency (13.56 MHz) plasma device. Applications include placement of telecommunications satellites into graveyard orbits at the end of their lifetime and propulsion to the planets. The physics of a lower power (20-100 W) electrothermal capacitively coupled thruster, Pocket Rocket, is being developed in parallel for applications to small-size low-cost "CubeSat" satellites. This microthruster is being modeled using Particle In Cell and fluid computer simulations and can be modified and developed as a radiofrequency electron source. In collaboration with the Research School of Astronomy and Astrophysics at the ANU, the Space Plasma, Power and Propulsion laboratory has designed and built a large thermal vacuum chamber at Mount Stromlo, WOMBAT XL, to study the physics and performances of our series of plasma thrusters for space vehicles.**

I. Introduction

A large number of electric propulsion systems are presently operational on satellites: these include resisto-jets, gridded ion beam and Hall effect thrusters, the latter two requiring hollow cathode neutralisers [1]. The propellant choice ranges from inert gases such as non-reactive xenon through molecular gases to highly reactive chemicals such hydrazine. It is a long road from basic plasma research into propulsion to system development and testing, followed by space launch and mission control and this is long, costly and risky. It necessitates dedicated infrastructure for space qualifications on Earth and for launch into space which pose considerable problems for small university groups who commonly cannot afford to pay for all the regulations and policies. However, recently new opportunities have emerged with the development of Cubesat satellites (1 Unit defined as 10x10x10 cm^3 at ~1 kg), Cubesat arrays (6 Units at ~6 kg) and small satellites (~30-50 kg) which are more suited to technology demonstration. The Cubesat platform offers a low-cost effective path to space for universities who are primarily interested in teaching.

II. Plasma Generation

Plasmas can be created by using DC and rf methods. For space applications many types of plasma excitation have been employed; for example the ion gridded thruster has been developed using either direct current (i.e. Kaufman thruster), radiofrequency (i.e. RIT thruster) or microwave (i.e. Hayabusa1&2) excitation [1] excitation systems. Their high performance characteristics result from the separation of plasma generation and ion acceleration so that for high current, high voltage systems the power for ion acceleration far exceeds the power necessary for plasma generation. Nevertheless, they require electrode grids immersed in the plasma to extract and accelerate ions and these ions need to be neutralised by electrons produced by a separate Hollow Cathode-type plasma generator to allow for plasma plume detachment and thrust generation. These neutralizing systems add another level of complexity to the thruster and require a separate power supply and gas control

III Space Propulsion

Most space propulsion activities are performance-driven with the main parameters being power and fuel efficiencies. Plasma propulsion systems typically provide less thrust than chemical propulsion systems, must be deployed in space and present a higher degree of complexity. Radiofrequency (rf) plasma systems with one end of the cavity directly open to space, with or without an expanding magnetic field affecting plume detachment, are currently under investigation. Small, medium and large vacuum chambers are used to study the physics and performances of some recent radiofrequency plasma thrusters including a low pressure (~1mTorr) conical Helicon source (HDLT: Helicon Double Layer Thruster) and a high pressure (~1 Torr) cylindrical micro-plasma source (PR: Pocket Rocket). RF power and gas subsystems need to be developed and integrated for spacecraft testing in larger thermal-vacuum chamber such as the Australian WOMBAT XL.

IV Helicon Double Layer Thruster (HDLT)

The Helicon Double Layer Thruster (HDLT) excites a plasma using an inductive antenna operating at 13.56 MHz that can excite helicon waves. Typically, the antenna is situated close to the throat of a magnetic nozzle having a peak magnetic field of ~100 Gauss; the nozzle can be produced using a single or pair of solenoids or by using permanent magnets arranged in a particular configuration. For the plasma volumes we have been using (about 1 litre) the optimum operating pressure is somewhat less than 1 mTorr with a flow of a few 10s of sccm. Under these conditions the plasma expanding along the diverging magnetic field creates a self-consistent electric field which accelerates the plasma ions and can be considered a form of electric double layer. The potential drop is such that sufficient electrons can escape from the plasma source to neutralize the ion beam and hence the HDLT can be considered a true plasma thruster.

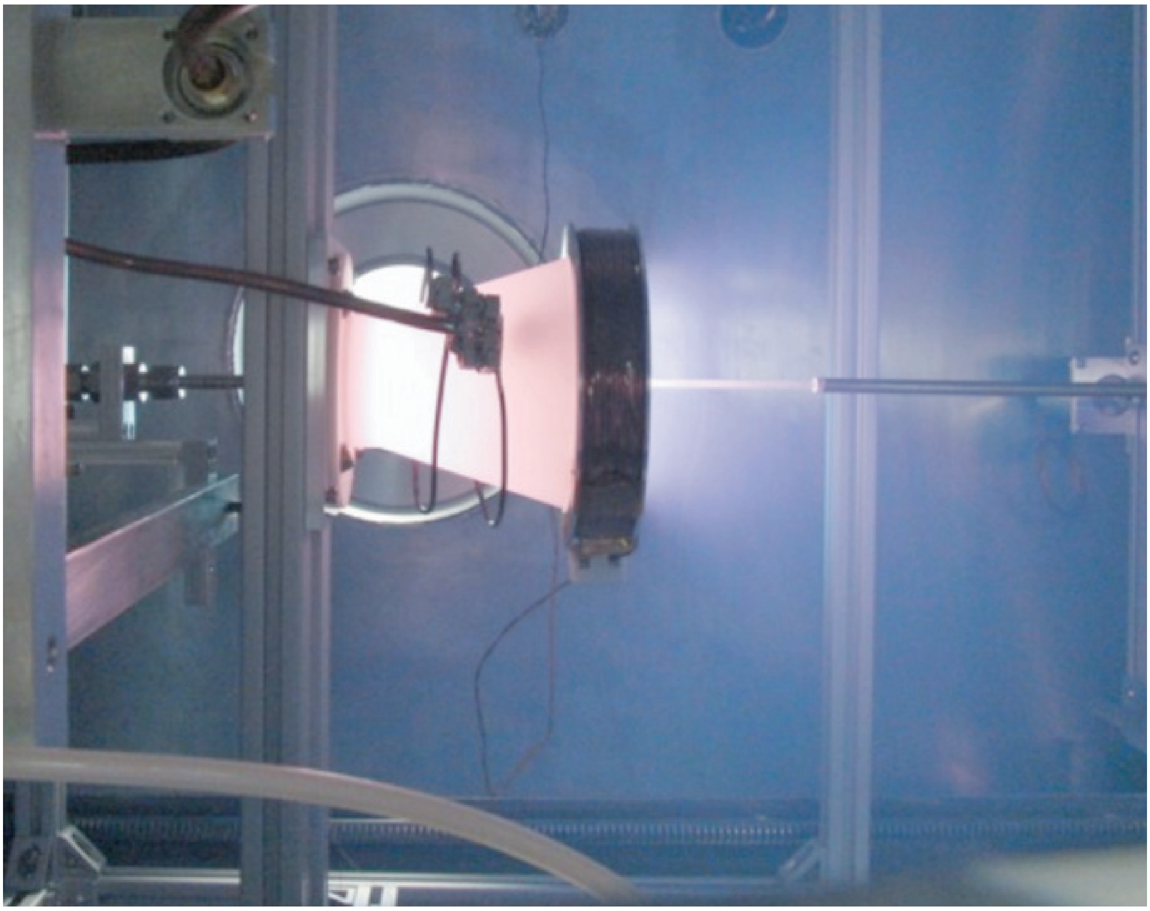

Figure 1. Basic laboratory prototype of the HDLT.

Measurements in vacuum on thrust balances show a thrust of about 1 mN/100 Watts input rf power [2]. A range of gases have been successfully tested, both atomic and molecular including “green” propellants and all show the same basic physics suggesting that the physics of the system is dominated by the electrons with the ions responding to the electric fields set up by the electron dynamics. A mixture of NH_3 and N_2O ws used to simulating hydrazine to demonstrate that the thruster could be employed for for moving geostationary satellites into a “graveyard” orbit using residual fuel from the apogee boost motor. Figure 1 shows a simplified laboratory prototype of the thruster operating in vacuum on a thrust balance using passive components to match a frequency agile rf generator to the loop antenna seen about midpoint on the “glowing” ceramic nozzle. Depending on power input and prototype geometry, the specific impulse ranges from 200 to 2000 s in argon [3].

V Pocket Rocket (PR)

Pocket Rocket is a small compact thruster (2 cm in length and a few mm in diameter) and is aimed at micro- and nano-satellites which have little power available [4]. In this case, the plasma is employed to heat the gas via charge exchange collisions and ambipolar flow to create a form of electrothermal thruster which has its heating mechanism in the centre of the flowing propellant rather than on the thermally lossy walls. The specific impulse is ~100 s but it has high efficiency in producing thrust at low input power (<100 Watts). Pocket Rocket is a low-volume, low-cost, low-weight, RF plasma thruster which can operated with ‘green’ and safe propellants, typically argon. It can easily be operated as a cold gas thruster.

Figure 2. Pocket Rocket prototype immersed in vacuum.

The capacitively coupled rf generates a high density plasma at about 1 Torr having a volume less than 1 millilitre that serves as an intermediary in the power flow but is not directly involved in producing thrust. Two effects having distinct time-scale contribute to neutral heating: ambipolar diffusion heats the neutrals via ion-neutral collisions (microsecond time scale) and radial wall heating resulting from ion neutralisation heats the neutrals on a time scale of tens of seconds [5].

Theoretical calculations show that a few 10s of Watts input power in the plasma results in gas temperature of 1000-2000 K. This is verified experimentally by ro-vibration spectroscopy. The basic physics and engineering of the discharge is studied by using a computational fluid dynamics code with an additional plasma module, a particle-in-cell simulation code with an axial pressure gradient and by using nano-second optical emission based spectroscopy. This thruster has now been installed on a thrust balance in vacuum and is presently being tested with gas flow systems and on-board rf systems. The luminous plume of the plasma flowing afterglow can be seen in Figure 2.

VI Advanced Instrumentation Technology Centre (AITC)

The Space Plasma, Power and Propulsion (SP3) laboratory has three operational vacuum chambers of various size and pumping capability and equipped with thrust balances and plasma diagnostics: *Irukandji* and *Wombat* are located on the main campus of the ANU in Canberra City and *Wombat XL* is housed at Mount Stromlo about 20 km distant in the mountains. The largest facility, *Wombat XL* has been recently commissioned, a 3 metre diameter 6 metre long system (Figure 3) housed in a large experimental hall named the Advanced Instrumentation Technology Centre (AITC) [6]. The pumping rate for air is 150,000 litres per second and allows HDLT experiments in a much more space like environment. In particular we are interested in investigating the form of the electron energy probability function when there is no downstream plasma as found in smaller systems with lower pumping rate.

Fig. 3. *WOMBAT XL*.

The AITC also hosts a large clean room, a satellite shaker and an anechoic chamber. This newly established infrastructure defines Canberra as a national and Asia-Pacific space hub already hosting many partnerships with industry. It is set up as a platform for optimum training and mentoring of the next generation of space scientists and engineers.

VII Conclusions

The research and development status of emerging radiofrequency thrusters and their sub-systems are being conducted at the Australian National University in the context of advances in plasma physics, space science and electric propulsion.

VIII Acknowledgements

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