Plasma Physics of CubeSat Electric Propulsion Thrusters

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Abstract. Spacecraft Electric Propulsion (EP) has been foreseen as a promising technology for over more than a century and whilst ionic propulsion has made a first demonstration in 1964, EP has only recently started to compete with classical propulsion techniques of the like of chemical and cold gas thrusters [1, 2, 3, 4]. This latency can be in part at- tributed to the slow development of the technology due to a poor or partial understanding of some of the fundamental plasma physics at work in well established and alternative types of EP techniques.

This PhD conducted at the University of Auckland in collaboration with the Australian National University (ANU) aims to bring a significant contribution to the field. The PhD focuses first on improving a limiting design feature of well established ion thruster types, namely their electron source. Then, the research will aim at deepening the fundamental plasma physics understanding of plasma transport mechanisms in a non-uniform mag- netic field typical of a so-called Helicon Plasma Thruster (HPT).

RADIOFREQUENCY MICRODISCHAGE NEUTRALISER

Hollow cathodes are the preferred electron sources for the primary plasma discharge creation and space-charge neutralization of ion thruster technologies [5]. The inherent fragility and finite operational lifetime of some key components make hollow cathodes one of the constraining factors on the lifetime of ion gridded and Hall effect thrusters. They are also known to be potential single point of failure. Depletion of the electron emitting insert, erosion of the keeper electrode and cathode tip from ion sputtering as well as failure of the heater are examples of such weaknesses. [6, 7] Based on the Pocket Rocket, an electrothermal plasma thruster designed by the Space Plasma Propulsion and Power (SP3) group at ANU, the neutraliser Pocket Rocket (ePR) is foreseen as a replacement to hollow cathodes [8]. ePR will by-pass design flows of hollow cathodes. It does not require a heater, making it an instant-on device as equilibrium operation takes a few microseconds, compared to several minutes for hollow cathodes [9, 5]. Moreover, the ePR driven electrode is shielded from the plasma and is therefore not subject to erosion or contamination.

The initial PhD work focussed on developing an experimental bench to host the ePR. 1A dedicated vacuum chamber and pumping system was designed and assembled. It achieves a background pressure of 10^{-7} Torr and a working pressure of $10^{˘4}$ Torr with 100 SCCM Ar flowing through the ePR. A custom-made RF power supply and matching network can provide up to 50 W at 13.56 MHz to the ePR driven electrode. Fig.3 shows the test bench in its current state. The stock Pocket Rocket was modified to study its capabilities to operate as an electron source. As current balance needs to be maintained while extracting electrons, an adequate sink for ions needs to be present in the ePR. For this purpose, an electrode was fitted in the plenum of ePR and gets biased at negative potentials to acheive ion collection. An electrode is placed downstream of the ePR plume to collect the electrons simulating a positively charged ion thruster beam. A sketch of the ePR can be seen in Fig.2. Unoptimized initial results shown that up to 20

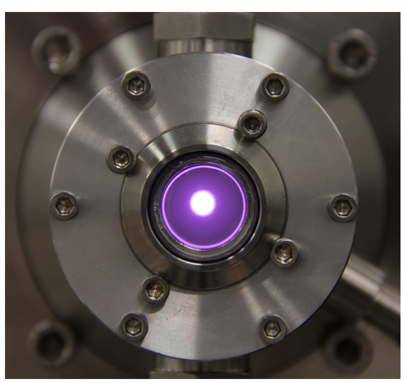

FIGURE 1. Argon discharge in ePR, as viewed through the plenum window.

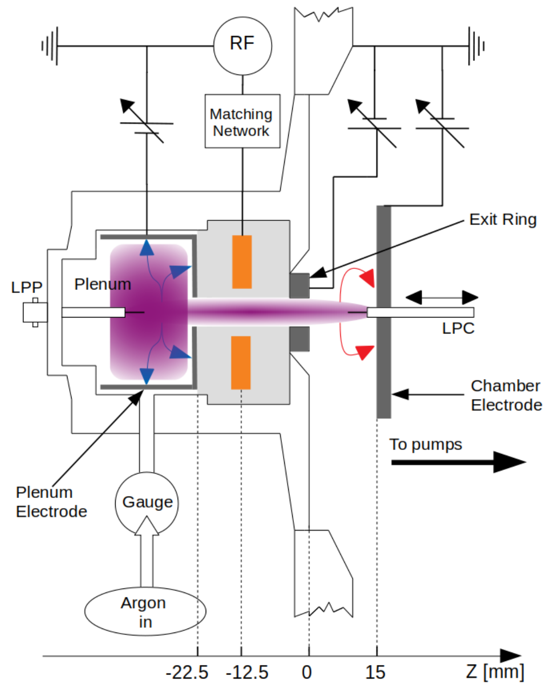

FIGURE 2. Sketch of the ePR, with a set of collecting electrodes allowing it to operate as a neutraliser.

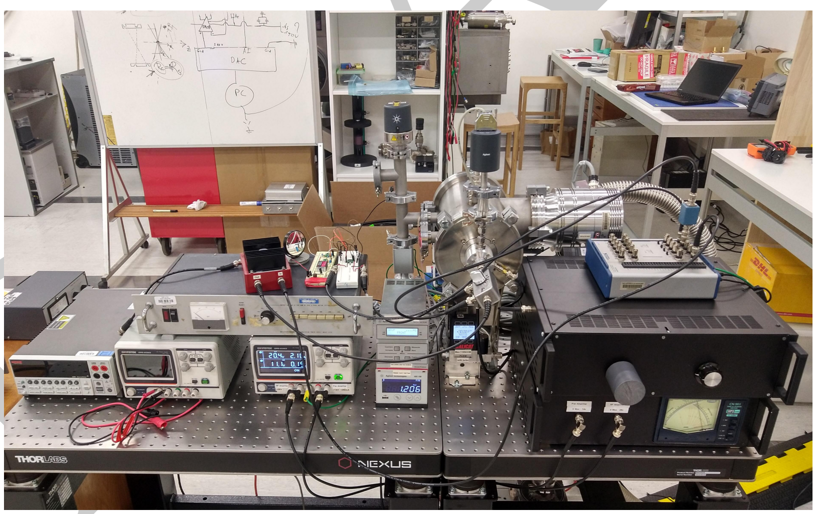

FIGURE 3. The ePR experimental bench with custom-made power supplies and diagnostics.

mA of electron current can be extracted from ePR for 10 W of RF power [10].

The way forwards relies on developing a dedicated diagnostics system composed of computer controlled set of planar and RF compensated Langmuir probes as well as an emissive probe to reliably characterize the ePR plasma and identify modes of higher plasma density production whilst keeping the RF power and mass-flow rate at a minimum. Fig.4 shows a fitted current-voltage curve obtained by a planar Langmuir probe and the deduced plasma parameters, obtained with newly developed custom- made diagnostics circuits.

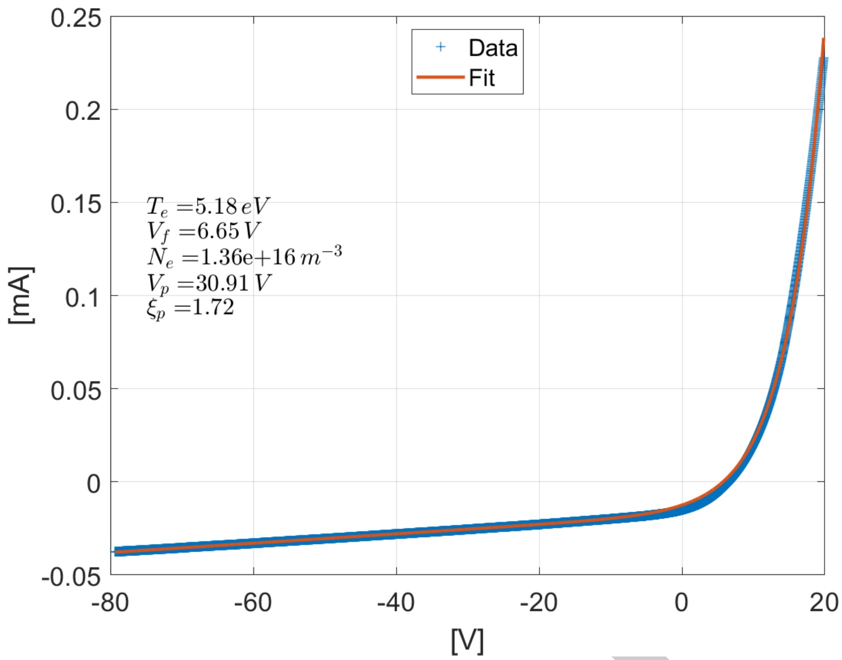

FIGURE 4. Example of a Langmuir probe IV curve recently obtained with custom-made diagnostic circuits.

PLASMA TRANSPORT MECHANISMS IN NON-UNIFORM MAGNETIC FIELDS

The second focus of this PhD is on physical processes of the Helicon Plasma Thruster (HPT). The HPT is a promising alternative to proven engines (ion gridded and Hall ef- fect). Structurally simple and with no moving parts, a HPT is made of a cylindrical 3dielectric source tube, surrounded by a RF antenna as a source of energy and a set of DC solenoids as a source of magnetic field, necessary to support the plasma creation and transform the plasma thermal energy into momentum through a so-called magnetic nozzle. A cartoon of a HPT is visible in Fig.5. Despite two decades of research, the most advanced HPT prototype still under-perform compared to established thrusters, with a thrust of 67 mN, a specific impulse of 3256 s and a thruster efficiency of 17.8 % at 6 kW [11]. A incomplete understanding of the fundamental physics of key processes at work in the HPT is responsible for those modest numbers: energy deposition by helicon waves, plasma acceleration in the magnetic nozzle, transport processes and thermodynamic of a magnetized plasma and plasma losses mechanisms.

The research at the University of Auckland is carried on the plasma transport pro- cesses and the thermodynamics inside a HPT, from the source tube to the magnetic nozzle. For that purpose, the ePR experimental bench is being upgraded to replicate the SP3 Echidna experiment, visible in Fig.6. This experiment was specifically designed to study the transport of energized plasma species along the magnetic field lines and the cooling processes of electrons trapped along magnetic field lines, which play an important role in the HPT thrust generation.

Huia, the system being developed at the University of Auckland replicates the geo- metrical features of Echidna with the specificity of being capable of operating at variable RF frequencies in the range 25 MHz to 42 MHz compared to the fixed 13.56 MHz of Echidna. The up to 1 kW discharge will take place in a 1.5 m long glass tube surrounded by two movable solenoids capable of applying a varying topology magnetic field of up to 1200 Gauss. The plasma properties will be scanned by a movable diagnostic shaft over the entire plasma column. A Computer-Aided Design version of Huia is visible in Fig.6. The work will start by investigating the frequency dependency of the phenomena previ- ously observed in Echidna [14]. A combination of planar and RF compensated Langmuir and emissive probes will be used for this purpose. Then, a combination of spectral line analysis and high speed footage will allow for characterization of the fast (microseconds) plasma transport processes taking place from plasma breakdown up to equilibrium. Fi- nally, RF compensated probes and Retarding field energy analyzers will be used to characterize the electron heating

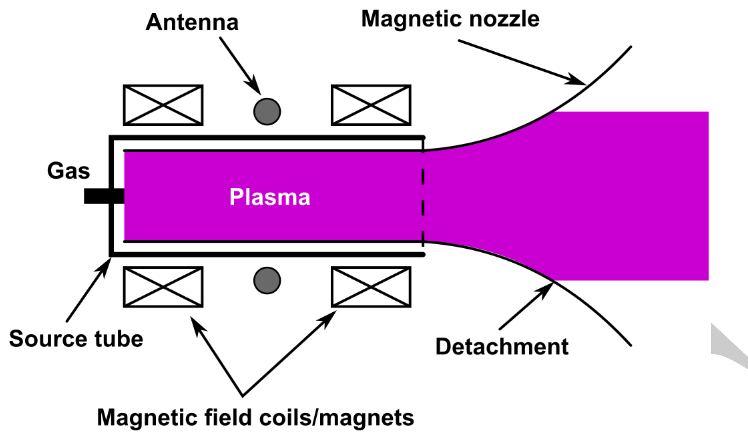

FIGURE 5. Cartoon of a Helicon Plasma Thruster with its various components. Adapted from [12].

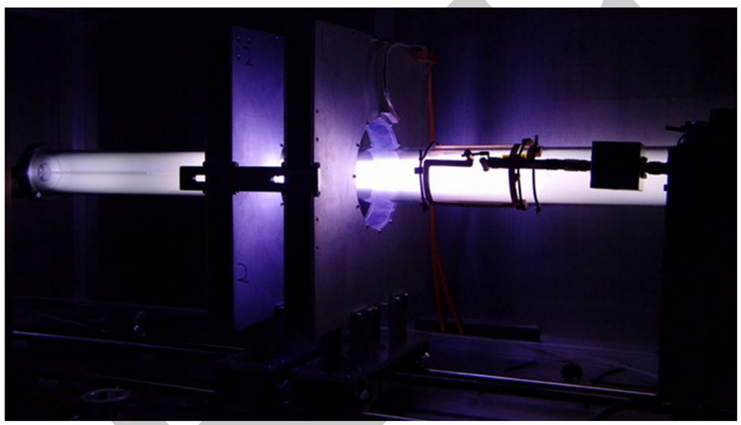

FIGURE 6. A RF plasma discharge into the SP3 Echidna experiment. Adapted from [13].

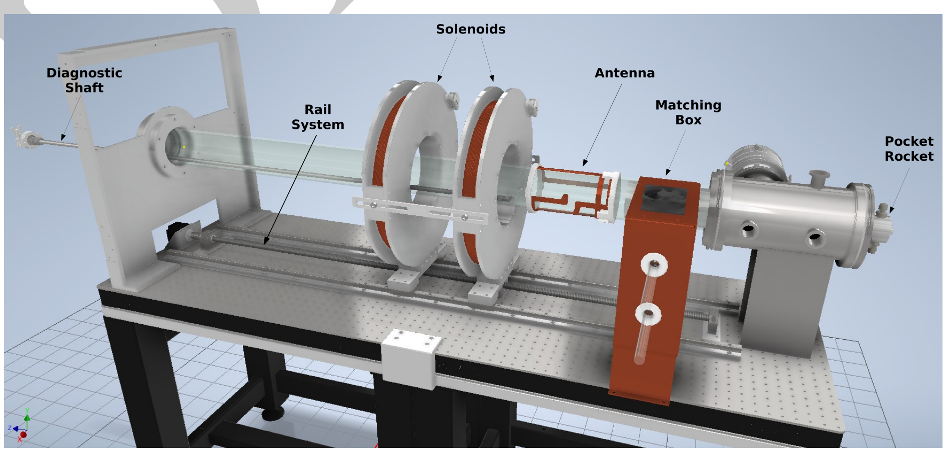

FIGURE 7. Computer design of Huia with the Pocket Rocket for scale comparison.

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