Helicon Double Layer Thrusters

IEPC-2005-290

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

C. Charles, P. Alexander, C. Costa, O. Sutherland, R.W. Boswell
Plasma Research Laboratory, RSPHYSSE, The Australian National University, Canberra, ACT 0200, AUSTRALIA

L. Pfitzner, R. Franzen
AUSPACE, Canberra, AUSTRALIA

J. Kingwell, A. Parfitt
Cooperative Research Centre (CRC) for Satellites Systems, Canberra, AUSTRALIA

and

P.E. Frigot, J. Gonzalez del Amo, E. Gengembre, G. Saccoccia
Propulsion and Aerothermodynamics Division, European Space Agency, ESTEC, The European Space Agency, The Netherlands

Abstract: The Helicon Double Layer Thruster (HDLT) concept is based on the recent discovery of a current-free electric double layer (DL) in a helicon plasma expanding in a diverging magnetic field. The potential drop of the DL is situated in the physical and magnetic nozzle and accelerates the ions generated in the helicon plasma source. The supersonic ion beam measured downstream of the double layer can be used for thrust in a space craft. The HDLT is simple, has no moving parts, no electrodes, and no need for a neutraliser.

I. Introduction

Current-free electric double layers (DLs) can spontaneously form in helicon plasmas expanding in a diverging magnetic field [1,2,3]. It was recently suggested that the supersonic ion beam measured downstream of the double layer could be used as a source of thrust in a new type of magneto-plasma thruster [1], defined as the Helicon Double Layer Thruster (HDLT). Another type of magneto-plasma thruster is the Variable Specific Impulse Magnetoplasma Rocket [4].

Electrics DLs occur naturally in a variety of space plasma environments (aurorae, solar wind, extragalactic jets...) and are being characterized using satellites. Terrestrial laboratory experiments have been succesfully demonstrated for decades in the case of current-driven DLs and more recently of current-free DLs. Most theoretical and simulation work have involved DLs with a current and there is virtually no theory on current-free DLs available in the literature [5], except Perkins's work [6]. The concept of the HDLT, based on the experimental characterization of the current-free DL using a retarding field energy analyser, is presently discussed.

II. The "Chi Kung" experimental set up

A. Chi Kung

The "Chi Kung" experimental set up consists of a horizontal helicon reactor consisting of a plasma source tube 31 cm in length and 15 cm in diameter attached to a 30-cm-long 32-cm-diam aluminum chamber [7]. A glass plate is inserted at the closed end of the source. A double saddle field antenna surrounding the source tube is used to feed rf (13.56 MHz) into the system and two solenoids surrounding the source tube are used to create an expanding magnetic field from the source (typically 60 to 200 G) to the chamber (a few tens of gauss). The gas can be injecteed near the thruster exit or at the closed end of the helicon source.

B. Diagnostics

The DL is diagnosed using a retarding field energy analyser [8] which provides spatial information on plasma parameters such as the plasma density, the plasma potential (and the potential drop of the DL), the ion beam density and velocity. The electron temperature is measured using a langmuir probe. The main parameters [9] associated with the DL are the gas pressure (typically less than 2 mTorr), the magnetic field (typically higher than 60 G) and the radiofrequency power. Additionnal parameters such as the source geometry, the gas pumping rate and the location of the gas injection are also studied.

III. Helicon Double Layer Thrusters

A. Thrust

The thrust in the HDLT is generated by an ion beam which exits the thruster at supersonic velocity (about twice the sound speed). The electric field of the DL is aligned with the magnetic field, contributing to low pitch angles for the accelerated ions. Although the magnetic field is necessary for the spontaneous formation of the DL, the thrust is derived from the reaction force provided by the electric field of the DL and the subsequent detachment of the plasma beam from the magnetic field and the thruster. The ion beam is detected from the center out to a radias corresponding to the plasma srouce tube and is not greatly affected by the expanding magnetic field. The beam velocity is constant across the thruster radius and the radial beam density has a bell shape.

The radial beam characterization 12 cm downstream of the double layer gives access to a measured beam divergence of less than 5 degres for argon [7,10]. This low divergence, which contributes to the net thrust generated by the beam, is in good agreement with computational studies of plasma detachment [11] in the HDLT.

The DL has been created for a variety of gases, argon, hydrogen [12], oxygen and xenon, the latter being the commonly used electric propulsion propellant. High beam exhaust velocities up to 15 km/s have been measured which will lead to high specific impulse and high propellant usage efficiency.

B. Features of the HDLT

The HDLT has no electrodes hence preventing electrode erosion over time. The radiofrequency power is transferred to the electrons of the plasma using an external double saddle field antenna placed around the source tube. There is experimental evidence that there are sufficient electrons to overcome the potential barrier of the DL since its strength is less than a wall sheath potential [7]. Hence the beam will be neutral and there is no need for a hollow cathode neutraliser. A temporal study [13] of this current-free DL has shown that it spontaneously forms during plasma breakdown and is stable thereafter (>200 microseconds). Hence the HDLT can be used in continuous or pulsed mode.

The helicon DL has been diagnosed in various experimental set ups worlwide using a variety of diagnostics (energy analysers [14], laser induced fluorescence [15]). Previous studies on helicon discharges have also demonstrated its extended scaling range both in terms of geometry and of radiofrequency power. In parallel with the experimental studies, recent Particle In Cell simulations of current-free electric DLs have been successfully developed [16,17].

C. Testing campaign of the HDLT prototype

A HDLT prototype with mechanical, electrical and thermal design based on Chi Kung's source was fabricated in order to carry out initial tests in a space simulation chamber at the European Space Agency (ESA). Preliminary testing of outgassing, thermal, rf and plasma operation were carried out in Australia by mounting the HDLT on the Chi Kung chamber and by using a 2000l/s turbo pump. The double layer and the supersonic ion beam were characterized for xenon with an effective pumping speed of 700 l/s. All tests were successful and the thruster was delivered to ESA's development center ESTEC early in April 2005.

At ESTEC, the HDLT was tested at pressures from 2×10^{-4} to 2×10^{-5} mBar and although a clear beam could not be discerned in the Langmuir ion saturation current, a new high-density plasma mode was discovered. It had maximum density in the centre at a pressure of 5×10^{-5} mBar which, if extrapolated back to the source assuming a $1/R^2$ expansion yielded a source plasma density of over 10^{12} cm^{-3}, correlating well with that expected from the input power of 500 W. The plasma source operated very stably for a wide range of pressure, rf power (up to 900 W) and magnetic field (up to 200 G) but somewhat differently to that expected from the ANU smaller vacuum chamber tests where a beam was easily observable using an energy analyser.

IV. Conclusion

The current-free electric helicon double layer was found in the Chi Kung experiment in April 1999. Analysis of its experimental characterization over the past few years suggests the validity of the HDLT as a new type of magneto-plasma thruster where propellant usage efficiency, safety and life time are of concern, i.e., for interplanetary travel or large Earth orbit raising manoeuvres. The first HDLT prototype was designed and completed by April 2005 in Australia. The thruster was subsequently tested in a space simulation chamber at ESTEC, ESA's development center in The Netherlands.

.

Acknowledgments

"This project is proudly sponsored by the International Science Linkages programme established under the Australian Government's innovation statement Backing Australia's Ability".

References

[1]Charles, C., and Boswell, R.W., “Current-free double-layer formation in a high-density helicon discharge,” *Appl. Phys. Lett.*, Vol. 82, No. 9, 2003, pp. 1356-1358

[2]Cohen, S. A., Siefert, N. S., Stange, S., Boivin, R. F., Scime, E. E., Levinton, F. M., "Ion acceleration in plasmas emerging from a helicon-heated magnetic-mirror device," *Phys. of Plasmas*, Vol. 10, 2003, pp. 2593-2598

[3]Xuan Sun, Biloiu, C., Hardin, R., and Scime, E. E., "Parallel velocity and temperature of argon ions in an expanding, helicon source driven plasma," *Plasma Sources Science and Technology*, Vol. 13, 2004, pp. 359-370

[4]Boswell, R. W., Sutherland, O., Charles, C., Squire, J. P., Chang Diaz, F. R., Glover, T. W., Jacobson, V. T., Chavers, D. G., Bengston,R. D., Bering, E. A., Goulding, R. H., and Light, M., "Experimental evidence of parametric decay processes in the variable specific impulse magnetoplasma rocket (VASMIR) helicon plasma source," *Phys. of Plasmas*, Vol. 11, 2004, pp. 5125-5129

[5]Raadu, M. A., “The physics of double-layers and their role in astrophysics,” *Physics Reports*, Vol. 178, Nb 2, 1989, pp. 25-97

[6]Perkins, F. W., and Sun, Y. C., “Double-layers without current,” *Phys. Rev. Lett.*, Vol. 46, Nb 2, 1981, pp. 155-118

[7]Charles, C., and Boswell, R. W., "Laboratory evidence of a supersonic ion beam generated by a current-free helicon double-layer," *Phys. of Plasmas*, Vol. 11, 2004, pp. 1706-1714

[8]Charles, C., Degeling, A. W., Sheridan, T. E., Harris, J. H., Lieberman, M. A.,and Boswell, R. W., "Absolute measurements and modeling of radio frequency electric fields using a retarding field energy analyzer," *Phys. of Plasmas*, Vol. 7, Nb 12, 2000, pp. 5232-5241

[9]Charles, C., and Boswell, R. W., "High source potential upstream of a current-free electric double-layer," *Phys. of Plasmas*, Vol. 12, Vol. 044508, 2005, pp. 1-4

[10]Charles, C., "Spatially resolved energy analyzer measurements of an ion beam on the low potential side of a current-free double-layer," *IEEE Transactions on Plasma Science*, Vol. 33, Nb 2, 2005, pp. 336-337

[11]Gesto, F. N., Blackwell, B. D., Charles, C., and Boswell, R. W., "Ion detachment in the helicon double-layer thruster exhaust beam," *Journal of propulsion and power*, 2005, accepted

[12]Charles, C., “Hydrogen ion beam generated by a current-free double-layer in a helicon plasma,” *Appl. Phys. Lett.*, Vol. 84, No. 3, 2004, pp. 332-334
[13]Charles, C., and Boswell, R. W., "Time development of a current-free double-layer," *Phys. of Plasmas*, Vol. 11, Nb8, 2004, pp. 3808-3812
[14]Sutherland, O., Charles, C., Plihon, N., and Boswell, R. W., “Experimental evidence of a double-layer in a large volume helicon reactor,” *Phys. Rev. Lett.*, 2005, accepted
[15]Xuan Sun, Keese, A. M., Biloiu, C., Scime, E. E., Meige, A., Charles, C., and Boswell, R. W., “Observations of ion-beam formation in a current-free double layer,” *Phys. Rev. Lett.*, Vol. 95, Nb 025004, 2005, pp. 1-4
[16]Meige, A., Boswell, R. W., Charles, C., Boeuf, J. P., Hagelaar, G., and Turner, M. M., "One-dimensional simulation of an ion beam generated by a current-free double-layer," *IEEE Transactions on Plasma Science*, Vol. 33, Nb 2, 2005, pp. 334-335
[17]Meige, A., Boswell, R. W., Charles, C., and Turner, M. M., "One-dimensional particle-in-cell simulation of a current-free double-layer in an expanding plasma," *Phys. of Plasmas*, Vol. 12, Vol. 052317, 2005, pp. 1-4