Vacuum Facility Effects on Quad Confinement Thruster Testing

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Abstract: The first flight unit of the 200 W class Quad Confinement Thruster will be demonstrated in orbit on the SSTL NovaSAR spacecraft. Key preparatory activities have involved extensive ground testing in order to identify the operational and performance envelopes of the thruster over a broad range of test conditions with the ultimate aim of accurately predicting the in-space behavior. In particular, experimental campaigns have been carried out at the Surrey Space Centre and ESA Propulsion Laboratory at ESA-ESTEC in the effort to determine vacuum facility effects on the measured parameters through a critical comparison of the results obtained in the different laboratories.

Nomenclature

DC	=	Direct Current
EPL	=	ESA Propulsion Laboratory (ESA-ESTEC)
ESA	=	European Space Agency
ESTEC	=	European Space Research and Technology Centre
HCN	=	Hollow Cathode Neutralizer
QCT	=	Quad Confinement Thruster
SSC	=	Surrey Space Centre
SSTL	=	Surrey Satellite Technology Limited

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PPU = Power Processing Unit
TRL = Technology Readiness Level

I. Introduction

THE Quad Confinement Thruster[1] (QCT) is a novel electric propulsion system invented in 2010 at the Surrey Space Centre (SSC), University of Surrey. The Technology Readiness Level (TRL) of the propulsion system was progressively increased during the following years under multiple industry-funded projects. In the last four years the device has undergone an industrialization process[2], led by Surrey Satellite Technology Limited (SSTL), aimed at the development of a flight model and an in-orbit technology demonstration. The first QCT flight propulsion system (comprising PPU and propellant feed control unit) will fly on the NovaSAR satellite.

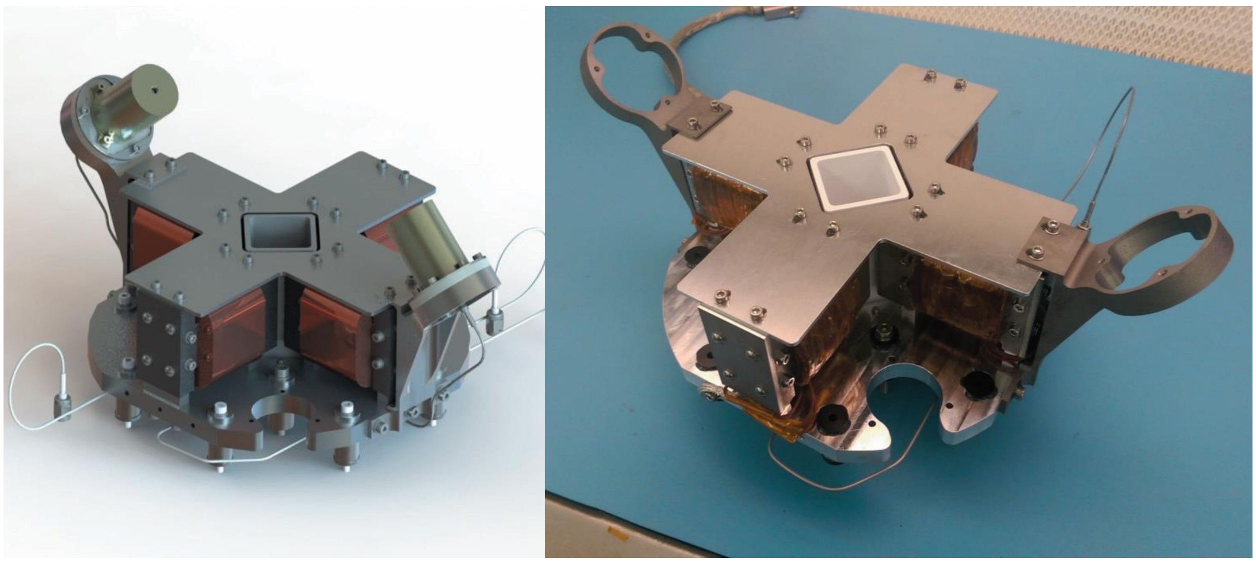

Figure 1. QCT-200 flight model.

The QCT is based on a DC-magnetized plasma discharge contained in a square-shaped boron nitride channel. The anode is located at the closed, upstream end. Neutral propellant (xenon) is injected at the periphery of the anode and is ionized through electron-impact collisions. An external barium-oxide hollow cathode provides primary electrons for ionization and neutralizes the ejected ion beam. The magnetic field is characterized by four cusps (Figure 2) located at the channel walls and, in combination with the longitudinal electric field, produces an $E \times B$ open electron drift. The magnetic field configuration can be manipulated by regulating the current flowing through the independently powered electromagnets; the distortion of the symmetry of the magnetic field produces a direct impact on the electron dynamics, resulting in a different electric field topology within the thruster channel and acceleration region. The shape of the acceleration front determines the direction of ion acceleration, therefore the manipulation of the magnetic field can indirectly relocate the center of thrust and modify the direction of the thrust vector. A previous three-dimensional mapping[4] of the plasma properties in the plume region of the thruster showed an 11 degree asymmetry of the plasma density distribution when two of the magnets were switched off. The characterization was performed using a Langmuir probe mounted on a three axis translation system. This potential capability of thrust vectoring without movable gimbals is one of the key characteristics of the thruster.

Following the successful proof-of-concept testing and several design iterations to optimize the prototype led by SSC-University of Surrey, in 2013 SSTL started an industrialization programme[2] aiming to produce a flight standard for use on small satellites. The programme includes the identification of a supply chain for components, the design and manufacturing of flight models, performance and endurance testing, along with the flight demonstration on board of NovaSAR satellite. Throughout 2016 several test campaigns were carried out using two 200 W QCT flight units in order to collect fundamental information on their operating envelope and performance under different test facility conditions. The understanding of the facility effects on the anode voltage-current operating characteristic and on the measured performance metrics is crucial in order to reliably assess the in-space behavior of the device.

The test campaigns have been carried out at the Surrey Space Centre electric propulsion laboratory and at the ESA Propulsion Laboratory (EPL) at ESA-ESTEC. A common test procedure has been defined and particular focus has been given to the background pressure effect, with each of the facilities having different dimensions and pumping capabilities.

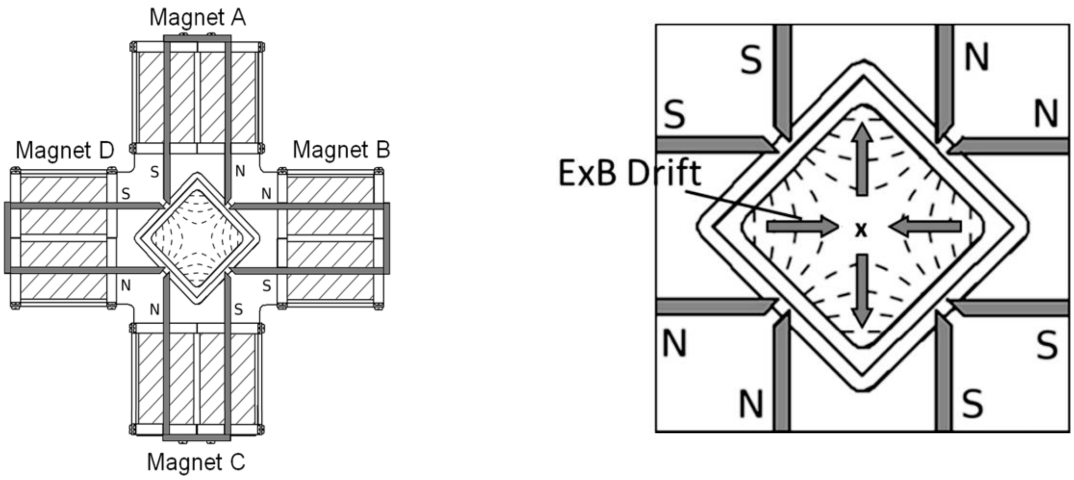

Figure 2. QCT magnetic field topology[3].

II. Test Campaigns

A. Surrey Space Centre Test Facility

The QCT flight unit was tested in the Daedalus electric propulsion facility at SSC. The vacuum chamber presents a diameter of 1.5 m and a length of 2.5 m. The pumping system includes a cryogenic pump and a turbomolecular pump in parallel with an overall pumping capacity of 12000 l/s (nominal for air). Background pressure is 7e-7 mbar without flow injection and within the range 1.2e-4 – 2.7e-4 mbar (uncorrected for xenon) during thruster operation with an overall flow rate in the range 6-12 sccm(Xe). The propellant flow rate to the anode and the cathode is regulated through Bronkhorst mass flow controllers.

Thrust measurements are performed using a pendulum thrust balance. The force generated by the propulsion system induces a displacement of a movable platform hung with metallic flexures. The displacement is measured by a Micro-Epsilon model ILD 1700-2 laser sensor with a resolution of 0.1 μm. The calibration is performed in vacuum with the thruster mounted on the thrust balance to include the stiffness of the cables and pipelines into the equivalent stiffness of the system. Multiple calibration force values are applied to the balance using a calibration mass which is moved horizontally using a rotational stage and a pulley system. The calibration factor is then computed through a linear interpolation of the force versus the measured displacement of the platform. Additional details can be found in previous works[1,3,5].

B. ESA Propulsion Laboratory Test Facility

The flight unit characterization activities included a test campaign at the ESA Propulsion Laboratory. The tests were performed in a 1.4 m long, 1.1 m diameter hatch attached via a 0.8 m diameter gate valve to the 5 m long 2 m diameter Corona vacuum chamber. The facility is equipped with a system of primary, turbomolecular, and cryogenic pumps. For these tests, the pumping speeds in the hatch and main chamber were approximately 17500 and 36100 l/s, respectively (note: not all pumps available for Corona facility were used during this test campaign).

For the tests shown in this paper, thrust measurements were conducted using the SSC thrust stand described in the previous section.

Figure 3. Surrey Space Centre Daedalus facility (on the left) and ESA Propulsion Laboratory Corona chamber (on the right).

C. Test Results

The thruster used in this study is a QCT-200 flight unit designed and manufactured by SSTL, identical to the one installed on board the NovaSAR spacecraft. The thruster is equipped with two hollow cathode neutralizers (one for redundancy), internally developed by SSTL.

The test matrix includes multiple scans in terms of mass flow rate, anode power and applied magnetic field. Propellant is xenon, supplied to cathode and anode, for all the tests carried out during this study. The thruster return (common connection of anode power supply negative pole and hollow cathode neutralizer return) is kept isolated from the facility ground and from the thrust balance; the thruster chassis is floating and connected to the thruster return through a 100 kΩ resistor.

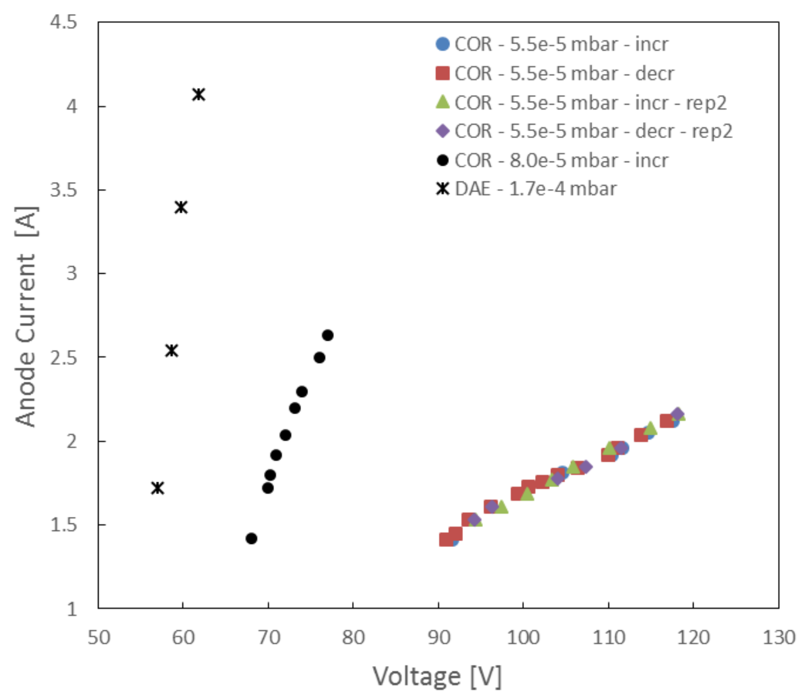

Figure 4. Voltage-current characteristics of the QCT operated in the Daedalus chamber at SSC and Corona chamber at EPL under different background pressure conditions.

The test campaign was primarily aimed at determining the facility effects on the thruster operation, in particular the influence of the background residual pressure inside the vacuum chamber. A common set of operating conditions has been replicated in Daedalus chamber at SSC and Corona Chamber at EPL. In the latter case, the redundant cathode has been used as an additional xenon mass flow input to increase the local neutral pressure in front of the thruster exit plane. Figure 4 compares the thruster anode voltage-current characteristics obtained in SSC-Daedalus with those achieved in EPL-Corona. For an anode flow rate of 8 sccm and a cathode one of 4 sccm, the chamber pressure settles around 1.7e-4 mbar in SSC-Daedalus, 5.5e-5 mbar in the EPL-Corona hatch, and 2e-5 mbar in the EPL-Corona main chamber respectively. Since the thruster is located close to the interface between hatch and main chamber, one can assume the local pressure in front of the exit plane to be equal to an intermediate value between the aforementioned ones. An additional xenon flow input through the redundant cathode produces an increase of the Corona hatch pressure up to 1e-4 mbar. The data reveal a strong influence of the test conditions: an increase of the background pressure drastically changes the slope of the voltage-current profile, shifting towards higher current-lower voltage regimes when the pressure is increased.

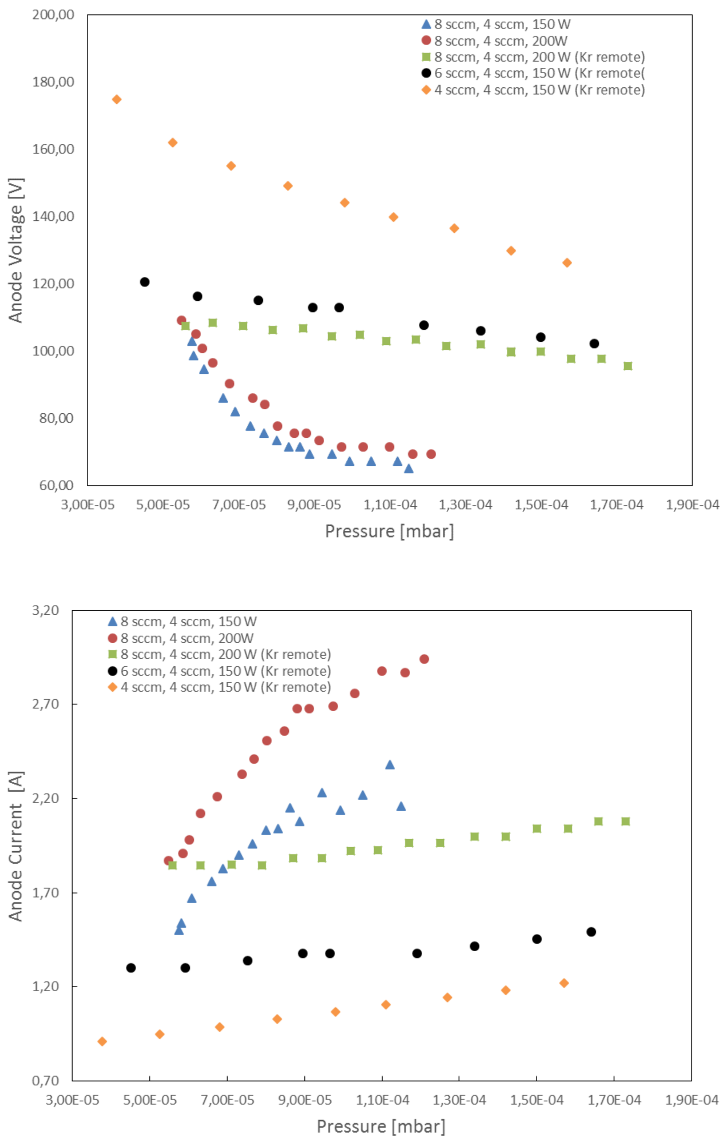

Figure 5. Anode current and voltage as a function of the background pressure.

This behavior is highlighted by Figure 5, illustrating the anode voltage and anode current as a function of the chamber pressure (EPL Corona hatch) for a fixed anode power level. Additional testing has been carried out implementing a different method to tune the background pressure, i.e. injecting a krypton mass flow through a chamber remote feedthrough. The effects on anode voltage and current remain the same, the former decreasing and the latter increasing as the pressure is progressively raised. However, the rates of change are less drastic than in the previous case (characterized by xenon injection through the HCN); indeed, the krypton injection point is located about 50 cm apart from the thruster, therefore the additional mass flow has a weaker influence on the local pressure in front of the discharge channel exit plane. The voltage-current profiles have been acquired for both increasing and decreasing ramps of the discharge power. The profiles show good overlapping without any evidence of hysteresis effects (Figure 4). Finally, the repeatability of the data has been verified performing multiple scans at the same discharge condition.

The results highlight strong facility effects on the QCT testing, as previously observed in the case of other electric propulsion systems, such as Hall thrusters[6]. In the specific case of the QCT the test conditions are critical, since the main plasma discharge within the channel is strongly coupled with the external plume whose properties depend on the residual neutral density. Visual observation of the plume reveals a semi-spherical plume structure in front of the exit plane with an extension of 5-8 cm centimeters. Laser-Induced Fluorescence measurements[7] have shown that the accelerating potential drop is located at the edge of this plume structure, well beyond the exit plane of the thruster, demonstrating that ion acceleration develops in a lower neutral density region. Therefore, a change of this last property might affect the potential distribution and the overall discharge regime.

Specific tests have been carried out to investigate the discharge regime at different magnetic field levels. Figure 6 illustrates the anode voltage and current for two different anode flows: 8 sccm and 6 sccm. In both cases the cathode flow was 4 sccm. As the discharge transitions from a glow mode to a magnetized mode, the anode current decreases and the anode voltage increases. This behavior is observed for both flow rates. Finally, a higher anode flow implies a higher discharge current at a fixed anode power level.

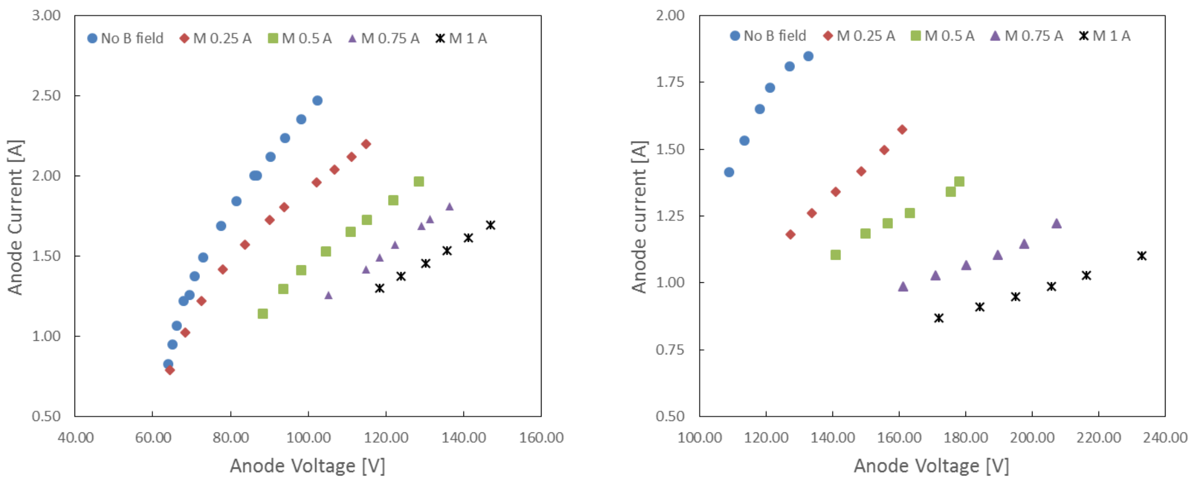

Figure 6. Voltage-current characteristics of the QCT operated in EPL-Corona chamber applying different magnetic field levels for two different anode mass flow conditions. On the left 8 sccm, on the right 6 sccm. Cathode flow is 4 sccm in both cases.

The impact of the facility effects on the thrust produced by the device were also investigated. Thrust measurements at different flow rates, discharge power, magnetic fields and vacuum chamber pressure have been performed. As an example, Figure 7 reports the thrust generated by the QCT as a function of the background pressure (on the left) and magnetic field (on the right) for two different anode power levels, namely 150 W and 200 W, for a flow rate of 8 sccm through the main discharge channel and 4 sccm through the hollow cathode.

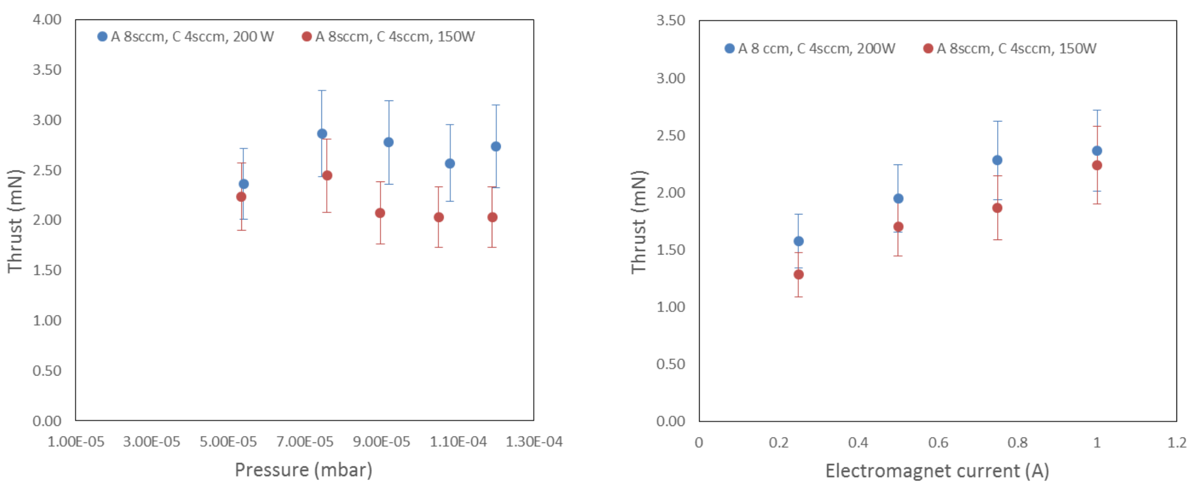

Figure 7. Thrust as a function of the background pressure (on the left) and of the magnetic field (on the right) for different anode power levels.

These measurements have been taken in EPL-Corona and the pressure has been tuned by using the redundant hollow cathode as the additional flow input. The measured thrust ranges within the interval 2.05 – 2.45 mN for the 150 W case, and 2.4 – 2.75 mN for the 200 W respectively, when the pressure is varied within the 5e-5 – 1.2e-4 mbar range. Considering the uncertainty of the measurement (estimated to be around 15%), the error bars present partial overlapping, preventing the identification of any specific trend.

Finally, the magnetic field scan, swept from 5 mT to 25 mT, demonstrates a monotonic increase of thrust for increasing magnetic field values.

III. Conclusion

The results demonstrate the relevance of understanding the facility effects. A QCT flight unit has been tested under variable conditions in two different vacuum chambers, one at the Surrey Space Center and one at the ESA propulsion laboratory. The QCT operating parameters and performance envelope were found to be strongly affected by the test conditions, in particular by the vacuum chamber background pressure. The latter influences both the discharge parameters, i.e. anode voltage and current, and the propulsive performance. The data collected during these test campaigns have allowed a better comprehension of the plasma discharge regimes needed to predict the in-space behavior of the thruster, whose first flight is planned on board of SSTL NovaSAR satellite. The definition of standard procedures, uniform uncertainty evaluation methods, and standard conditions for the space-simulation chambers are fundamental to obtain reliable and comparable results across the different test facilities.

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References

[1] A.K. Knoll, T. Harle, V. Lappas, M. Pollard. “Experimental Performance Characterization of a Two-Hundred-Watt Quad Confinement Thruster,” *Journal of Propulsion and Power*, 30(6) 1445-1449, 2014.

[2] O. Lane and A.K. Knoll. "Quad Confinement Thruster–Industrialisation & Flight Integration," *34th International Electric Propulsion Conference Proceedings*, IEPC-2015-36, 2015.

[3] A.K. Knoll, D. Lamprou, V. Lappas, M. Pollard, P. Bianco. “Thrust Balance Characterization of a 200 W Quad Confinement Thruster for High Thrust Regimes,” *IEEE Transactions on Plasma Science*, vol. 43, no. 1, 2015.

[4] A.K. Knoll, U. Shafiq, V. Lappas, M. Perren. "3-Dimensional Mapping of the Plasma Properties in the Plume Region of the Quad Confinement Thruster," Space Propulsion Conference 2012 Proceedings, 2012.

[5] A. Lucca Fabris, A.K. Knoll, T. Potterton, O. Lane, P. Bianco, K. Dannenmayer, T. Schönherr, J. Gonzalez del Amo. "An Interlaboratory Comparison of Thrust Measurements for a 200 W Quad Confinement Thruster," *Space Propulsion Conference 2016 Proceedings*, 2016, SP2016-3124797.

[6] T. Randolph, V. Kim, H. Kaufman, K. Kozubsky, V.V. Zhurin, M. Day. “Facility effects on stationary plasma thruster testing,” *23rd International Electric Propulsion Conference Proceedings*, IEPC-1993-093, 1993.

[7] A. Lucca Fabris, C.V. Young, A.K. Knoll, M.A. Cappelli. “Ion Acceleration in a Quad Confinement Thruster,” *35th International Electric Propulsion Conference Proceedings*, IEPC-2017-252, 2017.