Ring Cusp Ion Engine Development in the UK

IEPC-2015-130／ISTS-2015-b-130

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Michele Coletti[1]
Mars Space Ltd, Southampton, SO145FE, UK

Neil Wallace[2]
ESA - ESTEC, Noordwijk, The Netherlands

Stephen B. Gabriel[3] and Daniele Frollani[4]
Mars Space Ltd, Southampton, SO145FE, UK

and

Huw Simpson[5]
QinetiQ, Farnborough, GU14 0LX, UK

In this paper the design and first experimental results obtained on a ring cusp T6 breadboard engine will be presented. The engine magnetic design will be quickly introduced and then the experimental results obtained in discharge and beam mode presented. The engine has proved to be able to deliver a discharge cost improvement of about 30% when compared to a standard Kaufman T6 working at the same thrust level. The engine performance in discharge only mode measured at QinetiQ and ESA-ESTEC have been found to be in close agreement and the beam performances have been found to be in agreement with the theoretical expectation obtained using the 0D engine model developed at JPL. Future work will include the optimization of the discharge chamber and ion optics design.

Nomenclature

$\dot{m}_c$	=	mass flow rate of Xenon to the cathode
$\dot{m}_f$	=	mass flow rate of Xenon to the discharge chamber
I_A	=	discharge current
Isp	=	specific impulse
V_A	=	discharge voltage
V_{beam}	=	beam voltage

[1] Director, michele.coletti@mars-space.co.uk
[2] Electric Propulsion Engineer, TEC-MPE, neil.wallace@esa.int
[3] Managing Director, stepehn.gabriel@mars-space.co.uk
[4] Research Engineer, daniele.frollani@mars-space.co.uk
[5] Project and Business Development Manager, hbsimpson@qinetiq.com

I. Introduction

AT present commercial spacecraft operators are actively proposing the adoption of electric propulsion (EP) for significant orbit raising maneuvers on GEO telecomm satellites in addition to NSSK maneuvers.

The duration of these maneuvers is strongly influenced by the thrust level and, since the total available power is limited by array sizing for the payloads, ultimately by the specific power (W/mN) of the EP system. The W/mN of the EP system is therefore increasingly recognized as a key technology selection discriminator.

The T6 gridded ion engine system currently being qualified by QinetiQ for BepiColombo [1] operates at specific power of ~33 W/mN. This is driven by the specific impulse at which the system operates (4300s) and was originally designed for this performance primarily because of the Isp requirements of BepiColombo.

Reducing the W/mN requires the Isp to be reduced which in-turn requires the beam voltage to be reduced. Reducing the beam voltage in isolation is relatively simple however to meet the demands of improved orbit manoeuvres duration requested by the telecoms market, it is also necessary to increase the thrust level.

This means that a higher ion beam current density and extracted beam current is necessary which also means higher discharge plasma densities and higher discharge powers. This will unavoidably increase the internal dissipation and therefore the temperature of the electrical and mechanical interfaces to the thruster. These are already identified as critical interfaces and are driving the design and complexity of the thruster and harness and also imposing upper limits on the performance capability that can be offered.

The existing T6 GIE utilizes a Kaufman discharge chamber configuration (Figure 1 a) that currently operates at a discharge efficiency of ~260eV/ion. In comparison a ring-cusp alternative (Figure 1 b) could be designed to operate at ~150eV/ion and efficiencies as high as 120eV/ion have been reported by NASA JPL [2]. As a consequence an evolution of the current QinetiQ Gridded Ion Engine technology with the adoption of a ring-cusp discharge chamber is of significant commercial interest.

In addition to the improvements in electrical efficiency, the ring-cusp configuration also promises a simplification of the thruster mechanical assembly and a simplification of the power supplies within the PPU. The latter can be achieved because the RC discharge chamber uses permanent magnets instead of solenoids, and therefore a solenoid power supply is no longer required.

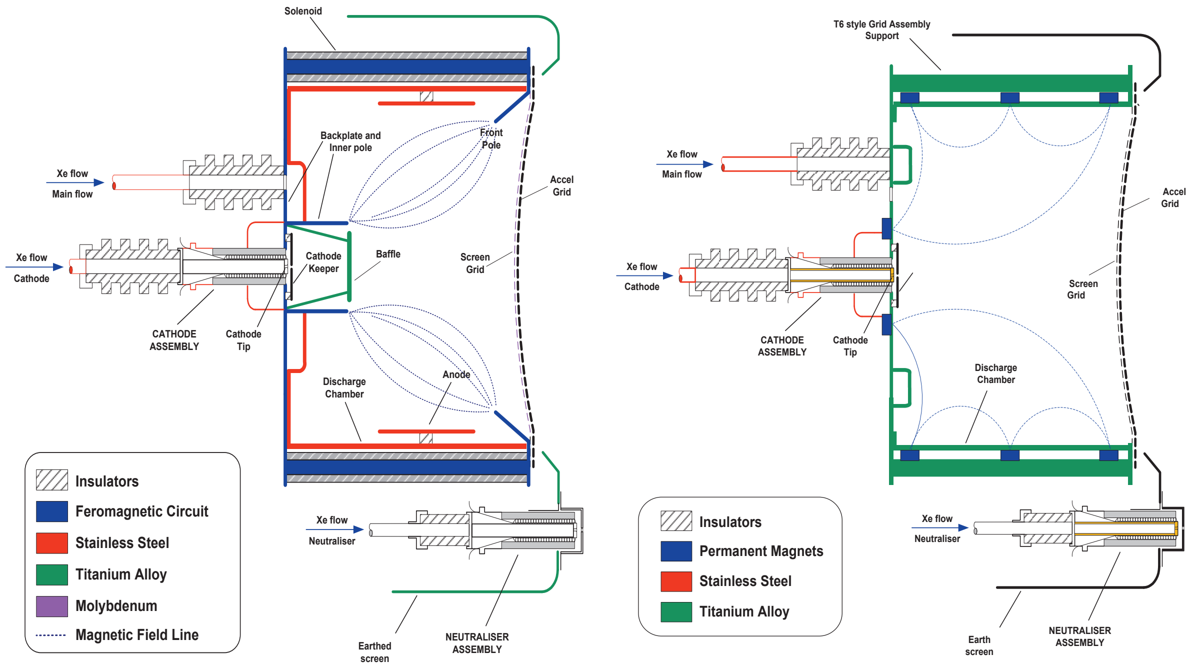
On the basis of the aforementioned technical advantages, in 2013 QinetiQ and Mars Space Ltd have started a development programme under both ESA and UK national funding to develop a Ring Cusp T6 ion engine that will be optimized for telecommunication satellite applications. At present the first ring cusp T6 (T6RC) breadboard prototype has been produced and tested at QinetiQ and ESA – ESTEC. In this paper the results obtained so far will be presented together with the plans for future work.

II. RC T6 breadboard design

A first Ring Cusp T6 (T6RC) breadboard prototype has been produced reusing existing T6 components (Figure 1 and Figure 2). This has allowed a quick and inexpensive assembly of the engine but at the same time has constrained the physical dimensions of the discharge chamber. In particular the differences between the T6RC and a Kaufman T6 (T6K) are:

- the removal of
    - the baffle and inner pole.
    - the T6K solenoids (in the case of the RCT6 prototype non-magnetic equivalents of the solenoid cores have been retained because they are used to support the existing grid assembly).
    - the discharge chamber anode.
- and the addition of
    - three magnetic rings placed around the discharge chamber.
    - one magnetic ring placed upstream of the cathode.
    - an insulator ring between the discharge hollow cathode and the discharge chamber (since in a T6K the discharge chamber walls are at cathodic potential).
    - insulators between the discharge chamber and the front pole piece / screen grid (since in a T6K the front pole piece and screen grid are also at cathodic potential).

Everything else is unchanged between the two engines, hence the T6RC breadboard will use the same cathode and the same gridset already used with the T6 Kaufman. Considering all this and that in the UK ion engines have historically used Kaufman discharge chambers rather than ring cusp configurations it is clear that the main objective of this breadboard is to demonstrate that a T6RC can provide performance improvements with respect to the current T6K design, and to acquire knowledge regarding the operation and design of such types of ion engine.



a) **b)**

Figure 1. Schematics of: a) Kaufman T6 and b) Ring Cusp T6

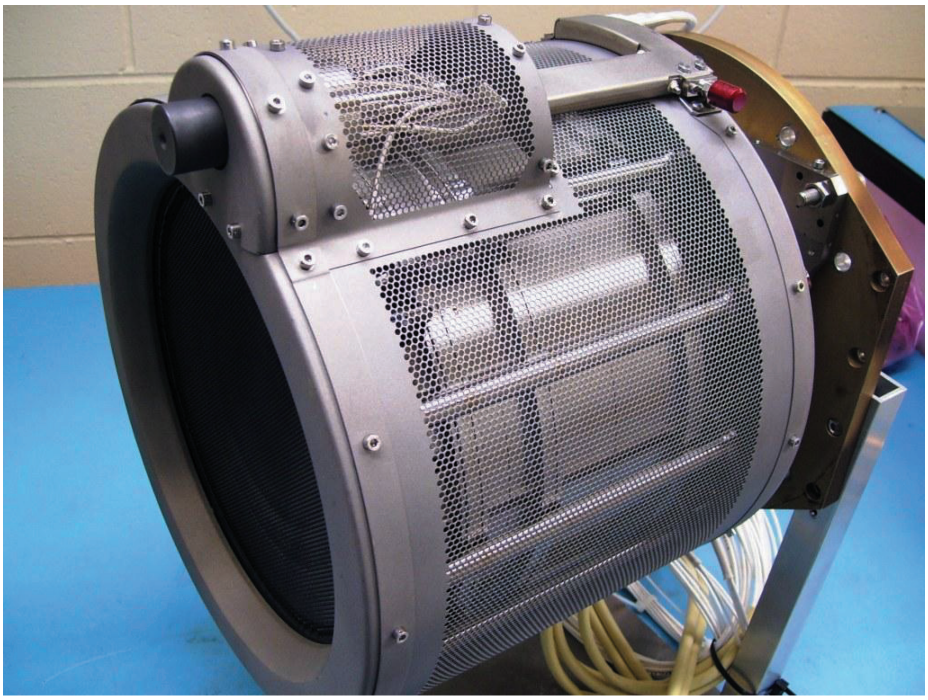


Figure 2. The T6RC prototype

Moreover it must be noted that the ion optics used is clearly not optimized for the T6RC (since its geometry is optimized for the plasma profile produced by the T6K) hence the results that will later be presented regarding the performance of the engine are to be considered only as a preliminary assessment of what can be achieved.

A. Magnetic design

As reported above most of the T6RC breadboard design has been inherited by the T6K. The only part left to design was the position and strength of the magnet rings used to produce the ring cusp shaped confinement.

A Comsol™ model has been used to study the magnetic field topology allowing us to easily change the number, strength and position of the magnets. It was decided to use an even number of magnets to ensure that the magnetic field minimum is on-axis, which, as reported in [3] encourages the primary electrons to move throughout the discharge chamber improving the discharge chamber efficiency and plasma profile flatness. The goal of this design activity was to choose a configuration that will produce:

- a large field free area on the inner part of the discharge chamber to obtain a uniform plasma density distribution in the discharge chamber.
- a constant low value of the magnetic flux density along the grid radius to aid in the production of an optimal radial plasma density profile.
- a last magnetic field closed contour with a value of the order of about 60G as found in the NEXIS thruster [4] to allow good electron confinement and discharge stability
- a divergent magnetic field shape close to the grids to try to increase the flatness of the plasma profile

A configuration with three magnetic rings placed on the discharge chamber sidewall and one ring placed around the hollow cathode was chosen. The rings were made using Samarium Cobalt grade 2:17 28/20. Simulating several different configurations it was found that the use of a double layer of magnets on the hollow cathode ring was beneficial in strengthening the magnetic field contours immediately around the cathode where the primary electrons are launched into the discharge chamber hence minimizing discharge losses to the backplate. Moreover it was also found that reusing the T6K magnetic front pole piece (that is also part of the grid mounting structure) without any modification was effective in constraining the magnetic field produced by the downstream ring resulting in lower field strength at the periphery of the discharge chamber at the plane of the grids.

A map of the magnetic field inside the discharge chamber for the chosen configuration is reported in Figure 3 where a last closed contour with a value of about 60G can be noticed. Also the magnetic field trends on the centerline and along the grid radius are reported in Figure 4.

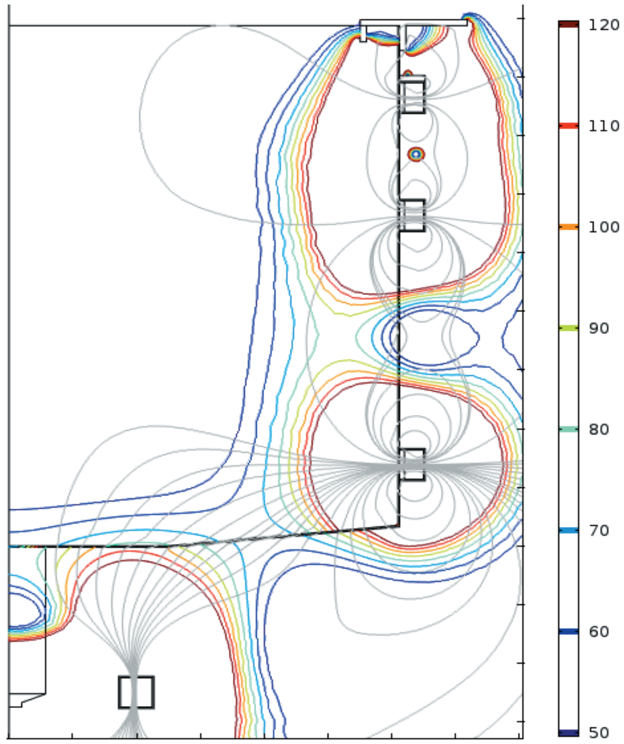
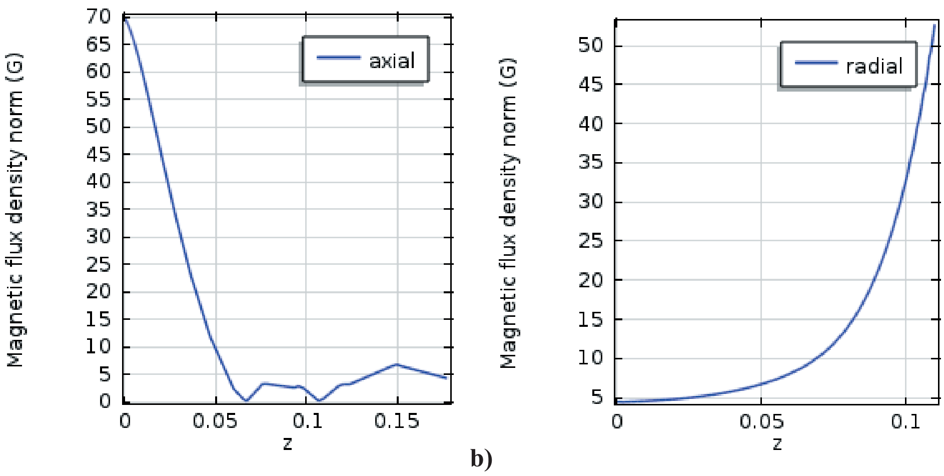


Figure 3. Simulation of the T6RC magnetic flux density contours. The legend is in Gauss



a) b)

Figure 4. Pole piece magnetic flux density a) along the thruster centreline, b) along the grid radius

B. Magnetic characterization of the discharge chamber

The magnetic field inside the RC discharge chamber has been measured to validate the magnetic model used to select the magnet strength and position. The magnetic field measurements have been performed using a 3 axis Lakeshore MMZ-2518-UH magnetic probe. The probe has been mounted on the arm of a CMM machine and an automatic routine written to ensure reliable probe positioning and repeatable measurements. The measurement grid consisted of 11 points in the radial direction and 9 points in the axial direction. In addition to this, 2 radial points and 5 axial points were added outside the discharge chamber. The measurement grid is reported in Figure 5 and a picture showing the measurement setup with the T6RC discharge chamber and the magnetic probe is presented in Figure 6.

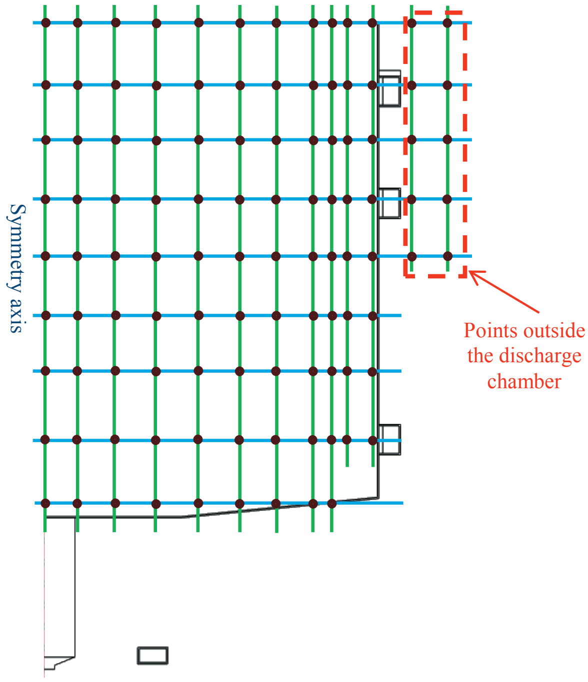


Figure 5. Measurement grid, the red dots are the measurement points

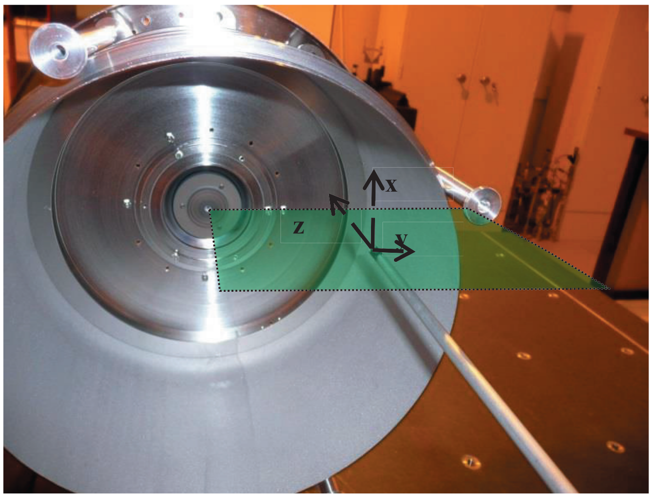
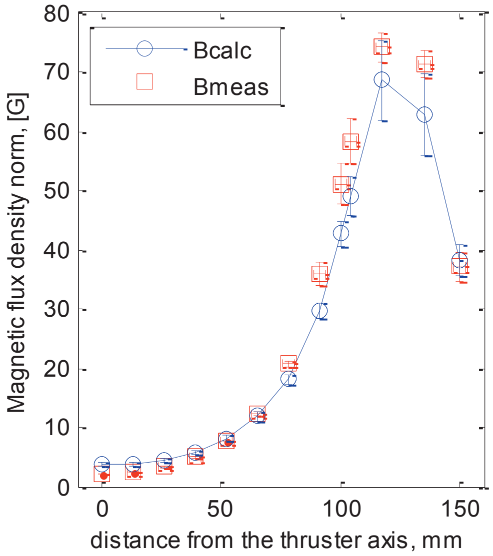
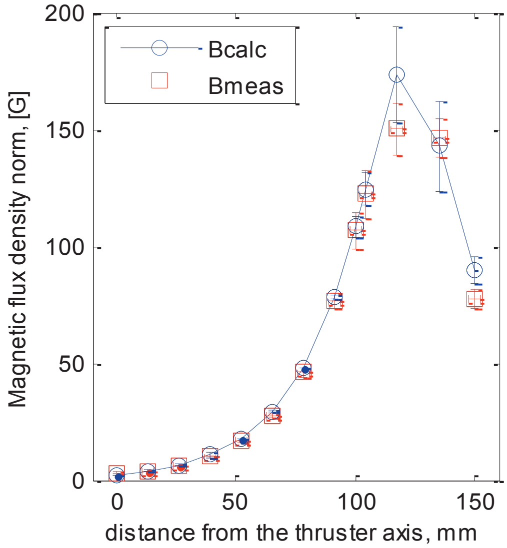


Figure 6. Magnetic field measurement setup showing the orientation of the probe axis. The plane on which the probe moves (Figure 5) is in light green.

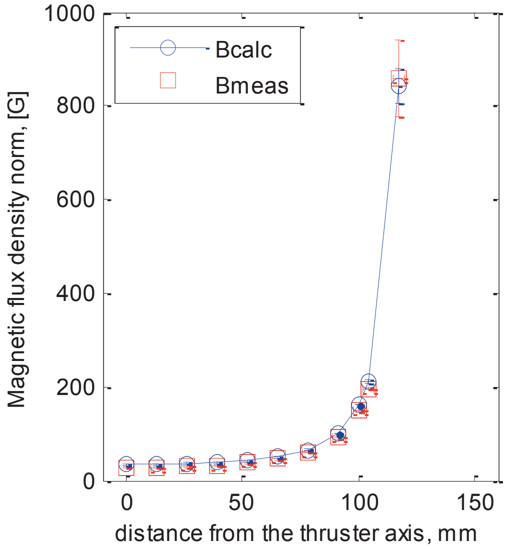
The measurements obtained have been compared with the model predictions. The comparison between experimental and numerical data is reported in Figure 7 below for the discharge chamber downstream and upstream sections and for a section half way along the discharge chamber length.



a)



b)



c)

Figure 7. Magnetic field measurements and numerical prediction: a) at the discharge chamber downstream end, b) half way along the discharge chamber length, c) at the discharge chamber upstream end

The results obtained from the magnetic model have been found to show a good quantitative agreement with the measurements showing errors that are generally below 5G or 10% of the measured value. In particular the model indicated a last closed contour value of about 65G. The discrepancy between the measured and calculated data in the 60 to 70G region has been evaluated and the average error obtained is 4.5%. It was then concluded that the magnetic field simulation model was providing reliable results and the activity moved on to testing of the T6RC.

III. RC T6 QinetiQ testing

Testing of the T6RC includes test campaigns at QinetiQ, for discharge mode and beam-on mode testing, and at ESTEC, for discharge mode tests only. In this section the results of the tests carried out at QinetiQ are reported.

A. Discharge only testing

The first round of tests had the goal of verifying that the discharge chamber was operational and to record the discharge voltage for various setpoints in discharge only mode. The thruster was mounted in one of QinetiQ small (1 m diameter x 2 m length) vacuum chambers with the cathodes and grids connected to ground potential and a single power supply powering the discharge chamber anode. The T6RC was tested with discharge currents in the range 8 – 19A and total mass flow rates from 1.7 to 2.7 mg/s of Xenon. The results obtained in terms of discharge voltage have been reported below in Table 1.

Table 1. T6RC discharge only setpoints

Setpoint	I_A [A]	V_A [V]	$\dot{m}_f$ [mg/s]	$\dot{m}_c$ [mg/s]
1	8	19.6	1.06	0.7
2	10	19.5	1.06	0.7
3	10	19.91	1.06	0.7
4	12	20.2	2.1	0.7
5	14	19.6	2.66	0.7
6	14	20.47	2.66	0.6
7	15	24.17	0.7	0.55
8	19	21.97	2.27	0.5

The first thing that was noticed during the tests was that the discharge voltages were lower than those normally obtained with the T6K (normally in the range 20 to 30V) as expected from a RC type discharge chamber.

After the discharge voltage was acquired for all setpoints the experimental campaign moved forward to beam on testing of the T6RC.

B. Beam on testing

The T6RC was tested extracting a beam in the LEEP2 vacuum chamber. The thruster was not installed on a thrust balance, hence all the thrust, Isp and efficiency values reported below are based on electrical parameters only. The objectives of this test were:

- to run a ring cusp ion engine extracting a beam on for the first time in the UK.
- to obtain a preliminary set of performance data at beam currents and Isp comparable to those of a Kaufman T6 (about 4300s Isp and thrust ranging from 75 to 145 mN) to understand the performances that can be achieved by a RC ion engine .
- to obtain a preliminary set of performance data at beam currents comparable to those of a Kaufman T6 but at low Isp.
- to investigate the presence of any major issues that will need to be addressed in the future.

The engine was tested using a beam voltage of 1850V (as in the Bepi Colombo Kaufman T6) and 1000V. When a 1850V beam voltage was used the accel grid was set to -265V whereas when a V_{beam}=1000V four different values of accel grid voltages (-1115, -850, -550, -265) were used. The results obtained during the test are reported below in Figure 7.

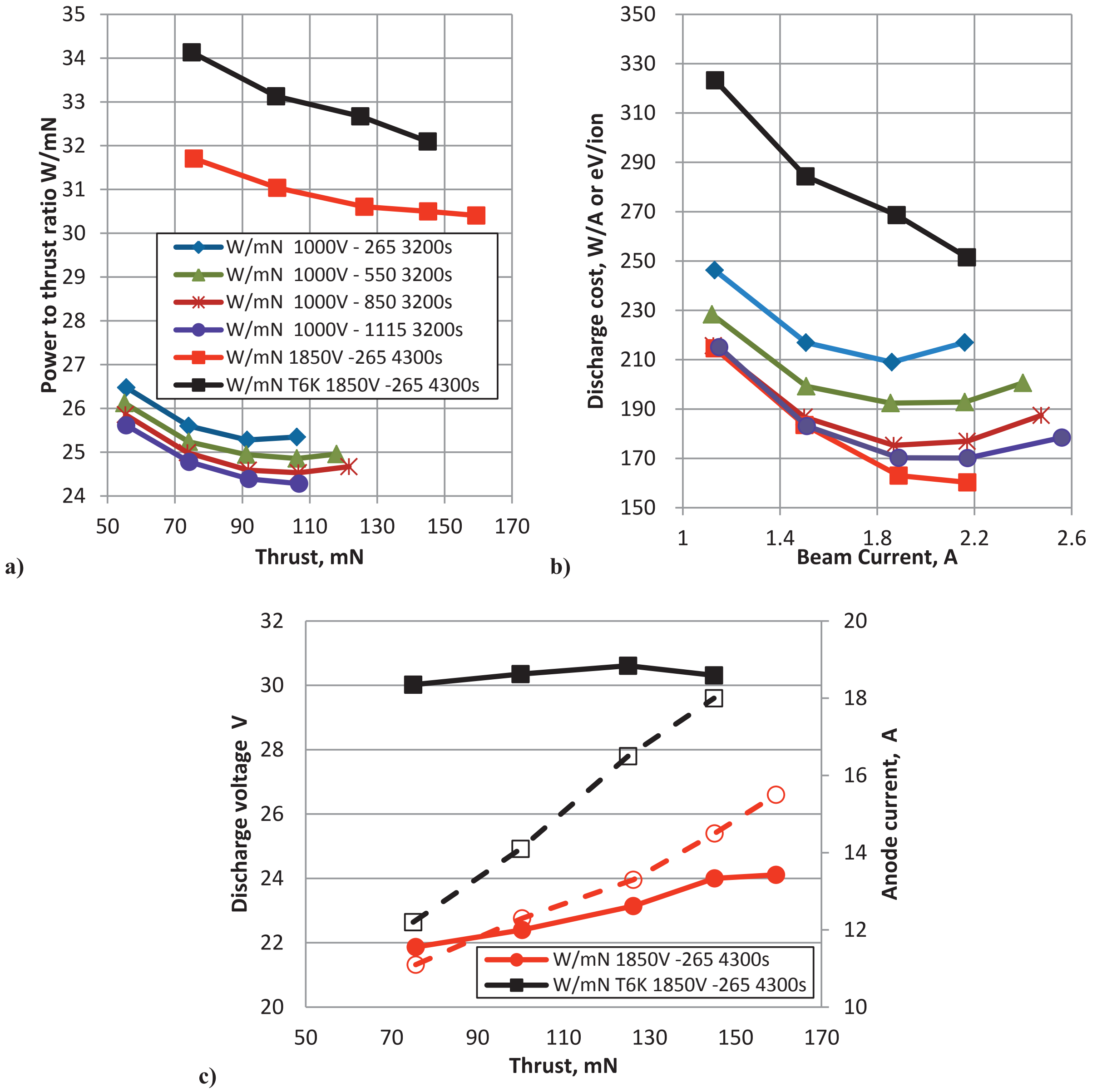


Figure 8. T6RC performance: a) Power to thrust ratio trend with thrust, b) discharge cost trend with beam current, c)discharge voltage (solid lines) and discharge current (dashed lines) trend with thrust

As it can be seen from Figure 8 the T6RC was already able to provide significant improvements in terms of discharge cost and W/mN in comparison to a Kaufman T6. In particular the anode voltage has been reduced by at least 5V and the discharge cost has been reduced by about 30%. The reduction in discharge cost will result in strong power savings with respect to a Kaufman T6 especially in conjunction with low Isp operation (where the discharge cost has a higher impact on the overall efficiency). The reduction in anode voltage will also sensibly decrease the double ion content decreasing the screen grid and accel grid erosion rates hence allowing for an increase in the engine lifetime or an increase in beam current (hence thrust) at the same lifetime currently achieved by a Kaufman T6 grid set.

In particular the discharge cost tends to decrease (improve) with increasing thrust level equivalent to increasing discharge currents and increased anode voltages. In Figure 8 it should also be noted how the trend in discharge cost is non monotone; in fact the eV/ion decreases up to about 1.8 – 2 A of beam current and then increases again. This change in the discharge cost trend happens when the anode current needs to be pushed to values above 17A (and in particular close to 19A) to achieve the desired beam current. It must also be noted that increasing the anode current from 15-16 A toward 19A normally resulted in a strong discharge voltage decrease that caused a marked loss in performances. The reason for this is not very clear at present and will be investigated in the future.

From Figure 8 it is also clear how operating at accel grid potential closer to zero increases the discharge cost and the W/mN. This can be explained noting that decreasing the absolute value of the accel grid voltage will reduce the extraction voltage drop hence decreasing the Child-Langmuir limited perveance of the grids. This means that extracting high beam current becomes more and more difficult as the accel grid potential is made less negative hence explaining the increase in discharge cost that can be seen moving from the 1000/-1115V towards the 1000/-265V case.

The overall results obtained during this first beam test were considered successful with the T6RC being able to deliver thrust levels compatible with those currently delivered by the T6K and at the same time delivering discharge costs as low as 160 eV/ion.

IV. RC T6 ESA testing

After the tests at QinetiQ were completed the engine was shipped to ESTEC to perform a round of discharge only tests in a different facility. The electrical ground support equipment (EGSE) available at ESTEC does not allow the extraction of an ion beam for an engine the size of the T6, hence the goal of these tests was to verify the discharge only data acquired at QinetiQ in an independent facility.

The T6RC was tested at the exact same point tested at QinetiQ and reported in Table 1. The results obtained at ESTEC are reported in Table 2.

Table 2. T6RC discharge only result obtained at ESA-ESTEC

Setpoint	I_A [A]	$V_{A\ ESTEC}$ [V]	$\dot{m}_f$ [mg/s]	$\dot{m}_c$ [mg/s]	$V_{A\ QinetiQ}$ [V]	$V_{A\ ESTEC} - V_{A\ QinetiQ}$ [V]
1	8	18.5	1.06	0.7	19.6	-1.1
2	10	19.5	1.06	0.7	19.5	0
3	10	19.8	1.06	0.7	19.91	-0.11
4	12	19.8	2.1	0.7	20.2	-0.4
5	14	19.3	2.66	0.7	19.6	-0.3
6	14	19.7	2.66	0.6	20.47	-0.77
7	15	23.9	0.7	0.55	24.17	-0.27
8	19	21.4	2.27	0.5	21.97	-0.57

Looking at Table 2 it can be seen how the agreement between the data obtained at ESTEC and at QinetiQ is always very good with an average error of about 0.5V. Even if based on discharge only data, these results confirm the T6RC performance observed at QinetiQ providing some degree of confidence in the performance obtained at QinetiQ.

V. T6RC modelling

The results obtained experimentally at V_{beam}=1850V were compared with the predictions that can be obtained using the 0D model developed by Goebel and Katz [5]. In order to use the 0D model some parameters regarding the engine magnetic field and geometry, the ion optics design and cathode performance need to be known. The inputs regarding the magnetic field inside the discharge chamber have been taken using the prediction provided by the Comsol ™ magnetic model. The grid transparency to ions, the potential at the exit of the discharge cathode, the ion optics Clausing factor and the heavy particle temperature instead need to be defined more arbitrarily.

The grid transparency to ions has been fixed to 80% in line with the numerical data obtained with FFX simulations [6], the value of the HC exit potential has been fixed to 10V and the Clausing factor to 0.5. The temperature of the heavy particle has been assumed to be 470K in line with thermocouple measurements of the discharge chamber temperature taken during the QQ beam on testing.

The main output of the 0D model is the value of the beam current. This has been compared to the measured values in Figure 9.

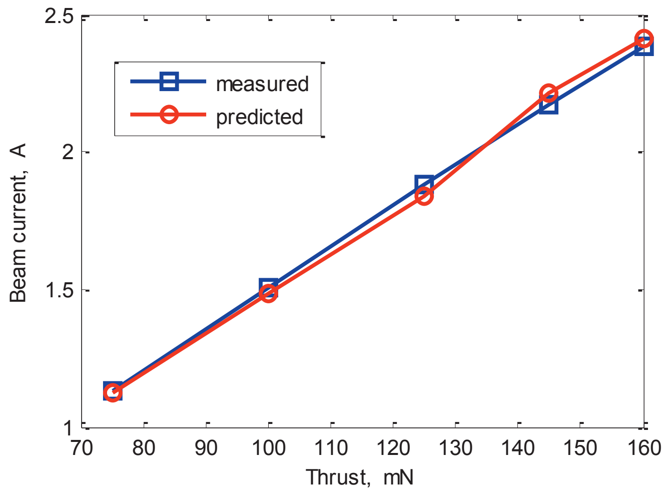


Figure 9. Measured and the predicted values of beam current for the T6RC at a beam voltage of 1850V

From Figure 9 it is possible to notice that a very good agreement has been obtained between the numerical and experimental data with a maximum error of about 2%. As already said for the comparison of the discharge only data the agreement between the numerical and experimental values of the beam current provides some degree of confidence in the goodness of the beam on performance measured at QinetiQ (or at least does not disprove them).

VI. Conclusion and future work

In this paper the data obtained during the first test of a T6 Ring Cusp breadboard prototype has been reported. The engine has shown the capability of providing an improvement in terms of discharge cost of up to 30% and a reduction in discharge voltage of about 5V with respect to a Kaufman T6. The results obtained in discharge only mode at QinetiQ have been confirmed by tests carried out at ESA-ESTEC whereas the beam performance have been found to be in quantitative agreement with the prediction of the 0D model developed at JPL [5]. However it must be noted that the engine performance presented in Sec. III.B have been derived from electrical parameters hence are not 100% reliable. Nevertheless the close agreement between the measurements and the simulation lead us to believe that the real engine performance should be close to what has been presented here.

The next step in the ring cusp development program will consist in the improvement of the engine thermal design and in the design of a discharge chamber and ion optics optimized for the requirements of the commsat market.

Acknowledgments

The work reported in this paper was funded under UK Technology Strategy Board contract NSTP/101198/001/ASTR and ESA Contract No. 4000111394/14/NL/PA. The authors would also like to thank Mr Eduard Bosh Borras for his invaluable help during the tests carried out at ESA-ESTEC.

References

[1] N.C.Wallace. *"Testing of the Qinetiq T6 Thruster in Support of the ESA BepiColombo Mercury Mission for the ESA BepiColombo Mission"*. 4th Int Spacecraft Propulsion Conference . 2004.

[2] J.Snyder, J.R.Anderson, J.L.Van Noord, and G.C.Soulas. Environmental Testing of the NEXT PM1 Ion Engine. 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, Ohio, USA . 2007.

[3] R.Wirz and D.M.Goebel. *Effects of magnetic field topography on ion thruster discharge performance*. Plasma Sources Sci.Technol. Vol 17. 2008.

[4] D.M.Goebel, J.Polk, and A.Sengupta. *Discharge Chamber Performance of the NEXIS Ion Thruster*. 40th AIAA Joint Propulsion Conference, Ft.Lauderdale, Florida, USA, July 11-14 . 2004.

[5] D.M.Goebel, R.E.Wirz, and I.Katz. *"Analytical Ion Thruster Discharge Performance Model"*. Journal of Propulsion and Power Vol Vol. 23 (No. 5), 1055-1067. 2007.

[6] M.Coletti. *Simulation of the QinetiQ T6 Engine Ion Optics and Comparison to the Experimental Data*. 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,Hyogo-Kobe, Japan . 2015.