

Performance Measurements of a High Powered Quad Confinement Thruster.

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The Quad Confinement Thruster employs a convex magnetic field bounded by four cusps to weakly confine electrons and thus create a high density plasma. An electric field sustained between a rear anode and an external hollow cathode provides ion acceleration. In this study the first performance measurements of a permanent magnet high powered QCT (QCT1500) are reported. Direct thrust measurements were made, using a pendulum type thrust balance, as a function of the anode power up to maximum power of 800 W. A symmetric quadrupole field strength of 950 G was used throughout and the krypton propellant flow was varied from 10-30 sccm. Thrust levels between 3-10 mN at specific impulses of 200-1600 s were recorded.

Nomenclature

SSC	= Surrey Space Centre
QCT	= Quad Confinement Thruster
EP	= Electric Propulsion
DAQ	= Data acquisition
IEFD	= Ion energy distribution function
RFEA	= Retarding field energy analyser
v_e	= Exhaust velocity
$\dot{m}$	= Mass flow

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I. Introduction

The Quad Confinement Thruster is a novel technology which employs a convex magnetic field bounded by four cusps to weakly confine electrons and thus create a high density plasma. An electric field sustained between a rear anode and an external hollow cathode provides ion acceleration. The QCT has the advantage that manipulation of the quadrupole field can be used to steer the ion beam, which has been shown to produce a 22 degree total steering capability.¹ Figure 1a illustrates the field geometry (dotted black lines) within the plasma channel. The four outer cusp points serve to reflect electrons from regions of high field to low field. This results in electrons becoming weakly confined to the central magnetic ‘null point’ at which a local plasma density maximum has been observed.¹ This magnetic null point extends throughout the channel length and provides a relatively low resistance path for electrons travelling towards the anode. This serves to reduce the anode voltage and consequently the voltage does not typically rise above 100 V. This is a major advantage as satellite power supplies will not be required to provide high voltages to the thruster, allowing simpler, lower mass supplies to be used. A number of thrusters currently in development use a cusped field geometry. The ‘hemp’ and DCF thruster utilises a series of cusps lining the source plasma boundary in order to reduce the flux of ions to the dielectric walls and hence reduce ion wall losses^{2,3} The QCT1500 has been developed to extend previous investigations and assess the performance characteristics at higher quadrupole field strengths and higher anode powers. This paper presents preliminary experiments in which the performance of the QCT1500 is measured using a thrust balance while operating at high quadrupole field strengths and high anode powers.

II. Experimental Equipment

A. QCT1500

Figure 1a shows the QCT1500 schematically and Fig. 2a shows the thruster hardware. The magnetic field extends through a cylindrical boron nitride plasma channel of 45 mm radius and 90 mm depth. For the current experiments, a strong magnetic field was investigated using 4 NeFeB permanent magnets. These are in contact with several soft iron rails which conduct the magnetic flux into the plasma channel. By convention, the applied field is measured at the edge of the plasma channel and between an arbitrary pair of diametrically opposed magnets. A finite element analysis simulation of the magnetic field within the plasma channel is shown in Fig.1b and corresponds to the red line shown in Fig. 1a. The hollow cathode was positioned 20 cm above the front face of the thruster and the keeper aperture was aligned with the edge of the plasma channel, as indicated in Fig. 1a.

B. SSC pendulum thrust balance

The SSC pendulum thrust balance has been designed to measure the performance of plasma thrusters and has been used to characterise a range of technologies including RF plasma and hollow cathode thrusters^{4,5} A IDL1700 optical laser displacement sensor is used to measure the displacement of a target affixed to the ‘moving plate’ (see Fig. 3) with respect to the laser origin in response to an applied force. The thrust balance is calibrated by recording the displacement of the moving plate of the balance in response to the application of a known force. This is accomplished by displacing a known mass, attached to the moving plate by a light inextensible thread, through a series of horizontal steps. The force applied to the moving plate may then be calculated and related to the balance displacement measured by the laser. The balance has an accuracy and precision of 0.1 mN.

C. Pegasus Vacuum facility

The Pegasus vacuum facility consists of a 1 m radius by 1.5 m length steel cylinder, connected to a rotary roughing and turbo molecular pump. The combined pumping speed is approximately 1700 l/s and allows a base pressure of approximately 1×10^{-6} mBar to be maintained, as measured by a PTR90 vacuum gauge. The chamber is electrically grounded and is used as the common electrical ground for all thruster circuits.

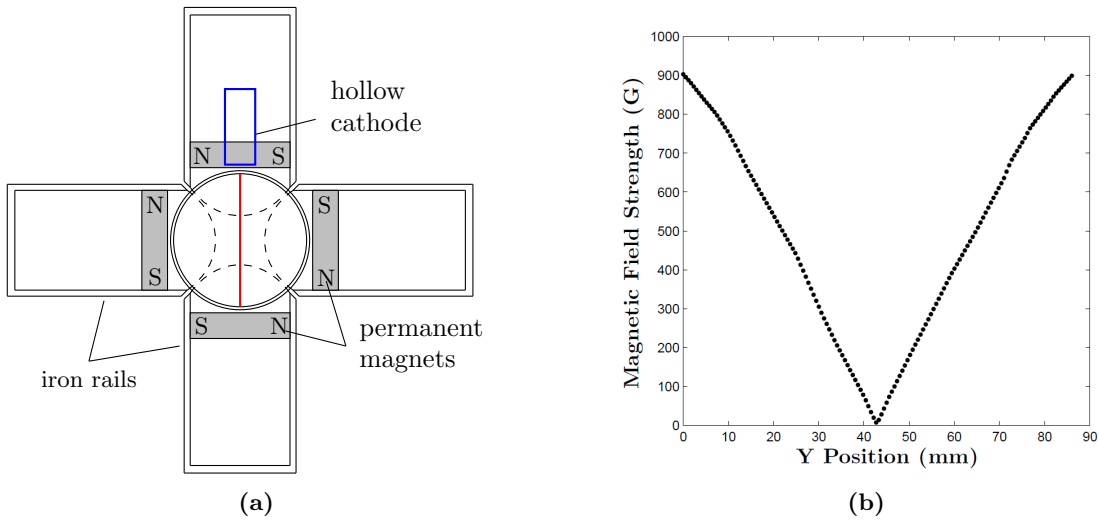


Figure 1: Front schematic view of the QCT1500 (left) and finite element simulation of the magnetic field profile (right). The simulated magnetic profile corresponds to the solid red line shown in the schematic view. Dashed lines in 1a illustrate the magnetic field topology. The positioning of the permanent magnets and hollow cathode (blue) are also indicated. Note that the cathode was placed 20 cm above the exit of the plasma channel.

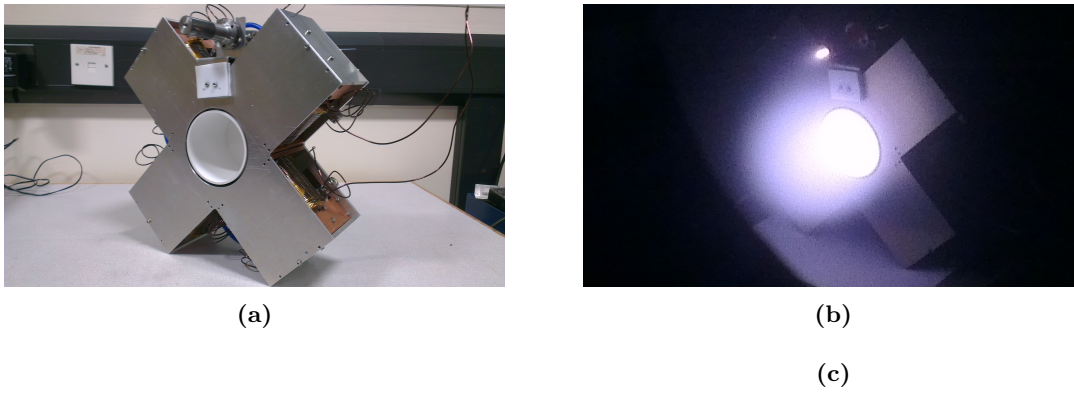


Figure 2: Photograph before (left) and during (right) the initial firing of the QCT1500. The thruster structure is insulated from the grounded chamber using a plastic mat, allowing the whole system to electrically float. Note that the cathode appears here in an alternate configuration to that used during these experiments shown. The cathode position for the current experiments is indicated in Fig. 1a

III. Experimental Method

A. Thrust measurements

The following procedure was used to measure the thrust produced. The thruster was started and set to the desired operating point. The DAQ was started and data is acquired for 40 s, after which the discharge was deactivated and data is acquired for a further 40 s. This process was repeated 10 times for each operational set point. The difference between the balance displacement while the thruster is on and off was correlated to the thrust produced using the balance calibration constant.

IV. Results

Figure 2b shows the QCT1500 firing, viewed from the rear of the vacuum chamber, looking upstream and into the plasma channel.

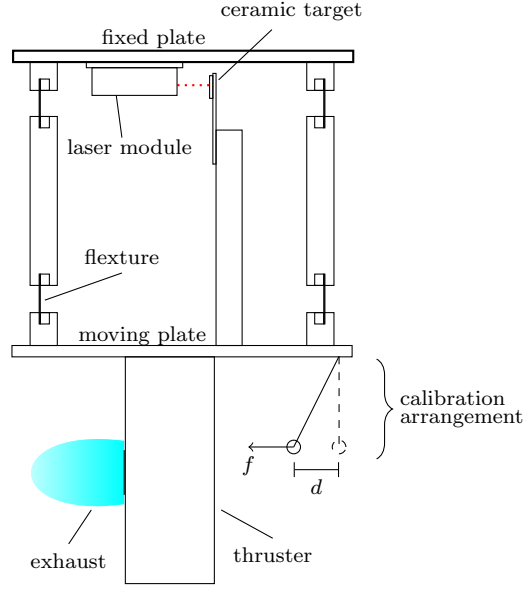


Figure 3: Side view schematic of the SSC thrust balance and mounted thruster. The calibration apparatus is also shown.

Fig. 4a shows the thrust as a function of the power supplied to the anode. Immediately obvious is that the thrust does not increase by any significant amount as the propellant supplied to the anode is increased. The cold gas thrust produced from the krypton propellant flow can be calculated from Eq. 1,

$$F = \dot{m}v_e \quad (1)$$

as 0.14 mN, where $\dot{m}$ is the propellant flow and v_e is assumed to be the sound speed of gaseous krypton. While this small increase in thrust is approaching the sensitivity of the thrust balance, it is generally observed that increased plasma channel pressure leads to an increased plasma density and a corresponding increase in thrust at a given power. It appears that at high flow rates the propellant is under utilised and is not therefore significantly contributing to the performance of the thruster. At lower propellant flows, the specific impulse of the thruster at high power approaches 1600 s at a thrust level of 10 mN. Figure 4a shows that across the three flow conditions, and most obviously for 10 sccm, a steeper increase in the performance is measured for anode powers above ~ 500 W. A visual inspection of the plasma during operation at this power revealed a change in the colour of the plasma from the characteristic light purple to a blue hue. This may indicate the production of Kr^{2+} ions which may form a higher energy exhaust beam.

V. Conclusions and future experiments

The performance of the QCT1500 thruster has been demonstrated through direct thrust measurements for the first time yielding a maximum performance of 10 mN, at 1600 s specific impulse. These results are the first in a series of experiments which aim to understand the potential performance of the quad confinement thruster concept at higher powers. While the efficiency of the quad confinement thruster concept has been shown to reach higher levels than in previous experiments, it is still uncertain at this stage to what extent each of the cathode position, magnetic field strength and channel geometry are influencing the thruster operation. The magnetic field strength used in this experiments is 950 G, which for thermal ion energy of 0.2 eV, results in an ion gyro-radius of approximately 10 mm. This suggests that at these field strengths the ions may be somewhat confined and may be retarded from detaching from the quadrupole field. This may have the effect of reducing the overall performance. Future performance measurements at lower magnetic field should be completed to assess the impact of the magnetic field on ion detachment. The thrust produced did not appear to increase with increasing anode propellant flow. The hypothesis that the propellant is currently under utilised will be tested in future in-channel electron density measurements. The apparent production of double ionised krypton for anode powers above 500 W should be confirmed through spectroscopic measurements.

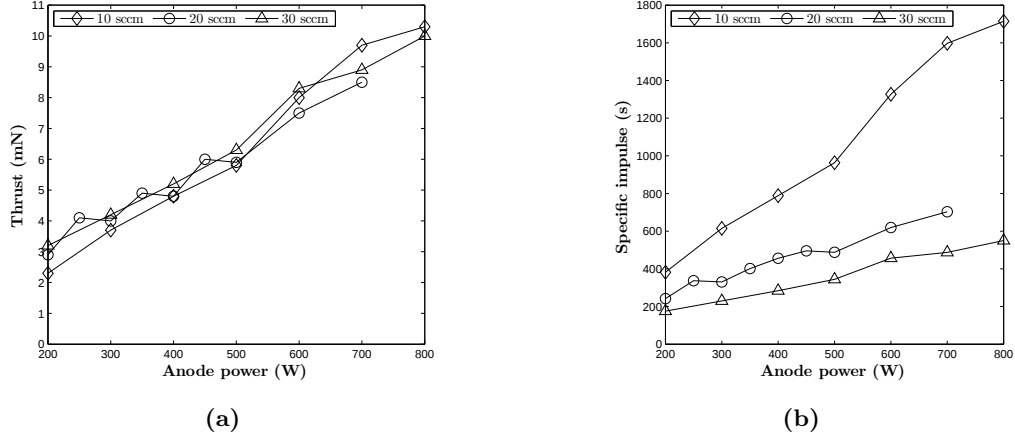


Figure 4: Thrust (left) and specific impulse (right) as a function of anode power for 10, 20 and 30 sccm of krypton propellant flow.

The resulting high energy beam which may be produced can be measured through IEDF measurements of the exhaust plasma using an RFEA.

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