

Development and Commissioning of an Electric Propulsion Test Facility

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Abstract: Evaluating, understanding and verifying performance is an essential element of the product development life cycle. The QinetiQ Electric Propulsion Test Facility (EPTF) has been developed over a number of years and consists of a number of chambers and a range of advanced diagnostic techniques for testing high power Electric Propulsion thrusters, systems and sub-components. This paper provides an overview of the capabilities of the EPTF and describes in detail some of the recent developments that have been implemented to support the verification, qualification and acceptance testing of the EP system for the BepiColombo mission to Mercury.

Nomenclature

<i>BOL</i>	=	<i>Beginning Of Life</i>
<i>DPA</i>	=	<i>Digital Photogrammetric Analysis</i>
<i>EMC</i>	=	<i>ElectroMagnetic Compatibility</i>
<i>EMI</i>	=	<i>ElectroMagnetic Interference</i>
<i>EP</i>	=	<i>Electric Propulsion</i>
<i>FCU</i>	=	<i>Flow Control Unit</i>
<i>GFRP</i>	=	<i>Glass Fibre Reinforced Plastic</i>
<i>RF</i>	=	<i>Radio Frequency</i>
<i>LEEP</i>	=	<i>Large European Electric Propulsion chamber</i>
<i>PCDU</i>	=	<i>Power Control & Distribution Unit</i>
<i>PPU</i>	=	<i>Propulsion Power Unit</i>
<i>RPA</i>	=	<i>Retarding Potential Analysers</i>
<i>SEPH</i>	=	<i>Solar Electric Propulsion Harness</i>
<i>SEPP</i>	=	<i>Solar Electric Propulsion Pipework</i>
<i>SEPS</i>	=	<i>Solar Electric Propulsion System</i>
<i>SEPT</i>	=	<i>Solar Electric Propulsion Thruster</i>
<i>TCF</i>	=	<i>Thrust Correction Factor</i>
<i>TIP</i>	=	<i>Thermal Interface Plate</i>
<i>TIPC</i>	=	<i>Thermal Interface Plate Controller</i>
<i>TRP</i>	=	<i>Temperature Reference Point</i>

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I. Introduction

Electric propulsion systems are being developed by QinetiQ to meet two current applications. One is the High Power Electric Propulsion System (HPEPS) for station keeping, orbit-topping and end-of-life de-orbit for geostationary orbit (GEO) telecommunications satellites. The second application is the ESA science mission to the planet Mercury, BepiColombo¹, where the system will provide the impulse necessary during the inter planetary cruise.

In parallel, QinetiQ has developed a number of key test facilities and a range of diagnostic and support equipment to qualify and conduct acceptance testing of the EP Systems. The facility currently consists of two large vacuum chambers, LEEP2 & LEEP3, which are capable of testing both HETs and gridded ion thrusters. Each chamber has a beam probe for capturing the ion flux to determine the thrust vector and can also be equipped with either a thrust balance for accurate real-time thrust measurements or a thermal interface plate for test activities that require thermal cycling. A third chamber, LEEP1, has recently been reconfigured to include an RF transparent section for EMC measurements and has been used successfully to evaluate the EMI emissions of the QinetiQ T6 thruster. The modifications to the LEEP1 chamber and the EMC test campaign are discussed in detail later in the paper.

The facility also includes a number of small chambers for sub-component tests. A range of diagnostic and measurement tools including a Digital Photogrammetric Analysis (DPA) system, a Co-ordinate Measuring Machine (CMM), an X-ray and a Vision Engineering machine are available to support the test activities. The paper will describe how these are used to support the test campaigns and help to maximise the accuracy and efficiency of the test results.

This paper describes the range of test chambers that QinetiQ has available at its headquarters in Farnborough UK and provides details of some of the key thruster control, monitoring and diagnostic equipment that are used alongside them. This includes equipment for the measurement of thrust and the thrust vector, to perform thermal cycling and to assess the thruster EMC characteristics. Finally, a number of the key test campaigns that have been completed and that are currently underway for the BepiColombo programme are described.

II. Test Chambers

The QinetiQ EP test facility comprises a number of Large European Electric Propulsion (LEEP) chambers and a range of smaller vacuum chambers that together provide the capability to conduct a comprehensive range of qualification and acceptance tests for EP propulsion systems.

A. LEEP2

LEEP2 is often the main chamber used to support thruster qualification and acceptance testing. The configuration of the vacuum chamber can be seen in schematic form in Fig. 1 and Fig. 2 shows a photograph of the chamber with a thruster installed. The largest section of the chamber is 3.8m diameter x 4m long. The conical section is 0.9m long and the small section is 2.6m diameter x 5m long.

Thrusters are located at the junction between the 2.6m and conical sections and the ion beam(s) are directed towards the chamber door/target. This configuration minimises any thruster chamber interactions. The ion beam target is a water cooled graphite clad design and the walls of the chamber are protected using a stainless steel/graphite liner.



Figure 1. LEEP2 schematic showing location of thruster and typical T6 beam divergence angle



Figure 2. The LEEP2 vacuum chamber

The chamber's cryogenic pumping capacity of 100,000 l/s Xenon is achieved through a combination of four cold panels, each of which is shielded from the thruster by LN2 cooled baffles, and two Cryotubs. It is designed to enable the operation of electric thrusters at Xenon flow rates of up to 30 mgs^{-1} , whilst maintaining a vacuum of better than 2×10^{-4} mbar. This gives the facility the capability to test large Hall Effect thrusters, which typically have significantly higher Xenon flow rates than the gridded ion thrusters developed in-house by QinetiQ.

The test section has a semi-circular beam probe system fitted with 11 Faraday Cups or RPAs that measure the ion flux density to determine plume characteristics such as thrust vector and beam divergence. It can also be equipped with either a thrust balance for obtaining real-time thrust measurements or a thermal shutter and shroud for thermal cyclic testing.

A large (5m x 3m) portable clean room has recently been procured to sit alongside the LEEP2 chamber, this providing the necessary environment for handling flight components, such as power supplies and flow controllers, during system integration and acceptance tests.

The majority of the qualification tests for the BepiColombo T6 thruster and the flight thruster acceptance test programme were performed in LEEP2.

B. LEEP3

LEEP3 has been specifically developed for extended duration EP testing. It was used for BepiColombo SEPS system testing and is currently being used for the BepiColombo endurance test programme.

The LEEP3 facility is 3.3m diameter x 7.2m long and can pump 200,000 l/s Xenon, giving a base vacuum level of 5.0×10^{-7} mbar and 9.0×10^{-6} mbar with a Xenon flow rate of $\sim 3.5 \text{ mg/s}$ (equivalent to a single T6 thruster running at 145mN). This is achieved through a combination of six cold panels, each of which is shielded from the thruster by LN2 cooled baffles, and two Cryotubs. A water cooled chevron style graphite target minimizes back sputter and therefore helps to reduce the beam out rate due to facility effects. Recent measurements with a Quartz Crystal Microbalance (QCM) have shown that the back sputter rate seen in LEEP3 is lower than that measured in LEEP2, thus verifying the predicted performance of the target design.

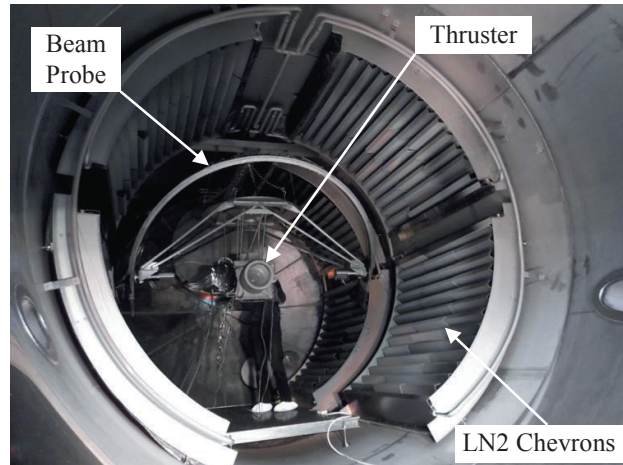


Figure 3. T6 thruster installed in LEEP3

Figure 3 shows a thruster mounted in LEEP3. The LN2 cooled chevrons that are protecting the cold panels are clearly visible. The chevrons eliminate the view factor to the chamber wall and maintain the base temperatures of the cold plates (typically 15-20K).

The chamber has an identical beam probe system as LEEP2 and can similarly be configured for operation with a thrust balance or a cold shutter and shroud for thermal cycling.

A large (5m x 3m) clean tent positioned alongside the chamber provides the necessary environment for housing flight components, such as power supplies and flow controllers, during system integration tests.

C. LEEP1

Thruster EMC testing is conducted inside a modified Thermal Vacuum Chamber, LEEP1. The existing vacuum chamber has been modified and extended by inserting an RF transparent section of GFRP $\sim 1.6 \text{ m}$ diameter x 3.0 m long and the thruster is positioned in the centre of this section. The RF transparent section is surrounded by a $4 \text{ m} \times 3 \text{ m} \times 3 \text{ m}$ screened enclosure lined with 300 mm RF absorbing material (see Figure 5 & 6) to achieve an RF anechoic test environment. While the design aims to meet Mil-Spec 461F by providing an ambient RF noise level inside the enclosure that is better than 6 dB below the RF noise level outside, it is recognised that the intrusion of the vacuum chamber presents a compromise over a more ideal construction. Consequently, it was necessary to perform a series of RF evaluation tests in the enclosure to characterise its RF environment. The results of such evaluation tests will be used in conjunction with the thruster EMC test results to ensure a credible EMC assessment is made.



Figure 4. External view of LEEP1 chamber

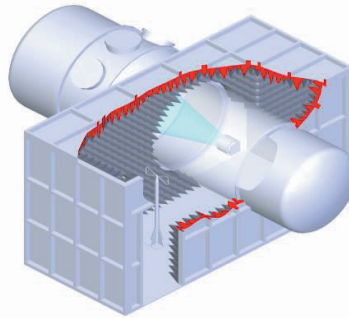


Figure 5. LEEP1 schematic showing RF chamber



Figure 6. View inside RF chamber

D. Small chambers

As well as the three large vacuum chambers described above QinetiQ operate a number of smaller chambers for the bakeout, evaluation, qualification and acceptance of thruster sub-components and other small items of equipment. These range in size from 0.5m to 1.0m diameter, the largest of which can be used to operate a T6 size of thruster in discharge mode for initial diagnostic tests. Figure 7 shows two of our most frequently used chambers, which have a 1.0m and 0.5m diameter respectively. Both of these can be used to thermally cycle components from 200°C to -150°C.

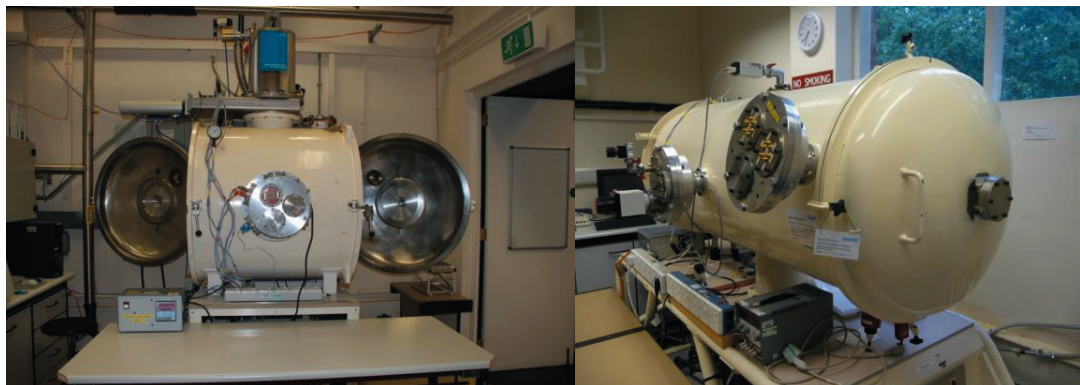


Figure 7. The 1.0m diameter (left) and 0.5m diameter (right) thermal vacuum chambers

E. Supporting equipment

The facility includes a number of clean rooms, clean tents and workshops that house a range of equipment that are available to provide essential support services in-house during the manufacture, assembly, integration, inspection and test of hardware. The clean rooms and clean tents range from portable These include vacuum furnaces, an EB welder, a spark eroder, an X-ray machine for measuring grid thicknesses and a CMM machine.

III. Test Equipment

A. Thermal Vacuum

For thermal vacuum testing the thruster is mounted onto a thruster thermal interface plate (TIP) via thermal gaskets to give a good thermal contact, thereby ensuring that the temperature reference point (TRP) at the base of the thruster can be controlled easily. The thermal interface plate features LN2 cooling and heating via cartridge heaters whose power input is controlled via the TIPC (thermal interface plate controller). This arrangement allows the thruster interface to be accurately controlled over a range of temperatures (-180°C to +200°C).

A thermal shroud, in the form of a thin multi-layered aluminium box section, is mounted on to the interface plate via a thermal gasket such that the temperature of the TIP will be conductively transferred to the shroud whilst minimising radiation heat exchange with the chamber walls.

An active LN₂ cooled actuated cold shutter is positioned in front of the thruster and is deployed for the cold cycle and cold dwell only. Immediately before the cold start test (at the end of the cold dwell) the cold plate is moved out of the way of the thruster so that beam operations are not impeded. When deployed the plate is cooled with LN₂ and is designed to eliminate the view factor of the front of the thruster to the (relatively warm) chamber walls; this cools the front of thruster (grids) during the cold dwell and at the start of the cold start test to simulate pointing out towards deep Space. Actuation is achieved using a vacuum compatible stepper motors which are controlled from a dedicated PC using custom software. Figure 8 shows the cold shutter assembly in the deployed (closed) position and the semi-circular beam probe arm in the horizontal (0°) position.

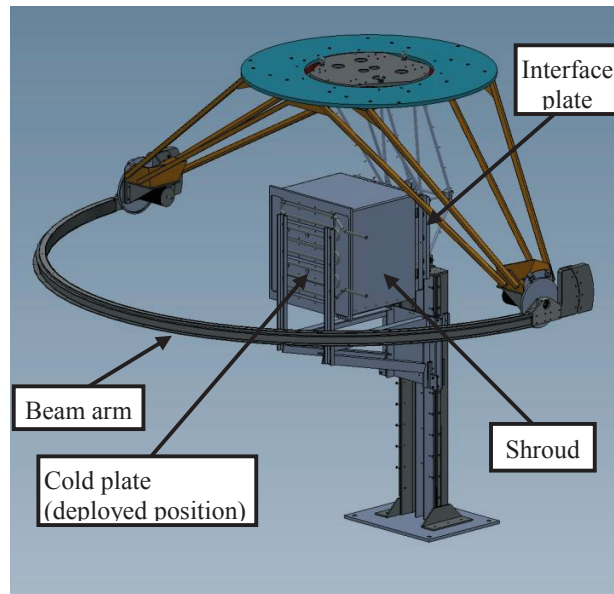


Figure 8. Thermal system assembly with cold shutter in closed position

B. Thrust Balance

Thrust measurements are performed with a single axis thrust balance designed for operation with the T6 thruster. The principle of operation is based on an actively controlled pendulum that supports the thruster under test. In operation, the control system applies a variable current to a solenoid which generates an equal and opposite thrust to that generated by the test thruster such that deflection of the pendulum is nulled. The balance specification details are listed in Table 1 and a photograph of the balance with a T6 thruster fitted can be seen in Fig. 9.

In order to minimise the potential for thermal drift, the entire device is manufactured from low thermal expansion material and a thermal control system has been implemented to maintain the solenoid at constant temperature.

Table 1. Summary of thrust balance specification

Parameter	Specification
Operating mode	Steady state thrust
Thrust range	1 - 500 mN
Thrust uncertainty	± 0.75 mN
Bandwidth	0.1 – 0.0001 Hz
Calibration	See below
Thruster mass	Up to 15 kg

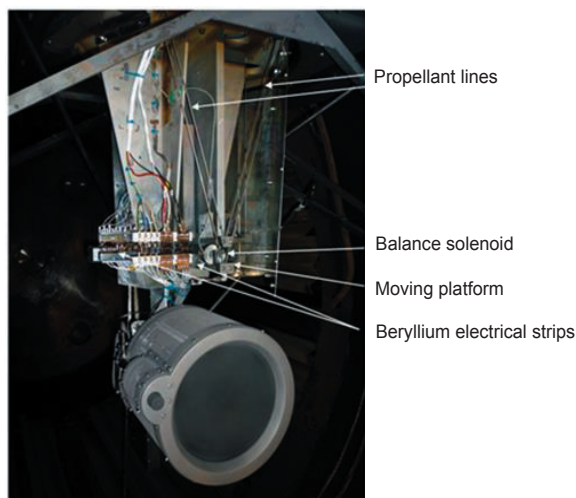


Figure 9. Thrust balance with a T6 thruster installed

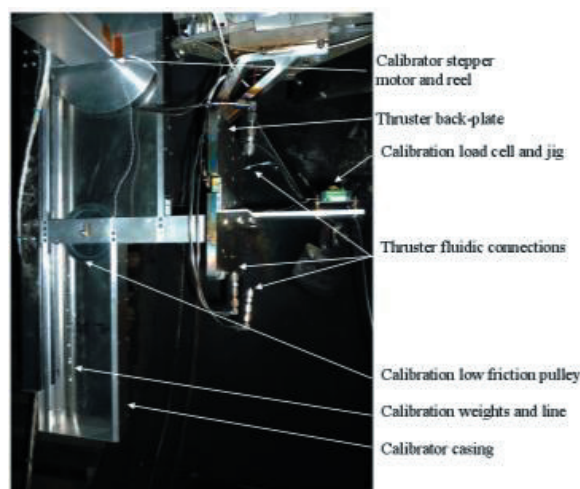


Figure 10. Thrust balance calibration system

Calibration of the thrust balance is performed immediately after a thrust measurement. This is done with a calibrator system (Fig. 10) which applies a known calibrated force to the balance. The calibrator allows a series of weights to be sequentially suspended from a connecting line to the thrust balance platform. A very low friction needle point pulley allows the line to turn through 90° and connect perpendicularly onto the thruster back plate. By knowing the exact force applied to the balance by the suspended weights and characterising this force against the thrust balance output a calibration curve (mN/Volt) can be generated. The calibration curve can then be used to quantify the response of the balance during thruster firings.

C. Beam Probe

Both LEEP2 & LEEP3 are equipped with a high accuracy / resolution array of retarding potential analysers (RPA), which are configured as Faraday cup detectors. This system allows the ion flux and beam divergence of the thruster ion plume to be characterised with high resolution to divergence angles of up to 90° . The probe array consists of a semi-circular beam, to which probes can be fixed at any point, with the probes no closer than 1000 mm to the centre of the device; see schematic Fig. 8 and photograph Fig. 11. Aperture bias and current collector cables are routed along the beam arm. The probe array is situated such that any collimated instruments are directed towards the centre of the thruster, irrespective of the probe array position. The probe mounting arm is supported at two points, at the array support bearing and by the array positioning actuator. The arm is moved using high accuracy vacuum stepper motors and its position can be resolved to an accuracy of within $\pm 0.01^\circ$.

The control system is resident on a personal computer and provides the user interface, data acquisition and control of the array positioning system. The system is designed to allow either manual or autonomous operation of the probe array. Ion currents collected by the probes are amplified, digitised and stored by the control system for subsequent analysis. At low thrust levels and wide angles to the thruster axis, the ion currents collected can be small and therefore susceptible to noise. Minimisation of data corruption is achieved by the use of triaxial cables and connectors between the probes and the DAQ hardware.

Typically the beam probe is operated with eleven Faraday cups distributed along the beam and data are collected as the arm is swept through the thruster ion plume at 2° steps. Data analysis is automatic and can be presented in a range of formats, including a three-dimensional representation (Fig. 12). Accuracy of the thrust vector measurement is within 0.4° .

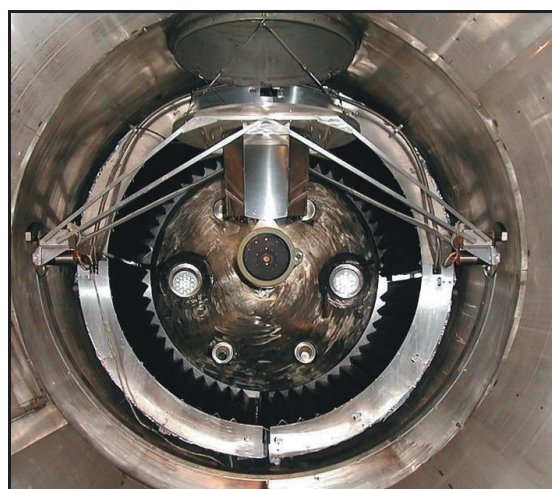


Figure 11. The beam probe system in LEEP2

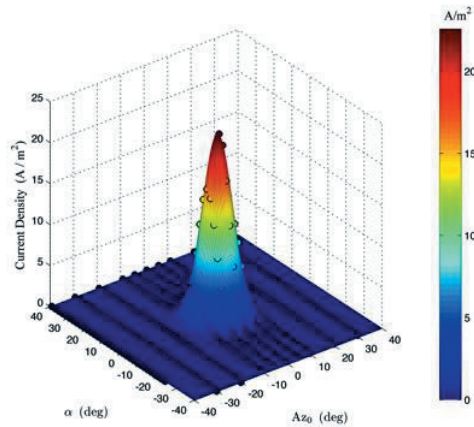


Figure 12. Current density from beam probe

D. Digital Photogrammetric Analysis

QinetiQ routinely use a Digital Photogrammetric Analysis (DPA) system to accurately record the position of the thruster(s) in the chamber relative to the beam probe system to maximise the accuracy of the beam divergence and thrust vector measurements.

DPA allows a user to create a 3D model of any object by taking multiple photographs of it from different positions / angles. It is used because it is highly accurate, very mobile and yet simple to use. In addition, the software package is compatible with CMM software so there are minimum data transfer issues.

The DPA system avoids the use of mirror cubes and theodolites, which heavily restrict the degree of freedom that a user has when trying to obtain spatial or alignment information.

The system uses a camera, special coded and uncoded targets that are placed on the object and the surroundings, gauge bars, a reference origin and analysis software. The DPA method itself overlaps multiple photographs of similar targets to produce a consistent reference field. In effect it triangulates every target to common viewpoints, which then are iterated to produce a consistent reference frame. The more photographs taken from different angles, the higher the accuracy can be. At least 3 targets must be common to pairs of photographs but there is essentially no limit to the amount of photographs that can be taken.

Figure 13 shows the reference cross and the two calibrated scale bars (with associated coded targets) that are used to create a local reference frame for the measurements: these items are placed next to the beam probe and thruster but the exact position is not important, as long as they are clearly visible in the photographs taken during the DPA measurements.

Once all the targets have been positioned, multiple photographs are taken using the specially calibrated camera from various positions around the beam probe arm, the Alignment Device and the scale bars. The images are then processed by the software, which uses several pictures of each target to triangulate its position. As soon as enough photographs are taken, the software displays recognised targets and calculates their positions in the local reference frame formed by the reference cross and the scale bars. The accuracy to which each target position is determined by the software is also supplied once all images have been processed: obviously, the more photographs taken, the higher the accuracy. In particular, the 1σ standard deviation on the positions of the Faraday Cups is typically less than $\pm 100\mu\text{m}$.

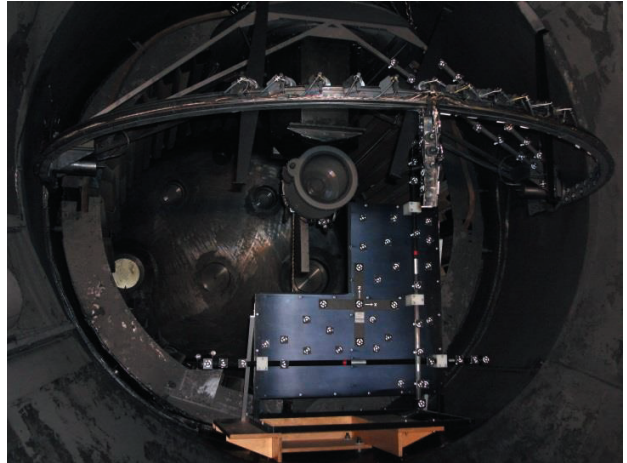


Figure 13. DPA system setup in LEEP2

E. Twin Thruster

For some spacecraft architectures the thrusters are in close proximity to each other and are required to operate simultaneously to meet the mission's peak thrust requirements. Twin thruster tests are required to investigate interaction effects and QinetiQ have therefore developed a capability to mount and operate two thrusters simultaneously in LEEP2

For the twin thruster tests the primary thruster is mounted in the same way as for the single thruster test. It is this thruster that all of the key performance parameters, including thrust vector, are measured on. The second thruster is positioned below the primary thruster on an adjustable mount that allows the angle between the two thrusters to be adjusted, simulating the effect of any pointing mechanism. Each thruster has a protective shroud that is positioned over the grids when it is not in operation to minimise contamination due to sputter released from the carbon target.

IV. Chamber Performance Comparison

It is important that the performance of the thruster being tested is independent of the test chamber that it is being tested in. We have therefore tested a benchmark T6 thruster in a number of configurations in both LEEP2 and LEEP3 chambers in quick succession to confirm that the electrical parameters and thrust vector is consistent and independent of operating environment.

Initially the thruster was tested in LEEP3 in its standard configuration. The test was then repeated in the same chamber, but with the thruster rotated through 180° around its axis on the thruster mount to verify that thruster performance was independent of thruster orientation within the chamber. Finally, the thruster was moved to LEEP2 and the performance test repeated a third time.

Figure 14 presents the measured thrust vector in polar representation for the three tests described above. All of the results are in close agreement and well within the 2 σ measurement uncertainty ($\pm 0.4^\circ$).

Measured electrical parameters were also in excellent agreement between the three test campaigns, confirming that the operational performance of the thruster is not affected by the chambers.

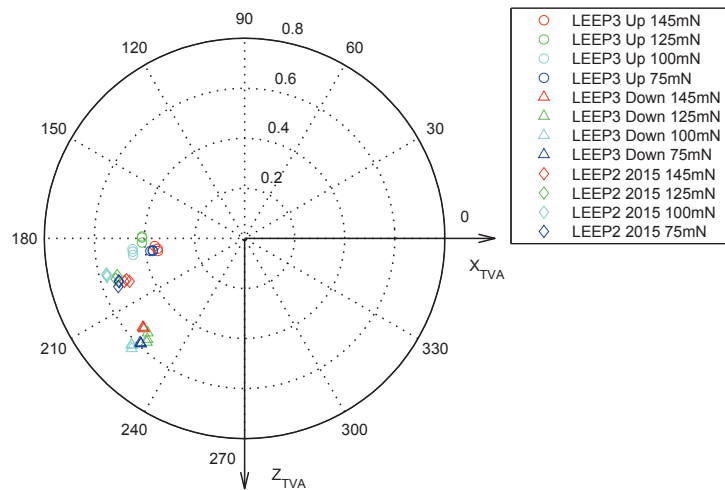


Figure 14. T6 Thrust Vector (polar representation) measured in the LEEP2 and LEEP3 Test Facilities

V. Typical Test Campaign

The BepiColombo project has made use of the full suite of chambers and support equipment during its extensive component and system qualification and acceptance programme.

A. Sub component

A wide range of sub-components have undergone performance and qualification testing at QinetiQ during the BepiColombo programme. Examples of tests that have been completed include the pre-assembly bakeout of components, qualification and acceptance testing of flight pipework, life testing of cables, qualification of harness and splice plates and the end of life performance evaluation of thruster components.

B. Thruster Qualification & Acceptance

The thruster qualification programme has a number of discrete elements. Prior to initial operation of the thruster after it has been installed in the chamber and put under vacuum a outgassing and commissioning sequence is required. The purpose of this activity is to ensure that the thruster is not damaged in any way by water vapour and atmospheric gases absorbed into the thruster materials, and to allow time for the thruster operating parameters to stabilise prior to the performance tests.

The first stage of thruster qualification is to measure the thruster performance to allow a number of Solar Electric Propulsion Thruster (SEPT) specific requirements to be verified. At the same time the Beginning Of Life (BOL) Thrust Correction Factor (TCF) across the thrust range is derived. The purpose of this is to determine the relationship between ideal thrust, as calculated from beam voltage and beam current telemetry, and actual thrust, as measured by the thrust balance. This is required in order to remove the necessity of a thrust balance from every thruster test configuration and to minimise the risks associated with performing other performance requirement verification activities.

The performance and TCF data are acquired at the four nominal thrust points defined for the BepiColombo project, which cover the full thrust range. This provides a polynomial relationship between TCF and beam current which can later be extrapolated to the beam currents needed for actual thrust levels. This approach allows a direct comparison with previous thruster test data, all of which have been performed at these settings.

Once the BOL data have been obtained and the performance of the thruster verified against the system requirements it is subjected to vibration and shock testing, which is completed at an external facility.

Following vibration and shock testing the thruster performance is checked to confirm that there has been no degradation before it undergoes thermal cycling.

A typical thermal vacuum test sequence for thruster qualification is given in Fig. 15. The thruster is started from ambient temperature and driven to max power (145mN) whilst controlling the TIP to the max temperature condition. Once thermal stability has been achieved a set of performance and beam probe measurements are taken prior to the first cold cycle.

For the first cold cycle an 18 hour cold dwell is performed to ensure that sufficient time is allowed for the qualification temperatures to be achieved across the whole thruster, with the grids taking the longest time to reach the temperature target. On the first cold start the thruster is first taken to min power (75mN) to demonstrate acceptable performance at min conditions and then ramped up to 145mN, whereas on all other cycles the cold dwell is 9 hours and the thruster is immediately ramped to max power in order to thermally cycle the hardware efficiently between min and max conditions. Performance and beam probe measurements are taken at the end of each hot dwell and at intervals during the ramps from cold.

The flight thrusters are subjected to a cut down version of the qualification test campaign, applying acceptance rather than qualification test levels. The T6 thruster qualification programme for the BepiColombo project is described in more detail in Ref. 2.

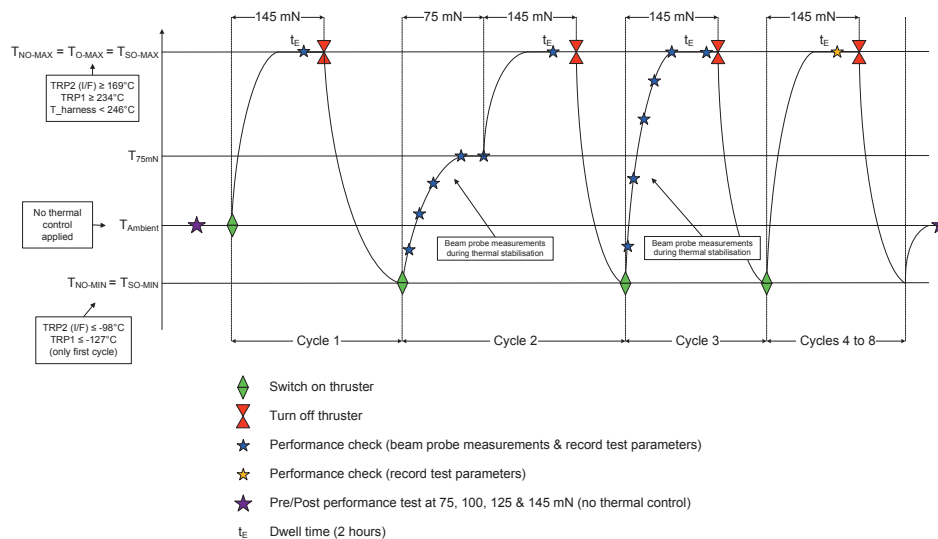


Figure 15. Typical thruster thermal vacuum qualification test

C. SEPS Endurance Test

During the SEPS qualification programme the EQM SEPT is subjected to an 8000hr endurance test to demonstrate its compliance with the requirements. Operational and performance parameters are monitored throughout the endurance test and their trend analysed and extrapolated to prove that the SEPS is able to achieve the total impulse, number of cycles and total firing time required by the BepiColombo mission.

The test will be interrupted at 2000hr intervals of elapsed operating time for inspection of the grids and the other SEPT components subject to the wear-out mechanisms. The screen and accel grid erosion will be measured and used to validate the ion optics model predictions. In order to successfully terminate the endurance test the extrapolated erosion trend shall not result in a non-compliant end of life condition of the grids.

During each 2000hr test phase the thruster is operated at maximum thrust. Thrust vector measurements are taken at regular intervals during the 2000 hours to check on thrust vector migration. In addition, the thruster is switched off periodically and allowed to cool for a few hours before restarting to verify its starting reliability.

Operating the thruster safely twenty four hours per day without continuously manning the control room brings its own specific challenges that need to be overcome to ensure that the endurance test runs without incident. Both the thruster, via its EGSE control software, and the facility are continuously monitored in case of any anomalous behavior. If an event occurs that takes the thruster or the facility outside of pre-defined operational parameters the thruster is automatically shutdown and the facility manager and test lead notified via SMS message and e-mail so that appropriate action can be taken.

Each day the thruster performance data for the previous twenty four hours are automatically transferred from the control PC to a data server and processed via a Matlab based analysis routine to show trends in the main system parameters. An example of the data collected during the first part of the endurance test is given in Fig. 16 below; each data point represents the three-hour average of the telemetry sampled at 1 Hz by the EGSE with the thruster in stable conditions (i.e. excluding beam-outs and thruster initialisations).

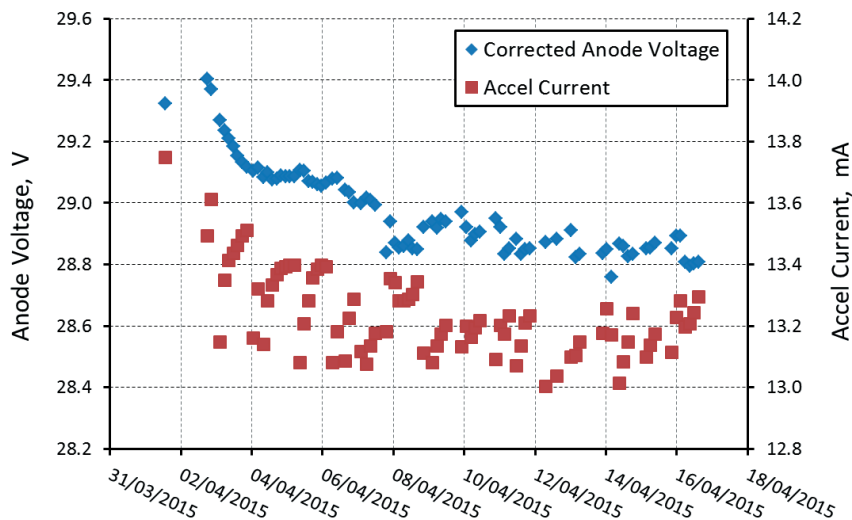


Figure 16. Example data from Endurance test

D. System Qualification & Acceptance Coupling Tests

The aim of the BepiColombo Solar Electric Propulsion System (SEPS) AIV programme is to verify the EQM and FM SEPS hardware in a representative (to the flight configuration) test set-up and verify SEPS requirements. The BepiColombo SEPS AIV programme is divided into a number of activities, which when coupled with the component qualification and acceptance test programmes, will validate the system design.

The SEPS Coupling Test^{3,4} provides a complete representative chain, with the PPU, FCU and SEPT connected together via representative connections for the SEPH and SEPP. Performance tests of the SEPS are conducted, and validation of key system requirements performed during this test phase. The coupling test is, itself, split into two parts:

- a. PPU and FCU outside the vacuum chamber.

This allows detailed measurements of the PPU and FCU inlet and outlet characteristics to be captured using high frequency oscilloscopes. It is especially important to capture the transient events associated with a beam out and automatic system recovery. Beam outs are significantly more likely to occur during vacuum chamber testing due to sputter, which originates from the target, falling between the grids and causing a loss of isolation. During this test the effect on thruster (and system) performance of the pressure oscillations likely to be present in the Xenon flow line due to the upstream pressure regulator can be assessed.

VI. Conclusions

QinetiQ have developed an extensive suite of test facilities and support equipment for qualification and acceptance testing of Electric Propulsion systems and sub-components. The facilities have been used extensively to support development of the ESA BepiColombo mission to Mercury.

Acknowledgements

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