A DESCRIPTION OF THE NEW 3.8M DIAMETER HIGH POWER ELECTRIC PROPULSION TEST FACILITY AT QINETIQ FARNBOROUGH, UK

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INTRODUCTION

From August 2001 to March 2002 QinetiQ converted an existing 3.8m diameter vacuum that had been used for solar simulation testing into a facility capable of running higher power gridded and Hall effect thrusters. This facility is now available for the development of QinetiQ's in-house T6 ion engine development and also for European and international use. This paper summarises the recent work that has been completed by QinetiQ in development of this new capability and describes its key performance features.

The vacuum chamber was originally configured for solar simulation. Commissioned in 1965 for the testing of the UK X-Series of spacecraft it was used extensively over three decades for the testing of complete spacecraft and components. As the size of spacecraft increased this facility became of limited use, and coupled with a rapid increase in European testing requirements for the electric propulsion market QinetiQ made the decision to convert the facility to develop and test its T6 ion engine and the thrusters of other commercial organisations.

FACILITY DESIGN

The automated testing of high power, high mass flowrate Hall Effect Thrusters (HET) has a number of implications for facility design, the most critical of which are listed below:

- Certain elements of the thrusters operate at elevated temperatures (1100ºC) and due to the nature of their use they have to be manufactured using materials which often react adversely with volatile substances such as oxygen, pump oil etc. As a consequence the only acceptable means of pumping is cryogenically.
- The principal propellant gas is xenon. The selection of this gas is made from a thruster design perspective. However the relatively low vapour pressure of xenon means that low temperatures (< 50 K) must be achieved before xenon is pumped. This unfortunately eliminates low cost pumping systems such as LN_2 and forces the adoption of more expensive helium systems.
- Accurate characterisation testing requires as low a vacuum pressure as possible i.e. to simulate as closely as possible the conditions that would be experienced in space. This requirement is in direct conflict with the propellant flowrate passed through the thruster and subsequently into the chamber. As a result facilities must be equipped with extremely large pumping systems.
- The thrusters produce energetic ion beams which are highly erosive in nature. As a result extensive measures must be taken to prevent sputter damage to the materials used in the construction of the vacuum chamber. This is particularly the case directly in line with the ion beam where facilities have to be fitted with ion beam targets. These are usually clad in graphite, which is generally accepted as being the best, readily available material at resisting ion sputter damage.
- The power of the ion beam can be very significant with thrusters of as much as 10 kW beam power currently under development. As a consequence the ion beam target must be designed to dissipate this power input.
- Although EP systems are very efficient they have very low thrust levels. As a consequence the thrusters are operated for extended periods. This means that test programmes are often many weeks in duration and life testing is often measured in years. This means that facilities have to be very reliable and capable of autonomous operation.

Taking into account all of the design criteria described previously the chamber configuration can be seen in Figure 1 and elements of the design are presented in later sections of this paper.

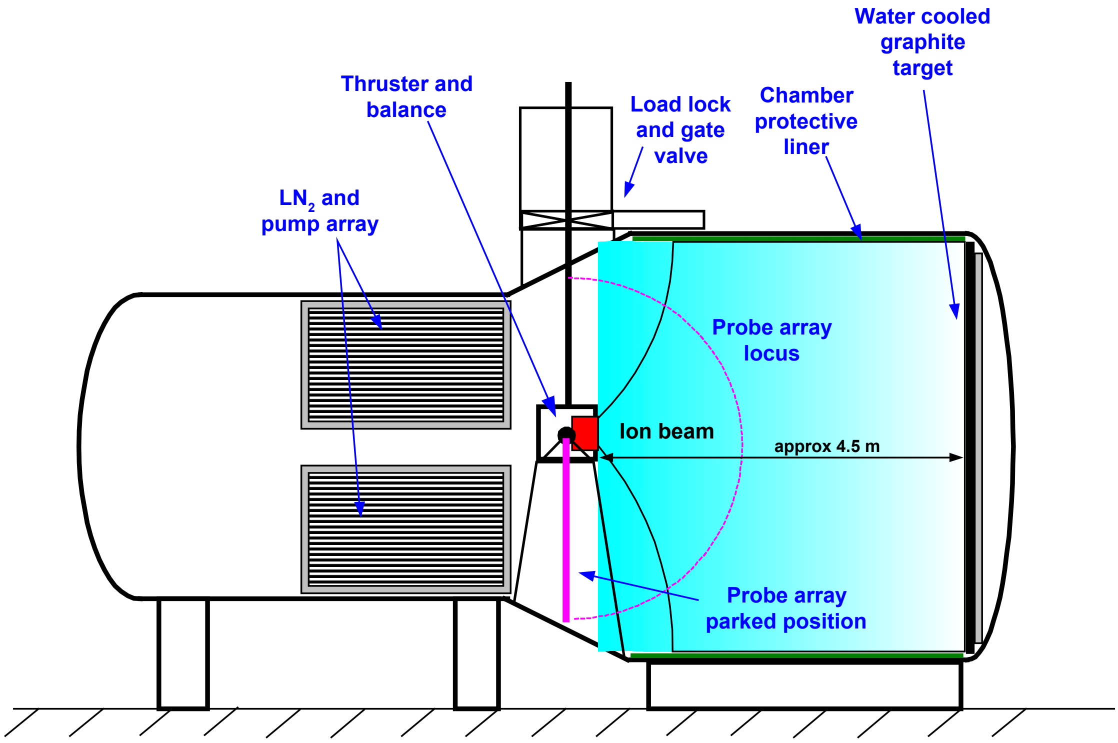

Figure 1 Schematic of LEEP2 Test Facility

The thruster exit plane is located at the chamber mid-point firing towards the chamber door. This location was selected to minimise thruster chamber interactions and leave the 2.6 m diameter section free for pump arrays. The ion beam target is located on the chamber door and is a bakeable, water cooled graphite clad design. The walls of the chamber are protected using a stainless steel sacrificial liner. This liner is equipped with electrical heaters to facilitate outgassing following exposure to atmosphere. The xenon pumping array is located in the 2.6 m diameter section, not behind the target as usually configured for HET testing. A 1 m diameter load lock is located on the top of the chamber which can be isolated from the main chamber via a gate valve. The thruster and thrust balance assembly is lowered from the load lock on to a platform such that the geometric centreline of the thruster is aligned with the centreline of the chamber and an ion beam probe array. The probe array consists of 15 retarding potential analysers (RPAs) and can be swept through the ion beam with a radius of 1 m.

The vacuum facility is equipped with an emergency generator that allows unlimited operation of essential equipment. This generator automatically activates within 30 seconds of power loss to the facility. The load lock pumping system is scaled to allow operation from this generator, allowing the thruster to be maintained under vacuum conditions indefinitely.

All of the gate valves used in the facility are pneumatically actuated using dry nitrogen. This approach allows the valves to be operated in the event of loss of power. All valves are isolated from the nitrogen supply during normal facility operation to prevent accidental or unscheduled operation. The use of dry nitrogen as the actuating gas also eliminates any risk of thruster and cathode oxidation which could occur in the event of a valve piston seal leaking.

The chamber has also been equipped with a xenon reclamation system that is used to recover a substantial portion of the cost of xenon usage.

VACUUM CHAMBER

The configuration of the vacuum chamber can be seen in schematic form Figure 2 and a photograph in Figure 3. The largest section of the chamber is 3.8 m diameter x 4 m long. The conical section is 0.9 m long and the small section is 2.6 m diameter x 5 m long.

LEEP 2 rear quarter view **LEEP 2 front quarter view**

Figure 2 LEEP 2 Vacuum test facility chamber configuration

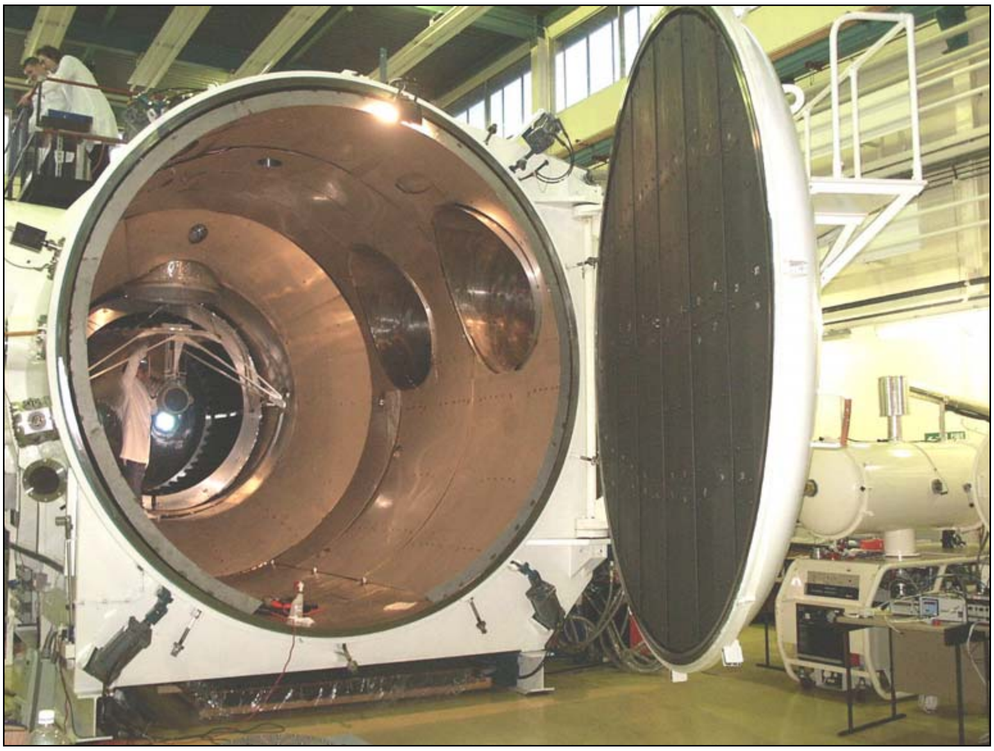

Figure 3 3.8m Ø EP Test Facility

CHAMBER EVACUATION

Chamber roughing is achieved using a high-throughput mechanical booster with a pumping speed of 3400 m^3h^{-1} backed by a two stage rotary pump with a pumping speed of 500 m^3h^{-1}. High vacuum pumping is achieved using 2 x 600 mm diameter cryogenic pumps augmented by a large xenon cryogenic pumping array.

The facility is designed for the operation of electric thrusters at xenon flow rates of up to 30 mgs^{-1} (which equates to 1.4×10^{20} atoms per second), whilst maintaining a vacuum of 2×10^{-4} mbar. This requires a pumping speed of 29×10^3 litres per second. The cryogenic pumping speed of xenon, assuming a gas temperature of 300 K and a sticking coefficient of 1.0, is 5.5 $l.s^{-1}.cm^{-2}$. A pumping speed of 29 x 10^3 ls^{-1} therefore requires a minimum pumping area of 5.3 x 10^3 cm^2.

In order to condense xenon on the pump panel, at the vacuum pressures specified a temperature of < 50 K is required. At such low temperatures the cooling power is limited, therefore radiant heat from the walls of the vacuum chamber, which are at room temperature, must be restricted. This is achieved by the use of LN_2 cooled baffles. The presence of these baffles however impedes the flow of gas, reducing the pumping speed for a specific area of pumping surface. A relatively opaque baffle system introduces a restriction to the pumping speed of approximately 70%. Assuming the use of such a baffle arrangement the pumping area requirement increases to 1.8 x 10^4 cm^2 (1.8 m^2).

The solution adopted for the xenon pumping system achieved a high pumping speed at minimum cost. Leybold T-120 single stage cold heads were selected with circular aluminium panels of radius 0.7 m, providing a total pumping area of 1.5 m^2 per panel and cold head combination. A total of 4 x 1.5 m^2 panels and cold heads were chosen because this configuration could be readily accommodated within the 2.6 m Ø section of the chamber. This configuration provided a maximum operating pressure of < 2 x 10^{-4} mbar, with the thruster operating and < 1 x 10^{-5} mbar, with the thruster and propellant mass flow disabled.

ION BEAM TARGET

An ion beam target was located on the door of the facility. It is a flat, graphite clad, circular configuration with a diameter of 3.8m. Graphite tiles were fixed to a series of pipes through which cooling water is passed during thruster operation. Cooling water is provided from a closed loop water chiller.

A flat target configuration was selected for two reasons. The first is that the cost of graphite cladding was minimised. Secondly the sputter rate produced by the impinging ion beam was also minimised by presenting a surface normal to ion impact, particularly near the centre of the target where the ion beam density and energies are greatest.

A closed loop water chiller represents the most cost-effective approach to cooling the target. This is especially the case when operating large high power thrusters where the energy dissipated by the ion beam in the target is high.

Before thruster operation, the graphite is baked to accelerate outgassing by passing hot water through the pipes which heats the graphite above 100ºC. This approach has been demonstrated to eliminate the issue of severe target outgassing when the thruster is activated. This has caused a number of problems in EP test facilities in Europe and the USA and can result in outgassing periods of many days before thruster operation can be commenced.

The central graphite tile on the target is equipped with an erosion depth monitor. This indicates when the graphite cladding requires replacement and therefore eliminates the possibility of thruster contamination due to the sputter deposition of the target substrate materials.

Positioning the target on the door facilitates easy access and therefore minimises the cost of target refurbishment. It also eases the possible future use of ion beam diagnostics positioned on or near the target.

Figure 4 shows the target during assembly of the test facility.

Figure 4 Ion beam target assembly

CHAMBER DIAGNOSTICS

The vacuum facility is equipped with a range of standard diagnostics including;

- Pirani gauges for 1000 mbar to 3 x 10^{-3} mbar.
- Penning gauges for 1 x 10^{-2} mbar to 1 x 10^{-8} mbar.
- Mass spectrometer for monitoring of vacuum partial pressures.
- Thermocouples to monitor LN_2 baffle and ion beam target temperatures.
- Silicon diodes to monitor xenon pump panel temperatures.

A dedicated Personal Computer (PC) is located in an adjacent control room and monitors the data from these and other diagnostics at a frequency of 1Hz and archives to disk. This PC also provides a 1Hz “go / no-go” pulse to the thruster control computer which inhibits thruster operation in the event of any facility parameter being out of tolerance.

In addition to this general diagnostic capability QinetiQ have also incorporated a thrust balance and an ion beam probe array into the vacuum chamber to support the recent ESA trends towards increased parametric analysis of ion engines.

Thrust Balance

The chamber is equipped with a single axis thrust balance designed for operation with the T6 thruster. The balance was provided by the National Physical Laboratory (NPL) and is based on a design developed for ESA Field Emission Electric Propulsion (FEEP) testing. The principle of operation is based on an actively controlled pendulum that supports the thruster under test. In operation, the control system generates an equal and opposite thrust to that generated by the test thruster such that deflection of the pendulum is nulled. The critical balance specification details are listed in Table 1 and a photograph of the balance with a T6 thruster can be seen in Figure 5.

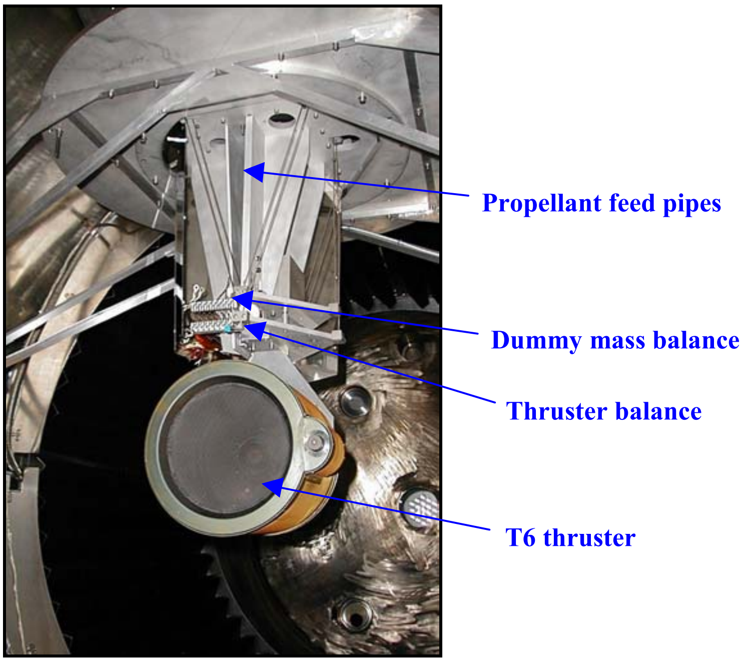

Figure 5 Photograph of the thrust balance with a T6 thruster fitted

The protective covers normally fitted to the thrust balance have been removed to show the construction of the balance system.

Parameter	Specification
Operating mode	Continuous, steady state thrust
Thrust range	1 - 500mN
Thrust accuracy	± 2.5mN
Bandwidth	0.1 – 0.0001 Hz
Zero drift and gain shifts	< 2.5mN (3 sigma) over whole bandwidth
Calibration	Remote calibration facility (balance can be calibrated in situ)
Alignment tolerance	0.1^{o} angular, 0.5 mm linear (all axes)
Thruster mass	Up to 15 kg

Table 1 Summary of thrust balance specification

In order to minimise the potential for thermal drift the entire device is manufactured from low thermal expansion material. To overcome the inherent problem of null-point drift due to residual thermal and mechanical drift, and low frequency vibration, a second, identical pendulum balance (with a dummy mass to represent the thruster) and control system is included. Its output gives a direct measure of the low-frequency noise and null-point drift, which is then subtracted from the output of the balance carrying the thruster.

Ion Beam Probe Array

The 3.8 m Ø EP test facility is also equipped with a high accuracy/resolution array of retarding potential analysers (RPA), which can be configured as Faraday Cup Probes (FCP). This system allows the ion flux and beam divergence of the ion plume to be characterised with high resolution to divergence angles of up to 90 degrees. The probe array consists of a semicircular 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 in Figure 6 and photograph in Figure 7. Aperture bias and current collector cables are routed along the beam. The probe array is situated such that any collimated instruments, e.g. the RPAs/FCPs and Quartz Crystal Microbalances (QCM), 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.

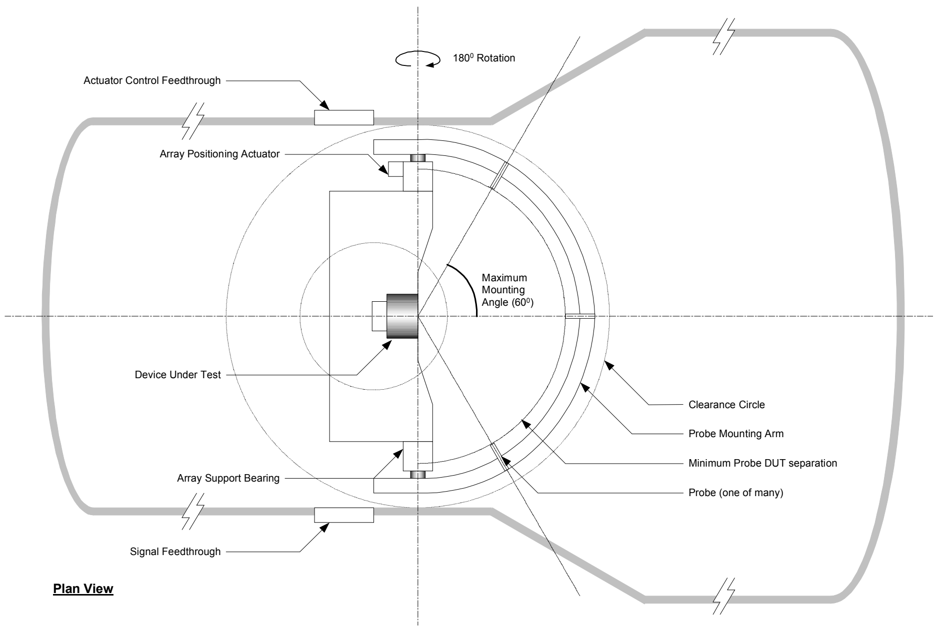

Figure 6 Schematic of large diameter ion beam probe array

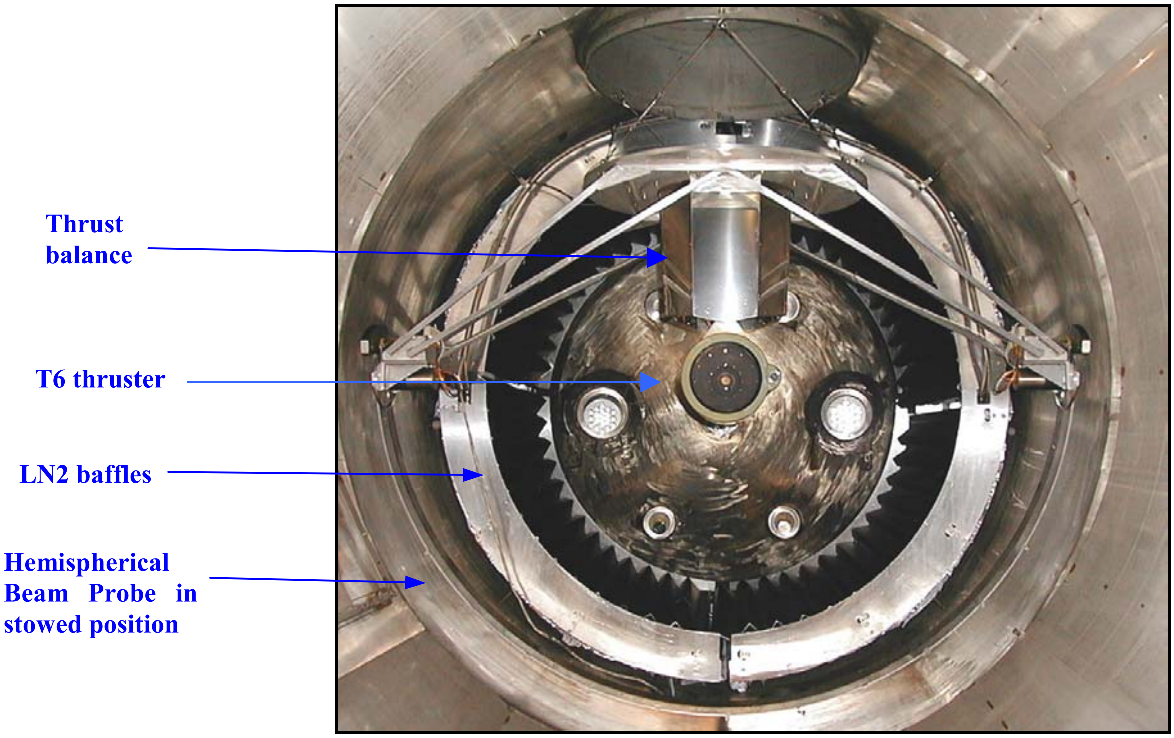

Figure 7 Photograph of the ion beam probe array within the 3.8m vacuum facility

The control system is resident on a personal computer (PC) 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 Data Acquisition (DAQ) hardware.

PROPELLANT SUPPLY SYSTEM

Thrusters can be operated using either flight type controllers or a laboratory control system. A schematic of the system is shown in Figure 8. Control of any inert gas is possible using digital mass flow controllers (MFC). Each MFC is configurable between 0 to 30 mg s^{-1} and the accuracy is better than 1% of the setpoint. Five MFCs were selected to provide as broad a range of flows as possible and these can be readily substituted for MFCs of alternative ranges.

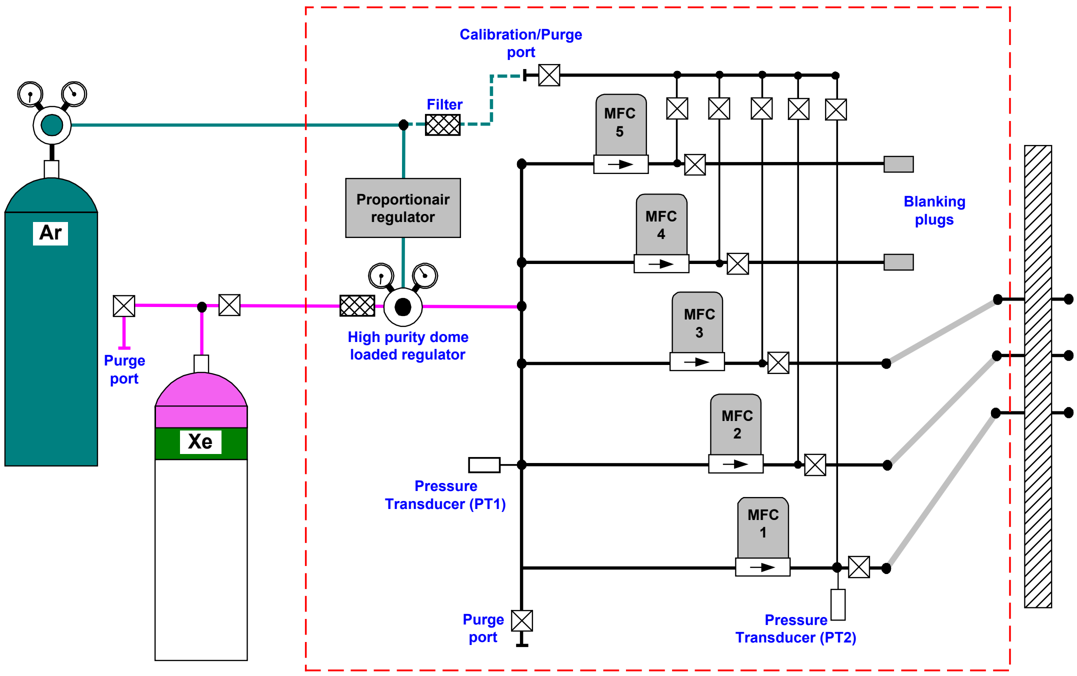

Figure 8 Propellant Feed System

ELECTRICAL POWER AND DATA ACQUISITION

QinetiQ separated the power supplies from the data acquisition system to maintain a high degree of signal fidelity. The overall architecture is shown in Figure 9. Clearly for different engines under test different Power Processing Racks (PPR) are required, but the Data Acquisition System (DACS) can be used for all thrusters if it is given the appropriate modifications. The DACS records thruster-relater data including data from the thrust balance and propellant feed system.

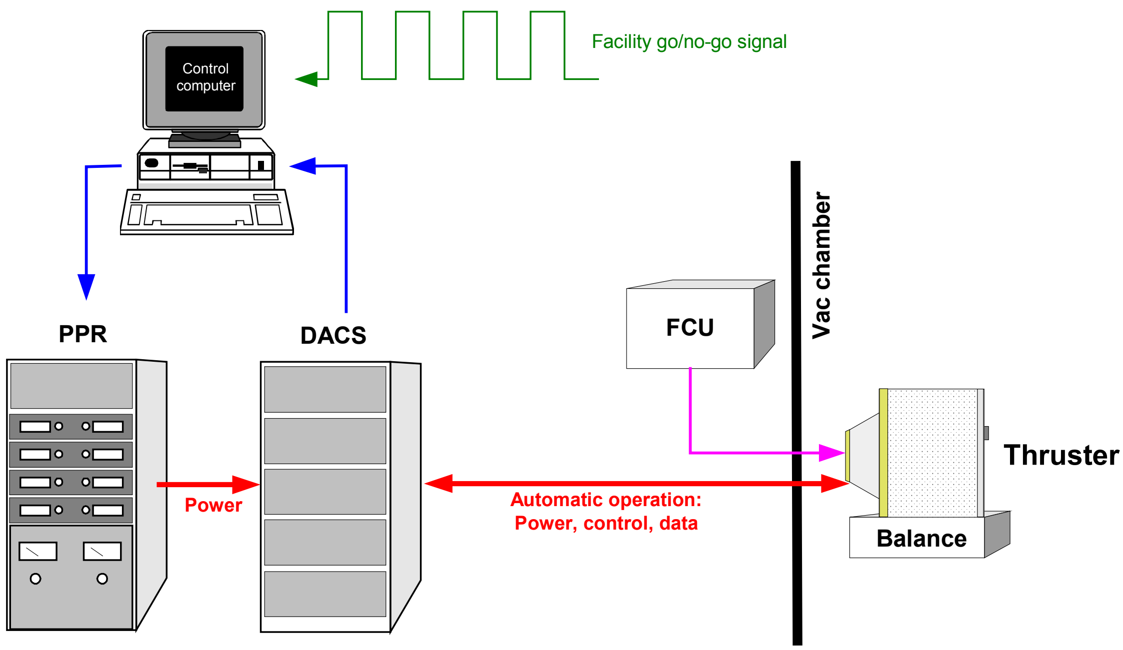

Figure 9 Electrical Power and Data Acquisition Architecture

Automatic data acquisition is obtained from the following three sources.

1. The DACS acquire data from the PPR relating to thruster operating parameters, the xenon supply and thrust balance.
2. A facility monitor acquires data relating to the vacuum facility status and operating conditions.
3. A beam diagnostic control system acquires data from the ion beam probe array.

The on-board clocks on each of the three systems are synchronised. Synchronism is automatically maintained via the local area network on which the systems are linked allowing the cross-referencing of data wherever necessary.

All the data collected by the test bench is automatically copied to a remote back-up computer situated in a different building to the test bench. Each month all data stored on the backup computer is transferred to CDROM. These CDROMs (and any other records such as photographs etc.) are then stored in a separate building to the test bench and back-up computer.

The test bench is equipped with four levels of surveillance that will simultaneously monitor the status of the bench. These surveillance levels are:

- 1st level: Software surveillance of thruster via DACS.
- 2nd level: Hardware surveillance of thruster via DACS.
- 3rd level: Power supply current and voltage limitations.
- 4th level: Vacuum facility surveillance.

This strategy allows the test bench to function without operator presence in total security, clearly essential for long duration life-testing in excess of 1000 hours.

CONCLUSIONS

QinetiQ’s LEEP2 test facility came on-line in March 2002 and is now available for testing both the T6 gridded ion engine and other thrusters.

REFERENCES

1. Wallace, N C, and Simpson, H B, “The lifetest of UK-10 ion thruster cathodes and neutralisers; implications for facility design”, Proc *Second European Spacecraft Propulsion Conference*, Noordwijk, Holland 27-29 May 1997, ESA SP-398