QinetiQ High Power Electric Propulsion System and Architectural Options for Future Applications

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Abstract: **QinetiQ has been working on high power electric propulsion systems for over two decades. Building upon the success of the T5 gridded ion thruster, QinetiQ started the development of the T6 5kW Kaufman thruster in the late 1990s. The T6 thruster and system have now been environmentally qualified for the ESA BepiColombo mission to Mercury. The BepiColombo system offers a high specific impulse performance across a thrust range of 75mN to 145mN, but the T6 has demonstrated a wider performance capability. An industrialisation programme is being implemented in order to drive down the thruster's recurring price without design changes. Further cost savings are being achieved through design for manufacture, and the thruster's mechanical robustness is being enhanced to ensure compatibility with a wider range of launch vehicles and mounting arrangements. In parallel, QinetiQ is developing a T7 thruster. The key difference compared to the T6 thruster is the choice of a ring cusp magnetic field distribution which increases the discharge efficiency and decreases the power to thrust ratio of the system. T6 and T7 based systems benefit from the strong heritage and system design knowledge that QinetiQ has gained during design development and qualification for BepiColombo. The use of system building blocks (thruster, power processing unit, flow control unit) allows a large variety of system architectures. These are suited to a range of commercial applications requiring orbit raising and North-South station keeping manoeuvres. The choice of architecture can be made on a case by case basis depending on the mission performance, redundancy and cost requirements.**

Nomenclature

e	=	elementary charge
I_b	=	beam current
$\dot{m}_{tot}$	=	total thruster input propellant
m_{Xe}	=	atomic mass of xenon
P_b	=	beam power
P_{tot}	=	total thruster input power
T	=	produced thrust
T_{elec}	=	maximum achievable electrical thrust

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I.Introduction

Since the 1970s, Electric Propulsion (EP) has been used on spacecraft for station-keeping, orbit raising and primary propulsion. EP has traditionally had applications for telecommunications and science missions, but increasingly it is also being considered for Earth observation, navigation and orbit debris removal. QinetiQ has been an active player in this arena and its T-series Gridded Ion Engines (GIE) have been under development since the 1960s. The 10cm T5 GIE was successfully flown on ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission, during which both flight engines operated flawlessly, with a single engine accumulating over 36,000 hours of thrust operation [1]. Building upon the success of the T5, QinetiQ started the development of the 22cm T6 5kW Kaufman thruster in the late 1990s [2]. The T6 thruster and system have recently completed their environmental qualification for the ESA/JAXA BepiColombo mission to Mercury and the thruster is currently undergoing lifetime verification. QinetiQ has now started the development of a T7 thruster in response to the market need for high-power GIE with improved capability in terms of lifetime and power to thrust ratio.

EP systems offer both institutional and non-institutional spacecraft platforms a significant advantage in mass over traditional chemical systems. GIE have very high Specific Impulse (Isp), resulting in reduced propellant load and hence the opportunity to reduce the cost of launch, enlarge the payload or extend a satellite's operating life. These commercial advantages are being exploited by satellite manufacturers worldwide. QinetiQ's strategy is to take its EP products from the relatively complex and technically challenging science domain into the operational and commercial sectors, including telecommunications and navigation satellites. To achieve this QinetiQ has been active in developing its high power T6 and T7 systems for repeatable sales, as described in this paper.

Section II presents a detailed description of the T6 thruster, including working principle and performance. It also details the T6 industrialisation and design enhancement programme. Section III presents the T7 thruster description and target performance. In section IV we give an overview of the electric propulsion system building blocks with a more detailed description of the power processing units and flow control units for T6 and T7. Section V shows the various system architectures available and their applications.

II.QinetiQ T6 thruster

A. T6 thruster description

The QinetiQ T6 Kaufman thruster (Fig.1) is a Kaufman-type GIE featuring two 22cm diameter grids for ion extraction and acceleration. A hollow cathode located at the base of the discharge chamber emits electrons for ionization of the xenon propellant. A weak magnetic field is created by solenoids which surround the discharge chamber and can be used to fine-tune the ionization process to allow efficient operation over a wide range of conditions. A second hollow cathode, often referred to as the neutraliser cathode, is used as an external electron emitter to neutralise the positive ion beam and prevent the spacecraft from becoming negatively charged. The T6 thruster has recently completed its environmental qualification for the ESA/JAXA BepiColombo mission to Mercury [3] and is currently undergoing lifetime verification.

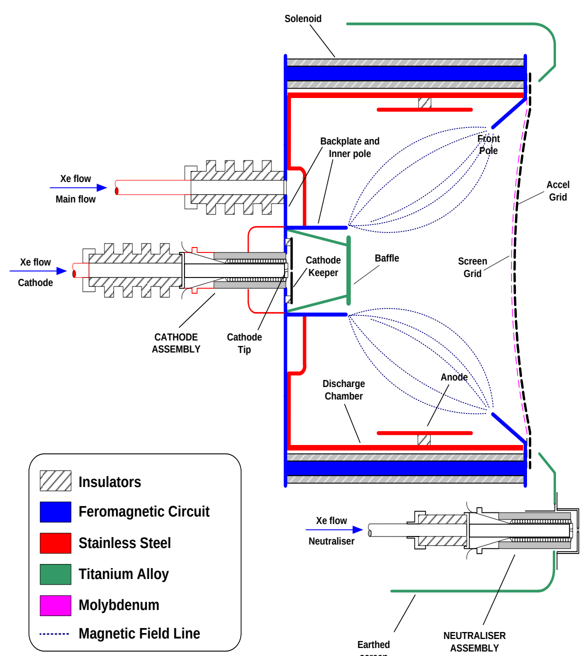

Figure 1. T6 Kaufman Schematic.

B. T6 thruster performance and operations

The T6 thruster performance has been extensively characterized at the BepiColombo operating point, which uses a beam voltage of 1850V and an accel voltage of -265V throughout the BepiColombo thrust range of 75mN to 145mN [3]. Thrust levels outside of this range have also been historically characterised with the T6. A performance map (thruster versus Isp) of the T6 thruster is shown in Fig. 2. The plot identifies the current limitations of the thruster at each boundary of the performance envelope. The red markers show real test data. These include the BepiColombo setpoints at 1850V, and also setpoints from a recent T6 test performed at lower beam voltages. In order to examine specific power performance gain QinetiQ performed a test programme considering a range of alternate operating points at low beam voltages (1200V, 1100V and 1000V, all with the accel voltage fixed at -933V) with no change to the thruster's grid design. As expected the lower beam voltage results in a lower specific power at the cost of a lower specific impulse. Operation at 1100V can be compared directly to the 100mN BepiColombo setpoint to illustrate operation of the T6 in dual mode. Both setpoints operate at similar powers with approximately 118mN/2900s at 1100V and 100mN/3765s at 1850V. This shows the flexibility of the T6 design since the grids used for this test were not

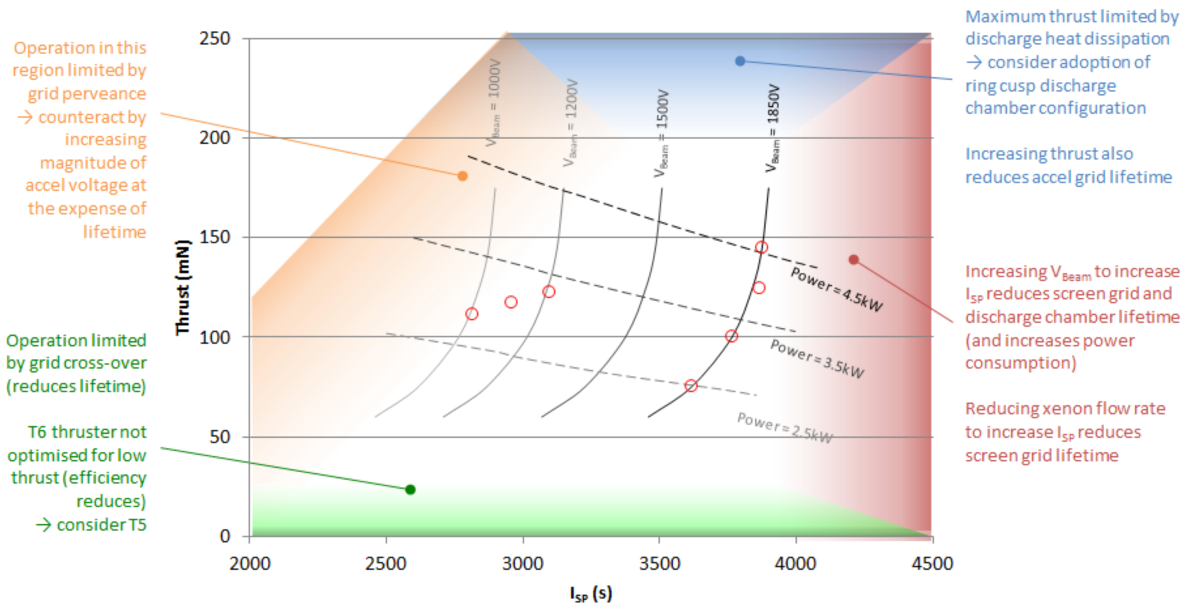

Figure 2. Performance Mapping of the T6.

specifically optimised for dual mode operation. The lowest specific power achieved in these tests was 26.9 W/mN at 1000V beam voltage.

- Start-up operations

Historically two operational constraints have limited the initialisation time and first activation time of T6 based systems. The first one, common to most space hardware, is the outgassing period required for the two hollow cathodes for first activation in space or following any atmospheric exposure for ground operations. The outgassing sequence is performed to remove any volatiles, particularly molecules containing oxygen that may cause oxidation of the cathode emitters and prevent discharge ignition [4]. To date, QinetiQ has applied a very conservative outgassing duration to ensure that volatiles are almost completely removed. However, tests have shown that outgassing follows a decaying exponential trend and the majority of volatiles are removed in a relatively short time period. In order to address market requirements for EP orbit raising shortly after launch, a test is being performed to confirm that a shorter outgassing sequence does not have any adverse effects on the cathode.

- Very low power discharge mode (eclipse)

QinetiQ has also recently characterized the capability of the T6 thruster to sustain a very low power discharge mode, where the objective is to minimize the input power and wastage of propellant. It was demonstrated that the main discharge can be sustained with xenon flowed through the discharge cathode at the nominal rate but with no additional xenon flow into the discharge chamber, thus minimizing propellant throughput. The anode and magnet current were then reduced to the minimum level where a stable discharge was maintained, in order to minimize the input power. This resulted in operation at 205W total power. This operating mode may offer advantages during orbit raising manoeuvres when the thruster can be maintained in this low power discharge mode during eclipse, and rapidly returned to thrust mode once full power is restored.

C. T6 industrialization for commercial applications

The industrialisation process seeks to bring down the recurring price of the T6 thruster without introducing design changes affecting form, fit and function of the thruster which would compromise the BepiColombo qualification heritage.

This is primarily being achieved through: supply chain rationalisation, transition from internal to external manufacture, , improved production batch optimisation, and efficiency improvements in production and test.

- Supply chain rationalisation

Key component suppliers have been identified and their capabilities validated; where possible a consolidation of manufactured parts to fewer suppliers (but with redundancy of manufacturing capability across these suppliers) has been considered with the aim of further cost reductions through increased volume per supplier. The number of suppliers has been reduced by approximately 35%.

- Transition from internal to external manufacture

At the start of the industrialisation programme 16% of drawn parts were manufactured by QinetiQ, this number will fall to 1% for the next GIE build.

- Volume manufacture initiatives

In order to realise cost savings of volume manufacture, the production methodology will migrate to a manufacturing cell based approach, optimising process batch sizes and utilisation of equipment. Ultimately further cost savings might be achieved by transitioning assembly through a staged outsourcing strategy.

- Acceptance test cost reduction

On a recurring basis, a series of savings have been identified to optimise the scope of acceptance testing compared to the full development and qualification test regimes applied, focused on the specific objective of the stage of testing but without compromising the breadth of verification finally delivered at the end of the test sequence. For example:

- Exclusion of the pre-vibration firing test resulting in only a single firing test being performed after completion of successful vibration test
- Limiting thruster performance measurements to two defined thrust levels (rather than at numerous thrust levels across the thrust range)
- Test setup improvements to reduce the duration of the test chamber integration sequence
- Automating testing and generation of test reports

III.QinetiQ T7 thruster

A. T7 thruster description

More recently QinetiQ has started the design work on a new thruster. The T7 builds upon the heritage of the current T6 Kaufman type ion thruster developed by QinetiQ. It is also an electron bombardment GIE and shares many design features with the T6. The key differences compared to the T6 are the magnetic field distribution in the discharge chamber and the geometry of the anode. The T7 uses a ring-cusp magnetic field distribution [5] generated by a series of circumferential permanent magnets placed around the discharge chamber. The anode in this configuration becomes the discharge chamber which is now isolated from the discharge cathode. The ring cusp configuration results in a more efficient main plasma discharge [5]. This improved efficiency directly reduces the specific power achieved by the engine.

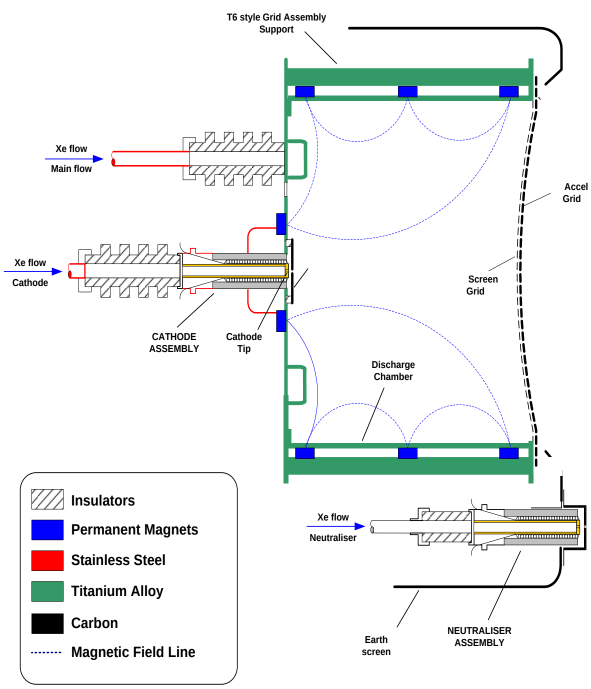

Figure 3. T7 Ring-cusp Schematic.

Furthermore, the power dissipated within the discharge chamber is significantly reduced. This yields the significant benefit of being able to increase the discharge chamber plasma density, and hence extracted beam current and thrust, whilst respecting temperature limitations such as those imposed by the cable harness. The main discharge and neutraliser cathodes and the grids follow the same design as the T6.

B. T7 Performance Target

Table 1 shows the T7 thruster target performance envelope. Table 2 shows the corresponding thruster efficiencies, where T is the thrust produced by the engine, $\dot{m}_{tot}$ the total thruster input propellant, P_{tot} the total thruster input power, P_b the beam power (beam voltage multiplied by beam current), I_b the beam current, T_{elec} the maximum achievable electrical thrust, m_{Xe} the atomic mass of xenon and e the elementary charge. These are based on theoretical considerations, early ring-cusp T6-RC prototype testing and initial modelling. They are realistic best case assumptions. In the near term, the nominal operating target is 5kW with a longer term maximum target power of 7kW. The high Isp and high thrust modes define the boundaries of the target performance. The high Isp mode at 1850V beam voltage benefits from the heritage of the BepiColombo system. In this mode the target specific power of the thruster is 31W/mN. The high thrust mode will be defined by a lower beam voltage circa 1000V, with a target specific power of 24W/mN. Note that the T6 has already demonstrated 27W/mN at this voltage and that the T6-RC prototype (see next section) demonstrated 25W/mN at 1000V.

	Nominal		Stretch	
	High Isp	High thrust	High Isp	High thrust
Thruster input power (kW)	5.0	5.0	7.0	7.0
Thrust (mN)	161	208	226	292
Isp (s)	4299	3182	4299	3182
Total efficiency	0.68	0.65	0.68	0.65
Beam voltage (V)	1855	1016	1855	1016
Beam current (A)	2.4	4.2	3.3	5.8

Table 1. T7 thruster target performance envelope.

		High ISP	High Thrust
Total efficiency	$\frac{T^2}{2\dot{m}_{tot}P_{tot}}$	0.68	0.65
Electrical efficiency	$\frac{P_b}{P_{tot}}$	0.89	0.85
Discharge cost (eV/A)	$\frac{P_{tot}-P_b}{I_b}$	238	183
TCF	$\frac{T}{T_{elec}}$	0.950	0.950
Power/Thrust (W/mN)	$\frac{P_{tot}}{T}$	31.0	24.0
Mass utilisation	$\frac{I_b m_{Xe}}{e\dot{m}_{tot}}$	0.85	0.85

Table 2. T7 target thruster efficiencies.

C. T7 development plan

QinetiQ has recently started the design development of the T7 in partnership with Mars Space. One of the first steps of this work was the successful build and operation of a T6-RC prototype. This prototype was built around the backbone structure of a T6 thruster and adapted to adopt a ring cusp magnetic field distribution. The thruster operated successfully over a wide range of thrust and Isp levels, demonstrated a more efficient main discharge than the T6 Kaufman and a specific power of approximately 25 W/mN at 1000 V beam voltage. Key components of the T7 such as the main discharge and neutraliser cathodes will be based on the T6 design. Target areas for potential cost reduction through design for manufacture have been identified within the T6 design, and these will be considered within the T7 design development process with the objective of achieving a low cost product.

IV.T6 and T7 based systems

A. Generic electric propulsion system / building blocks

Fig. 4 shows the typical scope of the electric propulsion system, where the key elements are a Power Processing Unit (PPU), a Flow Control Unit (FCU) and a thruster. These are often referred to as the building blocks of the system.. In most cases the thruster is mounted on a pointing mechanism to steer the thrust vector, depending on the requirements of the firing manoeuvre and to track centre of mass migration over life. The pointing mechanism is controlled directly by the AOCS system.. This one to one system architecture is the basis for more complex architectures (see section 0), for which switching of a PPU between different thrusters and FCU is sometimes required. QinetiQ has gained a strong heritage and system design knowledge during design development and qualification for GOCE and BepiColombo. The next sections detail the functionality and characteristics of the T6/T7 PPU and FCU. This includes information on the units qualified for the BepiColombo T6 based system but also the improvements made to these units through more recent programmes.

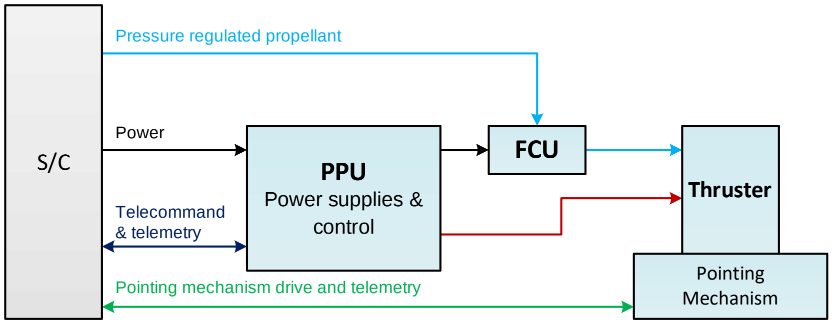

Figure 4. Generic electric propulsion system schematic.

B. PPU

The PPU provides the required functionality to power and control the thruster and the FCU as commanded by the satellite's on-board computer. The PPU also provides the necessary telemetry and telecommand interfaces to control and monitor all thruster functions. QinetiQ has a long collaboration history with CRISA. This includes the development and qualification of T5 and T6 [6] based systems for the GOCE and BepiColombo missions respectively. The CRISA high power PPU is compatible with MIL Std 1553 communications and a 100V power bus. The PPU includes a hardware controller capable of autonomous operation, including starting the thruster, maintaining the desired thrust level, recovering from beam events and shutting down in a controlled manner when so commanded. A wide range of FDIR functions are also incorporated. The spacecraft computer only needs to load the PPU with the required operating parameters, command it to turn the selected thruster on, and then command the thruster off at the end of the manoeuvre.

The functional diagram of a T6 PPU is shown in Fig. 5. In the T7 case the diagram is very similar but the magnet supply is not required and the cathode heater can be driven by the discharge anode supply, eliminating the need for the magnet/cathode heater supply. In order to minimise the mass and volume

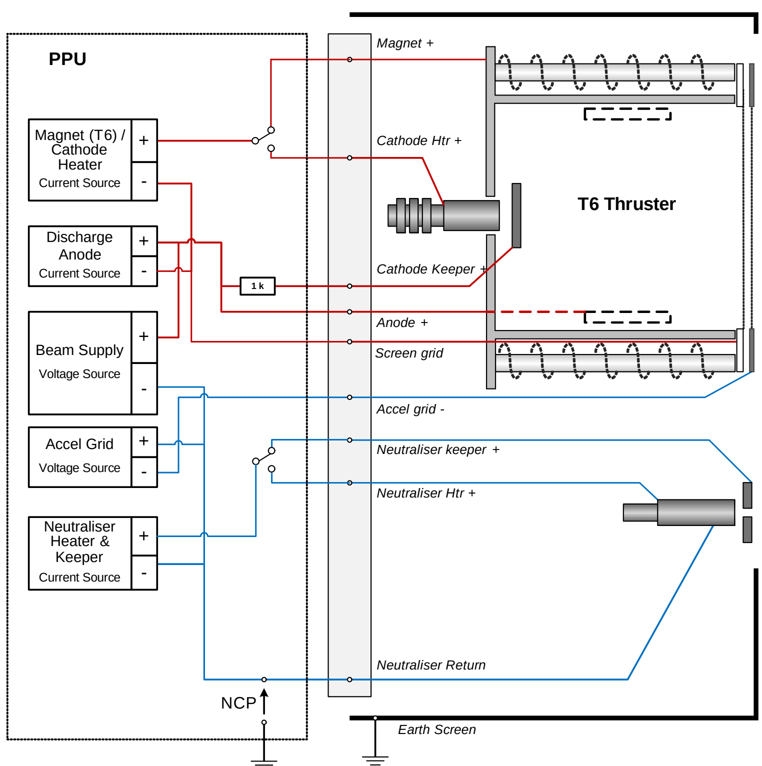

Figure 5. PPU functional schematic for T6 systems.

of the PPU its design takes advantage of the fact that a number of the thruster control functions can be supplied by a common power supply without impact to the performance or operation of the system. These are referred to as multifunction power supplies. This results in a total of five power supplies being required to power the T6 and four for the T7 thruster:

- Neutraliser heater
  / Neutraliser keeper supply
- Accel grid supply
- Beam supply
- Discharge anode supply
- Magnet / Cathode heater supply (not required for T7)

The PPU is formed from two distinct elements: the Discharge, Accel and Neutraliser supplies (DANS) and the Beam Supply (BS). For BepiColombo the PPU comprises one BS (comprised of several beam modules, BM) and two DANS to offer an internally redundant design. This results in an innovative architecture with complex switching (see section 0 for more details), extensively tested during various coupling tests by QinetiQ [7]. Activities are on-going to industrialize the PPU design primarily to reduce its recurring cost. The latest industrialized design of the PPU is composed of two physically separate sub-units for the DANS and BS. The use of separate sub-units for the DANS and BS offer a number of advantages:

- Mechanical and thermal designs (and other aspects of the design) can be established independently for the BS and for the DANS
- Manufacture and testing of the BS can be performed fully independently from the DANS

A further major difference in the industrialized design is the exclusion of integral Thruster Switching Units (TSU) within the PPU, originally internal to the PPU in the BepiColombo design. It is foreseen that TSUs can be added as external components if needed to meet varying EP mission requirements. These improvements are also being taken into account in the development of the T7 PPU, which is now in the early stages of development under the GIESEPP programme (Gridded Ion Engine Standardised Electric Propulsion Platform, www.giesepp.com).

C. FCU

Each FCU supplies one thruster with three separate xenon propellant feeds to the T6/T7 thruster's main discharge cathode, neutraliser cathode and main discharge flows at the required flow rate. The FCU is supplied with xenon at a low inlet pressure provided by the EPR. For the BepiColombo FCU, developed by Bradford, this pressure can be between 2.5 and 3.5bar and varying by any rate up to 0.1bar/s by the platform's upstream high pressure propellant supply assembly. It is compatible with either 'mechanical' or 'electrical' pressure regulator technology options.

The FCU is comprised of three main active components; Isolation Valves (IV); Proportional Flow Control Valves (PFCV) and Low Pressure Transducers (LPTs), as well as in-line particulate filters and flow restrictors.

The FCU is configured to ensure failure tolerance by means of two in line mechanical inhibits between the common upstream pressure system and any of the three downstream flow paths. Controlled by the PPU, the FCU is able to vary the propellant mass flow rate delivered to the thruster to ensure optimum system performance for the demanded thrust level.

The FCU includes a filter at its inlet to protect the system from particulate contamination. Immediately downstream of this filter there is a single mono-stable isolation valve, after which the flow path divides into three parallel branches for the neutraliser, cathode and main flow feeds. The main flow and cathode feed branches each contain a proportional flow control valve, pressure transducer and fixed restrictor. The neutraliser feed branch contains a mono-stable isolation valve and a fixed restrictor only. Each valve type, IV or FCV, is capable of achieving the necessary internal leak tightness when closed, and both are normally closed devices so that in the event of a loss of power to those valves they would automatically close. Any combination of valves can be opened independently or simultaneously for test, venting and purging operations on ground or in orbit. The overall configuration of valves ensures that there are 2 in-series inhibits between the inlet and each outlet, so that in the event that any one valve fails open or leaks excessively the propellant upstream of the FCU can be isolated.

The existing T6 FCU functional design is compatible with the requirements of a T7 system and minimal development is needed. Both systems will only differ by the range of flows required for each line. In the frame of the GIESEPP programme, QinetiQ are working with AST and other members of the consortium to use AST's innovative technologies with QinetiQ thrusters.

V.Architectural options

QinetiQ's ion engines and the supporting building blocks described in Section IV can be configured into several alternative schemes. These schemes are described below and where currently being exploited in flight or ground development, further details are also given. The EP systems are capable of achieving a wide range of operational requirements, from low to high power applications, whether at a constant thrust level, multiple thrust levels or variable thrust level operations.

Thrust vectoring is achieved in T6 systems via pointing mechanisms. However due to the wide range of pointing requirements for different applications, these mechanisms are excluded from the EP system discussed in this paper.

The system architectures are broadly split as follows:

- Single Thruster Chain (as used by GOCE);
- Baseline orbit raise and station keeping;
- Fully-redundant four thruster chain (as developed on BepiColombo);

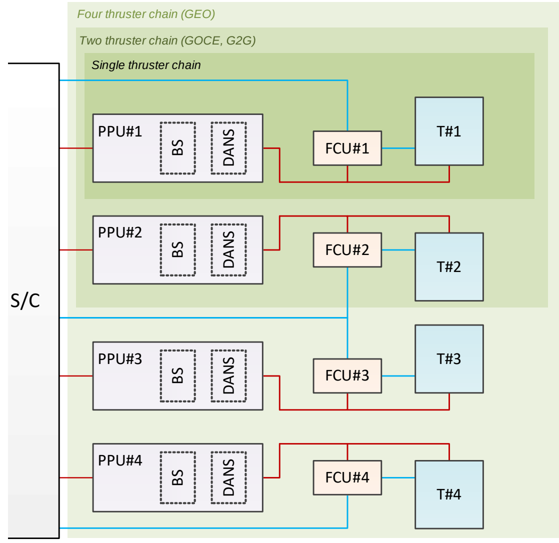

Figure 6. Single thruster chain architectures.

D. Single Thruster Chain

The simplest architecture is the provision of a single thruster, flow control unit and power supply, and this architecture was adopted by Airbus Defense and Space for the GOCE mission (Fig. 4). QinetiQ notes that for GOCE, the thrusters were provided by QinetiQ, but the system architecture and system delivery was performed by Airbus for this mission. It is comprised of two identical branches, one in cold redundancy, and in total being comprised of the following principal elements (GOCE elements in brackets):

- 2 x thrusters (T5)
- 2 x PPUs (IPCU, Crisa)
- 2 x FCUs (PXFA, Bradford)

The same system architecture can be used for orbit raising manoeuvres with a T6 or T7-based system. In nominal conditions, i.e. in the absence of any system element failure, the architecture allows the simultaneous operation of two thrusters. This architecture represents the expected EP system to be used to achieve the orbit raise for the future European Galileo 2nd Generation (G2G) spacecraft constellation. However in the case of G2G spacecraft power constraints are expected to limit the orbit raise to be achieved by firing only one thruster, with the second chain providing redundancy.

Adding two more thruster chains to the architecture allows both orbit-raising and station keeping operations for GEO telecommunication applications. In nominal conditions, i.e. in the absence of any system element failure, the architecture allows the simultaneous operation of four thrusters in orbit-raising mode. The system enables a redundant pair of thruster chains for station keeping manoeuvres too.

E. Baseline GEO orbit raise and station keeping

During the initial stages of QinetiQ's High Power Electric Propulsion System (HPEPS) programme, which is for the development of a GEO-telecommunications solution, several in-depth trade-off activities at system and equipment level were performed from which the baseline system was defined. The system architecture is presented in Fig. 4 and comprises:

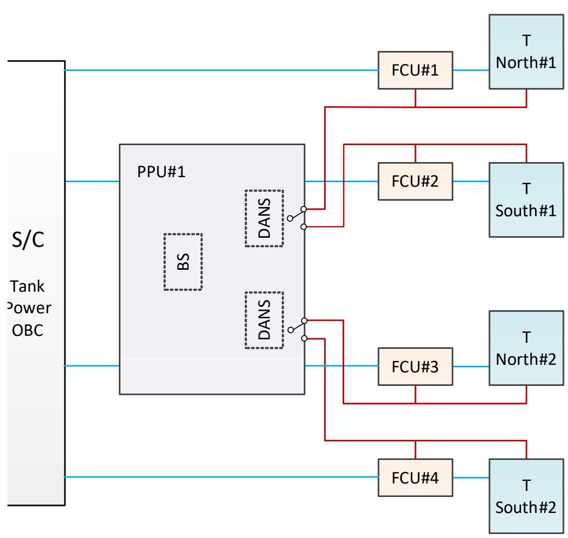

Figure 7. HPEPS architecture.

- 4 x thrusters (T6)
- 4 x FCUs (XFCU, Moog Bradford), each dedicated to a specific thruster
- 1 x PPU (PSCU, Crisa), internally redundant, incorporating two sets of DANS
- 4 x pointing mechanisms, one per thruster

The HPEPS has a number of features that have been included from the outset of the system design to minimise cost and to ease spacecraft system level AIV activities.

The first important feature is that unlike existing NSSK EP systems there is only a single PPU unit. The required redundancy level is maintained because it contains two completely independent sets of power supplies associated with the operation of the thruster Discharge, Accel and Neutraliser supplies (DANS). Each DANS also includes all drivers for the FCUs and communications with the spacecraft. Each DANS is able to operate one of two thrusters selected by a thruster switch unit (TSU) on its output. The beam supply is modular and is comprised of 3 beam supply modules (BSM). Each module has the power capability to provide ~50mN (for T6) and, therefore, only two modules are required to meet the station keeping EP requirement. The third BSM provides a failure tolerant system. For the T6 system, the power supplies within each DANS are able to operate an individual thruster up to a thrust level of ~150mN.

This feature allows the mass of the PPU to be readily tailored to best suit the thrust level requirement of any application, without an extensive development or re-qualification programme. It also achieves a dry mass saving over the conventional 2 x PPU architecture because with two PPUs there would be 4 BSMs in total, whereas with the HPEPS approach only 3 are required.

System control is achieved using re-configurable sequences on FPGA controllers within each DANS. The only commands required from the spacecraft controller are thrust level, ON and OFF. All system parameters are available to the spacecraft on request. A critical lesson learnt from the Artemis mission was that all system parameters should be monitored and made available, even though in principle many of these should be constant. Hence every system parameter that is available is monitored and can be interrogated. The baseline HPEPS architecture is constrained to only support single thruster firing at any one time.

F. Fully-redundant four thruster chain (BepiColombo)

The full versatility of the QinetiQ EP system is expressed through the needs of ESA'S BepiColombo mission. There are two critical BepiColombo requirements that affect the implementation of a suitable system architecture, and lead to a design that is more tolerant to failure than would be required on a GEO telecommunications application. The first is that BepiColombo requires two T6 thruster simultaneous operations at a combined thrust level of 290mN, hence two PPUs are necessary. The second is that the 290mN must be assured throughout the transfer and therefore four BSMs are required in each PPU for redundancy. The SEPS architecture is illustrated in Fig. 8, and consists of the following equipment:

- 4 x T6 ion engines from QinetiQ
- 2 x PPUs (Crisa), with two DANS each
- 4 x FCUs (Moog Bradford), each dedicated to a specific thruster
- 4 x pointing mechanisms (RUAG), one per thruster (not considered part of QinetiQ's system for BepiColombo)

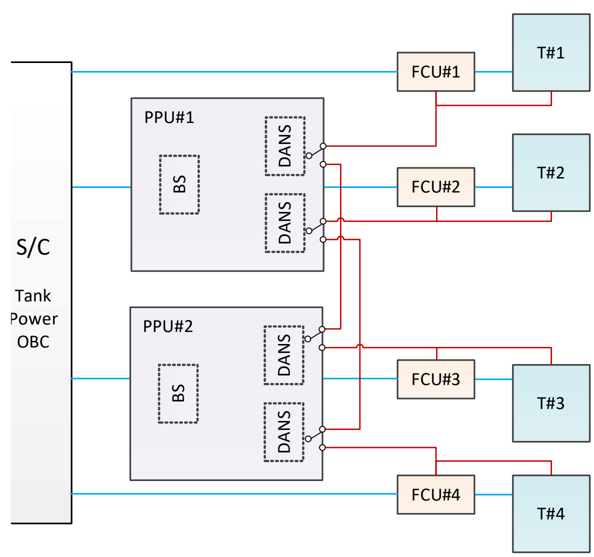

Figure 8. BepiColombo architecture.

Critical to the system design is the redundancy and cross-strapping philosophy. The selected configuration of two PPUs with fully symmetric cross-strapping of T6 units to PPU outputs gains maximum benefit from the symmetry of the four engine configuration. This provides the most robust response to any system element anomaly. It also allows the ability to maintain equal distribution of total impulse between operational T6 units with any single unit failure in a BSM, DANS, FCU or a T6. This in turn minimises the thruster life time requirement.

The resulting design provides for an elegant AIV sequence and plan. The number of units is minimised (only two PPUs without auxiliary electronic boxes), mounting and demounting units is straightforward with the integrated splice plate and the number of operating modes for testing is minimised. In addition, system mechanical and electrical symmetry mean that thermal behaviour will have fewer operational patterns to verify.

VI.Conclusion

QinetiQ has been working on high power electric propulsion systems for over two decades. The T6 5kW Kaufman thruster is at the centre of the recently qualified BepiColombo high power system. On top of its qualified wide power throttling capability, the T6 thruster has recently demonstrated operation at much lower beam voltages. This allows operation at lower specific power levels and offers two distinct operating modes for orbit raising (maximised thrust) or station keeping (maximised Isp). QinetiQ has now started the development of the T7 ring-cusp discharge thruster which will further reduce specific power. The T7 will benefit from the cost reduction through design for manufacture. Both thrusters are at the centre of QinetiQ's high power electric propulsion systems. These benefit from the strong heritage and system design knowledge gained during design development and qualification for BepiColombo. The systems also benefit from the long collaboration history that QinetiQ has with CRISA for the PPU and Bradford for the FCU. These building blocks make up the propulsion system which can be shaped into numerous system architectures. The choice of architecture can be made on a case by case basis depending on the mission performance, redundancy and cost requirements.

Acknowledgments

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