QinetiQ's T6 and T5 Ion Thruster Electric Propulsion System Architectures and Performances

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Abstract: This paper describes Electric Propulsion systems based around QinetiQ's T5 and T6 gridded ion thrusters. The equipment 'building blocks' (thruster, power processing unit and flow controller) that make up the systems are described. Typical GOCE in-flight performance results are presented. The range of EP architectures that can be derived from the T6 EP system building blocks are presented to meet needs of commercial telecommunication and navigation satellites and ESA's BepiColombo mission to Mercury. The paper briefly presents the evolutions of the T5 and T6 EP systems.

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I. Introduction

Over the past decade, the team formed by QinetiQ, Crisa (an Airbus Defence and Space company) and Moog Bradford has participated in two flight programmes where the Electric Propulsion System has been based on QinetiQ's Kaufman type Ion thrusters.

The first of these EP systems consisted of the QinetiQ T5 (10cm diameter) thruster, powered by the Crisa Ion Propulsion and Control Unit (IPCU) and supplied xenon by the Moog Bradford Proportional Xenon Flow Assembly (PXFA). It was developed for the ESA Gravity and steady state Ocean Circulation Explorer (GOCE) mission[1] and was launched in March 2009, to deliver over the mission lifetime faultless performance, providing continuous atmospheric drag compensation in the range of 1 to 20mN.

The second EP system consists of the QinetiQ T6 (22cm diameter) thruster powered by a 5kW Power Processing Unit (PPU), which was a high power development based on the GOCE IPCU heritage, and the Xenon Flow Control Unit (FCU) again designed by Crisa and Moog Bradford respectively. This EP system is currently being qualified to propel the ESA BepiColombo mission to Mercury[2] and for telecommunication and navigation spacecraft applications. It is capable of operation between 30 to 230mN, although on BepiColombo it is being qualified for 75 to 145mN.

The paper describes the EP system architecture for BepiColombo and its 'building blocks', namely the T6 gridded ion engine, xenon flow controller, power supply and control, pointing mechanism and harness technology. The potential range of EP system architectures that can be realised from the 'building blocks' to meet the needs of orbit raising telecommunication and navigation spacecraft as well as the needs of GEO spacecraft station keeping and de-orbiting spacecraft at end of mission are presented with a summary of their performances.

The paper also describes EP system architectures, based on the T5 gridded thruster and evolutions of the GOCE IPCU, along with a summary of their performances, to meet the needs of orbit maintenance for small spacecraft missions.

II. System Building Blocks

QinetiQ's systems use the following components:

- Kaufman Ion Engine (T5 or T6, for low and high power applications respectively);
- Power Processing Unit (IPCU, PPU, PSCU for different mission applications);
- Flow Control Unit (PXFA or FCU for low and high power applications respectively);
- Interconnecting harness, pipework (mission specific);
- Pointing Mechanism (mission specific).

A. Kaufman Ion Engine

QinetiQ's heritage is primarily in its heritage, experience and capability in the development, build and test of its Gridded Ion Engines. Development has focused on two models, the 700W T5, and the 5kW T6 ion engines, also often called thrusters.

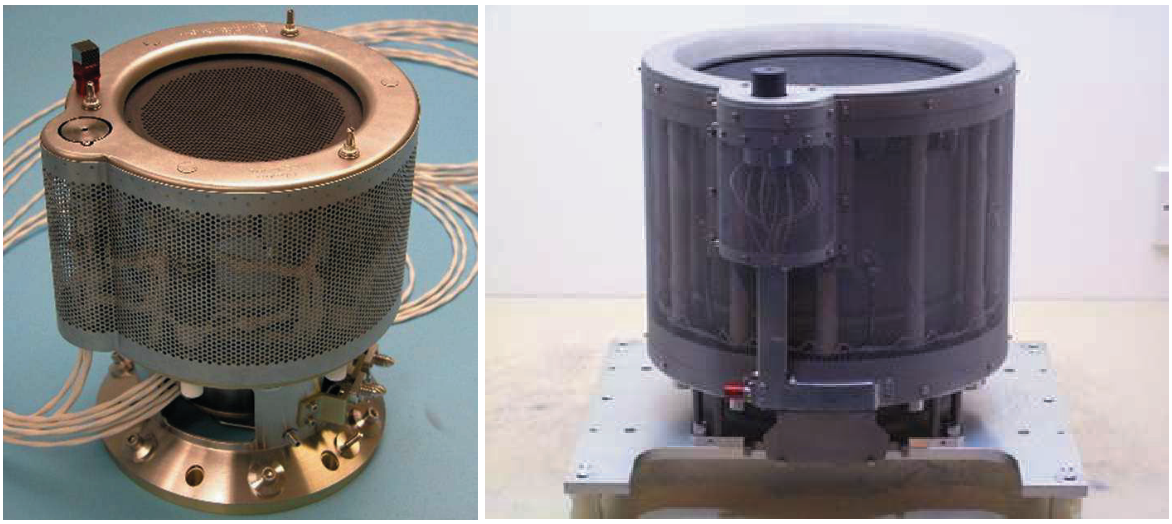

Figure 1. Photograph of T5 (left) and T6 (right) Ion Engines

The ion engine is shown schematically in Fig.2. It is of conventional Kaufman configuration[4], with a direct current (DC) discharge between a hollow cathode and a cylindrical anode used to ionise the propellant gas. The efficiency of this plasma production process is enhanced by the application of a magnetic field within the discharge chamber generated using 6 or 12 circumferential solenoids, for T5 and T6 respectively. A 10cm or 22 cm diameter grid system, forming the exit to the discharge chamber, extracts and accelerates the ions, to provide the required thrust. The velocity of the ejected ions depends only on the beam potential; whereas the thrust is a function of this and the ion beam current. An external hollow cathode, referred to as the neutraliser, emits the electrons necessary to neutralise the space charge of the emerging ion beam.

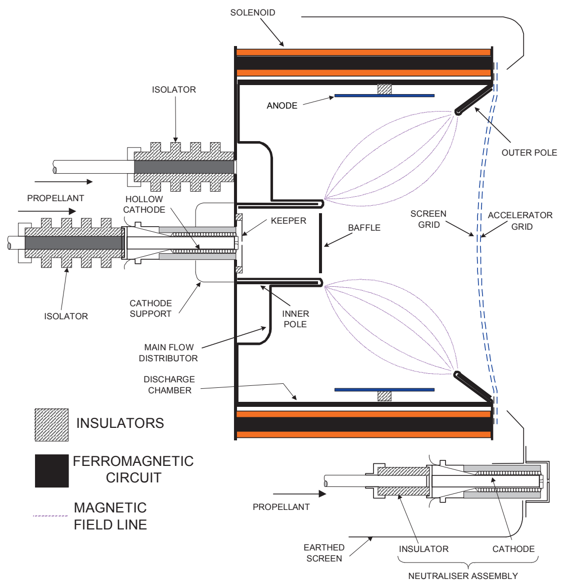

Figure 2. Schematic of T6 Kaufman thruster

The flow of propellant through the cathode and neutraliser is fixed regardless of the thrust level and therefore this does not require individual regulation. The main propellant flow branch is supplied through a flow controller, which adjusts the flow rate to match the desired thrust level.

The discharge chamber is biased at the beam potential and is isolated from the thruster enclosure by eight ceramic isolators.

The ion optics system is a concave twin grid arrangement composed of a graphite accel grid in conjunction with a molybdenum screen grid. The grid assembly is designed to maximise the achievable thrust level and total impulse capability whilst minimising ion beam divergence and thrust vector drift. The grid mounting arrangement of the T6 is based on the T5, and both have been extensively characterised for thrust vector stability and long-term drift.

For the GOCE mission, the T5 thruster was equipped with an integral alignment interface (referred to as the alignment bracket) to allow the geometric axis of the thruster to be canted by up to 2.5 degrees to the spacecraft mounting interface plane. Once integrated to the alignment bracket the assembly is referred to as the ion thruster assembly (ITA). For BepiColombo, the thrusters are mounted on pointing mechanisms.

The Beginning of Life (BoL) performance for the T6 thruster is illustrated in Fig. 3.

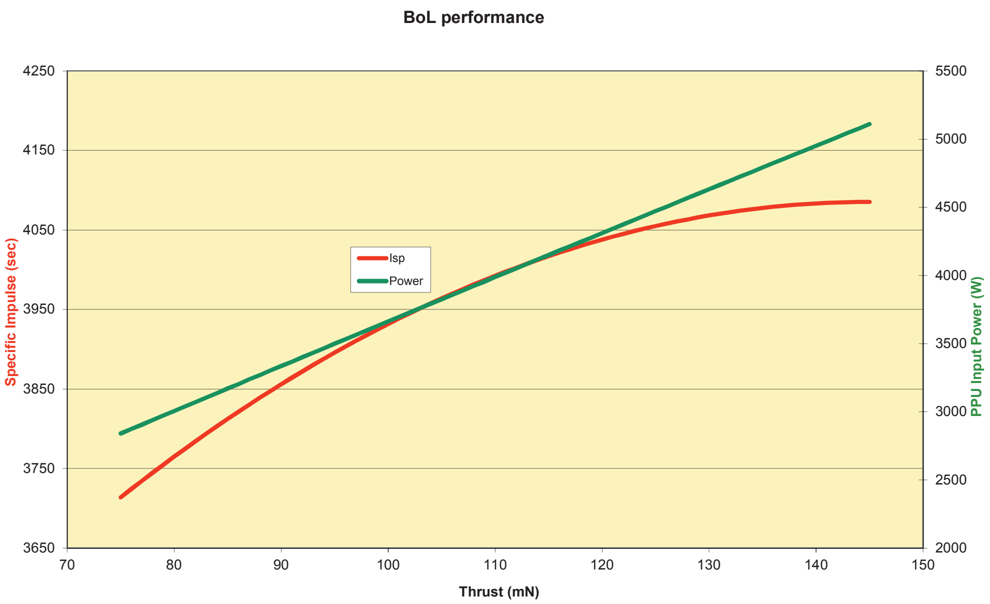

Figure 3. T6 Kaufman thruster performance

B. Power System

The T5 ion engine is powered by the IPCU[5], and the T6 by the PPU. Both units were developed, qualified and supplied by Crisa (Spain) and were designed to provide all of the power supplies and control functions for the thruster and the flow control systems, and are presented in Fig. 4 and Fig. 5.

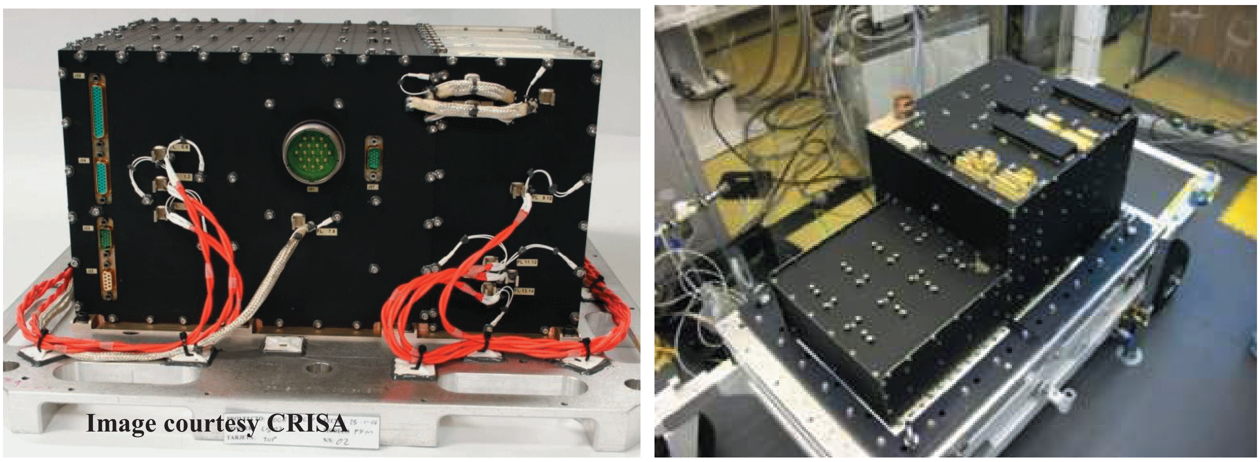

Figure 4. Photograph of IPCU (left) and PPU (right)

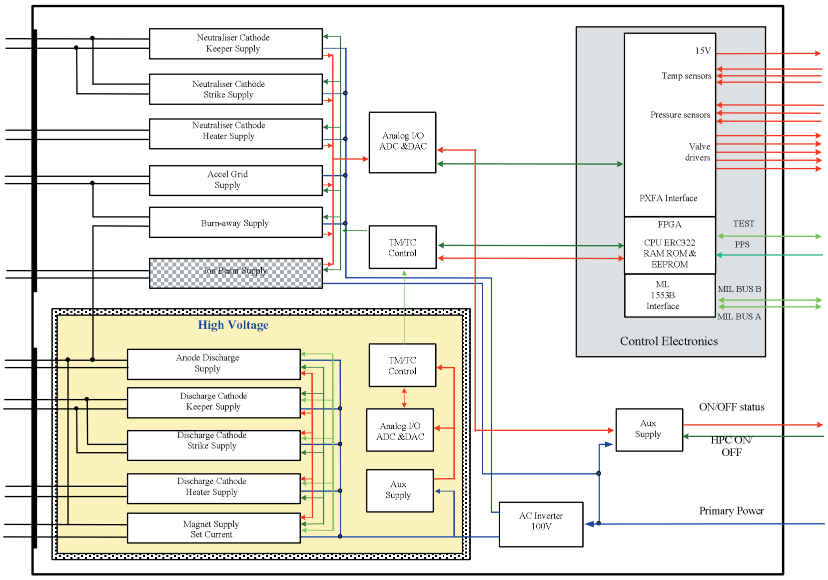

Figure 5. Schematic of IPCU

The Crisa power supply provides the required functionality to power and control the thruster and the flow control system as commanded by the satellite's on-board computer. It also provides the necessary telemetry and telecommand interfaces to control and monitor all thruster functions. It is compatible with Mil Std 1553 communications and a 100V power bus.

The IPCU that was successfully flown on GOCE contained a total of 11 separate power supplies as illustrated in Fig. 2. In order to minimise the mass and volume of the higher power PPU, its design takes advantage of the fact that a number of the thruster and FCU control functions can be supplied by a common power supply without impact to the performance or operation of the system. This results in a total of 5 power supplies being required to power the T6 Thruster. The 5 power supplies are as follows:

- Neutraliser Heater (Primary & Redundant) + Neutraliser Keeper supply. The keeper can be powered by the same supply as the heater, because the two are not required to operate simultaneously.
- Accel Grid Supply.
- Beam Supply.
- Anode + Cathode Keeper supply. In the case of the Cathode keeper, it is operated in parallel with the Anode supply.
- Magnet + Cathode Heater (Primary & Redundant) supply.

Where supply functions share a common transformer within the PPU, the changeover between supplies is only performed when the supply is in a shutdown state i.e. hot switching is eliminated.

The 5kW power supply has been designed to be modular in concept, and in essence consists of two main facilities: a high voltage Beam Supply Module (BSM) and the colocation of the Discharge, Accel and Neutraliser Supplies (DANS). Each DANS also includes all drivers for the XFCUs 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.

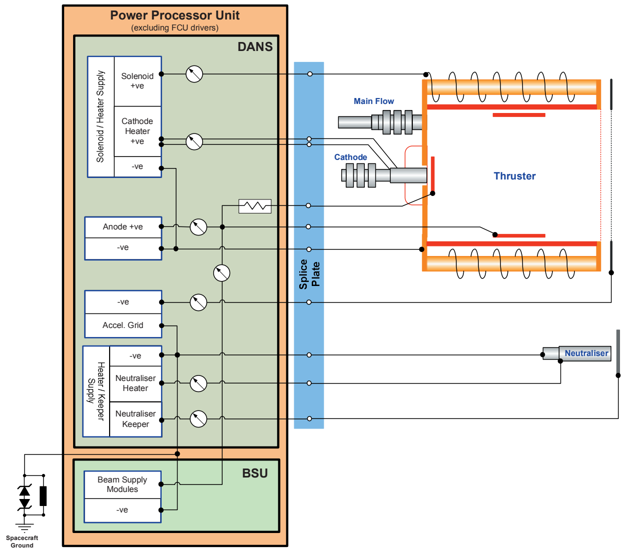

Figure 6. Thruster power supplies schematic

The IPCU contains an integral ERC 32 CPU microprocessor that allowed the implementation of the IPA Thrust Control Algorithm, developed by QinetiQ. The control algorithm[6] allows the IPA to be commanded by a single thrust demand from the spacecraft computer.

The PPU includes a hardware controller capable of autonomous operation, including starting the T6, 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 T6 on, and then command the thruster off at the end of the manoeuvre.

In 2013, Crisa completed a development programme for the IPCU. This programme developed an Engineering Model PPU (known as the IBB) which implemented the multifunction power supplies (concept from T6 PPU) and a new high voltage power supply (by Airbus Defence and Space Germany). The IBB achieved:

- Decrease of ~30% on FM Recurrent cost;
- Decrease of 20% on overall PPU mass.

C. Flow Control System

The T5 ion engine is supported by the PXFA, and the T6 with the FCU. Both units were developed, qualified and supplied by Moog Bradford Engineering (The Netherlands) and were designed to provide constant flowrates to the T5 Cathode and Neutraliser and vary the Main flow according to the demanded thrust level.

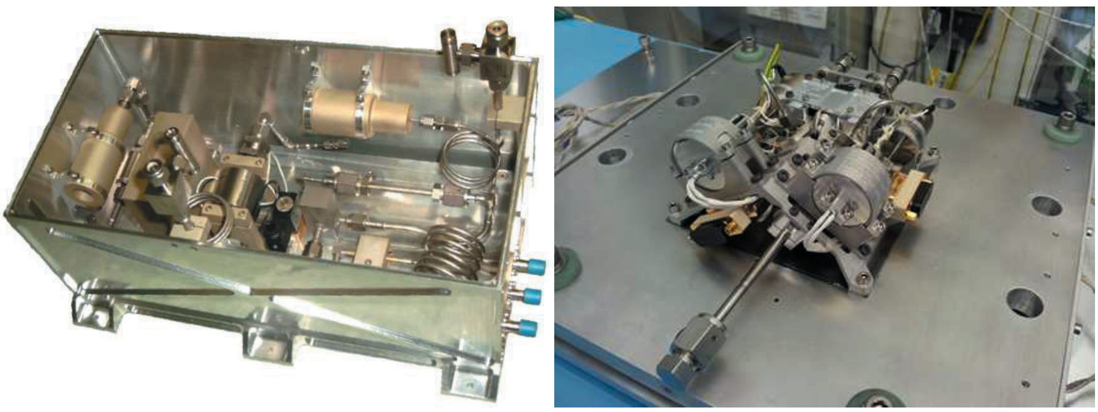

Figure 7. Photographs of PXFA with top removed (left), FCU (right)

Each FCU supplies one thruster with 3 separate xenon propellant feeds to the T6 thruster's Discharge Cathode, Neutraliser Cathode and Main Flows at the required flow rate. The FCU is supplied with xenon at any inlet pressure 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' HPR technology options.

The FCU is comprised of 3 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.

It is configured to ensure failure tolerance by means of 2 in line mechanical inhibits between the common upstream pressure system and any of the 3 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.

It uses a proportional valve in closed loop control with a pressure transducer to control the pressure at the inlet to a fixed restrictor (at constant temperature).

It also 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 3 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.

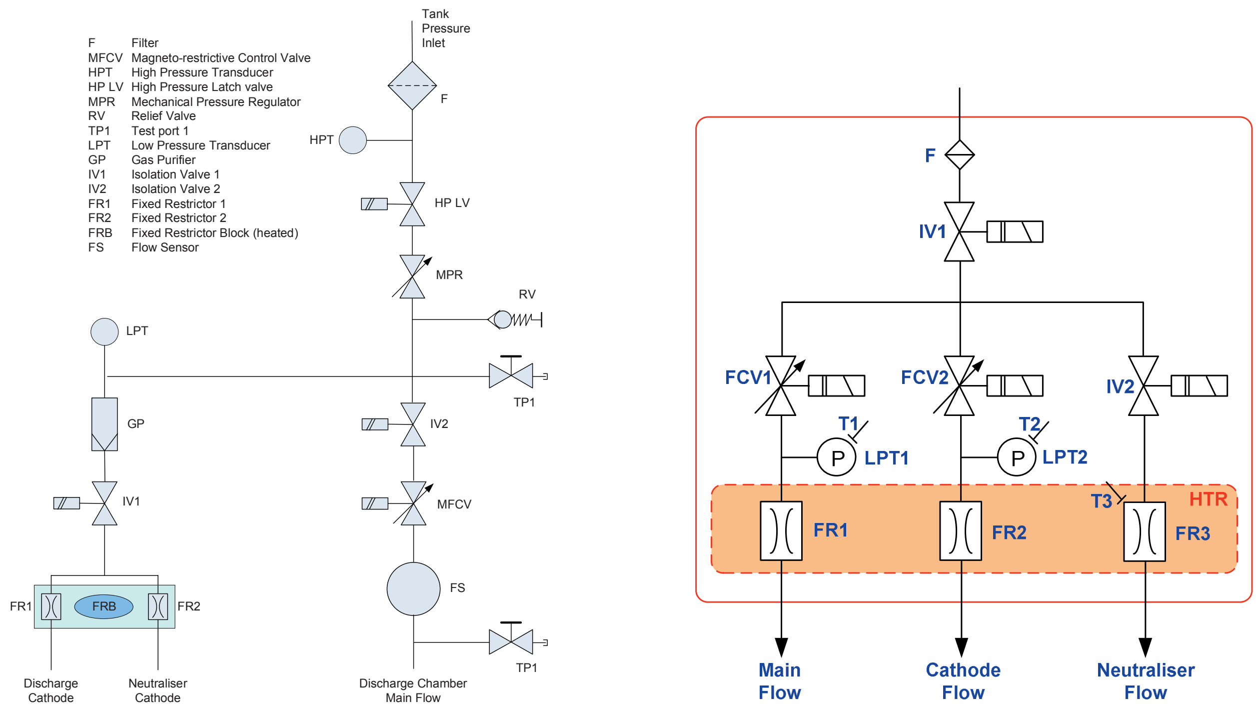

Figure 8. Functional diagram of the PXFA (left) and FCU (right)

E. Harness

At an early stage of the HPEPS and BepiColombo programmes it was recognised that the harnesses between the PPU, thruster and FCU were a critical system element and that it was imperative that the system engineering of these harnesses must be performed concurrently with the thruster. For this reason, QinetiQ leads the definition, design and qualification of the SEPS harness.

The harness design is driven by the high voltage, high current and high temperature operation in conjunction with the need to traverse the moving interface presented by the pointing mechanism. It was also recognised that to allow the mechanism and harness integration to be performed without the thruster present (earlier thruster designs always included an integral flying lead design) it was necessary to introduce connector termination blocks on the thruster.

The harness assembly is composed of the following components:

- T6 Splice Plate (TSP) (located on the satellite structure);
- T6 mobile harness: from T6 TSP (routed across the mechanism mobile interface) to the thruster terminal blocks ;
- Fixed harness: from PPUs to TSPs;
- FCU Harness: from PPU to FCU.

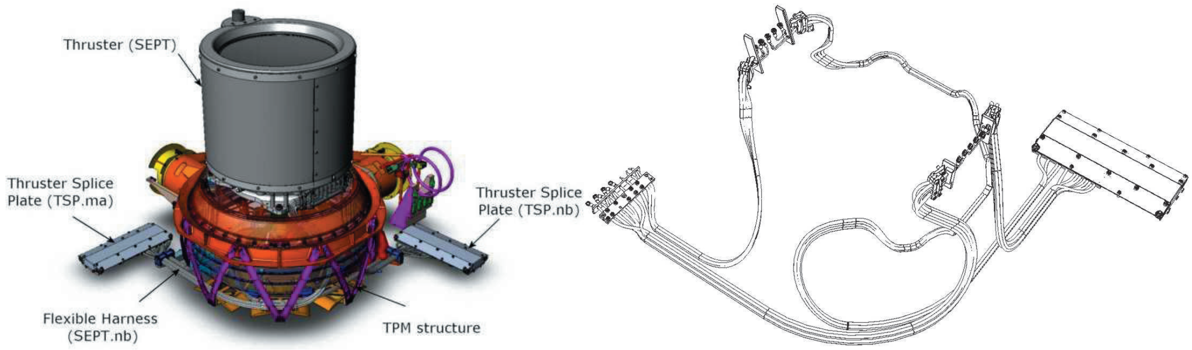

Figure 9. BepiColombo TPM, T6 & mobile harness (left) and mobile harness & TSP (right)

F. Pipework

Similar to the harness, the fluidic connections between the FCU and the T6 thruster were deemed to be a critical system element and concurrent engineering design of this pipework was performed alongside the thruster, FCU, pointing mechanism and spacecraft. As with the harness, QinetiQ led this design and development programme, to ensure an optimised, system-level approach.

The pipework design is driven by low mass flow rates, very low global leak rates and high temperature operation in conjunction with the need to traverse the moving interface presented by the pointing mechanism. As with the harness, it was also recognised that a two-piece design (mobile and fixed) allows for pipework integration to the mechanism to be performed without the thruster being present.

For each FCU-T6 thruster branch, the pipework is composed of the following sub-assemblies:

- Fixed pipework routing over the s/c structure
- Mobile pipework routing over the pointing mechanism

Depending on the position of the FCU with respect to the thruster and pointing mechanism the fixed section of the pipework can be eliminated from the design completely.

Each pipework sub-assembly consists of a set of three tubing sub-assemblies (Main, Cathode and Neutraliser flows) manufactured from 1/16th-inch (1.58 mm) AISI 316L stainless steel seamless tubing with a 30 gauge (0.30 mm) wall thickness. This material has a sufficiently high fatigue strength to permit it to withstand the flexing in the mobile pipework as a result of pointing mechanism movements.

D. Pointing Mechanism

RUAG Space Austria (RSA) has an on-going activity to design and qualify specifically for T6 an Electric Propulsion Pointing Mechanism (EPPM) design and configuration that is at present not specific to a particular European telecommunication platform. There is also a parallel activity under BepiColombo for the design, qualification and manufacture of the flight thruster pointing mechanisms (TPMs). The developments are separate because of the different angular pointing requirements of the two missions.

The EPPM consists of a mobile platform interfacing with a single T6 thruster. The thruster can be pointed around two perpendicular axes due to a two-axis rotation mechanism and dedicated drive units. The mobile plate is kept locked in a specific reference position during the launch phase by a Hold Down and Release Mechanism.

The main parts of the EPPM are:

- Mobile Platform;
- Two-Axes Pointing Mechanism;
- Hold-Down and Release Mechanism (HDRM), same as the BepiColombo HDRM;
- Damping system underneath the HDRM;
- Harness and piping support for the T6 Thruster.

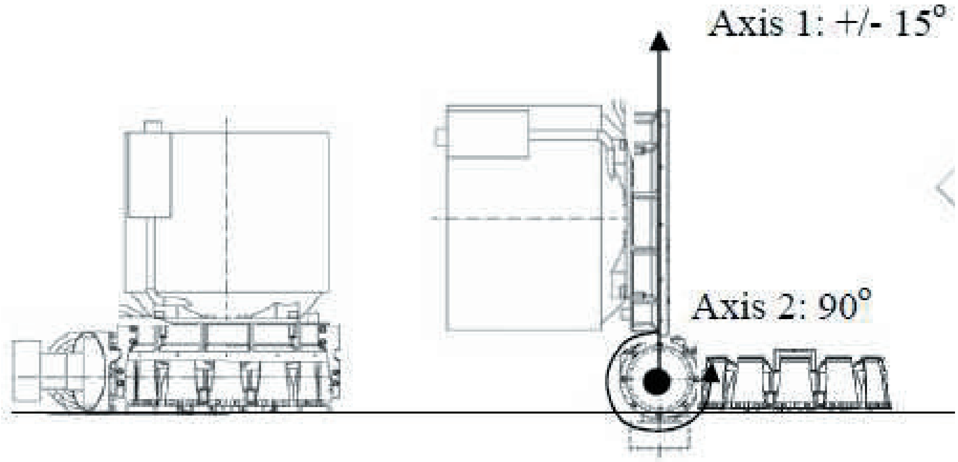

Figure 10. Single thruster EPPM design in stowed and maximum deployed configurations

III. System Architectures and Solutions

QinetiQ's ion engines and the supporting building blocks described in Section I can be configured into several alternative schemes. These schemes are described below, and where currently being exploited in flight or ground devleopment, further details are also described. 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 very different pointing requirements, these mechanisms are not common to HPEPS and SEPS. The SEPS boundary is defined as excluding the pointing mechanism. For HPEPS a pointing mechanism is being developed by RUAG Space Austria (referred to as the electric propulsion pointing mechanism or EPPM) – this is further described below along with the common building blocks: T6, PPU, FCU, harnesses and pipework.

The system architectures are broadly split as follows:

- Single Thruster Chain (as used by GOCE);
- Baseline orbit raise and station keeping (as developed on HPEPS);
- Fully-redundant Four Thruster Chain (as developed on BepiColombo);
- Alternative orbit raise and station keeping architectures.

E. 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 Systems for the GOCE mission. 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. This architecture was successfully used and flight data is presented below.

A schematic of the GOCE Ion Propulsion Assembly (IPA) architecture[3] is presented in Fig. 11.

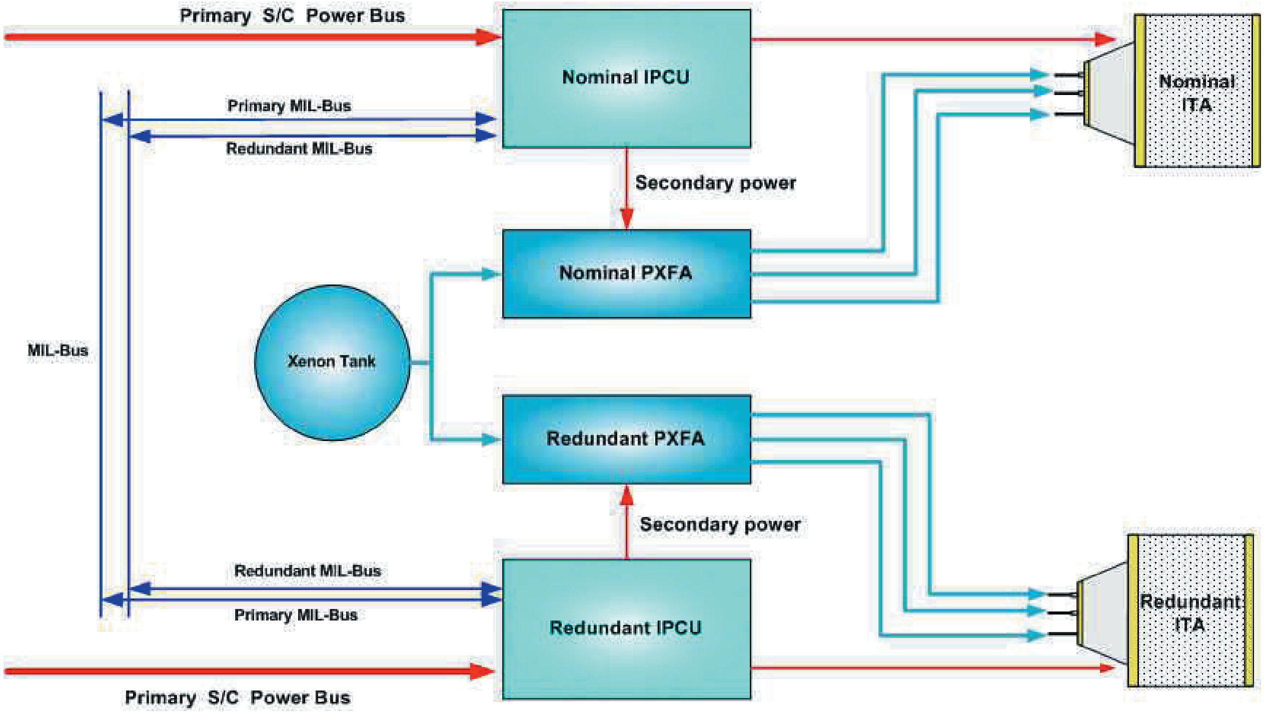

Figure 11. Schematic of GOCE IPA

It is comprised of two identical branches, one in cold redundancy, and in total being comprised of the following principal elements:

- 2 x T5 Ion engine from QinetiQ;
- 2 x IPCU from Crisa;
- 2 x PXFA from Moog Bradford.

Commissioning of both branches of the IPA was performed between the 30th of March and the 3rd of April 2009, each branch requiring 2 days. The data from this commissioning from one of the branches is presented in Fig. 12. Initially an orbit at 3mN was performed followed by an orbit at 20 mN. In all cases the ITA performance was identical to that encountered during ground system acceptance testing.

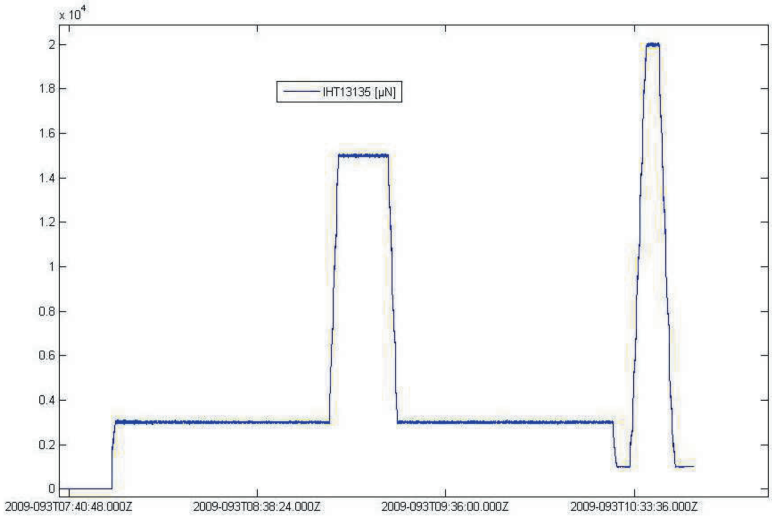

Figure 12. Initial IPA commissioning data

Immediately following launch it became apparent that the atmospheric density at the GOCE orbital altitude was significantly lower than anticipated during the development, qualification and acceptance test programme. This has resulted in the majority of the IPA operations being performed at the lower end of the thrust range, between ~0.6 to 8.0 mN, the resultant lower Xenon usage at these thrust levels enabled the overall GOCE mission to be extended to be more than twice its planned 22 month mission. The GOCE spacecraft commenced full science data acquisition in September 2009 and continued until 21 October 2013 when the Xenon fuel was finally exhausted and the GOCE spacecraft deorbited on 11th November 2013. Prior to deorbit the redundant thruster branch was operated and found to have same performance after 4 years hibernation.

Over the GOCE mission the IPA has operated continuously, with the exception of a short period in the latter half of February 2010 when the spacecraft experienced an anomaly that resulted in IPA operations being suspended for the duration of the anomaly investigations. Overall the prime branch of the IPA was operated for more than 36,000 hours. An example of the IPA demanded thrust is presented in Fig. 13 which shows 6 orbits on the 31st October 2009. The thrust demand varies between 3.5 mN to 0.7 mN. Also presented on this figure is the Accel grid current (in red) which also varies with thrust level as expected. The peak thrust demand is associated with the spacecraft passing over the Earth's equator and minimum as the spacecraft passes over the poles.

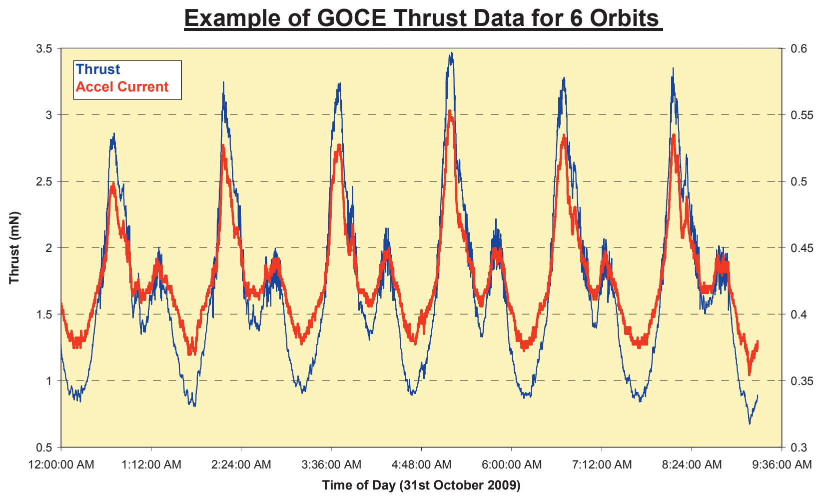

Figure 13. Example of IPA thrust demand

F. Baseline Orbit-raising and Station-keeping

During the initial stages of QinetiQ's 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. 14 and comprises:

- 4 x T6 thrusters;
- 4 x Xenon Flow Control Unit (XFCU) assemblies, each dedicated to a specific T6;
- 1 x PSCU, internally redundant, incorporating two sets of DANS;
- 4 x Splice plates, harness and pipe work;
- 4 x EPPM, one per T6.

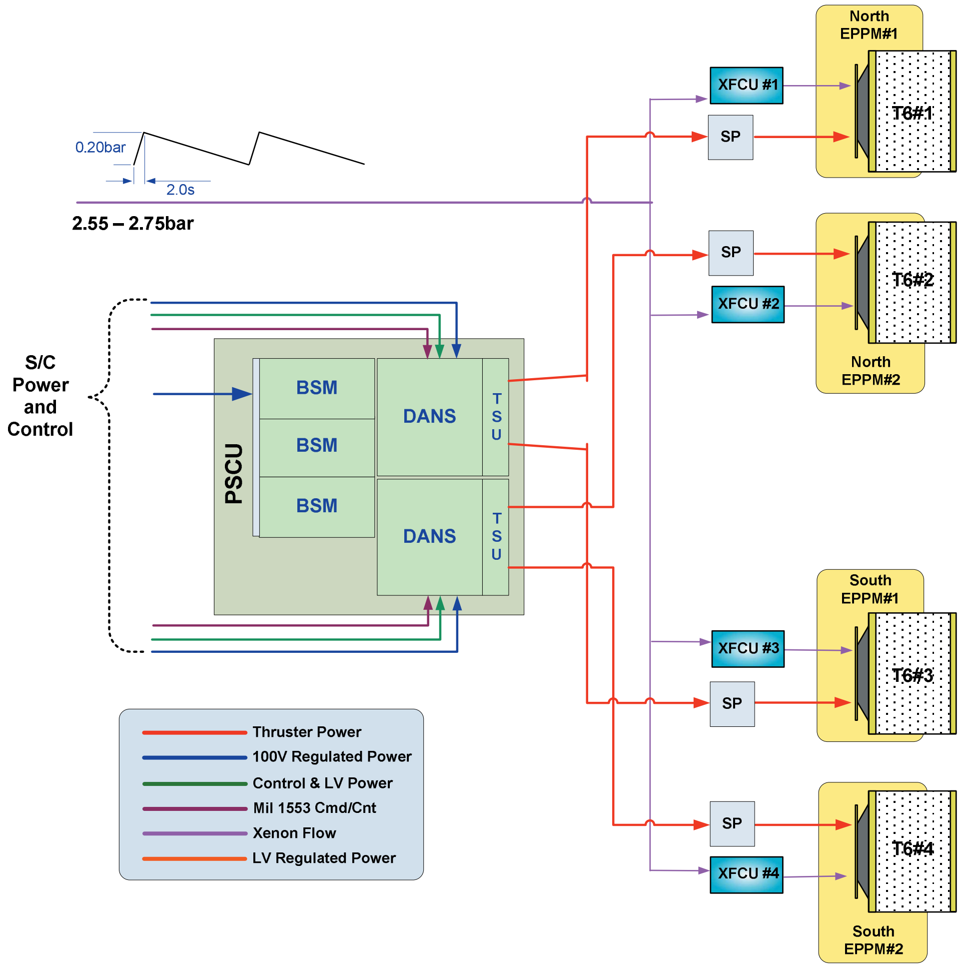

Figure 14. Architecture for commercial communications satellite (NSSK and orbital repositioning).

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 XFCUs 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 and, therefore, only two modules are required to meet the station keeping EP requirement. The third BSM provides a failure tolerant 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 PSCU 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.

The output of the beam supply can also be switched to a test port used during spacecraft level AIV. This means that during spacecraft level testing all of the HPEPS electrical and fluidic interfaces and unit functionality can be verified by operating the thruster discharges. Note that with a gridded ion engine the anode and neutraliser discharges may be operated without extracting an ion beam. This verifies that all the electrical and propellant interfaces in the system are correct. The beam supply can also be enabled and driven into an EGSE load with the discharges operational. In this manner the PSCU can be operated at full power and all fluidic and electrical interfaces verified without the need to extract an ion beam. This means that the vacuum chamber in which thruster testing is performed does not need to be designed to cope with a high power ion beam and all of the additional concern this entails, e.g. spacecraft surface contamination by target sputter material can be eliminated.

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 supporting single thruster firing at any one time.

G. Fully-redundant Four Thruster Chain

The full versatility of the T6-based 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 thruster simultaneous operations at a combined thrust level of 290 mN, 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. The SEPS architecture is illustrated in Fig 15, and consists of the following equipment:

- 4 x T6 ion engines from QinetiQ;
- 2 x PPUs from Crisa consisting of two sets of DANS each;
- 4 x FCUs from Moog Bradford:
- 4 x splice plates, harness and pipework from QinetiQ;
- *Pointing Mechanism from RUAG (not considered part of QinetiQ's system for BepiColombo).*

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 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.

The performance of a T6 thruster with PPU and FCU has been evaluated through coupling tests at QinetiQ.

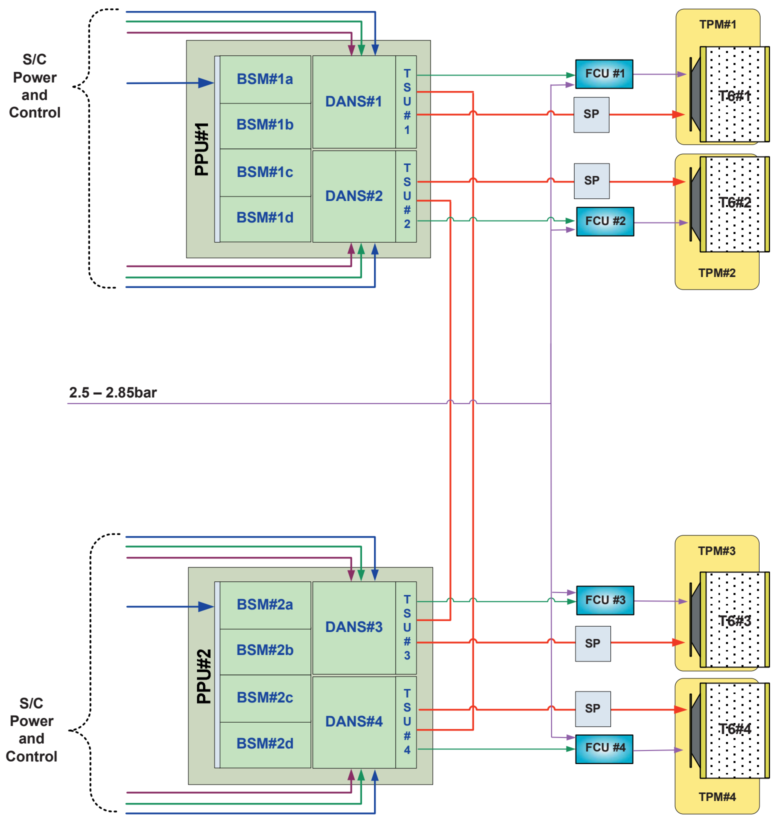

Figure 15. SEPS architecture providing guaranteed simultaneous thruster operation and impulse sharing

H. Alternative Orbit-raise and Station-keeping Architectures

The modularity adopted at the outset to QinetiQ's development of the T6-based systems (and SEPS) leads to a range of other configurations, including the following:

- Architecture 1: 290mN for orbit raise only;
- Architecture 2: 290mN for orbit raise and SK, with maximum reliability;
- Architecture 3: 290mN for orbit raise and SK, with reduced reliability;
- Architecture 4: 435mN operation;
- Architecture 5: Simultaneous firing of four engines.

Architecture 1: 290mN for orbit raise only

In Fig. 16 we present an EP system configuration that would enable 2 thrusters to be fired simultaneously. In nominal conditions, i.e. in the absence of any system element failure, the architecture allows the simultaneous operation of 2 thrusters, and is therefore suited to orbit-raising applications.

This is similar to the system used on GOCE, although at the higher power levels applicable for the T6 thruster and therefore also the appropriate building blocks.

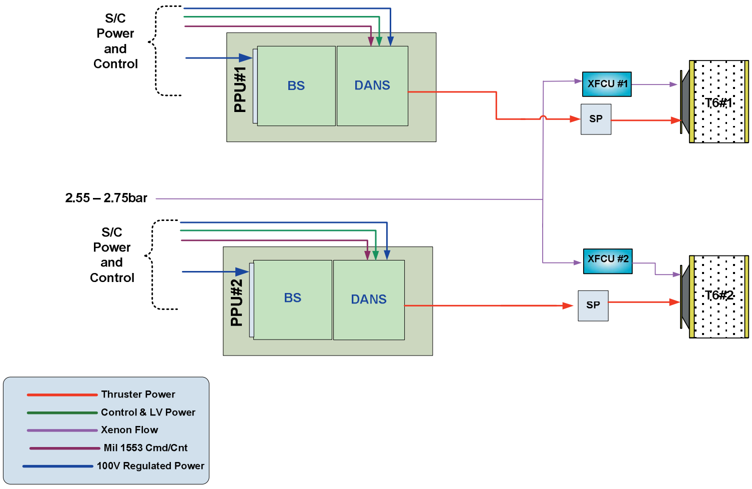

Figure 16. Architecture 1: to support simultaneous firing of 2 thrusters

Architecture 2: 290mN for orbit raise and SK, with maximum reliability

Architecture 2 is the same as the BepiColombo SEP architecture, shown in schematic form in Fig. 15, will guarantee the operation of any single thruster at up to 145mN, and any pair of thrusters at up to 145mN each (290mN in total).

The thruster switch units (TSU) in each PPU enables either PPU to operate any of the 4 thrusters. Also, the TSU of one PPU can be operated from the adjacent PPU and therefore the output of either can be a disconnected in the event of a complete failure of a PPU.

Architecture 3:290mN with reduced reliability

In this option the PPUs are simplified by removing the TSUs on the outputs, in turn eliminating the cross-strapping harness. This configuration will guarantee the operation of any single thruster at up to 145mN and either the north/south#1 pair or the north/south#2 pair of thrusters at up to 145mN each (290mN in total). The removal of the TSUs and cross-strapping harnesses reduces system complexity and dry mass.

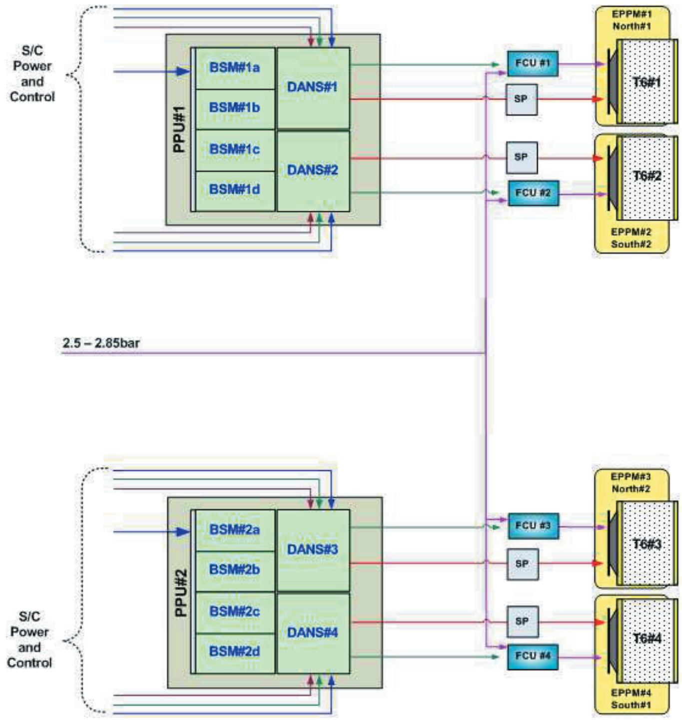

Figure 17. Architecture 3 schematic (290mN with reduced reliability)

Architecture 4: 435mN operation

This is shown in schematic form in Fig. 18, includes three, non-redundant PPUs. The same PPU modular building block are employed, but only a single functional string is included in each. Reducing the volume and mass of each individual PPU. This configuration will guarantee the operation of any single thruster at up to 145mN and either the north/south#1 pair or the north/south#2 pair of thrusters at up to 145mN each (290mN in total). This architecture also facilitates the simultaneous operation of 3 thrusters providing a total thrust level of 435mN in the nominal condition.

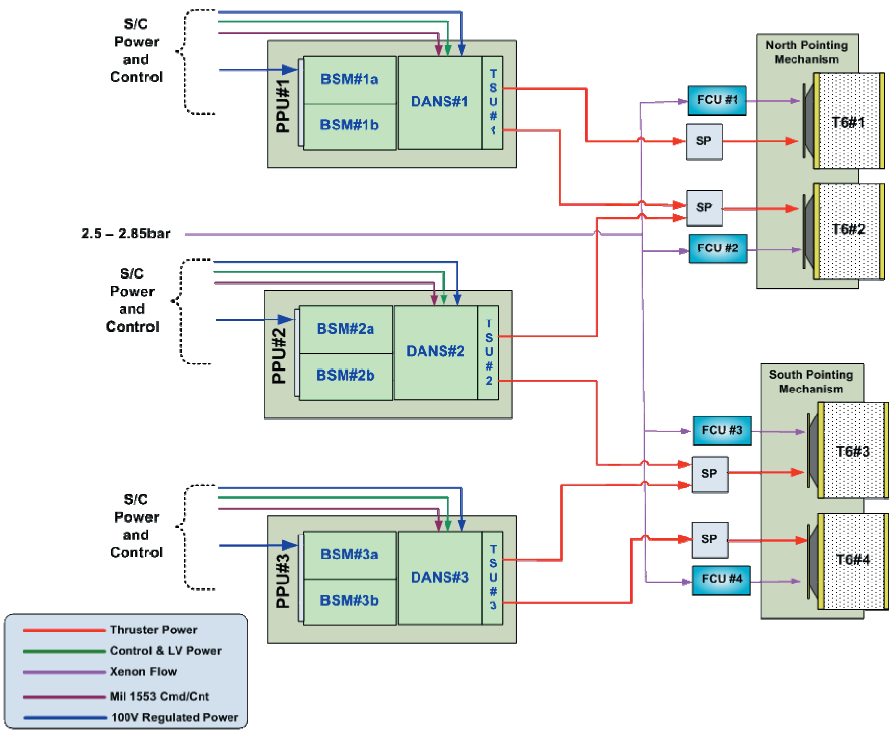

Figure 18. Future EP architecture based upon an ongoing PPU development

Architecture 5: Simultaneous firing of four engines

In Fig. 19 we present an EP system configuration that would enable 4 thrusters to be fired simultaneously. In nominal conditions, i.e. in the absence of any system element failure, the architecture allows the simultaneous operation of 4 thrusters in orbit-raising mode.

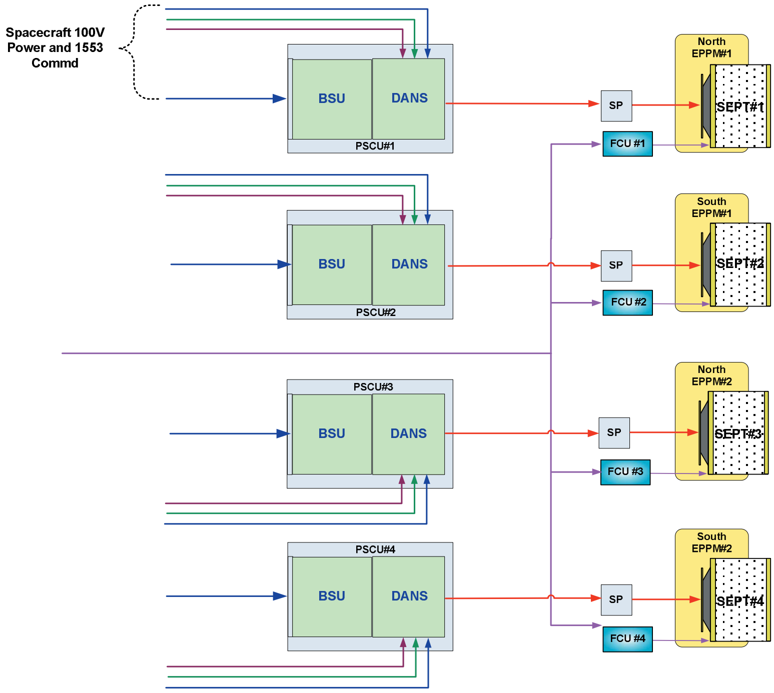

Figure 19. Future EP Architecture schematic – to support simultaneous firing of 4 thrusters

IV. Comparison of System Architectures

Table 1 presents a summary of the architecture options and the baseline HPEPS architecture presented above.

Table 1. T6 EP System Architecture Summaries

Reference	Baseline HPEPS	No. of T6 & FCU	No. of PPU	System Mass (kg)	Max. no. of thrusters fired at same time	Max. thrust (mN)	Input Power (kW)
Baseline	Baseline orbit raise and SK	4	1	131.2	1	145	5
Arch #1	Orbit raise only, 290mN	2	2	65.0	2	290	10
Arch #2	290mN with maximum reliability	4	2	138.8	2	290	10
Arch #3	290mN with reduced reliability	4	2	137.0	2	290	10
Arch #4	435mN operation	4	3	108.0	3	435	15
Arch #5	Simultaneous firing of four engines	4	4	130.0	4	580	20

V. QinetiQ System Evolution Programme

QinetiQ and Crisa are actively engaged in developing the building blocks for the systems described in this paper. In general, these relate to:

- Industrialisation of the T6 and PPU to achieve improvements on the unit recurring cost;
- Development of a higher specific power thruster, the ring cusp ion engine.

I. Industrialisation of T6 and PPU

To assist the T6 EP systems entry to the telecommunication and navigation markets where recurring price is a major selection factor both QinetiQ and Crisa (supported by Airbus Defence and Space Germany) have entered into industrialisation activities to reduce the recurring cost of the thruster and PPU respectively. The industrialisation activities are currently funded under ESA’s European Galileo Evolution Programme (EGEP).

Cost reduction of the T6 thruster is primarily being achieved by introduction of out-sourcing for component manufacture.

The cost reduction of the PPU is being achieved by a range of design changes including:

- Simplification of PPU control and power architecture;
- Optimization of power supplies control;
- Integration of discrete logical functions into a single FPGA;
- Use of new high voltage interfaces;
- Redesign of high voltage (HV) power supply to increase the power density and minimize the use of HV potting.

J. Development of T6 Ring Cusp Thruster

The development of a T6 thruster using a Ring Cusp discharge chamber is currently underway at QinetiQ supported by Mars Space Ltd. The results of initial tests of a prototype T6 Ring Cusp thruster are reported in Ref 7.

A schematic of the Ring Cusp thruster is shown in Fig. 20.

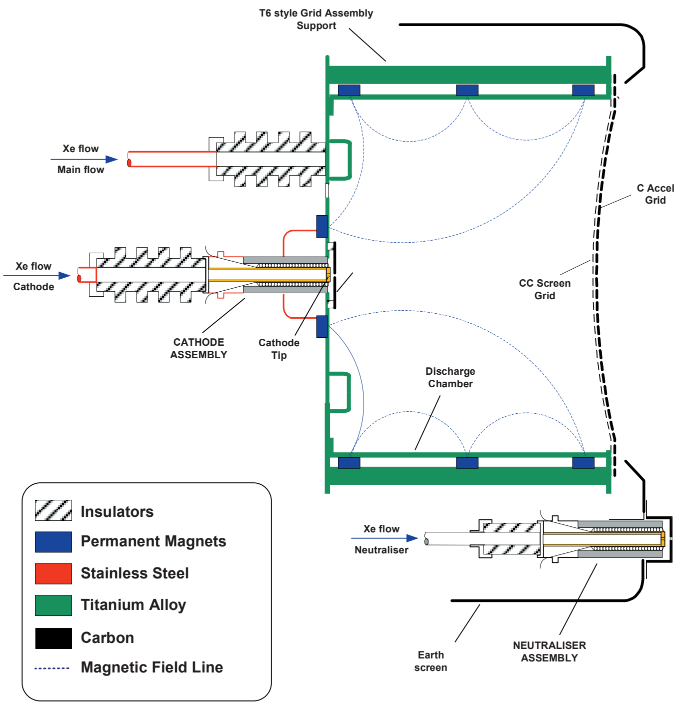

Figure 20. Schematic of T6 Ring Cusp thruster

In contrast to the Kaufman thruster design, shown in Fig. 2, a number of simplifications to the design are made:

- Solenoids are remove and replaced by permanent magnets;
- Ferro-magnetic structure eliminated ;
- Discharge baffle eliminated;
- Discreet anode eliminated.

The reduction in the number of components in the T6 Ring Cusp thruster give recurring cost reductions compared to the existing T6 Kaufman thruster. In addition the T6 Ring Cusp thruster allows one of the five power supplies in the PPU to be eliminated, this solenoid supply is also a high voltage referenced supply and consequently its removal reduces mass and heat dissipation in the PPU – overall enabling recurring cost reductions for the Ring Cusp PPU to be realized.

In addition to offering lower recurring cost the T6 Ring Cusp thruster also has an improved electrical efficiency and therefore reduced power to thrust ratio W/mN.

Even greater reductions to the power to thrust ratio (often referred to as Specific Power (SP)) can be achieved by operating at lower beam and Accel voltages. Fig. 21 presents relationship for Isp as a function of beam voltage (shown in BLUE). Two SP relationships are presented, one for a Kaufman style discharge chamber (shown in PINK) and the other for a Ring Cusp discharge chamber (shown in BLACK).

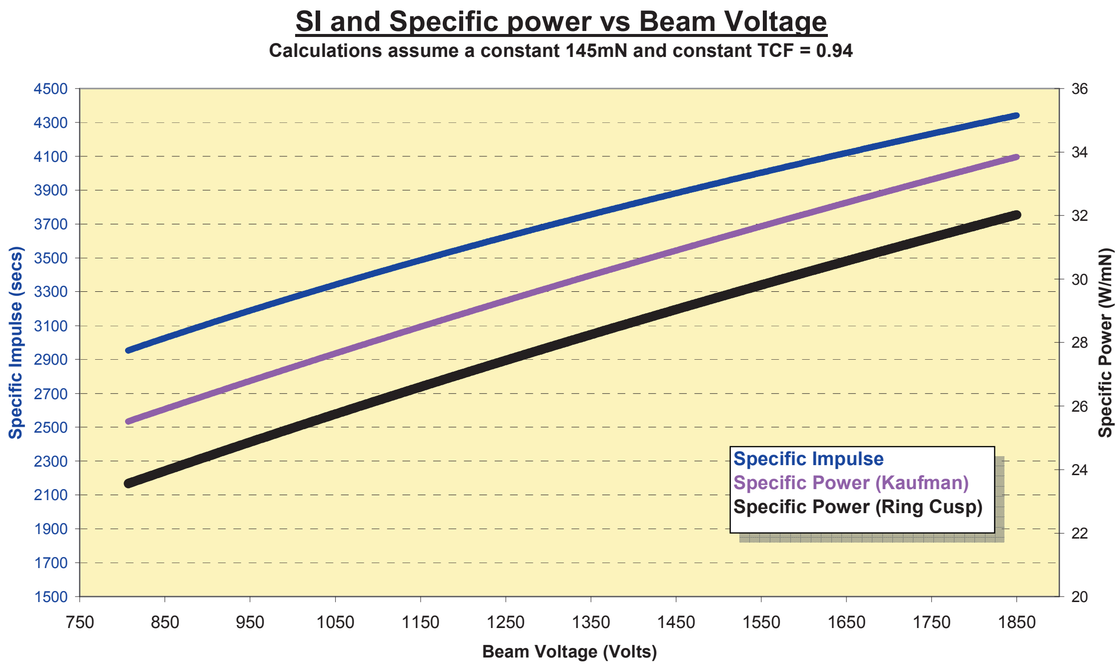

Figure 21. Isp and SP as a function of beam voltage

The T6 EP systems for BepiColombo (SEPS) and the HPEPS proposed for telecommunications and navigation are operated at a beam voltage of 1850V and an Accel Voltage of -265V, in order to achieve a high Isp figure (>4000s). If a higher thrust from a limited input power was required we can see from Fig. 21 that operation at lower beam voltages would be required. Isp and SP are directly related. Increasing SI unavoidably incurs a higher SP (W/mN). Consequently maximising the thrust capability with a finite available power level means that the Isp of the system must be compromised in order to reduce the SP and therefore increase the thrust capability.

Reported in Ref 7, the T6 Ring Cusp thruster achieved ~24.5 W/mN (at 3200s Isp), an improvement in SP of approximately 35%, when operated at a beam voltage of 1000V and an Accel Voltage of -1115V, compared to a T6 Kaufman thruster operated at its nominal beam voltage of 1850V and an Accel Voltage of -265V and an Isp of 4300s.

VI. Acknowledgments

We acknowledge the support from the GOCE and BepiColombo teams within ESA, Airbus Defence and Space UK and Airbus Defence and Space Germany. In addition, we acknowledge Crisa & Airbus Defence and Space Germany and Moog-Bradford Engineering for their efforts in developing the PPU and FCU. We also acknowledge ESA(TEC), and UKSA, Innovate UK and CDTI for their financial support for the development and qualification of HPEPS and for the industrialisation of the T6 thruster and PPU.

VII. References

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