# BepiColombo SEPS Coupling Test Architecture and Coupling Test Performance Results

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**Abstract: This paper presents the test set-up and results of the BepiColombo SEPS Coupling Test conducted at QinetiQ Farnborough in 2014 and the subsequent coupling test results of the PCDU (Power Conditioning Distribution Unit), Battery and RIU (Remote Interface Unit). As part of the validation of the BepiColombo SEPS interfaces, a dedicated SEPS Coupling Test was performed, this included the PPU (Power Processing Unit), FCU (Flow Control Unit) and the SEPT (Solar Electric Propulsion Thruster). The system was coupled together and operated at full power with a number of diagnostics configured to demonstrate compatibility, results of which are summarised in this paper. An extension to this test included other key items of the MTM (Mercury Transfer Module), such as the PCDU, Battery and the RIU. The full chain was operated at 10KW (5KW into a load rack). Key system sequences were tested and the main power and control interfaces monitored using diagnostics, the results of which are summarised in this paper.**

## Nomenclature

BOL = Beginning of Life
DANS = Discharge Accel and Neutraliser Supply
EOL = End Of Life
FCU = Flow Control Unit
HPEPS = High Power Electric Propulsion System
PCDU = Power Conditioning Distribution Unit
PPU = Power Processing Unit
RIU = Remote Interface Unit
SEPS = Solar Electric Propulsion System
SEPT = Solar Electric Propulsion Thruster

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# I. Introduction

BepiColombo is the joint European/ Japanese scientific mission to Mercury[8], the innermost planet of our solar system. The mission features a special "3 in 1" spacecraft, consisting of an assembly of 2 orbiters, and a transfer vehicle. The MPO is the European Mercury Planetary Orbiter carrying the ESA payload, while the MMO is a second spacecraft, the Japanese Mercury Magnetospheric Orbiter built under the auspices of JAXA. Both scientific spacecraft's are brought to Mercury by the Mercury Transfer Module (MTM) containing propulsion and power systems for the cruise phase.

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, BepiColombo[1], where the system will provide the impulse necessary during the inter-planetary cruise. The BepiColombo composite spacecraft is illustrated in Fig. 1.

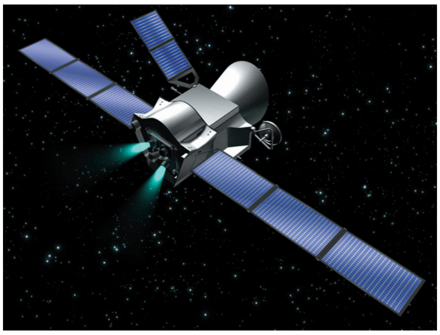


**Figure 1. Artist's impression of BepiColombo Composite (image courtesy of ESA)**

QinetiQ has completed a successful Technology Demonstration Activity (TDA)[2;3] of a T6 thruster to retire the high risks associated with Europe's first use of electric propulsion for a major science mission. This activity investigated new requirements such as sustained, stable operation over long thrust arcs, the simultaneous operation of two thrusters at high power in close proximity, low thrust interruption rates and the harsh thermal environmental requirements due to the proximity to the Sun.

The Solar Electric Propulsion System (SEPS) for BepiColombo was awarded to QinetiQ in 2009 following an open competition. SEPS is based on the HPEPS and benefits from its wide operating range, robust design and its ability to be easily adaptable to a wide range of platforms and applications.

# II. System Architecture

## A. Common Building Blocks

The QinetiQ electric propulsion systems are composed of the T6 thruster, a power supply and control unit (PPU – developed by Airbus DS), Xenon flow control units (FCU – developed by Moog-Bradford Engineering) and associated harnesses. These hardware elements are common to both HPEPS and SEPS. In addition the consortium members are the same as the successful GOCE programme[4,5] and build on the heritage and experience developed during this programme.

The resultant QinetiQ electric propulsion system is capable of achieving a wide range of operational requirements, from low to high power applications whether constant thrust level, multiple thrust levels or variable thrust level operation is required.

Thrust vectoring is achieved in both systems via pointing mechanisms but due to the very different pointing requirements these mechanisms are not common to HPEPS and SEPS. The SEPS system boundary excludes the pointing mechanism and consequently is not covered in this paper. 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 and FCU.

### *1. QinetiQ T6 Thruster*

The T6 thruster was first designed in 1995 to meet the needs of science and telecommunication missions in the 21st century. The thruster was developed using experience and scaling laws identified during the early stages of the QinetiQ T5 development. Since 1995, the T6 design has undergone extensive development to optimise performance and lifetime and make effective use of advances in materials for insulators, grids and the ionisation chamber. All of this has been achieved and demonstrated within the BepiColombo Technology Demonstration Activity (TDA), the Grid Technology Research Programme (TRP) and the HPEPS development and qualification programmes, sponsored by ESA.

The T6 thruster is shown schematically in Fig. 2. It is of conventional Kaufman configuration[6], 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.

A 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.

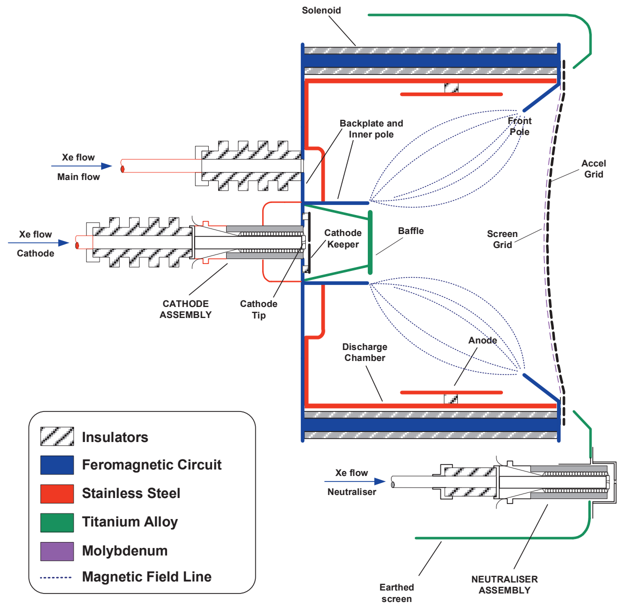



**Figure 2. Schematic of T6 thruster**

### *2. T6 Thruster Harness*

At an early stage of the HPEPS programme it was recognised that the harness between the thruster and the PPU was a critical system element and that it was imperative that the system engineering of the harness must be performed concurrently with the thruster. The 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 in isolation to the thruster (earlier thruster designs have always included an integral flying lead design) it was necessary to introduce a connector block on the thruster.

To maximise heritage the harness design employs the same commercially available ePTFE (corona resistant) coaxial high voltage cable technology qualified on the GOCE programme with the T5 ion thruster.

### *3. Power Supply and Control*

The Power Supply and Control Unit (PPU) provides the required functionality to power and control the T6 thruster and the Flow Control Unit (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.

In order to minimise the mass and volume of the PPU its design takes advantage of the fact that a number of the thruster and XFCU 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. This is illustrated in Fig. 3.

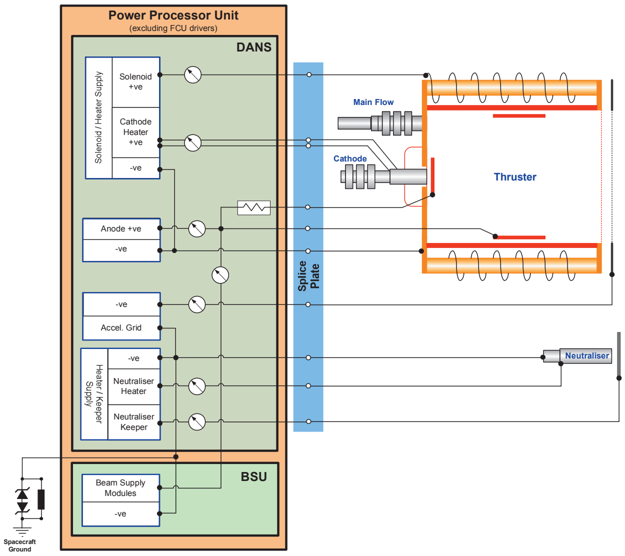



**Figure 3. Thruster power supplies schematic**

The 5 PPU thruster supplies are as follows:

1. Neutraliser Heater (Primary & Redundant) + Neutraliser Keeper supply
   The keeper can be powered by the same supply as the heater as the two are not required to operate simultaneously.
2. Accel Grid Supply
3. Beam Supply

4. Anode + Cathode Keeper supply
   In the case of the Cathode keeper, it is operated in parallel with the Anode supply.
5. Magnet + Cathode Heater (Primary & Redundant) supply

The Cathode heater and the solenoids share the same supply, as they are not required to operate simultaneously.

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.

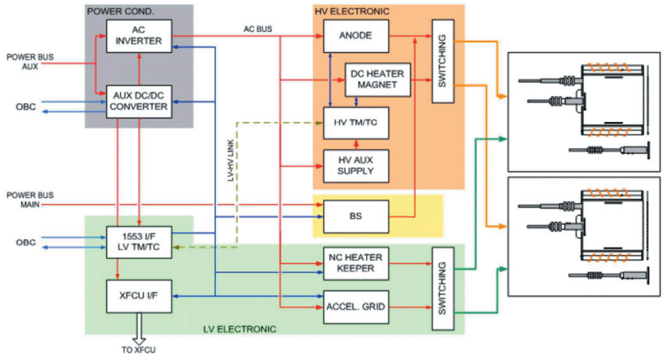



**Figure 4. Schematic of PPU architecture**

In addition to the above nominal functionality, the PPU design makes use of the high current capability of the Anode supply to provide a grid clearance function. This functionality means that should a conductive particle cause an electrical short between the Accel and Screen grids, and in the event that this particle does not 'self-clear', the Anode supply can be switched to the Accel grid to 'burn-away' the contaminant.

The PPU architecture is illustrated in Fig. 4. The PPU design incorporates a Faraday housing as was employed in the IPCU for GOCE. In this design the high voltage referenced power supplies; i.e. the anode, solenoids, cathode keeper and cathode heater supplies, are enclosed in a housing which is floated at beam potential and the whole unit is isolated from the unit chassis via conventional ceramic isolation techniques. This concept has 2 major advantages. The first is that it virtually eliminates difficulties associated with parasitic elements within the high voltage (HV) referenced supplies, e.g. unexpected current paths for the common mode currents are contained within the enclosure. Secondly the power supplies can be readily designed without having to deal with any HV isolation design complexities, i.e. isolation is achieved once using simple ceramic stand-offs, because the components within the supplies are referenced to the HV enclosure.

The PPU is a single item of equipment in the T6 HPEPS. Comprising of 2 main functional elements, the beam supply and the DANS [2off].

Beam supply: The beam supply is comprised of up to 5 parallel beam supply modules. In the case where 3 beam modules are required to fulfil the mission requirement a 4th beam supply module is also included for redundancy. As such the beam supply is tolerant of a single Beam Supply Module failure, i.e. 4 for 3 parallel redundancy.

DANS: There are 2 DANS assemblies within the PPU, providing 2 for 1 parallel redundancy. The outputs of each DANS are switched to either one of the north thrusters or one of the south thrusters.

The PPU is able to be a single piece equipment, with significant mass and cost savings, and provides all the necessary redundancy and failure tolerances required within that equipment. This also enables the S/C level thermal control to be simplified because the heat loads are always in the same place, i.e. provision does not need to be made for dissipation in two locations.

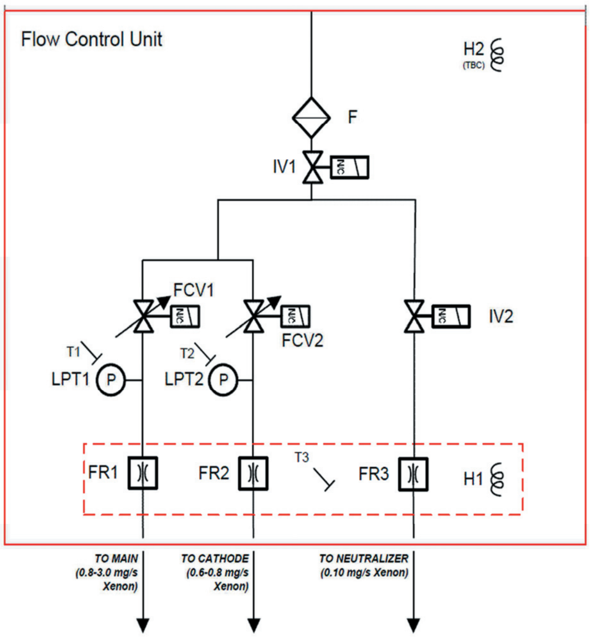



**Figure 5. Functional block diagram of the FCU**

### *4. Flow Control Unit*

During thruster operation the Flow control unit (FCU) when powered will deliver propellant at the required mass flow rates to a single thruster.

The FCU 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).

The pressure based control method is a simple and robust solution for the Main and Cathode flow control.

- It is a direct method of control based on the basic parameters determining the mass flowrate, i.e. pressure, temperature and the physical restriction.
- Pressure sensing is considered to be more dependable than mass flow sensing which is less susceptible to temperature variations.
- It is preferable to minimise the variety of functional components and control methods in a single design. In this solution the Main Flow and Cathode feeds will use the same flow control components and method

A functional block diagram for the flow controller is shown in Fig. 5. The FCU includes a filter at its inlet to protect the system from particulate contamination.

Immediately downstream of the inlet filter there is a single mono-stable isolation valve, after which the flow path divides into 3 parallel branches for the Neutraliser Feed, Cathode Feed and Main Flow Feed.

The Main Flow Feed 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. The Neutraliser Feed can be operated independently of the Main Feed and Cathode Feed.

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 failing open or leaking excessively the propellant upstream of the FCU can be isolated

## B. EP System Architectures

The primary function of the HPEPS when defined in 2004 was to provide on-station NSSK for geostationary telecommunication satellites. HPEPS is also capable of performing satellite orbit top up and repositioning manoeuvres e.g. to graveyard at the end of mission.

In July 2003 QinetiQ was awarded a contract by ESA to perform the necessary pre-development activities of an ion propulsion system for the Large Platform Mission Project (AlphaBus) in a NSSK role.

During the initial stages of the programme, in-depth trade-off activities at system and equipment level were performed from which the baseline system has been defined. The system architecture is presented in Fig. 6 and comprises:

- 4 x T6 thrusters, each incorporating a dedicated Neutraliser.
- 4 x Xenon Flow Control Unit (XFCU) assemblies, each dedicated to a specific T6.
- 1 x PPU, incorporating two sets of Discharge, Accel and Neutraliser supplies (DANS) a modular failure tolerant beam supply.
- 2 x Electric Propulsion pointing mechanisms (EPPM)
- 4 x Splice plates
- Harness and pipe work.

The HPEPS is readily adaptable for a variety of applications and mission types. Variations of the HPEPS architecture are currently being proposed to provide electric propulsion for the European Galileo Second Generation System and Electra (a telecommunication satellite).

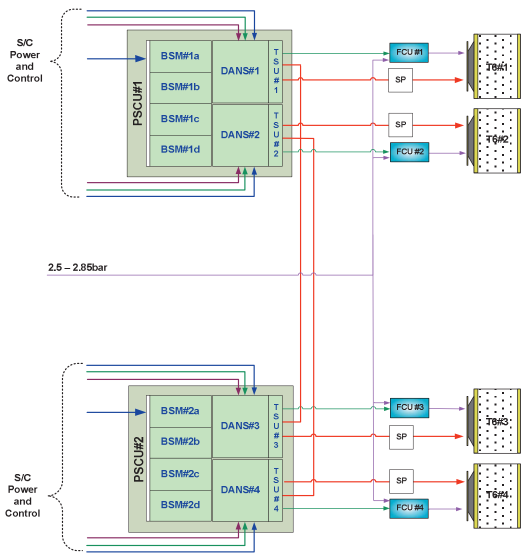



**Figure 6. SEPS architecture providing simultaneous thruster operation and impulse sharing**

There are two critical differences between the GEO telecommunications and BepiColombo applications. 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 hence an additional 4th BSM is required in each beam supply in each PPU. The SEPS architecture is illustrated in Fig 6.

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 behavior will have fewer operational patterns to verify.

## III. SEPS (EQM) Coupling Test

### A. Objectives

The purpose of the SEPS (EQM) Coupling Test was to perform compatibility tests between the PPU, Thruster and FCU as a confidence verification of the coupled SEPS hardware. The confidence checks are primarily limited to electrical compatibility, FDIR checks and demonstration of beam-out tolerance/beam-out recovery. Due to the configuration of the test (PPU and FCU outside of the vacuum chamber) it was possible to exploit the use of GSE diagnostics to allow for interrogation of key interfaces and verification of some requirements that would not have been possible with the hardware mounted inside the chamber.

The SEPS Coupling Test Part 2a provides confidence checks of the following:

- Electrical compatibility of PPU, EM FCU & Thruster
- Assessment of PPU automatic command and control sequences
- Assessment of PPU FDIR functionality
- Assessment of FCU control algorithms and Thruster/PPU coupling
- Assessment of nominal SEPT operation at min/max operating criteria for PPU input voltage and FCU inlet pressure
- Nominal and redundant (cross-strapped) harness compatibility

### B. Test Set-Up

The Coupling Test was executed with the PPU and FCU located outside of the vacuum facility, this allowed attachment of key diagnostic equipment, to validate the key interface (mainly PPU to Thruster and FCU to Thruster), this was achieved by attaching Voltage/Current probes on the primary and secondary lines of the PPU which allowed data to be collected on the steady-state and transient effects during operation. On the outlet of the FCU, three pressure transducers were attached to the pipework to allow information to be gathered on the immediate downstream pressure of the FCU during the dynamic and steady-state performance tests, this allowed us to assess the performance of the FCU flow control valves. All of the above would not have been viable inside of the vacuum chamber.

Figure 7 shows the top level schematic of the test set-up, whist Fig. 8 shows a picture taken of the test that was conducted in QinetiQ's LEEP3 (Large European Electric Propulsion facility No.3) Test Facility earlier this year.

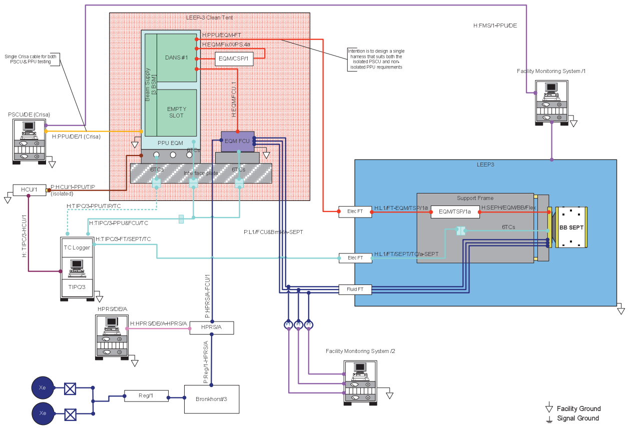



**Figure 7. Schematic of SEPS (EQM) Coupling Test**

The main objective of the test from the outset was to ensure that all of the interfaces between the SEPS hardware are flight representative (i.e. harness and pipework), taking in to account the electrical and fluidic feed-throughs to break the vacuum vessel. With regards to the pipe interface, apart from the small volume increase due to the addition of the inline pressure transducers (minimal overall impact), the pipe length, diameter and wall thickness were selected to exactly match the flight interface and design. The harness, for obvious reasons had to break the vacuum seal, and be long enough to attach to the PPU (mounted externally to vacuum vessel) and route around the inside of the chamber, this led to an overall increase in test harness length compared to the flight system. This was adequately addressed with the following design enhancements.

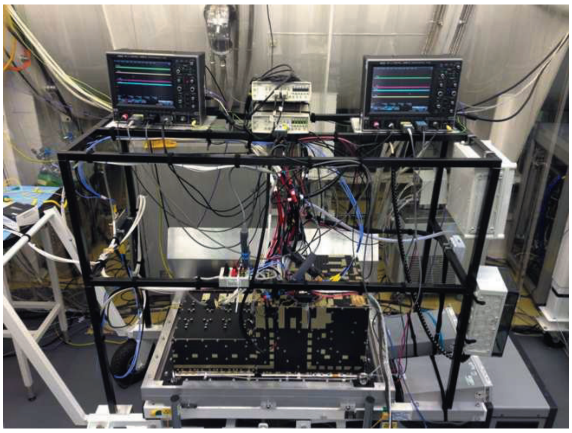


**Figure 8. Picture of the SEPS (EQM) Coupling Test Set-Up**

*1. SEPH Test Harness Design*

When it came to performing the coupling tests between the PPU and SEPT, the necessary test configuration of having the SEPT in a vacuum chamber and the PPU outside the chamber precluded the use of a test harness constructed to the same design as the spacecraft harness, yet there was a desire that the test harness should be as representative of the spacecraft harness as possible.

Owing to the constraint imposed by the physical location of the PPU and SEPT with respect to the position of the vacuum chamber electrical feed-through port, the test harness length needed to be almost twice as long (7 m) as the spacecraft harness (nominally 4 m). This additional length would increase the harness electrical resistance and, with the additional contact resistance of the feed-through connectors, there was concern that this additional voltage drop could affect the operation of the Thruster. The test harness was therefore to be designed with flight representative resistances – particularly on the lines carrying the highest currents.

Compared to the spacecraft harness several of the multi-cored lines have been reduced to just one. To maintain current carrying capacity and minimise their resistance, thicker gauge cable has been used for these and other lines.

In order for the harness to be attached to the PPU and SEPT splice-plate terminals, the same connection layout and core configuration as on the spacecraft harness design had to be utilised.

In order to provide confidence that the test harness design performance would be satisfactory, an analysis was performed to compare the electrical impedance characteristics of the test and spacecraft harnesses.

The analysis of volt-drop due to resistance showed that, in the anode circuit, a volt-drop of just 200 mV higher with the test harness than the spacecraft harness could be expected and that this increase could not adversely affect the Thruster performance. Apart from a small (1 mV) volt-drop increase on the Acceleration grid line of the test harness, all other test harness lines showed a reduction in volt-drop compared to the spacecraft harness.

Although the Thruster is driven by DC power supplies, its dynamic plasma discharge behaviour and transient beam-out events mean that voltages and currents have frequency/time dependencies that could be affected by the reactive properties (capacitance and inductance) of the harness to the extent that Thruster performance is affected. Estimates indicated that the test harness capacitance could be more than twice that of the spacecraft harness and that the inductance maybe up to five times greater for some lines. However, other reactive components in the PPU/Thruster circuits, such as power supply output capacitors, have values that are one or more orders of magnitude greater that the total harness values. This meant that, despite relatively large differences in capacitance and inductance between the test and spacecraft harnesses the differences were unlikely to affect thruster performance.

## C. Performance

### *1. SEPS Operation Modes and FPGA Functions*

This Section presents an overview of the manner in which a SEPS functional chain is controlled. A SEPS functional chain is defined as a thruster, its associated FCU, any electronics which is dedicated to that thruster, and all interconnecting harness and pipe-work.

As the primary propulsion system of the spacecraft during interplanetary flight, the SEPS takes demands from the spacecraft and delivers the required thrust. Firmware resident within a Field Programmable Gate Array (FPGA) in each DANS, controls the output of various power supplies and FCU, and allows the system to be throttled between any thrust levels within the operational range.

The FPGA interfaces to all of the power supplies and FCU drivers (i.e. FCU controllers) within each DANS and also commands the Beam supply modules. The FPGA is programmed to perform a number of tasks which include the following.

- Communications interface to the spacecraft On-board Computer (OBC).
- Thruster and PPU safety interlocks.
- Command and control of all the power supplies and FCU drivers.
- Sequences for the automatic operation of the associated Thrusters and FCUs.
- Provision of SEPS FDIR
- Provision of all Telemetry

Each functional chain of the SEPS can be commanded either manually or automatically. In Manual mode the FPGA can be commanded via direct external commands to control all power supplies and FCUs as instructed, with the exception of commands prohibited by the safety interlocks. In automatic mode a SEPS functional chain is commanded using sequences internal to the FPGA designed to perform the following functions.

- Neutraliser start up
- Main Discharge Cathode start-up
- Discharge only operation
- Thrust control
- Grid short clearance

Figure 9 presents the top level State diagram for a single DANS and shows the relationship between DANS states. The green state is the OFF state where the system is completely shut down. The blue states are those that allow system setup and FCU activities, and the purple states are those that allow other power functions.

State transitions may be induced by four possible sources: On/Off electrical signal (labelled as HP in the figure) from the spacecraft, commands issued by the OBC (labelled as S/C in the figure), FDIR internal to the DANS and by normal progression through a control sequence (labelled as Auto in the figure). Each state transition is numbered and a key identifies which source(s) may cause that particular state change.

In manual operation each DANS will allow the operation of PPU and FCU functions as demanded directly by the OBC or ground operator. Thruster out-gassing and FCU venting and purging are conducted under manual control (in MANUAL state).

In Automatic Mode the operations are designed to provide hands free starting of the thrusters and maintain thrust control. Each DANS is designed to automatically sequence the power supplies and FCU drivers to allow the following automatic sequences to be performed.

- starting of the cathodes,
- maintaining the discharges,
- controlling the thrust (with beam on, also includes automatic beam-out recovery),
- automatic short clearance

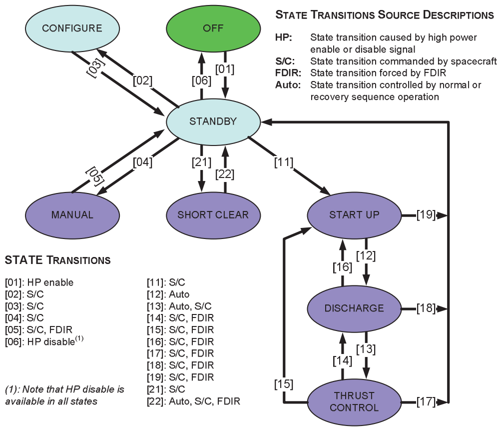



**Figure 9. SEPS Modes/Transitions**

During THRUST CONTROL each DANS allows updated operating parameters from the OBC to be adopted to allow the thrust level from any operating Thruster to be varied without interruption in operation.

Transition between Thruster DISCHARGE and THRUST CONTROL shall be commanded via the OBC. However during automatic beam-out recovery the local controller will be able to transition between DISCHARGE and THRUST CONTROL autonomously.

*2. Electrical Performance*

The primary purpose of Coupling Test is to verify electrical compatibility of the PPU, FCU and Thruster and demonstrate that the Thruster and FCU perform nominally when driven by the PPU. The verification will also extend to the PPU driving the Thruster in a redundant harness configuration, representing the redundant switching of the PPU from the primary DANS terminals to the switched terminals through the Cross-Strap Splice Plate. The tests are performed in discharge and at the four nominal thrust levels of 75mN, 100mN, 125mN and 145mN at various input conditions: min BOL, nominal and max EOL conditions. The minimum SEPS input case refers to the condition where the SEPS is only provided with the minimum FCU inlet pressure & minimum PPU spacecraft power bus voltage (98V).

Table 1 shows the performance results with PPU input Voltages of 98V and 100V and also with Min BOL and Max EOL FCU Input conditions at 145mN thrust. DANS#1 represents the direct (short) harness configuration, where DANS#2 represents the cross-strap (longer) harness.

The data shows excellent agreement in engine performance between the various input conditions, with the small voltage differences being attributable to different harness configurations or flowrate to neutraliser due to the fixed restrictor in the FCU. The results demonstrated the electrical compatibility of the SEPS equipment.

| | | 145 mN | | | | | |
|---|---|---|---|---|---|---|---|
| | | DANS #1 | | | DANS #2 | | |
| | | 100 V | | 98 V | 100 V | | 98 V |
| | | Min BOL Static (2.667 bar) | Max EOL Static (3.504 bar) | Min BOL Static (2.667 bar) | Min BOL Static (2.667 bar) | Max EOL Static (3.504 bar) | Min BOL Static (2.667 bar) |
| $V_M$ | (V) | 16.83 | 16.78 | 16.97 | 17.80 | 17.77 | 17.85 |
| $I_M$ | (A) | 0.869 | 0.866 | 0.875 | 0.873 | 0.870 | 0.872 |
| $V_{A-}$ | (V) | 32.08 | 32.06 | 31.80 | 33.28 | 33.29 | 33.24 |
| $V_{A-}$ | (V) | 29.86 | 29.80 | 29.46 | 29.59 | 29.57 | 29.50 |
| $I_A$ | (A) | 18.04 | 18.04 | 18.12 | 18.05 | 18.05 | 18.13 |
| $V_{NK}$ | (V) | 16.77 | 14.76 | 16.74 | 17.78 | 15.61 | 17.52 |
| $I_{NK}$ | (A) | 4.19 | 4.19 | 4.19 | 4.20 | 4.20 | 4.20 |
| $V_B$ | (V) | 1845 | 1845 | 1845 | 1845 | 1845 | 1846 |
| $I_B$ | (A) | 2.17 | 2.16 | 2.18 | 2.17 | 2.17 | 2.18 |
| $V_{Acc}$ | (V) | -265 | -265 | -265 | -265 | -265 | -265 |
| $I_{Acc}$ | (mA) | 14.88 | 14.69 | 14.65 | 14.43 | 14.18 | 14.63 |
| NRP | (V) | -10.73 | -10.95 | -11.11 | -11.54 | -11.68 | -11.46 |
| $T_{TRP1}$ | (°C) | 158.5 | 158.5 | 159.3 | 158.3 | 158.4 | 162.0 |
| $T_{TRP2}$ | (°C) | 84.2 | 84.4 | 86.8 | 84.0 | 84.2 | 95.1 |

**Table 1. SEPS 145mN Electrical Compatibility Verification Data**

*3. Thrust Control/Ramp*

When commanded by the OBC, the SEPS is capable of autonomously going to a desired thrust level in predetermined steps. The PPU starts the cathode heaters, enables the flows to the three branches, initiates the discharge, goes into thrust mode (which is maintained for 20minutes) and ramps the thrust from 0 to 75mN in 16 steps, the thrust is then paused at 75mN for 10minutes and ramped onwards up to the desired thrust level at a rate of 0.5mN/s.

The SEPS coupling test was required to demonstrate this capability and to verify that all the ramp profiles were achievable in terms of thruster electrical data and input power requirements. The minimum SEPS power demand, for a given thrust level, usually occurs with the thruster in thermal equilibrium. The peak power conditions, usually arise just when the thruster achieved the desired thrust level. The thruster initial conditions are important in determining peak power demand; the colder the engine at the moment of discharge strikes, the higher the peak power demand in a ramp. Consequently, to determine the SEPS peak power demand, the engine was subjected to an extended cold condition prior to discharge initiation. Moreover, this profile was carried out at minimum FCU input pressure and minimum power bus input voltage which demonstrated the SEPS ability to achieve the required thrust levels at the worst case PPU and thruster input conditions.

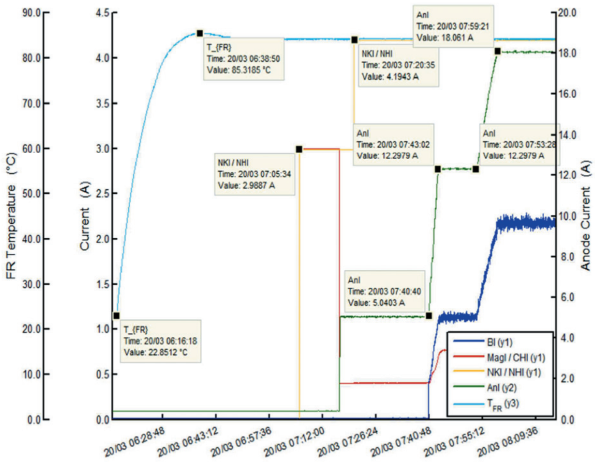



**Figure 10. Representative thrust ramp to 145mN**

Figure 10 shows the timing information and electrical data for the representative thrust ramp to the maximum SEPS capability of 145mN. The cathode and neutraliser heaters were initiated first and when the heater voltage reached a predetermined value, the neutraliser heater/keeper supply is disabled and switched to apply the output to the keeper. The neutraliser discharge is struck and maintained at a constant current value of 4.2A. Similarly when the cathode heater supply reached its predetermined value the anode power supply is enabled with a constant current value of 5A to strike the main discharge. Simultaneously the heater/magnet supply is disabled and switched to apply output to the magnet, which is enabled at a constant current value of 0.4A. After a period of discharge dwell, the beam supply is enabled and the thruster is ramped up to 75mN in 16 steps. After a period of dwell at that thrust level, the PPU then proceeds to ramp up the thrust using the flight representative 0.5mN/s criterion, till the full thrust level of 145mN is reached.

Once at the desired 145mN beam current, the thrust control algorithm uses the beam current as the primary feedback parameter. Any thrust level has an associated anode current whereas the solenoid current is variable (between minimum and maximum limits) and is used to 'trim' the discharge conditions and therefore the beam current. It can be noted that almost as soon as the desired anode and beam currents are achieved, the magnet current begins to ramp down as the engine warms up. This also has an associated effect on the anode voltage, which also begins to drop as the engine heads towards thermal equilibrium.

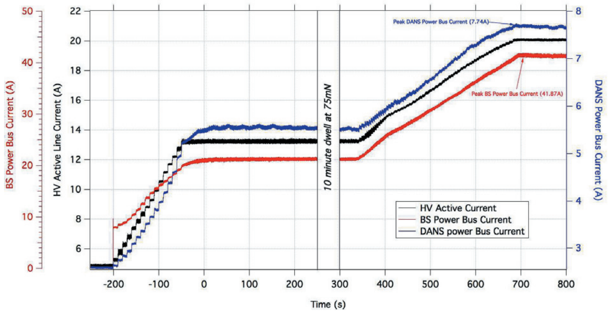



**Figure 11. Power bus data for representative thrust ramp to 145mN**

Figure 11 displays the Power demand profile during the representative thrust ramp obtained using a scope. The figure is an amalgamation of two separate 500sec of scope data, which encompass the end of the discharge dwell period, the 16 initial steps and (separated by the 10minute dwell at 75mN) the ramp to 145mN. Critically it manages to capture the peak bus current demand, with their location and magnitude indicated on Fig. 11.

The thrust control and ramp tests have verified that the SEPS has successfully executed an autonomous thrust ramp from a cold condition to 145mN thrust at peak power demand and at the worst SEPS PPU and thruster input conditions.

*4. Thrust Quantization*

The SEPS coupling test presented an opportunity to measure the minimum thrust step increment capability of the SEPS (referred to as SEPS thrust quantization). The thrust steps were inferred by measuring the beam current step directly at the beam test port using an oscilloscope to obtain the quantized waveforms and then post processing the data. The thrust increments were achieved by modulating the Magnet Current by the smallest possible increments (i.e. 1 hex = 3mA, 2 hex = 6mA and 3 hex = 9mA) at each of the nominal thrust levels: 75mN, 100mN, 125mN and 145mN.

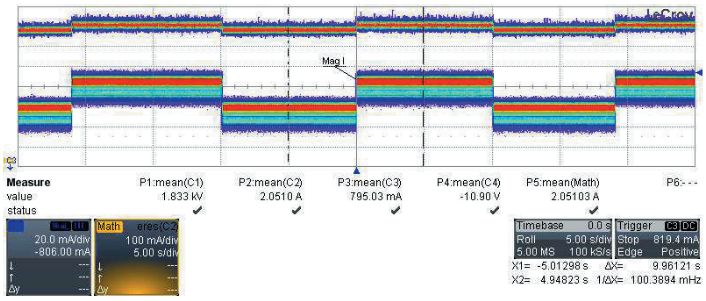



**Figure 12. 145mN Thrust Quantization Persistence Trace**

Figure 12 shows the obtained 145mN Beam and Magnet current steps and illustrates the use of the scope's built in persistence function to visually highlight and recover the steps from the trace noise.

The results have shown that the SEPS is capable of stepping the thrust in as little as 21µN to 177µN steps depending on the thrust level.

*5. Beam-Out Recovery*

In a beam-out, a piece of sputter or debris (nominally generated during ground testing) intercepts the gap between the screen and accel grid, which causes a short. The short circuit will cause transient currents in the beam supply modules. This is the most taxing and demanding condition for a gridded ion engine system. The SEPS must: (1) Demonstrate a tolerance to a beam-out condition i.e. electrical compatibility of the supplies with transients (2) Include means for detection of the transient and a transient counter (in case a high beam out frequency is a symptom of another underlying problem) (3) Be able to autonomously recover from the beam event and return to its prior thrust level within a set time.

Scope current and voltage probes were attached to critical lines into and out of the PPU to obtain high frequency monitoring of the beam-out events and subsequent recovery. It became soon apparent that the SEPS exhibited 2 types of beamout/recovery behaviour which depended on the length of time it took to clear the grid short, this will be described shortly. Firstly we will describe the general features of a generic beamout and recovery phase concentrating on the longer timescales. Figure 13 shows scope traces of such a beam-out and recovery case at 145mN.

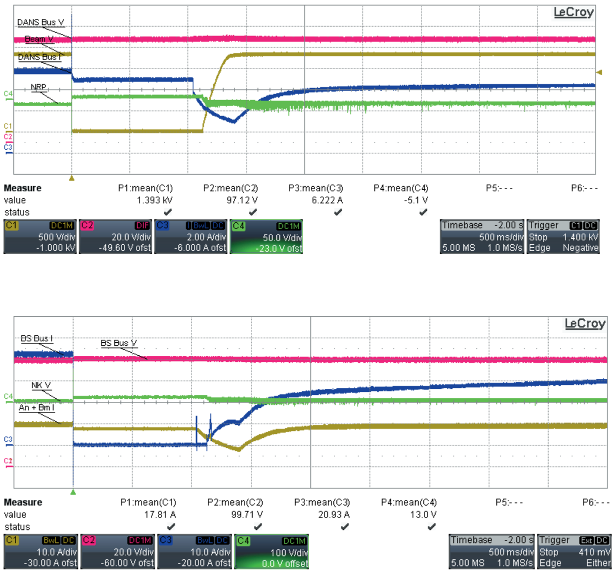



**Figure 13. Beam out and recovery at 145mN (Scope data)**

In Fig. 13 the top scope plot traces of the NRP, Beam and DANS Bus voltages and DANS Bus current are shown. In the bottom scope plot, traces the Neutraliser Keeper and Beam Supply Bus voltages and Anode+Beam and Beam Supply Bus currents are shown.

At the onset of the beam-out, the Beam voltage collapses resulting in the expected reductions in the NRP voltage and the Beam Supply Bus current. The Anode+Beam current is also seen to reduce to the discharge only current of 18A (discharge current at 145mN minus Beam current). Approximately 1s later the Anode supply is commanded to reduce to 5A and the Beam Supply is re-enabled. Following the establishment of the beam, the Anode + Beam current begins to ramp back up to the value for the original thrust point (with both Power Bus currents following the trend) and the beam-recovery sequence is then complete.

A Type I beam event is shown in Fig. 14. It is characterized by a grid-short duration $t_s$ >1.5ms. The AnI+BmI is shown as the Black trace in this plot. An initial 50A transient appears when the short occurs and exhibits the expected decay as the output filters discharge. The current then stabilises at ~25A for a short period and then reduces to ~20A. This is understood to be the 2nd stage in discharge of the Beam Supply Modules (BSMs) regulation stages where the supplies enter a current control mode. At ~1.5ms the short-circuit condition has persisted for the time needed for it to be recognised by the hardware as a beam-out and at this point the BSMs are disabled and the current reduces to the Anode (only) current, which is 18A at 145mN. This beamout type leads to the nominal beamout recovery described above.

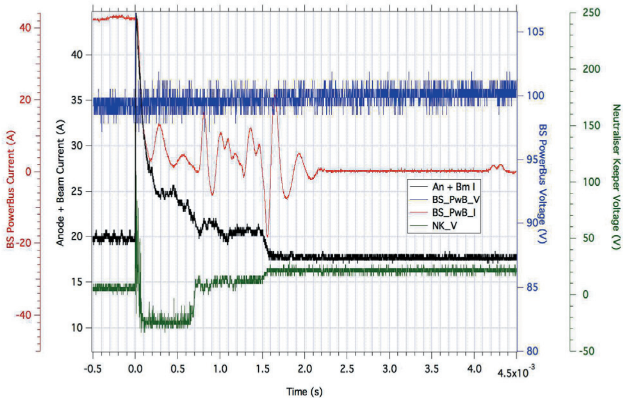



**Figure 14. Type-I beam-out event from CT1EF (grid short >1.5ms)**

A Type II beam event is shown in Fig. 15, where the evolution of the Beam and Accel grid currents and voltages are presented respectively and is characterized by a grid-short duration of $t_s \leq$ 1.5ms. As with a Type-1 event, the transient starts with a 50A pulse and collapse of the Beam voltage as the output stage of the BSMs discharge. However, the grid short disappears at ~1.1ms, which is insufficient time for the hardware system to recognise this as a beamout. As a consequence, the Beam voltage immediately starts to recover and when the voltage reaches the Accel grid enable threshold, the Accel supply is enabled. The Beam current drops, indicating that Electron Backstreaming (EBS) was present before the Accel grid was enabled. The presence of EBS adds to the nominal Anode current initially preventing the AnI+BmI reducing to 18A.

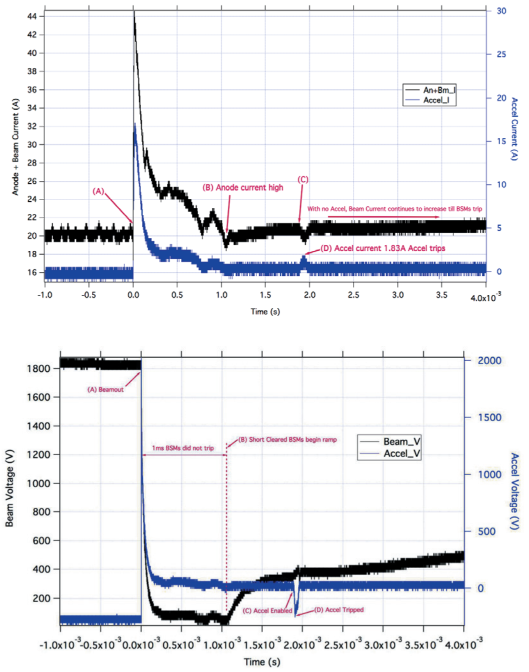



**Figure 15. Type-II beam-out event (grid short <1.5ms) – Beam and Accel supplies currents and voltages**

The Accel grid very rapidly current limits, however, and is disabled because the plasma density is still very high with the Anode discharge still operating at 145mN levels. The Beam voltage continues to increase and therefore so does the EBS until the BSMs also start to current limit. This condition is maintained for the required 1.5ms until the hardware recognises the beamout and the standard recovery process is initiated. Note that the ultimate result is the same as Type-I (i.e. the system automatically recovers from the beam-out).

Crucially, the rapid rise of the beam-voltage during Type II beamout can lead to large dI/dt on the power bus currents (a rate of 4400A/s was recorded). It was therefore essential to verify the complete MTM power chain against these beamouts to demonstrate its ability to operate without interruption.

*6. Failure Detection Isolation and Recovery and Hardware Protection*

A number of surveillances and hardware protections are built into the SEPS to protect the system and to improve reliability. Surveillances resident in the PPU is active in all DANS states by default apart from CONFIGURE, STANDBY and OFF (with some exceptions). Hardware protections are implemented as hardware trips and hence are active in all DANS states apart from OFF.

The surveillances are designed to detect unusual SEPS behaviour’s and when one of these occurs either abort the operation to prevent/minimise damage to the SEPS or initiate auto recovery to maintain safe operation.

All possible surveillances have been tested with the thruster in a representative environment. An example of one tested during SEPS coupling test part 2a, was the High Anode Voltage surveillance, this was artificially triggered by reducing the main flow into the thruster and allowing the Anode Voltage to exceed (pink trace in Fig. 16) its pre-programmed threshold. The surveillance automatically recognised this event and took the preventative action to avoid anomalous behaviour (i.e. on this occasion, ramping the Magnet down – blue trace in Fig. 16). For the purposes of the plot, the main flow demand is shown in the brown trace.

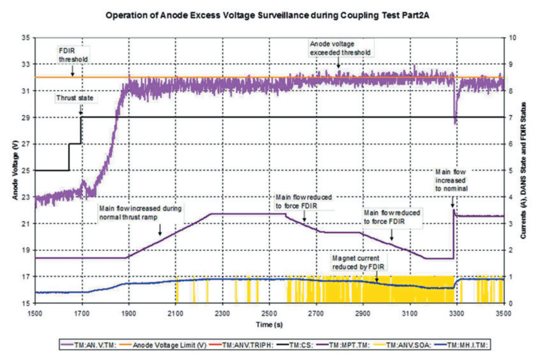



**Figure 16. Anode Over-Voltage FDIR**

### D. System-Level validation of Electric Propulsion System

The Electrical Propulsion System is part of the transfer module MTM. The overall electrical power architecture is shown in Fig. 17. The MTM features a power subsystem capable of providing more than 11 kW of solar power, powering both the 2 ion propulsion thrusters on the MTM, as well as the MPO spacecraft command & control, and instrument and MMO heater power during cruise.

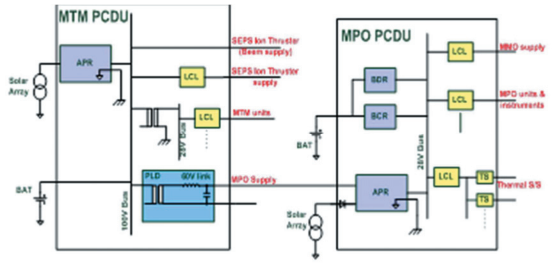



**Figure 17. BepiColombo Power S/S Schematic**

Top level control of the MEPS/SEPS (mounted in the MTM) is from the OBCs mounted in the MPO. All SEPS configuration tasks are undertaken by the OBC, with the PPUs (Power Processing Units) managing only lower level SEPS functions.

Verification of the complete MTM power chain along with the command and control from the MPO was an essential feature of the system verification – which could not, however, be performed at spacecraft level due to the need to fire the thrusters in a dedicated test facility under vacuum. Thus, a system-level validation test was performed concentrating on the compatibility of the SEPS with the MTM power subsystem controlled from MPO simulator.

The main objectives of this system test were

- To verify SEPS compatibility with power subsystem under all load cases up-to maximum thrust
- Demonstrate power bus quality in terms of ripple and Frequency Domain emissions, for the 100 V main bus as well as the derived supplies 28 V (for MTM-internal usage) and 60 V (for powering the MPO module)
- Verify power S/S stability during beam-outs
- Verify suitability of SEPT thruster simulator for use in future system tests (system thermal vacuum, system EMC)
- Verify SEPS command & control

#### 1. *System level Test Set-Up*

The block diagram of the system validation test is shown in Fig. 18. It features:

- The MTM power subsystem comprising PCDU, battery, and Solar array simulator,
- Control electronics comprising the MTM interface unit RIU and a simulated MPO OBC (MIS),
- The Solar Electric Propulsion Subsystem comprising SEPT thruster installed in vacuum chamber, PPU and FCU;
- In addition, a SEPS simulator capable of drawing equivalent power simulating a second operating thruster branch.

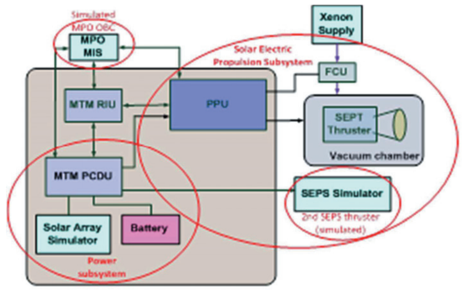



**Figure 18. Block diagram of system validation test set-up**

Figure 19 shows the set-up at QIQ test facility in Farnborough, with PPU on the bottom left, MTM units PCDU, BAT and RIU to the right, and the vacuum chamber in the background.

Besides standard EMC measurements in time domain and frequency domain the set-up comprised high-resolution storage oscilloscopes to allow simultaneous measurement of some 16 voltage and current parameters during beam-out measured using high voltage and high current probes at PCDU as well as on PPU secondary side (interface to SEPT).

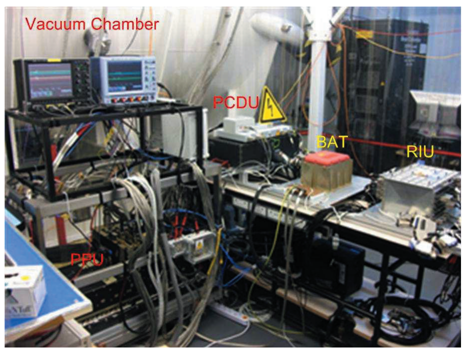



**Figure 19. Photograph of the BepiColombo SEPS/PCDU Coupling Test (QQ Farnborough)**

#### 2. *Steady state operations*

Initial testing was performed with the PPU powering a simulated SEPT thruster, rather than a real engine. This allowed checking of all command & control sequences prior to operation with the thruster. Moreover, reference measurements were performed, on time domain (TD)

power ripple on the various power busses under different load conditions (75 mN upto 145 mN full load). Frequency domain (FD) measurements were performed under full load only. Subsequent testing was a repeat of the former test with the PPU operating the real SEPT in vacuum.
Stability of the power subsystem was ultimately demonstrated under full load (2 x 5 kW, one of which was a real thruster operated in vacuum, while the other thruster was simulated by ohmic loads).
The tests comprised both voltage and current measurements in frequency and time domain on the 3 power busses implemented on the MTM. Figure 20 shows the FD voltage emission on the 100 V main bus, comparing real thruster (pink) and simulated thruster (light blue/ dark blue with additional ohmic load simulating twin thruster operation). The bus performance is compliant to the requirements under all load conditions. Moreover it can be seen that the bus performance with simulated thruster is very similar to the real thruster at frequencies beyond 10 kHz.
Appropriate similarity was also measured on the other power busses, see Fig. 21 for the MTM 28 V bus as another example. The same applies for current emissions, refer to Fig. 21 showing PPU beam supply current with both real (green) and simulated thruster (blue).

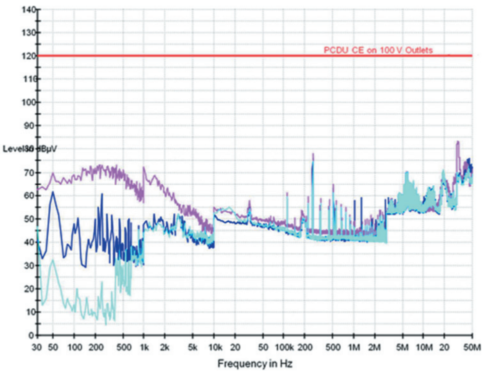



**Figure 20: 100 V bus (unprotected), Voltage FD, SEPT @ 145 mN (pink) vs. PPU LS (light blue) vs. PPU LS + SEPSSIM (blue)**

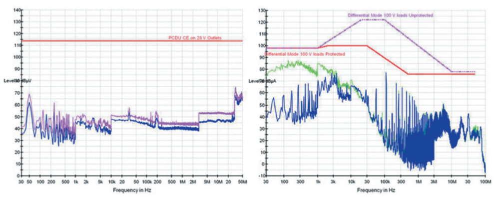
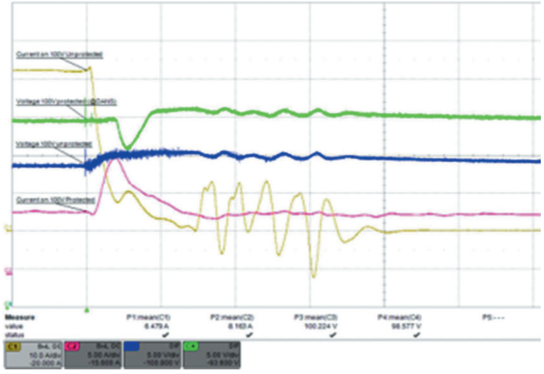


**Figure 21: Left - 28 V bus, Voltage FD, SEPT @ 145 mN (pink), vs. PPU LS @ 145 mN (blue), Right - PPU Conducted emission, BSM unprotected, current FD DM, SEPT @ 145 mN (green), vs. PPU LS @ 145 mN (blue)**

Ripple and spikes on the 100 V main bus are almost independent of thrust level (min. thrust level 75 mN compared to max. 145 mN). While there is little impact on the 60 V bus, on however the 28 V however bus spikes increase from 300 mVpp to 1200 mVpp depending on thrust level. Similar results have been measured with simulated thruster (ohmic load). This ripple is acceptable on system level as it does not impact any other MTM equipment, so full compatibility could be demonstrated. Moreover all units connected to 28 V bus have passed a conducted susceptibility test with adequate margin.
To a large extent the current ripple is absorbed by capacitors implemented in the PCDU, hence battery current ripple is negligible which is thus not needed for bus stabilization.

3. *System behaviour during beam-outs*

During the PCDU coupling test, 10 beam-outs were encountered and a representative collection of durations and current shapes (in terms of transient slopes, rise/fall times etc.) was obtained. A typical beam-out from the PCDU coupling test is shown in Fig. 22 – 25. SEPS supply voltages and currents are shown in Fig. 22 and Fig. 23. The plots show the large current spikes on thruster side (Fig. 25) and the associated voltages (Fig. 24).
Although the beam-out event and its recovery is accompanied by large current transients on the main bus interfaces (42 A drop at beam-out), the voltage ripple on the main bus remains very stable at about 1000 mVpp and shows little variation of the average bus voltage, thanks to large capacitor banks implemented in the PCDU. The 28 V bus ripple drops from 1200 mVpp to only 300 mVpp while the thruster beam power is off (see Fig. 23), reaching former levels during beam-out recovery.
The test showed that the most critical impact of a beam-out transient is a temporary increase of DANS current (see Fig. 22). This current is limited by a Latch Current Limiter inside the PCDU, leading to a voltage drop on the DANS supply line (voltage shown in green). As the minimum bus voltage was always well above the DANS undervoltage protection threshold, there is however no risk of unit switch-off.



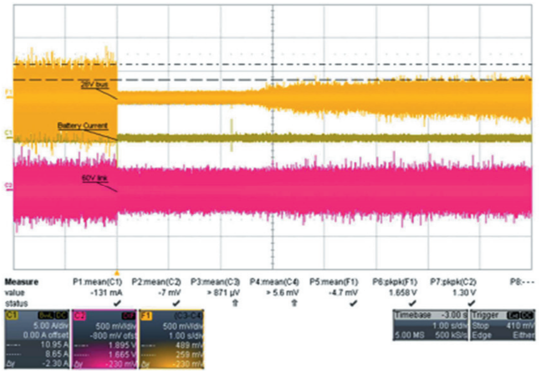
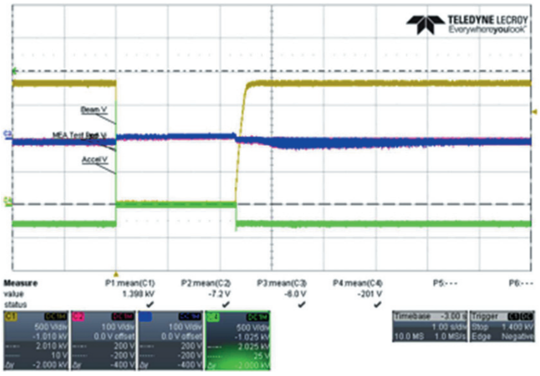



**Figure 22. SEPT Beam-out, Scope 3: BSM/ DANS, (yellow/ blue: current/ voltage beam supply, red/ green: current/voltage DANS supply)**

**Figure 23. SEPT - Beam-out, Scope 4: Power S/S, long time scale (brown: battery current, yellow: 28 V bus volt-age, pink: 60 V bus voltage)**



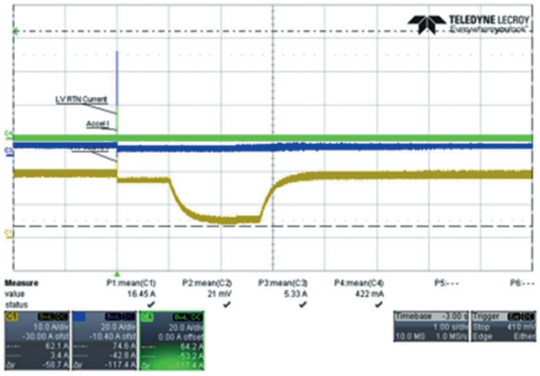




**Figure 24. SEPT - Beam-out, Scope 1: beam voltage (yellow), NRP voltage (blue), Accel grid voltage (green).**

**Figure 25. SEPT - Beam-out, Scope 2: HV current (yellow), LV RTN current (blue), Accel grid current (green)**

There are no detrimental transients observed on the battery interface (max. 5 A only), which is hence not affected by beam-out transients. Impact of secondary side transients on other MTM equipment has been addressed[9].

*4. Summary and conclusions of SEPS/PCDU Test*

The entire system-validation lasted about 6 weeks, comprising of about 2 weeks operation with simulated thruster (for debugging and reference), 2 weeks for thruster operation and electrical measurements, and 2 weeks beam-out transient capture.

The tests demonstrated the stability of all power busses under all load conditions (simulated and real thruster, twin thruster operation), as well as during beam-outs. There were no power bus disruptions during any thruster transient, the system recovering autonomously in all events.

As an important aside, it could be demonstrated that the SEPS electrical behaviour with simulated thruster is very similar to operating the real SEPT, which validates that future system level tests using thruster simulator are fully representative wrt. Electrical/ EMC performance.

## IV. Future Tests

### E. SEPS Coupling Test Part 2b

Following on from the success of the SEPS EQM Coupling Test, there are further planned tests to demonstrate the EQM equipment's compatibility. One of these will be a second iteration of the coupling test, with the SEPS hardware configured in a fully representative chain inside of the vacuum facility (i.e. no break in the electrical harnesses between the PPU and SEPT). Diagnostics are still possible between the Unit Tester (UT) and PPU, as the UT is outside of the vacuum chamber, therefore DANS and BS power bus monitoring is possible. As well as providing a representative test bench for the SEPS, many spacecraft level AIV activities will be validated during this test campaign as well as operational procedures to validate flight operations.

*1. Test Objectives*

To provide a platform for qualification of the SEPS system. The main purpose is to perform performance analysis of coupled SEPS hardware. It also demonstrates specific PPU-Thruster interactions including the control algorithms, beam-out recovery, FDIR etc. and is a means of formal requirement verification.

The SEPS coupling test would also provide verification of the following: Electrical compatibility of anode, heater/magnet, accel, neutraliser keeper/heater, beam; FCU electrical interfaces; FCU control loops (algorithm); SEPS command and control sequences including thrust ramps; Electrical compatibility of supplies with transients (e.g. beam outs) including Beam-Out Recovery; Look-up tables; Modes/Mode transitions; TM/TC; FDIR; PPU minimum inlet voltage; FCU flow variation.

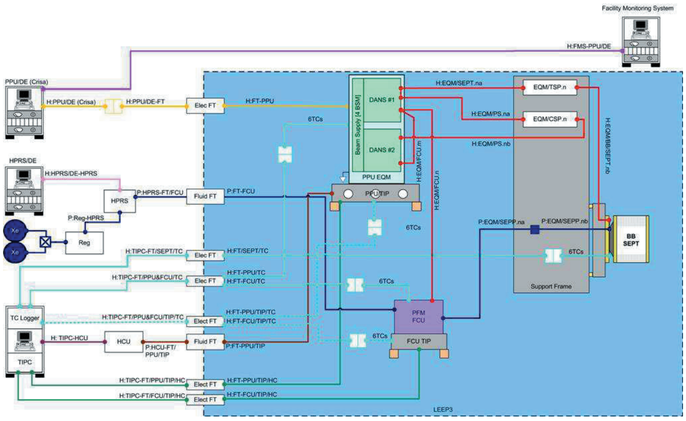



**Figure 26. Schematic of SEPS Coupling Test Pt2 Set-Up**

*2. Test Set-Up*

The test set-up has been designed so that the SEPS hardware will be located in the QinetiQ LEEP3 Vacuum Chamber (schematic shown in Fig. 26 and CAD representation shown in Fig. 27). Careful integration activities have been planned so that all of the electrical connections to the PPU are made on a support trolley in a clean room outside of the vessel and the entire PPU is lifted into the rear of the chamber where it will be mated with the thruster and FCU. Due to the well-known problem of ground testing contamination whilst firing a thruster in a vacuum chamber (back sputter), the PPU and FCU will be suitably shielded from the target sputter, minimising performance issues or test anomalies during the test campaign. The PPU will be thermally controlled by the means of a heater chiller unit (HCU), this will provide thermal control of the unit when it is at full operational power and during hibernation periods, when the unit is off, all of which have been fully demonstrated in previous test campaigns or respective shakedowns.

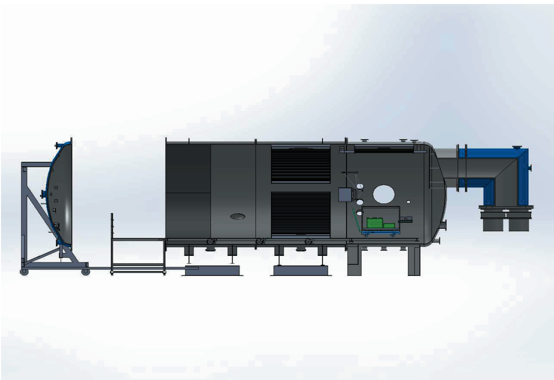


**Figure 27. CAD Model of PPU/FCU inside of LEEP3**

The test will reply on both PPU TM/TC and an integrated Bus Monitor (allows real time interpretation of engineering parameters) to validate requirements, both in the ‘direct’ and ‘switched’ modes, across the thrust range and in all of the operational modes.

## F. SEPS EMC Test

The conventional approach for EMC tests of the PPU and FCU is unfortunately not directly applicable to the SEPT because in order for it to be energised and thus radiating E and H fields, it must be under vacuum within a substantial electric propulsion vacuum test facility. The same is true in the case of Radiated Susceptibility tests. These vacuum chambers are invariably metal (usually stainless steel or aluminium) and hence the conventional EMC test configurations cannot be applied.

To validate the EMC requirements of the SEPS hardware, the SEPT will be placed inside a large vacuum chamber, with the centre section constructed from an RF transparent material (glass fibre), which is in turn placed inside a large anechoic screened room.

The EMC test campaign will entail measurements of power quality, conducted and radiated emissions, and radiated susceptibility of the BB SEPT driven by the EQM PPU.

*3. Test Objectives*

The EMC tests to be performed shall address the following requirements:

- Power Quality
- In-rush Current
- Voltage Transients
- Conducted Emissions (CE)
- Conducted Emissions on Primary Power Leads (frequency domain)
- Conducted Emissions on Primary Power Leads (time domain)
- Radiated Emissions, E-Field (REEF)
- Radiated Emissions, H-Field (REHF)
- Radiated Susceptibility, E-Field (RSEF)
- Radiated Susceptibility, H-Field (RSHF)

The measurement of REEF, REHF, RSEF and RSHF require the Equipment Under Test (EUT) to be inside an electromagnetically screened enclosure to reduce the background RF noise to minimum levels. The emissions and susceptibility of the EUT can then be measured using a series of different antenna, receivers and transmitters covering the frequency range of interest.

*4. Test Set-Up*

The SEPT EMC testing is conducted inside a modified Thermal Vacuum Chamber, located at the QinetiQ Space Test facilities, Farnborough (illustrated in Fig. 28). The existing vacuum chamber has been modified by inserting an RF transparent section of GFRP ~1.6m diameter x 3.0m long. The RF transparent section will be enclosed by a screened enclosure lined with RF absorbing material. 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 will be 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 SEPS EMC test results to ensure a credible EMC assessment is made.

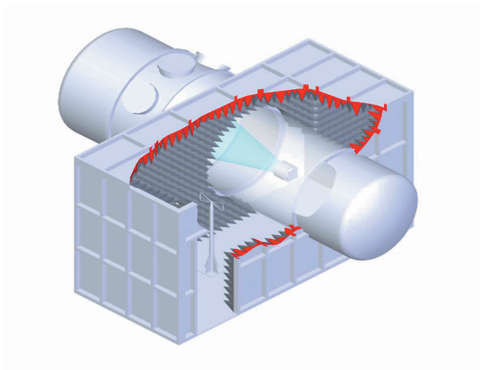


**Figure 28. EMC Test Facility**

As in the previous Coupling Tests, the switchover between the long and short harness is achieved autonomously by switching the DANS outputs to the representative harnesses. All of the operating thruster EMC testing will be conducted with the thruster inside the RF transparent section of the vacuum chamber, shrouded by the screened anechoic room. The PPU will be outside the screened room for these tests. A top level configuration is presented in Fig. 29 showing the hardware location for the thruster and SEPS testing. This particular diagram shows an antenna for E field radiated emissions / susceptibility. However, the EGSE and PPU would be configured similarly for all the SEPS and thruster tests emissions / susceptibility.

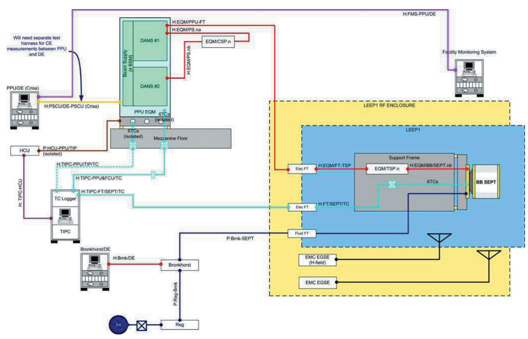


**Figure 29. EMC Test Set-Up**

## G. Future spacecraft level testing

Future system tests will comprise a TV test campaign on the MTM module. During this test real thrusters can be operated only in discharge mode with limited power consumption, due to test facility constraints (no graphite target available), while full PPU and PCDU load conditions will be achieved by operating simulated thrusters, whose adequacy has been demonstrated with the tests described above. Another major system test will be an EMC test with 2 PPUs operating in twin thruster mode, powering simulated thrusters. This test will allow demonstrating the impact of a (simulated) beam-out on the second thruster branch, as well as the final check of power bus quality during twin thruster operation.

# V. Conclusion

This paper has presented the BepiColombo SEPS coupling test that was successfully completed in 2014 using QinetiQ EP test facilities at Farnborough. The SEPS coupling test was a major risk retirement activity.

The SEPS coupling test demonstrated the electrical compatibility and system interactions at qualification level. In addition, the SEPS coupling test demonstrated the systems automatic recovery following a beam interruption (these beam interruption events are enhanced due to ground testing effects). Finally the SEPS coupling test demonstrated autonomous operation and control of the SEPS.

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