Development and Qualification Status of the Electric Propulsion System for the BepiColombo Mission

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Abstract: BepiColombo is an ESA funded mission, in co-operation with JAXA, which will deliver 2 separate spacecraft into orbit around Mercury in 2024. The transfer to Mercury involves a large velocity increment for the spacecraft, which is provided by an electric propulsion system. The T6 ion thruster, developed by QinetiQ, with a specific impulse level of approximately 4200s has been selected for this electric propulsion system. Four thrusters in total are required to achieve the mission total impulse requirement with adequate redundancy. The high total impulse leads to approximately 580kg of Xenon being required, which drives the design of the Xenon storage and feed system.

Prior to the start of the main phase of the BepiColombo project, a dedicated thruster technology demonstration programme was conducted, under direct ESA funding and direction. This was specifically aimed at addressing the impacts resulting from simultaneous operations of 2 thrusters, and operation of the thrusters in the harsh thermal environment near Mercury.

The BepiColombo electric propulsion system development and qualification activities are addressed incrementally, at equipment, assembly at overall subsystem level. The development and qualification of each of the equipments follows a classical approach wherever possible. Design and test activities are also to be performed for each of the main assemblies, coupling the equipments within these. Key interactions between the assemblies, and the remainder of the spacecraft, are also addressed by specific analysis and test activities.

I. Introduction

The BepiColombo mission will place 2 spacecraft into different orbits around Mercury. ESA has overall responsibility for the mission whilst JAXA will provide the MMO (Mercury Magnetospheric Orbiter). Astrium Satellites is the prime contractor and is responsible for providing the MPO (Mercury Planetary Orbiter), and the necessary transfer propulsion capabilities.

The use of electric propulsion for orbital transfer between bodies within the solar system is now established, with its use on the Deep Space 1[1], Smart-1[2], Hayabusa Explorer[3] and Dawn[4,5] programmes. This follows the increasing use of electric propulsion for large telecommunications satellites, primarily for North-South station-keeping.

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The BepiColombo mission, funded by ESA (and in co-operation with JAXA), exploits this heritage. A substantial energy reduction is needed to reach Mercury. The high specific impulses which can be provided by electric propulsion systems offer the ability to achieve this large velocity increment with significantly reduced propellant mass when compared with chemical propulsion systems. As a mission to Mercury will also inherently require flight trajectories with reducing sun-earth distances, the power available from the solar arrays will increase as Mercury is approached, ensuring adequate power for electric propulsion operations.

The design, development and qualification of the BepiColombo electric propulsion system is based on previous developments and flight heritage of similar electric propulsion technologies, from a variety of applications.

II. The BepiColombo Mission

A. Mission Objectives

Mercury is an extreme of our planetary system. Since its formation, it has been subjected to the highest temperature and has experienced the largest diurnal temperature variation of any object in the solar system. It is the closest planet to the Sun and has the highest uncompressed density of all planets. Solar tides have influenced its rotational state. Its surface has been altered during the initial cooling phase and its chemical composition may have been modified by bombardment in its early history. Mercury therefore plays an important role in constraining and testing dynamical and compositional theories of planetary system formation.

To date, only the American probes Mariner 10 and Messenger have returned significant data from Mercury. Although these data have been fully exploited, a lot of gross features remain unexplained. Many conclusions are still speculative and have evoked a great number of new questions.

The main scientific objectives of the BepiColombo mission are:

- Investigation of the origin and evolution of a planet close to its parent star
- Investigation of Mercury's figure, interior structure, and composition
- Investigation of the interior dynamics and origin of its magnetic field
- Investigation of the exogenic and endogenic surface modifications, cratering, tectonics, and volcanism
- Investigation of the composition, origin and dynamics of Mercury's exosphere and polar deposits
- Investigation of the structure and dynamics of Mercury's magnetosphere
- Test of Einstein's theory of general relativity

The mission will achieve these objectives by delivering 2 separate spacecraft into orbit around Mercury, namely the Mercury Magnetospheric Orbiter (MMO) and the Mercury Planetary Orbiter (MPO). For further details regarding the instrumentation carried by these orbiters, see [6,7]. These 2 spacecraft will be placed into different orbits around Mercury. The MPO has an initial polar elliptic orbit, with an altitude of between 400 and 1508 km; the MMO also has an initial polar elliptic orbit, with an altitude of between 400 and 11824 km.

ESA has overall responsibility for the mission whilst JAXA will provide the MMO. Astrium Satellites is the selected prime contractor and is responsible for providing the MPO and the necessary transfer propulsion capabilities.

B. Mission Analysis and Electric Propulsion System Design Drivers

The baseline mission is for the spacecraft to be launched by Ariane 5 from Kourou in July 2016, with Mercury arrival and orbit insertion from January 2024. The mission analysis and optimisation has resulted in the need for both chemical and electric propulsion systems to achieve the mission requirements. The selected mission profile uses the launcher for direct injection into an interplanetary trajectory. The electric propulsion system is then used over a number of thrust arcs, with intermediate coast phases, finally using a gravitational capture, via the Mercury-Sun Lagrange point, into a weakly bound Mercury orbit. A dual mode chemical propulsion on the MPO is used for lowering into the final operational orbits; this is then used for orbit and attitude control of the MPO during the operational phase of the mission.

The overall mission analysis and transport optimisation has been performed by Astrium Satellites and ESA, and is reported elsewhere[6,7]. The key driving requirements and parameters for the electric propulsion system have been selected as follows, based on the mission requirements and technology capabilities:

Thrust range	120 to 290 mN
Total impulse	22.5 MNs
Average specific impulse	4200s
Propellant budget	580 kg
Input power at maximum thrust	10.5kW

III. Spacecraft Configuration

The composite spacecraft configuration for the BepiColombo mission is illustrated in Figure 1. A standard Ariane 5 launch adapter is used to connect the spacecraft to the launcher. The spacecraft comprises the following elements:

- The Mercury Transfer Module (MTM) contains a conventional bipropellant chemical propulsion system, and the electric propulsion system used for the transfer to Mercury. It also contains the corresponding power generation hardware
- The MPO, as well as providing scientific instrumentation, provides all communications, data handing, and control functions for the complete spacecraft, as well as the housekeeping function for the Mercury orbital phase of the MPO operations. This module includes a dual mode propulsion system for Mercury orbit insertion
- The MMO provides scientific instruments, as well as its own housekeeping and communications functions for operations after separation from the remainder of the composite spacecraft
- The MMO Sunshield and Interface Structure (MOSIF) is a sunshield to protect the MMO during the mission cruise phase

All parts of the spacecraft are 3-axes stabilized, with the exception of the MMO which is spin-stabilized after separation from the composite spacecraft.

The spacecraft configuration and design is described further in [8].

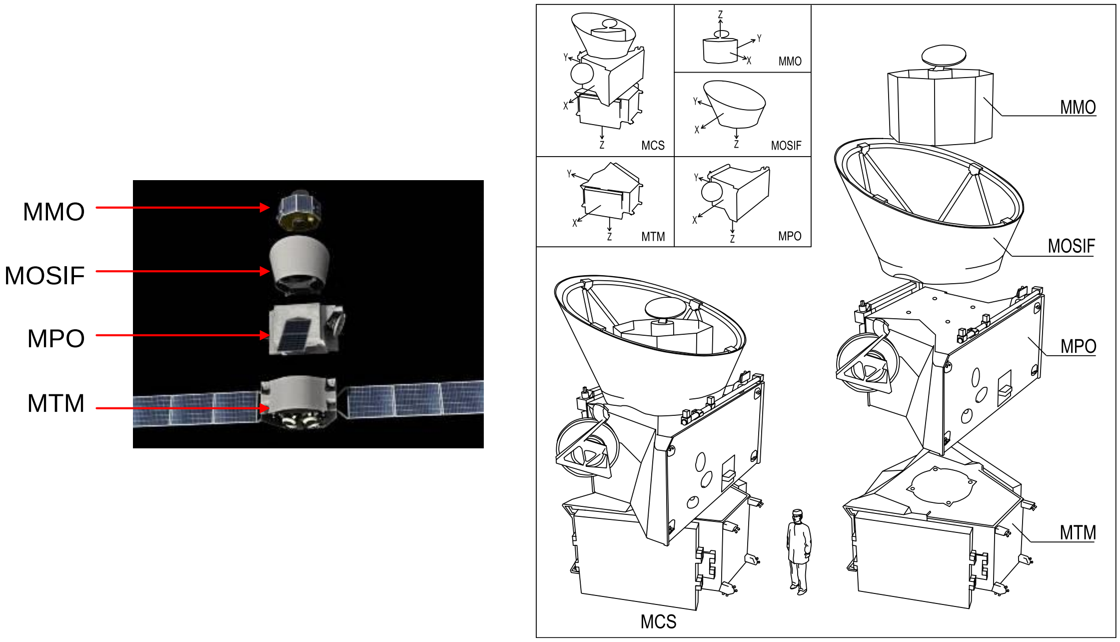


Figure 1. BepiColombo Configuration and Module Staging.

IV. Electric Propulsion System Design

A. Requirements

The selection of the electric propulsion system requirements has been based on a compromise between the need to provide adequate thrust to achieve the transfer within the given time frame (including planning for contingencies), maximizing the specific impulse (to minimize the propellant mass requirements), and minimizing the power requirements (to minimize the power generation system mass). The need to achieve a suitable compromise between thrust, specific impulse and input power is inherent in using electric propulsion systems, as increasing the thrust or specific impulse will increase the power requirement. The T6 gridded ion thruster, developed by QinetiQ, has been selected for this mission to meet these requirements.

The BepiColombo mission also introduces a number of additional design constraints for the electric propulsion system, in particular the ability to withstand the high solar heat load (corresponding to 10 solar constants at Mercury); operation of 2 thrusters simultaneously; and a high level of autonomy (to avoid excessive ground operations during the long thrust periods).

The thermal impacts of the high solar heat load are mitigated by the inclusion of a sun shield; thruster operation in direct sunlight is required only from 0.87AU upwards.

With respect to the autonomy requirements, during the electric propulsion thruster operations, on-board monitoring of the electric propulsion system is included; in case any anomaly or failure is encountered, the corresponding hardware is disabled, and the propulsion system autonomously reconfigured and restarted. This reconfiguration will be limited to an autonomous switch-over from a primary to a redundant (pre-defined from the ground) operational chain. It should be noted that any reconfiguration of the operating thrusters also requires reconfiguration of the overall spacecraft, as the thruster and spacecraft pointing angles, and overall AOCS, are impacted. This is described further in [9].

Operation of 2 thrusters simultaneously has been demonstrated up to the highest thrust levels required by BepiColombo, with no adverse interactions being seen. The impacts of twin thruster operations are described further in [10].

B. System Configuration

In order to achieve the required thrust range and life capability, 4 thrusters are used, with 1 thruster being used initially at thrust levels between 120 and 145 mN, and then 2 thrusters being used simultaneously to achieve the required thrust levels of between 145 and 290mN, as the available power increases.

The total accumulated mission firing time (including all margins) is 47446 hours, corresponding to an average total thrust of 132mN (to deliver the mission total impulse requirement of 22.5MNs). 3 thrusters are required to achieve this overall mission life with adequate margin and confidence (with the total impulse and firing time being shared between these thrusters), and the 4th thruster is provided for redundancy.

Each thruster is mounted on its own pointing mechanism; these are used to correct the thrust vector due to CG evolution over the mission life. The thrusters and mechanisms are configured in a square arrangement on the bottom face of the MTM, and then operated so that the thrust vectors are nominally pointed as follows.

- During single thruster operations, the thrust vector passes through the spacecraft CG
- During operation of adjacent thrusters, the operating thrusters are parallel to one another with the overall net thrust vector passing through the spacecraft CG
- During operation of opposite thrusters, both operating thrusters are parallel to the spacecraft longitudinal axis

C. Electric Propulsion System Architecture Overview

The overall scope of BepiColombo MTM Electric Propulsion System (MEPS) is as follows:

- A Xenon storage and feed system, comprising storage tanks, valves, filters, and pipework
- Thrusters, with their associated power supplies and flow control units, This assembly, including the interconnecting harness and pipework, is referred to as the SEPS
- A pressure regulation system, comprising the high pressure regulator and its driving electronics. This assembly, with its interconnecting harnesses, is referred to as the HPRS
- Pointing mechanisms, each supporting a single thruster, and their associated drive electronics. This assembly, with its interconnecting harnesses, is referred to as the TPA

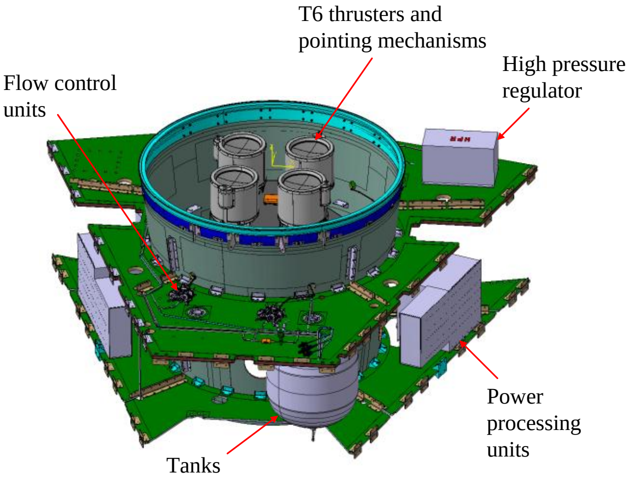
The MEPS layout and the corresponding product tree are shown in Figure 2.

The PRE and TPE are shown as functionally distinct units in this product tree; however, these are combined into a single electronics unit designated Thruster Pointing and Pressure Regulation Electronics (TPPRE).

1. *SEPS*

The SEPS comprises 4 T6 thrusters, and the supporting power supplies and flow control units. All internal control within the SEPS is provided within the PPU, which then interfaces directly with the thrusters and FCUs as described below.

In order to support simultaneous operation of any pair of available thrusters, including after any single failure, the SEPS is configured so that each thruster can be operated by either a "local" or "remote" PPU, as shown in Figure 3. This is necessary due to restrictions on the PPU operations. The PPU configuration is discussed further below (including the definition of the DANS and BSU); the main constraint that this imposes for the SEPS operations is that only one DANS in each PPU can be used at any one time. The local connections use harnesses 1, 2, etc.; the remote connections also use the cross-strapping harnesses PS1, PS2, etc. So for example, in order to operate thrusters 1 and 2 simultaneously, thruster 1 is operated from PPU1/DANS1 locally (using only harness 1), and thruster 2 is operated from PPU2/DANS3 remotely (using harnesses 2 and PS3). This then results in 2 different harness lengths to each thruster for which the SEPS has to be designed and verified.



Acronym	Name
MEPS	MTM Electric Propulsion System
├ XST	Xenon Storage Tank
├ FDV	Fill and drain valve
├ TIV	Tank isolation valve (NC pyro)
├ XEF	Xenon filter
├ HPRS	High pressure regulation system
│ HPR	High pressure regulator
│ ├ HPT	High pressure transducer
│ └ LPT	Low pressure transducer
├ PRE	Pressure regulator electronics
└ PRH	Pressure regulator harness
├ SEPS	Solar electric propulsion system
├ SEPT	Solar electric propulsion thruster
├ FCU	Flow control unit
├ PPU	Power processing unit
├ SEPH	SEPS harness
└ SEPP	SEPS pipework
├ TPA	Thruster pointing assembly
├ TPM	Thruster pointing mechanism
├ TPE	Thruster pointing electronics
└ TPH	Thruster pointing assembly harness
└ MEPP	MEPS pipework

Figure 2. MEPS Layout and Product Tree

The T6 is a Kauffman type gridded ion thruster, and is illustrated in Figure 4 below. The thruster has demonstrated the ability to achieve thrust levels from 75 up to at least 200 mN, and has an estimated operating life capability in excess of 26000 hours, providing good margin against the mission requirements. The operating principles of this thruster are described in a previous paper [7].

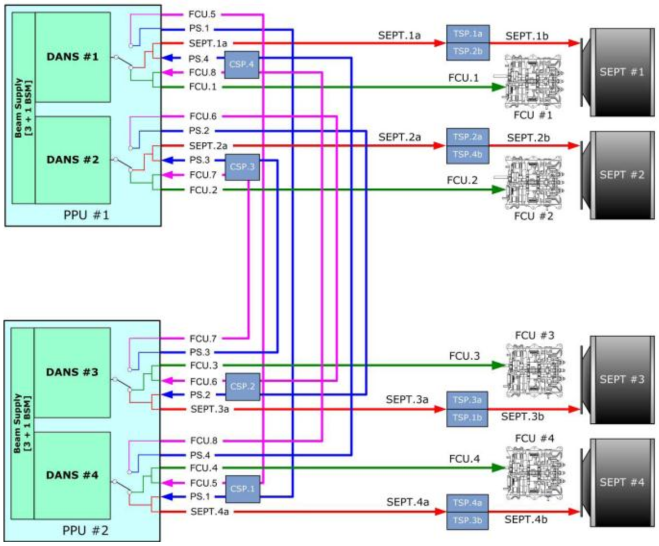


Figure 3. SEPS Harnessing Arrangement

Figure 4. T6 Electron-Bombardment Ion Thruster *(reproduced by permission of QinetiQ)*

The PPU has been developed by Crisa, and is illustrated in Figure 5. It should be noted that the configuration of the PPUs for BepiColombo is slightly different to that for HPEPS; this is discussed later in this paper.

Each PPU is comprised of the following elements:

- Discharge Anode Neutraliser Supply (DANS) (2 off). This contains the control electronics, an AC inverter, high and low referenced SEPT supplies, thruster switches, FCU drive electronics, and auxiliary power. The high voltage referenced supplies provide power to the loads within a SEPT which are referenced to the discharge chamber (this is at beam potential less the anode voltage).
- Beam Supply Unit BSU). This contains Beam Supply Modules (BSM) (4 off), as detailed below.

The overall PPU configuration is such that it provides internal redundancy, with 2 parallel DANS, the BSM operating in a "3 out of 4" redundancy scheme, and the BSU being able support either DANS. The Beam Supply Unit (BSU) is comprised of 4 parallel Beam Supply Modules (BSM) configured in a fail-safe architecture. These BSM are connected in parallel and thus supply the full beam potential but only a fraction of the total beam current. Only 3 BSM are required to meet the BepiColombo maximum thrust requirement of 145mN (per thruster), the fourth module being provided for redundancy. Each BSM is protected by a latch current limiter (LCL).

All SEPS electrical and communications interfaces to the spacecraft are through the PPUs. Power is provided from a 100V regulated main bus. Command, and control and return TM is via a 1553 bus, or direct high level TM/TC.

The FCU has been developed by Moog Bradford, and is illustrated in Figure 6. Flow rates to the discharge chamber and cathode (which are varied according to the thrust level) are controlled by means of variable flow control valves feeding into fixed restrictors (using pressure control); the neutralizer flow (which is fixed throughout the mission) is controlled thermally. The flow control algorithms are implemented within the PPU.

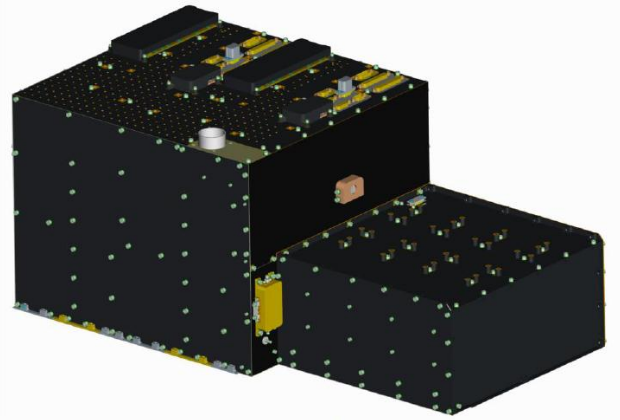


Figure 5. PPU *(reproduced by permission of QinetiQ/Crisa)*

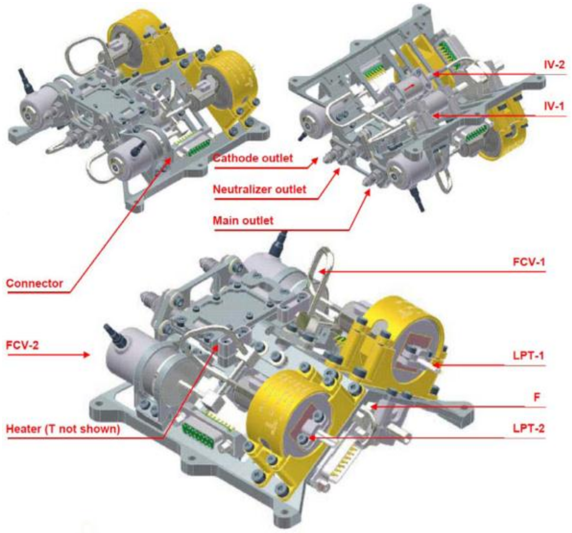


Figure 6. FCU *(reproduced by permission of QinetiQ/Moog Bradford)*

2. *Feed System*

The Xenon feed system sizing is driven by the high total impulse and thrust levels required to achieve the BepiColombo mission. These result in the need to store and deliver up to 580 kg of Xenon (including all losses and residuals), at flow rates of up to 7.5 mg/s (worst case with 2 thrusters firing simultaneously). The only other known mission which requires such a high level of Xenon processing is Dawn, which has a Xenon budget of approximately 450 kg[4,5].

Astrium satellites have based the BepiColombo Xenon feed system design on the extensive heritage gained on their Eurostar 3000 platform, which requires up to 300 kg of Xenon[11,12]. The feed system maximum pressures are 150 bar in the high pressure section, and 5 bar in the low pressure section.

The main changes required for BepiColombo compared to Eurostar 3000 are a larger tank volume, and increased capacity (throughput, flow rate, and inlet pressure) of the Xenon regulation system (HPRS). A configuration using 3 tanks has been selected to provide the required volume (366 litres total tank volume is provided), and also to fit within the MTM configuration constraints, as shown in Figure 7. The tanks are provided by Arde.

An electronic regulation scheme designated HPRS (which comprises the regulator and its drive electronics) has been selected, with the following key requirements:

- Regulation from tank pressure down to nominally 2.5 to 3 bar outlet pressure
- Fully redundant, and avoidance of any single point failures
- Provision of 3 independent barriers between the high and low pressure sections
- Provision of redundant high and low pressure sensors

The HPR is a development of the Xenon Regulation and Feed System (XRFS) currently in operation of Eurostar 3000. It is developed and manufactured by EADS Astrium UK. This is a "bang-bang" type regulator; a plenum is filled with Xenon on opening a regulation valve; when the pressure reaches a pre-defined threshold, the regulation valve is closed and the plenum pressure drops as Xenon is consumed by the thrusters. The regulation is controlled by the PRE, which stores the upper and lower regulation thresholds. The developments required for the BepiColombo application are described later in this paper.

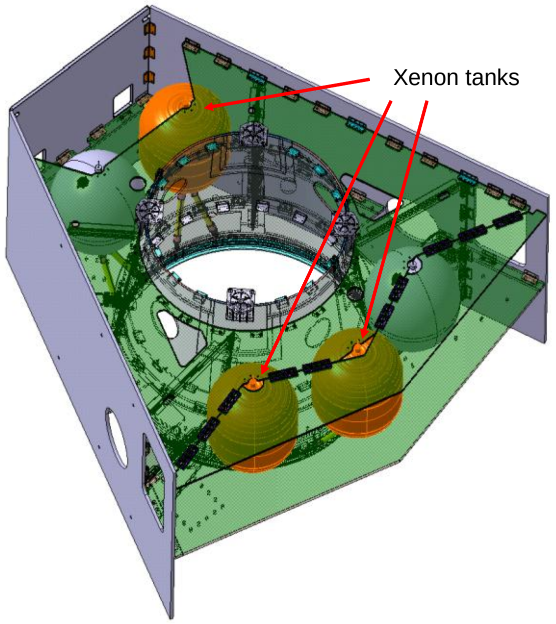


Figure 7. Xenon Tank Accommodation

All HPRS electrical interfaces to the spacecraft are through the TPPRE.

3. *TPA*

The TPA is supplied by RUAG Space GmbH (RSA), Vienna, and consists of the drive electronics and 4 thruster pointing mechanisms. Each pointing mechanism supports an individual T6 thruster in the stowed configuration during launch, by means of a dedicated Hold-Down and Release Mechanism (HDRM). The HDRM is equipped with a single, central release actuator. The HDRM is also equipped with an elastomer damping system that reduces the launch loads on the thruster to an acceptable level.

Upon release of the HDRM, the Pointing Mechanism Platform can be tilted around two perpendicular axes. This motion is facilitated by two geared high detent torque rotary actuators. For the design of the mechanism, existing building blocks are reused in order to minimize effort and development risk.

The TPM has a large pointing range; a total range of >24° around each axis is required to achieve all the various thruster firing combinations and associated pointing requirements.

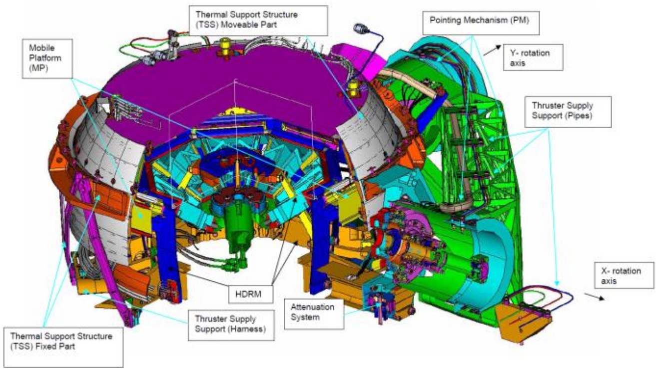


Figure 8. Thruster Pointing Mechanism *(reproduced by permission of RSA)*

The TPA design has an interconnection scheme as shown in Figure 8; the whole system consists of one nominal and one redundant TPE, each able to operate any 2 out of 4 TPMs simultaneously. (Note that this figure also shows the connections from the PRE within the TPPRE, to the HPR).

All TPA electrical interfaces to the spacecraft are through the TPPRE.

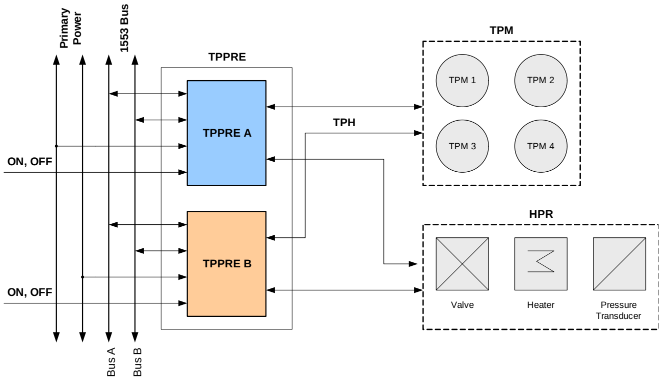


Figure 9. TPA Interconnection Scheme *(reproduced by permission of RSA)*

V. Development and Qualification Activities and Status

The BepiColombo electric propulsion system development activities and qualification activities are addressed incrementally, at equipment, assembly at overall subsystem level, as described in the following sections.

A. Technology Demonstration Activities

Prior to the start of the main implementation phase of the BepiColombo project, a dedicated technology demonstration activity (TDA) programme was conducted by QinetiQ on the SEPS, under direct ESA funding and direction. This was specifically aimed at addressing the following issues related to the ion thrusters:

- Impacts resulting from simultaneous operations of 2 thrusters, including EMC effects and plume interactions (see [10] for further details)
- Operation of the thrusters in the harsh thermal environment near Mercury

It should be noted that at this stage of the programme, the selection of the SEPS supplier was still open, and so parallel TDA programmes were performed by QinetiQ and Astrium ST, both directed and funded by ESA.

At the time of performing the TDA, the orientation of the spacecraft, and consequently the ion thrusters, with respect to the Sun were not defined, and therefore this test programme was designed to assess the worst case thermal scenario that the T6 ion thrusters could encounter. Following the thermal analysis of single and multiple T6 thrusters in near Earth and near Mercury thermal environments in a range of solar illumination orientations, this worst case scenario was identified as when the thruster is illuminated from the side.

A major difficulty with simulating the solar illumination conditions in the near Mercury environment is that the only realistic way in which it can be achieved is by using an array of xenon arc lamps, as these produce the most representative radiative energy spectrum, and the energy can also be directed through the ion beam onto the ion extraction grids. However, it was not possible to implement this approach for this test. As a consequence it was decided to adopt a compromise solution by using a heater collar placed concentric with the side of the thruster.

During normal operation the thruster is cooled almost entirely by radiative losses; a fraction of this energy is radiated from the side of the thruster. By placing the collar in close proximity, this radiative link is broken causing the thruster to effectively heat itself, forming a temperature gradient across the structure. Additional thruster heating is then achieved by heating the collar to a high temperature.

The thruster was operated for a period of approximately 40 hours in nominal thermal conditions, i.e. those prevailing in the test facility. Following this period the heater collar was placed in to close proximity with the thruster. The power applied to the heater collar was then adjusted until the indicated temperature of the thruster discharge chamber, adjacent to the heater, indicated the desired temperature. When this temperature was reached thruster operation was then maintained for a minimum of 10 hours, after which the heater array was retracted and the thruster allowed to cool naturally to nominal operating temperatures. This sequence was repeated 10 times with each ‘hot’ cycle being performed with 10% higher temperatures on the discharge chamber. During this test, beam probe sweeps where taken (with the thruster at thermal equilibrium) immediately before the heater was applied and then with the heater applied. Movements in the vector were seen, of the order of ± 0.2°.

In addition to these test, QinetiQ performed extensive endurance testing of the thrusters (over 5000 hours of operation), to gain confidence in their life capability.

These tests confirmed that the thrusters could be considered to be at technology readiness level (TRL) 5 for this mission.

B. Preliminary System Design

1. MEPS Design

The overall preliminary system design was performed as part of the Phase A study and the initial part of the implementation phase, leading to a MEPS PDR (as part of the system PDR). This preliminary design phase covered the following issues:

- Trade-off of various system configurations
- System and equipment sizing activities (e.g. thruster life requirements, Xenon storage requirements)
- Establishing the overall system architecture, taking into account the mission requirements and hardware capabilities (in particular, the outcomes from the SEPS TDA testing)
- Establishing the overall MEPS physical configuration, in conjunction with the spacecraft configuration
- Definition of the requirements for the assemblies and equipments, leading to selection of the suppliers for the SEPS, TPA, HPRS, tanks, and valves and filters

During this phase of the project, it was decided to merge the PRE and TPE functions (which are part of the HPRS and TPA respectively, and with RSA selected as the supplier for both) into a single electronics unit (the TPPRE), in order to optimise the overall system mass and power demands.

The requirements for various parts of the MEPS evolved during this preliminary design phase, mainly due to increasing spacecraft mass, and reduction on the predicted specific impulse from the SEPS (see below); this led to some growth in the tank sizing.

2. Assembly Level Design

The definition of the requirements for the lower tier equipments within the main assemblies (e.g. for the thruster, PPU and FCU within the SEPS) has been performed by the corresponding assembly supplier. This led to a complete set of specifications and PDRs, from assembly down to equipment level.

The preliminary design phase of the HPRS encompassed analysis of the overall regulation control philosophy, and establishing the requirements for the HPR and PRE equipments.

C. Equipment Development and Qualification

The development and qualification of each of the equipments within the MEPS follows a classical approach wherever possible. Some deviations to this were found to be needed during the course of the project, as described below. PDRs, EQSRs and/or CDRs have been held for all equipments and these are all closed. For each equipment requiring a dedicated qualification programme, qualification reviews are held prior to equipment final delivery.

1. Xenon Tanks

The tanks are based on existing qualified designs and manufacturing processes, optimised to meet the BepiColombo volume, Xenon mass and accommodation needs. The tank design follows standard fracture mechanics design rules following MIL-STD-1522A, and has been qualified using a dedicated qualification model, subjected to full environmental, pressure life cycle testing and burst tests. This qualification is complete.

2. Valves, Filters and Pipework

The pyro valve and Xenon filter are identical to those units used on the Eurostar 3000 PPS[11,12], and did not require any additional development or qualification activities. Similarly, the pipework uses the same diameters, material and processes as used on Eurostar, and only differs in terms of its routing.

The FDV is of the same design as the units used on the BepiColombo CPS[8]; this design of FDV has already flown on previous programmes.

3. HPR

The main modifications for the HPR with respect to the Eurostar XRFS required to achieve the BepiColombo requirements are as follows[8, 13]:

- Doubling of the plenum volume (from 1 to 2 litres) to accommodate the increased Xenon throughput; this is achieved using 2 plenums of 1 litre each
- Change in restrictor sizing to enable higher flow rates
- Definition of the seal material
- Adoption of a European pressure transducer
- Reconfiguration of the mechanical design

The HPR has been qualified using an EQM, supplemented by a life test for the regulation valve. HPR testing was performed using EGSE to replicate the TPPRE. All qualification activities are complete.

The PRE is developed and qualified as part of the TPPRE, as described below.

4. Thruster

The T6 thruster was originally developed for telecommunications applications, under the ESA funded HPEPS programme. However, its potential application for science and exploration missions, and in particular BepiColombo, was also taken into account, and specific issues related to this were included in the design and a dedicated test programme. This included the impacts of dual thruster operations[10], and operation under high external heat loads.

Thruster development activities have been performed on 2 models, the breadboard and TDA engines. During the course of the BepiColombo development programme, 2 major issues had to be addressed:

- It was found that the screen grid was susceptible erosion. This has been managed by changing the operating conditions to reduce the internal discharge voltages
- The overall grounding scheme for the SEPS was changed from a fully grounded to floating arrangement, to address concerns relating to neutraliser operations associated with twin thruster operations, and spacecraft interactions (see[10] for further details)

The life capability of the thruster is to be verified using a correlated combination of endurance testing and erosion modelling. The thruster is being qualified using an EQM, which is currently in test. An STM unit has been manufactured and delivered, and is used to support higher level structural and thermal testing.

5. PPU

The PPU is based on developments for the HPEPS programme (where this unit is designated PSCU); the HPEPS EQM unit is complete, and has been used to support initial coupling tests of the SEPS.

The configuration of the PPUs for BepiColombo is slightly different to that for HPEPS, in order to support the operation of any 2 out of the 4 thrusters simultaneously, and also to ensure sufficient power to operate up to 145 mN, including in the event of the loss of a beam supply module. The main difference is in the number beam supply modules to be used, as BepiColombo runs at higher thrust (and hence power) levels.

The PPU includes an FPGA for control of the thruster operations, and this has been subject to its own review cycle as part of the PPU design reviews. This includes updates to the FPGA required as a result of the SEPS coupling test 1 results.

The PPU is being qualified using a conventional EQM and PFM approach, and the EQM unit are currently in build.

6. FCU

The FCU is a new item; although many of the components (isolation valves, pressure transducers, etc.) are recurring designs from other programmes, the FCU also incorporates a proportional flow control valves and closed loop flow control which are new for BepiColombo.

The FCU is being qualified using an STM (for the structural qualification) and PFM approach, The STM build and test programme is complete, and the PFM is currently in test. An EM FCU has also been produced, to support the SEPS coupling tests.

7. *TPM*

The TPM is based on a design for the HPEPS programme, modified to meet the geometrical and pointing needs for BepiColombo. A breadboard model was built and tested, to verify the design concept. This included representative sections of SEPS pipework and harness, which have to pass over the mechanism and are subject to flexure as the TPM is moved.

The TPM is being qualified using a dedicated qualification model, which is currently near the end of its test programme (only the life test and final inspection still have to be completed). This also includes representative sections of SEPS pipework and harness during the qualification test programme.

8. *TPPRE*

The TPPRE has been designed taking into account requirements from the TPA and the HPRS. As well as the actuator drive and sensor acquisition circuits required, it includes a dedicated FPGA to provide the closed loop control of the thruster pointing and pressure regulation. This has been subject to its own review cycle as part of the TPPRE design reviews. A breadboard TPPRE has been built and tested.

The TPPRE is qualified using an EQM and PFM approach. The EQM is has completed its test programme, and will be used next to support TPA and HPR level assembly tests, described below. Although the PFM unit is fully redundant, the EQM represents only one functional branch; the other half has mass dummies for the environmental qualification.

D. Assembly Level Development and Qualification

In addition to the equipment development and qualification, design and test activities are required for the main assemblies (SEPS, HPRS and TPA).

1. *SEPS*

The SEPS has a number of coupling tests to be performed, which bring together the thruster, PPU and FCU to confirm that they all operate correctly.

- Coupling test 1 is a confidence test, and using the breadboard thruster, EM FCU and HPEPS EQM PSCU. This included testing with short and long harness lengths, corresponding to local and remote PPU to thruster configurations. The PSCU and FCU were placed outside the vacuum chamber, to maximise the level of diagnostics available. This test programme is complete, and has resulted in some modifications to the PPU being required to ensure correct SEPS operations
- Coupling test 2 is a formal qualification test programme. This test will use the EQM PPU, EM FCU and breadboard thruster. The initial part of this test will be conducted with the PPU and FCU outside the vacuum chamber to enable sufficient diagnostics to confirm the changes to the PPU have had the desired effects. The final part of this test will be conducted with all items placed within the vacuum chamber and connected with EQM harness and pipework to the greatest extent possible within the physical constraints of the facility.
- The SEPS EMC tests will characterise the radiated emissions from the SEPT when driven by a fully representative PPU. This will be performed in a test chamber which has been adapted to provide an RF-transparent section and anechoic room. This test will use the breadboard thruster, driven by the EQM PPU and EM or PFM FCU.
- The SEPS endurance test is performed using the EQM thruster, starting with EGSE driving the thruster and with the EM FCU and EQM PPU (or HPEPS EQM PSCU) being introduced as early as possible in the test.

For flight acceptance, each thruster will be operated with its own FCU and each DANS which can control that thruster, and with representative harnesses and pipework.

2. *HPRS*

The EQM HPR and TPPRE are to be tested together, to verify correct operation of the overall HPRS. Coupling test of the flight units is deferred until spacecraft level testing, due to schedule conflicts; the HPRS and PRE and PRE tested with EGSE simulating the PRE and HPR functions respectively.

3. *TPA*

The QM TPM and TPPRE have been successfully tested together, to verify correct operation of the overall TPA. Similarly, the flight TPMs and TPPRE are to be tested together prior to delivery.

E. MEPS Level Development and Qualification Activities

Specific issues related to interactions between MEPS equipments and assemblies are addressed by dedicated analysis and test activities, as follows.

1. *Thruster / TPM Mechanical and Thermal Interactions*

Detailed analyses of the potential mechanical and thermal interactions between the thruster and TPM have been performed; in addition, dedicated vibration and thermal vacuum tests were performed on the STM thruster / TPM assembly prior to these items being fitted to the STM MTM. This was in order to mitigate any remaining risks, ahead of the MTM and MCS thermal vacuum and mechanical tests, which provide the final verification of the overall mechanical and thermal behaviour.

The STM thruster / TPM assembly is shown in Figure 10. The testing of this assembly showed good correlation with the coupled predictions.

2. *Thruster / TPM EMC Interactions*

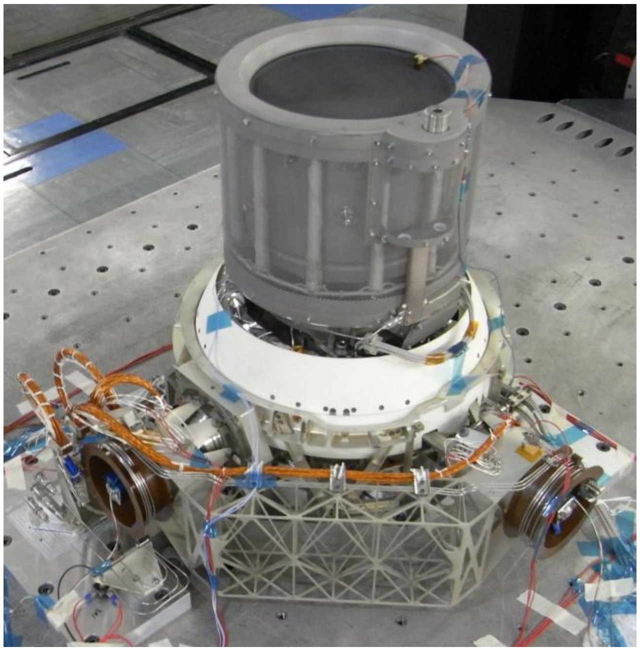


Figure 10. STM Thruster / TPM Assembly

The close proximity of the thruster (and SEPS harness) and TPM may result in unexpected EMC interactions between these items. The main concern is that the EMC emissions from the thruster may interfere with sensitive items on the TPM, in particular the hall sensors used for position sensing, resulting from the following:

- Magnetic fields generated by the thruster solenoids, and from the harnesses
- Radiated emissions (magnetic and electric) from the thruster and harnesses, including those arising from large current and voltage transients during thruster start-up, shut-down and beam-out events

The SEPS emissions have been estimated by QinetiQ based on previous T5 thruster measurements, and modelling to provide extrapolation up to the T6 design and operating conditions; these have then been specified to RSA as environmental requirements for the TPA, who have assessed the impacts of these for the TPM. The overall EMC interactions have also been analysed by Astrium, to identify particular problem areas which may require further tests. The magnetic field from the thruster has been measured directly, at locations critical for the TPM.

The remaining concerns relate to the impact of large current transients during thruster operations, as these may induce unacceptable voltage transients within the TPA. It should be noted that as these are transient events, it is only necessary for the TPA to survive these without damage or loss of overall pointing control; a transient (of the order of milliseconds) performance loss is of no consequence for the overall MEPS operations. A coupled EMC analysis has shown good margin in this respect, and a dedicated test is to be performed to retire any remaining risk associated with uncertainties in the EMC coupling. This test will inject current transients in to the SEPS harnesses mounted on the QM TPM, whilst the TPM is being operated by the EQM TPPRE, and voltages and TM on the TPA will be measured to confirm that there is no adverse impact. These transients are of the order of 45 A/µs, which were measured during beam-out events during SEPS coupling test 1.

3. *Pressure Ripple Impact on the SEPS Operations and Performance*

The HPRS operations introduces a pressure ripple at the FCU inlet, with a magnitude of up to 0.35 bar and rate of change of pressure up to 0.1 bar/s. The SEPS has been designed with this requirement in mind, and the FCU designed to compensate for this. During FCU and SEPS testing, an HPR simulator is used to reproduce this ripple. There is also provision in the programme for feeding the SEPS directly with the EQM HPRS, to provide final verification of this interface if required.

4. *SEPS Operations Impacts on the Power System*

The SEPS can interact with the power system as follows:

- Conducted emissions from the PPU interfering with the power bus regulation and control

- Large current transients inducing over or under voltage conditions; a particular concern for the MEPS is that e.g. a beam-out event may trip the LCLs on both PPUs or the PCDU, leading to an unwanted system shut-down

The power bus interface to the PPUs is the subject of dedicated requirements set by Astrium, and to be verified by QinetiQ and Crisa during the PPU and SEPS test programme. These transients were measured during SEPS coupling test 1, and identified a high transient on the power bus during a beam-out event. A small modification to the PPU is being implemented to minimise any impacts of this on the PCDU, and this will be confirmed during SEPS coupling test 2. There is also provision in the SEPS test programme to couple in the PCDU, to verify correct end-to-end operation of the PPUs with the power system, and with an operating thruster; this is currently planned be added to the EMC SEPS test, although this may be brought forward to SEPS coupling test 2 depending on the PCDU availability.

F. MEPS Testing at MTM and Spacecraft Level

The MEPS is subjected to a series of tests during the spacecraft AIT programme, to provide final verification of the system integrity and also to ensure that the AIT activities have not adversely affected the equipment status.

It is not feasible to operate the thrusters once the system is integrated onto the spacecraft, as operation in air is prohibited (establishing any discharge is impossible, and activation of certain parts of the thrusters in air can cause permanent damage); and the thermal vacuum facilities used for spacecraft test are not normally capable of supporting the flow rates associated with operating thrusters. Hence for most of this test programme the thrusters and FCUs are electrically disconnected from the PPUs, and these connections are routed through to simulators. The same applies to operations during thermal vacuum testing of the spacecraft, where it is necessary to run the PPUs at high power to provide the correct thermal load into the MTM.

The MEPS integration is split into 3 phases, with testing performed in each phase as discussed below.

The feed system (tanks, pipework, HPR, FDVs, pyro valve and filter) has been integrated into the MTM prior to shipment of this module to the next level of spacecraft integration (this was completed in August 2013). The TPA and SEPS are not integrated at this stage, as the hardware is under build and test by RSA and QinetiQ (and their subcontractors where appropriate). As the TPPRE includes the PRE which is used to control the HPR, HPRS level tests cannot be performed until the TPA is fully integrated. The pipework interfaces to the FCUs is capped using Swagelok fittings to enable testing of this part of the MEPS prior to the FCUs being fitted at a later stage. The following tests have been successfully completed on this part of the MEPS:

- Proof Pressure: The MEPS feed system has been subjected to proof pressure, and inspected to ensure there was no deformation or permanent set. This was done in 2 stages - the tank section was tested in parallel with the MTM CPS in a designated safe “bunker” area; and the pipework downstream of the tank isolation valve, including the HPR and low pressure section, were tested separately. The pressure transducer calibrations were checked during the pipework proof tests.
- External Leakage: This was performed at MEOP, in conjunction with the proof pressure tests described above. The tank section was tested using a conventional box leak test approach, where the pipework sections were tested by pressure decay.
- HPRS Internal Leakage: The internal leakage was measured globally, and for each individual valve.
- HPRS Functional Test: The valve operational characteristics were checked, and the flow rate through each branch of the HPR measured to ensure no blockage had been introduced during integration.

The following test will be performed on the MEPS after final integration of the SEPS and TPA, and during the overall spacecraft test campaign. It should be noted that once the MEPS is fully integrated to the MTM, the PPUs and TPPRE are not directly accessible, and all testing which requires operation of these units has to be performed via the spacecraft 1553 and power buses.

- The complete TPA (TPPRE, TPMs and interconnecting harness) will be integrated to the thruster floor (which is still available at Astrium UK). This complete assembly will be checked out to confirm the correct interconnections and function, following the procedures used by RSA for their TPA level tests. The equipped thruster floor will then be sent for the next level of integration and test.
- The low pressure pipework and proof tests will be repeated after FCU integration, to verify the integrity of the weld joints connecting the FCUs to the pipework.
- External Leakage, HPRS internal leakage, and HPRS functional tests will be repeated after MCS mechanical tests.

- HPRS functional test: The HPR will be exercised via the TPPRE, to confirm correct connection between these items, and to confirm the interfaces between them. This will include pressure transducer calibration spot checks, valve actuation, and heater operation.
- Thruster and FCU initial connection: This checks the correct electrical connection of the PPU to the thrusters and FCUs, as part of the overall SEPS integration process
- FCU flow rate and functional tests: These tests check the FCU flow rates, and functions of the valves.
- Electrical functional test: This checks the PPU and TPPRE command acceptance and TM, and SEPS configurations.
- SEP thruster activation simulation: The PPU is set to run the equivalent of a thruster firing sequence, up to full power.
- Thruster and FCU final connections: This checks the continuity of the PPU to thruster electrical connections, after these have been finally been made at the end of the spacecraft test programme.

VI. Conclusion

The BepiColombo electric propulsion system requirements and design are dominated by high specific impulse and total impulse needs, leading to a configuration of 4 ion thrusters, with either one or two thrusters being used simultaneously to achieve the required thrust level. Each thruster is mounted on its own pointing mechanism; this configuration enables operation of any single or pair of thrusters. The Xenon storage and feed system requirements are driven by the high total Xenon processing requirements.

A development and qualification programme has been established for the complete electric propulsion system, applied incrementally from equipment up to complete system qualification. A dedicated test programme has been completed, addressing specific issues related to the BepiColombo mission for the thruster, prior to the start of the main programme.

PDRs, EQSR and CDRs for each of the equipments are complete, and QRs are being held as and when the qualification for each newly-qualified equipment has been completed. The only equipments for which qualification still has to be finalised are the thruster, PPU and FCU.

Assembly levels test have been completed for the TPA, and initial tests for the SEPS. The final SEPS assembly and HPRS assembly level tests are still to be completed.

Potential mechanical and thermal interactions between the TPM and thruster have been verified using STM units. EMC interactions between the SEPS and TPA are to be verified by a dedicated EMC test.

The integrity of the feed system has been verified by proof, leak and functional checks prior to delivery of the MTM. Tests required following final integration of the TPA and SEPS have been identified.

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