BepiColombo – MEPS Commissioning Activities and T6 Ion Thruster Performance During Early Mission Operations

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Abstract: BepiColombo is an ESA cornerstone mission to Mercury in collaboration with the Japan Aerospace Exploration Agency (JAXA). A key element of the mission is the transit from Earth to Mercury using electric propulsion. While not the first deep space mission to use electric propulsion, it is the first such mission to another planet.

The MTM Electric Propulsion System (MEPS) is based around T6 gridded ion thrusters mounted on thruster pointing mechanisms, together with power processing units, flow control units, xenon storage tanks and a pressure regulation system. The MEPS was put through an extensive commissioning process after launch during which each functional unit was thoroughly and systematically checked out. Following commissioning BepiColombo embarked on the first thrust arc, from mid-December 2018 to mid-February 2019, during which the thrusters were operated in pairs.

Performance during early flight operations, covering commissioning and the first thrust manoeuvre, is described. Performance predictions, made prior to launch, have been validated using in-flight performance data. It is concluded that the MEPS is performing as expected in line with the BepiColombo mission requirements.

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I. Introduction

BepiColombo is an ESA cornerstone mission to Mercury executed in collaboration with its partner the Japan Aerospace Exploration Agency (JAXA), designed to place two spacecraft into orbit around Mercury. Airbus Defence and Space is the overall System prime and is additionally responsible for the development and provision of the Mercury Planetary Orbiter (MPO) and the Mercury Transfer Module (MTM). JAXA is responsible for the development and provision of the Mercury Magnetospheric Orbiter (MMO).

The BepiColombo spacecraft has a dedicated transfer module, which provides all the propulsion and power needed to deliver the two orbiters to Mercury[1]. This makes extensive use of electric propulsion (EP) through a number of thrust arcs. The use of electric propulsion for orbital transfer between bodies within the solar system is now well established, with its use on the Deep Space 1, Smart-1, Hayabusa Explorer, Dawn and Hayabusa2 programmes. This follows the increasing use of electric propulsion for large telecommunications satellites.

The BepiColombo mission 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.

This paper presents results from operation of the electric propulsion system, during commissioning and the first thrust arc. Performance will be compared to expectations based on ground testing.

II. MEPS Operations

A. Spacecraft operations

BepiColombo spacecraft operations are conducted at ESA/ESOC, Darmstadt, Germany, using the typical setup for ESA deep space missions. Contact with the spacecraft is established with the ESA 35m network of ground stations, located in Madrid (Spain), New Norcia (Australia) and Malargüe (Argentina). A ground station contact typically has a duration of around 10-12 hours. The number of station passes varies depending on the level of activities. For commissioning operations in the first few months after launch, daily contact was made, while the baseline for quiet cruise is one station pass per week.

The portion of the downlink telemetry rate routinely allocated to spacecraft non-science telemetry – i.e. all telemetry providing spacecraft status information required for operating the mission – amounts to about 2 kbit per second (256 Bytes per second). While for special operations, like MEPS commissioning, significantly higher housekeeping generation rates may be used, in general in-flight spacecraft status information is much more limited than what is available during ground testing.

Following launch on 20th Oct 2018, the Launch and Early Orbit Phase (LEOP) during the first 2.5 days of the mission was conducted with 24/7 ground station coverage and the support teams working in shifts around the clock, performing the most critical spacecraft checkout and configuration activities. Following the end of LEOP, Near-Earth Commissioning Phase (NECP) operations took place from 22nd Oct to 16th Dec 2018 and were supported by daily station contacts. The aim of this phase was to perform a full spacecraft checkout (platform and payload) with on-site support by the spacecraft manufacturer, subcontractors and the scientific instrument teams.

B. MEPS commissioning

The MTM Electric Propulsion System (MEPS) comprises four main elements:

- Xenon storage tanks
- Thruster Pointing Assemblies (TPA)
- High Pressure Regulation System (HPRS)
- Solar Electric Propulsion System (SEPS)

Further details of each of these systems can be found in Ref. 1. Commissioning of the various MEPS elements was performed during NECP, initially with the MEPS out of the Attitude and Orbit Control System (AOCS) loop but with AOCS engaged for later thrust operations. In practice these activities were interleaved but for simplicity the commissioning of the three major parts of the MEPS was as follows.

1. *Thruster Pointing Assemblies (TPA)*

The TPAs are locked for launch. Once in orbit, after checking the lock status, the TPAs were released and status checked. Each TPA was then activated and driven to its initial position, with position feedback indicating correct operation.

2. *High Pressure Regulation System (HPRS)*

At the start of HPRS commissioning all temperatures and pressures were read and confirmed to be within expected limits. The low pressure section (upstream of the FCUs) was at 2.39 bar. This was slowly vented, over some 8 hours, to less than 40 mbar by opening valves in the FCUs. This section was then re-filled from the tanks, using the HPRS, back to the nominal FCU inlet pressure range ready for SEPS purging, completing HPRS commissioning.

3. *Solar Electric Propulsion System (SEPS)*

The SEPS comprises the T6 Solar Electric Propulsion Thrusters (SEPT), Power Processing Units (PPU), Flow Control Units (FCU) and their interconnecting electrical harnesses and pipework (Fig. 1). The SEPS has the most complex commissioning sequence of the three MEPS subsystems and is described in detail in section III. SEPS commissioning includes thrust production and therefore the spacecraft was required to be in EP Control Mode (EPCM), with AOCS active, for this part of the commissioning sequence.

See Ref. 1 and Ref. 2 for a detailed overview of MEPS-related operations. Following commissioning of the MEPS during NECP BepiColombo was ready to enter the Cruise Phase of the mission and begin the first thrust arc.

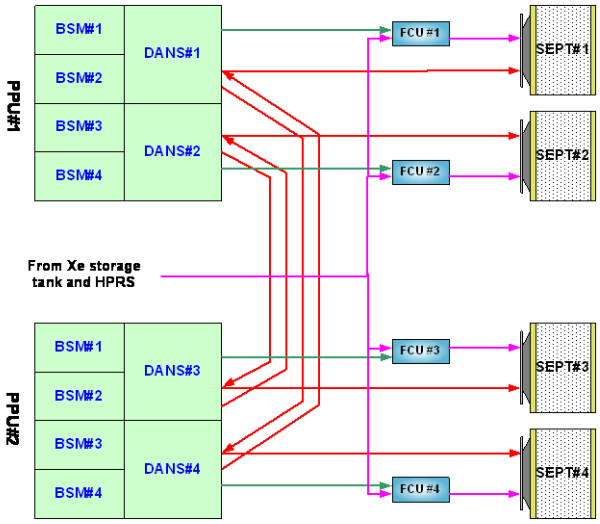

Figure 1. SEPS architecture

C. First thrust arc

The end of NECP was driven by the need to start the first solar EP arc of the mission (SEP1) in December 2018, constituting the first extended EP usage in flight. EP operations are characterised by (i) complex EPCM entry operations requiring several hundred commands and taking up to 5.5 hours, (ii) constraints on S/C visibility with its moveable antennae (Medium or High Gain Antenna) when in the attitude required in EPCM, (iii) the need for regular interruptions of thrusting for performing orbit determination, and (iv) constraints on the available power requiring management of the commanded thrust levels.

The SEP1 arc was run in dual thruster mode, first using thrusters 1 and 3, later on thrusters 2 and 4.

- Two thrusters were used in this arc. While balanced thruster usage was also a consideration, thruster selection was mainly driven by MGA/HGA visibility, with thruster pair [1,3] allowing HGA coverage in EPCM up to 23/12/2018, and thruster pair [2,4] allowing MGA coverage from 10/01/2019 up to the end of the arc.
- In terms of ground station contacts, a weekly “navigation pass” was taken, when EPCM was interrupted to gather radiometric data undisturbed by the slight variations in thrust direction and magnitude, required for performing an orbit determination with sufficiently high accuracy. Two ground station contacts were taken per week to monitor S/C status in EPCM, allowing a regular check of S/C performance and faster reaction time to unexpected EPCM interruptions.
- The thrust level was gradually changed over time due to the change of distance to the Sun, limiting the maximum power available for firing the thrusters.

III. SEPS commissioning sequence

A sequence was developed to safely commission the SEPS in order to check the correct operation of each unit within the system prior to start of the Cruise Phase.

PPU venting. Since the PPU generates high voltages there is the potential for Paschen breakdown should a low residual air pressure remain within the PPU when the high voltage supply is turned on. Therefore a minimum of 48 hours was required to ensure the PPU had vented and outgassed. This was comfortably accommodated within the period allocated for check out of other spacecraft systems.

Relay setting and checking. The SEPS contains electromechanical relays to allow selection of alterative configurations as part of the redundant design. It is possible for such relays to change position when subject to launch vibrations. If an attempt were made to use the SEPS with a relay in the wrong position it could lead to incorrect system operation or, in the worst case, failure of additional parts within the SEPS. Thus a sequence was developed to first cycle all the relays to reset any which had moved position. This is followed by relay checking, using the available telemetry to ascertain the actual position of each relay.

Venting and Purging. The SEPS is qualified to operate with a mean inlet pressure of 3.029 bar. In case of any leakage through the high pressure section of the xenon supply system the valves in the FCU are opened to vent the system and reduce the pressure. Then each SEPS branch (FCU, pipework and SEPT) is purged with a steady flow of xenon to remove any trapped air and residual trace impurities in the system. The volume downstream of the FCU is exposed to air when on the ground and can absorb atmospheric gases which must be fully expelled before operation.

Outgassing. The surfaces of the SEPT materials may adsorb atmospheric gases prior to launch. These can potentially damage some thruster components if outgassing occurs at high temperature. Hence a two-stage outgassing process is applied. Firstly 24 hours of cold outgassing are completed after purging. Then the cathode heaters are energised at a low level to gently warm the cathodes and accelerate the outgassing process. Both primary and secondary heaters are powered for 24 hours each. Note that a significantly reduced outgassing period has been successfully tested on the T6 for future missions but for BepiColombo the extended duration was retained. After outgassing the SEPS is ready to establish the discharges.

However, given that the cathodes had been exposed to air for around 12 months prior to launch, during spacecraft integration, a further outgassing and emitter conditioning step was implemented on BepiColombo. This is a technique commonly used during ground testing to maximise the probability of starting the cathodes first time and was successfully used during the MTM thermal vacuum testing in ESTEC's Large Solar Simulator chamber. This involved applying a series of full power heater cycles, for 15 minutes each, followed by a cool-down period.

At this point the process of starting each thruster can commence in earnest. The first step is to start the discharges in both the thruster discharge chamber and the neutraliser. Both discharges are started simultaneously. The main discharge is maintained at normal low power for 20 mins then, for commissioning only, the power is increased by raising the anode current to the maximum. This process conditions the cathodes for thrust operation. The high power discharge is run for two hours then reduced back to low level.

The thruster is then ready to transition into thrust mode. The beam and accel supplies are enabled and a beam is produced. Initial thrust is about 30 mN which is ramped up over about 2 minutes to 75 mN, the minimum nominal thrust level. At this point a dwell of 10 minutes occurs, to allow the thruster to warm up gradually and avoid large thermal gradients within the thruster. This step has now been demonstrated to be unnecessary for the T6 but a cautious approach was retained for BepiColombo. The SEPT should be operated for a minimum of 3 hours to allow the thruster to reach full thermal stabilisation. There was sufficient time during one pass to maintain a dwell at 75 mN for 3 hours, after which the thrust level was ramped up to 125 mN for a further 2 hours.

At this point each thruster is fully commissioned and can be operated using the normal start-up sequence.

The final step for SEPS commissioning was to operate thrusters in pairs. The hydrid dual firings tested the pair-combinations which can be interchanged using the cross-strapping harness (SEPT1/SEPT4 and SEPT2/SEPT3). The initial short firings were followed by an extended five hour firing which confirmed that there were no unexpected interactions between two thrusters operating simultaneously. The baseline configuration planned to be used throughout the mission is SEPT1/SEPT 3, and SEPT2/SEPT4, alternating pairs to ensure even accumulation of life. These configurations will only be changed in the event of a failure, in which case alternative pair-combinations would be used. The actual timeline for SEPS commissioning is shown in Figure 2.

Figure 2. Electric propulsion commissioning 20th Oct – 7th Dec 2018

IV. In-flight commissioning performance prediction

A. Model requirements

QinetiQ was requested to provide predictions of the exact performance expected during commissioning. This went beyond the normal system performance modelling already conducted as part of the core programme. The motivation behind this was that, due to difficulties regarding calibration of the FCU flow rates, it was desired to check the flow rates during commissioning. While it is not possible to measure flow directly, any variations in flow have an impact on thruster electrical parameters which can be monitored via telemetry. In particular anode voltage is sensitive to flow rate and can be used to assess if the correct flow is being delivered to the thruster. Furthermore, anode voltage is an important parameter determining thruster lifetime and hence any anomalous anode voltages would require investigation.

A model was constructed with the aim of predicting, as accurately as possible, the values of the thruster electrical parameters which would be expected to be observed. Modelling was restricted to operation in thrust mode only, after thermal stabilisation was reached, at a constant thrust. For each parameter three sets of values were produced. Firstly, the nominal value. Note that some parameters, such as beam current, are specified as a result of the thrust value demanded by the OBC. Others, such as anode voltage, are not controlled to a value by the PPU but adopt values necessary for equilibrium in the plasma behaviour, which in turn is influenced by the controlled parameters (such as beam current) and environmental characteristics such as temperature. Hence the predicted nominal value of such parameters must be derived from ground test data.

The second set of parameters corresponds to the upper and lower limits which can occur if every part of the system were operating within their specified tolerances. Again, this is fairly straightforward for the directly controlled parameters, as the range is determined by the tolerances of the controlling elements. For the PPU this is either the voltage or current regulation accuracy. The maximum tolerances of these parameters was specified to the PPU supplier based on the overall performance accuracy requirements for the mission as well as the acceptable range over which the thruster is able to operate in a stable and consistent manner. For the FCU the calculation is more complicated. The FCU does not measure flow rate directly. Instead it must be determined from the pressure inside the FCU and the characteristics of the flow restrictor. Both are influenced by temperature which is measured at both points. The tolerances in the pressure and temperature measurements, combined with calibration uncertainties, led to an assessment of the overall flow rate uncertainty. Flow rate affects a number of electrical parameters at the thruster, in particular anode voltage and accel grid current. Hence the model also had to take into account the relationship between flow variation and each electrical parameter to derive an additional uncertainty term.

The resulting set of upper and lower values represents the range within which the SEPS may operate and still be considered within specification.

The model went further than this to produce a third set of parameter limits, which were bespoke predictions for each branch of the SEPS, accounting for the model-to-model variations between the flight units. Since each unit (SEPT, PPU, FCU, harness) had been characterised during ground acceptance testing, it was possible to build up an expected, or "most likely", performance, using the data for each unit connected within a SEPS branch. Since each unit was nominally well within its specified tolerance range, this expected performance would be more precise and therefore potentially more sensitive to detecting small variations in flow rate.

B. Modelling in-flight performance

The nominal performance of each flight thruster was derived from ground acceptance testing of the four flight models. Acceptance testing was carried out at a limited number of operating setpoints within the overall T6 operating envelope. Therefore it was necessary to interpolate the ground test data to match the operating points which were eventually selected for flight.

C. Correcting for ground test effects

A significant challenge in designing the model was compensating for the effects of ground test facilities on measured performance. In particular, the environment within a vacuum chamber is different to that in space and has a small but measurable impact on thruster performance. There are several differences which have to be accounted for, including vacuum chamber background pressure, differences between test harnesses and pipework, and ground instrumentation accuracy.

When operating a thruster in a vacuum chamber the background pressure is typically in the range $5x10^{-6}$ to $5x10^{-5}$ mbar, limited by the thruster mass flow rate and the xenon pumping speed of the facility. This residual gas is mainly xenon and some of this re-enters the thruster through the grids, in effect contributing a small extra flow into the discharge chamber, known as back-ingestion. This changes the ionisation ratio at a given beam current and therefore affects the anode voltage. In space the background pressure is effectively zero so there is no back-ingestion.

To achieve the same performance in flight as on the ground, and to compensate for the lack of background pressure, flight flow rates are slightly increased compared to the ground flow rate for any given thrust level. This compensation has been calculated according to the clausing factor method[3], calculated for the SEPT grid geometry. This correction has also been independently validated. Firstly, the effect of varying flow rate on anode voltage was characterised on the ground over a range of flow rates (via the thruster main xenon feed). Secondly, the background pressure in the vacuum chamber was varied by injecting xenon directly into the chamber, while keeping the thruster flow fixed. From the change in background pressure, the effective back-ingestion flow was computed according to the model above; the expected effect on anode voltage could then be determined using results from the flow rate test. It was found that the predicted effect was the same as the observed change, thus confirming that the back-ingestion calculation was correct.

With this information it was possible to extrapolate from the ground test data to in-flight conditions. Measured anode voltages on the ground could be corrected using the measured vacuum pressures and correcting for the difference between the actual ground and intended flight flow rates.

The other parameter which is affected by main flow rate is accel current. This current is mainly due to impact of charge-exchange (CEX) ions on the accel grid. The ions are produced when fast ions in the beam strip an electron from a slow-moving neutral, leaving a slow-moving, positively-charged ion close to the negatively charged accel grid. These interactions can happen either within the bore of an accel grid hole or in the region immediately downstream from the thruster. The rate of CEX ion production is related to the density of neutral atoms in these regions, which is in turn influenced by the flow rate and background vacuum pressure.

QinetiQ performed tests to characterise the relationship between accel current and vacuum pressure, by deliberately injecting xenon into the chamber. Separately the flow rate was varied and thus the relative contributions of the two effects could be quantified. From this empirical data, the accel current as measured on ground, at a given background pressure and flow rate, could be corrected for flight conditions.

A similar exercise to the anode voltage described above was applied to the neutraliser keeper voltage. Again, test data using different neutraliser flow rates was used to create a simple empirical model of

neutraliser keeper voltage as a function of flow rate then used to extrapolate measured performance of the flight models using the in-flight flow rate.

D. Harness correction

During ground testing the electrical parameters are normally measured using electrical ground support equipment (EGSE) located outside the vacuum chamber, with harnesses connecting, via chamber feedthroughs, to the thruster inside the chamber. While attempts have been made to make these cables as close as possible, in terms of impedance, to the flight cables, the different lengths, routing and construction make achieving an exact match impossible. Therefore the voltages, as measured at the EGSE, must first be corrected to remove the voltage drop through the harness to obtain the voltages at the thruster's electrical connector. Then the voltage drop through the flight harness is added to obtain the voltage expected at the PPU, which is where the voltages are monitored on the spacecraft. This process is further complicated by the temperature-dependence of the cable resistivity. The model therefore includes a correction for this. The MTM thermal monitoring system does not include sensors directly on the harness and therefore the temperature was inferred from thermal modelling of the MTM. Since commissioning was performed at 1 A.U. and with one thruster at a time, without sufficient time to reach full thermal equilibrium, a cold thermal model case was used to set the flight harness temperatures. These were in the range 15°C - 20°C for the fixed harness (within the MTM) and 15°C - 85°C for the flexible harness, routed across the TPM up to base of the SEPT.

E. Success criteria

The purpose of the model was to provide some more objective criteria for assessing performance of the SEPS during commissioning, but did not form part of a formal acceptance process. So although pass/fail criteria were defined, these were for guidance rather than for mission go/no go decisions. The upper and lower limits generated by the model did not include any allowance for the uncertainties associated with the modelling process. Therefore any results just outside specification may be acceptable.

The primary success criteria were that in flight each branch of the SEPS should perform within specification. Note that the assessment only applied to thrust mode – no formal assessment of discharge mode was required. The actual performance during commissioning is compared to the model predictions in the next section.

V.SEPS commissioning performance

A. Overview

Due to the limitations of ground station visibility (described in Section II C), commissioning activities needed to be performed in blocks of around 10 hours (except for certain operations which could continue while the spacecraft was out of contact). In addition, the steps required to prepare the spacecraft prior to thrust operations further restricted the time available. Hence SEPS commissioning was divided into three phases:

- Venting/purging/outgassing
- Discharge
- Thrust

SEPS commissioning began on 29/10/2018, with the initial steps of venting, purging and outgassing. This phase continued until 14/11/2018 and was completed without any issues. Note that some of these processes continued even while the spacecraft was out of contact.

During ground testing discharge and thrust commissioning would normally be conducted in series with no break and this has been found to provide a reliable method for starting a thruster after a period of atmospheric exposure. In flight it was necessary to split the discharge and thrust elements of commissioning into separate ground station passes. It was decided to commission each SEPT in discharge mode first, then move to thrust mode.

B. Discharge commissioning

Discharge commissioning began on 16/11/2018 with SEPT1 and SEPT3 simultaneously. SEPT1 started at the first attempt but the SEPT3 neutraliser initially failed to start. Unfortunately, due to the way the failure recovery system was configured, both thrusters were stopped by the OBC. It was subsequently

decided to perform discharge commissioning on each thruster individually, rather than in pairs. All SEPTs subsequently started successfully after a few attempts, which is normal behaviour seen during ground test following a long period of atmospheric exposure. Discharge commissioning was then successfully completed on all SEPTs.

Figure 3 illustrates the behaviour of number of key thruster parameters during commissioning, showing the thruster mode changes. During cathode heating the heater voltage increases as the temperature of the cathode (and hence resistance) rises. Once the cathode is hot enough to sustain thermionic emission the discharge was ignited with the anode current regulated at 5A. The anode voltage can be seen to slowly increase during this time as various parts of the thruster change temperature. After 30 min the anode current is increased to 18A for high power discharge (the main flow is also increased). Anode and magnet voltage can be seen to evolve as the thruster continues to warm up and reach thermal equilibrium.

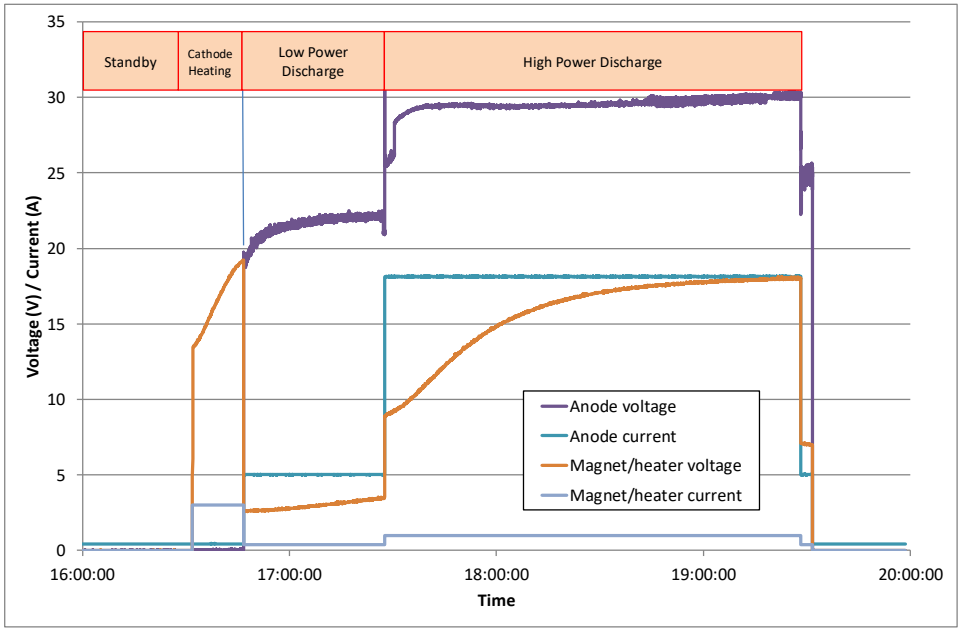

Figure 3. SEPT1 key parameters during discharge mode commissioning.

Figure 4 shows further parameters, including the pressures on the three FCU flow branches and neutraliser voltage. The main and cathode branches are actively controlled by the FCU, hence the pressure remains constant. The neutraliser branch is not regulated within the FCU and so reflects the sawtooth pressure from the HPRS. This ripple is reflected in the neutraliser keeper (NK) voltage; the same behaviour is seen in ground tests where the HPRS ripple is replicated by fluidic ground support equipment (FGSE). Note also how the frequency of the sawtooth increases as the overall flow rate is increased, as expected.

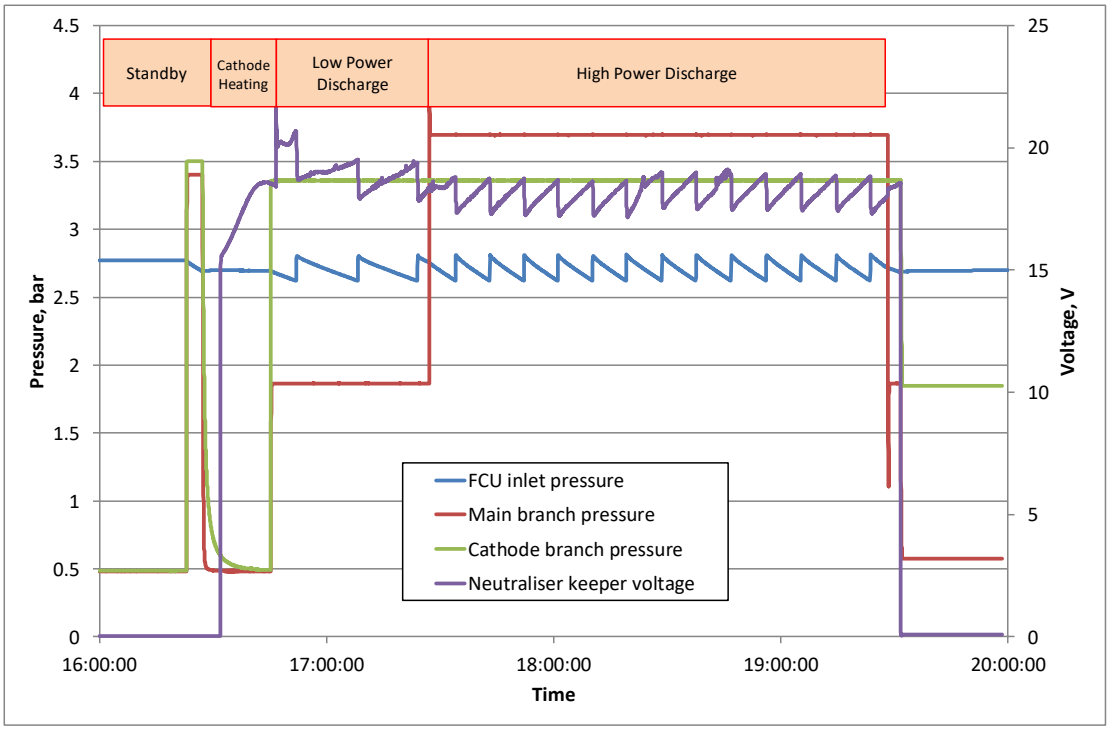

Figure 4. SEPT1 key flow and neutraliser parameters during discharge mode commissioning

Although the model described in section IV applied to thrust mode only, predictions for both low and high-power discharge operation were derived, based on earlier thruster qualification tests. All the flight parameters were as expected except for magnet voltage which was slightly lower than expected during low power discharge. This is thought to be due to lower temperatures in the solenoids compared to ground test. By the time of commissioning the SEPTs had been in space, shielded from direct sun, for around one month and the temperature reference point was typically below -60°C at the start of the discharge sequence, hence the solenoids would take longer to reach their normal operating temperature compared to ground test conditions.

C. Thrust commissioning

The same parameters for SEPT1 during thrust commissioning are shown in Figure 5 and Figure 6, while the temperature (measured on the SEPT mounting ring) is shown in Figure 7. Key points to note are:

- Beam voltage shows a number of drop-outs – these are caused by beam-outs, with the automatic recovery sequence re-establishing the beam in each case. A high beam-out rate is expected during commissioning.
- Anode voltage rises sharply when the beam is enabled, in order to maintain the required discharge current while ions are extracted from the discharge chamber. It overshoots slightly then starts a slow decline. This is due to the thruster settling as it heats up. There is a further increase when thrust level is increased. The noise is typical, reflecting the nature of the plasma load.
- The rise in magnet voltage reflects the changing temperature of the thruster (see Figure 7).
- All other parameters remain very stable throughout thrust commissioning.

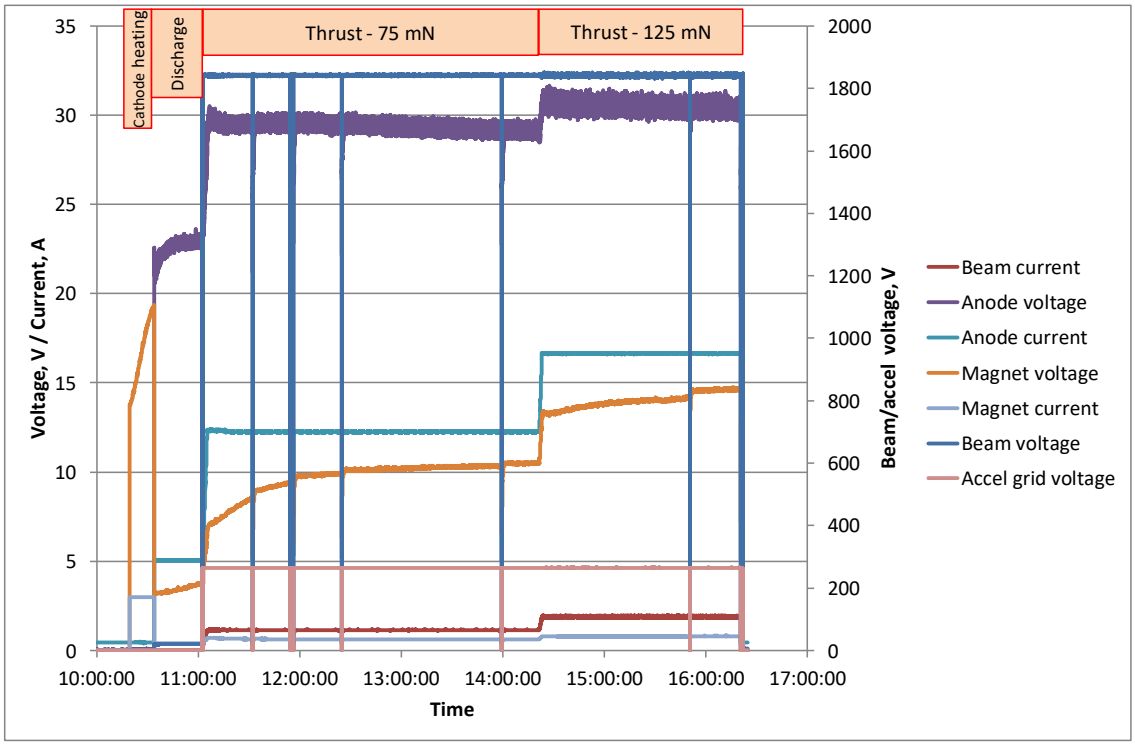

Figure 5. SEPT1 key parameters during thrust mode commissioning

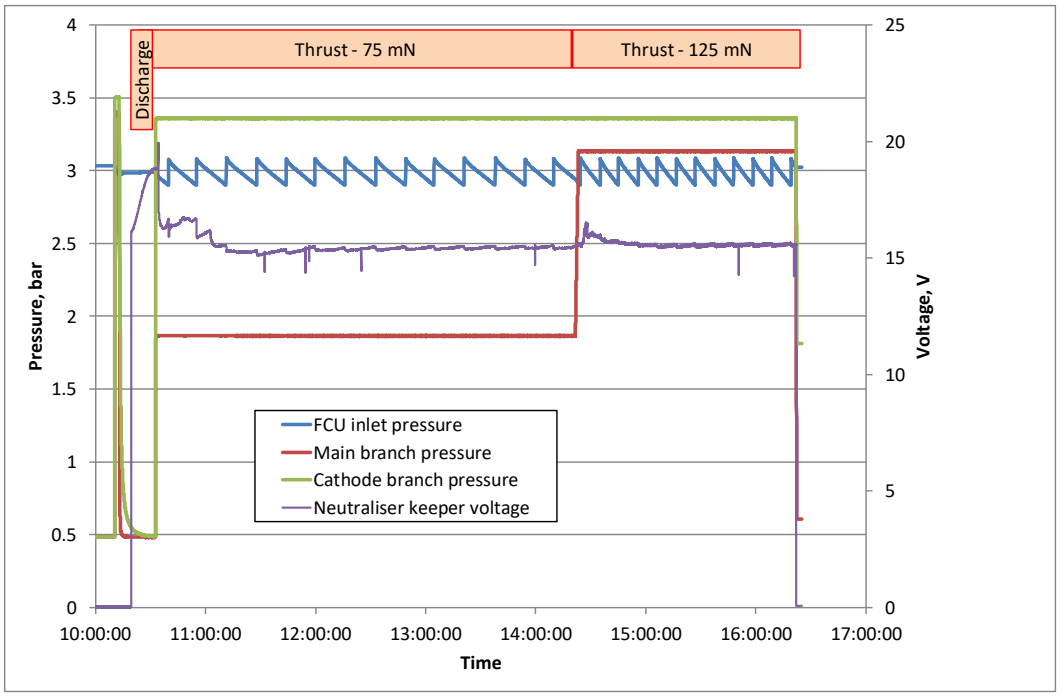

Figure 6. SEPT1 key flow and neutraliser parameters during thrust mode commissioning

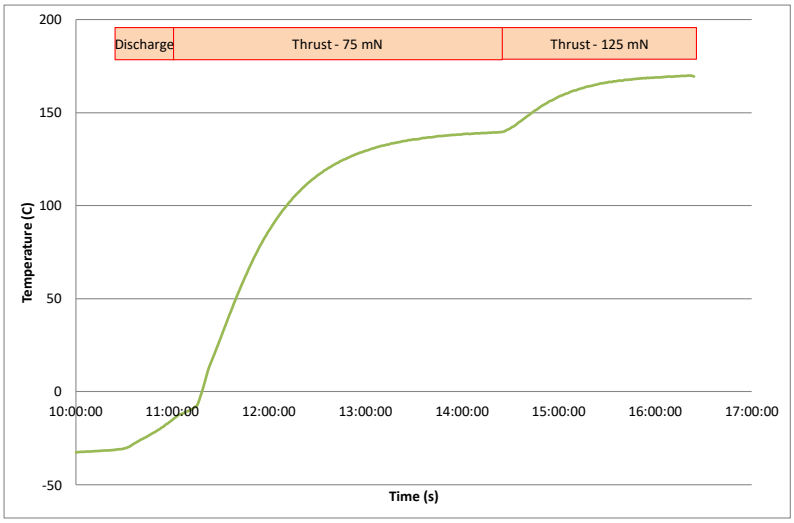

Figure 6. SEPT1 temperature during thrust mode commissioning

D. Comparison of performance with model predictions

As described in section IV, predictions of the thruster electrical parameters had been made prior to commissioning using a model developed from ground test data. Since the model used steady-state data, i.e. when the thruster had been operating for a total of around five hours (three hours at 75 mN and two hours at 125 mN) and was approaching thermal equilibrium, equivalent flight data was extracted, from the last 10 minutes of thrust operation, then averaged to remove noise.

A set of colour coded bar charts was produced to visualise the data. Green represents the "most likely" range, based on the characterisation of the individual SEPS branches; yellow represents "within specification", i.e. within the specified tolerance; amber represents outside this range. As can be seen in Figure 7, all parameters fell within their specified ranges with one exception.

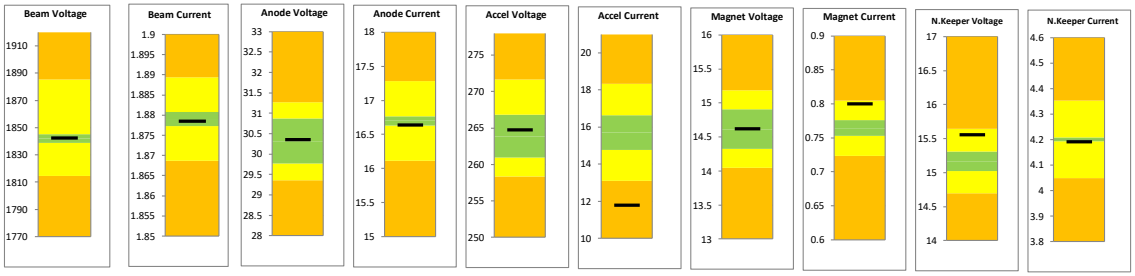

Figure 7. SEPT1 predicted and actual parameter values
Green indicates the "most likely" range, yellow is "within specification", amber is "outside specification": actual flight values are shown as a black bar.

Accel current was found to be noticeably lower than predicted and this was consistent across all thrusters (figure 8). A low accel current is good as it implies lower rate of ion impingement and hence longer grid lifetime. The explanation for the low accel current is a combination of two factors. Firstly, the empirical model used to extrapolate ground test data to flight predictions was developed using limited data and it is likely that the prediction has significant uncertainties which are not accounted for in the bar charts. If these uncertainties are included then the flight data would be considered "within specification". Physical modelling of the grids, performed by NASA JPL, indicated in-flight accel currents much closer to those observed.

Secondly, the accel grid current used as a reference for predicting flight performance was measured on the flight models after only 5 hours of thrust operation in the final operating condition determined from qualification testing[4]. The grids may therefore have undergone further burn-in after this, when sharp edges

from the manufacturing process are rounded off by the beamlets, resulting in a lower measured accel current.

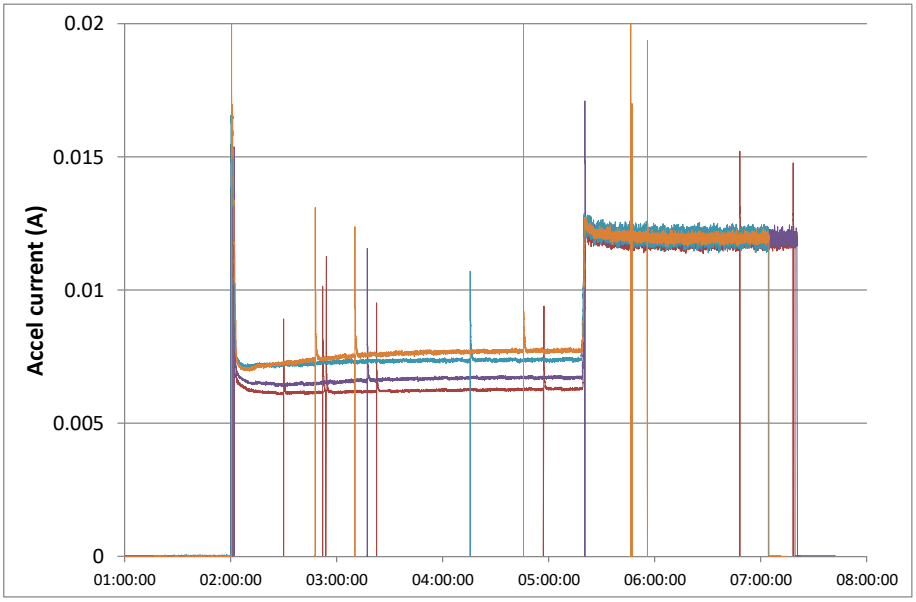

Figure 8. Accel current trend for all four SEPTs

E. Anomalies

Very few issues occurred during SEPS commissioning. A couple of anomalies were noted during the beam-out recovery sequence. Both of these were traced to issues with the timing of various checks within the OBC and PPU which, for a particular pattern of beam-outs, caused either an unwanted thruster switch-off or a delay to recovery. Neither event was harmful and adjustments were made to the settings to reduce the probability of recurrence. This illustrates the difficulty of designing, and especially testing, a system to cope with events which are essentially random and cannot be produced on demand during testing, but also the benefit of having a flexible, programmable system able to be tuned in flight.

Minor adjustments were made to some other settings within the Failure Detection, Isolation and Recovery (FDIR) functionality on the basis of the data collected during commissioning.

VI.First thrust arc

A. First thrust arc timeline

Following successful commissioning of the MEPS the first of 23 planned thrust arcs on the journey to Mercury commenced on 17/12/2019. The thrust arc was subdivided into sub-arcs of approximately one week duration, separated by navigation passes. There were two main reasons for this. Firstly, due to limitations with antenna visibility while the spacecraft was oriented for thrust, it was necessary to terminate thrust to re-orientate the spacecraft to allow download of telemetry using the high gain antenna. Secondly, the lack of thrust during the pass meant that accurate spacecraft tracking could be obtained using ranging and Doppler measurement. This was later used to determine actual thrust levels achieved during the sub-arcs.

The first three sub-arcs (SEP1-1 to SEP1-3) utilised SEPT1 and SEPT3 operating as a pair, and the remaining six arcs used SEPT2 and SEPT4. Figure 9 shows the timeline of the first arc. There were three unplanned thrust interruptions. The first, on 19/12/2018, was due to a trip of the Neutraliser Recovery FDIR which subsequent analysis showed to be over-sensitive to noise. A similar event occurred on 28/12/2018. Following analysis the FDIR was reconfigured to reduce the sensitivity and no further trips of this FDIR occurred. On 14/02/2019 the spacecraft went into safe mode as a result of a non-SEPS issue.

The final sub-arc was therefore delayed until spacecraft recovery operations had completed (not shown in figure 8).

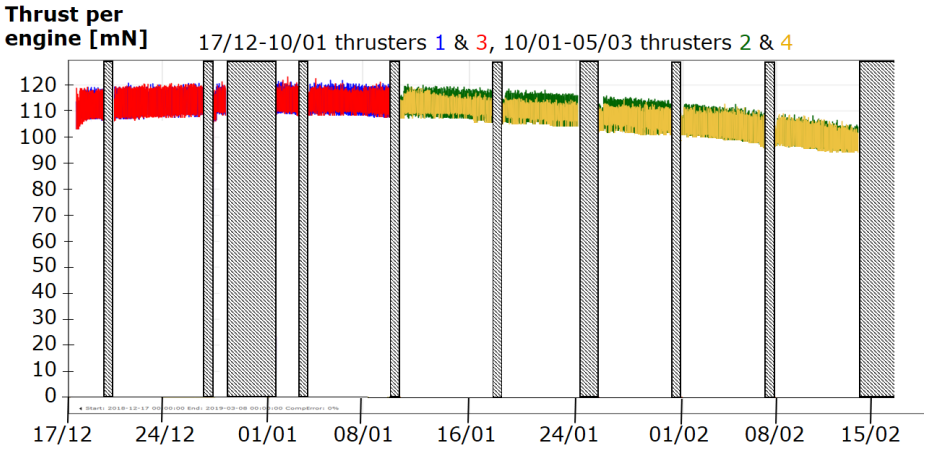

Figure 9. Thrusters and thrust levels used during EP1 arc. Greyed out periods indicate when the thrusters were OFF (S/C in Normal Mode).

B. Analysis of thruster data

Because of the success of commissioning and the close agreement of flight data with predictions, there was no need to conduct such detailed analysis of the thrust arc data. However, some limited analysis has been performed on two parameters: anode voltage, because of its importance in relation to thruster lifetime; and accel current, because it was lower than predicted during commissioning.

During commissioning thruster telemetry was acquired at 8 Hz (the maximum rate). Data for sub-arcs SEP1-1 to SEP1-3 was acquired at the same rate, in case of initial teething problems, but was reduced to the normal Cruise Phase data rate (once every 30 s) for the remainder of the arc.

Anode voltage had been very close to the predicted values during commissioning, although it can be seen in Figure 4 that the voltage was reducing during the 5 hour thrust period. The anode voltage continued to reduce during the thrust arc, settling at a value around 0.6 V lower than during commissioning. This behaviour has been seen in ground test of new thrusters and is attributed to two factors. One is settling of the thruster components, especially the grids, as the thruster reaches full thermal equilibrium. The other is that the cathode continues to "condition", whereby the low work-function surface of the emitter achieves optimum performance only after a period of operation in vacuum. The small drop in anode voltage is good news as it provides even greater lifetime margin over the required mission duration.

In case the anode voltage had been higher than expected, a back-up plan had been established to increase the xenon flow rate which would result in a reduction in anode voltage. As explained earlier, the relationship between flow rate and anode voltage had been established during ground testing. However, due to the constraints of ground testing, translation into flight performance carries increased uncertainty. Therefore it was agreed with ESOC that the final sub-arc would be operated at a higher main flow rate in order to provide further data on the flow-voltage relationship, without any of the complicating factors associated with ground test.

The increased flow rate was anticipated to result in a reduction in anode voltage of around 0.4 V. In fact the reduction was even better at around 0.6 V. Because of the favourable delta-V requirements of the October 2018 launch, the spacecraft has more than enough propellant to comfortably accommodate the increased flow rate. Therefore it was agreed to adopt the new flow rate for the remainder of the mission. The thruster lifetime demonstrated in the Endurance Test[4] is based on the original flow rate and therefore the lifetime under flight operating conditions will be greater, even allowing for all uncertainties. The predicted thruster lifetime provides significant margin over the required mission lifetime.

C. Beam-out analysis

Beam-outs (or recycles) are known phenomenon affecting all gridded ion thrusters. They occur when the strong electrical field between the two grids is disrupted causing an arc. The disruption is usually attributed to a small piece of conductive material, sputtered from one of the grids, entering the space between the grids and distorting the field sufficiently to cause a breakdown. This effectively short-circuits the grids resulting in an immediate spike in beam current. This is detected by the power supply which turns off to prevent damage. The sputter particle is vaporised by the arc so the beam supply can be immediately restarted. The rate of beam-outs is typically much greater during ground testing because the beam target in the vacuum chamber generates additional carbon sputter particles.

The beam-out rates for all four SEPTs were fairly constant throughout the first thrust arc. The average rate was 0.2 per hour, which is approximately 20% of the rate seen during ground testing. This is comparable to the ratio between flight and ground for GOCE which is consistent with the hypothesis that beam-out rates in ground test are greatly increased by sputter generated by the beam target within the facility. Previous long duration EP missions have seen beam-out rates fall over time[5,6]. Further data is required from future thrust arcs to see how the beam-out rate evolves.

During a beam-out recovery the beam supply is switched off for 2 s. Once it is re-enabled, the thrust ramps up gradually, so the effective lost thrust time is about 9 s. This is a constraint imposed by the PPU – the thruster is capable in principle of restarting immediately to full thrust. Nevertheless, beam-outs contribute only 0.05% loss of thruster availability.

D. Thrust measurement

Actual thrust cannot be measured directly onboard BepiColombo. Instead, thrust is calculated using the thruster electrical parameters (beam current and voltage) and the thrust correction factor (TCF). TCF accounts for a number of effects which reduce the thrust below the theoretical maximum. These include beam divergence (the angle between ion trajectory and thruster centreline reduces effective thrust) and doubly-charged ion ratio (an ion which is doubly-ionised does not produce the same thrust as two singly-charged ions). This calculation is subject to uncertainties relating to the accuracy of current and voltage measurement by the PPU and calibration of the TCF on ground.

TCF was originally determined from a range of development and qualification thrusters. A later assessment was made using a new thruster and one which had accumulated significant operating hours. From these results, a new TCF was derived, which was approximately 2% higher than the earlier value. At this point the initial software load for the spacecraft had been finalised and it was decided to conduct the first thrust arc using the earlier TCF value. It was therefore expected that thrust as calculated onboard would be about 2% lower than true thrust.

ESA used Doppler and range measurements from the ground stations to accurately determine the orbit of BepiColombo[7]. Combining these data with models of the spacecraft thrust allowed accurate estimation of the actual thrust delivered during each sub-arc, with an overall accuracy of ±0.5%.

Figure 9 shows the predicted thrust using two different models. The nominal model uses the demanded values and assumes perfect thrust vector alignment. The “onboard” model uses thrust calculated from SEPS electrical parameters as well as true TPM pointing angles. The onboard model is considered more accurate.

The comparison between the onboard thrust model and actual thrust, as determined from ground Doppler and range measurements, shows that actual thrust was around 2.0%-2.2% higher than calculated. This is exactly what was expected given the difference between the old and new TCF values. A further corroboration of the true TCF value was obtained during the final sub-arc when the flow rate was increased. This increases TCF, mainly due to the lower rate of doubly-charged ion production, and an increase of about 0.3% was predicted. The measured thrust increase was in fact 0.4%.

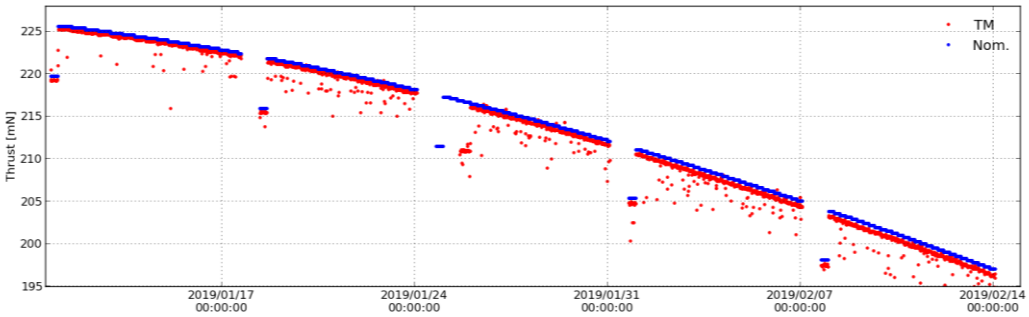

Figure 9. Comparison of predicted and actual thrust for SEPT2 & 4.
Blue: Thrust calculated from nominal thrust model
Red: Thrust calculated from SEPS and TPM telemetry

These results show that thrust magnitude is consistent with ground test measurements and can be predicted with very high accuracy. The effect of changing operating parameters, such as flow rate, is well understood. It is intended to use the new TCF values for the remainder of the mission so that delivered thrust is as close as possible to demanded thrust.

VII.Conclusion

Commissioning of the BepiColombo MEPS has been very successful. All units have been confirmed to be fully operational following launch. Furthermore, commissioning proceeded to plan, with only minor issues to be resolved, mainly relating to FDIR settings which were found to be too sensitive. The MEPS was designed to be flexible, allowing adjustment by simply uploading new parameters from ground, and this philosophy has proved to be of benefit.

Performance of the thrusters during commissioning was in line with predictions made using ground test data, extrapolated to account for the difference between flight and ground test conditions. The only exception was accel grid current, found to be lower than expected, but nevertheless considered acceptable. The excellent agreement between model and reality is also confirmation of the ability to accurately predict performance.

Finally, predicted thrust levels have been independently validated using ground tracking data and found to be in very good agreement, over a range of thrust levels. This enables the remainder of the mission to be planned and executed accurately with minimal need for adjustments.

Nomenclature

AOCS	Attitude and Orbit Control System
BSM	Beam Supply Module
CEX	Charge Exchange (Ion)
DANS	Discharge, Accel and Neutraliser Supply
EGSE	Electrical Ground Support Equipment
EP	Electric Propulsion
EPCM	Electric Propulsion Control Mode
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
FCU	Flow Control Unit
FDIR	Failure Detection, Isolation and Recovery
GOCE	Gravity field and steady-state Ocean Circulation Explorer

HGA	High Gain Antenna
HPRS	High Pressure Regulation System
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LEOP	Launch and Early Orbit Phase
MEPS	Mercury Electric Propulsion System
MGA	Medium Gain Antenna
MMO	Mercury Magnetospheric Orbiter
MPO	Mercury Planetary Orbiter
MTM	Mercury Transfer Module
NECP	Near Earth Commissioning Phase
NM	AOCS Normal Mode
OBC	On-board Computer
PPU	Power Processing Unit
PRE	Pressure Regulation Electronics
S/C	Spacecraft
SEP	Solar Electric Propulsion
SEPS	Solar Electric Propulsion System
SEPT	Solar Electric Propulsion Thruster
TCF	Thrust Correction Factor
TPA	Thruster Pointing Assembly
TPE	Thruster Pointing Electronics
TPM	Thruster Pointing Mechanism

References

[1]Gray, H., Bolter, J., Kempkens, K., 2019. BepiColombo – The Mercury Transfer Module. *36th International Electric Propulsion Conference (IEPC 2019), Vienna, Austria.*

[2]Steiger, C., Montagnon, E., Budnik, F., Manganelli, S., Altay, A., Striedter, F., Gray, H., Bolter, J., Wallace, N., Sutherland, O., "BepiColombo – Solar Electric Propulsion System Operations for the Transit to Mercury", *36th International Electric Propulsion Conference (IEPC 2019), Vienna, Austria.*

[3]Goebel, D. and Katz, I, *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, JPL Space Science and Technology Series. Appendix G.

[4]Clark, S., Randall, P., Lewis, R., Marangone, D., Goebel, D., Chaplin, V., Gray, H., Kempkens, K., Wallace, N., "BepiColombo – Solar Electric Propulsion System Test and Qualification Approach", IEPC-2019-586, *36th International Electric Propulsion Conference, Vienna, September 15-20, 2019*

[5]Yim, J., Soulas, G., Shastry, R., Choi, M., Mackey, J., Sarver-Verhey, T., "Update of the NEXT ion thruster service life assessment with post-test correlation to the long-duration test", *35th International Electric Propulsion Conference (IEPC 2017), Georgia Institute of Technology, USA*

[6]Garner, C., Rayman, M., Brophy, J., "In-Flight Operation of the Dawn Ion Propulsion System-Arrival at Ceres", *Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT (IEPC 2015), Kobe-Hyogo, Japan*

[7]Bellei, G., "BepiColombo - Assessment of SEP thrusters performance during the first manoeuvre from Orbit Determination", European Space Agency BC-ESC-TN-50018