Twin Engine Tests of the T6 Ion Engine for ESA's BepiColombo Mercury Mission

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Abstract: This paper describes a series of tests to demonstrate and characterise twin simultaneous firing of two T6 Solar Electric Propulsion Thrusters (SEPT) in support of the BepiColombo mission. The propulsion system was operated over a wide range of operating conditions covering the thrust range: 75mN (single engine) to 290mN (dual thrust), which is the thrust envelop requirement for the mission. The tests were conducted with a link between the two Electrical Ground Support Equipment (EGSE) racks, which can be opened and closed. This enabled three distinct modes of operation at each thrust level: 1) Twin SEPT Single Neutraliser 2) Twin SEPT Dual Neutralisers with common neutraliser returns 3) Twin SEPT Dual Neutralisers with isolated neutraliser returns. No significant variation in a single SEPT's performance was observed when one or two SEPTs were operating. Beam probe plume measurements were carried out on the BB SEPT using specially modified Faraday probes with collimating tubes that reject ions from the second engine. The results demonstrated the stability of the BB SEPT thrust vector when the second engine is operated and showed minimal interaction between the engine plumes. The investigation also shed some light on the relative benefits of the various possible SEPT grounding schemes to the spacecraft. The results have demonstrated the presence of a cross-neutralisation current between the two SEPTs when the neutraliser returns were commoned. This is shown to be driven by the difference in Neutraliser Coupling Potential (NCP) between the two neutralisers. In the isolated EGSE case, it was discovered that Twin SEPT operation actually led to a reduction in the required SEPT NCP due to the presence of a denser coupling plasma downstream. This result is important for the design of an isolated Power Processing Units (PPU) as it shows that designing for a single engine's NRP is the worst case to be experienced in the mission. The lower NRP also means that the SEPT neutraliser is expected to experience reduced erosion levels when operated in twin SEPT twin isolated neutraliser configuration.

Nomenclature

BB	=	BreadBoard
BOL	=	Beginning of life
CEX	=	Charge Exchange
EGSE	=	Electrical ground Support Equipment
EOL	=	End of Life
ESA	=	European Space Agency
FCU	=	Flow Control Unit

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FGSE	=	Fluidic Ground Support Equipment
ISAS	=	Institute of Space and Astronautical Science
JAXA	=	Japan Space Exploration Agency
MMO	=	Mercury Magnetospheric Orbiter
MPO	=	Mercury Polar Orbiter
MTM	=	Mercury Transfer Module
NCP	=	Neutraliser Coupling Potential
NEUT	=	Neutraliser
NRP	=	Neutraliser Reference Potential
PPU	=	Power Processing Unit
RPA	=	Retarding Potential Analyzer
SEPS	=	Solar Electric Propulsion System
SEPT	=	Solar Electric Propulsion Thruster
TDA	=	Technology Demonstration Activity

I. Introduction

The BepiColombo mission is the 5th cornerstone of the Cosmic Vision scientific program of the European Space Agency (ESA). It is an interdisciplinary mission to Mercury in collaboration between ESA and ISAS (Institute of Space and Astronautical Science)/JAXA (Japan Space Exploration Agency) under overall responsibility of ESA.

The BepiColombo mission consists of two scientific orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO), which are dedicated to the study of the planet of Mercury and of its magnetosphere. The transfer of the orbiters to Mercury orbit is to be performed using a solar electric propulsion system (SEPS) developed, qualified and manufactured by QinetiQ. The solar term in SEPS refers to the power generation by solar arrays used to operate the system. The system is based around QinetiQ's T6 ion thruster, which has been extensively described elsewhere[1].

This paper describes a series of tests to demonstrate and characterise twin firing of T6 engines in support of the mission. The mission calls for a thrust level greater than 145mN during 80% of its thrust arcs, which will requisite twin-engine firing. The test articles comprised of the Technology Demonstration Activity (TDA) T6 engine and the BepiColombo Breadboard Solar Electric Propulsion T6 Thruster (BB SEPT).

The propulsion system was operated over a wide range of operating conditions covering the thrust range: 75mN (single engine) to 290mN (dual thrust), which is the thrust envelop requirement for the BepiColombo mission. The tests were conducted with a link between the two Electrical Ground Support Equipment (EGSE) racks, which can be opened and closed. This enabled three distinct modes of operation at each thrust level: 1) Twin SEPT Single Neutraliser [not to be discussed in this paper] 2) Twin SEPT Dual Neutralisers with common neutraliser returns 3) Twin SEPT Dual Neutralisers with isolated neutraliser returns.

II. Test Set-Up

A. Overall test set-up

Fig. 1 shows the overall hardware test setup for the twin thruster test. Each of the SEPTs had a dedicated EGSE rack and a Control/DAQ PC. The SEPT EGSE Racks will be used to provide electrical power to the SEPT during the test and will acquire electrical data to allow assessment of the SEPT performance. Control of the SEPT power supplies in the EGSE is through computer control, as is the acquisition of electrical data. The SEPT EGSE will also be used to control the Xenon Fluidic Ground Support Equipment (FGSE). An oscilloscope is used to monitor the beam current to capture rapid changes in thruster performance not captured by the SEPT EGSE, if any are present.

B. LEEP2 Test Facility Description

The LEEP2 vacuum chamber is located at QinetiQ Farnborough. The configuration of the vacuum chamber can be seen in schematic form in Fig. 2. The largest section of the chamber is 3.8 m diameter x 4 m long. The conical section is 0.9 m long and the small section is 2.6 m diameter x 5 m long.

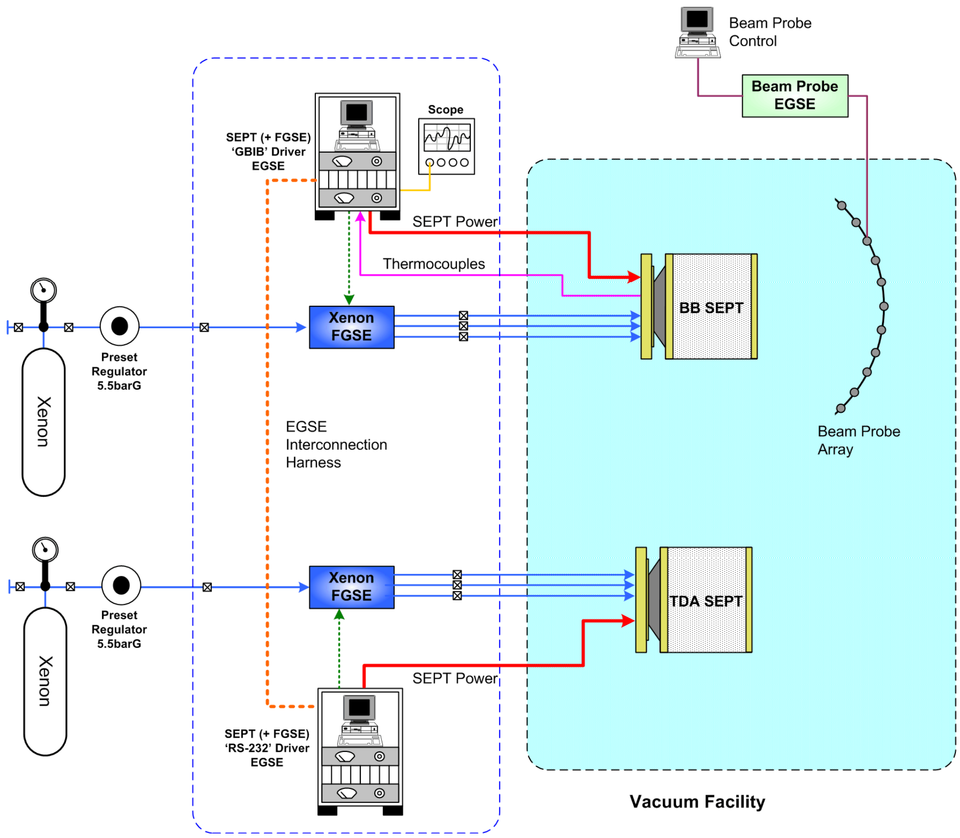


Figure 1. T6 thruster Twin-engine set-up

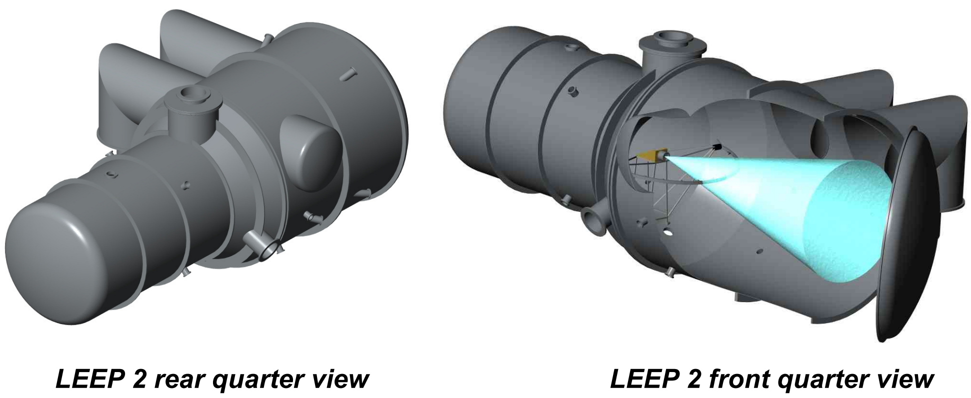


Figure 2. LEEP 2 Vacuum test facility chamber configuration

Thrusters are located at the junction between the 2.6 m and conical sections and the ion beam(s) are directed towards the chamber door/target. The relative position of the thrusters during the twin thruster testing is illustrated in Fig. 3.

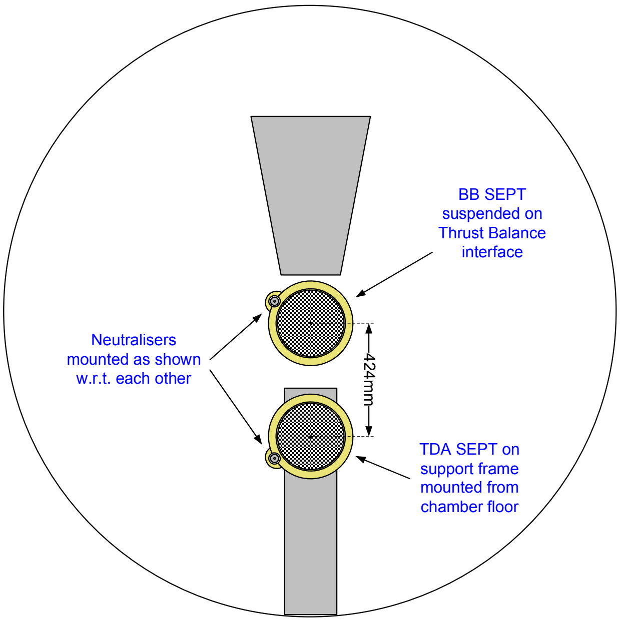


Figure 3. Relative position of BB and TDA SEPT for twin thruster testing (view looking into LEEP 2 facility)

The 424mm separation between the engines represents the minimum baseline separation between two operating SEPTs in the BepiColombo mission. Fig.4 shows a photo of the twin-engine test at the maximum throttle point.

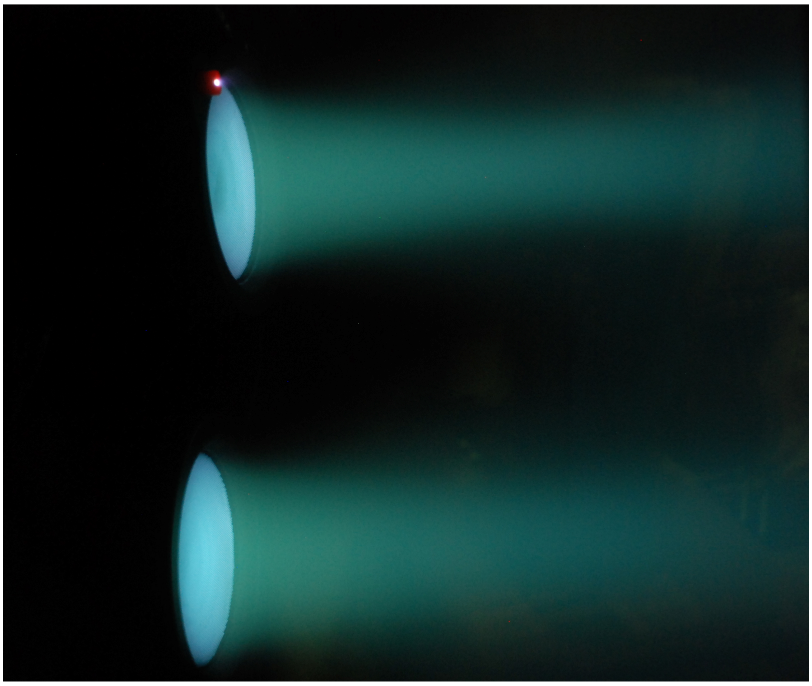


Figure 4. BB and TDA SEPTs during dual thruster operation at maximum combined throttle point in LEEP2 vacuum facility

LEEP2 test facility is also equipped with a high accuracy/resolution array of retarding potential analysers (RPA), which, for this test programme, will be configured as Faraday cup detectors. This system allows the ion flux and beam divergence of the BB thruster ion plume to be characterised with high resolution to divergence angles of up to 90 degrees. The cup collectors are biased so as to reject the Charge Exchange (CEX) ion current and collect only the high-energy beam ions. Specially designed graphite collimator tubes were installed on the probes to reject ions emanating from the TDA thruster to allow determination of the impact of twin-engine operation on the BB thruster. Three beam probe sweeps were taken and averaged at each of the test conditions described in section IV to give the results presented. The sweep to sweep variation was found to be less than 0.07deg in thrust vector and 0.05deg in beam divergence.

C. Electrical Setup

The electrical setup of the twin-engine test is shown in Fig. 5. A switchable link (Link 1) is installed between the two EGSE racks, which enabled the commoning of the neutraliser return lines of both SEPTs. Two ammeters were installed in the neutraliser line (on the neutraliser side relative to the link, see figure 5). This arrangement allows the assessment of the level cross neutralisation (where one neutraliser contributes to the neutralisation of the beam from the other SEPT) when the link is closed.

D. Test Parameters

The parameters describing the operating points to be used during the coupling test are provided in Table 1.

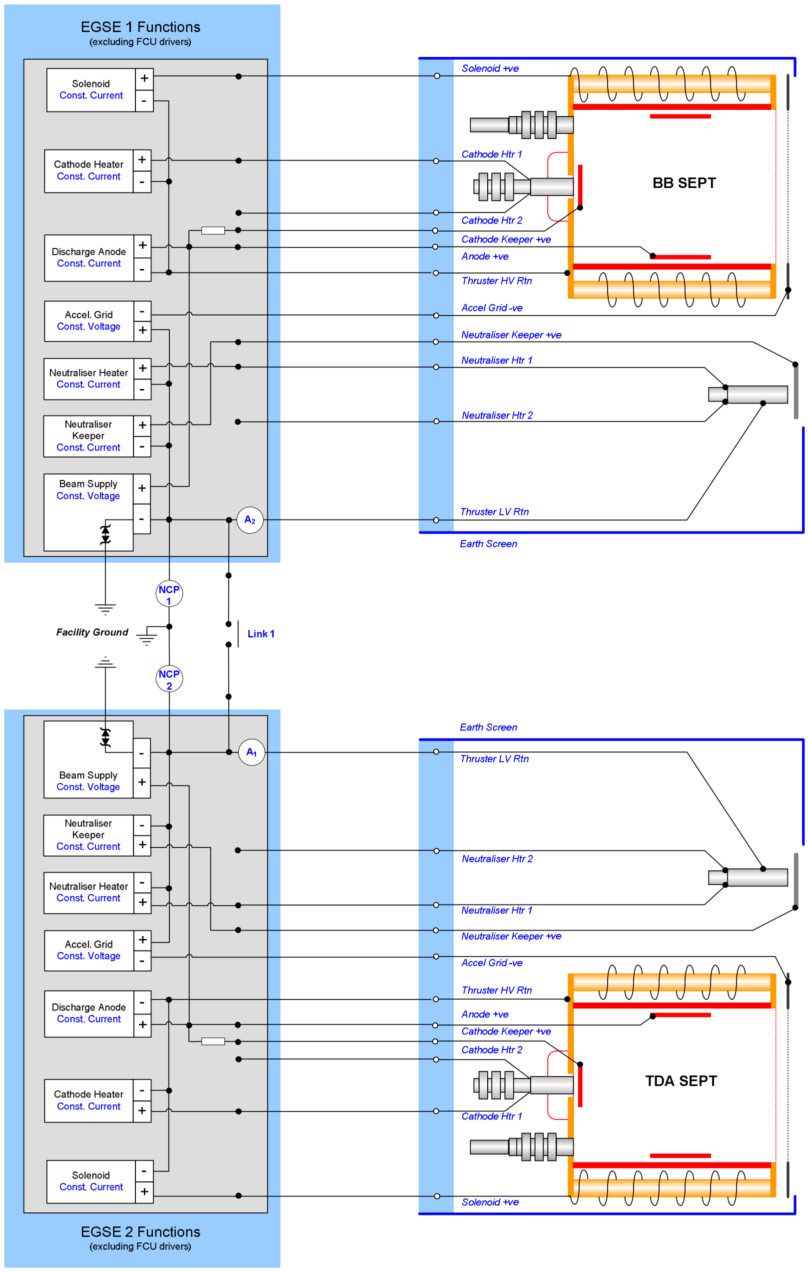


Figure 5. Electrical schematic of twin SEPT test setup

Table1. Thruster Operating Points

Set-point (mN)	Beam Current (A)	Main Flow (mg/s)	Anode Current (A)	Neut Keeper Current (A)
75 (Nominal)	1.10 (1)	1.043 (2)	12.2	4.2
145 (Nominal)	2.14 (1)	2.535 (2)	18.0	4.2

Note 1: Beam voltage 1850 V, Accel voltage -265 V
Note 2: Neutraliser flowrate 0.2 mgs^{-1}, Cathode flowrate = 0.69 mgs^{-1}

III. Pre-Twin Engine test activities and commissioning SEPTs

Prior to the start of any twin thruster testing it is necessary to commission and verify the performance of the individual SEPTs. These activities were carried out to establish the operational characteristics of each engine individually and to benchmark each engine's characteristics creating a baseline for the twin-engine test. There were four main objectives to these tests:

1. Commission the BB SEPT: This test campaign represents the first time that the BB SEPT was operated. As a consequence it is necessary for the performance of this device to have stabilised prior to performing any testing from which unit or system performance may be derived and that the performance of the unit itself is acceptable.

2. Determine the electrical characteristics of each the BB and TDA SEPTs for later comparison with Twin-Engine test results.

3. Determine the BB SEPT Beam characteristics and to calibrate for variations in profile due to effects other than TDA engine operation, three tests were conducted:
   a. Acquire beam probe characteristics with the BB at both 75mN and 145mN with TDA off. This will form the two baselines for our relative thrust vector shift measurements
   b. Acquire beam probe characteristics with the BB at 145mN and TDA off but flowing maximum propellant throughput equivalent to 145mN. This is done to determine the effect, if any, of facility pressure and CEX on BB thrust vector and beam divergence.
   c. Acquire beam probe characteristics with BB at 145mN and TDA off but TDA solenoids operating at maximum the maximum current of 1.2A. This is done to determine impact, if any, on BB thrust vector and beam divergence of the magnetic field of another SEPT in close proximity.

   All the results from this activity will be discussed in section V.

4. Demonstrate the ability of the Faraday cup collimators to reject ions originating from the TDA SEPT, to this objective two tests were conducted:
   a. Acquire beam probe characteristics with the TDA at both 75mN and 145mN with BB off.
   b. Acquire beam probe characteristics with the TDA at 145mN and BB off but flowing maximum propellant throughput equivalent to 145mN.

   In each of the tests in this activity, the total current collected during a sweep was three orders of magnitude less than those seen during lowest thrust setting of the BB engine. The results gave confidence in the collimators' ability to reject ions emanating from the TDA SEPT.

IV. Twin SEPT & Twin Local Neutralisers Test procedure

This sequence of tests is intended to assess the impact of twin SEPT operations and the twin neutraliser-grounding scheme on SEPT performance.

The general test sequence is summarised and presented in Fig.6. The rationale underpinning the test steps is presented in the text below.

The thrusters are initially operated at one of three set points:

1. **Dual Thruster operation with BB at 75mN and TDA at 75mN**: Both SEPTs are operated at their minimum thrust levels of 75mN each (combined thrust of 150mN). This represents the minimum thrust achievable with two SEPTs operational.
2. **Dual Thruster operation with one SEPT at 145mN and the other at 75mN**: This represents the intermediate thrust range of the BEPI SEPS with the maximum thrust differential between the two engines. Most of the testing in this sequence was carried out with the BB SEPT at 75mN and the TDA SEPT at 145mN. However, at the end of the test the engine thrust levels were reversed for the plume mode onset tests because of the susceptibility of the TDA EGSE to noise generated by plume mode operation.
3. **Dual Thruster operation with BB at 145mN and TDA at 145mN**: During this step both SEPTs will be operated at their maximum thrust levels of 145mN each (combined thrust of 290mN). This represents the maximum thrust achievable with two SEPTs operational.

Following this step and the recording of the thruster and plume parameters, the link between the thruster returns is then closed to common the neutraliser returns. This is done to determine the link current that would flow between the two PPUs if a common grounding architecture were adopted on BepiColombo. A beam probe scan is also conducted to assess impact, if any, of common grounding on thrust vector and beam divergence.

The next six steps assess the impact of asymmetries brought about due to flow-rate and Keeper current regulation accuracies (provided by the Flow Control Unit (FCU) and PPU respectively) on neutraliser operation and grounding for a given twin thrust setting. This is done by first reducing the BB keeper current by 100mA and increasing the TDA keeper current by 100mA. Reducing the BB flow rate by 0.02 mg/s and increasing the TDA flow by 0.02mg/s introduces the flow set error. We identify evolution of NRP, keeper voltage, keeper voltage noise and tip temperature at maximum variation in flow and keeper set errors. The asymmetry in the return currents to the SEPTs is determined by closing Link 1 to common the return grounds and the effect of the keeper and flow rate set errors on this current is quantified. This will be the maximum expected asymmetry during nominal neutraliser operation.

The subsequent test step deals with the absolute worst case for asymmetry in operation at twin thrust level; whereby one neutraliser is operating with a positive set error while the other is in plume mode. The BB neutraliser is brought into plume mode by reducing the flow rate to 0.13-0.14mg/s and slowly reducing the keeper current until the onset of plume mode is apparent. We identify the evolution of Neutraliser NRP, keeper voltage, keeper voltage noise and tip temperature at this setting. The asymmetry in the return currents to the SEPTs will also be determined by closing Link 1 to common the return grounds and the effect of a single neutraliser operating in plume is quantified. This will be the maximum possible asymmetry during this thrust setting.

The SEPTs are then brought back in the next step to nominal settings and the link current is again measured to ascertain if there exists any hysteresis in the results.

This completes the test sequence for a given dual engine thrust setting. The thrusters are throttled to (and stabilised at) the next combined thrust setting before the sequence is repeated.

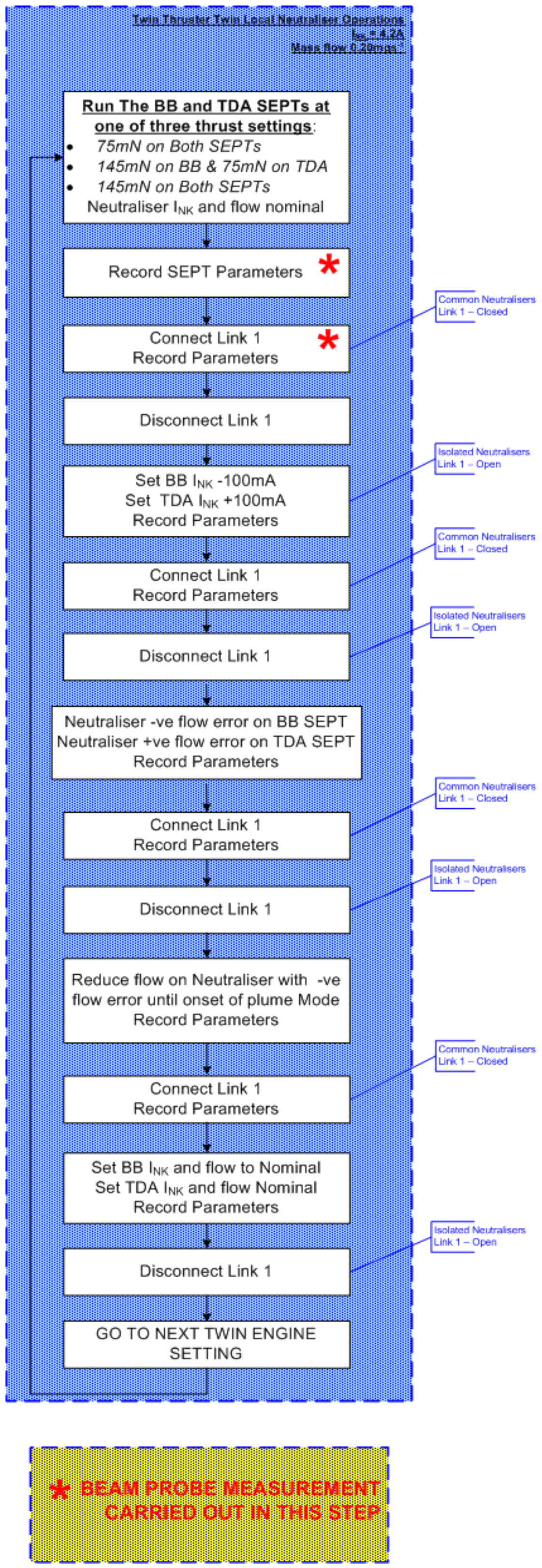


Figure 6. Twin-engine twin neutraliser general test sequence

V. Data Analysis and Discussion of Major Trends

In this section the main results are recast in a format that facilitates comparison and enables the salient features to be gleaned.

The analysis section is divided into three main sections. The first summarises the beam probe test results during the twin-engine tests.

The second deals with the effect of dual engine operation on SEPT systems isolated from the spacecraft and each other. The results will be of significant importance to the design of an isolated SEPS PPU architecture.

The third section deals with observations on dual engine operation in SEPT systems with commoned neutraliser returns. The results are important to the design of a spacecraft with common grounded SEPS PPU architecture.

A. Effect of twin-engine operation on BB SEPT Thrust Vector and Beam Divergence

As mentioned previously, three beam probe sweeps were performed for each of the conditions indicated in the previous sections. The sweep results are used to determine the thrust vector and beam divergence of the BB SEPT at the respective operating point.

Thrust generated by a gridded ion thruster is a result of the net force acting on the screen and accelerator grids; the Thrust Vector defines the magnitude and direction of the thrust, representing the impulse at the grids. The direction of the Thrust Vector is determined from the centroid (maximum) of the 2D spatial profile of beam current density measured by the rotatable beam probe system.

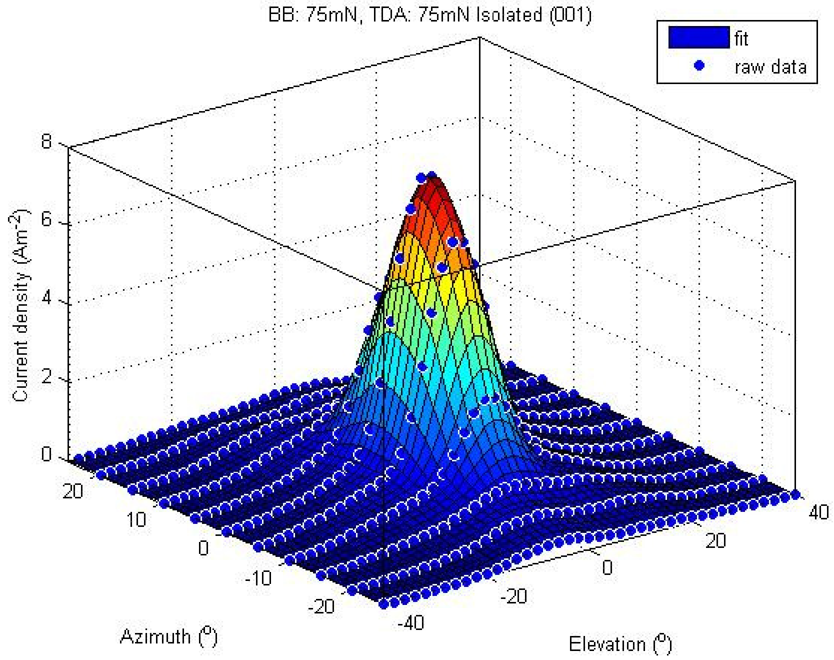
A 2D integration is performed on the measured beam current density to determine a value for the total measured beam current. Beam divergence (defined as the half cone angle that incorporates 95% of the total beam ions) can therefore be determined by iteration to find the angle, which includes 95% of the total measured beam current.

Example results of the beam probe sweeps are shown in Fig.7 and Fig.8 each showing a 3D and a 2D contour plot of the probe sweep. Fig.7 shows the results when both the BB and TDA SEPTs operated at 75mN. Fig. 8 shows the results when both the BB and TDA SEPTs operated at 145mN.

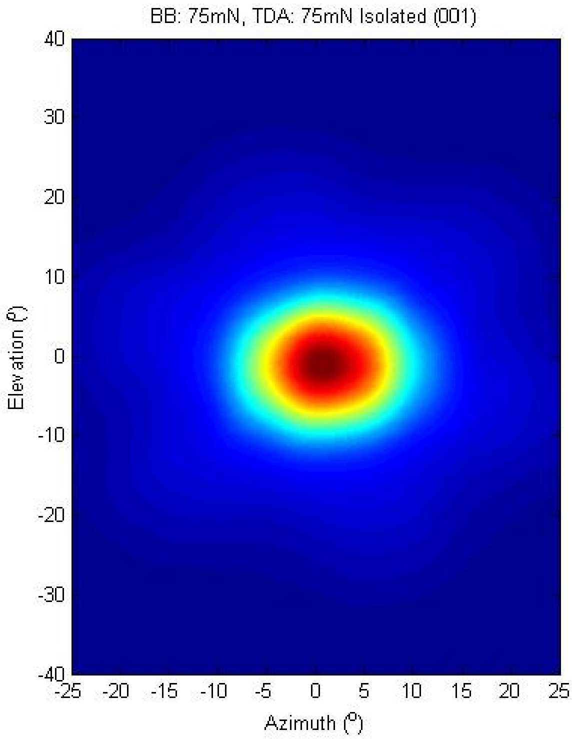
The calculated results of thrust vector, beam divergence and total collected beam current are then compared to the respective case where the BB is on at the same thrust level but TDA is completely off; which forms our baseline.

Table 2 shows each test case where the BB is at 75mN for all TDA operating cases (single neutraliser operation is also included for comparison) and the calculated relative shift in ion beam parameters from the baseline case of BB at 75mN and TDA thruster off.

Table 3 shows each test case where the BB is at 145mN for all TDA operating cases (single neutraliser operation is also included for comparison) and the calculated relative shift in ion beam parameters from the baseline case of BB at 145mN and TDA thruster off.

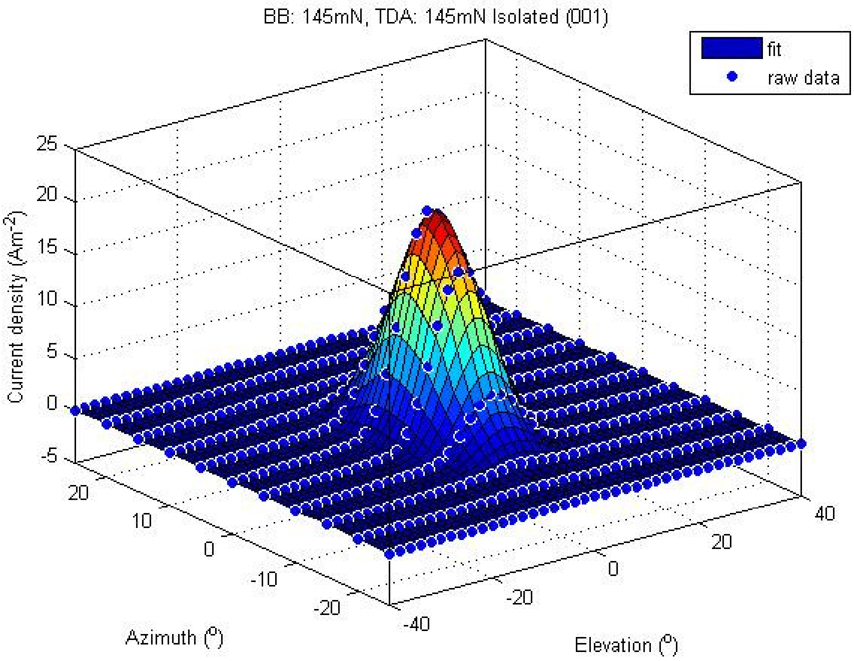


(a)

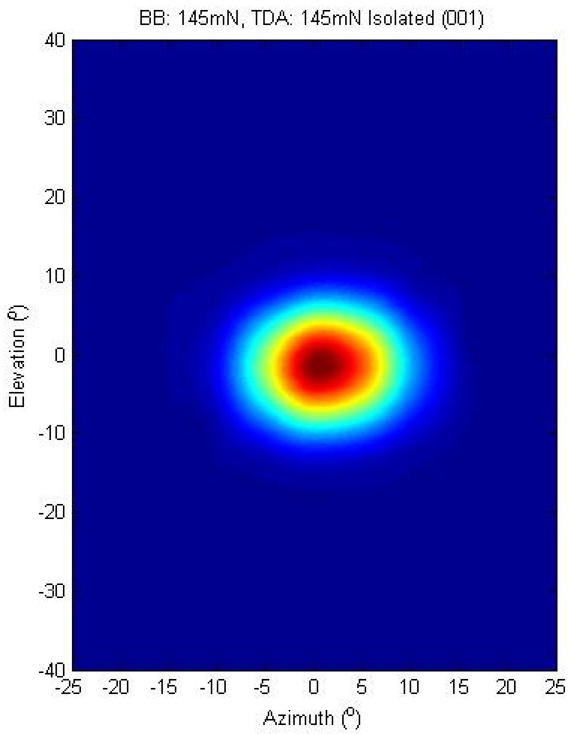


(b)

Figure 7. 3D (a) and 2D (b) Contour plots of BB SEPT plume (75mN) with TDA SEPT at 75mN and isolated EGSE grounds



(a)



(b)

Figure 8. 3D (a) and 2D (b) Contour plots of BB SEPT plume (145mN) with TDA SEPT at 145mN and isolated EGSE grounds

Table 2. Comparison of the change in ion beam parameters for the BB SEPT operating at 75mN with TDA SEPT at various operating conditions (also included in the results are cases for single and dual neutraliser operation and commoned and isolated EGSE)

Set-point	Relative shift in Horizontal Thrust vector angle* (deg)	Relative shift in Vertical Thrust vector angle* (deg)	Relative change in beam Divergence* (deg)	Relative change in integrated beam current* (A)
BB 75mN/TDA 75mN (single BB neutraliser)	0.040	-0.027	0.048	-0.058
BB 75mN/TDA 75mN (single TDA neutraliser)	-0.056	0.030	0.215	-0.060
BB 75mN/TDA 75mN (Twin isolated neutralisers)	0.112	-0.126	0.223	-0.089
BB 75mN/TDA 75mN (Twin common neutralisers)	0.076	-0.169	0.238	-0.120
BB 75mN/TDA 145mN (Twin *isolated* neutralisers)	0.016	-0.200	0.334	-0.155

***The data gives the change in beam parameter relative to the baseline case of BB at 75mN and the TDA SEPT off**

Table 3. Comparison of the change in ion beam parameters for the BB SEPT operating at 145mN with TDA SEPT at various operating conditions (also included in the results are cases for TDA off but flowing 145mN equivalent mass flow, TDA off but the solenoids active at maximum current, single and dual neutraliser operation and commoned and isolated EGSE)

Set-point	Relative shift in Horizontal Thrust vector angle* (deg)	Relative shift in Vertical Thrust vector angle* (deg)	Relative change in beam Divergence* (deg)	Relative change in integrated beam current* (A)
BB 145mN/TDA off (145mN flow through TDA)	-0.003	-0.034	-0.207	0.176
BB 145mN/TDA (TDA solenoids run at 1.2A)	-0.104	0.068	0.255	-0.013
BB 145mN/TDA 75mN (single TDA neutraliser)	-0.151	-0.007	-0.445	0.053
BB 145mN /TDA 145mN (Twin isolated neutralisers)	-0.179	-0.098	0.462	0.075

***The data gives the change in beam parameter relative to the baseline case of BB at 145mN and the TDA SEPT off**

Comparing the results to their respective baselines, the maximum observed shift in horizontal thrust vector angle was only 0.18deg. The observed shift in vertical thrust vector angle was also small at 0.2deg. The maximum change in beam divergence was only 0.46 deg.

The results in summary demonstrate the following:

1. There is no influence on the beam of an operating SEPT due to flow of gas or magnetic circuit of another SEPT in close proximity

2. Beam interactions during twin SEPT operations were minimal. Integration of the beam profiles and comparing them to the baseline case also indicate small differences in the collected beam currents

3. The SEPT beam was also immune to the neutraliser grounding scheme in the case of twin neutraliser operation and also to the use of a single or dual neutraliser architecture to neutralise the twin beams.

B. Effect of dual engine operation on the NRP of isolated systems

This section will focus on the test results related to the effects of isolated dual engine operation on the performance of a SEPT.

Each of the following 4 tables shows a SEPT at a given thrust level comparing the effect of the state of the other SEPT on the first engine's performance with the EGSE link disconnected.

Specifically:

Table 4 shows relevant performance parameters of the BB SEPT at 75mN with the TDA SEPT (a) Off (b) at 75mN & (c) at 145mN.

Table 5 shows relevant performance parameters of the TDA SEPT at 75mN with the BB SEPT (a) at 75mN & (b) at 145mN.

Table 6 shows relevant performance parameters of the BB SEPT at 145mN with the TDA SEPT (a) Off (b) at 75mN & (c) at 145mN.

Table 7 shows relevant performance parameters of the TDA SEPT at 145mN with the BB SEPT (a) at 75mN & (b) at 145mN.

Table 4. BB SEPT 75mN data at several TDA thrust settings and Isolated EGSE racks

Date	03/12/2010	07/12/2010	08/12/2010
TDA thrust level	**Off**	**75mN**	**145mN**
Link position	open	open	open
Link current ***(mA)*** (**+ve means from BB neut to TDA**)	0	0	0
Beam Current (*A*)	1.095	1.098	1.098
Anode Voltage(*V*)	28.48	26.19	26.10
Anode Current (*A*)	12.209	12.2	12.2
Neutraliser Keeper Voltage (*V*)	18.89	19.99	20.06
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2
Accel Grid Current (*mA*)	7.43	9.61	12.17
NRP (*V*)	-8.34	-7.98	-7.57
Neutraliser Tip Temperature (*deg C*)	1015	1015	1005

Table 5. TDA SEPT 75mN data at several BB thrust settings and Isolated EGSE racks

Date	07/12/2010	09/12/2010
BB thrust level	**75mN**	**145mN**
Link position	open	open
Link current ***(mA)*** (+ve means from BB neut to TDA)	0	0
Beam Current (*A*)	1.1181	1.157
Anode Voltage(*V*)	26.48	26.54
Anode Current (*A*)	12.18	12.2
Neutraliser Keeper Voltage (*V*)	17.02	17.04
Neutraliser Keeper Current (*A*)	4.2	4.2
Accel Grid Current (*mA*)	7.60	10.33
NRP (*V*)	-8.19	-7.50
Neutraliser Tip Temperature (*deg C*)	1010	985

Table 6. BB SEPT 145mN data at several TDA thrust settings and Isolated EGSE racks

Date	03/12/2010	09/12/2010	09/12/2010
TDA thrust level	**Off**	**75mN**	**145mN**
Link position	open	open	open
Link current ***(mA)*** (+ve means from BB neut to TDA)	0	0	0
Beam Current (*A*)	2.139	2.144	2.14
Anode Voltage(*V*)	27.50	25.97	25.69
Anode Current (*A*)	18	18	18
Neutraliser Keeper Voltage (*V*)	16.47	18.59	18.32
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2
Accel Grid Current (*mA*)	14.77	15.25	17.68
NRP (*V*)	-9.89	-9.95	-9.46
Neutraliser Tip Temperature (*deg C*)	1070	1085	1085

Table 7. **TDA SEPT 145mN data at several BB thrust settings and Isolated EGSE racks**

Date	08/12/2010	09/12/2010
BB thrust level	**75mN**	**145mN**
Link position	open	open
Link current ***(mA)*** (**+ve means from BB neut to TDA**)	0	0
Beam Current (*A*)	2.135	2.151
Anode Voltage(*V*)	25.76	25.43
Anode Current (*A*)	18	18
Neutraliser Keeper Voltage (*V*)	15.79	15.68
Neutraliser Keeper Current (*A*)	4.2	4.2
Accel Grid Current (*mA*)	15.24	17.05
NRP (*V*)	-10.03	-9.65
Neutraliser Tip Temperature (*deg C*)	1070	1050

1. We note first that there appears to be an appreciable drop in BB anode voltage when the TDA engine is switched on (refer to Table 4 and Table 6). The voltage change is 2.2V when the BB is at 75mN and 1.5V when the BB is at 145mN. Increasing the thrust level of the TDA from 75mN to 145mN produces only a small further reduction in BB anode voltage of the order of 10s of mV. Initially this was assumed to be due to back-ingestion of neutrals into the BB (due to higher vacuum pressure from TDA operation), which tends to increase the discharge efficiency and lowers the required anode voltage. However, cross-checking with previous tests when only xenon gas was flowed into the TDA (at the 145mN settings), the resulting reduction of anode voltage observed on the BB was again only 10s of millivolts. One plausible explanation for the reduction is the conditioning of the BB SEPT, the first tests with the TDA off were carried out early in the program. This is also supported by the fact that, once the BB has been conditioned, the anode voltage results for the TDA SEPT at exactly the same conditions agree to within 44mV.

2. The neutralisers operating at a given thrust level showed approximately the same temperature. The maximum difference between the temperatures in each table is approximately 25^{o}C, which is within the error in pyrometer reading. This indicates that there has been no change in the neutraliser emission mechanism with thrust level of the second engine.

3. One significant result of these tests has been the observation that each of the Tables above shows that NRP of a SEPT reduces (gets closer to zero) by increasing the thrust level of the second SEPT.
   In a plasma source, such as the hollow cathode, the plasma mitigates the space charge limitations of an ordinary thermionic emitter. There are ions, which neutralise the electron's space charge and allow the electron current to couple to the beam via a "plasma bridge" facilitating the transfer of charge and significantly reducing the required voltages. If we have two SEPTs: SEPT1 and SEPT2; the operation of SEPT2 increases the plasma density downstream of SEPT1 creating a denser and more efficient plasma bridge between SEPT1's neutraliser and SEPT1's beam. The increased efficiency of the plasma bridge translates to a lower effective impedance between the neutraliser and the beam, which in turn lowers the potential required to emit the correct electron current to neutralise the beam. We note that increasing the thrust level of SEPT2 results in increased plasma downstream of SEPT1, which in turn reduces the NRP of SEPT1 further, which is the general observation from the above results.
   Furthermore, if we follow the Accel current in each of the above tables we note an increase in Accel current of SEPT1 with increase in the thrust level SEPT2. This can be partially attributed to increased vacuum chamber pressure (The test case of BB running at 145mN and TDA flowing gas equivalent to 145mN the measured BB accel current was 15.71mA). Further work is necessary to assess the relative effects of increased chamber pressure and higher density plasma bridge during twin-engine operation, as this might imply higher accel grid erosion rates during twin-engine operation.

A further, dramatic, demonstration of the effect of a dense secondary plasma on an engine's NRP can be shown in the effects of operating the second engine's neutraliser in plume mode. Table 8 compares the operating parameters of (a) the BB and TDA SEPTs at 75mN at nominal conditions with (b) their operating parameters when the BB neutraliser is in plume mode, both states with the EGSE link open.

Table 9 compares the operating parameters of (a) the BB SEPT (at 145mN) and TDA SEPT (at 75mN) at nominal conditions with (b) their operating parameters when the BB neutraliser is in plume mode, both states with the EGSE link open.

Table 10 compares the operating parameters of (a) the BB and TDA SEPTs at 145mN at nominal conditions with (b) their operating parameters when the BB neutraliser is in plume mode, both states with the EGSE link open.

Table 8. Effect of BB neutraliser plume mode operation on isolated SEPTs, BB 75mN &TDA 75mN

Engine	BB	TDA		BB	TDA
Test Conditions	**nominal**	**nominal**		**BB in plume mode**	**flow and keeper positive set errors**
Thrust level	**75mN**	**75mN**		**75mN**	**75mN**
Link position	open			open	
Link current *(mA)* (+ve means from BB neut to TDA)	0			0	
Main Flow rate (mgs^{-1})	1.043	1.046		1.043	1.046
Neutraliser Flow rate (mgs^{-1})	0.2	0.2		0.14	0.22
Beam Current (*A*)	1.097	1.118		1.096	1.107
Anode Voltage(*V*)	26.21	26.48		27.10	26.77
Anode Current (*A*)	12.20	12.18		12.20	12.20
Neutraliser Keeper Voltage (*V*)	20.02	17.02		21.69	16.59
Neutraliser Keeper Current (*A*)	4.2	4.2		2.98	4.3
Accel Grid Current (*mA*)	9.86	7.6		10.45	7.06
NRP (*V*)	-8.05	-8.19		-27.52	-5.85
Neutraliser Tip Temperature (*deg C*)	1005	1010		930	1010

Table 9. Effect of BB neutraliser plume mode operation on isolated SEPTs, BB 145mN & TDA 75mN

Engine	BB	TDA		BB	TDA
Test Conditions	nominal	nominal		BB in plume mode	nominal
Thrust level	145mN	75mN		145mN	75mN
Link position	open			open	
Link current *(mA)* (+ve means from BB neut to TDA)	0			0	
Main Flow rate (mgs^{-1})	2.5417	1.046		2.5417	1.046
Neutraliser Flow rate (mgs^{-1})	0.2	0.2		0.13	0.2
Beam Current (*A*)	2.144	1.157		2.137	1.103
Anode Voltage(*V*)	25.97	26.54		26.41	26.64
Anode Current (*A*)	18.00	12.20		18.00	12.20
Neutraliser Keeper Voltage (*V*)	18.59	17.04		19.68	17.00
Neutraliser Keeper Current (*A*)	4.2	4.2		3.8	4.2
Accel Grid Current (*mA*)	15.25	10.33		19.9	10.4
NRP (*V*)	-9.95	-7.50		-28.09	-3.03
Neutraliser Tip Temperature (*deg C*)	1085	985		1020	985

When a neutraliser was operating in plume mode during this test sequence, it was always operating at low keeper currents and neutraliser flow rates (these being required to force a BOL Neutraliser in to EOL Plume conditions). The plasma emanating from the neutraliser is not sufficient to neutralise the SEPT's beam. In response, the NRP of the neutraliser becomes significantly more negative. The large negative potential accelerates primary electrons from the neutraliser increasing ionisation collisions with downstream neutrals. This electron multiplication will be sufficient to neutralise the beam, with the sum of the primary and resulting secondary electron currents equal to the beam current. This is seen in the BB SEPT results in Table 8 to Table 10.

A side effect of the BB neutraliser operating in plume mode is that the plasma downstream of the TDA SEPT is also denser than it otherwise would be in normal operation. This is due to the fact that a significant proportion of the BB neutraliser plasma creation taking place downstream in plume mode. This results in a dramatic reduction in the NRP required by the TDA SEPT to couple to its beam. As can be seen in Table 9, the NRP of the TDA neutraliser changed from -7.5V in nominal BB neutraliser operation to only -3.03V when the BB neutraliser was in plume mode, a reduction of 59.5%.

For isolated systems, the results in this section demonstrate that increasing the plasma density downstream of SEPT 1 (by either increasing the thrust of SEPT 2 or by taking SEPT 2's neutraliser into plume mode) lowers the required NRP of SEPT 1 to couple to its beam.

These results are of significant importance for the design of SEPT systems isolated from the spacecraft and each other and the design of an isolated SEPS PPU architecture. It demonstrates that the operation of a second SEPT has a benign influence on the operation of the first, reducing neutraliser tip and keeper plate erosion. The results also show that, from the perspective of the neutraliser, designing and endurance testing for a single engine's NRP is the worst case for an isolated architecture.

Table 10. Effect of BB neutraliser plume mode operation on isolated SEPTs, BB 145mN & TDA 145mN

Engine	BB	TDA		BB	TDA
Test Conditions	nominal	nominal		BB in plume mode	flow and keeper positive set errors
Thrust level	145mN	145mN		145mN	145mN
Link position	open			open	
Link current *(mA)* (+ve means from BB neut to TDA)	0			0	
Main Flow rate (mgs^{-1})	2.5417	2.5417		2.5417	2.5417
Neutraliser Flow rate (mgs^{-1})	0.2	0.2		0.13	0.22
Beam Current (*A*)	2.140	2.151		2.138	2.135
Anode Voltage(*V*)	25.69	25.43		24.62	25.53
Anode Current (*A*)	18.00	18.00		18.00	18.00
Neutraliser Keeper Voltage (*V*)	18.32	15.68		19.45	15.35
Neutraliser Keeper Current (*A*)	4.2	4.2		3.67	4.305
Accel Grid Current (*mA*)	17.68	17.05		22.05	17.99
NRP (*V*)	-9.46	-9.65		-30.62	-7.24
Neutraliser Tip Temperature (*deg C*)	1085	1050		1005	1065

C. Factors affecting cross-neutralisation link current during dual engine firing

This third section deals with observations on dual engine operation in SEPT systems with common neutraliser returns. The results are important to the design of a spacecraft with common grounded SEPS PPU architecture.

There are two main initial observations:

1. Firstly the tests have demonstrated the existence of currents between the two engines when the returns have been commoned.
2. It was discovered that the SEPT neutraliser with the lowest NRP (closest to zero) with the link open *always* supplied the other SEPT system with neutralising current when the link was closed (i.e. the link current always came from lower NRP neutraliser). To conclusively demonstrate this observation an interesting series of tests was conducted, to be described in the following subsection.

1. Effect of utilisation on NRP and link current

It was hypothesised that the neutral flux streaming from the engine presented the electrons from the neutraliser with a possible route for reducing the neutraliser coupling potential. The neutrals can contribute to the beam neutralisation process via a mechanism illustrated in Fig. 9.

The neutraliser bridge plasma directly provides electrons to only partially neutralise the beam. A number of neutraliser electrons undergo ionising collisions with the engine neutrals. The products of the ionising reaction are: the initiating primary electron, a secondary electron and a slow ion. The resulting electron multiplication provides enough electrons to fully neutralise the beam ions. The resulting slow ion moves to and recombines at the neutraliser, maintaining current balance.

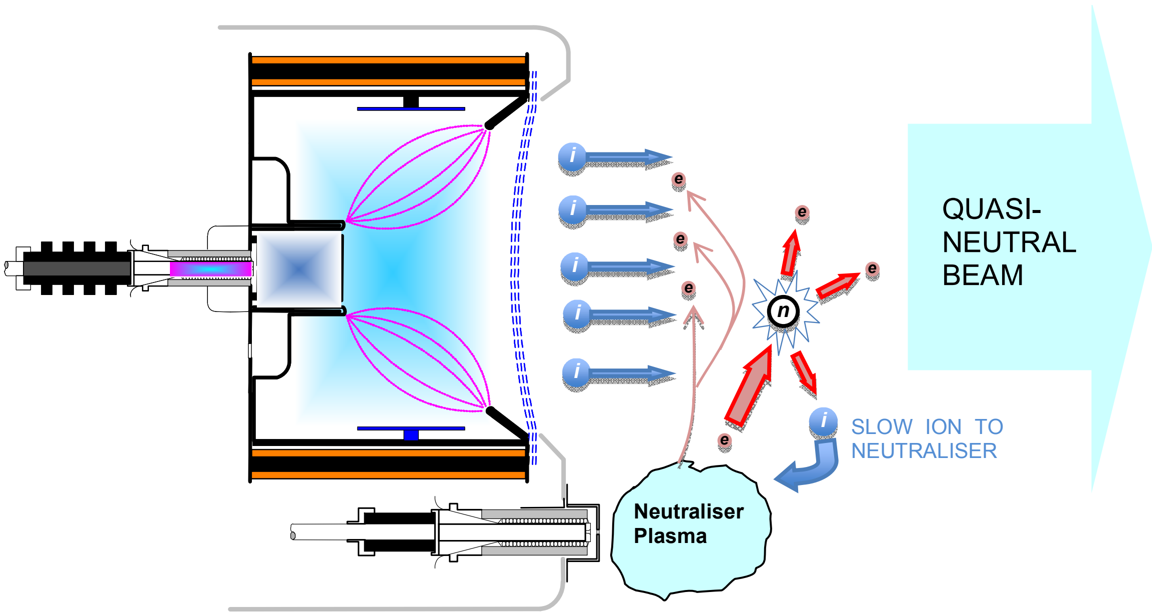


Figure 9. Illustration of the contribution of engine neutral flux to beam neutralisation

This will mean that the neutraliser can then provide the required current at a significantly reduced coupling potential. To prove this theory, during the initial phase of the twin-engine single neutraliser test, the BB SEPT was operated independently and its NRP was monitored while it's utilisation was varied. The number of neutrals streaming out of the engine was varied by reducing the engine utilisation from 90% (nominal) [NRP= -15.69V] to 85% [NRP= -15.32V] and then increasing it to 100.8% [NRP= -17.32V], a change in NRP of 2V. (*NB*. the utilisation of an ion engine can exceed 100% as the typical equation used to calculate utilisation does not take into account the presence of doubly charged ions). The test has shown that an engine with high utilisation (low number of neutrals streaming from the engine) has a high NRP, while conversely an engine utilising less neutrals has a lower NRP, validating the importance of neutrals in the neutraliser coupling mechanism.

Although it was felt that a cross-neutralisation current *will* develop between the two SEPTs, there was no presentiment of the driving forces behind the cross-neutralisation current. For example, it was thought that the neutraliser temperature might determine which one of the two neutralisers will dominate, with the hotter neutraliser (emitting more electrons) providing a lower impedance path and hence dominating the twin SEPT neutralisation. The tests have demonstrated that this is not the case, as the results in the next section for the 75mN/145mN test case (see Table 13 and Table 14) will show, it is the lower temperature neutraliser (75mN) that provided the link current. The only universal determining factor for which neutraliser provided the link current was the NRP. The neutraliser with the lowest NRP (closest to zero) with the link open, was the one that always provided the link current when the link was closed.

This can be understood by the following argument: The neutraliser NRP gives a measure of the ease of the coupling of a given neutraliser to the SEPT beam. The more negative the NRP the worse the coupling to the beam. Therefore, during the twin-engine twin-neutraliser test, the neutraliser with the closest NRP to zero will find it easier to couple to the second engine's beam and hence will provide the link current.

As described earlier in this section, a SEPT's utilisation gives us the ability to indirectly manipulate the ease of coupling a neutraliser to a beam. This gave an opportunity to conduct an interesting test in which the utilisation of the BB SEPT was changed from nominal to 85% and then to 100.8% with the link open and closed and the effect on the link current is monitored at 290mN combined thrust level. The results are shown in Table 11.

At nominal conditions, the BB thruster had an NRP of -9.58V and the TDA SEPT had an NRP of -9.73V with the link open. Reducing the BB utilisation increased the neutral flux from the engine and reduced the required coupling potential to -9.38V. No change was observed on the TDA SEPT NRP. When the link was closed at the 85% utilisation condition, the SEPT with the closest NRP to zero (BB SEPT) provided a link current of 60mA to the TDA SEPT. The link was opened and the utilisation of the BB SEPT was increased to 100.8%. This reduced the neutral flux from the engine and made the NRP more negative at -9.98V, with the TDA SEPT NRP again almost unaffected. Now the TDA has the closer NRP to zero and we consequently get a link current of 88mA in the *reverse direction* going from the TDA neutraliser to the BB SEPT when the link is closed.

The reader must note that the results with the link open in Table 11 have shown no appreciable change in neutraliser operating conditions, i.e., the tip temperature of both neutralisers were the same throughout and their keeper voltages were the same. Yet by changing the BB utilisation (and by proxy the NRP balance between the SEPTs) we have managed to change the cross-neutralisation current by 148mA and reverse it's direction. This demonstrates that the link current is *solely* a function of the relative NRPs or, in other words, the relative coupling of each neutraliser to its beam.

2. Effect of Thrust level and neutraliser operating parameters on link current

In this sub-section we explore the effect of changing the neutraliser operating parameters (keeper current and flow rate) on the resulting link current between the SEPTs

Each of the following 4 tables shows the performance parameters of each SEPT at a given thrust level, both before and after the link between the EGSE is closed, comparing the effect of changing the operating parameters on the resulting link current.

Specifically:

For BB and TDA SEPTs both at 75mN, Table 12 summarises the performance parameters of both SEPTs with changing neutraliser conditions and the link open and closed.

For BB SEPT at 75mN and TDA SEPTs at 145mN, Table 13 summarises the performance parameters of both SEPTs with changing neutraliser conditions and the link open and closed.

For BB SEPT at 145mN and TDA SEPTs at 75mN, Table 14 summarises the performance parameters of both SEPTs with changing neutraliser conditions and the link open and closed.

For BB and TDA SEPTs both at 145mN, Table 15 summarises the performance parameters of both SEPTs with changing neutraliser conditions and the link open and closed.

The reader has to bear mind that the SEPS thrust level and neutraliser's operating parameters influence the link current by changing the SEPTs' NRP balance, with the NRP balance being the determining factor as has been demonstrated in the previous section.

a. Effect of differential SEPT thrust level on link current

The NRP of a given engine decreases (becomes more negative) as the thrust level is increased. The neutraliser becomes more negative in potential in order to extract the extra electron current required by the beam. If the two SEPTs operate at two different thrust levels, the individual NRPs will be naturally different. The SEPT with lower thrust (NRP closer to zero) will provide the link current to the SEPT with the higher thrust.

Looking at the following four tables at nominal neutraliser conditions the NRP difference with the link open was: (a) 0.14V at BB 75mN/TDA 75mN, which resulted in 9mA link current when the link was closed. (b) 2.46V at BB 75mN/TDA 145mN, which resulted in 558mA link current when the link was closed. (b) 2.46V at BB 75mN/TDA 145mN, which resulted in 558mA link current when the link was closed. (c) 2.45V at BB 75mN/TDA 145mN, which resulted in 540mA link current when the link was closed. (d) 0.2 V at BB 145mN/TDA 145mN, which resulted in 64mA link current when the link was closed.

Additional tests were carried out in which the BB SEPT was operating at 145mN and the TDA SEPT was in discharge only mode. At nominal neutraliser conditions the NRP difference with the link open was 10.14V, which resulted in a link current of 1.152A from TDA neutraliser to BB SEPT. This means that the TDA neutraliser provided 54% of the current required to neutraliser the BB SEPT's beam. Fig. 10 illustrates the dependence of link current on the difference between the thrust of the two SEPTs and on the difference of the NRPs between the two SEPTs. The results clearly indicate the increase in link current due to increase in the difference in thrust between the two engines.

Table 11. Effect of change in BB engine utilisation on Link current, both engines at 145mN

Engine	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA
Test Conditions	Nominal	Nominal	Utilisation reduced to 85%	Nominal	Utilisation reduced to 85%	Nominal	Utilisation increased to 100.8%	Nominal	Utilisation increased to 100.8%	Nominal
Date	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010	10/12/2010
Time	13:07	13:07	13:30	13:30	13:35	13:35	14:17	14:17	14:25	14:25
Thrust level	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**	**145mN**
Link position	open		open		closed		open		closed	
Link current (*mA*) (+ve means from BB neut to TDA)	0		0		60		0		-88	
Main Flow rate (mgs^{-1})	2.5417	2.5417	2.6874	2.5417	2.6874	2.5417	2.2	2.5417	2.2	2.5417
Cathode Flow rate (mgs^{-1})	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Neutraliser Flow rate (mgs^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Beam Voltage (*V*)	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
Beam Current (*A*)	2.140	2.147	2.141	2.143	2.140	2.143	2.138	2.135	2.137	2.135
Anode Voltage(*V*)	25.58	25.36	24.06	25.06	24.03	25.07	30.02	25.32	30.00	25.33
Anode Current (*A*)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Solenoid Voltage (*V*)	16.43	13.73	14.52	13.49	14.48	13.56	19.44	13.31	19.35	13.45
Solenoid Current (*A*)	0.949	0.710	0.846	0.710	0.844	0.710	1.103	0.709	1.088	0.709
Neutraliser Keeper Voltage (*V*)	19.12	15.65	19.18	15.46	19.09	15.58	19.17	15.58	19.27	15.53
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Accel Grid Voltage (*V*)	265	265	265	265	265	265	265	265	265	265
Accel Grid Current (*mA*)	17.731	16.86	19.99	17.02	20	17.03	14.71	16.6	14.75	16.6
NRP (*V*)	-9.58	-9.73	-9.38	-9.73	-9.47	-9.62	-9.98	-9.67	-9.79	-9.84
Neutraliser Tip Temperature (*deg C*)	1080	1055	1080	1050	NR	1045	1075	1050	1065	1050

Table 12. Effect of neutraliser parameters on link current, both engines at 75mN

Engine	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA
Test Conditions	nominal	nominal	nominal	nominal	keeper negative set error	keeper positive set error	keeper negative set error	keeper positive set error	flow and keeper negative set errors	flow and keeper positive set errors	flow and keeper negative set errors	flow and keeper positive set errors	BB in plume mode	flow and keeper positive set errors	BB in plume mode	flow and keeper positive set errors
Date	07/12/2010	07/12/2010	07/12/2010	07/12/2010	07/12/2010	07/12/2010	07/12/2010	07/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010
Time	14:54	14:54	15:43	15:43	16:39	16:39	16:58	16:58	10:05	10:05	10:21	10:21	10:39	10:39	10:51	10:51
Thrust level	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN	75mN
Link position	open		closed		open		closed		open		closed		open		closed	
Link current (*mA*) (+ve means from BB neut to TDA)	0		9		0		-34		0		-38		0		-799	
Main Flow rate (mgs^{-1})	1.043	1.046	1.043	1.046	1.043	1.046	1.043	1.046	1.043	1.046	1.043	1.046	1.043	1.046	1.043	1.046
Cathode Flow rate (mgs^{-1})	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Neutraliser Flow rate (mgs^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.18	0.22	0.18	0.22	0.14	0.22	0.14	0.22
Beam Voltage (*V*)	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
Beam Current (*A*)	1.097	1.118	1.098	1.118	1.097	1.097	1.097	1.097	1.097	1.107	1.098	1.107	1.096	1.107	1.098	1.118
Anode Voltage(*V*)	26.21	26.48	26.01	26.45	26.21	26.28	26.23	26.30	26.86	26.62	26.87	26.75	27.10	26.77	26.91	26.81
Anode Current (*A*)	12.20	12.18	12.20	12.19	12.20	12.20	12.21	12.19	12.21	12.20	12.21	12.20	12.20	12.20	12.21	12.20
Solenoid Voltage (*V*)	10.10	9.05	10.36	9.10	10.79	8.90	10.86	8.90	11.78	9.03	11.86	9.13	12.27	9.18	11.87	9.20
Solenoid Current (*A*)	0.653	0.500	0.665	0.499	0.689	0.489	0.693	0.489	0.746	0.510	0.751	0.510	0.775	0.510	0.753	0.510
Neutraliser Keeper Voltage (*V*)	20.02	17.02	20.01	17.08	20.09	17.08	20.26	17.02	20.78	16.51	20.84	16.51	21.69	16.59	22.96	15.64
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2	4.2	4.1	4.3	4.1	4.305	4.1	4.3	4.1	4.3	2.98	4.3	2.98	4.3
Accel Grid Voltage (*V*)	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265
Accel Grid Current (*mA*)	9.86	7.6	11.21	8.9	10.328	8.07	10.15	7.96	9.52	6.84	9.54	6.95	10.45	7.06	9.72	7.18
NRP (*V*)	-8.05	-8.19	-7.94	-8.03	-8.13	-8.00	-8.08	-8.10	-8.29	-8.11	-8.19	-8.21	-27.52	-5.85	-10.16	-9.44
Neutraliser Tip Temperature (*deg C*)	1005	1010	1010	1015	1005	1020	1000	1020	1000	1015	995	1010	930	1010	870	1050

Table 13. Effect of neutraliser parameters on link current, BB 75mN & TDA 145mN

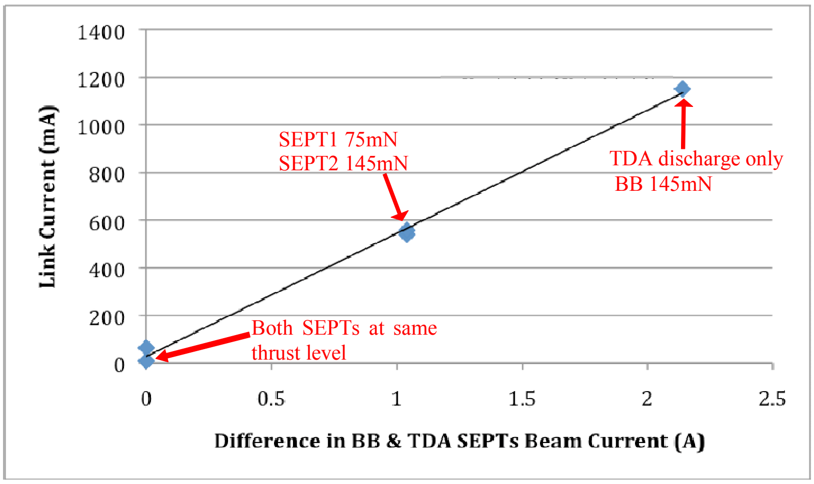
Engine	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA
Test Conditions	nominal	nominal	nominal	nominal	keeper positive set error	keeper negative set error	keeper positive set error	keeper negative set error	flow and keeper positive set errors	flow and keeper negative set errors	flow and keeper positive set errors	flow and keeper negative set errors
Date	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010	08/12/2010
Time	13:28	13:28	15:01	15:01	15:22	15:22	15:43	15:43	16:06	16:06	16:25	16:25
Thrust level	75mN	145mN	75mN	145mN	75mN	145mN	75mN	145mN	75mN	145mN	75mN	145mN
Link position	open		closed		open		closed		open		closed	
Link current (mA) (+ve means from BB neut to TDA)	0		558		0		596		0		588	
Main Flow rate (mgs^{-1})	1.043	2.5417	1.043	2.5417	1.043	2.5417	1.043	2.5417	1.043	2.5417	1.043	2.5417
Cathode Flow rate (mgs^{-1})	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Neutraliser Flow rate (mgs^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.22	0.18	0.22	0.18
Beam Voltage (V)	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
Beam Current (A)	1.098	2.135	1.098	2.135	1.098	2.135	1.098	2.143	1.097	2.143	1.098	2.143
Anode Voltage(V)	26.10	25.76	25.88	25.72	25.78	25.72	25.74	25.74	25.65	25.93	25.60	25.96
Anode Current (A)	12.20	18.00	12.20	17.99	12.20	18.00	12.20	17.99	12.20	18.00	12.20	18.00
Solenoid Voltage (V)	11.61	13.28	11.05	13.15	10.85	13.18	10.72	13.19	10.50	13.39	10.38	13.41
Solenoid Current (A)	0.723	0.700	0.693	0.689	0.681	0.689	0.674	0.689	0.661	0.699	0.654	0.699
Neutraliser Keeper Voltage (V)	20.06	15.79	19.04	16.45	20.51	15.81	19.07	16.54	19.63	16.18	18.37	16.90
Neutraliser Keeper Current (A)	4.2	4.2	4.2	4.2	4.3	4.1	4.3	4.105	4.3	4.1	4.3	4.1
Accel Grid Voltage (V)	265	265	265	265	265	265	265	265	265	265	265	265
Accel Grid Current (mA)	12.17	15.24	12	15.04	12.11	15.15	12.153	15.12	12.307	15.26	12.418	15.26
NRP (V)	-7.57	-10.03	-8.82	-9.02	-7.40	-10.12	-8.77	-9.03	-7.46	-10.14	-8.76	-9.01
Neutraliser Tip Temperature ($deg C$)	1005	1070	1045	1040	1020	1065	1055	1025	1025	1040	1070	1015

Table 14. Effect of neutraliser parameters on link current, BB 145mN & TDA 75mN

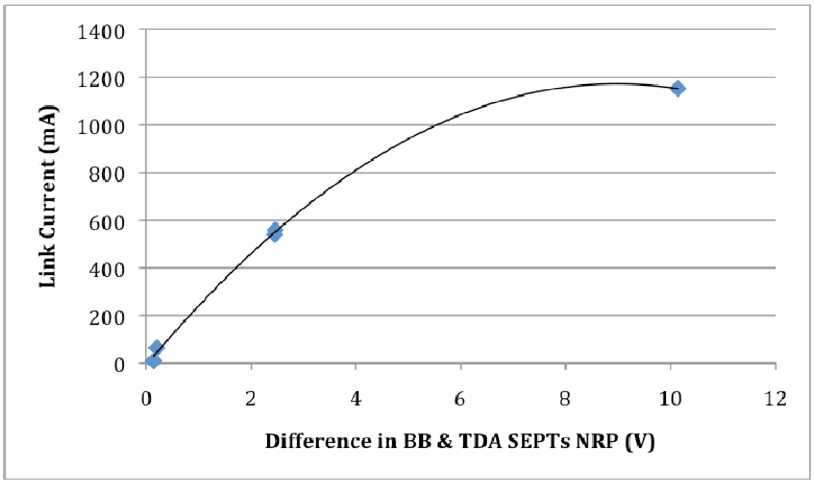
Engine	BB	TDA	BB	TDA	BB	TDA	BB	TDA
Test Conditions	nominal	nominal	nominal	nominal	BB in plume mode	nominal	BB in plume mode	nominal
Date	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010
Time	10:15	10:15	10:35	10:35	10:47	10:47	11:07	11:07
Thrust level	**145mN**	**75mN**	**145mN**	**75mN**	**145mN**	**75mN**	**145mN**	**75mN**
Link position	open		closed		open		closed	
Link current (*mA*) (+ve means from BB neut to TDA)	0		-540		0		-635	
Main Flow rate (*mgs*$^{-1}$)	2.5417	1.046	2.5417	1.046	2.5417	1.046	2.5417	1.046
Cathode Flow rate (*mgs*$^{-1}$)	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Neutraliser Flow rate (*mgs*$^{-1}$)	0.2	0.2	0.2	0.2	0.13	0.2	0.13	0.2
Beam Voltage (*V*)	1850	1850	1850	1850	1850	1850	1850	1850
Beam Current (*A*)	2.144	1.157	2.140	1.157	2.137	1.103	2.141	1.142
Anode Voltage(*V*)	25.97	26.54	26.00	27.36	26.41	26.64	26.03	26.74
Anode Current (*A*)	18.00	12.20	18.00	12.20	18.00	12.20	18.00	12.20
Solenoid Voltage (*V*)	15.65	10.89	15.65	10.22	16.43	10.21	15.53	10.04
Solenoid Current (*A*)	0.902	0.590	0.910	0.550	0.955	0.550	0.908	0.540
Neutraliser Keeper Voltage (*V*)	18.59	17.04	19.64	16.18	19.68	17.00	23.24	16.17
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2	4.2	3.8	4.2	3.77	4.2
Accel Grid Voltage (*V*)	265	265	265	265	265	265	265	265
Accel Grid Current (*mA*)	15.25	10.33	15.26	10.4	19.9	10.4	15.45	10.3
NRP (*V*)	-9.95	-7.50	-9.05	-9.05	-28.09	-3.03	-9.11	-8.92
Neutraliser Tip Temperature (*deg C*)	1085	985	1050	1015	1020	985	985	1015

Table 15. Effect of neutraliser parameters on link current, both engines at 145mN

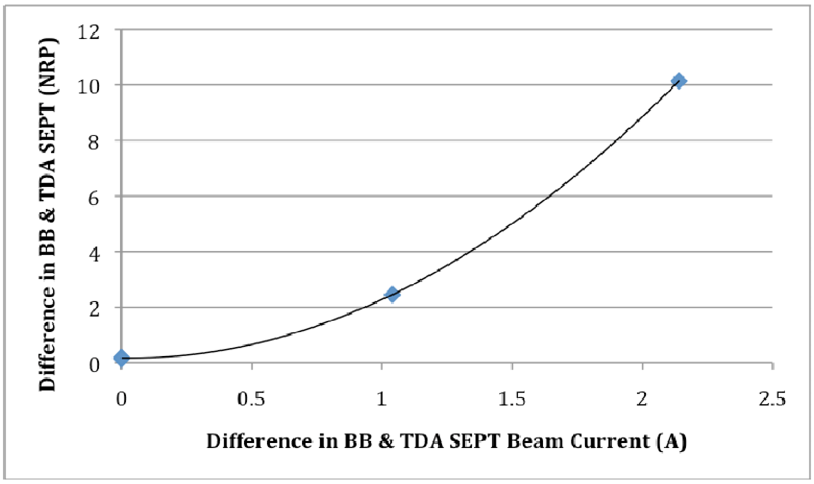
Engine	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA	BB	TDA
Test Conditions	nominal	nominal	nominal	nominal	keeper negative set error	keeper positive set error	keeper negative set error	keeper positive set error	flow and keeper negative set errors	flow and keeper positive set errors	flow and keeper negative set errors	flow and keeper positive set errors	BB in plume mode	flow and keeper positive set errors	BB in plume	flow and keeper positive set errors
Date	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010	09/12/2010
Time	11:34	11:34	13:34	13:34	14:03	14:03	15:01	15:01	15:37	15:37	16:04	16:04	16:24	16:24	16:50	16:50
Thrust level	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN	145mN
Link position	open		closed		open		closed		open		closed		open		closed	
Link current (*mA*) (+ve means from BB neut to TDA)	0		64		0		9		0		70		0		-111	
Main Flow rate (mgs^{-1})	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417	2.5417
Cathode Flow rate (mgs^{-1})	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Neutraliser Flow rate (mgs^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.18	0.22	0.18	0.22	0.13	0.22	0.13	0.22
Beam Voltage (*V*)	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
Beam Current (*A*)	2.140	2.151	2.140	2.158	2.142	2.139	2.140	2.139	2.141	2.154	2.140	2.140	2.138	2.135	2.140	2.151
Anode Voltage(*V*)	25.69	25.43	24.47	25.44	24.25	25.29	24.58	25.39	24.47	25.50	24.28	25.30	24.62	25.53	24.49	25.69
Anode Current (*A*)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	17.99
Solenoid Voltage (*V*)	15.18	13.32	13.91	13.64	12.52	13.44	14.35	13.35	13.87	13.56	12.47	13.38	12.61	13.69	13.03	13.69
Solenoid Current (*A*)	0.882	0.710	0.816	0.710	0.746	0.700	0.840	0.700	0.817	0.710	0.744	0.699	0.755	0.719	0.778	0.719
Neutraliser Keeper Voltage (*V*)	18.32	15.68	18.54	15.78	18.70	15.70	18.73	15.69	19.40	15.34	19.32	15.45	19.45	15.35	20.62	15.31
Neutraliser Keeper Current (*A*)	4.2	4.2	4.2	4.2	4.1	4.3	4.1	4.3	4.1	4.305	4.1	4.305	3.67	4.305	3.576	4.304
Accel Grid Voltage (*V*)	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265
Accel Grid Current (*mA*)	17.68	17.05	18.25	17.29	18.52	17.35	17.85	16.895	17.93	16.8	18.13	16.83	22.05	17.99	18.311	16.79
NRP (*V*)	-9.46	-9.65	-9.39	-9.53	-9.24	-9.53	-9.49	-9.56	-9.43	-9.62	-9.39	-9.50	-30.62	-7.24	-9.82	-9.69
Neutraliser Tip Temperature (*deg C*)	1085	1050	1075	1050	1070	1055	1075	1060	1055	1065	1060	1055	1005	1065	995	1070



(a)



(b)



(c)

Figure 10. Dependence of link current on (a) The difference in thrust level between the two SEPTs (b) The difference of the NRPs of the two SEPTs and (c) The difference in SEPTs NRP that results from thrust difference between the two engines

b. *Effect of neutraliser operating parameters on link current*

The way that small changes in the neutraliser flow and keeper current influence the NRP is not very clear, as can be seen in the previous four tables. However, for non-plume mode operation with both engines at the same thrust level, the link current due to the combined set errors was small at 70mA or less. For positive errors, when the link is open, flow and keeper errors led to increasing the NRP, which can be understood as the neutraliser forming a denser plasma and a better bridge between it and the beam. For negative errors the neutraliser plasma is more diffuse and the opposite effect takes place. Therefore the link current when the link is closed is expected to be larger when keeper and flow errors are introduced than when the neutralisers operate in nominal mode. *This is the case when BOTH errors are introduced, but not necessarily the case when just the keeper error is introduced*. This might probably be due to the low relative value of the error.

What is clear is the effect of large changes in neutraliser operating parameters. When the BB SEPT neutraliser is taken into plume mode by significantly reducing the flow and keeper current, the BB NRP increases significantly when the link is open. Closing the link always results in the largest link current observed in each of the above four tables. The relative magnitudes of the resulting link currents are however not yet understood. For example, it is not yet clear why the 75mN/75mN case results in a higher plume mode link current (almost 8 times) than the 145mN/145mN case. This is still a subject of ongoing assessment and it is hoped more light will be shed on this in the future.

VI. Conclusion

The operation of a twin SEPT system with a single neutraliser and with a twin neutraliser system with alternative grounding systems has been investigated by a series of tests at QinetiQ's LEEP2 facility.

- Beam probe sweeps have demonstrated that no impact on the beam properties from twin-engine operation or the grounding system used in a twin neutraliser case.
- In the isolated EGSE case it was found that twin SEPT operation actually led to a reduction in the required SEPT NRP due to the presence of a denser coupling plasma downstream. This result is important for the design of an isolated PPU as it shows that designing for a single engine's NRP is the worse case to be experienced in the mission. The lower NRP also means that the SEPT neutraliser is expected to experience reduced erosion levels when operated in twin SEPT twin isolated neutraliser configuration.
- The results have demonstrated the presence of a cross-neutralisation current between the two SEPTs with common returns driven by the difference in Neutraliser Coupling Potential between the two neutralisers.

References

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