The MiDGIT Thruster: Development of a Multi-Mode Thruster

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A novel miniature gridded ion thruster is under development which could be capable of performing both coarse and fine control manoeuvres and achieving thrust levels down to 1µN or less. The thruster concept involves the differential control of ion beams extracted from a common plasma discharge to achieve very low thrust levels, but also operation as a conventional single-ended thruster to achieve mN thrust levels at high specific impulse. Prototype and breadboard models of the thruster have been tested. A radio frequency inductive discharge is used for the ionization process. Single-ended operation of the thruster demonstrated thrust levels between 250µN-480µN using an accelerator grid voltage and beam potential of 95V/950V respectively. The maximum thrust was increased to ~780µN by operating at a higher beam potential of 1300V. The extraction of two stable ion beams from a common discharge was also successfully demonstrated. Differential control of the ion beams was initially investigated by independently varying the voltage supplied to separate accelerator grids, but it was concluded that this method of control would not achieve the 1µN-150µN for fine thrust mode. Tests to confirm differential control by variation of RF power on each end of the thruster are ongoing.

Nomenclature

e	=	electron charge, C
I	=	current, A
M	=	particle mass, kg
T	=	thrust, N
V	=	potential, V

Abbreviations

DMM	=	digital multi meter	*PSU*	=	power supply unit
EP	=	electric propulsion	*RF*	=	radio frequency
ICP	=	inductively coupled plasma	*RFG*	=	radio frequency generator
LEEP	=	Large European Electric Propulsion facility	*sccm*	=	standard cubic centimeters per minute
MiDGIT	=	miniaturized differential gridded ion thruster	*SWR*	=	standing wave ratio

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I. Introduction

FORMATION flying of spacecraft has been extensively studied as a means to significantly improve the resolution and sensitivity of interferometry and Earth observation missions compared to that achievable with a single platform[1,2]. Precision control of spacecraft constellations will require very accurate, low thrust and low noise propulsion systems. High thrust levels will also be required for orbital manoeuvres of the constellations. A set of generic propulsion requirements for formation flying missions is provided in Table 1.

Thrust range (fine)	1 – 150µN
Thrust range (coarse)	150µN to >1mN
Thrust resolution	<0.5µN
Thrust noise (1mHz – 1Hz)	1.65µN/√Hz up to 100µN
Thrust linearity and bias	0.5µN
Thrust repeatability	0.5µN (0.5mN coarse)
Thrust response time	60ms
Specific power	<50W/mN (coarse)
Specific impulse	>1500s @1mN, >90s @12µN
Total impulse	40kNs
Beam divergence	<25°
Lifetime	21900 hours

Table 1. Generic propulsion requirements for formation flying missions.

A small number of miniature electric propulsion (EP) devices exist which are capable of providing the very small impulse bits at micro-Newton thrust levels required for precision attitude control[3]. Due to a low thrust-to-power ratio however they are not appropriate for milli-Newton thrust applications. Propulsion systems baselined for formation flying missions often combine cold gas thrusters for coarse attitude control with miniaturized EP thrusters for fine attitude control. A system utilizing a single type of thruster would be advantageous for reducing system mass, complexity and cost and therefore a need for a precision, low thrust micropropulsion device with a wide throttling range exists.

The RIT-µX propulsion system, utilising miniature radio frequency (RF) ion thrusters developed by the University of Giessen, has recently been proposed as an all-electric µN-mN propulsion system[4]. A thrust range of less than 1µN to several mN, as demanded by some of the more complex formation flying missions under study [1], is inherently difficult to achieve from a single conventional ion thruster. The RIT-µX system is therefore designed around a set of different sized thrusters with interchangeable grids that can be selected in combination to meet specific thrust requirements for a mission. The minimum thrust level achievable with one configuration is ~5µN with a range up to 200µN [5]. Thrust levels less than 1µN have not yet been demonstrated.

A development program has been initiated by the Electric Propulsion Group of QinetiQ in collaboration with the University of Southampton to develop a miniature ion thruster, based on a novel adaptation of conventional ion thruster technology, which would be able to provide both precision and coarse propulsion capabilities with thrust levels down to 1µN or less. It has been proposed that an unprecedented throttling range with sub-µN thrust resolution could be achieved through differential control of opposing ion beams extracted from a single thruster. The Miniaturized Differential Gridded Ion Thruster (MiDGIT) is designed so as to achieve precise µN thrust levels through differential beam control but to also have the capability of being used as a single-ended thruster for mN thrust levels. Such a design of thruster could provide system advantages such as reduced system mass and complexity through shared components and would also provide greater redundancy. This paper reports on the design considerations and ongoing development of the MiDGIT thruster.

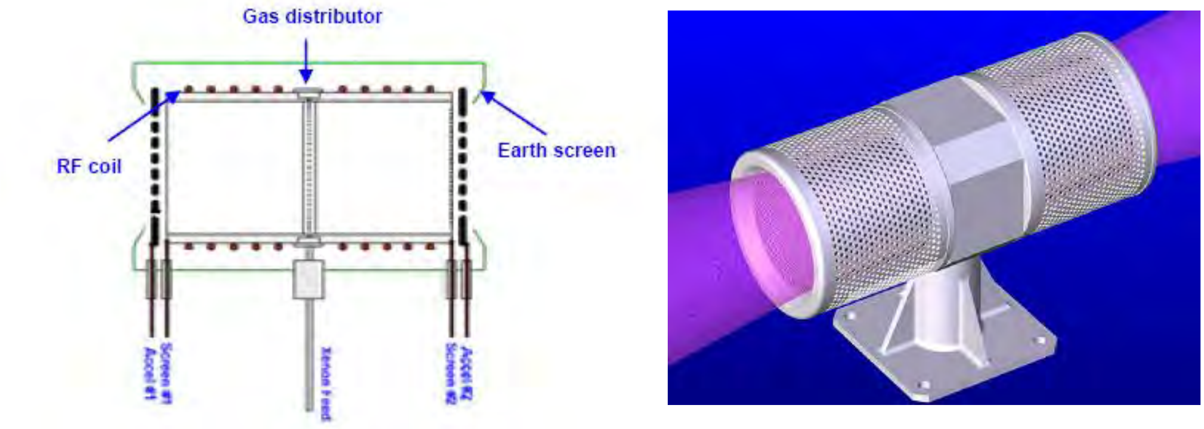

Figure 1. The basic configuration of the MiDGIT Thruster

II. The MiDGIT Concept

The MiDGIT thruster is proposed as a sub-μN to mN thruster. Precision thrust up to a required level of ~150μN is expected to be achieved by differential control of separate ion beams extracted through grid sets at opposite ends of a common discharge chamber. Conventional ion thrusters exhibit a minimum threshold in generated thrust due to the balance of power with discharge losses and also due to neutral efflux from the thruster. The very low μN thrust levels required for formation flying missions are very difficult to achieve. The concept of *differential* ion beam control however would allow an ion thruster to operate at stable (though higher) discharge conditions but achieve very low thrust levels by producing a net imbalance in the currents of extracted ion beams. More notably, if opposing ion beams can be perfectly matched this would theoretically permit throttling down to null thrust. Higher thrust levels in the mN range could be achieved by the MiDGIT thruster by blocking neutral flow to one half of the discharge chamber using a gating mechanism and thrusting out of the active end as for conventional single-ended ion thrusters.

A radio frequency (RF) inductive plasma discharge is used for the ionization process in the MiDGIT. Inductively coupled plasma (ICP) discharges generate plasma with high electron density at low pressures without the need of internal electrodes[6]. This simplifies the design of the thruster and improves operational lifetime. In general, an ICP source consists of a cylindrical ceramic vessel surrounded by a conducting coil to which an oscillating current is applied. The time dependent magnetic field of the coil penetrates the vessel inducing an azimuthal electric field in the plasma. Electrons are excited by the induced field which then collide with and ionize gas molecules creating a self-sustaining discharge. Plasma density is controlled by RF power and gas flow rate, as these affect the ionization rate through the energy transferred to plasma electrons and the electron-neutral collision frequency [6]. An increase in power primarily increases the plasma density however rather than the energy of the electrons. The electron temperature within RF ion thrusters is therefore lower than within other types of ion thruster, often measured to be in the range 2-5 eV[7].

A schematic of the basic configuration for the MiDGIT thruster is given in Figure 1. The differential concept restricts the position of a gas distribution system to be located centrally along the discharge chamber. Two RF coils are used; one located either side of the gas distributor. An earth screen is positioned around the RF coils and discharge chamber to shield external components from electromagnetic fields. The extraction grid sets at either end of the thruster consist of an accelerator grid and a screen grid. The screen grid also acts as an anode to collect electrons equivalent to the number of ions extracted. Measurement of the screen grid current therefore allows monitoring of the ion beam.

A. Suggested Thrust Modes

1. Differential (Fine) Thrust Mode

Thrust level is controlled in conventional gridded ion thrusters by controlling mass flow rate and power at a fixed beam voltage. It is known however that variation to the electrostatic field between the screen and accelerator grids of ion optic systems affects the geometry of the plasma sheath formed upstream of the grids [8]. The geometry of the sheath affects the focusing of the extracted ion beam and to a small degree, the ion current that can be extracted.

A method proposed for controlling ion beam current during differential operation of the MiDGIT is by fine adjustment of the voltage applied to the accelerator grid whilst the thruster is operated at a set mass flow rate and RF power. Very precise thrust down to very low levels may therefore be achieved by creating a net imbalance in the thrust generated from opposing ion beams. Controlling the thruster during differential operation will rely on resolving the individual currents of separate screen grids. Gas will be injected into the full volume of the discharge chamber by a gas distributor located mid-way along its length. It is assumed that the neutral efflux from each grid set will be the same with this configuration. Therefore, any net thrust component from neutrals should be cancelled.

The disadvantage of differential beam control for achieving very low thrust levels however is that specific impulse will be poor compared to a conventional thruster. Overall system advantages of using a thruster with both precision and coarse propulsion capabilities however may offset any extra propellant requirements.

2. Single-Ended (Coarse) Thrust Mode

During coarse thrust control, larger variations in thrust will be required. The MiDGIT will therefore be operated as a conventional gridded ion thruster. The accelerator grid voltage will be fixed whilst the mass flow rate and RF power will be varied to control beam current. To achieve specific impulse values higher than during differential operation and comparable with conventional ion thrusters, a mechanical shutter will be activated to close off one end of the discharge chamber, directing neutral flow into one half of the discharge volume. Two mechanical shutters will be required; one either side of the central gas distributor. It is suggested that each shutter should consist of a single ceramic plate moved by piezoelectric actuators. Only the coil on the active end of the thruster will be powered during single-ended mode, with the redundant coil left in open-circuit.

III. MiDGIT Thruster Development

Test campaigns were conducted on prototype and breadboard models of the MiDGIT thruster to investigate design issues, provide verification of the differential concept and demonstrate preliminary performance. Testing was performed in-house at the QinetiQ Large European Electric Propulsion (LEEP) facilities.

A. Test Facility

Thruster characterization of both the MiDGIT prototype and breadboard models was performed within the loadlock of the LEEP-1 vacuum facility (displayed in Figure 2). The loadlock consists of a 0.75m diameter x 1.40m cylindrical glass vacuum chamber, permitting observation of the thruster assembly at all times. A Pfeiffer Balzers TCP5000 turbopump system, backed by a Pfeiffer DUO 120A roughing pump, was used to pump the chamber to a base pressure of 5×10^{-6} mbar. Grafoil sheets were used as beam targets during ion beam extraction.

An interface plate was assembled to which the MiDGIT prototype or breadboard models could be mounted. The plate was designed so that the different models could be easily interchanged. The thruster, secured within a ceramic cradle, was mounted on a FR4 mounting block. A hollow cathode neutraliser was mounted to one side of the thruster for use during ion beam extraction. A 40W tungsten filament was also mounted close to the thruster for use as an electron source for discharge ignition. The interface plate provided terminal block connections for the high and low voltage grid connections, low voltage connections for the neutraliser assembly, RF connections for the induction coils and means to secure the gas feed pipes.

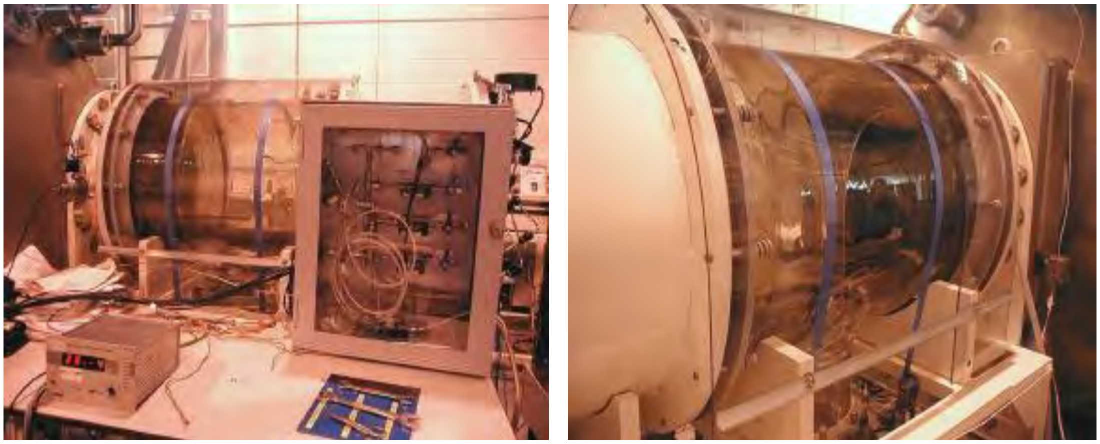

Figure 2. Loadlock chamber of LEEP-1 facility.

RF power was applied by a radio frequency generator (RFG) consisting of an IFR 2031 variable frequency signal generator (1-13 MHz) connected to an Amplifier Research 75A250A 75W RF power amplifier. RF frequency and power were both controlled via the signal generator. An MFJ-934 antenna matching unit was connected between the signal generator and thruster to manually match the impedance of the RF source to that of the induction coils. An indication of forward and reflected RF power in Watts was provided by means of a power meter incorporated into the antenna matching unit. The signal generator however was connected via GPIB to LabVIEW to log the signal frequency and forward RF power (in dB) during thruster operation. The transmission lines between the RF generator and thruster were measured to have a loss of 0.67, which was taken into account to estimate forward power into the RF coils.

The units for the RFG were mounted within a rack including 3 Glassman 60V, 5A low voltage power supplies. These were used to power the neutraliser keeper and heater electrodes and also the 40W tungsten filament. A separate high voltage rack was also assembled consisting of a 1kV Glassman PSU for the Beam supply, two 1kV Bertran high voltage supplies for the accelerator grids, two Agilent floating DMMs to measure Beam current, two DMMs for the accelerator grid currents and 1 DMM to monitor the Beam voltage.

Mass flow to the thruster and neutraliser were controlled independently by an Aera ROD-4 control unit connected to two Aera FC-D980C mass flow controllers, having a full-scale flow range of 5.0 sccm and 10 sccm respectively.

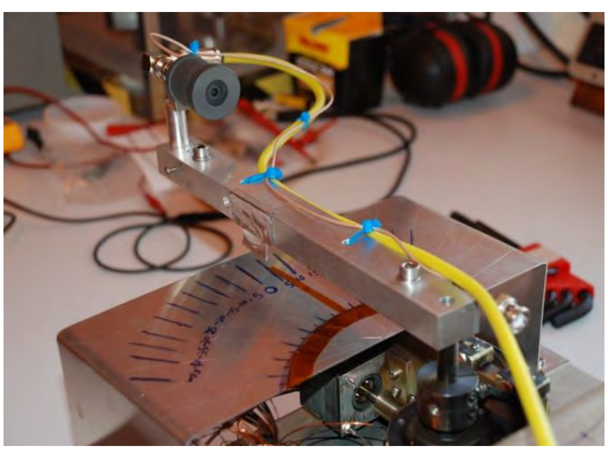

Figure 3. Rotatable beam probe assembly with gridded faraday cup.

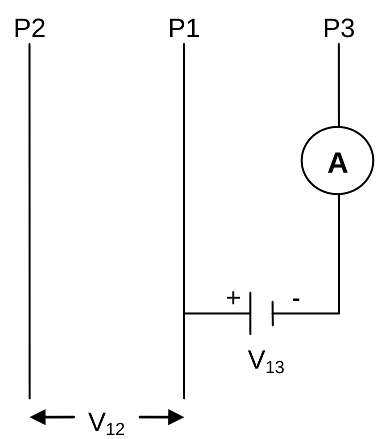

Figure 4. Triple Langmuir probe circuit for direct-display of electron temperature and density.

To ignite a discharge, flow to the thruster was commanded whilst the RF frequency and power were set on the signal generator. The impedance of the RF source and induction coils were matched by manually tuning the matching circuit for minimum SWR. The power to the tungsten filament was then ramped up to provide a source of electrons. Once a discharge had been ignited, the power to the filament was switched off and the matching unit again tuned for minimum SWR and the discharge left to stabilize. During beam extraction, the hollow cathode neutraliser was operated at a flow rate of 0.41 sccm and current of 1.4A. The beam and accelerator grid potentials were then applied by manual control of the Glassman PSUs to extract ion beams.

A rotatable beam probe system (displayed in Figure 3) was mounted within the chamber to obtain radial profiles of the extracted ion beams. The beam probe consisted of a single screened faraday cup mounted on a rotatable arm driven by a motor. The faraday cup was positioned 21cm from the exit plane of the thruster and rotated about a vertical axis coincident with the centerline of the grid set. The faraday cup was aligned by mechanical alignment and the probe arm rotated by manual control of the driver motor. Probe current was read directly from a Keithley 6157A electrometer. The faraday cup was biased to a potential of 50V, whilst the retarding grid was biased to -90V by a Glassman XM 120-0.5 power supply.

Several Langmuir probes were constructed for investigating discharge parameters. Each probe consisted of a 0.12mm diameter tungsten wire inserted through a single-bore alumina tube. The exposed tip of tungsten wire was cut to a length of 6mm to ensure that the probe could be considered an infinite cylinder and end effects neglected. Three individual probes were used in a „Triple Langmuir probe"configuration as outlined by Kamitsuma for direct display of electron temperature and density estimates [9]. The electrical configuration for the three probes is displayed in Figure 4.

B. Breadboard Characterisation

The MiDGIT prototype model highlighted a number of design issues concerning the performance of the thruster but successfully demonstrated the feasibility of extracting two ion beams from a common discharge. Results of the prototype tests have been reported previously[10, 11]. An image displaying the extraction of two ion beams from the MiDGIT prototype in differential configuration is given in Figure 5.

Outputs from the prototype test phase led to a number of design changes being incorporated into an improved breadboard model. The internal diameter of the discharge chamber was reduced from 33mm to 28mm. An annular gas distributor was also incorporated into the walls of the discharge chamber to provide a uniform internal diameter along the length of the chamber and radial injection of neutrals. The discharge chamber was machined from alumina in three sections consisting of two main ionization regions, each 32.75 mm in length, and a central region incorporating the gas distributor. Ceramic shutter gates were also machined from alumina that could be slid manually across the diameter of the discharge chamber either side of the distributor, as displayed in Figure 6. Two induction coils were wound directly onto the discharge chamber, each with 6 turns of copper wire and a pitch of 3.2 mm. The extraction grid sets consisted of a molybdenum screen grid and graphite accelerator grid, each fabricated with 55 apertures (shown in figure 6). The grid design was based on that of the T5 ion thruster grids, which are optimized for an accelerator grid voltage of 250V and beam voltage of 1176V.

Figure 5. Image of two ion beams extracted during differential operation of the MiDGIT prototype.

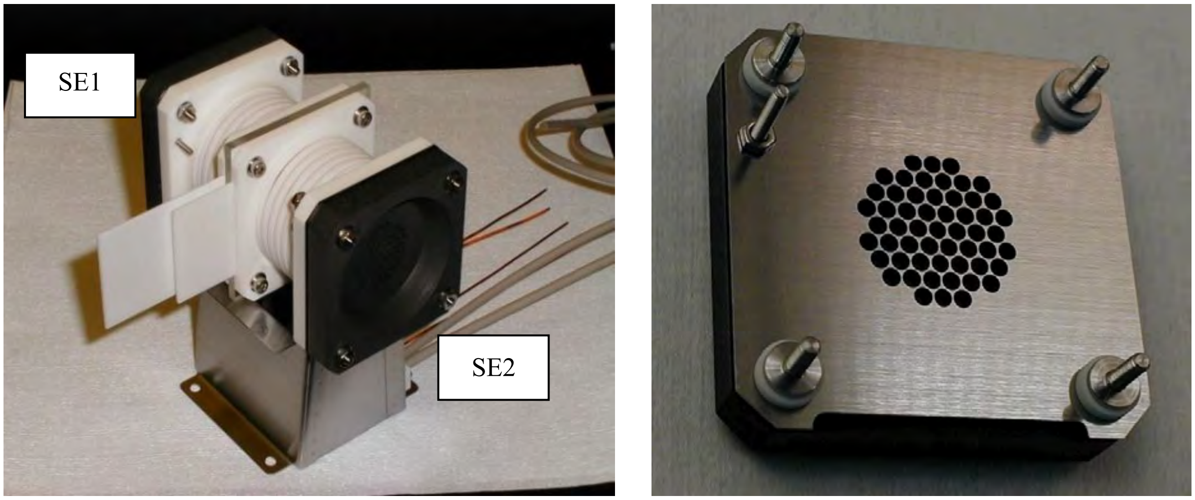

Figure 6. Components of the MiDGIT breadboard model.
The discharge chamber is displayed with manual shutters and earth screen removed. The extraction grids were fabricated with 55 apertures each as shown.

1. Single-End Performance

Performance tests were conducted on both ends of the MiDGIT breadboard thruster in single-ended mode. The ends of the thruster were identified as in Figure 6. The thruster was operated on Xenon at various discharge conditions at a frequency of 5.25 MHz with an accelerator grid voltage of 95V and beam voltage of 950V (due to limited output of the power supply). The background pressure during operation was of the order 6.0 x 10^{-5} mbar. Results for the SE1 and SE2 configurations were comparable. An image of the MiDGIT breadboard thruster operating in single-ended mode is shown in Figure 7.

Thrust was estimated from the measured beam current using:

$$T = I_B \sqrt{\frac{2V_B M}{e}} \tag{1}$$

where V_B is beam voltage, M is the mass of a Xenon ion and e is the electron charge. No thrust correction factor was assumed.

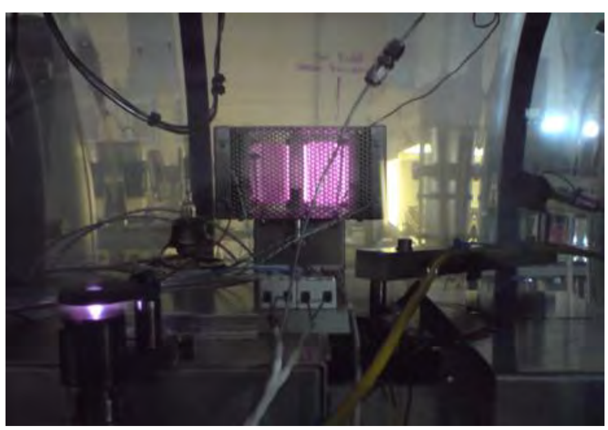

Figure 7. The MiDGIT breadboard thruster operating in single-ended mode with a hollow cathode neutraliser.

Discharge conditions such as plasma density and beam voltage affect focusing of the ion beam extracted and for certain conditions can result in direct impingement of ions on the accelerator grid. The onset of direct impingement of beam ions establishes an upper limit for achievable thrust as the actual net thrust output at this point is lower than that predicted by the measured beam current. Impingement of ions also limits thruster lifetime through erosion of the grids and must be avoided.

A plot of RF power against thrust for different flow rates, operating with an accelerator/beam voltage of 95V/950V, is given in Figure 8 for the SE2 configuration. The accelerator grid current was also monitored and results indicated that direct impingement of ions on the accelerator grid occurred at RF powers above 17.5W and flow rates greater than 0.050mgs^{-1}.

Propulsion requirements also limit specific power during coarse thrust mode to 50W/mN. Figures 9 and 10 display estimated thrust and specific impulse against specific power for the SE2 configuration. It can be seen that a thrust range of approximately 250μN–480μN can be achieved for the operating conditions listed in Table 2. Thruster efficiency, determined from the product of mass utilization efficiency and electrical efficiency which are shown in Figure 11, was found to be poor for this configuration of thruster and these operating conditions. Increases to mass utilization efficiency by reduction of flow rate occur only at a cost of electrical efficiency and this must be considered when operating a RF ion thruster.

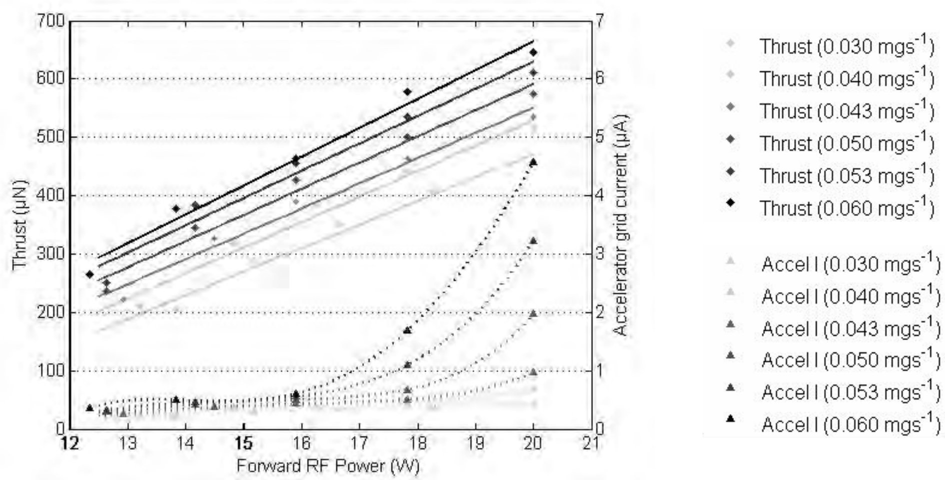

Figure 8. Estimated thrust and measured accelerator grid current for different RF power and flow rates for the SE2 configuration.

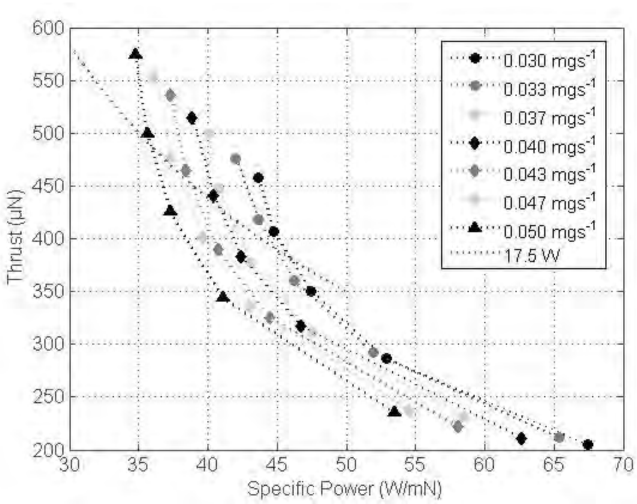

Figure 9. Estimated thrust against specific power for the SE2 configuration.

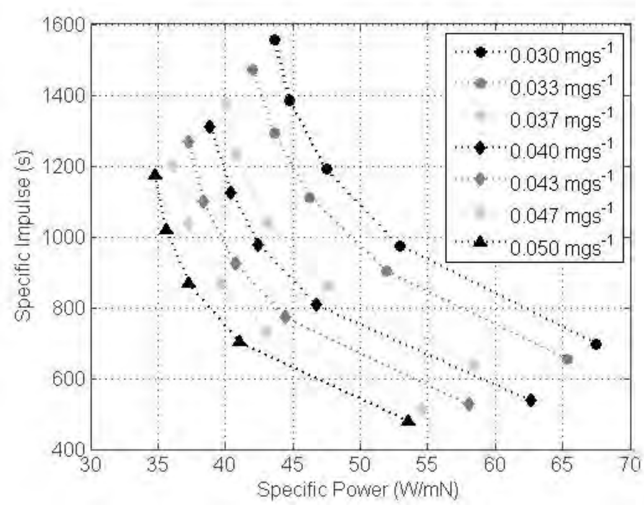

Figure 10. Specific impulse against specific power for the SE2 configuration.

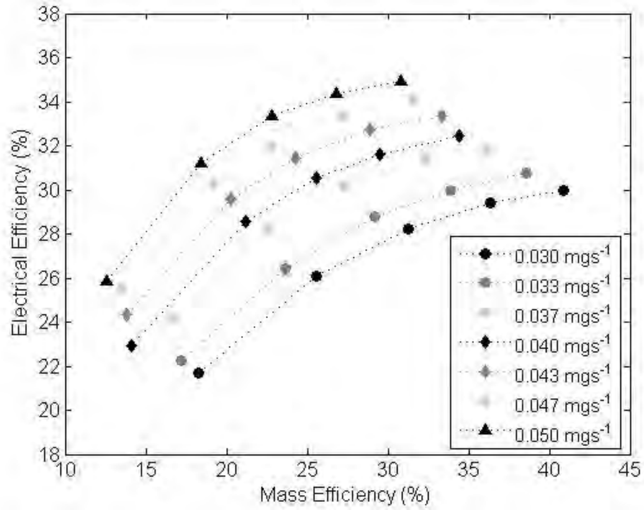

Figure 11. Electrical efficiency against mass utilization efficiency for the SE2 configuration *(neglecting neutraliser power and flow rate)***.**

Thrust range	250µN - 480µN
Flow rate	0.03 mgs^{-1} - 0.05 mgs^{-1}
Forward RF power	13W – 18W
Operating frequency	5.25 MHz
Grid apertures	55
Beam potential	950V
Accelerator potential	95V
Background pressure	6.0 x 10^{-5} mbar

Table 2. Initial performance for single-ended operation of the MiDGIT breadboard model.

Radial scans of the ion beams extracted from SE1 and SE2 were obtained for different thrust levels, from which beam divergence was estimated. The beam probe was scanned twice for each thrust level and data averaged. The averaged data was then fit with a shape-preserving spline, which provided the best fit to the data at the edges of the beam. The plots for SE1 are given in Figure 12. The beam divergence was observed to be <15^{o} for all thrust levels operating with an accelerator voltage of 95V.

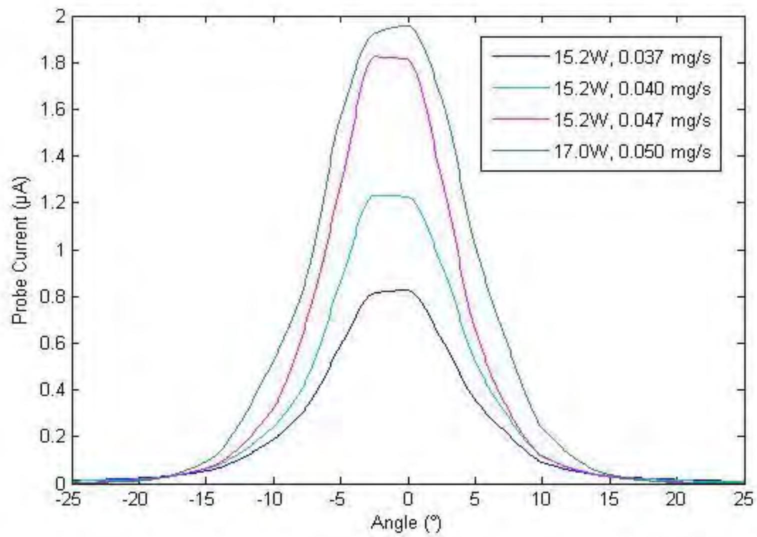

Figure 12. Radial beam profiles for SE1 for different thrust levels.

Three individual Langmuir probes were inserted through adjacent apertures at the centre of each grid set in a triangular pattern to obtain estimates of the discharge conditions for SE1 and SE2. These Langmuir probes were used in a „Triple Langmuir probe" configuration to estimate electron temperature and electron density [9]. The ratio of ion temperature to electron temperature was assumed to be $T_i/T_e \sim 0.01$ and a voltage of 30V was applied between two of the probes, whilst the third was left floating. The probes were inserted a distance of 6mm into the discharge chamber. Estimates obtained for various discharge conditions are displayed in Figure 13. The plasma density is observed to increase linearly with RF power as expected, whilst the electron temperature remains relatively constant. The electron temperature estimated is slightly lower than would be expected and the electron density possibly overestimated (though n_e is of the expected order of magnitude). Comparison of experimental measurements obtained with triple Langmuir probes and single RF compensated probes by Kamitsuma suggests that plasma density may be overestimated by a factor of three using cylindrical triple probes[9]. Improvements to the triple Langmuir probe system for the MiDGIT thruster are being conducted.

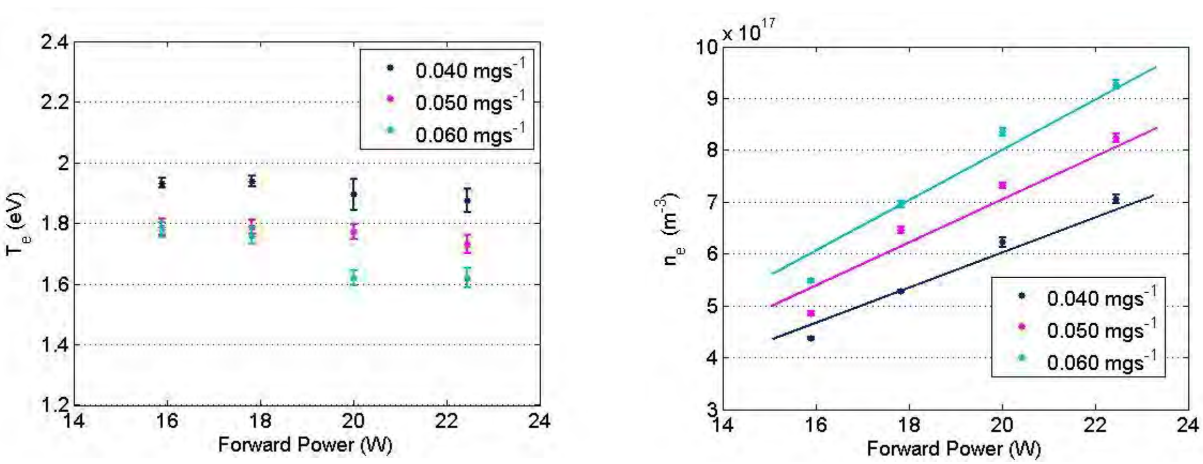

Figure 13. Estimated electron temperature and density for different RF power and flow rates.

It was proposed that the upper limit on the thrust achieved by the MiDGIT breadboard model, dictated by the onset of direct ion impingement, could be improved by operating the thruster under lower vacuum and at higher beam voltage (the extraction grids being optimized for a beam voltage of 1176V). The MiDGIT breadboard thruster was therefore operated within the LEEP-3 vacuum facility by QinetiQ. The background pressure was improved to 2.0 x 10^{-5} mbar during operation and the beam voltage increased up to 1300V using a higher voltage power supply. Higher RF powers and flow rates were required to reproduce the same beam and accelerator grid currents that were measured during the tests in the LEEP-1 facility. This was believed to be due to changes in the gas feed lines and greater loss of the RF transmission lines due to increased length and was not taken as indicative of changes in thruster performance. The maximum thrust was increased up to 780μN operating at a beam voltage of 1300V and for the conditions specified in Table 3.

Max Thrust	~780μN
Flow rate	0.10 mgs^{-1}
Forward RF power	30W
Beam potential	1300V
Accelerator potential	250V
Background pressure	2.1 x 10^{-5} mbar

Table 3. Operating conditions of the MiDGIT breadboard model for maximum thrust.

2. Differential Mode Performance

Stable discharges were achieved in the differential configuration also at an operating frequency of 5.25 MHz (as displayed in Figure 14) indicating that the MiDGIT thruster could be operated with a fixed frequency source. Ion beams were extracted for the conditions listed in Table 4.

Differential control by variation of the accelerator grid voltage was investigated by manually increasing and decreasing the applied voltage in small increments. A positive beam current variation with increasing accelerator grid voltage was only observed to occur at high flow rates (>0.050mgs^{-1}) and RF power (>25.4W) implying high plasma density conditions. The maximum variation observed was not significant, equating to approximately 10μN-15μN. It was concluded that this method of differential control would not achieve the 1μN-150μN thrust range required for fine thrust mode.

It was observed during initial testing however that variation of the RF power on each end of the thruster could provide a method for differential beam control. Tests are ongoing to confirm whether differential control by variation of RF power will meet the requirements for fine thrust mode.

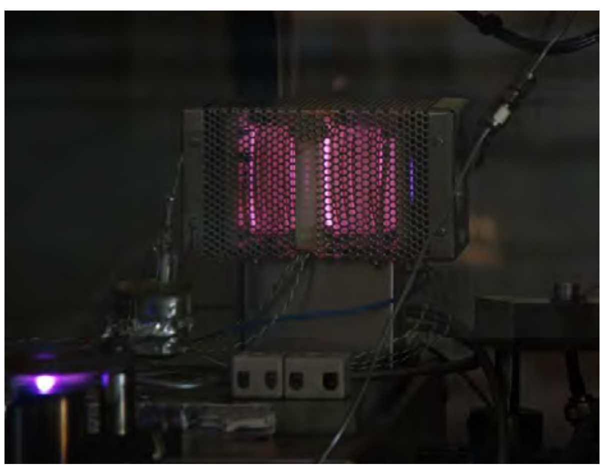

Figure 14. The MiDGIT breadboard thruster operating in differential mode with a hollow cathode neutraliser.

Flow rate	0.04 mgs^{-1} - 0.05 mgs^{-1}
Forward RF power	24W – 28W
Operating frequency	5.25 MHz
Beam potential	950V
Accelerator potential	95V
Background pressure	6.0 x 10^{-5} mbar

Table 4. Operating conditions of the MiDGIT breadboard during extraction of two stable ion beams.

IV. Conclusion

Prototype and breadboard models of the MiDGIT thruster have been tested to investigate design issues and provide verification of the concept of differential ion beam control for achieving very low thrust levels.

Single-ended operation of the thruster initially demonstrated thrust levels between 250μN-480μN and specific impulse of 600s–1100s, operating with non-optimal grid potentials. Maximum thrust, limited by direct ion impingement on the grids, was increased to 780μN by operating at a higher beam potential of 1300V and accelerator grid potential of 250V. Beam probe measurements identified that beam divergence was <15° for all thrust levels, even with low beam potential. The requirements for coarse thrust mode can not be achieved with the current configuration of the MiDGIT thruster. However, significant improvements in performance should be possible by operating the thruster with an optimized RF supply to minimize power losses and through further improvements to the grid design. Conventional RF ion thrusters have demonstrated suitable thrust ranges for coarse thrust mode[5]. It is therefore expected that minimal changes to the MiDGIT thruster should allow the requirements for coarse thrust mode to be easily achieved.

The extraction of two stable ion beams from a common discharge was successfully demonstrated for flow rates between 0.04 mgs^{-1} – 0.05 mgs^{-1} and RF powers <30W, operating at the same frequency as for single-ended mode. The MiDGIT thruster can therefore be operated with a fixed-frequency source. Differential control of the ion beams was initially investigated by independently varying the voltage supplied to each of the accelerator grids but it was concluded that this method of differential control would not meet requirements for fine thrust mode. Variation of RF power on each end of the thruster was observed to provide a suitable method and tests to confirm performance are ongoing. It is expected that coil geometry and discharge chamber length will significantly affect the efficiency of the MiDGIT thruster during differential operation and these are to be optimized.

Acknowledgments

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