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Development of a Differential Radio Frequency Ion Thruster for Precision Spacecraft Control

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A novel miniaturized gridded ion thruster is under development by the Electric Propulsion Group of QinetiQ in collaboration with the University of Southampton to provide a single propulsion system capable of providing both coarse and fine spacecraft control manoeuvres. The thruster concept is expected to provide sub micro-Newton thrust control and resolution by the differential control of opposing ion beams extracted from a common plasma discharge. A radio frequency inductive discharge is used as the ionization process. Prototype and breadboard models of the thruster have been manufactured and tested at the EP facilities of QinetiQ. Following discharge and geometry investigations, two simultaneous ion beams were successfully extracted at RF input powers between 45W - 50W and flow rates between 0.06 mgs^{-1} - 0.11 mgs^{-1}. Single-ended operation of the thruster enabled thrust levels of 200μN-480μN at RF powers between 22W – 29W and flow rates of 0.03 mgs^{-1} - 0.05 mgs^{-1}. Further analysis of thruster performance and investigations into the differential control of the ion beams continues.

Keywords: Ion thruster, radio frequency, inductive discharge, differential control, formation flying.

1. Introduction

The ability to fly spacecraft in precise formations will allow new possibilities in space science and exploration. Formation flying missions currently under study by the European Space Agency typically involve the simulation of very large virtual antennae or telescopes by mounting scientific instruments on several spacecraft but controlling the spacecraft to act as if they were a single, much larger instrument [1],[2]. Such use of constellations will enable significant improvements in resolution and sensitivity important for fundamental physics and deep space observations [3],[4]. Precision control of constellations will require very accurate, low thrust and low noise propulsion systems.

It has been identified that very low thrust levels in the 1-150 μN range with sub-μN resolution will be essential for the precise pointing of spacecraft for formation flying missions [5]. Additionally, higher thrust levels in the mN range will be required for orbital manoeuvres of the constellation. Thrusters will need to operate over long periods of time to offset constant solar pressure disturbances and therefore, it will also be important that thrusters provide high specific impulse to reduce propellant requirements.

The high thrust accuracy and low thrust noise of electric propulsion (EP) systems have made them attractive for formation flying missions. In general, EP devices generate thrust by either electrically heating gas which is then expanded through a nozzle or by using electrostatic or electromagnetic fields to extract and accelerate ions from plasma. A small number of miniature EP devices exist which are capable of providing the very small impulse bits at μN thrust levels required for precision attitude control [6],[7]. Due to a low thrust-to-power ratio however, they are not appropriate for mN thrust applications.

It is evident that multiple propulsive tasks can not currently be performed by a single propulsion system. A combination of cold-gas thrusters and miniaturized EP thrusters are often baselined for formation flying missions. Use of a single system would be important however for reducing system mass, complexity and cost. A need for a precision, low thrust micropropulsion device with a wide throttling range therefore exists.

A development program has been initiated by the Electric Propulsion Group of QinetiQ (UK) in collaboration with the University of Southampton to develop a novel miniature ion thruster with both precision and coarse propulsion capabilities. It has been proposed that an unprecedented throttling range and thrust resolution could be achieved through the differential control of opposing ion beams. The Miniaturised Differential Gridded Ion Thruster (MiDGIT) will be sized to achieve μN thrust levels through differential control but will also have the capability to be used as a single-ended thruster for mN thrust levels.

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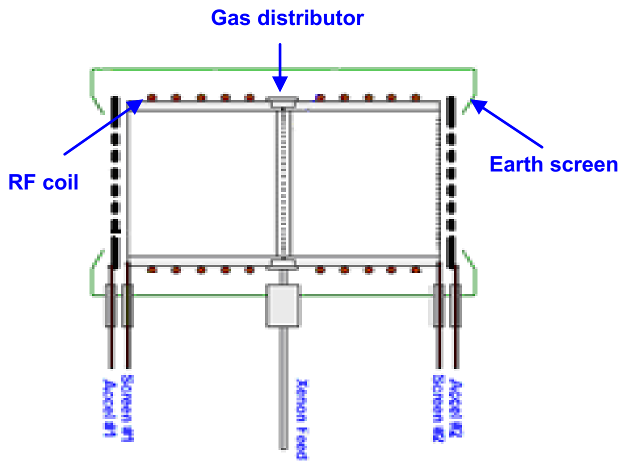

Figure 1. Schematic of MiDGIT discharge chamber.

This paper reports on the development of prototype and breadboard models of the MiDGIT thruster and continuing investigations into the differential control of opposing ion beams for precision thrust.

2. The MiDGIT Concept

The MiDGIT thruster is proposed as a sub-μN to mN thruster. Precise thrust levels up to several 10's μN are expected to be achieved through the differential control of opposing ion beams extracted through separate grid sets of a common plasma discharge chamber. It has previously been reported 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],[9]. 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. It is proposed for the MiDGIT thruster that ion beam current shall be finely adjusted by varying the voltage applied to the accelerator grid. Precision thrust may then be achieved by creating a net imbalance in the thrust generated from opposing ion beams. Higher thrust levels up to 1mN at high specific impulse will be achieved by blocking neutral gas flow to one side of the discharge chamber using a gating mechanism and exhausting out of the active end as for conventional single-ended ion thrusters.

A radio frequency inductive plasma discharge will be used for the discharge mechanism, as in conventional Radio Frequency (RF) ion thrusters. Inductively coupled plasma (ICP) discharges generate plasma with high electron density at low pressures without the need of internal electrodes [10].

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, consisting of a gas feed line, gas distributor and isolator, to be located centrally along a cylindrical discharge chamber. Xenon gas is used as the propellant. Two RF induction coils will be used; one located either side of the gas distribution system. An earth screen positioned around the RF coils and discharge chamber shields external components from electromagnetic fields. The extraction grid sets at either end of the thruster will consist of an accelerator grid and a screen grid. The screen grid will also double as an anode to collect electrons equivalent to the number of ions extracted. Measurement of the screen grid current will allow monitoring of the ion beam current.

The extraction and independent control of more than one ion beam from a common discharge has not previously been reported for an ion thruster. A key aim of this research is the verification of this principle. A good understanding of the discharge processes occurring within the thruster will be important.

3. Power Absorption and Discharge Modes of Inductively Coupled Plasma

The thruster will use an inductive discharge for ionization of the Xenon gas. Plasma density in inductively coupled plasma 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 respectively [10].

When varying RF power to an ICP, an abrupt change from a low-intensity plasma to a much brighter plasma is often observed [11]. The low density plasma observed at low power is generally attributed to stray capacitive coupling between the induction coil and plasma due to any potential difference existing between coil terminals. This discharge mode of an ICP is usually termed the 'capacitive' or 'E-mode'. On increasing RF power and source current, a sudden jump in plasma density and luminosity occurs. The discharge is then driven by true inductive coupling and this mode is termed the H-mode. The electron density characteristically increases by one or more orders of magnitude during an E-H transition, indicating a large change in coupling efficiency [11]. The production of a high density inductive plasma is essential for the operation of efficient radio frequency ion thrusters.

The power absorption of inductively coupled plasma can be related to the RF source impedance, current and voltage through a transformer model, with the plasma as a 1-turn secondary coil of an air-core transformer. This has been analyzed for a cylindrical ICP discharge by Gudmundsson and Lieberman [12]. They also coupled the transformer model with a global plasma model to calculate the minimum RF current required to sustain a discharge in the inductive mode [12]. They found that the field required to maintain a discharge increases with decreasing neutral gas pressure at low pressures (<100 mTorr) and increases with increasing pressure at higher pressure (>100 mTorr). The neutral pressure in miniature RF ion thrusters is typically <10 mTorr and it is important to optimize the neutral pressure in the discharge chamber through geometry of the thruster [13].

4. MiDGIT Thruster Development

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

4.1 Test Facility

Thruster characterization of both the MiDGIT prototype and breadboard models was performed within the loadlock chamber of QinetiQ's LEEP-1 vacuum facility. 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 x 10^{-6} mbar. Grafoil sheets were used as beam targets during ion beam extraction to reduce arcing and sputtering of the chamber. A SMA vacuum feedthrough was used for transmission of the RF lines.

RF power was applied by a radio frequency generator (RFG) consisting of an IFR 2031 (1-13 MHz) variable frequency signal generator connected to an Amplifier Research 75A250A 75W RF power amplifier. RF frequency and power were both controlled via the signal generator. A MFJ-934 antenna matching unit was connected between the signal generator and thruster to manually match the impedance of the RF signal 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 running on a local PC to log the signal frequency and total RF power (in dB) at a rate of 1Hz during thruster operation.

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 isolator mounting block, as displayed in Figure 2. A hollow cathode neutraliser was mounted to one side of the thruster for use during ion beam extraction. A 40W tungsten filament (not shown) was also mounted close to the thruster for use as an initial 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. Two Agilent floating digital multi-meters were used to measure the beam current.

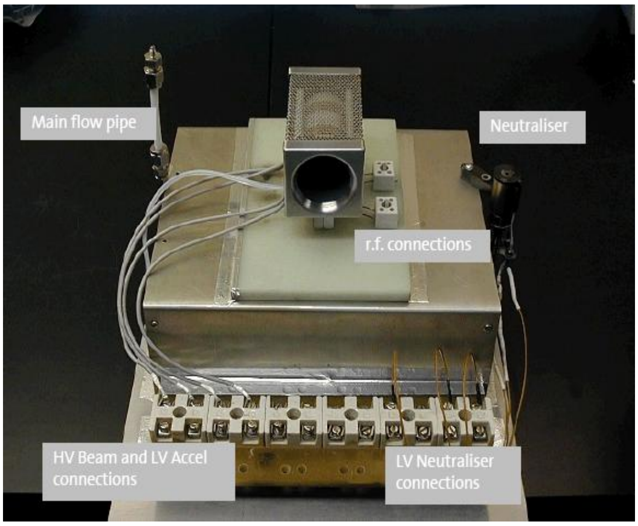

Figure 2. Mounting plate with attached neutraliser and flow pipes for the MiDGIT thruster.

4.2 Prototype Investigations

A prototype of the MiDGIT thruster was constructed to address early design issues by investigating different configurations for the thruster and to provide an indication of baseline performance. The prototype consisted of a 38mm OD x 70mm cylindrical alumina tube with two induction coils. The internal diameter of the discharge chamber was 33 mm. The gas feed consisted of a 3.2 mm diameter PTFE pipe. The two induction coils were connected in series for differential mode, whilst only one was powered for single-ended operation. The discharge chamber was manufactured in sections so that different gas distributor assemblies and blocking plates could be positioned in the middle of the discharge chamber for operating the thruster in differential and single-ended modes. Different coil assemblies could also be wound around the exterior of the discharge chamber for investigating coil geometry. The accelerator and screen grids each initially consisted of a 121 hole graphite grid. Discharges in the single-ended and differential modes were initially achieved at high flow rates of approximately 0.40 mgs^{-1} and it was found that RF powers greater than 50W were required to maintain a stable discharge in the differential mode. Neutral pressure within the discharge chamber is mainly governed by the grid open area. Therefore, a reduction in the number of holes in the screen grid was proposed to provide an increase to the discharge pressure within the thruster and therefore a reduction in the required flow rate.

The screen grid of the MiDGIT prototype was replaced with one of 37 apertures. The accelerator grids were not replaced due to limited resources. This configuration

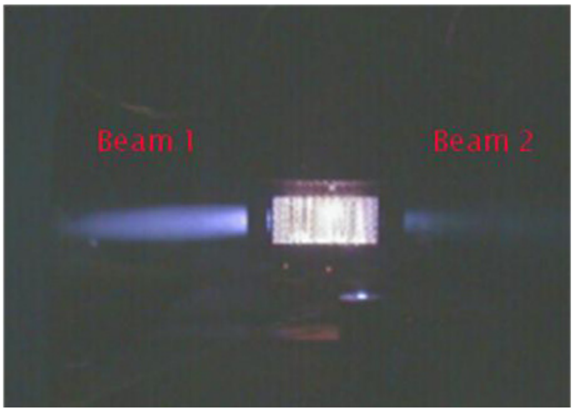

Figure 3. Image of two ion beams extracted in differential mode.

RF Power	45W – 50W
Flow rate	0.06 mgs^{-1} – 0.11 mgs^{-1}
Coil turns, N	6
Background pressure	5.0 x 10^{-4} mbar

Table 1 – Initial operating conditions for the MiDGIT prototype.

enabled the flow rate to be reduced to a minimum of 0.06 mgs^{-1} for a stable discharge in the differential mode. Power levels remained above 50W however.

The power absorbed by an inductive plasma can be related to RF source parameters through the transformer model. For a given power, it can be evaluated that $I_{rf} \propto 1/N$ and $V_{rf} \propto N$ [10]. To reduce the power levels for the MiDGIT prototype, the number of turns of each induction coil was reduced from 8 to 6, whilst the pitch was doubled from 1.8mm to 3.2mm.

Ion beams were then successfully extracted for both the single-ended and differential modes for the conditions listed in Table 1. The formation of homogenous plasma was found to be important for the extraction of two simultaneous ion beams from a common inductive plasma discharge [5],[14]. An image displaying the extraction of two ion beams from the MiDGIT prototype is given in Figure 3.

4.3 Breadboard Characterisation

The MiDGIT prototype model demonstrated the feasibility of extracting two ion beams from a common discharge but highlighted design issues concerning the performance of the thruster. These design considerations were incorporated into the design of a MiDGIT breadboard model.

The internal diameter of the discharge chamber for the MiDGIT breadboard was reduced 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 [14]. The discharge chamber was machined in three sections consisting of two main ionization regions and a central region incorporating the gas distributor. Ceramic shutter gates were machined from alumina that could be slid manually across the diameter of the discharge chamber either side of the distributor, as displayed in Figure 4. The two induction coils were wound directly onto the discharge chamber, each with 6 turns of copper wire and a pitch of 3.2mm. The screen and accelerator grids were each fabricated with 55 apertures. The ends of the thruster were labeled as in Figure 4.

Performance tests were performed on both ends of the thruster in single-ended mode. The results for the SE1 and SE2 modes were comparable.

Thrust was estimated from the beam current using:

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

where V_B is the beam voltage, m_i is the mass of a Xenon ion and e is the charge of an electron. Discharge conditions such as plasma density and beam voltage affect focusing of the extracted ion beam 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.

A plot of RF power against thrust for different flow rates is given in Figure 5 for the SE2 configuration. The results indicate that a thrust range of approximately 200μN–480μN can be achieved over the flow rates and power levels listed in Table 2 before direct impingement of ions on the accelerator grid occurs. Higher thrust levels up to 1mN will require a greater number of grid apertures and further optimization of the discharge to increase coupling efficiency.

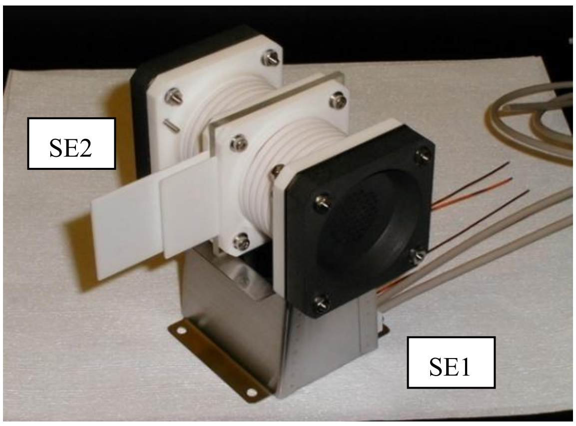

Figure 4. The MiDGIT breadboard model displaying manual shutters.

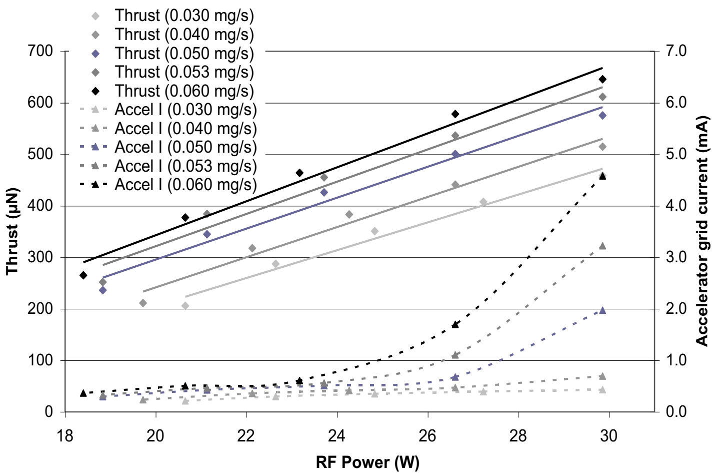

Figure 5. Measured thrust for different RF power and flow rates for the SE1 configuration.

RF Power	22W – 29W
Flow rate	0.03 mgs^{-1} – 0.05 mgs^{-1}
Coil turns, N	6
Thrust range	200µN - 480µN

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

Variations in measured beam current with varying accelerator grid potential are being analysed further alongside other performance data to determine thruster performance for the differential control mode.

5. Conclusion

Test campaigns on prototype and breadboard models of the MiDGIT thruster have recently been completed. Outputs from the prototype test stage led to the design of an improved breadboard model. Changes to the grid open area, coil geometry and gas distribution system were made. Characterisation of the MiDGIT breadboard showed a reduction in power and flow demand and early analysis indicates that for single-ended operation, thrust levels between 200µN-500µN can be achieved for flow rates of 0.03 mgs^{-1} – 0.06 mgs^{-1} and powers of 22W - 29W. The extraction of two stable ion beams from a common inductive discharge has been successfully demonstrated. Verification of the control of the two ion beams in differential mode by variation of the accelerator grid voltage requires further analysis.

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