Helicon Magnetoplasmadynamic (HMPD) Thruster Concept

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Abstract

A new MPD thruster has been proposed that is designed to postpone the transition to the inefficient and destructive "onset" condition. The thruster utilises a dual-stage design with a primary helicon ionization stage coupled to a secondary MPD thruster nozzle. It is theorized that this dual-stage approach will significantly postpone the "onset" condition during which destructive anode spots form, eroding the cathode and significantly reducing the efficiency of the MPD thruster. Preliminary results have indicated that it is indeed possible and advantageous to de-couple the two stages. It has been shown that in the presence of an external plasma the arc initiation voltage is significantly reduced compared to the arcing potential of the same configuration without an external plasma. It has also been shown that it is possible to increase the arc current in the presence of an external plasma by varying the density and electron temperature in the external plasma. Most importantly it has been identified that the mean free path of the external plasma is the critical factor affecting the coupling of the two stages. A mean free path smaller than the characteristic length of the thruster ensures that the external plasma will induce ionisation events between the electrodes of the arc, thus ensuring that the two stages are indeed coupled.

Nomenclature

J = MPD Arc Current
J_{th} = MPD Random Thermal Current
$\dot{m}$ = Thruster Mass Flow Rate
I_{sp} = Specific Impulse

I. Introduction

Magnetoplasmadynamic (MPD) thrusters offer a unique capability in the electric propulsion family, being able to provide both high thrust and high specific impulse (I_{sp}). The promise of this capability has been researched extensively[1,8] but there are a number of problems which prevent MPD thrusters from being used in current missions. The main problems relate to the propagation of instabilities in the thruster during operation. These instabilities have the effect of lowering the efficiency of the thruster as well as damaging the thruster surfaces.[6] It is the intention of this theoretical and experimental process to design a mechanism and/or process that prevents the onset of these instabilities. A further goal is to pursue a design that is more compatible with a variable mission role. The importance of the capabilites provided by the MPD family of thrusters should not be underestimated. The future of interplanetary manned and unmanned exploration will necessarily involve the use of electric propulsion sys-

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tems capable of higher and higher power levels. Due to the inherently low thrust density of Ion and Hall effect devices, it would be impracticable to use these types of thrusters beyond power levels of a few megawatts which corresponds to thrust levels of a few hundreds of Newtons. Even thrust capabilities of this size would require a large number of thrusters covering hundreds of square meters, the same power and thrust levels could be achieved with a modest sized MPD. For these reasons it is important that the current limiting factors of the MPD thruster be resolved in order to allow missions to be designed around the favourable characteristics offered by the MPD class of thrusters.

II. Limiting Aspects of Existing MPD Thrusters

It has been found that MPD thrusters suffer a critical instability that lowers their efficiency and operational lifetime. This problem arises primarily from the operation of the high power arc responsible for the thrust capabilities of the thruster.

A. Anode Erosion and "Onset"

It has been found in both MPD thrusters and normal arc discharges that the formation of anode spots, anode erosion and related instabilities, e.g. the kink instability, are responsible for significant efficiency and performance losses.[1] The anode starvation theory has some impetus[6] and it is believed that the $J^2/\dot{m}$ instability is due to spot anode attachment vapourising anode material. This material is then ionised by incoming electrons which in turn cause more anode erosion. The onset of this spot mode transition is believed to be when the ratio J/J_{th} exceeds unity,[6] where J_{th} is the random thermal current which is given by:

$$J_{th} = nq\sqrt{\frac{qT_e}{2\pi m_e}} \quad (1)$$

As this is the transition point we must increase J_{th} in order to prevent "onset". From Eq. (1) we see that we can increase either the plasma density or increase the electron temperature to increase the thermal current and delay the "onset" condition. The electron temperature and density are both related to the ionisation mechanism, mass flow rate ($\dot{m}$) and power balance.

B. Variable Mission Role

Both manned and unmanned interplanetary missions will require variable propulsive characteristics over the length of the mission. In the interests of reducing the complexity of mission design it would be desirable to be able to offer multiple capabilities in a single thruster. This would mean the ability to operate at both high thrust and high specific impulse modes. The current MPD thrusters do not achieve this goal and thus it would be desirable that we design the thruster to provide this capability.

III. Prior Research

There has been a great deal of research in recent years based around the helicon plasma source[2,3] The helicon plasma source is ideal as it offers a high density, high efficiency plasma source with excellent scope for a variety of thruster configurations. Existing work has focussed on the development of helicon sources[10] using magnetic nozzles (High Power Helicon), helicons using ICRH (Ion Cyclotron Resonance Heating)[7] (VASIMR) and helicons using a Lorentz-force current-sheet-interaction[5] (FARAD). The predominate design characteristic of these thrusters is the use of two independent stages coupled together to form a thruster. It is the dual stage design that allows the optimization of the plasma production and thrust stages, resulting in increased performance and efficiency of the thruster.

IV. Description of the Concept

This concept draws on the strengths of these previous designs, whilst introducing an entirely new concept. The helicon source is a mature plasma source and the extent of the current research on the helicon source has shown its suitability to the space environment. Unlike other designs which have introduced new thrust mechanisms, this concept utilises the well developed MPD thruster design. MPD thrusters can be imagined as a two component device providing ionisation and then thrust. In describing the MPD thruster in this way it can be seen that to choose the ideal ionisation conditions, irrespective of the thruster operating point, it is necessary to decouple the ionisation and thrust stages of the MPD thruster. By decoupling the two stages it is possible to ionise the propellant gas at a consistent ionisation condition, providing the thrust stage with this ionised propellant. The benefit of this decoupling offers two distinct advantages over the current designs.

1. The electron temperature and density can be manipulated by the ionisation mechanism in the primary stage. By altering the electron temperature and density in the ionisation stage it is possible to choose

the critical limit of the $J^2/\dot{m}$ ratio. In altering the plasma properties produced by the ionisation stage the thruster can operate outside the onset instability regime. This would allow a variable thruster operating point as well as ensuring the extended lifetime of the thruster by preventing anode and thruster erosion.

2. It is possible to choose the operating condition of the thruster by manipulating the plasma production, arc initiation and power balance. This allows the thrust and specific impulse to be scaled across a range of values to achieve operation for the appropriate mission regime. It is now unnecessary to consider the role of the plasma creation and thus it is possible to discharge the current that provides the requisite thrust while still obtaining the ionised propellant from the first stage of the thruster. The benefits gained are that the thruster will be suitable for a variable role on missions, switching from primary thruster (at high thrust values) to station keeping (at low thrust and high I_{sp} values). Using this analysis it is proposed to separate the ionisation and thrust stages of the MPD thruster into two physical stages (Fig. (1)).

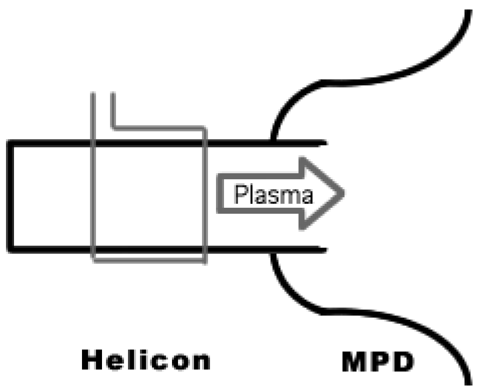

Figure 1: Design of a New Helicon MPD Thruster

A. Primary (Ionization) Stage

The present ionisation mechanism is a by-product of the geometry required to achieve thrust and, thus, is not optimised for the task of ionisation. Furthermore the ionisation conditions are determined by the thruster operating point. Higher thrust demands higher current flow and thus different ionisation conditions will prevail. At low power operation, where the MPD has shown significant inefficiencies, the arc mechanism may not be creating favourable ionisation conditions, leading to excessive power being lost in the creation of the arc, thus accounting for the low efficiencies measured. The first stage would be solely responsible for the creation of the plasma which would then flow into the second stage of the thruster. The first stage should be able to ionize the requisite percentage of the mass flow rate and as this stage does not contribute to the thrust we require that it be highly efficient. By limiting the power consumed in the primary stage the power to the MPD stage is maximized for a fixed output power supply. The logical choice for this primary stage is a helicon plasma source. The helicon plasma source has shown flexibility in operation over a wide range of power levels[2] and ionisation percentages. It is highly efficient and has been sufficiently developed[2,3] to pose minimal problems for its integration into this thruster concept.

B. Second Stage

The second stage utilises a traditional MPD thruster nozzle and is responsible for accelerating the plasma created in the first stage. Although Fig. (1) is simplistic it highlights the primary design considerations of the attachment of the secondary stage to the primary stage. The plasma flows out of the helicon into the MPD nozzle where it can be accelerated using the known MPD thrust mechanism. The outer rim of the tube coupling the primary and secondary stages is the cathode and the MPD nozzle is the anode. The geometry is almost identical to existing MPD devices except for the fact that the MPD is no longer responsible for the ionisation of the thrust medium.

V. Advantages of the Helicon MPD Concept

A. Prevent Onset

This design offers the possibility to prevent and/or delay the transiton of the arc discharge into the "onset" condition. The ability to create the plasma in the primary stage irrespective of the thruster operating conditions ensures that the desired plasma parameters can be obtained over the full operational range of the thruster. As shown earlier, if it is possible to manipulate the density and electron temperature values within the plasma, then the arc current density that will cause "onset" to be initiated can be determined. The use of a helicon enables us to attain a plasma with the required properties and thus "choose" the current at which "onset" will occur. By judiciously choosing the operating conditions of the thrust stages it is then possible to ensure that the thruster never operates in the "onset" condition and thus it is possible to use the MPD thruster effectively over a broad operational range.

B. Enhance Mission Effectiveness

The ability to "select" the operational plasma parameters has significant benefits for the operational capability of this thruster. In existing MPD designs the single operational point has meant that balancing the requirements of thrust, specific impulse and preventing "onset" has limited the capability of the design. By de-coupling the stages the operational conditions that allow us to balance the three requirements can be chosen. In achieving this it is theoretically possible to operate the thruster over a wide range of thrust and specific impulse values, which is of significant importance when choosing a thruster that maximizes mission effectiveness.

VI. Theoretical Analysis of the Concept

A. Helicon Plasma Production

The fundamental component of this concept is the flexibility of the helicon plasma source in the primary stage. The importance and necessity of the helicon ionization stage is as follows:

- Radial Electron Temperature Uniformity - It has been shown that the helicon discharge has a relatively radially uniform electron temperature distribution.[9] This uniformity ensures that the electrons moving into the MPD thrust stage have the characteristics required to delay the onset condition. From Eq. (1) it has already been seen that the higher the electron temperature, the higher the thermal current and thus the higher the thrust level before "onset" occurs. The radial uniformity means that helicon provides the best chance of preventing "onset" as there is a minimal low electron temperature tail. Measurements taken in the High Power Helicon (HPH) have shown that electron temperatures of between 5-10eV are possible. These temperatures are 3-6 times larger than the electron temperatures found in existing[6] MPD thrusters. This increase in electron temperature translates into an increase of 2-3 times the thermal current capability of existing thrusters, delaying "onset" by a significant margin.

- Radial High Plasma Density Uniformity - The density of the plasma created in a helicon also shows a uniform radial distribution. Once again this uniformity translates into a higher thermal current capacity in the thruster, which translates into higher thrust capacity before "onset" begins. Measurements on the High Power Helicon (HPH) have shown that the helicon is capable of achieving peak densities of $10^{21}m^{-3}$ and thus a uniform radial density of $10^{19}m^{-3}$ or $10^{20}m^{-3}$ should be attainable. Once again the peak densities found in such high power helicon discharges are at least an order of magnitude greater than the densities found in existing MPD thrusters[6].

- Axial Increase in Plasma Density - Previous research has shown that in a helicon discharge, there exists a downstream density peak.[4] The geometry of the primary and secondary stages can be optimised to place this downstream peak in the vicinity of the MPD arc. This increase in density will translate into higher thermal current limits in the MPD arc which again ensures a delay in the initiation of the "onset" condition. Although the downstream density peak has implied lower electron temperatures[4] in the downstream region, the geometry of the thruster can be chosen to give favourable values for both parameters.

- High Efficiency Ionization Mechanism - The ionization mechanism in an MPD arc is much less efficient than in a helicon, losing significant energy in collisional losses for each ionization event that takes place. Using a helicon results in reduced ionization losses which translates into more available power for the MPD arc, thereby increasing the thrust potential for a given power supply. It has been shown that approximately 200eV[9] of energy is required to ionise gas in an arc which is considerably more than the 30-50eV[9,10] required for a helicon discharge.

The High Power Helicon[10] is of significant interest and importance to this concept as it has already demonstrated plasma properties favourable to this thruster concept.

B. Onset Prevention

In examining the plasma properties of the High Power Helicon (HPH), the thermal current as a function of electron temperature and density can be plotted and this is shown in Fig. (2). The values for each parameter are well within the range expected of a helicon plasma source and show the capability of the dual-stage thruster to outperform its predecessor. The thermal current limits predicted by this graph are thus a good approximation to the thermal current limits in this dual stage thruster design. In existing MPD thrusters[6] the electron temperatures in the MPD are between 1-3eV and the plasma densities are of the order $10^{19}m^{-3}$-$10^{20}m^{-3}$. The High Power Helicon (HPH) can already provide a plasma that can increase the electron

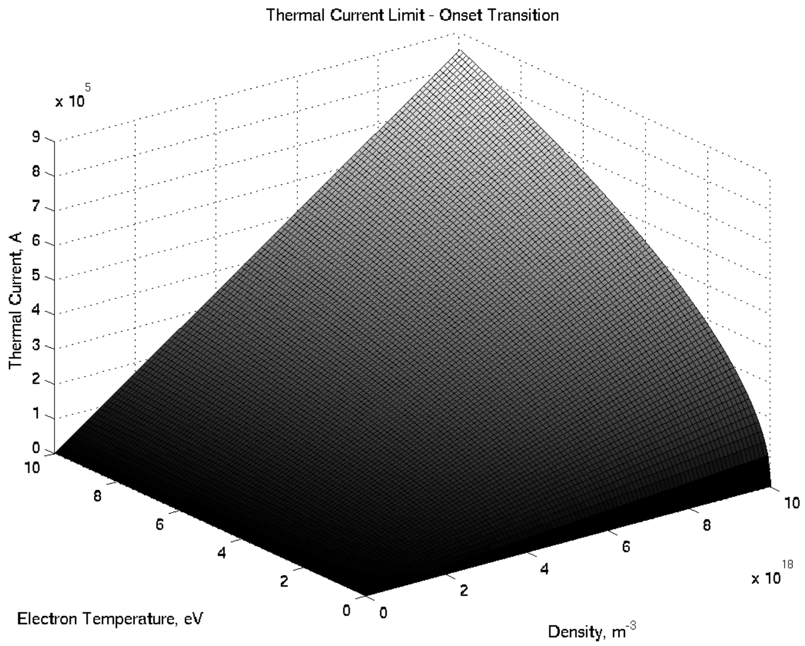

Figure 2: Theoretical Onset Transition Current

temperature by a factor of 3-6 and the density by a factor of 10.

C. Arc Formation

The arc formation process has been extensively studied and it has been shown that the formation of an arc is preceded by the formation of a glow discharge. The glow discharge forms at a certain sparking potential caused when the electron - ion flux is sufficient to induce the discharge. Similarly when the discharge transitions from the glow to an arc, it is a critical particle flux that induces the transition. Normally the particles are created by the application of a voltage to a neutral gas, thus inducing breakdown. In the design of the dual-stage thruster it is possible to remove the responsibility of the creation of the ion-electron particle flux from the MPD stage and rely upon the primary ionization stage. In providing the particle flux necessary for breakdown and arc initiation, it is hypothesised that the arc and breakdown initiation will occur at lower voltages and thus lower input energies. The lower input energy has important implications for pulsed mode MPD thrusters, by reducing the arc formation energy the arc will initiate sooner, increasing the thrust potential and reducing the pulse width to achieve the same thrust. Effectively the same thrust will be obtained using less power. Furthermore by initiating the arc at lower energies it is possible to operate the thruster in a lower energy mode.

This new design should alleviate the low power efficiency problems that have plagued existing MPD designs.

VII. Experimental Proof of Concept

It was impossible to determine the effect of this hypothesis directly as I was unable to gain access to an MPD, an helicon or a sufficiently large vacuum chamber. Therefore smaller experimental verifications were used to prove that the concept of a dual-stage MPD thruster is eminently feasible. The goal of the experimental component is to find the plasma parameters necessary for the successful coupling of the two stages, as well as showing that the arcing potential is reduced in the presence of an externally created plasma. It was also desired to show that manipulation of the plasma creation can be used to induce performance changes in the secondary stage. Without an MPD or helicon it is impossible to directly measure the effect of this concept on the "onset" transition. However, using the aforementioned experimental verifications, combined with the results from the High Power Helicon (HPH) there is no reason to think that this concept will not work as predicted.

A far more critical issue is the manner in which the two stages must be coupled in order to work effectively and it is this that will verified and analyzed.

A. Glow Discharge

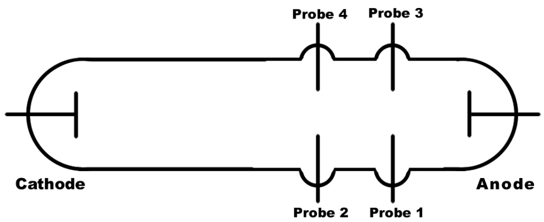

Figure 3: Glow Discharge Experimental Configuration

A glow discharge was used and is shown schematically in Fig. (3). Although the glow discharge is not an MPD arc it shares a commonality that allows direct comparison. The discharge tube is pumped down to a pressure of $\approx 10^{-3}$ Torr and a steady flow of nitrogen gas is admitted to achieve the desired pressure level. The anode and cathode are attached to a high voltage power supply capable of providing 3kV. A second high voltage supply capable of providing 5kV is attached between probes 2 and 4.

B. Reduction of Sparking Potential

The sparking potential between probes 2 and 4 was measured at varying gas pressure levels. A plasma was then initiated by the high voltage source at the anode and cathode and the sparking potential between the probes recorded, once again for varying gas pressure levels. As there is an external plasma the sparking potential should probably be referred to as the arcing potential and whilst the arcing and sparking potentials are different quantities, it is the relationship between their potentials that is of most concern. Whilst the glow discharge is a far cry from the high power arc in an MPD it provides a preliminary proof-of-concept. The geometry of the discharge is similar to that of the conceptual thruster, in that the external plasma is moving in a direction perpendicular to the direction of the arc. As can be seen in Fig. (4) the arc creation energy is lowered significantly by the presence of an external plasma. This result is as expected but is a powerful vindication of the concept. By lowering the sparking potential we have shown that the arc can be created more easily, with lower energy and at an earlier time after the pulse is initiated. By examining the Townsend breakdown mechanism[9] and the glow-to-arc transition,[9] it can be seen that they are governed by the point at which there are sufficient free electrons to carry a current between the electrodes. By passing an external plasma past the electrodes the ionization rate is increased, increasing the number of free electrons and thus reducing the potential required to initiate current flow through the plasma.

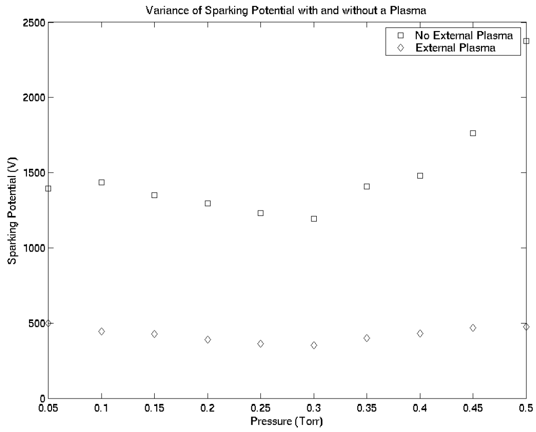

Figure 4: Sparking Potential with and without an External Plasma

C. Effect of an External Plasma on Arc Parameters

The second measure obtained from the glow discharge was the dependence of the current on the external plasma parameters. This is an important measure as it shows that variations in the plasma properties created in the primary stage can be used to manipulate the thrust and operational point of the second stage. This measure also highlights the variance in current capacity that can be achieved by manipulation of the plasma parameters, which goes some way to showing the benefits of de-coupling the thrust and ionization stages. In order to manipulate the externally produced plasma properties the creation voltage of the glow discharge is varied. When the plasma creation voltage is increased it is observed that a more intense discharge forms in the tube, signifying a higher density and/or higher electron temperature in the plasma. By fixing the probe voltage and the plasma pressure the current passing between the probes can be measured as the plasma density and electron temperature are varied. This is done for different pressures to show that the results are comparable across a wide range of pressure levels.

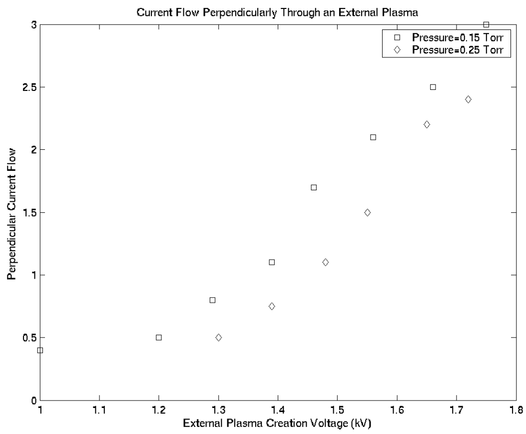

Figure 5: Current Flow between Two Probes Immersed in an External Plasma

In Fig. (5) it can be seen that as the density and electron temperature are increased, by an increase in the plasma creation voltage, the resistance of the plasma decreases and we obtain an increased current between probes 2 and 4. This result shows that as the density and electron temperature are increased, the ionization rate is also increased and combined with the increase in plasma density the number of free electrons has risen. This translates into larger discharge currents between probes 2 and 4.

D. A New Thruster

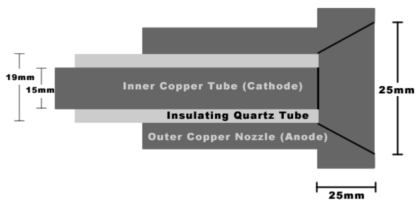

Figure 6: Cross Section of the Experimental "MPD" Thruster

Subsequently a hollow cathode plasma source was obtained and a small "MPD" thruster built. The thruster was essentially an inner copper tube that was isolated from the outer copper nozzle by a quartz pipe. The dimensions of the thruster were necessarily small due to the dimensions of the plasma source. The goal of this thruster was to show that the concept is feasible. The anode (outer copper nozzle) and the cathode (inner copper tube) were connected to a high voltage power supply capable of providing 5kV with a current of 10mA. This configuration (Fig.7) had the thruster mounted with the hollow cathode positioned in such a way as to inject a stream of plasma through the thruster.

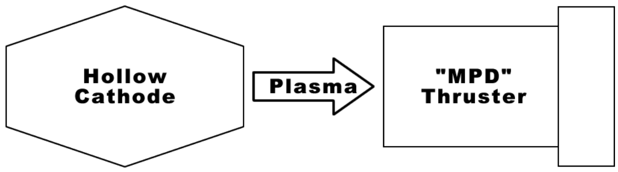

Figure 7: Experimental Configuration of the Thruster in Thrust Mode

Before the hollow cathode discharge was initiated it was found that the thruster would not form an arc. When the hollow cathode discharge was initiated the thruster was shown to arc when the pressure reached a level of 100 mTorr, which corresponded to a mean free path of about 30mm. The arcing was reasonably constant and reflected the fact that the presence of a plasma decreased the energy required to create the arc. The importance of this result is discussed in the next section.

E. Mean Free Path

When the plasma had a mean free path of approximately 30mm (the characteristic length of the thruster nozzle) it was noted that the externally created plasma reduced the sparking potential of the thruster assembly. Similarly in the glow discharge it was clear that an increase in the density and electron temperature of the discharge resulted in a significant decrease in the potential required to create an arc. When the current at varying distances in the glow discharge is measured it was found that an increase in distance resulted in an increased current. Our interpretation of this result is that the mean free path is the critical factor when coupling multiple stages. In the thruster test, the separation of the electrodes was small and the electron energies were high, resulting in a large mean free path. This means that the external plasma creates less ionisation in the vicinity of the electrodes and thus only contributes slightly to the formation of the arc. In the glow discharge the mean free path is smaller (1-2cm), due to lower electron energies and higher pressures and thus the external plasma is able to cause significant ionization in the vicinity of the electrodes, significantly reducing the potential required to create an arc. Using the same glow discharge shown in Fig. (3) the distance between the anode and cathode was varied by changing the probes that were connected to the power supply. The current as a function of separation distance is shown in Fig. (8). In examining Fig. (8) a linear correspondence between the current between the probes and the distance between them can be seen. Larger distances result in larger currents due simply to the fact that over a larger distance there are more electron mean free paths, resulting in more ionisation events and thus more free electrons and a larger current. These results imply that the ability to couple the primary and secondary stages is based on the mean free path of the plasma. By choosing a mean free path smaller than the characteristic length of the thruster it is possible to induce significant ionization in the vicinity of the MPD electrodes, which will result in the aforementioned advantageous behaviour of the thruster.

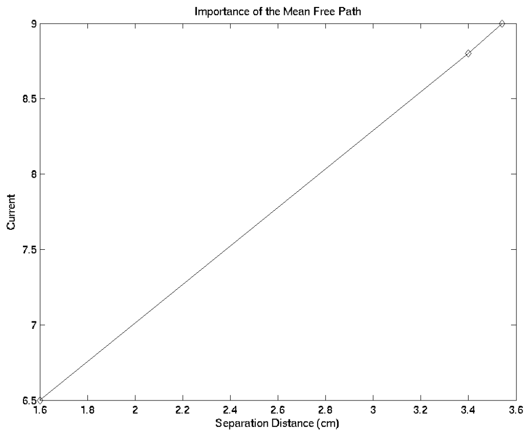

Figure 8: Importance of the Mean Free Path Parameter

VIII. Conclusions

A design for a modified MPD thruster utilising a dual-stage design has been presented. The dual-stage MPD thruster utilizes a primary helicon ionization stage coupled to a traditional MPD thruster nozzle. The following advantageous behaviour has been identified:

- The two stage design allows the plasma production to be optimised in the primary stage allowing an increase in the thermal current and thus the delay or prevention of the "onset" condition.
- Preliminary measurements have shown that the presence of an external plasma reduces the arcing potential of a given geometry and allows the current flow of an electrode geometry to be governed by the properties of the external plasma. This reduces the energy required to initiate the arc and allows the thruster to operate over a wide thrust range.
- The mean free path of the plasma in the primary stage has been identified as the critical factor affecting the coupling of the two stages. The mean free path must be less than the characteristic length of the thruster, smaller mean free paths will increase the efficiency of the coupling.
- These preliminary results provide evidence to support the feasibility of this concept, providing the possibility to increase the efficiency and delay the initiation of the "onset" condition in the thruster. The results also suggest the new design has made the thruster more suitable for variable mission roles.

These preliminary measurements now need to be translated into a thruster demonstration. The geometry for the thruster is not complicated and is based on meeting the requirements of the mean free path, downstream density and electron temperature and MPD arc geometry. The operational requirements are identical to those of existing MPD thrusters with the additional operational requirements of the helicon source, which are well understood.

IX. Acknowledgments

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