Magnetically Enhanced Vacuum Arc Thrusters for NanoSats

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Abstract. The implementation of a pulsed axial magnetic field to the plasma of a Vacuum Arc Thruster collimates the ions within the plasma plume which increases the thrust directed along the normal. The magnetic field is generated by a capacitive discharge coil which generates magnetic field strengths up to 50 mT (milliTesla). A first order numerical model was developed to determine if the influence of magnetic fields on ion density distribution could be predicted accurately. Numerical simulations using particle-in-cell methods show close correlation with experimental methods. The correlation between the experimental and numerical method for describing the plasma plume ion density distribution for various magnetic field strengths will be discussed.

1. Introduction

VATs use plasma propulsion techniques to generate thrust through vacuum arc technology. The highly ionized and directional plasma generated by the vacuum arc create minuscule, precise amounts of thrust. Vacuum Arc Thrusters (VATs) were originally studied in the 1960s-70s [1] and have regained attention due to the improvements in electrical and mechanical systems available today. The VAT may very well be the next major step in electrical propulsion systems that drive unmanned exploration into the solar system.

VATs have proven to be a a desirable method of propulsion to its low overall mass (¡ 1kg), low power usage (1 - 100 W), and implementation of low cost materials. These micro-thrusters have lower weight requirements due to the absence of propellant storage tanks and flow controls valves. The low weight requirements and high thrust efficiencies, in comparison to conventional combustion engines, make the VAT a desirable method of propulsion of nanosats. Nanosats are loosely defined as a satellite that weighs between 1 kg to 10 kg.

This paper introduces a study conducted in describing the effects of pulsed magnetic fields on the ion density distribution of VATs both experimentally and numerically. Understanding the influence of pulsed magnetic fields on ion density distributions allows for potential thrust improvements on current VAT designs.

2. VAT Design Theory and Performance

The VAT performance relies on a high current arc discharge between two metallic electrodes separated by a dielectric. The arc discharge between these electrodes is initiated by a momentary high voltage pulse triggered by a PPU (Power Processing Unit). Once the discharge is triggered, the high current arc vapourises and ionises the cathode material which accelerates into free space from the cathode spot in the form of a highly ionised plasma ([3]). Once triggered, the discharge is sustained. The acceleration of the plasma from these cathode spots (where the arc terminates on the cathode) results in an ejection of ions at very high speeds, on the order of 10^4 m/s ([4]).

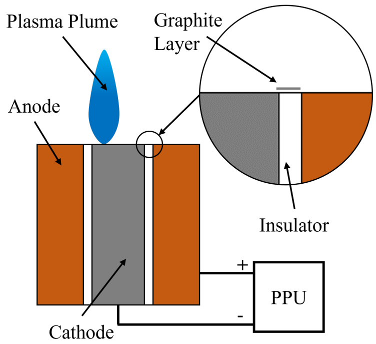

Figure 1. VAT Plasma

Two different research methodologies were applied; an experimental and a numerical simulation approach.

3. Experimental Approach

The Ion Density Distribution (IDD) about the central emission spot on the plasma was measured for various magnetic field strengths to quantify its influence on the IDD and thus the directional momentum properties of the ions within the plasma.

3.1. Thruster Design

The VAT design was based on a coaxial design, with a solid iron cathode rod placed within an alumina ceramic insulation tube surrounded by a solid copper anode ring (**Cu**), as shown in Figure 2. This design was implemented due to its high degree of symmetry along the centre line of the thruster. The generation of the initial arc between the cathode and anode was achieved by coating the surface of the insulator with a thin conductive graphite layer which provides a momentary path of low resistance between the anode and the cathode. When a relatively low voltage of several hundred volts is applied between the anode and cathode, breakdown occurs at minuscule imperfections along the conductive surface. These tiny discharges generate enough metal vapor to initiate a larger arc discharge. Once the main arc has been initiated, the metal droplets from the cathode redeposit on the surface of the insulator and thus replenish the conductive layer on the insulator surface. This method allowed for the vacuum arc thruster to operate between 3500 - 4500 pulses before the graphite layer had to be reapplied.

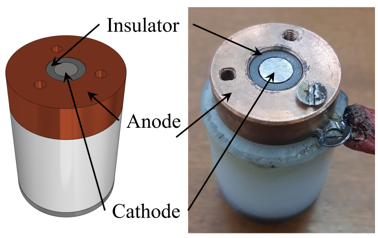

Figure 2. VAT Design

3.2. Experimental Electrical Setup

The VAT plasma was generated by a Power Processing Unit (PPU). A schematic of the PPU is shown in Figure 3. When designing the PPU it was important to generate a reliable circuit capable of creating high density vacuum arc discharges with long discharge periods (2.0 - 2.5 mS). The operation of the VAT discharge was dependent on several circuit parameters, namely the capacitance and inductance of the components used within the circuit. A range of circuit parameters were tested, such as the capacitance, inductance and supply voltage. A more capacitive circuit produced greater reliability in triggering and thus it was decided that the inductance would be approximately 50 μH.

The inductance was generated with a toroidal inductor with a ferrite core. When testing the capacitance, it was decided to use a capacitance of 1.1 mF. The pulse length and pulse frequency was controlled with a standard microcontroller with a high voltage insulated-gate-bipolar-transistor (Infineon IRG4PH50SPBF IGBT).

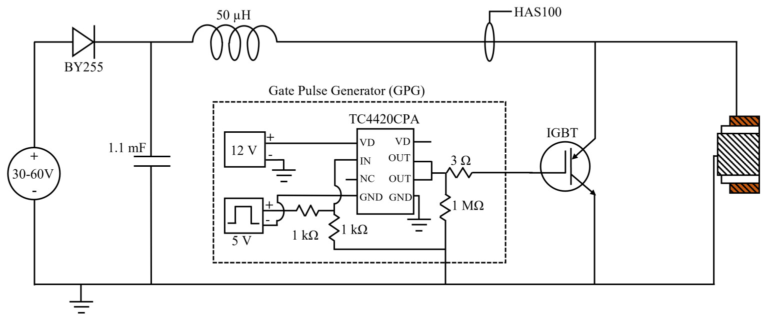

Figure 3. Power Processing Unit circuit

The implementation of a pulsed magnetic field was achieved with a capacitive discharge circuit capable of generating high currents through a magnetic coil, see Figure 4. The circuit was designed to discharge the built up charge through the coil for a desired pulse length. An important aspect of the design was the ability to control the pulse length of the magnetic field to ensure that the plasma discharge experiences a constant magnetic field during the arc discharge. The magnetic field coil was then placed around the VAT such that the plasma experienced the greatest magnetic field induction through the centre of the coil.

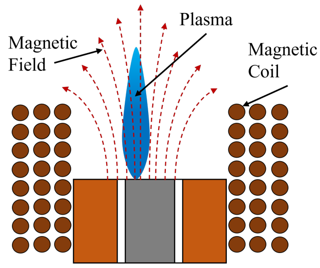

Figure 4. Magnetic coil

3.3. Ion Density Distribution Measurements

The IDD was measured using a Faraday cup probe within the low pressure vacuum chamber. The main purpose of the Faraday cup probe was to measure the ion density distributions at various angles about the plasma and at various distances from the plasma, as shown in Figure 5. These measurements would provide insight into the the ion distribution and the shape of the thrust-producing plasma plume. The determination of the IDD allowed for a detailed description on the extent to which the magnetic field deflects the ions within the plasma.

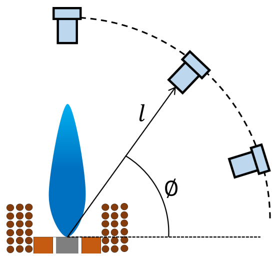

Figure 5. Faraday cup setup

4. Numerical Simulation

In addition to the experimental approach, a numerical first-order, particle-in-cell (PIC) model was developed. This particle in-cell-model was used to determine whether a numerical algorithm could be used to predict the ion density distribution of a VAT plasma. As a first order approximation, the effects of self-consistent electromagnetic fields were assumed to be negligible, as well as any particle-particle collisions. The model generates particle positions which follow a typical cosine distribution which has been experimentally validated [5]. For a cosine distribution in polar coordinates, the current density at a radius, l, and angle, ϕ, defined from the surface normal of the cathode surface due to mass generated in area dA on the surface is:

$$j_{ip}(l,\phi) = \frac{j_{ic}\cos\phi}{\pi l^2} dA$$

where $j_i c$ is the ion current flux from the cathode surface.

Once the particles had been generated and placed within the simulation domain, a Boris particle push was performed. The Boris method is the de facto standard for particle pushing in plasma physics codes. This method is phase space volume conserving which is used to advance a charged particle within electromagnetic fields. To conserve momentum throughout, appropriate boundary conditions were chosen. Particles which had been pushed passed a specified distance were re-injected into the simulation domain at the cathode spot with its original starting orientation. This ensured momentum conservation and allowed the model to reach stability once each particle had been re-injected into the domain.

5. Results

5.1. Experimental Results

When conducting the experiment, two significant measurements were taken, the arc discharge current I_{arc}, measured with a high current transducer, and the ion current I_{ion}, measured with the Faraday cup probe. The ion current was used to describe the ion density distribution about the plasma emission spot. These measurements were taken simultaneously with a sampling rate of 200 MS/s. Figures 6 and 7 show a typical measurement result. The behavior of a vacuum arc discharge is inherently stochastic, hence a general pulse averaging scheme was implemented over a series of 128 consecutive pulses. The ion current readings are proportional to the arc discharge current (typically 10% of the arc discharge current[6]), and thus it was important to normalize the ion current with its associated arc discharge current. As can be observed in Figure 6, the arc discharge current is constant throughout all measurements taken for various angles. After performing a statistical analysis of the experimental results it was found that there was a maximum standard deviation of $\sigma = 14.802$ A and a maximum standard error of $SE = 0.6436$ A and a maximum percentage error of 1.26%. However, as the angle about the centre line of the thruster increases, the ion current measurement decreases significantly, see Figure 7. This suggests that the majority of the ions emitted from the cathode spot are directed along the centre line of the thruster. The experimental procedure was then repeated after introducing the magnetic field intending to collimate the ions along the center line.

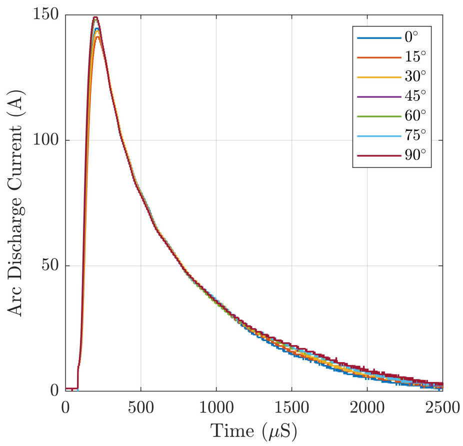

Figure 6. Arc Current measurements

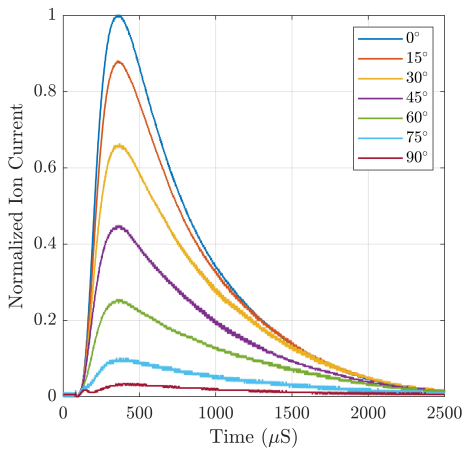

Figure 7. Normalized Ion Current

By normalizing the results of the magnetised ion current to the unmagnetized ion current, we saw the ion distribution is significantly influenced by the magnetic field, as shown in Figure 8. The variation in distribution is relatively low between magnetic field strengths of 20-50 mT, however with a significant increase in all peak ion distributions in comparison to the unmagnetized distribution. The magnetic field results in an increase in ion distribution at low angles and a decrease in ion distribution at higher angles. There is a major deviation from the theoretical distribution around 45 degrees. This deviation is as a result of the magnetic coil obstructing the path of the ions emitted from the cathode spot.

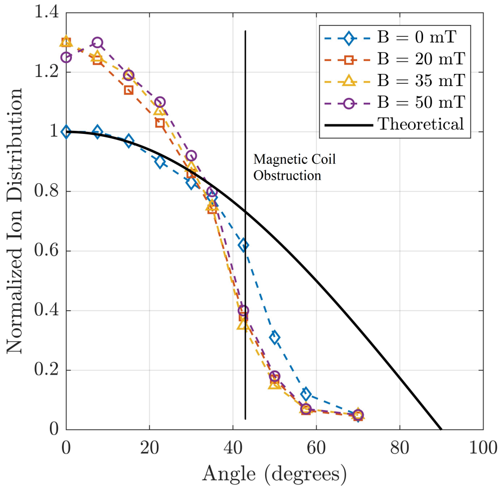

Figure 8. Ion Current density for given angles about the plasma plume

5.2. Numerical Simulation Results

With the application of a 50 mT magnetic field, shown in Figure 10 there was a significant increase in ion collimation along the normal. It was then possible to quantify the density differential as a result of the magnetic field using the unmagnetized plasma in Figure 9.

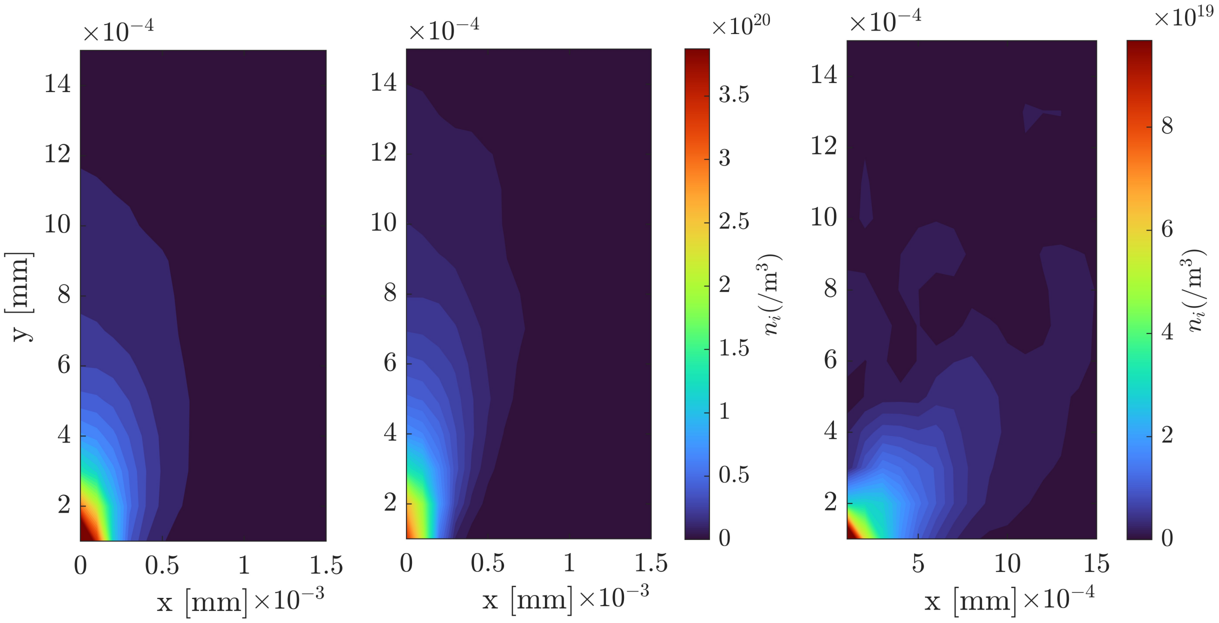

Figure 9. Unmagnetized Plasma

Figure 10. Magnetized Plasma

Figure 11. Density Differential Contour

A significant difference can be found near to the cathode spot and at the edge of the plasma plume, as shown in Figure 11. The difference at the edge of the plasma plume is a result of the magnetic field having a greater influence on the ions with a velocity vector parallel to the centre line of the plasma plume. Using these results, it was then possible to compare the simulated results with the results obtained from the experiment. When comparing the experimental and numerical simulation results in Figure 12, the unmagnetized distribution correlates closely with the theoretical curve, with the exception of high angles where there is a more gradual drop in ion density. The magnetised distribution, however, follows a similar trend to that of the experimental distribution despite having a lower peak ion density closer to the centre line. These discrepancies could be attributed to several factors. The particle motion is dependent on the mass and charge of the ions. These variables are inherently arduous to determine for any given material, and ion mass and charge selection within the simulation which may have resulted in this error. Additionally, due to the negated parameters within the study it is possible that the self-consistent electromagnetic fields may cause a higher electric potential closer to the cathode spot which would result in particles being subjected to an increased acceleration due to like-like charge interactions. Thrust coefficients were used to quantify the amount of thrust produced by the ions along the centre line. An unmagnetized VAT was found to have a thrust coefficient of 0,67. The VAT magnetized with a field strength of 50 mT resulted in a thrust coefficient of 0,7.

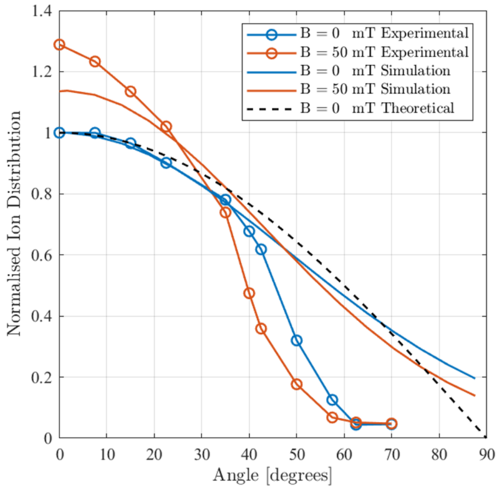

Figure 12. Experimental and numerical ion density distribution results

6. Conclusions

A study on the influence of pulsed magnetic fields on ion density distributions was conducted through experimental and numerical methods. It was observed that the magnetic field has an effect on the overall ion density distribution. The numerical model closely follows the trends obtained from the experiment, however discrepancies exist in peak ion distributions at higher angles. The increase in ion density distribution along the centre line results in the collective momentum of the emitted ions within the plasma being shifted along the normal, resulting in an increase in overall thrust. This proves that the introduction of a pulsed magnetic field to the VAT plasma plume results in an increase in thrust. Further studies should be carried out to determine the effects and extent thereof of the mass and charge assignment of the ions in the simulation. The possibility of reducing any error whether by including the self-consistent electromagnetic fields within the numerical simulation can also be explored.

7. References

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