Micro-Cathode Arc Thruster Development and Characterization

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The performance of the micro-cathode arc thruster (μCAT) and coaxial micro-cathode arc thruster (CA-μCAT) have been investigated. In particular, mass consumption rate of these thruster variants was measured. Using the mass consumption rate, the specific impulse of the μCAT was calculated from the thrust data and compared to the ion velocity measurements. This comparison suggests that plasma plume is highly ionized. Moreover, two thruster performance have been compared. The potential application for both thruster have been discussed in the paper.

Introduction

Micro-cathode arc thruster (μCAT) is a micro-Newton level vacuum arc propulsion system has been investigated and studied, which has been known as its compatible for nano-satellite applications due to its low operating voltage, low mass, and its simplicity to be integrated into the spacecraft operating system[1,2]. In general, the μCAT vacuum arc is established by using tubular ring geometry with a same inner diameter anode and cathode separated by insulator[3,4,5,6]. With adding directional magnetic field on μCAT, an expected cathode spot motation in the azimuthal direction has been found[4,5] which is critical for cathode metal uniform erosion of cathode material.[4] Moreover, the drift speed of 40000 50000 ms^{-1} at 0.3 T magnetic field was measured and dependences of thrust and total ion output on the magnetic field strength[4,5].

The magnetic field dependent is that the cathodic plasma expands away from the cathode in a direction normal to the surface; the plasma will be trapped inside of the thruster channel. The magnetic field could increase of thruster output and thrust due to the plasma flow transformation into the axial flow. While it has to be point that the thrust increase not only depend on the total output, also caused by increase of ion velocity by magnetic field. However, apart from the transportation effect caused by magnetic field, a approach have been tried to increase the total ion output and thrust without being limited by geometry.

A new coaxial thruster geometry with a relatively small diameter anode which is surrounded by an insulator and a cathode was designed namely coaxial micro-cathode arc thruster (CA-μCAT). The plasma spark was generated in the edge of the cathode and insulator surface, without being blocked by the channel of thruster itself. In this paper, performance of μCAT and CA-μCAT were characterized. Measurement of cathode mass consumption rate was measured as function of magnetic field for both μCAT and CA-μCAT and performance characteristics of these thruster variant were compared.

I. Experimental Details

A. Thruster Design

The schematics of the μCAT and CA-μCAT is shown in Figure 1. The Figure1 (a) shows the schematics of μCAT equipped with tubular titanium electrodes aligned in axial direction. Electrodes are separated by 1mm thickness ceramic ring. Figure 1 (b) shows the schematics of the CA-μCAT in which the tubular titanium electrodes are place in concentric annulus direction separated by a 1.5 mm thickness insulating tube. For both design, the insulators surface were coated with carbon paint with resistance on the order of 1-10 KΩ in order to initiate the arc. Following pulsed are based on triggerless concept due to thing film deposition during the arcing as described in[7,8] Furthermore, the cathode tube (titanium electrode) is pushed by spring which works as two mainly functions. First, it is design for a simple and a robust feed mechanism which spring will push the cathode tube forward when the discharge etched the cathode tube material. Second, spring is connected to the power process unit to apply negative potential to the cathode electrode.

As shown in Figure 1, magnetic field coil and magnetic core are mounted outside of the electrodes to provide specify distribution magnetic field. The coil is designed to use 0.5 mm diameter copper wire winded up to 700 turns. It is co-axial with the electrode axis and a magnetic core (steel 1020) has the shape of a washer with a thickness of about 2 mm in attempt to generate special distribution magnetic field. In the previous works in[3,4] it has been notice that magnetic field plays a critical role for efficiency of plasma plume transportation process of in μCAT. More experiment details will be discussed about the magnetic field effect on CA-μCAT in the following chapter.

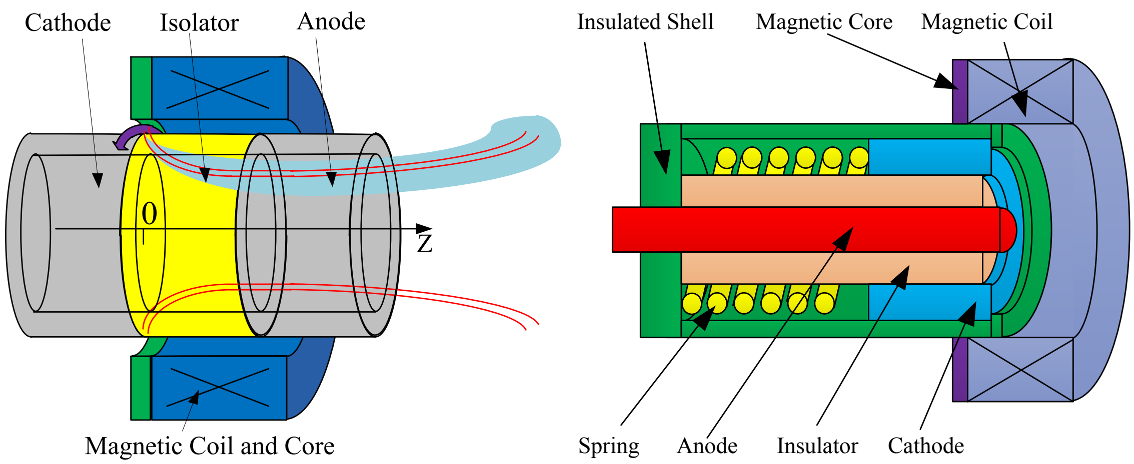
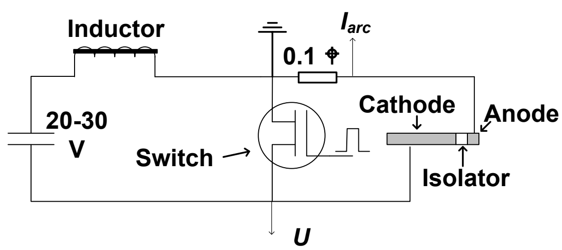


Figure 1. Schematic of micro-cathode arc thruster (a) and concentric co-axial micro-cathode arc thruster (b).

B. Power Supply

An inductive energy stores system has been designed to as power process unit (PPU) for the - μCAT and CA- μCAT. The Figure 2 shows the schematic of the PPU. When the PPU semiconductor is transistor a triggered pulse of about LdI/dt will be apply between the electrodes. This leads to a breakdown and arc discharge between the electrodes. More details about PPU please see Ref,[3] Anders1998.



In order to produce a low mass system, the Power Process Unit was constructed using a embed micro-process unit as shown in the Figure 3, a programmable AT MEGA328 chip is used to generate drive pulse for both thruster and magnetic field coil. The total size of driver system (without inductor) is 0.8×0.8×1.5 inch as shown in the Figure 3 almost same size of quarter coin. In the PPU, the IGBT switch that could survive with maximum current 120A and voltage 1200V was used. By varying the length of the trigger signal, the whole programable system could control the level of the current in the switch and thereby the energy stored in the inductor can also be adjusted. Obviously, varying the input signal as well can change the repetition rate of the individual pulse.

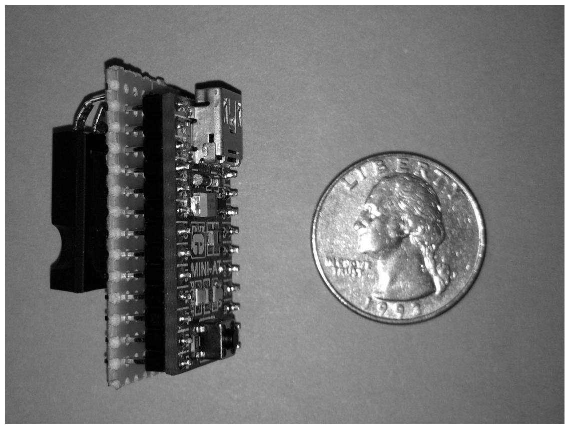


Figure 3. Power process unit with embed programable system. The dimension of system is 0.8×0.8×1.5 inch.

II. Thruster Performance

The new configuration of CA-μCAT design is based on the previously development of the μCAT. It is known that the cathodic plasma expands away from cathode in a direction normal to the surface. In particular case of the μCAT, (see Figure 1), the cathodic plasma expands away in a direction normal to the inner surface of the cathode tube. In order to change the plasma expands direction into axis direction, a magnetic field was applied to transport the plasma and increase the total output of the thruster. The Figure 4 shows the average ratio of total ion current over the arc current. One can see that with increase of magnetic field, the ratio increase significantly to around 3.5% which corresponds to the efficiency of cathodic jet transport through the thruster channel of about 45%.[5] On the other hand the new configuration of CA-μCAT is designed in a coaxial direction in which the plasma will expands in normal to the surface of the insulator. Comparing the geometry shown in Figure 1 of μCAT and CA-μCAT, one can notice that the new geometry will not be limited by the plasma transportation effect of magnetic field. The Figure 5 shows the average ratio of total ion current over the arc current for CA-μCAT. In fact, one can find that the ratio of ion current over the arc current keeps constant which around 3.5% which is the maximum ratio of μCAT with maximum magnetic field. The ratio of total ion current over the arc current does not depends on the magnetic field for new configuration of thruster.

Ion velocity measurements (using the initial peak method as described in Ref[5]) as a function of a magnetic field were performed. It was found that the magnetic field leads a increase the ion drift velocity from 20 km/s to about 50 km/s. The Figure 6 and Figure 7 show the average drift velocity of μCAT and CA-μCAT. It is clearly seen that the average ion velocity increased 3-4 times with the added magnetic field of 0.3 T when comparing to the 0T magnetic field. Moreover, the ion velocity is around 2×10^4 m/s in the case of 0 T magnetic field, which is typically velocity (cathode electrode material is Titanium) at 0 T magnetic field coincides with the experiment data in Ref.[9] Thus both thruster variants exhibit the dependence of the ion velocity on the magnetic field.

Cathodic material consumption rate has been measured by a high accurate mass balance with the accuracy of about 0.001mg. Thrusters were fired around 20000 pulsed at each magnetic field strength. The mass

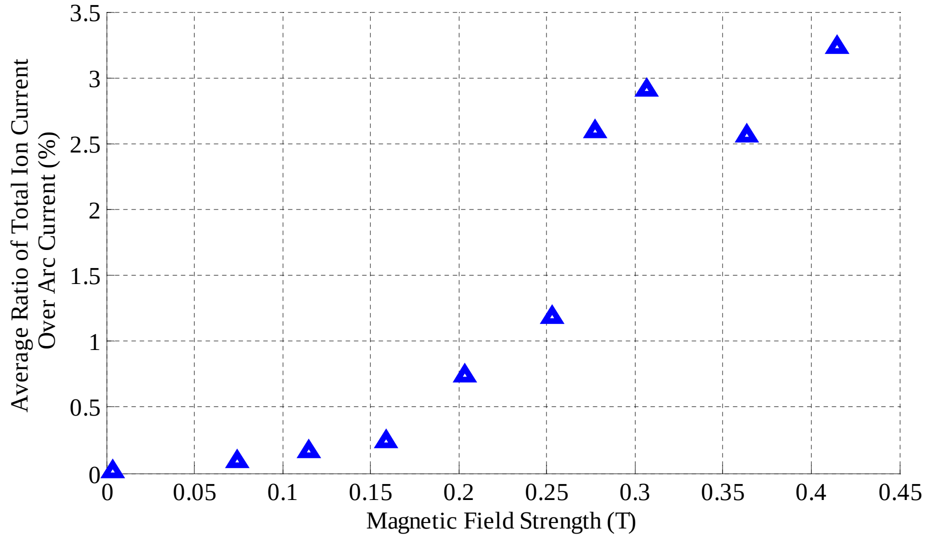


Figure 4. Average fraction of total ion current over the arc current with different magnetic field for μCAT.

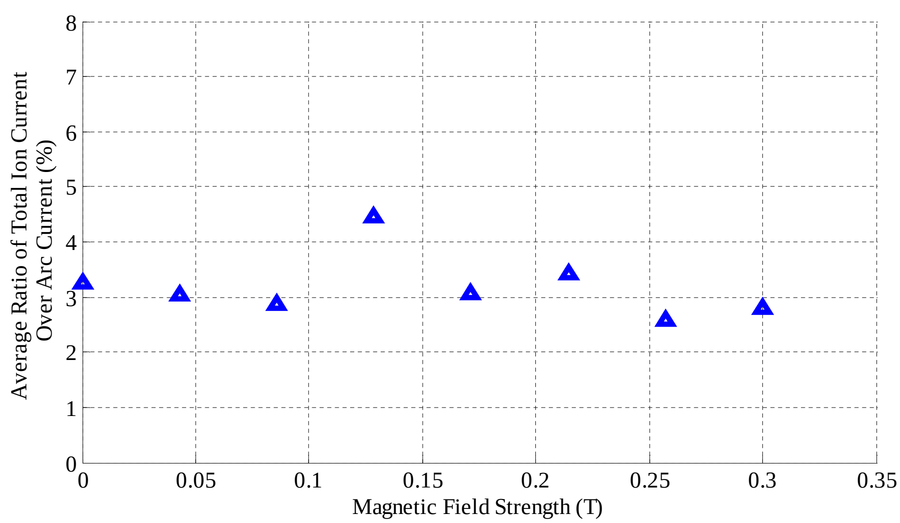


Figure 5. Average fraction of total ion current over the arc current with different magnetic field for CA-μCAT.

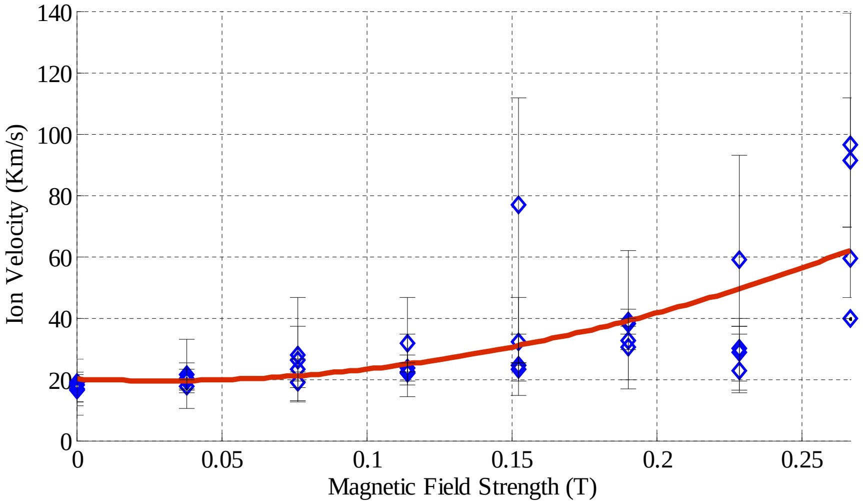


Figure 6. µCAT average ion drift velocity with different magnetic field applied, which measured with four grids initial peak method.

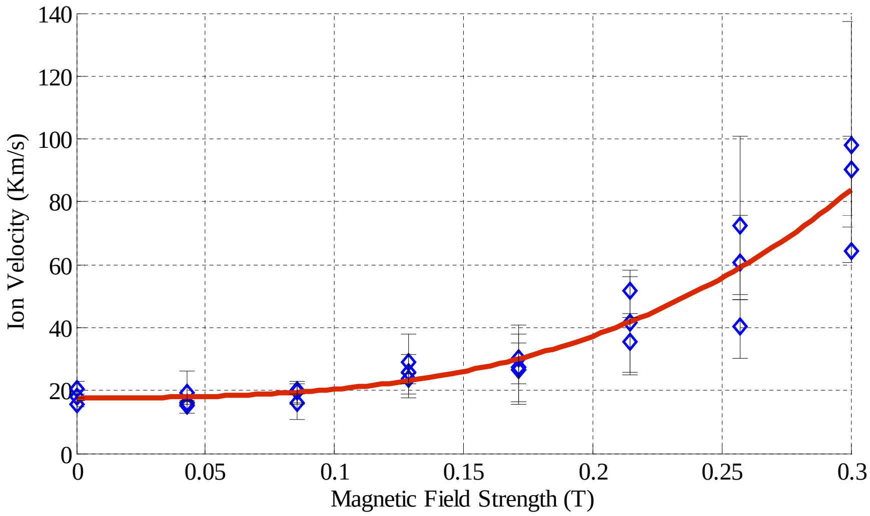


Figure 7. CA-µCAT average ion drift velocity with different magnetic field applied, which measured with four grids initial peak method.

changes have been recorded to build a function between the average cathodic material consumption rate and magnetic field strength. The arc current was recorded to compare the performance for two thrusters to be used to calculate the mass consumption per charged Coulomb. Generally, cathodic material consumption rate in proportion to the arc current. The Figure 8 shows the thruster cathode material consumption rate, which plotted with different magnetic field strength.

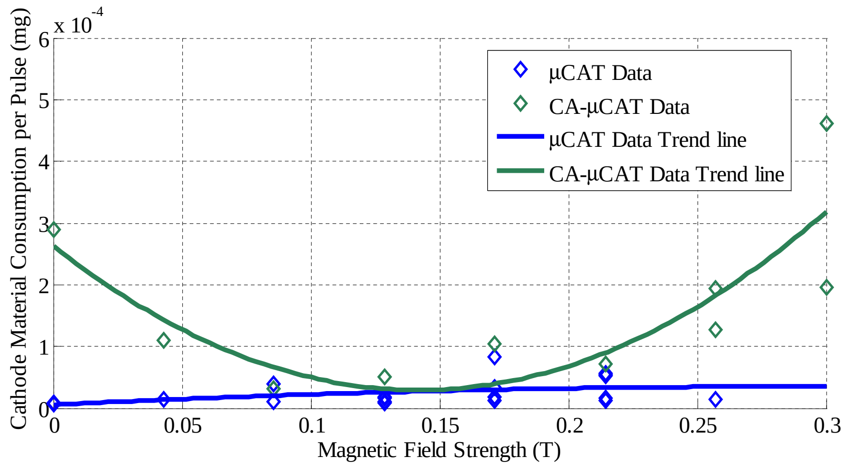


Figure 8. μCAT and CA-μCAT cathode material consumption rate with different magnetic field strength.

From Figure 8, one can notice that, μCAT cathode mass consumption rate increased around 6 times with increase of the magnetic field strength. The increase of mass consumption rate could be explained by increased plasma transport along the magnetic field. In the CA-μCAT variant, magnetic field is not required for plasma transport as shown above. This leads to a different dependence of the mass losses with respect to the magnetic field.

The Figure 9 shows the cathode material consumption rate per charged Coulomb.

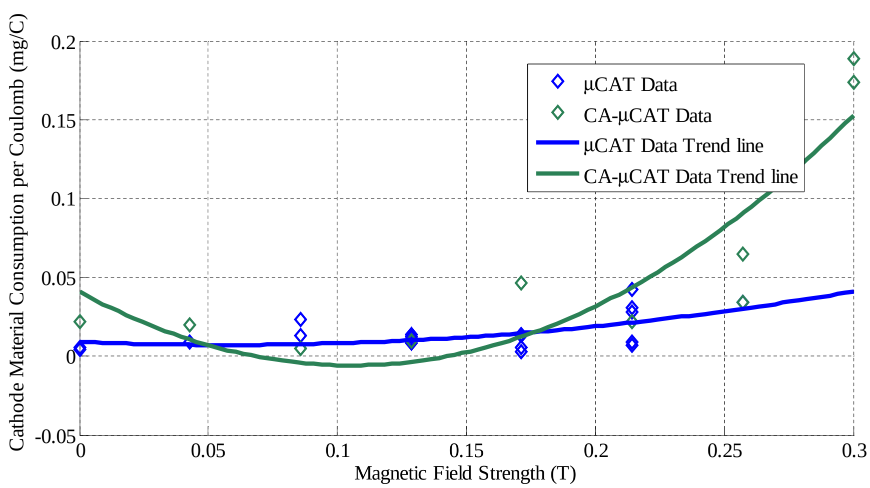


Figure 9. μCAT and CA-μCAT cathode material consumption rate per charged Coulomb.

Using the experimental data for thrust (See Ref[6]) μCAT velocity was calculated as shown in the Figure 10. Compared with the direct velocity measurement of μCAT as shown in the Figure 6. The ion drift velocity was close to that measured directly and in the Figure 6.

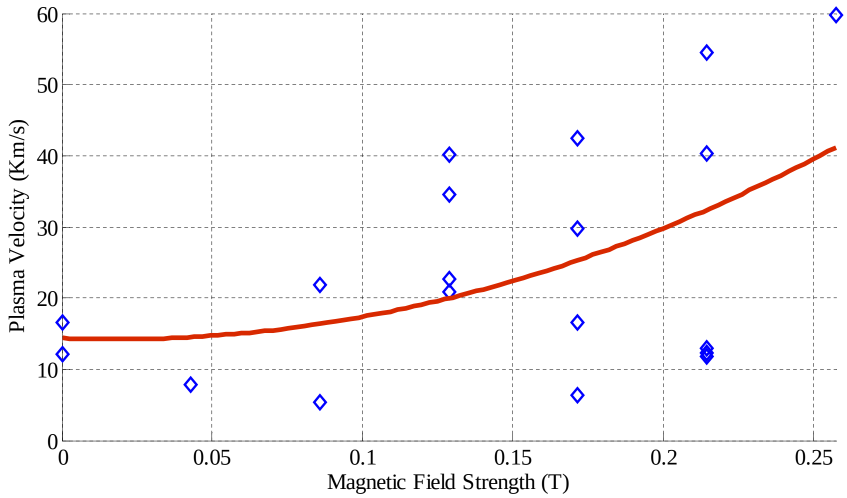


Figure 10. Basing on the thrust data and mass consumption data, the ion drift velocity was calculated using the equation of $Vion = Impulse/Mass$

The comparison demonstrate that plume accelerated by the μCAT consist of ions mainly.

III. Conclusions

The performance of two types thruster have been discussed in this paper. The new configuration of CA-μCAT was designed and it was shown that magnetic field is not required for efficient transport.. Plasma velocity measured by time of flight technique and derived from thrust and mass consumption measurements suggest that plasma jet is highly ionized plasma. A further work will focus on the direct thrust measurement and efficiency study. Nevertheless, both design already proved to be good candidates for micro-Newton range thruster for cube-satellite.

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