Paper # SSC13-VII-9

Micro-Cathode Arc Thruster for PhoneSat Propulsion

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ABSTRACT

The George Washington University (GWU) has developed a CubeSat-class thruster called the Micro-Cathode Arc Thruster (μCAT). The μCAT is a high Isp (2000-3500s), solid metal fueled, low average power (<0.1 W when operating) micro-thruster of small cross section (5 mm), with a mass of less than 200g, and no pressurized tanks. Electric current forms a plasma discharge between a concentric cathode-anode configuration. Thrust is produced through arc discharge, eroding some of the cathode material in a uniform manner, to exit at high velocity, during which it is accelerated through the nozzle by a Lorentz force. Thrust can be controlled by varying the frequency of pulses, with a demonstrated range to date of 1-50 Hz, (1 μN - 0.05 mN). The μCAT design achieves uniform electrode erosion, and has demonstrated over two months of continuous operation during trials. The system operates at low voltage, accepting unregulated DC power from the spacecraft bus. The corresponding exhaust plume is 99% percent ionized, with near zero backflux. NASA Ames Research Center and GWU are investigating applications of μCAT sub-systems for attitude and orbit correction of a PhoneSat spacecraft.

INTRODUCTION

Vacuum arc discharges that ablate and consume cathode material in a vacuum produce fully ionized plasma jets having high velocity. Such devices have been investigated for propulsion applications since the 1960s (see the 1, 2 review paper and references therein). Metal plasma is formed at the cathode spots with highly directional velocity normal to the cathode surface[3]. The exhaust speed is on the order of 10^4 m/s and thus can be used as a propulsion source directly[4]. The unique physical conditions achieved in vacuum arcs offer several potential advantages of these devices[5]. Due to the solid propellant being used, a gas feed system becomes unnecessary. This simplifies the thruster design significantly and decreases the thruster mass while also avoiding the possibility of gas leakage that could decrease the thruster efficiency[6]. The plasma generated in the cathode spot is highly-ionized, improving the efficiency of the device[3]. The vacuum arc thruster can be operated in discrete pulses with no sacrifice in plasma production efficiency[5]. This control allows for fine-tuning of spacecraft maneuvers. However, the non-augmented direct design still suffers from some limitations. First, the force generated per pulse is non-adjustable for each specified cathode material, and the thrust level can be adjusted only by varying the pulse duty cycle. Secondly, as the plasma is generated from cathode spots and transported out of thruster channel by plasma pressure gradient alone[3], the thrust directional efficiency is strongly dependent on the geometry of the thruster electrodes. In the case of a co-axial geometry with a Ti cathode, this efficiency is approximately 0.06%[7], which is very low. Thirdly, the direct design suffers from a non-uniform cathode erosion which effectively limits the lifetime of the thruster[7]. Similar issues exist with other ablative microthrusters such as micro-Pulsed Plasma Thruster[8].

Table 1. Comparison of existing micro-thrusters

	µCAT (GWU)	PPT (Clyde Space)[9,10]	PPT (Busek Co) [11,12,13]	Electrospray (MIT) [14,15,16]	Electrospray (Busek Co) [11,12]	VAT (Alameda)[17]
System mass, g	200	160	550	45	1150	600
System volume, cm^3	200	200	500	300	500	200
Propellant	Metal	Teflon	Teflon	Liquid	Liquid	Metal
Isp, s	3000	590	700	3000	800	1500
Propellant mass, g	40	10	36	20	75	40
Delta-V (for 4 kg satellite), m/s	300	15	63	150	151	151
Efficiency, %	15	4.7	16	71	31	9.4
Thrust to mass ratio, µN/g	0.63	0.03	0.18	0.5	0.65	0.22
Ionization degree	High	Low	Low	High	High	High
Cost	Low	Low	Low	High	High	Low
TRL	4	6	6	2-3	5	4

Adopting a novel approach

Recently, a novel thruster design, the micro-cathode arc thruster (µCAT), was developed and investigated. This thruster improves on the vacuum arc discharge thruster by applying specially designed an external magnetic field. As demonstrated in this paper, the presence of the magnetic field mitigates the disadvantages of the existing thrusters. The unique magnetic field conditions achieved in a vacuum arc offer several potential advantages in these devices[18]. The focus of this paper is on experimental characterization of this thruster, in particular, to address the influence of the magnetic field on the ion beam. µCAT exhibits certain regularities in its behavior with a magnetic field that allows simple models of thruster performance. These help with understanding the operations of the thruster.

The µCAT micropropulsion subsystem, which is being developed for use in space Attitude and Orbit Correction applications, is presently a very active research program at George Washington University's Micropropulsion and Nanotechnology Laboratory (MpNL). In December 2012, the basic GWU microthruster technology was selected by NASA Ames Research Center, via a Center Innovation Fund 2013 research grant, "Micro-Cathode Arc Thruster PhoneSat Experiment", as a potential in-space propulsion system for LEO operations of a PhoneSat, a 1U Cubesat form factor spacecraft bus. Elsewhere, the µCAT family of technologies are also being investigated for in-space propulsion needs for a wide range of spacecraft, including Nanosatellites (1-10 Kg) to satellites larger than Microsatellites (~100 Kg) in a variety of mission scenarios. Under the auspices of the ongoing PhoneSat Experiment, experimental hardware and software components are being designed and tested. The goal of the project is to integrate multiple µCAT sub-systems, with the PhoneSat bus avionics, to demonstrate commanding of the thrusters for Attitude control and orbit maneuvers. To test control systems, an Android App compatible with the PhoneSat bus will be developed that will control 2+ thrusters and test it in a vacuum chamber by the end of August 2013.

Since 2009, MpNL developed several successful configurations of Microthrusters: Ring Electrode, Coaxial Electrode, and Alternating Electrode, which exhibit different performance and operational characteristics, such as thrust, operational lifetime, EM/RF emission etc. Evaluation of the requirements for additional sub-systems that are needed for integration with any small satellite platform including enclosures, power converters, plasma power units/pulsed power units, high current and low current printed circuit boards, telemetry sensors, command processors, is currently underway at the MpNL. An Electromagnetic Compatibility (EMC) investigation plan has been chalked out with the assembly of an EM/RF test and measurement equipment stack covering HF (1-30 MHz) to SHF (~10 GHz), with automated control. At the present time, the NASA Technology Readiness Level (TRL) range of the basic μCAT technology has been evaluated to be 4 (Start), and over the course of the ongoing investigation project(s) will increase, to 6 (End), implying the base technology has been evaluated as having the required characteristics of "System/subsystem/component validation in relevant environment" and is suitable for maturing to "System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)".

COMPARISON OF EXISTING MICRO-PROPULSION SYSTEMS

The comparison of main propulsion technologies operating in the range low powers of <10 W is presented in Table 1.

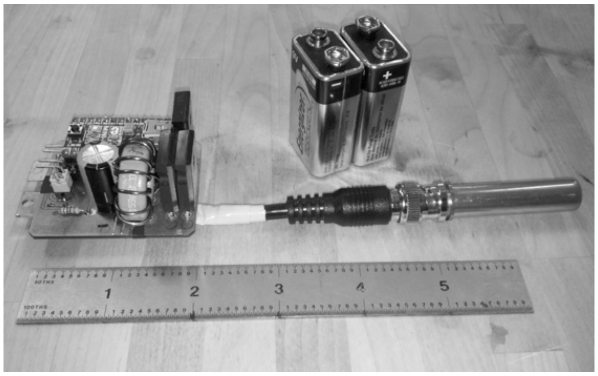


Figure 1(a) μCAT with Plasma Power Unit (PPU)

Utilization of metal propellant allows μCAT system carry larger amounts of propellant in smaller volume in comparison with ion thruster and PPT technology utilizing gas and Teflon propellants respectively. It is seen that μCAT subsystem has mass and volume characteristics comparable or exceeding those of competing technologies. In addition, μCAT is providing highest I_{sp} of about 3500s due to high speed of the plasma produced by cathodic arc. Both of these factors (large amounts of carried propellant and high I_{sp}) ensure leadership of μCAT technology in the Delta-V parameter. μCAT is characterized by ionization degree close to 100% in the plasma jets in comparison with <10% for PPT technology[6]. Low ionization degree is a critical issue, since it causes strong back flux to the satellite and results in contamination issues. Finally, μCAT technology is characterized by very high overall efficiency and thrust- to-mass ratio in comparison with competing technologies.

MICRO-CATHODE ARC THRUSTER

In this Section we briefly describe the μCAT system. The μCAT is a simple electric propulsion device that combined with a magnetic coil and an inductive energy storage power processing unit (PPU) results in a low mass (<100g) system. A picture of the μCAT system and two types thruster are shown in Fig. 1 (a), (b) and (c). Fig. 1(b) shows the schematic design of the ring electrodes μCAT (RE-μCAT), which consist of an annular titanium cathode and similar diameter annular copper anode of 1mm width. The annular ceramic insulator tube having same inner and outer diameters and a width of about 1mm was used as separator between the arc electrodes. Fig.1(c) shows the schematic design of the coaxial μCAT. Instead of the ring electrodes, this design employs cylindrically shaped cathode and anode.

Fig.2 (a) presents a schematic of the thruster and the power processing unit (PPU) system. The mass of the PPU is small (<100g), resulting in a low-mass system. PPU equipped with an inductive energy storage system has been designed as shown in the Fig. 1 (a), (b). When the trigger pulse is applied to a semiconductor Insulated Gate Bipolar Transistor (IGBT) switch, the energy is accumulated in the inductor, while when the trigger

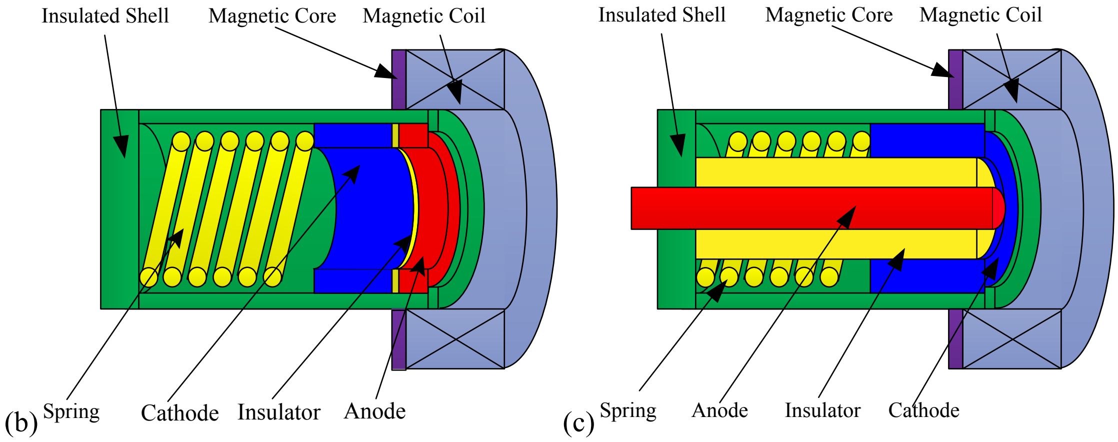
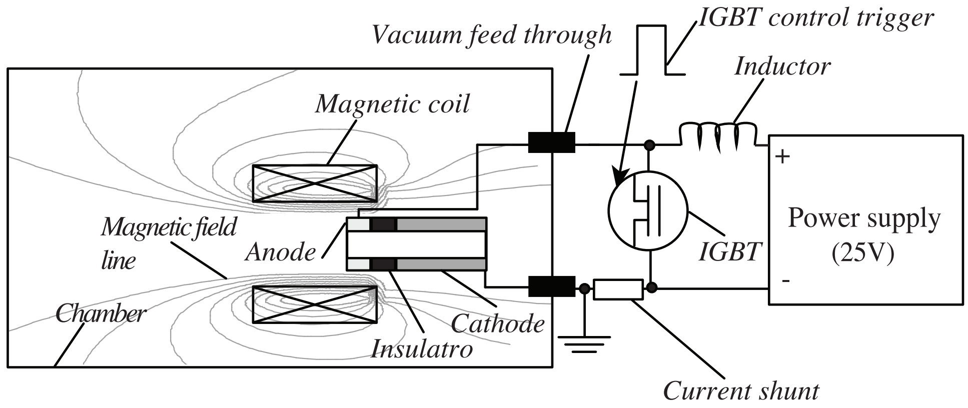


Figure 1(b) Schematic Design of Ring Electrode μCAT
Figure 1(c) Schematic Design of Coaxial Electrode μCAT

pulse ends, a surge voltage with the magnitude proportional to *LdI/dt* is generated on the inductor and applied to the electrodes. This leads to a breakdown and initiation of arc discharge between the electrodes. A coil has been applied outside of the thruster to produce a magnetic field as indicated in Fig.2 (a). The field strength was simulated using Finite Element Method Magnetics (FEMM) magnetic field simulation software. The direction of the magnetic field could be simply reversed by reversing the coil current.

(2a)



(2b)

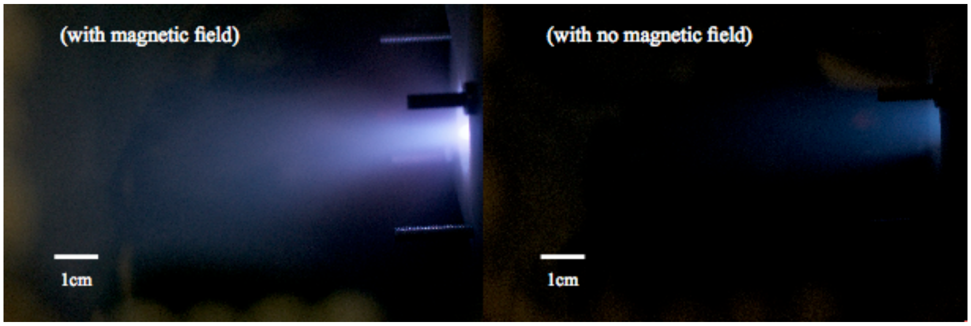


Fig. 1. (a) Schematic of micro-cathode vacuum arc thruster experimental arrangement.

(b) CCD camera observation of plasma plume with magnetic field (left figure, B=300mT) and with on magnetic field

The μCAT operates by producing a fully ionized plasma at the inner surface of the electrode. The plasma is formed at the cathode spots[3,5], and expands into the vacuum zone under the applied magnetic field gradient[18]. The effect of the magnetic field on the thruster operation is clearly visible in Fig.2 (b). This figure shows a CCD camera observation of the RE μCAT firing in the vacuum chamber without and with an added magnetic field (B=0.3T).

THRUSTER CHARACTERIZATION

In this Section we describe detailed characterization of the thruster device and its performance characteristics. The discharge voltage remains approximately constant during the pulse as shown in Fig.3 while it was found that the voltage generally increases with the magnetic field. A typical sample of μCAT arc current and discharge voltage evolution is indicated in Fig.3 (magnetic field strength of about 100mT). Typically, during the discharge process, the current that was flowing through the solid-state switch is fully transferred to the cathode spots. Consequently, the current dropped down from around 80~100A to 0A (for around 100~400μs varied with magnetic field strength as shown in Fig.4). A previous work of Keidar et. al.[5] indicated that an axial magnetic field located near the anode region plays an important role, and indicated that the arc voltage increases when a magnetic field is applied. The experiment results agree with this theoretical predication.

The plasma formed by a vacuum arc is created at the cathode spots. Previously, optical methods were employed and it was observed that the cathode spot consists of either a homogeneous bright region or cells and fragments with a typical total size of about 10-100 µm [19, 20]. The µCAT is equipped with a coil that provides magnetic field strength in the range of 0-300mT. The observation of cathode spots motion under magnetic field was first studied in the 1960s[21,22]. It is known that the presence of a transverse magnetic field at the cathode surface produces arc rotation in the **-J**×**B** direction.[18] The observed vacuum arc cathode spot rotation has had important implications for propulsion since the benefits are observable that the cathode spot rotation leads to a uniform cathode erosion, which is critical for assuring long thruster lifetime. In our previous work[7,14]. The µCAT cathode spot rotation has been measured with different magnetic field strength utilizing 4-probe assembly Langmuir probes. Four single probes were located along the azimuth direction inside the thruster channel and the four probes ion current measured results are shown in Fig. 2. The rotation speed was calculated using a quarter of circumference of the thruster inner surface divided by the delay time between each two neighbor peaks. The average rotation speed is shown in Fig. 6. It was found that the spot rotation speed increased about 5 times (from 20m/s to 100m/s) as the magnet field strength increased (from 0T to 300mT). More detailed description of this effect can be found in Ref.[23].

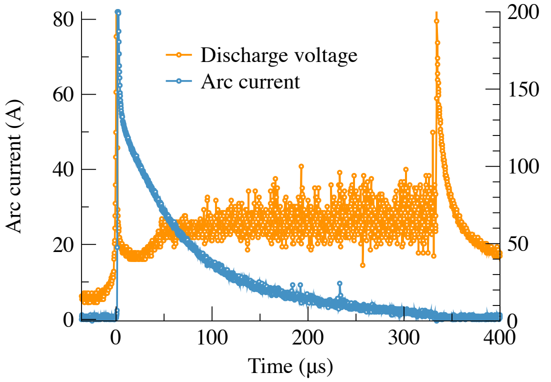


Figure 3 Evolution of µCAT arc current (blue line) and discharge voltage (yellow line) in the case of a magnetics field of about 100mT.

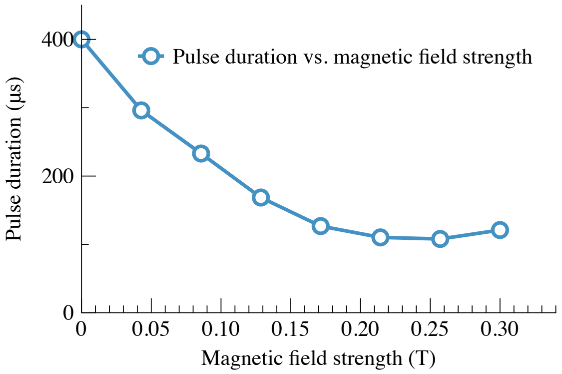


Figure 4 Thruster pulse duration evolution with different magnetic field strength. [16]

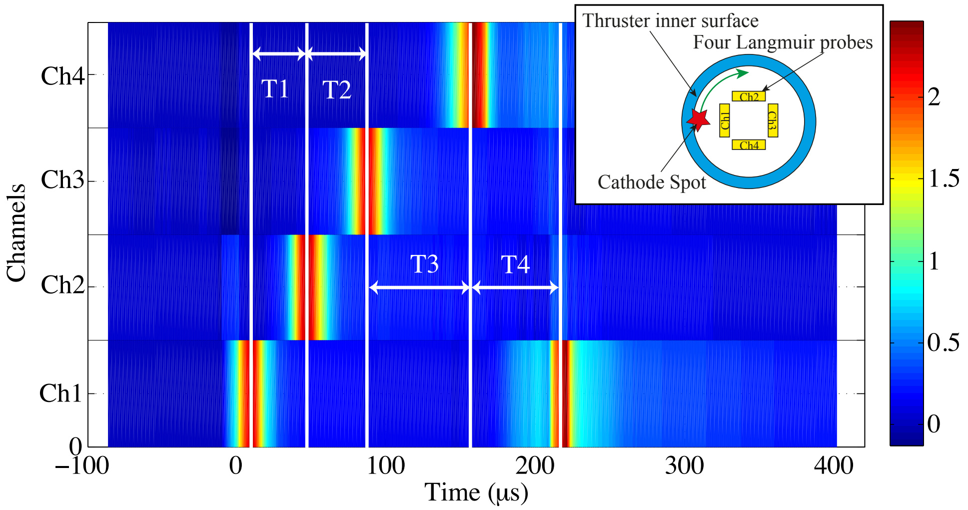


Fig. 5. Example of four Langmuir probes method to measure the cathode spot rotation speed. [7]

It was also found that the applied magnetic field increased the thruster erosion rate. In this work the mass consumption rate was measured utilizing a highly accurate mass balance. The results are shown in Fig. 7. These results show that the increase in the magnetic field leads to an increase of mass consumption rate by a factor of 3 from around 1×10^{-5} mg/pulse at zero magnetic field strength to around 3×10^{-5} mg/pulse at 0.25T magnetic field. It is mainly due to magnetic field affecting the transport of the metal plasma out of the thruster channel.

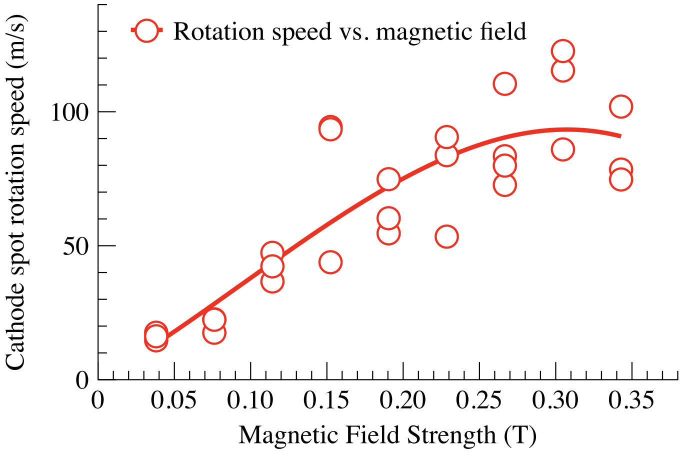


Fig. 6. Distribution of µCAT cathode spot rotation speed with different magnetic field strengths.

The ion velocities in the plasma jet generated by the micro-cathode arc thruster (µCAT) were measured by means of time-of-flight (TOF) method equipped with enhanced ion detection system (EIDS)[24]. Fig.8 shows the ion velocity distribution as a function of the distance from the cathode with the magnetic field strength as a parameter. Two characteristic regions have been identified. First region (approximately up to 80mm from the cathode) is the inter-electrode region in which plasma is being produced and accelerated by pressure gradient due to electron-ion coupling, i.e. by gas dynamic mechanism[3]. The second region (80-150 mm) is the plasma expansion inside and outside the thruster where ion acceleration was observed. One can see that the average ion velocities increased with magnetic field and with distance from the plasma source.

The micro-cathode thruster is designed to produce thrust from µN to tens of µN. Thus accurately resolved thrust bit measurements have to be conducted to access this force. To this end, a specialized measurement system known as the thrust stand mass balance (TSMB) has been used to measure forces in the µN to mN range. The thrust measurement with different strength of magnetic field has been discussed in Ref [25]. More detailed description of this TSMB and thrust measurement can be found in[26],[27]. The impulse bit measurement as a function of a magnetic field strength is shown in Fig.6. One can see that the average impulse bit increases from about 0.1 µN-s at zero magnetic field up to about 1.15 µN-s in the case of 0.3 T magnetic field. Thus, it can be concluded the impulse bit increases by about ten times when the magnetic field is applied.

Let us compare the thruster performance without any magnetic field and with a magnetic field of B=0.3 T. Table 2 shows this thruster performance comparison for the impulse bit, pulse duration, average thrust, mass loss per Coulomb, and Isp measurements. It can be seen that the magnetic field leads to an increase of velocity and thus specific impulse by a factor of 1.5. Also, most importantly for propulsion applications, the magnetic field could lead to an impulse bit increase by a factor of 10.

Table. 2, thruster performance with and without magnetic field (with pulse repetition rate 1Hz).

Magnetic field, *T*	Impulse bit, *µNs*	Pulse Duration, *µs*	Average thrust during the pulse, *mN*	Mass loss per Coulomb, *µg/C*	Isp, *s*
0	0.11	400	0.26	5.0	1900
0.3	1.1	120	8.8	52	3100

CONTAMINATION ANALYSIS

We have performed analysis of the possible thruster contamination due to the backflux. Experimental set up for this study is shown in Fig.9. Measurements of the ion saturation current at different angles are shown in Fig. 10. One can see that due to the fully ionized plasma state the plasma jet the thruster has divergent cone of about 45deg half-angle as shown in Fig.10. No ion current is detected on 0-degree probe suggesting that there is no backflux from the plasma plume.

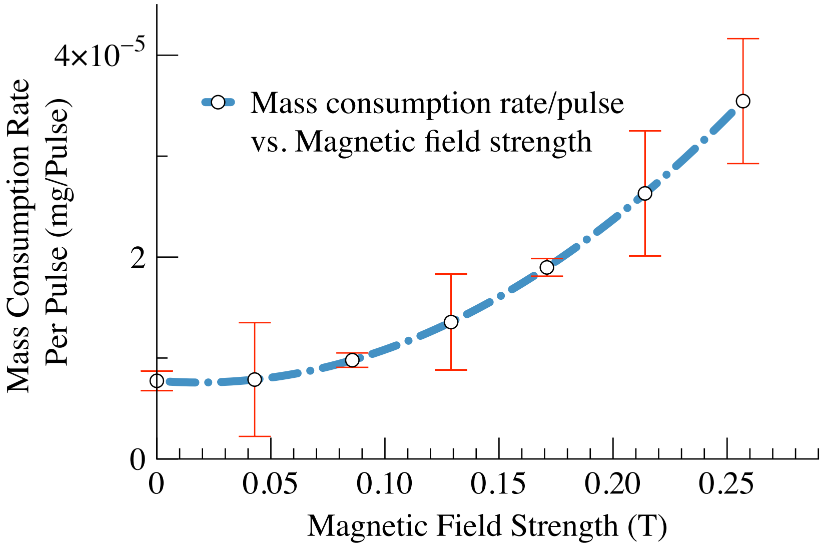


Fig. 7. Thruster cathode material erosion rate with different magnetic field strength.

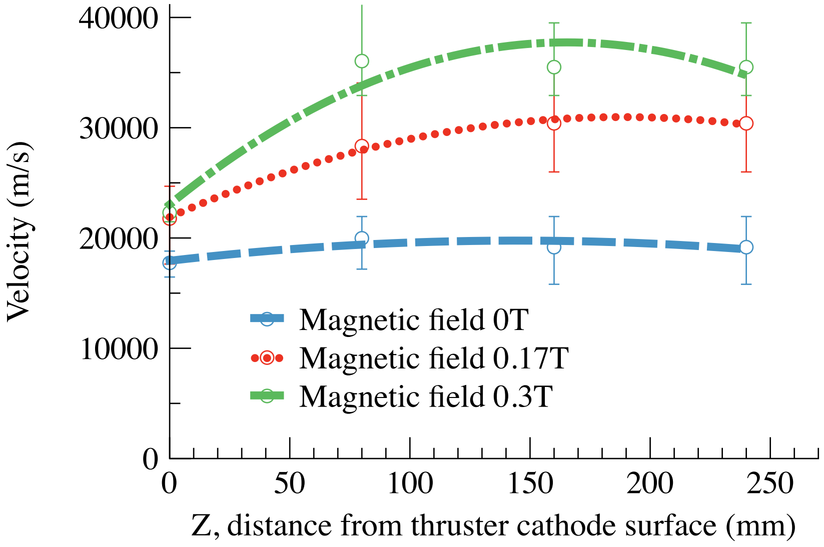


Fig. 8. Ion velocity distribution as a function of the distance from the cathode with the magnetic field strength as a parameter.

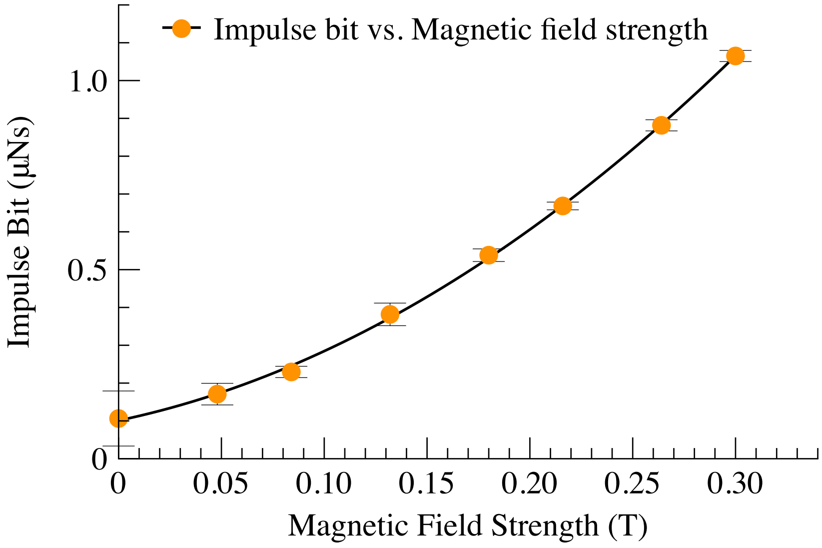


Fig.8. Impulse bit as a function of a magnetic field strength.

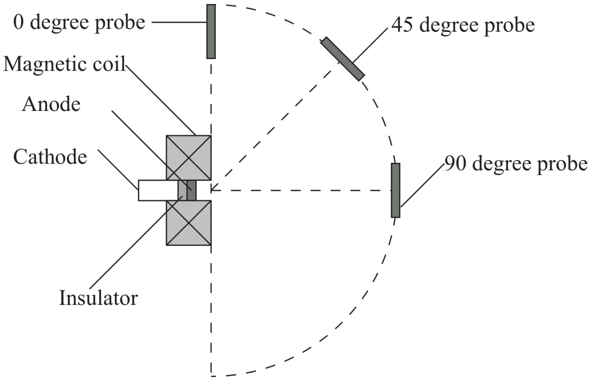


Fig. 9. Experimental set up for contamination measurements

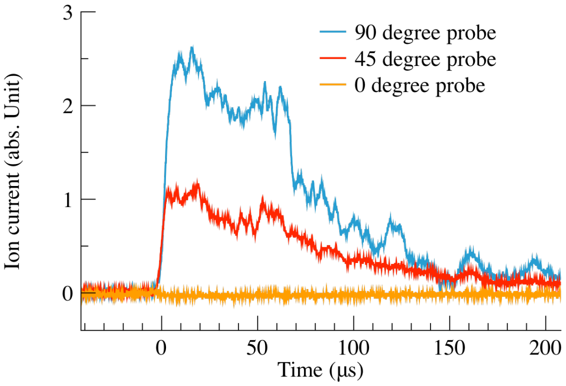


Fig. 10. Measured ion current to the probes. Probe locations are shown in Fig.3.

CONCLUSIONS

In this paper, a characterization of μCAT has been presented. It has been found that the magnetic field strongly affects thruster characteristics increasing the specific impulse and the impulse bit. The cathode spot motion was observed and results indicated that the magnetic field leads to cathode spot rotation that is critical for uniform cathode erosion. The plasma plume distribution outside of the thruster channel has been presented to analyze the effect of magnetic filed on plasma plume. μCAT equipped with magnetic field operates efficiently and gives great flexibility in specific impulse and impulse bit by simply varying the magnetic field strength.

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