Micro-cathode arc thruster improvement by the second MPD stage

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Abstract: In this study, we examine the improvement of thrust and thrust-to-power ratio of pulsed coaxial micro-cathode arc thruster (µCAT) by addition a second stage which uses magneto plasma dynamical (MPD) approach. Using the indirect thrust measurements on a thrust stand, we demonstrate that such two-stage µCAT-MPD thruster can generate average thrust up to 0.21 mN with thrust-to-power ratio up to 15 µN/W and specific impulse up to ~3400 s, having the mass of thruster of around 80 g and power consumption of less than 16 W.

Nomenclature

I_{arc}	=	arc current (in the first stage)
U_{arc}	=	arc voltage (in the first stage)
I_{MPD}	=	current in the second (MPD) stage
U_{MPD}	=	MPD stage voltage
P_{arc}	=	average power in the first stage
P_{MPD}	=	average power in the second stage
P_{PPU}	=	average power in Pulsing Power Unit (PPU) of the first stage
T	=	average thrust
TPR	=	thrust-to-power ratio
I_{sp}	=	specific impulse
t	=	time

I. Introduction

MICRO-cathode arc thrusters (µCATs) are propulsive engines suitable to propel small satellites like cubesats[1], because they are small, light-weight, low-power and they produce a typical thrust of 1-10 µN at a specific impulse of 1000-2000 s. As the average mass of newly-developing cubesats increases, larger levels of thrust will be required. Therefore, a research toward increasing the thrust levels of the existing thrusters seems to be highly relevant. One of the ways to increase the thrust of the µCAT is the addition of a second stage which can additionally generate and/or accelerate more plasma. In turn, the second stage based on Magneto Plasma Dynamical (MPD) approach[2] looks as the most attractive, because its acceleration mechanism is electromagnetic (due to the Lorentz force), so there is no need to have a system with multiple grids with dangerous high voltage for ions acceleration. The Lorentz force created in such MPD thrusters is traditionally used over decades in pulsing plasma thrusters (PPT) [3-5]. MPD thruster expels quasi-neutral plasma, so there is no need to have a lifetime-limited and power-consuming

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cathode-neutralizer – on the small satellites the power and amount of propellant for cathode-neutralizers are strictly limited[6]. In this study, we demonstrate that using MPD approach as the second stage, we can increase in many times the thrust of μCAT simultaneously with its thrust-to-power ratio and specific impulse.

II. Experimental Setup

A single coaxial μCAT, with a central copper cathode and an outer annular copper anode was used as the first stage (preliminary source of plasma). The plasma created by the first stage was expelled toward the opening of the accelerating MPD electrode with a positive dc bias U_{MPD} of up to 63 V. The thruster stage face and accelerating electrode opening were located in the central plane of the axially-magnetized permanent magnet with induction of ~ 0.2 T (Fig. 1, a). The photo of the thruster prototype is given in Fig. 1, b.

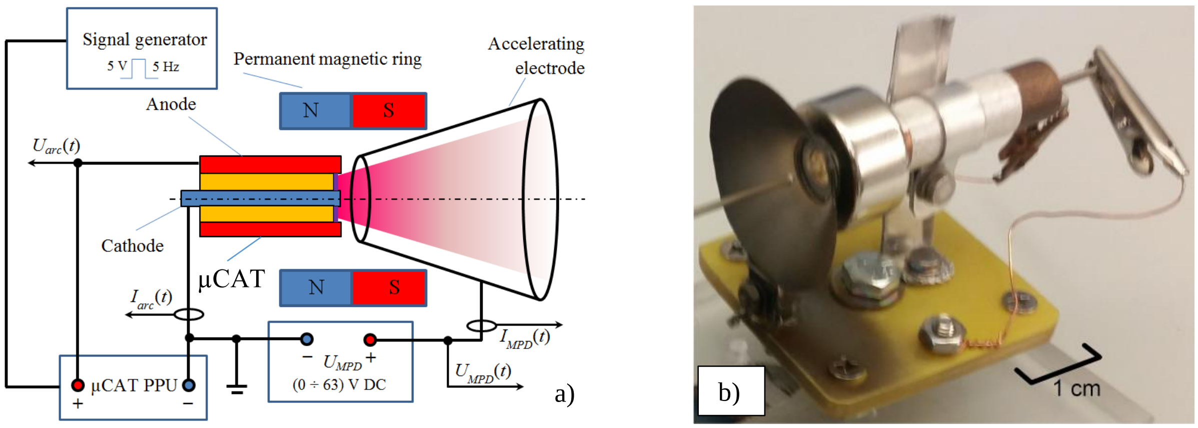

Figure 1. Experimental setup schematic (a), and photo of μCAT-MPD thruster prototype (b)

Large electron current J toward the positively-biased accelerating MPD electrode, as a result of interaction between the radial component of magnetic field B_r resulted in Lorentz force $J \times B_r$, which in turn leaded to the acceleration of the plasma toward the accelerating electrode opening. Since accelerating electrode voltage U_{MPD} could be easily varied by its power supply, the thrust gain was also controllable. For the first stage Pulsing Power Unit (PPU) we employed a well-known inductively storage pulsing circuit which stored energy in a ferrite-core inductor of 550 μH and released it to first-stage of the thruster after connecting them with a powerful Insulated-Gate bipolar transistor (IGBT) gated by a rectangular-pulse signal generator setting the firing pulse repetition rate f. Detailed description of such PPU can be found elsewhere.[7,8] The thruster was fired at a relatively low pulse repetition rate of 10 Hz in order to avoid thermal de-magnetization of the magnet. The thrust was measured indirectly by fixing the thruster on a thrust stand base, placing the thruster exhaust in front of the light-weight plate mounted on a movable arm of micro-newton-level torsional thrust stand described in details elsewhere[9]. This thrust stand was designed and manufactured in The George Washington University, and it is capable to resolve pulsing thrusters' average thrust starting from ~2 μN. The reason for using the indirect thrust measurement method was due to the mass of thruster (~80 g) which was relatively high to withstand for the thrust stand arm in its present configuration. Thrust-to-power ratio TPR was measured by dividing the indirectly-measured average thrust T over the sum of average powers, dissipated in the first stage P_{arc}, in the second (MPD) stage P_{MPD}, and in the Pulsing Power Unit (PPU) P_{PPU} according to the following formula:

$$TPR = T/\left(P_{arc} + P_{MPD} + P_{PPU}\right) = T\Big/ f\left(\int_0^{\tau_{arc}} I_{arc}(t)U_{arc}(t)dt + \int_0^{\tau_{MPD}} I_{MPD}(t)U_{MPD}(t)dt + \int_0^{\tau_{PPU}} I_{PPU}(t)U_{PPU}(t)dt\right), \quad (1)$$

where τ_{arc}, τ_{MPD} and τ_{PPU} are current pulses durations in the first stage, MPD stage and in PPU, respectively.

Specific impulse I_{sp} was calculated by multiplying the average ion velocity v_i by the gravitational acceleration on Earth surface g (9.8 m/s^2):

$$I_{sp} = v_i g \quad (2)$$

The average ion velocity v_i of the plasma from thruster exhaust was determined by a time-of-flight method using the time delay in ion signals peaks from the two negatively-biased grids separated by a known distance[10]:

$$v_i = \left(\frac{s_{12}}{t_{12}} + \frac{s_{23}}{t_{23}} + \frac{s_{13}}{t_{13}} \right) \bigg/ 3, \tag{3}$$

where s_{12}, s_{23} and s_{13} are the distances between thruster first stage face and the first grid (s_{12}), between the both grids (s_{23}), and between the thruster first stage face and the second grid (s_{13}), t_{12}, t_{23}, t_{13} are the respective times between the peaks of first-stage arc current, and ion current signals from each grid.

III. Results and Discussion

Results on thrust T and thrust-to-power ratio TPR of µCAT-MPD thruster, as well specific impulse, as function of U_{MPD} voltage, are given in Fig. 2.

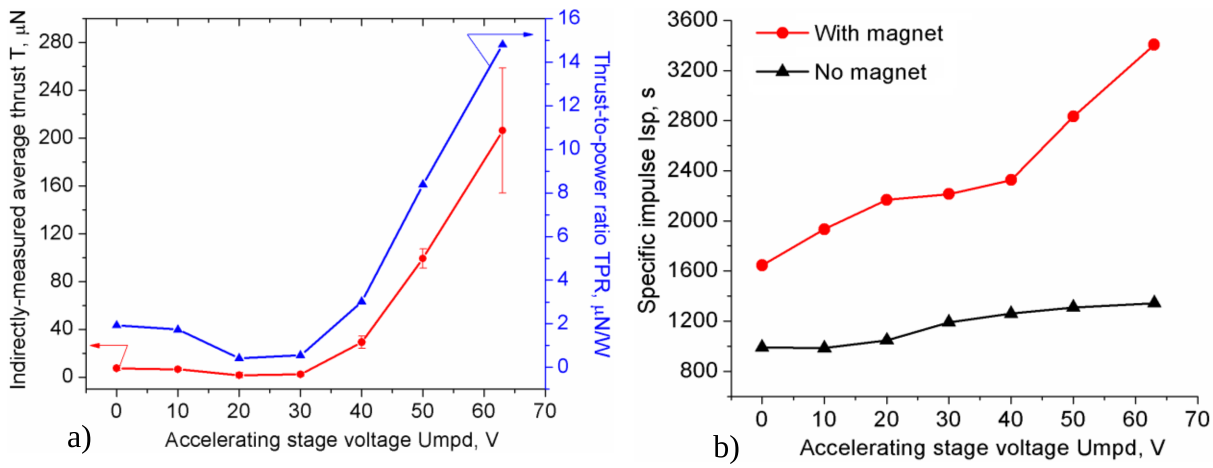

Figure 2. Indirectly-measured thrust together with thrust-to-power ratio of the thruster with magnet (a), and specific impulse of the thruster with and without magnet (b), versus the accelerating stage voltage.

From Fig. 2 (a) one can see that at low U_{MPD} voltages (0-30 V), the thrust and TPR values (2-10 µN and 0.5-2 µN/W) remain low and comparable with the respective parameters of single-stage µCATs achieved before without any acceleration stages. However, after U_{MPD} voltage increase from ~30 V to its maximal value of 63 V, both thrust and TPR rapidly grow and reach 210 µN and 15 µN/W, respectively. Note that thrust and TPR growth at high U_{MPD} voltages (Fig. 2, a) does not demonstrate any trends to saturation; this looks promising and could mean that we can get even higher thrust and TPR levels by applying higher than 63 V U_{MPD} voltages. The presence of the magnetic field, as follows from the Fig. 3, strongly effects on the average power dissipated in the first or the second (MPD) stages.

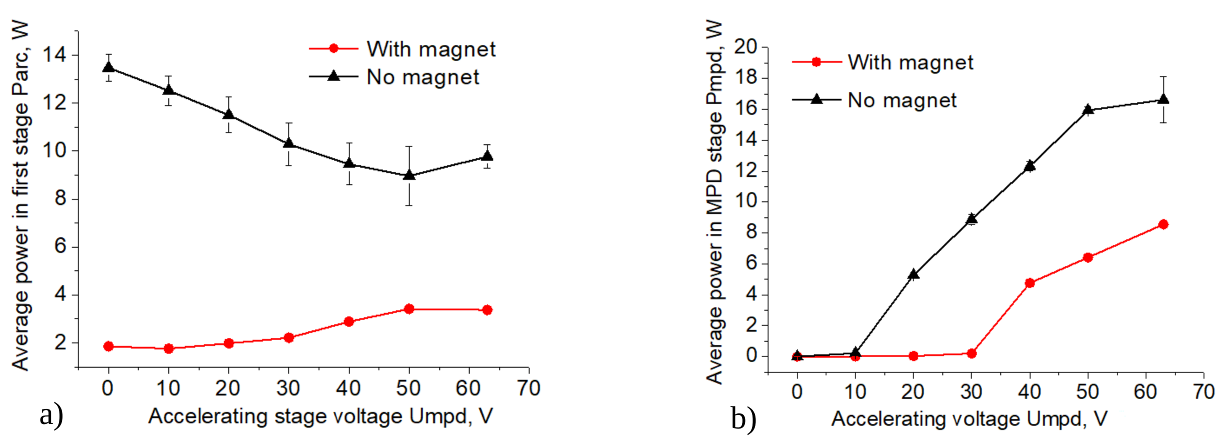

Figure 3. Average powers dissipated in the first stage (a) and in the second MPD stage (b), as function of U_{MPD} voltage, for the thruster in "with magnet" and "no magnet" configurations.

Without magnet, the power dissipating in the first stage P_{arc} practically does not depend on U_{MPD} and remains comparable with the P_{MPD} power; in this regime, the arc tends to switch to dc mode during each discharge pulse. However, with magnet, P_{arc} power abruptly drops just to several watts, and after certain U_{MPD} voltage, the highest power now is dissipating in the MPD stage, but P_{MPD} with magnet is much less than P_{MPD} without magnet. These results mean that the magnetic field positively effects on the thruster performance, decreasing the power losses in the first stage, preventing switching into dc arc, and enhancing the plasma creation and acceleration in the second stage.

Note, however, that the total power, consuming by thruster (the sum of powers $P_{arc} + P_{MPD} + P_{PPU}$), varies from ~2 W to ~16 W which indicates that our μCAT-MPD thruster can be still considered as a low-power device.

In Fig. 2 (b), one can see that the presence of magnetic field clearly effects on ion velocities and therefore on specific impulse – without magnetic field, I_{sp} just slightly grows with U_{MPD} and stays within 1000-1200 s. With the magnetic field, I_{sp} is much higher (~1600 s at $U_{MPD} = 0$), and increases almost twice (up to ~3400 s) with the growth of U_{MPD} to its maximal value of 63 V. Such increase of specific impulse together with thrust and TPR versus accelerating stage voltage with the presence of magnetic field clearly indicates the significant improvement of μCAT performance by the addition of the second MPD stage.

IV. Conclusion

We demonstrate an improvement of thrust, thrust-to-power ratio and specific impulse of micro-cathode arc thruster by addition of the second stage based on MPD approach. Such improvement happens due to generation of strong Lorentz force due to interaction of large electron current towards independent positively-biased second-stage accelerating electrode, and external non-uniform magnetic field created by a permanent magnet and having both axial and radial components. Further experiments will be required to characterize the long-time performance of such μCAT-MPD thruster.

Acknowledgments

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