Development Status of Microwave ion Thruster M5 for Small and Micro Satellites

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Kangwu Zhu[1] and Xuewen Yu[2]
Shanghai Aerospace Control Technology Institute, Shanghai, 201109, China

Meijiang Zhou[3]
Innovation Academy for Microsatellites of CAS, Shanghai, 201203, China

and

Yuntao Li, Luofeng Han, Wenbin Huang
Shanghai Aerospace Control Technology Institute, Shanghai,201109 , China

Abstract: According to the requirements of small and micro satellites for low power ion propulsion, a new 150W ion thrust based on microwave electron cyclotron resonance (ECR) principle is developing. The design status of three generations of thruster and test results are described. The thruster has multi-ECR zones which means larger discharge surface, and immersed microwave antenna can feed the microwave to ECR zones directly. Therefore, the M5 thrust has high discharge efficiency. The test results show that when thruster works on nominal condition with 0.6sccm xenon input at 23.5W microwave input power, the discharge loss is 670W/A, and the thrust can achieve 2mN thrust and 3450 specific impulse. The structure of M5 ion propulsion system is introduced, and the performance of system is listed. The system can work in a wide working conditions, and it has many advantages than other counterparts. Therefore, the M5 ion propulsion system has good application prospect for small and micro satellite.

Nomenclature

ω_{ce}	=	angular frequency of electron cyclotron resonance, rad/s
f	=	frequency of microwave, Hz
e	=	elementary charge, C
m	=	mass of the electron
B	=	magnetic field strength, T
λ	=	thrust correction factor
η_e	=	electrical efficiency
η_m	=	mass utilization efficiency
η_T	=	efficiency of propulsion system
I_b	=	beam current, A
V_b	=	beam voltage, V

[1] Senior Engineer, Research and Development Center, and zjuzkw@zju.edu.cn.
[2] Senior Engineer, Research and Development Center, and xuewenyu@163.com.
[3] Senior Engineer, Research and Development Center, and jiangmeizhou@hit.edu.cn.

$\dot{m}_p$	=	mass flow rate of xenon input, kg/s
$\dot{m}_v$	=	volume flow rate of xenon input, sccm
I_{sp}	=	specific impulse, s
T	=	thrust, N
p_s	=	input power of propulsion system, W

I. Introduction

The electrical thruster especially the ion thruster with high specific impulse can reduce the weight of small and micro satellite significantly[1]. Generally, the power of ion thruster used in medium-large satellites is 500-5000W. However, limited by the solar power of small and micro satellites, only the micro ion thrusters with low power can be used. For 100-200kg class satellites, the ion thrusters with power between 100-200W can output 1-4mN thrust with the specific impulse between 1200-3000s[2]. The micro ion thrust can be used for orbit raising and maintenance, formation control, deep-space propulsion mission, and deorbit.

Therefore, In recent years, the studies on micro ion thrusters have got more and more attentions and the technologies of micro ion thrusters have got great improvements. Wirz in JPL developed a 3cm diameter miniature xenon ion thruster with high efficiency based on micro hollow cathode[3]. And the MiXI ion thruster is planning to be used in cube satellite for lunar exploration mission[4]. The radio-frequency ion thruster is another extensively developed ion thruster for its simply working principle and long working life[5-6]. The RIT series in Germany, the BIT series in America and the LRIT series in China are three typical RF ion thruster products[7]. A modular RF ion thruster call as “Neptune” has been developed by TRUSTME® company for commercial satellite market.

The microwave electron cyclotron resonance (ECR) ion thruster is another choice for micro electrical propulsion. JAXA has developed a low power microwave ECR ion thruster called as μ1 for 50kg micro satellite[8]. The μ1 obtained an ion beam current of 3.3 mA using 1W net microwave input power with 0.15sccm xeon and 37% propellant utilization efficiency. The Pennsylvania State University is developing the Miniature Microwave Ion Thruster (MMIT) with 0.1mN projected thrust for cube satellite. The microwave frequency of MMIT is 4.9GHz, and the start power is 2.6 W at mass flow rates of 0.15 sccm of argon[9]. In China, the development of microwave ion thruster has gone on for more than 12 years[10]. Zhang designed and tested a 5cm 2.45GHz ECR ion thruster. An ion beam current of 6mA has been obtained when microwave input power is 30W. Yang studied the 10cm microwave ion thruster based on JAXA’s μ10, and three generations of 10cm ion thrusters have been developed and tested[11].

On the basis of the above microwave ion thrusters, a new high efficiency M5 microwave ion propulsion system is developing in Shanghai Aerospace Control Technology Institute, China. The M5 propulsion system is designed for 100-200kg micro satellite. The power of system is 80-200W to obtain 1-3mN thrust and 2000-3000s specific impulse. In this paper, the development status of M5 propulsion system will be described. Section II covers background information and equations for thrust. Section III covers the design changes and considerations employed for optimization. Section IV provides the experimental results. Section V describes the M5 ion propulsion system design. Section VI summarizes the progress made on the current M5 iteration and future development project for the thruster.

II. Background

In the microwave ion thruster, the plasma is generate due to the coupling of magnetic field, electron and microwave. The angular frequency of the cyclotron motion for a given magnetic field strength B is given by

$$\omega_{ce} = \frac{eB}{m} \tag{1}$$

For the microwave frequency 4.2GHz and the bare electron charge and mass, the resonance condition is met when B=0.15T. Therefore, the plasma generation surface or the ECR surface is the magnetic equipotential surface where B equals 0.15T.

The following equations are used to calculate the important performances of thruster and propulsion system. The thrust of the ion thruster with xenon is[12]

$$T = 1.65\gamma I_b \sqrt{V_b} \times 10^{-3} \tag{2}$$

Assuming the ion thruster with a 10-deg half-angle beam divergence and a 10% doubles-to-singles ratio results in λ= 0.958.

The specific impulse of the ion thruster with xenon is

$$I_{sp} = 123.6\gamma\eta_m \sqrt{V_b} \tag{3}$$

The electrical efficiency of the thruster is defined as

$$\eta_e = \frac{I_b V_b}{I_b V_b + p_o} \tag{4}$$

The efficiency of ion propulsion system is

$$\eta_T = \frac{T^2}{2\dot{m}_p p_s} = \gamma^2 \eta_m \eta_e \tag{5}$$

III. M5 Ion Thruster Design

In µ10, the microwave power is translated into the ECR zone by a waveguide and there is only one ECR surface formed by a pair of permanent magnets installed in the trumpet type waveguide discharge chamber. If we can increase the of quantity of ECR zone, the more microwave power can be absorbed, and the higher discharge efficiency can be obtained. Based on the above assumptions, multi-ECR zones are established in M5 ion thruster by two axial magnet rings and 3 or 4 radial magnet rings. And the microwave is fed to the ECR zones directly by a coaxial antenna. The shape of antenna and the relative position of antenna to ECR zone are two important design parameters. Due to the temperature of the thrust at work is low, only about 150-160°C, a flat two-grids ion optics is used. To avoid the probability of short circuit between screening grid and accelerator grid, the spacer of two grids is 1mm.

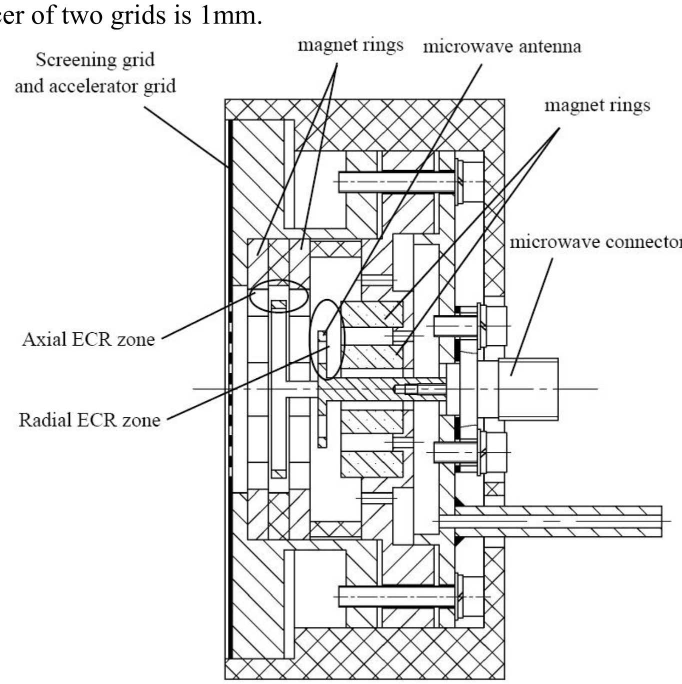


Figure 1. The structure of M5 ion thruster.

So far, three generations of M5 ion thruster have been designed and tested. The first generation M5 had been ignited successfully in July, 2017, as shown in Fig.2 and Fig.3. The inner diameter of discharge chamber is 52mm, and the effective diameter of beam is 48.5mm. At first, 3 grids C-C ion optics has been used, the thickness of grids is 1mm. The diameters of holes in screening grid, accelerator grid and decelerator grid are 1mm, 0.6mm and 0.85mm respectively. However, because of that the thickness of grids is too big, the beam current is only 5-6mA when input microwave power is 30W. And then, a two grids Mo ion optics has been redesigned. The thickness of screening grid is 0.4mm, while the thickness of accelerator grid is 0.7mm. The diameters of holes in screening grid and accelerator grid are 2.7mm, and 1.62mm receptively. The beam current was increased to 45mA with 30W microwave power at 1.2sccm xenon input. The material of permanent magnets is NdFeB and its working temperature is 180°C. In a long working test, after working for 2 hours with 30W input microwave power, the discharge process of thrust was stop suddenly because that the permanent magnets was degaussed by high temperature.

(a) C-C grids (b) Mo grids

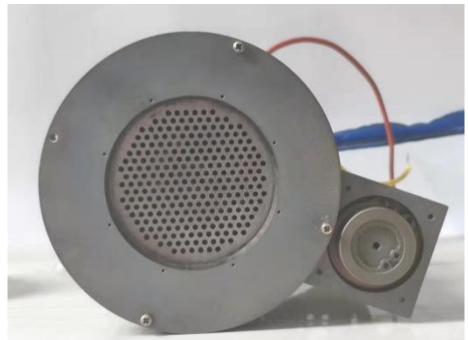
Figure 2. First generation M5 ion thruster.

Figure 3. Beam extraction test of first generation M5 ion thruster.

To improve the temperature stability, the second generation M5 ion thruster has been redesigned as shown in Fig.4. In M5-2, the material of permanent magnets is changed to samarium cobalt with 350°C working temperature. The thickness of grids are 0.25mm both. The diameters of holes in grids are 1.91mm and 1.14mm respectively. A MC-1 miniature microwave cathode is integrated with the thruster. Test results prove that the thruster can be fired with low microwave power at about 10W, however the maximum beam current is smaller than expected value, and the discharge efficiency is worse than M5-1. The issue of temperature stability has been solved, the thrust can work continuously. The total working time of M5-2 thruster is more than 3000h. The test result can be seen in Fig.5. Although, the MC-1 microwave cathode can emission 100mA electron with 20W microwave power at 1sccm xenon input, the cathode cannot be fired easily and its power consumption is high.

Based on the M5-2, to improve the discharge efficiency, the third generation M5-3 thruster has been designed. The inner diameter of discharge chamber is increased to 65mm, and the diameter of beam is increased to 58mm. The gas distributor structure is optimized and the microwave feed structures, including antenna isolator and joint are enhanced. A MC-2 2cm microwave cathode which can emit 100mA electron with 10W microwave power at 1sccm xenon input, is integrated with the thruster. The M5-3 thruster can be seen in Fig.6.

(a) After the assembly



(b) After 3000h test

Figure 4. M5-2 microwave ion thruster.

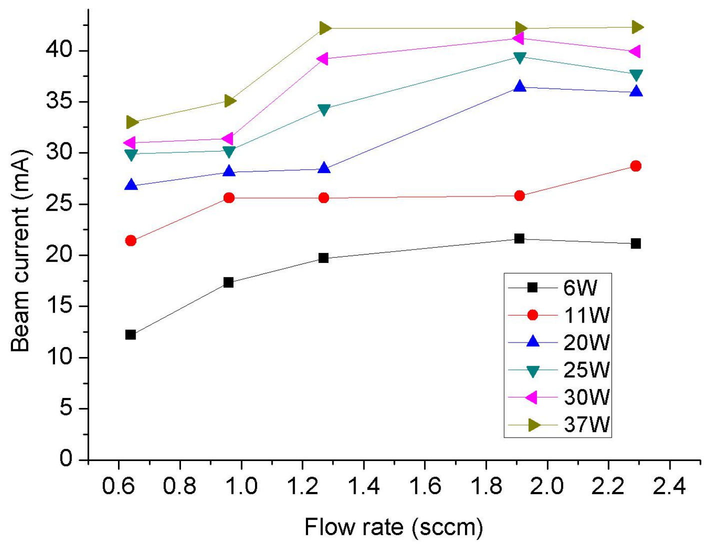


Figure 5. Beam current vs. flow rate and power of input microwave.

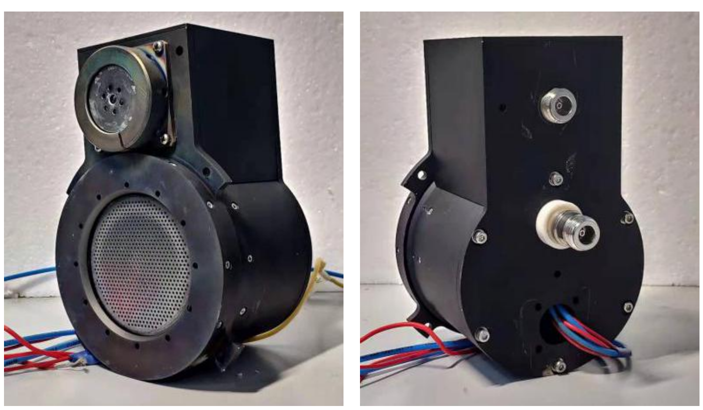


Figure 6. M5-3 microwave ion thruster.

IV. Test Results of the 3rd generation M5 ion thruster

The preliminary performance tests of M5-3 have been completed in the Space Electrical Propulsion Laboratory of Shanghai Aerospace Control Technology Institute in August, 2019. The diameter of vacuum chamber is 1.5m and the length is 3m. The vacuum degree at thruster working is 1×10^{-3}Pa. The beam extraction and plume neutralization process has been shown in fig.7. The ignition microwave power of M5-3 thruster is less than 12W at 1sccm xenon input. The thruster can work stability in entire working range.

Figure 7. The test of M5-3 microwave ion thruster.

The beam current is obtained by screening current minus accelerator current, and the thrust and specific impulse are calculated by Eq.(2) and Eq.(3). The beam current and specific impulse when screening voltage is 1500V and accelerator voltage is -300V are shown in fig.8 and fig.9.

The test results prove that the M5-3 thruster can work in a wide range of parameters. The largest thrust is 5.5mN (90mA beam current) with 3sccm xenon when microwave input power is 35.2W. The highest specific impulse can achieve 4740s with 0.4sccm xenon at 35.2W microwave input power.

The desired performance is 2mN thrust with high specific impulse. Therefore, 0.6sccm xenon input at 22.3W microwave input power is chosen as the nominal working condition that the thrust is 2.02mN with 3450s specific impulse, and the discharge loss is 670W/A.

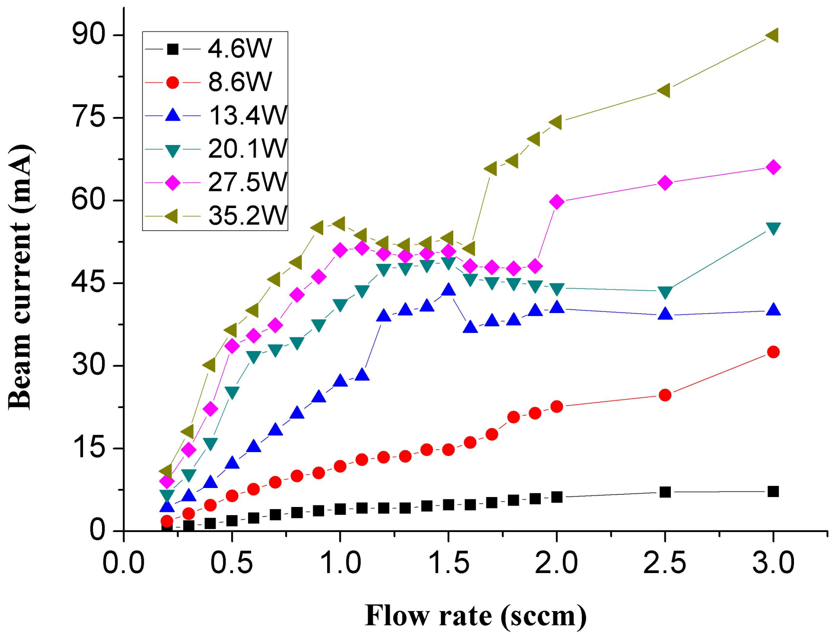


Figure 8. Beam current of M5-3 thruster.

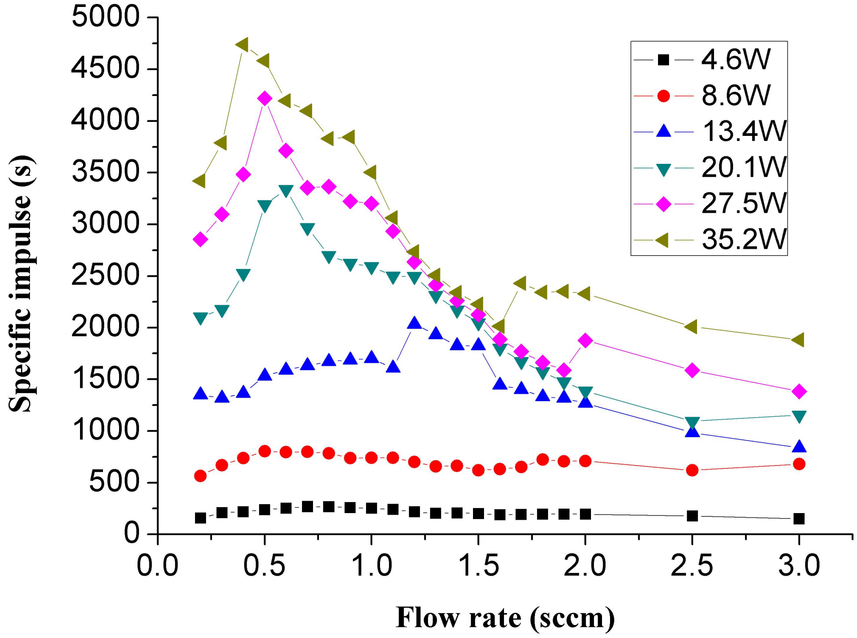


Figure 9. Specific impulse of M5-3 thruster.

V. M5 Ion Propulsion System

At present, the M5 ion propulsion system is developing for 100kg micro-satellite. In consideration of the low efficiency of microwave amplifier, and high xenon consumption of microwave cathode, two cold-redundant hot cathode will be used to replace the MC-2 microwave cathode,as shown in fig.10.

In the propulsion system, two thrusters are used, one for orbit raising, and one for deorbit control. Other parts include power supply electronics, microwave amplifier with two channels, carbon fiber xenon tank with integration pressure control valve, micro flow control module, and other attachments, as shown in fig.11.

The weight of system with 1.5kg xenon is 9.2kg. The maximum output microwave power is 25W and the maximum input microwave power to thruster is 22.3W. The propulsion system has 4 typical working conditions, as shown in Tab.1.

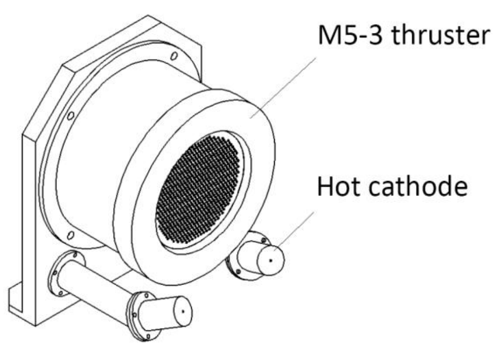


Figure 10. M5 thruster with hot cathode.

Table 1. Typical working conditions of M5 ion propulsion system

	I_b/mA	V_b/V	$\dot{m}_v$ /sccm	T/mN	I_{sp}/s	p_s/W	η_T/%
Nominal	33	1500	0.6	2	3450	140	24.5
High thrust	49.2	1500	1.4	3	2200	166	19.6

High specific impulse	30.8	2000	0.5	2.2	4465	152	31.4
Low power	24.6	1200	0.7	1.3	1973	94	13.9

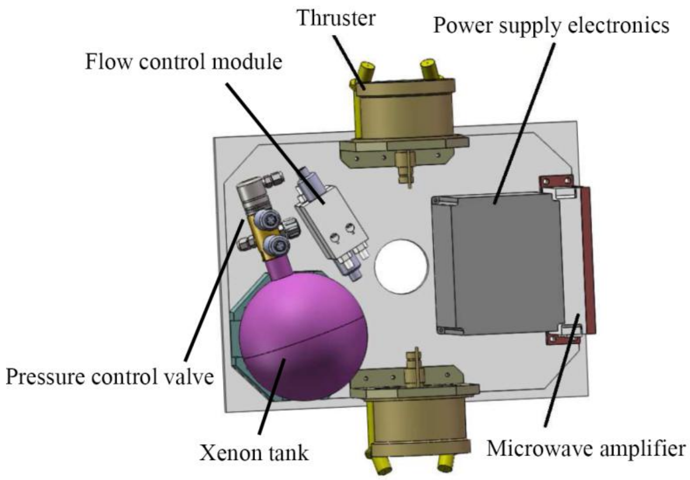


Figure 11. Layout of M5 ion propulsion system.

VI. Conclusion and Future Work

A M5 thruster is designed for 100kg micro satellites, and it is one of the M series ion thrusters (M2,M5,M10,M30) which are developing in Shanghai Aerospace Control Technology Institute. The M5 thrust has the advantages of instant startup, simple structure, long working life, easy operation, large range working conditions control and high reliability. Compared with other counterparts such as low power Hall thruster, the M5 thruster has longer life and higher efficiency. Therefore, the M5 ion propulsion system has achieved the design goal and can be potentially used in small and micro satellites.

At present, the longest life test for M5 thruster is 3000h. Although in theory, the microwave ion thruster has no cathode, the performance degradation of antenna by reason of plasma erosion and contamination has not got clear answer.

In the next research stage, the plasma and plume diagnosis will be carried out to further improve the discharge performance. The longest lift of M5 thruster will be test, while that the performance degradation process and influence factors will be studied.

The M5 propulsion system test and optimization is carrying out, and the propulsion system has chance to be launched in next two years.

Acknowledgments

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