Thrust Performance in a 5 kW Class Anode Layer Type Hall Thruster

IEPC-2015-459p／ISTS-2015-b-459p

Presented at Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan July 4 – 10, 2015

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Abstract: As a part of the collaborative research and development project in Japan for practical use of high power anode layer type Hall thruster, 5 kW class anode layer Hall thruster (RAIJIN94) have been developing and evaluated the thrust performance of it. The thrust was measured in the ion engine endurance test facility at ISAS/JAXA using a pendulum thrust stand developed at the University of Tokyo and University of Miyazaki. The thrust performance of 3 kW operation of RAIJIN94 (anode mass flow rate of 9.8 mg/s and cathode mass flow rate of 0.5 mg/s), that is, the thrust, specific impulse, and the thrust efficiency is 160 mN, 1600 sec and 0.42, respectively. The thrust performance depends on magnetic field configuration, that is, the strength of the magnetic field and the ratio of trim coil to inner/outer coil.

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Nomenclature

F	=	thrust
g	=	acceleration of gravity
I_b	=	ion beam current
I_d	=	discharge current
I_{sp}	=	specific impulse
$\dot{m}_a$	=	anode mass flow rate
$\dot{m}_c$	=	cathode mass flow rate
$P_{cathode}$	=	cathode power consumption (heater and keeper)
P_{coil}	=	coil power consumption
V_d	=	discharge voltage
η_t	=	thrust efficiency

I. Introduction

HIGH power electric propulsion system would be in the phase for practical application in the near future. It will be used propulsion system as a main propulsion of the Cargo for manned mission to Mars[1,2], as well as that for the construction of heavy space structures like the space solar power system[3,4].

There are many candidates for High power electric propulsions and anode layer type Hall thrusters[5,6] are one of the candidates for them since they offer an attractive combination of high thrust efficiency, exceeding 50%, with a specific impulse range of 1,000-3,000 s, a high ion beam density and expected long lifetime.

For practical use of the anode layer type Hall thruster, collaborative research and development project in Japan has started, the integrated system is termed as “RAIJIN” that stands for Robust Anode-layer Intelligent Thruster for Japan IN-space propulsion system.[7,8] This project consists of four parts: the development of the thruster head and high-current cathode, cluster system unification, and mission analyses (see Fig.1). As a part of the development of the thruster head, a 5 kW class anode layer Hall thruster system has been developing. We report on a thrust performance of this thruster, thrust, thrust efficiency, specific impulse.

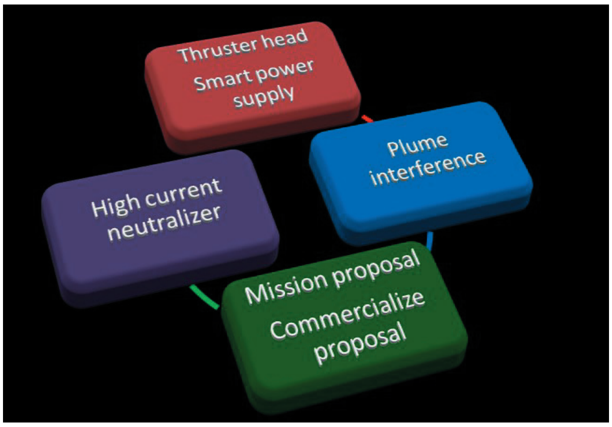


Figure 1. Project configuration of "RAIJIN".

II. Experimental Setup

A. Test Facility for performance measurement

Tests are conducted in a vacuum chamber[9] of 2 m diameter by 5 m length, which was evacuated by four cryogenic pumps (44,000 l/s for xenon), maintaining the pressure below 6.6×10^{-3} Pa (for xenon) during thruster operation with total mass flowrates of 140 sccm (13.5 mg/s). Pressure was measured using an ionization gauge, which set at almost the top of the thruster behind a shroud. The chamber baseline pressure is below $1\text{x}10^{-5}$ Pa. High-purity (99.999%) xenon gas was used as the propellant. Mass flow rates were controlled using Moog -051X368-01 for anode mass flow and 051X368-02 for cathode flow. FMT1680PYM-4VL24 was used as an anode mass flow meter, FMT1680PYM-4VL24 for cathode mass flow meter.

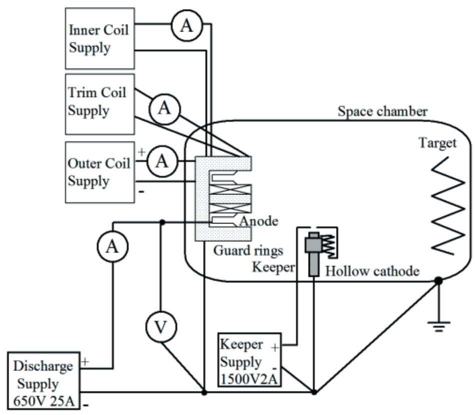


Figure 2. Schematic of electric circuit.

Thrust stand calibration is conducted with a set of five known weights in a pulley system assembly. The overall uncertainty in thrust is conservatively estimated at ±5%. The thrust stand detect force derived from the leaking magnetic field from the thruster, and this leads difficulty to optimized the magnetic field. In this study, the thrust was measrured the difference of the sensor signal(thrust signal) between on/off each condition while the magetic field is kept constant. Figure 2 shows the schematic of electric circuit. Cathode kept at the ground voltage for the safety, since 1500 V was applied to the keeper when the cathode ignites. There is a titanium floating target at 5 m downstream of the thruster.

Beam profile and ion energy distribution function also measured using small chamber, which was evacuated by two cryogenic pumps (22,000 *l*/s for xenon). Ion beam profile was measured using ion collector and retarding potential analyzer.[10)]

B. 5 kW class anode layer type Hall thruster

Figure 3 shows a photo of the 5 kW class anode layer type Hall thruster used in the current experiments. The inner and outer diameters of the acceleration channel are 60 mm and 94 mm respectively. An inner solenoid coil and four outer solenoid coils create a predominantly radial magnetic field in the acceleration channel, as shown in Fig. 3. Coil turn of inner coil and outer coil is the same. In this study, the ratio of inner coil current to outer coil current is fixed as one, that is, the inner coil current and outer coil current is the same. The Trim coil current is set as 0 A except two case(mass flow rate of 9.8 mg/s and discharge voltage of 300V).

The magnetic flux density is varied by changing the coil current. The calculated magnetic field distribution along the channel median is shown in Fig. 4(a) and the calculated magnetic field lines is shown in Fig. 4(b) (each coil current is 1.2 A, calculated using Magnum4.0, Field Precision LLC.). The origin of Fig.4 is the exit of the acceleration channel, and the radial magnetic flux density has peak (B_r=0.053 T) at z = +2 mm (positive is exit direction, and negative is anode direction). This value is almost the same as the measured one (within the 5% uncertainty). Magnetic flux density is higher on the inner wall and decreases with radius, since the magnetic flux between the poles is conserved.

The separation between the acceleration channel wall and the anode is 1 mm. The thruster has a hollow annular anode, which consists of two cylindrical rings, with a propellant gas fed through them. The gap between the tip of the anode and the exit of the acceleration channel is fixed at 3 mm.

A hollow cathode (Veeco, HECS) was used as an electron source. A pendulum-type thrust stand developed at University of Miyazaki and the University of Tokyo is used for the thrust measurements.

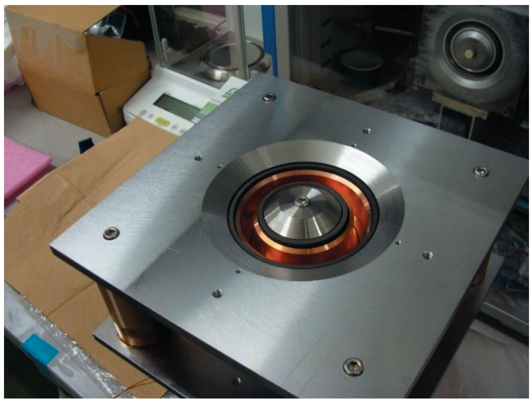
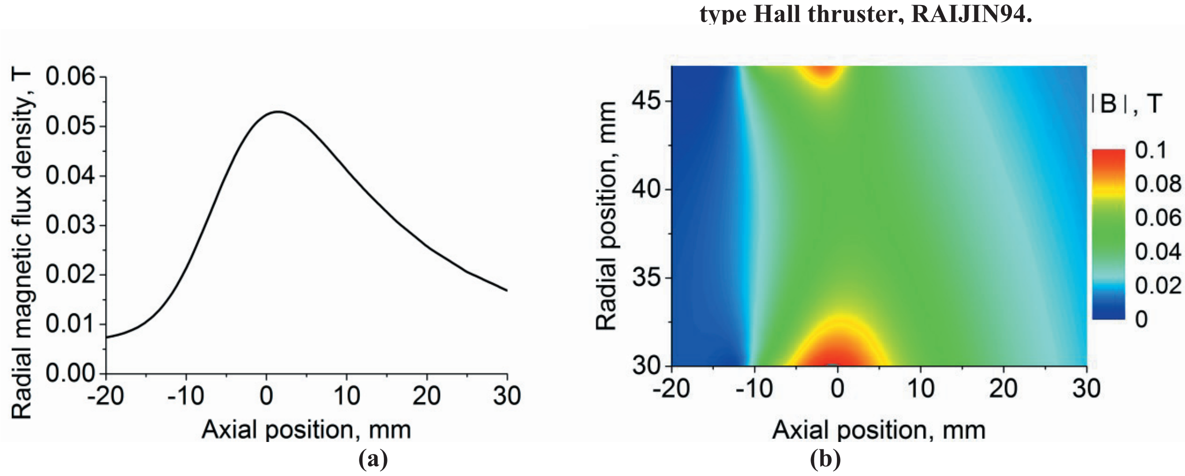


Figure 3. Photo of the 5 kW class Anode layer type Hall thruster, RAIJIN94.



(a) (b)

Figure 4. Magnetic field configuration of the Hall thruster, RAIJIN94. (a) Calculated Radial magnetic flux density profile along the channel median (outer coil current = 1.2 A, inner coil current= 1.2 A) (b) Calculated magnetic flux density distribution(outer coil current = 1.2 A, inner coil current= 1.2 A), Calculated using calculated using Magnum4.0, Field Precision LLC.

III. Results and Discussion

In order to evaluate the performance of Hall thrusters, specific impulse, I_{sp}, and thrust efficiency, η_t, are defined as,

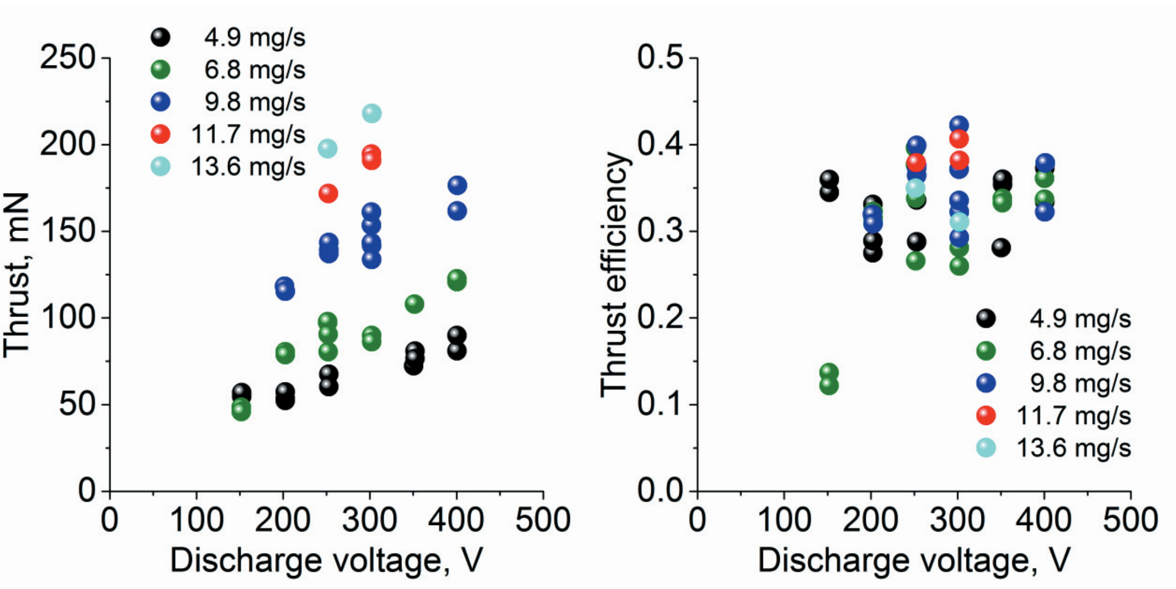
$$I_{sp} = \frac{F}{(\dot{m}_a + \dot{m}_c)g}$$
$$\eta_t = \frac{F^2}{2(\dot{m}_a + \dot{m}_c)\left(V_d I_d + \sum P_{coil} + P_{cathode}\right)} \qquad (1)$$

Figure 5 shows the thrust, thrust efficiency vs. discharge voltage for five mass flow rates, 4.9 mg/s, 6.8 mg/s, 9.8 mg/s, 11.7 mg/s, 13.6 mg/s. The designed mass flow rate is 20 mg/s, we cannot operate our thruster at the condition of $\dot{m}$ a > 13.6 mg/s, this would be due to the lack of cathode capacity (maximum emitterd current is 17.5 A). The thrust increase with the increase in discharge voltage, as conventional Hall thrusters show. We measure several magnetic field strength at the same discharge voltega and mass flow rate.

The thrust increase with the mass flow rate and the maximum thrust in this series is 220 mN at mass flow rate of 13.6 mg/s and power consumption of 5,200 W. The thrust efficiency shows unique tendency compared to conventional Hall thrusters. The strong relation between thrust efficiency and mass flow rate/discharg voltage is not seen, that is, thrust efficiency is gradually improved with the increase in mass flow rate/dischage voltage. It might because magnetic field strength and shape has not optimized, yet.

Figure 6 shows the specific impulse vs. thrust efficiency. The tendency is similar to conventional Hall thrusters, that is, with increae in specific impulse, the thrust efficiency is increase. The specific impulse achieved at 1,800 sec at dischare voltage of 400 V and mass flow rate of 9.8 mg/s at power consumption of 4 kW.

Figure 7 shows the thrust for three trim coil currents, -4 A and 0 A and +4 A at inner and outer coil curret of 1.2 A, mass flow rate of 9.8 mg/s, discharge voltage of 300 V. The thrust at tirm coil current of 0 A is minimum and the the trim coil current of -4 A is maximum. The calculated magnetic field at three coil currents shows in fig. 8, this shows magnetic field wide toward upstream, hollow anode side, at trim coil current of -4 A. This might lead to ionization region goes into inside the hollow anode, and propellant utilization will be improved. In the case of the trim coil current of +4 A, the magnetic field pushed to exit side, this would leads to push the ionization region to outside the acceleration channel, therefore, the electron energy loss on the wall will be decreased and propellant utilization would be improved compared to that with trim coil of zero.



(a) (b)

Figure 5. thrust and thrust efficiency on discharge voltage for five mass flow rates in the 5 kW class anode layer type Hall thruster developed at Kyushu University. (a) Thrust vs. discharge voltage for various magnetic field (b) Thrust efficiency vs. discharge voltage for various magnetic field

We measured plume characterisitics at mass flow rate of 4.89 mg/s and dischage voltage of 250 V and inner/ outer coil curret of 0.4 A. The ion beam profile whose ion energy > 100 eV shows in Fig. 9. eliminating the charge exchange efect

The discharge current in this condition is 4.4 A and the integrated ion beam currrent is 3 A. The average ion beam energy is 200 eV. These results suggests that improvement of the thrust performance need to improve the propellant utilization , in this condition, propellant unitlization, I_b/I_d, is 0.83.

We also pay attention of the lifetime of the thruser, for the next step. For the longer lifetime, the plasma generation should be near the chanel exit or extaneal channel, however, it will lead the degradiation of the propellant utilization. Figure 11 shows the photo of the RAIJIN94 plume, it seems most of the ionizaiton would be occurred at the median of the acceleration channel. This suggest that this plasma generation would also have a long lifetim, as well as extanal plasma generation. We have a plan to measreu erosion rate of RAIJIN94 usign cavity ringdown spectroscopy,[11-12] and it will reveal the effect of the plasma generation. Anyway, we have to improve the thrust performance through the optimization of the magnetic field, and acheve the goal as shown in Table 1.

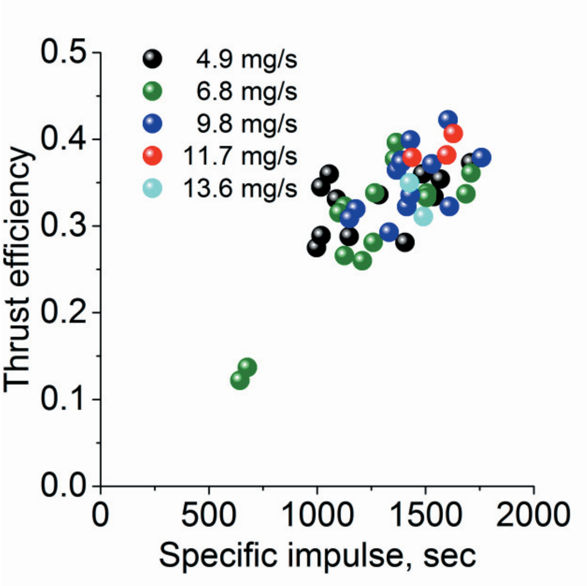


Figure 6. Specific impulse and thrust efficiency of 5 kW class anode layer type Hall thruster

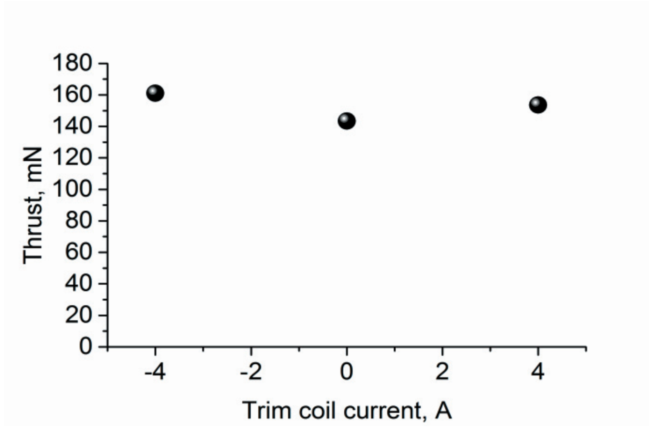
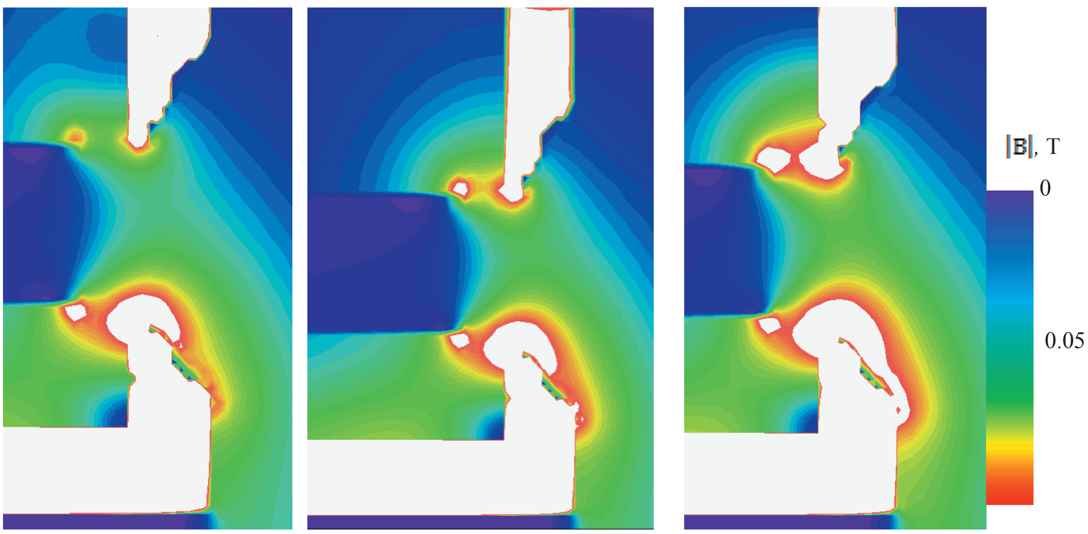


Figure 7. Thrust vs trim coil current, *at mass flow rate of 9.8 mg/s, discharge voltage of 300 V and inner coil current and outer coil current of 1.2A.*



(a) (b) (c)

Figure 8. magnetic field configuration. (a) trim coil of-4 A(b) trim coil of 0 A (c) trim coil of 4 A, calculated using Magnum3.0, Field Precision LLC

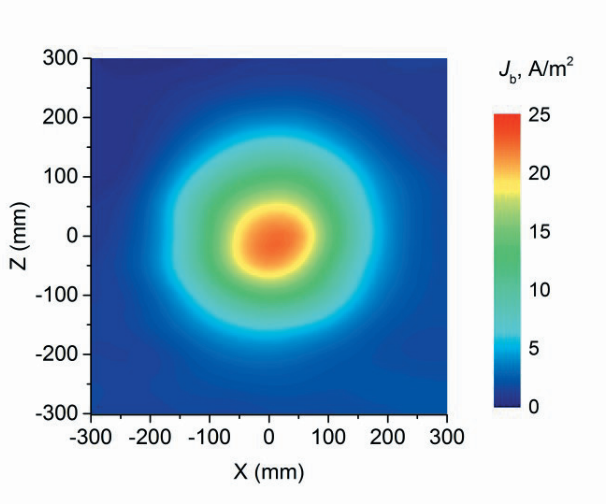


Figure 9. Ion beam profile of the RAIJIN94, at xenon mass flow rate of 4.9 mg/s, discharge voltage of 250 V, 750 mm downstream of the thruster exit

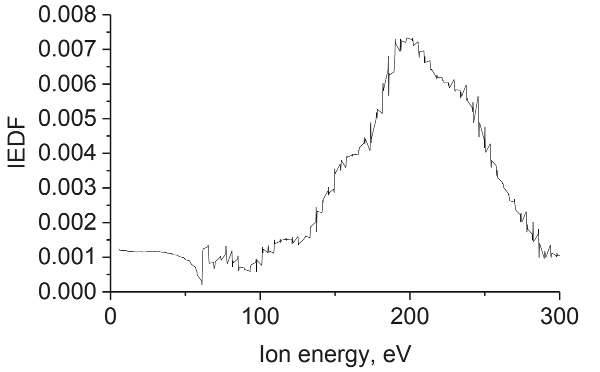


Figure 10. Ion energy distribution function of RAIJIN94, at xenon mass flow rate of 4.9 mg/s, discharge voltage of 250 V, 750 mm downstream of the thruster exit.

Figure 11. Photo of the RAIJIN94

Table 1. thrust performance of 5 kW class anode layer thruster

	Anode flow rate	Cathode flow rate	Power	Thrust	Isp	efficiency
Experiment	9.8 mg/s	0.5 mg/s	3 kW	160 mN	1600 sec	0.42
Goal	20 mg/s	1.0 mg/s	6 kW	360 mN	1700 sec	0.52

IV. Conclusion

5 kW class anode layer type Hall thruster, RAIJIN94 have been developed and evaluate the thrust performance of it. The specific impulse achieved at 1800 sec at dischare voltage of 400 V and mass flow rate of 9.8 mg/s at power consumption of 4 kW. The optimization of magnetic field(ratio of inner coil current/outer coil current/rtim coil, strength) would improve the thrust performance and we will do with the revised thrust stand developed at the Univ. to Tokyo.

Acknowledgments

This project was supported by Japan Aerospace Exploration Agency under cooperative research.

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