Experimental Study of Magnetic Field Effects on SPT Performance

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ABSTRACT

Stationary Plasma Thrusters (SPT), also known as Hall Effect Thrusters (HET) are one of the matured electric propulsion thrusters used by different space agencies for spacecraft orbit raising and NSSK operations. Higher I_{sp} and higher reliability offered by these thrusters make them standout in this category. ISRO has taken steps to develop SPTs of various power levels to cater the Indian space programme. Magnetic field profile is the heart of these SPTs, which will confine the electrons for better ionization of propellant and helps in creating strong electric field to accelerate the charged ions. The magnetic field strength affects the ceramic liner erosion which in turn determines the life of the thruster. In this study, the effects of magnetic field on thruster performance are examined experimentally. The SPT used in these experiments is a 85mm mean diameter thruster operated at 700W discharge power. The test facility used is a cylindrical vacuum chamber with 1.6m diameter and 4m length, equipped with roughing pumps, turbo molecular pump, cryo pump and Xenon cold heads. The vacuum level in the chamber during the testing of the thruster was 2.6×10^{-5} mbar of Xenon. Discharge current, discharge current oscillations and plasma plume profile were monitored at different magnetic fields. The magnetic field is tuned by varying the magnet coil currents. The 3D profiles of the magnetic field were measured using an automated 3D magnetic field mapper system. Discharge current oscillations are acquired through a high sampling oscilloscope and plume angle estimated based on measurements with Faraday probe. In this paper the performance of SPT in terms of discharge current oscillations and plume angle is presented with different peak magnetic field strengths from 78G to 171G. The mean discharge current, divergence angle are lower at 143G. High frequency modes are observed to be exit at 0.9A and 0.7A of coil current corresponds to magnetic field of 100G and 78G..

Keywords: *Stationary Plasma Thrusters, Electric Propulsion Thrusters, Magnetic field mapper and Plume angle*

1. INTRODUCTION

Electric propulsion thrusters have been dominant in spacecraft propulsion over last few decades. Their capability in delivering higher specific impulse makes them stand out over tradition chemical propulsion systems. Stationary Plasma Thrusters (SPT) also known as Hall Effect Thrusters (HET) is one of the matured thrusters in electric propulsion. These thrusters are widely used for orbit raising and NSSK operation and interplanetary missions by various space agencies. At present thousands of SPTs are under operational. Indian Space Research Organization has also taken initiative in developing these thrusters to cater Indian space programmes. Liquid Propulsion Systems Centre, one of the core centres of ISRO, had taken up this responsibility and developed SPTs of different power levels.

SPTs consists of a coaxial channel with anode at bottom and cathode outside the channel. The primary electrons generated by the cathode tends to move towards the anode in the channel, while the radial magnetic field produced by the combination of inner and outer magnets make them confine in the channel and produces Hall current in azimutal direction, resulting strong electric field in the channel. The propellant coming from the bottom of the channel through anode gas distributor will be ionized by electron impact ionization process

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and accelerated by the electric field and produces thrust.

The magnetic field plays a crucial role in confine the electrons for better propellant utilization and thrust generation. This magnetic field also produce repulsion of ions from walls of the channel by the electric field, thus reducing the channel erosion. Several theoretical and experimental work carried out on the studies of magnetic field effects on SPT performance. [1-4]

In this work, magnetic field effects on the SPT performance are studied through discharge parameters, discharge current oscillations and divergence angle.

2. EXPERIMENTAL SET-UP

Experiments are carried in a cylindrical vacuum chamber with diameter 1.6m and length 4m. The chamber is equipped with pumping system consists of roughing pumps, turbo molecular pumps, cryo pumps and cryo cold heads. The pumping system is maintaining the vacuum at 2.6×10^{-5} mbar with Xenon flow rate of 3.0 mg/s. SPT of mean diameter 85 mm is chosen for these studies. This hardware is designed for optimizes performance of 1.5kW with 3.2mg/s anode flow rate. However due to the facility limitations, in the present studies, the hardware is operated with ~700W at 300V discharge voltage and anode flow rate of 3mg/s. The magnetic field strength is varied in these studies by varying magnet coil current.

2.1 *MAGNETIC CIRCUIT*

The magnetic field in the SPT is generated using combination of one inner magnet, four outer magnets magnetic circuit. The typical magnetic field profile simulate with ANSYS Maxwell software is given in Figure. The magnetic field is strong near the exit of the thruster channel and rapidly decreases towards the anode and slowly decreases towards the outside. The relation between discharge voltage, channel width, maximum radial magnetic field and other parameters of SPT is given by [5],

$$\frac{\sqrt{U_d}}{wB_{rmax}} \cong \sqrt{\frac{\nu_{iz}}{\nu_e}} \sqrt{\frac{e}{M}} \frac{1}{K_W(e^{\langle\alpha\rangle L_{ac}^*} - 1)} \quad (1)$$

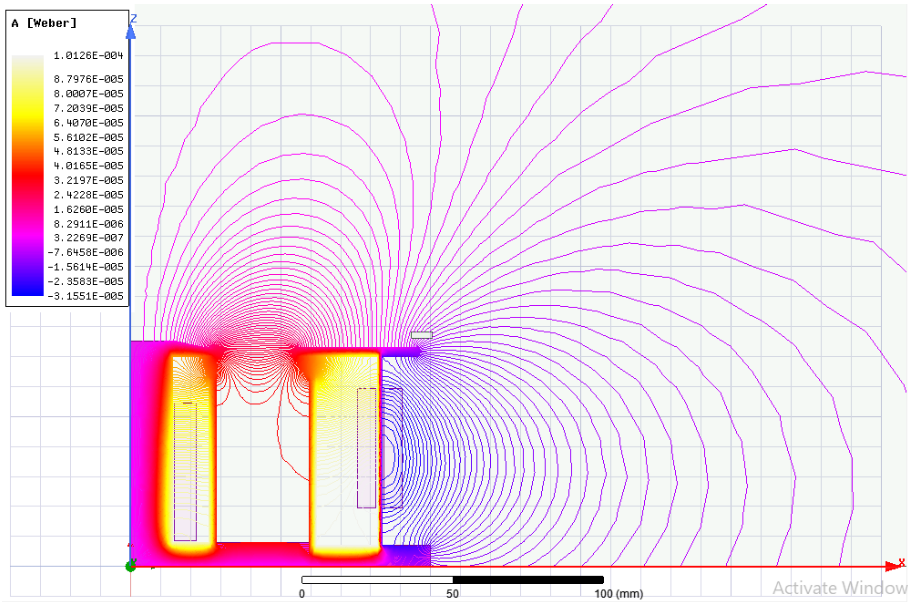

Figure 1: Axi-symmetric magnetic field simulation in the SPT

2.2 *Faraday probe*

A nude Faraday probe consists of a collector and gaurd ring is used in these experiments to measure the ion current density in the plume of the thruster. The collector has diameter of 10mm. The collector and gaurd ring are biased externally with -15V to collect the saturated ion current and repel the electron current. Potential drop across the shunt resister of 1kΩ measured using digital oscilloscope to estimate the probe current. The probe is installed on a rotating C-arm of radius 50cm to measure the ion current density in the plume at different angles. The divergence angle is estimated with charge weighted average method [6-8]

2.3 *Discharge current oscillations*

Discharge voltage is applied between anode and cathode using commercial power supply. A filter circuit is place between thruster and power supply to protect the power supply from discharge current oscillations. The voltage across a 1Ω resistor is acquired through scope for measuring discharge current oscillations with a high sampling rate of 500KSa/s.

3. Experimental Results And Discussions

Magnetic field profiles are measured with 3D automated magnetic field profiler, which is specially designed for 3D mapping of magnetic fields. The radial profile long the channel for 1.3A magnet current is as shown in Figure 1 (left) with bottom to top indicates anode to exit of the channel. The center line in the plot indicates the center line of the channel and horizontal line is the exit of the channel. The line profile along the center of the channel is shown in Figure 2 (right). The magnetic field is highest at the exit and almost reaches to zero gauss towards the anode. The center line magnetic field profiles with different magnet current are given in Figure 4. The magnetic field is highest for 1.6A of magnet coil current and decreases as decrease in the coil current as given in Table 1.

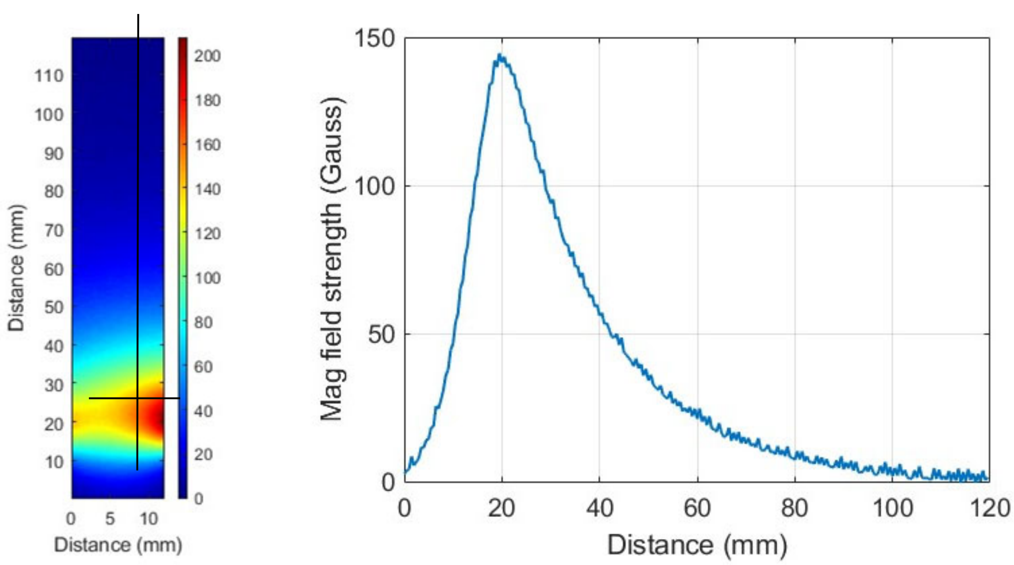

Figure 1: Radial magnetic field (Gauss) profile along the channel (left); Magnetic field line profile along the center line of the channel for 1.3A magnet current (right)

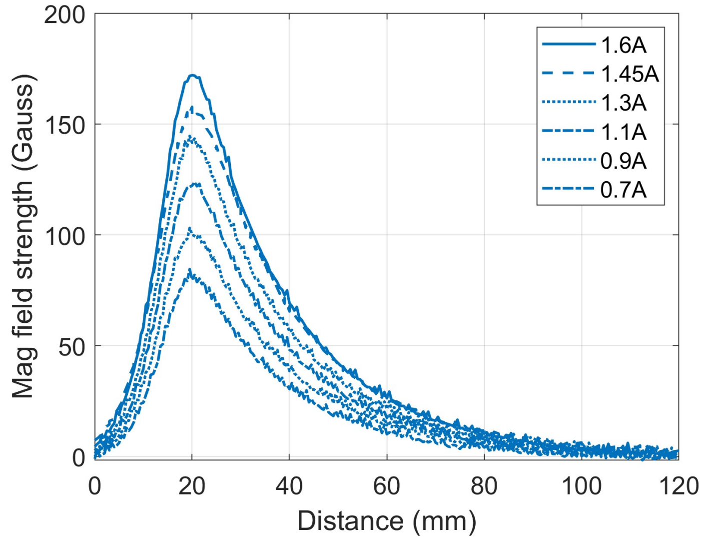

Figure 2: Magnetic field profile along the center of the channel

Table 1: Peak magnetic field strength with respect to coil current

S.No.	Magnet coil current	Peak Magnetic field strength (Gauss)
1.	1.6	171
2.	1.45	154
3.	1.3	143
4.	1.1	121
5.	0.9	100
6.	0.7	78

Discharge current oscillations with coil current are presented in Figure 3. The frequency spectra of discharge current oscillations obtained from FFT is given in Figure 4. The mean discharge current and RMS values of AC component of discharge currents with coil current are given in Table 1. The mean discharge current is lowest at 1.4A and increases on both sides of 1.3A coil current. The RMS value of AC component of discharge current is steadily decreasing for coil current from 1.6A coil to 0.7A and significantly decreasing below 1.1A. This indicated the peak -peak oscillations are decreasing with coil current but mean discharge current increases with lower coil current. The breathing mode frequency is in the nominal range of 22 to 35kHz with the presence of harmonics. High frequency modes are present at 0.7A and 0.9A of magnet currents. This indicates the existence of different instabilities at these coil currents.

Due to the limitations in the facility, the ion current density profile was measured from -40 deg to +50 deg about the thruster axis. The data is fitted and extrapolated to -90 to +90 deg using Lorenzian fitting. The typical fitted curve of ion current density profile measured with Faraday probe is given in Figure 5. The ion current density profiles with coil current are given in Figure 6. The ion current density in the plume steadily decreases for magnet coil current from 1.6A to 0.7A, while total discharge current increases as discussed. This indicates the electron current component in the discharge current is increases with decrease in coil current. Hence electron confinement becomes weak for coil current below 1.1A. The divergence angle also increases with decrease in the coil current showing poor confinement of plume towards the lower values of coil current.

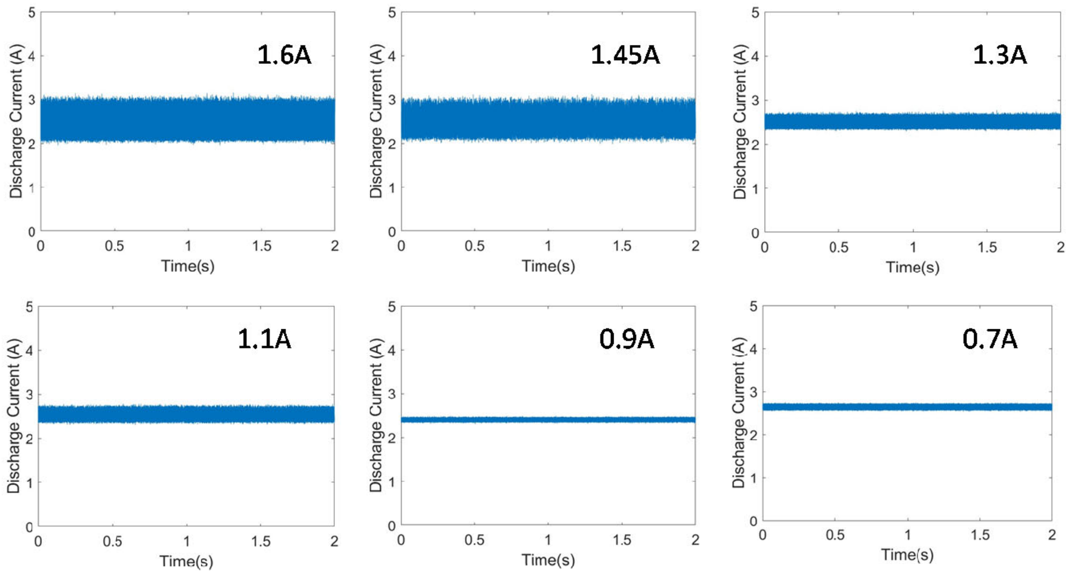

Figure 3: Discharge current oscillations with varying magnet current

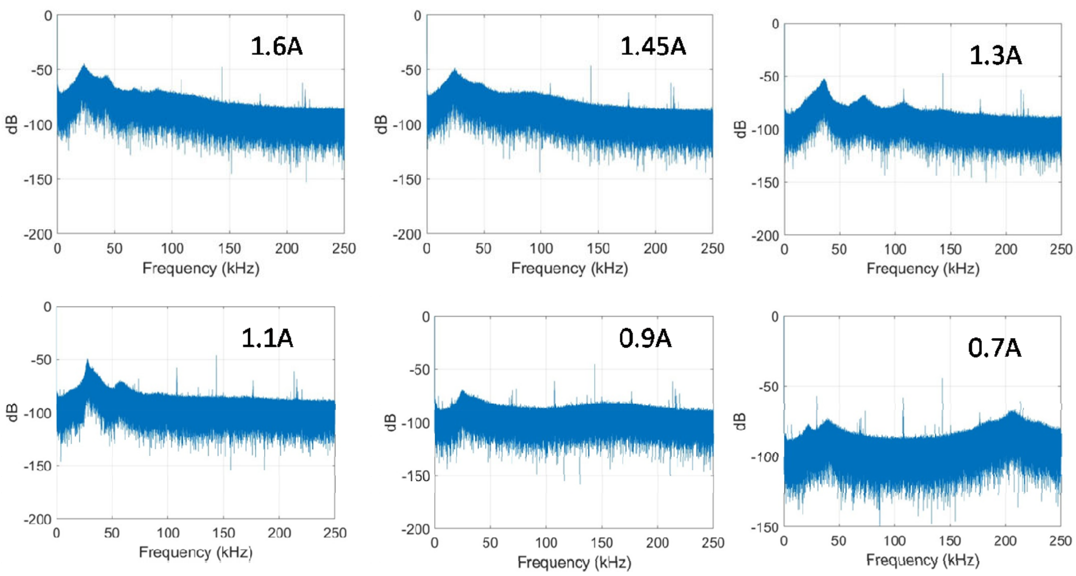

Figure 4: Frequency spectra of discharge current oscillations with magnet current

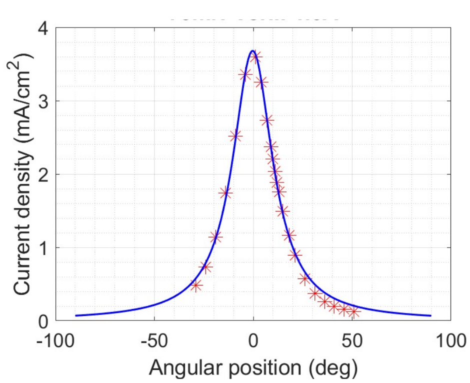

Figure 5: Ion current density profile

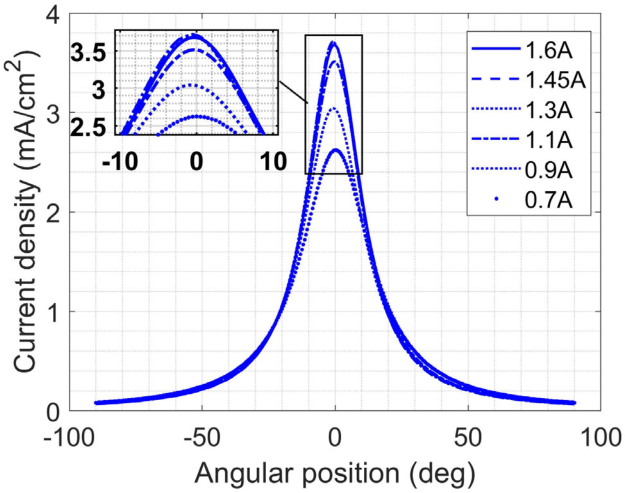

Figure 6: Ion current density profiles with different magnet currents

Table 1: Summary of results

Magnet Current (A)	Peak magnetic field strength (G)	Mean Discharge Current (A)	RMS	Frequency kHz	Divergence angle (deg)
1.6	171	2.48	0.17	23.2,45.7,69.2	39.4
1.45	154	2.47	0.12	24.6,48.7,91.4	39.3
1.3	143	2.50	0.07	35.6,72,108	39.3
1.1	121	2.52	0.07	28,57.2	39.8
0.9	100	2.40	0.02	24.7,153	40.4
0.7	78	2.63	0.03	22.2,39.7,205	41.6

5. Conclusions

The theoretical estimation of optimum magnetic field is obtained as for 300V discharge voltage for the particular hardware in study. The overall experimental results indicating the thruster performance is optimum for coil current of 1.3A corresponding to peak magnetic value of 143G. The increase in the mean discharge current, divergence angle and presence of high frequency components indicating the magnetic field strength is not adequate for the better plasma confinement below 1.1A of coil current corresponding to below 121G.

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