Magnetic Field and Current Density Probe for Steady State AF-MPD Thrusters

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Alexander Behnke* Adam Boxberger† Georg Herdrich‡
Institute of Space Systems (Institut für Raumfahrtsysteme), University of Stuttgart,
Pfaffenwaldring 29, 70569 Stuttgart, Germany

Abstract: Thrust generation in applied field magnetoplasmadynamic thruster is related to the axial, radial, and azimuthal currents in their plume. A magnetic field probe based on hall sensors was build up for determining these currents by measuring the magnetic field induced by them. The probe is designed for the operation in the plume of the 100 kW thruster SX3. This method is limited to the determination of time-averaged current densities.

Nomenclature

B	= magnetic flux density
E	= electric field strength
j	= current density
t	= time
ϵ_0	= electric constant
μ_0	= magnetic constant

I. Introduction

Applied field magnetoplasmadynamic thrusters (AF-MPDT) combine relatively high thrust densities with adequately high specific impulses and are suitable for high power applications. At the Institute of Space Systems (IRS) the 100 kW AF-MPDT SX3 has been developed and built-up. Experimental characterizations have shown thrust efficiencies higher than 46.5% with an applied field of 400 mT.[1] Different acceleration modes in AF-MPDT have been identified which are related to the axial, radial, and azimuthal currents in the plume.[2] These currents can be calculated from the magnetic field they induce. To measure the B-Field in the plume of the thruster a magnetic field probe was built up. With the measured magnetic flux density distribution and the current density distribution calculated from it the discharge can be characterized. This can increase the understanding of the operational behavior of the thruster and its thrust generation. Also this data can be used for the verification of numerical simulation tools and helps with the further optimization of the thruster. Similar measurements were done by Schock[3] who measured magnetic fields with a hall probe on a rotating shaft and calculated current density distributions in the plume of an AF-MPDT.

*PhD Student and Research Associate, Institute of Space Systems, behnke@irs.uni-stuttgart.de.
†PhD Student and Research Associate, Institute of Space Systems, boxberger@irs.uni-stuttgart.de.
‡Head of electric propulsion and plasma wind tunnels, Institute of Space Systems, boxberger@irs.uni-stuttgart.de.

II. Hall Probe

The hall probe is an intrusive plasma probe equipped with hall sensors, which was built to calculate the current densities from the measured magnetic field. The current density

$$\vec{j} = \frac{\mathrm{rot}\vec{B}}{\mu_0} - \mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t} = \frac{1}{\mu_0}\begin{pmatrix} \frac{\partial\vec{B}_z}{\partial y} - \frac{\partial\vec{B}_y}{\partial z} \\ \frac{\partial\vec{B}_x}{\partial z} - \frac{\partial\vec{B}_z}{\partial x} \\ \frac{\partial\vec{B}_y}{\partial x} - \frac{\partial\vec{B}_x}{\partial y} \end{pmatrix} - \mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t} \tag{1}$$

can be calculated with the Maxwell-Ampère equation with the flux density B, the electric field strength E, the time t, the magnetic constant μ_0, and the electric constant ϵ_0. To calculate the partial derivatives of B, it is necessary to measure the magnetic field at six different points. Therefore, determining j time-resolved requires to measure the magnetic flied at six positions in three directions at the same time. Because this is not applicable with an intrusive probe, the current densities and the magnetic field are assumed to have a stationary and an oscillating part. The B-Field is measured and time-averaged at the different positions one after another, and the current density is determined time-averaged. The plasma rotates around the thruster axis, therefore the time-averaged current density is assumed to be axially symmetric. With these assumptions equation 1 can be written in cylindrical coordinates with $\frac{\partial}{\partial\phi} = 0$ and $\frac{\partial\vec{E}}{\partial t} = 0$ to

$$\vec{j} = \frac{1}{\mu_0}\begin{pmatrix} -\frac{\partial\vec{B}_\phi}{\partial z} \\ \frac{\partial\vec{B}_r}{\partial z} - \frac{\partial\vec{B}_z}{\partial r} \\ \frac{1}{r}\frac{\partial}{\partial r}\left(r\vec{B}_\phi\right) \end{pmatrix} . \tag{2}$$

On this way the number of points where the B-Field has to be measured reduces to four and the whole measurement can be done in one plain intersecting the thruster axis.

A. Design of the Probe

A schematic drawing of the probe is shown in Fig. 1. It consists of three hall elements and a Pt1000 resistance thermometer placed in the tip of the probe (1), a water cooled copper structure (2), copper pipes for data and cooling water (3), and a boron nitride (BN) insulation between copper and plasma (4). The sensors are mounted on a replaceable sensor holder so they can be upgraded. Copper and Boron nitride have a magnetic susceptibility in the order of -10^{-5} so their influence on the measured field is small. The probe is cooled by water running through four cooling channels in the shaft of the probe. For checking the cooling system, a thermal simulation with the Siemens NX thermal / flow solver was done. The probe is connected to a 20 bar cooling water supply, and it is assumed that 14 bar reach the probe, which leads to a mass flow of 70 g/s cooling water. The probe is designed to operate in the plume of the 100 kW thruster SX3. For the simulation it was assumed that 62% of the electrical power of the thruster go to the plume. This plume power was divided by the anode cross section to get a surface power density, which decrease downstream with the increase of the plume cross section. In the simulation this surface power density was applied to the thruster facing surfaces of the probe, 10% of the power on the front

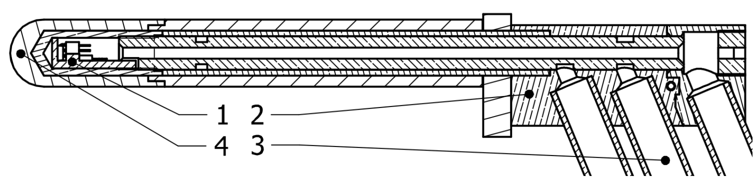

Figure 1. Schematic drawing of the hall probe.

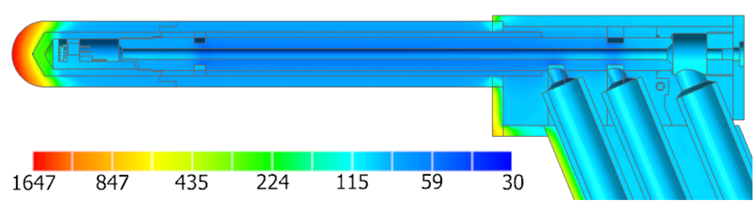

Figure 2. Thermal simulation of the probe in the plume of the 100 kW thruster SX3, Temperatures in °C.

surfaces was additionally applied to the side surfaces. The simulation was done with a model of the probe with an extended BN shielding in the rear of the probe. The result of the simulation with the tip of the probe in the plane of the anode can be seen in Fig. 2. The temperature at the tip of the probe reaches 1650 °C, the sensors have temperatures around 90 °C. A simulation at the same position with 60 kW electrical power showed a maximum temperature of 1050 °C and around 60 °C for the sensors.

B. Sensors and Electronics

In the probe three AKM HG-372A hall elements are used. They have a linear measuring range up to 300 mT with a deviation 2%. Their temperature dependency is 0.07 %/K and the maximum temperature is 125 °C. Also a Pt1000 resistance thermometer is used to monitor the probe temperature and calibrate the hall elements. In the positioning table an electronic box is placed which supplies the sensors with 0.5 mA constant current and amplifies the measured voltages to a range up to 10 V. The sensors on their holder can be seen in figure 3. The hall sensors are placed orthogonal to each other to measure the B-Filed in all three dimensions.

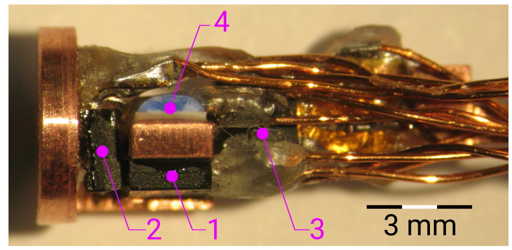

Figure 3. Sensor holder with hall sensors 1-3, and Pt1000 4.

III. Experimental set-up

The set-up of the experiment can be seen in figure 4. It consists of the hall probe, the thruster SX3, the vacuum tank, and the data acquisition. The vacuum tank has a diameter of 2 m and is 5 m long. It has a cooling water supply of 20 bar and 5 bar. With a central vacuum facility a pressure of ~ 0.5 Pa can be achieved in the tank and a high power DC facility provides up to 6 MW electrical power. More information regarding the facility can be found at Boxberger[1]. The probe is mounted on a water cooled three-axis positioning table inside the tank. The table itself can be moved in the Z direction, and has a range in the three directions of X: 385 mm, Y: ± 70 mm, and Z: 325 mm. It is controlled by an ISEL stepper motor controller. This controller is connected with a PC which can command and log the probes position. The amplified signals of the probe are measured with a LeCroy WaveSurver oscilloscope.

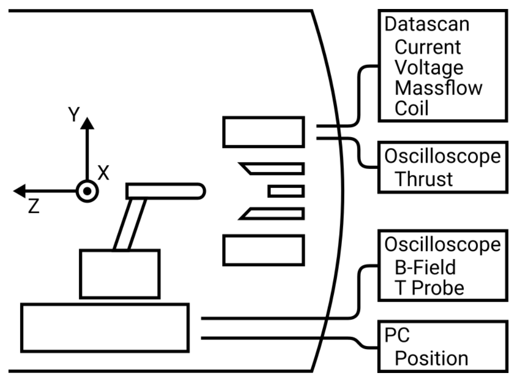

Figure 4. Experimental set-up.

The water cooled stationary AF-MPDT SX3, shown in figure 5 has an anode diameter of 86 mm. It was tested with discharge powers from 12 kW to 100 kW and arc currents up to 750 A. Its applied field is generated by a water cooled coil with a nominal flux density of 400 mT. The thruster was tested with single channel WT20 hollow cathodes with different diameters and with a heated single channel LaB_6 hollow cathode. The propellant can be ejected at the cathode and anode independently which was done up to 120 mg both mass flows combined. Recent tests have shown an efficiency of 46.5% with a thrust of 0.94 N and a discharge power of 31.6 kW.[1] The operational parameters of the thruster are collected with a Datascan 7000 and saved on a PC. The thruster is mounted on a thrust balance, the thrust is measured with a KD40S-5N force sensor.

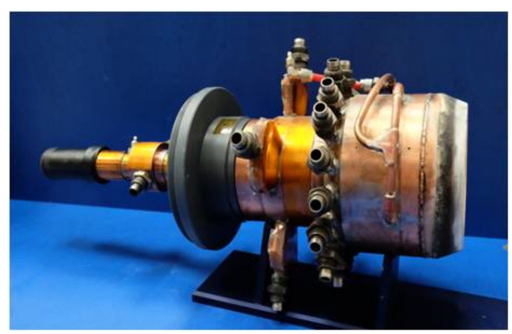

Figure 5. 100 kW thruster SX3.[4]

IV. Test description

Before the measurements in the plume the applied field is characterized with the probe. For determining the current densities in the plume of SX3 at first the thruster has to be ignited and set into a stable operating condition. The magnetic flux density is measured at equally distributed points in rows and columns on the X-Z plane intersecting the thruster axis. Because for the calculation of the current density at one point the B-Filed at four points around it has to be known, the array of measuring points has to be sized accordingly. The measuring time at a single point has to be long enough that the oscillations of the B-Field can be neglected. Afterwards the magnetic flux densities are temperature calibrated, the applied field is subtracted from them, and the current densities are calculated.

V. Conclusion

A hall probe for measuring magnetic flux densities was build up. Thermal simulations show that it can cope with the conditions in the plume of the AF-MPDT SX3. For determining time-resolved current densities it would be necessary to measure at six positions at the same time, because this is not applicable only time-averaged current densities can be identified with the probe. With these assumptions its sufficient to measure only in a plane of the plume one point after the other.

The next step is to determine the current density distributions in the plume of SX3 thruster in different operational regimes, and look at them with respect to their expected thrust mechanisms. Previous tests have mainly been done in three voltage regimes. The first condition is shown in figure 6, the thruster was operated with approximately 90 V discharge voltage and an applied field of 100 mT. This condition is expected to have a high fraction of self-field acceleration. The second condition, shown in figure 7 is with medium voltages around 170 V, an applied field of 400 mT, and comparable currents. Here the swirl acceleration is expected to be dominant. A third mode with even higher voltages around 220 V, which is shown in figure 8, was found in the latest test campaign[1].

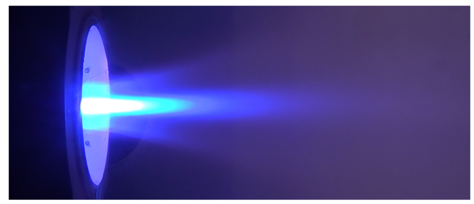

Figure 6. Thruster SX3, 90 V, 100 mT.[4]

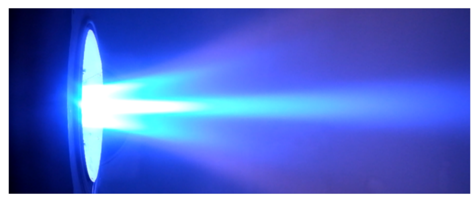

Figure 7. Thruster SX3, 170 V, 400 mT.[4]

Figure 8. Thruster SX3, 220 V, 400 mT.

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[2]Kodys, A. D., Choueiri, E. Y., "A Critical Review of the State-of-the-Art in the Performance of Applied-field Magnetoplasmadynamic Thrusters," *41th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA Paper 2005-4247, 2005.

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