The Design and Development of a 30-GHz Microwave Electrothermal Thruster

IEPC-2011-162

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

Erica E. Capalungan,[1] Michael M. Micci,[2] and Sven G. Bilén[3]
The Pennsylvania State University, University Park, Pennsylvania 16802, USA

We report initial results on the design and development of a 30-GHz MET suitable for use as a propulsion system on a CubeSat platform. Electromagnetic modeling was used in the design of the 30-GHz thruster to determine the optimal input antenna size and length. A 2.4-mm antenna size was chosen with a length that is flush with the bottom of the cavity. Modeling also shows how accuracy in machining of the cavity radius affects thruster performance. The modeling results indicate that radius inaccuracies on the order of ±0.1 mm result in mode distortion, shifting of the resonant frequency, lowered electric field strength, and poor power transfer to the cavity. The expected power requirement for plasma ignition is 5–10 watts. Initial testing is being performed at a pressure of 30 Torr using helium as the propellant.

I. Introduction

Research on the microwave electrothermal thruster (MET) at The Pennsylvania State University has been ongoing since the early 1980s. This research is focused on the development of the MET as an efficient and reliable form of electric propulsion for use in space. The research effort primarily has been experimental in nature, although more recently has included computational modeling of the thruster physics.[1,2] Thrusters operating at different frequencies have been designed and successfully tested with a variety of propellants and chamber pressures. The first thruster developed at Penn State operated at a frequency of 2.45 GHz; subsequent research explored higher frequencies of operation: 7.5 GHz, 8 GHz and 14.5 GHz. By increasing the frequency of the thruster and thereby decreasing the size, plasma generation can occur at lower input power with increased performance.[3,4]

The MET operates by heating a propellant with a microwave-generated, free-floating plasma. The propellant is exhausted through a gas-dynamic nozzle to generate thrust. The basic layout of the MET is shown in Fig. 1. The thruster consists of a cylindrical cavity that is geometrically sized to create a standing wave, focusing the electric field at several locations in the cavity. The electric field breaks down the gas where the electric field strength is highest, forming a free-floating plasma in a properly dimensioned and designed cavity. The MET operates in the TM_{011}^{z} mode. This mode concentrates the electric field at the ends of the

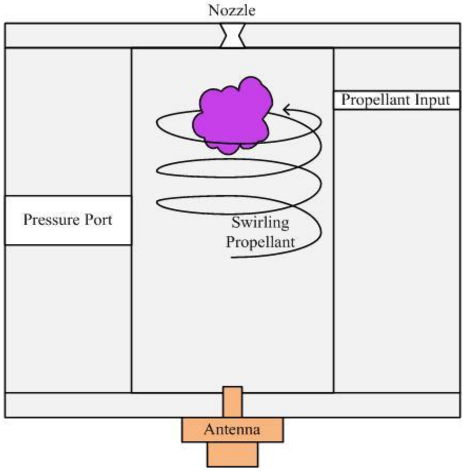

Figure 1. MET basic layout and operational overview.

---

[1] Graduate Student, Aerospace Engineering, and ee.capalungan@gmail.com.
[2] Professor, Aerospace Engineering, micci@psu.edu
[3] Associate Professor, Engineering Design, Electrical Engineering, and Aerospace Engineering, sbilen@psu.edu

cavity and the midplane.

By sizing the cavity correctly and concentrating the electric field at its ends, a plasma can be created near the entrance to the nozzle. This is the ideal location for the plasma to form because it allows for the most transfer of thermal energy to the propellant by the plasma. The two ends of the cavity are conductive plates. The antenna is located at the bottom and the nozzle is located at the top. The microwave energy enters the cavity through an antenna chosen specifically for the cavity dimensions and operating frequency. The propellant enters the cavity tangentially and near the nozzle entrance. This entrance method is chosen for two reasons. First, the tangential entrance creates a swirling effect acting as a means of cooling the thruster walls. Second, the plasma is stabilized along the center of the cavity. The heated propellant exits through a converging–diverging nozzle to create thrust. The pressure port is present to allow for internal pressure measurements during operation.

The plasma is ignited at low pressures—at pressures below 50 Torr—and sustained at higher pressures. The MET has several advantages over other electric propulsion devices. One advantage is the absence of an electrode, the main component that limits the lifetime of arcjets. Another advantage is the free-floating plasma. By removing contact between the plasma and the walls, there is less thermal heat loss and less material erosion.

This paper concerns the design and development of the MET operating at a frequency of 30 GHz. Previous research has shown that by increasing frequency and thereby decreasing thruster size, a plasma can be created with lower input power. By utilizing a higher frequency, the thruster decreases in mass and physical size allowing room for more payload or use on smaller satellites. To package a propulsion system small enough to be used on a 3U CubeSat, for example (see Fig. 2), would greatly expand the mission capabilities of the CubeSat platform. Also, by increasing the operational frequency, the power requirements for the propulsion system decrease. If the propulsion system uses less power, this can translate to a lighter power supply or it can allow the excess power to be used by other subsystems onboard the spacecraft.

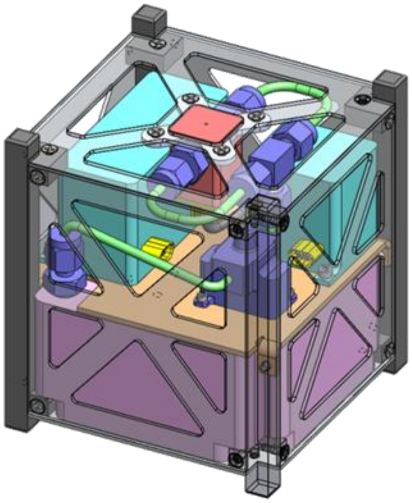

Figure 2. 1U CubeSat Module

II. Thruster Design

The primary objectives for the design of the 30-GHz MET are that it operates in the TM_{011}^{z} mode and the dimensions are such that the resonant frequency is 30 GHz. The previous generations of thrusters have shown that the TM_{011}^{z} mode is ideal for producing a free-floating plasma located near the nozzle entrance. This location for the plasma allows for the maximum thermal energy transfer to the propellant. The resonant frequency of 30 GHz is well suited for the physical size requirements of the thruster. A frequency in the range of 20–30 GHz yields thruster dimensions, input power requirements, and total system mass that are ideal for use on a CubeSat.

The secondary considerations for the design of the thruster are the input power, pressure sealing capabilities, propellant input location, and the ability to visually confirm that a plasma has formed during experimentation. An input power of up to 10 W is the expected power needed to generate and maintain a plasma. For the initial testing of the thruster, a vacuum cap is attached to the end of the nozzle to allow the thruster to exhaust to vacuum conditions. In order to achieve the vacuum, the thruster must be sealed well enough such that it can sustain a pressure below 25 Torr. Through previous experiments, this is the maximum pressure for which a plasma can be generated. In order to know that the partial vacuum has been achieved, a pressure transducer port is designed into the thruster geometry. The limiting factor in this thruster is the physical size constraints of the propellant feed. Finally, for experimental purposes, a visual confirmation that the plasma has been lit is desired. Prior METs have used machined-in windows, but the size of this thruster does not lend itself to the use of the same type of window.

The first stage in the design of the thruster is to specify the thruster's dimensions. The cavity dimensions are chosen such that they induce a plasma near the nozzle entrance, as previously discussed. The resonant frequency, operational mode, and height-to-radius ratio were used to derive the dimensions of the chamber. The height-to-radius ratio determines the field configuration at the cavity's mid-plane. A higher height-to-radius ratio results in a lower concentration of the electric field at the mid-plane. The desired outcome is to have the maximum electric field strength at the ends of the cylindrical cavity. A ratio of 3.5 was selected for the 30-GHz thruster based on the performance of prior MET designs. With a resonant frequency of 30 GHz, an operational TM_{011}^{z} mode, and a height-to-radius ratio of 3.5, the cavity radius is 0.41 cm. Using the radius and the ratio of 3.5, the height of the cavity is about 1.43 cm. A model of the thruster is shown in Fig. 3.

Instead of multiple injectors, a single propellant line with a propellant adapter is inserted near the nozzle entrance of the thruster. Due to the small size of the thruster, it is expected that one propellant line will be sufficient. A pressure transducer is attached to the thruster using an adapter. The pressure transducer allows for pressure measurements of the cavity for experimental purposes.

The nozzle has an entrance diameter of 0.0059 inches (0.0150 cm) and an exit diameter of 0.0087 inches (0.0221 cm). An O-ring groove is used to seal the nozzle plate to the cavity body. The microwave power enters the cavity through an antenna that is inserted through the bottom of the cavity. Another O-ring groove is used to seal the bottom plate to the cavity body. The ideal antenna for the 30-GHz MET should create a strong electric field near the entrance to the nozzle. The antenna for the thruster was chosen based on the results of the electromagnetic modeling of the cavity and antenna options.

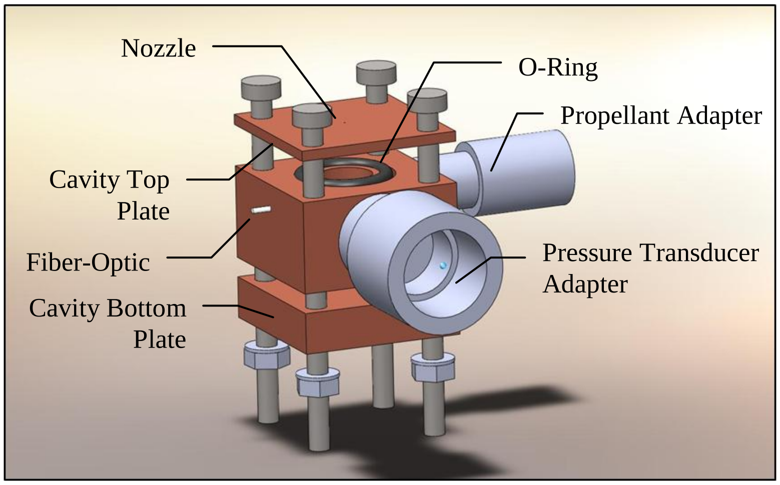

Figure 3. Design features of the 30-GHz MET.

III. Electromagnetic Modeling

COMSOL Multiphysics software was used to model the electromagnetic behavior inside of the MET cavity. The modeling was performed in order to provide insight into three design considerations for the 30-GHz MET. First, an antenna must be chosen that provides excellent microwave power coupling to the cavity. The maximum power transfer to the cavity is dependent on the dimensions of the antenna. Each of the antenna options for the thruster was modeled in COMSOL. The electric field intensity near the nozzle entrance and the resonant frequency of the cavity were analyzed for each of the antennas. Second, the length of the antenna can be altered to provide the best power coupling to the cavity. Three different antenna lengths and the thruster cavity were modeled with COMSOL. The electric field intensity near the nozzle entrance and the resonant frequency of the cavity for each of the antenna lengths were of particular interest. Third, due to the small physical size of the thruster and the high accuracy of machining required, it may not be possible to produce the exact thruster dimensions as modeled in COMSOL. Cavities with slightly larger and slightly smaller diameters were created and analyzed in COMSOL in an effort to understand how cavity diameter affects the electric field strength and resonant frequency.

A. Antenna Size Optimization

For maximum power to be transferred to the cavity, an optimal antenna must be selected. The optimal antenna dimensions scale with the physical size of the cavity. Commercial availability of antennas must also be considered. The cavity has a radius of 0.41 cm so there are three antenna sizes that would physically fit. The antennas are designated based on their connection type: SMA, SSMA, and 2.4-mm. Physically, the SMA antenna is the largest and the 2.4-mm antenna is the smallest. The dimensions of the antennas were specified when creating the geometry of the cavity and antenna in COMSOL. The simulations yielded the magnitude and field lines of the electric field for an input power of 10 W. Figure 4 shows both quantities in the y–z plane at the center of the cavity. The electric field strength scale ranges from 0 V/m to a maximum of 1.5×10^6 V/m.

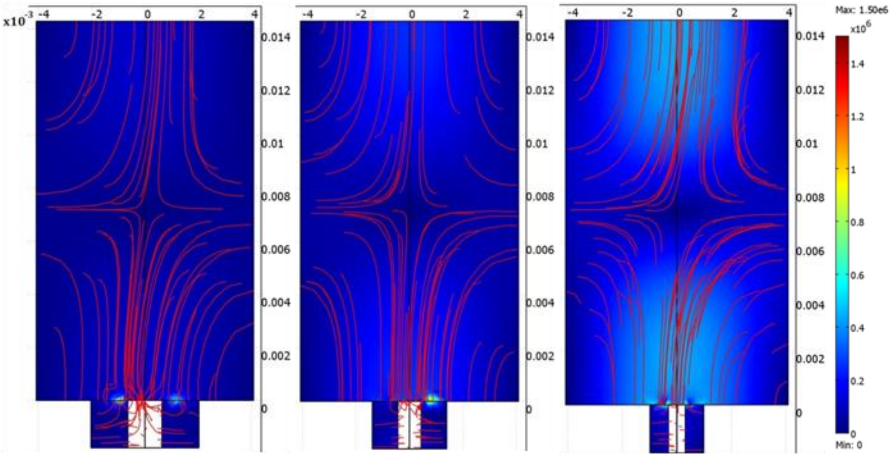

Figure 4. Electric field magnitude (V/m) contour plot and field line plot at 30 GHz for SMA (left), SSMA (center), and 2.4-mm (right).

Figure 4 shows that the field lines for all three cases are similar to one another and exhibit the behavior of the TM_{011}^{z} mode. Based on the larger color gradient shown in the contour plots of the three cases, the 2.4-mm antenna displays higher electric field strength near the top and bottom of the cavity than either the SMA or SSMA geometry.

Another aspect of antenna selection that must be evaluated is the resonant frequency of the cavity for each of the antenna geometries. A line plot of electric field strength versus frequency for an axial point that is 0.014 m from the bottom of the cavity was created for each of the antennas. This point was chosen because it is located at the top of the cavity near the nozzle entrance where the plasma will form. The frequency sweep can be seen in Fig. 5. The strongest electric field was obtained with the 2.4-mm antenna and it occurred closest to the desired resonant frequency of 30 GHz. Although the TM_{011}^{z} mode characteristics were attained in all three simulations, the strongest electric field and the desired resonant frequency were obtained using the 2.4-mm antenna, thus the 2.4-mm antenna is the ideal choice for this cavity.

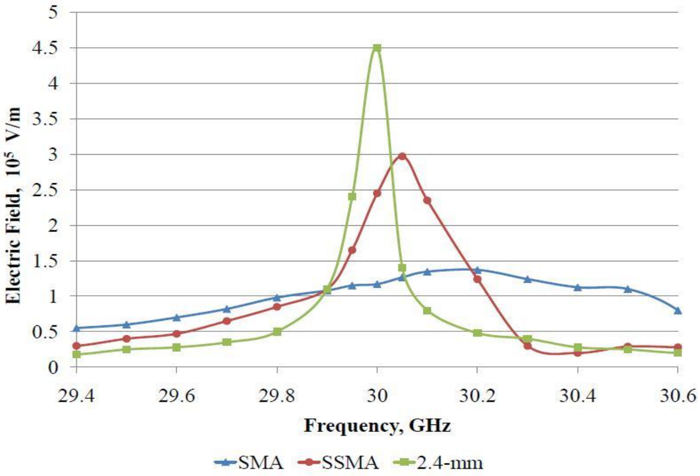

Figure 5. Frequency sweep of the electric field strength for the SMA, SSMA, and 2.4-mm Antennas.

B. Effects of Antenna Length

The length that the antenna protrudes into the cavity affects the resonant frequency of the cavity and the electric field strength. Previous MET research has shown that there is an ideal length for the antenna that provides the highest electric field intensity near the nozzle entrance. The antenna lengths modeled are 0.0 mm (flush with the bottom cavity wall), 0.5 mm, and 1 mm. The electromagnetic modeling and frequency sweep indicated that the antenna length of 0.0 mm maintained the resonant frequency and provided the highest electric field strength. The extended length of 0.5 mm resulted in a resonant frequency shift to 30.3 GHz and a decreased electric field strength. The extended length of 1.0 mm resulted in a resonant frequency shift to 29.6 GHz and a decreased electric field strength.

C. Effects of Variations in Cavity Radius

The dimensions of the cavity strongly influence the performance and resonant frequency of the MET. Due to the tight manufacturing tolerances of this thruster, the effects of slight variations in cavity radius were examined. Models were created of the flush 2.4-mm antenna with a cavity radius that is ±0.1 and ±0.2 mm from the exact cavity radius of 4.0857 mm. The electric field strength contour plots and field line plots for all four radius changes indicated a dramatic decrease in electric field strength and distortion of the mode. A frequency sweep was performed from 28.5 GHz to 31 GHz for each of the cavity sizes to determine how the resonant frequency of each cavity was affected by the change in radius. The results are shown in Fig. 6. The frequency span was performed on a single point in the cavity, which is located along the axis of the cavity at a *z*-distance of 0.014 m.

From this analysis, it is concluded that variations in cavity radius on the order of 0.1 to 0.2 mm are significant. The variations impact both the electric field intensity at the nozzle entrance and the resonant frequency of the cavity. For the simulated geometries, the peak electric field occurred within 50 MHz of the resonant frequency and quickly dropped off.

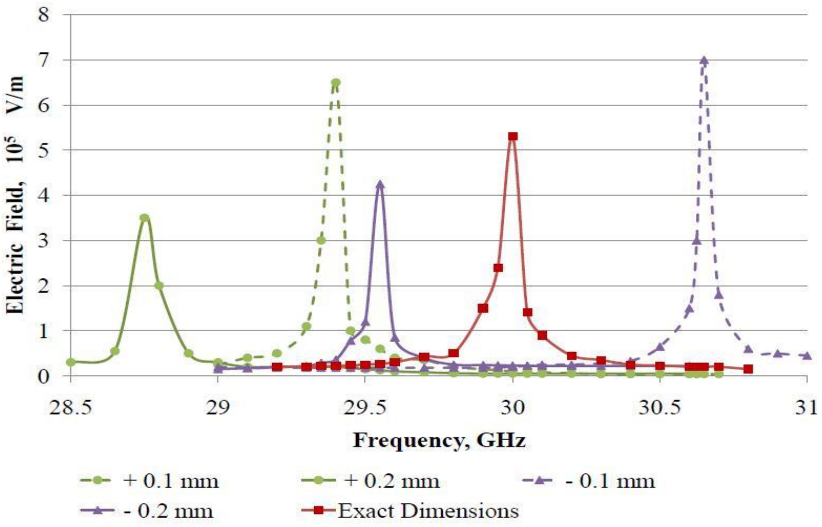

Figure 6. Frequency sweep of the electric field strength for the exact cavity radius, ±0.1 mm, and ±0.2 mm.

IV. Preliminary Testing

With the thruster fabricated and the experimental setup completed, preliminary testing of plasma ignition in the 30-GHz MET has begun. The fabricated thruster is shown in Fig. 7. The maximum power available from the microwave source and TWTA is 2.94 watts. This is less than the expected amount of power needed to generate a plasma but a higher powered source was not available. For the preliminary testing, the antenna length was not reduced to 0.0 mm and instead was left at its manufactured length of 1.78 mm. The length was left intact with the idea that it is easier to remove excess length later than it is to add the antenna length back.

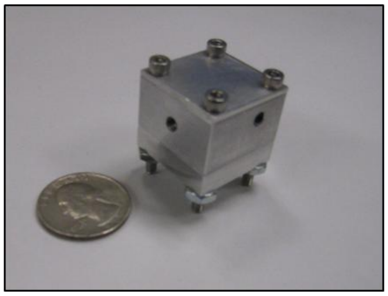

Figure 7. Fabricated 30-GHz MET.

In order to ignite a plasma, cavity pressure must be lower than 30 Torr. This pressure has been difficult to obtain due to a pressure leak through the center part of the antenna. The pressure leak through the antenna has prevented achieving pressures below 80 Torr. An alternative antenna transition was used to attempt to stop the leak but has proven to be erratic. It was noted that when the antenna transition was under bending stress, the leak was sealed. In this position, testing commenced to attempt to ignite a plasma at 30 GHz with 2.94 watts, a pressure of 30 Torr, and an antenna length of 1.78 mm.

Initial testing did not result in plasma formation. The lack of input power, being off of the cavity's exact resonant frequency, and potentially the length of the antenna may have prevented ignition. The thruster was connected to a vector network analyzer (VNA) to determine the exact resonant frequency of the cavity. The VNA measurement indicates that the actual resonant frequency of the cavity is 29.939 GHz. At this frequency with the 2.4-mm antenna and an antenna length of 1.78 mm, the power coupling was about 6 dB. This coupling is not sufficient for plasma ignition.

The antenna length directly impacts the power coupling to the cavity as well. The antenna was pulled out slightly from the cavity, producing the effect of a shorter antenna. This resulted in much better power coupling. The VNA measurement for this shorter antenna configuration resulted in power coupling of at least 25 dB. The next step will be to systematically test different antenna lengths on the network analyzer until an optimal length resulting in power coupling of at least 30 dB is obtained. Results from the network analyzer have also provided the exact resonant frequency of the cavity. This resonant frequency will also aid in igniting a plasma in the future.

V. Conclusion and Future Work

This thruster was designed to operate at 30 GHz and in the TM_{011}^{z} mode. In order for the thruster to have a resonant frequency of 30 GHz, the necessary dimensions of the thruster cavity were a radius of 0.40857 cm and a height of 1.4299 cm. The cavity is cylindrical and has a conducting plate on each of its ends, one for the antenna entrance and one for the nozzle. During testing the thruster required a vacuum cap to provide a vacuum environment into which to discharge the nozzle exhaust. Various O-rings were used for sealing connectors to the cavity and epoxy was used in the areas where O-rings were not effective. Initial testing is being performed using helium as the propellant, which enters the cavity via a propellant feed located near the nozzle entrance. A fiberoptic is used to visually confirm plasma generation during testing.

Using COMSOL Multiphysics, the thruster was modeled to determine the optimal antenna type, antenna length, and the importance of accurate machining of the cavity's radius. The modeling resulted in the selection of a 2.4-mm antenna with a length that is flush with the bottom of the cavity. By varying cavity sizes in COMSOL, it was determined that the machining of the cavity radius must be as close as possible to 0.40857 cm. Inaccuracies on the order of ±0.1 mm resulted in poor power transfer to the cavity, low electric field strength, shifted resonant frequency, and mode distortion.

Once the fabrication of the thruster and the experimental setup was complete, preliminary testing commenced. Initial testing was at 30 GHz with an input power of 2.94 watts and a cavity pressure of 30 Torr. A 2.4-mm antenna with a length of 1.78 mm was used. Initial testing did not result in plasma ignition. The thruster was then placed on a network analyzer to determine the cavity's exact resonant frequency and to analyze the power coupling. The results indicate that the resonant frequency is exactly 29.939 GHz and the power coupling can be improved by reducing the antenna length.

Future work will focus on obtaining plasma ignition with the 30-GHz cavity and data collection to understand its operational characteristics. Work on a CubeSat propulsion module may shift the frequency down from 30 GHz into the 20–30 GHz. The reason for this is that we can maintain a small form factor, but are able to utilize microwave components that are more readily available and microwave power amplifiers with increased efficiency.

Acknowledgments

E.E.C. would like to thank M. Micci and S. Bilén for their help and support throughout this project.

References

[1] Bilén, S. G., Valentino, C. J., Micci, M. M., and Clemens, D. E., "Numerical Electromagnetic Modeling of a Low-Power Microwave Electrothermal Thruster," AIAA Paper 2005-3699, 41st AIAA Joint Propulsion Conference, 2005.

[2] Hopkins, J. R., DeForce, C., Micci, M. M., Bilén, S. G., and Chianese, S. G., "Modeling and Direct Thrust Measurements of an 8-GHz Microwave Electrothermal Thruster," Proceedings of the 47th AIAA Joint Propulsion Conference, San Diego, CA, Aug. 2011.

[3] Adusumilli, R. P., *Performance Evaluation and Optimization of High Power 14.5-GHz Miniature Microwave Electrothermal Thruster*, M.S. Thesis, The Pennsylvania State University, 2011.

[4] Souliez, F. J., Chianese, S. G., Dizac, G. H., and Micci, M. M., "Low-Power Microwave Arcjet Testing: Plasma and Plume Diagnostics and Performance Evaluation," Ch. 7 in *Micropropulsion for Small Spacecraft*, edited by M. M. Micci and A. D. Ketsdever, Progress in Astronautics and Aeronautics, Vol. 187, AIAA, Reston, VA, pp. 199–214, 2000.