Design of an ECR Gasdynamic Mirror Thruster

IEPC-2009-210

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

Ricky Tang[1], Alec D. Gallimore[2] and Terry Kammash[3]
University of Michigan, Ann Arbor, MI, 48109, USA

Abstract: The gasdynamic mirror (GDM) is a magnetic confinement device that can function as an effective plasma thruster by accelerating its propellant without the endurance limitations imposed by electrodes. An important part of the acceleration mechanism is due to the self-generated electric field set up by the ambipolar potential resulting from the rapidly escaping electrons from the GDM chamber that leave behind an excess of positive ions. The geometry of the GDM is that of a simple magnetic mirror, with a magnetic field configuration resembling that of a meridional nozzle where the fluid flow velocity is everywhere parallel to the magnetic field lines. The magnetic field strength is stronger at the ends, called mirrors, than at the center, producing a turning force that helps confine the plasma ions long enough for heating before being ejected through one of the mirrors that serves as a magnetic nozzle. In order to achieve better confinement and to provide plasma stability, the system is designed with a large aspect ratio (length >> plasma radius). Unlike a 'collionless' mirror system, the requirement of a high density inside the GDM ensures that the ion-ion collision mean free path is much smaller than a characteristic length of the system, typically its length, which underlies the confinement principle of the GDM. Depending on the heating mechanism and the power source, the GDM is capable of producing a range of performance to satisfy potential future space missions. The near term application of the GDM is as a plasma thruster, and in this paper, we propose an experimental design of a GDM thruster driven by a microwave source.

Nomenclature

B = magnetic field
E_L = particle escape energy
e = electron charge
f = frequency
k = density scale length
L = plasma length
m = particle mass
R = plasma mirror ratio
T = temperature
v_{th} = ion thermal particle velocity
Z = charge number
ϕ = electrostatic potential
ν_{ei} = electron-ion collision frequency
τ = confinement time

---

[1] Graduate Student, Department of Aerospace Engineering, tangr@umich.edu.

[2] Arthur F. Thurnau Professor, Department of Aerospace Engineering, alec.gallimore@umich.edu.

[3] Stephen S. Attwood Professor Emeritus, Department of Nuclear Engineering and Radiological Sciences, tkammash@umich.edu.

I. Introduction

SPACECRAFT propulsion dictates mission feasibility. Electric propulsion (EP) such as ion and hall thrusters has to date enabled missions that would otherwise be impractical or undesirable with traditional chemical rocket systems. These are typically high velocity, i.e. high Δv, missions, such as comet encounter, sample return, outer Solar system or deep space robotic missions, that EP is well suited for due to its much higher specific impulse (Isp) significantly reducing the amount of propellant needed. One of the drawbacks, however, is the inherent low thrust-to-weight ratio of most EP systems. Nevertheless, current flight-tested EP technologies (ion and hall thrusters) can adequately address missions that are beyond the capability of chemical systems but do not necessarily require a relatively fast mission time. Since an EP engine operates continuously, it can propel a spacecraft to very high velocity over a period of time. However, even current EP technologies fall short when it comes to highly energetic missions or high-mass, deep space missions, such as fast sample returns from the outer planets and Kuiper belt and future cargo or manned Mars missions, where a fast transit time is desirable. Such missions require a high thrust, high Isp system. The magnetoplamadynamic (MPD) thruster has been suggested as a candidate due to its potential for high thrust in combination with high Isp. However, electrode erosion has been one of the major obstacles in the development of MPD thrusters. The gasdynamic mirror (GDM) propulsion system, which is the topic of this paper, is another concept with the potential to address these highly energetic missions, while circumventing the issue of electrode erosion because it is an electrode-less design. In addition, the design has the potential to meet both near and long term mission goals.

II. Concept Description

Simply put, the gasdynamic mirror[1,2] is a magnetic mirror confinement system in which the propellant (in the form of a dense plasma) is confined for a period of time while being heated before being accelerated through the magnetic nozzle to produce thrust. The underlying confinement principle is based on the premise that the plasma density and temperature will have such values as to make the ion-ion collision mean free path much shorter than the plasma length. Under these conditions the plasma behaves like a fluid, and its escape from the system would be analogous to the flow of a gas into vacuum from a vessel with a hole. The magnetic configuration of the GDM is that of a simple magnetic mirror in which the magnetic field strength at the ends (mirrors) is stronger than that in the central section, and the fluid flow velocity is everywhere parallel to the magnetic field lines. The stronger field at the mirrors allows the plasma to be confined long enough to be heated by injected power (such as microwave power) before it emerges through the mirror to produce thrust. Upon inserting the plasma into the magnetic bottle, the electrons escape rapidly through the mirrors due to their small mass, leaving behind an excess of positive charge that manifests itself in a positive electrostatic potential. The electric field generated by this ambipolar potential accelerates the ions while slowing down the electrons until both species leave the mirror at equal rates, thereby producing a charge-neutral propellant beam. Because hotter electrons produce larger electrostatic potential, hence larger accelerating electric field, the proposed thruster can be viewed as a variable thrust device if the input power source can be readily manipulated and adjusted to match the thrusting requirements. Moreover, the GDM plasma thruster will be magnetically "asymmetric" to further control the flow of the propellant and bias the flow of propellant to the thrusting end, and in conjunction with adjustable input power it could provide variable specific impulse and variable thrust.

In an effort to circumvent the major magnetohydrodynamic (MHD) instability known as the flute or Rayleigh-Taylor macroscopic instability, the GDM thruster will have a large aspect ratio (length-to-diameter ratio) in order to minimize the concave (towards the plasma) curvature of the magnetic field lines along the length of the device which drives such plasma instability modes. Studies have shown the MHD modes to be stable for large mirror ratios (magnetic field strength at mirror to that at center) in a high aspect ratio GDM.[3] Furthermore, large mirror ratios along with the high collisionality manifested by the small ion collisional mean free path tend to close the "loss cone" region in velocity space of the plasma particles and prevent a major microinstability from arising. High collisionality also tends to isotropize the plasma particles temperature (mean energy) parallel and perpendicular to the field lines, thereby eliminating the source for another microinstability. Though not as dangerous as the MHD modes, these microinstabilities can lead to local turbulence and enhanced diffusion across the magnetic field lines. The MHD modes can however be particularly harmful since they can lead to plasma break-up in timescales shorter than those needed for confinement that allow for adequate heating by the external power source. Moreover, experiments have demonstrated that the GDM is capable of supporting high β plasma,[4] where β is defined as the ratio of plasma pressure to magnetic field pressure. In short, with careful design, we could circumvent major plasma stability problems that can prevent the proposed thruster from functioning effectively as described. Although sizable magnetic fields would be required for plasma confinement in high power operation, mass minimization of the propulsion device can be achieved with the use of high-temperature superconducting magnets currently being investigated and hopefully developed in the time frame of interest. With the impressive progress being made in the development of high power microwave sources (gigawatts of power at giga-hertz frequencies), the evolution of the GDM thruster into a megawatts device for deployment in cargo and human interplanetary missions appears to be very promising.

A. Physics Model

A physics model was developed to model the plasma dynamics inside the GDM.[5] Since the plasma in the GDM is highly collisional and behaves like a continuous medium, the fluid analysis forms the basis for the physics model. The model addresses the effect of diffusion due to collisions and the contribution of the electric field in the ion and electron fluxes. Since the ambipolar potential dictates plasma behavior and is central to the operation of the GDM propulsion concept, its magnitude must be determined to predict the amount of energy the ions gain. Another important aspect the model addresses is magnetic field asymmetry. As mentioned previously, the field strength at the two mirrors must be different in order to bias ion flow towards the thrusting end to increase thrust and reduce loss. Other major quantities of interest obtained from the model include the various plasma parameters, such as temperature and ion energy, as well as the system attributes, such as size and magnetic field strength.

The following outlines some important equations from this model. A detailed derivation as well as definition for some of the quantities can be found in Ref. 5. The ambipolar potential for an asymmetric GDM is given by Eq. (1a).

$$\left(1-\frac{2}{3}x^2\right)\left[1-erf(x)\right]+\frac{2}{\sqrt{\pi}}x\exp\left(-x^2\right)=\frac{\delta_T+\delta_D}{2T_e}+\frac{2}{3}\frac{m_e}{m_i}Z^2x^2 \tag{1a}$$

$$\delta_j \equiv \frac{L}{4R_jk}m_e\nu_{ei}\left(\frac{8T_i}{\pi m_i}\right)^{1/2} \qquad x\equiv\sqrt{\frac{3e\phi}{2T_e}} \tag{1b}$$

Once the potential is known, it can be used to evaluate the electron and ion escape energies, given by the following expressions.

$$E_{Le}=\frac{\left(5-2x^2\right)\left[1-erf(x)\right]+\frac{2}{\sqrt{\pi}}\left(5+\frac{4}{3}x^2\right)x\exp\left(-x^2\right)}{2\left(1-\frac{2}{3}x^2\right)\left[1-erf(x)\right]+\frac{4}{\sqrt{\pi}}x\exp\left(-x^2\right)}T_e \tag{2}$$

$$E_{LiT}=\frac{2+\frac{m_e}{m_i}Z^2\frac{T_e}{\delta_T}x^2}{1+\frac{2}{3}\frac{m_e}{m_i}Z^2\frac{T_e}{\delta_T}x^2}T_i \tag{3}$$

Since E_{Le} and E_{LiT} are the average energies of escaping electrons and ions as they leave the plasma chamber, the ambipolar potential must be added to (subtracted from) the ion (electron) energy to obtain their energies outside the chamber. Therefore, the average energy of an escaped electron outside the plasma chamber is $\left(E_{Le}-e\phi\right)$ and that of an escaped ion is $\left(E_{LiT}+e\phi\right)$.

Finally, the loss rate or confinement time τ_T depends explicitly on the ambipolar potential and the mirror ratio according to the following expression.

$$\tau_T=\frac{R_TL}{v_{th}\left[1+\left(m_e/m_i\right)Z^2\left(e\phi/\delta_T\right)\right]} \tag{4}$$

$$v_{th} = \sqrt{\frac{8T_i}{\pi m_i}} \tag{5}$$

III. Proposed Thruster Design

The magnetic mirror is one of the oldest thermonuclear plasma confinement concepts. Although the GDM was initially proposed as a fusion propulsion concept,[2] in which a plasma, such as deuterium-tritium, would be confined at thermonuclear temperatures to achieve self-sustaining, steady-state fusion reaction that powers the system, the fact that the GDM is nothing more than a plasma confinement and acceleration device means that the concept is very versatile and can be scaled to satisfy near and long term applications depending on available technologies. In particular, with an external power source, the GDM can function as an electrode-less plasma thruster. For this, we propose the use of a microwave power source. Figure 1 illustrates the proposed concept.

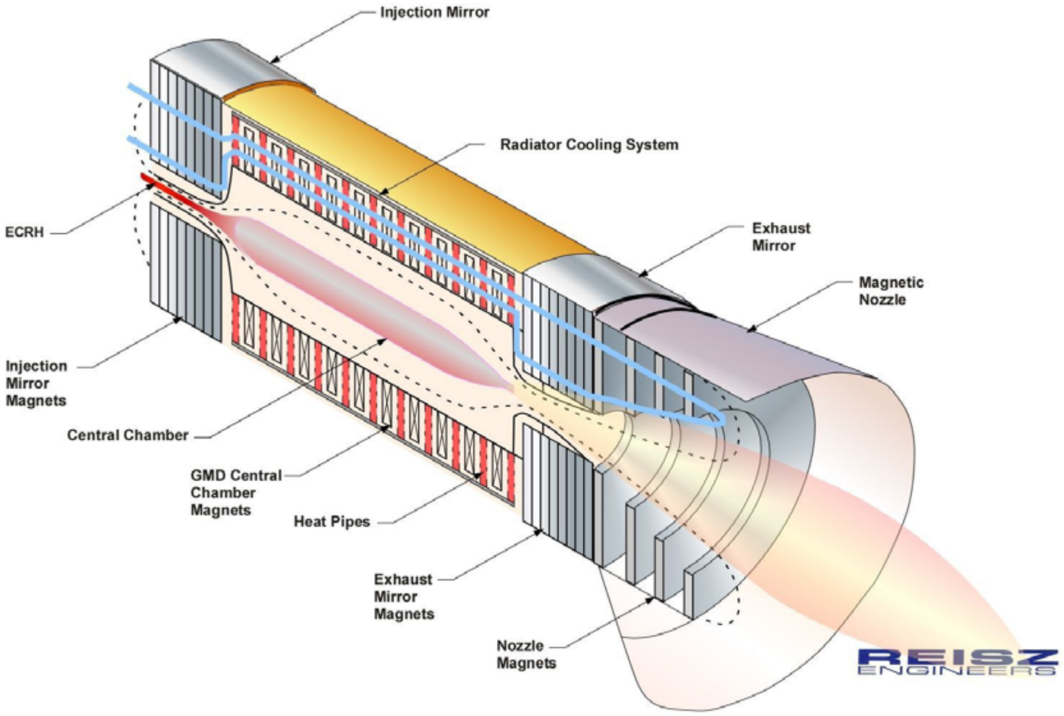

Figure 1. Conceptual drawing of an ECR-GDM thruster. Courtesy of Reisz Engineers.

Due to the strong resonant interaction with free electrons, electron cyclotron resonance heating (ECRH) is able to produce a high density plasma on the order of $10^{18} – 10^{19}$ m^{-3} with an electron temperature of several eV's. An ECR plasma source is particularly suited for the GDM. The magnetic coils required for ECRH is already part of the GDM configuration, and the ionization zone will be in the GDM chamber where the electron cyclotron frequency matches the microwave frequency. In order for the microwave to be absorbed by the plasma, the wave must be launched from the high magnetic field side, i.e. region with decreasing field gradient. This condition can be readily satisfied by the GDM, since it has higher magnetic field at the mirrors than at the center. The microwave will be launched axially through the non-thrusting mirror and absorbed inside the chamber.

A. Microwave Source

A magnetron operating at 2.45 GHz will serve as the microwave power generator, with microwave power varying between 1 to 2 kW. Figure 2 illustrates the system configuration. WR284 waveguide is chosen for the system. Although the established frequency range for WR284 is 2.60-3.95 GHz, it is widely used in 2.45 GHz set up with great success and is the preferred choice for 2.45 GHz operation at average power levels up to 6 kW. It is more compact than WR340 (which has an established frequency range of 2.20-3.30 GHz) and is less costly. In addition, WR284 waveguide components are readily available from various vendors.

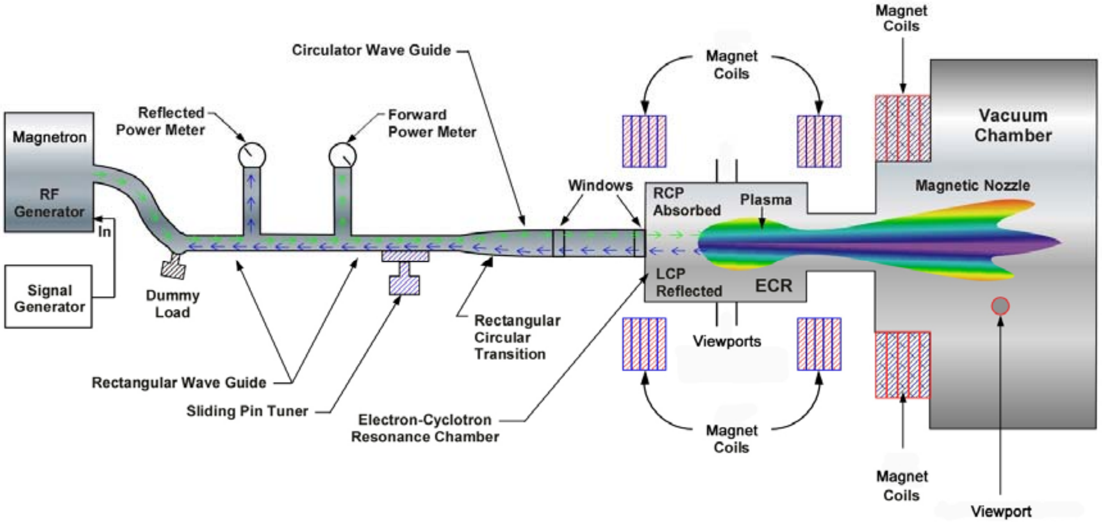

Figure 2. Experimental setup for the microwave source.

A 3-port circulator connected to a dummy load is placed after the waveguide launcher to absorb any reflected power and prevent damage to the magnetron. Downstream from the circulator is a dual-directional coupler with a pair of crystal detector diodes allowing us to monitor the forward and reflected microwave power via meters. A manual 3-stub tuner is placed upstream of the microwave window for impedance matching. Finally, a rectangular-circular transition waveguide converts the dominant TE_{10} mode in the rectangular waveguide into a circularly polarized wave for launching into the plasma generator.

B. Mode Converter

In order to provide a strong resonant interaction with the plasma electrons, the wave needs to be right circularly polarized, with its electric field vector rotating in the same direction as the electron motion in the presence of a magnetic field. When the wave frequency matches the electron cyclotron frequency, resonance occurs and energy is efficiently transferred from the wave to the electrons. Equation (6) gives the resonant magnetic field B_{ECR} for a given wave frequency f_{RF}. For $f_{RF} = 2.45\,\text{GHz}$, resonance occurs in region with $B_{ECR} = 875\,\text{G}$.

$$B_{ECR} = \frac{2\pi m_e}{e} f_{RF} \tag{6}$$

Since standard waveguides are rectangular, it is necessary to convert the linearly polarized TE_{10} wave into the lowest order circularly polarized TE_{11} mode. The first step is therefore to convert the wave into a linearly polarized TE_{11} wave by connecting the rectangular waveguide to a circular waveguide. Bathker demonstrated a compact and efficient way of doing this by using a single-section, quarterwave guide wavelength impedance-and-mode-changing transition (transformer),* which is more compact than a typical taper and usually better performing. It preserves mode purity (the TE_{11} output) and is shown to be higher-order mode free.[6] Based on this technique, to connect the rectangular WR284 to a circular TE_{11} waveguide of diameter 3.329″ requires a waveguide with dimensions of $a = 3.075''$ by $b = 2.112''$, the corners of which are to be truncated by the 3.329″ diameter. Figure 3

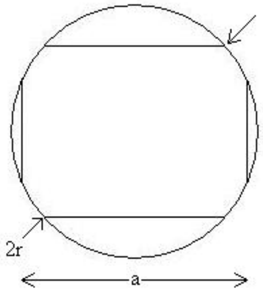

Figure 3. Cross section of the transition waveguide for connecting a rectangular waveguide to a circular TE_{11} waveguide of diameter $2r$.

---

* Bathker, D. A., "Simple Rectangular to Circular Microwave Waveguide Transitions," 2004. http://www.ham-radio.com/sbms/techpapers/K6BLG/circ_rect.html

illustrates the cross-section of this transition waveguide. Its length is 2.165″, calculated based on the quarterwave guide wavelength.

Once the wave is converted to the TE_{11} mode, it propagates down the circular waveguide and eventually enters the polarization converter,[7] which is formed by squeezing (with a precision vise) the circular waveguide between two stainless steel blocks forming a flattened circular shape with an effective major (r_2) and minor (r_1) axis. The converting section is oriented such that these axes are tilted 45° with respect to the polarization of TE_{11} wave. This causes the original TE_{11} wave to split into two equal-amplitude linearly polarized TE_{11} waves with polarization being parallel to the major and minor axes, respectively. The two waves travel at different phase velocities, and after propagating a sufficient distance to cause a 90° phase difference, which is the condition that determines the length of the polarization converter, the waveguide returns to the circular shape and the two waves recombine and become a circularly polarized wave, which then continues to propagate toward the plasma chamber. The orientation of the converting section relative to the polarization of the original TE_{11} wave determines whether the resultant wave is right or left circularly polarized. Chang et al.[7] constructed a converter operating in the *S* band and optimized for 2.45 GHz with a 97% conversion efficiency, and we will utilize their design. The section, made of aluminum, is 33 cm long with an average radius of ~4.6 cm and a major-to-minor radius ratio (r_2/r_1) of ~1.06, which translates into $r_1 = 44.66\,\text{mm}$ and $r_2 = 47.34\,\text{mm}$.

C. Magnetic Field Configuration

Our current proof-of-concept design of the ECR-GDM device consists of three main sections: an upstream mirror that serves as the ECR zone, a central section, and a downstream mirror that serves as part of the magnetic nozzle. In addition to serving as the ECR plasma generator, the upstream mirror is where the highest magnetic field occurs in order to bias the ion flow to the downstream mirror/magnetic nozzle. The high field gradient also limits plasma backstreaming, which if allowed to occur could break the ceramic microwave window. The central section is the plasma confinement section and should ideally have a high aspect ratio and uniform magnetic field as described in Section II. Finally, the magnetic field of the downstream mirror is an important design parameter, since it plays an important role in determining the propulsive capabilities of the GDM.[5]

Figure 4 shows the axial magnetic field for our design. The rectangular boxes at the bottom of the figure represent the magnet coils and their position. The overall system is 33″ in length, and the three sections can be seen in the figure, with the upstream mirror starting at the *x* = 0 position. Our design of the upstream mirror currently

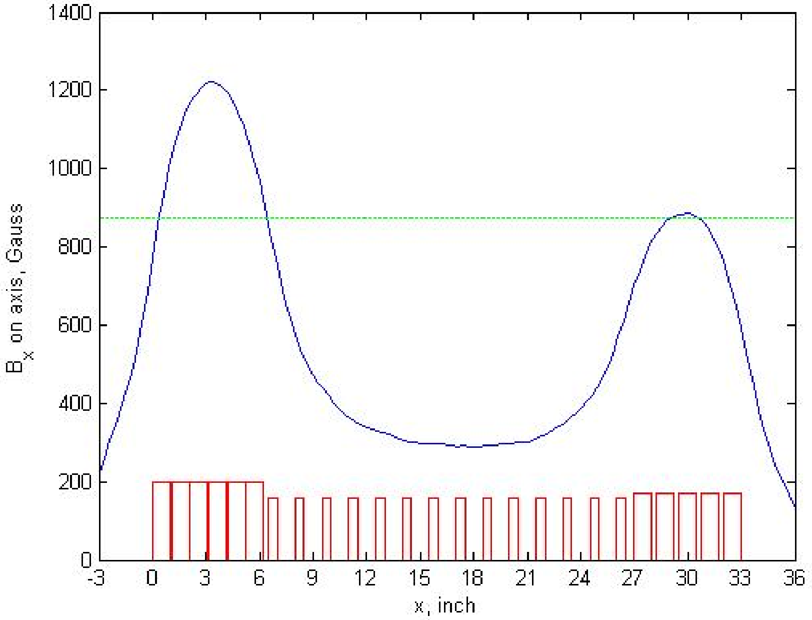

Figure 4. Axial magnetic field profile for our current design. The rectangular boxes represent the width and position of the magnet coils of the GDM. The green dotted line denotes the resonant magnetic field of 875 G.

consists of 6 coils, each with 147 turns and a current of 25 A per turn. The central section consists of 14 coils, each with 241 turns and 3.5 A per turn. More coils can be added to increase the aspect ratio and the region of uniform magnetic field if desired. The downstream mirror consists of 5 coils, each with 152 turns and 20 A per turn.

The horizontal line in Fig. 4 denotes the resonant magnetic field of 875 G for a 2.45 GHz microwave source. As we can see, this occurs right at the entrance of the upstream mirror and also at the 'throat' region between the upstream mirror and the central section. Naturally, we want resonance and plasma formation to occur at the latter location. This can be easily accomplished by a combination of methods. For instance, by injecting the neutral gas near the 'throat' region using a quartz tube, slightly adjusting the magnetic field so that only the desirable resonance zone remains, and putting the microwave window inside the upstream mirror such that the upstream resonance zone is effectively outside of the vacuum system. Finally, the 875 G region in the downstream mirror is of no significance since the microwave energy will have been absorbed by the plasma before it reaches that point.

IV. Conclusion

In this paper, we have described the gasdynamic mirror thruster concept and outlined a proof-of-concept design for an experimental ECR-GDM device that we plan to build and test. Electron cyclotron resonance heating was chosen because of its strong interaction with free electrons and because it lends itself readily for plasma formation in the GDM. We note that the magnetic field configuration presented here, while relatively detailed, is not necessarily finalized. Small tweaks can be made easily to the design for instance to further increase the field strength at the upstream mirror or increase the mirror ratio of the downstream mirror. Likewise, additional coils can be added to the central section to increase its aspect ratio and magnetic field uniformity. The goal of our experiment is to characterize our ECR plasma, such as plasma density and temperature profiles as well as ion energy distribution, and obtain other plume measurements. Magnitude of the ambipolar potential is another quantity we would like to investigate in order to validate its effectiveness in accelerating the ions.

Acknowledgments

R. Tang would like to thank Reisz Engineers of Huntsville, AL, for giving him permission to use their images.

References

[1] Mirnov, V. V., and Ryutov, D. D., "Linear Gasdynamic System for Plasma Confinement," *Sov. Tech. Phys.*, Vol. 5, 1979, pp.279.

[2] Kammash, T., and Lee, M. J., "Gasdynamic Fusion Propulsion System for Space Exploration," *Journal of Propulsion and Power*, Vol. 11, No. 3, 1995, pp. 544-553.

[3] Nagornyj, V. P., et al., "Flute Instability of Plasma in a Gasdynamic Trap," *Nuclear Fusion*, Vol. 24, 1984, pp.1421.

[4] Zhitlukhin, A. M., et al., "Confinement of a Hot Plasma with $\beta \sim 1$ in an Open Confinement System," *JETP Letters*, Vol. 39, 1984, pp.293.

[5] Kammash, T., and Tang, R., "Propulsive Capability of an Asymmetric GDM Propulsion System," *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Sacramento, CA, July 2006.

[6] Bathker, D. A., "A Stepped Mode Transducer Using Homogeneous Waveguides," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 15, No. 2, 1967, pp. 128-130.

[7] Chang, T. H., et al., "Dual-Function Circular Polarization Converter for Microwave/Plasma Processing Systems," *Review of Scientific Instruments*, Vol. 70, No. 2, 1999, pp. 1530-1534.