Beam Propulsion

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ASEN 5053 Rocket Propulsion

Chuck Vaughan

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Introduction

Beam power can be described as the transmission of electromagnetic radiation or particles from a source to a vehicle that requires power [5]. The most common beam power source today is the sun. The sun transmits electromagnetic energy which is used in a limited capacity on earth and is the primary source of energy for satellites in space. However, the energy from the sun is across many frequencies thus it is necessary to design solar cells that can pick up these frequencies, which results in a loss of efficiency. It is with this thought that the concept of beam power was born. Several different technologies have been pursued with the idea of sending very concentrated beams of electromagnetic energy over vast distance to power spacecraft. The potential payoffs of this technology would result in lighter spacecraft and potentially much higher speeds then conventional chemical propulsion systems. The following paper will discuss two of these concept areas: Microwave Beam Propulsion, and Magnetized Beam Plasma Propulsion. All of these concepts are in their infancy and have yet to be proven with a full scale test. This paper will take a look at two studies that were formulated to test the concept of these two ideas. This will result in a closer look at the technology used to generate the beam power, the tests that were conducted to prove the concept, and possible future applications. The following is a deeper discussion of each concept.

Microwave Beam Propulsion

Microwave power transmission was first conceived in 1968 by Dr. Peter Glaser. He envisioned a large satellite in geosynchronous orbit that would gather power using solar cells and beam the energy back to earth. This idea has been expanded upon in recent years to include the transmission of microwaves to distance satellites and spaceships as a means of propulsion. In 1983 a team of Japanese scientists successfully transmitted energy though the ionosphere to two rockets. Then in 1995 Professor Nobuyuki Kaya and his team were able to transmit electricity to an airship from the earth surface [4]. Today microwave transmission is still constrained to small scale concept tests because of its enormous cost. One recent test held by Mitsubishi Heavy Industries tested the efficiency and feasibility of microwave transmission in a lab environment. The concept that was tested was based on the idea of a 1 to 10 GW power satellite at 36,000km transmitting at frequencies between 2.45GHz and5.8GHz [2]. The following is a description of the equipment used and the results from the test.

System Architecture and Design

The system consisted of three parts: The microwave power transmission subsystem, the beam forming and control subsystem, and the microwave receiving and power rectifying subsystem. The system diagram can be seen below in figure 1 [2].

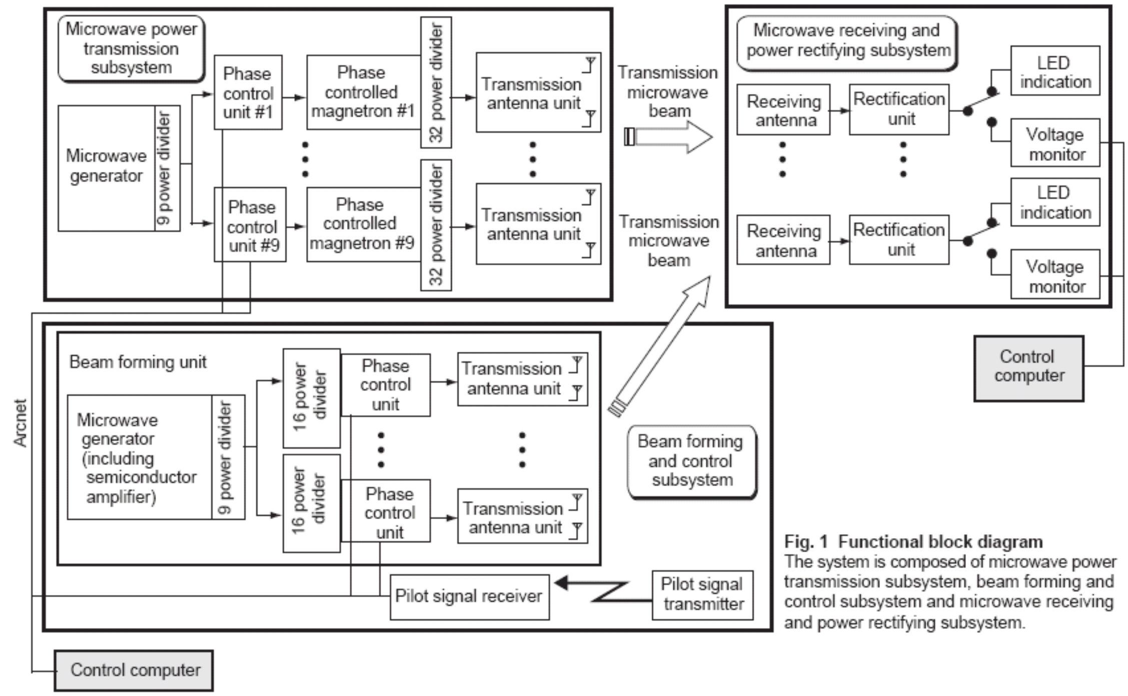

Figure 1: Microwave system block diagram [2]

The microwave power transmission subsystem uses magnetrons as a means of generating the microwaves. Magnetrons are high powered vacuum tubes that are commonly used to generate microwaves in radar applications. The figure below gives a cross section description of the Magnetron.

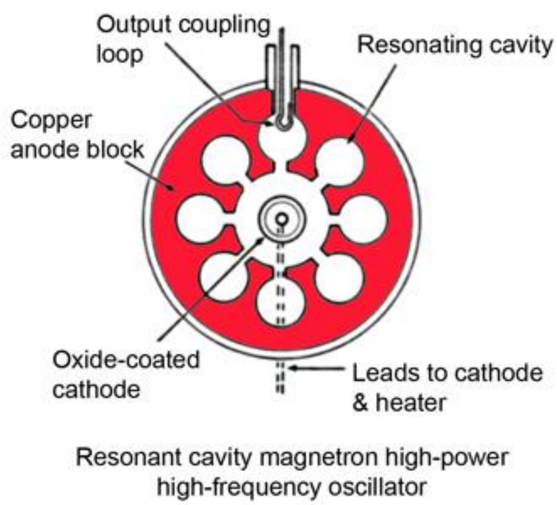

Figure 2: Magnetron Cross Section [3]

The center of the Magnetron cathode is powered by high DC voltage. The Cathode tube is surrounded by magnets that create a perpendicular magnetic field. This causes the electrons in the cathode to move outward in a spiral motion. The electrons then move past the resonating cavity which creates a high radio frequency. This field is then attracted using an antenna and fed into a wave guide. The wave guide then sends the microwaves to the beam forming and control system. The system operates by having several magnetrons working together to help control the transmission phase thus allowing for beam steering. Because of the frequency standardization featured in the magnetron it is possible to use one oscillator that is connected to all the Magnetrons to create a uniform signal. The system will use 9 Magnetrons 288 antenna pieces with a total power output of 1.26KW. The hardware for this subsystem can be seen below in figure 3 [2].

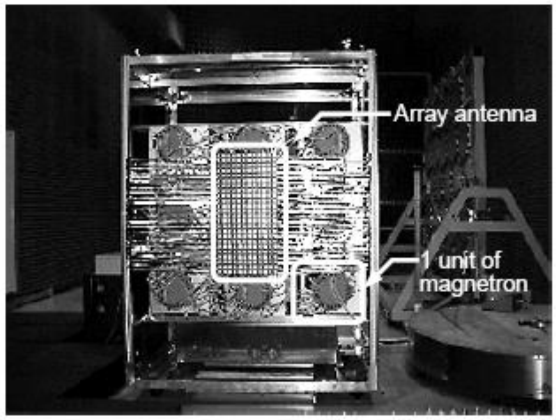

Figure 3: Microwave Generator and Transmitter Subsystem [2]

The second part of the system is the Beam forming and Control aspect of the system. The system uses semi-conductor amplifiers as the means of beam control. Semi-conductor amplifiers are simply amplifiers used for “low power” applications of signal boosting. The microwave power is first magnified using the amplifiers. The frequencies are then standardized using a Phase Locked Loop system. To ensure accuracy the system is equip with a pilot signal transmitter and receiver so the receiver can communicate to the transmitter its accuracy. The beam forming system can be seen below in figure 4 [2].

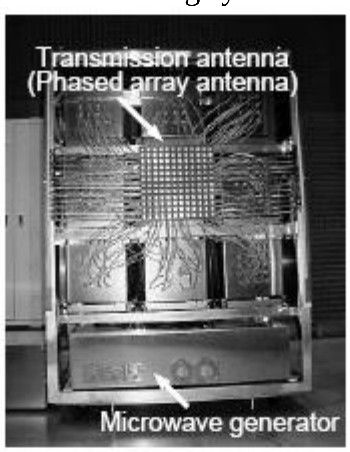

Figure 4: Beam Forming and Control subsystem

The final subsystem is the receiving system. This subsystem was designed to be transportable, because of the need to be a safe distance from people due to the high power density. The system consists of several small receiving and rectifying panels that can be easily assembled together. Also the system as a whole can detect the incoming angle of the signal as discussed earlier. A description of the incoming angle can be seen below in figure 5 [2].

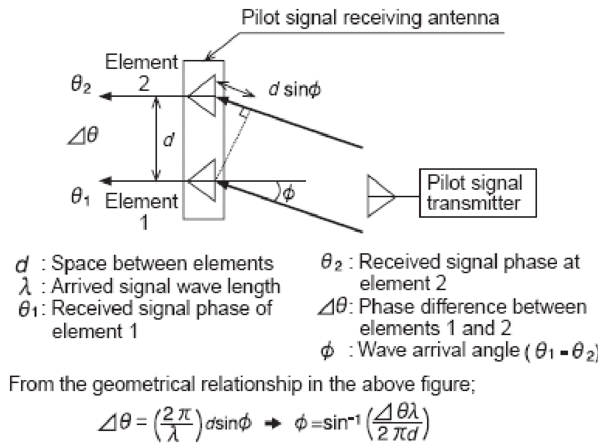

Figure 5: Receiver Phase Angle Detection [2]

Experimental Results

The results of this experiment show promises for this technology. The two main areas of concern for beam power are the beam steering ability and the amount of power absorbed by the receiver. Figure 6 shows the results form the beam steering tests.

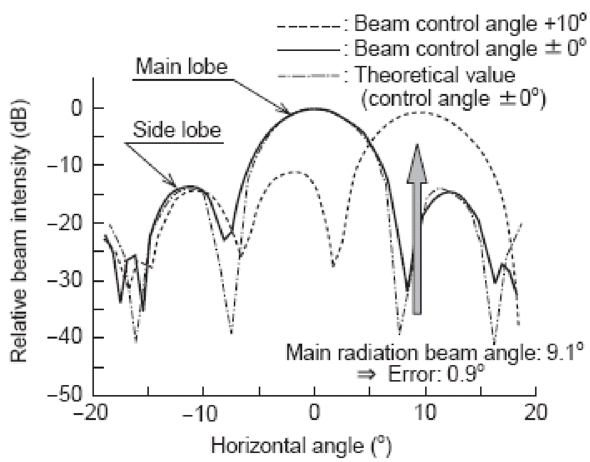

Figure 6: The plot shows the beam power received relative to the reviver angle. [2]

This plot shows that beam steering is a good method for steering the microwave transmission. This is important because receiver for a propulsion system is not always going to be orthogonal to the antennas. This will ensure that losses will not be incurred due to angle changes. Also the antenna is able to rectify a maximum of 71.8% of the microwave power received. This means that of the original power from the plant a total of 50.6% makes it to the engines if electrical conversion is being used [2].

Applications

There are two main applications for a microwave beam power propulsion system: Thermal propulsion and electric propulsion. Thermal propulsion is a direct use of the microwaves to heat up a propellant. For this type of application it is necessary to try and maximize the Isp.

Equation 1: Isp Equation [6]

$$I_{Sp} = \frac{1}{g_0}\sqrt{\frac{(2\gamma)}{\gamma - 1}\left(T_c R / \overline{M}\right)}$$

This equation indicates that the two most important factors in the propellant are the Temperature and the molecular mass. Because the power source is separate from the propellant the only factor that can be controlled is molecular mass. For this application hydrogen would be best suited because it has the smallest atomic mass however it disassociates at high temperatures, so helium can also be used [6]. This type of engine has efficiency between 65% and 85%. Thus if we assume a maximum 85% efficiency a total of 59.9% of the original power plant power will be used for propulsion purposes. The thrust that the spacecraft receives is described in the equation below:

Equation 2: Thrust Equation [6]

$$T = \frac{2\eta P}{I_{sp} g_0}$$

This equation says that the thrust is dependent on the power and efficiency of the engine. Typical issues that are run into with this equation is that there is a practical limit to its use because as the power increases so does the mass of the spacecraft. However, if beam power is being used then the power source is separated from the spacecraft, so it is no longer a limiting factor. The result is potential unlimited thrust. Spacecraft that rely on microwave power could greatly increase in their speed without changing any of their design. The more powerful the transmitter the greater the speed attained. The plot below shows the curve of thrusts vs. transmitted power.

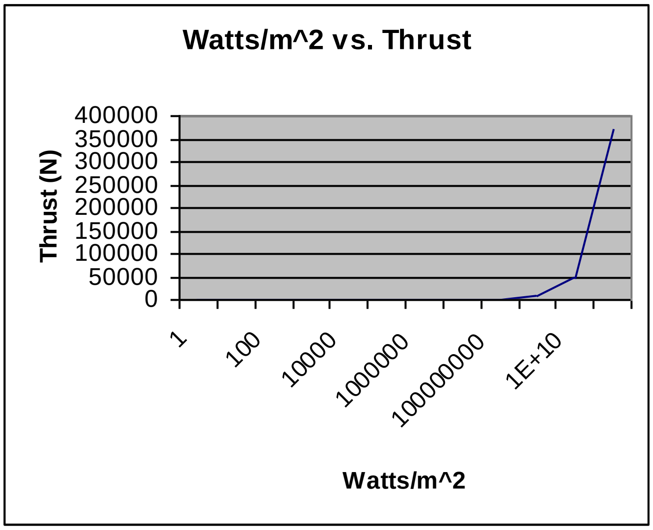

Figure 7: Transmitted Watts/m^2 vs. Thrust Generated

This plot uses the equation $E_b = \sigma T^4$ to determine the temperature rise from the microwave power transmission. This plot assumed the use of hydrogen as the propellant. It was assumed that the propellant tank was a black body, so the emitted energy is equal to the absorbed energy. The temperatures were then used to calculate the Isp's using equation 1 and then the thrust was found using equation 2. The results of this plot show a great potential for high speed thermal electric power. The limiting factor is the ability to generate the large power requirements from the microwave generation station.

The second way that microwaves can be used is by converting the energy back into electricity to run an electrostatic engine. As was stated earlier, the conversion back to electricity would result in 50.9% efficiency. This does not take into account the losses from the engine. With the addition of the engine losses the total system efficiency is approximately 40.7%. The most preferred ion to used in an electrostatic thruster is Xenon, which has a $123\frac{Isp}{\sqrt{Volts}}$ value [6]. For the purpose of examining how thrust changes a voltage of 128 was chosen. The result was an Isp of 1391s. This was then entered into equation one with changing vales of power. The figure below shows the change in propulsion.

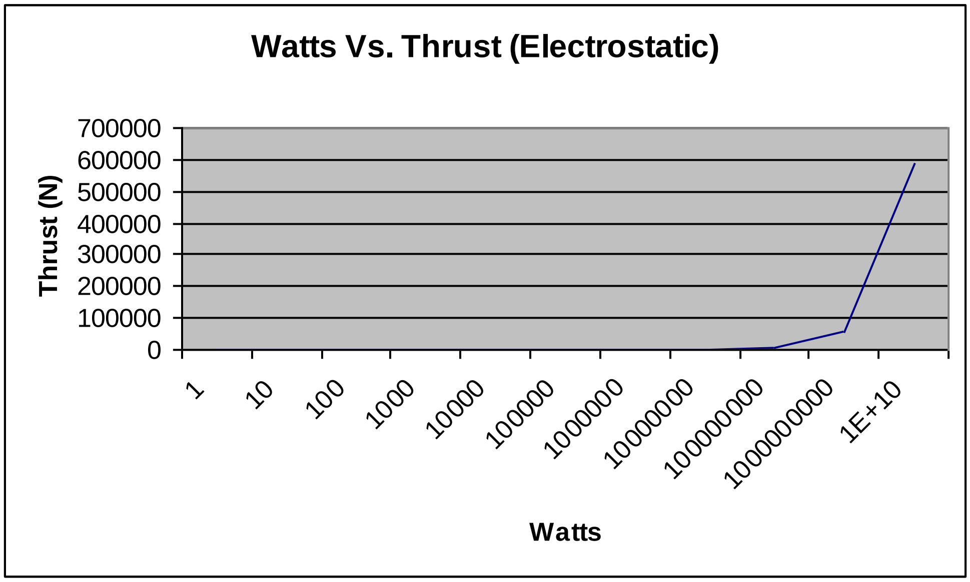

Figure 8: Thrust vs. Watts for an electrostatic engine

Again this technology shows an exponential increase in thrust as the power transmitted increases. Both of these technologies require very large amounts of power to generate high thrusts. The advantage of microwave power transmission is that the weight of the spacecraft will not need to increase with the power. The technology necessary to develop these large power supplies still needs to be developed, but this study does show that when it is we have the ability to use it for propulsion purposes.

Magnetized Beamed Plasma Propulsion

The second form of beam transmission that will be looked at is called Magnetized Beamed plasma propulsion. This concept expands on the use of propulsion systems such as the Magnetoplasmadynamic (MPD) thruster that have already been used. The MPD system in particular uses argon or hydrogen for propellant and has Isp's ranging from 2000s to 10000s. Thrusts between 20 and 100 N have been reported. These systems produce a radial electric field and an induced plasma field to accelerate the plasma from the engine. However the magnetic field can cause the plasma to be attracted back onto the spacecraft, which results in inefficiencies. A solution to this problem is to add magnetic nozzles to help focus the plasma and keep it from being attracted back to the spacecraft. If efficient magnetic nozzles can be created then there is the additional possibility that the plasma can be beamed from a power station to a spacecraft. The potential of this technology can make possible sub-orbital transfers, low earth orbit maneuvers to GEO as well as interplanetary missions. This discussion will examine the results of a proof of concept by. R. Winglee and T. Ziemba [1]. In their report they examine the concept in three main areas: Computer simulation, lab prototyping and potential uses. The following report will examine their results in these areas.

System Architecture and Design

The concept of plasma flow is determined by three main ideas: The ratio of bulk speed to the ion thermal speed, plasma beta (the ratio of plasma pressure to magnetic pressure, and the ratio of ion gyroradius, which is the radius of a charged partial in a magnetic field, to the size of the magnets. If beta is low then the plasma will travel along the magnetic field lines and contribute nothing to the thrust, the higher the value of beta the greater the ability of the plasma to break the magnetic field and leave the spacecraft. The thrust is also affected by a large gyroradius which can cause the plasma to travel in a pattern that is not optimized. The magnetic field is important because it helps stabilize the plasma beam. The following figure shows what this would look like [1].

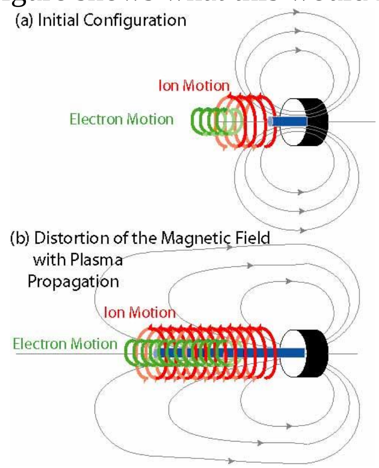

Figure 9: a) low energy density beam b) high energy density beam [1]

Part (a) from figure 9 shows the motion of the plasma in the case where beta is small and the ratio of ion gyro-radius is large. The second part of the picture shows the how the magnetic field will change if a larger beta is used and the ion gyro-radius is small. The rotation of the ions and the electrons generates a current which intern creates its own magnetic field. The result is a denser plasma beam that can distort the original magnetic field. The stretching of the magnetic field is important because it helps stabilize the plasma beam. Then if the spacecraft in which the power is being beamed also contains a dipole this will allow for the two systems to be tied together and a stabilizing magnetic field to be produced around the entire plasma beam [1]. This can be seen in figure 10 below.

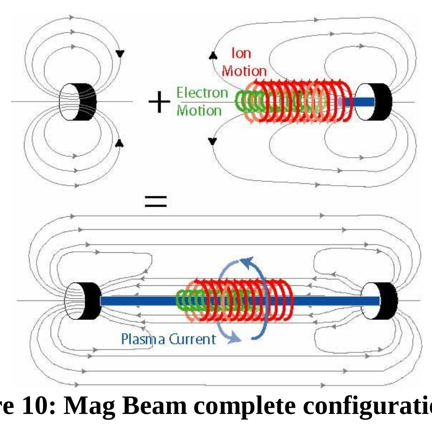

Figure 10: Mag Beam complete configuration [1]

This system will create a magnetic attraction between the two systems; however the plasma force will be much greater than the magnetic attraction. The difficulty in this setup is creating an initial plasma beam that is power dense enough to create this extended stabilizing magnetic field. The idea being tested is to use magnetic nozzles to keep the plasma from spreading along the magnetic field lines. This will allow the plasma to move far enough away from the generator to escape its magnetic pull [1]. The setup of the system can be seen below in figure 11.

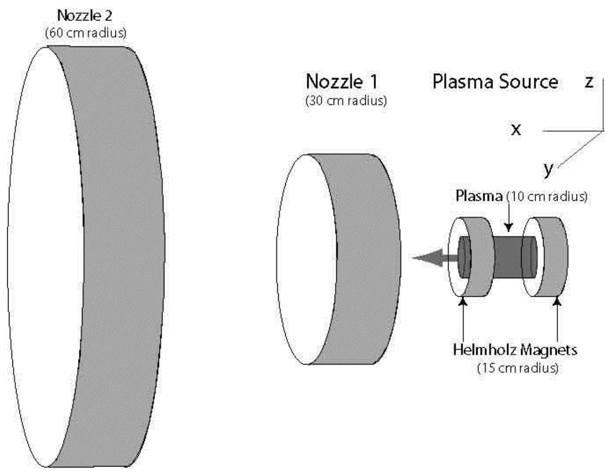

Figure 11: Magnetic Nozzle Setup [1]

The nozzles proposed not only help maintain the beam but also increase the efficiency of the engine.

Computer Simulation Results

The computer simulations were conducted to create a theoretical basis to measure the experimental results. The computer simulation uses a simulated setup as seen in figure 11. The first simulation was conducted assuming no magnetic nozzles. The Helmholtz coils are assumed to have a 15cm diameter and a field strength of 200G. The plasma was injected at 30km/s with a beta of .5 [1]. Figure 12 shows the propagation of the plasma under these conditions.

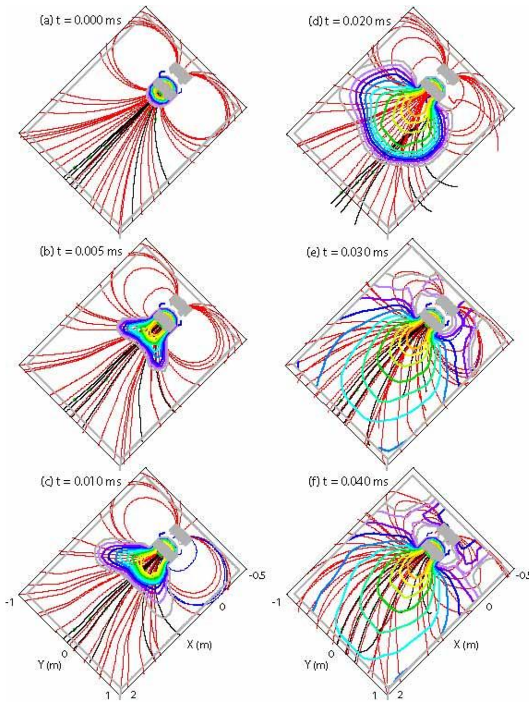

Figure 12: Plasma propagation with out magnetic nozzles [1]

The plasma in figure 12 is seen to suffer from substantial spreading, with the majority of the plasma escaping the magnetic fields. The wide angles that the plasma is leaving at cause the system to be less efficient [1]. Next, a nozzle is added to the system to see what a difference it makes to the plasma spreading.

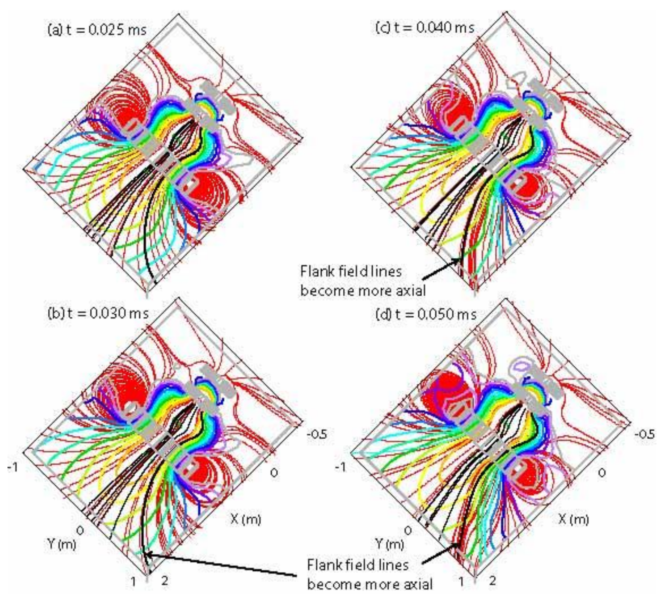

Figure 13: Plasma propagation with one magnetic nozzle [1]

The plots indicate that the addition of the nozzle causes greater plasma density and a greater propagation of the plasma in the x-direction. This plot also shows that as time goes on the system begins to experience self focusing due to the generation of a magnetic field by the plasma [1]. To further test these findings a second magnetic nozzle was added to the system.

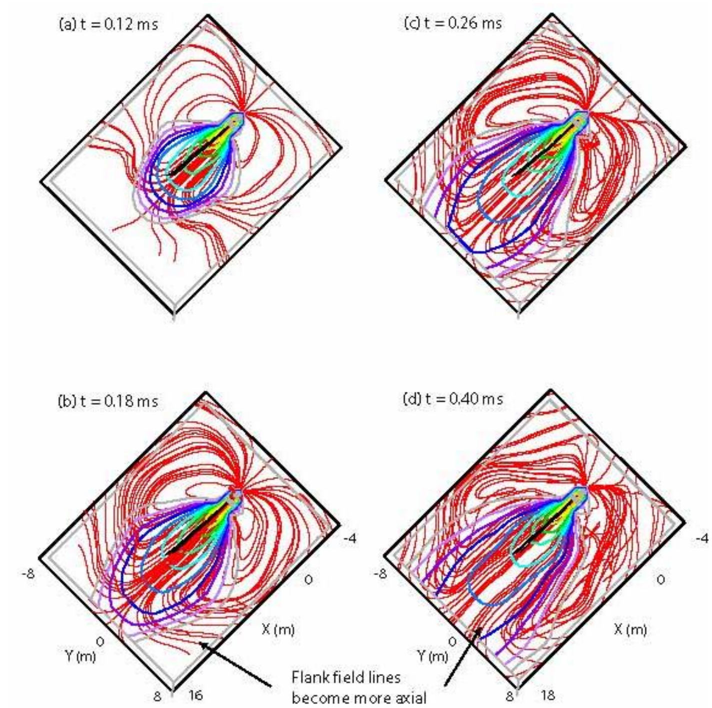

Figure 14: Plasma propagation with the addition of a second magnetic nozzle [1]

The plot shows that the addition of a second magnetic nozzle further increases the beam density as well as the self focusing. Parts (b) and (d) are compared in the plots and they show how the field lines become more axial as time increases. This means that as the beam travels over large distances it will be able to maintain its density with little loss [1]. The simulation results show the potential such a system. The next step is to test these results with an experiment.

Experimental Results

The experimental results attempt to demonstrate that the results found in the computer simulation can be duplicated in a laboratory test prototype. The system is going to use a 10KW-100KW HPH generator and operate between 300 KHz and 1 MHz. The propellant chosen for the experiment was argon. The system will have two magnetic nozzles at 30cm outer diameter. The first nozzle has a fixed poison from the HPH of 10cm, while the second nozzle is on a moving track. Plasma probes will be mounted along the chamber to measure the density. The first test is too see how the plasma diffuses with no magnetic nozzles [1].

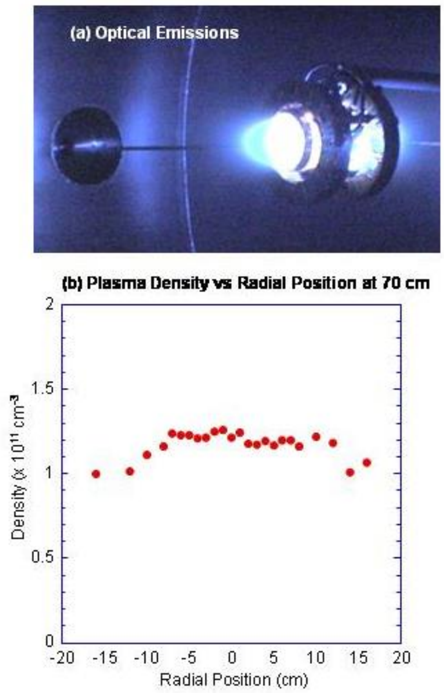

Figure 15: Plasma density as distance increases from the HPH with no nozzles [1]

This profile shows the density of the plasma 70cm from the HPH. From the picture it is clear that the plasma is spreading. The plot shows the density relative to the radial position. This clearly shows that the plasma is very diffuse at this distance [1]. The next experiment called for the addition of one magnetic nozzle.

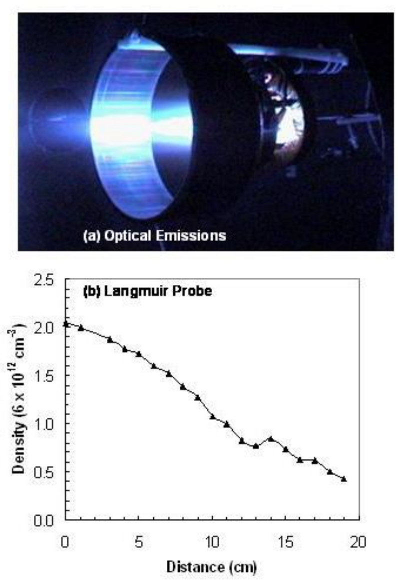

Figure 16: Plasma flow with the addition of one magnetic nozzle

The addition of one magnetic nozzle showed a 6 fold increase in plasma density at 65cm. This can be visually seen in figure sixteen, the plot shows how the plasma density is decreasing as it leaves the HPH [1]. It should be noted that the y-axis on figures 15 and

16 have the difference of a factor between them. The final test was to see how adding the second magnetic nozzle impacted the beam density.

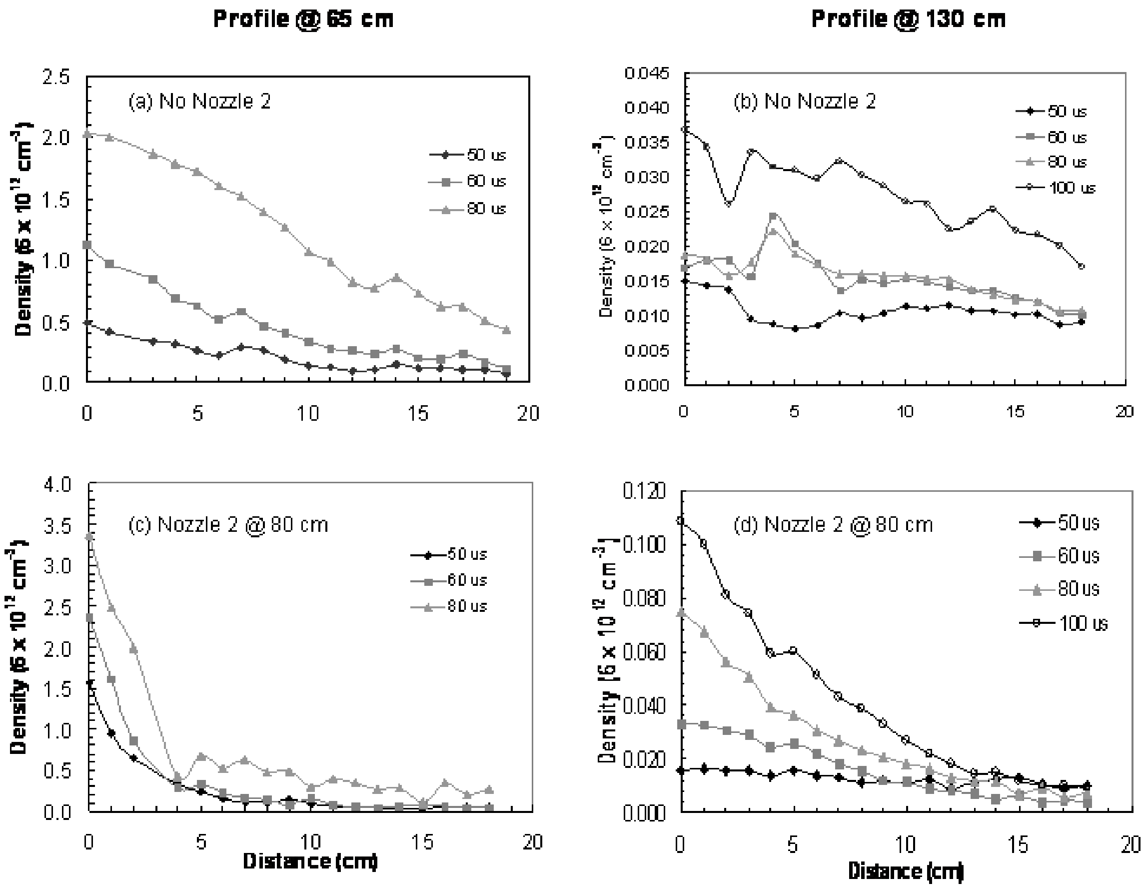

Figure 17: Beam density at different nozzle locations [1]

These plots show how the plasma converges to a density at different times and distances. What these plots suggest is that the addition of a second nozzle more quickly causes the plasma to settle to its natural density. The results also found that as the distance from the HPH increases the beam width converges to a diameter of 20cm with one nozzle. The addition of the second nozzle causes the diameter to converge to approximately 10cm. What this suggests is that the plasma beam is using self-focusing to maintain the beam width. Thus with a high power system it would be possible to send a plasma beam tens of thousands of kilometers. With this data gathered Dr. Winglee and Dr. T. Ziemba theorized about conditions that would limit the beams use. They found that plasma instabilities occurred when the beam travels through atmospheres with equal density to the beam, namely the ionosphere. Also ambient magnetic fields would effect the beam propagation as well as diffusion of the beam over great distances [1]. Despite these limiting factors several scenarios were created where this technology could be applicable.

Future Applications

The scenarios that are suggested assume a very large platform for the Mag beam and a 10,000kg payload for a spacecraft. Because the fuel and power are not on the spacecraft the equations used can simply be the momentum equation: $M_{payload}\,\Delta V = 2\,M_{propellant}\,V_{propellant}$. The reason for the 2 is that it is assumed that the beam is reflected off the payload. The first scenario calls for a sub-orbital satellite to be raised to a LEO orbit. It would require a change in velocity of about 3km/s. If an Isp of 2000 were used and it is assumed that there is only a 5 minute window to create this velocity the Mag beam would need to 500MW of power to the spacecraft. It would take a total of 10 of these maneuvers to break even, relative to chemical rockets. If then from this low earth orbit the spacecraft was to be launched into a geosynchronous orbit a change of velocity of 1.5km/s is needed. This would only cost the Mag beam 1000 kg of propellant, far less then a traditional rocket launch. From this point if an interplanetary mission were desired an additional 3km/s is required for an escape velocity. A traditional rocket would require 65,000kg of propellant. The costs benefit of using the mag beam would be realized in 1 to two launches [1]. These scenarios can be seen in the figure below.

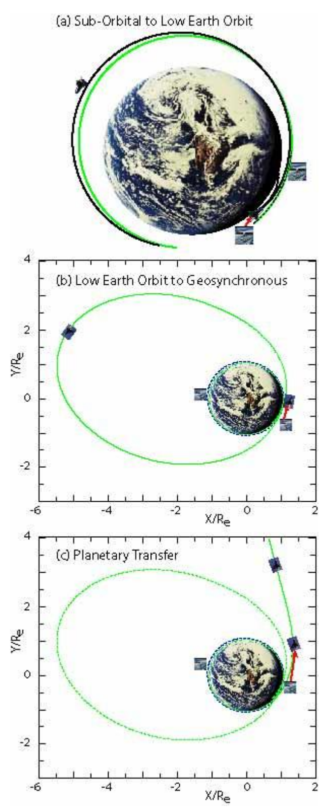

Figure 18: mission scenario descriptions [1]

For a fast mars transfer, velocities in excess of 20km/s are required with an Isp of approximately 4000s. The Isp can be changed by simply using a different propellant in the mag beam system. To achieve this transfer, 7000kg of propellant would be required as well as a mag beam station at mars that can slow the spacecraft when it is approaching mars. The amount of mass required for a standard rocket mission would be 2x10^7 just for the outward portion of the mission. For applications such as mars exploration a mag beam propulsion system would be very desirable.

Conclusion

We are already beginning to see the drawbacks from traditional chemical rockets. Their large propellant requirements limit the amount of payload that can be moved in space. The ability to separate the power system from the rest of the spacecraft would eliminate the exponential increase in spacecraft weight. Either of the two designs discussed above could prove to be the answer to this problem. The microwave transmission allows for power to be transmitted and converted into electricity or heat. It is a very versatile technology that will still give lots of steering control to the pilot of the spacecraft. The mag beam proposal offers huge propellant savings from conventional rockets and removes both the power system and the propellant from the spacecraft. This technology has the ability to provide a very large change in velocity in a short period of time, similar to traditional chemical rockets. Both of these technologies are in their infancy and have years before they are ready to be used in a full scale application. However the preliminary tests show a promising future for this technology. Beam propulsion could possibly be the key to the next generation in space exploration.

References

1) Winglee, R, and T Ziemba. Magnetized Beam Plasma Propulsion (MagBeam). NASA's Institute for Advanced Concepts. 2005. 16 Dec. 2007.

2) Iizuka, Kenji, Keiichi Morishita, Hiroki Makimura, Kozo Hashimoto, Osamu Hasegawa, Tomohisa Kimura, Hiroshi Matsumoto, and Naoki Shinohara. Technology and Applicationsof Microwave Power Transmission. Mitsubishi Heavy Industries. 2004. 16 Dec. 2007 <www.mhi.co.jp/tech/pdf/e406/e406340.pdf>.

3) "Resonant Cavity Magnetron Diagram." Google Image. 13 Nov. 2007 <http://content.answers.com/main/content/wp/en/9/99/Resonant_Cavity_Magnetron_Diagram.png>.

4) Gomes, Pedro. "Microwave Power Transmission." Infosatellite.Com. 20 Jan. 2003. 7 Nov. 2007 <www.infosatellie.com/news/2003/01/p200103microwave.html>.

5) Frisbee, Robert H. "Advanced Sace Produlsion for the 21 Century." Journal of Propulsion and Power 19 (2003): 1129-1154. 7 Nov. 2007 <culearn.colorado.edu>.

6) Kantha, Lakshmi H. "Electric Propulsion." Rocket Propulsion. University of Colorado. 7 Nov. 2007 <culearn.colorado.edu>.