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An RF Plasma Thruster for Use in Small Satellites

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Abstract. New England Space Works is developing an RF plasma thruster for use in small satellites. The RF plasma thruster is an excellent choice for small satellites because it is compact, low power, and does not require high voltages to operate. Specific impulse can be varied over a range of 1500-3000 seconds. Electric propulsion is finally entering the spacecraft mainstream. Deep Space 1 was the first spacecraft to use an ion thruster as primary propulsion and electric propulsion is in use for north-south stationkeeping on many communications satellites. Research is active on electric propulsion for small satellites, although limited to date by the low power available. The RF plasma thruster avoids the cathode propellant losses (important at low power) of Hall and ion thrusters and is more efficient than the PPT. In addition, no voltages higher than 28 volts need be supplied to the thruster. A wide range of gas flow is acceptable, so a blowdown propellant feed is possible. A breadboard thruster has been operated over a power range of 5-50 watts.

Introduction

Electric propulsion offers the promise of a great reduction in propellant required for in space propulsion. Specific impulse can be 3000 seconds or better, compared to less than 500 seconds for the best chemical thrusters. The increased specific impulse can be used to lower spacecraft mass or to make possible missions which simply cannot be done with chemical rockets. This promise has started to be met today. NASA launched Deep Space 1, the first spacecraft to use ion propulsion as primary propulsion. Several communications satellites have been launched which use electric propulsion for north-south stationkeeping and final orbit raising. Hughes (now Boeing) has estimated that propellant mass is reduced by a factor of ten on its comsats which utilize ion propulsion. Comsats are an excellent early application of electric propulsion both because of the high delta v requirements and the large amount of power available. In fact, it is not necessary to add electric power for propulsion. The electricity needed to charge batteries for eclipses is sufficient to run the thrusters. As confidence in the thrusters is gained with experience it is expected that electric thrusters will come into use in most applications with significant delta v requirements which do not have high thrust requirements.

The most mature technologies today are the gridded ion thruster, the Hall thruster, and the PPT. The ion thruster is mainly used at medium (kilowatt range) power with a specific impulse of around 3000 seconds or above. The Hall thruster is also used at medium power at a specific impulse of approximately 2000 seconds For a particular mission a tradeoff is made between time to perform the velocity change and the propellant required, so sometimes a lower specific impulse is desired, since thrust is higher at a lower specific impulse. The Hall thruster is also more compact. It is a plasma device and is not limited by space charge effects. On the other hand the ion thruster has a narrower plume. Research on increasing the power and specific impulse ranges for both devices is active.

The PPT (Pulsed Plasma Thruster) is used at low powers. A solid teflon bar is spring mounted. An arc across the end both vaporizes the teflon and accelerates the resulting plasma. It is a very simple device, but suffers from low efficiency because teflon continues to vaporize after the end of the pulse and is not accelerated. The power is generally less than 100 watts and can be reduced to any desired level by reducing the pulse repetition rate. The PPT is also excellent for providing a precise impulse bit per pulse.

There is currently significant effort allocated to low power Hall and ion thrusters, so as utilize the higher efficiency of these thrusters. There are several challenges to doing so. The Hall and ion thruster both use a hollow cathode to produce a plasma as well as a main propellant feed. At low powers the cathode propellant usage can approach or even exceed that of the main propellant feed, greatly reducing efficiency. In low power thrusters wall losses become relatively more important, again reducing efficiency. In addition, tolerances become finer in low power thrusters, making fabrication more difficult.

The RF plasma thruster can solve these three problems, while having other advantages and disadvantages compared to Hall and ion thrusters. There is only a single propellant feed, so there are no hollow cathode losses. The magnetic field is aligned parallel to the walls, reducing wall losses with magnetic insulation. There are no fine tolerances in fabrication.

In the sixties a variety of electric thruster concepts were tried, including the Hall, gridded ion thruster, and the RF plasma thruster[8]. In the United States, the gridded ion thruster became the favored concept. The Hall thruster was de-emphasized primarily because of instabilities, the RF plasma thruster because of poor efficiency. In the former Soviet Union, a lot of effort was thrown at the Hall concept and Hall thrusters (called SPT for Stationary Plasma Thruster by the Russians) began to appear on Russian spacecraft after 1972, although this was not known in the West until after the Cold War. It is the goal of the present work to mature the concept of the RF plasma thruster. Modifications have been made to address previous shortfalls in RF plasma thruster performance.

Principle of RF Plasma Thruster Operation

In an RF plasma thruster[3], plasma in a magnetic field is heated with RF excitation, and flows out axially, producing thrust. Only electrons are heated directly by the RF. The electrons flow out much more rapidly than the ions due to high thermal velocity. A potential is created which retards electrons and accelerates ions to maintain quasineutrality. The magnitude of the potential may be found by equating electron and ion currents. All of the ions flow out with a velocity set by the potential.

$$j_{ion} = n_e e \sqrt{\frac{2\phi}{M}}$$

where:

j_{ion} = ion current **(1)**

n_e = electron density

e = electron charge

ϕ = plasma potential

M = ion mass

Only electrons which have energies greater than the plasma potential escape. The electron temperature of the escaping electrons is the same as the original electron temperature after they pass through the potential. The electron current may therefore be written as

$$j_e = n_e e \sqrt{\frac{2k_BT_e}{m}}\, e^{\frac{-e\phi}{k_BT_e}} \qquad \textbf{(2)}.$$

where:

T_e = *electron temperature*

m = *electron mass*

k_B = *Boltzman constant*

Equating electron and ion currents leads to the following relationship between the plasma potential and the electron temperature.

$$e^{-\frac{e\phi}{k_BT_e}} = \sqrt{\frac{mk_BT_e}{M\phi}} \qquad \textbf{(3)}$$

For a given ion mass (singly charged) this relation leads to a fixed ratio between the plasma potential and the electron temperature. This ratio, with the potential in volts and the electron temperature in electron volts is plotted versus ion mass in Figure 2. Some examples for particular gases are 5.35 for xenon, 4.8 for argon, and 3.2 for hydrogen. Thus, in xenon an electron temperature of 100 electron volts leads to an ion energy of 535 electron volts.

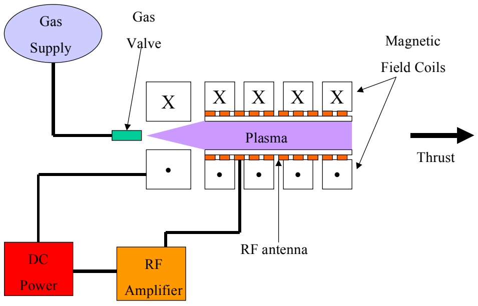

Figure 1. The RF Plasma Thruster

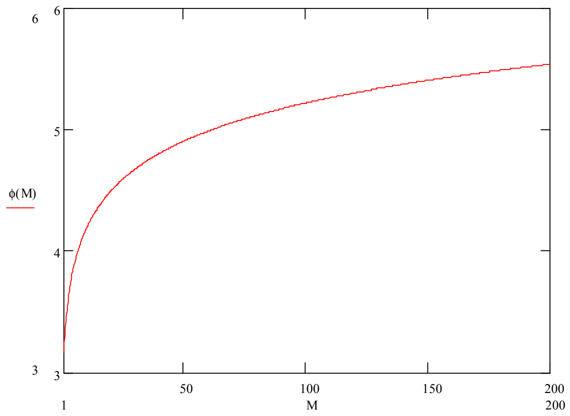

Figure 2. Plasma potential (volts) as a multiple of electron temperature (eV) versus ion mass

The energy cost per ion is the ion energy, electron energy, and ionization and excitation losses. The ion energy is the plasma potential. Excitation and ionization losses are typically twice the first ionization level for noble gases. The other major loss is due to the RF conversion efficiency. Including these factors, the efficiency may be written as:

$$\eta = \frac{\eta_{RF}E_i}{2U_i + E_i + \frac{E_i}{\alpha}}$$

η = *efficiency*

η_{RF} = *RF conversion efficiency* **(4)**

E_i = *ion energy*

U_i = *first ionization energy*

α = *ratio of ion energy to the electron temperature*

Using the efficiency calculation, the power in watts required to produce a millinewton of thrust is plotted versus specific impulse in Figure 3. As in other electric thrusters, xenon is preferred as the best compromise between convenience and efficiency. Mercury was used in early electric thrusters because of its high mass, but has been discontinued for environmental reasons. Specific impulse is increased by lowering the gas flow at a given RF power.

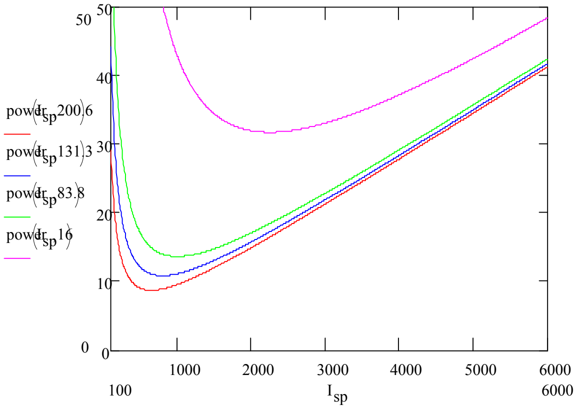

Figure 3. Predicted power in watts required per millinewton of thrust plotted versus specific impulse. Traces from top to bottom are oxygen, krypton, xenon, and mercury.

Advantages of the RF Plasma Thruster

Long Lifetime

There are no grids or electrodes in contact with the plasma to erode and fail. Lifetime will probably be limited by component failure, e.g. power RF transistors.

Low Contamination

Low contamination also derives from the lack of grids or electrodes. There are no metals to be sputtered off into the exhaust plume.

Compactness

The plasma is quasineutral, so thrust density is not limited by space charge effects as it is in the gridded ion thruster. The density can also be higher than in the Hall thruster, where the ion collisional path length should be longer than the thruster. The result is a more compact thruster.

Variable Specific Impulse

The specific impulse can easily be varied by changing the ratio of RF power to gas flow. This can be quite useful, for example by using lower specific impulse and higher thrust to raise a satellite in a shorter time and then switching to higher specific impulse to conserve propellant while stationkeeping when speed is no longer of the essence. The wide range of specific impulse possible also allows a simple blowdown propellant feed rather than a more complicated regulated flow. The specific impulse would increase as the gas flow decreases over the course of a mission if the power remained constant.

Manufacturing Simplicity

No close tolerances are required, which will decrease manufacturing expense.

Low Voltage Required from Spacecraft

A potential is created within the plasma by RF heating. The spacecraft needs only to supply the voltage required by RF transistors, typically 10-30 volts, rather than the hundreds of volts required to accelerate ions directly.

Single Gas Feed

No separate hollow cathode is required, either for neutralization or to provide a plasma to extract ions from. This is especially important for small thrusters, where the fraction of propellant lost through the hollow cathode can be quite high. It is also simpler.

High Propellant Utilization

High plasma density leads to full ionization of gas, so propellant is not wasted by escaping as neutrals.

Ability to Use Any Propellant

Since there are no grids or electrodes, the propellant can be anything which can be gasified, including highly reactive substances. An example is oxygen, readily available as an in situ resource on most bodies in the solar system. Oxygen could also be used as the propellant in a “green” water rocket.

Challenges for the RF Plasma Thruster

The primary challenges for the RF plasma thruster are efficiency and detachment of the plasma plume from the magnetic field lines.

Efficiency

Some of the efficiency problem is intrinsic to the RF plasma thruster. These parts can only be minimized or offset by efficiencies elsewhere. We believe that other parts can be eliminated, and we have made a start in this direction with a breadboard thruster.

Most early work with RF plasma thrusters[4-8] was done with Electron Cyclotron Resonance Heating (ECRH) of the plasma. In fact, this type of thruster is still usually called an ECRH thruster. A problem with ECRH heating is that an electron tail develops. There is a runaway effect, since collisional losses decrease a particles gain energy. All the excess energy above the plasma energy is wasted, so the electron tail can result in poor efficiency. In the thruster discussed here, lower hybrid heating is used. Landau damping heats the electrons and does not develop a tail.

Another advantage of lower hybrid heating is that the RF energy travels in well defined resonance cones within the plasma, making it easier to keep power off the walls.

Another feature of this thruster is the use of “good” curvature of the magnetic field lines within the thruster. It is well known from the fusion program that “bad” curvature (field lines bending outward) leads to MHD instability and rapid radial loss. Some previous thrusters used good curvature, notably Sercel at JPL, but most did not. Sercel used a trumpet shaped magnetic field configuration to provide an axial force on the electrons rather than for MHD stability.

A breadboard thruster[1] using lower hybrid heating and good curvature has achieved an estimated greater than 50% transfer of energy from RF to plasma, about a factor of ten greater than previous work. This is a first effort, without a lot of optimization. It is hoped that this number can be improved to close to 100%; there is good reason to believe this will be successful from the history of RF heating of plasmas in the fusion program.

Two items that are intrinsic to the RF plasma thruster are the electron temperature and the conversion of DC power into RF. The plasma in an RF plasma thruster has a higher electron temperature than that in an ion thruster or Hall thruster. Since only ions produce usable thrust, this electron energy is wasted. We minimize this loss by maximizing the ratio of the potential to electron temperature, first by using a heavy gas, and then possibly by altering the electron distribution function with the heating. RF generation is intrinsically less efficient than DC generation, but quite efficient RF amplifiers do exist. This is also aided by the switch from ECRH to lower hybrid, since lower frequencies are use. Lower frequencies are easier to generate more efficiently.

In addition to minimizing the intrinsic efficiency losses, some offsets are possible. The magnetic field configuration parallel to the walls leads to better magnetic insulation, reducing wall losses. There are also no hollow cathode losses, which in small thrusters can lead to an efficiency loss of a factor of two or more. We believe that these offsets could well lead to the RF plasma thruster being more efficient than ion or Hall thrusters, especially for low power thrusters.

Plume Detachment

Because magnetic field lines do not end, the plasma plume must detach from the field lines int he exhaust, or the particles will circle around and there will be no thrust. No RF plasma thruster to date has shown this, but modeling suggests a couple of ways this could happen and experiments are being planned to test the models.

One way to plasma detachment is loss of particle adiabaticity[3,5,7], which effectively demagnetizes the particles. The ions are already not magnetized because their collision rate is higher than the ion cyclotron frequency. However, the electrons are magnetized and the ions follow the electrons because of the electric field that would develop if they did not. However, as the magnetic field rapidly declines in the exhaust we expect that adiabaticity would be lost and the plasma would detach.

A second way is a comparison of the energy in the plasma to the magnetic field energy. We would expect that the magnetic field could no longer contain the plasma when its energy drops below the thermal energy contained within the plasma. The ratio of plasma thermal energy to magnetic field energy is called $. We would expect detachment to occur when $ =1. As pointed out by Franklin Chang-Diaz of the VASIMR project[2], this point is also where the ion velocity exceeds the local Alfven speed. He makes the argument that detachment should occur at the sonic point because no communication can pass from further down in the plume back to the thruster.

We believe plasma $ argument is especially compelling, but experimental observation of plume detachment is necessary to prove the RF plasma thruster concept is viable.

Breadboard Thruster Experimental Results

The primary experimental results were:

- Successful utilization of a mode in which the bulk of the RF power is absorbed deeper within the plasma, leading to a narrower plume and fewer wall losses. The narrow plume is due to the lower hybrid wave, shown as mode I in figure 4. Figure 5 is not the lower hybrid mode; it is probably the helicon mode. The lower hybrid mode is achieved by raising the magnetic field until it is accessible. The transition is very sharp. The difference between figures 4 and 5 was achieved with barely a touch on the magnetic field knob.

- Operation over a range of 5-50 watts

- Electron temperature of 60 eV achieved, implying a high ionization level. Other RF plasma experiments to date have not exceeded 20 eV.

- Preliminary estimate of greater than 50% of RF power appearing in jet.

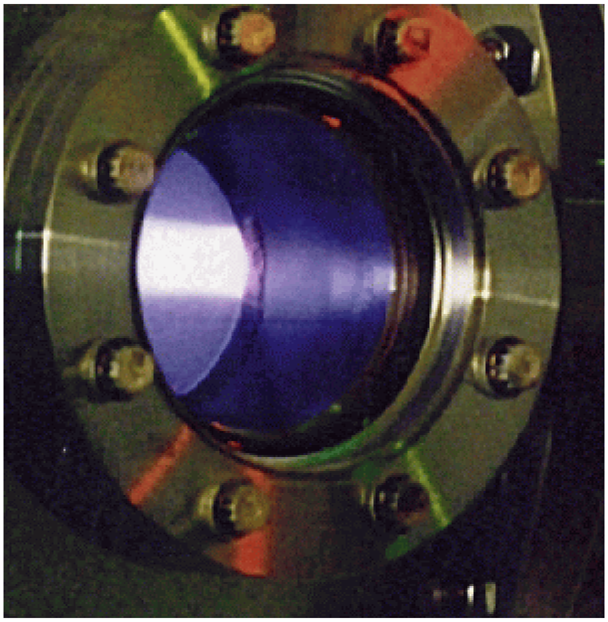

Figure 4. Mode I, lower hybrid

- Plume direction controlled by magnetic field at thruster exit.
- Plume detachment not observed. Calculations show that the experimental area is too short to expect observation of plume detachment.

These results are a significant advance in the state of the art for RF plasma thrusters. Although plume detachment was not observed, the results of the experiments and modeling suggest several ways to pursue this. One is of course simply to get a bigger vacuum chamber. A second is to build a smaller solenoid for the thruster so the magnetic field lines will curve more sharply on leaving the thruster. The third is to reduce the magnetic field by decreasing the parallel wavelength imposed on the plasma by the antenna and reducing the RF frequency.

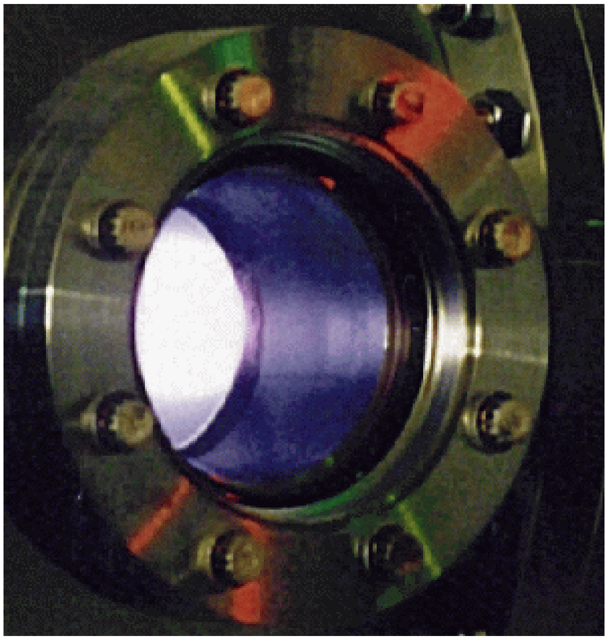

Figure 5. Mode II

Conclusions

Electric propulsion can be very useful for small satellites as well as large one, either by reducing propellant mass or making possible missions that would otherwise be impossible. The RF plasma thruster has some unique properties that may make it especially suitable for small spacecraft including compactness, low power capability, and low voltages operation. Further work is necessary raise the maturity level of the concept, especially in the area of plume detachment.

Acknowledgments

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