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Solar Electric Propulsion and Lifetime of Gridded Ion Thruster

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Abstract

Solar electric propulsion uses electricity generated from solar arrays to ionize the atoms of the propellant (xenon) to provide acceleration to the spacecraft/satellite. The main benefits of using solar electric propulsion for such missions are shorter flight times, more frequent target accessibility and the use of a smaller launch vehicle than that required by a comparable chemical propulsion mission. Energized by electric power from on-board solar arrays the electrically propelled system uses 10 times less propellant than conventional chemical propulsion system. Typically two main type of thrusters are used in solar electric propulsion i.e. ion thruster and The Hall Thruster.

In the ion thrusters the anode pushes or directs the incoming electrons from the cathode. But the anode is not maintained at a very high potential. So the charges are likely to diverge a bit from their actual path. Divergence leads to the charges interacting against the surface of the thruster. Just as the charges ionize the xenon gases, they are capable of ionizing the surfaces and over time destroy the surface and hence contaminate it. Hence the lifetime of thruster gets limited. The aim of the research is to discover the ways by which the lifetime of ion thrusters can be increased. One of the ways to increase the lifetime of the thrusters is to use micro – solenoid magnets instead of using ring cusp magnets which are conventionally used to prevent the interaction of electrons from the ionization walls of the discharge chamber.

Apart from increasing the lifetime of the ion thrusters the research also intends to discover ways by which power can be provided to the Solar Electric Propulsion Vehicle for lowering and boosting the orbit of the spacecraft and also provide substantial amount of power to the solenoid for producing stronger magnetic fields. This can be successfully achieved by using the concept of Electro-dynamic tether which will serve as a power source for powering both the vehicle and the solenoids in the ion thruster and hence eliminating the need for carrying extra propellant on the spacecraft which will reduce the weight and hence reduce the cost of space propulsion.

***Keywords**:* Electro – dynamic tether, Ion thruster, Lifetime of Ion Thrusters, Solar Electric Propulsion Vehicle

1. Introduction

An ion thruster is a complex assembly of ionization chamber, accelerating grids and a neutralizer. It is characterized by the acceleration of the ions that are produced within the ionization chamber by the process of electron bombardment. The principle of the ion thruster is based on the fact that high energy particles (electrons) collide with a neutral propellant atom (typically xenon) to form a positively charged ion. This interaction of positively charged ion and negatively charged electron leads to the production of gas having no

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electric charge called the plasma. The electrons are generated by the process of thermionic emissions by the hollow cathode and are attracted to the walls of the ionization chamber. After the generation of electrons by the cathode, propellant is added into the ionization chamber for electron bombardment. Typically high strength ring cusp magnets are used to prevent the electrons from hitting the walls of the ionization chamber, it also increases the ionization probability. The positive ions thus formed drift towards the positively charged electrode called the screen grid that contains thousands of precisely aligned holes at very high voltage. From the screen grid the ions are accelerated at very high speed towards the negatively charged electrode called as the accel grid. From the accel grid the ions are accelerated out from the ion thruster at the exit which helps in the determination of thrust. However at this stage electrons are ejected from the neutralizer to make the beam neutral otherwise the ions would be drawn back into the thruster and reduce thrust and also lead to erosion of the spacecraft.
Hence the design of grids is a very crucial factor for the operation of the ion thruster. The ion thrusters should be designed in such a way that it minimizes beam divergence which leads to loss of thrust and also minimize sputter erosion and spacecraft contamination caused by the exchange of charged ions. The ion thruster must also be designed to minimize impingement of ions on the grids and extract maximum number of ions produced by the ionization chamber and also proliferate the thruster efficiency by reducing the loss of neutral ions from the discharge chamber.

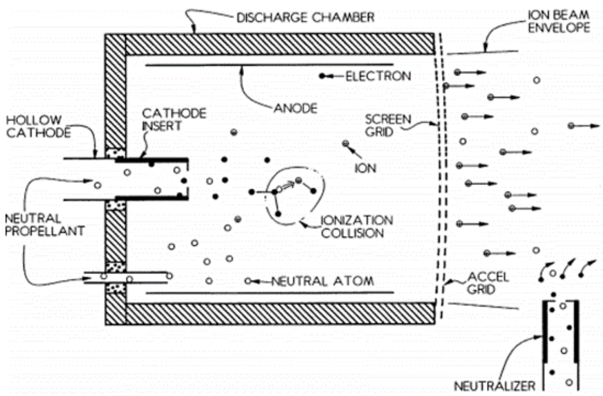

Figure 1: Schematic of ion thruster

2. Life expectancy of gridded ion thrusters

The lifespan of ion thrusters is an imperative aspect however one of the life limiting factors for the ion thruster is sputter erosion that is caused by the ions that bombard the grid surface. Sputtering in the ion thruster occurs due the influence of low energy ions that are produced in the ionization chamber by high density plasma. Hence for this reason the voltage in the ionization chamber is kept adequately low otherwise the ions will cause the grids to erode and fail. Low energy ions that are generated by the high density plasma are accelerated as they approach the aperture axis and form a beam, however the ions that miss the axis of aperture are forced into the accel grid at very high speed and this leads to sputter erosion and wearing away of the grid. To overcome this a screen grid with reduced thickness is placed coherently in line with the accel grid. To limit the energy and rate of sputter erosion, the screen grid should be held at or above the cathode potential. The construction of the grid system should be such that mobile ions that are getting transformed into beams do not influence the accel grid and cause erosion.

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However it has been observed that the fast moving ions and slow moving neutral atoms are emitted through the grid holes and a small percentage of these ions capture an electron. Such a charge exchange can lead to sputter erosion and failure of the grid as the current produced by the ions are focused into the holes of the grid which is a life limiting factor. The lifetime of the thruster can be drastically extended by decreasing the magnitude of negative voltage. If the magnitude of voltage on the accel grid is not sufficiently negative then it will lead to the phenomenon of electron back streaming which will reduce the overall thruster efficiency. On the other hand if the voltage is made positive then it will lead to the problem of divergence in the accel grid which again is an undesirable phenomenon.

To overcome the problem of divergence a third grid called decel grid is positioned downstream of the accel grid having a potential equal to the surrounding space plasma. The decel grid provides physical shielding against erosion by focusing the beamlets and thereby reducing the divergence. The hole diameter of the decel grid is quite small so that the grids are able to extract maximum ions from the plasma generated within the ionization chamber. However expansion of the grid holes may lead to the loss of propellant from the ionization chamber which would result in the reduction in efficiency of the thruster. Hence the decel grid leads to longer lifetime of the grid system and generates less sputtered material that can deposit on the spacecraft and prevents spacecraft contamination.

3. Effect of accelerator grid voltage on the lifetime of ion thruster

As emphasized in the above section that, for effective operation of the ion thruster, the grid voltage must be sufficiently negative. It has been shown that a lower accelerator grid voltage will lead to smaller erosion and longer lifetime of the thruster. It also helps in the prevention of undesirable phenomenon like electron back streaming.

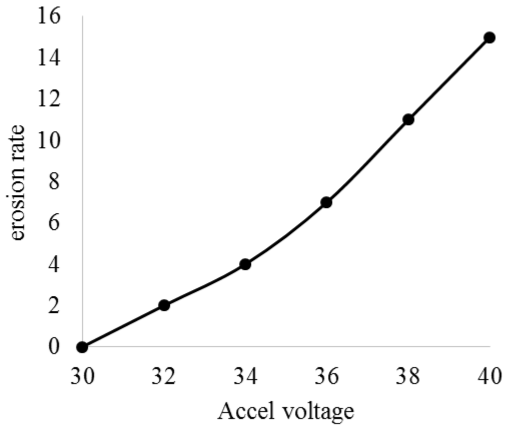

Figure 2: Impact of accelerator grid voltage on the erosion rate of ion thruster

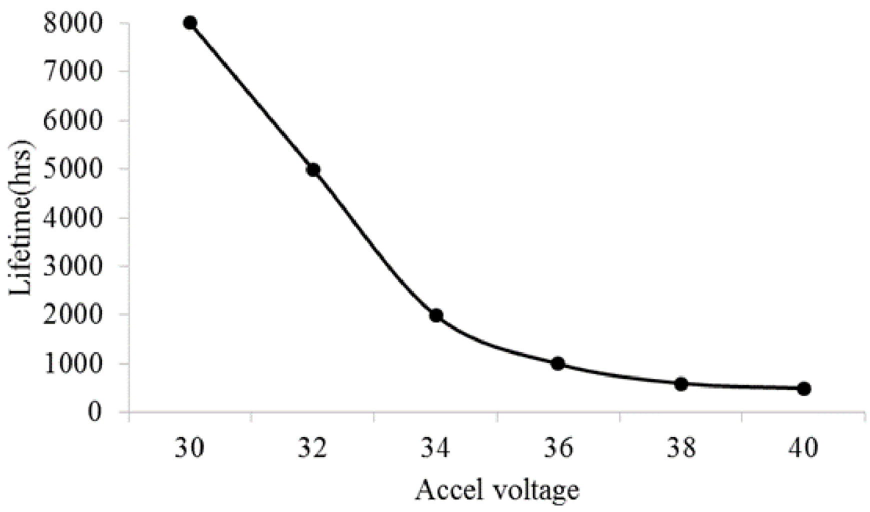

Figure 3: Impact of accelerator grid voltage on lifetime of ion thruster

4. Structural strength of ion thruster grids

Molybdenum is commonly used as the structural material for ion grid thrusters, however replacement with carbon-carbon composites have excellent properties. The carbon-carbon grids are superior to molybdenum because molybdenum leads to thermal expansion in the grids while carbon-carbon composites provide low coefficient of thermal expansion. Moreover in carbon-carbon composites the erosion caused due to sputtering of xenon ions is very low. The lifetime of the screen and accelerator grids is reduced by the sputtering erosion caused by the exchange of ions, however the use of carbon-carbon composites can reduce the effects to large extent. One of the ways by which the carbon – carbon composites can be made structurally stronger is by making circular apertures or slit apertures on the composite material by using the technique of photochemical etching as it would prevent the grids from corrosion and also prevent any kind of grid deformation as it does not exert any mechanical stress. Although mechanical drilling could also be used instead of photo chemical etching, however mechanical drilling would remove a lot of carbon fibre from the composite material. This being a major drawback, the process of photochemical etching seems to be a more viable option. The carbon composite materials also enhance the strength and flexural modulus compared to pure graphite and molybdenum. Pyrolytic graphite (PG) can also be used as an alternative for accelerator grid electrodes.

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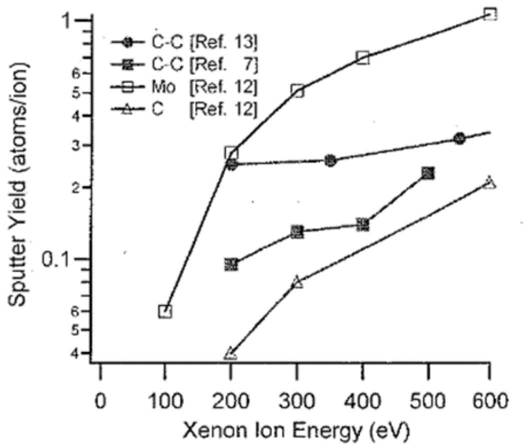

Figure 4: Comparison of Sputter Yields for Thrust Grid Materials

5. Reduction in aperture diameter

The aim of the research is to increase the lifetime of the ion thrusters. In the preceding sections various methods have been discussed like using different grid configurations and use of carbon composite materials to increase the ion thruster lifetime. Nevertheless, this section will focus on how the lifetime of thrusters can be improved by reduction in diameter of the accel grid apertures. The performance of the thruster can be maximized by increasing the thruster efficiency and this can be achieved only by the declination in the loss of neutral atoms. The aperture diameter is decreased to eradicate the interference of ions on the accel grid that would cause erosion due to energy of the ions which leads to wearing away and disintegration of the ion thruster. It is possible by modifying the thruster geometry to reduce the radius of the grid apertures. The equation for magnetic field produced by a current loop is given by:

$$B = \frac{\mu I}{2} \frac{a^2}{(a^2 + z^2)^{3/2}}$$

where 'a' is the radius of the current loop and the 'z' is the distance normal to the plane of the current loop at which the magnetic field is to be measured. The field strength at the centre of the current loop is determined at z = 0 and the equation reduces to:

$$B_z = \frac{\mu I}{2a}$$

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which denotes that strength of the axial component of magnetic field is inversely proportional to the radius of the current loop. This signifies that large fields can be produced if the aperture radius is small.

The data below represents the variation of magnetic field with the aperture distance:

Radius of aperture (m)	Magnetic field (Gauss)
0.5	0.012566
1.0	0.006283
1.5	0.004188
2.0	0.003141
2.5	0.002513

The graph shows the variation of the magnetic field produced inside the discharge chamber and the radius of aperture (current = 1 Ampere). It clearly signifies that as the radius of aperture of accel grid increases the magnetic field produced decreases. Hence it is preferred to reduce the aperture diameter of the accel grid, as it limits the loss of neutral atoms which helps in increasing the performance of the thruster and hence increases the magnetic field which in turn improves the lifetime of the ion thruster by reducing grid erosion caused by charged exchange ions and divergence.

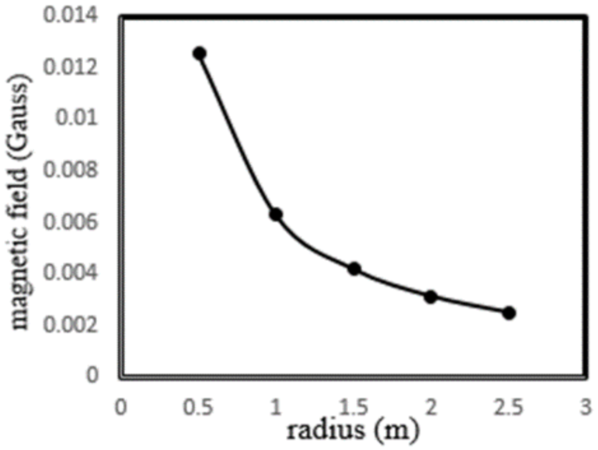

Figure 5: Variation of magnetic field with aperture radius of accel grid

6. Micro-solenoid magnetic field

The aim of the research is to study the ion thrusters and discover the ways by which the lifetime of the thrusters can be increased. One of the main reasons for decreased lifetime of ion thrusters is grid erosion. This section of

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the paper concentrates on the reduction of grid erosion by micro – solenoidal magnetic fields. As highlighted in the previous sections of the paper that the primary source of sputter grid erosion is:

a) Impact of charge exchange ions on the grid
b) Impact of non – focused ions from the discharge plasma.

Therefore any means or any system by which the number of energy ions impacting the grid can be reduced will add to the lifetime of the ion thruster. Usually ring cusp magnets are used in the operation of ion thrusters. However the aim is to reduce the damage caused by the charge exchange ions on the grids by introducing micro – solenoidal magnetic fields which would be operated by current running through the grid apertures provided by the tether wire, which shall be discussed in the subsequent section of the paper. The micro – solenoidal magnets form mini magnetic nozzles which guide the beam ions through the aperture and at the same time also helps in diverting the charge exchange ions from directly impacting the grids. The magnetic field produced by the micro – solenoidal magnets will guide the ions which would prevent direct impact on the grids. The magnetic field produced by the micro – solenoidal magnets will be created by the current running through each grid hole that would be powered by the tether wire. The electric field should be oriented in such a way that ions are attracted to the grid. On addition of magnetic fields, the ion will experience a force called the Lorentz force given by:

$$\boldsymbol{F} = q[\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B})]$$

As deliberated in the above section that whenever a neutral atom near the exit of the thruster grid system comes in contact with a fast moving propellant ion then small percentage of these ions capture an electron and this leads to charge exchange. This factor predominantly causes grid erosion. Hence the erosion of the accel grid due to charge exchange ions and direct impact of unfocused ions from the discharge plasma are the life limiting factors for an ion thruster. These charged ions impact the high velocities in the accel grid. It also causes the beamlets to be less focused and this leads to the phenomenon of divergence in the ion thruster. Such a charge exchange also leads to contamination of the spacecraft and also results in the enlargement of the accel grid holes which further leads to number of performance losses like electron back streaming and corrosion of the grid material which ultimately leads to the structural failure. Hence it is for this reason that the grid aperture diameter is reduced significantly to increase the magnetic field. The larger the magnetic field produced by the micro – solenoids the lesser would be the exchange of ions and divergence. Reduced divergence and exchange of ions lead to increased lifetime of the ion thruster.

7. Fundamental physics of ion thrusters and micro – solenoid magnetic fields

The science behind the ion thruster is based on the fundamental laws of electrostatics and magneto statics. Three types of charged particles play crucial role in the ion propulsion system i.e. neutral atoms, atoms that loose electrons and thus form positive charged ions and the electrons which are negatively charged ions. The predominant forces which are acting on the charged particle in an ion thruster are electric and magnetic forces. The source of electric force is the electric field that is generated by the charges and is given by the Coulomb's law of electrostatics:

$$F = k\frac{q_1 q_2}{r^2}$$

where k is the Coulomb's constant, q_1 and q_2 are the charges of particles 1 and 2 respectively which are separated by a distance r. It may also be represented as:

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$$F = \frac{q_1 q_2}{4\pi\varepsilon_o r^2}$$

Coulomb's law gives rise to an electric field which can be defined as:

$$E = \frac{F}{q} = \frac{kQq}{qr^2} = \frac{kQ}{r^2}$$

where E is the electric field and Q is the charge of the source particle. The above equation can be re – written as:

$$F = qE$$

The motion of the charged particle in an electric field is also governed by Newton's 2nd law:

$$ma = m\frac{dv}{dt}$$

For a charged particle: $ma = qE$

The motion of the charged particle in the presence of magnetic field is determined by the Lorentz force given by:

$$F = q(v \times B)$$

This is the force that is produced by the charged ions in the presence of micro – solenoidal magnets which form mini magnetic nozzles which helps in guiding the beam ions and prevents divergence.

The motion of a charged particle in a magnetic field is circular, the magnetic field provides the necessary centripetal acceleration and can be also be expressed as:

$$ma = q(v \times B)$$

A particle in a uniform magnetic field with no electric field and having an initial velocity v has a 'cyclotron gyration' of motion which is given by:

$$m\frac{dv}{dt} = qv \times B$$

The magnitude of the force experienced by a charged particle moving at right angles to a magnetic field is given by:

$$F = ma = qvB$$

This force imparted is balanced by the centrifugal force:

$$F = \frac{mv^2}{r_L}$$

Where r_L is the radius of the resulting path.

The radius of the charged particle is given by:

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$$r_L = \frac{mv}{qB}$$

From the above equation it can be clearly inferred that the larger the velocity of the particle or larger its mass the larger its radius of motion. Contrariwise, the greater the charge or the magnetic flux density the smaller the radius.

If there are both an electric and magnetic field present the total force on the particle is the total Lorentz Force given by:

$$\boldsymbol{F} = q[\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B})]$$

If the particle is placed in a region where the magnetic field and the electric field are at right angles to each other then the particles travel along a path called 'cycloid'. The cycloid motion or a helical motion is very important in the use of grid embedded magnetic fields to prevent grid erosion that is induced due to charge exchange ions.

$$qE = qvB$$

$$\boldsymbol{v} = \frac{\boldsymbol{E}}{\boldsymbol{B}}$$

Only particles or ions with velocity $v = \frac{E}{B}$ will pass undflected through the grid aperture.

8. Electro – Dynamic Tether Power

Electrodynamic tether is one of the areas on which there is tremendous research going on in many space agencies. Electrodynamic Tethers (EDTs) are long conducting wires that are deployed from satellite. They can create kilovolts of potential difference across them using earth's magnetic field and orbital velocity. This development of potential is consistent with the electromagnetic laws. Generally in order to generate potential difference of order of kilovolts, tethers which are few kilometers long need to be used. The use of tethers to power satellite is a topic that is intriguing many.

In our ion propulsion system, the concept of using micro solenoids so as to increase the lifetime of the thruster has been introduced. But the solenoids need to be powered and that should be in a way that power needs of other equipment or the weight of satellite is not compromised with. A possible solution to this problem can be the use of tether. A tether of small length capable of producing tens of volts can be used. Tethers can be used for high power probing in the ionosphere. By applying the basic electromagnetic equation of potential difference across a conductor in moving magnetic field

$V = Blv \sin \theta$, the length of tether needed can be calculated. The tether will also apply some drag downwards but the drag would be negligible for such small sized tether. The tether can then be used to power the solenoids. In order to make current flow, the wire connecting tether and solenoids can be made to lose electrons by electron guns. The stream of electrons coming out can further be used to neutralize the positively

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charged ions coming out from the thruster. Thus this method can be power and weight efficient method of providing current to the solenoids.

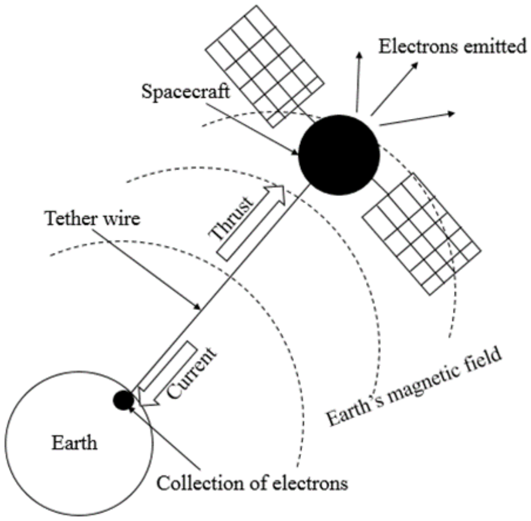

Figure 6: Representation of Electrodynamic Tether system to power spacecraft

The above diagram represents a spacecraft and ED tether. As the spacecraft orbits the earth with velocity v, it cuts across the earth's magnetic field lines $\vec{B}$ and from Faraday's law of Electromagnetic Induction an emf is generated that is given by $E = \left|\vec{v} \times \vec{B}\right| \times l$ in the tether wire. This EMF produces a potential in the tether wire. In this system one part acts as anode (electron collecting) contractor and another an electron gun as cathodic (electron ejecting) contractor. The positive potential attracts and collects electrons from the ambient plasma through the electron collector. The collected electrons are driven as current in the tether wire. A rechargeable battery connected to the tether is placed which can be recharged and thus generate necessary power for the micro – solenoids in the discharge chamber.

9. Conclusion

Solar Electric Propulsion is a necessity of interplanetary journey in the current scientific environment. It has come a long way and many long duration missions have been launched with this technology. But still due to its very low thrust to mass ratio, it can only be used in space. So there is huge scope of development in increasing the thrust of ion thrusters. But higher thrust means more ions per unit time which directly increases the erosion and decreases the lifetime of thrusters. So the endurance of the thrusters need to be improved before we increase the thrust for long periods. Many pre-existing methods and some new methods have been suggested in this paper. The use of micro solenoids for reducing erosion is quite a new idea and research on this is going on. Further if we are able to use tether to generate enough power for the solenoids without creating significant drag, then ion propulsion will be most viable method for interorbital travel.

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