Overview On Electric Propulsion Systems

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Abstract- This paper provides a brief overview of electric propulsion systems and their working. Novel systems and designs for electric propulsion is classified as electrothermal, electrostatic, electromagnetic and even hybrid systems which can be two or more types combined. The various types described here include DC heated Resistojets, Arcjets, Field emission electric propulsion thrusters, magneto-plasma dynamic thrusters, Hall Effect thruster, Colloid and Electrospray thrusters, High efficiency multistage plasma thruster, Pulsed plasma thruster, Electrode-less thrusters, VASIMR, and the gridded and radio frequency ion engines. Each thruster system can be used on the basis of the mission characteristics and determining factors may include cargo weight, thrust required, power budgets, simplicity etcetera. Choice of propellant can also be varied according availability. This paper hopes to provide a basic knowledge of these systems and their properties.

Index Terms- Resistojet, Arcjet, FEEP, HET, Taylor cones, MPDT, ELT, Electrospray, VASIMR, HEMPT, QCT, GID, RF ION, PPT, azimuthal orbit, ECR, RF couplers.

I. INTRODUCTION

A WHAT IS AN ELECTRIC PROPULSION SYSTEM?

An Electric Propulsion(EP) system is a class of electrically powered spacecraft propulsion system with components arranged that make use of electric/magnetic fields to accelerate a propellant and convert electric energy to kinetic energy from power systems of the spacecraft. EP systems usually use much less fuel than chemical rockets because they operate at a higher specific impulse (higher exhaust speed) than chemical systems, the thrust is much weaker compared to chemical systems, but electric propulsion can provide that small thrust for a long time. EP systems can eventually accelerate to really high speeds and hence work better than chemical systems for deep space missions.

The typical EP system consists of a power processing unit(PPU), a fluid management system or propellant components, an optional pointing mechanism and the crucial thruster component. The power system supplies regulated dc bus power to the PPU, where the PPU processes raw power to suit the thruster, as well as to heaters, valves, etcetera. The piping usually includes series and parallel valves, pyrotechnically opening or closing valves, etcetera, the designing of precise flow controls and valves are not an easy task as they are required to conation flow for long periods of time. Commands are supplied by the computer of the spacecraft, which also handle a variety of signals from pressure, sun, magnetometers, passive and other sensors.

The balance of the EP system is quite burdensome to designers as it requires the most effort and also is bulky and expensive. Fortunately, the system is not that different from the familiar cold-gas or monopropellant systems, except from a few PPU details.

Electric thrusters work by accelerating propellant atoms to high velocities. The velocity, thrust and specific impulse are directly proportional from a given amount of propellant. The propellant velocity can be increased even more in electric thrusters by charging up propellant particles and accelerating the charged particles with high voltages. The most efficient electric thrusters used today are ion thrusters and Hall thrusters. In chemical propulsion, the energy produced is limited by how much energy there is in the chemical bonds of the propellant. For different types of missions there are operational challenges such as electric transfer from GTO to GEO, station keeping, interorbital transfer, interplanetary cruise, fine agile attitude control, Long-endurance missions, etc. The addition of energy to the wor king fluid from some electrical source is seen in all EP systems in various physical structuring designs. The propellant and operation can be chosen according to requirement for mission, propellant can be xenon(most common due to it being unreactive and easily ionized and has a high atomic mass) or other noble gases, materials with low melting point like indium, cesium etcetera, chemical monopropellants or solid propellants. Operation can be pulsed or steady and the gas acceleration can be hybrid, thermal, electromagnetic or electrostatic. The gross performance of any electrothermal thruster is crudely forecast by means of a rudimentary one-dimensional energy argument that limits the exhaust speed of the stream from an expanded nozzle to velocity $\leq\sqrt{2C_pT_c}$, where Cp is the specific heat at constant pressure per unit mass of the propellant and Tc is the maximum tolerable chamber temperature(Ghostscript wrapper for C:\TEMP\AcademicPress).

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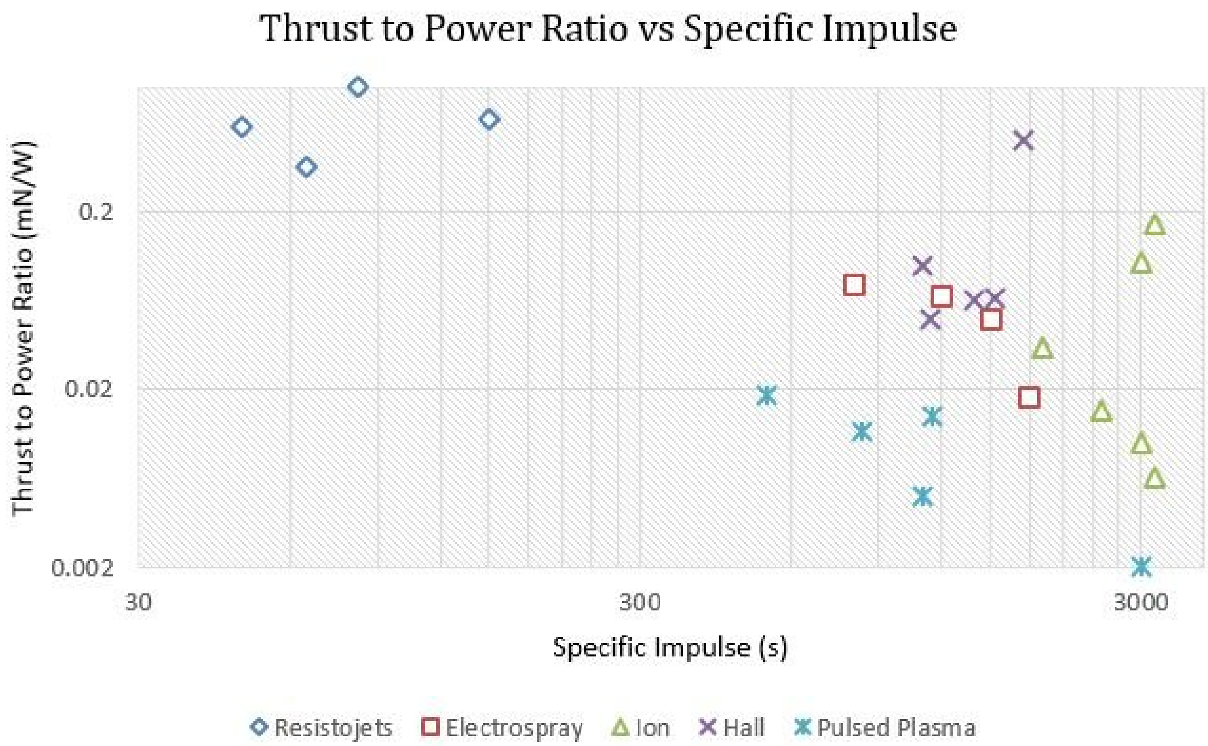

Tummala, A.R. & Dutta, A.. (2017). An Overview of Cube-Satellite Propulsion Technologies and Trends. Aerospace. 4. 10.3390/aerospace4040058.

II. DC HEATED RESISTOJETS

Resistojets are an electrothermal thrust device that provide propulsion by heating the propellant by passing gaseous propellant around an electrical heater, sending electricity through a coiled resistor that consists of a hot incandescent filament, usually around tubes to be heated radiatively externally with the gas passing through the tube and getting heated, the expanded gas is expelled through a conventional nozzle to generate thrust. This heating increases specific impulse as √T by reducing gas flow rate through nozzle area. Any gas compatible with the high temperature heater according to suit of mission. Resistojets have also been proposed as means of using biowaste as reaction mass, particularly with catalytically decomposed Hydrazine which fortunately has familiar fuel systems as in hydrazine monopropellant applications. The heaters have a low input voltage and so do not require special power conditioning. A spacecraft power system requires a regulator due to the high voltage variations(>20%). In case of heater failure, as plume is not ionized and has no threat of dangerous or unusual heater failure, operation in non-superheated mode can continue. Platinum and alloy strengthened platinum were studied, pure platinum was seen to have weak thermal resistance to the high heater temperatures, disregarding their anti-oxidative property. Two types of dispersion-strengthened platinum are currently available: one is strengthened with yttria and with zirconia(pmr-v32-i1-002-010.pdf) Although the platinum-thoria alloy was compatible with requirements of thermal, oxidative and strength issues, it is no longer manufactured. Current materials allow a maximum specific impulse of 300 sec as the temperature is limited to 2700 K, using hydrogen can give a specific impulse of 840 sec (approx) but hydrogen is not an overall optimal propellant. The main factor affecting specific impulse is molecular weight of propellant hence hydrogen is just not effective compared to oxygen, xenon, ammonia, methane and nitrogen. Efficiency ranges from 65%-85%.

The resistojet is the simplest of all EP designs, is easy to control and has simple power conditioning, but have the lowest specific impulse of all EP systems, has substantial loss of heat and gas dissociation. The heat transfer provided to the gas stream from the coil is not efficient, indirect heating and erosion of material is common. Some new designs work to reduce heat loss from coils by wire designed parallel or perpendicular to the propellant stream, and some designs have geometric structures to be immersed in the stream for heating by current flow as the stream flows around the body.

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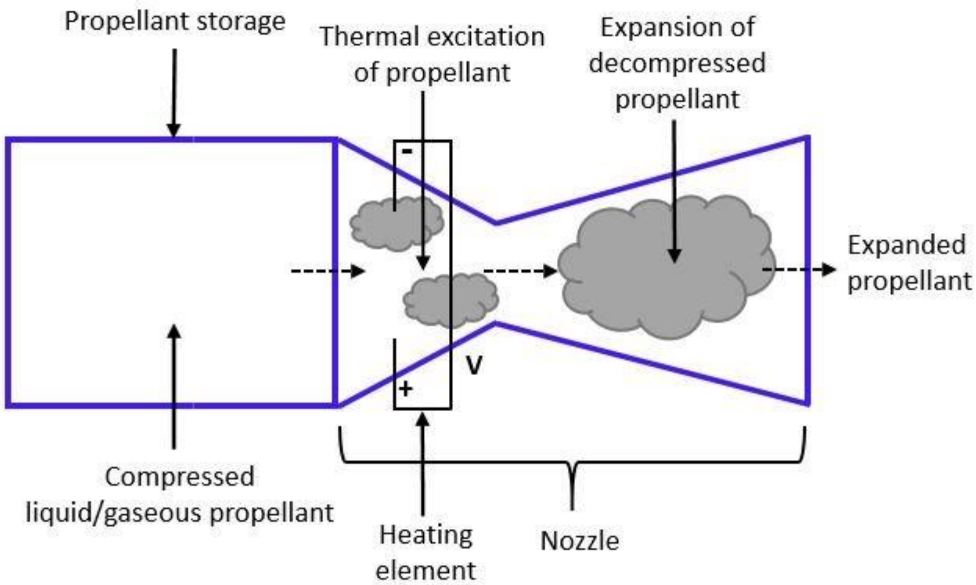

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III. ARCJETS

This electrothermal configuration is substantially more complex than the resistojet. Arcjets use an electric arc to heat the propellant directly between a concentric upstream rod cathode and a downstream rod anode, depositing power internally which makes it so the temperature limitation and losses in transfer from walls to gas are overcome. The anode also acts as the supersonic nozzle. The arc core has a range of temperature of 10,000– 20,000 K and the intermediate layer at about 2000 K, hence the flow at nozzle neck is extremely non uniform and the flow at the core is practically absent. This leads to high specific impulse as it reduces fluid flow without affecting pressure integral. The non-uniformity of the stream reduces the efficiency of propulsion as when heat is added uniformly across the stream, the maximum thrust is obtained. The general thrust equation is then given by:

F = (m dot * V)e - (m dot * V)0 + (pe - p0) * Ae ;

There are substantial losses in dissociation and power that was used to ionize the arc gases. Local heat losses are included that consist of near-electrode voltage drops. Similar to resistojets, the gas to be used will have to be considered according to mission and craft specifics and as with resistojets, hydrazine is a preferred choice as an evolutionary development from other monopropellants and familiarity of use. Arcjets using hydrazine can reach up to 600 sec of specific impulse, but the thrust efficiency limits to about 35%-50%, which could be acceptable as per priority of power savings or fuel. Hydrazine operated arcjets have power of about 1.5 kW and up to 6000m/sec exhaust velocity Future designs should allow the arc to cover a larger area and reduce thermal losses and resulting damages. Hydrogen as a fuel can again seem to be optimal as specific impulse reaches up to 2000 sec but low storage density and cryogenic nature of the fuel; it might become practical for missions with continuous thrusting, where the tank could be cooled by the evaporation of the feed(JOURNAL OF PROPULSION AND POWER Vol. 14, No. 5, September – October 1998). Ammonia can reach specific impulses of 800-900 sec but EP system is complex which can be unsafe for handling. The PPU is complex and requires at least a DC-DC conversion for the voltages are higher than average DC bus voltages and is often heavy to control the negative impedance characteristic of the arc, with special transitions. Erosion at high powers and bulky electrical systems are also drawbacks.

The constricted arcjet arrangement includes a central upstream cathode and a downstream anode ring, which maximizes the of heat transfer by heating the stream of gas in small cross-sectional areas. Arcjets do pose dangers related to the range of stagnation pressures used(arc stability)limiting blowdown system to the arcjet portion becoming relatively small. Arcjets are an intermediate among EP systems but could be a viable option for its high power savings, larger satellite payload, propellant efficiency and specific impulse features.

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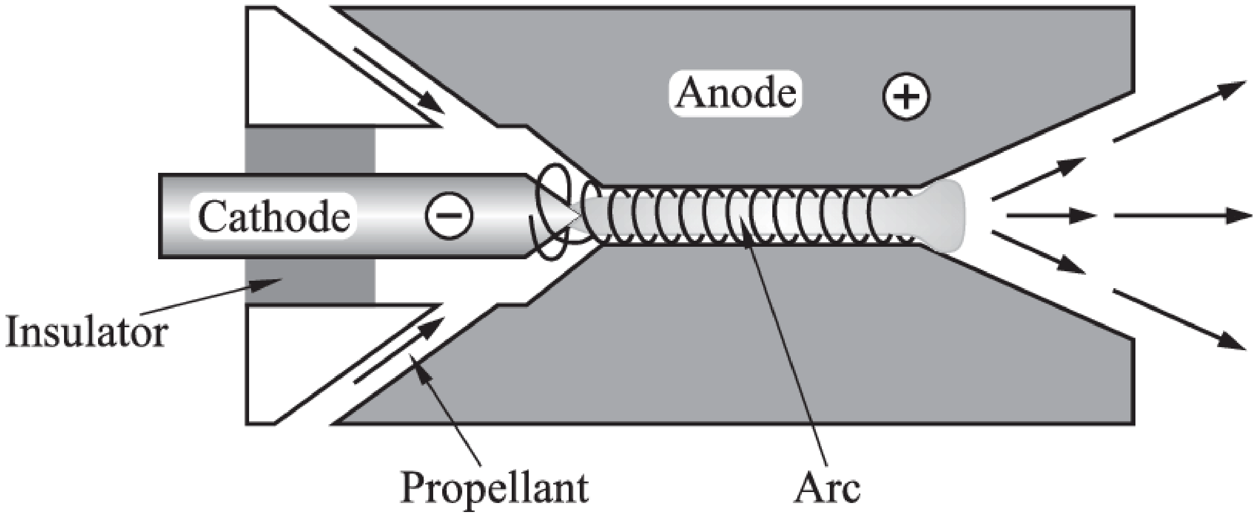

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IV. HALL EFFECT THRUSTERS(HET)

The Hall-effect thruster is an electrostatic ion accelerator that utilizes a cross-field cycloidal motion discharge of ions accelerated by an electrostatic field in the stream of propellant to generate plasma, the plasma electrons interact with a magnetic field to produce the electrostatic field which is described by the Hall Effect. The perpendicular fields electrostatically accelerate the ions to high velocities. The magnetic coils are set perpendicular to the main discharge for simplicity and some additional control can be established. This type of thruster is both an electrostatic and electromagnetic EP system. The electrons follow a particular closed drift path perpendicular to current flow and magnetic field(Hall Effect). The structure a Hall thruster consists of an annular discharge chamber with a radial magnetic field between a cylindrical ferromagnetic pole and an external ferromagnetic ring. the chamber forms an exit for the accelerated ions one end. The electrons travel from the cathode to anode in an externally applied electric field, the radial magnetic field results in a perpendicular force from both fields, causing them to drift in an azimuthal direction(hence formed Hall current). When the electron is being moving towards the anode(accelerated), the gyroradius increases than when it is moving towards the cathode(decelerated), giving rise to a net azimuthal drift(Hall effect). the electrons are proficiently trapped in an azimuthal orbit near the area of maximum field strength. Axial electron mobility is eradicated, allowing the plasma to sustain a very high electric field along the axis of the discharge chamber. An external cathode is present, which provides additional electrons to neutralize the accelerated ions from the discharge chamber.

Hall thrusters require relatively simple power conditioning and provide desirable specific impulse range, but since the only propellant that can be used safely is xenon, it does not provide any choice in propellant, very few models like the HT 5K HET allow use of alternate propellants like krypton. The motion of the Hall current leads to a high beam divergence, lowering thrust axially. Erosion unfortunately takes place within the chamber. The thrusters optimize performance at very low power. Exhaust velocities can reach up to more than 65000 m/s and their power ranges from around 200 W up to tens of kW. They have propellant efficiencies of well over 50%, thrust efficiency of about 45– 55% and a thrust of more than 70mN, they have high specific impulse of 1,000–8,000 sec. there is a 5% loss in specific impulse due to propellant flow in the hollow cathode. The wide plume angle poses concern as it aligns at around 40 degrees to solar arrays and other delicate areas. Current fluctuations and some conditions may cause communications problems if the plume disrupts the antenna pattern. There are no dissociation losses even with the plume mostly or fully ionized, but it has higher operating voltage. The low gas density ensures almost collision-less stream drift, leaving the positive ions to freely accelerate downstream. So, it is much larger than an arcjet of similar power but still more compact than ion engines. The thrust, specific impulse and power can be controlled trolled through the voltage and current is controlled by the flow rate by either varying the gas viscosity in the feed capillaries thermally or with electromechanical valves. The PPU has to manage magnetic current, flow and plasma shifts, making it much more complex than the arcjet. Some designs thruster designs include the ceramic-lined stationary plasma thruster(SPT) and the metal-walled thruster with an anode layer(TAL). The thruster specific impulse and efficiency is sort of less than that in ion thrusters, but the thrust is higher and the device is quite simple and requires lesser power apparatus to operate.

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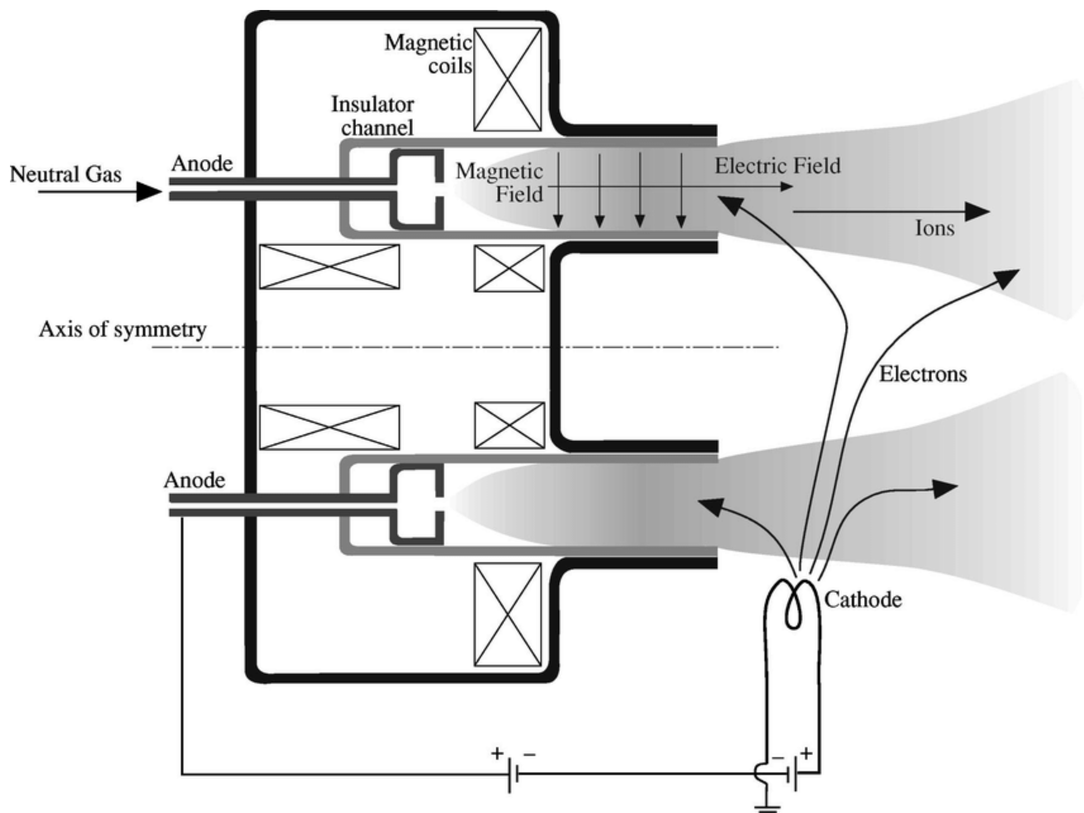

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V. PULSED PLASMA THRUSTERS(PPT)

A pulsed plasma thruster (PPT) is an electromagnetic thruster that utilizes a pulsed discharge to ionize a fraction of a solid propellant ablated into a plasma arc, and electromagnetic effects in the pulse to accelerate the ions to high exit velocity. The pulse repetition rate is used to determine the thrust level. These unique thrusters are driven in short pulse bursts of approximately 10 micro sec of high instantaneous power(10MW approx), although the instantaneous power provided by the thruster is significantly higher than the total power consumption which ranges around 10-100 W the energy for use is stored in a capacitor bank charged from the primary power supply and are delivered rapidly across the electrode propellants by a spring pushing the solid bar. They use a solid propellant, mainly Teflon or the most commonly used propellant today, Polytetrafluoroethylene(and some alternatives like acrylic plastic, polythene, PTFE variations with added LiOH and InBr or carbon or multilayared laminated propellant, Hydroxyl-terminated polybutadiene). An ignition of the spark plug, which can be either a low energy high-voltage spark gap discharge or a semiconductor spark plug, initiates the discharge delivering negligible energy. the self-induced magnetic field from the instantaneous current creates a magnetic pressure in the ionized layer similar to the gas kinetic pressure and both accelerate the gas slug close to the Alfven velocity, at which the kinetic and the ionization energies are equal. The thruster is a single compact unit, making it safe, a given device can operate over a wide range of mean power or thrust by varying the repetition rate. The specific impulse can reach up to 5000 sec or even more. The efficiency is only around 8-30% with the thruster extremely large for this and ones with higher efficiencies developed in the 1960s(GF-PPT systems). The higher efficiencies can probably be achieved by pulse tailoring, nozzle recovery of the thermal energy and using higher instantaneous power. There are dangers from the toxic reaction products of Teflon reactants and major disadvantages of plume contamination and widening. There have been newer models using liquid fuel injected PPTs which have similar or larger pulse durations and other similar features, and improved performance and ensure clean plume status. Some examples of liquid propellant used are pentaphenyl trimethyl trisiloxane, liquid perfluoropolyether, Ethylene tetrafluoroethylene, water, alcohol etcetera. Gas injected propellant thrusters, although very rare, provide high efficiencies and clean plume but strain implementation in spacecrafts which have limited volumetric capabilities(CubeSats) but liquid propellants promise to overcome the limited success of solid and gaseous propellants in small satellites and spacecraft like CubeSats.

Future innovation with capacitors and storage units can help reduce mass of the unit, and some research suggest discarding the electromagnetic valves for simplicity in the form of simple ablative pulsed plasma thruster(major disadvantages of this thruster the low efficiencies and spacecraft contamination) Reliability and precision control are major benefits of the PPT and are suitable for light propulsion applications. ESPs or electric solid propellants are gaining interest for their applications in propulsions with exothermal decomposition of an electrically ignited propellant that can continue till electricity is removed, one material with higher specific impulse and conductivity is a Hydroxyl-Ammonium-Nitrate (HAN) based material. Another

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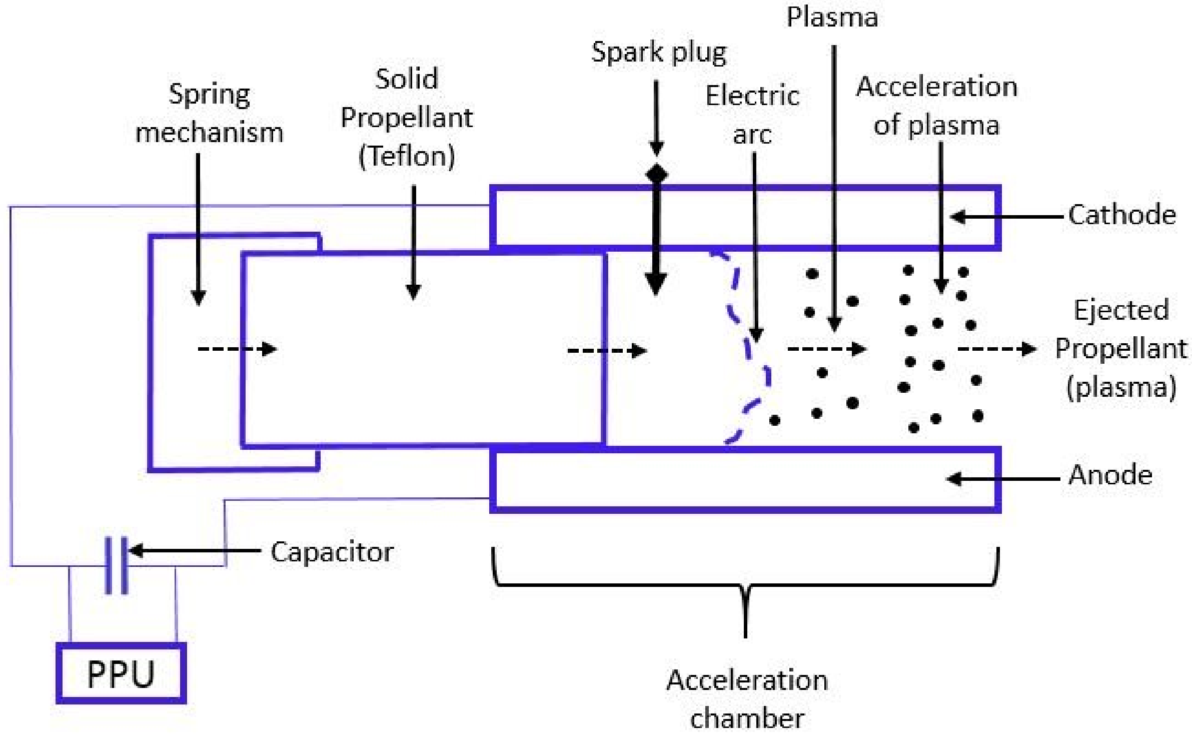
material researched was Sulphur, specifically for application in CubeSats.



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VI. RADIO FREQUENCY ION THUSTER(RF ION)

This thruster idea has been around since the 1910s and still remains one of the most popular. Ion engines are a form of electrostatic propulsion that ionizes a gas(mostly inert gases) by removing electrons hence forming a cloud of positive ions as exhaust, these thruster designs make use of a variety of plasma generation techniques for ionizing the most part of the propellant, the conventional technique is called electron bombardment and a novel technique being researched at NASA is called electron cyclotron resonance(ECR) which uses high-frequency radiation with a strong magnetic field to heat electrons in the gas letting them break away from the atoms and ions are extracted from the plasma so formed. The coulomb force along an electric field is the accelerating component. Electrons are produced by a hollow discharge cathode, at the center of the engine on the upstream end, from where they flow out of the cathode and attract towards the discharge chamber walls which are highly positively charged and have strong magnets placed so when the electrons approach the walls, they are redirected into the chamber. The propellant injected from the downstream end(which has electrodes placed to produce electric fields for acceleration) ionizes, and flows towards the upstream end, maximizing time spent in the discharge chamber for higher ionization efficiency. The downstream end has a second hollow cathode in the perimeter of the thruster for neutralization. The set of electrodes are most commonly gridded structures and ion optics which will be discussed ahead. Between the accelerator grid and upstream ions is the thrust force, and the exhaust velocity depends upon the voltage applied across the optics, hence they are limited only by voltage across the optics unlike the chemical systems which depend on thermal resistance of the rocket nozzle. The thruster has two main units for management: the PPU, which converts the electrical power from the source into that required by each component of the thruster, and the PMS, which controls the flow of propellant from the tank to the thruster and hollow cathodes. The PPU provides voltages as per requirement of the optics and discharge chamber and currents per the hollow cathodes. These PPU and PMS systems do not have moving parts in modern designs and are managed by a central computer. The magnetic field only plays a secondary role guiding the electrons.

The Ion engines provide less thrust per unit area as they work optimally in higher specific impulses of around 2000 to more than 10,000 sec but provide significantly better operating framework and plasma control. This results in very long lifespans (10000 hours demonstrated) and less beam divergence although a 30 degree slant from solar arrays is necessary. The PPU systems is quite complex in comparison to other systems but are very technologically mature, all points to making them a preferred choice for deep space missions and other complex maneuvers like interplanetary orbit transfers. Ion thrusters have one of the highest efficiencies of up to 80% and significantly high specific impulse exceeding 10,000 sec.

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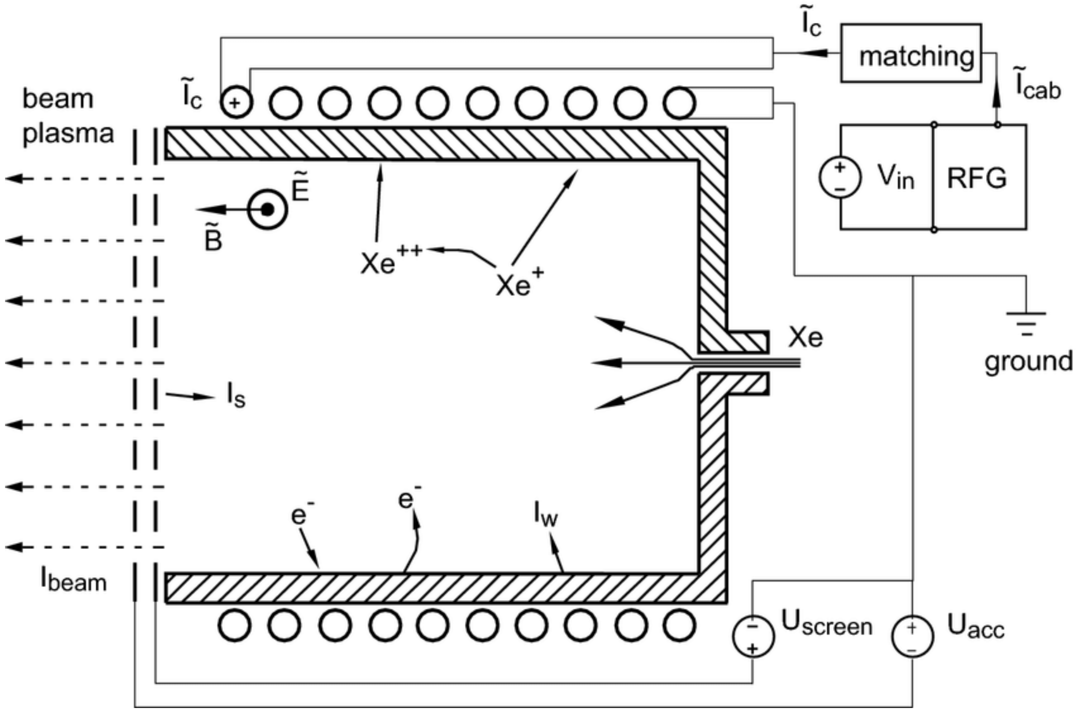

[Pham Tran, Quang & Shin, Jichul. (2020). Better Prediction of the Performance of a Radio-frequency Ion Thruster. Journal of the Korean Physical Society. 76. 137-144. 10.3938/jkps.76.137. A zero-dimensional analytical model for an RF discharge ion thruster has been improved to predict the thruster performance better. Improvements were made by incorporating most physical phenomena expected in an RF ion thruster, such as secondary electron emission, double ionization, a variable Clausing factor, grid optical transparency, and an ion confinement factor affected by the electromagnetic field. Clausing factors were calculated for each flow rate by using a Monte-Carlo technique. The grid optical transparency was calculated using an ion optics simulation. The ion confinement factor was also calculated for each flow rate by using the calculated magnetic field strength obtained from magnetic field simulations. The ion confinement factor turned out to have the greatest effect on the results while minor corrections were achieved by other processes. Comparison with previously reported analytical solutions and experimental data showed improved prediction of the thruster performance for various size and power ranges**.**

VII. GRIDDED ION ENGINE(GID)

The gridded ion engines are a popular and very common design of the Ion thruster systems for use due to its high efficiency and low thrust, it is almost the same as the description given above for ion engines. On one side of the discharge chamber is a double-grid structure, with distances between each aperture of the order of 1 mm, 1-2 large across which the acceleration voltage is applied. Ions are extracted electrostatically from plasma through biased grids and are then accelerated to high velocity at voltages around 12kV the ion grid and optic electrodes comprise a large number of coaxial apertures, where each set acts as a lens that focuses ions though the grid electrically. The ions generated in regions of positive are attracted toward the accelerator grid as the grid's potential is negative and are guided through the apertures resulting in ion jets across the grid, adding up to form the ion beam. This system can compare to classical chemical systems as propulsion speeds reach up to 90 km/s. the propellant is injected in the downstream end of discharge chamber and are bombarded with electrons for ionization. Electrons emitted from cathode can be accelerated by potential difference with anode, microwave heating, or be accelerated by an alternating electromagnet that induces oscillating electric field that leads to self-sustaining discharge(radio frequency ion thruster). The ions are accelerated by the potential difference between the first grid(screen) and second grid(accelerator) resulting in a final ion energy which depends on the plasma's potential. Space charge limit, which is the concepts that limits the extracted current, as electron are absent in the grid gap, to a level at which repulsion by ions would keep new ions from venturing in. a common ending for thruster lifespan is insufficient negative potential in the grid, which is a cause for failure of a system of prevention of electrons from streaming back into discharge plasma from the plasma beam outside, which is ensured by the negative voltage of the accelerator grid.

VIII. HIGH EFFICIENCY MULTISTAGE PLASMA THRUSTER (HEMPT)

This ion thruster design of EP system is a relatively new concept and a part of electromagnetic propulsions developed by Thales Deutschland GmbH in the early 2000s. An applied magnetic field by periodic permanent magnets (PPMs), is axially oriented in most channel regions, it includes a chemically inert propellant (xenon, krypton etcetera) is injected into a discharge chamber at the anode at the bottom or upstream end, the discharge chamber is made of dielectric ceramic tube that separates the plasma from the PPM system which alternates the polarity of the magnetic coils(called

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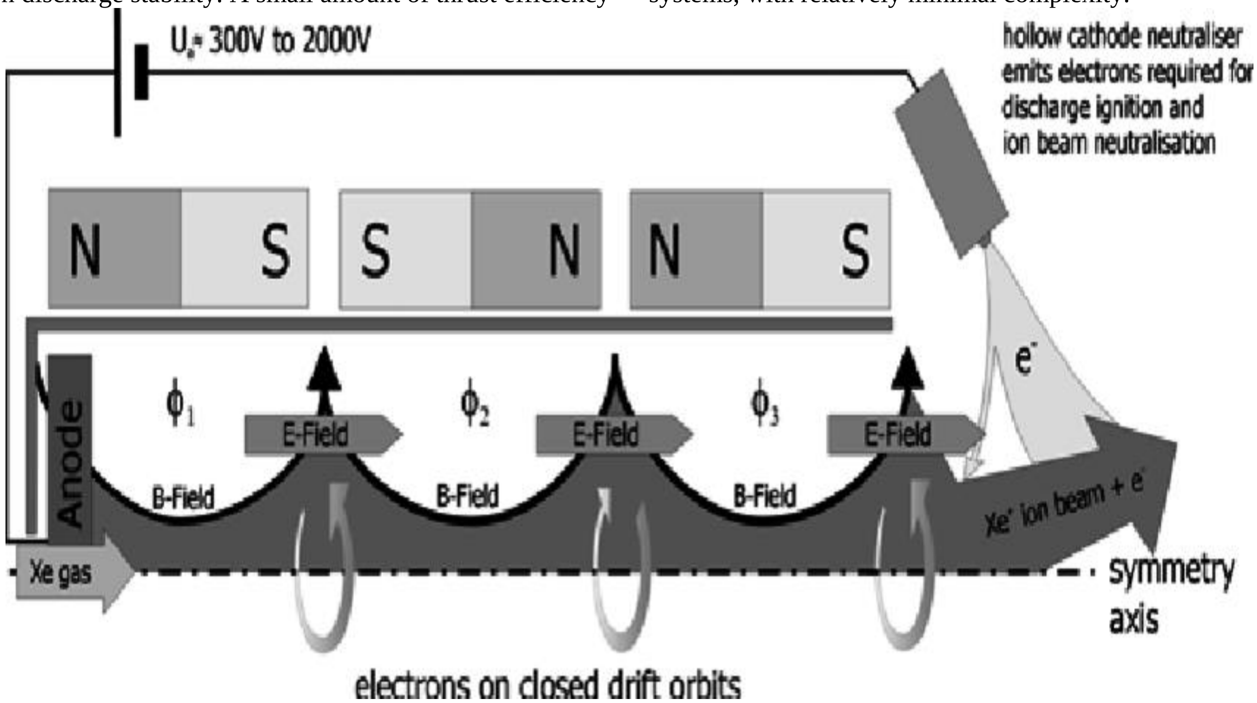
cells) set across the length of the discharge tube, hence confining most electrons to the magnetic cells and reduces electron contact with the channel walls. The radial orientation of magnetic field is only at spatially confined magnetic cusps resulting in low particle fluxes towards the dielectric discharge chamber wall. A plasma source in the form of a hollow cathode placed outside the thruster emits electrons to ionize the propellant and neutralize the ion beam. The strong radial magnetic field applied holds the electrons in a drift motion as per Lorentz force(ExB). There have experiments to show a steep potential gradient between the first and second cells hence contributing to most of the acceleration of the ions, the second and third cells contribute to ion beam formation discharge stability. A small amount of thrust efficiency and output are compromised due to energy transfers from collisions of the high energy particles with the walls of the chamber, these collisions can also result in wall erosions, but as the magnetic cells keep the ions well away from walls, they do not face this problem and have longer lifespans and efficiencies. The acceleration voltage ensures a high specific Impulse resulting in a significant reduction of propellant consumption, they offer a wide range of thrust making them extremely flexible. The specific impulse is usually in the range of 3000–4000 sec which can reach up to 10,000 sec and efficiency can reach to an amazing 80%. As seen, the thruster has unique features that gain attention as they have the potential to overcome most drawbacks faced by other EP systems, with relatively minimal complexity.



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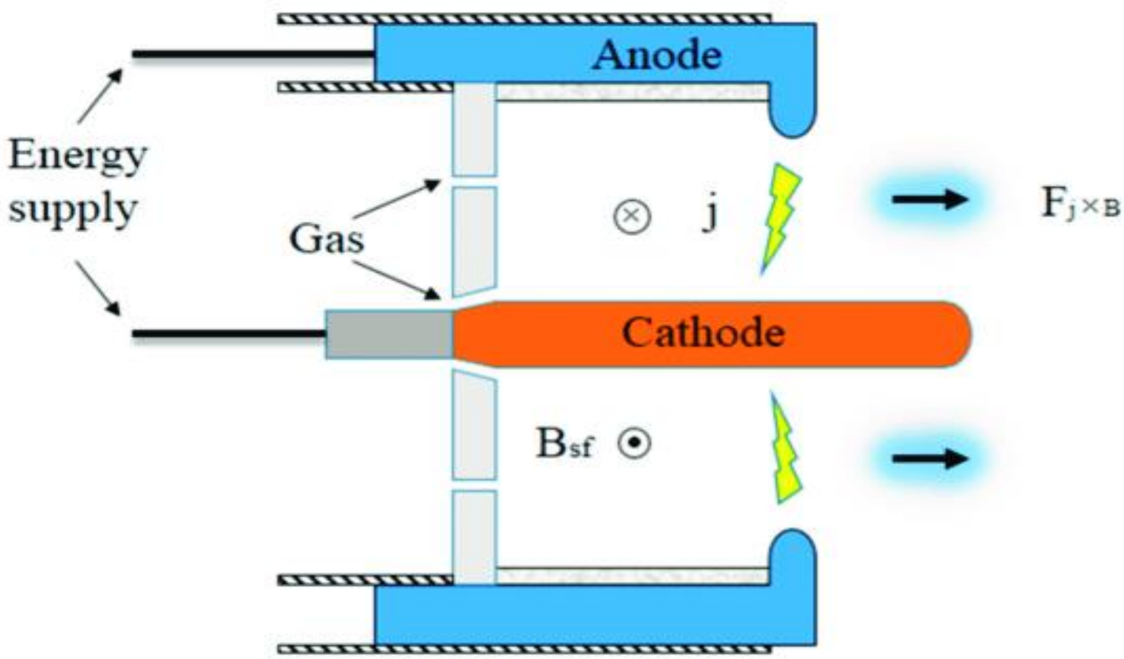
IX. MAGNETO-PLASMA-DYNAMIC THRUSTER(MPDT)

An MPDT is an EP system which uses the Lorentz force-the force on a charged particle by an electromagnetic field-to generate thrust. The kinetic energy is gained from indirect heating and direct acceleration, there are also minor electromagnetic effects, like a "swirl" and Hall acceleration. Generally, an acceleration chamber with magnetic and electrical fields(produced by power source) propels ionized propellant gas by the Lorentz force generated from the current flowing in the plasma and the magnetic field(either induced by current or externally applied) out as exhaust. Specific impulse and thrust are directly proportional to the power input. The current though the plasma, therefore, imparts a significant part in the creation of Lorentz force, which has an important part in the exhaust direction. This force has three components- along the thruster axis(adds to the thrust) and toward (pushes the plasma towards to the center) and perpendicular to both of these around the axis(generates a swirling effect, contributing to thrust and spreading the arc radially. The two main types of the thruster are applied-field and self-field thrusters, the central difference is in applied field the magnetic field is applied externally. The self-field thrusters have a cathode extending through the middle of the chamber, it uses a strong radial current between concentric electrodes, resulting in a magnetic pressure(directly proportional to thrust) and an azimuthal magnetic field, with a drift current. This is quite similar to PPTs except for the geometry. Applied field thrusters may use a Helmholtz coil, a solenoid around the exhaust chamber to produce magnetic field, or a permanent magnet ring around the volume occupied by the arc, it produced meridional lines of force, arranged so as to diverge as a plume toward the exit, this force creates an azimuthal electron drift current. Many pressure, thermal and other components result in the operation being complex to understand(hence research and development is lagged), but makes it efficient in lower powers. **P**ropellants such as xenon, neon, argon, hydrogen, hydrazine, lithium, other noble gases etcetera have been used, where lithium is usually seen to being the best performer as it reaches efficiencies of over 40%(at low power and specific impulse of 2000 sec) while noble gases have only up to 35% efficiency(at very high specific impulse of 3500 sec) and an added advantage being that it reduces erosion on central cathode significantly. Among noble gases, argon is the most important performer. Hydrogen has shown to have much higher efficiencies of over 50% and specific impulse of over 5000 sec. In applied field design, the magnetic fields can be manipulated independent of the amount of charge running through the cathode and anode resulting in a possibly extended lifespan. MPDTs have to potential of reaching exhaust velocities exceeding 110,000 m/s, about 25 times better than liquid rocket systems and extremely high specific impulses and thrust(200N), making it the highest performer among EP systems and is regarded as a leading candidate for complicated future space missions with high payloads. The magnets however require cooling as they can heat up resulting in their properties getting degraded over time. At low power, the cooling can be done passively, at medium power, the cold gas propellant can help in cooling before being heated by the anode(this process is called regenerative cooling), the high power performing magnets which are usually the best for the thruster require a secondary cooling cycle and refrigeration system with pumps, compressors and radiators. Electromagnets do however have an advantage to change strength of the field within a range, increasing electricity and cooling if coil degrades overtime, but this isn't an option with permanent magnets, it is worth taking time for decisions with the magnetic field generation components as it is one of the lifetime limiting components of the thruster. A Helmholtz coil can theoretically tune your drive system in various ways, like pumping up the strength to constrict the plasma more if there's a lower-mass stream, but once the plasma has enough charge through it, the self-field contribution increases, which could be an advantage as at sufficient power, coil or magnets are unnecessary, resulting in a simpler, less temperature sensitive system, hence most high powered systems use self-field MPD.



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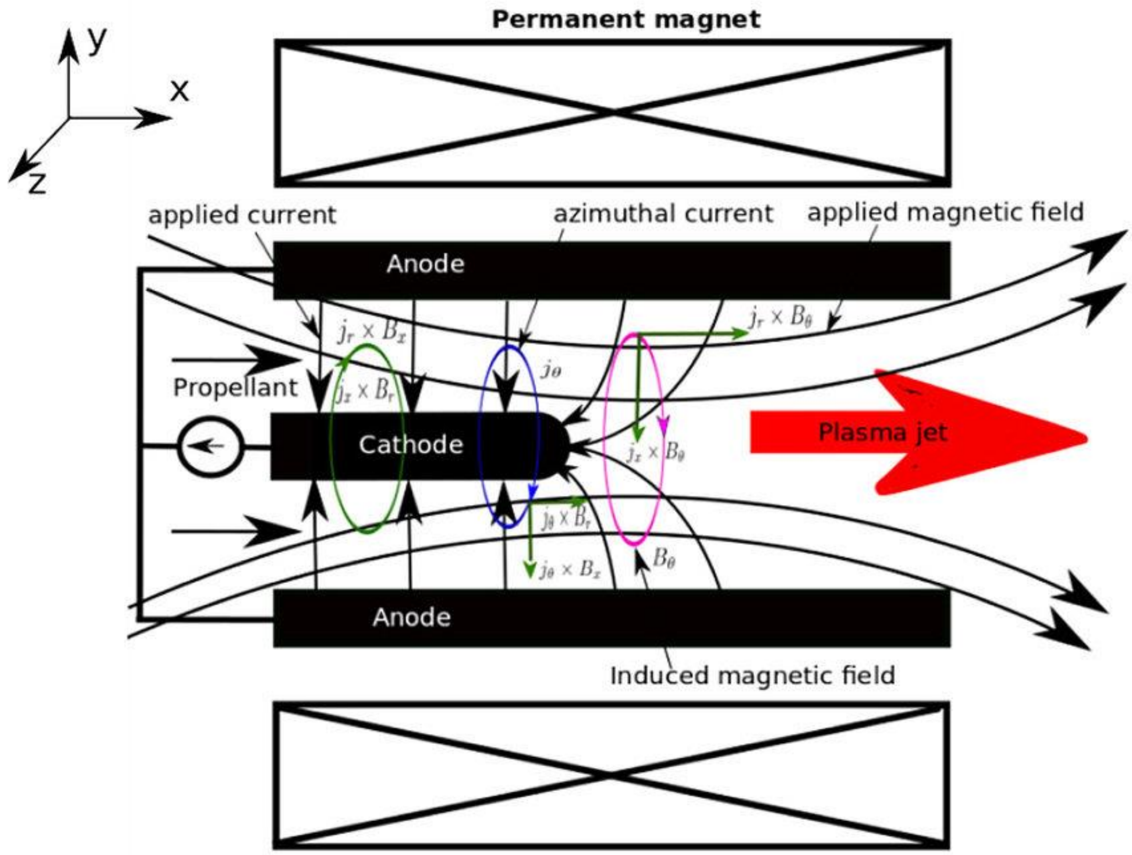

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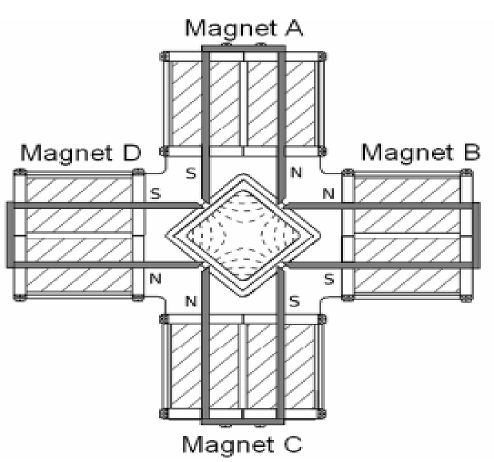
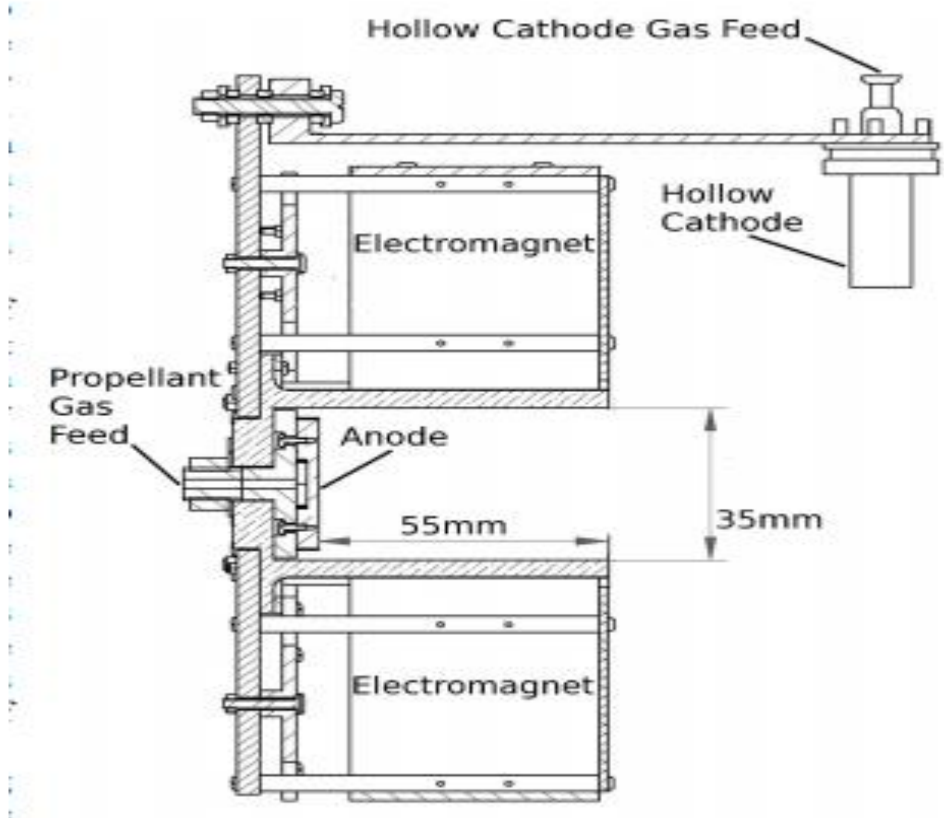
X. QUAD CONFINEMENT THRUSTER(QCT)

The QCT developed by the Electric Propulsion Group of the Surrey Space Centre in 2009, is a new plasma propulsion design. It has a unique magnetic topology- The magnetic field contains a quadruple arrangement of eight electromagnets, four apexes at the midsections of the channel walls and a fifth apex at the center of the channel, producing an open ExB drift, this set up is for the magnetic fields to weakly confine electrons within the channel and enhance the ionization efficiency and the ions remain unaffected by this magnetic field leading to acceleration by an axial electric field present between the cathode and anode of the thruster. The momentum of these ions leaving the thruster generates thrust. Another way of describing this system is that it consists of a perpendicular magnetic field between the external cathode neutralizer and a metallic anode. It overall resembles the HET system with a few key differences. The QCT operates at low anode voltages and it can vector thrust without the use of mechanical joints. It has very poor thrust efficiency of less than 7% and depends deeply on the magnetic field, specific impulse reaches to around 800-900 sec, more or less. The change in magnetic field causes relocation of the center of thrust and ion acceleration, providing a new ability to actively vector the direction of thrust without the need for moving parts that may prove useful to future spacecraft missions.





XI. FIELD EMISSION ELECTRIC PROPULSION THRUSTER(FEEP)

The FEEP is a complex electrostatic ion thruster EP system design that consists of an accelerator electrode, propellant, neutralizer, reservoir, an emitter and a power source. It is based on ionization of a liquid metal, and subsequent acceleration of the ions by a strong electric field. The Field Effect, which refers to generating a spray of charged ions from a strong electric field, is the main principle in use. On requirement of thrust a high potential difference is set up between the emitter and accelerator to create a high electric field, potential difference between the electrode and the free surface of the liquid metal propellant is balanced by it's surface tension and it thus enters a regime of local instability from all the combined effects, and the surface deforms into protruding cusps or equilibrium cone shapes called Taylor Cones at the surface of the liquid, due to strong field intensities(110 V/m or more) in the tip of this cone, spontaneously ionized propellant jet or spray is formed and are expelled at high velocities in bulk of the liquid through a micrometric slit emitter with the help of an accelerator. Liquid metal propellant is injected through a narrow channel by capillary forces, usually the emitter is two steel halves(or any other suitable material) and a nickel layer in sprayed on one of the emitters outlining the desired channel that ends at the emitter tip. The emitter is generally positively charged and accelerator negatively. An externally placed neutralizer like a cathode or a field effect microtip array provides electrons for overall neutrality of the ejected stream. Performance is optimized with metals or alloys, preferably alkali metals, with properties like high atomic weight, low melting points, good wettability and low ionization potentials like rubidium, cesium, indium and mercury, which ensure high mass efficiency and simplicity in overall thruster structure by discarding pressure chambers etcetera. Another design of FEEP is one based on the concept of Micro-electromechanical system, in which the thrusters, valves, and control electronics may be integrated into a single chip or a stack of chips or needle arrays. An added advantage of slit emitters compared to stacked chips array is the self-adjusting mechanism controlling the emission site formation and redistribution on the liquid metal surface, whereas the Taylor cones can only exist on the fixed tips in the stacked array, which make it consistent with one particular operating condition. Some benefits of the FEEP includes, high specific impulse(6000-12000 sec), very high, near instantaneous switch on/switch off capability, and high-resolution throttle ability **(**enabling accurate thrust modulation in both continuous and pulsed modes), drag free control over thrust, low noise in thrust, remarkably high thrust efficiency (close to 100%), Absence of moving parts-no valves and no pressurized gases, Self-contained propellant reservoir, high exhaust velocity of around 100,000m/sec, extremely low fuel usage. The thrust per unit power is very small (16 mN/W), which limits applicability to low-thrust precision control and the thrusters are mainly used for microradian, micronewton attitude control on spacecraft. The FEEP is one of the few EP systems that do not rely on gas-phase ionization, which is important in micro-propulsion(like for

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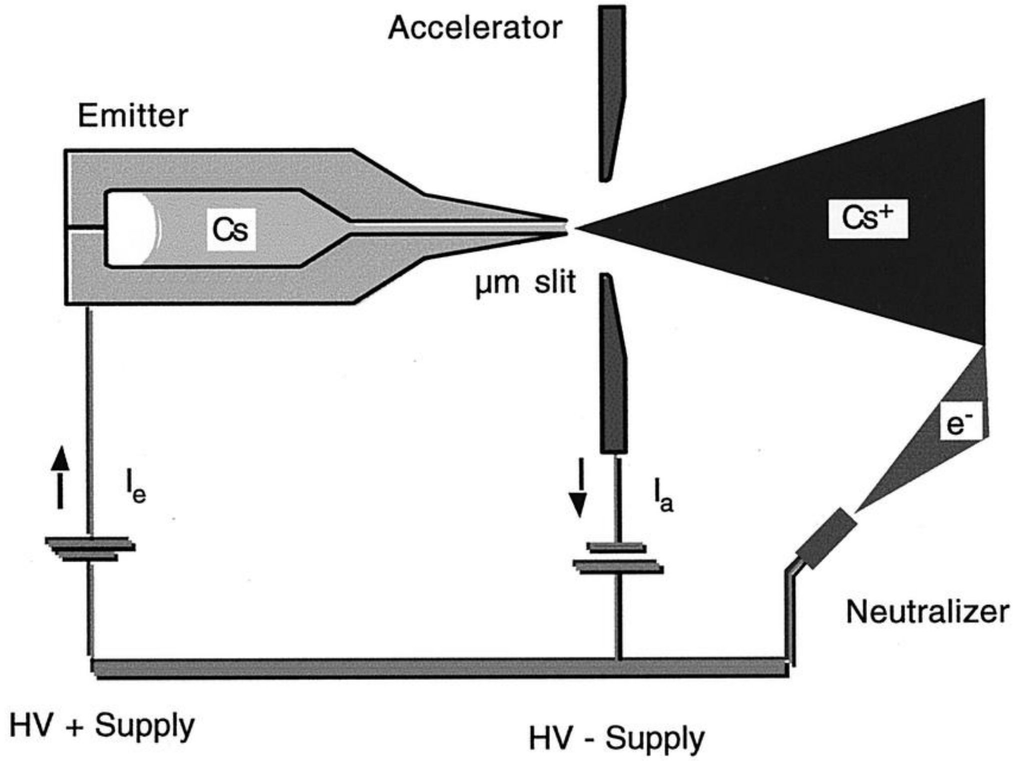
CubeSats). Another secondary problem is the high sensitivity to surface contamination.



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XII. COLLOID AND ELECTROSPRAY THRUSTERS

These thrusters have been in research since the 1960s, they were developed with a goal to yield higher thrust density and would be efficient at lower specific impulse than ion engines, but this technology was put on hold for application due to the overshadow fine thrust control by the high power requirement for the very low thrust that the thruster provides. But with modernization, and interest and applications for their use in small satellites it is coming to light with developed systems to ensure significantly less power. The concept of electrospray is extraction of ions from the previously described Taylor cones for propulsion with the same creation process as above, it produces ionized aerosol droplets of liquid propellant without the complex electromechanical plumbing for pressurization and vaporization but result in nearly 100% ionization and involvement of no moving parts. It allows for very controlled and a wide range of thrust just as described above. The colloid thruster breaks the propellant into tiny droplets instead of ions for ionization and accelerates them. The main drawback was that they required a large amount of power to produce minimal desired specific impulse. Recent work has developed colloidal engines with efficiency of 65% with specific impulse range of around 1000 sec that operate with voltages of 15– 25 kV. This system makes it perfectly suitable for micro-propulsion applications requiring high DV at good thrust/power ratios.

The propellants are usually non-metallic, low-volatility ionic liquids like doped glycerol and formamide. Like other ion thrusters, its benefits include high efficiency, high thrust density, and high specific impulse, fine attitude control, efficient acceleration of small spacecraft over long periods of time. They do not use much power overall and have extremely low total thrust. They are usually not suitable for main propulsion.

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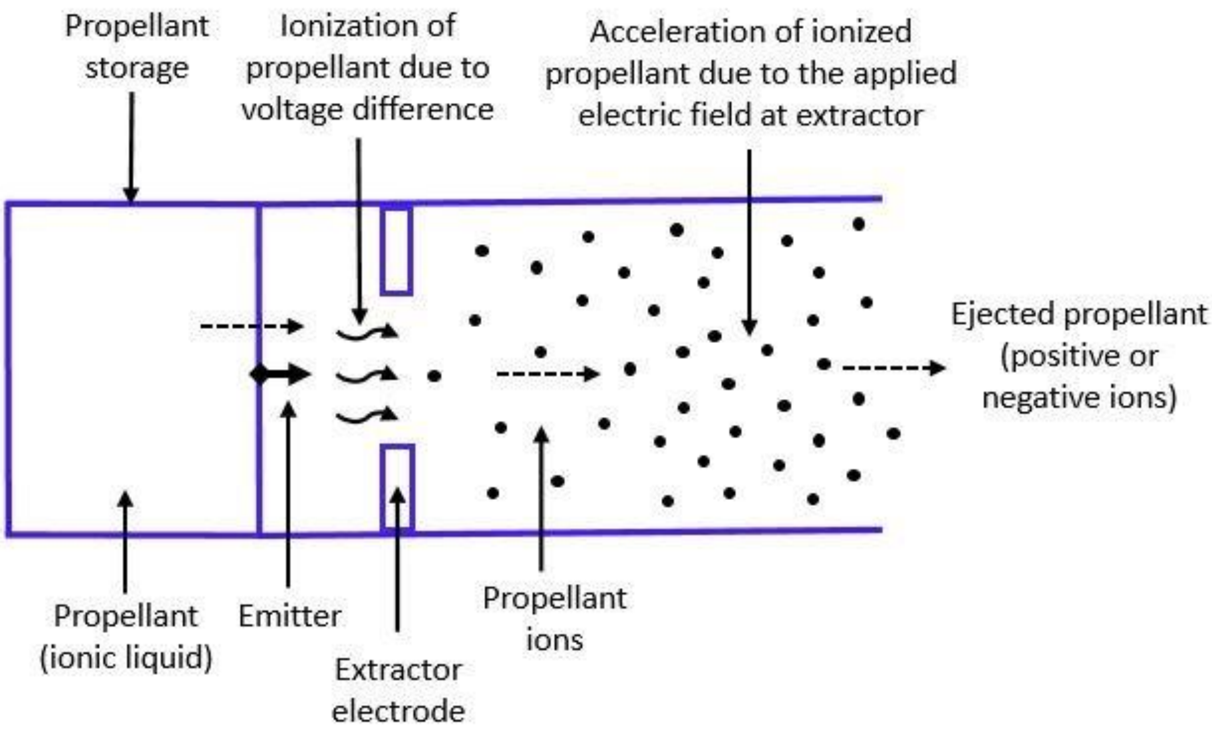

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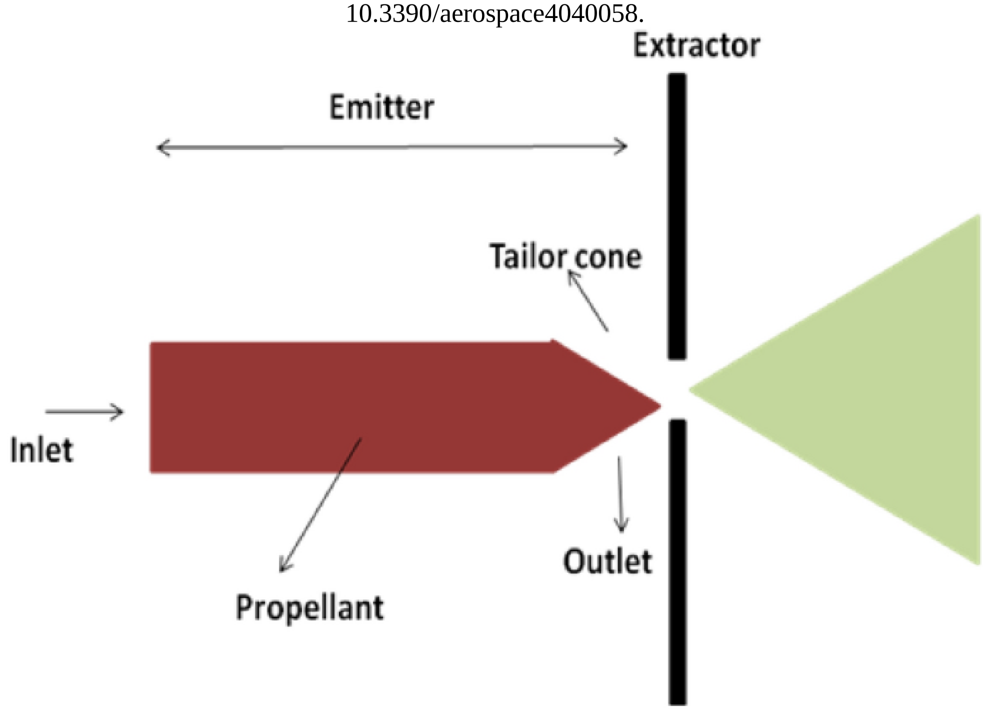

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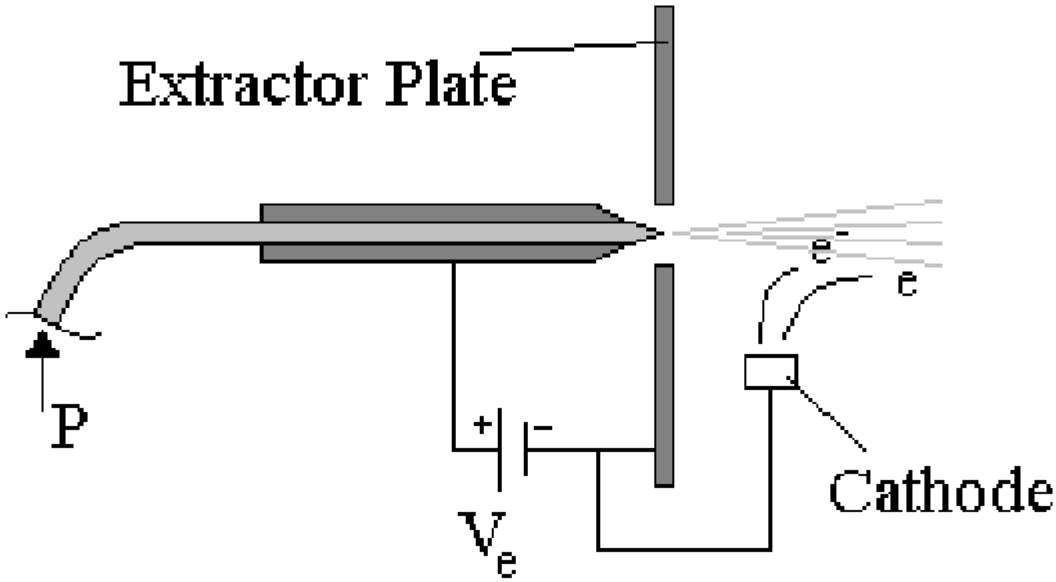

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XIII. ELECTRODE-LESS THRUSTERS(ELT)

This thruster is a novel design with a goal to efficiently accelerate any propellant to high exhaust velocities of around10000-40000 m/s and to operate in high power of more than 100kW, with a simple electrode- deficient, lightweight design with an almost limitless operational lifetime. It uses a rotating magnetic field drive for ionization of the propellant gas, the propellant is injected at the upstream end of thruster where it is ionized by bombarding the propellant with electrons, or by a steady electrical discharge between two electrodes or even by applying an alternating electric field via a capacitive, inductive discharge or even a helicon discharge, as the ionization is directly subjected to a magnetic field, it can utilize other ionization mechanisms such as the ion cyclotron resonance (ICR), electron cyclotron resonance (ECR) or lower hybrid oscillation. Solid propellants can be vaporized and ionized by EM waves. The ionized propellant in the plasma form is then diffused to the acceleration stage where it is accelerated by magnetized ponderomotive force in an non-uniform magnetic and electric field(high frequency) which are both applied simultaneously. The thruster drives an azimuthal current to form a Field Reversed Configuration (FRC), which is a closed toroidal magnetic plasma set up, compressing an axial electric field against the conductive rings in the perimeter of the thruster chassis. The FRC converts the thermal energy into thrust as it expands, this is repeated in time difference the order of milliseconds, providing a seemingly constant thrust. The acceleration process is not limited by grid electrical screening or the Hall effect parameter of plasma density hence providing large thrust density. One noticeable feature of the thruster is the absence of an external neutralizer due to all plasma species being accelerated in the same direction, it is also inherently multi-staged and is optimized at all stages manually, independently. The thruster can be controlled at constant power as per requirement of higher thrust or specific impulse. The thruster also eradicates contamination and erosion issues as it has no contact between the plasma and the electrodes, making them significantly more durable than most other thrusters that use electrodes. They have low fuel mass usage than the chemical thrusters at the same thrust levels, the large thrust density allows faster missions.

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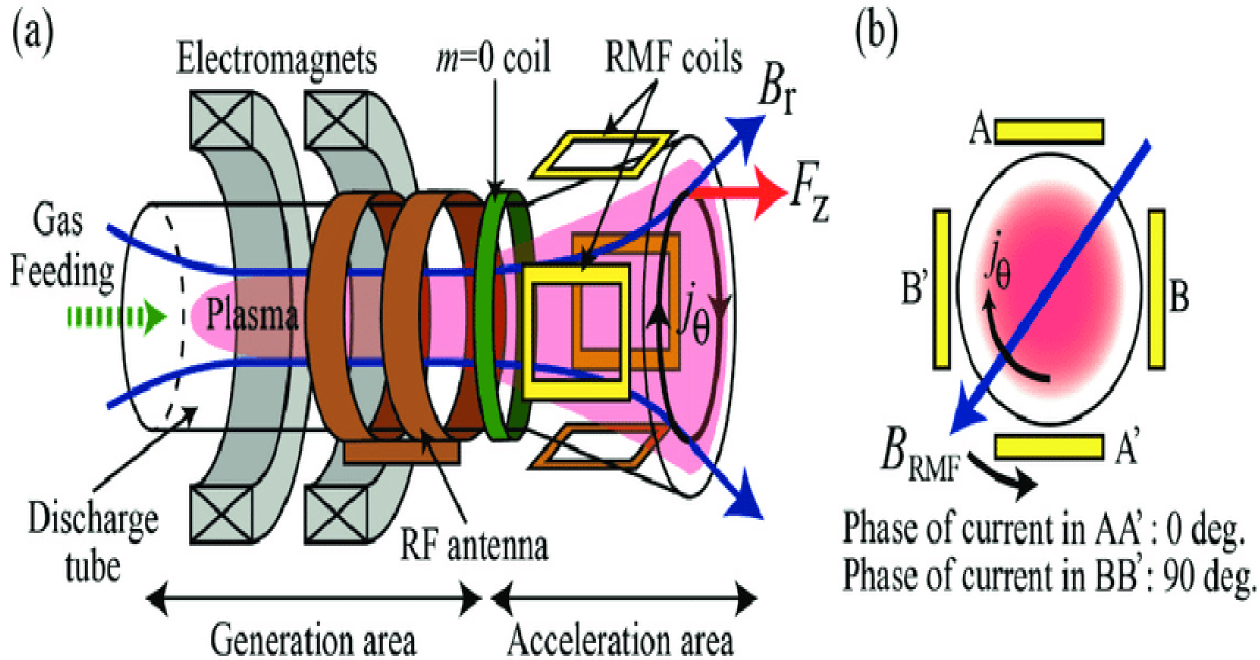

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XIV. VARIABLE SPECIFIC IMPULSE MAGNETO-PLASMA ROCKET (VASIMR)

The VASIMR engine is a very novel design of plasma-based propulsion systems with extremely promising applications and features, it is a type of electrothermal propulsion, it works by ionizing and heating a neutral, inert propellant using radio waves. A propellant is injected into a hollow channel surrounded by electro-magnets and an electric power source is used to heat and ionize fuel into plasma, a series of two radio wave (RF) couplers(mostly Helicon couplers which ionize gas by launching helical waves), which turn the propellant gas into superheated plasma, which is then accelerated by the electric fields. The plasma is called cold plasma though it’s temperature can be as high or little more than the Sun's surface. The Ion Cyclotron Heater, the second coupler, emits electro-magnetic waves in resonance phase ions as they travel through the engine slowing down orbital speed the plasma particles, this heats the plasma to temperatures around 173 times the sun’s surface. The magnetic fields direct the plasma in towards the exhaust consisting of a magnetic rocket nozzle that converts the plasma thermal motion into a focused jet, creating thrust for the spacecraft, which can be varied allowing it to vary its acceleration. This exhaust can reach extreme velocities of the order of 180,000 km/hr. The cyclotron waves push only on the ions as they orbit in the magnetic field lines. The ions are immediately ejected from the nozzle before they achieve thermalized distribution. The ions leave the nozzle with a very narrow energy distribution as the energy of the ion cyclotron wave is uniformly transferred to the plasma in a single-pass cyclotron absorption process. It also may sport a special mode to sacrifice fuel efficiency and provide additional speed if required, hence it can either have low thrust and high specific impulse or high thrust and low specific impulse. Some propellants that can be used are hydrogen, helium and deuterium, argon, neon, krypton ammonia, iodine, potassium, rubidium, xenon and can be adapted to other solid or liquid propellants that do not pose a risk for the spacecraft. It has efficiency exceeding 70% and specific impulse of about 2000-5000 sec and scales to power of the order of megawatts of. The entire engine is magnetically shielded from the plasma, is also electrode-less and has almost no moving parts hence increasing durability and decreasing erosion. Some major drawbacks are that the strong magnetic fields and electromagnets may cause interference with other devices on board and cause unwanted torque from magnetosphere interactions. This effect can be counteracted making a net zero-torque magnetic quadrupole, by placing two thruster units packaged with magnetic fields oriented in opposite direction. This engine provides the power density needed for sustainable human exploration.

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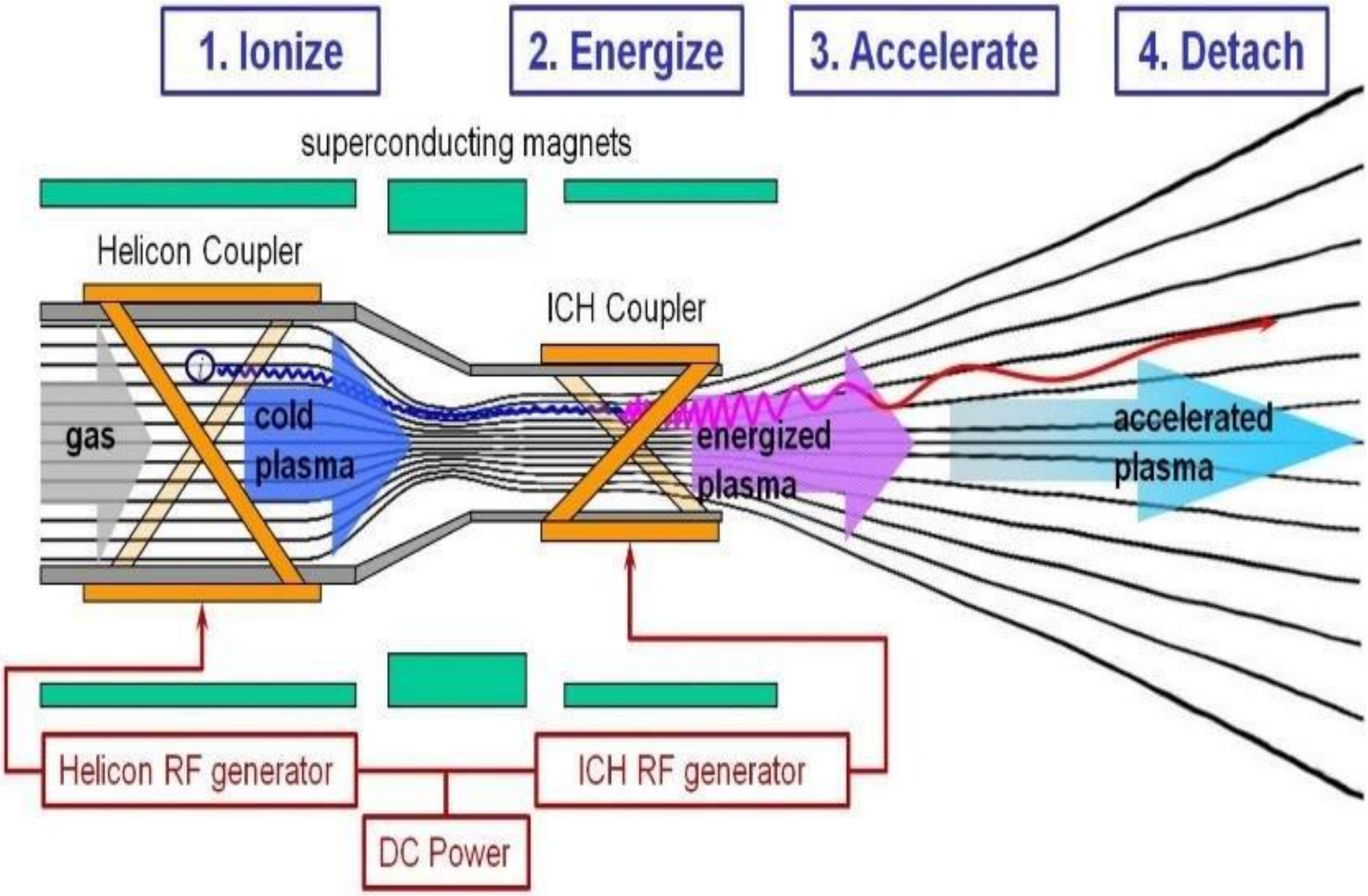

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	resistojet	arcjet	GID/RF ion	HET	Colloid	FEEP	VASIMR	QCT	ELT	MPDT	PPT	HEMPT
type	electrothermal	electrothermal	electrostatic	electrostatic	electrostatic	electrostatic	hybrid	electromagnetic	electromagnetic	electromagnetic	electromagnetic	electrostatic
efficiency	65-85%	35%-50%	30-90%	45-55%	50-65%	95-100%	70-87%	5-7%	50-55%	35-65%	8-30%	70-80%
thrust	0.5–60	50-68	0.01–75	0.25-12	30-50	1.6-10	36-40	8.6-10	1.2-15	2.5-25	0.05–10	0.01-2000
specific impulse	150-850 sec	130-2200 sec	1500-18000 sec	1000-8000 sec	900-3000 sec	6000-12000 sec	2000-5000sec	800-900sec	1000-6000sec	5000-6000sec	1400-2700 sec	3000-10000 sec
power	450-700W	150-600W	20-250W	200W-2kW	15-25kW	90-150W	200-300kW	20-200W	100kW	100-300kW	50-200W	150-300W
exhaust velocity	3500 m/s	20000m/s	90000 m/s	50000 m/s	12000 m/s	100000m/s	180000m/s	10000m/s	10000-40000m/s	110000 m/s	14000m/s	28000 m/s

XV. FUTURE?

Everyone is familiar with the sight of blazing fire and smoke when a rocket is launched into space, but as great as the thrust it produces may be, it's certainly not efficient. The hopefully not-so-far future may even hold EP systems with thrust as good as or greater than conventional chemical propulsion systems. The costs for EP systems is predicted to cut down largely in about 10-20 years. Some major challenges to be addressed are facility effects, lifetime extension challenges, prototyping or making simulations and predictive models for incompletely understood systems, power and propellant improvements, etcetera. Currently, most EP systems derive power from solar systems, but if the field must develop, there have to be developments in nuclear reactor systems, NASA'S kilopower project already seems to be letting go of the limits solar EP brings by harnessing in-space fission reactors. But even without unpredictable fission reactors, solar EP systems can produce an amazing amount of energy that is the stuff of science fiction, with huge cargo, efficiencies, and speeds. There is no doubt electric propulsion systems will be the dawn of many futuristic systems with major applications in all fields but most importantly space exploration and research.

New age satellites are preferred to be small and cost effective, the most popular being CubeSats, which are an affordable means to perform scientific and technological studies in space, hence have been studied diversely. CubeSats

XVI. CONCLUSION

This paper hopes to have provided a condensed overview of electric propulsion systems, which a very novel propulsion system but has undergone rapid development for applications in the real world which is predicted to continue undeniably breaking stereotypes and bringing fiction to reality. The descriptions and points made here will become obsolete with future development in possibly a short enough time.

The author apologizes in advance for any points that may have been missed.

XVII. APPENDIX

This table provides a concluding condensed comparison for the electric propulsion systems described in this paper, other information that the reader may want to acquire can be referenced from the links to all references provided below.

XVIII. PEER REVIEWS

IMPROVEMENT AS PER REVIEWER COMMENTS

ACNOWLEDGMENT

I would like to show my gratitude to Brahmastra aerospace systems for sharing their pearls of wisdom with me during the course of this research, and I thank the reviewers in advance for their so-called insights, although any errors are my own and should not tarnish the reputations of these esteemed persons. Lastly, I'd like to thank myself for managing time for this paper, the first of my research, to be possible.

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