A REVIEW ON ION THRUSTER PLASMA GENERATORS

Aditya Rajan Iyer

Student, Jain University International Institute of Aerospace Engineering and Management, Bangalore- 560078

Abstract - Ion thrusters are characterized by electrostatic acceleration of ions extracted from the plasma generators. This paper discusses the construction and working principles of plasma generators used in space flight, we would discussing the four primary thruster designs namely the DC ion generator, Kaufmann generator, RF generators & Microwave generators.

Key Words: T_g - Grid transparency, n_0 - Neutral gas density, n_e - Plasma electron density, v_a - Ion acoustic velocity, v_e - Electron velocity, σ_i - Ionization cross section

V - Discharge chamber volume, $\langle\sigma_i v_e\rangle$ - Reaction rate coefficient

1. INTRODUCTION

An ion thruster comprises of three major components namely, **the plasma generator**, **neutralizing cathode** and **accelerating grids.** The discharge cathode and anode constitute the plasma generator, ions formed in this region undergoes acceleration in the grid. The plasma generator is at a higher positive potential and in enclosed in a **plasma screen** biased at space craft potential, to prevent accumulation of electrons on positive biased surfaces. The **neutralizer cathode** prevents a charge imbalance with the space craft by providing electrons at the same rate as the ions.

Plasma generators utilize **direct current (DC), radio frequency (RF)** and **microwave** discharges to create plasma. The performance of the thruster depends on **plasma generator efficiency** and **accelerator grid designs**, they have high impact on the thruster's **specific impulse** and **thrust** produced. **NEXIS** a thruster developed in **JPL** has an I_{sp} of over **7000s** and a lifetime of **10,000hrs,** owing to their high specific impulses and lifetimes they are a promising means of propulsion.

1.1 Ideal Plasma Generator

Before looking into the different types of plasma generators it is reasonable to look into the performance of a theoretical generator. The ideal plasma generator has fixed discharge volume which encloses the plasma fully, the ions from plasma flows directly to the accelerating grid which constitutes the **Bohm current**. The beam current is represented as ($\frac{n_i v_a e A T_g}{2}$) where some part of the current is lost to the accelerating grid and decelerating grid.

Ions production rate in the discharge chamber is given by the equation, $I = n_0 n_e e\langle\sigma_i v_e\rangle V$ the **reaction coefficient** is the ionization cross section spread over Maxwellian electron velocity distribution.

Power is conserved in an ideal plasma generator where the power that is put in the thruster comes out as power in the form charged particles and radiation. The total power input in the generator is given by the equation: $P_{in} = I_P U^+ + I^* U^* + I_i \varepsilon_i + \frac{n_e V}{\tau}\varepsilon_e$ On further expansion of the equation we see that it depends on the **excitation cross section** and **reaction rate coefficient** summed over all possible excited states. ($I^* = \sum_j n_o n_e e\langle\sigma_* v_e\rangle_j V$)

The **discharge losses** can be defined as the power input by the beam current from the thruster and can be represented by the equation

$$\eta_d = \frac{2n_0\langle\sigma_i v_e\rangle V}{v_a A T_g}\left[U^+ + \frac{\langle\sigma_* v_e\rangle_j}{\langle\sigma_i v_e\rangle}U^*\right] + \frac{1}{T_g e}\left[2.5k + kT_e \ln\left(\frac{A_a}{A}\sqrt{\frac{2M}{\pi m}}\right)\right]$$

As evident from the equation the **discharge losses** directly depend on the grid transparencies, the first term of the equation represent **production of ions** and **excited neutrals** and the second term represent **heating the electrons** that are lost to the walls.

The major power loss is excitation at low mass utilization where the electron temperature is low, the ion and electron convection losses increases due to high mass utilization efficiency since the neutral density decreases, this also results in an increase in electron temperature, increasing the plasma potential thus increasing the energy lost per ion or electron. Even for an ideal xenon thruster the power supply must 7.5 times the ionization potential i.e. 12.6eV in order to overcome these losses.

In reality the discharge losses are significantly higher due to imperfect confinement and domination of either of the loss mechanisms discussed, hence requiring higher power supplies.

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 08 | Aug 2020 www.irjet.net p-ISSN: 2395-0072

2. DC Generators

The DC electron discharge plasma generator employ a **hollow cathode source** and anode potential discharge chamber with magnetic multipole boundaries for plasma generation and ionization. Electrons extracted from the cathode are injected in the discharge chamber where they ionize the propellant gas, the magnetic confinement increases the electron path length so as to increase the ionization efficiency before they get lost in the anode. The ionized beam is then focused on the grids which get accelerated electrostatically.

A major part of a DC discharge thruster is the design of the magnetic field for ion and electron confinement. The discharge chamber geometry and magnetic field line shape influence generator performance to a great extent.

Solenoidal or **slightly divergent magnetic fields**, requires the on- axis electrons to undergo collisions before completing the discharge circuit. **Strongly divergent magnetic fields** were utilized for a uniform beam profile and to curb discharge losses. The **radial magnetic confinement** also produce uniform plasmas with good efficiencies, so did the **cusp version of the divergent magnetic field.**

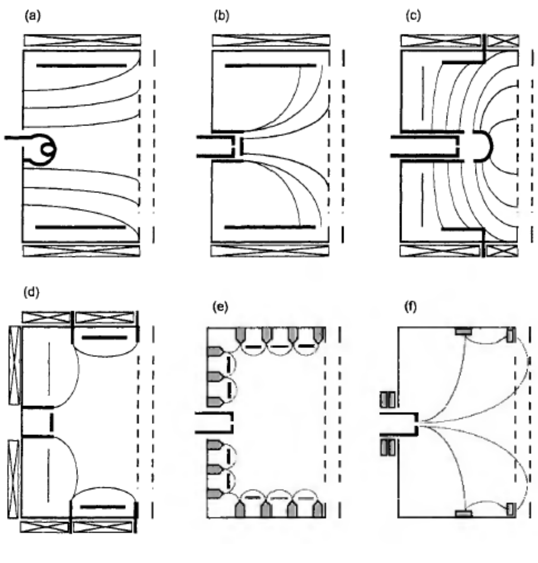

Fig-1 Magnetic field types (a) mildly divergent, (b) strongly divergent, (c) radial field, (d) cusp field, (e) magnetic multipole field, (f) ring-cusp fields.

There are mainly two type of magnetic field geometries used the **multipole magnetic field ring cusp thrusters** and **divergent solenoidal thrusters.** Ring cusp thrusters use alternate polarity permanent magnets rings place around anode- potential thruster body. Energetic electrons are injected at the cathode where they demagnetize sufficiently to bounce off the magnetic field until they lose energy due to collisions before at ending up at the anode.

There are some design verticals associated with the DC plasma generators which are describe in brevity. The alternating polarity magnets are oriented perpendicular to the thrust axis, the configuration provides magnetic confinement of electrons and electrostatic confinement of ions due to **ambipolar** potentials at the boundary due to the traverse magnetic fields. Asymmetries at the end of the line cusp adversely affects electron confinement and thruster efficiency. The magnetic field strength above the magnetic array is described by the equation

$$B_y(x,y) = \frac{\pi w B_0}{2d}\cos\left(\frac{\pi x}{d}\right)e^{\frac{-\pi y}{d}}$$

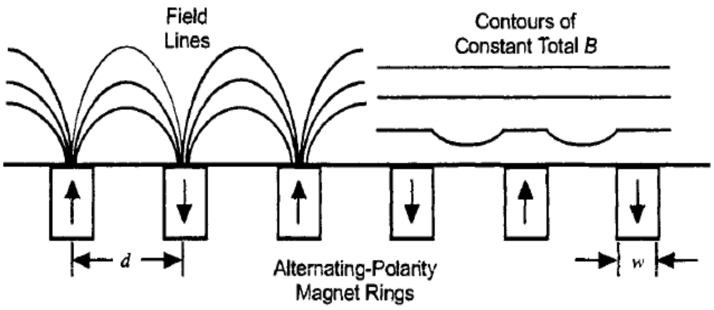

Fig-2 Magnetic multipole boundaries.

The primary electrons generated bounce around in the chamber, make an ionization or excitation collision before getting lost in the anode. The primary current lost at the anode cusp is given by $I_L = n_p e v_p A_p$. The probability that an electron will make a collision and not get directly lost in the anode is given by $P = \left[1 - \exp^{(-n_0 \sigma V / A_p)}\right]$.

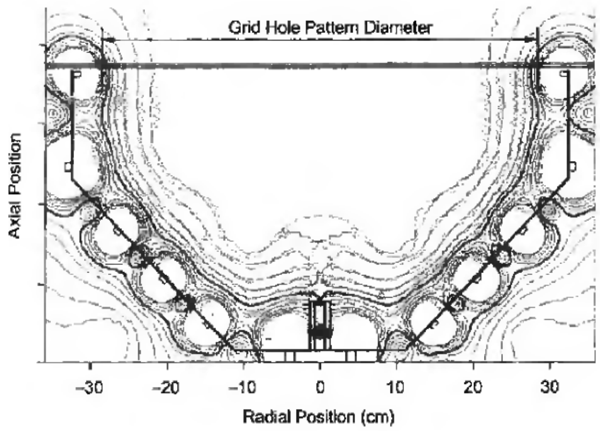

Fig-3 Magnetic field contours in NEXIS thruster.

Ions in the discharge chamber are produced by both primary electrons and the tail of the **Maxwellian** distribution of the plasma electrons. The total number of ions in particles per second is given as: $I_p = n_0 n_e \langle \sigma_i v_e \rangle V + n_0 n_p \langle \sigma_i v_p \rangle V$

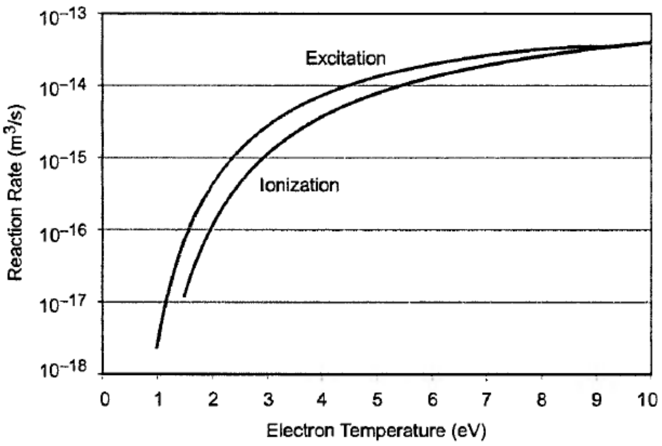

Fig-4 Plot showing ionization and excitation rates at different electron tempratures.

The electrons exceeding the second ionization potential in Maxwellian distribution produce double ions if the electron temperature in chamber is high. This must be considered while computing for beam current and mass utilization efficiency.

It is also very important to compute the neutral gas flow that escapes the chamber which is simply calculated as gas injected in the discharge chamber minus gas particles that are ionized and extracted from the ion beam given by the equation $Q_{out} = Q_{in} - \frac{I_b}{e}$ where Q_{out} can be expressed as $Q_{out} = \frac{1}{4} n_0 v_0 A_g T_a \eta_c$. In DC discharge thrusters the discharge loss is given by $\eta_d = \frac{I_d V_d + I_{ck} V_{ck}}{I_b}$ on further expansion of the equation illuminates some of the design features that improve the discharge efficiency. Higher discharge voltages result in lower discharge losses, higher grid transparency, smaller ion confinement factor, small primary loss area and wall areas reduce the discharge losses. The **discharge stability** of the and the discharge losses hold a close relationship, the stability of the discharge after extensive study is found to rely on the **magnetic field design** in order to get a stable discharge a large anode area is preferred which in turn reduces the efficiency, the tradeoff between thruster efficiency and discharge stability is important aspect in generator design.

3. KAUFMANN THRUSTERS:

The Kaufmann thruster features a strongly diverging axial magnetic field which shields a cylindrical anode electrode located near the wall of the discharge chamber. The electron transport totally depends of the cross field diffusion. The flux of electrons due to cross field diffusion is given by $\Gamma_e = \mu_\perp nE - D_\perp \nabla n$. The electron collected at the anode is the flux that diffuses through is the magnetic field times the Boltzmann factor at the sheath:

$I_a = (\mu_\perp nE - D_\perp \nabla n) e A_{as} e^{-e\phi / kT_e}$, majority of the parameters calculated for DC discharge thrusters remain same for the Kaufmann thruster, but we can neglect few terms.

The magnetic field lines do not intersect the anode and the primaries are too energetic, by virtue of which we can neglect the losses of the primary current at the anode I_L. As previously shown if the traverse magnetic field strength exceeds **50G** the radial electric field is near zero, meaning that the ion loss rate is 1/10th the **Bohms** current, hence we can avoid the ion current to the anode term to the first order. In ring cusp thrusters the ions flowing back to the hollow cathode was neglected, in Kaufmann thrusters a baffle place in front of the hollow cathode in order to flatten the density profile. Since the magnetic field is strongly divergent the axial plasma density gradient is high and the plasma density at the baffle is also high, for these reasons the current to the cathode I_k cannot be neglected. The need for a higher discharge voltages in Kaufmann thrusters compared to ring cusp thrusters where discharge losses for a Kaufmann thruster with a constant total cathode voltage of 16V, low discharge losses are arise for 35V discharge voltage and higher discharge losses arise when the discharge voltage is reduced to 30V.

This is because primary electron energy in the discharge chamber is near the threshold energy for ionization and the discharge efficiency decreases as more ionization is required from the plasma electrons. Also lower discharge voltage causes the plasma potential to go significantly negative relative to anode potential which causes the discharge to be unstable. The strong axial magnetic field restricts electron motion to the anode for cross field diffusion, high neutral pressures are required in the discharge chamber for electron- neutral collisional diffusion, thereby low mass utilization hence relying on collective instabilities to increase diffusion rate to obtain sufficient electron loss to support discharge. The instabilities are mainly the $E \times B$ driven and Bohm diffusion creating significant noise in the discharge that can appear in the beam current. The baffle which is used to force the electrons off axis for uniform plasma profile is susceptible to ion bombardment sputtering and plasma losses in the dense plasma regions of the cathode. The problem of sputtering reduces the life of the thruster but alternate materials mitigate the problem.

The primary electrons are injected purely off axis meaning the plasma profile or beam profile is hollow or peaked depending on the cross field diffusion and mobility throughout the discharge chamber. The magnetic field is sufficient to confine the ions by electrostatic and ambipolar effects to obtain good efficiency but not that high which can give an electron current for a stable discharge. If the field is too strong or the anode area is too small the plasma potential goes negative relative to the anode. On inspection a negative plasma potential relative to the anode the **primary** energy is decreased for a given discharge voltage, strongly affecting the discharge efficiency. The discharge voltage cannot be increased arbitrarily due to ion sputtering at the baffle and electrodes, excessive double ion production will significantly reduce discharge efficiency. The geometry of Kaufman thrusters is good for efficiencies, since the plasma potential is not allowed to go negative with respect to the anode constraining the design space for electrodes and fields.

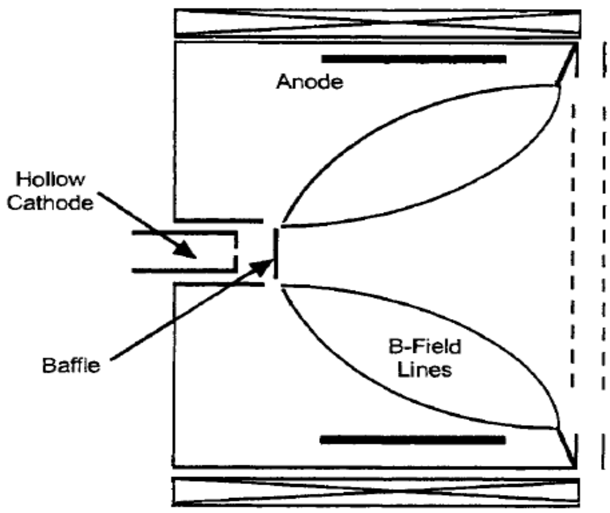

Fig-6 Schematic of a Kaufmann thruster with hollow cathode and baffle.

4. RF THRUSTERS (RADIO FREQUENCY):

The ion thrusters discussed above utilize a thermo ionic hollow cathode and DC discharge power supply to inject electrons in the discharge chamber. To eliminate power supply issues with the hollow cathode and DC electric discharge an alternative design is used which employs electromagnetic fields to heat the plasma electrons which ionizes the gas. A low frequency RF energy is applied to the antenna structure which is coupled to the electrons. In the simplest of configurations an RF coil is wrapped around an insulating chamber with a gas feed. The chamber can cylindrical, conical or hemispherical in shape and is connected to an ion accelerator with either two or three grids. The plasma floats relative to the first grid, high voltage is applied between the grids to accelerate ions through the first grid forming the beam. The RF coil is connected to a RF power supply which provides the power to generate the plasma. There is usually no applied magnetic field in RF thrusters although it can be applied to enhance the discharge performance. The entire discharge chamber is enclosed in a metallic screen or structure to eliminate electron collection from space plasma and neutralizer cathode for net neutralization of the beam. The typical frequencies used in these thrusters is 1MHz, at these frequencies the penetration of the fields is limited by skin depth in the plasma. This produces an attenuation of the electric fields and magnetic fields towards the axis. The axial magnetic field induced by the RF current is given by: $B_z = \frac{NI}{\mu_0} e^{i\omega t}$, the induced electric field in the RF thruster in azimuthal direction is given by: $E_\theta = \frac{-i\omega r}{2} B_{zo} e^{i\omega t}$ where B_{zo} is the peak axial magnetic field and r is the distance from the axis. The induced electric field exists in one direction for roughly half a period, which for a 1MHz frequency is 0.5 microseconds. The electrons do not see the oscillating component of the electric field because they transit the interaction region close to the antenna in a time much less than this value. A $5\,eV$ electron will traverse a distance of 1m in 1 microsecond, therefore will traverse the electric field many times within the half cycle, the electrons see a DC electric field and are accelerated. The probability of an electron making a collision is given by the equation: $P = 1 - \exp^{-n_0 \sigma x}$ here x is the distance traversed by electron .The minimum pressure at a temperature T in the plasma chamber of an RF thruster for breakdown to occur is

$$P_{\min}[torr] = \frac{-1.04 * 10^{-25}}{\sigma x} \ln(1-P)$$

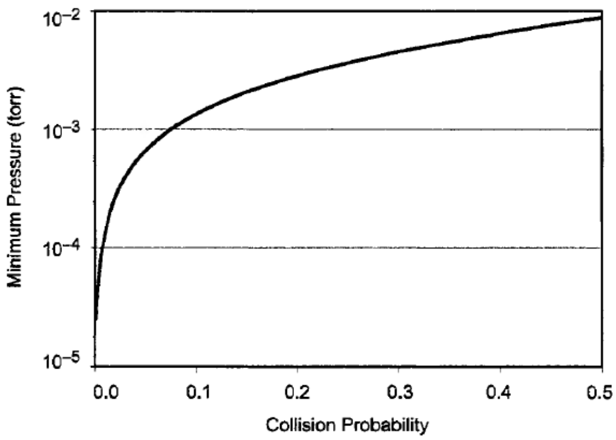

Fig-7 Plot between minimum pressure and collision probability.

Minimum pressures are in the range of 10^{-2} to 10^{-3} torr. Once igniting the plasma the required electron collisions to provide the heating in the RF electric fields can be supplemented by coulomb collisions, between the plasma electrons, which reduce the operating pressure and permit high mass utilization efficiency to be achieved. If the minimum gas pressure is provided the discharge will when the field either large enough to excite the few electrons naturally present in the chamber or causes field emission to occur. An alternate method for electron injection is using a spark generator or the neutralizer cathode which provides the seed electrons for the interaction with RF field. The antennas in the RF thruster are susceptible to **sputter-erosion** ultimately limiting the life of the thruster. This can be minimized by encasing the antenna in an insulator or by making the thruster body by an insulating material and mounting the antenna exterior to the plasma volume. This is applied in **RIT-XT** thruster where the body of the thruster is made of alumina and high conductive material like copper is coiled around the insulator. The discharge losses reported is much lower than showed in the example, this is because the AC magnetic field from the RF coil can provide some confinement for the plasma and reduce the flux to the discharge chamber walls. The magnetic field induced by the RF coil is given by the equation: $B\left[gauss\right]=10^{4}\mu_0 NI$, to produce a 2A beam in a 20cm thruster at 230 eV/ion the input power to the antenna is 460W the RF supplies are 90% efficient so power of 511W would be required, which suggest that **0-D** particle and energy balance can provide reasonable performance estimates. RF thrusters have only Maxwellian ambipolar ion and electron loss rates, which simplifies the discharge loss expression making it easy to analyze few geometric parameters for discharge loss optimization. As the discharge chamber length decreases the antenna axial extent also decreases, reducing the electric field interaction region and decreases the AC axial magnetic field strength due to end effects in the solenoid coil. The ability to breakdown neutral gas initially and couple the RF energy to the electrons may be compromised as length decreases.

Dielectric discharge chambers are susceptible to mechanical problems in fabrication, environmental testing and launch and life issues from coating of the insulator surface with conductive layers, the structural issues are addressed by use of a ceramic discharge chamber with an exterior mounted antenna to provide rigidity for launch survival. The discharge losses for a RF thruster is still higher than a well-designed ion bombardment thruster but its simple design makes it easy to analyze and predict performance of the thruster. It eliminates any cathode life issues and utilizes fewer power supplies to operate the discharge.

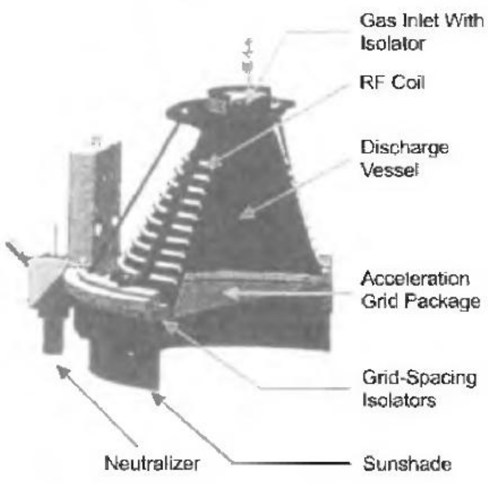

Fig8-Conical RF thruster.

MICROWAVE THRUSTERS:

An alternative of producing plasma in the thruster is to generate plasma using electromagnetic fields at microwave frequencies. Electromagnetic waves can propagate and be absorbed in plasma under certain conditions, if the microwave frequency is too high or the plasma density is too low microwave radiation is completely reflected from the plasma. If microwave does propagate in the plasma, microwave energy is coupled to the plasma by resonant heating of the electrons in a magnetic field in the presence of collisions. The magnetic field required to achieve this resonance is significant and pressure required to achieve sufficient collisions to start the discharge can be relatively high. The propagation of microwaves in a plasma is best understood by examining the dispersion relationship. It is described by Maxwell's equations given by first two and the subsequent three is the electromagnetic behavior on linearizing both the equations:

$$\nabla\times E=-\frac{\partial B}{\partial t}$$

$$\nabla\times B=\mu_0\left(J+\varepsilon_0\frac{\partial E}{\partial t}\right)$$

$$E=E_0+E_1$$

$$B=B_0+B_1$$

$$J=j_0+j_1$$

E_0, B_0, j_0 are equilibrium values of the electric and magnetic field and currents and E_1 , B_1, j_1 are the perturbed values in the electromagnetic fields and current. By applying suitable conditions and assumptions and through meticulous derivation the dispersion relation for electromagnetic waves can be expressed as:

$$\omega^2 = \frac{n_e e^2}{\varepsilon_0 m} + c^2k^2 = \omega^2{}_p + c^2k^2$$

The expression can be further solved for the wavelength of the microwaves in the plasma

$$\lambda = \frac{2\pi c}{\sqrt{\omega_p^2 - \omega^2}} = \frac{c}{\sqrt{f_p{}^2 - f^2}}$$

, where f_p is the real plasma frequency and f is the microwave frequency, if microwave frequency exceeds the plasma electron frequency then the microwaves will not propagate in plasma and will be reflected. The table showing the cutoff frequencies and plasma densities from a xenon plasma at 3 eV .

Plasma density (cm^{-3})	Cutoff frequency (GHz)	J ($\frac{mA}{cm^2}$)
10^9	0.285	0.0118
10^{10}	0.9	0.118
10^{11}	2.846	1.184
10^{12}	9.0	11.84
10^{13}	28.46	118.4

The microwave energy is coupled to the plasma by electron cyclotron resonance heating where microwave frequency corresponds to the cyclic frequency of the electrons in a magnetic field, the resonant frequency is the electron cyclotron frequency given by the expression $\omega_c = \frac{|q|B}{m}$.

The use of microwave radiation enables direct heating of the plasma electrons but for the wave to add energy to the electrons, collisions must take place else energy received by the electron during acceleration on each half cycle of its cyclotron motion is taken back by deceleration of electron in the next half cycle. The probability of collision depends on the **electron- neutral collision mean free path**, an electron entering the interaction region gyrates around the magnetic field lines. Through tedious calculations it can be said that for xenon gas at room temperature for electrons with a temperature of 2ev, to achieve an order of 10% of the electrons colliding with neutral gas atoms for 5-10cm long resonance region requires a minimum pressure of 10^{-3} torr. Magnetic fields of high strength (>1kG) and microwave frequencies (>2.8GHz) are required for production of current densities of (1A/ cm^2), due to difficulty in producing such high magnetic fields throughout the discharge volume the resonance region is often localized to a small region in the thruster volume and plasma is allowed to expand to the grids along divergent magnetic fields. The microwave radiation in this ECR source is coupled into rear of the discharge chamber through a wave window and a quartz liner is used in the resonant region to ensure that the hot electrons are not lost to the metal walls of the chamber. The magnetic field in this region is produced by electromagnets, with a strong divergence field to spread the plasma over the grid region at the exit of the discharge chamber. The performance of the microwave thruster can be examined with the 0-D model. The discharge loss for generic microwave thruster producing 1A of xenon ions, with a 20cm diameter grid with 80% grid transparency is of the order of 200ev/ion. Both ideal and microwave source cases assume ionization by Maxwellian electrons and perfect radial confinement but the microwave case includes plasma loss to the rear wall. Microwave ion source designers mitigate the back wall losses by imposing a stronger magnetic field upstream the resonance zone, creating a magnetic mirror confining the plasma reducing axial losses. Electrons having sufficient initial perpendicular velocity are reflected from increasing magnetic field as their parallel energy is converted to rotational energy. The parallel velocity depends on the R_m also called the **mirror ratio** the velocity expression is given by $v_{\parallel} > v_{\perp}\sqrt{R_m - 1}$, so by putting a value of 5 for R_m we can infer that electrons having a parallel velocity twice the perpendicular velocity is lost. For a volume ionization **ECR** source a significant fraction of the discharge chamber must be filled with a strong magnetic field to satisfy resonance condition. If it were to be produced by a solenoid then it would incur large energy costs, if it were to be produced by permanent magnets then the weight of the magnetic material required to produce this field would cause weight penalties. This problem can be mitigated by using magnetic multipole boundaries that produce strong magnetic fields at the discharge chamber using ring or line cusp magnet configurations. Injection of microwave radiation between cusps, either by cutoff waveguides inserted between the rows, by slotted waveguides run along the rows, or by antenna structures placed between the rows, will couple the microwaves to the high magnetic field interaction region. The magnetic field in the cusp region decreases from the surface which means that very strong magnets are required to produce the resonant field at any significant distance from the wall. Electrons that gain energy from microwaves can be easily lost along the field lines to the walls due to their finite parallel velocity. Optimal **ECR** designs using permanent multipole magnets will have the resonance region as far from the wall as possible and will produce a large mirror ratio approaching the wall to reflect the electrons to avoid excessive direct loss.

Electrons that are heated in the resonance zone sufficiently to ionize the propellant gas generate plasma on the near surface magnetic field lines. Coupling the plasma from the resonance region or the surface magnetic layer to the volume of the thruster is problematic due to the reduced cross field transport. In other thrusters the ion production was a volume effect, convective losses a surface effect so thruster efficiency can be scaled as volume to surface ratio. The plasma density is limited by both cutoff and the magnitude of the resonant field, high current density requires high magnetic field and high microwave frequencies, they have been restricted to low current densities and small sizes. The most successful design is the **MUSES-C**, using extremely strong **samarium cobalt** magnets with achievable mirror ratios of 2-3, the current density is over 1A/ cm^2 using a 4.2GHz microwave source having a discharge loss of 300 eV / ion at 85% mass utilization efficiency.

Sources of microwave frequencies in gigahertz range, such as **travelling- wave tubes** and **magnetrons** have efficiencies in the 50%-70% and the power supply to run them is 90% efficient. Around 10% to 30% of the microwave energy is reflected back into the **recirculator**. The microwave source and recirculator usually represent a significant mass and volume addition to the ion thruster region a lot of compatibility verticals have to be addressed for microwave thruster design.

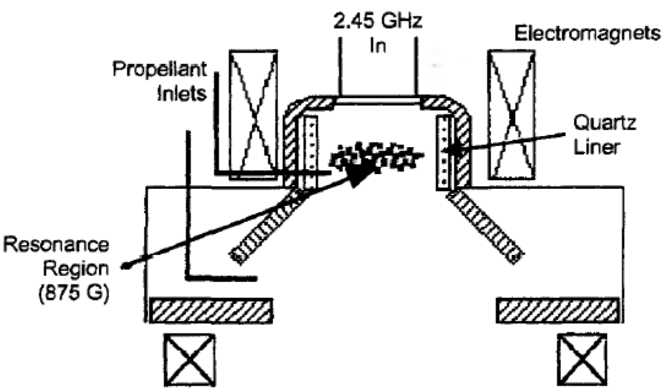

Fig-10 Schematic of a microwave thruster with the resonance region.

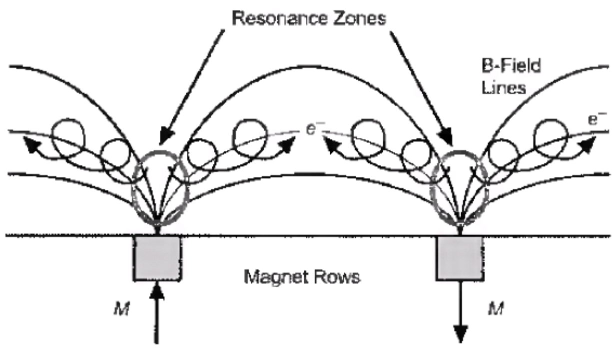

Fig-11 Magnetic field lines between two magnet rings and the resonance zones.

5. CONCLUSIONS

Plasma generators are a critical component of the ion thrusters, which predominantly determines the performance and efficiency of the thruster. Advance research in realms of **plasma physics**, **material sciences**, **computational codes** and **instrumentation** help design an optimized thruster. Advancement in **superconductivity** penchants towards a powerful ion generator as they can generate very strong magnetic fields through the bulk of the generator with fraction of weight, increasing thruster efficiency manifolds. A lot of research is being done in ion thruster geometry where **annular** geometries result in desired parameters, experiments also suggest a synergy with **magnetic field** and **nozzle size** (preferably a wide nozzle). From the above discussed ion generators **DC ion generators** are a widely accepted design used in many missions but have a major issues with power supply, ion confinement and discharge losses whereas **microwave** and **RF thrusters** though not extensively used eliminate issues of **power supply**, but issues **of low power & thrust** still remain a problem to tackle, ion propulsion though an exotic and dissident method of propulsion, in the coming years will form the basis of space exploration

REMAINING LIST OF NOTATIONS

U^+ - Ionization potential of propellant gas

U^* - Excitation potential of gas

τ - Average electron confinement

ε_i - Ion energy carried to the walls

ε_e - Electron energy carried to the walls

I^* - Excited neutral production rate

σ_* - Excitation cross section

n_i - Ion density

A - Total ion loss area

A_a - Electron loss area

A_g - Area of the grid

n_o - Neutral atom density

v_o - Neutral gas velocity

T_a - Optical transparency

η_c - Clausing factor

V_d - discharge voltage

V_c - Cathode voltage drop

V_p - Potential drop in plasma

V_{ck} - Keeper bias voltage

I_b - Beam current

I_{ck} - Current keeper electrode

A_{as} - Anode surface area exposed

μ_0 - Permeability of vacuum

B_{zo} - Peak axial magnetic field

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