Concept Study of Radio Frequency (RF) Plasma Thruster for Space Propulsion

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Abstract: *Electric thrusters are capable of accelerating ions to speeds that are impossible to reach using chemical reaction. Recent advances in plasma-based concepts have led to the identification of electromagnetic (RF) generation and acceleration systems as able to provide not only continuous thrust, but also highly controllable and wide-range exhaust velocities. For Future Space Propulsion there is a pressing need for low pressure, high mass flow rate and controlled ion energies. This paper explores the potential of using RF heated plasmas for space propulsion in order to mitigate the electric propulsion problems caused by erosion and gain flexibility in plasma manipulation. The main key components of RF thruster architecture are: a feeding system able to provide the required neutral gas flow, plasma source chamber, antenna/electrodes wrapped around the discharge tube and optimized electromagnetic field coils for plasma confinement. A preliminary analysis of system performance (thrust, specific impulse, efficiency) is performed along with future plans of Space Propulsion based on this new concept of plasma mechanism.*

Key Words: *radio frequency, thruster, plasma, electric propulsion, magnetic confinement, space propulsion*

1. INTRODUCTION

Recently a high interest in electromagnetic propulsion arose within the space community. Electric propulsion offers several advantages over chemical rocket engines for in-space propulsion, including higher thrust efficiency, lower propellant mass for any given mission and large plume exhaust velocities. Space electric propulsion has become a suitable alternative to classical chemical propulsion due to its multiple strengths. In electric propulsion, the propellant is accelerated with energy from an external electric power source, such as solar panels or nuclear reactor, instead internal chemical energy stored in fuels.

Given the increment of spacecraft velocity (Δv) desired in a specific mission and the dry mass of the spacecraft (m_f), the required propellant mass is given by the Tsiolkovsky`s equation: [1]

$$m_f = m_0\left(e^{\Delta v / v_e} - 1\right) \tag{1}$$

The amount of propellant needed to accelerate a given mass to a given velocity depends exponentially on the exhaust velocity v_e. As v_e increases, the mass ratio m_f / m_0 increases as well. Ideally this ratio should be as close to 1 as possible, so the spacecraft will require as little propellant as possible. Thus, chemical rockets are fundamentally limited systems for a number of mission types. A higher specific impulse I_{sp} enables larger missions (larger Δv) with the same amount of propellant; therefore it allows a reduction in propellant consumption in a given mission. The specific impulse is limited by the energy delivered per unit mass of propellant:

$$I_{sp}^2 = \frac{P}{\dot{M}} \tag{2}$$

where P is the total power available, and $\dot{M}$ is the mass flow rate. In the electric propulsion system, I_{sp} is limited by the total on board power. Thus, by selecting a low $\dot{M}$ it is possible to achieve a higher value of I_{sp}. As a consequence, operating at high I_{sp} and low $\dot{M}$ will give a low thrust F, since $F = I_{sp}\dot{M} = 2\dot{\eta}_T P / I_{sp}$. In this case a trade-off will be imposed between thrust and specific impulse; electric propulsion is restricted to the high I_{sp} and low F regime, which is more efficient but requires longer propulsion time [2]. Electric propulsion has become a relevant player in many low-thrust missions including station keeping in geostationary satellites, orbit rising, interplanetary flight.

Taking into account the potential of electric propulsion, a large variety of plasma thrusters have been developed in the last decades. These can be also classified depending on forces that dominate in the plasma: 1) electrothermal, when the plasma is heated up first and then expands gasdynamically, transforming the potential energy into kinetic energy, 2) electrostatic when strong electric fields are implied to accelerate ions directly in a region of non-neutral plasma, 3) electromagnetic when both electric and magnetic fields are combined to apply a Lorentz force to a quasineutral plasma.[3]

In spite of their strengths, these systems suffer from erosion of the electrodes which limit the lifetime and efficiency of the device, as well as the loss of plasma to the internal walls that lowers the thrust efficiency. Moreover, in all cases, the ion beam must be neutralized in order to avoid a negative charge inside the thruster which would ultimately block its operation. In order to overcome these problems helicon plasma thruster (HPT) and variable specific – impulse magnetoplasma rocket (VASIMR) have emerged as a promising solution, offering the performance of an electric thruster with the additional advantages of high flexibility, lower complexity, extended lifetime and reduced costs compared to other technologies. On the other hand, no neutralizer cathodes are required since the plasma is quasi-neutral due to ambipolar diffusion.

HPT prototypes are often classified according to the magnetic circuit they use and the power range in which they operate. Several research groups have developed HPTs that use permanent magnets, mostly in the low power range below 1kW. The Permanent Magnet Expanding Plasma (PEMP) built at the University of Tokyo, the Helicon Plasma Hydrazine Combined Micro (HPHCOM) funded by the European 7th FrameWork Programme and the Compact Helicon Plasma Thruster designed at the Institute of Nuclear Research of the Ukrainian National Academy of Science are some examples of HPTs that use permanent magnets to generate the required magnetic field. On the other hand, worldwide there are prototypes that use electromagnets. In the low-to-mid power range the Helicon Double Layer Thruster (HDLT) developed by the Australian National University can be identified. It is operated in the 200-800 W power range, with a magnetic strength of 100-200G and an antenna which emits at the frequency of 13.56 MHz. Direct thrust measurement suggests that the HDLT delivers up to 6 mN of thrust and 800s of specific impulse using argon as a propellant. [4]

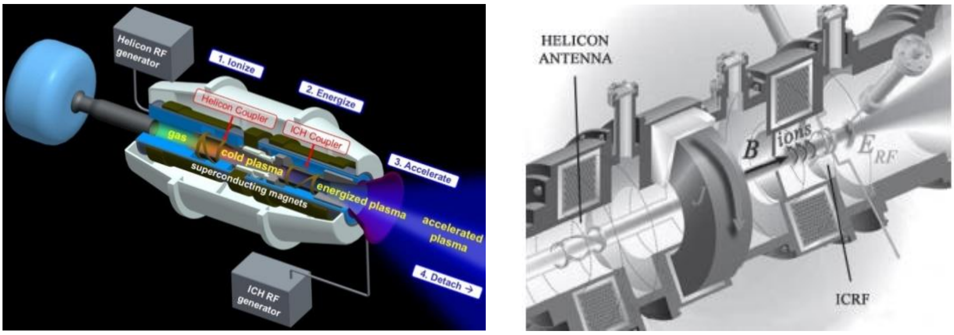

Fig. 1 – VASIMR concept [5]

The mini Helicon Thruster Experiment (mHTX) designed at MIT operates with a higher magnetic strength, 1500-1800 G. The nominal power was around 700-1000W. Compared to HDLT, it reaches a higher degree of ionization, with more than 90% of ionized gas. Nowadays researches have focused on RF excitation frequencies and permanent magnets instead of the solenoids. Permanents magnets are attractive for propulsion applications since they require no power supply. By designing the magnetic field geometry correctly, similar densities and ion beam energies have been obtained compared with that the original studies using solenoids.

The last prototype is the Variable Impulse Magnetoplasma Rocket (VASIMR) developed and patented by the Ad Astra Rocket Co. VASIMR incorporate an Ion Cyclotron Resonance Heating stage downstream the Helicon stage [6]. The main difference between these two technologies is the mechanism of energy deposition in the plasma. In HPT, electrons are excited by helicon radio-frequency waves (in the MHz range), while in ECR plasma thrusters electrons gain energy by resonant absorption of whistler waves (in the GHz range).

Table 1. Helicon Plasma Thruster prototypes, summary of propulsive performances [4]

Prototype	Power (W)	Thrust	$I_{sp}(s)$	η (%)
HDLT	≈ 1500	6 mN	800	1 ÷ 3
mHTX	700 ÷ 1500	20mN	2000	10 ÷ 20
HPHCOM	50	1.5mN	1200	13
PMEP	700	3mN	500	1
HPHT	2000 ÷ 5000	1-2N	> 2000	55

All these thrusters use magnetic nozzles that avoid plasma-wall interaction, having the flexibility to adjust the magnetic field shape and strength in flight in order to modify the plasma expansion.

The RF plasma thruster concept is entirely scalable to high power (kW to MW) operations in order to obtain high thrust level (order of N) and even higher specific impulses (order of 1000 s or more), with the additional advantage of requiring no high-current cathode, accelerating grids or neutralizer that presently limit the operating lifetime.

2. PRINCIPLES OF OPERATIONS

For Future Space Propulsion there is a pronounced need for low pressure, high mass flow rate and controlled ion energies. All these requirements have motivated us to extend the whole research project to enterprise a study regarding RF Plasma Thruster, a new type of plasma propulsion system. In the study process, some interesting physics was encountered, relating to the absorption and propagation of helicon waves and diverging magnetic field of the thruster. Thus, this paper highlights the main propulsive performances and design parameters.

The typical design of the RF plasma thrusters received the attention of the research community thanks to a simple architecture, two stages being distinguished: the production stage inside the RF plasma source and the acceleration stage in the nozzle. The nozzle is expected to convert thermal energy into axial kinetic energy and to deliver in this manner an increase of thrust from the interaction with plasma.

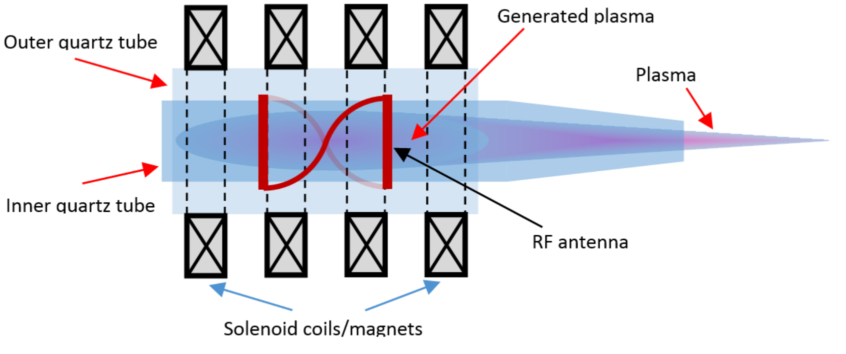

Fig. 2 – HELICON - based concept

The RF Plasma Thruster is composed of the following main key parts. A discharge tube where the plasma is produced, typically a quartz tube of different size and shape, a RF antenna wrapped around the discharge tube that emits usually within the range 1-27 MHz, the most frequent frequency being the 13.56 MHz of various topologies (Nagoya- III type, helical, annular). The RF power is produced due to antenna, thanks to the RF subsystem, consisting on power units, an amplifier and a matching box which adapts the RF power to the plasma electromagnetic behaviour [7]. The matching network is an important electric component that connects the antenna to the RF power generator. Since the plasma typically has an impedance in the order of 1Ω, while the RF power generator has a standard impedance of 50Ω, the match-box needs to adjust the plasma impedance to the 50Ω impedance of the generator.

Moreover a feeding system is used in order to provide the necessary neutral gas flow. A set of several electromagnets or permanents magnets surrounding the discharge tube will provide the required magnetic field for plasma confinement and plasma expansion, forming a divergent magnetic nozzle topology. The nominal applied magnetic field is typically chosen in the range of hundreds to thousands Gauss. The magnetic field pays a triple function: prevent plasma losses to the lateral walls, virtually build up the magnetic nozzle, and allow the RF waves to propagate deep into the plasma columns. On the other hand the DC magnetic field serves to restrict electron radial mobility and direct the plasma towards the outlet of the discharge chamber. Reducing radial electron mobility is generally desired to limit wall neutralizations, as this is a loss mechanism that reduces the efficiency of the plasma discharge. In addition, the helicon wave requires the presence of an axial DC magnetic field in order to propagate.

The key of RF plasma source is the RF driven helix like antenna, which has the potential to energize the flow of initial neutral gas into a magnetized plasma with high ionization density. In fact, the absorption of RF energy is more than 1000 times faster than the theoretical rate due to collision.[8]

The produced thrust is delivered to the system due to interaction of plasma currents with the applied magnetic field.

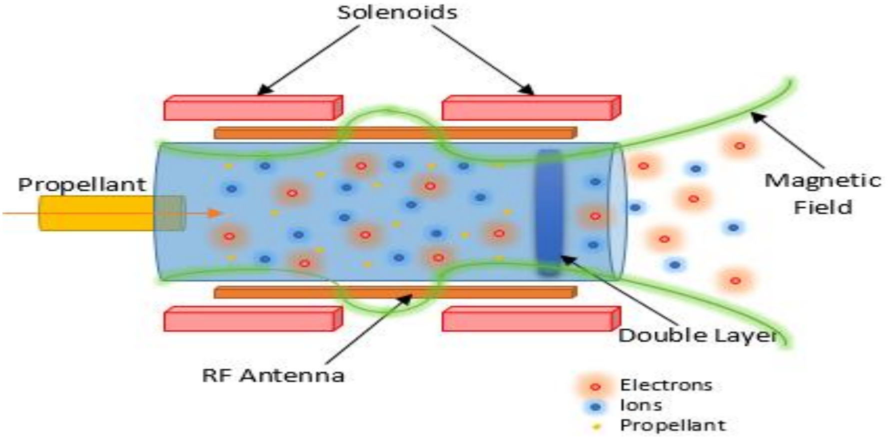

Fig. 3 – Diagram of Helicon Plasma Source

A helicon plasma source is a highly efficient device capable of creating a high density, low temperature plasma using RF waves transmitted from an antenna. Helicon wave that propagates through plasma, deposit energy into the plasma. The RF energy is deposited into the free plasma electrons, creating an energy distribution within the electron population.[9] The electron energy distribution can be manipulated by changing various operational parameters, such as RF power, RF frequency, and applied DC magnetic field strength.

3. HELICON WAVES IN PLASMA

The main advantages of HPT are: the lack of electrodes, good throttability that can be achieved by varying the mass flow and the applied power, the wide range of propellants that can be employed and the possibility to scale it to very large powers. One of the most important characteristic of the HPT is the ability of the helicon source to produce a higher plasma density than other sources (with values in range of 10^{18} - 10^{20} m^{-3} already achieved in laboratory) at near-full ionization, allowing in this way a higher thrust density and compactness.

There are many types of waves that can propagate through plasma, such as plasma waves, electrostatic waves, electromagnetic waves and ion acoustic waves. One subset of electromagnetic waves is called a whistler wave, which is a right-handed, circularly polarized wave that has a frequency much less than the electron cyclotron frequency. A magnetic field cannot do work on a particle but can only change the direction of the particle`s velocity. In a bounded plasma, whistler wave are known as helicon waves and propagates inside the plasma coupled with a superficial, short-wavelength Trivelpiece-Gould wave [10]. This is known as “blue mode” regime, which is viewed as the most efficient operation point, in contrast with inductive mode, in which helicon waves penetrate only superficially in the plasma.

If an axial magnetic field is present then a particle with a velocity component perpendicular to this will undergo a circular motion around the magnetic field lines. The frequency at which the particle rotates in the magnetic field is known as the cyclotron frequency:

$$\omega_c = \frac{qB_0}{m} \tag{3}$$

Helicon waves in gaseous plasma were first discovered by Lehane and Thonemann and later studied extensively by Boswell, who demonstrated that high density plasmas could be produced by helicon wave excitation with a radio frequency (RF) generator; in fact the absorption of RF energy was more than 1000 times faster than the theoretical rate due to collisions. As stated earlier, helicon waves are low-frequency whistler waves, which are well known to propagate with only right-hand circular polarization in free space. Bounded by a cylinder, these electromagnetic waves develop a large electrostatic component which allows having either right or left-hand polarization.[11]

Helicon discharges have been studied experimentally in many machines with uniform magnetic fields of the order 0.1 T. The first such machine, built by R.W.Boswell in Australia, reached a density of almost 10^{20} m^{-3}. A collisionless mechanism such as Landau damping is being involved to explain the high density. The imposition of a radial boundary condition by the discharge chamber wall changes the nature of the helicon wave from electromagnetic to partially electrostatic. Plasma sources that use helicon waves for ionization are capable of efficiently creating high density, uniform plasmas in low pressure conditions without direct contact of the electrodes to the plasma.

Magnetic confinement of electrons combined with efficient antenna coupling, enables helicons to acquire higher densities than in other RF plasma at the same power.

Helicon discharges are sustained by electromagnetic waves propagating in magnetized plasma in the so-called helicon modes. The driving frequency in these discharges is typically in the radio-frequency range of 1 to 50 MHz but the industrial radio frequency of 13.56 MHz is commonly used. The name “helicon” comes from the fact that the wave rotates during its propagation in Z direction, carrying the electron in a helicon motion.[12]

The phase velocity of electromagnetic waves in magnetized plasma can be much lower than the speed of light. This provides the possibility to operate with wavelengths comparable with the discharge system size at radio frequencies that are below the microwaves frequency range.

Helicon waves are propagating electromagnetic whistler wave modes in an axially magnetized, finite diameter plasma column, in the frequency range $\omega_{ci} < \omega < \omega_{ce}$, where ω_{ci} and ω_{ce} are the ion and electron cyclotron frequencies, defined by:

$$\omega_{ce} = \frac{qB_0}{m_e} \tag{4}$$

$$\omega_{ci} = \frac{qB_0}{M} \tag{5}$$

The frequency is sufficiently high so that ions do not respond to the field and sufficiently low for the small inertia of the electron. Helicon sources are designed to allow helicon wave propagation with a frequency of 13.56 MHz and the optimum conditions of operation in argon are $n_e = 10^{18} m^{-3}$ and $B_0 = 5mT$. The important frequencies are consequently: $\omega_{ci} = 1.2\times10^4 s^{-1}$, $\omega = 8.5\times10^7 s^{-1}$, $\omega_{ce} = 8.9\times10^8 s^{-1}$, $\omega_{pe} = 5.7\times10^{10} s^{-1}$, being satisfied the condition: $\omega_{ci} << \omega << \omega_{ce} << \omega_{pe}$. [13]

The electric and the magnetic fields of the wave have the following form:

$$E, B \sim \exp j(\omega t - k_z - m\theta) \tag{6}$$

where m is the azimuthal mode number, k_z is the longitudinal wave number, and θ is the angle between the wave propagation vector and magnetic field.

In a magnetic field, the charged particles have a helix motion along the field lines, orbiting around them at Larmor radius at cyclotron frequency. When a particle meets a stronger field, its perpendicular velocity component increases and its parallel component is proportionally reduced in order to keep constant the total energy. In the centre of the magnetic mirror, the force is radial, having no effects on the parallel velocity, but as the particles enter the B field constriction section it will result in an imbalance that decelerates the particle. When particles move away from the constriction, field has an opposite effect and accelerates particles. The magnetic field does not work directly on the particles, enabling just the kinetic energy transfer.

The wave rotates as it propagates, introducing an azimuthal structure to the wave fields described by a mode number *m*. In a plasma produced by a helicon wave, energy is transferred from it to the valence electrons to produce heating by collisional or collision less mechanisms. The propagating character of the wave implies that the heating penetrates deeper in the plasma than inductive heating (localized in the skin depth) or capacitive heating (mostly localized in the RF sheaths). This achieves high ionization efficiency in large plasma volumes. Since the antenna is excited by the RF voltage, helicon plasma may operate in capacitive (E) mode al low power or in inductive (W) mode at medium power. The helicon mode (H) is activated when the power is large enough to provide the required plasma density in order to support helicon wave propagation. Therefore, helicon plasma is subjected to E-W-H transitions [10]. The combination of efficient wave heating and increased plasma confinement, make RF source attractive for highly ionized plasmas, with applications in plasma thrusters.

Bounded in a cylinder, whistler waves are considered waves of the form $e^{i(m\theta + k_z - \omega t)}$, propagating in a field $B = B_0\hat{z}$. In the limit of zero electron mass, the dispersion relation for helicon waves is:

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 \pm (\omega_{ce}/\omega)\cos\theta} \tag{7}$$

For $\omega << \omega_c$, only right-hand propagates, the dispersion relation for right-hand waves at an angle θ to $\boldsymbol{B}$

$$\frac{c^2k^2}{\omega^2}=1-\frac{\omega_p^2/\omega^2}{1\pm(\omega_{ce}/\omega)\cos\theta}\rightarrow\frac{\omega_p^2}{\omega\omega_{ce}\cos\theta} \tag{8}$$

If $k_z = k\cos\theta$, the dispersion relation can be written:

$$k_T=\frac{\omega}{k_z}\frac{\omega_p^2}{k_z\omega_{ce}c^2} \tag{9}$$

Defining $\beta = k_T$,

$$\beta=\frac{\omega}{k_z}\frac{\omega_p^2}{\omega_{ce}c^2}=\frac{\omega}{k}\varepsilon_0\mu_0\frac{n_0e^2m\mu_0}{\varepsilon_0 meB_0}=\frac{\omega}{k}\frac{n_0e\mu_0}{B_0} \tag{10}$$

In a finite cylinder, and assuming a uniform plasma density, the boundary condition on the total radial current density $\bar{J}_r$ the boundary condition for waves with $kR<<1$ leads to with J_m the Bessel function: [14]

$$m\beta J_m(k_\perp R)+k\alpha J_m^{'}(k_\perp R)=0 \tag{11}$$

Helicon sources based on excitation of the $m=0$ mode and the $m=\pm1$ mode have been developed. Since $m=0$ mode is axisymmetric and $m=+1$ mode has a helical variation, both modes generate time-averaged, axisymmetric field intensities. For $m=0$, $J_0^{'}(k_\perp R)=0$, which gives $k_\perp R=3.83$. For $m=+1$, limiting values are $k_\perp R=3.83$ for $k_z<<k_\perp$ and $k_\perp R=2.41$ for $k_z>>k_\perp$. [15]

$$\frac{3.83}{R}=\frac{\omega}{k}\frac{n_0e\mu_0}{B_0}=\frac{\omega}{k}\frac{n_0}{B_0} \tag{12}$$

The relation related above shows that for a given mode, the density should be proportional to *B*.

When the electron mass is kept finite, a second wave is excited along with the helicon wave, the TG mode. This is an electrostatic electron cyclotron wave localized near the radial boundary. The phase velocity of helicon waves along $\boldsymbol{B}$ is in the order of velocities of primary electrons. Most of the RF energy goes into the TG mode near the radial boundary, where the antenna is wrapped and only a small amount goes directly into the helicon mode. The TG wave then couples to helicon waves to form a combined TG-helicon wave. TG wave is an essential part of the RF coupling and it is not easily detected because it is normally localized to a thin layer near the surface.

From combination of Maxwell`s equations with the electron equation of motion results:

$$\delta\nabla\times\nabla\times B-k\nabla\times B+k_w^2B=0 \tag{13}$$

where $\delta=(\omega+i\nu)/\omega_c$, ν being electron collision frequency with ions and neutrals and

$$k_w^2=\frac{\omega n_0e\mu_0}{B_0} \tag{14}$$

But β_1, β_2 are roots of

$$\delta\beta^2 - k\beta + k_w^2 = 0 \tag{15}$$

The roots for $\delta k_w^2 << k^2$ are:

$$\beta_{1,2} = \frac{k}{2\delta}\left[1 \pm \left(1 - \frac{4\delta k_w^2}{k^2}\right)^{1/2}\right] \approx \frac{k}{2\delta}\left[1 \pm \left(1 - \frac{2\delta k_w^2}{k^2}\right)\right] \approx \begin{cases} k_w^2 / k \\ k/\chi \end{cases} \tag{16}$$

The (-) sign gives rise to H-mode and (+) sign the TH mode. The TG mode has large β and short radial wavelength, it is highly damped and localized near the boundary. [11]

Helicon sources have been developed based on excitation of $m=0$ and $m=+1$ modes. The $m=0$ is axisymmetric and $m=+1$ mode has a helical variation. The design of an RF antenna for an efficient power coupling should take into account its length related to magnetic and plasma density.

Different types of antennas have been tested, the most efficient being helical ones matching the helicity of $m=+1$. For reason not well understood, $m=-1$ waves rotating in the opposite direction do not propagate as well [16]. Magnetic confinement of electrons combined with efficient antenna coupling, enables helicons to acquire higher densities than in other RF plasma at the same power.

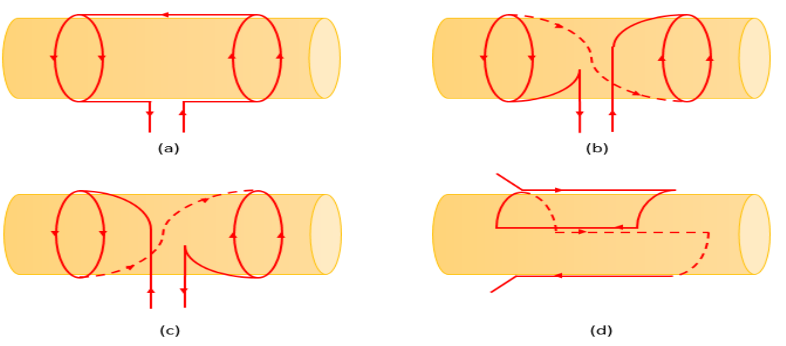

Fig. 4 – Antenna types used in the Helicon discharges: a) Netoya type III, b) Left Helical Antenna, c) Right Helical Antenna, d) Boswell Antenna

The phase velocities of helicon waves can be comparable with electron thermal velocities, thus allowing the possibility that electrons surfing on the waves can be accelerated to ionizing electrons.

The helicon mode energy is transferred is transferred to the plasma electrons as the mode propagates along the column by collision less Landau damping. Landau damping is a process by which a wave transfers energy to electrons having velocities near the phase velocity $V_{ph} = \omega / k_z$ of the wave. Chen (1991) has estimated the effective collision frequency ν_{LD} for Landau damping of the helicon mode as [10]

$$\nu_{LD} = 2\sqrt{\pi}\,\omega\varsigma^3 \exp(-\varsigma^2), \varsigma >> 1 \tag{17}$$

$$\nu_{LD}(\max) = 1.45\omega, \varsigma \approx 1.2 \tag{18}$$

where

$$\varsigma = \omega / (k_z \sqrt{2}\, v_{th}) \tag{19}$$

with

$$v_{th} = (eT_e / m)^{1/2} \tag{20}$$

4. PRINCIPLE OF PROPULSIVE MAGNETIC NOZZLE

The purpose of the magnetic nozzle is to guide and accelerate the ions beam of the plasma into an efficiently collimated plume in order to produce thrust. Thrust can be understood as the increment of the momentum of the supersonic beam.

For magnetized plasma the magnetic nozzle produce subsonic-supersonic acceleration process, converting internal energy into kinetic energy. An important characteristic of the magnetic nozzle is related by the possibility to be set in-flight the magnetic field shape and strength by acting on the coil current, being highly adaptable to different operation points, facilitating the design of dual-mode plasma thrusters with different trade-offs of thrust and specific impulses. A magnetic nozzle is an axisymmetric, divergent magnetic field that controls the expansion of a supersonic plasma jet.

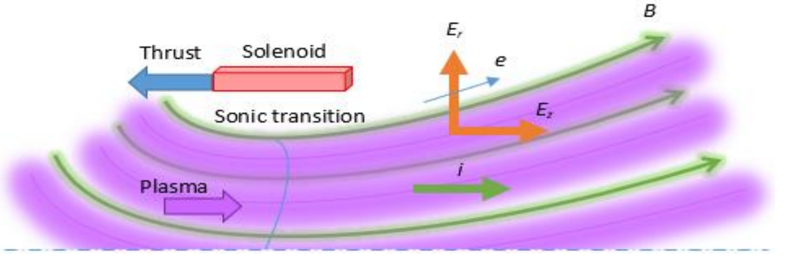

Fig. 5 – Ion acceleration in expanding plasma

During the expansion, the plasma internal energy is transformed into a supersonic beam through the self-created ambipolar electric field. It is based on current-free double layer acceleration that spontaneously forms in low-pressure plasmas. At low pressure the magnetic field causes the plasma to expand, and a potential structure known as double-layer forms spontaneously within the plasma. This double layer acts as a virtual electrode and accelerates ions to speeds of tens of electron volts. A double layer can arise when a dense plasma is injected into a diverging magnetic field. Current-free double layer consists of a positive and negative Debye sheath and connects quasineutral regions of plasma [17]. The motion of a charged particle in the presence of an electric E and magnetic field B is given by Lorentz force and the Newton`s second law:

$$m\frac{dv}{dt} = q[E(r,t) + v \times B(r,t)] \tag{21}$$

Current-free electric double layer which has the major role to accelerate ions and have been observed in recent years in various laboratory plasma experiments at low pressure in the presence of a diverging magnetic field. Thus, the thrust of such a system is produced when plasma is accelerated to supersonic speed by being forced through an electric double layer (a magneto-shock region with sudden drop in potential) created by rapidly expanding magnetic field very close to the open end of the tube.

To be called double layer (DL), a potential structure should respect the following conditions: the potential drop must be greater than the electron temperature and the electric field within the double-layer must be stronger than the outside the double layer. The DLs were observed to spontaneously form for pressures below around 0.25 Pa and for magnetic fields above 5 mT. Ions crossing the DL are accelerated to energies between 0-20 eV (depending on the neutral gas pressure), which is above twice the local sound speed [18]. The discovery of ion acceleration within DL plasma led to the development of a new space propulsion system.

A helicon thruster has the advantage that ions are accelerated by a sudden drop in space potential, called a "double –layer" in the plasma ejected by the source. If monoenergetic ions are accelerated to the Bohn velocity, with the acoustic velocity $c_s = (kT_e / M_i)^{1/2}$, the ion density in the falling potential will be larger than Maxwellian electron density and this will cause the potential to fall further creating the sheet on the wall. Maxwellian electrons and plasma density is given by:

$$n_s = n_0 e^{-\eta} \text{ where } \eta = -eV / KT_e \tag{22}$$

The Bohn energy is :

$$c_s = (kT_e / M_i)^{1/2} \text{ and } W_s = 1/2 M v_s^2 = 1/2 KT_e \tag{23}$$

In order to gain this energy, ions must been accelerated by a sheath potential $\eta = 1/2$. The quasineutral density at the sheath edge can be expressed by:

$$n_s = n_0 \exp(-1/2) \tag{24}$$

But the magnetic flux is conserved in the expansion from R_0 to R for each field line and since electrons are constrained to follow the field lines and thus the density and the field lines will present a variation with respect to R:

$$\frac{B}{B_0} = \frac{n}{n_0} = \left(\frac{R_0}{R}\right)^2 \tag{25}$$

The radius at which a sheath forms can be expressed as:

$$\frac{R_s}{R} = \left(\frac{n_0}{n_s}\right)^{1/2} = e^{1/4} = 1.28 \tag{26}$$

The ion sheath will form at a position where the field lines have increased their distance from the axis by 28 %. Ions passing through the potential drop of this sheath are suddenly accelerated to a supersonic velocity. [11]

Table 2. Typical parameters at the nozzle throat [18]

Magnetic field at entrance, B_0	1000 G
Plasma density at entrance, n_0	10^{18} m^{-3}
Electron temperature, T_e	10 eV
Thermal velocity, c_e	$1.3 \cdot 10^6 m/s$
Sound velocity, c_s	$4.9 \cdot 10^3 m/s$
Ion current density, j_i	$800 A/m^2$

Ion current, I_i	$0.25\ A$
Mass flow	$0.1\ mg/s$
Debye length, λ_d	$2.4 \cdot 10^{5}\ m$
Electron Larmor radius	$7.5 \cdot 10^{-5}\ m$
Ion Larmor radius	$2 \cdot 10^{-2}\ m$
Electron gyro frequency, ω_{ce}	$1.2 \cdot 10^{10}\ s^{-1}$

5. CONCLUSION

Within the electric thrusters, several technologies have been developed or are currently being studied (ion thruster, Hall thruster, MHD thrusters). In all cases, the ion beam must be neutralized in order to avoid a negative charge inside the thruster which would ultimately block its operation. The RF Plasma Thruster based on helicon waves has emerged as a promising solution, offering the performance of an electric thruster with the additional advantages of high flexibility, lower complexity, extended lifetime and reduced costs compared to other technologies.

Radio-frequency Plasma Thruster based on helicon source represent a recent innovative type of space thrusters, receiving the attention of the research community thanks to a very simple structure based on discharge chamber in which plasma is generated, an RF antenna for propellant ionization and a magnetic field which confines and accelerate plasma, the lack of neutralization cathodes and other electrodes immersed in the plasma, resulting in a potentially long lifetime and the potential of operating with different propellants.

High power density plasma propulsion would vastly improve human exploration of our solar system. The fusion energy research community has long known that magnetized plasma systems enable high energy density discharges. Radio frequency waves have proven to be efficient at plasma production in helicon devices, where a right-hand circularly polarized wave is launched into the plasma. Also in fusion research, ion cyclotron resonant heating has been very successful at production energetic ions without having electrodes or grids in contact with plasma. The same concept of RF production and heating of magnetized plasmas can be used for high performance propulsion. Efficient RF plasma production and injection into a strong magnetic field is crucial for the performance of thrusters.

Electrodeless propulsion may be a plausible candidate for different space mission scenarios, from satellite attitude control, drag compensation in LEO orbit, station keeping, and orbit transfer. Moreover, despite the significant challenges, RF Plasma Thrusters becomes an attractive choice for human and cargo missions to Mars and robotic missions with large science payloads.

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