

Feasibility Study of Laser Induced Plasma for Spacecraft Propulsion

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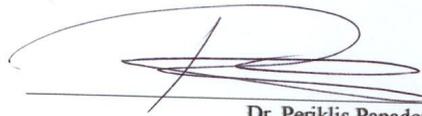
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ABSTRACT

FEASIBILITY STUDY OF LASER INDUCED PLASMA FOR SPACECRAFT PROPULSION

By Bhavya Tottempudi

Recent research in spacecraft propulsion is tending to plasma propulsion as an more effective means for deep space travel. This project focuses on studying the feasibility of using a laser induced plasma generation system for spacecraft propulsion. Plasma chemical processes involved in plasma generation are discussed along with the possible types of lasers that are suitable for the application in spacecraft propulsion. Assumptions are made to calculate ion flux from the laser induced plasma. A comparison is made with the ion flux of a plasma thruster under development on the VASIMR project. Results and future work is discussed.

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Introduction

Research in advanced spacecraft propulsion methods has been a continuous process in a general goal towards human space exploration ever since at least the first Moon landing. Electric propulsion is emerging as a leading candidate for advanced crewed missions such as the mission to Mars.. In fact, the mission Deep Space 1, with its ion propulsion, to Comet Borrelly proved that faster, more economical travel to outer space was possible in 1998. Along with ion propulsion, another key electron propulsion method that has been investigated is plasma propulsion.

Most of the research in plasma propulsion includes investigation of how best to use a primary energy source in generating sustained plasma. Associated challenges in developing this technology involve (but are not limited to) plasma instabilities, system performance uncertainties, required thermal protection, and type of propellant material best suited to generate a sustained plasmastream. Several types of energy sources are being investigated by researchers in order to design plasma thrusters that can generate high I_{sp} (of the order 10,000- 30,000 seconds, if not more). Such high I_{sp} enable faster space travel. An Isp of around 6,500s enables a cargo delivery to Mars in about 3-4 months, according to the projections of the VASIMR engine development team (Ilin, A.V., Chang Diaz, F. R., Glover, T.W., et al, 2012). One of the energy sources being researched are lasers. . Some lasers, like Ultrafast lasers, can generate high energy (in the range of about 1Petawatt). According to Kammash (2003), such lasers can generate Isp of about 3 million seconds when the propellant is a solid target upon which the laser is impinged to produce plasma. No known research has been found where the laser

generated plasma is from a gas propellant.. Thus, the goal of this project is to find and compare the ion fluxes from plasma generated by a laser beam projected into a gas medium, and of those from any other calibrated system to check the feasibility of laser generated plasma for space using a gas propellant.

. One of the reasons for considering a gas propellant is that in order to reduce the weight of the propellant carried, an alternative approach is to harvest required gasses from the deep space environment while en route. Hydrogen (H_2), being the most abundantly available gas in space, is the most considered for such an operation. Thus, hydrogen will be assumed as the gas propellant for the purpose of this project.

In order to obtain the goal of this project , a study of the processes that are involved in generating plasma, doing so using lasers, and what type of lasers to use has to be undertaken. Thus, the various dissociative processes involved in plasma generation will be discussed. Possible assumptions with regard to these processes to be made for a preliminary study in laser based plasma generation will also be postulated. Generating sustained and stable plasma that can be confined in the spacecraft before it's acceleration and exit is the key to a successful plasma thruster. The laser types will be discussed simultaneously with the assumptions made while discussing the plasma-chemical processes during plasma generation. In this report, first, the plasma-chemical processes will be discussed, then those laser systems will be discussed which are based on the associative energies required.

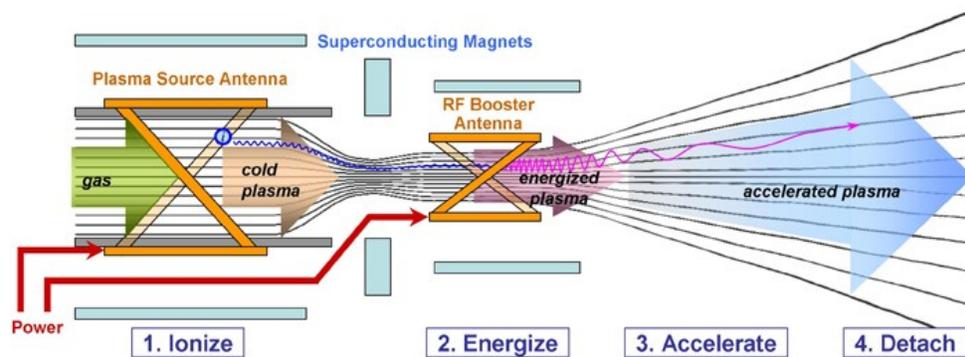
Literature Review

The basis for this project came from the thought that there is a necessity for faster space travel and from an existing concept towards that end. First, the need for a faster means of travel to deep space than the current chemical propulsion can provide, namely electric propulsion, an example of which was presented in the Introduction. To power the electric (i.e. plasma) thrusters, there is a concept that uses lasers as a means for maintaining trajectories for spacecraft that are also powered by the same lasers. The first phase of this concept is that spacecraft may be propelled into space and maybe even maintained in an Earth or planetary orbit using powerful ground based lasers (Forward, R. L., 1986). The next phase consists of “laser stations” that maybe positioned in space along interplanetary orbits, to allow them to pulse laser beams onto the spacecraft to propel them in their missions. But this means that the spacecraft can only go so far as the lasers are stationed. Thus, came the idea of studying the feasibility of having a laser-based plasma generating system on a spacecraft.

To start this study, a little insight into the current plasma propulsion methods is required. A search for “plasma propulsion” in the scholarly databases yielded information on many fronts in plasma propulsion. Several types of plasma propulsion were found, including but not limited to Magnetoplasmadynamic thrusters, Hall-effect thrusters, Pulsed plasma thruster, Helicon thruster, etc. Each of these is the most basic of the plasma thrusters under research and development, in terms of how the electric power input from the spacecraft power system is converted to energy for plasma generation. There were several variations found under each of the above categories, since it seems

that each research group focused on trying to bring about a prototype using one design directive through variation of propellant, energy source, acceleration mechanisms or protection systems. One such variation is the VASIMR.

VASIMR is an acronym for Variable Specific Impulse Magnetoplasma Rocket, a plasma propulsion engine in development by the Ad Astra Rocket Company (Ad Astra Rocket Company, n.d). The VASIMR uses radio waves (electromagnetic waves) to generate plasma from hydrogen gas (the propellant) and accelerates the plasma using magnetic mirrors to achieve high exhaust velocities of the exiting neutral plasma.



Figure

1. Schematic of VASIMR (Courtesy: www.adastrarocket.com)

VASIMR was chosen as the base plasma thruster design for this project since it seems the most adaptable to modification, for the purpose of this project. It is assumed that the energy source of VASIMR is replaced with a laser mechanism, and have the design retain the rest of its systems intact. The pulsed plasma thruster (PPT) could also have been chosen as a base for this project, but for the fact that the PPT uses a solid ablative propellant. As mentioned in the introduction, this project will assume the

propellant to be a gas, hence it was not possible to consider the pulsed plasma thruster as a base design.

Once the base reference for the propulsion system was identified, the next step was to identify laser systems that would be suitable for plasma generation. The details of the selection process will be presented in the theory and methodology sections. Along with studying laser systems, it is important to understand the molecular dissociation process while using lasers. This is the study of plasma chemistry. Based on this study, the chief ionization techniques can be identified and assumptions will be made to help understand the rate of ion/plasma production. This study will be presented in the theory section as well, but will be limited to the scope of the project.

Theory

Ionized gas is usually called plasma when it is electrically neutral (i.e., electron density is balanced by that of positive ions) and contains a significant number of the electrically charged particles, sufficient to affect its electrical properties and behavior (Fridman, 2008). All information on plasma chemistry provided in this section is obtained from Fridman.

Ionization degree is the ratio of density of the major charged species to that of neutral gas. When the ionization degree of a plasma approached unity, such a plasma is called completely ionized plasma. When the ionization degree is low, its a weakly ionized plasma. The transition zone between a plasma and its boundaries is called a *plasma sheath*. The properties of the sheath are different from those of the plasma itself. Like in any gas, the plasma boundaries influence the motion of the charged particles in the

sheath. These particles form a sort of electrical shield for the plasma, so that it is not affected by the conditions at the boundaries.

Thermal and Non-thermal Plasma

Temperature in plasma is determined by finding the average energies of the plasma particles, neutral and charged, and their relative degree of freedom (translational, rotational, vibrational and those of electronic excitation). This means that plasmas may have multiple temperatures. Electron temperature in plasma is initially higher than that of the heavy particles since electrons gain energy within an electric field and lose very little of that energy during collisions because of their light weight. Joule heating, from collisions between electrons and heavy particles, subsequently equilibrates their temperatures unless there is a paucity of time or energy, or there is a cooling element that prevents equilibration.

In collisional weakly ionized plasma, the temperature difference between electrons and heavy particles due to Joule heating, can be described as proportional to the square of the ratio of electric field (E) to the pressure (p). Temperatures of electrons (T_e) and heavy particles (T_o) tend to reach equilibrium only for small values of E/p. This is the basic requirement for *local thermodynamic equilibrium* (LTE) in plasma. These LTE plasma are characterized by their adherence to major laws of equilibrium thermodynamics, and by a single temperature in each space location. This kind of quasi-equilibrium plasma, where ionization and chemical processes are determined by temperature, are called *thermal plasma*.

There are several plasmas which do not exist in thermodynamic equilibrium. These plasmas are characterized by the different temperatures with respect to different plasma particles and different degrees of freedom. For these non-equilibrium plasmas, $T_e \gg T_o$, and the ionization and chemical processes are determined by electron temperature and not by temperature of the gas. Such plasma are called non-thermal plasma. They are generally generated at low pressures or lower power levels.

The ionization process is one of the first plasma-chemical processes that needs to be discussed. The rate of any plasma-chemical processes like ionization, excitation, dissociation, etc, depend on how many electrons have enough energy to help complete these processes. The energy level of an electron can be determined by using the *electron energy distribution function (EEDF)* represented by $f(\varepsilon)$. This function is the probability density for an electron to have energy ε . EEDF very strongly depends on gas composition in plasma and electric field. Sometimes, it can be determined by electron temperature (T_e), even in non-equilibrium plasmas. Thus, it can be described by the quasi-equilibrium Maxwell Boltzmann distribution function-

$$f(\varepsilon) = 2\sqrt{\varepsilon/\pi} (k T_e)^{-3} \exp(-\varepsilon/k T_e) \quad (1)$$

where k is the Boltzmann constant.

Elastic and Inelastic Collisions and their Fundamental Parameters

Elementary processes like ionization can be subdivided into the class of elastic or inelastic. “*Elastic collisions* are those in which the internal energies of colliding particles do not change; therefore kinetic energy is preserved”. Since kinetic energy is conserved, elastic processes end up only in geometric scattering and redistribution of the said kinetic

energy. The result of most *inelastic collisions* is the transfer of kinetic energy of colliding particles into internal energy. Sometimes, the internal energy of excited atoms or molecules may transfer into kinetic energy, typically of plasma electrons. Such a transfer is a result of what are called *superelastic collisions*.

Elementary plasma-chemical processes are dependent on six major collision parameters: *cross section*, *probability*, *mean free path*, *interaction frequency*, *reaction rate* and *reaction rate coefficient*. Cross section is an imaginary circle of area σ around one of the collision partners. If the center of the other collisional partner crosses this imaginary circle then the elementary reaction can take place. When considering an elementary process A+B the mean free path λ of collisional partner A with the other partner B can be calculated as

$$\lambda = 1 / n_B \sigma \quad (2)$$

where n_B is the number density (or concentration) of the particles B.

The interaction frequency ν of one collisional partner A with another partner B is the ratio of their relative velocity v to the mean free path λ .

$$\nu_A = n_B \sigma v \quad (3)$$

The elementary reaction rate is the number of elementary processes, ω , which take place per unit volume per unit time. The reaction rate for bimolecular process A+B is calculated by multiplying the interaction frequency of partner A with partner B, ν_A , and the number of particles in the unit density (viz, number density, n_A).

$$w_{A+B} = \nu_A n_A = \langle \sigma v \rangle n_A n_B \quad (4)$$

The factor $\langle \sigma v \rangle$ is the reaction rate coefficient. This factor is represented by k and can be calculated as below.

$$k_{A+B} = \int \sigma(v) v f(v) dv = \langle \sigma v \rangle \quad (5)$$

Classification of Ionization Processes

Ionization processes can be different for different plasma-chemical systems and can be classified into five groups.

1) Direct ionization by electron impact. When an electron has high enough energy to provide ionization of a neutral or previously unexcited atom, molecule or radical in one collision. These processes are important in cold or non-thermal discharges where electric field, hence electron energies, are high.

2) Stepwise ionization by electron impact. This is ionization of initially excited neutral species. These processes are important in thermal plasma where concentration of highly excited neutral species and ionization degree is high.

3) Ionization by collision of heavy particles. This type of ionization takes place during ion-atom, ion-molecule collisions, and during collisions between vibrationally or electronically excited particles, where the total energy of the collisional partners is greater than the ionization potential.

4) Photoionization. It happens when neutral particles collide with photons and form an electron-ion pair. It's mostly important in thermal plasmas.

5) Surface ionization (electron emission). This ionization mechanism is different from the other four and happens when ions, electrons and photons collide with different

surfaces, or simply by surface heating. This mechanism will not be considered for this project.

Coulomb Collisions

The elastic collision and scattering processes between electron-electron, electron-ion, and ion-ion are called coulomb collisions. An important consideration in this type of collision is that there is a strong dependence of the crosssections of the colliding partners on their kinetic energy. During elastic collisions, energy transfer is only possible as a transfer of kinetic energy. When particles of masses m , and M collide, the average fraction γ of kinetic energy transferred from m to M is given by-

$$\gamma = \frac{2mM}{(m+M)^2} \quad (6)$$

This equation becomes $\gamma = 2m/M$ for an elastic collision between electrons and heavy neutrals or ions since $m \ll M$. Thus, the fraction of kinetic energy transferred is very small ($\gamma \sim 10^{-4}$). The implication from this is that, there is significant amount of energy transfer only in collisions between electrons.

Direct Ionization by Electron Impact

The interaction of a high energy (ϵ) electron incident on the valence electron of a neutral atom or molecule results in direct ionization. Ionization occurs when the transferred energy ($\Delta\epsilon$) to the valence electron is greater than the ionization potential I . For a physical understanding of the process, the classical Thomson model is assumed. In this model, the valence electron is assumed to be at rest, and the interaction of the two colliding electrons with the rest of the atom is neglected. The differential cross section of

the incident electron while it transfers $\Delta\varepsilon$ to the valence electron can be given by the Rutherford formula as-

$$d\sigma_i = \frac{1}{(4\pi\varepsilon_0)^2} \frac{\pi e^4}{\varepsilon(\Delta\varepsilon)^2} d(\Delta\varepsilon) \quad (7)$$

Direct ionization takes place when the transferred energy is greater than ionization potential, ie. $\Delta\varepsilon \geq I$. The integration of equation (7) over $\Delta\varepsilon \geq I$ gives the *Thomson formula* which is the expression for ionization cross section by direct electron impact, given by-

$$\sigma_i = \frac{1}{(4\pi\varepsilon_0)^2} \frac{\pi e^4}{\varepsilon} \left(\frac{1}{I} - \frac{1}{\varepsilon} \right) \quad (8)$$

This expression is multiplied by the number of valence electrons Z_v . When $\varepsilon = 2I$ the Thomson cross section reaches the maximum value

$$\sigma_i^{max} = \frac{1}{(4\pi\varepsilon_0)^2} \frac{\pi e^4}{4I^2} \quad (9)$$

By integrating the ionization cross section $\sigma_i(\varepsilon)$ over the EEDF, the ionization rate coefficient $k_i(T_e)$ for direct electron impact ionization can be obtained similar to equation (5). Assuming Maxwellian EEDF, the rate coefficient can be represented as

$$k_i(T_e) = \sqrt{8T_e/\pi m} \sigma_o \exp\left(\frac{-I}{T_e}\right) \quad (10)$$

where $\sigma_o = Z_v \pi e^4 / I^2 (4\pi\varepsilon_0)^2$ and it is about the same as the geometric atomic cross section.

Stepwise Ionization by Electron Impact

When the concentration of excited neutral species in a plasma are high enough, there are two ways to provide the energy (I) necessary for ionization. The first way is by direct plasma electron impact, as in direct ionization. The second method is to convert the high energy of the electronic excitation of the neutral species into the ionization act. This is called *stepwise ionization*. Several steps are involved in this process. First, collisions between electrons and neutrals prepare highly excited species. Then, in a final collision, a lower energy electron is sufficient to provide ionization.

Summing up the reaction rate coefficients of each state of excitation, while taking into account their concentrations, will give the expression for the stepwise ionization reaction rate coefficient.

$$k_i^s = \sum_n \square k_i^{s,n} N_n(\varepsilon_n) / N_o \quad (11)$$

For maximum stepwise ionization rate, its possible to assume that electronically excited neutrals are in quasi-equilibrium with the plasma electrons, and that the excited states are characterized by Boltzmann distribution with electron temperature T_e :

$$N_n = \left(\frac{g_n}{g_o}\right) N_o \exp\left(\frac{-\varepsilon_n}{T_e}\right) \quad (12)$$

where N_n, g_n, ε_n are respectively number densities, statistical weights, and energies of electronically excited atoms, radicals or molecules. The index n is the principle quantum number. $g_n = 2 g_i n^2$ according to statistical thermodynamics, where g_i is the statistical weight of an ion. N_o and g_o are the ground state particle concentration and statistical weight.

The typical energy transfer from a plasma electron to an electron in an excited atomic level is about T_e . Thus, excited particles make major contribution to the stepwise ionization rate coefficient, viz equation (11), only when their energy is about $\varepsilon_n = I - T_e$. The number of states with this energy, and ionization potential I_n about equal to T_e has an order of n , when its known that $I_n \sim 1/n^2$. Using this information, and equations (11) and (12), following is obtained-

$$k_i^s \approx \frac{g_i}{g_o} n^3 \langle \sigma v \rangle \exp\left(\frac{-I}{T_e}\right) \quad (13)$$

Corresponding to an energy transfer between electrons of about T_e , the cross section σ can be approximated as $e^4/T_e^2(4\pi\varepsilon_o)^2$, velocity $v \sim \sqrt{T_e}/m$, and the principle quantum number from

$$I_n \approx \frac{1}{(4\pi\varepsilon_o)^2} m e^4 / \hbar^2 n^2 \approx T_e \quad (14)$$

Thus, the stepwise ionization rate coefficient can be written as

$$k_i^s \approx \frac{g_i}{g_o} \frac{1}{(4\pi\varepsilon_o)^5} \left(\frac{m e^{10}}{\hbar^3 T_e^3} \right) \exp\left(\frac{-I}{T_e}\right) \quad (15)$$

Comparing direct and step wise ionizations by taking a ratio of their rate coefficients.

$$\frac{k_i^s}{k_i} \approx \left(\frac{I}{T_e} \right)^{\frac{7}{2}} \quad (16)$$

where I is the ionization potential and

$$I \approx \frac{1}{(4\pi\epsilon_0)^2} m e^4 / \hbar^2 \quad (17)$$

Photo-Ionization Processes

A photon $\hbar\omega$ of wavelength λ may photo-ionize a neutral species A of ionization potential I (in eV) as shown

$$\hbar\omega + A \rightarrow A^+ + e, \lambda < \frac{12,400}{I(\text{eV})} \text{ \AA} \quad (18)$$

For ionization, the photon wavelength should typically be less than 1000 Å or ultra violet wavelengths. Due to low concentrations of high energy photons in most cases, photo-ionization is not as big a contributing factor as other types of ionization in the overall process. Sometimes though, this process plays a key role in providing seed electrons for the beginning of the ionization process.

X-Ray Lasers

For typical X-ray lasers, the wavelength range is between 3.56 – 46.9 nm. The pumping method used to build up the laser is either by laser produced plasma or through a fast discharge plasma. X-ray lasers are typically pulsed lasers usually with an output pulse duration of about 500 ps- 10ns, and an output energy/pulse of 10nJ to 1mJ. They may achieve maximum peak output powers of about 1-2 MW.

Population inversion in X-ray lasers have been generated by extremely high temperature plasmas, which are laser-produced using large high power pumping lasers. X-ray lasers are developed by focusing the pumping laser onto a solid target, through a cylindrical lens making the plasma elongated, made of materials that would be suitable to

make up the laser gain medium. X-ray laser wavelengths vary according to level of excitation by the pumping laser on the neutral element, hence they have a range. For higher laser output power, higher input laser energies would be needed to provide longer gain lengths, so the laser gain media has time to build up in intensity.

Typically, a powerful Nd:glass laser generating a laser line that is focused on a solid target material over the length of 1-5cm and width a few hundred microns help produce X-ray lasers. Because of the focus of Nd:glass laser on a solid material, this material is vaporized to form ions of the appropriate ionization stage. The gain duration through the amplifying medium is so short, depending on the placement of the mirrors, that only a few passes are necessary before the laser is ready. To produce an X-ray laser, an input laser energy of ten of thousands of joules is required within a few nanoseconds or less.

Methodology

The VASIMR is considered as a base, to help achieve the objectives of this project. The RF helicon source is replaced with a laser system, while keeping the rest of the systems in VASIMR design, like plasma confinement and acceleration system intact. Only one propellant, viz H₂ gas, is considered, in order to make benchmarking the results with pertinent VASIMR data simple. Research resulted in finding ion flux or ion production rates for different VASIMR configurations with different power requirements, shown in Table 1. (Bering, E. A., Brukart, M., 2006; Squire, J. R., Chang-Diaz, F.R., Glover, T., et al., 2008).

Table

Ion flux data for two VASIMR engine configurations

Engine type	Ion flux (ions /sec)	Gas
20KW Helicon power	3.1×10^{20}	Deuterium
50 KW Helicon power	1.7×10^{21}	Hydrogen

In this table the helicon power refers to the power input to the helicon antennae on the VASIMR. For this project, this power maybe assumed as the power available to run the laser source. Although deuterium is heavier than hydrogen, since both are neutral and stable molecules, it will be assumed that both are similar, in the sense that ions and electrons are generated for the purpose of this project. The presence of neutrons as separate entities will be neglected.

Since ion flux rates are available for benchmarking, now assumptions must be made in order to choose the right laser system for plasma generation. Since lasers are electromagnetic waves, of which one of the ranges are visible light, photo-ionization process maybe assumed for some of the lasers. But, a laser also supplies some power. So not only will the gas propellant be subject to photoionization, but also other forms of ionization like direct ionization and step wise ionization.

If it is assumed that photoionization will provide the seed electrons for further ionization of the gas propellant, then the maximum wavelength of the laser required is given by equation (18). Thus, for photoionization to take place, assuming that the hydrogen gas is in neutral molecular state, the wavelength range can be calculated as-

$$\lambda < \frac{12,400}{15.4 eV} \text{ \AA} = 805.2 \text{ \AA} = 80.5 \text{ nm}$$

Most lasers have wavelengths more than 80.5 nm. Thus, there are very limited number of laser systems that can be chosen, for which the assumption can be made that

photo-ionization will take place, and provide seed electrons for collisions and ionization to take place. Assume, for simplicity, that vibrational, rotational and electronic excitation is minimal in all species. Also assume that there is no recombination of ions, or electron attachment. Finally assume the photo-ionization is taking place under thermodynamically stable and equilibrium conditions.

Fridman (2008) provides the photo-ionization cross sections for H₂ and H. Since the molecular state is assumed, the photo-ionization cross section is $0.7 \times 10^{-17} \text{ cm}^2$. Knowing this value, we can find the mean free path between the seed electrons and rest of the neutral particles and ions from equation (2). Thus,

$$\text{Mean free path } (\lambda) = 1 / (0.7 \times 10^{-17}) n_B$$

Thus, the photo-ionization rate can be determined by equation (4) as

$w_{A+B} = (0.7 \times 10^{-17} \nu) n_A n_B$. The values for n_A , n_B , ν have to be obtained experimentally. This derivation of the reaction rate during photo-ionization, has been extremely simplistic based on assumptions made earlier. Calculation of a more realistic ionization rate is out of the scope of this project, as it involves experimental values, for which a setup is not available.

Making similar assumptions as in photo-ionization, and the assumption that direct ionization happens in the hydrogen atoms, not molecules, the rate of direct ionization from electron impact may also be calculated simplistically. From equations (4) and (5), we may obtain the reaction rate if the reaction rate coefficient is known. For hydrogen the number of valence electrons (Z_v) is one, the electron charge (e) is $1.6 \times 10^{-19} \text{ C}$, the ionization potential (I) = 13.98 eV, mass of electron (m) is $9.109 \times 10^{-31} \text{ kg}$. Then,

$$k_i(T_e) = \frac{4.14 \times 10^{26} \sqrt{T_e}}{\epsilon_o} \exp\left(\frac{-1}{T_e}\right)$$

Typical electron temperatures during plasma generation are 1-5 eV. Assuming the same value that has been assumed for VASIMR, we have $T_e = 5$ eV (Ilin, A. V., Chang Diaz, F. R., Squire, J.P., et al., 2002). Energy of the neutral atoms (ϵ_o) has to be determined experimentally. Then,

$$k_i(T_e) = \frac{7.58 \times 10^{26}}{\epsilon_o}$$

From this reaction rate coefficient, using equations (4) and (5) and knowing the number densities of electrons and ions, the ionization rate may be determined and from this the ion flux.

Once again, we hold the same assumptions, as in the case of direct ionization, while considering step-wise ionization. Equation (15) gives the reaction rate for stepwise ionization where the planck constant(\hbar) = 6.62×10^{-34} m² kg/s, as

$$k_i^s \approx \frac{g_i}{g_o} \frac{1.1 \times 10^{-124}}{\epsilon_o^5 T_e^3} \exp\left(\frac{-1}{T_e}\right)$$

In addition to the energy of the atom that is to be determined, for step wise ionization statistical weights of the ions and neutral particles are also unknown. To eliminate the statistical weights, using equations (16) and (17),

$$\frac{k_i^s}{k_i} \approx \left(\frac{6.745 \times 10^{-147}}{\epsilon_o^7} \right)$$

From this, if the energy of the neutral atom and the direct ionization rate is determined, it is possible to get the approximate stepwise ionization rate.

Once the ionization rates are known, the ion flux may be estimated. As can be seen from above calculations, experimentation is required, to get values like the number of electrons and ions, which are necessary for arriving at ionization rates, since assumptions have been made to simplify the theoretical calculations for these ionization rates. Furthermore, the ionization rate calculation has been taken on a case-wise basis, while in reality, all types of ionization processes might be taking place simultaneously. Thus, experimentation is required to verify what results the combination of ionization processes gives, and to see if any of the single ionization processes are comparable, in terms of ionization rates, with the combined process.. Since numerical values of the ionization rates are not possible at this juncture, a comparison of the ion flux for the VASIMR and for the laser generated system is not possible.

Now that ionization rates have been dealt with, the type of laser system assumed that is required to start the photo ionization process, has to be identified. To do this, all possible laser types are studied, to recognize the lasers with the wavelength range needed for photo ionization process to start. Since for hydrogen, the wavelength of the laser required to start photo-ionization should be less than 80.5 nm, according to Silfvast (1996) only X-ray lasers are sufficiently suitable.

Depending on the setup of the laser system which includes the gain media and pumping mechanism, several properties of the laser like it's wavelength, output energy/pulse and maximum peak output power can be determined. The power output of the laser system can be used to determine the energy being provided to the propellant gas

for plasma generation. Basic X-ray laser characteristics are presented in the theory section of this report.

Results and Discussion

The ionization rates of the propellant gas (H_2 for this project) would ultimately lead to arriving at the ion flux as the plasma is generated. Theoretical calculation of ionization rates is complex, and maybe possible when realistic assumptions are made. The scope of this project restricted the assumptions made for the theoretical calculation. Thus, only estimated values in terms of unknown factors were obtained. This is because, assumptions were made which would affect the reality of the plasma generation process. It was assumed that all plasma processes like recombination, electron attachment, ion collisions, the electric field interaction, the magnetic field interaction, radiation, statistical distribution, etc. were to be neglected. Ionization was the only plasma chemical process that was assumed to happen.

Another major assumption made was that the ionization process is kick started with photoionization. This limited the selection of the laser type, which need not be the case, since there are lasers now which are powerful enough to provide energy for direct and step ionization. This limiting assumption changed the study of the plasma chemical process, since the focus had to be the shifted from the energy transfer between the laser beam, and the atoms and molecules, to the initiating photoionization. So, instead of finding a laser to start the photoionization process, a laser with sufficient energy to maybe start a stepwise or direct ionization should be the target of the selection process.

Although there is nothing wrong with the selection of X-ray lasers as the plasma energy source, the disadvantage with this choice is that they need yet another laser to get started. Actually, they need the plasma generated by the first laser, impinging on a suitable solid substance, as their gain media to build the more powerful X-ray laser. One possible takeaway from this observation is, to ask whether it is possible to somehow divert a small amount of the propellant plasma to be the gain media for the X-ray laser. Even so, this X-ray laser system might be too complex to be the energy source on a spacecraft.

Even with all the right assumptions made, several factors come into play where experimentation is required to get numerical values for certain variables like number of electrons and ions produced, etc, without which the calculation would not be complete. This is what happened in this project. Realistic assumptions could not be made, and there was no support of experimental data, thus ion flux values could not be determined, making the benchmarking incomplete. Therefore, for a successful comparison of ion fluxes, a two pronged but simultaneous approach is suggested.

For this approach, first, plasma studies have to be conducted and the laser-gas interaction has to be studied. There has to be an understanding of which plasma chemical processes take precedence and what is the level of each type of plasma chemical process occurring. When the assumptions are made, the interaction maybe modeled on an analysis tool or an experiment has to be set up to give numbers like the ion density, electron density, energy of the plasma, energy of the neutral gas, etc. So first a modeling

tool has to be identified with the right set up, or the correct experimental set up has to be made.

While the selection process for the analysis is happening, the possible lasers for conducting the analysis or experiment have to be found. To make this selection, several factors might be considered. For example, whether the laser is pulsed or continuous wave. Usually, pulsed lasers are able to have higher peak power. So the energy output of the laser would be a factor. While considering the energy factor, one possibility that has to be identified is the amplification of the single laser beam to get a higher energy transfer into the propellant gas for plasma generation. The input power to the laser system would also be a factor for spacecraft. Finally, if possible, the weight of the laser system has to be considered.

Once the selection process is complete and the analysis model or the experiment has been setup, a comparison between the theoretical calculations (which are based on the realistic assumptions) and the values from the experiment or model have to be compared. If they match, then these numbers have to be checked with the ion fluxes from VASIMR. Matching the ion flux from the experiment with those of VASIMR shows that the I_{sp} for both systems might be close, since it was assumed that the plasma confinement and acceleration mechanism remain the same for both systems. This project can then be taken to the next step to figure out the actual acceleration mechanism and the resultant I_{sp} .

Conclusions and Future Work

The assumptions made, to allow for the scope of this project, turned the plasma generation process into a very basic one viz consisting of just ionization processes. Because of this, proper theoretical calculations could not be completed i.e., the ion fluxes could not be compared. In order to complete a feasibility study of this nature, usage of experimentation or analytical model (using more realistic assumptions) is a must. This, along with making assumptions that encompass all nature of plasma chemical processes.

For the successful completion of this study, recommendations for future work are summarized from Results section as follows. First, laser and light interaction has to be studied through more rigorous theoretical application. This study has to be supported with a proper experimental setup or analytical model. Laser types have to be identified based on output energy to start ionization, or, laser beam amplification has to be considered. Other factors would be input power to the laser, complexity of the system and weight of the system. A combined theoretical and experimental approach of this nature would yield ion fluxes that maybe the compared with the original VASIMR data to check for feasibility.

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