USE OF LASER PROPULSION IN ROCKETS AS A POTENTIAL SPACE PROPULSION SYSTEM

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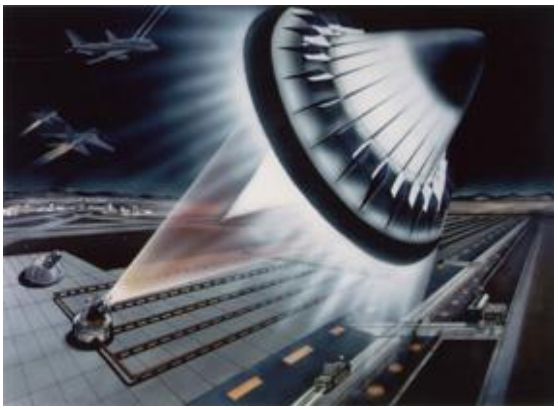
Abstract: With developments in the field of rocket propulsion, it was made possible for humans to launch satellites and send humans to space to explore the universe. But, each option available had problems associated with it, with efficiency and cost being the major factors of concern. But soon, a new method was developed to overcome these shortcomings. This method is known as Laser Propulsion, which used lasers as a propellant for itself to provide us with an efficient, clean, powerful and efficient propellant for rockets.

Introduction

The idea of using lasers as a potential rocket propulsive agent was first proposed by Eugene Sanger and Hungarian physicist Georgii Marx, and the idea of laser propelled vehicle was first proposed by Arthur Kantrowitz in 1972. Currently, the space-crafts being accelerated using beam propulsion are known as light-crafts. These crafts are significantly light-weight and smaller in size.



A lightcraft using Laser Propulsion

The light-craft being tested uses lasers for their flight. These lasers are ejected from the space-crafts, just like the procedure followed in chemical rockets, and are concentrated on a single point on the ground. The ground, under the intense heat of the concentrated laser beam, heats up to a temperature high enough to just make it explode, thus propelling the spacecraft, or “light-craft” as it is known at this point of time, upwards into a flight. These flights are usually of a short duration, with a light-craft being propelled by lasers, as a test flight, attaining a height of 72 metres (236 feet) in it’s short-duration flight which lasted for 10.5 seconds.

Two forms of Laser Propulsion have been devised.

1.On-board Laser Propulsion- In this, the spacecraft using laser propulsion has an on-board system which blends the use of the propellants being used for propelling the spacecrafts forward with it’s proposed use as an effective space debris removal weapon.

2. Off-board Laser Propulsion- Off-board laser propulsion uses energy source situated at the ground for it’s propulsion. Using of this

method removes the need for carrying on-board fuel for the rocket, thus reducing the payload mass and decreasing the overall weight being carried by the rockets, thus increasing their overall efficiency.

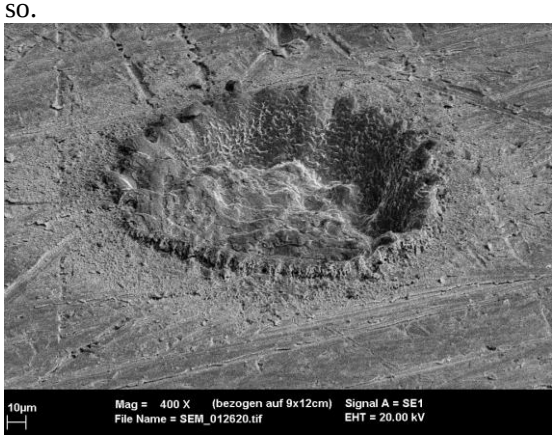
Types of Laser Propulsion

There are many forms of Laser Propulsion, which share the basic principle of function, but their working methodology differentiates them from other. We'll list and analyse them according to their performance and compare them against each other. They are-

1. Ablative Laser Propulsion

Ablative Laser Propulsion

Ablative Laser Propulsion (abbreviated as ALP) is a type of beam-powered propulsion where an external laser is used to heat the solid metal propellant, thus enabling it to produce immense heat and thus the resulting thrust produced is used to propel the spacecraft forward. Kantrowitz was the person who first suggested this method in 1971. It's a method wherein an impulsive force acting upon the spacecraft to be propelled, with the thrust acting upon it for a very short period of time, but up to a value so high that it launches the spacecraft upwards. The specific impulse of the ALP has been measured up to be 5000 seconds (49 kN s/ kg). Another advantage of this type of propulsion is that the air through which the spacecraft is travelling itself helps the spacecraft propel forward, thus adding to it's efficiency. Furthermore, ALP is capable of working even in space, where there is minimal or absolutely zero air density, a factor which makes it rest above all other options available in this field. It's specific impulse has been calculated to be 200 seconds to several minutes, with the time duration depending upon the propellant chosen and also the material chosen to be ablated under the influence of the high-intensity laser. The basic working principle of Laser Ablation Propulsion (LAP) is same as that of chemical propulsion, only difference being the type of fuel used, which is a chemical propellant in the case of chemical propulsion and heat generated due to heating of the ablated material in the case of Laser Ablation Propulsion. It is one of the most noticed and researched upon measures for rocket propulsion, although it has got recognition only in the last 20 years or so.



A crater formed by Laser Ablation

Mechanism

The process of laser ablation uses a laser source located at a remote location on Earth, which transmits laser from that source to the rocket carrying the payload by the means of laser propulsion. This mechanism works best in Low Earth Orbit (LEO) to Geostationary Orbit. It's mechanism consists of 3 major parts -
(i) power source, which transmits energy from Earth to the rocket using laser as it's power source.

(ii) electric system, wherein the laser is converted to act as a propellant

(iii) exhaust nozzle, from where the converted

energy exits creating thrust so high that it propels the rocket forward.

Calculations

To calculate the efficiency of Laser Ablation Propulsion, the following formula is used-

$$\rho C \, dT/dt = K \, [1/r \, d/dr \, (r \, (dT/dr) + d/dz \, (dT/dz)] + q_i$$

Where, ρ, C and K are the target density, specific heat and thermal conductivity and q_i is the target inner deposited power when the laser is heating the surface.

q_i can be expanded to be written as -

$$q_i = \{\int I_o \, (1-R) \, exp \, (-r2/b2-\int z)$$

Where I_o and b are laser power and the radius, R is target reflectivity, ∫ is the laser absorption coefficient in target.

2. Pulsed Plasma Thrusters

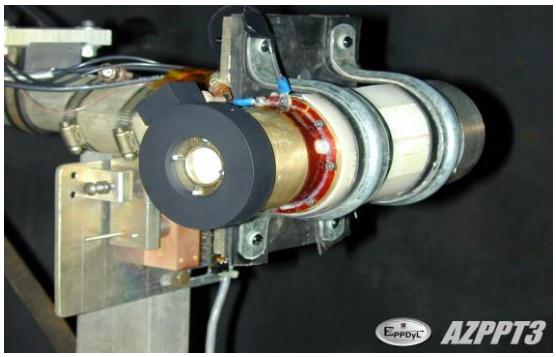
Pulsed Plasma Thrusters (abbreviated as PPT) is also known as plasma jet engine. It's a type of space propulsion using electric medium. They are generally credited to be the simplest form of electric space propulsion. They were first used in two Soviet Union probes, namely Zond 2 amd Zond 3 in 1964. An advantage of using PPTs over rockets working on chemical propulsion is that they provide a higher exhaust velocity to the spacecraft in which it is being used, although the fuel flow rate is low. And, owing to it's higher exhaust velocity, it is successful in providing larger interplanetary speeds to the space-crafts, up to the range of 20-70 km/s, which is way too large when compared to the exhaust velocity provided by chemical propulsion, which ranges between 2-4.5 km/s. This difference in exhaust velocity is 1 of the many points which prove the importance of electric propulsion over chemical propulsion.

Acceleration gradient for pulsed plasma propulsion using pulsed plasma thrusters is calculated by-

$$E = C \, x \, \sqrt{m_e} \, . \, \rho \, / \, \varepsilon_o$$

Where, E = electric field, C = speed of light in vacuum, m_e = mass of the electron, ρ = plasma density, and ε_o = permittivity of free space.

Applications: PPT are considered to be a good option for light-crafts having mass less than 100 kg. PPT are simplistic in design and have low costs, which adds to their benefits in usage in rockets. Low cost is one of the primary factor of their popularity and vast usage for the purpose of propulsion to be used in space.



Pulse Plasma Thruster

Parameters For Choosing A Laser for Laser Propulsion

Efficiency of Laser Ablation Propulsion also depends on the material we are using as an agent to heat, produce plasma and use the heat generated by heating that material to propel the spacecraft forward into flight. Mostly metals are used for performing the ablation process, due to the reason that they have very high melting and boiling point and also due to the fact that they produce large amount of heat and energy when heated. An interesting way of performing this process of ablation is to cover the material available with thermally converted type of the same metal having good absorption properties, as by the virtue of this property, it will absorb more heat, and would melt giving out higher amount of heat and temperature, thus creating more thrust for the engine to propel forward. There are some key parameters to be kept in mind while choosing a laser for laser ablation. They are-

A) Wavelength of the laser- A very important factor which needs to be taken care of is the wavelength of the laser so that it is absorbed at minimum depth. This will ensure large amount of energy deposition in a small area, which will help generate more thrust, as it is a known phenomenon that energy being radiated from a point source is more concentrated and effective, and gives out more heat and energy, for example- lasers, than energy being radiated out from a scattered source, for example- light being radiated from a bulb. So, wavelength of laser plays a key role in determining the efficiency of the laser ablation process.

B) Short pulse duration- The pulse duration refers to the time taken in the formation of the pulse from the heating of the material by the laser. Pulse duration should be minimalist so as to ensure maximum peak power and to avoid the dissipation of the heat into the surroundings, and rather using it to propel the rocket and space-crafts upwards. This principle works same as impulsive force being experienced by a body. Higher the impulsive force, more is the momentum and the speed attained by the body, in this case, space-crafts and rockets.

C) Pulse repetition frequency - Pulse repetition frequency refers to the number of pulses of a repetitive signal being received by the body per unit time. It is usually measured in pulses generated per unit time. This factor holds major importance in the process of propulsion through guided laser beams because if the pulse repetition rate is allowed to be low, then the material would eventually cool down due to the actions of atmospheric air on it, thus affecting the overall efficiency of the process in a negative manner, resulting in both efficiency and financial losses for the mission, owing to the fact that a major part of budget allotted to a space mission is spend on using a fuel requiring to be the most efficient and economical. So, the pulse repetition rate should be high, so as to trap the heat generated by the ablated material and use it up to it's full potential.

The pulse repetition frequency is measured by-

$$T = 1/PRF$$

Where, PRF refers to the frequency of pulse per second, and T refers to the pulse period of the PRF.

A phenomenon often associated with PRF is pulse spacing, which refers to the difference in the distances travelled by two successive pulses.

It is calculated using the formula-

$$Pulse\ Spacing\ (d) = Propagation\ Speed(V_{propagation})/PRF$$

D) Quality of the Beam - The quality of the beam plays a major role in this process as a beam, if not having proper focus-ability and homogeneity, will result in more take-off time, using more fuel, in this case laser, for it's take-off, thus resulting in wastage of fuel and resulting in an overall impact on the performance of the rocket using laser as it's propulsive agent in a negative manner.

These key parameters are responsible for selection of different types of lasers for the mission, depending upon the mission's requirements.

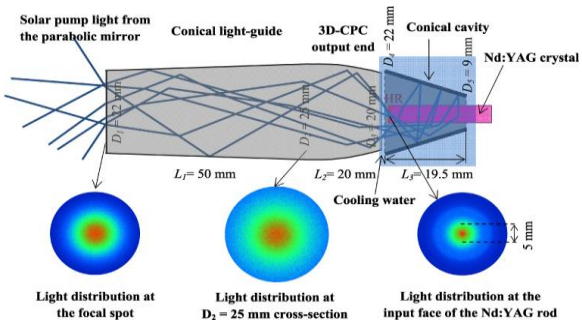
There are different types of lasers available to be used as a propellant for the rockets and space-crafts. They are-

(i) Solar Pumped Laser

Solar pumped laser is a type of laser which is used to propel the carrier vehicle forward, using the same principle followed in laser propulsion, of ejecting ions from the exhaust vent and making them hit the ground hard to produce enough heat and energy so as to propel the spacecraft and rocket forward, but a major difference here is that it emits the laser to be used to propel the spacecraft and rocket forward which uses solar radiation for pumping the medium responsible for creating lasers. A big advantage of using this laser is that it does not requires any artificial or external energy source. NdCrYAG laser is used for this type of laser.

Applications : Solar pumped laser is of great use in spacecraft propulsion, due to the fact that there's no electric grid or external power regeneration source in space from where the

spacecraft can inherit power for itself. So, because of this, the solar pumped laser finds it's applications in this field.

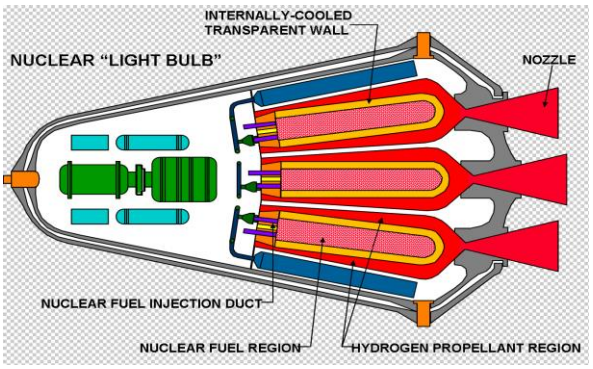


Mechanism of Solar Pumped Laser

(ii) Nuclear Pumped Laser

A nuclear pumped laser is a laser which uses the principle of nuclear fission for it's working. The energy being expelled out by the process of Uranium-235 being subjected to high neutron flux in a nuclear reactor core creates plasma in excited state, which then finally lases to produce energy. It was first developed in early 1970s. An advantage of using this type of laser is that it produces high amount of energy with low laser volume requirements. Also, nuclear energy is a clean source of energy, with less carbon emission compared to other forms. It produces heat of high intensity, thus giving out high output.

Applications: Nuclear propulsion is an ideal method for launching satellites or other man-made orbital bodies into space, because the process requires less fuel to be carried with them to space. An ideal condition for a spacecraft launch in space using laser propulsion requires the fulfilment of 4 conditions- (i) High intensity (ii) Short pulses (iii) good quality (iv) high power output.



Mechanism of Nuclear Pumped Laser

These lasers, apart from the additional available options, provide a clean, efficient and powerful source of energy to propel the rockets forward.

Type of Nozzle Used in Laser Propulsion

A very important aspect of any engine in the field of propulsion is the nozzle. Nozzles are basically the structures which control the flow of fluid through them, giving it direction and speed to propel the rocket forward. Basically there are 3 types of nozzle-

1. Convergent nozzle - Nozzles which are convergent in shape, means nozzle in which the area of inlet > area of the exhaust, is known as the convergent nozzle. They are responsible for producing very high thrust, as the decrease in the area of exhaust means the flow of exhaust gases through them would be at a greater speed, thus generating more thrust.

2. Divergent Nozzle - Nozzles which are divergent in shape, means nozzle in which the area of inlet is less than the area of outlet is known as the divergent nozzle.

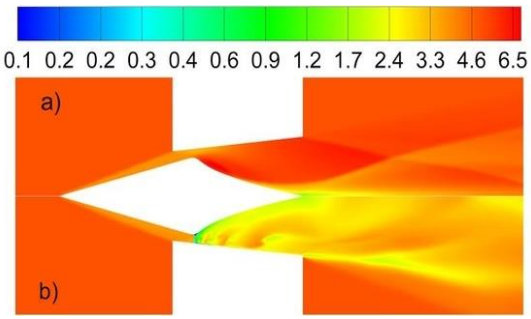
3. Convergent-divergent Nozzle - Nozzles which consist of both convergent and divergent sections in it, with the convergent part situated first, followed by the divergent part is known as the convergent-divergent or the C/D nozzle. Currently this is the most sought after and used nozzle, due to it's ability to propel the engine at Mach speeds (M) greater than 1 (M>1).

4. Conical Nozzle - In 2008, a group of scientists suggested use of conical shaped

nozzles for laser propulsion. But, the conical thrusters followed the principle of C/D nozzle only, with a thin neck followed by expanding outlet or exhaust.

This, thus proves that expanding nozzles and the converging-diverging nozzles are the best available options to be used as nozzles in laser propulsion, due to their ability to expel the exhaust gases at a very high velocity, and making the expelled gases expand on coming in contact with the atmosphere, thus creating thrust sufficient enough to propel the rocket forward at high speeds.

Currently, RAMJET engines are being considered to be used for laser propulsion, as RAMJET engines have the ability to go at supersonic speeds.

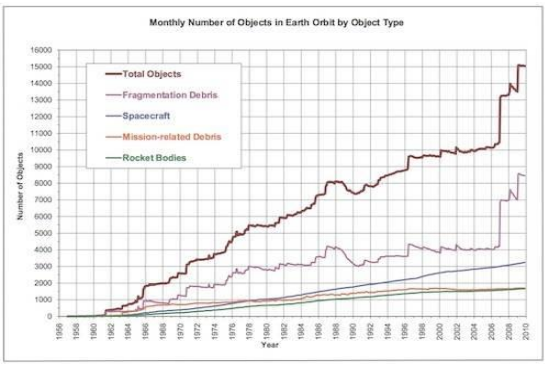


Pressure Distribution in a Supersonic Nozzle

<u>Advantages of Using Laser Propulsion</u>

Both laser and chemical propulsion are capable of launching rockets carrying payloads into space. However, their are some key parameters where laser propulsion takes an advantageous position over chemical propulsion. They are-

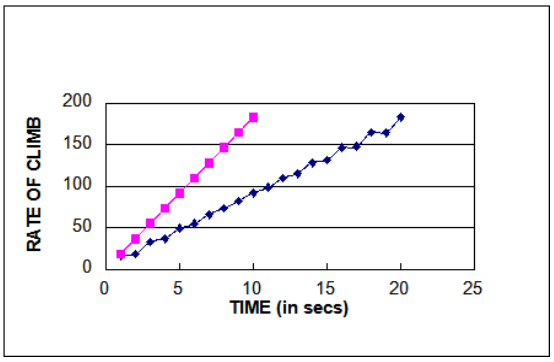
1. Use of the vehicle as a potential space debris removal system - Space debris are basically "space waste" which consist of various types of space waste like human waste, chunks of ice, rocks and dust, pieces of broken satellites etc. These space debris pose a grave threat to the orbiting bodies as they can hit and adversely affect the satellites and space stations, which may even result in their malfunction. The vehicle moving on laser propulsion can be made capable of shooting down the space debris from high- altitude orbits using a high-intensity and powerful laser beam, which may be aimed and shot using a laser gun, thus reducing the threat posed by them. This can be achieved by utilising the laser being used as a fuel, a part of which can be kept aside to be used as a means to shoot down the space debry using a laser gun, which can be fitted on-board. Right now the method in use is to aim and shoot the space waste from the Earth, ut since the distance to be covered by the beam is high, it would be required to be extremely powerful and precision in shooting of target would also be required. Fitting the space stations and other artificial orbital bodies with laser gun using laser from the propellant tank is a way to reduce space debry in it's way. This is a major advantage of laser propulsion over chemical propulsion as rockets accelerating on chemical propulsion have no means to shoot down the space debris and even if they want to, they will have to attach a separate mechanism for it, which would increase the payload mass.



Graph depicting the steady rise in the space debris

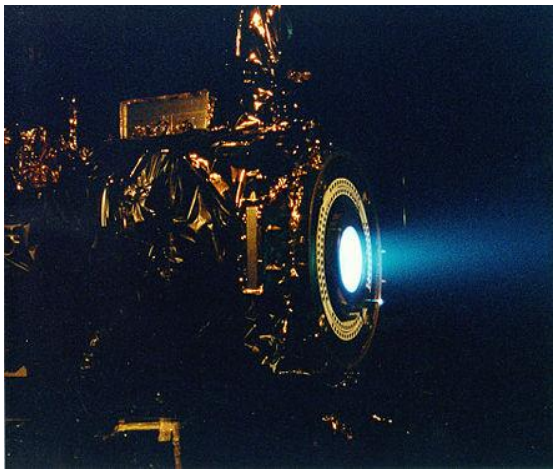
Photo Depicting Method of Elimination of Space Debris Using Laser

2. Impressive climbing rate - Although the light-crafts available at present do not have the capability to fly much higher, but neither did the first liquid fuelled rocket engine developed by Robert Goddard. The rocket engine developed by Robert Goddard climbed 41 feet in a flight which lasted for 2.5 seconds, whereas, on the other hand, the light-craft developed by Myrabo in 1997, climbed 233 feet in 12.7 seconds. So, on calculating the average of the two test flights done, the liquid fuelled rocket engine climbed at a rate of 16.4 feet/second, whereas the light-craft propelled by laser climbed at the rate of 18.3 feet/second, with a considerable gap of 1.9 feet/second.



Graph depicting the comparison between the average climbing rate of laser and chemical propelled rocket

3. Economical for launching small payloads in orbit - Laser propulsion is an ideal way for launching small payloads, which weigh <10 kg in to the geostationary or low Earth orbit. It has also been calculated that the launching cost of a small payload using laser propulsion could be as low as $100/kg. Rockets being launched through chemical propulsion can never be economical up to this extent for launch of smaller payloads, as the cost of fuel would eventually turn out to be a big obstacle in this direction.

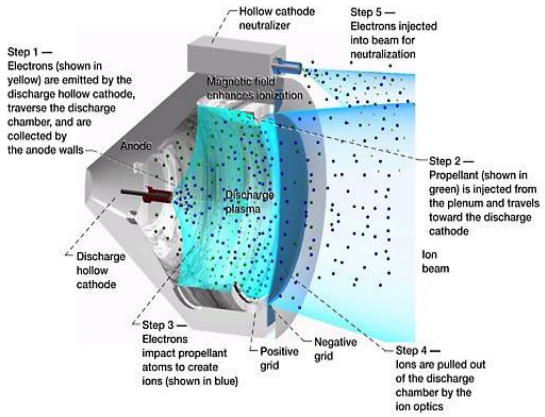


Payload Being Launched Using Laser Propulsion

4. Probable option for relativistic rocket - A relativistic rocket is a rocket which can achieve the speed of light or at least can fly at a speed nearby the speed of light.. A rocket flying at at least 50% the speed of light (0.5 c, where “c” is the speed of light) is classified as relativistic rocket. Using chemical propulsion in these kind of rockets would result in losses, due to vibrations and heat which would lower the specific impulse of rocket, whereas, by using laser propulsion, we can reduce these losses as the energy particles will be concentrated at a single point with high intensity, and the heat generated by ablated material is trapped in such a manner that it would not be allowed to escape from the sides, thus utilising all the ablated energy into propelling the rocket forward.

5. Continuous functioning- Recently, NASA developed a Xenon Thruster ion engine which worked continuously for 43,000 hours! This world record was set in Glenn Research Centre’s

Electric Propulsion Laboratory. It provided data which proved that the thruster produced continuous energy for 43,000 hours using only 770 kilograms of Xenon propellant. This is certainly a feat no chemical rocket engine can achieve!



Ion Thruster in Operation

Drawbacks of Laser Propulsion

As we all know, each kind of technology has it's own set of advantages as well as disadvantages, and laser propulsion is no different. Inspite of having a promising future in the field of space propulsion, there are a few drawbacks of this technology which needs to be taken care of before it's intensive application in the field of rocket propulsion. They are-

1. Limit of payload weight - A spacecraft being propelled using laser propulsion, known as light-craft, cannot be of a very heavy weight and also it cannot have very large dimensions.

2. Short duration of flight - The maximum duration of the light-craft powered by laser propulsion has been recorded to be 12.7 seconds, reaching a height of 233 feet, which is way too less compared to a rocket propelled by chemical propulsion.

3. Low altitude gain - Although the specific impulse of the laser propelled rocket is high, still, it is not able to sustain the momentum attained by it at the start of the flight and thus is not able to attain a height which might put it up in competition with the chemical rockets.

4. Lower thrust production - Till the time some extensive research on higher thrust production is not done in this field, as this field is still developing, unlike chemical propulsion where major advancements have already been achieved, we won't be able to extract some serious amount of output which might help it challenge the dominance of chemical propulsion in this field.

5. Weakening of signal with increase in distance - Even though laser is a sharp beam of light, but, after a point of time and covering a certain distance, it starts to spread, thus losing it's sharpness and focus-ability. This can be a major factor of concern if the method of laser propulsion is taken up for space propulsion programs in future. To overcome this, beams with longer wavelength should be considered for long-range operations, in accordance with the distance it has to travel from the ground source.

6. **Complex mechanism-** Mechanism associated with laser propulsion is more complex and costly to produce compared to chemical propulsion, also a major reason of limited usage of this type of propulsion. Mechanism of chemical propulsion is pretty easy to develop, specially for rockets riding on solid propellants, but rockets riding on laser propulsion would require some major changes in their mechanism, starting from electron beam generator, and other, which makes it way too complicated a technology to develop compared to chemical propulsion.

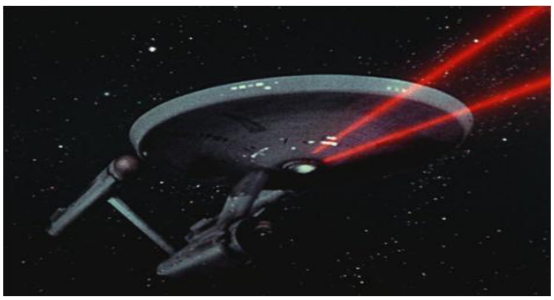
7. Need for tremendous power generation - Tremendous amount of energy needs to be generated to propel the rocket forward. Estimations have been made which state that in order to undertake even near-Earth or Moon missions, we would be needing i gigawatt of power, which is quite a lot of power to be generated by a beam.

8. Precision problems - If we use the current method in use for laser propulsion, which is, sending the beam of laser from the ground so as to propel the rocket forward, then, there is a possibility of signals getting spread out as they

reach farther. This would lead to decrease in the precision of guidance and thus affecting the overall efficiency of the mission. One possibility to overcome this drawback is to have a on-board power source, which will propel the rocket forward in a manner same as in the case of chemical propulsion.

Future of Laser Propulsion in the Field of Space Propulsion System

As of now, the use of laser propulsion is being restricted to propelling of light-crafts into space or geostationary orbits. Also, lasers are being used to shoot down orbital space debris by heating them up to a temperature so high that they would ultimately melt and may no longer be able to pose a threat to humans and space-crafts. As we have seen in this paper, till now, the technology of laser propulsion has not been explored up to an extent that it would facilitate supersonic propulsion of rockets to which it is being attached, although the idea is being worked upon by various scientists across the world. And then, the 'Star Trek' movies have already generated considerable amount of interest in the minds of people who didn't had even an iota of interest in this field.
Still, the future belongs to the laser propulsion for the reason that it is economical, powerful, and easy to use in the longer run. Recently, in early March, NASA's Dawn spacecraft reached and entered the orbital trajectory of Ceres, the dwarf planet, covering an astounding distance of 2.77 astronomical units, which converts to 414 million kilometres or 257 million miles, in an impressive time period of 8 years. These are quite some figures to achieve for a space-craft running solely on ion propulsion. The Dawn spacecraft is moving continuously rendering the services of Xenon gas, which is an inert gas. In this kind of mechanism, the xenon gas is enclosed in an charged container made of metal which accelerates it out of the thruster. And, following Newton's Third Law of Motion, which states that, 'To every action, there's equal and opposite reaction", the gas being ejected out of the thruster, applies a forward push to the Dawn spacecraft, which helps it keep propelling forward without any hindrance.

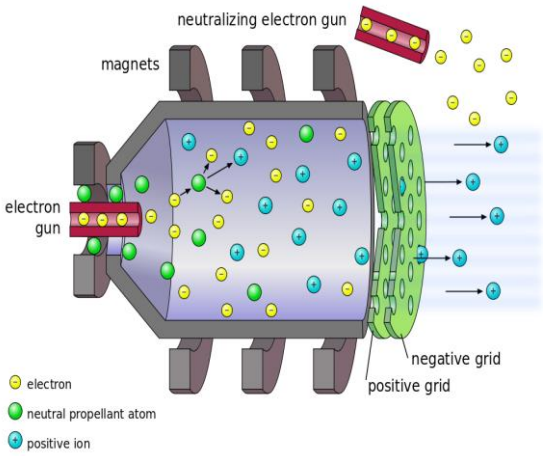


Spacecraft Using Laser Propulsion

Future of Laser Propulsion

Currently, the technology of laser propulsion is still in it's developing stage, with the world slowly realising it's importance and ability to provide us with a clean and efficient fuel. Works are going on in this field, with space agencies like NASA constantly working to make this technology available for human use. Some of their works regarding this are-

1. NASA's Evolutionary Xenon Thruster, or NEXT, is a ion drive developed by NASA which has given a phenomenal result by giving a working time of 43,000 hours.



NASA's Xenon Thruster

2. ISRO or Indian Space Research Organisation has also identified the importance of laser propulsion and it has started working on utilizing lasers as a mean to propel rockets to space which would carry satellites and put them in to orbit. The objective of developing and using this technology by them, as stated by Mr. K. Sivan, Director, Liquid Propulsion Systems Centre, is to reduce the satellite mass. This

technology will be initially tested on the communication satellites and if all goes well and as planned, this technology will be put to use to other kind of space mission undertaken by them as well.

Conclusion

Laser propulsion is a relatively new and unexplored form of rocket propulsion. Although experimental work on determining the use of lasers on rocket propulsion and in powering of space-crafts for interstellar travel has been in process for long, this technology has gained popularity only in the last 20 years or so. There's still some time before we can develop this technology in a way which can result in laser propulsion being a substitute or even a replacement for other means of rocket propulsion. Indeed there are some shortcomings of this technology, but with the advancement in science and technology, these hurdles can surely be overcome and we can be riding on space-crafts or maybe even airplanes riding on lasers, an idea which was termed as science fiction from long, thanks to the *Star Trek* movies, but would finally become a reality.

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