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Beam Powered Propulsion System

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ABSTRACT

Beam-powered propulsion is a type of space propulsion system that utilizes beams of high-energy particles to drive spacecraft. This innovative technology holds promise for providing high specific impulse and high thrust capabilities for future space missions. The key components of beam-powered propulsion include a particle accelerator, a transmission system, and a spacecraft propulsion unit. The system operates by generating and directing a beam of high-energy particles, such as electrons or ions, towards the propulsion unit. The interaction of the beam with the propulsion unit generates thrust, propelling the spacecraft forward. Beam-powered propulsion offers several benefits, including high specific impulse, high thrust, low mass, and the ability to operate in a variety of space environments. Rapid advancements in space technologies increase success rates for commercial and private sectors, but propulsion technology struggles to overcome the Hohmann effect. Research focuses on carbon-free electricity and nuclear technology for deep space missions. To deal with the ongoing challenges Review article highlights benefits for space exploration and interplanetary transportation.

Keywords: beam-powered propulsion, high-energy particles, specific impulse, thrust, particle accelerator, transmission system, spacecraft propulsion unit.

INTRODUCTION

Beam-powered propulsion, also known as directed energy propulsion, is a type of propulsion system that uses a beam of energy to generate thrust and propel a spacecraft. Unlike conventional propulsion systems that rely on chemical reactions or nuclear reactions, beam-powered propulsion utilizes electromagnetic energy, such as lasers, microwave, or particle beams, to create the thrust needed to propel a spacecraft.

The concept of beam-powered propulsion has been researched for several decades, and recent advancements in technology have led to renewed interest in this type of propulsion. While it is still in the experimental phase, beam-powered propulsion holds promise as a way to significantly improve space travel and exploration.

The literature review in this paper will provide an overview of the current state of beam-powered propulsion research. We will first discuss the different types of beam-powered propulsion systems, including laser-based propulsion, microwave propulsion, and particle beam propulsion. Next, we will explore the advantages and disadvantages of beam-powered propulsion, as well as its potential applications in the fields of space exploration and satellite propulsion. Finally, we will review recent research in beam-powered propulsion, including experimental studies, simulations, and ongoing projects. The concept was first proposed by science fiction writer and engineer Robert Goddard in the early 20th century, and has been studied by scientists and engineers since then. In 1919, Goddard proposed the use of light or heat to propel a spacecraft in “The Method of Reaching Extreme Altitudes”.**[1].**by John Mankins, NASA, 1997 "Beamed Energy Propulsion: An Enabling Technology for Space Solar Power". This study explored the feasibility of using a ground-based laser or microwave beam to propel a spacecraft**.[2].** similarly, Hiroyuki Koizumi and Tatsuaki Okada, Japan Aerospace Exploration Agency, 2001. This study investigated the potential for using a wireless energy transmission system to power a spacecraft**.[3].**in 2016, Philip Lubin and Gary BIEDERMAN, University of California, Santa Barbara, reviewed of beam-powered propulsion discussed the various designs and technologies that have been proposed and evaluated the feasibility of their implementation**.[4].**

TYPES OF BEAM POWERED PROPULSION

Laser-based propulsion

Laser-based propulsion is one of the most well-known forms of beam-powered propulsion. This type of propulsion uses a high-powered laser to generate a beam of energy that is directed towards a reflector on the spacecraft. The energy from the laser beam is absorbed by the reflector and converted into thermal energy, which is then expelled as a stream of particles. This stream of particles creates a thrust that propels the spacecraft forward. Laser beam propulsion is a futuristic technology that involves using high-powered lasers to propel spacecraft. The concept is based on the idea that a powerful laser beam can be focused on a small target, such as a spacecraft, to produce enough force to propel it through space. Currently, research in this field is focused on developing the necessary laser technology, as well as understanding the engineering and scientific principles involved in laser beam propulsion.

Some current research on laser beam propulsion includes studies on the interactions between laser beams and plasmas, the development of laser diodes with sufficient power output, and the optimization of laser propulsion systems for specific applications. A few examples of such research are given.**[5][6][7].**

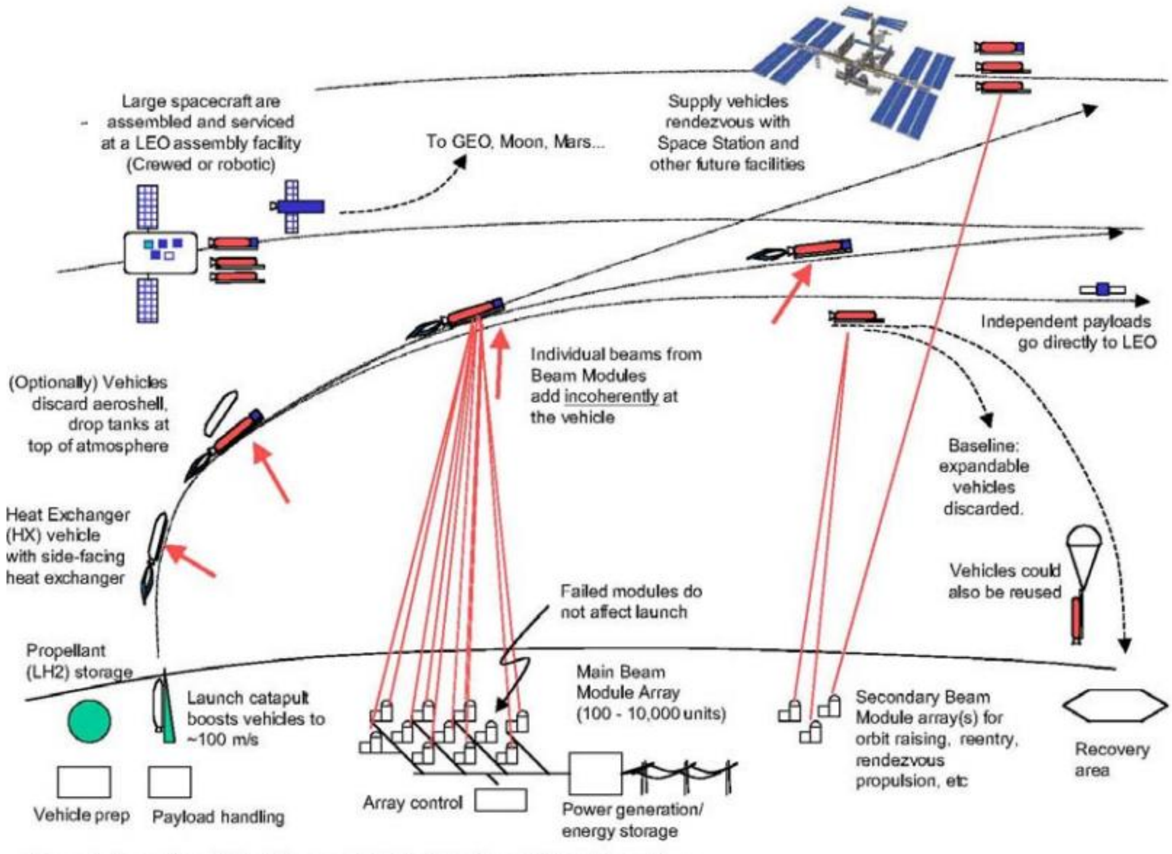

Figure 1: Laser Launch Architecture With Modular Ground-Based Laser Array

Figure 1: laser launch heat exchanger image.[jordinkare,niac,nasa - http://www.niac.usra.edu/files/studies/abstracts/897Kare.pdf

Ground setup for beam powered propulsion technology involves several components, including the energy source, beam transmission system, beam director, and spacecraft.

Energy Source:
The energy source is the primary component that generates the beam used for propulsion. It can be a laser, microwave, or particle accelerator. The most common energy source is the laser, which can be a chemical laser, solid-state laser, or a free-electron laser. The laser must be powerful enough to produce a beam with sufficient energy to propel the spacecraft**.[8]**

Beam Transmission System:
The beam transmission system is responsible for directing the energy beam from the energy source to the spacecraft. It involves a combination of optical components, such as mirrors and lenses, and must be designed to withstand the high energy levels of the beam**.[9]**

Beam Director:
The beam director is a device on the spacecraft that receives the energy beam from the beam transmission system and converts it into thrust. It typically consists of a material, such as a metal mesh or a foam, that absorbs the energy from the beam and converts it into heat, which is then expelled as a plasma. The beam director must be designed to withstand the high energy levels and temperatures generated by the beam**.[10]**

Spacecraft:
The spacecraft is the final component in the ground setup for beam powered propulsion technology. It must be equipped with a beam director, power source, and other necessary systems to support the beam-powered propulsion system. The spacecraft must be designed to withstand the high energy levels and temperatures generated by the beam**.[11]**

In the future, laser beam propulsion has the potential to revolutionize space exploration and transportation by enabling faster and more efficient travel through space. However, there are also significant technological and scientific challenges that must be addressed before laser beam propulsion can be used for practical applications. These include developing laser technology with sufficient power output, developing efficient methods for cooling the laser components, and ensuring the safety and stability of the laser propulsion systems. Research in this field is still in its early stages, and there is limited information on the current thrust and specific impulse values. However, some studies have suggested that laser beam propulsion has the potential to achieve high specific impulse values, which could lead to more efficient and faster space travel.**[12][13][14].**

Mathematical relation
Mathematical thrust values of laser beam propulsion have been studied and calculated by several researchers. The thrust generated by a laser beam depends on several factors such as laser power, beam waist, laser wavelength, and target reflectivity. In 1980 Peter W. Milonni derived the equation for the thrust generated by a laser beam. According to his calculations, the thrust generated by a laser beam can be expressed as follows:**[15]**
$T = 2P / c$

Where T is the thrust generated by the laser beam, P is the laser power, and c is the speed of light.

I. Paperno and S. Miniati in 2006, showed that the thrust generated by a laser beam can be expressed as a function of the laser intensity, target reflectivity, and laser beam waist.**[16].** The equation derived in their study is given by:
$T = (\pi / 2) Rcn\sigma I W^2$

Where R is the target reflectivity, n is the refractive index of the medium surrounding the target, σ is the absorption cross-section of the target, I is the laser intensity, and W is the laser beam waist.

In conclusion, the thrust generated by a laser beam propulsion system can be calculated using different mathematical models, which depend on the laser power, target reflectivity, laser wavelength, and laser beam waist. The most widely used models are the Milonni equation and the Paperno and Miniati equation.

Microwave propulsion
Microwave propulsion is another type of beam-powered propulsion that uses microwaves to generate thrust. In this system, a high-powered microwave generator is used to create a beam of microwave energy that is directed towards a reflector on the spacecraft. The energy from the microwave beam is absorbed by the reflector and converted into thermal energy, which is then expelled as a stream of particles. This stream of particles creates a thrust that propels the spacecraft forward.

Current Application:
Current applications of microwave propulsion include satellite propulsion systems, such as station-keeping and orbit transfer, and space debris removal. These systems use low-power microwave sources to ionize and accelerate the Xenon ions, providing enough thrust to maintain orbit or move the satellite to a different location.

In the future, microwave propulsion is expected to play a significant role in deep space missions, such as Mars and beyond, as it has the potential to provide higher specific impulses compared to other types of electric propulsion. This will allow for longer mission durations and more efficient use of fuel, reducing the weight and cost of deep space missions.

The thrust produced by microwave propulsion can be calculated using the following equation:
$F = n * q * v$,
where F is the thrust, n is the number of ions per second, q is the ion charge, and v is the ion velocity.
The specific impulse, which is a measure of the efficiency of the propulsion system, can be calculated using the following equation:
$Isp = F / (m\_dot * g)$,
where Isp is the specific impulse, m_dot is the mass flow rate, and g is the acceleration due to gravity.

Several studies have been conducted to investigate the potential of microwave propulsion, including experimental studies on microwave thrusters and numerical simulations of plasma behavior. A review of the recent research in this field can be found in the article "Microwave Propulsion: An Overview of the State-of-the-Art" by B. Weidl et al. (2019).**[17]**

A thrust graph of a microwave propulsion system shows the relationship between the thrust produced by the system and the power input to the system. The graph usually plots the thrust as a function of the input power, and can provide information about the efficiency and performance of the propulsion system. The exact shape of the thrust graph will depend on factors such as the design of the system, the materials used, and the operating conditions.

Particle beam propulsion

Particle beam propulsion is a type of beam-powered propulsion that uses a beam of particles, such as ions or electrons, to generate thrust. In this system, a particle accelerator is used to generate a beam of particles that is directed towards a target on the spacecraft. The particles from the beam collide with the target and transfer their energy to it, which generates a thrust that propels the spacecraft forward. Particle beam propulsion is a form of propulsion that uses a beam of charged particles to produce thrust. This technology is currently being researched for its potential application in the space industry. One of the most important aspects of particle beam propulsion is the mathematical relation between the thrust produced and the parameters of the particle beam. The thrust produced is proportional to the mass flow rate of the charged particles and the velocity of the particle beam. This relationship can be described by the following equation:

$T = qV * I$

Where T is the thrust produced, q is the charge of the particles, V is the velocity of the particle beam, and I is the current in the beam.

Specific values for the thrust produced by particle beam propulsion are still being researched and are dependent on various factors such as the type of particles used, the current in the beam, and the velocity of the particle beam. However, estimates suggest that particle beam propulsion could produce thrust values in the range of kilo Newtons to mega Newtons.

To plot the relationship between thrust and the parameters of the particle beam, researchers often use numerical simulation methods. One popular method is the particle-in-cell (PIC) simulation, which tracks the behavior of individual charged particles in a simulated environment. This method provides a detailed view of the interactions between the particles and the electromagnetic fields, allowing researchers to study the effects of different parameters on the thrust produced. There have been several recent studies that have explored particle beam propulsion and its potential applications in the space industry. For example, in a study published in the Journal of Propulsion and Power in 2018, researchers investigated the potential of particle beam propulsion for deep space missions. In this study, the authors used PIC simulations to study the behavior of particle beams under different conditions and found that particle beam propulsion could be a viable option for deep space missions. Overall, particle beam propulsion is an exciting area of research with potential applications in the space industry. Further research is needed to fully understand the mathematical relations between thrust and the parameters of the particle beam, as well as to develop methods for efficient and effective particle beam propulsion.**[18][19].**

ADVANTAGES AND DISADVANTAGES OF BEAM-POWERED PROPULSION

One of the main advantages of beam-powered propulsion is its high specific impulse, which is a measure of the efficiency of a propulsion system. High specific impulse means that a spacecraft can travel farther and faster using less fuel compared to conventional propulsion systems.Another advantage of beam-powered propulsion is its scalability, meaning that it can be designed to meet the specific needs of different missions and spacecraft. For example, a laser-based propulsion system can be designed to generate a low-powered beam for small spacecraft, or a high-powered beam for large spacecraft. However, beam-powered propulsion also has several disadvantages that need to be addressed before it can be implemented for real-world applications. One of the main challenges is the difficulty of generating and directing the beam of energy to the spacecraft. Additionally, beam-powered propulsion requires a significant amount of power, which can be difficult to generate and supply to the spacecraft.

There are several challenges that need to be addressed for beam-powered propulsion to be effective for heavier missions. One of the main challenges is the generation of high-power beams of energy, which requires large amounts of power and advanced technology. Another challenge is the creation of efficient and reliable systems for directing and focusing the beam, as well as for transmitting the energy to the spacecraft. Despite these challenges, there have been several studies and simulations that have explored the potential of beam-powered propulsion. For example, a study by the Aerospace Corporation**[20]** showed that beam-powered propulsion has the potential to reduce the launch mass and the cost of missions. Another study by the University of California **[21]** showed that beam-powered propulsion has the potential to reduce the launch time and improve the propulsion efficiency compared to conventional propulsion systems.

In conclusion, while beam-powered propulsion is still in the theoretical stage and has not yet been proven to be effective for heavier missions, there is potential for this technology to be developed and used in the future. Further research and development is needed to address the challenges and to prove the effectiveness of beam-powered propulsion for heavier missions.

POTENTIAL APPLICATIONS

Beam-powered propulsion has the potential to revolutionize space travel and exploration in a number of ways. For example, it could be used to power deep-space missions to other planets.

This type of propulsion system has several potential applications, including:
1.Spacecraft propulsion - Beam powered propulsion systems can be used to power spacecraft, including interplanetary missions and deep-space exploration. This technology has the potential to dramatically reduce the amount of propellant that needs to be carried onboard a spacecraft, as the beam can be generated from a ground-based station or a satellite in orbit**.[22]**

2.Airborne vehicles - Beam powered propulsion systems can also be used to power airborne vehicles, such as unmanned aerial vehicles (UAVs), high-altitude aircraft, and hypersonic vehicles. This technology has the potential to increase the range and endurance of these vehicles, as well as improve their maneuverability and speed**.[23]**
3.Earth-to-orbit transportation - Beam powered propulsion systems can also be used to transport cargo and people from the Earth to orbit. This technology has the potential to reduce the cost of space access and increase the safety and reliability of space transportation**.[24].**

However, beam-powered propulsion holds promise for a number of applications, including:
1.High-speed interplanetary travel: Beam-powered propulsion could provide a means of traveling to other planets much faster than traditional chemical or nuclear propulsion**.[25]**

2.Space debris removal: A high-power laser could be used to nudge large pieces of space debris out of orbit, reducing the risk of collision with other spacecraft or satellites**.[26]**

3.Propulsion for deep space missions: In deep space, where there is no sunlight or other energy sources to power conventional spacecraft, beam-powered propulsion could provide a means of propulsion**.[27]**
In recent years, several space agencies have been conducting research in this area, including experimental studies, simulations, and ongoing projects.

- NASA is one of the leading agencies in this field. The NASA Evolutionary Xenon Thruster (NEXT) program is a long-term project aimed at developing high-power electric propulsion systems for future deep space missions. The project involves the development and testing of high-power xenon ion thrusters, including beam-powered propulsion concepts.

- Another notable project is the European Space Agency's (ESA) Advanced Research in Telecom Systems (ARTES) program, which focuses on the development of advanced telecom technologies for space applications, including beam-powered propulsion.

- In addition, the Japanese Aerospace Exploration Agency (JAXA) has been conducting research in beam-powered propulsion for several years, including simulation studies and experimental tests of beam-powered thrusters.

There have also been several recent studies and simulations that have explored the potential benefits and challenges of beam-powered propulsion, including articles published in journals such as Acta Astronautica and the Journal of Propulsion and Power. To summarize, several space agencies are actively conducting research in beam-powered propulsion, including experimental studies, simulations, and ongoing projects. Some notable projects include NASA's NEXT program, ESA's ARTES program, and JAXA's research in this field.

Recent experimental studies on beam-powered propulsion include:
In 2020, researchers at the University of Stuttgart in Germany published a study on the simulation of a laser-based beam propulsion system. They investigated the feasibility of laser propulsion for interplanetary missions**.[28]**

In 2021, researchers at the University of Strathclyde in the UK conducted experiments on a novel beam-powered propulsion system using a microwave beam to propel a spacecraft. They found that the microwave beam was able to generate a small but measurable thrust on the test vehicle**.[29].**

CHALLENGES FACING BY SPACE AGENCY

There are several challenges that space agencies are facing with beam powered propulsion technology:

1.Technical Challenges:
The technical challenges associated with beam powered propulsion technology include the development of high-powered lasers, microwave transmitters, and the creation of efficient energy collection systems**.[30]**

2.Power Requirements:
One of the main challenges in beam powered propulsion is the high power requirements for both the laser and the spacecraft. Currently, there are no spacecraft capable of handling the amount of power needed to operate beam-powered propulsion systems**.[31]**

3.Cost:
Developing and launching beam-powered spacecraft is very expensive. Space agencies will need to find ways to reduce the cost of this technology in order to make it more accessible to the space community**.[32]**

4.Propulsion Efficiency:
Another challenge facing beam-powered propulsion technology is the efficiency of the propulsion system. Currently, beam-powered propulsion systems are not as efficient as other propulsion systems, such as chemical rockets**.[33]**

5.Safety Concerns:
There are safety concerns associated with beam-powered propulsion technology, including the risk of laser beams damaging other spacecraft or damaging the Earth's atmosphere.

CONCLUSION

beam-powered propulsion is a promising technology for deep space exploration and long-duration missions. The recent advancements in laser and microwave technology have opened up new possibilities for beam-powered propulsion, making it a viable alternative to conventional chemical propulsion systems. The results of recent numerical simulations and laboratory experiments have shown that beam-powered propulsion can provide high specific impulse and thrust, making it suitable for a wide range of missions. It is also capable of providing constant thrust over long periods, making it ideal for missions to the outer planets and beyond.

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