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Confined Z-Pinch Magnetic Nozzle: A New Approach to Space Propulsion System that Utilizes Trapped Charged Particles

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Abstract: This paper provides a theoretical overview of a Z-pinch magnetic nozzle plasma propulsion system designed for Low Earth Orbit (LEO). The system utilizes trapped charged particles from the spacecraft's environment and magnetic confinement to generate thrust, reducing the need for onboard propellants. By employing a magnetic mirror configuration, the plasma is confined and accelerated to create propulsion. The proposed propulsion system is tailored to function in the dynamic space radiation environment of LEO, particularly in polar orbits, accounting for variations in solar activity that affect trapped protons and electrons. The mechanism involves converting magnetic plasma energy into directed kinetic energy, facilitating efficient plasma detachment and momentum transfer to the spacecraft. This study examines the feasibility, design overview, and constraints of implementing this propulsion technology. Key challenges include the variability of the space environment, technological complexities, radiation effects, plasma detachment efficiency, energy requirements, and material durability. Overcoming these challenges through innovative engineering and rigorous testing is essential for successful implementation. The Z-pinch magnetic nozzle plasma propulsion system promises to advance space propulsion technology, offering a more efficient and cost-effective method for satellite operations in LEO. With further research and development, it has the potential to support future satellite missions and space exploration initiatives.

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1. Introduction

Space propulsion is essential for manoeuvring, orbit transfer, and maintaining orbits in Low Earth Orbit (LEO), where spacecraft must contend with aerodynamic drag and gravitational perturbations at altitudes ranging from 300 km to 2000 km [1]. Propulsion systems are critical; without them, missions cannot be sustained. Most existing thrusters, whether chemical or electric (such as Hall or ion thrusters), require on-board propellant to ionize gases and create plasma [2-3]. The required exhaust speed determines the mass of propellant needed and the propulsion technology used. To address the issue of propellant depletion, developing electrodynamic plasma propulsion systems based on trapped charged particles in LEO is necessary. This approach could reduce satellite mass and lower costs. We propose using confinement Z-pinch plasma thrusters, which utilize trapped energetic charged particles from the spacecraft's surrounding environment and are based on a magnetic mirror configuration. Deorbiting will become increasingly necessary in the future as numerous spacecraft are currently operational in space, serving various purposes such as Earth observation, communication, military activities, and space

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exploration. Since the launch of Sputnik in 1957, the number of operating satellites in LEO has surpassed 6718 as of 2023 **[4]**. Furthermore, this number is expected to rise significantly with the addition of 12,000 satellites in the Starlink constellation **[5]**.

2. Space Plasma Environment

The Z-pinch magnetic nozzle plasma propulsion system proposed in this paper is designed to operate in the dynamic space radiation environment of Low Earth Orbit (LEO). To understand the conditions under which this system will function, an analysis of the space radiation fluence encountered by a small satellite in a low-altitude polar orbit (Sun-synchronous, 98.5° inclination, 800 km altitude) over a three-year mission was conducted. This analysis considers both maximum and minimum solar activity periods. The space radiation environment in LEO, especially in polar orbits, is primarily influenced by trapped protons and electrons. These particles, originating from the solar wind and modulated by the Earth's magnetic field, pose significant challenges to satellite operations. Understanding their differential fluence is essential for designing robust satellite systems. During periods of maximum solar activity, the radiation environment intensifies due to increased solar wind and magnetic disturbances, leading to higher fluxes of high-energy protons and electrons. This necessitates enhanced radiation protection measures for satellite components. Conversely, during solar minimum, the fluence of both protons and electrons decreases, resulting in a relatively lower radiation environment, though still significant.

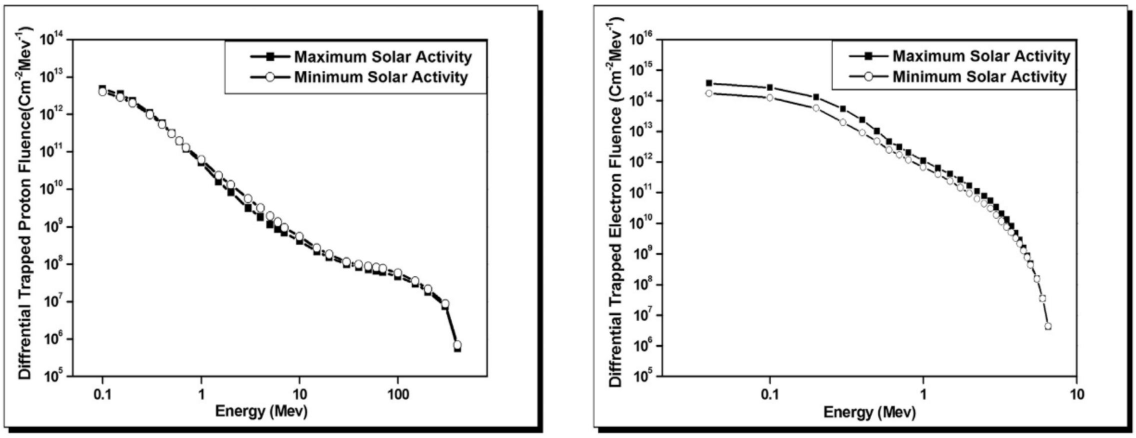

Figure 1. The data shows the differential fluence of (a) trapped protons and (b) electrons during a three-year mission, considering both maximum and minimum solar activity periods [6].

In the ionosphere, the electron density reaches a maximum of 10^6 cm^{-3} at an altitude of around 300 km, with the maximum plasma frequency reaching 10 MHz $f_p = 9 \times 10^{-3}\, n_e$ **[14]**. Herrera Martínez et al. **[13]** investigated the resistance of halide perovskites as a standard test for LEO at fluences of 1×10^{11} p/cm^2 proton at energies of 1, 5, 10 MeV.

3. Magnetic Nozzle

Space electric propulsion has become a popular alternative to classical chemical propulsion due to several advantages, one of which is a high specific impulse [7]. In electric propulsion systems, the propellant—trapped charged particles—is accelerated using energy from an external power source, such as solar panels or a nuclear reactor. This method helps overcome the limitations of Tsiolkovsky's rocket equation, which requires a specific amount of propellant mass to achieve a certain change in velocity (Δv).

$$\Delta V = I_{SP}\, g_0 \ln \frac{m_0}{m_f}$$

Where $I_{SP}\, g_0$ is the effective exhaust velocity, m_0 initial total mass, m_f final total mass without propellant. A magnetic plasma nozzle uses magnetic fields to create regions of higher magnetic field strength at the ends of a cylindrical plasma configuration. This setup controls the flow of plasma and generates thrust by accelerating the plasma in the axial direction. The magnetic nozzle functions similarly to de Laval nozzles used in chemical rockets, employing a diverging shape to convert and then divert the plasma, resembling a "Sausage Instability." The magnetic field must confine the plasma precisely to produce kinetic energy effectively.

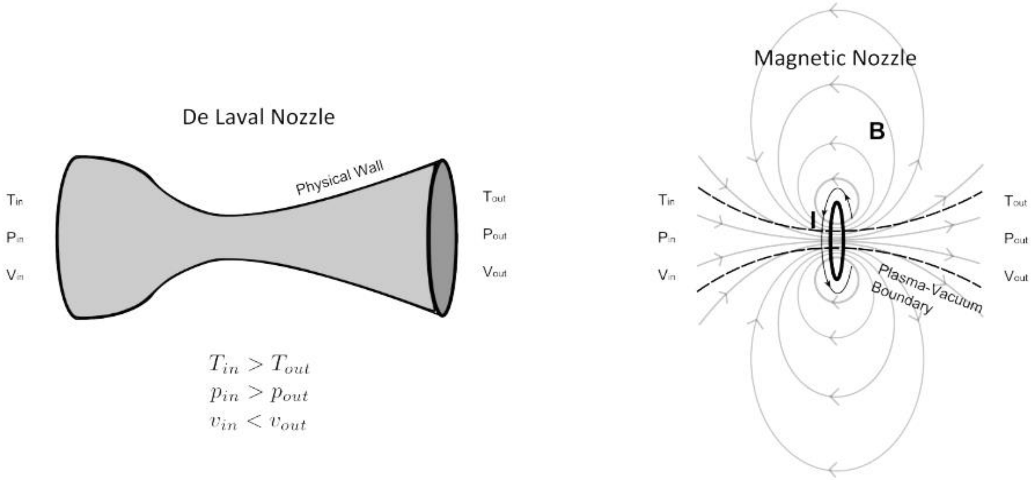

Figure 2. Magnetic Nozzle compared to De Laval Nozzle [17]

3.1. Three-Step Operation of Magnetic Nozzle

3.1.1. Conversion of Magneto plasma Energy to Directed Kinetic Energy:

Conversion of magneto plasma energy to direct kinetic energy is given by:

$$K_{total} = K_{\perp} + K_{||} = \frac{mV^2{}_{\perp}}{2} + \frac{mV^2{}_{||}}{2} = constant$$

The magnetic moment of a particle remains constant if the magnetic field changes slowly compared to the particle's cyclotron motion. This conservation results in the conversion of perpendicular velocity ($V_{\perp}$) to parallel velocity ($V_{||}$), akin to magnetic mirror physics. The total kinetic energy remains constant, and as the magnetic field decreases, $V_{||}$ increases, enabling thrust generation **[8]**.

3.1.2. Ion Acceleration via Electric Fields:

Ions can be accelerated by electric fields established through an electron pressure gradient. The higher mobility of electrons creates an ambipolar electric field, which accelerates ions. The formation of double layers, characterized by sharp potential differences, also aids in ion acceleration. Both mechanisms facilitate energy transfer from electron thermal motion to ion flow velocity **[9]**.

3.1.3. Efficient Plasma Detachment:

Plasma detachment occurs due to the loss of adiabaticity, electron inertial effects, or induced magnetic fields. The loss of adiabaticity demagnetizes particles when magnetic field conditions change rapidly, leading to detachment. Inertial detachment occurs when only one species demagnetizes, allowing plasma to flow through electric fields. Induced field detachment involves either field stretching (where plasma exceeds the Alfvén velocity) or self-demagnetization via diamagnetic currents. These processes enable plasma detachment while minimizing thrust losses **[10]**.

3.1.4. Momentum Transfer from Plasma to Spacecraft:

The momentum transfer from energy conversion and plasma detachment back to the spacecraft is governed by the Lorentz force, particularly the $\mathrm{J} \times \mathrm{B}$ terms, assuming non-relativistic flows:

$$\mathrm{J} \times \mathrm{B} = -\nabla\left(\frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}(\mathrm{B} \cdot \nabla)\,\mathrm{B}$$

Magnetic pressure confines the plasma, forming a current layer at the plasma-vacuum edge. Momentum transfer occurs primarily through forces between the induced currents in the plasma plume and those creating the magnetic nozzle. Induced azimuthal currents can be diamagnetic, opposing the magnetic field and producing thrust, or paramagnetic, enhancing the field and creating drag. Effective thrust requires diamagnetic surface currents to exceed paramagnetic volumetric currents **[11-12]**.

4. Z-Pinch

The Z-pinch technique, used for thermonuclear plasma fusion, is based on a confinement configuration that could be a promising method for developing space thrusters using the trapped charged particles in LEO. The simplest magnetic confinement arrangement is the Z-pinch equilibrium, which consists of an azimuthal magnetic field produced by an axial electrical current flowing through a plasma column. The plasma is compressed and contained by the Lorentz force ($J \times B$), which can be combined with the magnetic nozzle concept to produce a magnetic confinement Z-pinch. The radial force balance describes the equilibrium through the one-dimensional momentum equation from magneto hydrodynamics (MHD). A Z-pinch fusion space thruster can reach velocities of up to 10^5m/s, with specific impulses in the range of 10^6 seconds and thrusts up to 10^5 N **[15-16]**.

5. Advantages of Z-Pinch Propulsion

- ***High Specific Impulse:*** Z-pinch propulsion can potentially achieve much higher specific impulse compared to traditional chemical rockets, making it suitable for deep space missions.
- ***Compact Design:*** The system can be more compact than other types of fusion-based or advanced propulsion systems due to the direct use of magnetic fields for confinement.
- ***Efficient Plasma Confinement***: Magnetic confinement via the Z-pinch effect can be highly efficient, maintaining plasma stability and energy density.

6. Limitations

The proposed magnetic nozzle thruster, based on trapped charged particles in LEO combined with the Z-pinch concept, is a theoretical model that can be simulated using magnetohydrodynamics (MHD). The availability of trapped charged particles in LEO varies, with particle energies ranging from several electron volts (eV) to giga-electron volts (GeV), influenced by solar activity and geomagnetic conditions. This variability may affect the performance and efficiency of the propulsion system. Significant technological challenges include precise control of magnetic fields, plasma stability, efficient energy conversion, and momentum transfer to the spacecraft. Additionally, there may be substantial control challenges in using this system for Attitude Determination and Control Systems (ADCS). The components of the propulsion system, particularly those exposed to high-energy plasma and radiation, must be made of materials capable of withstanding these harsh conditions without significant degradation over time.

7. Conclusion

The development of a Z-pinch magnetic nozzle plasma propulsion system offers a promising solution for efficient, cost-effective propulsion, satellite orbit maintenance, and deorbiting in Low Earth Orbit (LEO). By harnessing the trapped charged particles in the space environment, this system can potentially reduce reliance on onboard propellant, leading to lighter and more economical satellite missions. The integration of magnetic confinement and plasma acceleration mechanisms presents a novel approach to overcoming the limitations of traditional chemical and electric propulsion systems. This represents a significant advancement in space propulsion technology. However, its successful implementation will depend on overcoming the identified limitations through innovative engineering solutions and rigorous testing in the space environment. With continued progress, this propulsion system could play a crucial role in the future of satellite operations and space exploration.

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9. Conflict of Interest

The author declare no competing conflict of interest.

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