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A direct fusion drive for rocket propulsion ☆

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ABSTRACT

The Direct Fusion Drive (DFD), a compact, anuetronic fusion engine, will enable more challenging exploration missions in the solar system. The engine proposed here uses a deuterium–helium-3 reaction to produce fusion energy by employing a novel field-reversed configuration (FRC) for magnetic confinement. The FRC has a simple linear solenoid coil geometry yet generates higher plasma pressure, hence higher fusion power density, for a given magnetic field strength than other magnetic-confinement plasma devices. Waste heat generated from the plasma's Bremsstrahlung and synchrotron radiation is recycled to maintain the fusion temperature. The charged reaction products, augmented by additional propellant, are exhausted through a magnetic nozzle. A 1 MW DFD is presented in the context of a mission to deploy the James Webb Space Telescope (6200 kg) from GPS orbit to a Sun–Earth L2 halo orbit in 37 days using just 353 kg of propellant and about half a kilogram of ^{3}He. The engine is designed to produce 40 N of thrust with an exhaust velocity of 56.5 km/s and has a specific power of 0.18 kW/kg.

1. Introduction

The future of space exploration, from robotic deep-space expeditions to manned interplanetary missions, will require high-thrust, high-exhaust velocity engines. These specifications shorten the transit time and reduce the mass of the spacecraft. Thus, operational costs, which for deep space missions can approach $50M USD per year, are lowered. For manned missions, the decreased transit time has the additional benefit of reducing the astronauts' exposure to cosmic radiation and zero-gravity conditions. Furthermore, on such missions, high-power propulsion is essential in the case of an aborted operation, as it would allow the astronauts to quickly return to Earth in case of an accident or emergency. The engine's exact specifications, particularly its power and specific impulse, will vary for each mission. Thrust can be further augmented by the injection of additional propellant and the use of multiple engines. Herein, one such mission is illustrated powered by the Direct Fusion Drive engine (DFD) with moderate power ($\approx$1 MW) and specific impulse of at least 5750 s.

Many proposed NASA and ESA missions require high-performance propulsions systems, as shown in Table 1. All of these power requirements are exceeded by the output of the DFD, which can potentially achieve up to 20 MW of power. Thus, the engine theoretically meets the anticipated requirements for deep-space and interplanetary manned missions. The 1 MW DFD will be presented in

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Table 1
Proposed NASA and ESA missions requiring high-power propulsion systems. The power was determined from the specific mass of the power sources.

Mission	Power (kW)	Power source	Engine	References
JIMO	180	Nuclear fission	Nexis ion & hall thrusters	[52]
Outer planets	95	Nuclear fission	Nexis Ion	[52]
200 AU	65	Nuclear fission	DS4G	[11]
200 AU	160	Solar panels	Ion	[11]
NEO 2004 MN4	210	Solar panels	Ion	[32]
NEO crew	350	Solar panels	Hall	[32]

Table 2
Comparison of propulsion technologies for deploying the James Webb Space Telescope. A Δu of 3.1 km/s, required for a low thrust transfer from GPS orbit to L2, is used as a baseline for comparison. The mass ratios are calculated using the rocket equation, using the initial mass m_i, final mass m_f, exhaust velocity u_e, and the total mission velocity change Δu. For the electric propulsion options, the energy source and its fuel are not specified as it is external to the propulsion system, therefore an advanced solar cell power system with specific power of 500 W/kg [26] is used for the most favorable comparison. Fusion propulsion usually does not involve direct propulsion, but uses the fusion engine as a power source for heating, thus thrust data is not included for D–T or p–^{11}B. The values for D–^{3}He are based on the results from the example mission in Section 4.

Type	Fuel	Propellant	Exhaust velocity, u_e (km/s)	Mass ratio, m_i/m_f (kg/kg)	Thrust, T (N)	Thrust-to-weight ratio	References
Chemical (RL-10)	LOx–LH$_2$	H_2O	4.6	1.96	1.1×10^5	60.53	[1,51]
Ion (typical)		Xe	30	1.11	0.24	4.6×10^{-4}	[40,50]
Ion (DS4G)		Xe	140	1.02	1.0	5.1×10^{-4}	[11]
Hall		Ar	20	1.17	1.1	1.6×10^{-3}	[13,46]
MPD		Ar	27	1.12	12	7.1×10^{-4}	[4,41]
Fission	U, Pu	H_2	7.0	1.56	3.3×10^5	30	[49,53]
Nuclear Lightbulb	^{233}U	H_2	18	1.19	4.1×10^5	1.31	[18,37]
VASMIR		Ar	49	1.07	5	9.3×10^{-5}	[3]
Fusion	D–T	^{4}He	1.3×10^4	1.00			
Fusion	p–^{11}B	^{4}He	1.2×10^4	1.00			
Fusion	D–^{3}He	^{4}He+ p	2.5×10^4	1.00	0.054		
DFD	D–^{3}He	D	56	1.06	40	6.5×10^{-3}	

the context of a mission to deploy the James Webb Space Telescope from a GPS orbit to a Sun–Earth L2 halo orbit.

Most other nuclear propulsion schemes, both fusion- and fission-based, only are realizable at power levels of GWs, at which point the mass of fuel, propellant, structure, and shielding severely limit their space flight capabilities. Nuclear thermal rockets, which have been demonstrated, prove very undesirable in comparison to the DFD. While they exhibit a high thrust-to-weight ratio, their exhaust velocity is only 7.5 km/s, a fraction of that of direct fusion rockets [5]. Fission engines face two further challenges: the potential risks associated with putting uranium and plutonium into orbit and the negative public sentiment about taking such risks. Fission electric schemes are limited in power conversion efficiency by the maximum temperature of the heat exchanger leading to low specific powers for the propulsion system [5]. Finally advanced fission rockets, such as nuclear pulse, gas core and nuclear light bulb, are even more theoretical than fusion- relying on technologies or materials that have yet to be developed.

Some specific advantages of a deuterium–helium-3 fueled (D–^{3}He) aneutronic fusion engine with thrust augmentation (*i.e.* the DFD) can be seen in Table 2, where it is compared against various engine configurations, including some conceptual designs. The electric propulsion options, which accelerate ions using electric fields with or without magnetic fields, require a separate power source and therefore the mass ratios given are underestimates. One electric propulsion system, the Dual-Stage 4-Grid system (DS4G), shows promise and analysis suggests performance similar to the fusion engine described in [12] and [11]. D–^{3}He fusion without thrust augmentation supplies too little thrust, making it impractical for most missions. Adding propellant significantly slows down the fusion products and raises the thrust to a more effective level for space travel.

2. Fusion background

Minimal neutron production is attractive for space propulsion because it reduces the required shielding as well as the engine size, mass, and cost. Additionally, the use of D–^{3}He increases the fraction of power available for propulsion by decreasing the energy and quantity of neutrons produced and completely eliminates the need to breed tritium (T), in stark contrast to the majority of current fusion research where the critical fusion reaction is precisely D-T. The p–^{11}B aneutronic reaction, though it produces the fewest neutrons of any fusion fuel mixture and has abundantly available fuel, is not considered here because there is strong uncertainty whether net power could be produced and because stronger magnetic fields and higher plasma temperatures would be required. Thus, D–^{3}He is the most promising fuel mixture and is the only one considered below.