A Direct Fusion Drive for Rocket Propulsion

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Abstract

The Direct Fusion Drive (DFD), a compact, aneutronic 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 ^3He . 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.

Keywords: fusion, propulsion, FRC, deuterium, helium-3, aneutronic

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 exact engine 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 (≈ 1 MW) and specific impulse of at least 5,750 s.

Many proposed NASA and ESA missions require high-performance propulsion 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 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.

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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]

Nuclear thermal rockets, which have been demonstrated, prove very undesirable in comparison to the DFD. Their exhaust velocity is only 7.5 km/s, a fraction of direct fusion rockets [5]. In addition, all fission rockets take great risk by putting radioactive materials such as uranium and plutonium into orbit, which if a breach occurs could contaminate large swaths of the planet. Thus, fission engines face two overwhelming challenges: a potential for catastrophic failure and strong negative public sentiment about taking such risks at all. 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 ($D-^3He$) 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]. $D-^3He$ 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.

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 $D-^3He$ 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 ₂ O	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	4He	1.3×10^4	1.00			
Fusion	p- ^{11}B	4He	1.2×10^4	1.00			
Fusion	$D-^3He$	$^4He + p$	2.5×10^4	1.00	0.054		
DFD	$D-^3He$	D	56	1.06	40	6.5×10^{-3}

Figure 1: Power balance in an aneutronic fusion propulsion system.

An RF generator heats the plasma, generating the fusion reaction, which releases Bremsstrahlung, synchrotron, and neutron radiation. The neutrons are absorbed by the shielding and the X-rays, by the helium blanket. Heat is converted through a Stirling Cycle engine, where electrical power is recycled back into the craft. Coolant in high-temperature superconducting (HTS) coils absorb some heat. Waste heat from the HTS coils and the thermal power conversion subsystem is rejected to space through radiators.

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–³He 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). The p–¹¹B 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–³He is the most promising fuel mixture and is the only one considered below.

The D–³He plasma admits both D–³He and deuterium-deuterium (D–D) reactions. Thus,

where the values in parenthesis are the energy of that particular fusion product. The D–³He reaction provides a higher power density than the D–D reactions, and both its reaction products are charged, allowing for direct control of the exhaust. For a thermal plasma with equal D and ³He densities, the fraction of the fusion energy carried by neutrons from the D–D reaction, f_p , is 1/3, from which it is difficult to extract useful thrust. If the tritium fusion products of equation (2) also fuse within the plasma, considerably higher fractions of power would be in the undesired neutron channel. To reduce this problematic possibility, two routes have been proposed. The simplest way is to reduce the deuterium fraction in the thermal plasma from the stoichiometric 1:1 mixture, though it would also decrease the power density, if the magnetic field is held constant. Alternatively, [48] and [31] have proposed an f_p -reducing method termed T-suppressed D–D fusion (or He-catalyzed D–D) in which the tritium is rapidly removed from the plasma before it can fuse. The tritium that is captured naturally transmutes to ³He after which it is injected back into the plasma as fuel. By this circuitous route, it should be possible to achieve an f_p as low as 5%. However, such a cycle only makes sense for mission durations considerably longer than the 12.3 year half life of tritium. Our RF plasma heating method (see Section 3.2) could reduce f_p to under 0.5%, by tailoring the ion energy distributions, based on [20].

3 Modular Fusion Engine Design

3.1 Overview

The reactor design we propose differs from [16] in size, heating method, and fuel. There, $p\text{-}^{11}\text{B}$ was selected, which requires five-times higher ion energies and produces far less fusion power *per* reaction. They also chose neutral beams for heating, requiring a plasma volume that is one hundred times larger, and is therefore more costly and less stable. The even-parity rotating magnetic field (RMF_e), see [10] and selected by [38], has been shown to have poor energy confinement, resulting in the need for a larger FRC as well. However, increasing the FRC size to the point where the plasma radius is more than 10 times the ion Larmor radius will lead to magnetohydrodynamic (MHD) instabilities. We selected the odd-parity RMF (RMF_o), instead, which is predicted to promote better energy confinement, hence allow smaller, more stable engines. The overall engine layout is depicted in Figure 1.

Plasma parameters were chosen by an iterative, self-consistent process design around the desired power an estimated energy confinement time (1/5 of classical and radiation losses) and the magnetic field capabilities of current high-temperature superconductors, incorporating a wide safety margin. Further refinements in the plasma modeling was performed to reduce neutron wall load. These included increasing the $^3\text{He}/\text{D}$ ratio in the plasma and control of the detailed velocity distributions of the D and ^3He . For the selected magnetic field, ca. 5 T, a range of ^3He and D average energies satisfied the mission requirements, with values of 100 keV and 70 keV being typical.

The feasibility of fusion itself has been demonstrated by the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET), and the Japan Torus (JT-60). TFTR has generated a record maximum of 10.7 MW, JET produced 16.1 MW, with a $Q \approx 0.6$, and JT-60 achieved a $Q \geq 1.25$ and a record ion temperature of 45 keV (where Q is the fusion energy gain factor or the ratio of nuclear energy produced to the energy needed to maintain the plasma). Our confidence in the DFD is furthered by the fact that it is far smaller and runs cleaner than the mainline fusion devices, hence improvements in operations can be made far more quickly and at far lower cost.

Many physics challenges remain before the RMF_o -heated FRC can be developed into a practical reactor. The predictions of excellent energy confinement, stability, efficient electron and ion heating, and current drive to fusion-relevant temperatures must be validated. Substantial progress has occurred in the first three areas. In 2010 and 2012, TriAlpha Energy Corp reported near-classical energy confinement time in their FRC, [9] and [56].¹ Our reactor needs energy confinement time only 1/5 as long as the classical. In 2007, an RMF_o -heated FRC, [22], achieved stable plasma durations 3,000 times longer than predicted by MHD theory ([45]); by 2012 that record was extended to over 10^5 times longer. Finally, theoretical studies by [28], [33], and [23] indicate that RMF_o will be able to heat plasma electrons and ions to fusion relevant temperatures. These are promising starts, but much research is needed at higher plasma temperatures and densities and with burning, *i.e.*, fusing, plasmas.

3.2 The RMF_o Method

As stated above, for an FRC reactor to burn its $\text{D-}^3\text{He}$ fuel mixture, the ^3He and D average ion energies must achieve values of around 100 keV and 70 keV, respectively. If energetic neutral beam injection were used for achieving this temperatures, the plasma would have to be over 4 m in diameter in order to “stop” the injected neutral beam. Such a large reactor would produce proportionally large amounts of power, near 1 GW. In RF heating methods, on the other hand, power can be absorbed over shorter distances. Using RMF_o allows the diameter of the plasma to be reduced to a half meter and produce 1 MW.

In RMF_o heating, the maximum ion energy is proportional to the RMF_o frequency, ω_{RMF} . Due to a constraint set by the RMF -generated current and the FRC’s magnetic field strength, ω_{RMF} decreases as the product of a plasma density times the square of the plasma radius. Thus, too large or dense an FRC is not well heated. An optimum FRC for RMF_o heating of ions to 100 keV and above has a radius in the range 20-30 cm. This places a lower limit on the confinement time required, no worse than a fifth of the classical value, as noted earlier.

Ion heating by RMF_o is highest near the O-point null line, near the center of the plasma’s magnetic axis, where it creates a time-varying azimuthal electric field, [28]. This periodically accelerates ions into betatron orbits and then decelerates them back into cyclotron orbits. Choosing the RMF_o ’s ω_{RMF} and amplitude properly allows ions to be

¹Classical confinement time occurs for Coulomb collision driven diffusion only. The confinement time of real plasma is often far less than the classical limit, [57].

pumped up, repeatedly, to energies near the peak in the D–³He fusion cross-section and then returned to the bulk temperature. This is a conservative process and satisfies the recirculating energy criterion derived by [44] to sustain, against collisions, a non-Maxwellian distribution that increases the fusion rate and decreases neutron production.

In a D–³He plasma, the trajectories of RMF₀-accelerated ions are predicted to form two betatron orbit streams close to the FRC's O-point null line: a D stream and an ³He stream. The deuterium stream ions have half the peak energy of the ³He ions, causing non-zero relative velocity between them. The transverse temperature of each beam is considerably lower than the beam's peak energy, hence deuterium ions collide with each other at a far lower center of mass energy than with ³He; accordingly, the D–D neutron production rate falls and f_p is reduced, [20].

Table 3: 1 MW fusion engine.

Temperatures are approximations for a full non-Maxwellian particle distributions generated and sustained by the RMF₀. The majority of the available electrical power is returned to the RMF₀ to heat the plasma. The vacuum vessel is sized based on the dimensions given below and fashioned from 1/8" stainless steel plating. Heat rejection mass is based on aluminum radiators from [29] and Eq. 10. The RF power generation mass is based on commercially available units from [55].

Parameter	Value
Beta	0.88
Plasma radius	0.25 m
Plasma length	5.0 m
Axial magnetic field	4.7 T
Ion temperature	100.0 keV
e [−] temperature	300.0 keV
Deuterium number density	5.3e+13 cm ^{−3}
³ He number density	1.6e+14 cm ^{−3}
e [−] number density	3.7e+14 cm ^{−3}
<hr style="border-top: 1px dashed black;"/> Masses	
Vacuum vessel mass	800 kg
Magnet mass	260 kg
RF power generation system mass	1050 kg
Heat rejection system mass	385 kg
Thermal power conversion system mass	2200
Shielding mass	1475 kg
Total engine mass	6170 kg
<hr style="border-top: 1px dashed black;"/> Power (Q ≈ 2)	
Fusion power	2.14 MW
RMF ₀ power	1 MW
Bremsstrahlung power	490 kW
Synchrotron power	992 kW
Neutron power	2.59 kW
Waste heat	563 kW
Available electrical power	1.25 MW
Propulsion power	1.13 MW

Further reductions in f_p can be gained from the differential in the energy-dependent fusion rates. As can be seen in Figure 2, if the bulk plasma has an average energy of 70 keV and the RMF₀ pumps the ³He up by 100 keV Figure 2, line *a* then it will pump the deuterium up by only 50 keV, Figure 2, line *b*. Thus, several effects—centrally peaked betatron orbits, low transverse beam temperature, reduced D-to-³He ratio, and higher ³He energy—combine to decrease f_p below 0.2% for an RMF₀-heated D–³He -fueled FRC.

Add to these effects that D–³He fusion produces neutrons that have only one-sixth of the energy of those produced by burning D–T and the larger surface to volume ratio ($\propto 1/\text{radius}$) for a small FRC compared to a large tokamak (20 cm vs. 10 m) and an additional 10,000-fold reduction of neutron power load on the wall is obtained. Overall, the

shielding requirements for this type of small, clean reactor are far less than for a D–T fueled larger fusion engine.

The RMF₀ method, in addition to reducing neutron production, also offers the possibility of a novel, direct energy-extraction method from the fusion products. The same rotating azimuthal electric field that heats the ions can be used to extract energy from the 3.6 MeV alphas and 14.7 MeV protons produced by D–³He fusion. Depending on phase, a maximum of 2/3 of their energy was seen to be extracted in single-particle Hamiltonian simulations. Inclusion of Coulomb scattering or RMF chirping is expected to increase the number of particles participating in this inverse Landau damping process. The reduction in particle energy is caused by an extraction of energy by the RMF₀ antenna. Thus, RMF₀ could provide both a high-efficiency way of extracting energy directly from the charged fusion products and maintain the center of mass ion energy for the D–³He collision near the peak of its reactivity, [42].

Figure 2: Fusion reaction rates (σv) vs center-of-mass energy (E_{cm}) for three sets of collision partners.

At ion energies below 250 keV, the D–³He fusion rate coefficient increases more rapidly with energy than does the DD rate coefficient.

3.3 One Megawatt Reactor System Design

The system design is based on on-going research with the Princeton FRC-2 (PFRC-2) and Magnetic Nozzle Experiment (MNX) at the Princeton Plasma Physics Laboratory. The PFRC-2 machine is shown in Figure 3. Based on 1/5 classical confinement time, a plasma radius of 25 cm is adequate for confining the high energy plasma needed to produce 1 MW of fusion power. This radius matches criteria set by the RMF₀ heating method. Table 3 displays all the design and calculated parameters for the 1 MW reactor, with modest changes in these parameters the fusion power could increase up to 20 MW. The plasma is shaped by the magnetic field: a separatrix divides the closed-field region (CFR) from the open-field region (OFR). Field-shaping coils that are magnetic flux conservers surround the plasma. Between the plasma and inner wall of the chamber is a scrape off layer (SOL). Figure 4 illustrates this magnetic field geometry. The chamber wall is composed of a helium cooling blanket for extracting thermal energy from the Bremsstrahlung radiation, neutron shielding, a medium- or high-Z material for X-ray absorption, and structural support. A cross-section of one realization of the reactor walls is depicted in Figure 5.

3.4 Fuel and Propulsion Subsystem

The fuel subsystem consists of cryogenic tanks, propellant lines, and a fuel heating system. The small amount of ³He needed for such a mission (≈ 0.5 kg, see Table 4) is well within current terrestrial production capability. The liquid deuterium and ³He are heated and converted to gases, injected into the FRC (probably as 10-20 keV neutral beams [14]), and heated to fusion temperatures. Deuterium propellant is pumped through the scrape off layer (SOL), where the fusion products rapidly slow down, exhausting the ash (including any of the undesirable T formed) and heating the SOL, increasing the thrust.

Figure 3: The Princeton Field-Reversed Configuration 2 device at the Princeton Plasma Physics Laboratory.
The current machine features a number of field shaping coils (white) that act as flux conservers, positioned axially along the reaction chamber.

3.5 Startup

Chemical combustion will be used to produce the power necessary power for starting the reactor. A few kilograms of H_2 , which produce 142 MJ each when combined with O_2 , is enough for start up. The power released from this reaction is injected the plasma, energizes the superconducting coils, and heats the plasma through the RMF_o system. The heat engine and incorporated generator would be used with this additional heat source.

Figure 4: Fusion propulsion system layout.

The magnetic field is shaped by field-shaping coils and axial field coils to form an ellipsoidal closed-field region (CFR) and an open-field region (OFR), between which lies the separatrix. The fusion reaction occurs round the O-point null line, in the CFR, and the products are ejected into the SOL. Propellant is injected into the gas box and flows through the SOL where it gets heated by the fusion products. The heated propellant flows out the nozzle coil and forms an exhaust plume, with ion energy E_i .

3.6 RMF_o Heating

The RMF_o heating system generates RF power proportionally to the 3He cyclotron frequency, such that

$$\omega_{RMF} = \alpha \omega_{ic} = \alpha \frac{ZeB}{m} \quad (4)$$

where Z is the atomic number, B is the magnetic field, e is the elementary charge, m is the mass of the ion, and $0.01 \leq \alpha \leq 0.1$. Given the axial magnetic field from Table 3, the ion cyclotron frequency for 3He is 61.6 MHz and a 0.6–6 MHz generator will be required.

The RF subsystem consists of the RF generator, coaxial cables, directional couplers, tank circuits, antennas, and RF diagnostics. The RF system must produce enough power to start and sustain the fusion reactions. When the fusion reactor is operating, smaller amounts of RF power are needed because fusion products provide some heating and current drive. The RF generator must produce power with high efficiency; most commercial units operate around

Figure 5: One megawatt reactor cross-section.

The outer edge of the magnetic fields (B) in the core plasma are surrounded by the SOL and a thin vacuum layer. Neutron shielding and the heat exchanger system protect the magnet coils, vacuum vessel, and RMF₀ antenna from radiation damage.

90%, [55]. This is accomplished by operating the power device as a saturated switch. The PFRC-2 has a 200 kW RF system and we estimate a peak startup RF power of 2 MW and continuous power of 1 MW will be required for the reactor to produce 2 MW of fusion power.

3.7 Superconducting Flux Conservers

Radial confinement is achieved by the coaxial solenoidal field-shaping coil array, commonly termed flux conservers (FCs), which can be seen in Figure 3. FCs are superconducting rings, approximately evenly spaced along the reactor length. The FCs in the PFRC-2 employ high-temperature superconducting materials set in a liquid nitrogen cooled copper mandrel. For a full discussion on the design, construction, and testing of the PFRC-2's FCs, see [39].

3.8 Reactor Chamber and Shielding

Even though $D-^3He$ is an “aneutronic” fuel, one of its $D-D$ side reactions produces 2.45 MeV neutrons. As the chamber is subjected to neutron bombardment, it becomes susceptible to several distinct changes in its material properties. The microstructure is altered such that it becomes up to five times stronger in tensile strength when exposed to MeV neutrons. However, at the same time, this process introduces weakness in the material as it becomes more brittle and prone to cracks and associated damage. Furthermore, the structure also experiences swelling as the atoms are structurally displaced to form voids in the material. In designing the reactor chamber, measures must be taken to promote fracture resistance and accommodate the dimensional alterations that occur given the neutron irradiation, [17]. Many of these shortcomings can be resolved with appropriate shielding. The low- Z material $^{10}B_4C$ strongly moderates neutron energies and attenuates their flux by absorption. $^{10}B_4C$ is a very sturdy, stable solid over a very large range of temperatures that is readily available in nature, safe to manufacture, inexpensive, and it does not exhibit any obvious structural deformities when irradiated. Since it is transparent to X-rays, Bremsstrahlung radiation can pass through it to a thermal power conversion system. To verify boron carbide numerically, Monte-Carlo simulations were performed assuming isotropic and forward scattering per [8] and using total and absorption cross-section results from MCNP and JEFF3.1[2]. Particles were tracked until reflection or absorption. The simulation found that less than 20 cm of $^{10}B_4C$ shielding would be required to protect the electronics from exposures in excess of one year.

X-ray shielding is also required to absorb stray Bremsstrahlung radiation that is not captured by the thermal power conversion system described in Section 3.8. Tungsten is one of the best attenuators on a per mass basis ([34]) and meets many of the material requirements for shielding including availability, manufacturability, and high temperature capabilities. We calculate that the Bremsstrahlung has a maximum energy of ≈ 150 keV and the transmitted power is given by

$$I = I_o \exp^{-\alpha t_m} \quad (5)$$

where I_o is the initial power, α is the measured attenuation coefficient and t_m is the so-called mass thickness, *i.e.* density $\times$ shield thickness. Tungsten at 150 keV has an $\alpha = 1.389 \text{ cm}^2/\text{g}$, therefore a million fold reduction in X-ray radiation would require a 0.64 cm thick shield. [30]

Figure 6: Magnetic nozzle coil configuration.

The throat and nozzle coils allow the magnetic field lines to shape the weakly-ionized propellant into an efficient exhaust plume.

3.9 Thermal Power Conversion

As noted above, it is possible to extract energy from the plasma using the RF system. Thermal power from synchrotron and Bremsstrahlung radiation can also be converted to electrical power using a Stirling cycle power generation system, [25]. Studies show that it has the best specific power of all thermal energy conversion systems. Other options are using a Brayton cycle ([36]) and direct conversion methods ([5]). At the temperatures of interest, the Brayton cycle appears to have a lower specific power and direct conversion methods have much lower efficiencies. The Bremsstrahlung can be efficiently removed by flowing helium gas through $^{10}\text{B}_4\text{C}$ heat exchanger tubes containing corrugated sheets of refractory medium-Z material ([24]). The Bremsstrahlung heats the high-Z materials to about 2000 K. A helium coolant extracts this energy and is used to drive a high-efficiency thermal cycle. With a thermal rejection temperature to space of 625 K, this results in a Carnot efficiency, η_C , of 69%, [19].

3.10 Magnetic Nozzle and Thrust Augmentation

The magnetic nozzle and thrust augmentation system allow directional control of the plasma and control of the thrust level and exhaust velocity. A magnetic nozzle, as described by [7], [54], and [21], redirects the flow from the FRC to free space. The nozzle consists of a throat coil and two or more additional nozzle coils to allow expansion and acceleration of the flow. Like the FCs, all the coils are superconducting but the radii of the magnetic nozzle coils are smaller than those of the FC, as can be seen in Figure 6. Magnetic nozzles have been found to be highly efficient, especially with weakly magnetized propellants, with $\eta_{\text{plume}} > 85\%$ in [35].

Thrust is increased by the addition of propellant, increasing mass flow and thrust at the expense of specific impulse, [47]. A suitable propellant would be deuterium, which would be injected as a cold gas into the gas box and from there enter the open-field region. The gas would be ionized quickly, forming a plasma similar to what is called, in tokamak terminology, a high recycling divertor, or even a detached plasma. The cold plasma will flow around the outside of the separatrix with electrons picking up energy from the fusion products and synchrotron radiation as it passes through the OFR. The shell plasma thus formed and heated will be quite similar to that already produced in gas dynamic traps, [6], having a density near $0.1 - 5 \times 10^{14}$ per cc and an electron temperature of 30–300 eV. The ions will be cooler. As the plasma leaves the reactor, acceleration of the ions to an energy 4–8 times the electron temperature will occur in a double layer near the nozzle throat, [21]. Within a few centimeters beyond the nozzle throat, the propellant will have acquired the desired 0.2–1.2 keV energy. Within the detached plasma regime, UEDGE simulations have shown efficiencies of at least $\eta_T=0.8$ for propellant flow from the gas box to the nozzle for our configuration, [15].

4 Example Mission

The DFD's performance was simulated in the context of a mission to deploy the James Webb Space Telescope in a 770,000 km halo orbit around the Sun–Earth L2 point, [27]. The spacecraft acts as a ferry and returns to low earth orbit for restocking and refueling and then can be re-used on further missions, including servicing the telescope. The design parameters of the spacecraft required for this mission are derived from the equations below and are listed in Table 4.

Table 4: Spacecraft design parameters.

The payload mass is for the James Webb Space Telescope. kW_e is the electrical power that needs to be processed by the thermal power conversion system.

Parameter	Symbol	Value
Payload Mass	m_p	6200 kg
Total Dry Mass	m_d	12370 kg
Total Fuel & Propellant Mass	m_f	353 kg
^3He Mass	m_{He}	0.53 kg
Specific mass of cooling system	M_r	1.76 kg/kW _e
Specific mass of fuel	σ_f	0.03 kg/kg
Specific power	α_p	0.18 kW/kg
Thrust	T	40 N
Exhaust velocity	u_e	56.5 km/s

The exhaust stream power required by the spacecraft to make this journey is

$$P = \frac{1}{2} T u_e \quad (6)$$

where P is power, u_e is the exhaust velocity, and T is the thrust [43]. As can be seen, given a constant power, the thrust and exhaust velocity can be traded against each other for mission optimization.

Figure 7: DFD-powered spacecraft carrying the James Webb Space Telescope.

The reactor is attached to the telescope by a pylon. The deuterium tanks, located between engine and the telescope, protect the latter from stray neutron radiation. The total engine length shown includes the propellant tanks.

Trajectory optimization depends on the rocket equation and propellant mass flow to calculate the fuel dynamics. The propellant mass flow is

$$\dot{m} = \frac{T}{u_e} \quad (7)$$

or in terms of power

$$\dot{m} = \frac{2P}{u_e^2} \quad (8)$$

where $\dot{m}$ is the rate at which mass is exhausted. The rocket equation is

$$\frac{m_d + m_f}{m_d} = \exp\left(\frac{\Delta u}{u_e}\right) \quad (9)$$

where m_d is the dry mass, m_f is the mass of the fuel, and Δu is the total required velocity change. The dry mass consists of the reactor, payload, and fuel tanks. The fuel tank size can be found iteratively using this equation's solution for fuel mass.

The radiator must be able to reject heat from the non-ejected fusion products, Bremsstrahlung radiation, and neutrons, where

$$P_{\text{heat}} = (1 - \eta_C)\left((1 - \eta_T)P_{\text{fusion}} + P_{\text{Bremsstrahlung}} + P_{\text{Synchrotron}} + P_{\text{Neutrons}}\right) \quad (10)$$

where P_x is the power from a given source and η_C and η_T are, respectively, the Carnot and thrust efficiencies from Section 3. Given the specific mass of the cooling system in Table 4 from [25], the mass of the total cooling system is calculated in Table 3. The radiators can be sized using the Stefan-Boltzman law, an emissivity (ϵ) of 0.86 as given in [29], with the Stefan-Boltzmann constant σ_{SB} , and a rejection temperature, $\mathcal{T}$, of 625K, the radiator surface area, A , is given by

$$A = \frac{P_{\text{heat}}}{\epsilon \sigma_{\text{SB}} \mathcal{T}^4} = 77 \text{ m}^2 \quad (11)$$

The available power and other key mission parameters are found in Table 4. For any particular total Δu there will be an optimal u_e that minimizes the mission mass, which can be easily found from the above equations. A conception of the spacecraft with the JSWT is shown in Figure 7.

An example trajectory is shown in Figure 8. This trajectory is simulated in a non-dimensional, circular restricted three-body problem for the Sun–Earth/Moon system. A baseline delta- v of 3.1 km/s is required for a spacecraft initialized in a GPS orbit with low eccentricity, with an additional 3.6 km/s required if starting from LEO. Additional work on the trajectory optimization and use of lunar gravity assist may reduce the required delta- v . Thrust is applied for approximately 11 days in a direction normal to the plane defined by the Earth-relative position vector and the orbit-normal vector. This causes the spacecraft to gradually increase the altitude of its Earth orbit as well as its eccentricity, spiraling out until it escapes Earth gravity. This is followed by a coast arc of nearly a week and then a 14 hour insertion burn occurs, decelerating the craft and allowing it to coast into a weakly stable halo orbit about L2 after 37 days. This trajectory was simulated with multiple iterations, adjusting the thrust to control mission duration, and changing the fuel mass and associated dry mass according to equation (8) until the required Δu was feasible.

5 Conclusions

We have presented the design for the Direct Fusion Drive based on the field-reversed configuration and RMF₀ heating, using D–³He reaction as an energy source. As an example, we presented a mission from GPS orbit to a Sun–Earth L2 halo orbit. Many of the key physics principles involved have been separately demonstrated. There still remain a number of questions regarding the operation and stability of the reactor, which we hope to answer with future PFRC and MNX experiments. The size, mass ratio, specific power, and thrust make the DFD an attractive option for longer missions, such as to Mars, and crucial for allowing safer and faster manned interplanetary missions.

Figure 8: LEO to Sun-Earth L2 halo orbit trajectory for the DFD-powered spacecraft.

This trajectory requires a Δu of 3.1 km/s from an initial altitude of 20,232 km. If the spacecraft was launched from LEO instead, the mission would require an extra Δu of 3.6 km/s and 13.8 days for the outbound spiral.

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Vitae

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