Direct Fusion Drive for a Human Mars Orbital Mission

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The Direct Fusion Drive (DFD) is a 1-10 MW nuclear fusion engine that produces both thrust and electric power. It employs a field reversed configuration with an odd-parity rotating magnetic

field heating system to heat the plasma to fusion temperatures. The engine uses deuterium and helium-3 as fuel and additional deuterium that is heated in the scrape-off layer for thrust augmentation. In this way variable exhaust velocity and thrust is obtained.

This paper presents the design of an engine for a human mission to orbit Mars. The mission uses NASA's Deep Space Habitat to house the crew. The spacecraft starts in Earth orbit and reaches escape velocity using the DFD. Transfer to Mars is done with two burns and a coasting period in between. The process is repeated on the return flight. Aerodynamic braking is not required at Mars or on the return to the Earth. The vehicle could be used for multiple missions and could support human landings on Mars. The total mission duration is 310 days with 30 days in Mars orbit. The Mars orbital mission will require one NASA Evolved Configuration Space Launch System launch with an additional launch to bring the crew up to the Mars vehicle in an Orion spacecraft.

The paper includes a detailed design of the Direct Fusion Drive engine. The engine startup/restart sys- tem and shielding are discussed. The computation of the specific power for the engine is presented along with a full mass budget for the engine. The paper includes the trajectory design and mission simulations.

I. INTRODUCTION

Human missions to the planets have been planned since before the engine of the Apollo program in the early 1970's. At that time the most advanced propulsion option was nuclear fission thermal rockets which heat hydrogen flowing through a reactor core. Several of these engines were tested in the late 1960's and early 1970's, before the fission engine programs were cancelled.

Recent work reports that the radiation data the Curiosity rover collected on its way to Mars found "astro-nauts traveling to and from Mars would be bombarded with as much radiation as they'd get from a full-body CT scan about once a week for a year." [1]. Add to that the harmful effects of muscle atrophy from long-term low-gravity, and mission speed becomes a clear priority to ensure the crew's health. Consequently, chemical or nuclear thermal rocket transfers would not be sufficient for human exploration to Mars and more distant destinations. The DFD powered transfer stage can get astronauts to Mars in months, significantly reducing radiation exposure and atrophy effects.

To demonstrate the potential of DFD technology, we

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developed a concept for a Mars orbital mission that uses NASA's Deep Space Habitat to house the crew [2]. Previous work demonstrated its capability for asteroid deflection [3], the robotic missions [4, 5], missions to the outer planets [6] and interstellar missions [7].

With a variable thrust augmentation system, the DFD allows for power generation up to 10 MW, which is ideal for interplanetary exploration. The Orion spacecraft would launch the astronauts into low Earth orbit where it would dock with the DFD transfer vehicle. The baseline vehicle is shown in Figure 1 docked with the Orion. It has five 6 MW engines. This provides redundancy and an abort capability in case of an engine failure. The engines provide both propulsion and electric power during the mission.
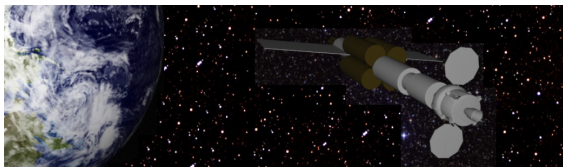

Figure 1: Orion spacecraft docked with the Deep Space Habitat on the DFD transfer vehicle.

II. DIRECT FUSION ENGINE DESIGN

Overview

he Princeton Field-Reversed Configuration Reactor (PFRC-R) would be a 2 m diameter, 10 m long, steady-state plasma device heated by a novel radio-frequency (RF) plasma-heating system, enabling the achievement of sufficiently high plasma temperatures for $D-^3He$ fusion reactions. An FRC employs a linear solenoidal magnetic-coil array for plasma confinement and operates at higher plasma pressures, hence higher fusion power density for a given magnetic field strength than other magnetic-confinement plasma devices. A linear solenoid is well-suited for producing a collimated directed exhaust stream that may be used for propulsion. A rocket engine based on the PFRC is designed to operate with a $D-^3He$ fuel mixture though, for decade-long missions, it may be operated with a tritium-suppressed D–D fuel cycle. Both fuels produce much lower levels of neutrons than deuterium-tritium, reducing shielding mass as well as waste energy unavailable for propulsion. In the PFRC-R, waste heat generated from bremsstrahlung and synchrotron radiation will be recycled through the RF system to maintain the fusion temperature. The features of this design are:

1. Odd-parity rotating magnetic field (RMF) heating for high stability and efficient heating

2. Non-equilibrium operation for reduced neutron production

3. Can operate with $D-^3He$ or tritium-suppressed D–D

4. Electric power extraction through the RMF coils

5. Combined thrust and electric power generation

6. Variable specific impulse and thrust through deuterium augmentation in the scrape-off layer

7. High temperature superconductors for plasma confinement and the magnetic nozzle that result in drastically reduced cooling requirements

8. Engines are from 1-10 MW in size which is an ideal range for space power and propulsion

9. Multiple engines can be combined to produce higher levels of thrust and power

Reactor

An important figure-of-merit for fusion reactors is β, the ratio of the plasma pressure to the magnetic energy density. Of all candidate magnetic-confinement fusion reactors, FRCs have the highest β, see [8] for a review of early FRC research. Accordingly, FRC magnets would be less massive than those for a tokamak of comparable power. High β is essential for burning aneutronic fuels, such as $D-^3He$, because they require higher ion energies to achieve the same fusion reactivity as D–T. FRC plasma-confinement devices have at least two other attractive features, notably, a linear magnet geometry [8] and a natural divertor. This structure provides an ideal attachment point for a magnetic nozzle, allowing for the control of the plasma exhaust and its plume angle, for use as a propulsive or power-producing device. The FRC is unique among quasi-toroidal, closed-field-line magnetic confinement devices in that it is simply connected. FRCs also have zero toroidal magnetic field, no internal conductors, and a line of zero magnetic field strength within the plasma encircling its major axis, termed the O-point null line. This O-point null line proves essential for our proposed method of RF plasma heating. Figure 2 on the next page shows the FRC's magnetic-field structure and the linear coil array. A separatrix divides a closed-field region (CFR) from the open-field region (OFR). Field-shaping coils that are magnetic flux conservers surround the plasma. The O-point null line, not shown, is a co-axial ring located on the magnetic axis, the center of the nearly elliptical CFR.
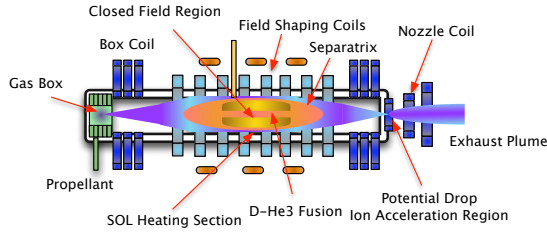
Figure 2: DFD Core showing the details of the PFRC reactor and the linear path of the propellant flow.

The reactor design we propose differs from that of Cheung [9] in size, heating method, and fuel. Cheung *et al.* selected p–^{11}B, which requires five-times higher ion energies and produces far less fusion power *per* reaction. Cheung *et al.* selected neutral beams for heating, requiring a plasma volume that is one hundred times larger, is therefore more costly and less stable. The heating technique selected in Miller [10] is called an even-parity rotating magnetic fields (RMF$_e$) [11], a method that has shown poor energy confinement, and requires larger FRCs. FRCs where the plasma radius is more than 10 times their ion Larmor radius are prone to magnetohydrodynamic (MHD) instabilities. To achieve better energy confinement, we instead invented odd-parity RMF, RMF$_o$, allowing for smaller, more stable reactors.

Many physics challenges remain before the RMF$_o$-heated FRC can be developed into a practical reactor. The predictions of excellent energy confinement and stability and of efficient electron and ion heating 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 [12, 13]. (Classical confinement time occurs for Coulomb-collision-driven diffusion only. The confinement time of real plasma is often far less than the classical limit [14].) Our reactor needs energy confinement only $1/5$ as large as the classical. In 2007, an RMF$_o$-heated FRC [15] achieved stable plasma durations 3,000 times longer than predicted by MHD theory [16]; by 2012 that record was extended to over 10^5 times longer. Finally, theoretical studies [17, 18, 19] 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.

Based on $1/5$-classical-confinement, 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 RMF$_o$ heating method. Modest changes in parameters could increase the fusion power up to $\approx$10 MW. Figure 3 shows the PFRC-2 experiment at PPPL. The black wires are the diamagnetic loops. The vessel is made of Lexan. The BN-covered superconducting flux conserving coils are visible in the interior.
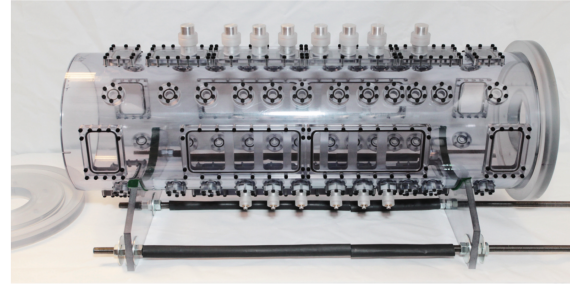

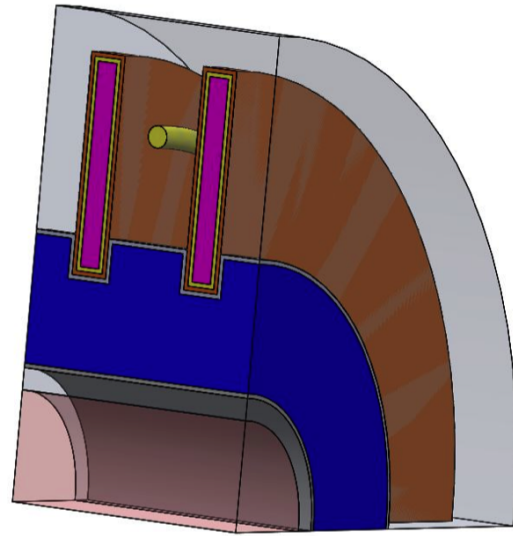**Figure 3:** PFRC-2 experimental reactor.

Engine Design

Table 1 on the next page gives the engine design for the DFD transfer vehicle. The table includes the mass of each subsystem, the power balance and plasma parameters. Other subsystems are summarize. More details are given in [3, 4, 5, 6, 7].

Table 1: DFD transfer vehicle engine design

Parameter	Value	Units
Gain	1.29	
Beta	0.88	
Radius plasma	0.25	m
Length plasma	5.00	m
Magnetic field	4.4	T
Temperature D	100.0	kEV
Temperature He3	100.0	kEV
Temperature e-	30.0	kEV
Number density D	7.10e+19	
Number density He3	2.10e+20	
Number density e-	4.91e+20	
Specific power	0.88	kW/kg
Mass		
Mass heating	2206.97	kg
Mass magnet	304.6	kg
Mass power generation	402.87	kg
Mass radiator	224.67	kg
Mass refrigerator	30.57	kg
Mass shield	780.50	kg
Mass total	3950.19	kg
Power		
Power bremsstrahlung	1.49	MW
Power fusion	5.70	MW
Power heat loss	1.85	MW
Power heating	4.41	MW
Power net	5.69	MW
Power neutrons	0.013	MW
Power recycled	4.03	MW
Power synchrotron	0.35	MW
Power thrust	3.47	MW

Figure 4: Shielding.

The shielding system was analyzed using Attila, a particle simulation code that solves problems in space, angle and energy. Research to date has only included neutrons from D-D reactions. There will also be neutrons from D-T reactions (as T is formed by one branch of the D-D reactions.

Startup Power

Chemical combustion will be used to produce the power necessary power for starting the reactor. A few kilogramsof H_2, which produce 142 MJ each when combined with O_2, is enough for start up. The power released from thisreaction is injected the plasma, energizes the superconducting coils, and heats the plasma through the RMF_o system. The startup system needs to run for approximately 10 seconds. The heat engine and incorporated generator would be used with this additional heat source. The O_2 would be recovered through electrolysis if necessary. During the mission if one engine shuts down, one of the other engines would be used to startup the shutdown reactor.

III. SPACECRAFT DESIGN

Overview

The Mars Transfer Vehicle with a docked Orion capsule is shown in Figure 4. The module to which the Orion is docked is the NASA Deep Space Habitat shown in Figure 5.

Shielding

The shielding system uses a 0.64 cm thick layer of tungsten to absorb the bremsstrahlung x-rays and a 20 cm layer of $^{1}0B_4C$ for neutron shielding. The heat from the bremsstralung is absorbed by helium gas flowing past the tungsten. The tungsten would reach a temperature of 2000 deg-K and ultimately be rejected to space by the radiators at 625 deg-K. Figure **??** on page ?? shows the shielding geometry.

Figure 5: Mars transfer vehicle.

Configuration

Figure 6: NASA Deep Space Habitat

Mass Budget

Table 2 gives the mass budget for the DFD transfer vehicle.

Table 2: DFD transfer vehicle mass budget

Component	Mass	Units
Orion.obj Subsystem Total	1.535e+04	kg
ECLS Subsystem Total	3.988e+04	kg
Propulsion Subsystem Total	8.981e+04	kg
Telemetry and Command Subsystem Total	14.62	kg
Miscellaneous Subsystem Total	1700	kg
Total	1.468e+05	kg

IV. MISSION DESIGN

Launch

The Mars mission uses the NASA Space Launch System for launch into low Earth orbit. NASA's Space Launch System is an advanced, heavy-lift launch vehicle which will provide an entirely new capability for science and human exploration beyond Earth's orbit. The SLS has two variants, 70 MT and 130 MT. The Mars orbital mission will require one 130 MT SLS launch, as the spacecraft weighs 129 MT. A separate launch brings the crew to the spacecraft in an Orion spacecraft. On-orbit testing and checkout is done prior to the arrival of the crew.

Earth/Mars Transfer

The round-trip mission to Mars, with a spacecraft powered by DFDs and carrying NASA's Deep Space Habitat, involves two orbit transfers which involve a long burn, a coasting period and another long burn. The spacecraft enters and departs Earth and Mars orbits using the DFD. No aerodynamic braking is required.

This double-rendezvous problem typically requires waiting for a full synodic period (i.e. the next time the two planets return to their current alignment), which is 780 days for Earth and Mars. The goal, however, is to make this roundtrip as quickly as possible. Therefore, the new roundtrip trajectory takes a "short-cut" of sorts, traveling inside Earth's orbit on the return flight. This enables the overall mission to be shortened to just 310 days, including a 30 day stay at Mars. The trajectory is shown in Figure 7.
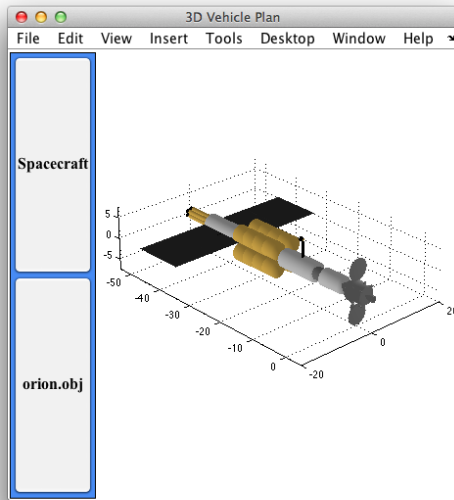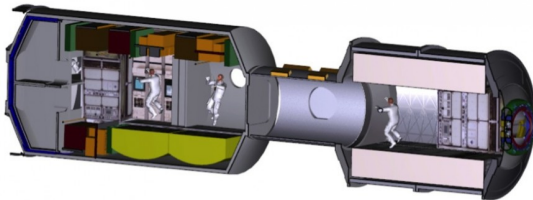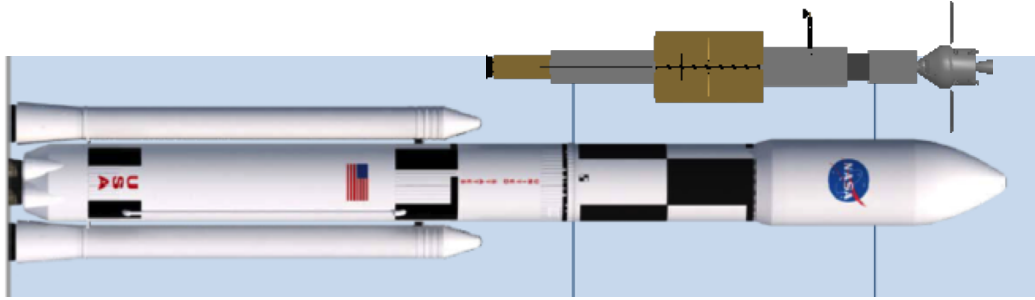
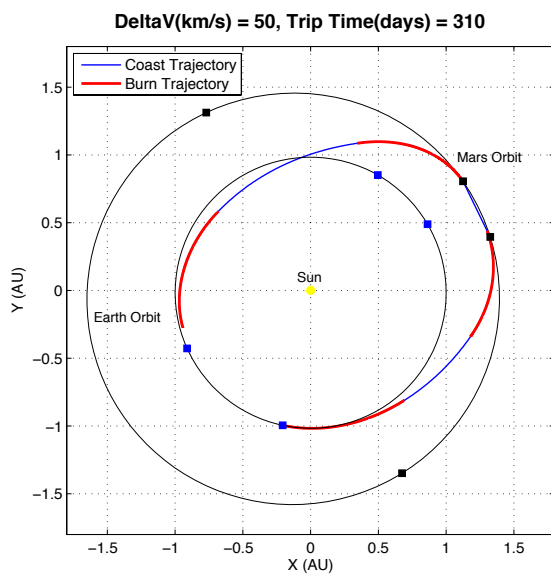**Figure 7:** SLS 130 MT variant with the Mars spacecraft superimposed.

Figure 8: A round trip mission to Mars takes only 310 days including 30 days in Mars orbit.

V. CONCLUSION

Direct Fusion Drive permits a high scientific return human mission to Mars Orbit in the 2030 time frame. The DFD transfer vehicle would form the basis of future space transportation as shown in Figure 8 on page 7. A terrestrial test engine could be in operation within 12 years at a cost of $76M USD, which is comparable to the cost of a single RTG.

REFERENCES

[1] Chang, A., "Astronauts face radiation threat on long Mars trip," *AP*, May 2013.

[2] Gebhardt, C., "Delving Deeper into NASA's DSH configurations and support craft," April 2012.

[3] Mueller, J., Knutson, A., Paluszek, M., Pajer, G., Cohen, S., and Glasser, A. H., "Direct Fusion Drive for Asteroid Deflection," No. IEPC-2013-296, October 2013.

[4] Paluszek, M., Thomas, S., Razin, Y., Cohen, S., and Farley, D., "Direct Fusion Drive for Advanced Space Missions," September 2001.

[5] Razin, Y., Paluszek, M., Hamand, E., Pajer, G., Mueller, J., Cohen, S., and Glasser, A. H., "Compact Aneutronic Fusion Engine," October 2012.

[6] Pajer, G., Razin, Y., Paluszek, M., Glasser, A., and Cohen, S., "Modular Aneutronic Fusion Engine," *Space Propulsion 2012*, AAF-EAS-CNES, 2012.

[7] Paluszek, M., Hurley, S., Pajer, G., Thomas, S., Mueller, J., Cohen, S., and Welch, D., "Modular Aneutronic Fusion Engine for an Alpha Centauri Mission," September 2011.

[8] Tuszewski, M. A., "Field Reversed Configurations," *Nuclear Fusion*, Vol. 28, No. 11, November 1988, pp. 2033.

[9] Cheung, A., Binderbauer, M., Liu, F., Qerushi, A., Rostoker, N., and Wessel, F. J., "Colliding Beam Fusion Reactor Space Propulsion System," *Space Technologies and Applications International Forum*, No. CP699, 2004.

[10] Miller, K., Slough, J., and Hoffman, A., "An Overview of the Star Thrust Experiment," *Space technology and applications international*
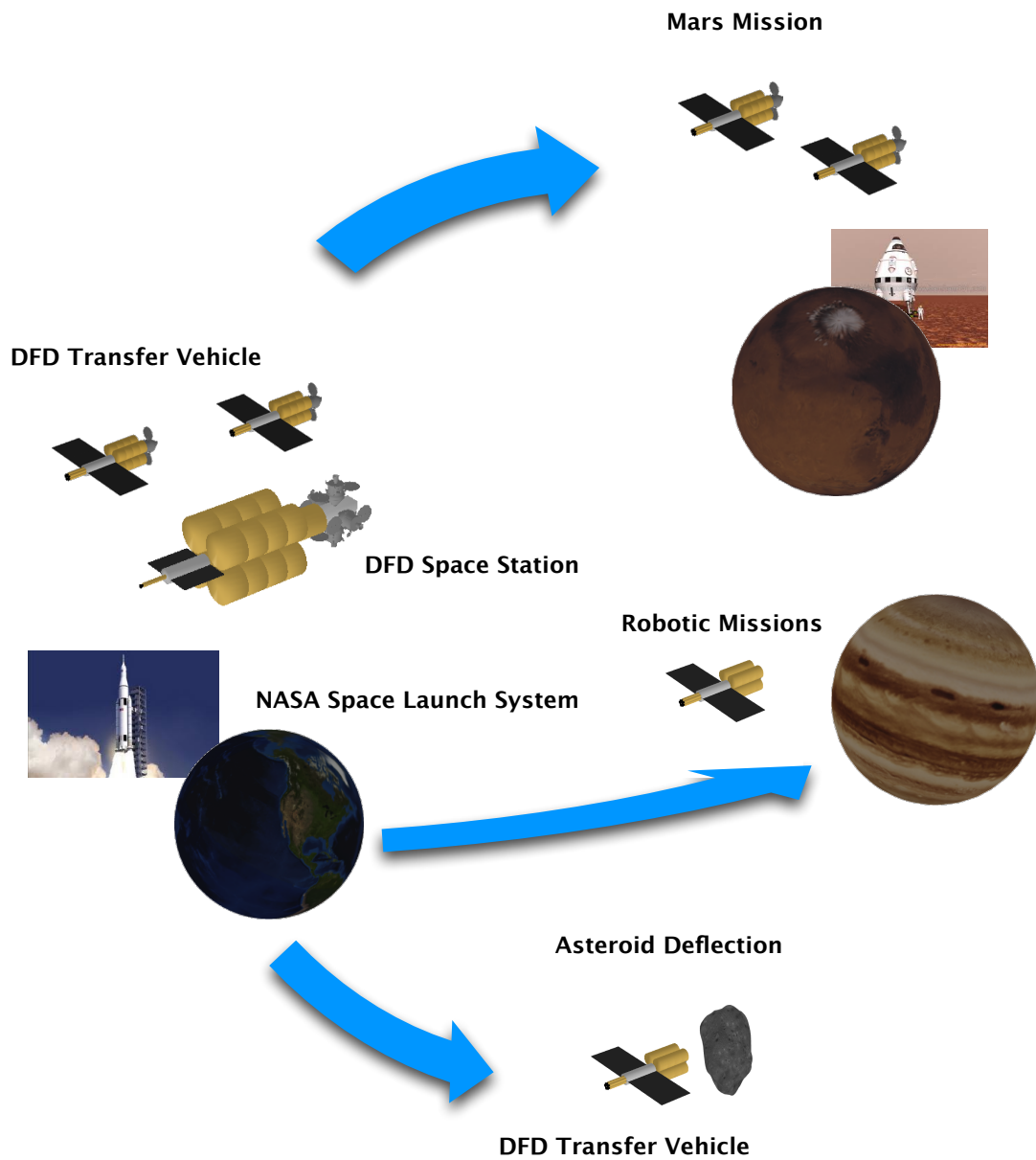
Mars Mission

DFD Transfer Vehicle

DFD Space Station

Robotic Missions

NASA Space Launch System

Asteroid Deflection

DFD Transfer Vehicle

Figure 9: Direct Fusion Drive will open space to new avenues of exploration and rapid industrialization.

forum, Vol. 420, AIP Conference Proceedings, http://depts.washington.edu/rppl/programs/stx.pdf, 1998, pp. 1352–1358.

[11] Blevin, H. and Thonemann, P., *Nuclear Fusion Supplement*, Vol. 1, 1962, pp. 55.

[12] Binderbauer, M., Guo, H. Y., M.Tuszewski, Putvinski, S., Sevier, L., and Barnes, D., "Dynamic Formation of a Hot Field Reversed Configuration with Improved Confinement by Supersonic Merging of Two Colliding High-Compact Toroids," *Physical Review Letters*, Vol. 105, 2010, pp. 045003.

[13] Tuszewski, M., Smirnov, A., and Thompson, M., "Field Reversed Configuration experiment through edge-biasing and neutral beam injection," *Physical Review Letters*, Vol. 108, No. 255008, June 2012.

[14] Wesson, J., *Tokamaks*, Oxford Univ. Press, Oxford, 3rd ed., 2004.

[15] Cohen, S. A., Berlinger, B., Brunkhorst, C., Brooks, A., Ferarro, N., Lundberg, D., Roach, A., and Glasser, A., "Formation of Collisionless High-β Plasmas by Odd-Parity Rotating Magnetic Fields," *Physical Review Letters*, Vol. 98, 2007, pp. 145002.

[16] Rosenbluth, M. N. and Bussac, M. N., "MHD Stability of Spheromak," *Nuclear Fusion*, Vol. 19, 1978, pp. 489.

[17] Glasser, A. and Cohen, S. A., "Ion and electron acceleration in the Field-reversed configuration with an odd-parity rotating magnetic field," *Physics of Plasmas*, 2002, pp. 2093–2102.

[18] Landsman, A. S., Cohen, S. A., and Glasser, A., "Onset and saturation of ion heating by odd-parity rotating magnetic fields in an FRC," *Physical Review Letters*, Vol. 96, 2006, pp. 015002.

[19] Cohen, S. A., Landsman, A. S., and Glasser, A., "Stochastic ion heating in a field-reversed configuration geometry by rotating magnetic fields," *Physics of Plasmas*, Vol. 14, 2007, pp. 072508.