Magnetic Fusion Engine

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A new concept for an interplanetary and interstellar missions is discussed, which is based on a compact spherical tokamak fusion reactor and can potentially revolutionize human space flights by providing safe and affordable in-space transportation.

The goal of this paper is an assessment of the concept employing the recent advances in fusion research. This concept, in contrast to other fusion concepts, utilizes the natural drift motion of charged particles in order to create a directed flux of energetic particles. The momentum of either energetic positive particles or fusion neutrons can be used either directly for propulsion or to heat the hydrogen propellant.

One-way trip times are expected to be on a short time scale, such as one to three months for the trip to Mars. Both the exhaust velocity and thrust of the engine may be modulated. This permits the engine to be optimized for a wide variety of missions.

Nomenclature

β	The ratio of plasma pressure to magnetic field pressure
ϵ	Inversed aspect ratio of tokamak plasma
$\langle p \rangle$	The averaged plasma pressure
σ_{DT}	The cross section of DT fusion reaction
τ_E^*	The energy confinement time
τ_E^L	The energy confinement time in LiWall (or Low recycling) regime
$f_{tritium}$	The fraction of tritium burned in the reactor
$k_{recycle}$	Recycling coefficient
n_D	The plasma deuterium density
P_α	The fusion α-particle power
P_{DT}	The total fusion power
P_{NBI}	The external heating beam power
T	Plasma temperature
V	The plasma volume
v_i	The thermal velocity of plasma ions

Subscripts

core	Value taken at the core of the plasma
edge	Value taken at the edge of the plasma
pl	The background plasma

I. Introduction

RECENT advances in fusion research may help to solve key problems that have previously slowed the development of fusion energy devices. Some of them are (*i*) the stabilizing effect of a liquid lithium wall,

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(*ii*) (as a result) the potentially almost complete burn-up of tritium in a deuterium tritium (DT) tokamak with lithium walls, and (*iii*) the use of magnetic field ripples to substantially reduce the fusion alpha particle population in the plasma in order to enhance the reactor efficiency. The latter has been recently suggested to be used as a source for direct plasma thrust in the tokamak fusion engine in Ref.[1] In this paper we further explore and give more detailed outline of a space thruster based on the spherical tokamak reactor, which would enable manned Mars exploration by permitting fast manned missions to Mars that would solve the problems of excessive cosmic radiation exposure and bone deterioration due to otherwise excessive time at zero-gravity. In addition, the high power thruster would provide an abort capability at any point during the mission, which is not possible with any other form of propulsion. The engine could also be applicable to Earth orbit transfer missions and replace all upper stages in use today. In addition, a burning plasma reactor can be realized at a power level as low as $0.5GW$ greatly reducing the development cost of the initial flight article.

The point design for Earth orbit and inner planet missions is a DT fusion spherical tokamak reactor that produces a nominal $2000N$ thrust with an exhaust velocity of $50km/s$. The thrust is produced using fusion alpha particles and other energetic ions ejected from the plasma through ripples in the magnetic field. This exhaust is mixed with hydrogen to achieve the required thrust and exhaust velocity. The thrust and exhaust velocity can be varied by changing the ratio of hydrogen to alpha particles making this engine suitable for all solar system missions. Current estimates show that the specific power of $1kW/kg$ can be expected, which is substantially better than nuclear fission or solar electric systems. A manned Mars mission with a crew of 6 and a 16.5 metric ton rover is presented using the magnetic fusion engine (MFE) as the propulsion system. The 452 metric ton spacecraft makes the round trip in 100 days, including a 30 day stay on the surface.

II. Introduction to Alternative Fusion Engines

Numerous conceptual designs for fusion thrusters have been developed. This section discusses several of these concepts. Initial work focused on open configurations such as magnetic mirrors partly because they look like thrusters. More recent work has focused on novel geometries and closed magnetic field configurations.

A major issue, besides achieving fusion, is exhausting the power. If it is done with the charged particles, they will tend to spiral around the magnetic field lines. In an open field configuration, such as a mirror machine, the particles will follow the field lines and may hit the vehicle on the other end resulting in no net force. For a fusion thruster to work, the charged particles must be neutralized. There are two issues. One is whether both ions and electrons leave the reactor so that the output is a plasma, as opposed to a charged particle, stream. The second is to get the ions and electrons to recombine. Work on magnetic nozzles has been ongoing to demonstrate recombination in the nozzle.[2] If only ions leave the reactor this problem becomes particularly significant in designs with very high exhaust velocities where the plasma makes up the entire exhaust stream.

An extensive and thorough review of fusion propulsion was done by Romanelli, Bruno and Regnoli[3] (see also[4] and a discussion in[1]). Reported specific powers range from 0.6 kW/kg for generic D-T fusion to 400 kW/kg for Magnetized Target Fusion. But most fall in the range of 1-10 kW/kg.

Alternative fusion engine concepts are:

1. Levitated dipole
2. Spherical tokamak with poloidal divertor
3. Gas dynamic mirror
4. Magnetic Target Fusion with plasma beams
5. Pulsed high density fusion rocket
6. Magnetic Target Fusion with liner implosion

These concepts are discussed in the following sections. Concepts 4-6 make use of the plasma field-reversed configuration (FRC). The field-reversed configuration is a compact plasma torus with little or no toroidal field.[5] It has a compact and simple geometry, translation properties, and high plasma β. The higher the β the lower the magnetic fields and the less massive the magnetic coils needed to maintain the pressure. The ease of translation is important because an FRC can be generated in one location, translated and then compressed in another location, an ideal situation for pulse fusion machines. FRCs also have a natural divertor, albeit bidirectional, which is beneficial for producing thrust. An FRC resides inside a cylindrical confinement vessel, also an advantage for thrust applications.

II.A. Levitated Dipole

Romanelli[3] and Teller[6] discuss the levitated dipole concept. The levitated dipole employs a toroidal coil that is levitated and produces the confining magnetic field. The combined field of the various coils produces a magnetic separatrix. Outside the separatrix a natural divertor configuration is formed. The presence of a magnetic separatrix can affect stability by enhancing MHD stability close to the separatrix and by locally destabilizing drift waves, although the latter could be stabilized by edge sheared flows similar to those observed in tokamaks in conjunction with improved confinement regimes. A major problem with the dipole is that the dipole has no physical connections to the outside of the reactor. Therefore it must be self-powered and be capable of maintaining its own thermal equilibrium. This alone is a very significant engineering problem.

II.B. Spherical Tokamak with Divertor

The spherical tokamak concept uses a closed magnetic field configuration, a tokamak, and a divertor to exhaust the plasma. The plasma is mixed with hydrogen and then passed through a magnetic nozzle. Williams, et. al.[7,8] have produced two versions of this concept. The first used a Neutral Beam Injector to heat the plasma and the newer version employed Higher Harmonic Fast Wave Heating[9] a form of radio-frequency plasma heating. Both versions use Helium-3 as the reactor fuel. This fuel has severe disadvantages. For one, it is not available except possibly through an expensive breeder program. The second is that its power density is very low leading to large reactors. In addition the poloidal divertor is massive and complex and it is not clear how to protect it from fusion alpha particles.

II.C. Gas Dynamic Mirror

The Gas Dynamic Mirror is a very long narrow magnetic mirror machine that through its geometry reduces the instabilities seen in previous mirror machines. However, to achieve the required plasma characteristics requires either very powerful mirror magnets or an unreasonable length. One method for solving these problems is the use of FRC in the region between the mirror and the main plasma chamber.[10] The FRC would act as a magnetic plug requiring mirror fields only strong enough to prevent FRC ejection through the mirror throat. This requirement is much less stringent than that required to prevent ion ejection through the mirror loss cone. The FRC is generated by inducing a rotating magnetic field in the plasma. If the magnetic field rotates at a frequency between the ion gyro frequency and the electron gyro frequency, the electrons will follow the rotating magnetic field and create an azimuthal electron current in the plasma that will generate the required FRC. If the electron-ion collision frequency is not too great, the FRC can be sustained indefinitely with minimal power requirements.

By themselfs, adiabatic magnetic traps or mirror machines initially attracted a lot of attention as candidates for the fusion reactor, but were proved to have a very low-energy confinement time, which is critical for building a self-sustained burning plasma reactor. Kinetic instabilities in earlier experiments, such as driven by the loss cone in the velocity space, prevented the plasma from achieving high-energy confinement times since achievable trapping magnetic fields are not strong enough to shrink the loss cone and achieve the required confinement. Recent experiments on mirror machines, such as the gas dynamic trap[11] device showed a road to achieve better stability and confinement properties of the plasma. However the confinement time is still at least an order of magnitude lower than in tokamaks, which places mirror machines behind tokamaks in the development of practical terrestrial fusion reactors. More complex geometries[10] suffer from the same problems.

II.D. Magnetic Target Fusion with Plasma Beams

Statham[12] discusses the magnetized target fusion with plasma beams (MTFB). Two spheromak plasmas are generated by theta pinch devices. These are launched and collide to form a field reversed configuration. The FRC is then compressed using a set of plasma beams that converge on the target location. The plasma beams are accelerated by magnetoplasmadynamic (MPD) accelerators. One advantage is that the high density plasmoid will absorb some of the neutrons thus adding the the energy of the plasmoid while mitigating neutron damage to the accelerators. The particular design has an exhaust plume with 2 GW of power and it is not clear how it would scale to smaller systems. The system is also very complex and radiation protection from fusion products is likely to be a challenge.

II.E. Pulsed High Density Fusion Rocket

In the Pulsed High Density Engine (PHD) concept[13] an FRC is created and translated in to a burn chamber with a high magnetic field in steady state. The FRC is compressed to fusion conditions and the resulting plasma mixed with slush hydrogen. The compression to fusion conditions is done with the high magnetic field but the plasma volume is very small leading to a system that is more compact than a tokamak. The fusion burn energy is added slowly to the FRC. The burn chamber is surrounding by a LiPb blanket that serves as a flux concentrator and a neutron absorber. The acceleration chamber would be about $25m$ in length but the field required for acceleration is only $4kG$. The channel is quite narrow and none of the coils are more than $20cm$ in diameter. The expanding FRC drives a flux compression directly producing electricity from the plasma thermal energy. The large size of the acceleration chamber makes this impractical for any satellite applications.

II.F. Magnetic Target Fusion with Liner

In a Magnetic Target Fusion with Liner (MTFL)[14] an FRC plasmoid heated to $500eV$ is created in the theta pinch duct. This is translated into the liner chamber. The plasmoid is compressed by the liner by driving a current through the liner. The plasmoid reaches $10keV$ and fusion energy is produced. The compression is non-uniform to cause the alpha particles to preferentially pass through the separatrix on the nozzle end. The alpha particles pass into the magnetic nozzle where they are mixed with hydrogen lowering the overall temperature to the desired $50eV$ and expanded through the nozzle. The lithium layer absorbs sufficient neutrons to produce the power needed to charge the capacitor bank and provide housekeeping power.

The liners are not vaporized and the crushed liners are recycled, remelted and reformed, to produce new liners. The system shares many components with the spherical tokamak to be described below. Plasmoids are one way to refuel a tokamak, for example. A major difference is that the MTFL concept does not require the high field coils required by the tokamak which make up most of the tokamak mass.

There are several issues with the liner system. One is the stress on the liners.[13] Another is the automated liner recycling mechanism, which is similar to a high speed automated naval cannon loader, but will be irradiated by the neutron flux. Another is the electrodes which may also have to be recycled.

III. Magnetic Fusion Engine (MFE) Details

III.A. The Tokamak Toroidal Reactor

The tokamak is represented by the strong toroidal magnetic field which confines the plasma. Single particles in such a field move along the magnetic field lines and perform the gyro motion perpendicular to the magnetic field direction. To compensate the additional perpendicular toroidal magnetic ambipolar drift of the gyro orbit, an electric current needs to be generated in the plasma. It creates a rotational transform for the particle longitudinal motion so that both electrons and ions are confined. Such a configuration is seen as the most practical for a fusion reactor. For background on tokamaks see Ref.[15]

Even though the tokamak concept is the most advanced and closest to the reactor design, its closed magnetic field lines are thought to make it an unusable system for direct thrust, unlike the adiabatic magnetic traps or levitating dipole Ref.[6] unless a divertor is employed.[7] So, if the energetic ion escapes the tokamak toroidal field due to the drift motion, there are no obstacles to prevent it from leaving the spacecraft. It has been shown[1] that due to magnetic field ripples and a statistically preferable direction of motion of energetic ions, this can create a thrust. Figure 1 illustrates this mechanism.

At the same time, tokamaks have been around for a few decades. They are extensively studied and are on the verge of being built as demo reactors.[16] Experimentally, they have already achieved conditions in which the power used for plasma heating almost equals the power released during the plasma discharge. New concepts with high plasma beta and low machine size emerged recently. One of these concepts is known as low-aspect-ratio tokamaks, or spherical tokamaks (STs), and was studied in the U.S. and UK with record

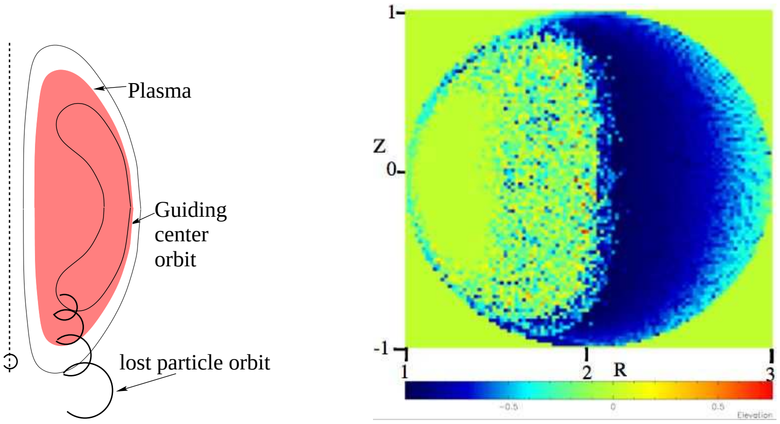


Figure 1. The sketch of the charged particle orbit (left figure) projected to the poloidal cross section of the tokamak. Shown are the initial, confined guiding center charged particle orbit and the real particle orbit after it became trapped in the well of the rippled toroidal magnetic field. Also shown is the color map (right figure, taken from[1]) of the vertical relative momentum carried by the energetic fusion ions, $3.52 MeV$ α-particles, born at each spacial point in the plasma poloidal cross section, which is circular in this example centered at R=2, Z=0. Dark blue color means that ion born at that position carries maximum negative vertical momentum equal -1, whereas red color corresponds to a particle moving straight up with momentum 1.

volume average achievable beta $\beta_{pl} \simeq 40\%$ with local beta approaching unity (see Ref.[17, 18, 19] and references therein). The use of liquid lithium can further improve the efficiency of ST.[20]

Self sustained plasma current is generated in a tokamak and is known as a bootstrap current (see Wesson[15]). It depends strongly on a fraction of trapped plasma ions. In a spherical tokamak such fraction is very large and approach 100% at the edge of the plasma, so that there is a possibility to create a steady state discharge limited only by the toroidal field time.[19]

The concept, which is in the center of our study, also differs from previous concepts which suggested using STs as power generators and sources of plasma[7, 4] (see also subsection II.B) in that the proposed concept does not require a magnetic divertor. A divertor creates a poloidal field that is comparable in magnitude to the toroidal field. Such a divertor would introduce magnetic field perturbations (error fields), which limits plasma performance.

Our study combines the most advanced fusion concept, the tokamak, with the direct plasma thrust making the whole concept of fusion powered spaceship attractive for deep space vehicles requiring high-power propulsion systems.

III.B. Direct Thrust Via Magnetic Field Ripple

In the toroidal magnetic configurations the charged particle is drifting along the axis of symmetry due to the gradient of the toroidal magnetic field. The direction of the drift depends on the sign of the particle charge. If the toroidal magnetic field is not perfectly axisymmetric, but has so called ripples, the charged particle can stochastically diffuse in the direction of the drift, get trapped in the magnetic well between the toroidal coils, and eventually be lost.[21] Typically only high energy particles are affected by this mechanism which can produce the direct thrust.

The magnitude of the ripples depends on the design of the toroidal coils system, in particular, their size, number of coils and the structure of the current distribution in the coils. This dependence can be used for controlling the thrust. For this purpose, the toroidal field coils can be designed in such a way, that the asymmetric harmonics of the current distribution, responsible for the ripple amplitude, can be controlled independently from the total current in the coils, for example, by using extra closed coils, which do not contribute to the total current.

In the plasma, only trapped particles are affected by this mechanism of loss. The amount of trapped particles is equal to $\sqrt{2\epsilon}$ of the total number of particles, where ϵ is a ratio of half width of plasma cross section to the major radius of the torus. It means that only a fraction of energetic particles will be affected. The rest of energetic particles will contribute to the energy balance of the burning fusion plasma. In order to create more thrust one can use the Ion Cyclotron Resonance Heating (ICRH) for charged particles, the technique widely used in the tokamak research. ICRH is efficient in scattering particles from the passing to the trapped domain in the velocity phase space, where particles will be affected by the ripples. With this process even background plasma Maxwellian tail ions will be forced to leave the reactor and create thrust as was demonstrated experimentally in ICRH plasma discharges in many tokamaks.

An immediate problem is that once being trapped in the toroidal field well particles start to move along the lines of constant magnetic field. On first glance this means that with adiabatic motion the charged particle can not leave the reactor. In fact, the plasma particles become trapped on the low field side of the tokamak, where the ripples are the most strong. Then moving along the $B = const$ lines the particle approaches the outer boundary of the toroidal magnetic field coil on the high field side. If the coils are designed in such a way, that the distance from the particle trajectory to the outer boundary of the coils becomes comparable to the Larmor radius of the particle, the particle becomes lost and contributes to the thrust. Such special design was verified in initial work,[1] but more research is necessary in order to have accurate estimate of the thrust. For example and important problem not answered in the initial study was whether escaping ions will impact the toroidal field coils.

One of the conclusions of our preliminary work[1] was that the design should favor ST like parameters, that is the radius of the toroidal field coils has to be close to the major radius of the torus. In addition, the number of coils on the order of 10 is required.

While terrestrial fusion research is concentrated around plasma confinement, in the proposed concept one would have to address the mechanisms of efficient trapped particle losses for creating the thrust, including losses of charged fusion products (e.g., α-particles) and background ions. Investigation of different scattering mechanisms, both classical and turbulent, which are responsible for diffusion in the velocity space and supply of the ripple-trapped particles in the plasma has to be reviewed.

III.C. Recent Advances in Magnetic Fusion

Since 1968, when direct measurements of the plasma temperature (0.8 keV) were made in T-3 tokamak in Kurchatov (Moscow), the tokamak concept became the leading one in the world fusion program. Essentially all other approaches to fusion (mirror machines, spheromaks, levitating rings, etc) were abandoned. (Stellarators, which are similar to tokamaks, are an exception, but technologically they are much more complicated than tokamaks, although they fit the proposed concept requirements). In 1978 plasma heating up to the temperature of 6 keV by neutral beam injection was demonstrated on PLT tokamak (PPPL, Princeton). Then, in 1994 fusion power of 10 MW lasting 1 sec was obtained on TFTR (PPPL, Princeton). At present, the international project ITER is in an initial stage with the goal of demonstrating in 15 years a fusion power of 0.5 GW for tens of seconds. Still, the present tokamak approach to fusion does not fit requirements for economic power production or, for much more challenging, space missions.

New ideas emerged in late 1998[22] when it was understood how to utilize unique properties of liquid lithium absorbing hydrogen isotopes. During the last 7 years these ideas gave birth to the “LiWall” concept of magnetic fusion.[20] For the first time, at least at the conceptual level, this concept made tokamak approach consistent with requirements of the power reactor and its development. Also, the idea of using tokamak configurations for direct thrust generation became thinkable.[1]

The crucial difference between the LiWall regime and conventional plasma is in the level of edge plasma temperature. The tokamak plasma is always in a contact with material walls, which are called plasma facing components or PFC. In the case of non-lithium PFC, plasma particles, which diffuse through the plasma boundary, hit the wall, exchange their energy with the wall particles, and then return back to the plasma as the cold neutrals. Such a “recycling” process has the fraction $k_{recycle}$ of returned plasma particles close to 1. It leads to a low edge temperature T_{edge} compared to the core temperature T_{core}, $T_{edge} \propto (1-k_{recycle})T_{core} \ll T_{core}$. In its turn, the difference between the core and edge plasma temperatures drives the so-called “ion temperature gradient” turbulence, which in present tokamaks is the major mechanism of energy losses from the plasma to the wall. In the current approach, the only way to enhance confinement is in increasing the size of tokamaks. This fact makes conventional plasma regimes unsuitable not only for space mission but for an economic power reactor, in general.

In the case of lithium coated PFC the recycling is suppressed by absorption[23, 24, 23] of the plasma particles by a lithium layer (which should be gradually replenished). Instead of unity, the recycling coefficient $k_{recycle}$ can be made small. If such a regime is complemented with core fueling of the plasma by Neutral Beam Injection (NBI), then the edge temperature will be automatically as high as the core temperature ($T_{edge} \simeq T_{core}$), thus, eliminating the dominant drive of turbulence and leading to much better confinement.

Experimentally recycling as low as $k_{recycle} \simeq 0.3$, sufficient for suppressing turbulence, was already achieved on CDX-U tokamak,[24] but the core fueling, unfortunately, was absent on this small machine.

The high edge temperature regime can change the very fundamentals of tokamak fusion.

1. In absence of turbulence, the energy confinement time could be enhanced by orders of magnitude up to the so-called "neo-classical" level. Numerous tokamak experiments, indeed, demonstrate such an excellent energy confinement (see, e.g.,[25]). In the present tokamaks this happen only inside localized zones where turbulence is suppressed by the plasma flow (the effect of "thermal barriers") or in so-called reversed shear zones. More recently tokamak FTU demonstrated "a strong turbulence suppression"[26] in the discharges with Lithium.

   Large energy confinement time allows for obtaining fusion power in small size machines, like spherical tokamaks. Such good confinement dramatically reduces the necessary external power for plasma ignition, which all together reduces complexity and the weight of systems necessary for achieving fusion power.

2. "Super-critical" ignition regime becomes feasible. Under good confinement the external neutral beem injection, NBI, can by used for both fueling and heating the plasma. In this case, a compact tokamak can be specially designed to release from the plasma most of energetic α-particles (produced by fusion reactions), e.g., by the same mechanism of ripple losses, which is proposed here for producing the thrust.

   Recall, that the conventional fusion approach aimes at achieving a self-maintained ignited (or close to it) regime when energy losses from the plasma are compensated by the α-particle heating of the plasma

   $$\langle p \rangle \, \tau_E^* \simeq 1 \ [\mathrm{MPa} \cdot \mathrm{sec}] \tag{1}$$

   This condition is, in fact, contradictory. Fusion power P_{DT} is proportional to $\langle p^2 \rangle V$ (V is the plasma volume) and, thus, the power production requires the highest possible plasma pressure $\langle p \rangle \simeq 1$ MPa. The increase of plasma volume is highly undesirable economically. It is also in conflict with the power loads on the plasma facing components and amplifies all problems with the plasma control. Based on the same ignition criterion, power production requires reduced energy confinement time $\tau_E^* \leq 1\,\mathrm{sec}$. On the other hand, igniting the plasma by a reasonable external power requires much larger τ_E^* (several secs) which, in the presence of turbulence, can be achieved only in large volume (and heavy) devices, like ITER (840 m^3 plasma volume).

   For conventional fusion enhanced energy confinement time during the operational regime would be disastrous in many aspects. So far, conventional approach to fusion addresses only a very limited (and not the most important) goal of approaching just ignition using the external power.

   In contrast, the LiWall ignition regime would be "super-critical" and completely controlled by the NBI heating

   $$P_{NBI} = \frac{3}{2} \frac{\langle p \rangle V}{\tau_E^L}, \qquad \tau_E^L \gg \tau_E^*, \qquad P_{NBI} \ll P_\alpha. \tag{2}$$

   Under this condition, the fusion α-particles can be thrown away from the plasma, and used directly for propulsion or for converting their energy into slower propellent with a larger thrust.

   For Ignited Spherical Tokamak (IST),[20] as reference example, with a total fusion power of 0.5 GW and, correspondingly, $P_\alpha = 100$ MW, if $\tau_E^L \simeq 10\tau_E^*$, only 10 MW of NBI power would be required. In fact this number can be even lower by noting that some of alphas will be contributing to the power balance. In this case NBI power will be determined by the fueling requirements.

   In super-critical regime there is no distinction between ignition and power production. Being possible in compact ISTs with a plasma volume $V \simeq 30$ m^3 it can be consistent with removal of α particles by the same mechanism, which is proposed here for propulsion.

3. In a super-critical regime only a small fraction of the power (i.e., $P_{NBI} \ll P_\alpha$) is exhausted with the ionized plasma particles to the wall. In this case the load on the plasma facing components are significantly reduced (or, in principle, these particles also could be utilized for thrust generation).

4. *In a super-critical ignition regime, burn up of tritium can be much higher than is conventionally expected.* This would be especially important for space mission applications. E.g., at a typical fusion plasma temperature of 16 keV, the fraction $f_{tritium}$ of tritium consumed for power production (relative to injected tritium), is given by

$$f_{tritium} = n_D \left\langle \sigma_{DT} v_i \right\rangle \tau_E^L \simeq 0.03 \cdot \frac{n_D}{10^{20}\ [\mathrm{m}^{-3}]} \cdot \frac{\tau_E^L}{[\mathrm{sec}]}. \tag{3}$$

   It can approach 1 at high τ_E^L. In conventional fusion this fraction is only $\simeq$0.02.

   Because of the possibility of high burn up of tritium, there would be no need for a tritium recycling system even for space flights lasting for several years. This is an additional simplification resulting from the proposed concept.

   The possibility of high burn up of tritium is unique for the proposed concept. All other known fusion based propulsion schemes (like mirror configurations), which rely on thrust from the plasma exhaust (where tritium represents about 50% of exhaust), are inefficient in using tritium.

5. High power density requires a high plasma pressure $\langle p \rangle \simeq 1$ MPa. Although such level of pressures has never been achieved in magnetic fusion experiments, NSTX spherical tokamak in PPPL demonstrated the 39 % record level of plasma beta[27] parameter, which is the ratio of the plasma pressure to the magnetic pressure at the plasma center (on NSTX machine in PPPL). This result, when extended to 3 T magnetic field (8 times higher than on NSTX), which is realistic from engineering point of view, give a solid scientific and technological ground for the concept of the Ignited Spherical Tokamaks Fusion Engine.

III.D. Magnetic Fusion Engine Outline

A conceptual diagram of the spherical tokamak fusion propulsion system is shown in 2. The core is the spherical tokamak with a lithium wall. The inner wall is covered with very thin fluid lithium layer propulsed by the toroidal current and magnetic field gradient from low to high field. It faces the plasma. This improves the stability of the plasma and unloads direct plasma particle flux to the first wall. Another, thick layer of lithium is called blanket located outside the first wall and is pumped through the reactor to absorb neutrons (most of the fusion power) and transfer heat through a heat exchanger to a Brayton cycle engine that produces electric power for the spacecraft systems. Most of the neutrons are not absorbed by the blanket lithium layer. Rather they are used to heat the hydrogen, much like in a nuclear fission thermal rocket. The outer lithium layer must be thick enough to absorb sufficient neutrons for the electrical power demands of the spacecraft. The minimum thickness for plasma boundary improvement is only a few mm. Significant neutron absorption requires thicker blanket lithium layers, on the order of a meter for proposed power reactors.

The plasma and fusion alphas from the reactor are exhausted via the ripple mechanism and is mixed in a mixing chamber with preheated hydrogen that is also used to cool the reactor. The inner lithium layer plays the important role of stabilizing the plasma but the balance of neutrons absorbed by the lithium in the blanket and the hydrogen is based on the desired exhaust velocity and thrust.

Provision must be made to start the reactor up. The RF drive is powered by ultra-capacitors or possibly high speed flywheels that are charged by the electric output of the reactor. If the toroidal and poloidal coils are superconducting, they will need a refrigerator to keep them cool. The radiator is connected to the output of the Brayton cycle and removes waste heat.

The DT reactor can be sized using a zero-th order model of the plasma. It is useful to compute an energy balance for the deuterium-tritium reactor. The reaction is

$${}^2_1D +^3_1 T \Rightarrow^4_2 He(3.5MeV) +^1_0 n(14.1MeV) \tag{4}$$

where the superscript is the atomic number and the subscript is the number of protons. The superscripts and subscripts must sum across the reaction. The helium atoms are charged and are confined by the reactor's magnetic field and are expelled by the ripple effect, while the neutron is absorbed by the lithium blanket that surrounds the first wall. The neutron reacts with the lithium to form helium and tritium

$${}^6_3Li +^1_0 n \Rightarrow^4_2 He +^3_1 T + 4.6MeV \tag{5}$$

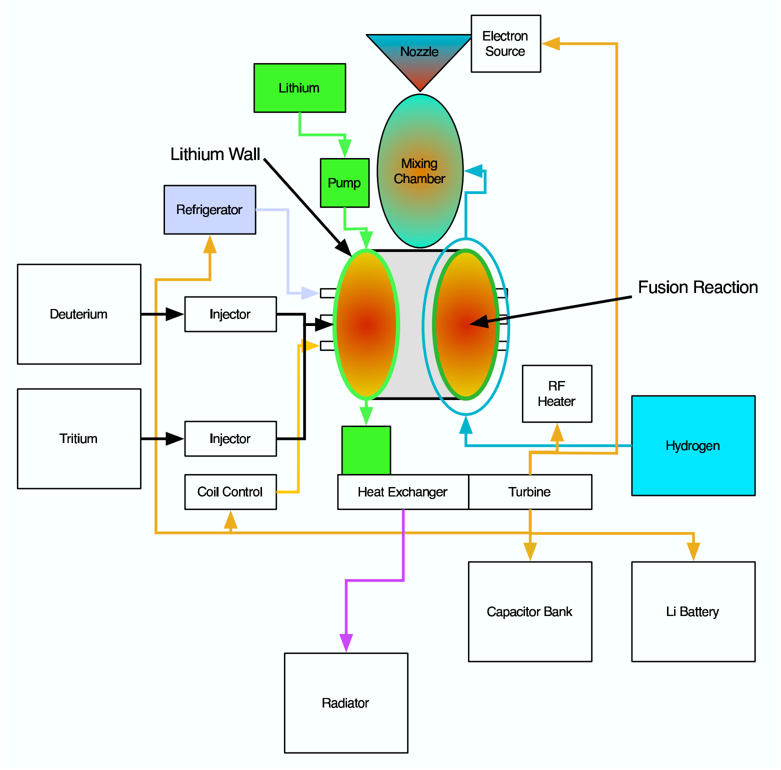


Figure 2. Schematic fusion propulsion system

We prefer ^6_3Li in the blanket over ^7_3Li because we do not want to generate more neutrons. This reaction breeds tritium but to simplify the design we don't plan to recycle tritium onboard. With almost complete burnup of the tritium its relative small amount (10 to $50kg$ depending on plasma confining condition) is sufficient for the whole mission.

3 shows the power flow in the system. Electricity flows are shown in orange. Particle flows are in black. Radiation is in yellow. Most flows are labeled. Ono et. al.[28] show that with an externally applied toroidal field a plasma pressure ratio, or β_T of 0.8 is possible in a spherical tokamak. This agrees with many other authors. This means that much smaller magnetic fields can be used to confine the plasma leading to a lower mass engine.

One can show that typical power in tokamak reactors with the plasma temperature on the order of $T = 10keV$ is at 18 MW/m^3. This leads to a volume of $30m^3$ in order to achieve reactor power $P_{DT} = 0.5GW$. With a typical aspect ratio of $A = 1.26$, the major radius is $R_0 = 1.1m$ and the minor radius is $a = R_0/A = 0.87m$ with the cross section of the plasma elongated vertically by a factor 1.8 . However, this volume does not account for the volume needed for confinement and lithium layer which increases the minimum size. Table 1 shows the indirect and direct specific powers and supporting parameters.

The tokamak specific masses can be based on Williams, et. al.,[7,8] but adjusted for the higher power density of the DT reactor compared to the He^3 reactor. The lithium blanket is based on the fraction of neutrons that must be absorbed to produce the required 1 MW of auxiliary power in the case of the direct thruster and the total power for the indirect thruster. The need to absorb all neutrons for the indirect case results in the large amount of required lithium. The converter is also based on Williams but the radiator number is from Angelo.[29] The specific power for the direct thruster is far higher than the indirect thruster and higher than is achievable with fission or solar panels. The reason it is not as high as other fusion schemes is that the neutron power cannot be used to generate thrust directly while other analyses assume that the fusion engine uses He^3 as a propellant. Unfortunately, there are no economical sources of He^3. However as it was argued in Ref.[1] direct thrust with DT fuel is possible for the deep space mission in which neutrons would play the role of the propellant. In such cases speed up to 1/6 of the speed of light could be achieved, which is the speed of fusion neutrons.

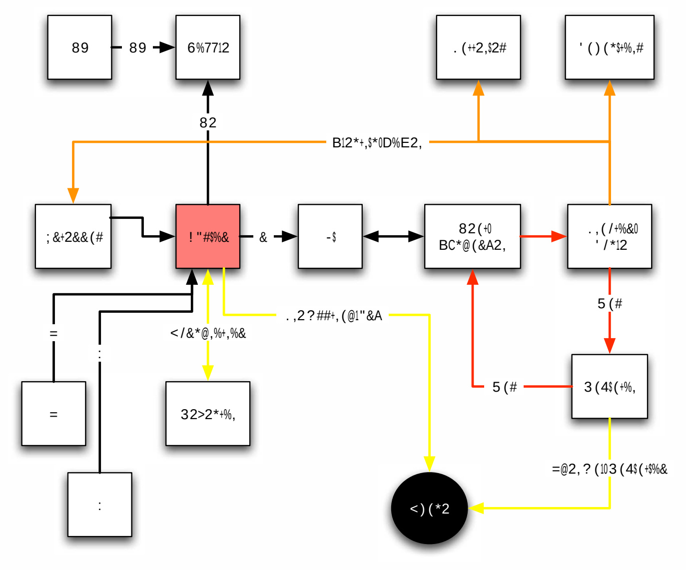


Figure 3. System energy balance and flow

Parameter	Indirect Thruster	Direct Thruster	Units
Conversion eff	0.33	0.33	
Engine eff	0.60	0.80	
Radiator Specific Mass	0.38	0.38	kg/kW
Tokamak Specific Mass	0.13	0.13	kg/kW
Engine Specific Mass	2.50	0.0013	kg/kW
Conversion Specific Mass	1.08	1.08	kg/kW
Fusion power	126.84	200.44	MW
Neutron power	107.45	169.80	MW
Radiator power	84.99	2.03	MW
Engine power	40.86	30.64	MW
Specific power	0.09	0.84	kW/kg
Lithium mass	9509.73	230.25	kg

Table 1. Specific power estimate

IV. High Power Propulsion Background

IV.A. Thruster Power

We will explain some fundamentals of high power propulsion to illustrate why fusion is the only realistic option that can meet requirements for high power Earth orbit operations and inner planet missions. High power electric propulsion is governed by the key equation for thruster power

$$P_t = \frac{1}{2}\frac{Fu_e}{\eta} \tag{6}$$

where P_t is the power going into the thruster, F is the thrust, u_e is the exhaust velocity and η is the thruster efficiency. The mass flow rate is related to thrust and exhaust velocity through the equation

$$F = \dot{m}u_e \tag{7}$$

To increase thrust and/or exhaust velocity we must increase power. For example, an engine producing an exhaust velocity of 50 km/s and a thrust of 1000 N requires 31.25 MW of power given a thruster efficiency of 80%.

The difficulty is finding a combination of thruster and power source that can produce the required thrust and exhaust velocity. Table 2 lists possible propulsion system engine options giving the range of exhaust velocities and demonstrated thrusts. SE stands for small engine. NERVA stands for Nuclear Engine for Rocket Vehicle Application. Ion thrusters, Arc jets, Electrothermal Hydrazine Thrusters (EHT) and Pulsed Plasma Thrusters (PPT) were omitted since they do not come close to meeting the desired thrust levels and/or exhaust velocities.

Table 2. Thruster options

Thruster	**u_e (km/s)**	**F (kN)**	**Reference**
MPD	50-100	0.1	NASA GSFC[30]
Hall Thruster	17 - 32	0.003	NASA-457M[31]
Nuclear Thermal	6.9 (SE)-8.1 (NERVA)	72 (SE) - 337 (NERVA)	Nuclear thermal rocket engine program[29]
RF	50-300	5 - 25	VASIMR[32]

Table 3 lists possible power sources. MPRE stands for medium power reactor experiment.[29] SPR is a design from the Advanced Space Nuclear Power Program. Note that the space nuclear reactors have specific powers that are barely better than the solar panel designs. Advanced solar panels are expected to attain 0.5 kW/kg. However, this does not include power conversion mass. In contrast to solar panels, a nuclear reactor generator can produce almost any voltage. It is difficult to make large solar panels with high voltages due to plasma effects around the spacecraft and the possibility of arcing through the plasma. For this reason power converters are required.

Table 3. Power sources

Program	**kW/kg**	**Type**
SP-100	0.036	Nuclear Fission Thermionic[29]
SPR-6	0.142	Nuclear Fission Rankine[29]
MPRE	0.197	Nuclear Fission Potassium Rankine cycle[29]
Multi-Junction Solar Cells	0.070	DS-1 SCARLETT[33]

Solar panels and nuclear reactors have both been used in space. Solar panels have been improved and continue to be improved by reducing the amount of material in the array and increasing the efficiency. The latter has been accomplished by reducing reflections and other losses and by increasing the number of junctions. Recent developments may lead to cells with conversion efficiencies in excess of 60%.[34]

The largest solar arrays in space are on the International Space Station. These arrays are 2500 m^2 and provide 110 kW. A 1000 N, 50 km/sec thruster would require solar arrays with 284 times the area. Even with 100% efficient cells the solar arrays would be 9 times the area which is completely impractical for any

Earth orbit application. In addition for deep space missions, the magnitude of the solar flux drops as $1/r^2$ where r is the distance from the sun making solar electric impractical for missions past Mars orbit.

The Russians have flown several operational space reactors. The most recent U.S. program is Prometheus. Prior to that the SP-100 program ran from 1983 to 1995 and reached an advanced state of development before being cancelled.

IV.B. Heat Losses and Radiators

Solar power systems require voltage converters to bring the voltage up to levels needed by many electric propulsion systems. Power Processing Units have specific masses (the inverse of specific power) of 2.5 kg/kW[35] and as much as 91% efficient. This means that 9% of the incoming power must be radiated to space via radiators.

All fission reactors require large radiators due to the thermodynamic limitations embodied in the Carnot efficiency, the maximum amount of energy that can be extracted from a thermal system. The Carnot efficiency is

$$\eta_c = \frac{T_h - T_l}{T_h} \tag{8}$$

The peak temperature is limited by the reactor materials and the minimum temperature by the ability of an energy conversion device to extract heat. The waste heat must be removed by radiators. Radiators are a major mass contributor in a space thermal power system. The maximum radiated power is

$$P_r = \sigma \epsilon A T_l^4 \tag{9}$$

assuming that there is no incoming heat flux. ϵ is the emissivity of the material, a number between 0 and 1. The total radiator mass is

$$m_r = \rho_r (1 - \eta_c) \frac{P}{\sigma \epsilon T_l^4} \tag{10}$$

where P is the generated power, σ is the Stefan-Boltzmann constant of $5.67051 \times 10^{-8} W/m^2 K^4$and ρ_r is the areal density of the radiator in kg/m^2. Substituting for Carnot efficiency we get

$$m_r = \frac{\rho_r P}{\sigma \epsilon T_h T_l^3} \tag{11}$$

It is interesting that the mass goes to infinity as T_l goes to zero. This is due to the strong effect of the quartic relationship between radiator temperature and radiated power. If we let $\zeta = \frac{T_l}{T_h}$ which ranges from 0 to 1, we get the more useful relationship

$$m_r = \frac{\rho_r P}{\sigma \epsilon \zeta^3 T_h^4} \tag{12}$$

which shows how important the temperature ratio is in a thermal system for sizing of the radiators. A radiator designed for space nuclear power[29] had a specific mass of 0.384 kg/kWt. Almost half of the mass is for radiator armor to protect the radiator from particle impact (up to $1 \times 10^{-5} g$).

IV.C. Performance

The performance of an electric propulsion system can be evaluated using a modification of the rocket equation which is

$$\frac{m_i}{m_d} = e^{\frac{\Delta V}{u_e}} \tag{13}$$

where m_i is the initial mass, m_d the dry mass, ΔV the total required velocity change and u_e the system exhaust velocity. Let s_p be the specific mass of the complete propulsion system in kg/W and s_f be the specific mass of the fuel tanks which is proportional to the mass of fuel. The dry mass is

$$m_d = \frac{s_p F u_e}{2\eta} + s_f m_f + m_p \tag{14}$$

where m_p is the payload. The rocket equation is now

$$\frac{m_d + m_f}{m_d} = e^{\frac{\Delta V}{u_e}} \tag{15}$$

This can be solved for the fuel mass which will be a function of the parameters and the thrust F. The solution is

$$m_f = \frac{(\gamma - 1)(\alpha u_e + m_p)}{1 - (\gamma - 1)s_f} \tag{16}$$

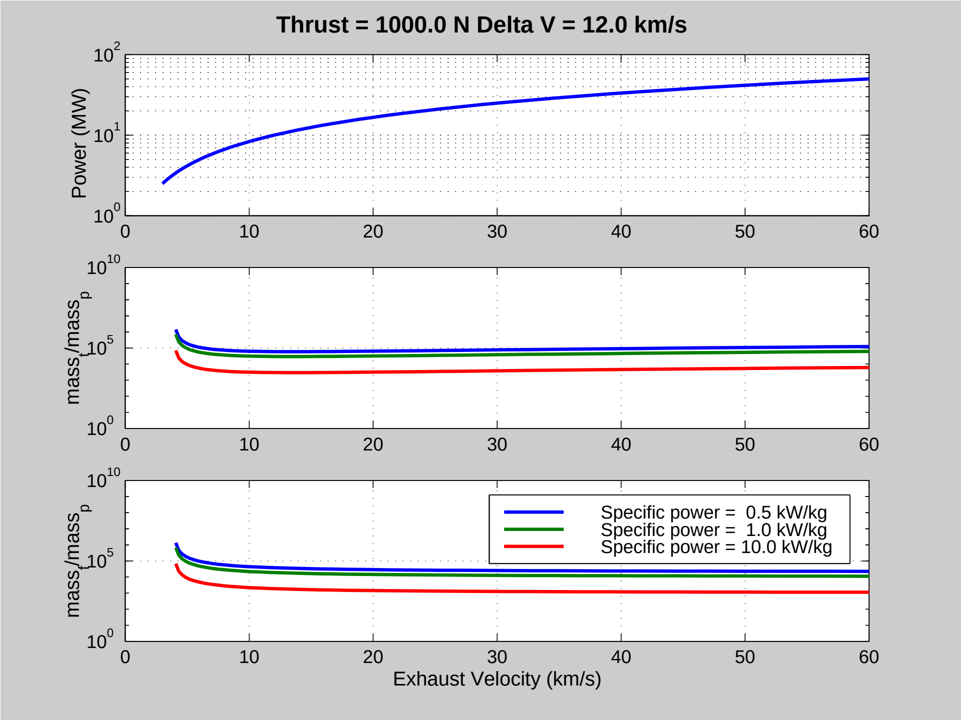
where $\alpha = \frac{s_p F}{2\eta}$ and $\gamma = e^{\frac{\Delta V}{u_e}}$.

For a given thrust level and parameters we can find the optimal exhaust velocity. This equation also has an interesting limit. As the exhaust velocity goes to infinity the fuel mass does not go to zero but reaches the limit

$$m_f = \frac{s_p f \Delta V}{2\eta} \tag{17}$$

This is a consequence of the linearly increasing mass of the power plant with u_e. Figure 4 shows the electric propulsion system fuel masses as a function of exhaust velocity and specific power for a 1000 N thrust level and a total velocity change of 12 km/sec, enough for a round trip to geosynchronous orbit from a 28.6 deg inclined low Earth orbit.

Figure 4. Electric propulsion system masses for LEO/GEO roundtrip

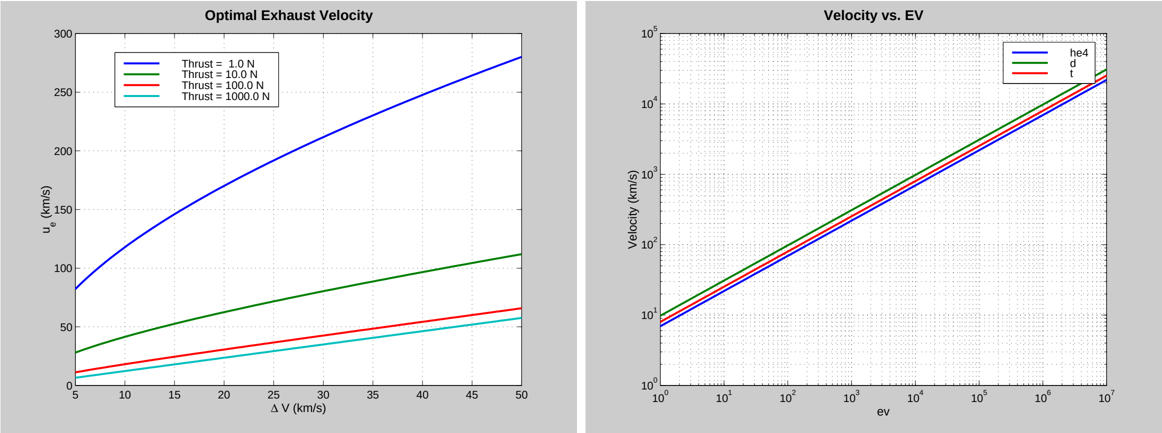


The optimal exhaust velocity for this maneuver is 15 km/s, found from the point on the graph where the mass in minimum, which is achievable by Hall thruster but not at a 1000 N thrust level. The top plot shows the total power required. The middle plot shows the ratio of total mass to payload mass and the bottom plot shows the ratio of fuel mass to payload mass. The lowest specific power is what might be achieved with an advanced solar power system. The highest is a figure quoted for He^3 fusion propulsion systems.

The optimal exhaust velocity is a function of specific power and the required thrust. Figure 5 show the optimal exhaust velocity as a function of total required ΔV. For fusion, the optimal exhaust velocities need to be compared with the equivalent temperatures in electron volts. The required exhaust velocity of 50 km/s corresponds to a temperature of 52 eV for He^4. This is far lower than typical fusion temperatures of 10 keV.

An exhaust velocity of 50 km/sec is optimal for 1000 N if the total required ΔV is 45 km/sec without refueling. This would allow for nearly 4 round trips to geosynchronous orbit without refueling. 1 kW/kg

Figure 5. Optimal exhaust velocity and velocity as a function of plasma temperature



and 10 kW/kg bracket the specific powers that are predicted for fusion systems. Consequently, we see that it would be difficult for any but a fusion powered systems to meet the specified requirements.

Chakrabarti[36] performs a similar analysis for interplanetary missions using round trip time, assuming no solar gravity, and parameterizes the results as a function of trip time. The results are much the same.

V. MFE Vehicle Design

One of most complete fusion propelled vehicle study is the Discovery II discussed by Williams et. al.[8] It was aimed to put a 170 metric ton (mt) payload into Jupiter orbit with a trip time of 250 days.

As we mentioned Discovery II relies on using poloidal divertors while the proposed concept uses the magnetic field ripple particle loss mechanism, which results in an outflow of charged particles.

We propose to employ the onboard cryogenic system (hydrogen propellant is maintained liquid by such a system) to operate the toroidal field coils as superconductors. To restart the fusion engine we can make use of a fraction of energy stored in the toroidal magnetic field superconducting coils. The proposed spacecraft uses single-gimbal control moment gyros (SCMGs) for attitude maneuvering and the propulsive system is only used for momentum unloading, which should be minimal. The design uses liquid hydrogen instead of slush hydrogen to simplify the fuel refrigeration system. For “short” missions, such as Mars mission, with total mission durations of about 3 months, artificial gravity is unnecessary. The following sections discuss the preliminary design of “short” missions. The proposed vehicle sketch is shown in 6.

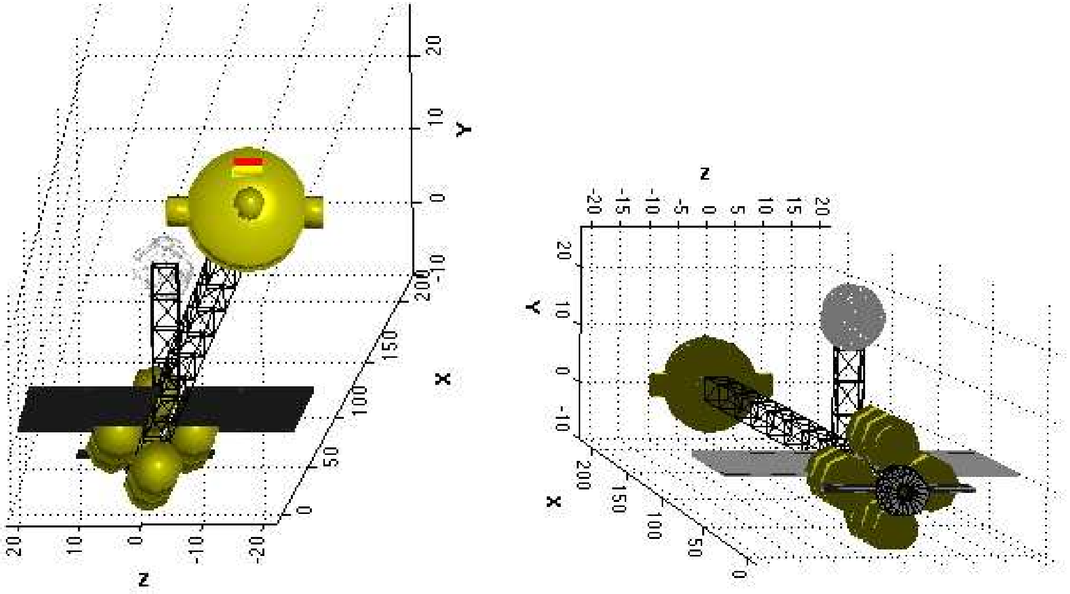
V.A. Requirements for MFE vehicle

The mission is to bring a 6 person crew to orbit Mars. A separate lander would bring the crew to the surface of Mars. The crew would spend 30 days on the Mars surface. The crew would travel the Martian surface in a rover and would live in the rover during their stay on Mars. The second stage of the lander would return the crew to the spacecraft leaving behind the over for future missions. The mission begins in low Earth orbit

- Earth escape
- Interplanetary flight
- Mars capture
- Mars escape
- Interplanetary flight
- Earth capture

The spacecraft would be assembled in Earth orbit. Assembly is done at a manned facility in low earth orbit with the capabilities of an Earth based Integration and Test Facility. Parts are brought into orbit by a fully reusable 2 stage to orbit vehicle that is sized to nominally bring 20 passengers to a manned space facility in

Figure 6. Mars Transfer Vehicle based on the fusion tokamak reactor. Four containers store liquid hydrogen. Separated from the hydrogen containers and a reactor is the payload block.



Earth Orbit. The first stage is a high speed (Mach 6+) aircraft and the upper stage a reusable winged or lifting body vehicle. The first stage is also usable as a commercial cargo and passenger transport. Using a modest sized vehicle amortizes the development costs over a much larger number of flights and eliminates the need for a heavy-lift vehicle.

V.B. Vehicle Elements

Table 4. Mars vehicles elements

Element	Mission Phases	Post mission status
Rover	Earth orbit to Mars surface	Left on Mars for future missions
Lander First Stage	Earth orbit to Mars surface	Not used again
Lander Second Stage	Earth Orbit to Mars surface to Mars Orbit	Left in orbit for future missions
Transfer vehicle	Earth orbit to Earth orbit	Reusable

The vehicle elements are listed in the table 4. The payload to Mars orbit is the crew habitat, lander and the rover. The payload back to Earth orbit is just the crew habitat. The rover mass is of 16.5 metric tons and is taken from a NASA design.[37]

V.C. Vehicle Design

The planetary and Earth to Mars spirals are computed using analytical approximations. The spacecraft masses are computed using analytical approximations for the various subsystems. The process starts by designing the Mars launch vehicle and then designing the lander. Once that is done the return from Mars to Earth is designed and then the Earth to Mars leg is designed resulting in a total vehicle design.

The total is twice the Delta-V for the Earth to Mars part of the mission.

V.D. Payload

The payload consists of the crew, the living quarters, supplies and the lander. As noted in the mission requirements the need is for 6 crew members to spend one month on the surface of Mars. The lander is two stages (much like the Apollo Lunar Module) but the upper stage is reusable and left in orbit for future

Table 5. Mars mission design

Parameter	Value	Units
Initial mass	469.9	mt
Mars Lander mass	48.2	mt
Mars launcher mass	15.6	mt
Number of crew	6.0	
Exhaust velocity	50.0	km/sec
Thrust	2.0	kN
Specific power	1.0	kW/kg
Reactor power	0.5	gW
Total Mission Duration	100.0	days
Mars Samples	1.0	mt
Mars Rover	16.5	mt
Mars Orbit	200.0	km
Earth Orbit	400.0	km
Round Trip Delta V	33.5	km/sec

missions. The lander also includes a rover which is left on the surface for future missions. In this way future missions can be of longer duration or support more explorers. Landing on Mars uses aerobraking for most of the velocity change with the rocket engine used for the final descent.

V.E. Energy Storage

The spacecraft will require energy storage to support its systems when the fusion reactor is not operating. It will also require electrical energy to startup the fusion reactor.

A rocket engine system uses hydrogen and oxygen which is burned and the exhaust channeled through a turbine. It can have very high specific powers. The exhaust can be electrolyzed to produce a regenerative system.

An alternative is to use a regenerative fuel cell. This uses the same fuel as the rocket engine but is combined with an electrolyzer to break the resulting water back into hydrogen and oxygen.

NASA Glenn Research Center proposed using a fission reactor as an auxiliary power unit. A fission reactor is nearly as complex as a fusion reactor thus the use of a fission reactor would greatly increase the cost and complexity of the system. In addition, fission reactors have poor specific powers.

Batteries are relatively simple and many different types have flown in space. With batteries there is a trade between specific power and specific energy. The higher the specific power the lower the specific energy. This can be helped by using ultra capacitors for short term power delivery. Ultra-capacitors by themselves have very low specific energies.

Spinning systems store energy in the rotational kinetic energy of a flywheel. These systems have very good combinations of specific power and energy but are mechanically complex.

Superconducting coils can be used for energy storage. The fusion reactor uses superconducting coils for plasma confinement and therefore must have the required refrigeration systems which account for much of the mass of this kind of energy storage. This option is discussed in the next section when we elaborate on the reactor restart option.

The table 6 summarizes energy storage system options.

V.F. Fusion Engine Restart

In general for successful manned and unmanned missions the possibility to restart the fusion engine must be a requirement. We are proposing to use a fraction of energy stored in the toroidal magnetic field superconducting coils, since the most of the energy during the restart will be spent to ramp up the poloidal magnetic field and plasma heating, both of which constitue only a fraction of the energy of the toroidal magnetic field.

In fact the size of the coils can be chosen basing on the required energy capacity, which is proportional to the volume inside the coils. With the volume inside the magnetic fieled coil $V_{coil} = kV_{pl}$, where k is the

Table 6. Auxiliary power system comparison

Device	Specific Power (kW/kg)	Specific Energy (W-hr/kg)	Reference
Rocket Engine Power Unit	152	2640	Pratt & Whitney RL-10
Regenerative Hydrogen Oxigen Fuel Cell	1.3	1000	Pratt & Space Shuttle
Fission reactor	0.2	3.2×10^5	SPR-6 Reactor Design
Lithium Ion Battery	4	90	NASA TM-2003-212730
Ultra capacitor	4	5	S. R. Hohm
Flywheel	12	200	S. R. Hohm
Superconducting Coil	4	0.4	S. R. Hohm

coefficient to evaluate, and V_{pl} is the plasma volume (according to our above estimates $V_{pl} = 30m^3$) and with the magnetic field on the axis $B_{0ax} = 3T$ we obtain the total energy inside the coils $106kMJ$. With plausible estimate for the averaged beta $\beta_{pl} = 30\%$ we find the required energy to heat the plasma to be $64MJ$ with the same power in the poloidal magnetic field coils. So that if the disruption of the discharge happens during the flight up to $64MJ$ energy has to be directed out of the toroidal magnetic feild coils to recharge the plasma and the poloidal field coils. This will result in the lower toroidal magnetic field

$$B_{ax}/B_{0ax} = \sqrt{1 - 0.6/k} \simeq 1 - 0.3/k,$$

which will modify the ignition condition and, hence, is required to be sufficiently small.

If we require for the magnetic field to be reduced by 10% at the end of the restart phase we have to construct the toroidal field coils with the volume three times larger than the plasma volume, i.e. $k = 3$. So that the energy confined in the coils has to be $318MJ$. Note that in this case the linear size of the coils has to be approximately 1.44 times larger than the plasma size.

V.G. Magnets

The reactor will use superconducting coils to produce the required magnetic fields to confine the plasma. The coils are composites of superconducting wire and copper or aluminum. The copper or aluminum is need to carry the current if the superconducting wire loses its superconducting properties. The coils must be supported by structure to resist the forces on the wires due to the interaction of the magnetic fields and wires.

VI. Conclusions and discussion

In this paper we have presented the conceptual design of the thruster based on the magnetic fusion compact, spherical tokamak-reactor. It employs the original idea of using ripple particle loss for direct thrust.[1]

In most of its specific elements the concept of "LiWall" regimes and Ignited Spherical Tokamaks has certain experimental confirmation. For example, the neoclassical level of plasma confinement in the absence of turbulence was observed, e.g., on TFTR,[25] FTU,[26] long time plasma stability in the case of high edge temperature was demonstrated on DIII-D machine,[38] highly reduced recycling when the plasma facing surfaces are coated with lithium and the absence of impurities was confirmed on T-11 and CDX-U tokamaks.[23,24,39] Technologically, ability to extract high heat fluxes by the lithium surface, widely used in heat tubes, was extended to tokamaks environment on T-11.[23] In the context of the super-critical ignition regime, modification for the combine purpose of plasma heating and fueling of the neutral beam injectors seem to be plausible, even for IST.

Development of the IST based thruster for the future space flights would have an additional, probably even more important, social mission of developing an unprecedented (≃0.5 GW in ≃30 m^3 plasma) neutron source as a necessary step for fusion energetics.

In terms of the MFE R&D Program it seems instructive to suggest three phases. The first is a program of the analysis of the key issues for the tokamak thruster including the ripple mechanism and mixing of hydrogen and plasma for lower exhaust velocity, higher thrust applications. In this first year a detailed systems analysis of the thruster may be performed to get the best possible estimates of the specific power of the system and to determine all critical design issues for application of this propulsion system to manned and unmanned missions.

The second phase is the construction of a test reactor to test all of the physics of the thruster. This would include the ripple effect, hydrogen mixing and nozzle. The reactor would work with a purely deuterium plasma and would be designed for pulsed mode. In parallel key subsystems would be built and tested independently.

The final phase would be the construction of a complete terrestrial prototype of a fusion propulsion system. All subsystems would be built and tested. Initial tests would use a deuterium plasma but final tests would use a deuterium-tritium plasma and would achieve fusion burn conditions for 100 sec pulse.

This program would not make use of any existing test cells but could take advantage of existing hardware whenever possible. It would not interfere with, or require redirection of, any other fusion programs. It is expected that as the program progresses it would benefit from, and would benefit, other fusion research efforts. Phase I would take 1-2 year, Phase II 4 years and Phase III 6 years. This would make the whole program to be completed within 10 years. This is in contrast with the 35 year fusion energy development path moving from ITER to a DEMO tokamak reactors,[16] which is because of much larger size of terrestial tokamaks as compared with the MFE concept of this paper.

Acknowledgments

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