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ABSTRACT

This paper presents qualitative and quantitative discussion of preliminary concepts for the application of steady state Field Reversed Configurations (FRCs) to nuclear fusion propulsion in space. A more or less spherical geometry (slightly oblate) FRC is chosen for a reduced mass, magnetically confined fusion reactor in a scenario characterized by a steady D-^{3}He fusion burn. Basic parameters are scoped for D-^{3}He FRC fusion power and reactor mass. A point design for a 8 GW (fusion) reactor is presented.

INTRODUCTION

Deep solar system flight missions, ranging from Jupiter to as far as the Kuiper Belt, are desired for the mid 21st century and beyond. Flight times must be short, especially for human travel, and productive payloads must be carried. Such missions demand rocket systems having high absolute power, high specific-power and high exhaust velocity, v_{ex}. [Specific power is α = (jet power)/(power system mass) v_{ex} (m/s) $\approx$ 10 I_{sp} (s).] Fusion power can supply the necessary power and rocket exhaust velocity, and the required nuclear fuel mass is low. Fusion research, especially tokamak research, has made great gains in the last decade, and more progress will follow. Particularly noteworthy are the rapidly growing understanding of the nature of the turbulence that has limited the magnetic confinement of hot, fusion-grade plasmas, and the concomitant ability to suppress turbulence and improve confinement.[1] For these and other reasons, fusion rockets are receiving renewed interest.

As in all nuclear systems, the need for shielding to protect sensitive components from high-energy ionizing radiation presents a challenge to attainment of high α in realistic designs. The mass of radiators, needed to reject heat from thermal conversion cycles, also reduces α. The D-T fusion reaction is unattractive for space, because it releases most of its energy in fast neutrons whose energy can only be harnessed via a thermal cycle. The D-^{3}He reaction is favored for space propulsion, because it yields only charged fusion products, whose energy can, in principle be used directly, without passing through thermal conversion. However, a D-^{3}He fuel mixture is ~50 times more difficult to ignite than D-T. Plasma confinement and heating must be exceedingly good to take advantage of D-^{3}He.

Among the many kinds of magnetically confined plasmas, Field Reversed Configurations (FRCs)[2] are potentially the most attractive for fusion space propulsion. FRCs are compact toroids — toroidal plasmas with a vanishing hole through the toroid, a property they share with spheromaks. Unlike spheromaks, FRCs intrinsically have $\beta \approx 1$, where $\beta = p/(B^2/2\mu_0)$ = (plasma pressure)/(magnetic field pressure). This makes efficient use of the magnetic field and the coil system mass. The magnetic field in the hot plasma core is small, greatly reducing synchrotron radiation loss and thereby opening the way to the high temperatures required for D-^{3}He burn. The magnet coils do not link the plasma, and plasma exhausts naturally to the external world. In principle, the exhaust plasma can be used directly for rocket thrust. Alternatively, the exhaust power can also be directly converted to electricity to power a separate, flexible, variable-thrust plasma rocket, such as VASIMR.[3,4] The reactor recirculating power and the much smaller space vehicle auxiliary power can probably be met by thermal conversion of bremsstrahlung radiation from the plasma.

STEADY-STATE FRC PROPULSION CONCEPT

Unlike pulsed fusion systems, where the fusion ignition energy must be invested in every pulse from energy converted and stored from the preceeding fusion pulse, a steady fusion burn reactor has a low recirculating power fraction. This helps to reduce mass. Steady loads also relieve components from fatigue damage. Steady state permits the use of superconducting magnets that require little power. Magnet mass will be seen in the next Section to be low, a direct consequence of $\beta \approx 1$ in the FRC. Since steadily burning fusion reactors produce large powers, they are best suited for missions requiring high power.

FRCs are traditionally considered to be pulsed plasmas.[2] However, FRCs have long been generated and sustained in steady state by rotating magnetic field (RMF) current drive in the small, spherical ROTAMAK experiments.[5] RMF is akin to the familiar induction motor, but in a plasma the induction torque is made to act preferentially on the electrons. The electrical power required is on the order of the plasma Ohmic drive power, which is negligible in hot plasmas at fusion temperatures. The low frequency AC power for RMF can be generated efficiently. RMF current drive was recently extended to conventional elongated FRCs.[6] These new experiments showed that plasma confinement improves during RMF.[7] Although the origin of the improved stability is not yet definitively identified, RMF is known to generate a weak internal *toroidal* magnetic field[8,9] and numerical simulations show such a field to be stabilizing.[10] Therefore, not only can FRCs be operated in steady state, they even appear to benefit from it.

Figure 1 is a sketch of a steady state, quasi-spherical (slightly oblate) FRC fusion reactor. The FRC plasma is confined by poloidal magnetic field produced by simple circular coils that encircle, but do not link the hot plasma. It is assumed that high-temperature superconducting magnet technology will available such that the coils will be limited only by mechanical stress imposed by the magnetic forces. A shield is needed to limit coil heating by neutrons emitted by minority DD and DT fusion in the plasma. If in the future the coil does not require refrigeration to e.g. ~100 K, the shield mass could be reduced accordingly. Bremsstrahlung radiation power is absorbed in the first wall, and it can be converted by a thermal cycle for plant recirculating power. Synchrotron power, though low among magnetic confinement concepts, must still be reflected as much as possible and absorbed in the plasma. Plasma diffusing into the scrape-off layer (SOL) carries the majority of the fusion power. It becomes rocket exhaust and/or is converted to electricity by an electrostatic direct converter. The relative plasma power flow between the rocket and the electric converter can be regulated to some extent by the difference between the magnetic mirror ratios of the two nozzle regions. If there is no electric converter, there can be two equal

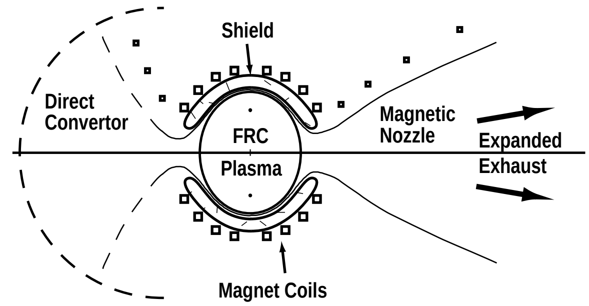

Fig. 1. Steady state, quasi-spherical (slightly oblate) FRC fusion reactor concept for space propulsion. A direct electric converter option is shown (dashed) on the left end.

rocket exhausts, each of which must be bent magnetically by 90° to aim the two thrusts in the same direction. The rocket exhaust temperature/density ratio, which determines the I_{sp}/thrust ratio, might be adjustable to some extent by the nozzle mirror ratio.

The FRC geometry is slightly oblate, in contrast to the highly prolate traditional FRC. There are two reasons for this choice. First, wall stabilization of large-scale MHD instabilities, and the tilt instability in particular, though weak, is stronger in oblate geometry. Even though FRC experiments are presently more stable than theoretically predicted, it seems prudent to choose the more stable configuration. Second, and more important, ignition is obtained with a smaller plasma volume in spherical than prolate FRCs, and smaller size reduces reactor mass. This follows from the fact that diffusive loss of plasma and energy, averaged over FRC magnetic surfaces, depends mainly on the square of the shortest distance between the hot core and the cool edge.[11] Thus, plasma elongation increases volume, but not confinement, if the diffusion coefficients are geometry independent.

The scaling of FRC confinement, both stability and diffusive transport, to plasmas of fusion interest is unknown at this time. Here it is assumed that the confinement will be sufficient at temperatures T ~ 100 keV and R_p ~ few meters. This means that the FRC diffusive loss must be as low or lower than that of an advanced tokamak.

FRC FUSION REACTOR SCOPING

This Section presents quantitative estimates of the FRC shield and magnet masses as a function of the plasma size, characterized by the plasma radius R_p in near-spherical geometry, and the total fusion power, P_f. The present study was too limited to quantitatively investigate and optimize the steady state, oblate, FRC fusion propulsion system. However, most of the system outside of the fusion and rocket core would be quite similar to the corresponding parts of the steady state ST (spherical torus or spherical tokamak) propulsion system that was recently studied in considerable detail at NASA Glenn Research Center by Williams *et al.*[12]

The first wall thermal power is

$$P_w = f_{heat} P_f / 4\pi R_w \quad . \tag{1}$$

Here f_{heat} is the fraction of P_f that heats the first few cm of wall (mainly bremsstrahlung and resistively dissipated synchrotron radiation power), and R_w is the first wall radius. P_w is plotted in Fig. 2 for $R_w = 1.1\ R_p$ and f_{heat} = 0.23. The latter number is from Ref. 12. The maximum allowable P_w is limited by heat removal technology to ~10^7 W/m^2. Therefore, multi-GW spherical plasmas must be at least R_p ~ 2–5 m in size.

The shield mass, treated as a uniform spherical shell, is

$$M_s = 4\pi\ R_s^2\ (\rho_s\ \Delta R_s). \tag{2}$$

Here R_s is the shield mean radius. The product of mass density ρ_s and shield thickness ΔR_s should be calculated from a neutron and photon shield code. Here the shield, including the first wall, is estimated to need about 750 kg/m^2 of neutron slowing and capture material and about 850 kg/m^2 of x- and γ-ray absorbing material. Thus, the shield and first wall total 1600 kg/m^2 and are about 0.7 m thick. A specific shield mass, defined as

$$(\alpha_s)^{-1} = M_s / P_f \quad , \tag{3}$$

is plotted in Fig. 3. Low power and large plasma radius yield unattractively large masses. The plasma should be as small as allowed by wall power considerations, e.g. $R_p \approx$ 4 m at 10 GW.

If the magnet coils are widely separated from one another, and if there are not many other radiation-sensitive components outside the coils, then the shield might only have to protect the front and sides of the coils. However, since neutrons scatter several times on average before being absorbed, this optimistic possibility seems rather unlikely.

Magnet system mass M_m scales as $(\rho_m/\sigma_m)\ R_m^3\ B_m^2$. Since M_m is quite insensitive to whether the magnet coils are treated as discrete bundles or a spherical shell, the simpler shell approximation is used here. Here ρ_m is the mass density and σ_m the stress, both averaged over the volume of the coil and its support structure. R_m is the mean magnet radius and B_m the magnetic field strength at the coil. It is related to the fusion power through the volume-averaged square pressure, $\langle p^2 \rangle \sim P_f / R_p^3$, and $\beta_m = \langle p^2 \rangle^{1/2} / (B_m^2 / 2\mu_0)$. For spherical FRCs, $\beta_m \approx 1$, with a weak dependence on the plasma pressure radial profile, confirming the high engineering β. Figure 4 shows $\langle p^2 \rangle^{1/2}$ vs. reactor size and power. At parameters allowed by the first wall loading, B_m < 10 T, small enough not to be restrictive. Figure 5 shows the calculated specific magnet mass,

$$(\alpha_m)^{-1} = M_m / P_f \quad . \tag{4}$$

Magnet mass is much less than shield mass. Therefore, future work should quantify the tradeoff among

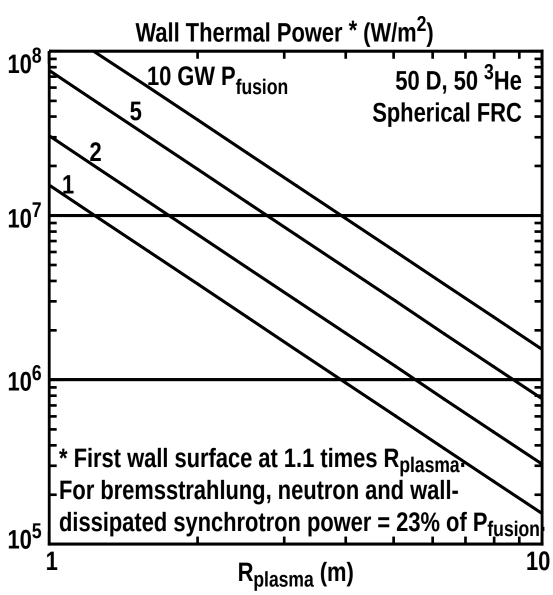

Fig. 2. P_w vs R_p with P_f as a parameter, for $R_w = 1.1\ R_p$ and $f_{heat} = 0.23$.

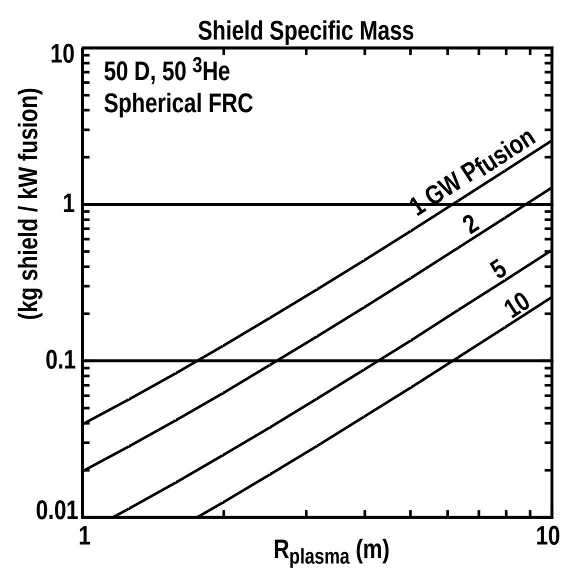

Fig. 3. Shield specific mass as defined in text. Same conditions as Fig. 2.

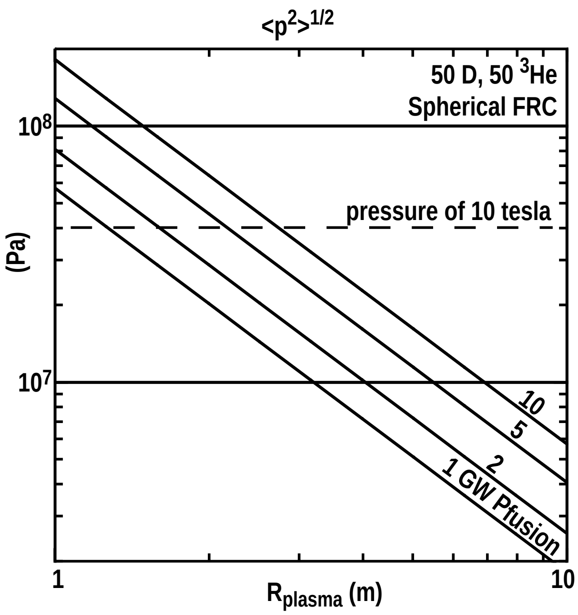

Fig. 4. Profile average (RMS) total plasma pressure vs R_p with P_f as a parameter.

shield mass, superconductor temperature requirements and refrigeration system mass, and the D-^{3}He fuel mix, which controls the mix of bremsstrahlung and neutron powers.

A POINT DESIGN

This Section presents parameters for a steady state FRC fusion reactor for space propulsion at a single operating point. In order to compare with the much more thorough NASA Glen ST-based system,[12] the FRC point design here is done for the same plasma fusion power, P_f = 8 GW. The FRC calculations are done for spherical geometry, rather than oblate, for simplicity. Selected results are given in Table 1.

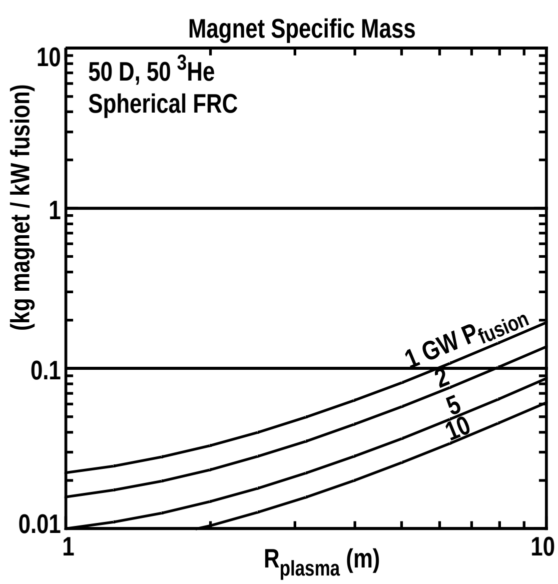

Fig. 5. Coil specific mass as defined in text. Same conditions as Fig. 2.

Table 1: FRC Fusion Reactor and Plasma Parameters

Fuel, assumed	50/50 D/^{3}He
First wall thermal power, assumed (W/m^2)	10^7
Plasma radius (m)	3.45
Plasma volume (m^3)	172
Shield specific mass (kg/kW)	0.0435
Shield mass (Mg)	348
RMS plasma pressure, $<p^2>^{1/2}$ (10^7 Pa)	2.50
Plasma internal energy (GJ)	6.45
Central plasma pressure (10^7 Pa)	4.90
$\beta_m = <p^2>^{1/2}/(B_m^2/2\mu_0)$	1
Average magnetic field at coil (T)	7.90
Magnet specific mass (kg/kW)	0.019
Magnet mass (Mg)	152
Shield + magnet mass (Mg)	500
Central temperature, assumed (keV)	100
Central ion density, D + ^{3}He (10^{20} m^{-3})	12.3
Central electron density (10^{20} m^{-3})	18.4
Plasma current (MA)	54
Required energy confinement time (s)	1.05
Number of contained ion gyroradii	~200

The high FRC β shows up in the unusually low (for D-^{3}He fuel) magnetic field and the correspondingly low magnet system mass. The shield mass is more than twice as great in this example. Future effort should optimize the propulsion system as a whole.

OTHER CONSIDERATIONS

The required energy confinement time given in Table 1 is the minimum confinement time consistent with having 6.45 GJ of plasma internal energy, 8 GW of fusion power and 23% or 1.84 GW in other than charged particles. It is probably an optimistic estimate. A confinement time of ~1 s in a plasma of this size is roughly on a par with advanced tokamak confinement. At the present time it is not known if FRC confinement can attain this level. Tokamaks, even STs, require much greater magnetic fields at the coils, and the toroidal field coils trap the plasma and make the implementation of direct exhaust rockets questionable. Therefore, research to discover the inherent limits of FRC confinement is both needed and justified.

The density and plasma current yield a normalized density, <n>/<J> that is about two times greater than the empirical rule of thumb limit of 10^{-14} $(A\ m)^{-1}$ that applies to tokamaks and reversed field pinches. J is the toroidal current density. In tokamaks this limit usually appears as a cooling or "plasma condensation" instability just inside the last closed magnetic surface. It is not known if this limit applies to FRCs, especially FRCs with very hot plasmas.

The fusion exhaust velocity is related to the average scrape-off layer plasma temperature, T_{SOL}, since the plasma is accelerated up to approximately the SOL ion thermal speed as it expands through the nozzle. For a 50/50 D/^{3}He plasma, a 250 eV plasma yields $v_{ex} \approx 1\times10^5$ m/s, and a 2.5 keV plasma yields $v_{ex} \approx 3\times10^5$ m/s. SOL plasmas of steady state laboratory FRCs strike a nearby wall and are strongly cooled, as in tokamak SOLs. With either a direct exhaust plasma rocket or a direct electric power converter the SOL exhausts to a very low density and is no longer in thermal contact with a solid surface. This SOL is akin to a magnetic mirror with similar end conditions. It is quite possible that T_{SOL} will exceed 2.5 keV, which would yield a higher exhaust velocity than desired for most space missions. In principle one can add cold material to the SOL upstream of the acceleration region to reduce T_{SOL}. At present it is not known how a hot FRC will respond to various SOL densities and temperatures. It will not be easy to investigate this problem experimentally in the laboratory, but the problem might be amenable to computational analysis.

The first wall need not be absolutely gas tight, but it must be tight enough that only a small fraction of the neutralized gas outside the SOL is lost. Otherwise, valuable mass would be lost having produced no propulsive effect. A suitably slotted first wall might permit the RMF current drive coils to be placed behind the wall, which would protect them from much of the wall heat load. The wall sealing and the RMF coil placement tradeoff must be studied.

SUMMARY AND CONCLUSIONS

The high β of field reversed configurations (FRCs) and their unlinked magnet topology appear to make possible a steady state D-^{3}He fusion power core appropriate for space propulsion. Since the specific power improves with total fusion power, this concept appears to be most appropriate for missions where a high power rocket must operate reliably for relatively long periods. Good plasma stability and confinement were assumed. FRC stability appears to be good in present and past experiments. FRC confinement is still quite uncertain, but it is encouraging that confinement improves with RMF current drive, hence with steady state operation. Continued and expanded FRC experiments are urgently needed to provide a firm physics basis for the concept. The brief study presented in this paper identified the shield as the largest mass component, and further study to reduce shield mass is recommended.

ACKNOWLEDGMENT

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