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SYNCHROTRON RADIATION FUSION DRIVE FOR SPACE PROPULSION

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This paper explores the idea of using synchrotron radiation generated by a fusion energy source to sustain a plasma thruster, a concept called synchrotron radiation fusion drive (SRFD). A high-temperature, high-magnetic-field fusion device will produce copious synchrotron radiation but will require excellent plasma energy confinement. The synchrotron radiation can be carried by waveguides and absorbed in a magnetic-mirror plasma thruster with appropriately resonant magnetic field profiles. Analyses of critical issues and systems plus preliminary parameters are presented. The basic SRFD concept appears feasible using conventional versions of the presently leading magnetic fusion configuration, the tokamak. The resulting design, however, does not achieve the performance of which the SRFD concept should be capable. Basing the design on a higher specific-power device for the synchrotron generator appears necessary to make SRFD truly attractive. Some possibilities for this generator include high-field, advanced tokamaks or linear fusion devices with high-field cells.

Introduction

Concepts for fusion space propulsion[1,2] arose almost as early as ideas for producing terrestrial fusion electric power. The attractive features of fusion energy for space applications include the high exhaust velocity of hot plasmas and predicted high specific power (thrust power/mass of power and thrust systems). The projected peformance of fusion rockets compared to various alternatives appears in Fig. 1.[3] Such capabilities would lead to fast missions or high payload fractions for long-range missions.

The fuel cycle of choice for magnetic fusion propulsion usually has been deuterium and helium-3 (D-^{3}He), for reasons discussed in the section on fuel cycles. Because D-^{3}He fuel requires relatively high plasma temperatures ($\geq$ 50 keV; 1 eV= 11 604 K) compared to deuterium-tritium (T) fuel ($\geq$ 5 keV), it produces copious synchrotron radiation ($\propto B^{5/2}T^{5/2}$, where $B \equiv$magnetic field and $T \equiv$plasma temperature) in high-magnetic-field configurations. Concepts

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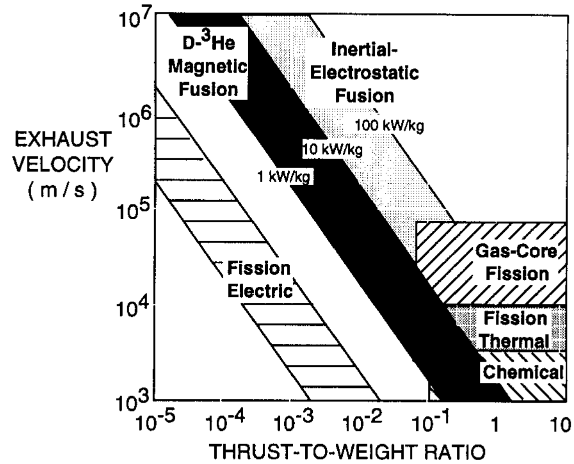

Fig. 1 Predicted performance of fusion rockets.

for utilizing synchrotron radiation for tokamak current drive[4] or direct conversion to electricity[5,6] have been proposed. The present paper examines another possibility, called synchrotron radiation fusion drive (SRFD) and shown in Figs. 2 and 3, that suitably resonant magnetic-mirror chambers could absorb waveguided, separately produced synchrotron radiation to sustain a plasma. Exhausting the plasma mainly out one end of these chambers would produce thrust.

This paper describes the results of the initial stages of this project. As such, critical issues have provided the primary focus rather than systems integration or overall figures of merit, and optimization has been minimal. Subsequent sections discuss plasma physics and fuel cycles, the synchrotron-radiation generator, waveguides, thrusters, protection of magnets from radiation, conclusions, and future directions.

Fuel Cycles

The main fusion fuel options for space applications are

$$\begin{aligned} D + {}^3He &\rightarrow p(14.68\ MeV) + {}^4He(3.67\ MeV) \\ D + T &\rightarrow n(14.07\ MeV) + {}^4He(3.52\ MeV), \end{aligned}$$

where p ≡proton, n ≡neutron, and ^{4}He ≡ α particle. The trade-offs between these fuels are that the D-T reaction has a higher cross section that peaks at a lower temperature, but the D-^{3}He fusion products are charged and much of this energy potentially becomes available for direct thrust. The D-T fuel cycle burns most easily, but it produces 80% of its energy

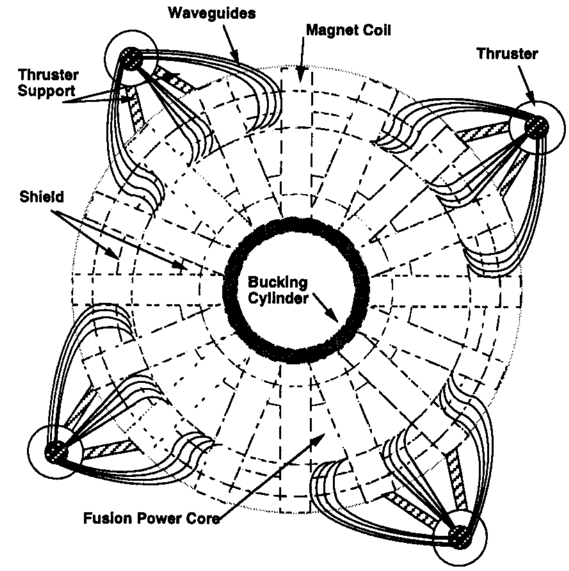

Fig. 2 Cross-sectional, midplane view of the synchrotron radiation fusion drive (SRFD) concept.

as isotropic neutrons, whose energy must be converted to electricity at relatively low thermal efficiency and with consequent large shielding and radiator masses. The fusion-product neutrons in the D-T case, unfortunately, cannot be used for thrust except by converting their thermal energy to electricity at relatively low efficiency and driving an electric thruster. The resulting large amount of waste heat to be rejected also requires a large radiator mass. For these reasons, most researchers have concluded that D-^{3}He fuel will give better performance for space propulsion.[7–10] The D-^{3}He fuel cycle is not completely free of neutrons, however, because of the reactions

$$\begin{aligned} D + D &\rightarrow n(2.45\ MeV) + {}^3He(0.82\ MeV)\ (50\%) \\ D + D &\rightarrow p(3.02\ MeV) + T(1.01\ MeV)\ \ (50\%) \end{aligned}$$

If the tritium produced in the second D-D reaction burns in the power-plant main fusion chamber, further neutrons are produced. Consequently, D-^{3}He fusion power cores typically have 1–5% of their total power in neutrons.

The field of D-^{3}He fusion research lay fallow for many years due to the scarcity of ^{3}He on Earth. The ^{3}He resource problem was solved, in principle, by the identification of a large potential resource of ^{3}He (~10^9 kg) on the Moon.[11,12]

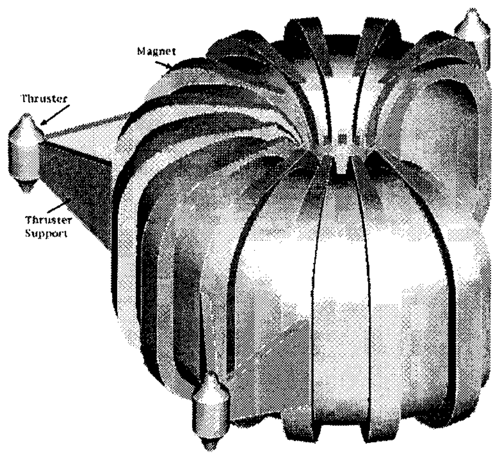

Fig. 3 Basic synchrotron radiation fusion drive (SRFD) configuration.

Although lunar ^{3}He mining will be a substantial endeavor, the existence of a lunar ^{3}He fuel depot is a consistent assumption on the time frame of the development of fusion energy and moderate-scale space operations. By the time large-scale space activities become routine, the immense ^{3}He resources of the gas-giant planets should be accessible, making ^{3}He an essentially inexhaustible fuel.

Synchrotron Radiation Physics

Synchrotron radiation, sometimes called cyclotron radiation, is generated by the gyration of electrons and ions around magnetic field lines. The loss of synchrotron radiation from a plasma involves a complicated process of emission, reflection from the chamber walls, and reabsorption during multiple passes through the plasma. For a given magnetic fusion configuration, the total synchrotron radiation power loss can be reasonably well approximated.[13,14]

The spectrum of the synchrotron radiation, however, is more difficult to calculate, and loss usually peaks at the tenth to twentieth harmonic for D-^{3}He plasma temperatures.[15] Because of Doppler broadening and the large number of harmonics involved, a continuous spectrum up to about the 30th harmonic is emitted. Reflections from the chamber walls tend to depolarize the radiation, so it can usually be assumed to have a random polarization. The chamber walls are chosen to be highly reflecting, while the waveguides penetrating the walls would be nearly total absorbers, so most of the synchrotron radiation produced would be lost out the waveguides rather than absorbed in the first wall.

To use synchrotron radiation effectively for propulsion, leverage must be gained by allowing a high fraction of the plasma losses to be in the form of synchrotron radiation. This places more stringent requirements on energy confinement, because the synchrotron radiation is an added energy-loss channel. The total synchrotron power loss is proportional to $(BT)^{5/2}$, so high synchrotron radiation fractions push parameters toward high magnetic fields and temperatures higher than optimum from a power-density viewpoint. About half of the total D-^{3}He fusion power could be allowed to leave the plasma as synchrotron radiation, which would require an increase in the energy confinement parameter $n\tau_E$ (density times energy confinement time) of about ten times over the needed value for D-T fuel.

Synchrotron Radiation Generator

The key difficulty in utilizing synchrotron radiation for fusion propulsion is that the magnetic fusion configurations which can most easily produce copious amounts of synchrotron radiation do not generally have power-to-mass ratios that are attractive for space applications. The synchrotron radiation source chosen for the initial phase of this project is a D-^{3}He tokamak fusion power plant operating at high temperature and high magnetic field to increase the synchrotron radiation emitted by the plasma. The design is based partly on conceptual designs of terrestrial D-^{3}He fusion power plants for electricity production.[16,17]

In order to maintain a power balance on the plasma in the presence of a large amount of synchrotron radiation, operation in the magnetohydrodynamic (MHD) second-stability regime is assumed; this permits a relatively high tokamak beta (ratio of plasma pressure to magnetic field pressure) of 15%. Key parameters for the synchrotron-radiation generator are summarized in Table 1. In order to maintain a plasma power balance and to provide control of the plasma, 100 MW is assumed to be injected into the plasma by an auxiliary heating system. Ion channeling[18] has been invoked to increase the fraction of fast ion energy deposited in the ions and thereby help sustain the high ion temperatures and fusion reactivity. Sufficient ion channeling is needed roughly to double the fast proton energy deposited in the ions.

Table 1 Synchrotron Generator Parameters for SRFD Space Propulsion System

Parameter	Value
Geometry	toroidal
Design basis	tokamak
Fuel	D-^{3}He
Fusion power, MW	4932
Input power, MW	100
Neutron power, MW	139
Transport power, MW	711
Bremsstrahlung power, MW	1754
Synchrotron radiation power, MW	2429
Synch. power fraction to waveguides	0.87
Ave. fuel-ion density, m^{-3}	2.2×10^{20}
Ave. ion temperature, keV	78
Confinement parameter ($n\tau_E$), m^{-3} s	3.37×10^{21}
β (plasma pressure/B-field pressure)	0.15
Major radius, m	7.0
Minor radius, m	2.24
Elongation	1.8
Plasma volume, m^3	1170
Plasma current, MA	46
On-axis B field in plasma, T	11
Peak B field on coils, T	19
Total first wall area, m^2	1080
Waveguide area at FW, m^2	108
Ave. Surface heat flux, MW/m^2	1.91
Ave. neutron wall load, MW/m^2	0.13
Total mass, Mg	~9000
Q, P_{fus}/P_{in}	48
Generator specific power, kW/kg	~0.55

An issue with tokamak plasmas is sustaining the plasma current for steady-state operation. The plasma current is 46.4 MA; this is generated partly by the so-called bootstrap current (31 MW) and the rest by synchrotron radiation. Synchrotron radiation generates a plasma current by removing the radiation asymmetrically through the waveguides in the toroidal direction; this produces a net force on the electrons and drives a toroidal current.

The He:D fuel density ratio is 1.3:1 in order to minimize neutron production due to side D-D reactions. D-^{3}He fusion reactions generate protons and ^{4}He, while D-D reactions generate tritium, so the net ion mixture in the plasma is 35% D, 45% ^{3}He, 9.6% protons, 9.4% ^{4}He, 0.2% tritium, and 0.8% impurity (taken to be beryllium because of the first wall material).

Waveguides

Highly overmoded waveguides can be used for transporting the synchrotron radiation from the plasma core to the thruster chamber. The waveguide walls must be excellent reflectors of synchrotron radiation and be made of material that allows high-temperature operation in order to radiate heat efficiently. The dispersion-hardened copper alloy Glidcop has been chosen for the waveguides, because it possesses excellent thermal and electrical conductivity. At temperatures of present interest, the thermal conductivity is approximately 300 W/m·K, while the electrical resistivity (1/conductivity) is a nearly linear function satisfying

$$\rho = (1.8624+7.041*10^{-3}T+2.15*10^{-7}T^2)\times10^{-8}\Omega\cdot\text{m},$$

where $T \equiv$temperature (°C). For an operating temperature of ~800 °C, the electrical conductivity is ~$1.3 \times 10^7\ \Omega^{-1}m^{-1}$. For a similar terrestrial design, waveguide losses were predicted to be less than 3-5% for circular waveguides with a ratio of length to diameter of 30,[19] and 3% was chosen for the present base case. Waveguide theory is reasonably well developed,[20] and optimized waveguides will be designed as the SRFD concept evolves.

A symmetric arrangement of the thrusters around the tokamak was chosen, because it simplifies the design of other systems, such as control and guidance systems. The design presented here consists of 48 waveguides of rectangular cross section (0.33 m width and 4.75 m height). This is ~30% lower than the total waveguide area (108 m^2) to which synchrotron generator case evolved, but the difference could be handled by relatively minor design modifications. Future, optimized generator cases are also likely to be at lower power levels, requiring perhaps even less waveguide area than used in this section. The waveguide lengths are approximately 10 m each. The waveguides are divided into four groups of 12, with each group feeding one thruster. One quadrant of the general configuration appears in Fig. 4.

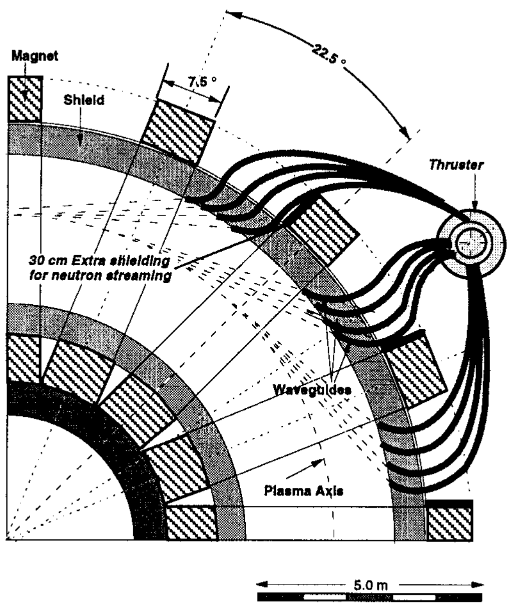

Fig. 4 Details of the waveguide geometry for the synchrotron radiation fusion drive (SRFD) concept.

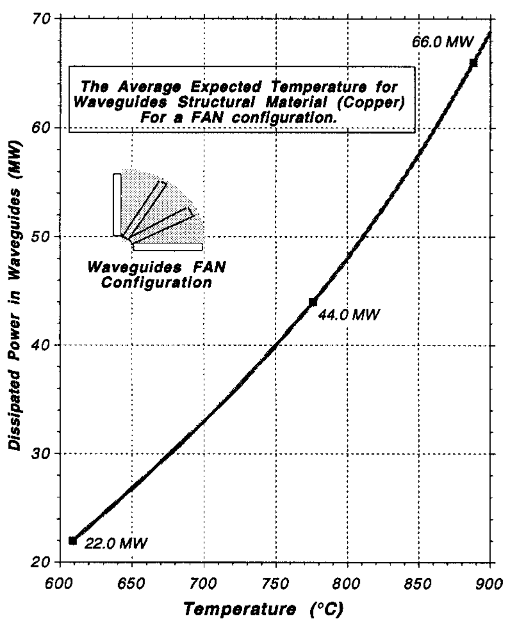

Fig. 5 Waveguide temperature compared to dissipated power.

To facilitate the use of the absorption of synchrotron radiation for plasma current drive, the waveguides are aimed tangentially to the plasma toroidal axis. The waveguide temperature as a function of the total power dissipated in all waveguides is shown in Fig. 5. The nominal base-case power of 63 MW dissipated would be radiated to space and lead to high waveguide temperatures (880 ^{o}C). If such power levels remain necessary for future optimized cases, more waveguides or the addition of radiators would possibly be needed to reduce this temperature. To allow the waveguides to radiate efficiently, the view factor between the waveguide walls and space was optimized. Several geometrical arrangements were examined, and a fan-like solution was chosen, as shown in the inset of Fig. 5. Waveguide parameters are exhibited in Table 2.

Table 2 Waveguide Parameters for SRFD Space Propulsion System

Parameter	Value
Number	48
Synchrotron power to waveguides, MW	2113
Power dissipated in waveguides, MW	63
Length, m	~10
Width, m	0.33
Height, m	4.75
Thickness, m	0.01
Reflector material	Cu
Reflector temperature, ^{o}C	880
Structural material	Ti

Thrusters

The thrusters will be linear magnetic-mirror plasma containment devices, with the plasma flow out one end reduced in order to give direct thrust out the other end. This can be accomplished, for example, by slightly increasing the magnetic-mirror field on one end, because the ion collisional mean free path is much larger than the device length and cumulative small-angle scattering dominates large-angle scattering. Almost all ions bounce between the magnetic mirrors many times before they scatter into the mirror "loss cone," so they will scatter into the low-field loss cone before they have time to diffuse sufficiently in angle to reach the high-field loss cone. Figures 6 and 7 illustrate this

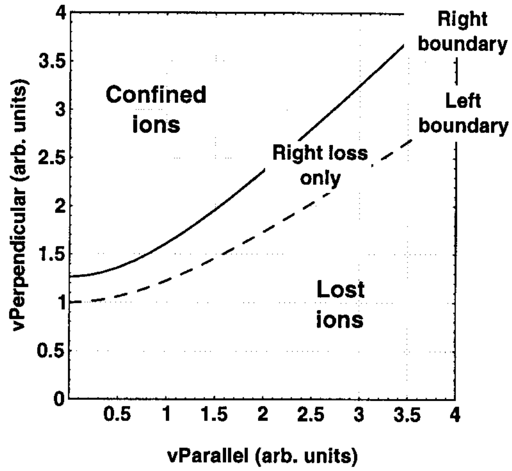

Fig. 6 Magnetic mirror ion phase space.

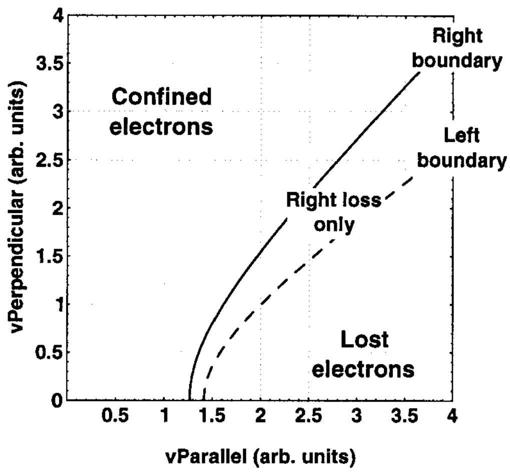

Fig. 7 Magnetic mirror electron phase space.

physics schematically for somewhat exaggerated parameters: relative left-right asymmetries of 3:2 in mirror ratio and 0.8:1 in electrostatic potential. The thrusters will be physically symmetric about their midplanes, so that thrust can be produced in the opposite direction by changing the relative magnitudes of the end coil currents and, therefore, their magnetic fields and the resulting magnetic mirror ratios.

No fusion power will be produced in the thrusters. The plasma will be sustained by absorption of synchrotron radiation carried by the waveguides from the fusion core. A copper envelope inside the magnets will surround the plasma, so that multiple passes of the incoming synchrotron radiation will occur and enhance absorption. The ends of this envelope will be open to allow escape of the plasma for thrust production. Efficient absorption will require optimization and compromises for the mirror thruster design, particularly with regard to the details of the magnetic field and the plasma parameters. This optimization has not yet been performed on the present design. Representative parameters for the case of a total system thrust-to-weight ratio of 10^{-3} are shown in Table 3. The consistency of these parameters with the synchrotron radiation absorption remains to be determined.

Two main options exist for the magnet configuration in the thrusters: (1) axisymmetric or (2) minimum-B. Axisymmetric coils will require radio-frequency (RF) power input for MHD stability. A minimum-B mirror automatically possesses MHD stability due to the inward curvature of its magnetic field, but its magnets are much more complicated and massive. The thrusters chosen for the present design are RF-stabilized axisymmetric magnetic mirrors. The waveguided synchrotron radiation will be aimed at the high magnetic fields near the mirror throat at angles nearly perpendicular to the field, because this is predicted to give good absorption.[21]

Each thruster is attached to the structure of two magnets by support legs. Titanium was chosen for the support-leg material, because it performs reasonably well at elevated temperatures. The total system mass is roughly 9000 Mg and the maximum system design acceleration has been chosen to be 10^{-2} Earth gravity, or about 0.1 $m \cdot s^{-2}$. Each thruster will, therefore, experience a force of ~0.225 MN along its centerline. Representative thruster parameters are given in Table 3.

Magnet Shielding

Adequate shielding of the superconducting magnet is required to reduce radiation effects in the magnet. An enriched LiH (90% ^{6}Li) shield is used to protect the superconducting magnet against neutrons and gamma rays. The LiH shield is selected because of its efficiency and low total mass. A 30 cm thick shield is used to protect the magnet from neutrons streaming from the plasma and through the waveguides. The calculations assumed 3 years of operation and special attention was given to the following:

Table 3 Representative Plasma Thruster Parameters for SRFD Space Propulsion System (Thrust-to-Weight Ratio = 10^{-3})

Parameter	Value
Number	4
Geometry	magnetic mirror
Fuel	H
Length, m	5
Ave. radius, m	1
Plasma volume, m^3	16
Ave. B field in plasma, T	6
B field at mirror throat, T	10
Peak B field on coils, T	12
Superconductor	NbTi
Structural material	Ti

- radiation damage to the copper stabilizer,
- nuclear heating induced in the coil case and winding pack,
- end of life fluence, and
- end of life insulator dose.

Radiation damage to the copper stabilizer increases the resistivity and affects the magnet stability. A low nuclear heating in the magnet is required to avoid high cryogenic loads. A high fast neutron fluence ($E_n > 0.1$ MeV) results in a significant degradation of the critical properties of the superconducting magnet. In addition, the end of life dose to the epoxy insulator should be kept low to insure its electrical and mechanical integrity.

In this paper, we used the limits adopted in the International Thermonuclear Experimental Reactor (ITER) Engineering Design Activity (EDA) for magnet protection.[22] Table 4 shows the results obtained at the end of life as well as the limits used in the analysis.

As shown in Table 4, a 30 cm LiH shield would provide the magnet with adequate shielding. The damage to the stabilizer, the end of life fluence, as well as the nuclear heating would be well below the limits set by ITER for magnet protection. Only the end of life insulator dose would be within a factor of two of the limits.

Table 4 Peak Neutronic Results for a 30-cm LiH Shield

	SRFD	Limits
Radiation damage to the copper stabilizer (dpa)	2.6×10^{-5}	6×10^{-3}
Nuclear heating in the winding pack (mW/cm^3)	0.143	1
Nuclear heating in the coil case (mW/cm^3)	0.373	2
End-of-life fluence ($E_n >$ 0.1 MeV)	3.75×10^{17}	1×10^{19}
End-of-life insulator dose (rad)	5.5×10^{8}	1×10^{9}

Summary and Future Directions

A summary of the total system parameters is given in Table 5. Each of the main systems—synchrotron radiation generator, waveguides, and thrusters—appears feasible. The present base-case SRFD design, however, because it is based on a 'conventional' tokamak, does not appear particularly attractive for space propulsion, except perhaps when extrapolated to very high power levels where economy of scale could become a factor. The base-case design, for example, does not achieve the performance predicted for direct particle exhaust systems that was illustrated in Fig. 1.

Table 5 Preliminary Total System Parameters for SRFD Space Propulsion System

Parameter	Value
Specific power, kW_{thrust}/kg	~0.2
Thrust power, MW	~2000
Total mass, Mg	~9000
Thrust efficiency, %	~40
Maximum design acceleration, m/s^2	0.01

Two main directions for improvement of the synchrotron radiation generator have been identified and will be pursued in subsequent phases of the present project: (1) advanced toroidal systems and (2) linear systems. Higher performance would be gained in both cases by operating at much higher specific powers than in conventional tokamaks. The plasma power density scales approximately as $\beta^2 B^4$ for constant density and temperature. Conventional tokamaks operate at low β values and near magnet technology limits, so they are unlikely to perform much better than the present base case.

Some advanced toroidal concepts might be able to operate at higher β values, and the resulting conceptual power-plant designs typically optimize at modest magnetic-field values. In such designs, it may be possible to raise the magnetic field as a whole. The spherical torus (ST)[23] or low-aspect-ratio tokamak is a prime candidate configuration for such operation.

High-power-density linear concepts, such as the field-reversed configuration (FRC)[24] and spheromak,[25] are intrinsically high-β systems. The optimum magnetic field for FRC-based conceptual designs is usually low ($\leq$5 T), resulting in little production of synchrotron radiation. One solution to the problem of generating synchrotron radiation may be to include a high-field section as part of a low-field solenoid in a linear system such as an FRC or tandem mirror. In principle, this should not reduce the MHD stability β limit significantly, but it should enhance the synchrotron production substantially in that section. In toroidal configurations the option of increasing the magnetic field in a single section does not appear viable.

Three other important future directions are (1) refining the accuracy of waveguide and thruster calculations, (2) optimizing performance, and (3) integrating the various systems into a coherent whole.

Acknowledgments

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