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Magnetic Configuration of a Reduced-Mass Gasdynamic Mirror Fusion Propulsion System[*]

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Abstract

The gasdynamic Mirror (GDM) Fusion Propulsion System is a simple mirror magnetic confinement machine in which the ion-ion collision mean free path is significantly shorter than the length of the device. Under these conditions the plasma behaves like a fluid and is governed by gasdynamic laws which show the confinement time to vary directly with the plasma mirror ration and inversely with the plasma thermal velocity. Large mirror rations are, therefore, desirable but they also imply large magnetic fields at the mirrors and that means large magnets and large vehicle masses. An effective way of dealing with this problem is to have a mirror machine whose central field extends and includes the mirror region but at a plasma radius that is normally dictated by the mirror ratio and the mirror magnet. This can be accomplished through the use of filed-reversal techniques, whereby a magnetic field of the same strength as the central field is generated at the mirror point at a radius that has already been determined by the conventional mirror analysis. A rotating magnetic field can be employed to induce the azimuthal current that gives rise to the desired field at the selected location. It is shown that the new magnetic configuration is quite feasible for a propulsion system and does result in a significant reduction of its mass.

Introduction and Basic Analysis

The GDM propulsion device is basically a simple mirror machine (see Fig 1) which confines a hot plasma long enough to allow fusion energy to be produced while allowing a certain fraction of its charged particle population to escape from one end to produce thrust. The plasma will be of such density and temperature as to make the ion-ion collision mean free path much shorter than its length. Under these conditions the plasma behaves like a continuous medium- a fluid, and its escape from the device is analogous to the flow of a gas into vacuum from a vessel with a hole. The confinement properties in GDM can b summarized as follows:[1]

$$\frac{\lambda}{R} << L \qquad (1)$$

$$R = \frac{R_o}{\sqrt{1-\beta}} \qquad (2)$$

$$\beta = \frac{nkT}{B_v^2/8\pi} \qquad (3)$$

$$\tau = \frac{RL}{v_{th}} \qquad (4)$$

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Here λ, is the collision mean fee path, R the plasma mirror ration, R_o the vacuum mirror ratio, L the length of the plasma, n the plasma density, T the plasma temperature, k the Boltzman constant, v_{th} the thermal velocity and B_v the central vacuum magnetic field. It has been show[2] that moderate size systems with stable plasmas are obtained for large R and β values, specifically $R = 100$ and $\beta = 0.95$. Since R is also the ratio of the plasma area in the center to that at the mirror, then $R = 100$ corresponds to a radii ratio of 10, and for the example given in table 1, $r_c = 5$cm and $r_m = 0.5$ cm. The same example also reveals that $B_v = 10$ Tesla, and from Eq(2) we see that $R_o = 22$ for $R = 100$ and that means that the mirror field in this case in $B_m = 220$ Tesla. This is an enormously large field whose mass is estimated at 300 mT making the total vehicle mass about 713 mT instead of the 413 mT shown in the table. The thrust of this study is to find ways by which the central field of 10 Tesla can be created at the mirror region at a plasma radius of 0.5 cm. This makes the plasma in effect experience a mirror ration of 100 without employing the massive mirror magnet. The use of the field-reversal technique allows us to accomplish such an objective, and that will be described in the next section.

Field-reversed Mirror Region

As noted above, the objective is to generate a field at the mirror equal to that of the central field but as the small radius dictated by the mirror ratio. We achieve this by creating a field-revesed configuration in the mirror region as illustrated in Fig 2. An approach used by the University of Washington[3] in creating field-reversed configurations can be employed in which a rotating magnetic field (RMF) with frequency ω is utilized. As illustrated in Fig 3, an antenna is employed to generate the RMF and that in turn induces the azimuthal current that gives rise to the desired magnetic field at the desired location. The conditions that must be satisfied are the penetration conditions given by

$$\omega_{ce} >> \omega >> \omega_{ci} \qquad (5)$$

$$\omega_{ce} > \upsilon_{ei} \frac{a}{g} \qquad (6)$$

The first implies that the frequency of RMF be much larger than the ion gyrofrequency in this field and much smaller than the electron gyrofrequency so as to guarantee that only the electrons participate in the formation of the azimuthal current while the ions remain effectively "frozen". The second condition ensures that collision of the electrons with the plasma ions (υ_{ei}) does not disrupt the formation of this current and that is guaranteed by making the effective collision frequency (the r.h.s. of Eq (6)) much smaller than the electron gyrofrequency ω_{ce}. The quantity "δ"is the classical skin depth give by

$$\delta = \frac{2\eta}{\mu_o \omega}^{\frac{1}{2}} \qquad (7)$$

where η is the plasma resistivity and μ_o the magnetic permeability. The quantity "a" in Eq (6) represents the radius of the "separatrix" where the magnetic flux function vanishes and it corresponds to the plasma radius at the mirror alluded to earlier. Noting that

$$\upsilon_{ei} = \frac{ne^2}{m_e}\eta \qquad (8)$$

where e is the electron charge, and m_e the electron mass, condition (6) can be rewritten as

$$\omega_{ce} > \frac{n^2 e^4}{m_e^2}\eta\omega\mu_o a^2 \qquad (9)$$

Noting further that we can also write for a deuterium ion

$$\omega_{ci} = 4.7 \times 10^3 B_w(G) \qquad (10)$$

where B_w is the rotating field strength in gauss, condition (5) can be satisfied by choosing

$$\omega = 500\omega_{ci} = 2.5 \times 10^6 B_w(\mathrm{G}) \qquad (11)$$

combining (11) and (9) we find

$$B_w > e^2\eta\mu_o(2.5 \times 10^{10})a^2 \qquad (12)$$

and if we apply this result to the GDM case at hand we obtain

$$B_w > 32\,\mathrm{G} \qquad (13)$$

It remains to find out whether the plasma in GDM is adequate to generate a field at a =0.5 cm equal to the central field. For that we employ the expression

$$B(r) = \frac{\mu_o e\omega}{2\pi}N(r) \qquad (14)$$

where the electron line density in a shell between 0 and a is given by

$$N(a) = \int_0^a 2\pi r n(r) dr \qquad (15)$$

Setting $B(a)$ = 10 Tesla, $n = 10^{22}\mathrm{m}^{-3}$, and ω from Eq. (11) we get

$$B_w = 78\,\mathrm{G} \qquad (16)$$

which automatically satisfies the penetration condition (13).

In order to estimate the mass savings that results from the use of the field-reversed configuration in GDM we turn to calculating the power required to drive the rotating magnetic field. Assuming that power goes into dissipation in the plasma (ohmic heating) we can write

$$\left(\frac{dW}{dt}\right)_{ohmic} = \int_0^{2\pi}\int_0^{a} \eta J_\theta^2 l r dr d\theta \qquad (17)$$

where l is the length of the plasma under the antenna. For the case at hand l =1m, and upon satisfying the remaining parameters we find that

$$\left(\frac{dW}{dt}\right) = 4.3 MW$$

Using the same scaling as employed in calculating the masses in table 1, we find that the mass of the power supply is about 0.145 mT. Which is drastically less than the 300 mT we would have had to use had we employed a mirror magnet to provide the mirror ratio we utilized in calculating the performance of the GDM propulsion system.

Conclusion

We have demonstrated in this paper the feasibility of employing field-reversal in the mirror region of the GDM propulsion system to effectively do away with large mirror magnets while allowing the plasma to experience the desirable large mirror ratio required for moderately sized systems. We have shown that the mass saving resulting from this approach is indeed very sizable, and the plasmas that characterize GDM propulsion are amenable to this scheme.

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[1] T.Kammash and M.J. Lee, J. Propulsion and Power **11**, 544 (1995)

[2] T. Kammash, M.J. Lee and D.I. Poston, J. Propulsion and Power **13**, 421(1197)

[3] K.Miller, J.Slough, and A. Hoffman, AIP Conf. Proceedings 420, Part3, p.1352(1198)

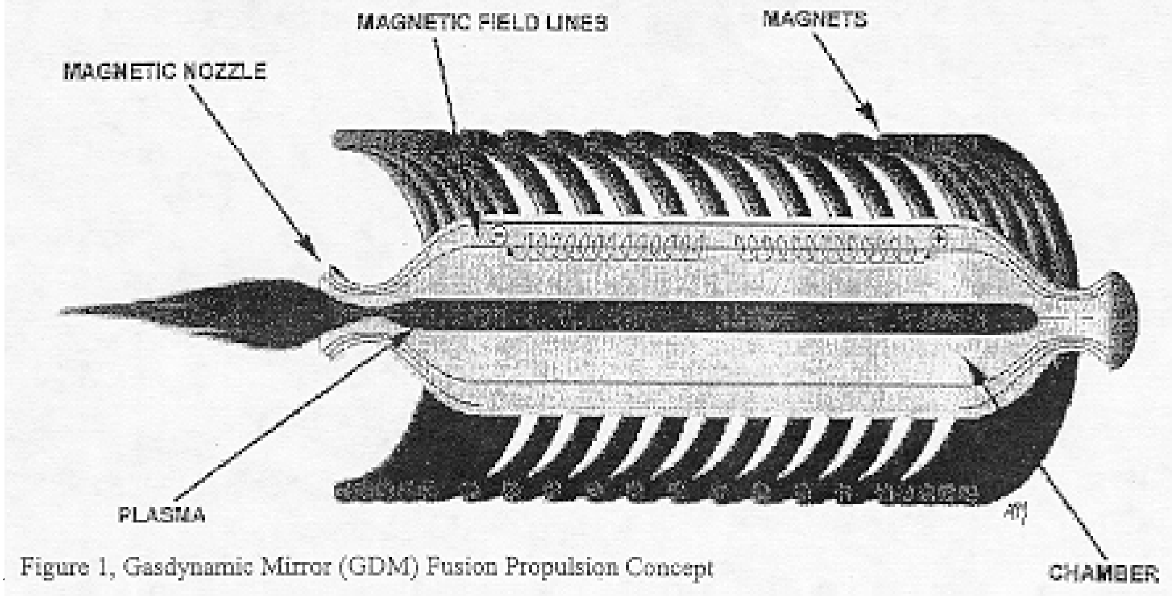

Figure 1, Gasdynamic Mirror (GDM) Fusion Propulsion Concept

Parameter	Value
Plasma Density (cm^{-3})	1 x 10^{16}
Plasma Temperature (keV)	10
Plasma Mirror Ratio	100
Beta Value	.95
Central Magnetic Field (tesla)	9.21
Plasma Radius (cm)	5
Plasma Length (m)	43.71
Confinement Time (sec)	4.07 x 10^{-3}
Fusion Power (MW)	2.73 x 10^{3}
Injection Power (MW)	2.24 x 10^{3}
Bremsstrahlung Power (MW)	58.17
Synchrotron Power (MW)	18.94
Neutron Power (MW)	2.19 x 10^{3}
Thrust Power (MW)	1.35 x 10^{3}
Thrust (N)	2.51 x 10^{3}
Reactor Mass	55.50
Injector Mass	45.40
Engine Mass (Reactor + Injector)	100.90
Thermal Converter Mass (Mg)	45.90
Direct Converter Mass (Mg)	27.50
Radiator Mass (Mg)	248.60
Total Vehicle Mass (Mg)	422.90
Specific Impulse (sec)	1.268 x 10^{5}
Specific Power (kW/kg)	13.40
Mars Round Trip Time (days)	169

Table 1, GDM Parameters for DT fuel cycle.