PHYSICS BASIS FOR THE GASDYNAMIC MIRROR (GDM) FUSION ROCKET

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Abstract

A detailed examination of the physics principles that underlie the operation of the GDM fusion confinement system is carried out in order to assess its transformation to a potential propulsion device. With an ion collision mean free path much shorter than its length, the plasma in GDM behaves like a fluid, and its escape from the chamber is analogous to the flow of a gas into vacuum from a vessel with a hole. A characteristic confinement time is shown to vary directly with the product of plasma mirror ratio and length, and inversely with the mean velocity of the plasma. Very efficient utilization of the confining magnetic field as reflected by a high beta (ratio of plasma pressure to magnetic field pressure) has been demonstrated analytically and experimentally. Presence of the plasma in the expansion region of the (mirror) magnetic nozzle leads to hydromagnetic stability for large mirror ratios that is further augmented by Finite Larmor Radius effects which are intrinsic to high aspect ratio devices. Confinement is also shown to be insensitive to "loss cone" microinstabilities and anisotropy-driven modes, while particles transport across the magnetic field is shown to be classical and negligible compared to axial transport under normal operating conditions. These and other considerations underscore the suitability of GDM as a propulsion device driven by fusion nuclear reactions. As such, it is further shown that it is capable of a propulsive performance that can lead to man's exploration of the solar system and beyond in relatively short times.

INTRODUCTION

Several magnetic and inertial fusion concepts have been proposed in recent years as potential propulsion devices that could meet the needs of space explorations of the near future. Invariably the suitability of these devices for such applications is based on a performance that assumes predictable plasma dynamics and confinement which may not have been established nor projected to be so anytime soon. Clearly, the less understood the underlying physics is the more challenging and distant the transition to an operating propulsion system will be. This is universally true, though to varying degrees, for all proposed fusion schemes with the possible exception of the gasdynamic mirror concept illustrated in Fig. 1. This device makes use of a simple magnetic mirror geometry in which a hot dense plasma is confined such that the ion collision mirror free path is much shorter than its length. Under these conditions the plasma behaves much like a continuous medium- a fluid. Its escape from the mirror end, which serves as a magnetic nozzle, is analogous to the flow of a gas into vacuum from a vessel with a hole as dictated by gasdynamic laws. In the remainder of this paper we will examine the confinement properties and address the various issues pertaining to plasma equilibrium, stability, and transport that underlie its ultimate utilization as a propulsion device.

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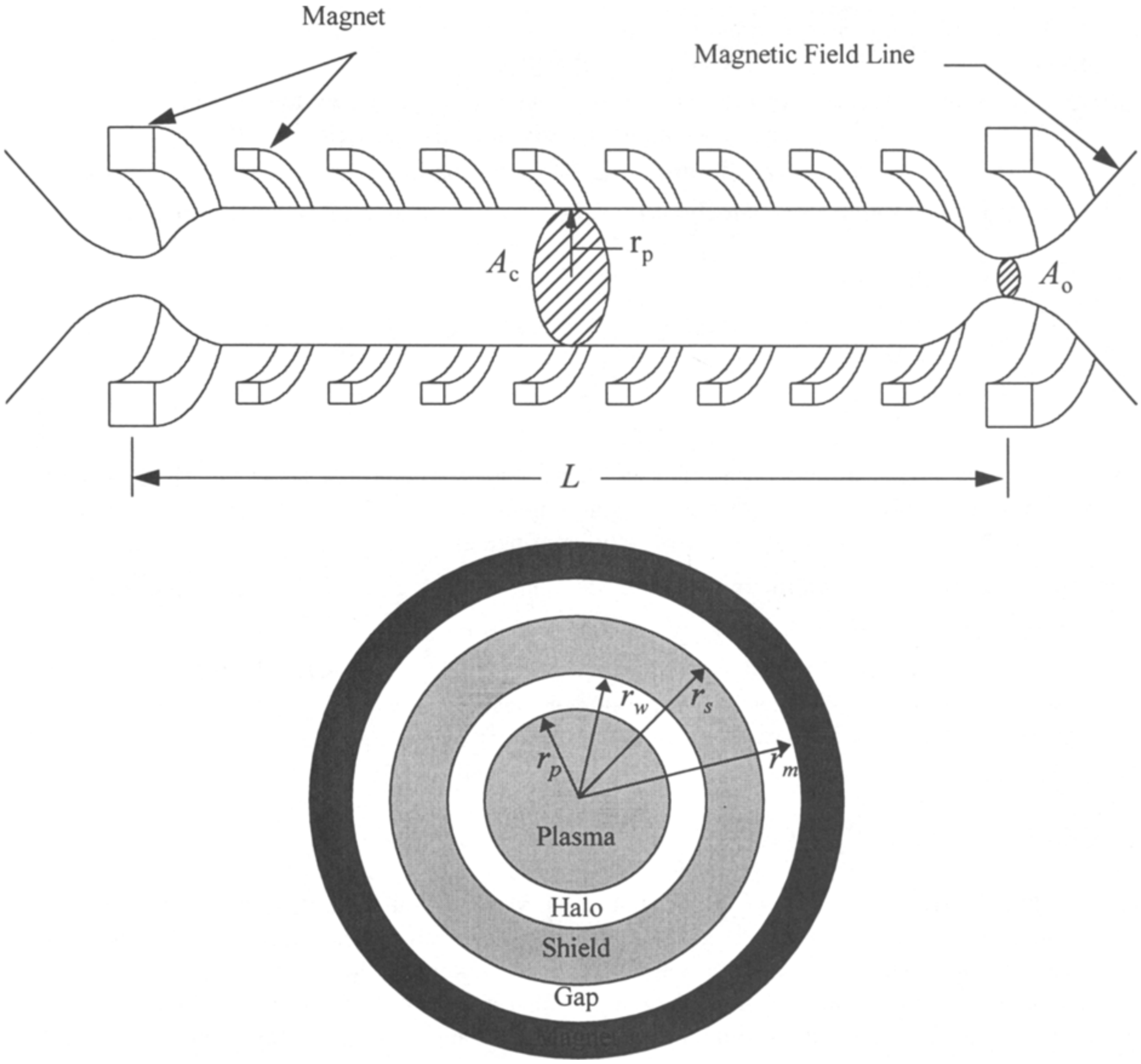

FIGURE 1. Schematic and Cross-Sectional View of the Gasdynamic Fusion Propulsion System.

CONFINEMENT PROPERTIES

The gasdynamic operating regime is characterized by the condition that the effective ion-ion collision mean free path with respect to scattering into the "loss cone" namely, λ/R, is much smaller than the length L :

$$L >> \lambda/R \ , \tag{1}$$

where R is the mirror ratio seen by the plasma. This mirror ratio is related to the vacuum mirror ratio, R_o, by:

$$R = \frac{R_o}{\sqrt{1-\beta}} \ , \tag{2}$$

where β is the ratio of the plasma pressure to the vacuum magnetic field pressure. It is a measure of how efficient the magnetic field is in confining the plasma, and because it is proportional to the density, n, it is also a measure of the fusion power density supported by the system. The particle confinement time, τ, can be readily obtained by dividing the particle flux through the mirror, $A_o n v_{th}$, where A_o is the area at the mirror and v_{th} the particles mean velocity, into the total number of particles in the device, namely $nA_c L$ where A_c is the area in the central region. Noting that $A_c / A_o = R$ it follows that :

$$\tau = \frac{RL}{v_{th}} , \tag{3}$$

This confinement time is utilized in a set of conservation equations which, when solved, yield the plasma parameters that characterize the steady state operation of GDM (Kammash 1995). It should be noted that unlike the "collisionless mirror", the confinement time given by Eq. (3) varies linearly rather than logarithmically with the mirror ratio, R, and inversely with $E^{1/2}$ rather than directly with $E^{3/2}$; and most importantly, with the length L rather than no dependence at all in the case of the collisionless mirror. As will be seen shortly, the quantity β plays a critical role in the design of the propulsion device since large values of this parameter mean smaller magnetic fields are required for plasma confinement. This, in turn, means smaller magnet masses, and ultimately smaller vehicle masses.

MACROSCOPIC STABILITY

Once the equilibrium properties of the plasma in GDM are established, it is necessary to ascertain whether such equilibria are stable to gross fluctuations as represented by magnetohydrodynamic (MHD) instabilities. These are commonly low frequency (compared to the ion gyrofrequency) long wave length oscillations, that could lead to major disruption of the plasma confinement in the system, with serious consequences to the propulsive performance and capability. These modes arise when the plasma is situated in a region where the magnetic field curvature is concave toward the plasma as is the case in ordinary mirror machines. In a high aspect ratio GDM the field curvature is neutral over most of the plasma and only in the transition region near the mirror does the curvature become concave. Beyond that, namely in the expansion region of the mirror (nozzle), the field curvature is convex, and due to the presence of plasma in this region it leads to stability of the whole system. This arises from the line integral criterion where it is clear that the curvature in GDM is predominately convex. It has been shown (Nagornyj 1984) that GDM plasma is indeed stable against these modes for large mirror ratios (≤ 70) and instability can arise if R becomes so large as to impede the plasma flow into the nozzle expansion region. Stability under these conditions is further augmented by Finite Larmor Radius (FLR) effects (Post 1987) generally expressed by the condition :

$$\frac{\gamma r_p^2}{\rho_i v_{th}} < 1 , \tag{4}$$

where γ is the growth rate of the instability, r_p, the plasma radius, ρ_i the ion Larmor radius and v_{th} the ion thermal velocity introduced earlier. Since $\gamma \sim 1/\tau$, where in the case of GDM, $\tau \sim v_{th}/L$ as indicated by Eq. (3), it follows immediately that Eq. (4) would be readily satisfied when $r_p/L << 1$ which is compatible with high aspect ratio devices. In short, it is reasonable to conclude that a high aspect ratio GDM propulsion device will be stable against MHD modes for large mirror ratios and for large β as has been demonstrated experimentally (Shitlukhin 1984).

MICROINSTABILITY

In contrast to MHD modes, microinstabilities are short wave length, high frequency modes that could lead to localized turbulence and enhanced diffusion. They are driven by density and/or temperature gradients, anisotropy in the velocity distribution of the plasma, and in the case of mirrors by deviations from a Maxwellian distribution due to escape through the ends. The latter are referred to as "loss cone" modes, and as noted earlier, validity of gasdynamic confinement as represented by Eq. (1) implies that the loss cone is always full. In other words, the scattering time out of the loss cone is much shorter than the escape time out of the mirror and as a result GDM is insensitive to these modes. Angular rather that perpendicular, injection of particles in the midplane minimizes "anisotropy" driven instabilities, and since the time it takes an ion to cool (drag) on the electrons is short, isotropy is reached rather quickly thereby limiting these modes from reaching dangerous levels. In view of these facts, crossfield diffusion in GDM is deemed to be "classical" in that particles perform a random walk across the field due to collisions, with a step size equal to the radius of gyration. Because of the axisymmetry, such diffusion is much smaller than "neoclassical diffusion which takes place in non axisymmetric devices such as tokamaks. Hence, in the absence of turbulence across field diffusion in GDM is negligible, and its performance is dictated almost entirely by the axial containment represented by Eq. (3).

ELECTROSTATIC POTENTIAL

Because of their small mass electrons tend to escape through the mirrors much more rapidly than ions, and as a result leave behind a plasma with excess positive charge. This gives rise to a positive electrostatic potential which slows down the electrons while accelerating the ions until the rate of escape of both species equalizes. Under these conditions axial confinement will be characterized by an "ambipolar" confinement time which must be utilized to describe the plasma dynamics in the system. The reduction in ion confinement due to the acceleration caused by the potential is made up for in the equilibrium condition by an increase in the length which in turn manifest itself in larger vehicle mass. A salutory effect however, compensates for this negative effect and appears in the enhanced ion velocity. This in turn leads to greater specific impulse and thrust which translate into a reduction in travel time. It also leads to a reduction in the electron temperature which contributes to a lowering of plasma pressure and the corresponding magnetic field which in turn leads to a reduction in the total mass. In short, the presence of the electrostatic potential gives rise to compensating mass effects while significantly enhancing the propulsive performance of the device.

ILLUSTRATIVE EXAMPLE AND CONCLUSION

In order to demonstrate the critical rate the plasma confinement parameters in the propulsive performance of GDM we choose an engine which consists of a reactor and the injector that supplies it with power to initiate the fusion reactions. We consider a fuel consisting of a 50-50 deuterium-tritium (DT) mixture which upon reacting generates neutrons and alpha particles. Because of the presence of hot electrons in the plasma they radiate bremsstrahlung and synchrotron radiation where power along with the neutron power can be processed by a thermal converter to produce electric power. The thrust power generated by the system is equal to the charged particle power associated with the charged particles that escape from one mirror which also serves as a magnetic nozzle. For equal mirror ratios an equal number of charged particles travel through the opposite mirror to a direct converter where their power is converted to electric power at some efficiency. The efficiencies of the various components namely the injector, the thermal converter and the direct converter determine the energy multiplication factor Q of the reactor required to make the system self-sustaining (Kammash 1997). We choose a beta (β) value of 0.95 and a mirror ratio R or 100 which we deem to be acceptable within the framework of stable plasma although the mirror ratio might be on the high side, and utilize these values in obtaining the steady state operating parameters of a GDM propulsion system. For a fuel density of 10^{16} cm^{-3}, a temperature of 10 keV, and assuming super conducting magnets and appropriate values for the efficiencies and masses of the various components we obtain the propulsion capabilities given in Table 1.

TABLE 1. GDM Propulsion Characteristics.

Plasma Length (m)	44
Plasma Radius (cm)	5
Thrust (N)	2.5×10^{3}
Thrust Power (MW)	2.2×10^{3}
Engine Mass (Mg)	101
Total Vehicle Mass (Mg)	423
Specific Impulse (s)	1.27×10^{5}
Specific Power (kW/kg)	13.4
Mars Round Trip (days)	170

In obtaining the round trip mission time to Mars we utilized a constant thrust constant specific impulse continuos burn acceleration/deceleration type of trajectory using the linear distance from earth to Mars when the launch time is compatible with the positioning of the earth between Mars and the sun, No gravitational effects of any of the planets is included and position changes during the mission are ignored. The amount of propellant (fuel) required for this mission was found to be small- less than 10% of the total vehicle mass. The smallness of the required propellant mass makes GDM a particularly attractive propulsion system for solar system exploration and beyond since it effectively removes launch window limitations while allowing such missions to be undertaken in relatively short times.

Acknowledgments

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Nomenclature

L	Plasma length	λ	Collision mean free path
n	Number density	τ	Confinement time
Q	Energy multiplication factor	A_o	Cross sectional area at mirror (throat)
R	Plasma mirror ratio	A_c	Cross sectional area at center
R_o	Vacuum mirror ratio	γ	Growth rate instability
v_{th}	Ion thermal velocity	r_p	Plasma radius
β	Ratio of plasma pressure to magnetic field pressure	ρ_i	Ion Larmor radius