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Magnetized Target Fusion for Advanced Space Propulsion

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Abstract

The magnetized target fusion (MTF) concept is an approach to thermonuclear fusion which is intermediate between the two extremes of inertial and magnetic confinement fusion. A magnetic field is used to suppress electron thermal conduction, but the fusion plasma is heated by compression and inertially confined during the fusion burn phase by an imploding liner or shell. Because the major energy loss mechanisms are suppressed, the work rate required to achieve fusion ignition is greatly reduced, which translates to a greatly reduced requirement for power input to the target. This allows electrical pulsed power machines (and possibly other devices) to be used as drivers. The potential advantages that such a relaxation of driver requirements may offer need to be explored. Thio proposed to dynamically form an MTF target plasma and compress it with a dynamically formed spherical liner, which compresses and heats the target plasma to fusion ignition conditions. This paper will discuss the fundamentals of MTF and the feasibility and technical challenges of Thio's novel approach to advanced space propulsion.

Theoretical Basis for MTF

MTF is intermediate between two very different mainline approaches to fusion: inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). Electron thermal conduction is the major energy loss mechanism for the wall confined, unmagnetized plasmas produced in most designs for ignition targets for inertial confinement fusion (ICF) [1]. MTF is based on the fact that a magnetic field suppresses electron thermal conduction in a sufficiently hot plasma. However, simply imposing a magnetic field on existing ICF ignition target designs does little to suppress electron thermal conduction, because the density is so high that the mean collision time in the plasma is short, leading to a small magnetization parameter, the cyclotron frequency - collision time product $\omega\tau$. This means that MTF must operate at a much lower density than ICF. Also, in the absence of conduction loss, bremsstrahlung would become the dominant ICF energy loss mechanism, which is another reason that MTF must operate in a lower density regime than ICF. By reducing the operating density and imposing a sufficiently high magnetic field, both conduction and radiation losses are reduced. For given fusion plasma mass, this leads to a larger target containing a gaseous deuterium and tritium (DT) fusion fuel at about 0.01 to 1 mg/cc.

The required level of magnetic field for insulation of the fusion fuel from loss to the surrounding wall is sufficiently low that the synchrotron radiation and the magnetic field energy are only small perturbations on the fusion fuel dynamics. If initially the plasma has a high ratio of thermal energy to magnetic energy $\beta = 2c_v\rho T/\mu_o B$, then if the plasma is compressed in all three dimensions, its β will increase during compression. With sufficiently reduced energy loss rates the plasma can be compressed relatively adiabatically to fusion temperatures by squeezing it with the confining shell or liner [2,3]. Then the rate of compression as determined by the implosion velocity and geometry of the confining vessel can be much lower than needed for ICF. In ICF the confining vessel is a spherical shell that is symmetrically and rapidly imploded to a very small final radius. One embodiment of MTF would be similar, except the implosion velocity could be more than an order of magnitude lower. Figure 1 illustrates the MTF concept.

Fusion Ignition

Fusion ignition, the transition to self-sustaining fusion burn, is not required for all fusion energy schemes, but ignition is what makes ICF a viable fusion energy concept. Fusion ignition relies on "self-heating", which means that the fusion energy release in the form of energetic reaction products (neutrons alpha particles for DT fusion) is at least partially deposited in the fusion plasma as these particles pass through it. For ICF the critical parameter that determines whether the fusion self-heating overbalances the energy losses from the fusion plasma is the areal density ρR. The areal density must exceed approximately 0.3 gm/cc for fusion ignition to occur. Because much higher areal density is required for significant energy deposition by neutrons, they deposit very little energy, and the DT alpha particles are the major source of self-heating for ICF and MTF. The efficiency of the burn that follows depends on the sum of the areal densities of the imploding parts of the target (fusion fuel plus imploded confining shell). Therefore, the target gain depends on the ρR as well.

For DT alpha transport in MTF an additional parameter is important. The ρR is augmented by a field times radius product BR for the magnetized plasma. Because the energetic charged particles in a magnetized plasma are turned in the field, their path in the fusion fuel is lengthened. In a hot plasma the magnetic field is essentially frozen in place relative to the plasma, so that the compression of the plasma by the imploded confining shell also compresses the field, which can reach many megagauss. The critical parameter is the gyroradius. If it is much smaller than the fusion plasma radius, then a significant part of the energy of charged fusion products will be deposited to self-heat the plasma. The critical value corresponds to a field times radius product (BR) of 0.3 MG-cm, but the higher the better. The very low ρR typical of MTF is significantly augmented by the high BR, so that fusion ignition can occur for MTF. In one study a particle tracking code was used to calculate the fraction of DT alpha particle energy deposited in spherical volume of homogeneous magnetized plasma with a pure azimuthal field (where $B(r) = B(R)$) [4]. Some results for that study are shown in Figure 2. Figure 3 for the case of a field produced by a uniform current density (for which $B(r) = rB(R)/R$) shows that the fractional deposition also depends on the distribution of the field.

Figure 4 shows a Lindl-Widner diagram (energy rate contours in the temperature-areal density phase space) for MTF. The region of ICF fusion is in the extreme upper left of the diagram. MTF extends the region available for self-sustaining fusion burn to much lower values of areal density (ρR).

Previous MTF-related Experiments

Previous MTF research included the Sandia National Laboratory "Phi-target" experiments [5, 6], the only series of experiments documented in available scientific literature in which a plasma known to be magnetized was compressed sufficiently to produce thermonuclear neutrons. This target resembled the Greek character Φ (see Figure 5). Despite the very interesting results from that series of experiments, the research was not pursued, and other embodiments of MTF concept such as the Fast Liner [2] were unable to attract the support needed for a firm proof of principle. A mapping of the parameter space for MTF [7] showed the significant features of this approach, which have steadily attracted more attention. Since the All-Russia Scientific Institute for Experimental Physics (VNIIEF) revealed their on-going interest in this approach to thermonuclear fusion, Los Alamos National Laboratory (LANL) and VNIIEF have done joint target plasma generation experiments relevant to MTF referred to as MAGO (transliteration of the Russian acronym for magnetic compression) [8]. The MAGO II experiment appears to have achieved on the order of 200 eV and over 100 kG, so that adiabatic compression with a relatively small convergence (10 to 15 in cylindrical geometry) could bring the plasma to fusion temperatures.

Reduced Driver Requirements

MTF promises a significant advance in fusion technology. Because in principle MTF targets are larger and can be imploded slower than is needed for an ICF target, the power and intensity required to drive an MTF target to fusion ignition are potentially orders of magnitude lower. However, for the same mass of fusion fuel the energy required for ignition is about the same. This is because the same thermal energy must be supplied to the fusion fuel to raise it to the ignition temperature [3]. Ignition of a particular fusion target requires that the fusion driver (laser, particle beam, or otherwise) simultaneously supply sufficient energy, power, and intensity to the target. For example, it is thought that at this time lasers are sufficiently powerful and intense to drive appropriate designs of ICF targets to ignition, but are not sufficiently energetic. The anticipated National Ignition Facility (NIF) at Livermore, California, is intended to provide all three, that is, sufficient energy, power, and intensity on target. The attractiveness of MTF is that the reduced power and intensity requirements needed for MTF targets could be provided by energetic pulsed power machines. Direct pulsed power has never been a contender as an ICF driver, because of an inability to supply the necessary power and intensity on target. However, some existing pulsed power machines can easily supply sufficient energy, power, and intensity for MTF experiments and are more efficient overall than laser or other beam drivers. For higher efficiency drivers, the lower gain targets expected for MTF should still be adequate for a viable fusion power system.

MTF Development Path

Magnetized target fusion (MTF) provides a development path for fusion energy that is mid-way between the two dominant approaches to fusion energy. We desire a scientific proof of principle which demonstrates that compression of a magnetized plasma heats it in accord with MTF theory. Previous MTF studies [3,7] have emphasized that existing pulsed power technology is adequate for a scientific proof of principle, and probably sufficient for experimental exploration beyond. This would allow an economical and significant advance of fusion science and technology. The reasons for this assertion were summarized above.

It should be noted that MTF is a concept that may have many diverse embodiments, some purely for experimental investigation of MTF, and others for applications such as fusion power production and space propulsion. We have taken the position that the most important first task for research on any fusion concept is to provide a proof of principle. Once that is done, the concept becomes a candidate for consideration as a possible approach to fusion propulsion or fusion energy production. However, it is necessary to motivate continued support of MTF research by pointing out its potential practical applications. For this reason, we use our current understanding of MTF to explore its potential application to space propulsion in the next few sections of this paper.

MTF for Propulsion

There are two ways to harness MTF for propulsion. One is to directly use the momentum of the expanding fusion-heated target material for thrust, and the other is to use MTF to provide fusion energy to power a thrust producing plasma jet or neutralized ion beam. Both of these approaches have advantages. The chief advantage of the indirect approach is that it decouples development of the energy supply from that of the rocket or thruster, which allows two independent development paths that can be merged at a later phase of system development. We will describe below only a direct system concept, but many of the components of such a system are similar to an indirect system. By pursuing one approach the other should also progress. More detailed analysis concurrent with early development of a direct system should form the basis for choosing the most attractive approach at a later date.

Since MTF is a relatively new concept in fusion, a thorough study of its potential for space propulsion has never been undertaken. As a prelude to systematically exploring how MTF can be packaged for space propulsion we have chosen to discuss a system based on Thio's standoff driver concept.

Standoff Driver Concept for MTF

One of the chief problems with many pulsed fusion concepts is that the burning fusion plasma would subject an unprotected driver to intense, potentially damaging radiation. Another is that a fabricated target of the required precision might be very expensive, even with mass production techniques. The standoff driver concept addresses both of these issues. Thio proposed to dynamically form a target plasma is by merging two oppositely directed spheromaks [9, 10]. The target plasma would then be compressed and heated by a dynamically formed gaseous shell formed by simultaneously directing dozens high velocity jets at the target plasma. For sufficient compression to occur, it is necessary to merge the jets into a relatively smooth shell and to keep the convergence needed to reach fusion conditions as low as possible. The latter requires that the target plasma have a high temperature just before compression begins. The basic concept is illustrated in Figure 6.

Thio used simplified physical models to analyze this stand-off target and driver concept. The colliding compact toroids (CTs) must be launched first, followed by the faster gas jets. The several radial gas jets are timed to merge into a contiguous shell shortly after the two compact toroids have formed the target plasma. Knapp did some preliminary modeling in 2 and 3 dimensions of the dynamics of the merging multiple gas jets to form a contiguous liner, and the merging appears to be feasible [11]. Knapp's calculations were Thio's justification for using a 1-D spherically symmetric quasi-steady-state gasdynamic model for the modeling the performance of this stand-off concept. The collision of the plasma liner with the target plasma launches shocks which travel inward through the target plasma and outward through the plasma shell. These provide preliminary heating of the target plasma and inner aspect of the liner. The contact velocity is determined by pressure continuity. The in-going shock is reflected at the center, but additional shocks are weak by comparison, so that the implosion is approximately an acoustic compression. By maintaining a radial convergence ratio less than 10, the development of Rayleigh-Taylor instabilities is minimized. Reaching fusion temperatures with a radial convergence of only 10 depends on achieving a temperature of about 100 eV in the target plasma before compression begins.

Various methods have been proposed to protect the plasma and gas guns from the intense, potentially damaging radiation emitted by the burning fusion plasma. One would method use less precise, but well-timed gas jets to shield the otherwise exposed guns. This would potentially reduce the level of robustness below that which the guns would otherwise have to meet. As a fusion energy reactor many of the ideas for utilizing the neutron energy and breeding tritium are similar to other pulsed fusion concepts such as ICF, but for space propulsion many of these ideas must be discarded.

Fusion Propulsion Embodiment of the Standoff Driver Concept

Many complications associated with terrestrial fusion experiments are eliminated by operation in space. For example, operation in the vacuum of space eliminates the need for the pumps and plumbing of a vacuum system. However, operation in space can also complicate other requirements, such as system cooling. Therefore, the tradeoffs for fusion based propulsion differ significantly from those for terrestrial fusion reactors intended for electrical power generation.

A conceptual study explored the feasibility of the stand-off driver MTF concept described above for space propulsion [12]. In the simplest configuration a single hemispherical "chamber" would allow the momentum of the target plasma explosion to be directed toward the open side of the hemisphere (see Figure 7).

Starting with the basic concept, it was possible to make several improvements. First, the merging multiple gas jets can carry additional cold fusion fuel, which is ignited by the central fusion burn. Second, the merging multiple gas jets can carry hydrogenous moderating material that is compressed with the liner so that it can absorb most of the 14

MeV neutron energy. Third, in principle, shielding material can also be carried in and compressed around the target. Fourth, a magnetic nozzle can be created, which is slightly compressed in reaction to the exploding target, and thereby induces a current for direct conversion to supply the circulating power. Fifth, by off-setting the aiming points and adjusting the CT and gas jet velocities, it is possible to create a moving center of mass, so that the target explodes in an optimum place in magnetic nozzle.

This concept proved to have very attractive features:

a) It provides for a very dense hydrogenous liner capable of converting more than 97% of the neutron energy into charged particle energy.

b) The fusion yield per pulse can be maintained at an attractively low level (< 1GJ) with a gain in excess of 70.

c) The magnetic nozzle can operate as a magnetic flux compression generator to provide the necessary circulating power for continued operation, yet still maintain a high nozzle efficiency.

d) The electrical energy from flux compression can recharge a capacitor bank or other energy storage without using a high voltage power supply.

e) The electrical circuit is comprised mainly of inductors, capacitors and plasma guns, without any intermediate equipment which allows a high rep-rate.

f) All fusion related components are within the current state of the art for pulsed power technology.

g) The scheme does not require any prefabricated target or liner hardware. All necessary fuel and liner material are introduced into the engine in a gaseous form and delivered to the fusion reaction region in a completely stand-off manner.

Conclusion

The standoff driver concept for MTF is being explored as the basis for an advanced space propulsion system. There are many advantages such a system appears to have. However, the progress of the underlying research has been slow due to restricted resources. Most urgent is the need for a firm proof of principle for MTF. An experiment is underway at Los Alamos to create a target plasma for injection into a metal liner for subsequent compression, but compression experiments at the US Air Force Research Center in Albuquerque, as constrained by current funding levels, are at least a year or two away. In addition, the underlying concepts and technology for the standoff driver concept need to be tested. Some standoff driver work is under way at NASA Marshall Space Flight Center, but currently at a low level.

Because most of the required pulsed power technology needed to test many of the basic concepts for MTF and the standoff driver concept is currently available, the cost of pursuing this approach to advanced space propulsion should be much less than many other approaches. Also, the progress could be rapid, which is an important factor when considering overall cost. The logical first step, that of obtaining a firm proof of principle for MTF, could proceed much more rapidly if adequate resources were available. While some theoretical work has been done, much more is needed. Also, more modeling with computationally efficient and improved MHD codes is needed. Support for the theoretical and computational work has of necessity taken a back seat to the more urgent experimental effort to provide a firm proof of principle. However, it is very desirable to coordinate the theoretical and computational work with the experimental effort in order to avoid meandering trails along the MTF development path.

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Figures:

Figure 1. Illustration of the MTF concept.

Figure 2. Some results for the fraction of DT alpha particle energy deposited in spherical volume for the case of a uniform current density ($B(r) = rB(R)/R$).

Figure 3. Fraction of DT alpha particle energy deposited in spherical volume for the case of a field produced by a uniform azimuthal field ($B(r) = B(R)$).

Figure 4. Lindl-Widner diagram (energy rate contours in the temperature-areal density phase space) for MTF.

Figure 5. Sandia Phi-target resembled the Greek letter Φ.

Figure 6. The standoff driver concept.

Figure 7. Diagram of a fusion rocket engine based on the stand-off driver MTF concept.

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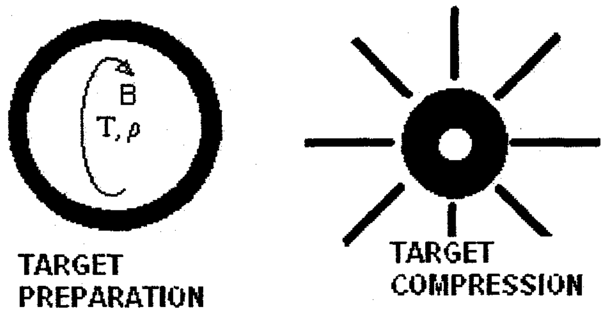


Figure 1. The MTF concept involves two steps, creation of a warm, magnetized plasma and compression by an imploding liner or shell.

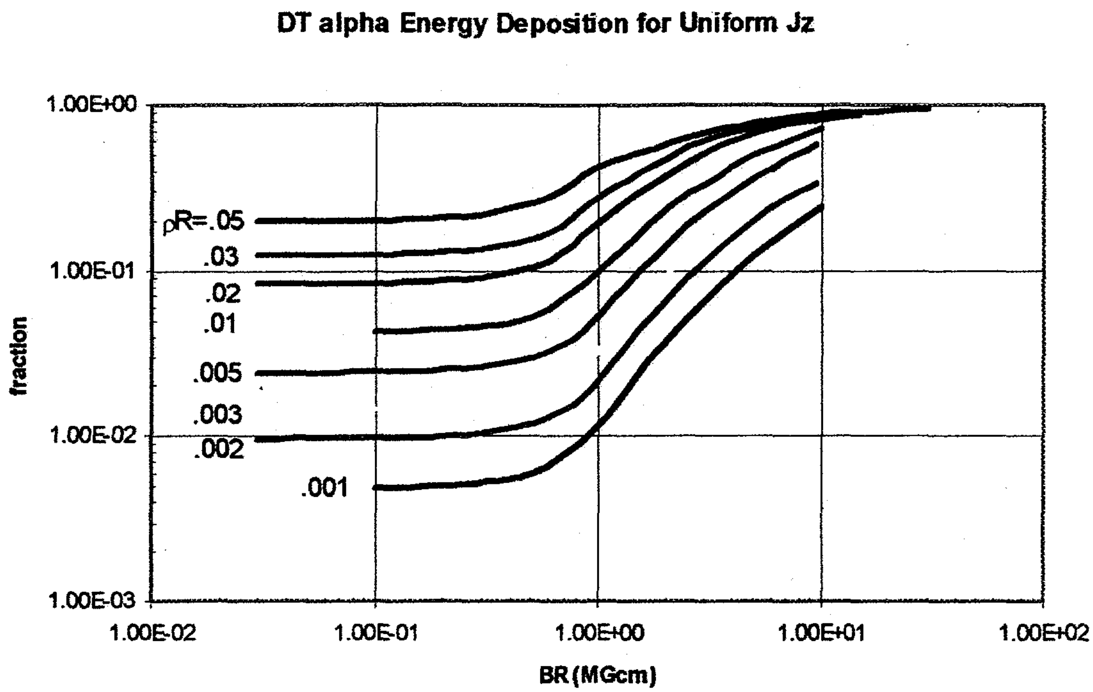
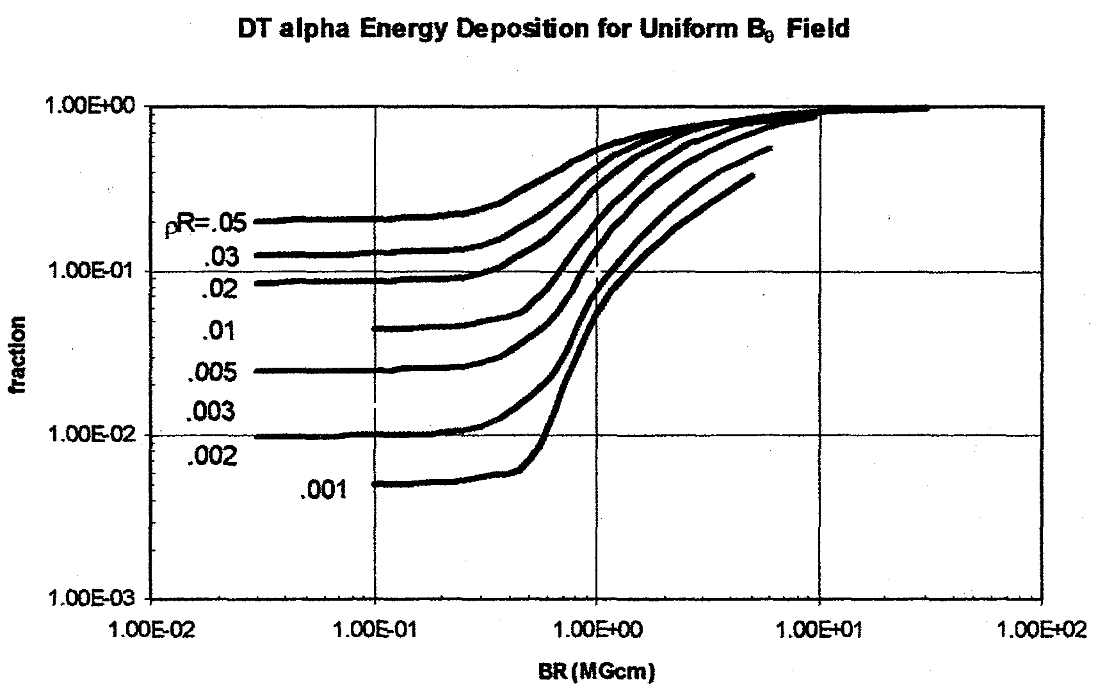


Figure 2. Some results for the fraction of DT alpha particle energy deposited in spherical volume for the case of a uniform current density (B(r) = rB(R)/R).



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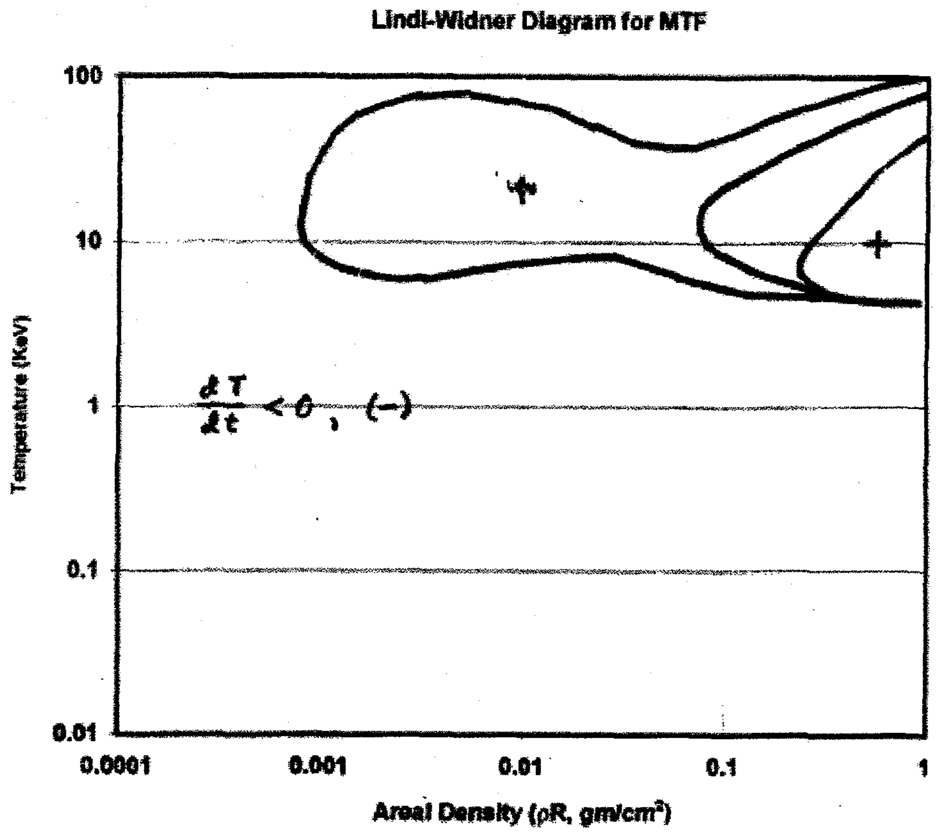

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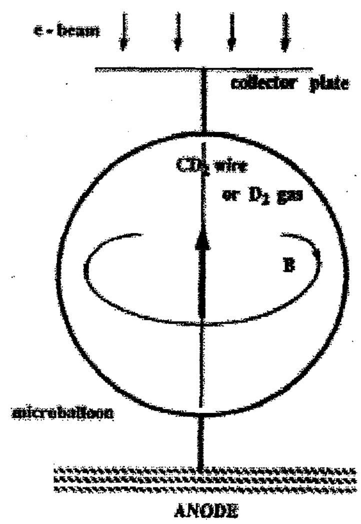

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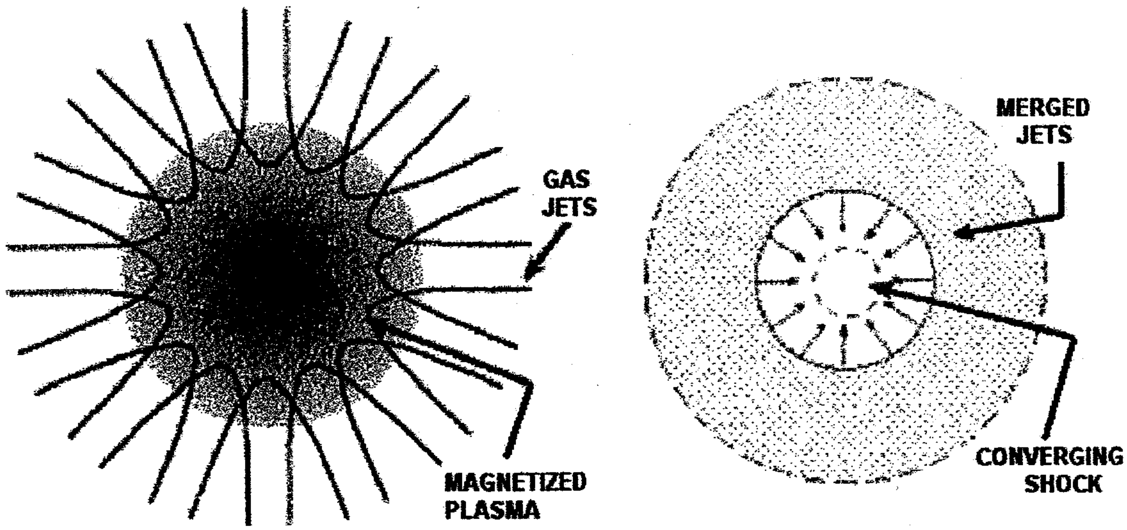

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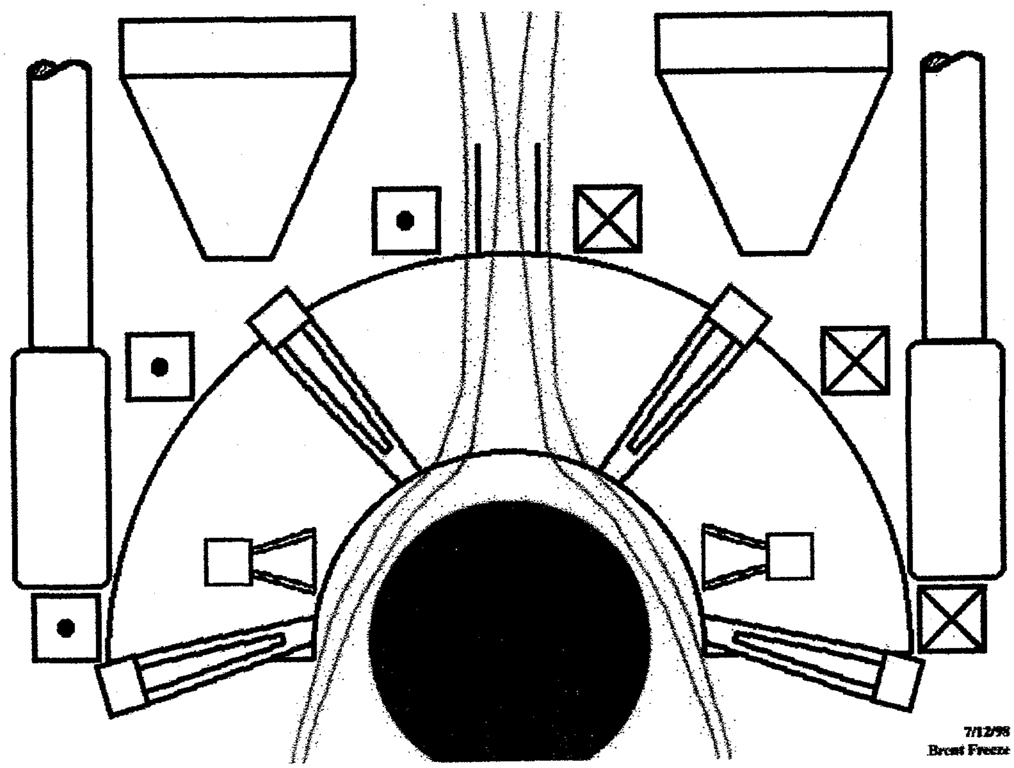

Figure 7. Diagram of a fusion rocket engine based on the stand-off driver MTF concept.