LA-UR- 01-6318

Approved for public release; distribution is unlimited.

Title: Magnetized Target Fusion and Fusion Propulsion

Author(s): Ronald C. Kirkpatrick

Submitted to: Space Technology and Application International Forum (STAIF-2002), Albuquerque, NM, February 3-7, 2002

LOS ALAMOS NATIONAL LABORATORY
3 9338 00854 6730

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (8/00)

Magnetized Target Fusion and Fusion Propulsion

Ronald C. Kirkpatrick
Los Alamos National Laboratory,
B229, Los Alamos, NM 87545
(505) 667-7208, rck@lanl.gov

Abstract Magnetized target fusion (MTF) is a thermonuclear fusion concept that is intermediate between the two mainline approaches, magnetic confinement and inertial confinement fusion (MCF and ICF). MTF incorporates some aspects of each and offers advantages over each of the mainline approaches. First, it provides a means of reducing the driver power requirements, thereby admitting a wider range of drivers than ICF. Second, the magnetic field is only used for insulation, not confinement, and the plasma is wall confined, so that plasma instabilities are traded in for hydrodynamic instabilities. However, the degree of compression required to reach fusion conditions is lower than for ICF, so that hydrodynamic instabilities are much less threatening. The standoff driver innovation proposes to dynamically form the target plasma and a gaseous shell that compresses and confines the target plasma. Therefore, fusion target fabrication is traded in for a multiplicity of plasma guns, which must work in synchrony. The standoff driver embodiment of MTF leads to a fusion propulsion system concept that is potentially compact and lightweight. We will discuss the underlying physics of MTF and some of the details of the fusion propulsion concept using the standoff driver approach. We discuss here the optimization of an MTF target design for space propulsion.

INTRODUCTION

Realization of a practical fusion propulsion system may enable NASA to undertake missions, which would otherwise be impossible. Of the three potential fusion-based technologies, space propulsion imposes the most stringent requirements for scale and mass. It is expensive to lift payloads into low earth orbit (LEO), and assembly in space to create large structures may require multiple LEO missions or a continuing LEO presence. We are seeking ways to avoid the apparent restrictions and costs that currently envisioned Mars and deep space missions might incur.

Magnetized target fusion (MTF) is a relatively unexplored controlled fusion concept that is intermediate between the two main-line fusion approaches, which lie at opposite extremes of operating density. MTF appears to have some advantages that are attractive for a space propulsion system (Kirkpatrick, 2001). Here we discuss only one set (of the many possible sets) of specific system component choices as an example of how MTF might be optimized for space propulsion.

DESIRED CHARACTERISTICS AND OPTIMIZATION

There are two factors that determine the overall weight of a space transportation system. The first is the mission goal, which for a particular propulsion system determines the payload and propellant masses. The second is the propulsion system and associated support equipment. However, the propellant mass requirement is partly determined by the mass of the propulsion system. The propulsion system has two offsetting characteristics that effect the required propellant mass, its weight and its time-integrated specific impulse. Therefore, it is important to reduce the propulsion system mass to the greatest extent possible and to increase the specific impulse as much as possible.

There are several factors that interact in determining the propulsion system weight and specific impulse. These factors are specific to the type of propulsion system that is designed. For example, electrical energy derived from a nuclear reactor could be used to accelerate light ions to extremely high velocity, providing the highest possible specific impulse, but such a system would likely be very expensive in terms of the mass of the equipment required for the management of waste heat. For each type of system there is an optimum design that delivers the best compromise for these two system characteristics, weight and specific impulse. The optimization that must be done is intimately connected with the details of the system design.

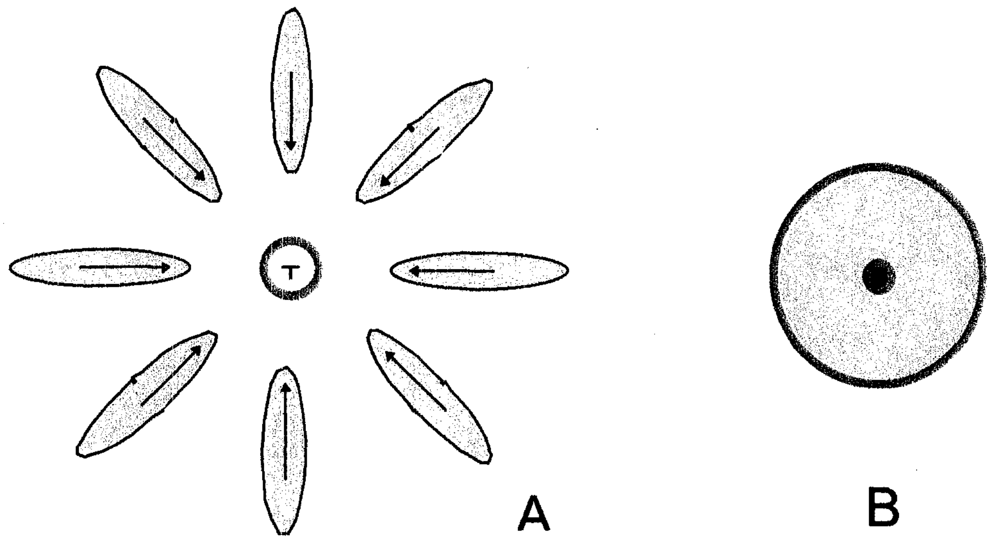

FIGURE 2. The Standoff Driver Concept: A, Multiple jets converge toward target plasma (T) and B, merge to compress the plasma to fusion temperatures.

OPTIMIZING AN MTF PROPULSION SYSTEM

One MTF propulsion system that has been proposed is based dynamic magnetized target plasma formation and compression using a stand-off driver approach (Thio, 1999). Figure 1 is an illustration of this approach. The basic idea of MTF is to use a converging inertial shell to compress an initially warm target plasma to fusion conditions, and to inertially confine the plasma during fusion burn and partially confine the thermal energy with a magnetic field. Because the magnetic field modifies the target physics, less powerful and intense drivers are needed for achieving fusion conditions. Therefore very efficient and reliable pulsed power systems become viable candidates for MTF target drivers. There are many potential embodiments of MTF, which multiplies the chances of finding an embodiment amenable to space propulsion. However, we confine our selves to the standoff driver embodiment of the MTF concept.

In order to obtain the highest specific impulse, one would like to maximize the fusion energy deposited in the minimum amount of target mass that is compatible with operation of the system. Also, to minimize the overall weight of the propulsion system, one would like to have very little energy and fusion burn products escape the target plasma after fusion burn has occurred. This would minimize the heat load on the components of the system. Maximizing the deposited energy per unit mass for the target and minimizing the energy that escapes the target require optimization of the target design and set a limit to the combination of these two desirable target characteristics. The ultimate arbitrator for how one weights each of these two desirable characteristics in the optimization process is the mission cost, so that a final optimization requires definition a mission goal, which is beyond the scope of what we are presenting here. We will simply present an example of the desired optimization, for which equal weight will be applied to each characteristic.

The target yield (i.e., the amount of fusion energy produced) is proportional to the target fuel mass and the fusion burn efficiency. Typically, the target is composed of a fuel region surrounded by an inert shell of material that is necessary to create the fusion conditions in the fuel region. The fusion energy will be deposited in both the fusion fuel and the inert shell, but some of the energy will escape, heating and irradiating at least some portion of the equipment used drive the fusion target. Some of the fusion energy may escape directly into space from the target region. That which does provides only a little impulse, and therefore is essentially wasted.

The key to both minimizing the escaped fusion energy and maximizing the energy per unit mass in the fusion fuel and inert surrounding shell is to maximize the retention of the fusion burn products with in the target through maximizing the target areal density, i.e., the product of density and thickness, or $\rho\Delta R$, (as well as the magnetic field flux density times radius parameter BR for MTF). Because for a given target design fusion ignition occurs in a narrow temperature range, maximizing the areal density amounts to maximizing the pressure times radius parameter PR for fusion ignition in the target at burn time. Depending on the type of fuel used in the target, for MTF maximizing BR may play a similar role.

TWO ROLES FOR HYDROGEN

For fusion fuels that produce copious neutrons, the areal density of hydrogenous material is very important. Because hydrogen has nearly the same nuclear mass as a neutron, in a "head-on" collision, the hydrogen nucleus can acquire all the neutron energy, making the neutron very susceptible to absorption by an appropriate background material such as boron or lithium. Therefore, hydrogen is the most efficient moderator for neutrons, and on the average reduces the neutron energy by about one-half per collision. Significant slowing of a neutron requires several grams/cm_2 of hydrogenous material. For fast (e.g., 14 MeV) neutrons more areal density is required. The mean free path for a 14 MeV neutron in deuterium or deuterium is about 5 gm/cm_2. The trajectories of the chargeless neutrons are uneffected by a magnetic field, so that the low PR, high BR of the MTF fuel region does little to retain the neutron energy. However, the surrounding shell can have a substantial areal density ($\rho\Delta R$) if it is compressed along a low adiabat.

As propellant hydrogen provides the highest specific impulse per unit of energy invested. The amount of energy deposited in fusion a target depends on both the yield of the target and its areal density (and possibly BR). Even for targets with low areal density, the specific energy density can be large. For example, for an ICF target optimized to use the minimum driver energy for fusion ignition, the energy invested in the shell surrounding the fusion fuel is four-fifths that in the fusion fuel (Colgate, 1993) and the mass of the shell is only a few times that of the fusion fuel. Even for a low ρR target, which may have less than 2 % burn efficiency and may let as much as 95% of the fusion energy escape the target, the average target temperature (before any significant expansion had occurred) would still be on the order of a few keV. For a surrounding shell in the target composed mostly of hydrogen this provides a specific impulse that exceeds 100,000 seconds. However, for a target optimized to simultaneously retain the fusion products and most of the energy, as well as to provide a high specific impulse, the specific impulse would not be as high. Also, the driver energy would not be the minimum required for achieving ignition.

TARGET DESIGN CONSIDERATIONS

Two factors are important for achieving the desired optimization. The first is the density at the time of fusion ignition and the second is the thickness of the surrounding shell. Second, he shell should be sufficiently thick to absorb the majority of the fusion energy, but not so thick that the specific energy deposited becomes too low on the average to supply the desired specific impulse.

One physical phenomenon that must be considered is the instability that develops when the high pressure in the fuel region accelerates the surrounding shell material. Not only the design of the target, but also the details of how the target is driven to ignition conditions will play a key role in the growth rate and ultimate consequence of the instability.

The ρR of the target is dependent on the initial density of the target components and on the history and magnitude of the pressure pulse used to assemble the target to fusion conditions. Using a pressure pulse that maintains a low adiabat for the shell allows the highest density for whatever the attainable maximum drive pressure may be. Alternatively, using the stand-off driver concept requires that the acceleration of the gas jets used to assemble a surrounding shell must be sufficiently slow to avoid any strong shocks that can raise the adiabat of the jets, and the interaction of the jets with possible inert target plasma material should not raise the adiabat of that material.

CONCLUSION

The design of an MTF target for use in a fusion propulsion system must be optimized for the particular propulsion system under consideration. The guidelines for such an optimization are unambiguous, but the achievable performance and important system characteristics have not yet been determined.

ACKNOWLEDGEMENTS

This work was partially funded by a NASA contract. The author gratefully acknowledges various contributions by his colleagues on the Los Alamos MTF team and at NASA Marshall Space Flight Center.

References:

R.C. Kirkpatrick, "Magnetized Target Fusion for Advanced Space Propulsion." Proceedings of the Space Technology and Application International Forum (2001).

Y.C.F. Thio, E. Panarella, R.C. Kirkpatrick, C.E. Knapp, F. Wysocki, P. Parks, and G. Schimidt, "Magnetized Target Fusion in a Spheroidal Geometry with Standoff Drivers," in Current Trends in International Fusion Research - Proceedings of the Second Symposium, Edited by E. Panarella. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6, Canada. 1999.

S.A. Colgate, A.G. Petschek, and R.C. Kirkpatrick, "Minimum Energy for Fusion Ignition, A Realistic Goal," LA-UR-92-2599, Los Alamos National Laboratory (1992).