LA-UR 94-4354

Conf-941182--1

TITLE: MAGNETIZED TARGET FUSION - AN OVERVIEW OF THE CONCEPT

AUTHOR(S): Ronald C. Kirkpatrick, NIS-9

SUBMITTED TO: Proceedings, 1st International Symposium for Evaluation of Current Trends in Fusion Research, Washington, DC, November 14-18, 1994

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISCLAIMER

MAGNETIZED TARGET FUSION
- An Overview of the Concept

Ronald C. Kirkpatrick
Los Alamos National Laboratory

ABSTRACT

Magnetized target fusion (MTF) seeks to take advantage of the reduction of thermal conductivity through the application of a strong magneticfield and thereby ease the requirements for reaching fusion conditions in a thermonuclear (TN) fusion fuel. A potentially important benefit of the strong field in the partial trapping of energetic charged particles to enhance energy deposition by the TN fusion reaction products. The essential physics is described. MTF appears to lead to fusion targets that require orders of magnitude less power and intensity for fusion ignition than currently proposed (unmagnetized) inertial confinement fusion (ICF) targets do, making some very energetic pulsed power drivers attractive for realizing controlled fusion.

INTRODUCTION

The first suggestion for using a strong magnetic field to suppress thermal conduction in a thermonuclear (TN) fusion fuel occurred in 1945 [1], but because a) the goal of fusion explosives was not immediately pursued and b) when TN fusion was finally pursued the availability of fission energy made suppression of thermal conduction unnecessary for achieving fusion, no experimental effort was made to utilize a magnetic field in a fusion fuel until many years later. When controlled TN fusion was first pursued in the late 1950's, the magnetic field was recognized as a means of not just reducing thermal conduction, but totally eliminating conduction to the walls of the plasma container by isolating the plasma physically within the reactor, that is, magnetically confining the fusion fuel. While this approach is very attractive, it has led to limitations on the nature of the fusion fuel and to complex difficulties that even 40 years later are the subject of intense research, without completely satisfactory solutions. The main limitation is the necessity to operate at relatively low pressure, hence low density in the fusion fuel. The simple criterion of Lawson then dictates the necessity of long energy confinement time. ,This leads to the chief difficulty of magnetic confinement fusion (MCF), that is, that it must be managed for a very long while, thus further aggravate the problem. In an extension of the arguments that led to the Lawson Criterion it has been pointed out that some practical considerations make the requirements on fuel confinement for a useful fusion reactor even more restrictive [2].

Since the time when controlled TN fusion was originally proposed, another controlled fusion concept called inertial confinement fusion (ICF) was invented. It relied on the ability of a laser to deliver a very powerful and intense light pulse to a target and drive it to the extremely high pressure necessary for TN fusion ignition in a very small volume. Because the total energy that would be released is limited by the amount of fuel in the target, and the laser pulse necessary to ignite the fuel is controlled, this explosive form of fusion is considered to be controlled. However, the energy necessary to reach fusion ignition seems just beyond the capabilities of presently available lasers. The light ion beam variant of ICF relies on more energetic technology which presently lacks the intensity necessary for ignition. ICF ignition requires simultaneously sufficient energy, power,and intensity delivered to the target. Attempts to provide the necessary driver for ICF have led to large and expensive programs.

Here, we advocate an approach that is intermediate between MCF and ICF, as currently pursued in the US national fusion programs. It is called magnetized target fusion (MTF) and seeks to capitalize on the advantages of the other two approaches, while avoiding their pitfalls. It is truly a different approach, not just a simple variant of either magnetic confinement or inertial confinement. Both strong magnetic fields and implosion with some form of driver are required. The restrictions and operating ranges thought to be necessary have been mapped out and are discussed below. In addition, previous relevant experiments are cited, briefly described,and discussed. The need for a definitive proof-of-principle experiment and the suitability for various applications is explored, but scarce. resources and lack of a working MTF device have limited our ability to do more than speculate about applications. An effort is made to show that some restrictions imposed on the other approaches to controlled fusion and their applications are greatly relieved by MTF. Also, we will explore the possibility of using D^3He as a TN fusion fuel for MTF.

PHYSICS PRINCIPLES FOR AN MTF TARGET

When discussing MTF, the word target is used in its broadest sense. MTF involves implosion of a target plasma, a plasma that must be dynamically formed either inside a region where it is imploded (or otherwise compressed) or outside, followed by injection into that region. For fusion, the target plasma must also be a fusion "fuel", for example, deuterium and tritium (DT) or deuterium and light helium (D^3He). Survey calculations [3] have shown that the target plasma must be created with a temperature T > 50 ev and a magnetic field B > 50 KG, and other calculations have shown that for successful implosion to ignition conditions in the MTF mode, the plasma mass must exceed some minimum mass (~1-10 μg of DT) [4]. This sets lower limits on the energies required for target plasma creation and implosion, but limits that are well within modern pulsed power capabilities.

The physics principles of MTF are:

1) Application of a strong magnetic field to reduce the thermal conduction through the target plasma to the shell (or "pusher") that contains and compresses it.

2) Operation at low density to reduce radiative losses from the target plasma.

3) Sufficiently large size and magnetic field to allow for turning the charged fusion reaction products within the target plasma as ignition conditions are approached.

4) Magnetic flux compression along with the relatively adiabatic compression of the target plasma.

5) Use of an auxiliary energy and current source to heat and magnetize the target plasma.

The last principle (i.e., 5) differs from ICF, where the first strong shock that emerges from the pusher into the DT fuel establishes the temperature and density from which subsequent compression proceeds. This is referred to as setting the adiabat for the compression, since subsequent shocks that follow may be considered to be weak by comparison,and rapid compression by a series of weak shocks approximates an adiabatic compression. Even without a magnetic field, the separate setting of the adiabat for subsequent compression should be very advantageous. This point is discussed in more detail the next section.

REQUIREMENTS FOR FUSION IGNITION

While many fusion concepts don't rely on ignition for economic viability, ignition generally lowers the threshold for economic viability. This point was made in a companion paper in this same proceedings [2]. By examining the energy balance and energy rate equations it is possible to define the physical requirements for fusion ignition. This has been done elsewhere [3-5], so here we will just encapsulate the results of such studies and discuss the implications.

Figure 1 shows a Lindl-Widner diagram for the ICF extreme of MTF (i.e., B=0). Here, the zero temperature rate contour is shown as a function of plasma areal density ρR and temperature T (where $T_e = T_i = T$ for convenience of presentation) for a DT fusion plasma for the case of no external energy being added ($-PdV/dt = -3c_v v/R = 0$). Fusion energy deposition overcomes thermal losses in the forms of bremsstrahlung, heat conduction from the hot fusion fuel to the cold (100 ev) inner wall of the target, and inverse Compton cooling, but only inside the contour in the upper right of the diagram. This contour is remarkably insensitive to other characteristics of the target such as mass and size. It is sensitive to the dominant fusion reaction for the fuel and to the square of the charge carried by the fusion fuel reactants. Almost all ICF studies are done with deuterium and tritium (DT) for the reactants, thereby both maximizing the fusion cross section and minimizing the charge of the reactants. Fusion ignition for ICF relies on compression work being done on the fuel by successive shocks. This moves the fuel from its initial cold state to fusion conditions, similar to the principle of a diesel engine. There are minimum values of T and rhoR for the fusion region (where the fusion energy deposited by the DT alpha reaction products overcomes the losses), and also a minimum value for their product rhoR times T, which is proportional to the product of plasma pressure times radius PR. For ignition to be achieved, it is necessary to attain or exceed the minimum PR, and to follow a (ρR,T) path for the compression that intersects the fusion region.

The maximum value of PR that can be achieved in an ICF target implosion is necessarily related to the energy in the implosion, and more specifically it depends on the mass of the pusher, the velocity of the pusher, and its material properties. The more energetic the implosion, the higher the the resultant PR. At the end of the compression, ideally from an energy perspective, all the energy of the implosion is shared as internal energy by the pusher and the fusion fuel. A simple analysis of this process shows that under optimum conditions, one fifth of the energy in the implosion can be transferred to the fusion fuel. Four fifths or more must remain in the pusher [6]. For marginal PR, the intersection of the (ρR,T) path of the compression with the fusion region must be at a single point, dictating that only a very narrow path in ρR and T plane (i.e., along a single adiabat) can provide ignition. This makes ICF ignition with marginal implosion energy very tricky, because the implosion must provide precisely the right first strong shock, yet must also have sufficient energy to carry the fusion fuel to a sufficient PR. This assumes that the initial density in the ICF target was precisely the design value, which demands rigorous control of the target fabrication and perhaps temperature control in the target chamber. This is why a separate setting of the implosion adiabat for the fusion fuel should be advantageous for ICF, but presently this is only attempted in a limited way through pulse shaping of the laser light.

Exceeding the minimum implosion energy that allows ignition for ICF greatly reduces the difficulty of achieving ignition, because the line of constant PR intersects an increasingly broader part of the fusion region as the value of PR is increased, thus allowing a broader band of adiabats to be followed for ignition. The role of instabilities and potential impurity injection into the fusion fuel adds further complications which have been discussed by Lindl [5] and others Lindl showed that implosion velocities somewhat in excess of 10 cm/μs were required for ICF ignition in the absence of impurities (Fig. 2), and on the order of 20 cm/μs was necessary for one level of impurities.

Colgate, et al. [6] have shown that for the case of no impurities the implosion velocity needed for ignition is closely linked to the value of PR needed for ignition and that smaller targets can be ignited if high implosion velocities are used. If fact the minimum mass, hence energy needed, for fusion ignition is very sensitive to the implosion velocity ($E \sim v^{-m}$, where m = 6 to 8). It is always true that at least the thermal energy of the portion of mass of the fusion fuel that actually ignites must be transferred from the pusher for ignition to occur. Because the fuel and the pusher never completely stagnate in ICF targets, more than this irreducible minimum is required.

MAGNETIZED TARGET FUSION IGNITION

When the effects of a magnetic field on the fusion fuel physics is considered, it becomes apparent that the two predominant effects are the reduction of the thermal conductivity and the partial trapping of the fusion charged reaction products. Other less important consequences include the necessity to compress the magnetic field along with the fusion fuel, the additional energy loss due to synchrotron radiation, and the inherent two-dimensional nature of the implosion and transport processes. In fact, the magnetic fields required for MTF are not sufficiently strong to significantly effect the dimensionality of the implosion or to cause significant synchrotron radiation. Compression of the field has great potential benefit in terms of enhancing DT alpha energy deposition (i.e., "self-heating") of the fusion fuel.

Figure 3 shows a Lindl-Widner diagram for the MTF case (B>0). This diagram was constructed in the same way as Figure 1, by plotting the contour of net zero heating plus cooling due to the relevant physical processes, including synchrotron radiation and the thermal conduction as inhibited by the magnetic field. An empirical relation was used to account for the effect of the field on the DT alpha energy deposition. This empirical relation is currently being improved (Fig. 4).

For a spherical target with a trapped azimuthal magnetic field, compression causes the field to increase as the inverse square of the radius. The same is true of the areal density ρR. The notable feature of Figure 3 is the appearance of an additional fusion region at much lower ρR than the one for ICF. Also, the size and shape of the ICF fusion region are somewhat modified. In the MTF fusion region, the plasma parameters of importance have very high values: The magnetic field decay time is much longer than an implosion time, the ratio of the thermal energy to the magnetic field energy (beta) is much greater than unity, the product of the electron cyclotron frequency and the collision time is large, and the ratio of the plasma frequency to the cyclotron frequency is large. All these parameters are favorable for classical behavior of the plasma and minimization of plasma instabilities. They are also well within the regime of resistive magnetohydrodynamics (MHD).

One notable aspect of the MTF fusion region is the very low value of PR necessary to access it. This means that the implosion need not be so energetic as is the case for ICF. Still, at least the energy necessary to supply the thermal energy at the time of ignition must be transferred from the pusher to the fusion fuel. Because all the energy loss rates are reduced in the MTF fusion region, the implosion velocity necessary to achieve ignition is drastically reduced. While over 10 cm/µs is required for ICF, less than 1 cm/µs seems adequate for MTF. This is shown in Figure 5, where the implosion velocity of 0.3 cm/µs shows a clear path from an initial 50 ev into the fusion region at turnaround (v=0).

While ignition with such low implosion velocities remains only a theoretical possibility until demonstrated, realization of MTF ignition with these low implosion velocities would have a major impact of the driver requirements for fusion ignition. First, as previously noted, the MTF targets are larger than ICF targets, on the order of a centimeter rather than a millimeter. With very low implosion velocities, the implosion time increases from nanoseconds to microseconds. This means that for about the same mass of fuel, the driver power required for achieving ignition is orders of magnitude lower than for ICF. Since the size determines the surface area of the target, the intensity on target can be even more orders of magnitude lower than the intensity needed for ICF. In fact, the minimum hohlraum temperature needed for indirect drive targets in ICF is closely tied to the intensity needed to drive the target to ignition. This means that indirect drive with MTF would require only tens instead of hundreds of ev temperature in the hohlraum. In fact, there is no incentive for indirect drive for an MTF target, because symmetry of implosion is not such an important issue as it is for ICF. Because the initial temperature is determined by the target plasma creation, and it can be made quite high, the convergence necessary for ignition can be quite small ($(T_{ign}/T_0)^{1/2}$ ~ 10 to 15) for spherical targets.

PAST EXPERIENCE

The most extensive series of MTF experiments were the Phi-target experiments conducted by Sandia National Laboratory in 1977 [7-9]. These experiments were conducted on a relativistic electron beam machine, which had a non-relativistic prepulse. The previous, simple target experiments conducted by Sandia represented their initial involvement in ICF. Fot their first experiments they had used spherical targets consisting of a thin shell containing deuterium gas mounted on a stalk attached to the anode of the e-beam diode. The relativistic electrons had high enough current to pinch the beam into a pencil sized column that impinged on the target from the cathode. Because the electrons were relativistic, the stopping length was large, and the fields in the diode (as disturbed by the target) caused the electrons to reflex through the target, providing relatively uniform energy deposition. Because the energy deposition was very uniform, the target shell exploded, with part driven radially outward and part inward. This enabled the e-beam machine to implode the targets quite symmetrically. However, for ICF in the usual sense, uniform energy deposition in the shell (and throughout the deuterium gas) limited the degree of convergence possible. This is because uniform deposition set the shell on a high adiabat, so that the implosion pumped most of the energy into internal energy of the imploding part of the shell, not into the deuterium fuel. Therefore, it was decided to abandon the e-beam machine in favor of a light ion beam machine. The advantage was that the light ions (protons in the first machine) had a very short range (and produced no bremsstrahlung in heavier metal shells), but the disadvantage would be loss of efficiency in producing the light ion beam and the necessity to focus it onto the target, because ions couldn't be pinched into a beam.

While the first proton beam machine was being designed, the Sandia team tried a novel idea on an e-beam machine. An electrode was mounted on the target between it and the cathode, so that it intercepted the non-relativistic pre-pulse from the cathode and discharged a current through the target. In fact, a CD_2 wire was added along the axis inside the target, which exploded due to the pre-pulse current. The collector, CD_2 wire inside, plus the stalk on the anode schematically resembled a Greek Phi, hence the name Phi-target. The discharge created a hot, magnetized plasma. When the pre-pulse ended and the relativistic pulse began, the imploding the shell to compress the magnetized plasma inside up to temperatures sufficient to produce neutrons. These were the first TN neutrons produced by the Sandia team [7].

The experimental campaign involved over two dozen targets, 15 of which were complete. The rest were fielded as null experiments (with bumps, holes, no electrode, etc.) in an effort to determine if some other physics might be responsible for the neutron production besides the compression of the hot, magnetized CD_2 plasma.None of the null targets gave measurable neutrons, but eight of the complete targets did, ranging from 5 to 25 million. These experiments are reported in more detail in an accompanying paper in this symposium [9].

Shortly after the Phi-target experiments some effort was made to model these experiments with one- and two-dimensional (1-D and 2-D) computer codes [10]. One of the few gas filled targets was chosen for modeling, because of computational limitations. First, a 1-D calculation was done to obtain the implosion dynamics of the e-beam driven shell, then a 2-D resistive MHD calculation was done using the interface motion from the 1-D calculation for the history of the outer boundary in the 2-D calculation during the implosion phase. The 2-D resistive MHD calculations showed that during the pre-pulse phase, the plasma had an overturning flow, but during the very short implosion, very little motion occurred. The plasma temperature reached about 400 ev in the calculations. The implosion trapped the field and compressed it up to about 1 MG. A convergence of about 20 was required to match the observed neutron yield. It was concluded that the experimental measurements as analyzed by the 1-D and 2-D codes were consistent with a TN origin for the neutrons.

In addition to the Phi-target experiments, there were liner-on-plasma ideas pursued at Los Alamos and at the Naval Research Laboratory (NRL). The Fast Liner Program in Los Alamos [11] succeeded in producing a plasma at 30 ev with an embedded field of about 10 KG, and in driving a solid liner symmetrically at about 1 cm/us. However, the plasma was thought insufficient for the purpose, and no experiment was done with a plasma inside the liner. The NRL Linus Program proposed to use a liquid liner to compress a fusion plasma, but no integrated experiments were ever done.

Electrically driven shock tube experiments at Columbia University [12] have been interpreted as evidence for classical (Spitzer-like rather than Bohm) reduction of the thermal by a magnetic field in a high (beta) plasma. Particle-in-cell calculations by Dawson,Okuda, and Rosen provide some theoretical understanding for this result [13]. When the plasma frequency is sufficiently high relative to the electron cyclotron frequency, plasma fluctuations don't persist long enough for Bohm diffusion to be an effective transport mechanism.

In Russia, during the days of the Soviet Union, the All-Union Scientific Institute for Experimental Physics (VNIIEF) had embarked on a program of high explosive pulsed power, one of the applications of which was magnetic implosion of a liner, and another of which was the creation of an energetic magnetized plasma. We have come to know the latter as the MAGO experiments [14]. In these experiments they were able to generate neutron producing magnetized plasmas in the range of 200 ev and 50 KG. In recent months, joint experiments with Los Alamos have confirmed these numbers. It would appear that all the requisite factors are in place to allow an integrated MTF experiment with explosive pulsed power, but it should also be possible to do MTF experiments in a beam on target configuration, similar to the Phi-target experiments that Sandia performed. The collaborative experiments are discussed more extensively in another paper in this symposium [15].

DRIVER REQUIREMENTS FOR IGNITION

Ignition of a fusion target that is imploded requires that the driver be able to deliver a pulse of energy that is simultaneously sufficiently intense, powerful, and energetic. Lasers are clearly sufficiently intense and powerful, but currently lack the necessary energy for ICF ignition. Pulsed power drivers such as light ion beams have for a long time had enough energy, possibly had sufficient power, but lacked the focusing, that is, intensity on target. No heavy ion beam driver exists yet, but one of the problems they must face is the necessity to use indirect drive. It appears that heavy ion drivers will be unable to deliver a sufficiently intense pulse to achieve the necessary hohlraum temperature for ICF fusion ignition. So, no driver is available for ICF ignition, except perhaps explosive fission sources. While a fission source could be invaluable for ICF research right now, it is not permitted currently and would not be a politically acceptable choice for a fusion power reactor in the foreseeable future.

Because MTF relaxes the power and intensity requirements needed for ignition in the MTF fusion region, pulsed power drivers become very attractive.

The great advantage of MTF in this regard is illustrated by Figure 6, in which the MTF targets are shown to operate at orders of magnitude less power than do ICF targets. It can be argued that MTF targets may have low gain (which should be true only for simple targets), but even if so, this would be more than offset by the fact that pulsed power drivers can have a high efficiently when properly designed to deliver energy to a matched load. In addition, one study of potential MTF targets explores the possibility of obtaining high gain [8].

CRITICAL ISSUES FOR MTF

While the previous experiments and calculational analyses are very encouraging, there are a few issues that need to be addressed for MTF.

Plasma instabilities are thought to be suppressed because the plasma is wall supported by the pusher, but hydrodynamic instability of the pusher is a possibility. Because MTF can operate at much lower pressures than ICF, material strength in the pusher may reduce the growth of hydrodynamic instabilities. Also, the pusher will be more nearly incompressible, so that the inner aspect of the pusher may continue to accelerate inward longer than is the case for ICF. While this may be advantageous from the standpoint of hydrodynamic instabilities, if the pusher does not stagnate, then not as much of the the energy in the implosion will be transferred to the target plasma before ignition occurs. This leads to a reduced gain for the target, but should not lead to failure to ignite.

The fact that the target plasma must be magnetized means that the field pressure must augment the particle (or plasma) pressure, so that those regions in the plasma where the field is stronger have some degree of buoyancy, leading to hydrodynamic turnover. This convective behavior could augment the (reduced) conductive heat flow to the wall. The degree to which convection augments conduction depends on the velocity of convection relative to the implosion velocity. A secondary effect of convection is the potential entrainment of wall material in the plasma flowing past the wall. This could have two consequences: the added thermal capacity of the material entrained and enhanced radiative cooling. The physics associated with these processes is understood, but the ability of our codes to model these processes is presently limited. For MTF in its simplest form there is no need to trap the radiation generated in the plasma, so that light elements suffice as ingredients of the wall (i.e., pusher). This means that the maximum value of the impurity nuclear charge Z can be kept to a minimum. The physics of the impurity radiation is well understood, but detailed treatment in a code does involve a significant computational effort. Some simple arguments lead to the conclusion that for light element impurities, the major process that enhances the radiation from the high temperature plasma is bremsstrahlung. The critical question is how much material will be entrained in the plasma. This issue needs to be addressed. If the DT targets have frozen DT layers inside the shell [8], then there would be no impurity, but the problem of added heat capacity would still arise.

Target plasma creation in the Phi-target discussed below was accomplished with a simple electrical discharge through a CD_2 wire or through a deuterium gas. This process was modeled for the case of discharge through the D_2 gas by Lindemuth and Widner [10]. It appears that the resistive nature of the D_2 gas while it was not yet hot allowed the magnetic field to diffuse into the D_2 plasma, thus providing a hot, magnetized plasma. We do not yet know what ranges of temperature, density and field can be produced by this approach. The high density Z-pinch has been modeled by Sheehey [16] and others and is now well understood for a range of conditions, but we still need to explore the range relevant to MTF. In addition, the calculations need to have experimental verification. Finally, the MAGO experiments seem to have produced a magnetized plasma of interest to MTF. These experiments are currently under scrutiny to see if the calculated parameters agree with the experimental measurements. If so, this may be a suitable target plasma for MTF.

THE POSSIBILITY OF AN ANEUTRONIC FUEL FOR MTF

Because both D^3He reaction products (a proton and a helium nucleus) are charged, the magnetic field can help retain up to five times more energy from the D^3He reaction than is possible for the DT reaction. However, this is offset by the higher bremsstrahlung radiation due to the light He nuclei. Marjorie Ward explored the possibility of using D^3He as an MTF fuel [17]; her Lindl-Widner diagram for D^3He is shown in Figure 7.

Notice that the MTF fusion region still is present for D3He, but it is diminished in size and at higher temperature than for DT. This is partly due to the assumption in the calculations that were used to produce this diagram, that is, that the ion and electron temperatures are equal. This is a very conservative assumption for D^3He. Additional calculations are needed to better define the MTF fusion region for D^3He. However, there is evidence that D^3He might be useful for MTF.

APPLICATIONS

No fusion concept has an application unless it performs adequately for practical use in the proposed application. Currently, there are only a few settings in which fusion performs adequately: the sun and TN weapons are two, but a few very low level, portable neutron sources also exist. Therefore, this discussion of applications for MTF is necessarily speculative, and assumes that MTF will provide a significant (but manageably small) source of TN fusion energy. The characteristics of a working MTF fusion scheme depend on whether a liner on target plasma or a beam on target approach works, as well as the type of driver employed. If the configuration of a working scheme is beam on target, then applications of MTF should be similar to those of ICF, that is, fusion energy production and perhaps space propulsion. If MTF takes the form of a liner on target plasma, then the range of potential applications may be narrow, e.g., some device like that proposed in the NRL Linus Program to provide fusion energy. Edward Teller doubts the energy production application of fusion, but believes fusion is necessary for space propulsion. This is because he believes that fission energy is a reality that is being embraced by the world (outside the US). Until something besides a bomb or the sun is demonstrated at useful power density, then all other applications are speculation. The emphasis should be on the demonstration of a working concept. Once this is done, I predict that many applications will be proposed. One application of fusion that receives little attention is transmutation. Thermalized neutrons can be used for medical isotope production and for converting cheap, abundant elements into rare, valuable ones. We know how well this works for fission reactors. Pulsed neutron sources may be more versitile.

SUMMARY

We have presented an overview of the MTF concept. Two accompanying papers at this symposium have discussed other aspects of MTF: Mary Ann Sweeny provided an account of the 1977 Phi-target experiments at Sandia National Lab in Albuquerque [9] and subsequent calculational studies [8]. Irv Lindemuth discussed the fledgling US/Russia collaboration on the MAGO experiments [15]. Other concepts presented here have overlap with MTF or in some cases may even embody all the basic principles of MTF [18].

The major contribution of MTF is that of matching the target to the presently available drivers. This means that it may be possible to demonstrate fusion ignition in the near term. We currently need a commitment of resources that will allow us to ascertain the truth of MTF. Only a small commitment would go a long way.

The time is ripe for exploring MTF. A relatively small investment of resources is all that is needed. The dividend may be large, and the payoff soon.

ACKNOWLEDGEMENTS

The author thanks I.R. Lindemuth, R.E.Reinovsky, and P.T. Sheehey for comments, research support, and computations that contributed to the work presented here. The efforts of many other individuals who are making contributions to the Los Alamos/VNIIEF collaborative MAGO experiments are also appreciated.

REFERENCES

[1] Landshoff, R., "Transport Phenomena in Completely Ionized Gas in the Presence of a Magnetic Field", Los Alamos National Lab report LA-466 (1945); Phys. Rev. 79 (1949) 904.

[2] Panarella, E., Proceedings, First International Symposium for the Evaluation on Current Trends in Fusion Research, Washington, D.C., (tutorial) November (1994).

[3] Lindemuth, I.R., and Kirkpatrick, R.C., "Parameter Space for Magnetized Fuel Targets in Inertial Confinement Fusion," Nucl. Fusion 23 (1983) 263.

[4] Kirkpatrick, R.C., Lindemuth, I.R., and Ward, M.J., "Magnetized Target Fusion, an Overview," to be published in Fusion Technology (1995).

[5] Lindl, J.D., "Physics of Ignition for ICF Capsules," Inertial Confinement Fusion Course and Workshop (Varenna, Italy, 1988 A. Caruso and E. Sindoni, ed.).

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

[7] Widner, M.M., "Neutron Production from Relativistic Electron Beam Targets", Bull. Am. Phys. Soc. 22 (1977) 1139.

[8] M.A. Sweeny and A.V. Farnsworth, "High-Gain, Low-Intensity ICF

Targets for a Charged-Particle Beam Fusion Driver", Nuclear Fusion 21 (1981) 41.

[9] Sweeny, M.A., Proceedings, First International Symposium for the Evaluation on Current Trends in Fusion Research, Washington, D.C., November (1994).

[10] I.R. Lindemuth and M.M. Widner, "Magnetohydrodynamic Behavior of Thermonuclear Fuel in a Preconditioned Electron Beam Imploded Target," Physics of Fluids 24 (1981) 753.

[11] A.R. Sherwood, B.L. Freeman, R.A. Gerwin, T.R. Jarboe, et al., "Fast Liner Proposal," Los Alamos Scientific Laboratory report LA-6707-P (August 1977).

[12] B. Feinberg, "An Experimental Study of a Hot Plasma in Contact with a Cold Wall", Plasma Physics 18 (1976) 265.

[13] Dawson, J.M., Okuda, H., and Rosen, B., "Collective Transport in Plasmas", in Methods in Computational Physics 16 (1976) 281.

[14] A.M. Buiko, V.K. Chernychev, V.A. Demidov, Yu.N. Dolin, S.F. Garanin, V.A. Ivanov, V.P. Korchagin, M.V. Lartsev, V.I. Mamyshev, A.P. Mochalov, V.N. Mokhov, I.V. Morozov, N.N. Moskvichev, E.S. Pavlovsky, S.V. Pak, S.V. Trusillo, G.I. Volkov, V.B. Yakubov, V.V. Zmushko, "Investigations of Thermonuclear Magnetized Plasma Generation in the Magnetic Implosion System MAGO," in "Physics of High Energy Densities," MEGAGAUSS VI, Albuquerque, NM (1992).

[15] Lindemuth, I.R., Proceedings, First International Symposium for the Evaluation on Current Trends in Fusion Research, Washington, D.C., November (1994).

[16] P.T. Sheehey, J.E. Hammel, I.R. Lindemuth, D.W. Scudder, J.S. Schlacter, R.H. Loveberg, and R.A. Riley, Jr., "Two-Dimensional Direct Simulation of Deuterium-Fiber-Initiated Z-Pinches with Detailed Comparison to Experiment," Phys. Fluids 4 (1992) 3698.

[17] M.S. Ward, Los Alamos National Laboratory memo X-1-93-.... (1993).

[18] Panarella, E., Proceedings, First International Symposium for the Evaluation on Current Trends in Fusion Research, Washington, D.C., November (1994).

FIGURE CAPTIONS

Fig. 1 Lindl-Widner diagram for the ICF case (B=0). The fusion region is where fusion energy deposition overcomes energy losses ($d\Theta/dt>0$) at turnaround (v=0). The fusion region is insensitive to the DT mass for the target.

Fig. 2 Lindl-Widner diagram with compression heating (v>0). Sufficient implosion velocity allows ignition to be achieved.

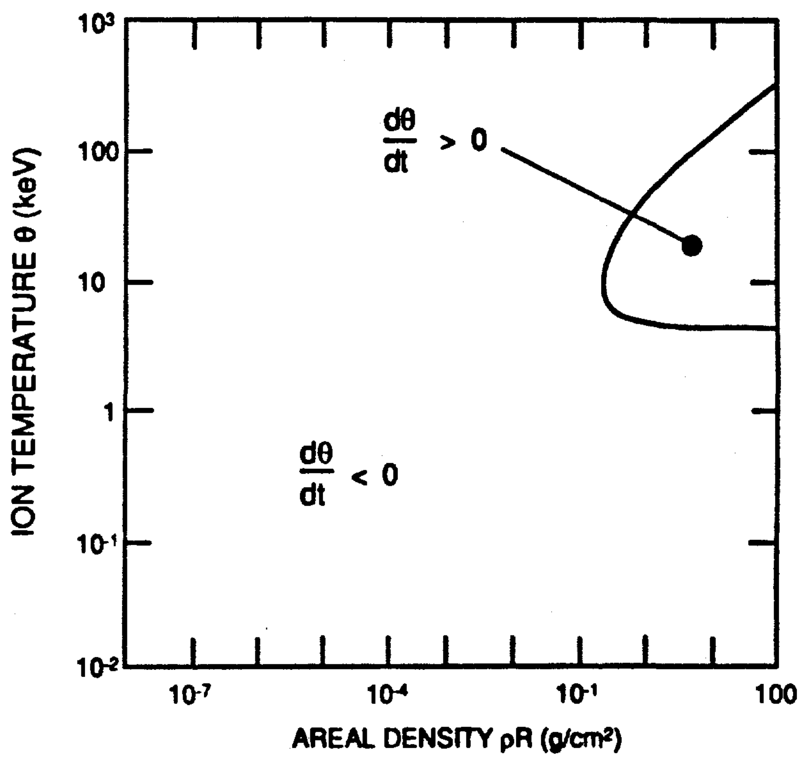
Fig. 3 Lindl-Widner diagram for the MTF case (B>0). The size and position of the MTF fusion region depends on both the field strength and the target plasma mass.

Fig. 4 Computed fractional energy deposition for a DT alpha particle in a 10 Kev DT plasma with a uniform magnetic field.

Fig. 5 Lindl-Widner diagram with overlayed zero temperature rate contours for various implosion velocities. Also shown on the plot are representative adiabats for cylindrical (C) ahd spherical (S) geometries and a line of constant pressure times radius $PR \sim \rho R x T$ (denoted by P).

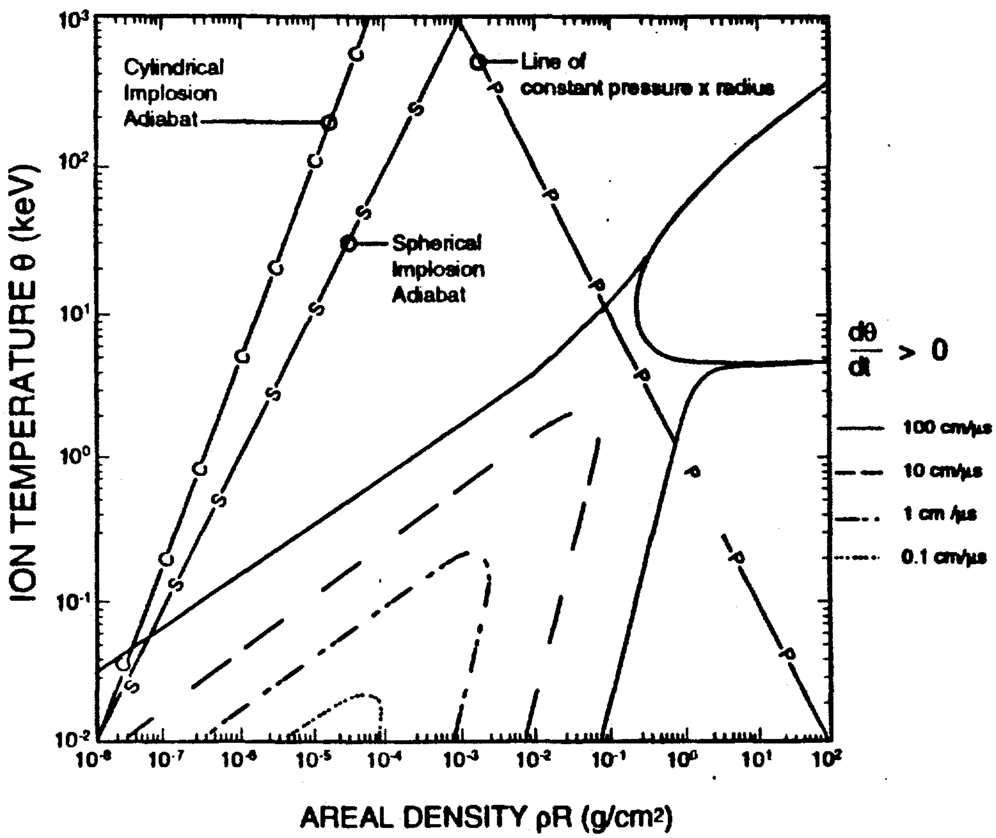
Fig. 6 The power and energy necessary for MTF targets. MTF targets should operate at low power (and intensity) on target.

Fig. 7 Lindl-Widner diagram for D3He. The conservative assumption that $T_i=T_e=T$ is made.



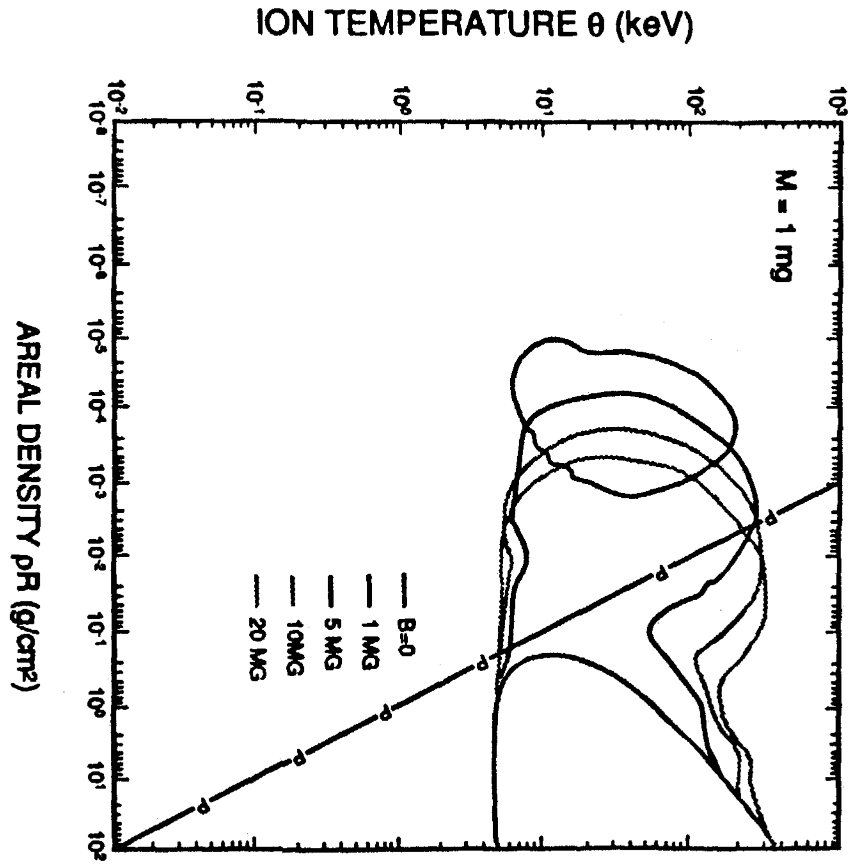
10^3
100
10
1
10^{-1}
10^{-2}
ION TEMPERATURE θ (keV)
$\frac{d\theta}{dt} > 0$
$\frac{d\theta}{dt} < 0$
10^{-7}
10^{-4}
10^{-1}
100
AREAL DENSITY ρR (g/cm²)

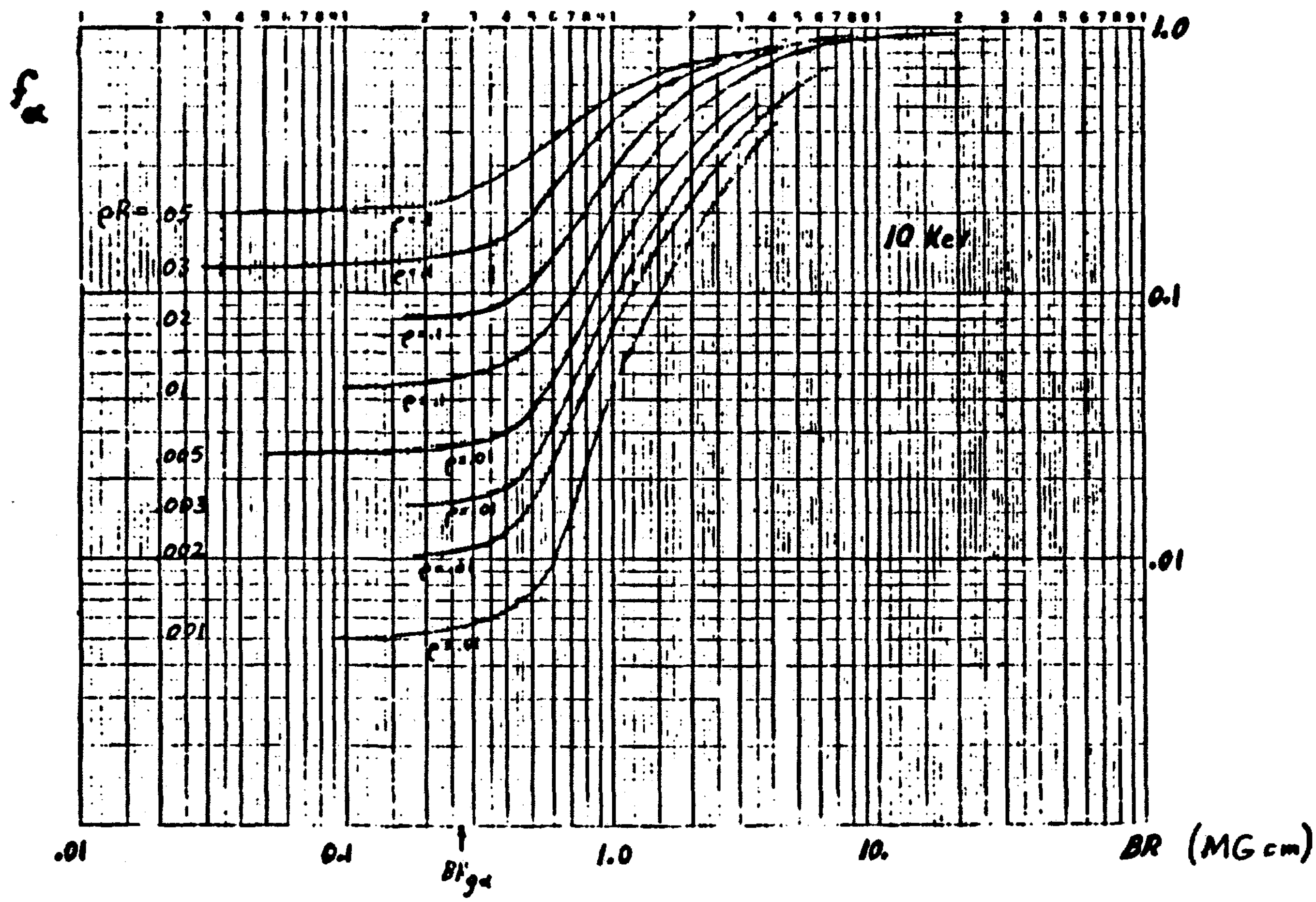
Fig. 1



Cylindrical
Implosion
Adiabat
Spherical
Implosion
Adiabat
Line of
constant pressure x radius
ION TEMPERATURE θ (keV)
AREAL DENSITY ρR (g/cm2)
dθ/dt > 0
100 cm/μs
10 cm/μs
1 cm /μs
0.1 cm/μs

Fig.2


ION TEMPERATURE θ (keV)
AREAL DENSITY ρR (g/cm²)
M = 1 mg
B=0
1 MG
5 MG
10MG
20 MG



f_α
ρR = .05
.03
.02
.01
.005
.003
.002
.001
10 Kev
1.0
0.1
.01
.01
0.1
1.0
10.
BR (MG cm)
$B r_{g\alpha}$

Fig. 4

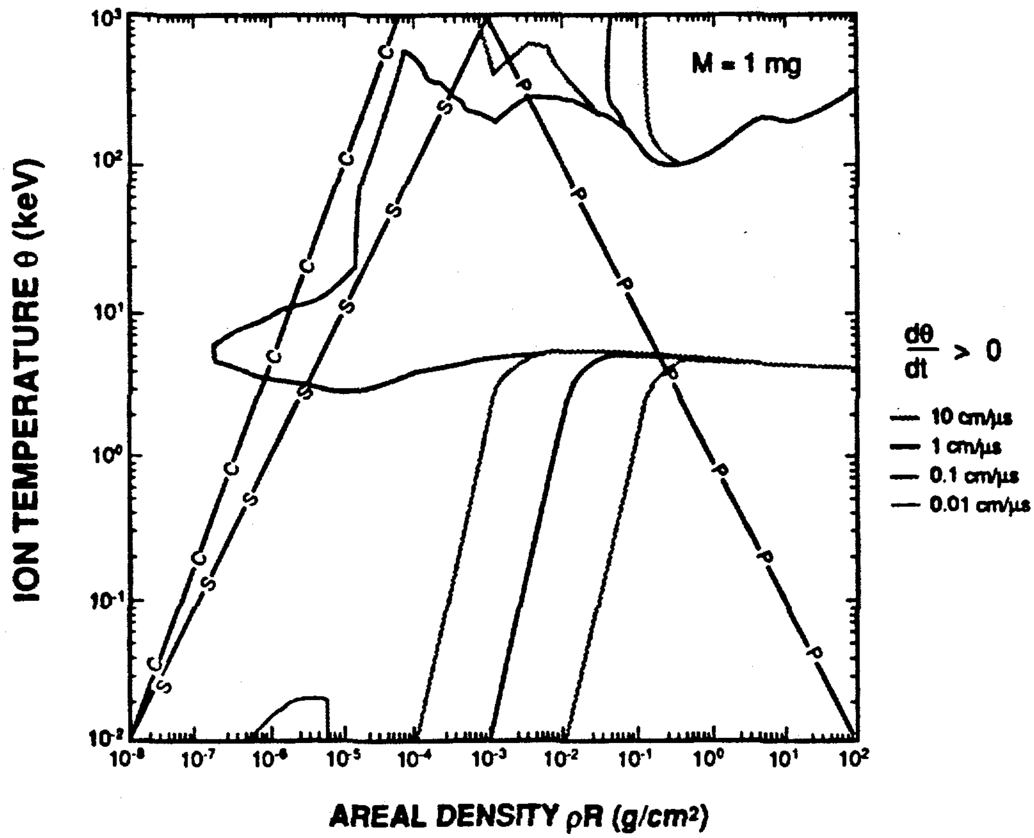
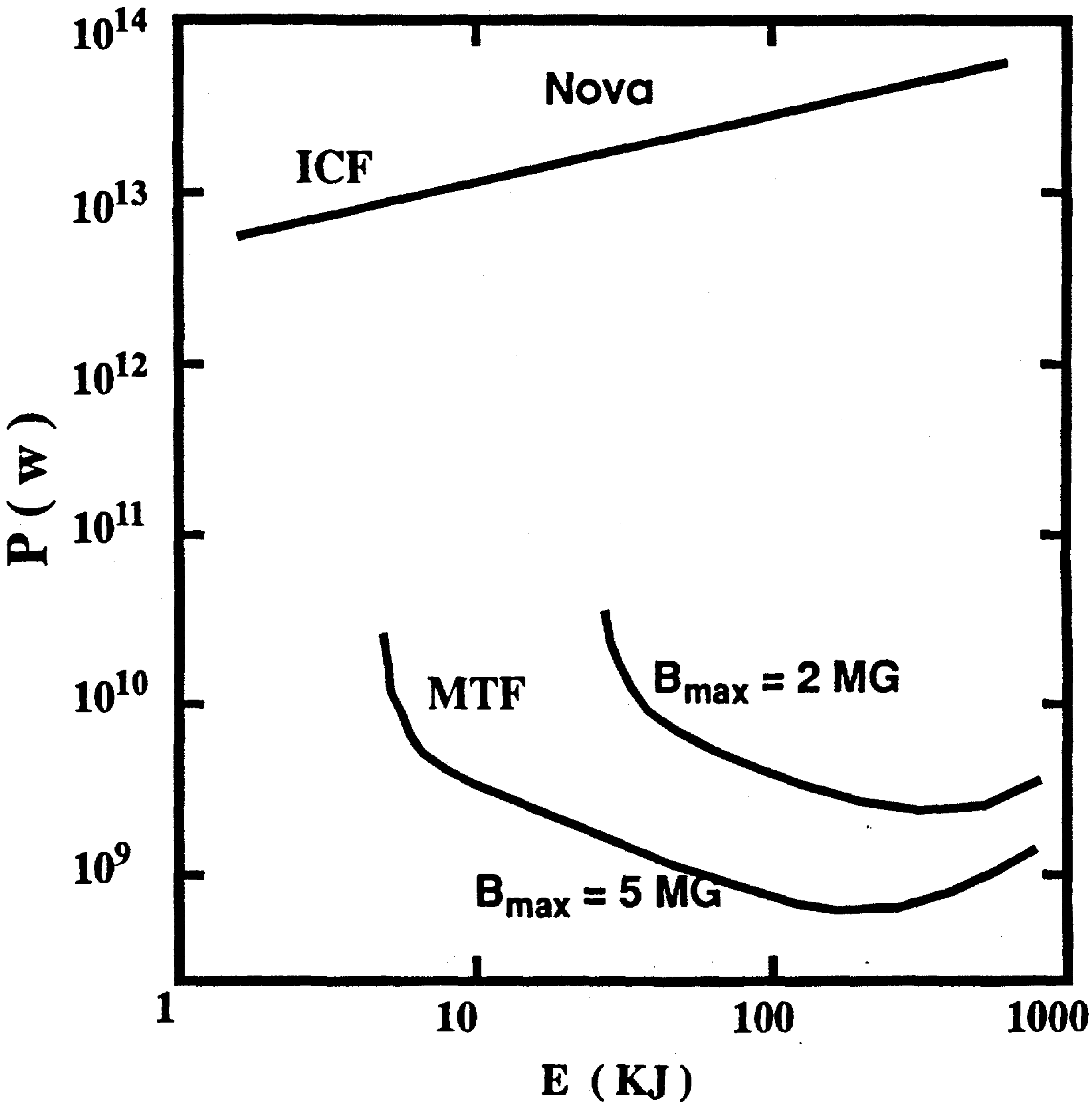

M = 1 mg
ION TEMPERATURE θ (keV)
AREAL DENSITY ρR (g/cm²)
dθ/dt > 0
10 cm/μs
1 cm/μs
0.1 cm/μs
0.01 cm/μs
C
S
P

Fig. 5



10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
P (w)
Nova
ICF
MTF
B_{max} = 2 MG
B_{max} = 5 MG
1
10
100
1000
E (KJ)

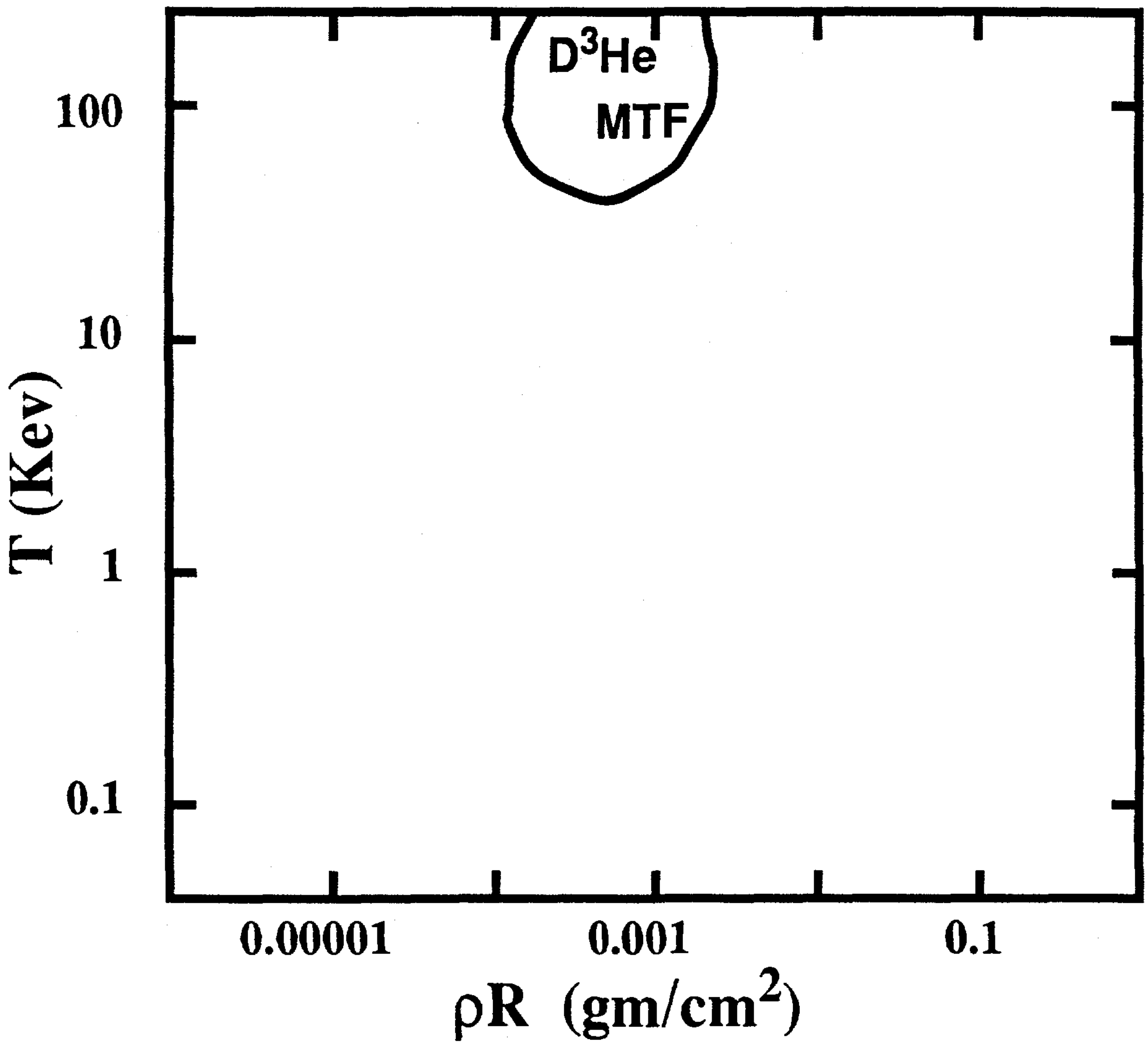


Fig. 7