Title: MAGNETIC COMPRESSION / MAGNETIZED TARGET FUSION (MAGO / MTF)

CONF-9703109-

Author(s): Ronald C. Kirkpatrick, Irvin R. Lindemuth,

Submitted to: Proceedings of the Second Symposium of Current Trends in International Fusion Research
Washington, DC
March 10-14, 1997

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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. The 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.

DTIC QUALITY INSPECTED 5
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
MAGNETIC COMPRESSION / MAGNETIZED TARGET FUSION

(MAGO / MTF), An Update

Ronald C. Kirkpatrick and Irvin R. Lindemuth
Los Alamos National Laboratory
Los Alamos NM, USA

ABSTRACT

Magnetized Target Fusion (MTF) was reported in two papers at the First Symposium on Current Trends in International Fusion Research [1, 2]. MTF is intermediate between two very different mainline approaches to fusion: inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). The only US MTF experiments in which a target plasma was compressed were the Sandia National Laboratory "Phi-targets" [3]. 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 [4] were unable to attract the financial support needed for a firm proof of principle. A mapping of the parameter space for MTF [5] showed the significant features of this approach. The All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) has an on-going interest in this approach to thermonuclear fusion, and 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). The MAGO II experiment appears to have achieved on the order of 200 eV and over 100 KG [6], so that adiabatic compression with a relatively small convergence could bring the plasma to fusion temperatures. In addition, there are other experiments being pursued for target plasma generation and proof of principle. This paper summarizes the previous reports on MTF and MAGO and presents the progress that has been made over the past three years in creating a target plasma that is suitable for compression to provide a scientific proof of principle experiment for MAGO / MTF.

INTRODUCTION

Magnetized target fusion (MTF) provides a development path for fusion energy that is mid-way between the two dominant approaches to fusion energy. An unambiguous demonstration that compression of a magnetized plasma heats it in accord with MTF theory is desired. Previous MTF studies [5,7] have emphasized that existing pulsed power technology is adequate for a scientific proof of principle (i.e., an unambiguous demonstration), 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 have been previously presented [1,2], but will be summarized here.

It should be noted that MTF is a concept that may have many diverse embodiments, some purely for experimental investigation of MTF, and potentially others for applications such as fusion power production and space propulsion. We take 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 energy production or other application. Therefore, we are reluctant to divert our effort from the first task, but concede that it is necessary to provide a plausible embodiment
of MTF for fusion power production and will do so at the end of this paper. However, it should be remembered that there may be many unanticipated applications of fusion. We shall try to anticipate only a few.

MTF PHYSICS

Magnetized target fusion is based on the fact that a magnetic field suppresses electron thermal conduction in a sufficiently hot plasma. Electron thermal conduction is the major energy loss mechanism for the wall confined, unmagnetized plasmas produced in most designs for fusion ignition targets in inertial confinement fusion (ICF) [8]. However, for ICF simply imposing a magnetic field on existing 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 $\alpha R$. Even if the magnetization were sufficient to erase the conduction loss, the next most important loss mechanism, bremsstrahlung, would take over. Therefore, MTF must operate in a lower density regime than ICF, so that both conduction and radiation losses are reduced. For similar fusion plasma mass, this leads to a larger target containing a gaseous DT fusion fuel at a density of 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 synchrotron radiation and magnetic field energy are only perturbations on the fusion fuel dynamics. If the plasma initially has a high ratio of internal energy to magnetic energy $\beta$, then it will always be so as the plasma is compressed. With sufficiently reduced energy loss rates the plasma can be compressed relatively adiabatically to fusion temperatures by reducing the volume of the confining vessel. With the reduced energy loss rates, 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 would be over an order of magnitude lower.

Fusion ignition 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 neutrons and/or energetic charged particles 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 $\rho R$. It must exceed approximately 0.3 gm/cm$^2$ for fusion ignition to occur. For this very low value of areal density, the neutrons deposit very little energy, so the DT alpha particles are the major source of self-heating. The efficiency of the burn that follows also depends on an areal density, but that of the imploding part of the target (fusion fuel plus imploded confining vessel), and therefore, the target gain depends on the $\rho R$ as well.

Because the energetic charged particles in a magnetized plasma are turned in the field, their path in the fusion fuel is lengthened. Since in a hot plasma the magnetic field is essentially frozen in place relative to the plasma, the compression of the plasma by the imploded confining vessel also compresses the field. These compressed fields can reach many Megagauss. The critical parameter for self-heating 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
pR typical of MTF is significantly augmented by the high BR, which makes it possible for fusion ignition to occur for MTF at lower pR than required for ICF. In one study [9] 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. Some results for that study are shown in Figure 1. Figure 2 shows the dependence of the fractional deposition on temperature for a pR of 0.001 gm/cm$^2$.

THE MTF ADVANTAGE

Because MTF targets are larger and can be imploded slower, the power and intensity for driving the 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, simply because the same thermal energy must be supplied to the fusion fuel to raise it to the ignition temperature [7]. Ignition of a given design of fusion target requires that the fusion driver (laser, particle beam, or otherwise) supply simultaneously sufficient energy, power, and intensity. For example, 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 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 admit as potential drivers for fusion targets existing and near-term 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, pulsed power machines can easily supply sufficient energy, power, and intensity for MTF and are more efficient overall than laser or other beam drivers.

TARGET PLASMA GENERATION

The benefit promised by MTF is not without cost. It is necessary to create a target plasma that is sufficiently warm, magnetized, and long lived that it can be compressed to fusion temperatures with the slower implosion provided by pulsed power drivers. Because the MTF concept relies on compression of the warm plasma from its initial temperature to fusion temperatures, the energy that resides in the warm plasma before compression is modest. For example, 100 mg of DT at 50 eV has only 500 J of internal energy, but at the temperature required for fusion ignition (~ 5 keV) 100 mg would have 50 kW, the bulk of which would have been added through compression following the target plasma creation. There are potentially several ways to create a target plasma.

In the Sandia "Phi" targets [3], an electrical discharge through the deuterium inside the plastic shell that acted as the confining vessel left a target plasma that was about 20 eV with a 10 KG field. In the Fast Liner experiments [4] at Los Alamos a 30 eV plasma with a field of 10 KG was produced with a Marshall gun. Our survey calculations [5] indicated that a 50 eV plasma with a 50 KG field is necessary for reaching fusion ignition. It should be noted here that there is a trade-off between initial target plasma temperature and the convergence required to reach fusion temperatures. While lower values of target plasma temperature and field can provide useful experimental data, the MAGO experiments have been interpreted as providing about 200 eV with a magnetic field of about 100 KG, and these values are what the MHD codes predict [6]. Therefore, the MAGO experiments appear to have demonstrated one method of creating a target plasma that is more than adequate for an MTF scientific proof of principle. However, we are still trying to better assess the life time of the MAGO plasmas. Because of the important implication of
successful target plasma generation experiments regarding an MTF proof of principle, we present here some details of our progress in this area.

ANALYSIS OF THE MAGO EXPERIMENTAL DATA

While some other yet untried approach may suffice to produce a target plasma, the MAGO experiments presently appear to provide a plasma with more than adequate properties, and no other approach has yet been experimentally demonstrated to give a more appropriate target plasma. Therefore, we have focused on a better characterization of the MAGO plasma. This is because a proof of principle experiment will tax the small resources presently devoted to MTF, so we don't want to proceed without some assurance that we have a valid starting point. The MAGO experiments use an explosively driven magneto-cumulative pulsed power generator. Therefore, necessarily some of the detectors on these experiments are expended. While some smaller scale experiments using fixed capacitor banks in the lab have been demonstrated, there is insufficient data for an assessment of the plasma temperature and density for these experiments. For this reason, there are only three experiments (all explosively driven MAGO shots) where we have data from a full set of diagnostics.

We note in passing that there is nothing inherent in MTF or the MAGO plasma formation system that requires the generation of electrical current through the use magnetic flux compression generators driven by high explosives. In the former Soviet Union, economic considerations prevented the development of advanced capacitor bank technology such as is now available in the US. Hence, Russian scientists concentrated on the much cheaper flux compression technology. In the process VNIEF scientists developed a capability that can produce higher electrical currents and energy (albeit, slower) than is available elsewhere. For the fusion scientist, flux compression technology enables experimentation that simply could not be performed in any other manner.

The plasma behavior in the MAGO experiments is complex. Here, we describe the computational picture as modeled by a 2-D MHD code at Los Alamos [10,11]. The cylindrical copper plasma chamber is divided into two parts as illustrated in Figure 3. Initially a slowly rising current of about 1-2 MA is introduced which flows around the chamber and through the center rod that supports the copper barrier between the chambers. This current creates a magnetic field throughout both chambers, but the rise time is too long to induce any ionization. A switch isolates the chamber from the explosive pulsed power generator while it continues to operate, building the current to about 10 MA. At that time an opening switch abruptly introduces a high voltage (an inductive “kick”) to the chamber. The high voltage ionizes the deuterium-tritium (DT) gas inside and causes discharges, first between the barrier and the cylindrical wall, and then across the insulator in the first chamber. The discharge across the nozzle weakly shocks the neutral magnetized gas in both chambers and weakly ionizes it. An inverse pinch in the first chamber drives the ionized plasma from that chamber through the annular nozzle where it is accelerated to velocities approaching 100 cm/us by the \( j \times B \) forces. This fast flow shocks down into the magnetized plasma in the second chamber, initially heating a small portion to temperatures exceeding 1 KeV in hot spots. This plasma quickly relaxes to a warm few hundred electron volts (\( \sim 200 \text{ eV} \)), but the brief high temperature hot spots provide on the order of \( 10^{13} \) neutrons in a half-microsecond burst. This burst of neutrons is incidental to the creation of the warm magnetized plasma. It is this warm, late time plasma in chamber 2 that we are interested in as a possible target plasma for MTF.

Because of quality of data, we have focused on the MAGO II experiment, which was performed at Los Alamos in October of 1994. Thus far, the most telling data regarding
The temperature history of the plasma generated appears to be the filtered silicon diode data for a line of sight through the second chamber, parallel to, and 6 cm from its axis [12]. The silicon diodes we used have a spectral response spanning photon energies from about 1 eV to 10 KeV and viewed the plasma along four lines of sight at the same radius through the second chamber. One diode had no filter, and both single material and composite filters were used to give different band passes for the other three. Only the three filtered diode signals could be used in an analysis of the plasma temperature history because the unfiltered diode saturated before any of others gave signals. Figure 4 shows the spectral responses of an unfiltered diode and the three filtered diodes. Figure 5 shows the signals for the three filtered diodes. It should be noted that the peak in the approximately 10^13 neutron output from MAGO II occurred near the time of the first peaks in the signals from these diodes and lasted less than a microsecond. With data for enough spectral band passes it would be possible to reconstruct the spectral history of the emission, but because of the data is very limited it is necessary to assume a spectral shape and test to see what shape provides the best fit to the data.

Figure 6 shows the characteristic plasma temperatures or energies deduced from the data for five assumed spectral types. While all the resulting temperatures and energies (with offsets) track together, that which has the best fit to the data is for an assumed bremsstrahlung spectrum. The second best is for an exponential. In addition, using the 1-D non-LTE radiation transport code ZAP to simulate the spectra expected from the MAGO II plasma (which had a 0.01 % neon impurity), the inferred temperature history of the plasma can again be inferred. It does not differ significantly from that for a bremsstrahlung spectrum. Figure 7 shows these results compared with the spatially averaged temperature calculated using a 2-D MHD code [10] to compute the expected plasma dynamics. Figure 8 shows the estimated density based on analysis of the data compared with the spatially averaged value from the MHD code. Both the temperature and density comparisons are remarkably close, suggesting an average plasma temperature of about 200 eV and an average density of about 10^18/cc for a few microseconds after the peak in the diode signals.

After about five microseconds, the diode signal levels rise abruptly and the inferred plasma temperatures all drop sharply. This could be due to a drastic change in the nature of the plasma, but it could also be due to a failure in the filtered silicon diode diagnostics. We did a detailed study of the generation of shocks in the diagnostic access holes for the filtered silicon diodes and concluded that the sharp rise in signals could be reasonably explained by destruction of the filters when a shock generated by an oscillating MHD piston arrives at the diodes. However, we must confirm this hypothesis in another experiment. The MAGO III experiment at VNIIEF in September of 1995 used three sets of seven filtered silicon diodes each to diagnose the plasma, but unfortunately the extensive data was not useable, partly because of saturation of the signals, and possibly because of shock arrival at the diodes. In the MAGO III experiment it appears that the supposed shocks arrived earlier than for MAGO II, which correlates with the higher calculated average temperature for the MAGO III plasma.

**OTHER TARGET PLASMA APPROACHES**

In the Sandia Phi target experiments the target plasma was created in a much simpler way than in the MAGO experiments. These targets contained either a CD₃ fiber or deuterium gas inside a small plastic shell and was driven by a relativistic electron beam, which had a non-relativistic precursor. An electrode was mounted on the cathode side of the target to intercept the non-relativistic precursor. This created an electric field that weakly ionized the gas or deuterated polyethylene (CD₃) fiber inside, leading to a discharge that created a warm magnetized plasma inside. The resulting 20 eV, 10 KG plasma was...
below the 50eV and 50 KG values, which (in the light of the survey calculations done a few years later [5]) we now think are needed for MTF. The main pulse deposited about 4 KJ of energy in the plastic shell, ionizing it and providing an exploding pusher behavior that compressed the target plasma inside [3]. The conditions created by the discharge in the Phi target were adequate to provide measurable neutron output (~ 5 to 25x10^6) at the end of the compression phase. It should be noted that this was energetically a very low level experiment in comparison to the MAGO experiments. Later, Sandia performed experiments using a capacitive discharge to confirm the initial target plasma conditions. No attempt was made by Sandia National Laboratory to improve on these conditions. A decision was made to abandon magnetized targets, because at the time they did not appear to scale to high gain. A later study indicated otherwise [13].

The seeming simplicity of the Phi target plasma generation and our interim experience with cryogenic fiber-initiated Z-pinches led us to recently re-examine the physics of the fiber-initiated Z-pinch. The intent of our initial work on cryogenic fiber-initiated Z-pinches (and that of ongoing research elsewhere) was to ohmically heat and magnetically compress an initially cryogenic DT fiber to fusion temperatures (i.e., "direct fusion"). Sheehey, et al., found that the fiber became very unstable [14], thwarting the goal of direct fusion. More recently, Sheehey has examined the role of a nearby cylindrical conducting wall in stabilizing the m=0 unstable modes [11]. The configuration examined was a 2 cm long cryogenic DT fiber inside a 2 cm radius copper cylinder with closed ends (a conducting can). The external circuit with parameters that approximate our small Colt capacitor bank introduce current between the fiber and the conducting walls of the can across an insulator that hydrodynamically closes the can. The current rises to 1 or 2 MA in 1 or 2 μs, a much slower rise than for the initial Z-pinch approach mentioned above. Sheehey found that when the unstable plasma expands out to the wall, it becomes wall supported and settles down to a sporadically re-adjusting Kadomtsev stable profile as shown in Figure 9. As the drive current dies away, the average plasma temperature remains high due to the continuing magnetothermal insulation maintained by internal currents.

We have initiated laboratory experiments to confirm this predicted behavior, but have no definitive results yet. The calculated target plasma generated in this manner appears to be suitable as a target plasma for MTF, and both the experimental results and computational analysis for the Phi targets provides some confidence that this effort will ultimately be successful.

**COMPRESSION OF THE TARGET PLASMA**

Following creation of a warm magnetized target plasma, it is necessary to compress it to fusion temperatures. In the Phi target, this was accomplished by the main electron beam exploding the plastic shell and thereby driving the inner aspect inward to act as a pusher that compressed the target plasma. According to the computational analysis done after the experiments [3], in order to explain the observed neutron yield it was necessary for the plasma to attain about 400 eV at peak compression (corresponding to a convergence of about 20 according to calculations). VNIIEF has proposed to start with a current driven (j X B) cylindrical liner for compressing the MAGO target plasma and to do subsequent experiments with a quasi-spherical geometry.

When the apparent parameters for the MAGO target plasma are used as the initial condition for a calculation with the survey code previously mentioned, a gain of more than 10 is predicted for an initial liner kinetic energy of 65 MJ [6]. We would not propose to use the large MAGO systems for energy production, but the result certainly suggests that
MAGO might offer a very affordable approach to a proof of principle and provide useful experiments for studying the physics of MTF.

Because the goal was generation of soft X-rays [15], in past, work on current driven liners focused on fast, low mass liners that become plasmas during the rapid acceleration phase. This is related to the level of current density necessary to reach a very high implosion velocity. The thinner the liner, the higher the current density. For given homogeneous liner properties above a certain implosion velocity the liner becomes a plasma. Because of the significant early ohmic heating of the liner, the imploding liner does a lot of work on itself during the final convergence. This provides high implosion velocity, but has an unfortunate consequence for fusion ignition. This is because near the peak compression when the fusion plasma energy loss rates are rising rapidly, it is not possible for a plasma liner to quickly couple its kinetic energy into the plasma to provide a compressional work rate that outstrips the losses. As the plasma liner becomes thick, the sound speed and thickness limit the compressional work rate to a relatively low value. Also, because of the high self-work by the plasma liner, the coupling efficiency between the liner and the plasma inside is low, leading to a low gain for any fusion energy scheme based on compressing the fusion fuel with a fast, magnetically imploded liner.

SOLID LINERS

At Los Alamos both computational and experimental work has been done on empty solid liner implosions using fixed capacitor bank and explosive pulsed power current sources, although not in an MTF context. More recently there has been a renewed interest in magnetically imploding liners that remain solid at the inner aspect throughout the implosion, so that they can be used as shock impactors [16]. Material strength delays some hydrodynamic instabilities and a cold, dense liner can couple better to a target inside. Two approaches are used for solid liners. One is to simply keep the implosion velocity below the limit, above which the liner vaporizes. Another is to use a composite liner for which an outer conductor vaporizes, but an inner insulator remains solid. Initial experiments that are relevant to MTF have used simple liners driven to about 10 Km/s, which is the limit for solid aluminum liners.

High energy liner (HEL) experiments continue at VNIEF in collaboration with LANL. In these experiments an empty liner is driven by large modular disk explosive pulsed power generators (DEMGs). Several DEMG modules are stacked together to provide the desired current delivery to the liner load. These generators operate on a time scale similar to the liners that they drive, leading to efficient electrical energy transfer into the dynamic load represented by a liner. In one experiment more than 20 MJ of kinetic energy was coupled to a liner that achieved a velocity of 7-8 Km/s [17].

At Los Alamos and elsewhere experiments on solid liners must use fixed capacitor banks and are consequently limited in energy delivery capability to the energy of the bank. The USAF Phillips Lab (now, Air Force Research Lab) has for many years operated an important pulsed power facility called SHIVA STAR. It has a 9 MJ, 25 MA capability, and has been used to drive the implosion of a quasi-spherical liner [18]. A magnetized warm (a few eV) plasma was injected through vanes that removed the magnetic field produced by the plasma gun into the space between the liner and a central rod. This provided a warm unmagnetized plasma that was used as a working fluid for transferring the energy from the liner to the rod. This was imaged by an X-ray backlighter. The liner symmetry was very good and the compression of a hollow central rod used as a diagnostic was very apparent. The MHD simulations of this process with the Mach-2 code compare favorably with the radiograph images.
Phillips Lab has proposed an experiment which would capitalize on their unique experience, that is, study the interaction of a magnetized plasma with the inner aspect of a liner.

LINER STABILITY

2-D MHD studies of magnetic Rayleigh-Taylor (MRT) instability for the high energy liner experiments indicate that MRT instability is not a major factor in the HEL-1 liner behavior [16]. However, these studies show that problems can arise where the liner slides along stationary electrodes that make contact with the cylindrical liner. Proper design of these contacts is potentially crucial to the success of a proof of principle based on compression of a target plasma by a cylindrical liner. In the Phillips Lab experiments the contact design appears to have been very successful.

PLASMA / WALL INTERACTION

Some 1-D and 2-D MHD calculations of compression of the target plasma are underway. One major concern, the plasma wall interaction problem, is being investigated, both analytically and computationally. The major concern is the introduction of impurities into the fusion plasma that could increase radiative losses from the plasma. While the ZAP code mentioned earlier can provide reliable calculations of enhanced radiation once the impurity level is known, we need to establish some measure of what impurity levels to expect. The Phi-target and MAG0 experimental results might suggest that the level of impurities introduced is tolerable, since the calculations, which have had no impurities, agree with the experimental data. However, it is possible that the target plasma formation phase is not as sensitive to impurities as the compression phase that follows. This aspect mainly depends on atomic number (Z) of the impurity.

There are other possible problems associated with the plasma/wall interaction. One is that the cooling of the plasma adjacent to the wall leaves that part of the plasma at lower \( \beta \), so that the magnetic pressure of that part becomes more important in the compression of the magnetized plasma. Also, because the regions of higher magnetic field in an inwardly accelerated plasma have a mass deficiency, buoyancy forces come into play that can create convection that enhances cooling. Also, the magnetic field has a tendency to diffuse into the wall, which generates ohmic heating (mainly in the wall) and reduces the strength of the field in the magnetized plasma. We have some modeling codes that include this physics, so the greatest modeling (and experimental) uncertainty is potentially the impurity problem mentioned in the previous paragraph.

ANALYTIC DT ALPHA TRANSPORT RELATIONS

We have done some work on quantifying the enhancement of the DT alpha energy deposition due to the magnetic field in a fusion plasma. In the past, several methods have been used to compute alpha confinement in a magnetically confined plasma [19], but the combination of accuracy and efficiency for these methods is not sufficient for the dynamic MTF plasma, in which the Larmor radius can be a substantial fraction of the plasma size, that is, span many gradient lengths. In principle, particle tracking (which was used to produce Figures 1 and 2) should be most accurate, but it becomes very expensive for a highly magnetized plasma, even for the case of a static plasma. There have been many DT alpha transport studies for ICF [20], but for ICF any magnetic fields that may accidentally occur are generally negligible, with the exception of the fast igniter [21]. In some MHD capable codes that account for the effect of the field on charged particle transport, a Fokker-
Planck formulation is used, which is diffusion-like in space. This becomes a poor approximation when the Larmor radius becomes long compared to the gradient lengths in the problem. Therefore, we have sought to devise a transport method that is at once sufficiently accurate and efficient to handle the dynamic MTF problems that we expect to encounter in the target design process.

Most numerical MHD models discretize the plasma, using many zones or cells to approximate a continuous distribution of plasma and field. To the first order, these zones may be approximated as homogeneous. For a homogeneous medium it is possible to obtain some useful analytic solutions that can greatly speed up the computation of the DT alpha trajectory through the plasma. By stringing together piece-wise the solutions for a set of homogeneous regions, it is possible to get an approximate result for the passage of the alpha through an inhomogeneous plasma. It may be possible to extend the analytic solutions to the case of linear gradients within a zone, which would greatly improve the accuracy, but the simpler problem is already challenging. In a hot fusion plasma the DT alphas lose energy to both electrons and ions, but to avoid complicating the mathematics, here we illustrate the approach by making the assumption that the DT alpha particles do not interact with the plasma ions. In such a case in a plasma above 1 KeV, the velocity decreases exponentially with time:

\[ v(t) = v_0 e^{-t/\tau}, \]

where \( v_0 \) is the initial velocity and \( t \) is the relaxation time due to Rutherford scattering with electrons. In an \((x,y,z)\) coordinate system with the magnetic field \( B \) in the \( z \) direction and the \( x \) direction in the direction of \( v \times B \),

\[ v_y(t) = v_{y_0} e^{-t/\tau} \cos(\omega t), \]
\[ v_x(t) = v_{y_0} e^{-t/\tau} \sin(\omega t), \text{ and} \]
\[ v_z(t) = v_{z_0} e^{-t/\tau}, \]

so that the path of a DT alpha particle entering a homogeneous region at the origin will be:

\[ x(t) = v_{y_0} t \left( w t - e^{-t/\tau} \left( \sin \omega t + \omega t \cos \omega t \right) / \left( 1 + \omega^2 \tau^2 \right) \right) \]
\[ y(t) = v_{y_0} t \left( 1 - e^{-t/\tau} \left( \cos \omega t - \omega t \sin \omega t \right) / \left( 1 + \omega^2 \tau^2 \right) \right) \]
\[ z(t) = v_{z_0} t \left( 1 - e^{-t/\tau} \right). \]

The equation for a plane in that coordinate system is \( A x + B y + C z = D \), where \( A = d_x/d, B = d_y/d, C = d_z/d, \) and \( D = d \). Here, \( d \) is the distance between the point of entry into a computational cell at \((0,0,0)\) and the plane defining one side of the cell. Defining the coefficients

\[ C_1 = v_{y_0} \tau \left( A \omega t + B \right) / \left( 1 + \omega^2 \tau^2 \right) + C v_{z_0} t - D, \]
\[ C_2 = v_{y_0} \tau \left( A - B \omega t \right) / C_1 \left( 1 + \omega^2 \tau^2 \right), \]
\[ C_3 = v_y \tau (B + A \omega t) / C_1 (1 + \omega^2 \tau^2), \]
\[ C_4 = C v_{z0} t / C_1 \]
solving
\[ e^{-t/\tau} \left[ C_3 \sin \omega t + C_3 \cos \omega t + C_4 \right] = 1 \]
for the minimum crossing time \( t \) (there are potentially several crossings), and substitution into the previous equations, provides the exit point \((x,y,z)\). Since there are more than one plane that define the cell, the minimum time among all of them must be found.

Tables can be made for the solutions to 
\[ a \sin x + b \cos x + c = e^{ak}, \]
and interpolation used to efficiently find solutions. This procedure should be extendible to the case of slowing by ions and electrons, but becomes more complicated simply because the paths for the DT alpha can’t be expressed analytically for that case. The mathematics becomes more involved, but some results are possible, and some transformation properties allow us to restrict the number of numerical integrations to just two per zone. Thus, the prospect for a method that will be suitable for application to MTF is good.

MTF FOR FUSION POWER

As noted in the Introduction, we are reluctant to spend much effort on MTF reactor concepts, because it detracts from the first priority: proof of principle. Here we provide one plausible embodiment of the MTF concept as a fusion power system. It is based on a target driven by a beam, so it has many of the features that one would expect in an ICF based fusion power system. The targets must be manufactured with at least one electrical connection, that for the anode. The fabrication tolerances are not a problem, because the target convergence will be only 10-15. We adopt the target designs studied by Sweeny and Farnsworth [13], which included both electron beam and ion beam variants. In these targets, the target plasma is created \( \textit{en situ} \) by a discharge. Then the beam energy is deposited in such a manner that a symmetrical compression ensues. Because of its high efficiency, an electron beam is preferred, but the ion beam has better coupling to the target. This constitutes an obvious trade-off that needs study.

The target must provide a substantial yield, but the close-in parts of the system must be protected, or be expendable, without serious economic consequences. There is a trade-off between the target yield and the shot rate necessary to provide the power to the electrical grid, but the average power of the energy dissipated in the close-in parts of the system remains the same for a given system power rating. The energy dissipation power must be handled primarily by heat removal, and this constitutes an opportunity for a heat based power generation approach.

In addition to the heat loading on the system, even for the advanced fuels such as \( D_2 \) and \( D^3 \)He, neutrons from DT fusion reactions that occur must be used to regenerate the amount of tritium needed for MTF ignition. Because the cost of tritium from diverse sources is highly variable, and the system envisioned regenerates the tritium it needs, except for startup, it is not necessary to consider the commercial value of tritium, only the cost of regeneration. The cross section for transmutation of \(^6\)Li to tritium is high for thermal neutrons, but low for energetic (e.g., 14 MeV) neutrons, so that the regeneration of tritium requires thermalization of the neutrons. Through this process the energy of the neutrons is delivered to the material that moderates them, again providing an opportunity
for a heat based power generation approach. Also, the transmutation reaction is exothermic (~4 MeV, versus the 3.5 MeV carried by a DT alpha particle) which releases additional heat. Running the fusion reactor requires as fuel the isotopes deuterium (\(^{2}\text{H}\)), which is naturally occurring, and lithium-6 (\(^{6}\text{Li}\)). It may also be desirable to add material to the moderator that acts as a neutron multiplier through (n, 2n) reactions. Ralph Moir has discussed the details of target chambers for ICF and the above processes have been researched exhaustively, e.g., [22].

The drivers must be capable of repetitive operation at an average power that is some fraction of the grid power supplied. Also, they must provide a beam that penetrates a high heat and particle flux environment in order to reach the target, possibly through some residual debris. Some parts of these drivers may have to endure an attenuated version of the target chamber environment. Therefore, drivers that are robust and have no costly precision parts near or inside the target chamber are preferred. An electron beam machine seems to be the most robust driver, but the beam transport or transmission lines that deliver the electrical current may be susceptible to damage in the near-chamber environment.

The simplest heat based power generation approach uses a heat exchanger to transfer the heat from a working fluid such as FLIBE [22] to produce steam. Beyond this step the technology is standard electrical utility fare. While there are potentially more efficient direct conversion schemes, they are not proven and rely on direct interaction of fields and currents with the fusion-heated plasma. Unless the pR of the fusion plasma is very high, the energy that comes out in the form energetic neutrons and the exothermic heat of transmutation is missed by direct conversion, and must be handled in some way, preferably to make electrical power rather than to be treated as waste heat. Therefore, direct conversion may be more attractive for relatively aneutronic fusion power systems. The high magnetic fields in MTF should enhance energy deposition by the 14.6 MeV D\(^{3}\text{He}\) fusion proton in low pR targets, so there is potential for an aneutronic MTF target. However, at this time it is premature to advocate MTF as an aneutronic approach to fusion energy, and indeed we have reluctantly provided the MTF based reactor concept discussed here.

Because any diagram of the electrical power generating system described above would be very similar to one for ICF (with appropriate substitutions), there is no need to present one here. If ICF is plausible as a fusion power approach, so is MTF. However, it should be remembered that the system discussed here is only one of many possible embodiments of the MTF concept. MTF has qualitative differences from the traditional ICF or MCF approaches to fusion (i.e., characteristic densities and time scales); therefore the tradeoffs in designing an MTF based reactor will be different and conceivably superior to traditional approaches.

**OTHER APPLICATIONS OF FUSION**

Besides regeneration of the tritium needed for a plausible MTF fusion power approach, the thermalized neutrons may have other valuable uses. For a long time nuclear fission reactors have been used to produce medical isotopes. Wide spread use of fusion could have a tremendous impact on the availability of currently rare isotopes for many uses. This prospect should not be overlooked. Also, pulsed exposure to high fluxes of neutrons can create different sets of isotopes than those produced in the continuous, low flux nuclear fission reactors. This prospect needs further exploration.

In addition, the economics of energy production don't apply to some potential applications of fusion. One of these is space propulsion. Here, the propulsion system
weight is an important factor in mission planning. This is because the propulsion system, payload, fuel, and other necessary items must be lifted into low earth orbit and the cost per unit weight is very high. In addition, the exhaust velocity plays an important role in determining the mass of propellant that must be expended to achieve a given velocity. A fusion propulsion system has a potential for very high exhaust velocities. Therefore, if a fusion system is developed that can be configured as a space propulsion system, then it would become very attractive for many missions that are now impractical.

CONCLUSION

MTF is a relatively unexplored fusion technology that is intermediate between two extremes, ICF and MCF. The prospect for MTF advancing fusion energy science is very good. Until a proof of principle is obtained, the questions about the viability of MTF as a reactor concept will abound. Therefore, the most pressing need is for a scientific proof of principle. The facilities necessary for obtaining this are available now, and with relatively modest funding, we could move quickly to attempt such a proof of principle experiment.

REFERENCES

8. J.D. Lindl, “Physics of Ignition for ICF Capsules”, Inertial Confinement Fusion Course and Workshop (Varenna, Italy, 1988, A. Caruso and E. Sindoni, ed.)


FIGURES

Figure 1. Fractional energy deposition as a function of BR for various areal densities (\(\rho R\)).

Figure 2. Fractional energy deposition as a function of \(T_e\) for given \(\rho R\) with BR=0 and BR=1 MG-cm.

Figure 3. Design of the MAGO plasma formation chambers. The numbers in circles mark sequence of key operation processes: 1) Electrical breakdown of the pre-magnetized gas occurring initially in the “nozzle” drives a shock into the right hand chamber. 2) A weaker breakdown follows about 1 \(\mu s\) later at the insulator and drives an inverse pinch toward the nozzle. 3) Plasma in left-hand chamber is accelerated through the nozzle, thermalizing to \(\sim 1\) KeV when it encounters the previously shocked plasma and producing neutrons. 4) After a 3-4 \(\mu s\) dynamic phase, the bulk of the plasma has relaxed to a “warm” (100-300 KeV) magneto-thermally insulated plasma.

Figure 4. Filtered silicon diode spectral responses. The bold solid curve is for an unfiltered diode. The unfiltered diode was over-driven, so the data was not useful.

Figure 5. MAGO II Filtered silicon diode signals.

Figure 6. Best fit temperatures for MAGO II data.

Figure 7. Temperature history using ZAP spectra.

Figure 8. Estimated history of average density along the diagnostic line of sight using ZAP spectra and \(N^2\) scaling.

Figure 9. Computed axial current contours (r-z 2 cm by 2 cm): left early (1.1 \(\mu s\)) unstable, expanding phase; (right) later (2.4 \(\mu s\)) stable, wall supported phase. Most of the current is concentrated near the axis of symmetry along the left side of each frame. The curved contour on the left is indicative of an \(m = 0\) instability.
solid: 1st, --- 2nd, - - - 3rd, .... 4th