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Title: Magnetized Target Fusion (MTF): principles, status, and international collaboration

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Magnetized Target Fusion (MTF):

principles, status, and international collaboration

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Abstract:

Magnetized target fusion (MTF) is an approach to thermonuclear fusion that is intermediate between the two extremes of inertial and magnetic confinement. Target plasma preparation is followed by compression to fusion conditions. The use of a magnetic field to reduce electron thermal conduction and potentially enhance DT alpha energy deposition allows the compression rate to be drastically reduced relative to that for inertial confinement fusion. This leads to compact systems with target driver power and intensity requirements that are orders of magnitude lower than for ICF. A liner on plasma experiment has been proposed to provide a firm proof of principle for MTF.

Introduction

The beginnings of magnetized target fusion (MTF) can be traced to Enrico Fermi and Andre Sakharov in the 1940's and 1950's. However, no research was done in this area of thermonuclear fusion for over two decades. In the late 1970's the MTF regime, as designated by other names, was recognized as an approach to thermonuclear fusion that is intermediate between the two extremes of inertial and magnetic confinement, but a poor understanding of the domain in which MTF should operate led to insecure funding and almost complete abandonment in the US. In that early research the most advantageous operating parameters were not recognized. Since then, some surveys have delineated the parameter space and more detailed studies have discovered some restrictions imposed by practical necessity. Also, the openness at the end of the Soviet era in Russia permitted contact between MTF researchers in Russia and the US, which blossomed into a collaboration intended to realize a relatively pollution-free source of electrical energy supply for the benefit of mankind.

The fusion cross section dictates that the thermal energy invested for a given mass of fusion fuel is comparable to other thermonuclear approaches. However, the use of a magnetic field to reduce thermal conduction and potentially enhance reaction product energy deposition allows the rho-R and compression rate to be drastically reduced relative to inertial confinement fusion (ICF). Only one series of experiments explored the complete process of magnetized target fusion. The early, integrated experiments in the US at Sandia National Laboratory in 1977 used a relativistic electron beam, which put only 4000 Joules into the target in about 100 ns. The Sandia experiments provided a "soft" proof of principle, but left many questions because of the low level of diagnostics available at that time. There is a tension between diagnostic access, data return rate, and cost of the experimental facility needed for a viable program. Other MTF experiments since the Sandia experiments have investigated only one or the other of the two steps involved in MTF, but today we are planning a liner on plasma experiment intended to provide a firm proof of principle. Since about 1993 there has been a renewed research interest in MTF. It has been heavily dependent on the experimental facilities of Russian MTF researchers, while in turn the Russians have benefited from some new diagnostic capabilities provided by the US, as well as other support.

MTF seeks to combine the some advantages of both magnetic confinement fusion (MCF) and inertial confinement fusion, while avoiding the difficulties of each. The idea is to create a magnetized and preheated target plasma and subsequently compress it to fusion temperatures. If net energy is to be realized from the process, more fusion energy production than the energy cost of the target preparation and compression must be realized. Depending on the efficiency of various energy transformations, this may require the fusion fuel to be ignited, that is, to make a transition from externally supported to self-sustained fusion burn. The magnetic field can reduce the electron thermal conduction of the plasma only if the density of the plasma is low enough and the magnetic field is strong enough to provide a large product of cyclotron frequency and mean collision time for the electrons (i.e., a magnetized plasma). As is also the case for ICF, electron thermal conduction is the major factor that determines implosion velocity required for fusion ignition, and reduction of the energy loss rate due to thermal conduction allows the compression heating rate for MTF to be drastically lower than for ICF.

In the process of compressing the magnetized fusion fuel, the embedded magnetic field is also compressed, and if sufficient compression occurs, then the magnetic field may become strong enough to enhance the fusion produce energy deposition within the fusion fuel. This is necessary for fusion ignition. However, for some embodiments of MTF, fusion ignition may not be necessary for a viable fusion energy system. Some work on energy deposition by charged fusion reaction products in a dense, magnetized plasma of MTF will be described below.

A major factor in the energy cost is the efficiency of the driver used to compress the target. The requisite target gain (input energy divided by output energy) is highly dependent on the driver efficiency. Likewise, the cost of a development path and the system cost and operating expense is highly dependent on the requisite driver technology. Reduction of electron thermal loss permits reduction of compression rate, and the necessity to operate at densities lower than that of ICF increases the size of the target, while the specific energy of the fuel required for fusion burn remains about the same. Because of this, the power and intensity on target that the driver must supply are drastically lowered, which admits the possibility of directly using pulsed electrical power to compress the target. Very efficient, inexpensive, and reliable pulsed power drivers are available, which means that even low gain magnetized fusion targets are attractive for fusion energy systems based on MTF. Nevertheless, one published numerical study [1] showed that high gain MTF targets driven by electron or light ion beams are feasible.

Magnetized target fusion is not without potential impediments to its realization. One of the major concerns is the plasma purity. Impurities enhance the fusion plasma energy loss through enhanced radiation. While the calculation of radiative energy loss rate is straight forward if the impurity species and concentration are known, the major uncertainty is the evolution of impurities during target plasma formation and compression. One envisioned embodiment of MTF seeks to avoid the introduction of impurities. That approach to MTF would dynamically form the target plasma by colliding two compact toroids (CTs) and use a dynamically formed shell of hydrogen or other light isotopes to compress the plasma to fusion conditions. This would certainly avoid contamination of the fusion fuel, but may incur a significant cost in terms of target gain. There are many such questions that must be explored before a viable MTF embodiment for fusion energy is identified. We will explore a few of these questions below.

While experiments at Sandia National Laboratory in 1977 appear to have confirmed the one of the underlying principles of MTF, the meager diagnostics and low levels of neutron yield left doubts expressed by many critics. These experiments have never been repeated, but later theoretical and computational analysis was consistent with the experimental results. Recently, the US Department of Energy has indicated a willingness to fund an MTF proof-of-principle experiment. This experiment would entail the compression of a reversed field configuration (FRC) plasma by a cylindrical liner, similar to both the suspended Fast Liner experiment at Los Alamos two decades ago [2] and unpublished work done by Kurtmalaev at Troitsk during the Soviet era. These experiments deserve an expanded discussion.

An on-going collaboration between Los Alamos and the All-Russia Scientific Research Institute for Experimental Physics (VNIIEF) has used an interesting Russian capability to provide electrical energy for plasma formation experiments in a unique plasma formation chamber. The Russians use explosive pulsed power, in which a magnetic field inside a helical coil is compressed by a copper shell driven by high explosives to create a pulse of electrical energy. These are called electromagnetic generators (EMGs). The pulse from a small EMG is introduced into the plasma formation chamber through a set of closing and opening switches. The early slow current creates a bias field, while a rapidly rising fast pulse breaks down the gas inside and the early discharge current creates a Lorentz force which accelerates the plasma from the first half of the divided chamber into the second half. This creates a warm plasma, which appears to typically persist for a few microseconds, potentially a sufficient time for compression to higher temperatures. Efforts to diagnose the plasma purity are currently under way. These experiments are very energetic, which is partly driven by the scale necessary for fielding detailed diagnostics such as magnetic field probes within the plasma. However, more recently similar experiments have been powered by a capacitor bank. Explosive pulsed power technology can easily supply many megaJoules of electrical energy, in sharp contrast to the limited energy of fixed capacitor banks.

The joint experiments are very energetic, and the destructive nature of the high explosives and a low funding level for the VNIIEF experiments have led to a low data return rate. Some capacitor bank experiments are now being done, and it appears that less energetic experiments using capacitor banks will capable of much higher data return rate with adequate diagnostics for promoting an understanding of MTF. Potentially, a great deal of progress that can be made on small machines such as those used for dense plasma focus (DPF) research in several institutions around the world. We will enlarge upon these aspects of an MTF experimental program, as well as the potential for other collaborations.

Principles of MTF

Magnetized target fusion relies on two principle features, one is usually associated with magnetic confinement fusion and the other with inertial confinement fusion. The first is the use of a magnetic field to reduce or control the energy loss from the fusion plasma. The intent is not to confine the plasma as in the case of magnetic confinement, but rather just to reduce the electron thermal conduction to manageable levels. The intention is to confine the plasma with material walls, which is the second feature. The inertia in the material walls to not only confines, but also compresses the plasma to fusion conditions. It should be noted that magnetized target fusion is not appropriately described as simply imposing a magnetic field on an ICF target. The target must be modified to allow creation of a target plasma, be enlarged to operate at a much lower density than ICF, and be designed to receive energy over a relatively long interval. Also, the magnetic field must be closed within the fusion plasma.

The magnetic field needed for suppression of the electron thermal conduction is much less than for magnetic confinement, so that the plasma can have a high thermal energy content relative to magnetic energy content, that is, the magnetized plasma can be high β (> 1). Depending on the geometry of the compression (e.g., cylindrical or quasi-spherical), the ratio of these energy contents will decrease or increase during compression. For the purpose of reaching fusion conditions efficiently, it is preferable to minimize the energy that is pumped into the magnetic field by using quasi-spherical compression. Nevertheless, for a proof-of-principle experiment, cylindrical compression should suffice.

Both the mean free path and the thermal velocity of the electrons in a plasma increase as the temperature increases, but because the velocity increases only weakly, the net result is a longer mean collision time. The mean free path is also dependent on the plasma density, and tenuous hot plasmas have long mean collision times. Therefore, a modest magnetic field suffices to magnetize a warm, low density plasma. For MTF, a field of 5 Tesla suffices to magnetize a 50 eV plasma at a density of about 10^{-6} gm/cc. Such a plasma proves to be barely sufficient as a target plasma. Higher initial fields and temperatures provide a margin of safety. Also, along an adiabat the magnetization of the plasma increases as compression proceeds. One expects the reduction of thermal conduction to behave classically for plasmas in which the plasma frequency is greater than the cyclotron frequency. Such is the case for MTF.

Fusion ignition may not be necessary for a viable MTF fusion energy system, but for high gain MTF targets, it is necessary. If fusion ignition is to occur, adequate energy from the fusion reactions must be returned to the fusion plasma so that it self-heats. Because an MTF target plasma has a very low density, the ρR at the end of compression remains low ($<< 0.3$ gm/cc). In order to self-heat, the path length of the charged reaction products in the fusion fuel must be increased, making the effective rho-R much higher than it would be without the field. In a homogeneous magnetized plasma with an embedded azimuthal field, this requires a field times radius parameter BR greater than about 1 MGcm. The parameter BR augments the plasma ρR.

If the initial temperature of the magnetized plasma is sufficient, then during compression the embedded field cannot not diffuse significantly, and the increase of BR during compression of the embedded magnetic field will depend on the field and compression geometries. For a quasi-spherical compression of an azimuthal field, or a cylindrical compression of a solenoidal field, BR is inversely proportional to the radius, but for cylindrical compression of an azimuthal field, BR doesn't change.

Target Plasma Formation

MTF needs an initial magnetized plasma with the following parameters: $T > 50$ eV, $B > 5$ T, and rho $\sim 10^{-6}$ gm/cc. Several techniques have been proposed for generation of such a plasma. The first is a simple discharge, which creates a diffuse Z-pinch. The Z-pinch is unstable, but if there are supporting walls close by, then the instability provides a mechanism that allows stepwise evolution of the plasma toward a Kadomsev-like profile. During the early stages of this evolution the plasma is sufficiently resistive that the field diffuses into the hot plasma, thereby providing the embedded field. Numerical calculations detail a similar process for the case of a discharge through a cryogenic deuterium fiber.

A reverse field configuration (FRC) has also been proposed as a target plasma. Such plasmas are formed from an initially weakly ionized gas by inductive discharges created by a sequenced set of coils. The FRC must be formed in a suitable chamber and then translated into a cylindrical liner for compression. Numerical calculations suggest that this can be done. Also, in the past FRC translation experiments have been encouraging. The compact toroid (CT), a more generic plasma configuration which includes the FRC as an extreme variant and the spheromak as another, is also a candidate for a target plasma. The FRC has a pure poloidal field, while the CTs have a significant azimuthal (i.e., toroidal) component. While the FRC may be limited in density, it could still provide a pure plasma suitable for a proof-of-principle experiment.

Another method of generating a target plasma was developed by our Russian collaborators at VNIIEF. It involves the use of a chamber that is driven by switched currents in order to create an initial bias field and then cause a sequenced discharge through the deuterium-tritium (DT) gas in the chamber. The transliteration of the Russian acronym which we use to refer to this chamber is MAGO. The chamber is cylindrical in shape with a barrier that divides it into two parts. There is a conducting rod through the center on which the barrier electrode is mounted and an insulator between the rod and end wall at one end. The current initially flows through the rod and electrode, through the far end wall, and back through the cylindrical outer wall and near end wall where the insulator is situated, thereby providing an initial bias field in the chamber. A sharp rise in the current causes a breakdown of the gas in an narrow annular nozzle between the central barrier electrode and the cylindrical wall, and then near the insulator. This drives a weakly ionized plasma through the annular nozzle where it is accelerated by Lorentz forces to high velocity. It shocks down in the second chamber on the other side of the barrier, initially creating isolated hot volumes of plasma responsible for a brief pulse of neutron emission, but then settles into a more quiescent warm plasma at about 200 eV according to calculations. The temperature achieved depends on the chamber design and the input current history. Some filtered silicon diode measurements suggest that this plasma can have a decay time of up to 10 microseconds, or more in some cases, depending on design variations and plasma purity.

Quasi-cylindrical compression of the MAGO plasma appears to be feasible. However, the question of plasma purity is currently being explored. The current for driving the MAGO chamber has been provided both by a capacitor bank and by explosive pulsed power. It is not the neutron producing phase of the operation of the MAGO chamber that is of interest, but rather the more quiescent warm plasma. If it is of sufficient purity, then it may be possible to compress it to fusion temperatures, which should be evidenced by a second pulse of neutrons.

Compression

The extreme rate of energy loss, mainly by thermal conduction, form an ICF target demands very rapid compressional heating. About 30 cm/μs implosion velocity is required for current designs of ICF targets. Fast implosion of small ICF targets (~ 1 mm) means that the targets have an acceptance time of only a few nanoseconds for the energy that drives the implosion. Because the energy for an ICF implosion must be delivered so rapidly and to a very small target, a laser is almost a necessity as a driver. In addition, for ICF the initial state of the plasma is determined by the same implosion driver that later must provide the energy to compress the fusion fuel up to about 5 KeV and a ρR of over 0.3 gm/cc.

Suppression of electron thermal conduction, the major loss mechanism in MTF, allows much slower compression to fusion temperatures. For MTF an implosion velocity as low as about 1 cm/μs is adequate and the direct application of electrical pulsed power on a microsecond time scale to implode a cylindrical or quasi-spherical shell will suffice. Establishing the initial state of the plasma and compression are two separate, independent steps for MTF. In principle, this allows a great deal more freedom in choosing the driver for compression, as well as more control over the initial state of the fusion fuel.

In the absence of significant energy loss, compression by a cylindrical liner raises the plasma temperature as the inverse four-thirds power of the radius of the inner radius of the liner, but for a quasi-spherical compression it would go as the inverse square. Also, the field inside the liner would increase is the inverse square if solenoidal, but only as the inverse of the radius if azimuthal. Therefore, the geometry will make a significant difference in the parameter space that looks attractive for MTF. For example, the field times radius parameter BR is important for enhancing the energy deposition by charged fusion reaction products, and for the cylindrical compression of an azimuthal field, flux conservation would dictate no increase in BR. If the initial BR were insufficient for enhancing deposition, then none would occur when fusion conditions were reached. Therefore, there is some advantage in using cylindrical liner to compress an FRC, rather than a target plasma generated by discharge through a cryogenic fiber aligned along the axis.

Simple fusion energy criteria

The bare minimum energy that must be supplied to raise a given mass M of plasma to fusion temperatures is its thermal energy (C_vMT) at that temperature T. For the practical reason that it is never possible to do this instantaneously and that therefore some energy will be shared by the plasma's surroundings, the actual energy needed is always significantly greater. Just how much greater depends on the details of the fusion energy system.

The Lawson criterion has long been cited as a necessary condition for fusion energy. It states that the product of plasma number density and confinement time ($N\tau$) must exceed about 10^{14} s/cc. Implicit in this criterion is a deuterium-tritium fusion plasma temperature of 10 KeV, instantaneous (loss-less) arrival at fusion conditions, and no self-heating. The basis for deriving this criterion is that the energy derived from fusion reactions must at least balance the energy invested in reaching the implicit 10 KeV fusion temperature. This constitutes an ideal unity gain ($G = 1$). Consideration of details of heating a DT plasma up to fusion conditions certainly requires a much higher value of the N-tau product [3], and of course for any practical fusion energy system, the fusion gain must significantly exceed unity to offset conversion efficiencies, etc.

Sufficient self-heating from energy deposition by the fusion reaction products to allow fusion ignition is essential for significant gain for an ICF target. Ignition is the transition from externally supported fusion burn to self-sustaining fusion burn, and can raise the fusion fuel to very high temperatures, so that rapid burn-up occurs. The ignition conditions for an ICF fusion plasma are well defined [4], but some authors continue to erroneously apply the Lawson criterion to ICF. The plasma must be brought to a state of rho-R > 0.3 gm/cm^2 and T > Tc, where Tc depends on the mode of fusion ignition. Tc = 2.3 KeV for equilibrium (or volume) ignition, but Tc = 4.5 KeV for non-equilibrium ignition. The central temperature must exceed about 10 KeV for hot spot ignition. These two criteria may be combined to yield a pressure times radius product PR, which must exceed ~ 400 Mbcm for equilibrium ignition and higher values for other modes of ignition. This immediately leads to the fact that the higher the pressure attainable in the fusion fuel, the smaller the energy required to ignite a fusion target ($E \sim \langle PR \rangle^3/P^2$). Since the pressure is derived from the implosion of the target, it depends on the implosion velocity and the density of the imploded shell that contains the fusion fuel: $P \sim \rho v^2$. Therefore, the implosion velocity v becomes of prime concern for the reducing the driver energy needed to ignite a fusion target. There are additional considerations that lead to a minimum implosion velocity for fusion ignition, again depending on the mode of ignition. These will be discussed later in the context of MTF.

The small size and fast implosion velocities for ICF lead to the requirement for powerful and intense drivers. In fact, the intensity, power, and energy on target that must be delivered by the driver to ignite an ICF target must all fall within an envelope for a given ICF target. The fusion physics restricts the compendium of these envelopes for the practical range of viable ICF target to an as-yet unattained realm. The US DOE is building the National Ignition Facility in the hope of entering this realm. Beyond ignition, there is a hope for demonstrating fusion target breakeven, or even $G > 1$. Ultimately, the requisite target gain for a viable ICF fusion energy system depends on the efficiencies in the balance of the system (e.g., the driver efficiency and the energy conversion efficiency). Target gain is determined by the fusion dynamics during disassembly, and can only be determined accurately by a complete fusion burn code. However, there are various approximate relations that provide an estimate of gain.

For MTF the magnetic field inhibits the electron thermal conduction, a major loss mechanism in ICF targets. If the field is not sufficiently strong to enhance the charged reaction product energy deposition when fusion temperatures are reached, then a Lawson-type criterion is appropriate for MTF. On the other hand, if self-heating is significant, then the MTF target can ignite, and ICF-like criteria become appropriate.

Parameter Space for MTF

The MTF parameter space is multidimensional and can be visualized through a number of cuts across fewer dimensions. Lindemuth and Kirkpatrick explored the parameter space of MTF in 1983 [5], and showed that MTF operates in a regime that connects to the ICF regime, but extends to very low implosion velocities at much lower densities than ICF as seen in a set of equal gain contours in the plane of initial implosion velocity and initial density. Kirkpatrick, Lindemuth, and Ward [6] showed that the rho-R required for fusion ignition is augmented by a field times radius product BR as mentioned above. Also, unlike ICF, there is a minimum magnetized fusion fuel mass, below which fusion ignition in the MTF regime is no longer possible.

There is some similarity between the Lawson $N\tau$ plotted as a function of assumed fusion temperature (a more general Lawson criterion) and the ($dT/dt = 0$) ignition conditions for ICF plotted in a ρR temperature plane. The reactivity of the fusion fuel dictates the form of both the relations. Plots of constant dT/dt contours in the (ρR, T) plane have been used by Lindl and others [7] for illustrating the essential physics of ICF. Such plots have been referred to as Lindl-Widner diagrams [6]. The similarity between the Lawson ($N\tau$,

T) plots and the Lindl Widner diagrams becomes a bit more understandable upon reflection. The disassembly time for an ICF target is proportional to the time for a shock to traverse the radius of the fusion fuel is $\Delta t = R/c$, which may be viewed as a approximation to the inertial confinement time. Also, the time tau in the Lawson criterion is determined by balancing the energy invested in the plasma against the net energy derived from fusion during that time, and that balance at low temperatures is dominated by the competition between bremsstrahlung and thermal conduction losses and gain by fusion burn. Similarly the $dT/dt = 0$ condition that prevails on the verge of ignition is mainly determined by the balance between bremsstrahlung and thermal conduction loss rates and fusion energy deposition. While there is similarity between the two relations, the physical arguments involved in their derivation are very different. The Lawson criterion does not take into consideration the dynamics of the fusion ignition and burn process, which is an essential feature of ICF. The dynamics of the fusion ignition and burn process is also an essential feature of MTF, so that it is most convenient to study MTF from the ICF viewpoint.

Survey calculations for MTF [5] have shown that it is necessary the generation of an initial warm (> 50 eV) target plasma with > 5 T embedded magnetic field and a density in the 10^{-6} gm/cc range. However, depending on the geometry, etc., higher values of initial temperature and field strength are acceptable, as well as a fairly wide range of initial density. The survey calculations were carried out by application of a "zero-dimensional" model that included the major fusion physics processes. Lindl-Widner diagrams do not include the dynamics, but with added accounting of physics processes like reduction of electron thermal conductivity by a magnetic field, etc., can be used to present the parameter space in which MTF operates. Also, they are very convenient for presenting snapshots of the dynamic approach to fusion burn in an MTF target. Basically, the MTF region lies at much lower values of rho-R and some what higher temperature than the fusion region for ICF. While the ICF fusion region in a Lindl-Widner diagram is almost independent of the fusion fuel mass, for MTF it disappears for fuel masses less than about 1 μg. For fuel mass greater than about 1 mg, the MTF region merges with the ICF region.

MTF Experiments

The Sandia Phi-target experiments and the VNIIEF MAGO chamber experiments bracket the scale of MTF experiments that have been undertaken. The level of effort for these two MTF experiments is as different as the scale, but there is a range of other relevant experiments that fall somewhere in between.

The Sandia Phi-targets were so called because the design had the appearance of the Greek letter Φ. Small collectors were attached to 3 mm diameter plastic microballoons, which without the collectors were typical of ICF targets being fielded at that time. These targets were mounted on the cathode of a relativistic electron beam machine. There was a non-relativistic prepulse that built up charge on the collector and created a discharge through the microballoon. The discharge left a warm, magnetized plasma inside the microballoon. The subsequent relativistic main pulse pinched to a beam that deposited about 4 KJ in the microballoon in about 100 ns. This both ionized the plastic and drove the inner aspect inward against the warm, magnetized deuterium-containing plasma. After a brief delay commensurate with the implosion of the inner aspect of the plastic shell, a burst of neutrons was observed. However, only 8 of the 15 intact targets gave yields between 5 and 25×10^6 neutrons. There were also as many as 24 null targets used in the experimental series, none of which produced measurable neutrons. It was concluded that the initial warm, magnetized, deuterium-containing plasma was essential for obtaining a neutron yield from these targets. Later numerical analysis of a typical target suggested that the observed neutron yield was commensurate with what would be expected [8].

Because the simple Phi-targets targets were not expected to lead to high gain, these un-funded experiments were not continued. However, they are unique for MTF, because they involved almost the complete range of physics issues that should arise in the two steps: generation of an initial target plasma and subsequent compression. The temperature in the target plasma reached only about 0.4 KeV according to calculations, so it did not enter the desired fusion ignition domain or provide any evidence of any self-heating. However, it was a remarkable result for such a small amount of energy deposited in the target with such low power and intensity. It has been termed a "soft" proof of principle for MTF, but unfortunately these experiments have never been repeated. The survey study done a few years later showed that the Phi-target fill density guaranteed the lowest neutron yield.

The MAGO experiments at the All-Russia Scientific Institute for Experimental Physics (VNIIEF) originally were optimized to maximize neutron yield. However, at the beginning of collaboration with Los Alamos National Laboratory (LANL) in the US [9] it was recognized that the neutron production phase was only a transient state in the production of a warm, magnetized plasma. Still this transient state provides an impressive DT neutron yield of 3×10^{13}. The operation of the MAGO chamber has already been described above. Here we will only add some details relating to data gathered in joint experiments. The main diagnostics used by VNIIEF were a) neutron emission history, b) neutron activation, c) magnetic probes to measure the changing magnetic field inside the chamber, and d) imaging of the neutron emission. The neutron emission history proved to be misleading, but the neutron imaging was fairly revealing, once coupled with 2-D MHD modeling results. Also, some of the major features in the magnetic probe data were reproduced in the modeling. In four joint experiments Los Alamos added to the diagnostic suite a) filtered silicon diode X-ray emission measurements, b) laser interferometry measurements of density, c) visible and UV spectroscopy, d) X-ray spectral measurements, and e) neutron activation measurements in a chamber filled with deuterium only. Los Alamos also attempted other diagnostics that were not successful, and not all those mentioned were fielded or entirely successful on all four joint experiments. The most uniformly successful Los Alamos diagnostic has been the filtered silicon diode measurements.

Two approaches have been used in an effort to interpret the filtered silicon diode data. First, the ratios of the diode responses have been used to estimate the plasma temperature for five possible types of emission from the plasma: blackbody, bremsstrahlung, exponential, flat spectrum out to a given energy, and a single strong emission line. The result for the best data analyzed data to date shows that the spectrum is approximately bremsstrahlung in nature with some lines from an intentional one one-hundredth percent neon impurity. The inferred temperature for the line of sight along which the diode data was taken rises over 400 eV during the neutron emission, but thereafter falls to about 200 eV, with a continuing decay to ~ 150 eV about 5 μs later when the diagnostics appear to fail. The failure appears to occur when shocks generated by a magnetized plug of plasma driven into the diagnostic access hole arrive at the filtered diodes. More extensive data has been obtained since that for which the results are cited here, but one set was too flawed, and the other only recently taken and not yet analyzed. The other approach to interpretation was to use the 2-D MHD calculations to derive an emission history for the plasma and consequently simulated filtered diode signals, which ware then compared to the measurements. From the comparison, it became apparent that an edge plasma must play a significant role, and that the 2-D calculations must be refined to resolve the plasma near the chamber walls.

The neutron imaging done by VNIIEF showed that the main emission came from an annular region in the second part of the divided chamber. This is roughly where the early 2-D MHD code calculations indicated that hotspots would occur during the first entry of the fast flow from the nozzle region into the second part of the chamber. Weaker emission also occurred in the annular nozzle, which is not predicted by the MHD code. However, theory and VNIIEF neutron anisotropy measurements indicate that the parts of the plasma goes through transient states for which MHD is not a faithful model. The magnetic probe data is well modeled by the MHD codes for a few microseconds, but not at late time. More recent calculations by VNIIEF with their new 2-D MHD code invokes insulator vapors to obtain agreement with the late time magnetic probe data. Such insulator vapors are a major concern, because if they develop and reach the warm, magnetized plasma in the second part of the chamber and contaminate it before compression can proceed, then the consequent enhanced radiative cooling may thwart heating to fusion temperatures. Nevertheless, the better understanding emerging from the joint experiments and computational studies is leading to new chamber designs intended to avoid some of these hazards now being recognized.

The liner-on-FRC proof-of-principle proposal mentioned above is still awaiting funding. It is similar in some ways to the Fast Liner work done in Los Alamos in the late 1970's. However, the Fast Liner proposal intended to use a Marshall gun to create the target plasma, and experiments on this aspect were progressing when the program was terminated. It was learned that the energy in the plasma formation was shared by the gun and the plasma in proportion to the volume occupied by each, which led to a less energetic plasma than anticipated. On the other hand, the liner part of the program proceeded very well, and a fairly symmetric 1 cm/μs implosion of a cylindrical liner was achieved. Kurtmalaev at Troitsk has discussed a compression of an FRC by a liner, but there are no published details. Two-dimensional MHD calculations in the US show that an FRC can be formed and translated in a cylindrical liner where it can be trapped. Calculations with another 2-D MHD code have shown that such an FRC can be compressed by the liner to fusion temperatures. However, neither code included modeling of the plasma-wall interaction.

Physics Issues

The main concern issue MTF is potential contamination of the fusion plasma by impurities during plasma formation or compression. While the treatment of the enhanced radiative energy loss that may result is computationally straight-forward, the computational prediction of the evolution of contaminants is very difficult. It is conjectured that impurities may boil off the wall as the plasma interacts with it during the plasma formation, translation, or compression phase for MTF. One proposed method of avoiding contaminants altogether will be described below.

The physics of a potential plasma-wall interaction is thought to occur when the heat from the plasma vaporizes a thin layer of wall material and that material finds its way into the magnetized plasma. Perhaps, the vapor is initially unionized, so that it moves through the magnetic field unimpeded. However, for an isobaric plasma, if the temperature is low near the wall, the density will be high, so that the wall vapor must diffuse into the progressively hotter plasma. In the process, the vapor will become ionized, so that it begins to feel not only the dense plasma near the wall, but also the inhibition of motion through the magnetic field. Most of this process should occur near the wall, so that a one-dimensional model should suffice to describe the major aspects of this part of the problem. However, it is also possible that the plasma near the wall will be flowing along the wall, entraining the vapor as it comes into close proximity to the wall. This part of the problem must in all likelihood be treated in an MHD calculation that follows the overall plasma flow. It may be necessary to use marker particles to track the penetration of the vapors into the plasma. A crucial aspect is the time scale for such a process. If it occurs on a short time scale, then it could present a substantial obstacle to compression of a target plasma by a material liner.

Another physics issue is the type of thermal transport that one should expect within the plasma. While in some settings Bohm-like transport has been documented, for MTF we think that the reduction of thermal transport by the magnetic filed should be classical, that is, it should be reduced by $(1+\omega^2\tau^2)$. However, if convective flow occurs, then the heat transport may still be rapid. Analysis shows that the large-scale convection is the most effective in carrying heat to a cold wall. Since 2-D MHD calculations should follow the large-scale flow quite adequately, we are confident that we can predict the effect of convective cooling in an MTF target plasma. Minor convection has been observed in some calculations, and on this basis we do not expect any major convective cooling to occur.

We have performed only a few 1-D calculations of an MTF target. These calculations were defined by first finding an optimal design with the zero-dimensional models used previously for survey calculations. The 1-D code ran very slowly because it was an implicit code and the initial target plasma had a high sound speed, while the implosion velocity was very low. In the end, the 1-D result was commensurate with the zero-dimensional result. Therefore, the 1-D calculation would seem to be unnecessary. However, for the detailed design of an MTF target, a 2-D code may be essential, because MTF targets are inherently 2-D. In order to speed up the calculations an implicit MHD code that allows shear flow should be used. Also, if an accurate prediction of fusion energy release is desired, adequate fusion burn physics must be included.

The fusion energy production in a proof of principle experiment or in an MTF fusion energy system that does not rely on self-heating of the fusion fuel is straight-forward. However, if fusion ignition is necessary for a viable MTF fusion energy system, then significant self-heating of the fusion fuel must occur. Accurate calculation of self-heating in an MTF plasma is complicated by several factors. For both ICF and magnetic confinement, methods have been developed for calculating the energy deposition by the charged reaction products as they are transported through the plasma. For ICF the assumption of a straight-line path greatly simplifies the problem. Also, Fokker-Planck and multigroup diffusion methods have been employed. For magnetic confinement particle tracking and guiding center methods have been applied to the case of static configurations in which the density is very low, so that the charged particles slow only very gradually over many gyrations. The MTF regime is intermediate between these two extremes. Significant slowing of the particle can occur over a single gyration, and the plasma is very dynamic. Therefore, a new method must be developed to accurately calculate the fusion self-heating in a dynamic MTF plasma. Thus far we have employed a particle tracking code to define the enhancement of DT alpha energy deposition in a static, uniform magnetized plasma with an azimuthal field. Little or no enhancement occurs for a field times radius product BR less than 0.3 MGcm, but significant enhancement occurs for BR greater than 1 MGcm. However, we are still in the process of developing an efficient method for handling the general dynamic case. A zone boundary crossing time can be defined, which has an analytic solution for slowing by electrons only in a hot magnetized plasma, but requires a numerical solution for the general case. The crossing time relations may be useful for implementing a Monte Carlo transport method and potentially other approaches as well.

Prospects for Fusion Energy

Reactor studies for ICF are generally applicable to MTF as well. However, some consideration must be given to the much lower level of technology and higher efficiency associated with potential MTF drivers. Also, depending on whether fusion ignition is possible for MTF, the target gain may be lower than that of an ICF target, and this could push MTF into a more energetic regime for economic viability. One potentially applicable study not specific to MTF has considered the use of MHD energy conversion [10]. When considering non-igniting MTF fusion energy systems this study is very encouraging.

A very innovative approach to MTF that seemingly avoids the threat of impurity contamination of the fusion fuel would collide two compact toroids (CTs) to form a magnetized target plasma and then dynamically form an imploded gas envelope to compress the target plasma to fusion energy conditions [11]. This idea draws on colliding CT work done by Dan Wells some years ago [12]. The imploding gas envelope relies on simultaneous and symmetric creation of high velocity gas jets that merge just after the two colliding CTs have formed the magnetized target plasma. Some 2-D and 3-D calculations of the merging process are encouraging. This approach is also being considered as the basis for a space propulsion system.

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