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IGNITION AND BURN IN INERTIALLY CONFINED MAGNETIZED FUEL

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ABSTRACT

At the third International Conference on Emerging Nuclear Energy Systems [1], we presented computational results which suggested that "breakeven" experiments in inertial confinement fusion (ICF) may be possible with existing driver technology [2]. We recently used the ICF simulation code LASNEX to calculate the performance of an idealized magnetized fuel target. The parameter space in which magnetized fuel operates is remote from that of both "conventional" ICF and magnetic confinement fusion devices. In particular, the plasma has a very high β and is wall confined, not magnetically confined. The role of the field is to reduce the electron thermal conductivity and to partially trap the DT alphas. The plasma is contained in a pusher which is imploded to compress and adiabatically heat the plasma from an initial condition of preheat and pre-magnetization to the conditions necessary for fusion ignition. The initial density must be quite low by ICF standards in order to insure that the electron thermal conductivity is suppressed and to minimize the generation of radiation from the plasma. Because the energy loss terms are effectively suppressed, the implosion may proceed at a relatively slow rate of about 1 to 3 $cm/\mu s$. Also, the need for low density fuel dictates a much larger target, so that magnetized fuel can use drivers with much lower power and power density. Therefore, magnetized fuel allows the use of efficient drivers that are not suitable for laser or particle beam fusion due to insufficient focus or too long pulse length. The ignition and burn of magnetized fuel involves very different dominant physical processes than does "conventional" ICF. The fusion time scale becomes comparable to the hydrodynamic time scale, but other processes that limit the burn in unmagnetized fuel are of no consequence. The idealized low gain magnetized fuel target presented here is large and requires a very low implosion velocity; use with an efficient driver should provide a viable nuclear energy system.

INTRODUCTION

In some 1945 Los Alamos lectures on thermonuclear fusion Enrico Fermi reported on work done by R. Landshoff [3] concerning a method of reducing thermal conduction from a deuterium plasma to its container walls. Heat loss by conduction was considered to be an important impediment to producing thermonuclear burning. It was pointed out that by imposing a sufficiently strong magnetic field parallel to the walls, thermal transport to the walls could be impeded. Since that early time magnetic thermal insulation has been employed in only a few ICF studies [1,2,4,5,6,7]. The idea is to produce a central region of preheated low density DT surrounded by a dense shell (the pusher). In the preheated region an azimuthal magnetic field is created concurrent with the preheating, so that when the target is imploded the magnetic field insulates the plasma from heat loss to the pusher.

Previously we developed a computer code MAGIT for a zero-dimensional model that can survey the parameter space for these targets [2]. For that study we took a pessimistic view toward the physical processes and looked for regions of gain in the parameter space. The assumptions included a low ratio of specific heats in the pusher, short thermal and magnetic field gradient lengths, no magnetic confinement of the fuel, no fusion burn product energy deposition, and termination of the calculation at the free-fall limit. The approach consisted of fixing all initial parameters except the initial fuel density ρ_o and the initial pusher velocity v_o. These two qualtities were then varied over several orders of magnitude, resulting in contours of constant gain in the (ρ_o, v_o) initial condition space. The magnetic thermal insulation effect creates a region in (ρ_o, v_o) space where the gain is greater than unity at much lower density and velocity conditions than for is the case in the absence of a magnetic field. This leads to greatly reduced driver requirements over what is believed necessary for conventional ICF.

LASNEX CALCULATIONS

In an effort to better assess the promise of magnetized fuel for ICF we have recently obtained a 1-D LASNEX calculation that implodes a preheated, premagnetized deuterium-tritium (DT) plasma. The configuration for the calculation was necessisarily idealized due to the small time steps imposed by the explicit time step algorithm in LASNEX. Previous calculations have addressed the problem of preheating and pre- magnetizing the plasma [7], so that for this study we assumed that the target contained DT initially at 50 ev with a frozen in azimuthal magnetic field of 30 KG. An initial velocity of 1.6 $cm/\mu s$ was used, but the performance of the target is not sensitive to this value. The initial gas pressure is only 100 atmospheres at 50 ev (10 times the magnetic field pressure), while the energy in the imploding aluminum pusher corresponds to 4 megabars. The initial energy in the implosion is 5.7 MJ, but could probably be reduced with no degradation in target performance. Because the calculation has no material strength, the inner aspect of the aluminum pusher rarefies and the interface between the pusher and the DT implodes at a higher velocity than the bulk of the pusher. The effect of this artifact is of no consequence, since the heat flow from the hot DT plasma to the pusher is effectively suppressed by the embedded magnetic field, and the implosion is nearly adiabatic. Once the DT reaches several Kev in electron and ion temperature the fusion alpha particle energy deposition is sufficient to overcome the radiative and conductive losses, as well as the expansion cooling that ensues after turn-around. It should be noted that a field times radius parameter of at least 0.3 MG cm is needed to significantly enhance the alpha particle deposition in the target. In this target a value of 5.6 MG cm is reached, suggesting that a significantly smaller target should also ignite. At the time the calculation was terminated due to an excessive time step restriction, 9 MJ of thermonuclear energy had been produced, corresponding to about three percent burn-up and a gain of only two. Low gain is characteristic of simple magtetized fuel targets, but we have previously suggested the posibility of high gain using a cold fuel layer [8].

LASNEX has limited magnetic field physics. It treats the alpha particle transport as a multigroup diffusion process and appropriately reduces the diffusion coeficients for both alpha transport and electron thermal conduction in accord with the value of the cyclotron frequency, collision time product ($\omega\tau$). This treatment is probably inadequate for the design of magnetized fuel targets that reach a field times radius parameter of only slightly more than 0.3 MG cm. Therefore, some effort has been expended to develop an improved treatment of alpha particle transport in the presence of a magnetic field [9].

PROOF OF PRINCIPLE

Several years ago Widner reported electron beam experiments using a glass micro balloon mounted on the anode [10]. A thin collector plate intercepted the non-relativistic prepulse and discharged a current through the deuterium in in the micro balloon, thus creating a hot magnetized plasma. The relativistic, focused main pulse then imploded the target and a neutron yield of about 10^6 was observed during the last 30 ns of the implosion. No yield was observer in the absence of the collector plate or when the implosion symmetry was purposely spoiled. Lindemuth and Widner made a detailed analysis with the computational tools available at that time [7]. They concluded that the neutron yield was consistent with a thermonuclear origin, and that no yield should be observed in the absence of preheat or premagnetization, or with inadequate compression by the main pulse.

Concurrent with this conference Buyko, Chernyshev, Demidov, et al. [11] are reporting on another pulsed power experiment employing magnetized fuel. They have also achieved significant neutron yields and project thermonuclear ignition with more energetic systems.

CONCLUSION

Magnetized fuel targets appear to be very promising in the quest for inertial confinement fusion with existing driver technology. We have demonstrated the feasibility of a magnetized fuel target and have mentioned some of the physics issues associated with magnetized fuel. It seems important to repeat and enlarge upon the Sandia experiments [10] in order to better assess the promise of magnetized fuel.

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