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THE PROMISE OF MAGNETIZED FUEL: HIGH GAIN IN INERTIAL CONFINEMENT FUSION

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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. Our computations used a simple zero-dimensional model to survey the parameter space available for magnetized fuel. The survey predicted the existence of a totally new region in parameter space where significant thermonuclear fuel burn-up can occur. The new region is quite remote from "conventional" parameter space and is characterized by very low fuel densities, very low implosion velocities, and, most importantly, driver requirements reduced by orders of magnitude [2]. Whereas our initial computations considered only the yield from a hot, magnetized central fuel, we have extended our simple model to include a "cold fuel" layer. In the same sprit as our earlier work, our extended model is intended to provide a starting point for more comprehensive investigations. Our extended model predicts that it is possible to obtain a large cold fuel burn-up fraction, leading to very high gain, and once again, the optimum parameter space is quite remote from that of conventional high gain targets. Although conventional drivers optimized for conventional targets are probably not optimum for magnetized fuel at its extremes, there is a continuum between the conventional parameter space and the new parameter space, suggesting a possible role for conventional drivers. However, it would appear that magnetized fuel warrants a complete rethinking of the entire driver/target configuration.

INTRODUCTION

In some 1945 Los Alamos lectures Enrico Fermi reported on work done by R. Landshoff [3] concerning a method of reducing thermal conduction from a deuterium plasma to the container walls. It was pointed out that by imposing a sufficiently strong magnetic field parallel to the walls, thermal transport to the walls could be impeded. At low density the energy loss from the deuterium-tritium (DT) plasma in an inertial confinement fusion (ICF) target is dominated by electron thermal conduction [4], so that magneto-thermal insulation can greatly facilitate fusion in a low density DT plasma

Several years ago Widner reported electron beam experiments at Sandia National Laboratory using glass micro-balloons mounted on the anode [5]. A thin collector plate intercepted the non-relativistic prepulse and discharged a current through the deuterium in the microballoon, thus creating a hot, magnetized plasma. The relativistic, focused main pulse then imploded the target and a significant neutron yield was observed. No yield was observed in the absence of the collector plate. Lindemuth and Widner made a detailed analysis with the computational tools available at that time [6]. 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.

Thermonuclear ignition may be defined as a condition in which a positive temperature rate ($\dot{\theta} > 0$) persists after the hydrodynamic work rate due to the implosion has gone away or reversed in sign [4]. Prior to ignition a minimum work rate (hence, implosion velocity) is needed to overcome the radiative and conductive losses from the DT plasma until the conditions necessary for ignition are reached. In conventional ICF the ignition conditions are often expressed as an ignition temperature and a minimum areal density, i.e., ρr. In fact, a range of values allow ignition, but there is a minimum for their product (hence a minimum Pr) that will allow ignition [7]. This minimum sets a minimum for the energy content of DT plasma that will allow ignition, and therefore a minimum for the energy in the implosion as well. Figure 1 shows a Lindl-Widner diagram with the conventional ICF ignition region in the upper right and the new magnetized fuel ignition region to its left. In fact with sufficiently strong fields, the two regions connect.

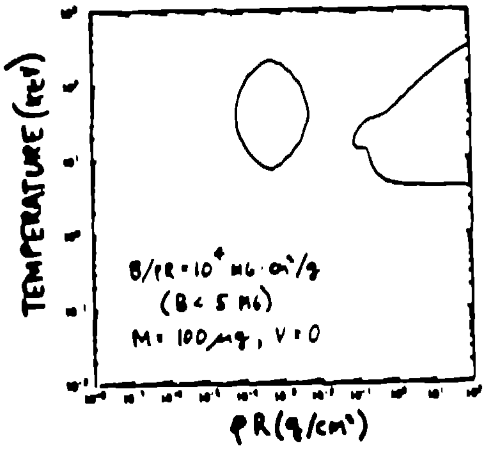

Fig. 1. Lindl-Widner diagram for zero velocity.

These ignition regions may reached in an ICF target by doing hydrodynamic work on the DT plasma, provided a proper adiabat is established initially.

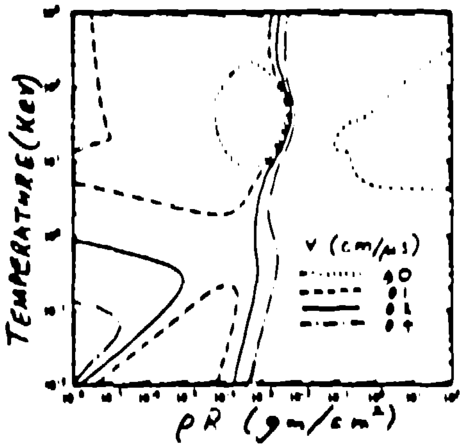

Fig. 2. Magnetized fuel targets work with exceedingly slow implosions.

Figure 2 shows a second Lindl-Widner diagram for several implosion velocities. It is apparent that the magnetized fuel ignition region can be reached with exceedingly slow implosions (v $0.3 cm/\mu s$), while the conventional region requires very fast implosions, with velocities as high as $30 cm/\mu s$. An accompanying paper describes a LASNEX calculation of a magnetized fuel target that ignited with an implosion velocity of $1.6 cm/\mu s$, but this is by no means the lowest that will allow ignition [8].

The power and power density required to drive magnetized fuel targets is orders of magnitude lower than for conventional ICF targets. This means that microfusion may be possible with current driver technology. The disadvantage of the simple magnetized fuel targets described above is that they have low gain. The purpose of this paper is to investigate the feasibility of using the magnetized fuel to light a cold fuel layer and thereby achieve high gain.

HIGH GAIN TARGETS

In the sprit of previous exploritory calculations, we have extended our zero dimensional model to include a cold fuel layer inside the pusher that surrounds the magnetized fuel. We have not considered the enhancement of fusion probability due to polarisation effects in either the magnetized fuel or the cold fuel. In addition, the survey calcualtions for the simple targets did not include any fusion burn product energy deposition, so that ignition was impossible, but in these calcualtions energy deposition had to be included. However, the enhancement of alpha particle deposition due to the field was not included in the zero dimensional model used for the calculations presented here.

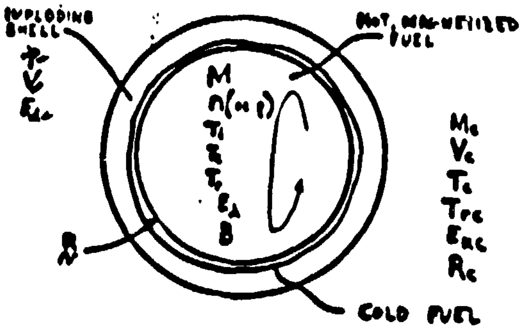

Fig. 3. Magnetized fuel target with cold fuel layer.

Figure 3 shows a magnetized fuel target with a cold fuel layer and the additional parameters that must be considered. For a cold mass to hot mass ratio of five, implosion energy to mass ratios can be found for energies as low as 30 KJ that will burn a significant fraction of the cold fuel and give an increase in gain.

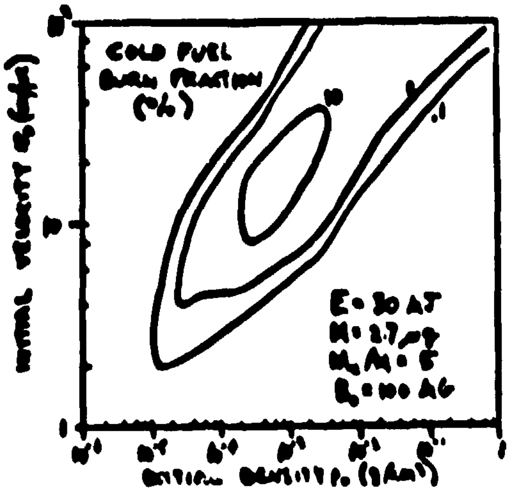

Fig. 4. Performance of a 30 KJ target.

The peak burn fractions occur for initial implosion velocities and DT densities significantly lower than required for conventional ICF targets. This is illustrated in Figures 4 and 5. The magnetized central igniter makes possible orders of magnitude greater gain and burn fraction than could be achieved with no magnetic field in the central igniter (but with the same initial preheat). For example, the 30 KJ target gives only 0.01% burn of the cold fuel and a gain of 0.4 with no magnetization, but 18% burn-up and a gain of 40 with an initial field of 100 MG.

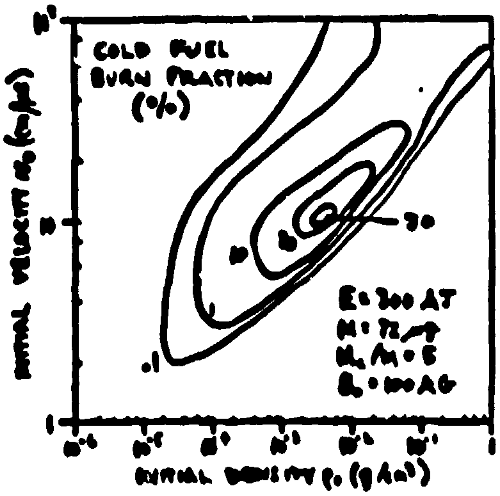

Fig. 5. Performance of a 300 KJ target.

The gain without the cold fuel layer would have been only 4. The 300 KJ target gives a maximum gain of 200 with a cold to hot mass ratio of 5. While the two examples given here achieve peak burn-up for implosion velocities of about 10cm/μs, significant burn-up and gain are possible with much slower implosions, velocities so low that conventional ICF targets won't ignite. The low implosion velocity and larger size of magnetized fuel targets makes the use of lower power, higher efficiency drivers very attractive. In fact the issue of high gain is much less important for systems employing such drivers.

CONCLUSION

We have used our zero-dimensional model to survey the parameter space for magnetized fuel targets employing a cold fuel layer. Our extended model predicts that it is possible to obtain a large cold fuel burn-up fraction, leading to very high gain, and once again, the optimum parameter space is quite remote from that of conventional high gain targets. While encouraging, other studies suggest that igniting a cold fuel layer with the hot, burning, magnetized fuel is difficult [9]. Additional studies are in progress that should improve our physics models and lead to a fuller understanding of magnetized fuel physics [10]. Inclusion of the enhancement of the alpha particle deposition due to the magnetic field in our zero-dimensional model could change the fractional burn-ups and gains reported here. Nevertheless, the results shown here are sufficiently encouraging to warrant continued study.

Although conventional drivers optimized for conventional targets are probably not optimum for magnetized fuel at its extremes, there is a continuum between the conventional parameter space and the new parameter space, suggesting a possible role for conventional drivers. However, it would appear that magnetized fuel warrants a complete rethinking of the entire driver/target configuration.

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