CONF-8610285--1-Rev.1

UCRL--93046-Rev.1

DE87 008743

Substantial Reductions of Input Energy and Peak Power Requirements in Targets for Heavy Ion Fusion

J. W-K. Mark and Yu-Li Pan

Prepared for publication in proceedings
of International Symposium on Heavy Ion Fusion
Washington, D.C.

October 6, 1986

Lawrence
Livermore
National
Laboratory

SUBSTANTIAL REDUCTIONS OF INPUT ENERGY AND PEAK POWER REQUIREMENTS IN TARGETS FOR HEAVY ION FUSION*

J. W-K. Mark and Yu-Li Pan
Lawrence Livermore National Laboratory, Livermore, California 94550

ABSTRACT

We describe two ways of reducing the requirements of the heavy ion driver for ICF target implosion. Compared to our estimates of target gain not using these methods, the target input energy and peak power may be reduced by about a factor of two with the use of the hybrid-implosion concept. Another factor of two reduction in input energy may be obtained with the use of spin-polarized DT fuel in the ICF target.

We have examined two ways of achieving substantial reductions in the input energy and peak power requirements for heavy ion targets compared to our estimates without these effects. These are: (1) hybrid implosion concept and (2) polarized DT fuel. We outline below the target physics consequences as well as some of the other necessary requirements. In particular, good ion beam illumination symmetry is needed by the hybrid implosion concept. We have used in our simulations the new strategy[1,2] for achieving illumination symmetry proposed by Mark and Lindl.

Our hybrid-implosion concept is designed to use the unique ability of ion beams to deliver energy efficiently and directly into a precompressed ablator. We divide the implosion of a high-gain ICF target into two phases (see Fig. 1): (1) compress the ablator to higher density using short wavelength laser or ion beams; (2) ion

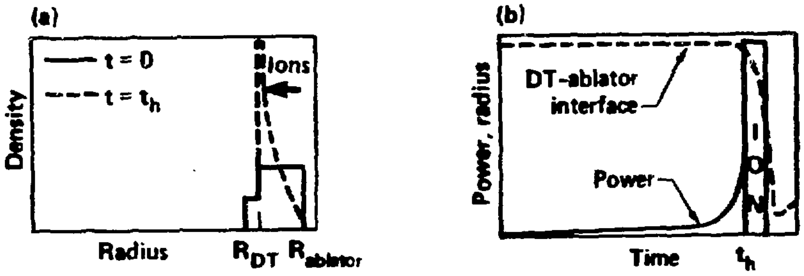

Fig. 1. Hybrid-implosion concept divides the implosion of a high gain ICF target into two phases (see text): (a) Ions deposit their energies in the compressed ablator; (b) Temporal profile of the driver power and the radius-time plot of the DT-ablator interface.

---

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

driver delivers energy efficiently into the precompressed dense ablator to provide the required ignition velocity with high hydro-efficiency at low convergence ratios.

The physical requirements during the first phase are similar to those demanded by all high gain ICF targets. Careful temporal pulse shaping of the driver power (see Fig. 1b) is necessary to set the DT fuel onto a low adiabat. Concurrently, the ablator is symmetrically compressed to higher density (see Fig. 1a). A high hydrodynamic efficiency is not crucial during this first phase because only about 20% of the total input energy is involved.

The second phase requires that ions be generated and transported efficiently to the compressed ablator. Little or no temporal power pulse shaping of the ion beam driver output is required (Fig. 1b). With the proper choice of ion species and kinetic energy, we can obtain very good coupling of the ion energy to the ablator and thereby maximize the hydrodynamic efficiency. Since about 80% of the input energy is supplied during this second phase, an increase in the hydrodynamic efficiency leads directly to reductions in the input energy and peak power requirements. We can make additional improvements in the hydrodynamic efficiency by tamping the implosion. This can be achieved by the generation of an ablation front on the outside of the ion deposition region (Fig. 2). Moreover, the ablation front can be made to move inward as a function of time to provide dynamic tamping for the ion deposition region. We note, however, that the tamping effect can only provide a modest additional improvement in the hydrodynamic efficiency because the pressure at the ablation front is relatively low. The major improvement in the hydrodynamic efficiency is due to the direct ion deposition into the precompressed ablator.

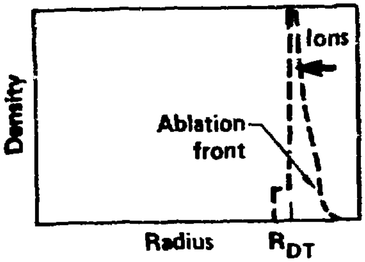

Fig. 2. Ablation tamps the ion deposition region to increase the hydrodynamic efficiency of hybrid-implosion.

The ablation front moves during the implosion of an ICF high gain target driven directly by short wavelength lasers. Normally, even with a good multibeam illumination scheme, there are "residual asymmetries" affected by the focusing geometry and average intensity profile of the laser beams. These beam parameters usually remain fixed during the target implosion. Thus, it would be difficult to have the optimal illumination symmetry as well as high coupling efficiency throughout the implosion with a limited number of beams. In contrast, the thin, dense, compressed ablator shell does not move appreciably during the deposition of the short heavy ion beam pulse in the second phase of the hybrid-implosion concept. For example, in one of our simulations the radius of peak ion deposition, R_{dep}, shifts from its average value by only 13% during the ion-pulse. This is sufficiently small to maintain illumination symmetry. We have also used the theory developed by Mark[2] to determine the choice of beamlet incident angles, beamlet number, currents and spatial shapes to remove most of the asymmetries in the target illumination. The selected axially symmetric illumination scheme is convenient for some reactor designs, particularly those with vertically flowing liquid metals. With this illumination scheme and 32 beamlets, we have attained <2% deposition asymmetries for a convergence ratio of 24. Details are similar to those of the Mark-Lindl, Ref. 1, and will not be discussed here.

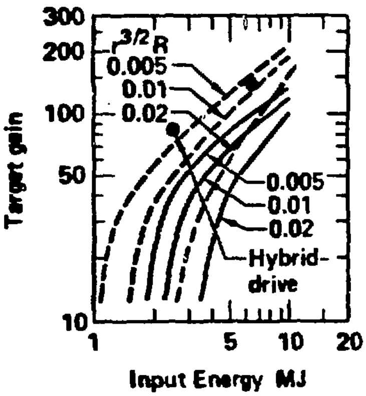

Fig. 3. Gain curves of the single-shell targets for several $r^{3/2}R$ values. The two hybrid-drive points are to be compared to the solid gain curves - unpolarized DT fuel. Dashed gain curves are for targets using 100% polarized DT fuel. Input energy is equal to the total energy deposited in the target.

Figure 3 shows the results of detailed calculations of single shell targets using the hybrid-implosion concept as compared to some of our other targets. Using unpolarized DT fuel, a target gain of about 90 is obtained at 2.5 MJ input energy. We used in the calculations 3 GeV Cs (or 5 GeV Pb) ions with a peak power of 150 TW focused to 3.4 mm spot diameter, D, ($r^{3/2}R \approx 0.004$). At higher input energy, we obtained a target gain of 140 at 6.6 MJ. This hybrid drive target used D = 5.1 mm with 4 GeV Cs (or 7 GeV Pb ions) at a peak power of 250 TW ($r^{3/2}R = 0.01$, unpolarized DT). The peak power and input energy at constant target gain and $r^{3/2}R$ are about a factor of two lower than those used in the unpolarized DT targets (Fig. 3).

Many proposed targets use direct drive ions (for early examples see Refs. 3-5) to generate efficient target drive. The difference lies in important details such as energy deposition in precompressed ablators and in the treatment of residual direct-drive asymmetries and convergence ratios. Other differences are target materials, in-flight aspect ratios, illumination schemes, etc.

Compared to the target described in Ref. 1 at fixed input energy, the hybrid-implosion target uses a smaller beam spot size and has smaller energy gain. This smaller spot size would place a tighter phase-space constraint on the ion beams. However, this tighter constraint is in part a design trade-off. When the same ablator material is used in the two targets, the hybrid-implosion target has about a factor of two smaller convergence ratio for the ion pulse. (This smaller convergence ratio is also true for hybrid drive versus the unpolarized DT targets of Fig. 3.) The reduction in the convergence ratio is the direct consequence of precompressing the ablator material to higher density and smaller radius before depositing the direct drive ion energy into the ablator material. Convergence ratio is defined here as the radius of peak ion energy deposition, R_{dep}, at the start of the ion pulse divided by the radius of the hot spot at ignition. The two targets also deal with the effects of the residual ion beam asymmetries differently. The same ion beamlet placement scheme is used in the two cases. The hybrid-implosion target tolerates the effects of the residual asymmetries by: (1) reducing the radial excursion in R_{dep} by choosing the proper duration, Δt, for the direct drive ion pulse (too short a Δt would sacrifice the advantage of lower peak power); (2) reducing the effective convergence ratio (further reductions in convergence ratio would reduce focal spot some more). In contrast, the target described in Ref. 1 controls the residual asymmetries by selecting the appropriate excursion in R_{dep}. This is done through choosing the proper amount of high-Z tamper material (convergence ratio has typically not been reduced).

The stability of an ICF high gain target is a very complex issue and is target design dependent. For the typical ablatively driven target, perturbations can grow at two (or more) interfaces during the implosion. One is the ablation front and the second is the fuel-ablator interface when the shock reaches the fuel (Richtmyer-Meshkov). These two unstable interfaces are physically separated by the ablator region. The ions delivered during the second phase of the hybrid-implosion concept deposit their energy in this region at or near the region of peak density and temperature. Since the ablation front is outside of the ion deposition region and this region is exploding during the dominant phase of the target implosion, we expect the deleterious effects due to the perturbations generated at the ablation front to be reduced by the ion deposition.

The hybrid-implosion concept is a new way to reduce the peak power and energy requirements of the heavy ion driver. A number of issues generic to direct drive symmetry and stability requirements need to be explored more fully. Ultimately, the utility of this concept will be determined by factors such as cost and other system issues.

Spin-polarized DT fuel can be used in single-shell targets driven by ion beams to reduce the input energy requirements. This reduction in the input energy requirements of an ICF target using spin-polarized DT fuel is the direct result of the higher nuclear reaction rate of such fuel (Refs. 6-9). Consequently, for the same areal density of DT fuel, a higher fraction of fuel undergoes thermonuclear burn. Thus the target gain with polarized fuel, at near fixed energy input is increased. Alternatively, for fixed target gain, the energy input is reduced when polarized fuel is used.

For constant target gain and isotropic burn product emission, simple analytical models predict an input energy reduction of between $\delta^{-2.5}$ and $\delta^{-3.0}$, where δ is the $\langle\sigma v\rangle$ multiplier and takes a value of 1.5 or 1.0, respectively, for 100% polarized or unpolarized DT fuel (Refs. 7,10). We define

$$\delta = 1.0 + 0.5(F_D F_T)$$

where F_D and F_T are, respectively, the polarization fractions of deuterons and tritons. We see that ϕ is only 1.125 for 50% polarization. Thus, significant reductions in the input energy occur only when the fractional polarization is very high.

The results of the simple analytical models suggest that, for completely polarized DT fuel, the input energy requirement can be reduced by a factor of 2.8 - 3.4. However, it is important to recognize that these analytic models assume the fuel has been assembled in the desired manner and ignition has occurred. How, or if, something approximating these idealized conditions can be achieved in an ICF target is not addressed by the models. We have addressed these issues by means of computer simulations. Our results are discussed below.

The target used in our study is similar to the direct drive target proposed by Pan and Hatchett (Ref. 9) for 0.265 μm laser driver. They used a single shell composed of DT wetted foam ablator and liquid/solid DT fuel. Figure 3 shows the gain curves of single-shell targets with and without polarized DT fuel for several $r^{3/2}R$ values. The factor, $r^{3/2}R$, where r is the target radius in cm and R is the beam ion range in g/cm^2, has been used previously to parameterize ion beam target gain (Refs. 11 and 12). A more accurate characterization of target gain requires more parameters than input energy E and $r^{3/2}R$. But for a comparison with additional physics where relative effects are of interest, these parameters should be sufficient (n.b. we assumed $0.1 \leq r/E^{1/3} \leq 0.2$, E in MJ). We note that the convergence ratio remains approximately constant with varying input energy. However, the peak implosion velocity increases with decreasing input energy. This reflects the more stringent ignition requirements of smaller targets. Ignition difficulty is the primary reason for the cutoff in these gain curves near threshold. Consequently, the exact locations of these thresholds are sensitive to the models used to simulate thermonuclear burn. But our conclusions are based only on the relative positions and not the exact locations of the polarized and unpolarized gain curves. Therefore, our results are insensitive to the model used in the computer simulation. At a constant target gain of about 100, we find the input energy requirement is reduced by about a factor of 1.8 for single shell targets using polarized DT fuel and $r^{3/2}R$ of 0.005.

As noted above, significant reductions in the input energy occur only when the fractional polarization is very high. Experimentally, a very high degree of polarization (99%) has been obtained with H_2 molecules at ultra low temperatures. Whether or not one can obtain a high degree of polarization with deuterium and tritium is not known. Experiments are in progress to polarize DT (Ref. 13).

REFERENCES

1. J. W-K. Mark and J. D. Lindl, "Symmetry Issues in a Class of Ion Beam Targets Using Sufficiently Short Direct Drive Pulses," elsewhere in this proceedsings.
2. J. W-K. Mark, Physics Letters, 114A, 458 (1986).

3. M. J. Clauser, Phys. Rev. Lett., 35, 848 (1975).
4. J. D. Lindl and R. O. Bangerter, Lawrence Livermore National Laboratory Report, UCRL-77042 (1975).
5. M. A. Sweeney and M. J. Clauser, App. Phys. Lett., 11, 1 (1975).
6. R. M. Kulsrud, H. P. Furth, E. J. Valeo, M. Goldhaber, Phys. Rev. Lett., 49, 1248 (1982).
7. M. D. Rosen, J. D. Lindl, and A. R. Thiessen, LLNL Laser Program Annual Report - 1983, pp. 3-5 to 3-9 (1984).
8. R. M. More, Phys. Rev. Lett., 51, 396 (1983).
9. Y. L. Pan and S. Hatchett, "Spin Polarized Fuel in ICF Reactor Targets," Lawrence Livermore National Laboratory Report, UCRL-94235, February (1986).
10. K. A. Brueckner and S. Jorna, Rev. Mod. Phys., 46, 325 (1974).
11. R. O. Bangerter, J. W-K. Mark and A. R. Thiessen, Phys. Lett., 88A, 225 (1982).
12. J. D. Lindl and J. W-K. Mark, Laser and Particle Beams, 3, 37 (1985).
13. P. C. Souers, E. M. Fearon, E. R. Mapoles, J. R. Gaines, J. D. Sater and P. A. Fedders, to appear in Jour. Vac. Sci. Tech., May/June (1986).