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REVIEW OF TARGET STUDIES FOR HEAVY ION FUSION*

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ABSTRACT

We present an updated set of gain curves for radiation driven ion beam targets. The improved target performance calculated with nuclear spin polarized fuel will also be discussed. We discuss the conditions required for efficient conversion to x-rays of ion beam energy. These requirements are compared with those obtained for lasers. Recent results on symmetry requirements for direct drive ion beam targets are presented.

INTRODUCTION

Classification restrictions prevent a comprehensive discussion of progress and issues for the radiation drive approach to ICF. However, the national ICF program under congressional mandate underwent an extensive review by the National Academy of Sciences in 1985. The Academy has published both a classified and unclassified summary of their findings. This review provides a favorable, independent evaluation of the progress of ICF.

Quoting from the report: "The classified Centurion-Halite program involves weapons and ICF groups in a theoretical and experimental effort to investigate design characteristics of efficient ICF targets. This program has thus far been very successful. The Centurion-Halite program involves very difficult experiments, and the program should be given sufficient time and funding to provide definitive results. We believe that it will be possible to complete the Centurion-Halite program within five years, with sufficient resources. A longer period of time may be required if there are funding limitations or serious technical problems."

The NAS committee also concluded that the planned Nova experiments were essential to assessing the potential of radiation driven ICF. Since the committee wrote its report, Nova has indeed begun to fulfill its potential. In its first high density implosion experiment, the Nova laser imploded a capsule to conditions which represent a significant advance in the fuel conditions attained in laboratory ICF experiments. These

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experiments, which had a neutron yield of $Y = 5 \times 10^{10}$ and a measured ion temperature of $\theta = 1.7 \pm 0.3$ keV had an estimated value of $n\tau \sim 2-4 \times 10^{14} \text{ s} \cdot \text{keV/cm}^3$ where τ is the confinement time and n the particle density. This value is as good as has ever been achieved on any laboratory fusion device and is particularly significant since the experimental results were very nearly equal to the 1-D implosion calculations. This is in contrast to earlier high density experiments in which experimental neutron yields were often lower than the calculated values by an order of magnitude or more.

Although the results of the Nova experiments were achieved with a laser, the implosion results for a radiation driven capsule apply to any driver which can provide the required radiation environment. This is particularly important to the HIF efforts since there is no target experiments program for these drivers.

X-RAY CONVERSION EFFICIENCY AND TARGET GAIN

To implode efficiently a capsule with x-rays, it is first necessary to convert efficiently the driver energy to x-rays. Both lasers and ion beams can achieve high x-ray conversion efficiency but they have opposite intensity scaling as shown in Fig. 1.

Fig. 1. Both lasers and ion beams can achieve high x-ray conversion efficiency but have opposite intensity scaling.

Plotted are the experimental conversion efficiencies on gold for wavelengths from $1/4\mu\text{m}$ to $1\mu\text{m}$ for lasers and theoretical results for three different ion ranges, in low-Z material. The ion conversion efficiency curves are from a simple analytical model which is a good match to optimized LASNEX calculations. The ion beam analog to the gold disk experiment, from which the laser data are obtained, is shown in Fig. 2a. Here, a low-Z radiator, an ion range thick, is surrounded by a lossless tamper whose function is to constrain the hydrodynamic motion to one-dimension.

Fig. 2a. A simple model provides an estimate of ion to x-ray conversion efficiency.

The incident ion beam intensity I (W/cm^2) is then partitioned into three components given by

$$I = R \, d\epsilon/dt + dK/dt + \sigma T^4 \quad (1)$$

where R is the ion range, ϵ is the specific energy of the radiator material, K is the kinetic energy and T is the temperature. The quantity K is obtained from an approximate solution of

$$\frac{Dv}{Dt} = -\frac{1}{\rho} \frac{dP}{dz} \quad (2)$$

and can be minimized by choosing a low density radiator material such as a foam. Conversion efficiency η is defined by

$$\eta_{\text{conv}} = \int \sigma T^4 dt / \int I dt \quad (3)$$

If the intensity is too low, the heat capacity losses dominate because the temperature for reasonable pulse lengths never gets high enough for efficient radiation. An example with $I = 3 \times 10^{14} \text{ W/cm}^2$ and $R = 0.1 \text{ g/cm}^2$ with a 10 ns pulse is shown in Fig 2b. At sufficiently high intensity, the radiator is quickly heated to a temperature at which σT^4 dominates and reradiates energy at the incident power. For example, in Fig. 2c at $I = 3.2 \times 10^{15} \text{ W/cm}^2$ with $R = 0.1 \text{ g/cm}^2$, an overall conversion efficiency of nearly 90% is achieved.

Fig. 2b. Low intensity gives low radiation temperature and high thermal losses.

Fig. 2c. High conversion efficiency requires high intensity which results in low kinetic and thermal energy losses.

Because of the differences in conversion efficiency versus intensity for lasers and ions, there are some important differences for various applications. Lasers get conversion efficiencies $\eta > 70\%$ for $I < 10^{14} \text{ W/cm}^2$ for $\lambda < 1/3\mu$. This is advantageous from a plasma physics viewpoint since all important instabilities are below threshold at this intensity. But the laser system would require many beams covering a large fraction of solid angle at the target to achieve this low intensity. Such architectures are cumbersome and poorly matched to the most attractive reactor designs. Laser experiments, using higher-Z and lower density radiator materials, are underway to increase the intensity at which $\eta > 70\%$ is achieved. For ion beams on the other hand, conversion efficiency increases with intensity and reaches values in excess of 80-90% if intensities of several times 10^{15} can be reached with typical beam parameters. This intensity need not be reached by each beamlet if there are many beams, but only in a small number of spots on target where many beams could overlap. Beams can cover a very small solid angle at the target which is ideally matched to one or two sided power production scenarios. On the other hand, as is clear from Fig. 1, it is extremely important that the ion beams come very close to reaching the design spot size. For typical design points, if the spot size were a factor of three larger than planned, so the intensity were an order of magnitude lower, x-ray conversion efficiency would drop to a very low value and the accelerator would no longer be useful for x-ray driven capsules.

When detailed calculations are done, we find, as shown in Fig. 3, that either lasers or heavy ions can achieve the conditions required for high gain. For ions, the gain curves can be

Fig. 3. Either lasers or heavy ion beams can achieve the conditions required for high gain.

approximately represented as a function of $r^{3/2}R$ and driver energy where r is the spot radius (cm) and R is the ion range (g/cm^2). A more accurate representation requires that r and R be treated as independent variables. Compared to the optimized laser designs, current heavy ion targets, because of lower x-ray transport efficiency, have a lower gain for a given x-ray conversion efficiency. Hence the maximum gain for ions is less than for the 80% conversion efficiency laser curve.

POLARIZED FUEL

A variety of advanced target approaches exist to increase target gain beyond those indicated in Fig. 3. One of these is the use of nuclear spin polarized fuel.^(1,2) The fusion cross section σ for DT reactions is given by

$$\sigma_{\text{pol}} = (1 + 1/2 P_D P_T) \sigma_{\text{unpol}} \quad (4)$$

where $P_{D,T}$ are the polarization fraction for D or T. With complete polarization, σ increases by a factor of 1.5. But because the increase is quadratic in the polarization fraction, 50% polarization only gives a 12.5% increase in cross section. If one ignores depletion, the burn efficiency is given by $\phi \propto \rho r \langle \sigma v \rangle$ where ρr is the product of the fuel density ρ and its radius r and $\langle \sigma v \rangle$ is the Maxwell averaged cross section. Gain is proportional to $\rho r \langle \sigma v \rangle / E_{in}$ which is proportional to $\rho r \langle \sigma v \rangle$ because $E_{in} \propto m$ where E_{in} is the incident driver energy and m is the fuel mass. For a fixed target then, with 100% polarization, the gain increases by a factor of about 1.5. For fixed gain, ρr can be reduced by a factor of 1.5. Assuming constant density, $\rho r \propto r \propto m^{1/3} \propto E_{in}^{1/3}$. Therefore, the driver energy might be reduced by a factor of $(1.5)^3 \approx 3$. The results of detailed calculations of ion beam targets with and without polarized fuel are shown in Fig. 4. We do find the 1.5 increase in target gain

Fig. 4. Spin polarized fuel gives higher gain.

for a fixed target but the energy reduction for fixed gain is less than a factor of 3. Because of a variety of non-hydrodynamic effects, the performance of smaller targets drops off more rapidly than $E_{in}^{1/3}$. Highly polarized DT has not been produced but studies are underway at Princeton, MIT, Syracuse and LLNL. Many depolarization mechanisms during an implosion have been studied² and no problems have been found.

DIRECT DRIVE

Assessing the prospects for direct-drive heavy-ion targets is more difficult than for radiation drive because much less of the information from current experiments is applicable. However, potential gains are substantially higher than those for radiation driven targets if the energy loss involved in obtaining symmetry is small.

An exciting development in the past year has been the emergence of low density, low-Z foams wetted with DT.³ These targets provide a nearly ideal direct drive target, similar to those originally proposed by Nuckolls for ICF. As shown in Fig. 5, this foam, wetted with liquid DT provides both the ablator and fuel. The vapor pressure of DT just above the triple point provides a nearly optimum gas mass for a hot spot. The main penalty for using this target, compared to a pure DT shell, is an increase in the ignition temperature as shown in Fig. 6. This temperature is defined by the

Fig. 5. Use of low density, low Z foam to define and stabilize the DT shell allows an attractive single shell target design.

Fig. 6. The ideal ignition temperature for wetted foams depends primarily on the foam density and composition. Highlighted bands are the ranges of densities where the materials shown are expected to meet the target and fabrication requirements.

point at which the alpha particle production rate for thermonuclear burn equals the bremsstrahlung rate. For $\rho = 0.1$ g/cc aerogel, a currently available SiO_2 foam, the ignition temperature increases from 4.5 keV for DT to about 13 keV. However for materials under development such as $\rho = 0.05$ CH, the increase is quite small and results in little change in target gain.

Typical direct drive targets have a convergence ratio, the ratio of the initial target radius to the final compressed radius, large enough that peak to minimum intensity variation must be held to about 1-2%. A variety of focusing schemes exists to achieve this kind of uniformity in principle, with adequate beam quality. However, these schemes typically produce optimal uniformity at a single target radius. If the radius of deposition varies strongly during the implosion, as is the case with short wavelength lasers, it becomes difficult to achieve uniformity without a very large number of beams. For ions, we have been able to design a target which largely avoids this problem as shown in Fig. 7. The target has a radial excursion of the peak in the energy deposition of only $\pm 8\%$. This is accomplished by making use of the relatively low energy loss of ions in high-Z material to provide a tamper on the explosion of the wetted foam target. By adjusting the mass of this tamper, we control the motion of the location of the energy deposition.

Fig. 7. Tamped direct drive ion beam targets can have low radial motion of peak deposition.

We have studied two methods, the minimum potential and Gaussian quadrature approaches to obtain symmetry for direct drive ion targets. The minimum potential approach has been widely used for direct drive laser targets. In this approach, beams are imagined to be charges on the surface of a sphere. The charges are allowed to move around on the surface until their potential energy is minimized. In the Gaussian quadrature approach⁴, beams are arranged on the rims of cones whose relative powers are given by Gaussian quadrature weights and whose angles are the zero's of the Legendre polynomials. This approach geometrically eliminates the lowest $2n-1$ perturbation modes in θ where n is the number of rings of beams and $m-1$ perturbations in ϕ where m is the number of beams on a ring. This method is amenable to analytic analysis but unequal beam powers are required to minimize the number of beams. Both methods give comparable symmetry in static, thin-shell models. LASNEX calculations indicate that results of the analytical thin shell model are reasonable for the Gaussian quadrature approach. The LASNEX calculations are done by taking a snapshot of the 1-D implosion at several times. At each of the selected times, the calculation is expanded to 2-D to obtain deposition as a function of angle and depth for a single beam. This deposition is then added analytically for all beams to produce the total deposition versus angle and depth. These calculations are not entirely self consistent since the flows are assumed to be spherically symmetric at each point. We are in the process of performing a 2-D approximation to the hydrodynamics which would self-consistently model the material response to nonuniformities. The current calculations and analyses indicate that the uniformity of deposition is nearly good enough with about 32 beams. Improvements to this estimate will require better calculations.

We can also calculate alignment tolerances using the thin shell model. For typical targets, the alignment tolerance (rms) appears to be 1-3% of the beam radius for 32 beams. This is a factor of 5-10 greater precision than is required by typical radiation driven targets.

The target in Fig. 7 has more than a factor of two higher gain than the radiation driven targets of comparable energy. Its value of $r^{3/2}R \sim .005$ is within a factor of two of that required by radiation drive targets but there is little flexibility in trading off range with spot size to meet this value. We are currently analyzing whether the higher gain is offset by the more complex beam geometry, more restrictive beam parameters and more stringent focusing requirements.

CONCLUSIONS

In conclusion, progress in radiation driven targets in the U.S. ICF program has been very encouraging over the past couple of years. Since heavy ion ICF targets can make use of much of this information, there is a strong motivation for a continued or accelerated machine development program. The critical issue, for heavy-ion accelerators, for radiation driven targets, is their ability to achieve focused intensities of order 10^{15} W/cm² for typical machine parameters. Direct drive heavy ion targets in principle have much higher gain than radiation driven targets but have more restrictive pointing requirements, less flexibility in accelerator parameters, and a more complex geometry. Without a heavy ion target experiment program, it will be nearly impossible to obtain sufficiently accurate answers to these questions for direct drive targets.

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