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HEAVY-ION INERTIAL FUSION: INITIAL SURVEY OF TARGET GAIN VERSUS ION-BEAM PARAMETERS *

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Abstract

Inertial-fusion targets have been designed for use with heavy-ion accelerators as drivers in fusion energy power plants. We have made an initial survey of target gain versus beam energy, power, focal radius, and ion range. This provides input for understanding the trade-offs among accelerator designs.

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In order to design efficient, cost-optimized particle accelerators as drivers for heavy-ion inertial fusion power plants, it is necessary to calculate target gain as a function of ion-beam parameters. The important ion-beam parameters are total beam energy E, focal-spot radius r, and ion range R, (the latter in units of mass/area). Peak beam power P is also an important parameter, but for a given target design, the power is a function of energy (or vice versa).

With this motivation, numerical target calculations were made using the Livermore LASNEX inertial fusion simulation code [1]. One would expect specific energy deposition to be an important parameter. The specific energy deposition is proportional to E/r^2R. Thus, one could hope that within some range of values of radius and range the gain might depend on r^2R rather than r and R independently. Therefore, we have attempted to describe the LASNEX results in terms of target gain as a function of E and $r^{\epsilon}R$, where the numerical data was fitted to within an accuracy of a few percent by $\epsilon \doteq 3/2$.

So far, our calculations have covered only a small range in r. They can be considered valid for $0.1 < r/E^{1/3} < 0.2$, where r is in cm and E is in MJ. The input energy scales roughly as target mass, therefore, the expression $r/E^{1/3}$ simply corresponds to the fact that the mass of a target scales as r^3.

We have considered single- and double-shelled targets such as illustrated in Fig. 1. Our results of target gain for single-shelled targets are shown in Fig. 2a, and the results for double-shelled targets are shown in Fig. 2b. The solid curves in Figs. 2a and b are best-estimate target gains for different values of $r^{3/2}R$, where r is the focal radius (cm) of the beam and R is the range (in gm/cm^2) of the ions. As a typical specific example, a 10-GeV lead ion-beam focused to $r = 0.2$ cm gives $r^{3/2}R = 0.0112$. Thus, the 0.01-gain curve would be roughly appropriate for this case.

Higher gains have previously been reported for inertial fusion targets [2,3]. But these higher gains are typically based on

1-dimensional simulations of ideal targets. Our corresponding calculations give the ideal curves shown in Figs. 2a-b.

In calculating the best-estimate curves, we have attempted to include the effects of fluid instabilities as well as reasonable imperfections in target fabrication and illumination symmetry which all affect target ignition and burn. Our assumptions are consistent with the conservative criteria used in Ref. [3].

The dashed lines correspond to the "best estimate" band calculated for short wavelength ($\lambda \leq 0.5\ \mu$) lasers [3]. In earlier reports, we assumed that the gain of heavy-ion targets would lie at the lower edge of this band. The present gains are typically higher and are based on improved calculations. But, we emphasize that these results are preliminary. Target performance for heavy-ion fusion may improve as other designs and modifications are pursued.

Thus, the dotted ideal curves in Figs. 2a-b represent reasonable upper bounds on gain for these types of targets. The difference between the ideal and best-estimate curves is indicative of large uncertainties in target gain; however, the relative gain for different $r^{3/2}R$ can be calculated with good precision.

The gain curves for single-shelled targets given in Fig. 2a are lower than those of double-shelled targets, but they decrease less rapidly with decreasing energy and are more interesting at lower input energy than those of double-shelled targets. This is especially true for ion-beam fusion because the lower target gain is compensated by the expected high efficiency of particle accelerators.

The economics of power production are strongly influenced by the product of driver efficiency and pellet gain [4,5]. It is commonly assumed that the product of driver efficiency and target gain should be at least 10-20. Ion accelerators are expected to have efficiencies of about 15-35% so that single-shelled targets give adequate gain. By contrast the projected efficiency of most laser systems is not greater than 10% [4] so that the use of double-shelled targets may be mandatory unless the best-estimate gain curves are too pessimistic. Single-shelled targets also have the advantage that they are simpler and easier to fabricate. However, for a given input energy, the power requirement for a single-shelled target is approximately twice as great as for a double-shelled target. The peak power requirement is given as a function of energy in Fig. 3. The numerical labels on the curves in Fig. 3 refer to different values of $r^{3/2}R$. As in the case of target gain, these curves are somewhat uncertain, but should be adequate for accelerator design. The pulse length is not equal to E/P because our targets require pulse shaping.

Figure 4 gives ion range as a function of ion kinetic energy for several representative ions. These curves are based on aluminum target material at a temperature of 200 eV and density of 0.2 g/cm^2. These numbers correspond to typical target conditions. Aluminum is chosen for illustrative purposes. The range is relatively independent of the material chosen, being approximately a factor of 2 larger for high-Z material than for low-Z. The dependence on temperature and density is rather weak for ions having velocities large compared to thermal electron velocities. For example, we calculate a 21% increase in range, relative to the curves in the figure, for 10-GeV lead ions incident on room-temperature aluminum at solid density. Note that heavier ions allow the use of higher kinetic energies and, therefore, lower beam currents than lighter ions.

References

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Figure Captions

Figure 1: Single- and double-shelled targets for inertial confinement fusion.

Figure 2: The solid curves give the best-estimate target gains of heavy-ion targets as a function of input beam energy. The curves are labelled by values of $(r^{3/2} R)$ where r is the spot radius in cm and R is the ion range in g/cm^2. The gain of short-wavelength laser targets is expected to lie in the band defined by the dashed lines. The curves labelled "ideal" do not incorporate conservative assumptions on target shell stability, etc. (see text). Fig. 2a is for single-shelled targets while Fig. 2b corresponds to double-shelled targets.

Figure 3: The peak power requirements are given as a function of input beam energy corresponding to the target gains recorded in Figs. 2a-b.

Figure 4: Ion range in g/cm^2 as function of ion kinetic energy. These curves are based on aluminum target material at a temerature of 200 eV and density of 0.2g/cm^2, corresponding to typical target conditions.

SINGLE AND DOUBLE SHELL I.C.F. TARGETS

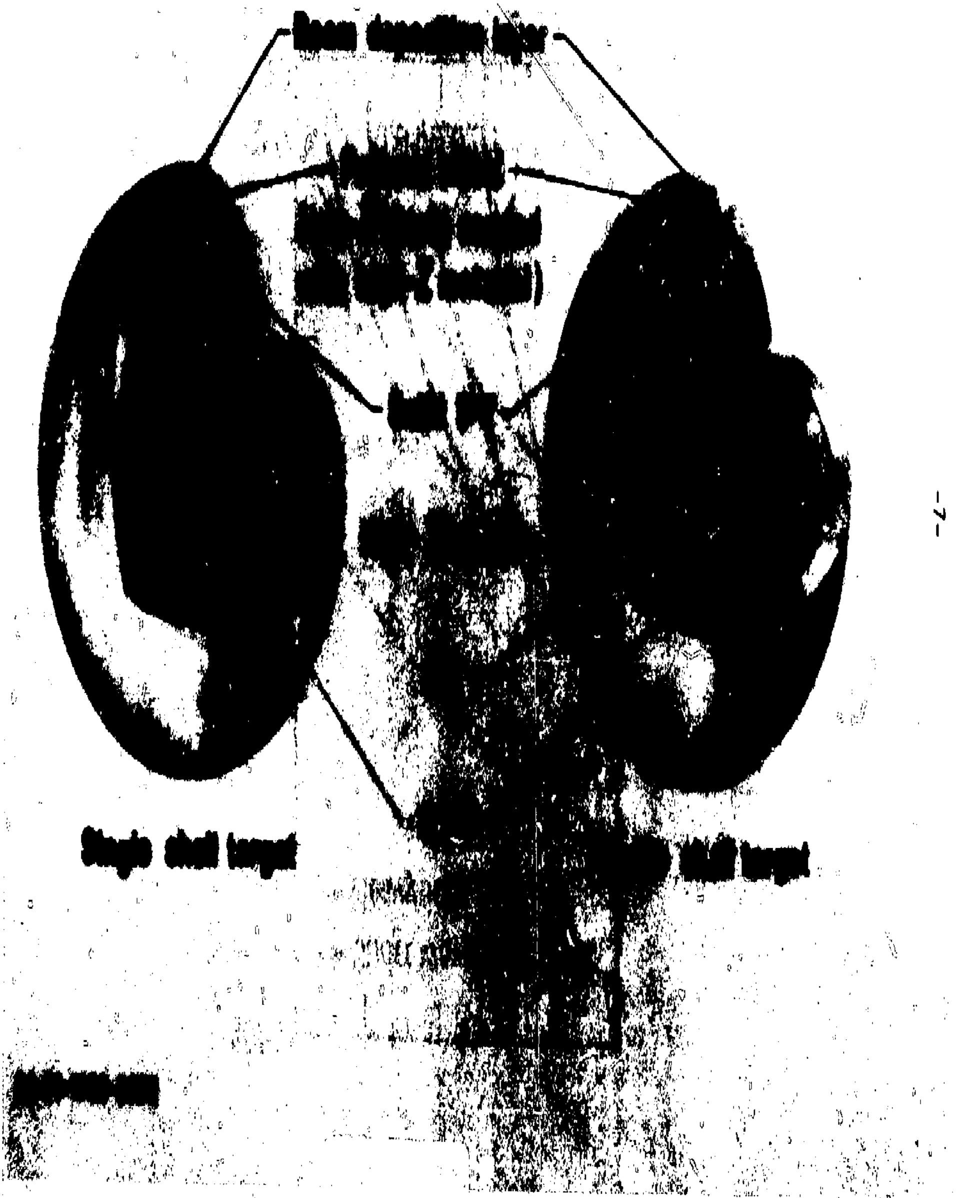
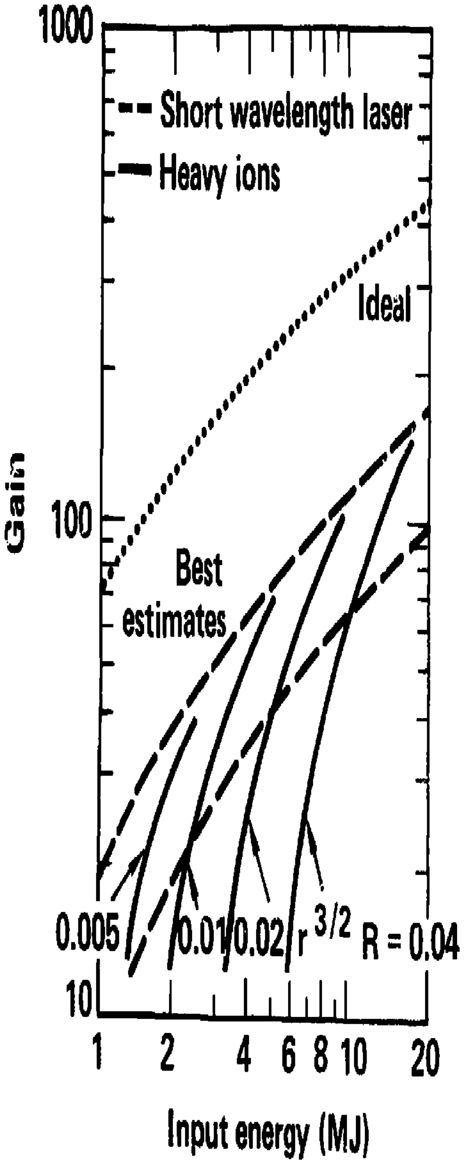


Figure 1



Gain
1000
100
10
Short wavelength laser
Heavy ions
Ideal
Best estimates
0.005
0.01
0.02
r 3/2
R = 0.04
1
2
4
6
8
10
20
Input energy (MJ)

Figure 2a

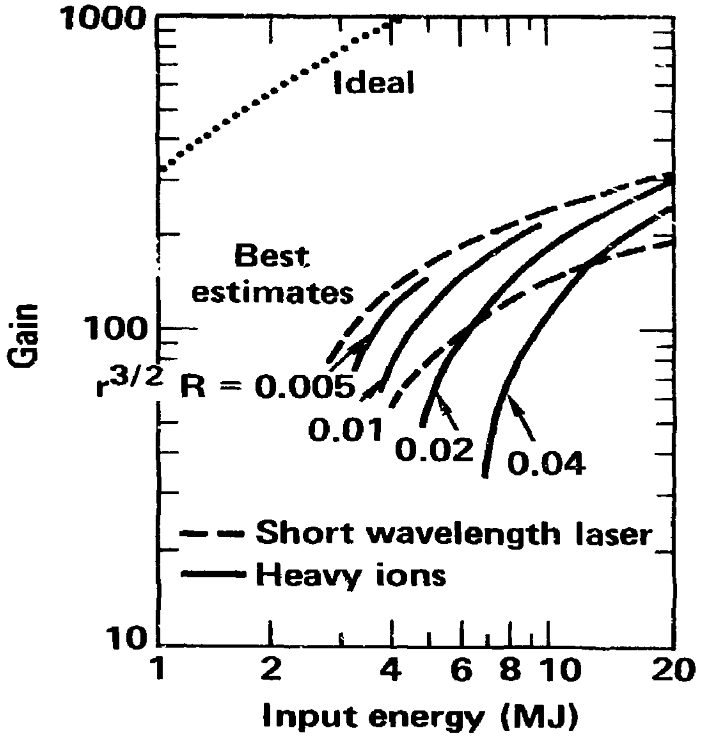

1000
100
10
Gain
Ideal
Best estimates
$r^{3/2}$ R = 0.005
0.01
0.02
0.04
Short wavelength laser
Heavy ions
1
2
4
6
8
10
20
Input energy (MJ)

Figure 2b

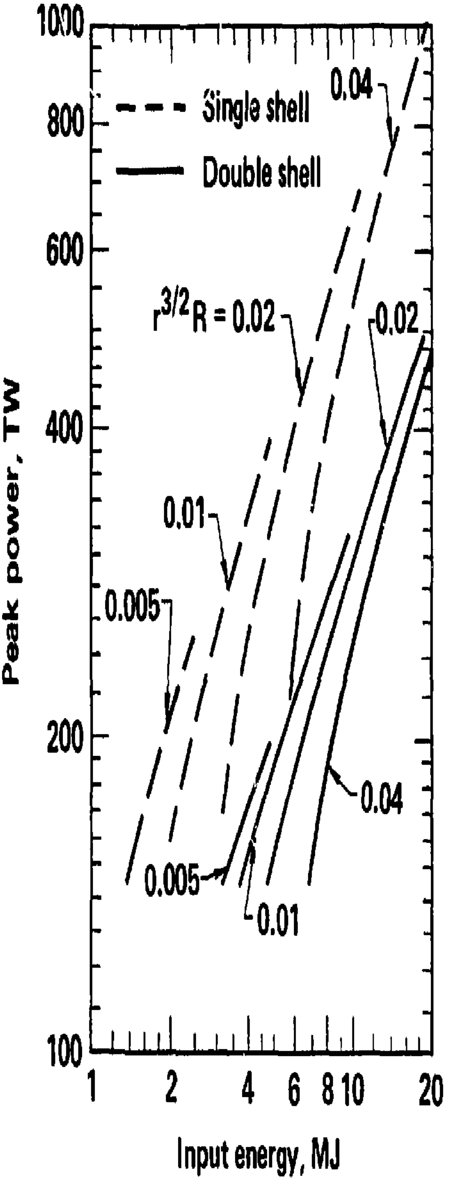

Peak power, TW
1000
800
600
400
200
100
Single shell
Double shell
0.04
$r^{3/2}R = 0.02$
0.02
0.01
0.005
0.005
0.01
0.04
1
2
4
6
8
10
20
Input energy, MJ

Figure 3

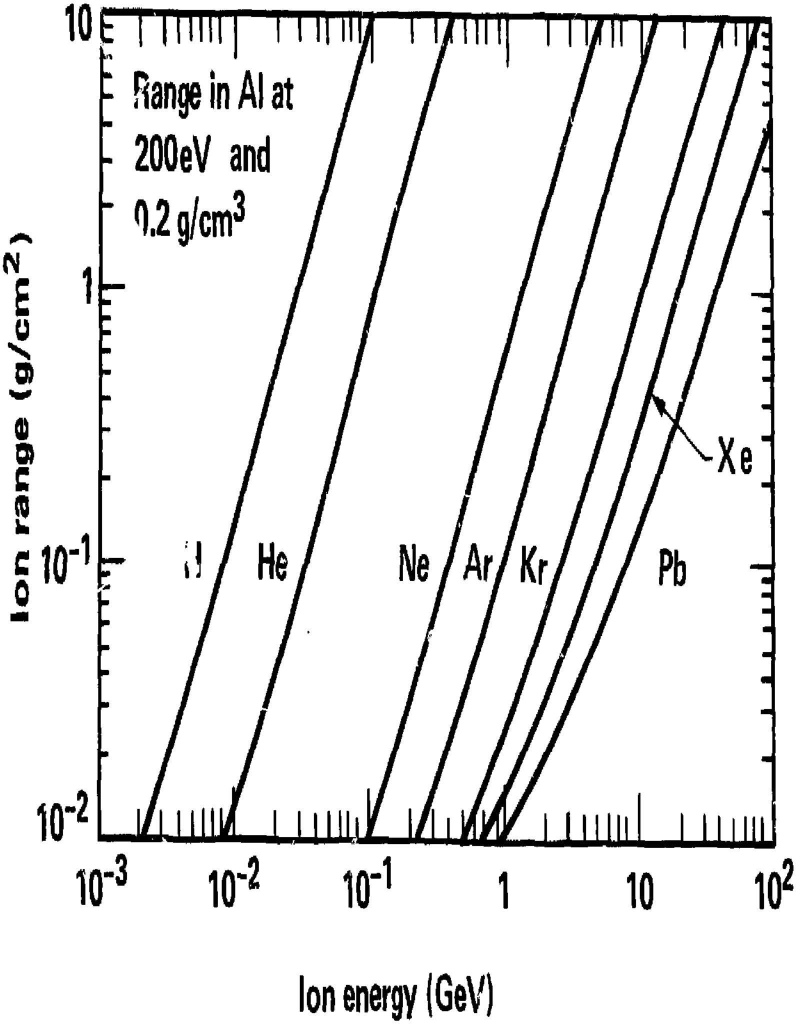

Range in Al at
200eV and
0.2 g/cm^3
H
He
Ne
Ar
Kr
Xe
Pb
Ion range (g/cm^2)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
Ion energy (GeV)

Figure 4