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THE INFLUENCE OF TARGET REQUIREMENTS ON THE PRODUCTION, ACCELERATION, TRANSPORT, AND FOCUSING OF ION BEAMS*

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ABSTRACT

We have calculated the energy gain of ion-driven fusion targets as a function of input energy, ion range, and focal spot radius.

For heavy-ion drivers a given target gain, together with final-lens properties, determines a 6-D phase space volume which must exceed that occupied by the ion beam. Because of Liouville's theorem and the inevitability of some phase space dilutions, the [illegible]ns's 6-D volume will increase between the ion source and the target. This imposes important requirements on accelerators and on transport and focusing systems.

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The feasibility of inertial fusion for commercial power production is strongly dependent on the energy gain attainable from fusion targets. The gain of an ion-beam-driven target depends on beam power as a function of time (or energy for a specified pulse shape), kinetic energy spectrum, and the focal properties of the ions. Under focal properties we include the configuration of beams illuminating the target, focal spot size, and angular distribution. The gain of laser-driven targets is dependent on the same parameters if one replaces kinetic energy by wavelength.

Estimates of gain as a function of these parameters have varied widely(1-5). Furthermore, except for studies based on 1-D calculations that largely ignore questions of stability and symmetry, much of the design work has produced only isolated examples of designs(1,3,4) without parametric relations allowing the optimization of the joint driver-target system. Therefore, it has also been difficult to compare different drivers.

TARGET GAIN

At Livermore, we are beginning to develop gain functions using a consistent set of assumptions for all beam parameters and drivers. Consider two typical target designs shown in Figure 1. Assuming acceptable preheat and implosion symmetry, the gain functions can be factored into two parts, one depending on the beam-independent physics occuring inside of the preheat shield and one depending on beam coupling efficiency. We define beam coupling efficiency as the fraction of beam energy transferred to the portion of the target inside of the preheat shields.

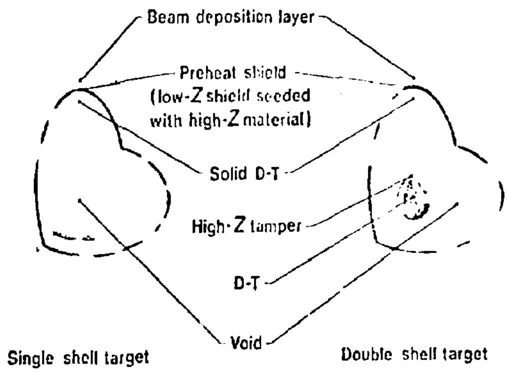

Fig. 1. Single and double shell I.C.F. targets.

In the remainder of this paper we adopt a conservative set of beam-independent assumptions that has been used at Livermore for several years (5,6). More optimistic assumptions improve the gain by roughly an order of magnitude.

Since we believe that ion range is calculable, it seems likely that the major physics uncertainties in ion-beam targets are beam-independent (7). Therefore, the relative gain for different ion-beam parameters can be calculated quite accurately.

So far, we have considered beams with sufficiently small values of energy spread and angular width that the target gain is independent of these variables. Also, we have only performed calculations satisfying

$$0.1 < r/E^{1/3} < 0.2,$$

where r is focal spot radius in cm and E is the total beam input energy in MJ. The expression $r/E^{1/3}$ arises from the fact that E is roughly proportional to target mass, and therefore r^3, for a given target design. We are currently extending our calculations to a wider range of parameters.

Specific en·gy deposition is an important parameter. It is proportional to E/r^2R where R is the ion range in units of mass/area. Thus, one could hope that, in our restricted parameter range, gain might depend on r^2R rather than r and R independently. With this motivation we attempted to describe the results of our numerical (LASNEX) gain calculations as a function of E and r^2R. This was not satisfactory. We then attempted to fit them as a function of E and $r^\varepsilon R$ where ε was allowed to vary. This is possible to an accuracy of a few percent with $\varepsilon = 3/2$. The results are given in Figs. 2 and 3 where target gain and peak power requirement are plotted as a function of input energy. Although these results are valid for all ions, the range of parameters is primarily of interest for heavy-ion fusion. The dependence of range on kinetic energy for a variety of ions is given in Figure 4.

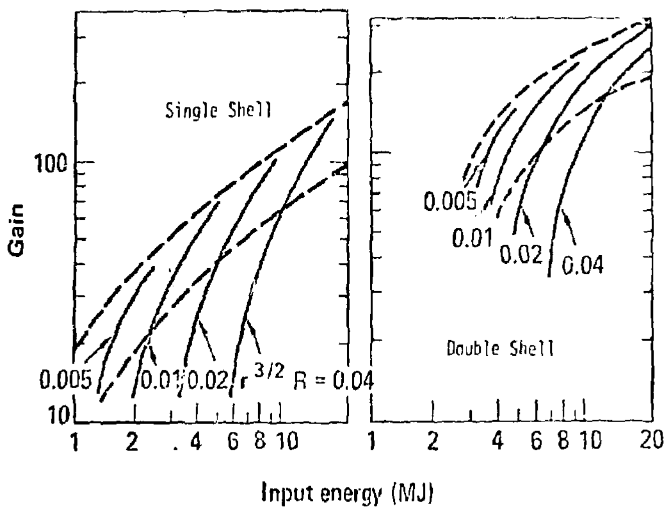

Fig. 2. Gain as a function of input energy. The curves are labeled by values of $r^{3/2}R$ where r is in cm and R in g/cm^2. The gain of short-wavelength laser targets is expected to lie in the band defined by the dashed lines.

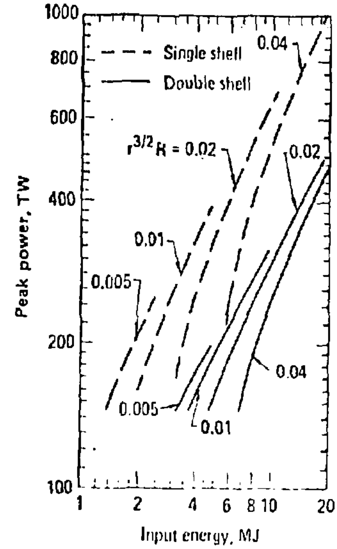

Fig. 3. Peak power requirement as a function of input energy for single and double shell ion targets.

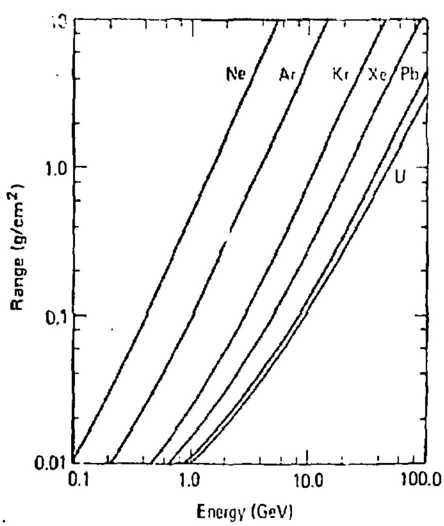

Fig. 4. Ion range in g/cm^2 as a function of ion kinetic energy. These curves are based on aluminum target material at a temperature of 200 eV and density of 0.2 g/cm^2, corresponding to typical target conditions.

Lindl has performed corresponding calculations for short-wavelength ($\lambda \lesssim 0.5\mu$) laser targets (5). For these targets the gain is expected to lie within the bands indicated by the dashed lines in Figs. 2a and 2b. In earlier reports (8,9) we assumed that the gain of ion-beam targets would lie near the lower edge of this band. Our current results are more optimistic.

THE SIX-DIMENSIONAL PHASE SPACE CONSTRAINT

A 6-D phase space volume is defined by ranges in coordinates x, y, z and momenta p_x, p_y, p_z. For fusion targets all six of these parameters have bounds, which if extended, will lower the gain. The curves of Fig. 2 display this effect for spot size which limits x and y. The beam length z is limited by the peak power requirement. If the angular divergence (proportional to p_x and p_y) or energy spread (p_z) is too large, an excessive fraction of the beam energy is deposited near the surface of the target, increasing radiative losses and reducing coupling efficiency (10). However, beam focusing and transport systems may place more stringent limits on the phase space volume. As an example, we consider heavy-ion r.f. linacs for which the constraints on angular divergence and momentum spread are determined by the known properties of final lenses.

Within a numerical factor the 4-D transverse phase space volume available to a beam is given by $V_4 = p^2 r^2 \theta^2$ where p is the beam momentum and θ is a small transverse angle. The (nonrelativistic) longitudinal 2-D volume is given by $V_2 = T\tau(\delta p/p)$ where T is the ion kinetic energy, τ is the pulse length, and $\delta p/p$ is the fractional momentum spread. The total 6-D phase space volume per ion is given by $V_F = nV_2V_4T/E$ where n is the number of beams. For an r.f. linac the 6-D phase space volume per ion is given by $V_L = (Mc\varepsilon_{\parallel})^2\varepsilon_{\perp}qef/I$ where M, c, $\varepsilon_{\parallel}$, $\varepsilon_{\perp}$, qe, f, and I are respectively the ion mass, light speed, transverse emittance, longitudinal emittance per r.f. bucket, ion charge, the frequency with which buckets emerge from the linac, and mean electrical beam current.

According to Liouville's theorem V_F must be greater than V_L. Dilution is expected in acceleration, storage, transport, and focusing so that $D = V_F/V_L$ must substantially exceed unity.

In most reasonably designed focusing systems the beam nearly fills the magnetic lens apertures. This is equivalent to the condition that $\rho(1-\cos\theta_L) \sim \rho\theta_L^2/2 < X$ where $\rho = p/(qeB)$ is the radius of curvature in a lens with pole-tip field B, θ_L is the angular change in the lens and X is the aperture. Actual lens systems involve focusing and defocusing elements so that the angle θ appearing in the expression for V_4 depends on differences in θ_L for the various lens elements. Thus, we write θ^2=GXqeB/p where G is a dimensionless constant to be determined by detailed lens design. For uncorrected lenses chromatic aberrations require that $\delta p/p \lesssim r/(2X)$. We allow the possibility of some chromatic correction using sextupoles by setting $\delta p/p = F_s r/(2X)$ where F_s might be 2 - 5. Combining the above expressions we obtain

$$D = \frac{Gc}{4\pi^{3/2}(mc^2)^{3/2}}\left[\frac{\tau T}{E}\left(\frac{2\pi r^2 T}{A}\right)^{3/2}\right]\left[\frac{I}{\epsilon_{\parallel}^2\epsilon_{\perp} f}\,nBF_s\right]$$

$= KF_{TI}F_L nBF_s$ where A is atomic number and m is proton mass. The first quantity in brackets, F_{TI}, depends on target and ion parameters. The second, F_L, is a figure of merit depending on linac parameters. The factor 2π in F_{TI} is included for historical reasons(11,12). We employ the following units: τ(nsec), T(GeV), r(cm), E(MJ), I(amp), $\epsilon_{\parallel}$(cm-mr), $\epsilon_{\perp}$(eV-sec), B(T) and f(MHz). The constant K is evaluated in Ref. (11) and is given by $K \sim 5\times10^{-3}$.

Gain as a function of F_{TI}, E and T can be calculated (12) using Figs. 2-4. The results of such a calculation for A = 238 are shown in Figure 5. The dependence on T is very weak as indicated by the horizontal lines.

To apply this analysis we must assume a set of r.f.linac parameters and also an expected phase space dilution factor from linac exit to target. Available linac designs are neither detailed nor optimized. Furthermore, dilution estimates are based on educated guesses rather than experience. The following choices can only be described as "representative" (11): I=0.3A, $\epsilon_{\parallel}$=0.2 cm-mr, $\epsilon_{\perp}$f=0.128 (eV-sec) (MHz), B=5T, F_s=3, n=24. It is reasonable to provide about four factors of 3 each for all kinds of dilutions. With such numbers,

$$81 \sim (5\times10^{-3})F_{TI}\ 60\cdot24\cdot5\cdot3,$$

so $F_{TI} \sim 0.75$. From Fig. 5 one sees that this value implies large E, double shell targets, and relatively low gain. On the other hand, larger numbers of beams, better linac brightness (13), and/or assurance of smaller dilutions could ease the constraint significantly. In any event, the constraint must be met; at present it appears to be important. The work described above provides a parametric treatment of the influence of target design parameters on this constraint and displays the cost (in reduced gain or increased E) of easing this constraint.

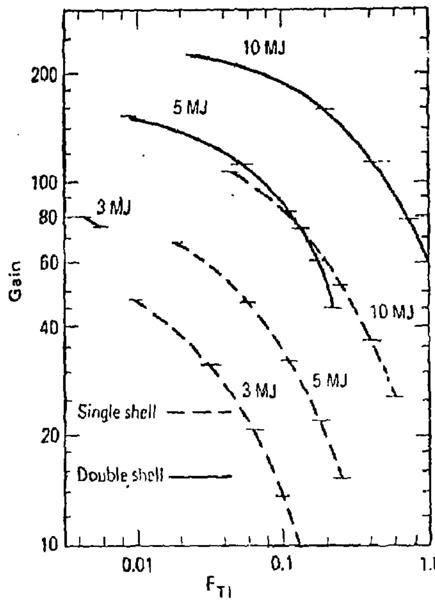

Fig. 5. Gain as a function of F_{TI} for single and double shell targets. These are evaluated for A=238. A small dependence on ion kinetic energy is indicated by the horizontal lines.

REFERENCES

1. Afanasfov'Yu. V., ev et. al., JETP Lett. 21, 68 (1975).
2. Clauser, M. J., PRL 35, 848 (1975).
3. Lindl, J. P. and Bangerter, R. O., Proceedings of the International Topical Conference on Electron Beam Research and Technology, Sandia Laboratory Report SAND 76-5122, 37 (1976).
4. Kindel, J. L. and Lindman, E. L., Nuclear Fusion 19, 597 (1979).
5. Nuckolls, J. H., Lawrence Livermore National Laboratory Laser Program Annual Report-1979. UCRL-50021-71, p. 3-2.
6. Bangerter, R. O., Mark, J. W-K., and Thiessen, A. R., Lawrence Livermore National Laboratory Report No. UCRL-84822 (1980), and Lawrence Livermore National Laboratory Laser Program Annual Report for 1981.
7. Bangerter, R. O., Proceedings of the Heavy Ion Fusion Workshop held at Argonne National Laboratory, Sept. 19-26 (1978). ANL-79-41, p. 415.
8. Brueckner, K. A., Editor, Assessment of Drivers and Reactors for Inertial Confinement Fusion, a report prepared for the Electric Power Research Institute, Palo Alto, CA (1980).
9. Meier, W. R. and Monsler, M. J., Lawrence Livermore National Laboratory Laser Program Annual Report-1979. UCRL-50021-79, p. 8-109.
10. Lindl, J. D., et. al., Lawrence Livermore National Laboratory Laser Program Annual Report-1976. UCRL-50021-76, p. 4-36. Also see paper presented at this conference by D. Meeker.
11. Judd, D. L., Proceedings of the Heavy Ion Fusion Workshop held at Argonne National Laboratory, Sept. 19-26, 1978. ANL-79-41, p. 237.
12. Judd, D. L. and Bangerter, R. O., Lawrence Berkeley National Laboratory Report HIFAN 163 (1981).
13. Maschke, A. W., Brookhaven National Laboratory Report BNL 51029 (1979).