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USING SUFFICIENTLY SHORT DIRECT DRIVE PULSES

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SYMMETRY ISSUES IN A CLASS OF ION BEAM TARGETS
USING SUFFICIENTLY SHORT DIRECT DRIVE PULSES*James W-K. Mark and John D. Lindl
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ABSTRACT

Controlling asymmetries in direct drive ion beam targets depends upon the ability to control the effects of residual target asymmetries after an appropriate illumination scheme has already been utilized. We address a class of modified ion beam targets where residual asymmetries are ameliorated. The illumination scheme used is an axially symmetric one¹ convenient for reactor designs. Residual asymmetries are controlled by limiting the radial motion of the radius R_{dep} of peak ion energy deposition. Limiting the motion of R_{dep} is achieved by lengthening the time scale t_s where changes in R_{dep} adversely affect asymmetries. In our example, t_s becomes longer than the duration Δt_D of the entire direct drive pulse train ($t_s > \Delta t_D$).

A number of authors have studied directly driven ion beam targets in inertial confinement fusion energy research (early instances include Refs. 2-4). For direct drive, a judicious placement of beamlets is of course essential. Beyond that, there are normally residual target drive asymmetries left over from beam overlap and beam profile shaping. These residual asymmetries must all be maintained at a tolerable level which is set by target parameters such as convergence ratio.

Careful beam placement and appropriate transverse beam-shape could reduce asymmetries in direct drive targets. But typically, there is a radius near which the illumination symmetry is optimized. In most such targets, this optimal radius eventually becomes displaced relative to the radius R_{dep} where the beam energy deposition reaches a peak. If left unchecked, a consequence is that asymmetries increase after some characteristic time t_s to an extent where target implosion is adversely affected. Viewed in this manner, the above condition on R_{dep} becomes a time constraint in that the direct drive pulse of duration Δt_D must satisfy $\Delta t_D < t_s$. This value t_s could frequently be smaller than the other target timescales such as the one for the total drive pulse.

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Specifically, the residual asymmetry of one illumination scheme¹ depends upon the deviation of R_{dep} from the beam focal spot radius R_{beam} (considered fixed in this paper). For this illumination scheme, R_{beam} is near the radius where symmetry is optimized. In our detailed example, it turns out that with 32 beamlets and imposing $|R_{dep} - R_{beam}| < 0.08 R_{dep}$, we could already reduce to $< 2\%$ the residual deposition asymmetries in a spherical target. In this paper a careful choice of the ratio of inertias in the outer tamper versus that in ablator allows us to lengthen t_s sufficiently. Thus, t_s is prolonged enough so that the entire $\Delta t_D \approx 62$ ns direct drive pulse train of a specific target satisfies $\Delta t_D < t_s$. (In targets where t_s has not been particularly changed by choices of target structure, we would expect instead that Δt_D be chosen, perhaps shortened, to become less than the existing essentially fixed t_s .)

Fig. 1 The direct-drive ion beam target used in the symmetry studies.

The target in question has the structure illustrated in Fig. 1. Before considering multi-dimensional effects of asymmetries, we first simulated the full hydrodynamics and DT burn of the target using the spherically averaged ion energy deposition. In this initial 1D simulation the beamlets have a realistic distribution of incident angles relative to the target surface but the ion energy deposited at each target radius r is averaged over the sphere with that radius. This can be viewed as simulating the radial distribution of the illumination by an extremely large number of beamlets. We will study later some effects of the residual angular asymmetries of 32 beamlets.

This target gives a 1D gain of $G = 160$ at 1.8 MJ of input (beam) energy with 2.6 mm spot radius. The drive pulse is illustrated in Fig. 1. We would like to point out that this type

of drive pulse can be generated in the final parts of the induction accelerator for heavy ion fusion as part of the process of compressing the pulse in length to reach peak power. In Ref. 5 for example, we show that such a pulse shape could be obtained by using a longitudinal velocity tilt consisting of three continuous linear pieces with different slopes. (Here the "tilt" is in the longitudinal momentum space of the beam pulse and refers to the fact that the beam tail is made to move more rapidly and thus catch up with the beam head so as to achieve peak power.)

The residual asymmetries we consider here arise from the use of a beam placement scheme¹ with axial symmetry about some direction z determined for example for the convenience of fusion chamber design (see Fig. 2).

Fig. 2 Geometry used in deriving the results given in Eq. (2). The angle γ_n is measured between the axis of beamlet n and an arbitrary point on the target (r, θ, ϕ) .

The beamlet incident directions (θ_j, ϕ_{jk}) all lie in several cones about the z -axis with cone angles θ_j determined by the Legendre-Gaussian quadrature points $x_j = \cos \theta_j$, $j = 1, 2, \dots, L_0$; and the azimuthal angles $\phi_{jk} = 2\pi k/M_j$, $k = 1, 2, \dots, M_j$. Here the constant L_0 determines the number of θ_j angles, and M_j are number of ϕ_{jk} angles for each j . The total number of beamlets is $N_0 = \sum M_j$. If the n -th beamlet is at (θ_j, ϕ_{jk}) , we assume that its deposition

profile in a spherical target is

$$E_n(r, \theta, \phi, t) = \sum_{j=1}^{M_j} \sum_{l=0}^{\infty} E_l(r, t) P_l(\cos \gamma_n) \quad (1)$$

where the angle γ_n is as illustrated in Fig. 2, $P_l(x)$ is a Legendre polynomial and w_j is the Legendre-Gauss quadrature weight corresponding to the quadrature point x_j . The result of summing E_n over all beamlets (over j, k) is 1

$$E(r, \theta, \phi, t) = A_{0,0} E_0(r, t) + \sum_{l=2L_0}^{\infty} A_{l,0} E_l(r, t) P_l(\cos \theta) \\ + 2 \sum_{m=0}^{\infty} \sum_{l=m}^{\infty} R_e(A_{l,m} e^{im\phi}) E_l(r, t) P_l^m(\cos \theta) \quad (2)$$

where the coefficients of the Legendre-functions cancel exactly for $m = 0$, $1 \leq l < 2L_0$ as well as for $1 \leq m < M_0$ and $l \geq m$, where $M_0 = \min(M_j)$. The coefficients $A_{l,m}$ of this final sum are determined by the geometry of this beam placement scheme and are given in Ref. 1.

For the 32 beamlet placement illustrated in Fig. 4c of Ref. 1, the largest non vanishing asymmetry term of the sum (2) is $(A_{8,0} E_8)$ while $(A_{0,0} E_0)$ is the spherically symmetric average deposition. In this paper we outline results of our study on the behavior of this coefficient $(A_{8,0} E_8)$, particularly for the target of Fig. 1.

Fig. 3 Residual drive asymmetry is shown as a function of R_{dep} , the radius of peak ion energy deposition in the target. The effect of shift in beam deposition radius versus focal spot radius is noted. Results using a thin deposition layer model (and judicious beam placement) are compared against realistic target simulations.

Firstly, the simple single layer model of Ref. 1 suggests that $(A_{g,0} E_g)$ varies with $(R_{beam} - R_{dep})$ as given by the solid curve of Fig. 3. Numerical results based on our simulations with the target of Fig. 1 give the $(A_{g,0} E_g)$ coefficients as plotted by the circles in Fig. 3. In the single layer model, all information on this coefficient is limited to a point in r -space. But in the target simulations, this coefficient oscillates in radius as indicated in Fig. 4 for a particular time (there are also variations in time). Only the peak value of Fig. 4 is used in Fig. 3. We may point out that the spherically symmetric $(A_{0,0} E_0)$ peaks at zone 45 with gradual decay further out but sharp decay inwards. The asymmetry coefficient $(A_{g,0} E_g)$ peaks rather sharply inside of this radius at zone 42. Presumably this is related to the well known fact that in the deposition of a single beamlet, the particles at the edge of that beamlet penetrates less deeply (larger target radius r) than the particles near the center which penetrate to smaller r values. When summed over many beamlets, it is not surprising that this effect could translate into larger asymmetries inside of the radius of peak energy deposition.

Fig. 4 The asymmetry coefficient $A_{g,0} E_g(r,t)$ actually varies in space and time with changes in signs. It is the peak values at each time which is compared with the thin layer model. The average effect could well be smaller.

In order to discuss the residual asymmetries in a direct drive illumination with 32 beamlets, a first impression is that we would have to introduce a 3D ray-trace even to study the 2D asymmetry term $[A_{g,0} E_g(r,t) P_g(\cos\theta)]$. However, from our summary Eqs.

(1) - (2) of the result of Ref. 1, we see firstly that we only need to obtain $E_g(r,t)$ from the effective deposition of one beamlet. This we performed by converting the spherically symmetric 1D problem of Fig. 1 into a 2D problem with zones in the (r,θ) directions. The energy of one single beamlet is then deposited in these zones with the beamlet axis along the axis of symmetry. Particularly for

heavy ion beams, this operation is quite accurately approximated by a 2D ray trace because the rays of a beamlet approach the target approximately as a cylinder due to the beam approaching a neck at the focal spot. Also the rays inside this cylinder are near parallel because of the small divergence angles involved.

We used 100 angular zones in θ per full circle in the target or roughly 10-15 zones per full cycle in $P_B(\cos\theta)$. We also used 1 to 2 $\times 10^4$ ion rays per beamlet so that there are almost 10^3 rays per angular zone. This number of rays is necessitated by the fact that we are firstly looking for an effect that is a factor $1-2 \times 10^{-2}$ the size of the spherically averaged main term. Secondly, the major asymmetries are near the end of the ion range and there are a number of radial zones (per angular zone) where these rays finally stop.

Although we have not as yet completed full 2D hydrodynamics, we have taken some pains to anticipate part of its effects in target performance. In particular, since the deposition asymmetries are small, the initial shocks are likely to propagate through the target at roughly the timing of the 1D calculations. For the peak power pulse, the spherically averaged effect of this shock is likely to be weakened and travel slower than indicated by 1D calculations because of the multi-dimensional implosion asymmetry. Thus we have timed the final pulse of Fig. 1 so that a weaker final shock gives even better target performance in 1D. We plan to perform 2D simulations to obtain our best estimate target performance.

In addition, we have not yet evaluated the full effects of random beam displacements from the intended axes. However, steps could be taken to make the target relatively insensitive to beam displacements. For example the requirements on beam-positioning accuracy might be reduced by a beam transverse profile which is rather flat in the middle. At present, we chose a parabolic transverse beam profile due to existence of an analytical model of asymmetries versus $(R_{\text{beam}} - R_{\text{dep}})$. Maintaining a flatter transverse beam profile is desirable for beam transport in the driver as well as in fusion chambers. We at LLNL have also participated in showing⁶ that the transverse profile can be modified as part of the final focus process.

In summary, we have shown that the beam deposition asymmetries in a spherical target can be kept to rather small levels by (i) judicious choice of beamlet placement and/or current; (ii) choice of the ratio of tamber inertia to ablator inertia (to slow down the rate of change of R_{dep} , the radius of peak ion energy deposition in target).

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