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Diagnosing ablator burn through in ignition capsules using $D_2+{}^3He$ gas filled surrogates

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If x-radiation penetrates the ablator of an ignition capsule too deeply or too little, ignition can fail. Typically an ablator areal density of $\sim 0.2\ g/cm^2$ remains at ignition time. 20% more or less flux in the final pulse of radiation driving the capsule can change that areal density by $\sim 0.1\ g/cm^2$ and halve the capsule yield. We propose a technique to measure ablator areal density in a surrogate capsule that would complement Cu activation [D. C. Wilson *et al.*, Phys. Plasmas **5**, 1953 (1998)]. Replace the DT ice layer by deuterium and ^3He gas. Diagnose the number and spectra of $D-{}^3He$ protons escaping the surrogate capsule with wedge range filters. For a $0.02\ g/cm^3$ gas fill and the optimal radiation drive, $1.2e+11$ protons escape with energies above 3 MeV and a peak at 5 MeV. If ignition would fail due to ablator burn through, $1.7e+11$ protons would escape but the peak moves to 11 MeV. If ignition would fail from too much ablator remaining, $3.2e+9$ protons escape the surrogate and the peak moves near 3 MeV. The D+D neutron yield remains roughly constant over this range. Wedge range filters would be able to diagnose these proton yields and peaks above ~ 4 MeV with a resolution of ~ 0.3 MeV. © *2006 American Institute of Physics.*
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I. INTRODUCTION

An inertial confinement fusion (ICF) ignition capsule may fail due to the over or under ablation of its outer shell. Uncertainty in the detailed time and spectral dependence of the *Hohlraum* radiation field, energy loss to laser backscatter, inadequate knowledge of spectral opacity, or even the thickness of the ablator can leave less or more than the expected ablator as payload, changing the implosion enough to cause the capsule to fail to ignite. Rather than measure the amount of material ablated from the outer shell, we propose to measure the areal density (ρr) of the few percent of the shell material that remains compressed near the end of the implosion in a surrogate capsule.

We propose using the $D-{}^3He$ proton and D–D neutrons created in a surrogate to measure the shell ρr, extending the previous work using the downshift of the 14.7 MeV protons to measure ρr of ICF capsules.[1,2] However, a ρr of $0.4\ g/cm^2$ will completely range out the protons.[1] A cryogenic layered ignition capsule must achieve a ρr of $\sim 1\ g/cm^2$ to ignite, and an ablator areal density of $\sim 0.2\ g/cm^2$ remains at ignition time. Thus we must use a surrogate capsule where the fuel ρr is as small as possible, letting ablator ρr slow down the protons. To keep the laser plasma interactions and the *Hohlraum* radiation hydrodynamics identical our surrogate capsule has the same ablator shell as the ignition capsule, but the cryogenic layered DT is replaced by a mixture of $1/3\ D_2$ and $2/3\ {}^3He$ gas. By choosing a gas density of $0.02\ g/cm^3$ we obtain a fuel ρr of $0.1\ g/cm^2$ and an ablator ρr varying from 0.1 to $0.3\ g/cm^2$. To obtain such a high deuterium density, the *Hohlraum* must be operated above the deuterium critical temperature of 38.4 K, where deuterium will not condense at any pressure. This will double the pressure in the gas filled *Hohlraum*, requiring a thicker laser entrance hole window.

For this study we have chosen the current NIF ignition design[3] using a beryllium ablator with radii of 838 and 1000 μm and a layer of DT to 743 μm. Copper is doped into the beryllium with concentrations varying from 0 to 0.7 at. %. The radiation drives on the capsule and surrogate are identical, as would be the *Hohlraum* plasma conditions. Since this capsule does contain copper, the ablator ρr could be diagnosed sampling copper neutron activation in the debris[4] in an ignition capsule itself. The proton range technique could be used to measure ρr in a surrogate capsule with any ablator.

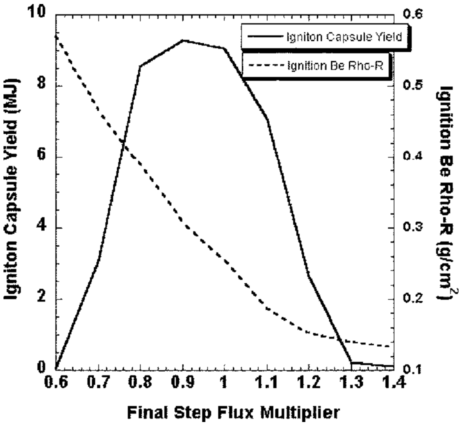

FIG. 1. Ignition capsule yield and ablator ρr variation with final drive flux.

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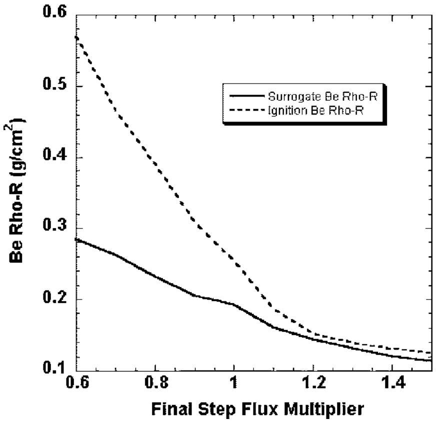

FIG. 2. Surrogate and ignition capsule ablator ρr variation with final drive flux.

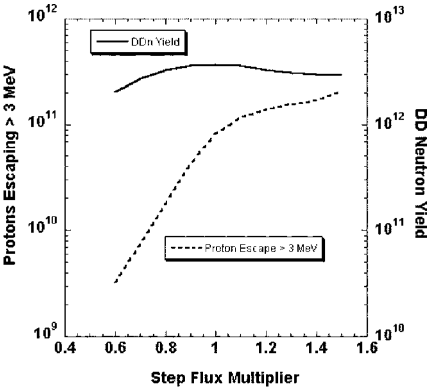

FIG. 4. Protons and neutrons escaping the surrogate capsule as final drive flux is varied.

II. THE SURROGATE CAPSULE

To model the effects of ablating too much or too little mass, we have modified the flux in the fourth and final radiation pulse driving both the ignition and surrogate capsules. Figure 1 shows the effects on yield and on ablator ρr remaining at peak burn rate. Too little or too much ablator ρr can cause failure. Figure 2 compares the ablator ρr in the surrogate capsule at peak yield rate to that in the ignition capsule. Near nominal drive and with more flux the ablator ρr is close to the ignition capsule ρr. At lower drives the ignition capsule has substantially more ablator ρr. This is caused by different convergences in the two capsules. With our choice of 0.02 g/cm^3 gas density the convergence ratio of the surrogate capsule is only 10, while the ignition capsule converges a factor of 22 before igniting. At this low convergence the surrogate is much less sensitive to hydrodynamic instability growth and drive asymmetry.

To diagnose burn through of the ablator, or low ablator ρr, the energy of the peak in the proton spectrum and yield will be measured. Figure 3 shows how that peak moves from 5 to 11 MeV as the yield decreases. Wedge range filters,[5] as in current experiments on the Omega laser but redesigned for NIF should be able to measure that peak between 4 and 14.7 MeV with an accuracy of ~0.3 MeV. This would lead to a relative uncertainty of ~0.004 g/cm^2 when comparing the ablator ρr in surrogate capsules. Below ~4 MeV the protons are being strongly attenuated by the ablator, and below 3 MeV the spectrum would be dominated by D+D protons. This absorption allows us to continue to diagnose excess ablator by quantifying the extent of the attenuation. Figure 4 shows the proton yields escaping above 3 MeV, as well as the neutrons produced, all of which escape. The ratio formed from the measured neutron yield and the escaping proton yield greater than 3 MeV is sensitive to the excess ablator ρr, as shown in Fig. 5. The ratio of proton to neutron production is a measure of the ion burn temperature, which must be corrected or adjusted in the surrogate calculation to obtain the measured neutron Doppler broadening temperature. A surrogate capsule could be adjusted to contain less gas and converge more if it were modeling a smaller ignition capsule, as is likely during the first year or so of NIF operation.

Because of the replacement of the ignition capsule's DT ice layer with $D_2 + {}^3He$ gas, the two capsules do not perform identically. The radial history of the ablator fuel interface is nearly identical up to burn in both capsules. The peak velocities at the fuel/ablator interface differ by 4%. The ablator ρr history of the surrogate leads the ignition capsule by ~100 ps and the final yield precedes the ignition capsule by ~50 ps. The radial histories also diverge in the final ~200 ps before burn when the surrogate ablator begins to decelerate. The higher adiabat of the surrogate fuel causes the capsule to converge a factor of 2 less. If the ablator ρr is affected by instability growth during the convergence from

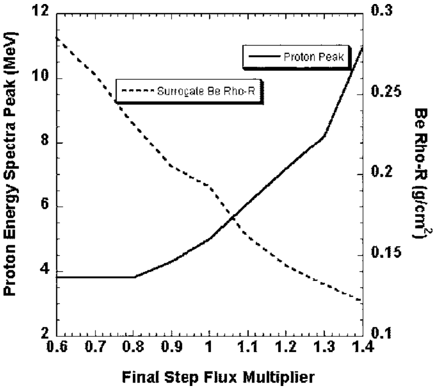

FIG. 3. Energy of the proton spectral peak and surrogate ablator ρr as the final drive flux is varied.

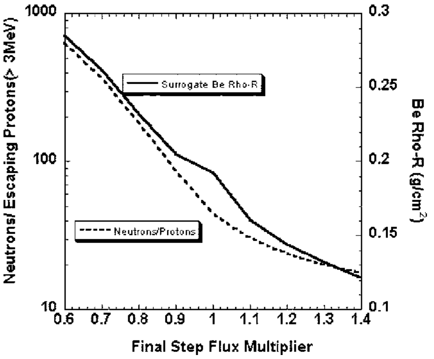

FIG. 5. Ratio of escaping protons to neutrons and ablator ρr as final drive flux is varied.

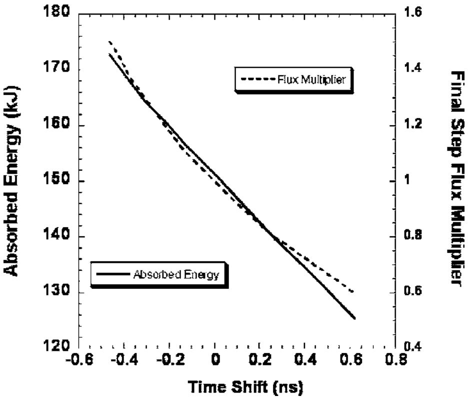

FIG. 6. Change in implosion time with final flux multiplier or equivalently the energy absorbed by the capsule.

10 to 22, the surrogate capsule may not show this effect. Furthermore the explosion at burn, which causes further instability growth, does not occur in the surrogate. For these reasons a measure of the neutron activation of the copper in a uniformly doped beryllium target would be a better measure of the ablator ρr remaining at ignition. With the nonuniform radial distribution of copper in a graded dopant ablator the measure would be more difficult to interpret.

However, the energy absorbed by each of the ablator layers in the surrogate and ignition capsule follow each other within a few percent until ignition. The implosion time, or time of peak yield rate, of the surrogate capsule can be used to diagnose the absorbed energy. Figure 6 shows how the absorbed energy is linearly proportional to implosion time with a slope of ~40 kJ/ns. A ±50 ps accuracy in measured implosion time would yield a ±2 kJ uncertainty in the absorbed energy if only the radiation flux changed. Unknown capsule variations would lead to more uncertainty. If the capsule contained 10% more gas, the peak yield rate would be 10 ps later and the absorbed energy 0.2 kJ higher. If the ablator were 2 μm thicker the implosion would be 40 ps later, and the absorbed energy increased by 1.5 kJ. If there were 0.05% copper in the specified pure outer beryllium, the implosion would be 40 ps later and absorb 6 kJ more. The first two uncertainties might lead to an overall ±3 kJ uncertainty, but lack of knowledge of the ablator composition would compromise the measurement.

III. COMPARISON WITH EXPERIMENTS

If this diagnostic technique is to be used we must be able to calculate the peak in the spectrum of protons escaping the capsule and the ratio of proton to neutron yield. To test our current ability we have modeled two directly driven implosions at the Omega laser, shots 37 642 and 37 995, with 880 μm diameter and 20.3 μm thick plastic shells filled with 6 atm D_2 and 12 atm ^{3}He gases. The calculated neutron yields using the Scannapieco and Cheng[6] mix model are within 30% of observed, but the ratio of proton to neutron yield is calculated a factor of 2 too low. Figure 7 shows the good agreement between the calculated and observed proton spectra. For this calculation both the stopping powers of Li and Petrasso[7] and the Brown *et al.*[8] were used to calculate the spectra. There was no difference. The mix modeling also changed the spectra little. However, Amendt[9] reports that the agreement between calculated and observed spectra is not as good with germanium doped plastic capsules in *Hohlraums*.

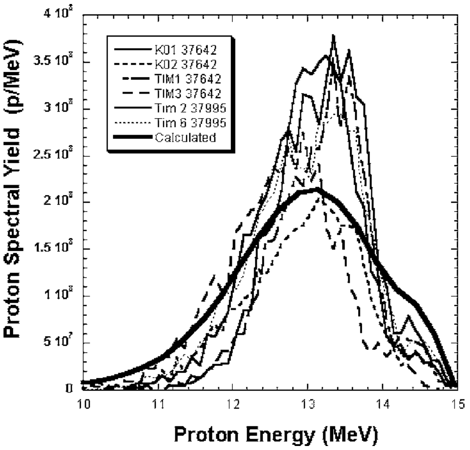

FIG. 7. Comparison of proton spectra measured for shots 37642 and 37995 with calculated.

IV. DISCUSSIONS

A surrogate capsule with D_2 and ^{3}He gases instead of a cryogenic layer of DT can diagnose improper ablation that would occur in the outer shell of an ignition capsule. By measuring the location of the peak in the escaping proton spectrum, burn through of the ablator is diagnosed in a 1 MJ ignition capsule. The ratio of D–D neutrons to protons escaping with energy greater than 3 MeV can diagnose when too much ablator remains. The implosion time of the surrogate capsule also diagnoses the absorbed energy which could be used to test capsule and *Hohlraum* energetics. The effects of 2D implosion asymmetries seen in direct[10] and indirect drive[9] experiments need to be explored. The ignition capsule with its higher convergence will respond more strongly to asymmetry. Furthermore the relationship between surrogate ρr and ignition ablator ρr as well as the concept's utility need to be explored under a variety of *Hohlraum* conditions. The viability of this proposed technique should be tested in experiments on the Omega laser.

ACKNOWLEDGMENTS

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