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Compensation for Time-Dependent Radiation-Drive Asymmetries in Inertial-Fusion Capsules

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An approach is presented to design inertial-fusion capsules compensated for time-dependent radiation-drive asymmetries. This approach uses in depth variable doping of the capsule ablator, i.e., the addition of small amounts of material to tailor the opacity. Simulations show that an inertial-fusion capsule, using a beryllium ablator variably doped with gold, can be designed to compensate for a constant P_2 radiation asymmetry as high as 20% and still produce nominal yield (80% of a symmetrically driven capsule). In contrast, without variable doping the P_2 asymmetry must be less than 2% to obtain nominal yield. Similarly encouraging results are obtained for modes P_1, P_4, and P_6. Simulations also demonstrate that variable doping can compensate for nearly arbitrary time-dependent radiation-drive asymmetries by varying the polar dependence of the doping fraction with depth.

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Inertial confinement fusion (ICF) is a promising approach to generating net energy from fusion [1]. In this approach the fusion fuel is compressed and heated by the implosion of a capsule driven by heating the outer surface. The achievement of ignition [2] requires compressing a portion of the fuel to create a ‘‘hot spot’’ with a minimum areal density of about 0.3 $\mathrm{g/cm^2}$ and temperature about 10 keV. In addition, a shell of cold dense fuel needs to be assembled around this hot spot to obtain high gain. The energy required to achieve these conditions decreases with the convergence ratio of the implosion (initial outer radius of the fuel divided by the radius of the hot spot). The physically achievable convergence ratio depends on the symmetry of the source which drives the implosion. Present designs for the National Ignition Facility (NIF) [2], which have convergence ratios exceeding 30, cannot tolerate asymmetries exceeding a few percent in the ablation pressure driving the capsule over a significant portion of the implosion. The baseline NIF ignition design uses indirect-drive where an energy source (laser, ion beam, z pinch) is converted into a nearly thermal spectrum of x-rays with peak radiation temperatures >200 eV. These x-rays are partially contained within a cavity (hohlraum) where the absorption and reemission of x rays from the walls of this hohlraum contribute toward symmetrizing the radiation field, which drives the capsule contained within. The ratio of the hohlraum wall radius over the radius of the capsule strongly affects the degree of radiation smoothing. Increasing this ratio improves the symmetry, but at the cost of decreasing the efficiency of delivering energy to the capsule. Precisely phased and located multiple energy sources, distributed ion beam deposition, and radiation shields are techniques used to improve the radiation symmetry [3–6], but it is still difficult to obtain adequate radiation symmetry and high efficiency at the same time. Thus it is desirable to have techniques that allow ICF capsules to implode symmetrically despite drive asymmetries.

Some attempts have been made toward this end [7], by adding a variable thickness layer, ‘‘shim’’, of high-Z material on the outside of the capsule. This shim is designed to be thicker (thinner) where the radiation temperature is expected to be higher (lower) than average. This work demonstrated that exterior shims can decrease the effect of asymmetries early in the pulse, but cannot remove asymmetries in the drive that are time dependent, e.g., a drive that starts pole hot and finishes equator hot. Furthermore, shims introduce a nonspherical component to the capsule, and thus the implosion cannot be purely spherical. Any nonspherical implosion develops nonradial flow, which is difficult to remove by any subsequent adjustment to the symmetry of the drive pressure. Ultimately it is the development of nonradial flow, which limits the magnitude of the asymmetry that can be compensated for with shimming or the use of nonspherical capsules.

In this Letter we describe a new approach to designing ICF capsules, which are compensated for radiation-drive asymmetries. The essence of the idea is to add small quantities of material (dopant) to the ablator to adjust the opacity to maintain constant ablation pressure even though the radiation intensity varies over the capsule surface. More dopant is added in regions of the capsule where the radiation temperature is higher than average and less where the temperature is lower. The angular variation of the dopant on the outermost surface of the capsule can be designed for the asymmetries early in the pulse with possibly different angular variations of the dopant being required at different depths corresponding to the radiation asymmetries that exist when the ablation front is at that depth within the ablator material. In this manner time-dependent radiation asymmetries can be mitigated. We show this approach can compensate for constant radiation asymmetries as large as 20%. It can also compensate for large time-dependent asymmetries. We present calculations for an indirectly driven capsule using a beryllium ablator, but the concept can be generalized to other ablators, e.g., CH, diamond, etc. Even capsules driven directly by lasers might benefit from this approach.

The simplest approach is to add one dopant, e.g., gold, to an ablator material such as beryllium. Gold is chosen because it is soluble in beryllium and has high opacity per unit mass. A series of LASNEX [8] simulations at several fixed radiation temperatures, T_0, were performed to determine the ablation pressure, P_{abl}, as a function of gold dopant fraction, f_{Au}, in a beryllium ablator. The drop in ablation, δP_{abl}, with increasing gold fraction can be thought of as an effective drop in the drive temperature, δT_{rad}, or intensity, I, determined using the relation, $P_{\mathrm{abl}}\ \alpha\ T_{\mathrm{rad}}{}^{3.5}\ \alpha\ I^{7/8}$. Curves relating $\delta I/I$ to f_{Au}, for the fixed ablation pressure of a pure beryllium ablator driven at T_0, are plotted in Fig. 1. The curves are the results of fit to the Lasnex results given by the expression

$$f_{\mathrm{Au}} = A(T_0)(\delta I/I) + B(T_0)(\delta I/I)^{4.45}, \qquad (1)$$

where T_0 is in units of 100 eV (heV), $A(T_0) = 0.0104T_0^{-2} - 0.00966T_0^{-1.6} + 0.00194$, and $B(T_0) = 10^{-8}(4.13T_0^{-7} + 1.62T_0^{-3} + 0.287)$. Only a few curves are plotted to maintain clarity, but this expression fits the Lasnex results very well over the radiation temperature range 0.8–2.4 heV.

The ablation pressure is generated at the depth within the ablator where the heating is maximal, the ablation front. We used a 1D simulation of the capsule implosion to locate the ablation front as a function of time. Then, given a particular radiation asymmetry as a function of time, the dopant fraction is determined as a function of polar angle for each layer by using Eq. (1) and the asymmetry at that time, which we express in terms of Legendre polynomials. The odd mode symmetries (P_1, P_3, etc.) are usually fairly small, whereas the even mode symmetry (P_2, P_4, etc.) can be substantial due to entrance holes, etc.

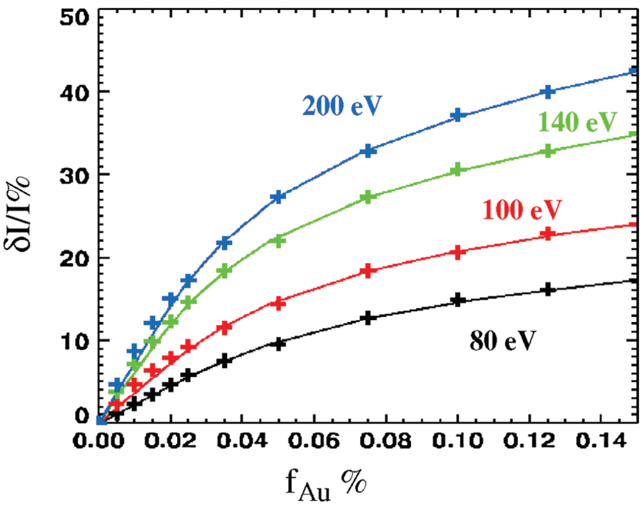

FIG. 1 (color). Radiation-drive intensity variations plotted as a function of gold dopant fraction for constant ablation pressure corresponding to the ablation temperature of pure beryllium at the labeled radiation temperature, T_0.

We chose the baseline capsule for the double-ended z-pinch driven hohlraum [5] as a starting point to study the effectiveness of the doping technique to mitigate P_1, P_2, P_4, and P_6 radiation asymmetries. According to Lasnex simulations [5] this capsule should yield approximately 520 MJ when driven by a pulse shaped radiation field rising to a peak temperature of 225 eV. The beryllium ablator is doped with 0.2% Cu to reduce preheat of the DT. We modified this design by first replacing the 0.2% Cu dopant with a nominal gold dopant, $f_{g0} = 0.035\%$, since this gold fraction corresponds to a $\delta I/I$ roughly in the middle of the range for the curves of Fig. 1, thus allowing the gold dopant to be reduced (or increased) to compensate for radiation intensities below (or above) the average. Because of the higher opacity of the gold dopant the drive temperature was increased by 4% and the ablator thickness was increased by 10%; thus, our modified capsule had an outer radius of 0.265 cm, a DT ice layer with an outer radius of 0.244 cm, and a DT gas center with an outer radius of 0.216 cm. Lasnex simulations with these modifications indicate a yield of 500 MJ with an energy margin at ignition of about 25%, quite similar to the original design.

Lasnex simulations were then performed with single mode asymmetries constant in time. Contour plots of the fuel density at ignition are shown in Fig. 2. In this figure the axis of symmetry is vertical and different simulations are shown on the left and right halves. Note that all of the simulations shown in this figure produced a nominal yield ($>80\%$ of symmetrically driven capsule). The radiation drive for the simulations in Fig. 2(a) has a $P_2 = 1.9\%$. The simulation on the left had a nominal fixed gold doping fraction of f_{g0}, while the simulation on the right had variable angular doping to compensate for the P_2 radiation asymmetry. The effectiveness of the variable doping is quite striking. Note that without the angular doping the capsule fails to produce significant yield at $P_2 = 2.0\%$ due to a jet of cold fuel at the pole which quenches the hot spot. Figure 2(b) shows two simulations with an applied P_6 radiation asymmetry of 0.49%. The simulation on the left had fixed gold fraction, f_{g0}, while the simulation on the right had variable doping. Again the difference is quite striking. Figure 2(c) shows the effect of further increases in the magnitude of the applied P_2, $P_2 = 6\%$ for the simulation of the left side and $P_2 = 12\%$ for the simulation on the right. The contour on the left exhibits a small P_4 distortion, while the P_4 distortion of the fuel contour on the right is quite pronounced even though only a P_2 asymmetry is applied to the radiation drive. This is probably due to inaccuracies of our angular doping algorithm and subsequent mode coupling due to the nonlinearity of the radiation-hydrodynamic response. Additional P_4 corrections were performed in the simulations shown in Fig. 2(d). The left contour has applied $P_2 = 12\%$, with essentially no indication of a P_4 distortion [compare with Fig. 2(c)]; however, some P_6 is evident. The simulation on

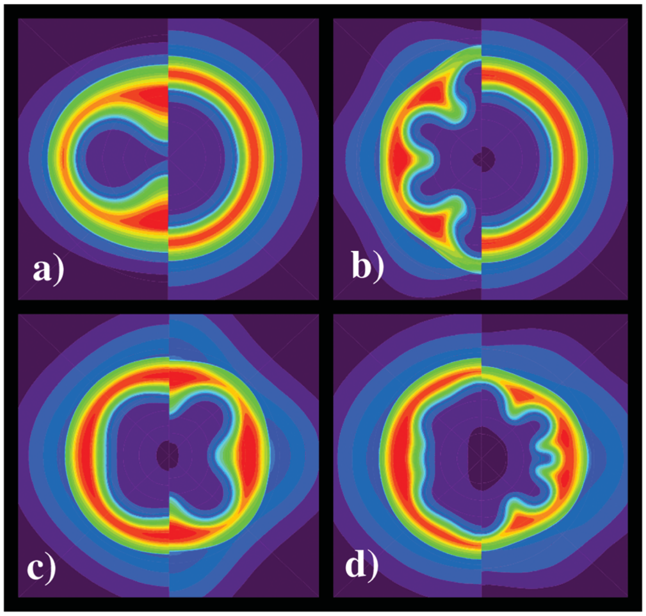

FIG. 2 (color). Density contours from Lasnex simulations at the time of ignition; (a) radiation-drive P_2 asymmetry of 1.9% without (left half) and with (right half) variable doping; (b) $P_6 = 0.49\%$ without (left half) and with (right half) variable doping; (c) two simulations with doping, $P_2 = 6\%$ (left) and $P_2 = 12\%$ (right); (d) $P_2 = 12\%$ (left) and $P_2 = 20\%$ (right) both simulations are doped to correct for P_2 with additional P_4 corrections.

the right side of Fig. 2(d) had an applied $P_2 = 20\%$ with both P_2 and P_4 terms in the doping algorithm. Although the contours show a marked P_6 distortion in the fuel density, this capsule attained nominal yield. It is likely that capsules can be designed for even larger applied P_2 asymmetry by including higher order corrections, P_6 etc. We leave this for future work since we have already obtained a capsule design that produces nominal yield with a P_2 asymmetry 10 times larger than can be tolerated for capsules without angular doping.

Similarly good results were obtained for all the modes that we studied. Without variable doping, our simulations indicated that the capsules produce a nominal yield with radiation asymmetry magnitudes (positive or negative) of $P_1 = 1.2\%$, $P_2 = 2.0\%$, $P_4 = 1.5\%$, or $P_6 = 0.48\%$. Capsules were designed using variable doping that produced nominal yields with $P_1 = 18.5\%$, $P_2 = 20.0\%$, $P_4 = 10.5\%$, or $P_6 = 8.5\%$, corresponding to a 15, 20, 7, and 17-fold improvement for each mode, respectively.

An example of a variable doping profile ($P_4 = 5.0\%$) is shown in Fig. 3. The curves are the gold fractions as a function of polar angle at different labeled radii within the ablator. Notice that, although the asymmetry is constant in time, the profiles change continuously with radius within the ablator, since the relationship between dopant fraction and intensity variation depends on the radiation temperature, see Fig. 1.

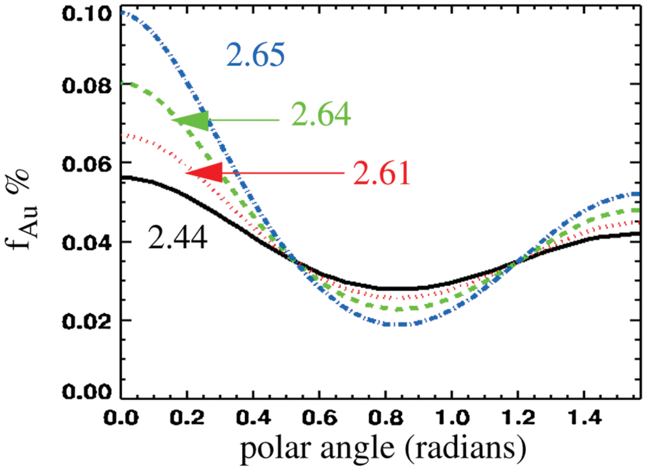

FIG. 3 (color). Gold fractions are plotted as a function of polar angle at several radii within the ablator. The capsule was designed to compensate for a $P_4 = 5.0\%$.

We designed four capsules for the radiation asymmetries: $P_1 = 13\%$, $P_2 = 12\%$, $P_4 = 5.0\%$, and $P_6 = 4.0\%$. We then determined the variation in applied radiation asymmetry that could be tolerated and still give nominal yield. We found that the variation for each mode was approximately the same as the variation that can be tolerated by a capsule without variable doping, but centered about the designed asymmetry. Specifically, these capsules can tolerate asymmetries of $P_1 = 13\% \pm 1.0\%$, $P_2 = 12\% \pm 1.6\%$, $P_4 = 5\% \pm 1.45\%$, and $P_6 = 4\% \pm 0.46\%$, respectively. This indicates that the radiation asymmetry must be measured with an accuracy that is independent of whether variable doping is used or not, but the value of the asymmetry can be much larger when variable doping is used. Second, we determined the variation in the dopant level that could be tolerated and achieve nominal yield for fixed radiation asymmetries by either increasing or decreasing the gold dopant fraction from the nominal design by a fixed factor throughout the ablator. We found that the variation was ±17%, ±27%, ±35%, and ±24%, for modes P_1, P_2, P_4, and P_6, respectively. Clearly other types of fabrication errors could occur, but these results indicate that the fabrication tolerances should not preclude variable doping as a practical means of countering radiation asymmetries.

We considered two specific examples of time-dependent asymmetries. First, a constant positive P_2 asymmetry for the first half of the radiation flux absorbed by the capsule and a negative P_2 of the same magnitude for the second half of the drive. The capsule with no variable doping gives nominal yield with $|P_2| < 5.7\%$, while the variably doped capsule can accept $|P_2| < 17.5\%$. Second, a radiation asymmetry that starts with $P_2 = -P_{2x}$ at the beginning of the radiation pulse and rises linearly to $P_2 = +P_{2x}$ at the time of ignition. A capsule without variable doping gives a nominal yield for $P_{2x} < 2.3\%$, while the variably doped capsule can accept $P_{2x} < 17\%$. These two examples demonstrate that variable doping can be used to counter rather large time-dependent asymmetries. It should be possible to counter even larger time-dependent asymmetries by improving the doping algorithm. In particular, we have assumed that the radiation asymmetry at a given time can be mapped to one layer within the ablator, but the radiation that reaches the ablation front is also affected by the opacity of the ablated plasma outside of the ablation front.

The symmetry of the radiation field on a capsule improves with increasing case to capsule radius, but at the expense of reduced efficiency. Similarly, capsules doped for drive asymmetries require a slightly increased drive temperature. We have not yet attempted to include both of these effects to obtain an integrated optimization. Our intent presently is just to prove the principle, but we plan to perform such optimizations for z-pinch driven capsules.

Since implosion asymmetries can couple to short wavelength perturbations making a capsule more susceptible to the Rayleigh-Taylor (RT) instability, variable doping may improve capsule robustness against RT instability. However, it is also possible that the variation in ablator density with a single dopant could couple to short wavelength perturbations. We plan to study these issues in future work and we note here that if a problem is uncovered, two dopants such as copper and gold could be used to eliminate the density variations with polar angle. These materials are soluble in beryllium up to 1% atomic, without significantly distorting the lattice [9]. Thus the density of the mixture is $\rho = n_{\text{lattice}}[(1 - f_{\text{Cu}} - f_{\text{Au}})M_{\text{Be}} + f_{\text{Cu}}M_{\text{Cu}} + f_{\text{Au}}M_{\text{Au}}]$, where n_{lattice} is the lattice number density, $(f_{\text{Cu}}, M_{\text{Cu}})$, and $(f_{\text{Au}}, M_{\text{au}})$ are the (atomic fraction, mass) of copper and gold atoms, respectively. Constant density is obtained by satisfying the relation $f_{\text{Au}} = (M_{\text{Cu}} - M_{\text{Be}}) \times (f_{\text{Cu0}} - f_{\text{Cu}})/(M_{\text{Au}} - M_{\text{Be}}) = 0.29(f_{\text{Cu0}} - f_{\text{Cu}})$, where f_{Cu0} is a fiducial maximum copper fraction corresponding to a density $\rho = 1.848(1 + 6.05 f_{\text{Cu0}})$. Since the opacity per unit mass increases with atomic number, the opacity increases with f_{Au} for a fixed f_{Cu0}. Note that we want the density to have no angular variation to keep the implosions symmetric, but it may be useful for stability reasons [10] to allow f_{Cu0} and hence the density to be a function of depth (radius) within the ablator. We have previously reported capsule designs using gold and copper dopants that can accept large asymmetries [11].

Variable doping might also be useful for laser direct drive capsules, where laser energy is deposited in the plasma blow-off and, subsequently, transported inward through electron thermal transport. The addition of high-z materials can decrease electron transport coefficient and thus the ablation pressure in a manner similar to radiation driven capsules.

In conclusion, we have demonstrated a technique to variably dope the ablators of ICF capsules to compensate for radiation-drive asymmetries. The essence of the technique is to use one or more dopants to modify the opacity to maintain constant ablation pressure even though the radiation intensity varies over the capsule surface. We have shown that this technique can be used to design capsules that can accept both constant and time-dependent drive asymmetries much larger than can be accepted without this technique.

The construction of variably doped capsules will require the modification of existing fabrication techniques. Typically spherical mandrels are coated with the desired materials and the mandrel is then removed. The specific orientation required for variably doped capsules precludes bounce coating, but could be attained by mounting the mandrels on stalks and then using masks to obtain sphericity and the desired polar variation of the dopant.

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