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THE STATUS OF THE ICF TARGET PHYSICS PROGRAM AT LAWRENCE LIVERMORE NATIONAL LABORATORY*

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Calculations of x-ray driven igniting implosions require several critical parameters which have been separately tested on Nova, viz., acceptable levels of SBS and SRS from plasmas equivalent to the plasmas in igniting hohlraums, quantitative understanding of radiation temperature in gas-filled hohlraums, demonstration of control of drive symmetry in gas-filled hohlraums, low levels of seeding of hydrodynamic instabilities from surfaces, especially cryogenic deuterium tritium ice, and quantitative understanding of the mix of cold fuel into a hot spot in high growth factor implosions.

1 Introduction

The proposed National Ignition Facility (NIF) has three principal missions: (1) nuclear weapons physics and effects; (2) to demonstrate ignition and thermonuclear gain by both x-ray driven and directly driven implosions; and (3) to act as a facility for high energy density science technology and other applications. Two dimensional calculations[a] have set the specifications for the NIF at 1.8 MJ at 0.35 μm in a highly shaped pulse peaking at 500 TW. There are several aspects of these calculations which need to be tested by experiments and a program of experiments[b] is continuing to demonstrate that most of the critical parameters of these calculations can be achieved in the laboratory. Their success has led to an increased confidence of ignition on the NIF.

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2 The Levels of SRS and SBS from Large Scale Plasmas

The non-linear theory of SBS and SRS cannot be accurately described in a large plasma. Consequently, we have taken the approach of producing a plasma which corresponds to the plasma in NIF hohlraums as closely as possible in the most important of the parameters corresponding to the NIF.[c] For NIF hohlraums, there are two rings of laser beams[a]. The inner beams propagate through a long region of low Z plasma and this plasma is well represented by the plasma formed by heating gas-filled (CH_4 and C_3H_8) thin plastic shells by nine, 0.53 µm heater beams. On Nova, only one of the 10 beams is fully diagnosed for measuring the backscattered light and transmitted light and this beam is used as an interaction beam at 0.35 µm at f/8 to mock up the range of intensities of the beams in NIF hohlraums. For the range of intensities of the NIF 0.5 - 2 10^{15} W/cm^2 at 10% n_c, the levels of SRS reflectivity are 2-7%. Adding 1.5 - 2.5 Å of bandwidth reduces the level of SRS slightly, although it changes the character by spectrally narrowing the backscattered light indicating that the level of filamentation is reduced. At 10% n_c, the level of SBS reflectivity is ~ 4%, with 1.5 - 2.5 Å of SSD and ~ 6% without SSD. However, the levels of SRS and SBS clearly anti-correlated with density. SBS falls with increasing density whereas SRS rises with increasing density. This is qualitatively accounted for by models in which the amplitude of SRS driven Langmuir waves are limited by secondary decay into ion acoustic waves.[d]

The plasma that the outer beams of the NIF encounters are similar to the plasma in a gas-filled 2.5 mm x 1.6 mm Nova hohlraum. Without SSD f/8 beams show 15-20% levels of SBS, a substantially higher level than for an f/4 beam because of the smaller propensity for filamentation. However, 1.5 Å or 3Å of SSD reduces the peak SBS reflectivity of the target to 2-6%.

3 Radiation Temperatures in Hohlraums

A simple power model for radiation temperature (T_R) in hohlraums balances radiation production ηP_L against wall - $(1-\alpha)\, A_{wall}\, \sigma T_R^4$, and hole - $A_{LEH}\, \sigma T_R^4$, losses[e]. A plots of T_R vs P_L/A_{wall} shows a simple scaling from 110 eV up to 300 eV for 1 ns square laser pulses and the 2.2 ns 3:1 shaped pulse (ps 22 ref 4) once P_L is reduced by a fraction to account for the laser up to the time of peak T_R[f].

For the time history of a shaped laser pulse, detailed two dimensional modeling is necessary. Default LASNEX predicts the temperature at the peak of a shaped pulse, but gives a temperature which is too low, probably due to the average atom opacity model being too low, by a factor of a few compared to more accurate models at low temperatures.

In gas-filled hohlraums (one atmosphere of CH_4 or C_3H_8) there is a reduction in T_R of 20 eV and 26 eV, respectively, compared to a vacuum hohlraum. Drive is reduced because more energy is in the gas and because the levels of SBS and SRS are higher compared to vacuum hohlraums for these unsmoothed laser beams. In modeling, these two effects account for 12-17 eV and 18-21 eV, reduction in T_R c.f. vacuum hohlraum for CH_4 and C_3H_8 gas-filled hohlraums, close to the observed values.

Although Nova is usually used to produce 1-3 ns laser pulse, it can also be used to produce long time scale radiation drive, by introducing some beams at a later time. Seven 2 nsec, 2 TW pulses on seven of the Nova beams have been staggered in time over 14 nsec to produce a 2 TW drive into a scale 3 hohlraum, producing a radiation temperature up to 85 eV for 14 nsec. A scale 2 hohlraum will probably produce 100 eV for 14 nsec. In another experiment, 4 nsec, 9 TW beams in a scale 1 hohlraum have produced $T_R = 180$ eV with an ablation pressure of 45 Mb for 4 nsec with a spatial uniformity of 6% in pressure over 1 mm.

Radiation losses can be reduced by increasing the x-ray opacity of the wall of a hohlraum. Gold has minima in its x-ray opacity at ~ 0.2 keV, ~ 0.8 keV and 2 keV. By mixing gadolinium with the gold, a material with close to overlapping maxima and minima is formed. Experiments[g] determining the velocity of the Marshak wave show that a 40% Au and 60% Gd "cocktail" produce a wall loss smaller by ~ 25% than pure Au. This would imply that using this "cocktail" for the NIF would provide 100-200 kJ of additional margin.

4 X-Ray Drive Symmetry in Gas-Filled Hohlraums

Ignition implosions require a time-integrated symmetry of x-ray drive to ~ 1% with time swings less than 15%. Nova has only two rings of beam, but reproducible and calculable[h] symmetry control is readily achieved with vacuum hohlraums to give time- integrated symmetry to ± 0.5%.

When a gas-filled hohlraum is used, there is an outwards shift in symmetry of ~ 150 μm[i] corresponding to a beam deflection of ~ 7°. Such a shift is not readily predicted by the hydrodynamics in LASNEX, but using a wave fluid code a beam deflection is predicted when a laser beam ponderomotively filaments in a plasma with a near sonic flow transverse to the beam[j]. One technique for measuring the symmetry in a hohlraum is to observe the emission in thermal x-ray (700 eV) from the inside wall through an observation slot[k]. With unsmoothed beam the emission is shifted slightly towards the laser entrance hole for gas-filled hohlraums compared to vacuum hohlraums. When a RPP smoothed beam is used the small shift is reduced, presumably because filamentation is reduced. An alternative method of measuring symmetry is to observe the shape of imploded capsules and we expect that the observed symmetry offset from LASNEX calculations in gas-filled hohlraums will be eliminated when we put smoothing on all 10 Nova beams.

5 Hydrodynamic Implosion Stability

An igniting implosion must have a hydrodynamic instability growth of ~ 500. Burn will be quenched if growth of perturbations from outer surface finish, inner surface finish, and drive asymmetry[l], adding in quadrature are too large. The inner surface of an igniting target is layered with cryogenic deuterium-tritium. The β decay of tritium naturally causes thicker regions of ice to be hotter and therefore sublime at a greater rate leading to "β layering" that produces an r.m.s. surface roughness of ~ 1 μm in a curved ice layer. This natural "β layering" can be enhanced[m] by applying an r.f. field which heats the free electrons in D-T gas causing enhanced smoothing. Heat fluxes up to 0.6 mW/cm^2 have reduced the r.m.s. surface roughness of cryogenic D-T ice in a 2 mm diameter cylinder from 1 μm to 0.5 μm, allowing more success margin for the NIF.

High growth factor implosions on Nova have recently been calculated with 3D codes[n]. Nova uses five beams either side to implode its capsules. The five-fold asymmetry coupled with imprecision in laser balance and P_1 mode asymmetry in the target calculates to reduce the yield to ~ 30% of clean 1D calculations for high growth implosions. In the near future, the five-fold drive asymmetry will be reduced by elongating in the azimuthal direction the laser spots on the inside of the hohlraum with kinoform phase plates. Furthermore, the four-ring feature of the NIF can be replicated by splitting the spots in two along the axial direction.

6 Conclusion

Many of the critical features of ignition hohlraums have been demonstrated on Nova. Issues remain and will be addressed by future experiments where beam conditioning kinoform phase plates with azimuthal spreading are introduced on all 10 beams of Nova.

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