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ASSESSMENT OF FIRST WALL DAMAGE FROM TARGET X-RAY EMISSION AND SCATTERED LASER LIGHT FOR THE NATIONAL IGNITION FACILITY

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Predictions for NIF ICF target x-ray emission are presented. Validation experiments confirm the key features of the x-ray emissions and their effects on the NIF chamber B_4C first wall. Predictions of a possible first wall 0.35-μm laser irradiation compared to more experimental results conducted to determine B_4C response all suggest B_4C is an acceptable first wall material.

The National Ignition Facility (NIF) will consist of a 1.8 MJ, 0.35 μm laser with 192 independent beamlets, a ~ 50-fold increase in laser energy over the Nova facility located at Lawrence Livermore National Laboratory (LLNL). The main pulse length will be ~ 4-5 ns. Beams are transported into the chamber in 2 × 2 groups and further in cones, of ~ 27° and ~ 53° oriented around each pole of the sphere, supporting the baseline inertial confinement fusion (ICF) indirect drive approach to ignition. The maximum routine yield will be 20 MJ, a ~ 300-fold increase in non-neutron emissions over current Nova experiments. NIF will be designed to eventually conduct as many as fifty 20-MJ shots in one year, in addition to shots of lower yield and no yield. The annual yield will be bounded by 1200 MJ.

Part of the criteria for setting the radius for the NIF chamber is the smallest value that results in acceptable x-ray damage to a first wall for a 20-MJ yield. Acceptable damage is partially defined as, at best, no material being evolved for a 20-MJ shot, or as a minimum, evolving less material from the first wall surface than is introduced by the target itself. Emitted material will deposit on the final optical surface, a fused silica debris shield, and contribute to beam obscuration, posing potentially significant but as yet unquantified maintenance concerns. Elimination or minimization of the first wall contribution may alleviate some of these concerns.

NIF First Wall X-ray and Laser Irradiation Threats

The baseline NIF ICF target we consider is a 1-cm long, 0.6-cm diameter, 0.3-cm laser entrance hole (LEH) and 30-μm thick Au wall. Accurate knowledge of the x-ray emission from NIF targets is critical to our study of first wall response. A series of 1-D LASNEX calculations have been performed that predict the x-ray emissions for yields ranging from 100 kJ to 20 MJ.

The x-ray output of the target is partitioned into two components in the LASNEX runs. First is the radiation 'leak source' that simulates LEH x-ray losses. The other part is the radiation flux on the outside surface of the gold for transmission through and emission by the gold hohlraum wall. Time history plots of each component were examined to determine the time interval for emission of 10% to 90% of the total energy. Shapes of spectral curves for each radiation were fit to blackbody (color) temperatures (BBT) to give one- or two-BBT fits for LEH emission and wall radiation. For calculation of fluences within the chamber, the assumed angular distributions were isotropic emission for wall radiation and

Lambertian distribution (cosine law) for x rays emitted from the LEH. Table 1 shows the results for laser energy on a disk, and yields of 100 kJ and 20 MJ.

Table 1. Predicted NIF ICF target x-ray emissions. Nova equivalent fluences are based on matching B_4C melt depths (or peak surface temperature if no melt occurs).

Yield (MJ)	Laser Energy (MJ)	X-ray Yield (MJ)	BBT (eV)	Pulse 10-90% (ns)	Peak NIF 1st Wall Fluence (J/cm^2)	Nova Equiv. Fluence (J/cm^2)
(disk)	1.50	1.05	200	3	0.66	0.76
0.1	**1.80**	**1.08**			**0.56**	**0.33**
		0.70	255	10	0.44	
		0.23	52	61	0.07	
		0.15	12	61	0.05	
20.0	**1.80**	**4.94**			**2.61**	**1.85**
		2.30	400	13	1.44	
		1.05	207	13	0.66	
		1.38	81	67	0.44	
		0.21	15	67	0.07	

A curve-fitting technique was used to approximate the x-ray output pulses obtained from the 1-D LASNEX simulations. The form of the curve fit is a double exponential, which is well suited to describing the x-ray pulse shapes. The rapid "turn on" of the LEH and wall emissions can be captured, as can the slow decay. The decay in the LEH x rays comes from the gradual hole closure and the cooling of the hohlraum interior. The wall emission decays with its temperature as energy is lost radiatively and as the material expands into the vacuum.

LASNEX is typically used to predict conditions inside the hohlraum in the time before and during the thermonuclear burn. The accuracy of LASNEX predictions of the x-ray emission from the exterior of the hohlraum wall was confirmed with two experiments on the Nova laser facility.[1] The total x-ray emission (including late time) from the thin wall (30 μm) of a gold hohlraum was measured with the Dante diagnostic[2] and compared to a LASNEX simulation. The timing of peak emission, rate of decay of emissions, and effective blackbody spectra agreed well.

NIF will be configured to allow the implementation of direct drive ICF experiments by designing into the facility the ability to create symmetrical target irradiation. This would be done during an extended maintenance period by changing up to half of the beamlet paths from indirect drive irradiation cone angles to near equatorial ports. Direct drive targets are fully illuminated by each beam. As the target implodes, significant amounts of incident laser light can be refracted to the chamber wall, presenting the possibility of unacceptable material removal.

Testing of candidate first wall materials to predicted x-ray fluences was done using x-ray emission from Nova hohlraum targets. Due to differences between the predicted NIF x-ray threat and the x-ray environments available on Nova (~ 220 eV spectrum and 2 ns pulse), an equivalent NIF fluence for Nova irradiation conditions had to be considered in interpreting results. For example, we predict that a Nova fluence of 1.85 J/cm^2 produces the same melt depth in B_4C as the predicted 20-MJ x-ray output shown in Table 1. We believe that the dominant material response is spall of partially melted material so that matching melt depths is appropriate. This experimental approach constitutes an overtest, since the shorter pulse on Nova

induces a greater peak stress in the material. Quantifying the degree of overtest is an area of ongoing investigation and provides a degree of conservatism to our results and conclusions.

Predictions of the laser first wall irradiation using LASNEX were performed by Weber of LLNL. The direct drive target chosen for analysis had a radius of 1.695 mm and was irradiated with a 1.6-MJ continuous laser pulse, with about 200 kJ in a foot pulse of 5.5 ns and the remainder in a 6-ns main pulse. The non-absorbed laser energy fraction becomes a few percent at ~ 7.5 ns resulting in a first wall laser pulse duration of ~ 4 ns. Results suggest that up to 40% of 1.6 MJ incident light can be directed toward the first wall. The peak fluence on the chamber wall is < 0.3 J/cm^2.

First Wall Responses to X-rays and Laser Irradiation

Boron carbide had the least material removed in Nova x-ray exposure experiments, as shown in Figure 1. Most samples show thermal stress cracking, and all materials show surface roughening above about 1.0 J/cm^2. Multple exposures cause additional roughness and the appearance of angular pits in the surface. The pits seem to be locations where small sections of thermally shocked material has been flaked off or popped out by the additional thermal loading. The models for predicting this ablation mechanism, including brittle crack nucleation/growth and statistical methods for the pop-out of isolated flakes, are being developed.

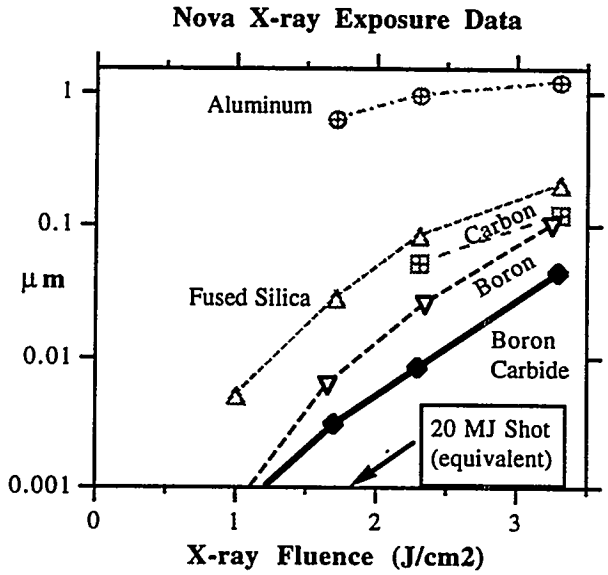

Figure 1. Estimated removal depths as a function of x-ray fluence for Nova experiments.

The small amount of B_4C that is removed by x-rays is likely caused by thermal crazing and spalling of small particulates. The degree of crazing and spalling

depends on the fluence and source of the B_4C. At 1 J/cm^2, corresponding to NIF disk and low-yield ignition shots, no crazing or spalling is present, but there is some evidence of surface melting. At 1.6 J/cm^2, corresponding to a 15 MJ yield, slight crazing appears after one shot on a polished surface, and a few percent of the surface spalls to a depth of about 0.35 μm on subsequent shots. At 2.3 J/cm^2, corresponding to a 30 MJ yield, substantial crazing occurs, and a higher surface covage of 0.5 μm pits are formed by spallation.

For 350-nm light irradiation of 2.4 ns, the threshold for significant B_4C surface melting is between 0.5 and 1 J/cm^2, and higher fluences induce thermal crazing of the surface similar to that observed for x-rays. The fluence damage threshold varies with pulse length. Thermal conduction and two-photon effects predict a $t^{0.5}$ dependence, but observed dependence is weaker. The primary mechanism for material removal at ≤ 1 J/cm^2 appears to be particulate spallation. Most of the spalled particules are < 5 μm. The onset of vaporization is ~ 1.5 J/cm^2, which would result in a thin absorbing film on the final optic and must be avoided for NIF.

Laser light is attenuated exponentially as it is absorbed in material, as long as the intensity is below a threshold for plasma formation at the target surface. The linear absorption coefficient decreases roughly exponentially with wavelength from 31 μm^{-1} to 3.9 μm^{-1} over the range of 350 to 1050 nm. That the observed damage threshold is several times higher for 1.053 μm light than 0.35 μm light is consistent with the smaller absorption coefficient. Results suggest the NIF first wall 3ω fluence is half the spall fluence and 1/4th the incipient vaporization fluence. These results suggest a diffraction grating that distributes unconverted NIF laser light uniformly to the first wall (0.7 J/cm^2 of 1,2, and 3ω), would be a superior solution to the wedged focus lens/absorbing glass first wall solution currently proposed.

Optics that had collected particulate debris from the laser-irradiated samples were subsequently tested for damage threshold at 0.35 μm. The 3ω light tends to clean B_4C particulates from the optic and provide some number of useful high fluence shots before the onset of severe damage. An optic with a clean damage threshold of 15 J/cm^2 that received particulate contamination survived 100 shots at 9 J/cm^2 with no damage and 3–5 shots at 13 J/cm^2 with acceptable damage. The average fluence for a NIF 1.8 MJ shot is ~ 7.5 J/cm^2. A similar optic having a 6-nm thick-film of B_4C formed from vaporization of the B_4C target at 1.5 J/cm^2 of 3ω light had a damage threshold of only 1 J/cm^2, indicating that fluences where B_4C vaporizes must be avoided.

Experimental results of both laser and x-ray irradiation indicate B_4C may be an acceptable first wall material for the 5-m radius NIF chamber.

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