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TARGET AREA DESIGN ISSUES FOR IMPLEMENTING DIRECT DRIVE ON THE NATIONAL IGNITION FACILITY

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ABSTRACT

The National Ignition Facility (NIF) will be configured in its baseline design to achieve ignition and gain using the indirect drive approach. However, the NIF primary criteria and functional requirements require the NIF design "to not preclude" the ability to conduct inertial confinement fusion experiments using the direct drive approach.

The direct drive approach requires symmetrical illumination of an inertial confinement fusion (ICF) capsule where each beam fully subtends the capsule. Therefore, the re-directing of 24 of the 48 NIF beamlines (each consisting of a 2×2 beamlet group) from ~30° and ~50° cone angles to ~75° cone angles located near the chamber 'equator' is required. This would be accomplished by adjusting intermediate transport mirrors such that the beams would intercept different final mirrors in the Target Bay and be directed into final optics assemblies attached to chamber ports positioned at the new port locations. Allowing space to be able to convert from one irradiation scheme to another while fully meeting the mechanical stability requirements for each approach is a significant challenge. Additionally, NIF user needs (features supporting weapons physics, weapons effects, inertial fusion energy, or Basic Energy Sciences) cannot be compromised by direct drive needs.

The target for direct drive, absent a hohlraum, emits much fewer cold x rays than in the indirect drive case. Further, the irradiation scheme, by its nature, may not result in the absorption of all of the 3ω light and therefore could create a unique hazard to the NIF chamber first wall of significant fluences of scattered UV laser light. This paper describes possible design features of the NIF Target Area to allow conversion to a direct drive capability, and discusses some of the differences in post-shot conditions created compared to indirect drive.

I. INTRODUCTION

The NIF will consist of a 1.8-MJ, 0.35-μm laser with 192 independent beamlets. This represents an approximately 50-fold increase in laser energy and ~15-fold increase in power 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 groups of 4 (2×2) and further in four cones, with two cones of ~27° and ~53° oriented around each pole of the sphere. Target experiments will be positioned from a horizontally-placed target inserter in a 5-m radius, 10-cm thick Al sphere. Diagnostics, mostly based in diagnostic manipulators, are mainly positioned around the mid-plane of the chamber.

Research at the University of Rochester Laboratory for Laser Energetics, LLNL, and elsewhere suggests ignition and gain for direct drive may be possible at laser energies at or below that projected for the NIF.[1] Although considered possibly higher risk due to the potential for Raleigh–Taylor instabilities disrupting capsule performance, the scientific benefits of being able to explore direct drive physics on the NIF are compelling and led to the decision to include the possibility of conducting such experiments.

To achieve direct drive, 24 of the 48 2×2 beamlines must be re-directed to near the mid-plane of the chamber. This is accomplished by placing additional turning mirrors in the Target Bay for selected beamlines that are utilized only when switching from one mode to another. Increased laser bandwidth is achieved by adjustments in the Master Oscillator Room. This may require an additional KDP crystal be inserted into the conversion array, causing a redesign of the conversion scheme. The kino-form phase plate used for indirect drive is replaced by a different diffractive grating that achieves the required 2-D random phase distribution in the beam. Twenty-four final optics assemblies are either re-positioned from their indirect drive

locations or added to the new direct drive locations. Laser light absorbers that absorb unconverted light on the chamber interior wall are moved, or new ones are added to manage the unconverted light emitted from the 'new' direct drive ports.

Differences in the post shot environment from indirect drive include: the absence of cold x rays, more severe first surface ion heating from target debris, a greater quantity of unburned tritium to evacuate per shot, a rapidly extracted target shroud, and a ~0.3 J/cm^2 fluence of 3ω (0.35 μm) laser light on the first wall. The effects of these differences are discussed.

II. BEAM REQUIREMENTS FOR DIRECT DRIVE

Primary criteria and functional requirements for direct drive implementation on the NIF have been proposed.[1] The laser pulse energy is 1.5 MJ, peak power is 450 TW, with a non-uniformity on target of 1%. Main pulse laser bandwidth is 1–2 THz, beamlet spot size at chamber center is 1–4 mm, and maximum pulse duration is 30 ns. Speckle smoothness in the main pulse is 2% and would be accomplished by implementing 2-D SSD (smoothing by spectral dispersion).

III. MECHANICAL LAYOUT DIFFERENCES FROM INDIRECT DRIVE

In order to transport the 24 beamlines from entering as for indirect drive to entering near the 'waist' of the chamber for direct drive, eight of the beams require the addition of three transport mirrors. The net difference in beam path increases from 7.9 m to 22 m. This has impacts on the front end of the laser, the pockels cells, and harmonic conversion systems. Table 1 below describes the specific beamline cone angle changes of indirect drive beams to direct drive beams that would be required to support direct drive on NIF.[2]

Table 1. Cone angles for Indirect Drive and Direct Drive Operations on NIF

Cone	# Ports	Indirect Drive	Direct Drive
1	4	23.5°	23.5°
2	4	30°	
3	8	46.5°	46.5°
4	8	50°	
5	12		74.85°

It is possible to redirect each of the 24 2 × 2 bundles from indirect to direct drive by horizontally translating one mirror in the target bay. All existing transport mirrors

assemblies are used to transport the beams and each 74.85° direct drive beam will require an additional set of transport mirrors for a total of 96 additional mirrors. This layout is shown in Fig. 1. Interferences with the NIF baseline diagnostics placement have been resolved, as has the repositioning of the vacuum system from the target chamber waist to the chamber pedestal. Floor 'cut-outs' allow space for installing final optics assemblies (FOA) for direct drive.

The current indirect drive solution to managing unconverted light is to use fused-silica-covered standard absorbing glass mounted on the interior chamber wall, as on Nova. The direct drive implementation would require re-positioning of the 24 'beam dumps' that have had their beams moved. Due to the larger spot size required for direct drive, 2–4 mm compared to 0.5 mm for indirect drive, the intensity modulations on the beam may be as high as 6:1 or more rather than the 3:1 expected for indirect drive, at the 'beam dump' location.[1] This may raise concerns about the survivability of the absorbers, which may be exposed to peak intensities $\geq$ 30 J/cm^2 in 2–3 μm spots that cover a few percent of the area of the fused silica cover.

IV. FIELDING CRYOGENIC DIRECT DRIVE TARGETS

Direct drive targets will contain up to 15 Ci of tritium per target. The total allowed inventory of tritium in the NIF is $\leq$ 500 Ci. Of this, 75 Ci has been allocated to targets sitting in target storage awaiting final fuel layering and insertion into the target chamber. Therefore, five direct drive targets can be in the NIF at one time.[3] Placing the target inserter/positioner in the vertical position, like Omega Upgrade, presents unique challenges for the NIF design due to limited access to this area. The target shroud positioner will likely need to be positioned opposed to the target positioner and may present further interferences. Therefore, the intent is to place the inserter in the horizontal position or integrate it with the elevator/lift assembly at the bottom of the NIF chamber. Techniques used to implement cryogenic direct drive on Omega will likely be adapted as is possible for NIF.

V. DIRECT DRIVE TARGET EMISSIONS

The direct and indirect drive targets for the NIF have substantial differences in emissions and consequently produce different effects. The NIF indirect drive target has been described in detail elsewhere.[4] It consists of a He/H gas-filled cylindrical gold hohlraum surrounding a fuel capsule with a doped plastic or beryllium ablator. The direct drive target is a spherical shell of DT fuel with a thin plastic ablator.[5]

The emission of x rays, neutrons, and debris by ICF targets play an important role in the design of the target chamber for NIF. The direct and indirect drive targets release rather different emissions. The calculated emissions are summarized in Table 2. Two variants of each target type were considered. The direct drive target is either pure DT or coated with a thin plastic shell. The plastic-coated version is of course more credible from a target fabrication and survival point of view; the pure DT case is presented only for comparison. Two indirect drive targets are also considered; one that just barely ignited and one with significant yield. The indirect drive targets are physically identical, but the lasers were not properly aligned inside the hohlraum in the 'barely ignited' target scenario. These calculations were performed by Peterson at Los Alamos National Laboratory (LANL) using the LASNEX computer code.

Table 2. ICF Direct- and Indirect Drive-Emitted Target Energy Balance Comparison

	Direct Drive		Indirect Drive	
Energy (MJ)	Pure DT	CH-Coated	Just Ignited	Large Yield
Laser	1.26	1.27	1.31	1.33
Fusion Yield	38.6	39.7	0.11	9.4
Neutron	32.4	33.1	0.08	7.1
X rays	0.4	0.4	0.45	2.0
Debris	7.04	7.44	0.89	1.63
Total	39.8	41.0	1.42	10.73

The two direct drive targets performed in a very similar way. The direct drive x rays, only 1% of the yield, were in both cases a 1.8-keV blackbody spectrum. The direct drive yield was 19% debris energy with the remainder made up of neutrons. The low fraction of energy in x rays is due to the fact most of the target is fully ionized at the end of the burn, so Bremsstrahlung is the dominant radiative emission process.

The indirect drive targets have a much larger fraction of their energy in x rays because the debris energy coming out of the capsule is converted into x rays by the collision between the capsule debris and the hohlraum case. The indirect drive x-ray spectra are much cooler than the direct drive spectra because the stagnation region between the capsule and case is much cooler than the DT core during burn. A major difference between x rays emitted by direct and indirect NIF targets is the angular dependence. Direct drive x rays are isotropic. Indirect drive x rays, when viewing the target facing the laser entrance hole, are much more intense and have a harder spectrum than when

viewing the hohlraum wall. Calculations of NIF target x-ray and debris emission with the BUCKY 1-D code that describe this difference in detail are presented elsewhere.[6]

VI. FIRST WALL LASER LIGHT IRRADIATION

Direct drive targets are fully subtended by the laser beam. As the target implodes, significant amounts of incident laser light can be refracted to the chamber wall (since the beam retains a fixed cross section), presenting the possibility of unacceptable material removal due to laser interaction with the wall. Predictions of the laser first wall irradiation using LASNEX were performed by Weber of LLNL.[7] 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 calculation consisted of modeling a hemisphere of the target and irradiating it with half of the 1.6 MJ of energy. Each beam was modeled as 50 individual rays uniformly distributed across the beam with each ray having equal energy, as shown in Fig. 2. As the capsule was compressed, LASNEX calculated the new power and angle of each ray as a function of the angle of incidence. The calculation used 50 equal bins to establish the angular distribution of the refracted rays over π radians (180°). The peak fluence on the far wall for a single beamlet is ~0.04 J/cm^2 at about 20° from a 0° angle of incidence. Integrating over the entire first wall for all 192 beams indicates the first wall laser fluence ranges from 0.18 to 0.25 J/cm^2. We have set 0.3 J/cm^2 as the bounding first wall UV laser irradiation threat.

VII. RESPONSE OF CHAMBER SURFACES TO DIRECT DRIVE TARGET EMISSIONS

The vaporization and melting of the NIF target chamber first wall has been calculated with the BUCKY code.[8] Target x rays and debris parameters from the BUCKY calculations presented in reference (6) are used as inputs for these calculations. Two sets of 1-D BUCKY calculations predict the x-ray and debris emissions for indirect drive in two directions: out through the hohlraum case, labeled the Case Spectrum, and out through the laser entrance hole, labeled the Oblique Spectrum. This case includes the effects of capsule plasma stagnation against the case wall. There were three materials considered: B, Al_2O_3, and SiO_2. Direct and indirect drive spectra were both considered. The NIF material response, as well as high-energy tritium ion deposition in the chamber walls, is discussed in more detail elsewhere.[9]

In these calculations, the BUCKY code deposits the x-ray and debris energy in the material and then uses the local energy density to determine whether the material is vaporized or melted. Both forms of energy are deposited in a time-dependent manner, which competes with the conduction of heat away from the surface. This results in a steep temperature profile in the target chamber material. The material that is above the melting temperature is assumed melted. The heat of fusion is ignored. Material is evaporated from the surface of the material at a rate determined by the surface temperature and the lattice separation energy. The results are summarized in Table 3.

No melting or vaporization was seen for B or Al_2O_3 from the x rays from the case or the oblique radiation from a 20-MJ indirect drive target. The response of SiO_2 to this radiation and debris has not been studied. A parametric study of the response of B and Al_2O_3 as a function of target yield has been performed. The results are given in Table 3. B experiences no vaporization or melting for either x-ray spectrum up to a target yield of at least 45 MJ, considered the maximum credible yield for NIF. Al_2O_3 is not damaged at either 100-kJ or 20-MJ yields for either spectrum, but is slightly melted at a 45-MJ yield. Therefore, these calculations show that B is a marginally better first wall coating material from the point of view of x-ray vaporization by indirect drive NIF targets.

The debris spectra from indirect drive targets is not well characterized, but some information has been reported.[10] Damage from indirect drive debris is very likely less severe than for direct drive targets for two reasons: the duration of the debris pulse that results from hohlraum disassembly is ~1 μs, a long time compared to thermal conduction times, and the amount of energy in debris for equal yields is ~2.5 times more for direct drive.

The target debris from direct drive targets can damage in-chamber materials. The target x-ray fluence is much lower than the debris fluence, and the x-ray spectrum is hard enough that the deposition length is long in the chamber materials so the specific energy in the material is relatively low. Therefore, as it is appropriate to neglect the effects of x rays, the melting and vaporization caused by the debris from a 40-MJ plastic-coated direct drive target has been calculated with BUCKY, using the debris spectrum discussed above. The results are summarized in Table 4. Here, B is clearly superior to Al_2O_3. Also the debris shield, which is made of SiO_2, will be damaged by this direct drive target yield.

Table 3. Wall Damage from Indirect Drive Target X rays

	B			Al_2O_3		
Target Yield (MJ)	0.1	20	45	0.1	20	45
CASE SPECTRUM						
X-ray Fluence (J/cm²)	0.28	0.91	1.68	0.28	0.91	1.68
Debris Fluence (J/cm²)	0.29	0.94	1.75	0.29	0.94	1.75
Vaporized Mass (mg/cm²)	0	0	0	0	0	0.01
Vaporized Thickness (μm)	0	0	0	0	0	.025
Melted Mass (mg/cm²)	0	0	0	0	0	0.1
Melted Thickness (μm)	0	0	0	0	0	0.25
OBLIQUE SPECTRUM						
X-ray Fluence (J/cm2)	0.26	.83	1.55	0.26	0.83	1.55
Debris Fluence (J/cm2)	0.32	1.02	1.89	0.32	1.02	1.89
Vaporized Mass (mg/cm²)	0	0	0	0	0	0
Vaporized Thickness (μm)	0	0	0	0	0	0
Melted Mass (mg/cm²)	0	0	0	0	0	.051
Melted Thickness (μm)	0	0	0	0	0	0.13

Table 4. Predicted First Wall Damage by 40-MJ Direct Drive Target Debris

	B	Al_2O_3	SiO_2
Vaporized Mass (mg/cm²)	0	.0035	0.079
Vaporized Thickness (μm)	0	0.009	0.35
Melted Mass (mg/cm²)	0	0.29	0.12
Melted Thickness (μm)	0	0.75	0.55

VIII. EFFECTS OF FIRST WALL LASER IRRADIATION

Experiments have been conducted to examine the response of B_4C to laser light irradiation.[11] For 350-nm laser light irradiation of 2.4 ns, the threshold for significant B_4C surface melting is between 0.5 and

1 J/cm^2. Higher fluences appear to induce thermal crazing of the surface in a pattern similar to that observed for x rays. The damage fluence 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 particles are < 5 μm. The onset of vaporization is ~1.5 J/cm^2. This is expected to result in a thin absorbing film on the NIF final optics and must therefore be avoided.

Laser light is attenuated exponentially as it is absorbed in the 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 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 predicted NIF first wall 3ω fluence for the direct drive scenario is half the spall fluence and one-fourth the 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, in that the fused silica 'beam dump' cover, which undergoes vaporization and damage at yields below 20 MJ, would no longer be needed. Such a grating appears feasible to develop.[13]

CONCLUSIONS

The NIF will be designed to 'not preclude' implementing direct drive ICF. The required re-positioning of beams would be accomplished by engaging pre-emplaced added transport mirrors in the target area bay. The increased beam path difference is compensated by modifications to the laser front end. The final optics assemblies would be modified through removal and rebuilding of the Integrated Optics Modules to incorporate the frequency conversion and smoothing by spectral dispersion required by direct drive. Unconverted light management for direct drive is accomplished by unconverted light absorbers moved to the required new locations, or implementation of a grating that disperses the unconverted light. Development of absorbers that can withstand higher frequency modulation may be necessary.

Direct drive targets contain five times more tritium than indirect drive targets presenting constraints on their use compared to indirect drive due to NIF tritium inventory and throughput limits. X-ray emissions from direct drive targets appear to be far less damaging than for indirect drive and do not present a threat to the NIF first wall. The debris emissions, on the other hand, at the maximum 20-MJ yield, appear to cause damage to fused silica beam dumps and possibly debris shields and is an area that would require further investigation. The first wall laser irradiation possible from direct drive shots can be withstood by B$_4$C at the 5-m chamber radius.

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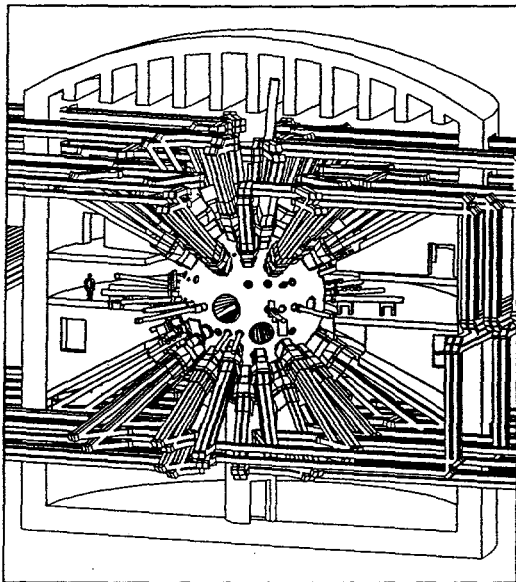
Laser target
indirect drive
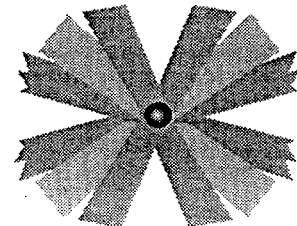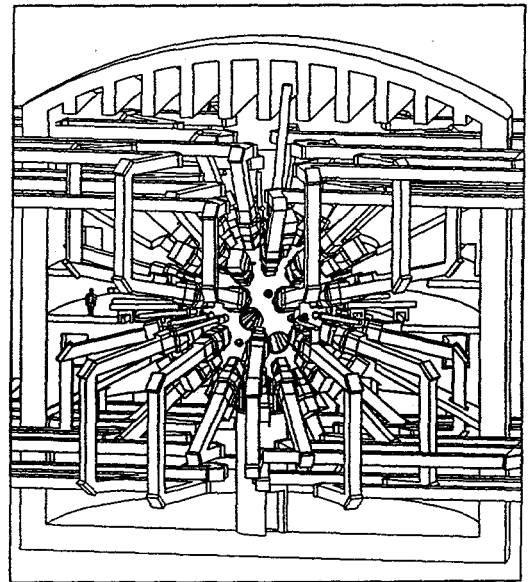
Laser target
direct drive

Fig. 1. The NIF indirect-drive system is designed to accommodate direct drive through the use of additional transport mirrors (96 in all) to redirect 24 four-beam clusters to the chamber 'waist'.

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TOBIN/ DIRECT DRIVE (p.7)

Peak wall loading is <0.3 J/cm^2

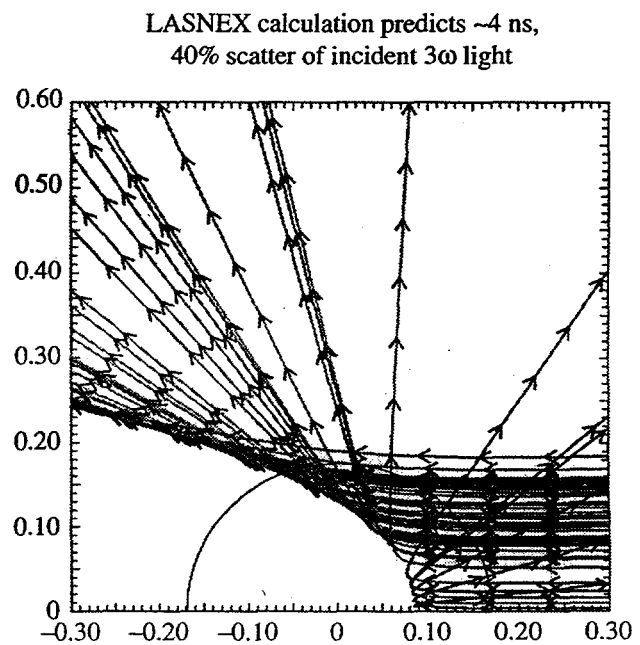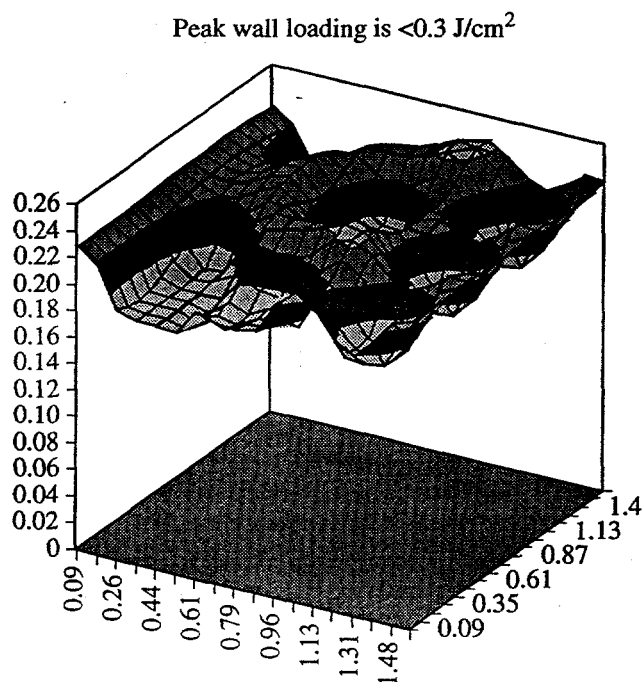LASNEX calculation predicts ~4 ns,
40% scatter of incident 3ω light

Fig. 2. NIF, operating in a direct-drive mode, will create a laser irradiation threat to the first wall. The capsule implosion for fixed beam spot size results in a significant 3ω fluence on first wall due to plasma interactions and a shrinking target.

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TOBIN/DIRECT DRIVE (p.8)