Optimization of Beam Angles for the National Ignition Facility

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Introduction

The National Ignition Facility (NIF), now being built at Lawrence Livermore National Laboratory, is a 1.8-MJ Nd-glass laser with 192 beamlets. The beamlets are grouped into 48 quads of 4 beamlets each. The spherical target chamber has 72 ports arranged in ten rings at latitudes 23.5°, 30°, 44.5°, 50°, 77.5°, 102.5°, 130°, 135.5°, 150° and 156.5°, with 4, 4, 8, 8, 12, 12, 8, 8, 4, and 4 ports, respectively, per ring evenly spaced azimuthally within each ring. The locations of the NIF ports have been chosen to optimize flexibility and performance so that three different drive options are possible—direct drive and two types of indirect drive. This article describes the rationale for choosing the final NIF beam angles to maximize flexibility regarding the three different drive options.

Inertial confinement fusion (ICF) has two main approaches: indirect drive[1] and direct drive.[2] In both cases, a thin, spherical, hollow shell (capsule) containing deuterium–tritium (DT) fuel is subjected to intense radiation, causing the shell to implode. The implosion compresses the fuel and brings it to a density and temperature at which a runaway nuclear fusion reaction occurs. In direct drive, a laser is used to directly irradiate the capsule. In indirect drive, the laser is directed into a hohlraum containing the capsule, generating secondary x rays that irradiate the capsule. In both approaches, the outer layers of the irradiated capsule are ablated, causing high pressures that compress the DT fuel, and raising the density and temperature to the point at which a nuclear fusion reaction occurs.

For significant burn to occur, it is important that the shell remain spherical up to the point of ignition, requiring, in turn, a very uniform radiation flux on the shell. The capsule must be compressed by a factor of 30 to 40 (Ref. 3), which requires a drive asymmetry of less than roughly 1%.

Drive asymmetry can be expressed as a sum of spherical harmonics:

$$f(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi) \ , \tag{1a}$$

where $Y_{lm}(\theta,\varphi)$ are the spherical harmonics,

$$\iint Y_{lm}(\theta,\varphi) Y_{l'm'}(\theta,\varphi) \sin(\theta) d\theta d\varphi = \delta_{ll'} \delta_{mm'} \ , \tag{1b}$$

l ranges from zero to infinity, and m ranges from $-l$ to $+l$. If the flux asymmetry is azimuthally symmetric, then $a_{lm} = 0$ for $m \neq 0$, and it becomes convenient to expand the asymmetry as a sum of Legendre polynomials:

$$f(\theta,\varphi) = \sum_{l} a_l P_l(\cos\theta) \ , \tag{2a}$$

where

$$\int_{-1}^{1} P_m(x) P_n(x) dx = \frac{\delta_{mn}}{n + \frac{1}{2}} \ . \tag{2b}$$

The NIF will allow for two indirect-drive options: cylindrical indirect drive and tetrahedral indirect drive. In cylindrical indirect-drive geometry, the hohlraum has the shape of a cylinder, with the laser entrance holes (LEHs) at the ends of the cylinder, and the laser beams are arranged in rings on the hohlraum wall. In the NIF, 48 quads of 4 beamlets each will be pointed to illuminate the hohlraum wall in two rings per side, an inner ring on the waist plane at 90° and an outer ring at about 50° from the hohlraum axis, as shown in Figure 1. Because of the approximate azimuthal symmetry and left/right symmetry, the capsule flux asymmetry has components consisting primarily of the even Legendre polynomials. As the hohlraum walls move inward, the location of the rings on the walls changes. The second Legendre polynomial P_2 of the capsule flux asymmetry can be eliminated in a time-varying way by varying the relative power between the inner and outer rings. The fourth moment P_4 can be averaged to zero by choosing a suitable hohlraum length. Higher moments are small because of the smoothing effect of x-ray transport between the walls and the capsule.[4]

Tetrahedral indirect drive, which uses a hohlraum that is spherical instead of cylindrical, is a new form of indirect drive.[5,6] Instead of two LEHs, four LEHs are arranged in a tetrahedral configuration. Figure 2 shows a tetrahedral hohlraum with some of its beams. This configuration leads to greater radiation losses, but there are some symmetry advantages. Instead of distinct rings on the hohlraum wall, the beams are scattered all over the hohlraum wall. In all formulations considered to date, an identical pattern of beams goes through each of the four holes, and it is this requirement that has impacted the selection of the NIF beam angles.

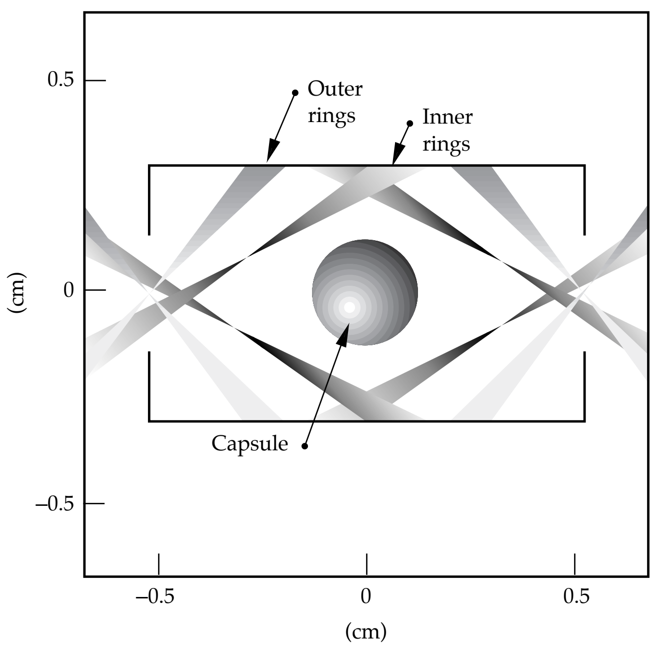

FIGURE 1. Cylindrical hohlraum, showing the inner and outer rings of beams and the capsule at the center. (50-04-0197-0162pb01)

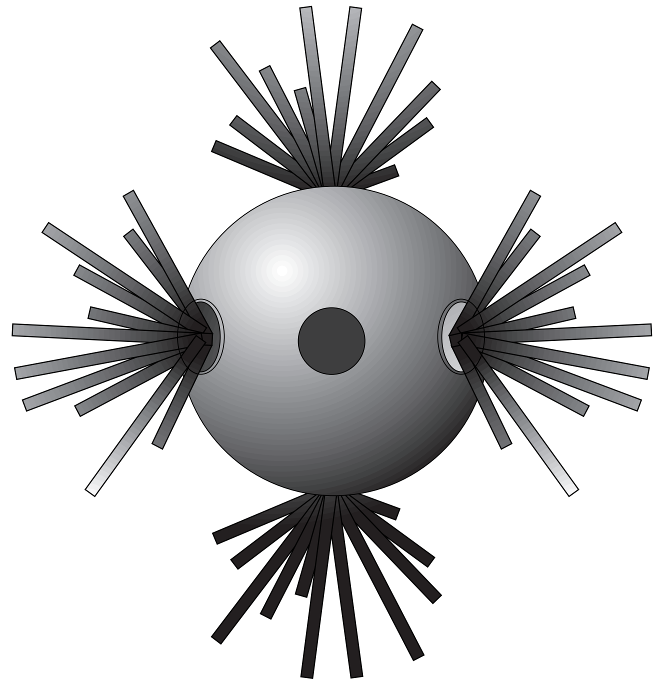

FIGURE 2. A tetrahedral hohlraum with eleven beams going through each laser entrance hole. (The hohlraum shown would be about 8 mm in diameter.) (50-04-0197-0163pb01)

Requirements of Cylindrical Indirect Drive

As shown in Figure 1, cylindrical hohlraums on the NIF will be illuminated by a ring of beams on the waist plane at 90°, called the inner rings, and by a ring of beams on each side at about 50°, called the outer rings. The flux asymmetry at the capsule will be mostly P_2 and P_4. The positive P_2 contribution from the outer rings must balance the negative P_2 contribution from the inner rings and the lack of radiation from the LEHs. As the albedo of the hohlraum wall increases, the importance of the lack of radiation from the LEHs increases, which makes P_2 more negative. As time advances, the walls move in, causing the emission of radiation to move out towards the LEHs, which makes P_2 more positive. Thus, the relative power balance between the inner and outer beams must be changed to keep $P_2 = 0$.

The first NIF target designs put the inner and outer beams on two lines of latitude per side on the target chamber at about 33° and 61°. In 1991, these angles were reduced to 26° and 54°. Later, we found it desirable to decrease the maximum angle to 50° to increase clearance through the LEH. As the design of the laser progressed, it was found that there was insufficient room on the target chamber for eight ports in each line of latitude. Thus, the eight ports at 26° were split into two rings of four ports each at 23.5° and 30°, and the eight ports at 50° were split into two rings of four ports each at 46.5° and 50°, with the azimuthal angles of each of the two subrings interleaved and evenly spaced. These angles were selected because they provided the minimum separation necessary for the ports to fit on the target chamber. We have now switched ring 3 from 46.5° to 44.5° to accommodate direct drive and to increase flexibility. Ring 3 can be moved outwards to form a two-ring configuration, or it can be moved inwards to form a three-ring configuration, as shown in Figure 3.

As shown in Table 1, we examined four sets of ring angles in detail. For the sets with ring 3 at 46°, ring 3 was moved in by 300 μm to form a 3-ring configuration, or it was moved out by 341 μm to form a 2-ring configuration. For each of these sets of ring angles, we moved ring 3 and ring 4 in or out together as a unit to assess the robustness of our hohlraum designs.

Figure 4 shows how the calculated yield, expressed in MJ, varied as a function of the outer beam offset. Each 2D calculation was integrated, in the sense that each included laser beam transport, beam deposition and x-ray production, transport of x rays from the hohlraum wall to the capsule, capsule implosion, and thermonuclear burn. The yield of the first set of ring angles, with ring-3 angle at 41.6°, decreases sharply as the

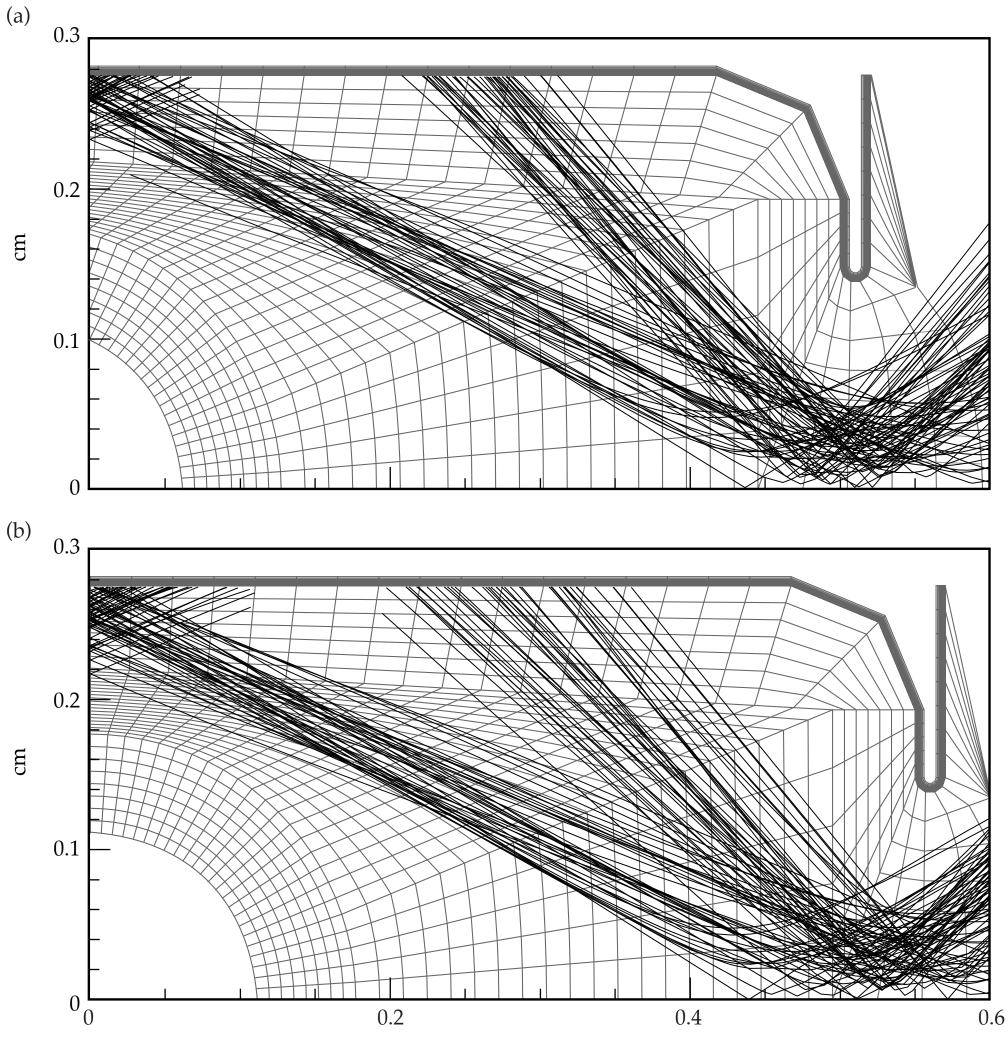

FIGURE 3. Moving ring 3 in or out can give a 2-ring-per-side configuration, or a 3-ring-per-side configuration. (50-00-0598-1164pb01)

TABLE 1. Four sets of ring angles studied, including ring-3 offsets.

Set number	Ring 1 angle (°)	Ring 2 angle (°)	Ring 3 angle (°)	Ring 4 angle (°)	Ring 3 offset (μm)
1	23.5	31.9	41.6	50	0
2	23.5	30	43	50	341
3	23.5	30	43	50	–300
4	23.5	30	46.5	50	0

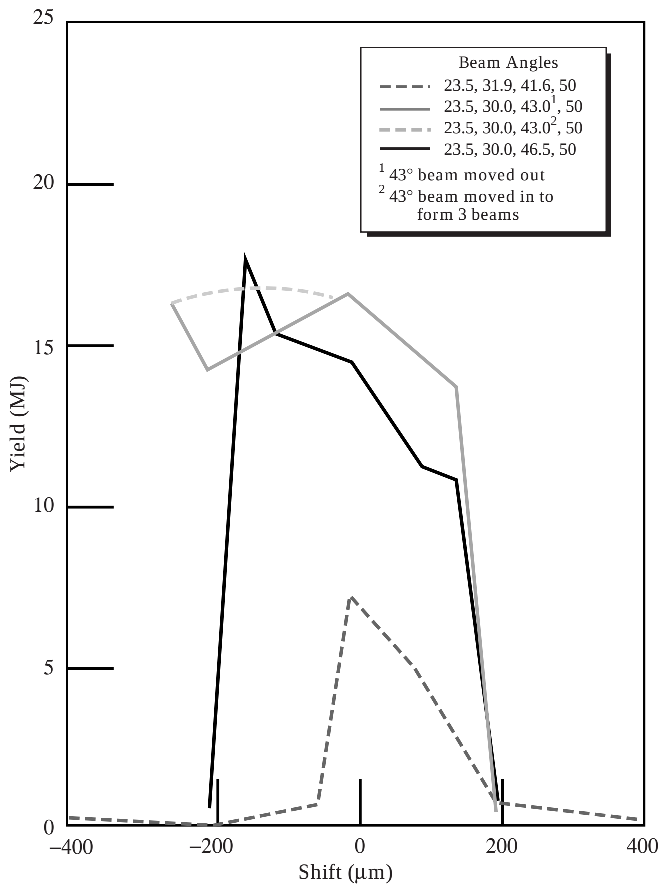

FIGURE 4. The yield vs shift in the outer ring for four different ring configurations. (50-00-0598-1165pb01)

beams are moved in because the beams hit the lip of the LEH. Undoubtedly, the proper offset would expand the range of usable yield. With this caveat, the robustness is relatively insensitive to the ring-3 angle. Because each laser beam is expected to have an rms pointing error of about 50 μm, any ring-3 angle between about 43° and 46.5° would have adequate robustness.

Two considerations drove our choice of the ring-3 angle. The first consideration was to maximize flexibility regarding different configurations. The smaller the ring-3 angle, the greater the distance those beams could be moved in or out before they hit the LEH. This consideration favors a smaller ring-3 angle. The second consideration was to accommodate ring 5 for direct drive. To avoid a ring of diagnostics on the equator, the ring-5 angle must be smaller than about 78°. As explained in the following section, direct-drive considerations imply that the ring-3 angle must then be larger than about 44°. We chose a value of 44.5° as a compromise between the two considerations.

Requirements of Direct Drive

In direct drive, the laser directly illuminates the capsule. Thus, we require that the laser intensity be uniform to about 1%. We expand the capsule flux asymmetry in spherical harmonics as

$$f(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi) \quad . \tag{3}$$

We assume that all beams produce the same azimuthally symmetric, normalized flux intensity $b(\theta)$ on the capsule, with a Legendre decomposition

$$b_l = \int b(\theta) P_l[\cos(\theta)]\, d\cos(\theta) \Big/ \int b(\theta)\, d\cos(\theta) \quad , \tag{4}$$

so that b_l is the reduction of mode l due to the beam pattern compared to a delta function. If w_i is the weight, or relative power, of the ith beam, it follows that[7]

$$a_{lm} = b_l \sum_k w_k Y^*_{lm}(\theta_k, \varphi_k) \quad . \tag{5}$$

On the NIF, the direct-drive option has considered $b(\theta)$ in the form of $b(\theta) = \cos^p(\theta)$, with p between 1 and 3, for which

$$b_l = \frac{\Gamma(p+2)\Gamma(l-p-1)\sin[(l-p)\pi/2]}{2^{l-1}\Gamma[(l+p+3)/2]\Gamma((l-p-1)/2)} \quad , \tag{6}$$

a function that decreases as $l^{-(p+3/2)}$. This smooths out the higher modes, so we must select the placement of beams to minimize the lowest modes. If each beam has equal power, which maximizes the available energy, then we require that

$$\sum_i Y^*_{lm}(\theta_i, \varphi_i)$$

be as small as possible for the lowest few modes. Given the NIF design, the most important mode to eliminate is $Y_{2,0}$, which is proportional to

$$P_2(\theta) = \tfrac{3}{2}\cos^2(\theta) - \tfrac{1}{2} \quad . \qquad (7)$$

With direct drive using four ports at 23.5°, eight ports at θ_3 such that $43° < \theta_3 < 46.5°$, and 12 ports on a fifth ring with θ_5 between 75° and 80°, we require that

$$4P_2(23.5°) + 8P_2(\theta_3) + 12(\theta_5) = 0 \quad . \qquad (8)$$

If we chose the desired value of $\theta_3 = 43°$, then $\theta_5 = 80.1°$, and the ports came too close to the diagnostic ports on the equator at $\theta = 90°$. Thus, we chose $\theta_3 = 44.5°$, with the corresponding selection of $\theta_5 = 77.5°$.

Requirements of Tetrahedral Indirect Drive

Tetrahedral indirect drive is a third option for ignition on the NIF. The hohlraum is spherical, with four LEHs arranged in a tetrahedral configuration. If exact tetrahedral symmetry were maintained, then the capsule flux asymmetry would have no components of modes $l = 1$, 2, or 5, and only one component of $l = 3$ and $l = 4$. Exact tetrahedral symmetry inside the hohlraum requires that the beams come in sets of 12, with three beams going through each of the four LEHs, all at the same angle to the normal of the respective LEHs.[5] To reduce costs, it was determined that the tetrahedral option would only use the ports already selected for cylindrical indirect drive and direct drive. This constraint precludes exact tetrahedral symmetry. We settled for a weaker symmetry in which each LEH has an identical configuration of beams going through it. Although this weaker symmetry brings in components of $l = 1$, 2, and 5, and extra components of $l = 3$ and $l = 4$, the flux at the capsule is still more symmetric than it would be if this weaker symmetry were violated.

The weaker symmetry constrains the azimuthal rotation of each ring of ports. The four LEHs are arranged with two of the LEHs at $\theta = 54.7°$ [$\arccos(\sqrt{1/3})$], $\phi = [0°, 180°]$, and two at $\theta = 125.3°$, $\phi = [90°, 270°]$. The two LEHs at 54.7° see a given ring of ports rotated 180° with respect to each other. Because the number of ports per ring is even, a rotation of 180° represents no change, so the two LEHs see an identical configuration of ports. The same argument holds for the two LEHs at 125.3°. To compare an LEH at 54.7° with an LEH at 125.3°, we transform $(\theta,\phi) \rightarrow (180° - \theta, 90° - \phi)$. Thus, for example, if ring 1 has a port at $\phi = 15°$, ring 10 must have a port at 75°, and so on for each pair of supplementary rings.

Several other constraints exist for the azimuthal rotation of each ring of ports. These constraints can be expressed most easily in terms of klicks, defined as $\{\phi_i\} = (\{0, 1, 2, \ldots, N\} + \text{klick}) \times 360°/N$, where N is the number of ports in a given ring, and klick k satisfies $0 \le k \le 1$. The weak symmetry constraint described in the previous paragraph is equivalent to $k(i) + k(10 - i) = 1$, where $k(i)$ is the klick of the ith ring.

We demand that the four ports of the first ring be evenly interwoven with the four ports of the second ring, so that $|k(1) - k(2)| = 1/2$. Similarly, $|k(3) - k(4)| = 1/2$. When combined with the first constraint, then we automatically also have $|k(7) - k(8)| = |k(9) - k(10)| = 1/2$.

To keep the laser from being damaged, we demand that if a beam should miss the target and reach the opposite side of the target chamber, it will not hit another port, where it would then reenter the amplifier chain. This constraint is optimized if $|k(1) - k(10)| = \{1/4 \text{ or } 3/4\}$, $|k(3) - k(8)| = \{1/4 \text{ or } 3/4\}$, and $|k(5) - k(6)| = 1/2$.

To reduce costs, as many ports on the ring at latitude 50° should lie on the same longitude as ports on the ring at latitude 77.5°. Then these aligned ports allow a beam to be switched between them with a fewer number of mirrors. This requirement is equivalent to $3k(4) - 2k(5)$ = an integer. Once satisfied, the corresponding constraint, $3k(7) - 2k(6)$ = an integer, is automatically satisfied as well. However, this constraint precludes $|k(5) - k(6)| = 1/2$. We relaxed this constraint to $|k(5) - k(6)| > 5/16$, which is adequate for the beams to miss the ports on the opposite side of the target chamber.

These five constraints have 16 possible solutions, as follows:

- $\{k(1), k(2)\} = \{1/8, 5/8\}$ or $\{3/8, 7/8\}$ or $\{5/8, 1/8\}$ or $\{7/8, 3/8\}$.
- $\{k(3), k(4), k(5)\} = \{3/8, 5/8, 5/16\}$ or $\{3/8, 5/8, 13/16\}$ or $\{5/8, 3/8, 3/16\}$ or $\{5/8, 3/8, 11/16\}$.
- $\{k(6), k(7), k(8), k(9), k(10)\} = 1 - \{k(5), k(4), k(3), k(2), k(1)\}$.

It has been difficult to choose among the 16 solutions on the basis of tetrahedral performance alone. The other options, cylindrical indirect drive and direct drive, are not affected by the klicks. By default, the laser designers have chosen the following set of klicks: $k = \{14,6,6,14,13,3,2,10,10,2\}/16$, with the corresponding azimuthal angles of 78.75°, 33.75°, 16.875°, 39.375°, 24.375°, 5.625°, 5.625°, 28.125°, 56.25°, 11.25°.

Beam Switching

When switching from cylindrical indirect drive to direct drive, the 12 beams going through the ports on latitudes 30° and 50° must be switched to the ports on latitude 77.5°. In general, it is important to minimize the change in longitude when switching from one latitude to another. The tetrahedral indirect-drive option can use any combination of 48 ports out of 72, subject to the constraint that one does not pick two ports that are linked by a beam that switches from one port to another. Thus, the choice of which ports to link when switching from direct to indirect drive affects the tetrahedral option. The most important consideration is that the linkages be symmetric with respect to the four tetrahedral LEHs, so that four-hole symmetry can be maintained.

In selecting which of the 72 ports to use for the tetrahedral option, we require that each beam go through its corresponding LEH at an angle greater than 20° so that it does not hit the capsule at the center of the hohlraum, and at an angle less than 60° so that there is more clearance through the LEH and the beam does not skirt too close to the hohlraum wall as it passes through the hohlraum. We also require that the beams not land too close to an exit LEH; otherwise, the exit LEH may close prematurely. These constraints could not be simultaneously satisfied with all 48 beams. Therefore, only 44 beams, with 11 beams per LEH, will be used for the tetrahedral option. Figure 5 shows which ports will be used by the tetrahedral option and how the beams will be switched between ports. The preliminary NIF design had a switching arrangement that precluded the use of four of these 44 beams, but the final design now allows the use of all 44 beams.

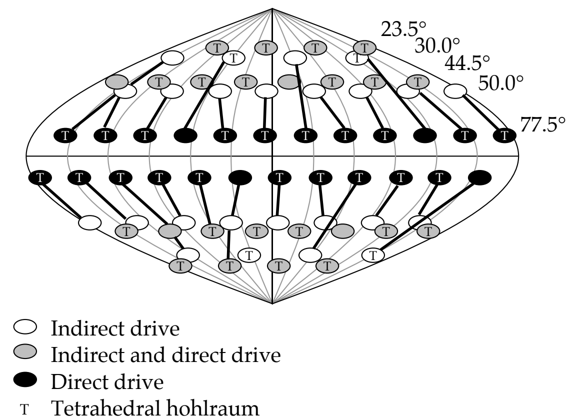

FIGURE 5. Map of beam ports, showing the linkages used in beam switching and which ports are used in the tetrahedral option. If two ports are linked, only one of them can be used for the tetrahedral option. (50-04-0197-0164pb02)

Final Beam Angles

When designing the laser, 24 beams had to be moved about half a degree so there would be room for the beamlines and mirror mounts. These beams are identified in Table 2, which shows the coordinates for the 72 NIF ports. The table also shows which ports are used by each option, and how the ports are switched from direct to indirect drive. For the tetrahedral option, it shows which of the four LEHs the beam goes through. Each beam port will be located within 1/4 inch (0.05°) of the designated location.

TABLE 2. Final beam angles (continued next page).

Port Number	Polar angle θ (°)	Azimuthal angle ϕ (°)	Moved	Direct (D), Indirect (I), or Tetrahedral (T)	Port switching
1	23.5	78.75	No	D I T1	–
2	23.5	168.75	No	D I T2	–
3	23.5	258.75	No	D I T2	–
4	23.5	348.75	No	D I T1	–
5	30.58	34.33	Yes	I	25
6	30	123.75	No	I T2	28
7	30.58	214.33	Yes	I	31
8	30	303.75	No	I T1	34
9	44.5	16.29	Yes	D I	–
10	44.5	62.46	Yes	D I T1	–
11	44.5	106.29	Yes	D I T2	–
12	44.5	152.46	Yes	D I T2	–
13	44.5	196.29	Yes	D I	–
14	44.5	242.46	Yes	D I T2	–
15	44.5	286.29	Yes	D I T1	–
16	44.5	332.46	Yes	D I T1	–
17	50	39.67	Yes	I	26
18	50	84.38	No	I	27
19	50	129.38	No	I	29
20	50	174.38	No	I	30
21	50	219.67	Yes	I	32
22	50	264.38	No	I	33
23	50	309.38	No	I	35
24	50	354.38	No	I	36
25	77.5	24.38	No	D T1	5
26	77.5	54.38	No	D T1	17
27	77.5	84.38	No	D T3	18
28	77.5	114.38	No	D	6
29	77.5	144.38	No	D T2	19
30	77.5	174.38	No	D T2	20
31	77.5	204.38	No	D T2	7
32	77.5	234.38	No	D T2	21
33	77.5	264.38	No	D T4	22
34	77.5	294.38	No	D	8
35	77.5	324.38	No	D T1	23
36	77.5	354.38	No	D T1	24
37	102.5	5.62	No	D T1	49
38	102.5	35.62	No	D T3	50
39	102.5	65.62	No	D T3	65
40	102.5	95.62	No	D T3	51
41	102.5	125.62	No	D T3	52
42	102.5	155.62	No	D	66
43	102.5	185.62	No	D T2	53
44	102.5	215.62	No	D T4	54
45	102.5	245.62	No	D T4	67
46	102.5	275.62	No	D T4	55
47	102.5	305.62	No	D T4	56
48	102.5	335.62	No	D	68
49	130	5.62	No	I	37
50	130	50.62	No	I	38
51	130	95.62	No	I	40

TABLE 2. Final beam angles (continued).

Port Number	Polar angle θ (°)	Azimuthal angle ϕ (°)	Moved	Direct (D), Indirect (I), or Tetrahedral (T)	Port switching
52	130	140.33	Yes	I	41
53	130	185.62	No	I	43
54	130	230.62	No	I	44
55	130	275.62	No	I	46
56	130	320.33	Yes	I	47
57	135.5	27.54	Yes	D I T3	–
58	135.5	73.71	Yes	D I	–
59	135.5	117.54	Yes	D I T3	–
60	135.5	163.71	Yes	D I T3	–
61	135.5	207.54	Yes	D I T4	–
62	135.5	253.71	Yes	D I	–
63	135.5	297.54	Yes	D I T4	–
64	135.5	343.71	Yes	D I T4	–
65	150	56.25	No	I	39
66	149.418	145.67	Yes	I T3	42
67	150	236.25	No	I	45
68	149.418	325.67	Yes	I T4	48
69	156.5	11.25	No	D I T3	–
70	156.5	101.25	No	D I T3	–
71	156.5	191.25	No	D I T3	–
72	156.5	281.25	No	D I T4	–

Conclusion

The NIF laser now being built will have 48 beams passing through 72 ports on the target chamber. The locations of the ports have been chosen to optimize the flexibility and performance of the cylindrical indirect-drive option, while allowing direct-drive and tetrahedral indirect-drive experiments to be performed.

Notes and References

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