# High-Yield Polar-Direct-Drive Fusion Neutron Sources at the National Ignition Facility

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Direct-drive implosions at the National Ignition Facility (NIF) that produce high neutron yields from DT-filled targets are of substantial current interest as high-fluence fusion neutron sources. These sources are routinely used for neutron radiation effects experiments in support of programs at the national laboratories. This summary describes the development of these sources, focusing on the target designs and the high-yield experimental results that have been obtained to date.

The targets used for these experiments, typically thin shells of glow-discharge-polymer plastic (CH)[1] filled with DT gas, are sometimes known as "exploding pushers"[2] because they resemble the targets that have consistently been used since the earliest implosions[3] to maximize neutron yield. The earliest targets were irradiated with short pulses of IR laser light that deposited energy largely into energetic electrons. These electrons passed back and forth through the shell, depositing their energy throughout the shell. The shell exploded, causing its inner portion to compress the fuel. Later experiments using UV laser light, including the current experiments, differ in that the shell is ablatively accelerated by the laser, but the shell still decompresses (explodes) as it moves inward, producing high ion temperatures through shock convergence but precluding the high densities needed for ignition. Cryogenic designs, in contrast, provide a path to ignition and gain, but the most convenient source on the NIF of high neutron fluxes is the exploding pusher.

A typical target is shown in Fig. 1(a): a 4-mm-diam, ~25-$\mu$m-thick CH shell, filled with 8 atm of DT. Experiments have typically used diameters ranging from 3 mm to 5 mm, depending on the laser energy. The design of an experiment at a given laser energy entails a number of considerations, particularly the 1-D design to optimize the yield and the pointing design to optimize implosion uniformity. The 1-D designs were done using *HYDRA*.[4] Figure 1(b) summarizes the results of thousands of 1-D runs in the form of a contour plot of yield as a function of the shell diameter and thickness for a laser energy of 585 kJ. The optimum design calls for a diameter of 3 mm and a thickness of 18 $\mu$m, the parameters of the shot known as "Little Guy." Targets that are too thin or have a diameter that is too small are fully imploded before all of the laser energy can be delivered. Targets in the upper-right quadrant are too massive to be accelerated sufficiently with the available laser energy. The hatched region represents targets that are too thin to reliably hold the 8-atm fill pressure.

The pointing designs were done using the 2-D hydrodynamics code *SAGE*, which includes a 3-D ray-tracing capability.[5] The need for beam pointing optimization arises because the NIF beams (grouped into 48 quads) are located in four rings in each hemisphere at angles ranging between 23.5° and 50° from the vertical axis. Most of the beams must be repointed toward the equator in order to provide close-to-uniform drive at all angles on the surface of the target, a concept known as polar direct drive.[6] The problem is complex because the best-focus phase-plate spot profiles, chosen to meet the requirements of indirect-drive designs, are different in size and shape for each ring of beams. The beams also need to be defocused so that their focal spots better match the target diameter, especially for the larger targets. It was shown in Ref. 7 that reasonable implosion uniformity can be achieved using the indirect-drive phase plates by a combination of appropriate repointings and beam-defocus distances.

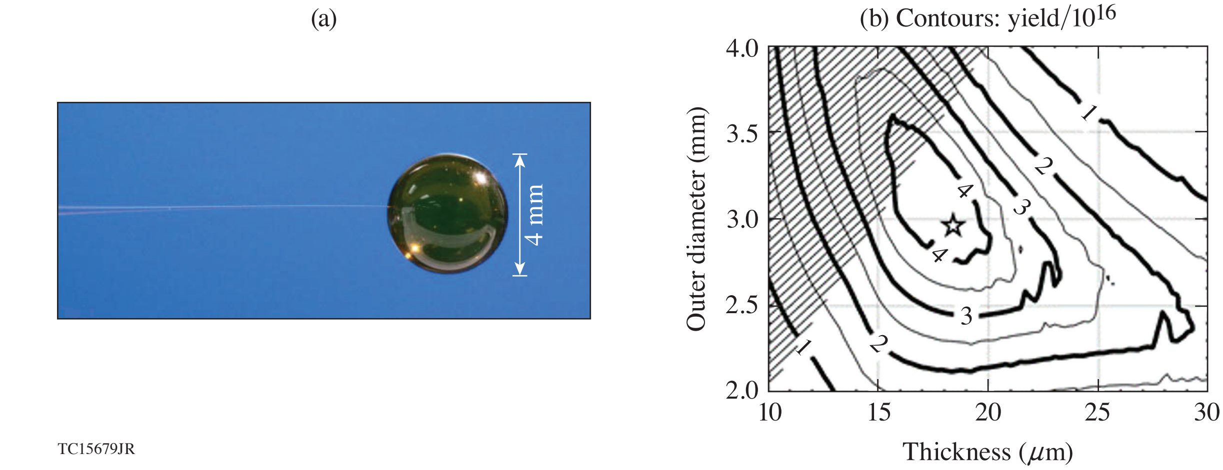


Figure 1
(a) A typical 4-mm-diam plastic target supported by a glass microcapillary fill-tube stalk. (b) Contour plot of neutron yield as a function of target thickness and diameter, based on a large number of 1-D simulations using the code *HYDRA*. This scan was done for a laser pulse delivering 585 kJ; the optimum parameter combination, indicated by the star, was used for the "Little Guy" shot.

Combining its 2-D hydrodynamics with its 3-D ray trace, *SAGE* is able to predict the 3-D implosion uniformity pattern over the target surface. Figure 2 is a contour plot of the deviation from the mean of the center-of-mass radius of the imploding shell, with red indicating overdriven and blue underdriven. The plot also shows the locations of the 192 beam ports (green squares) and their aim points (black circles) on the target surface. The rms deviation is just 20.5 $\mu$m after the shell has imploded 923 $\mu$m, corresponding to a 2.22% nonuniformity in the distance traveled, or equivalently in the average velocity. This is made up of a quadrature sum of 1.23% in the $\theta$ direction and 1.85% in the azimuthal ($\varphi$) direction, illustrating the importance of spreading the beams appropriately in the azimuthal direction.

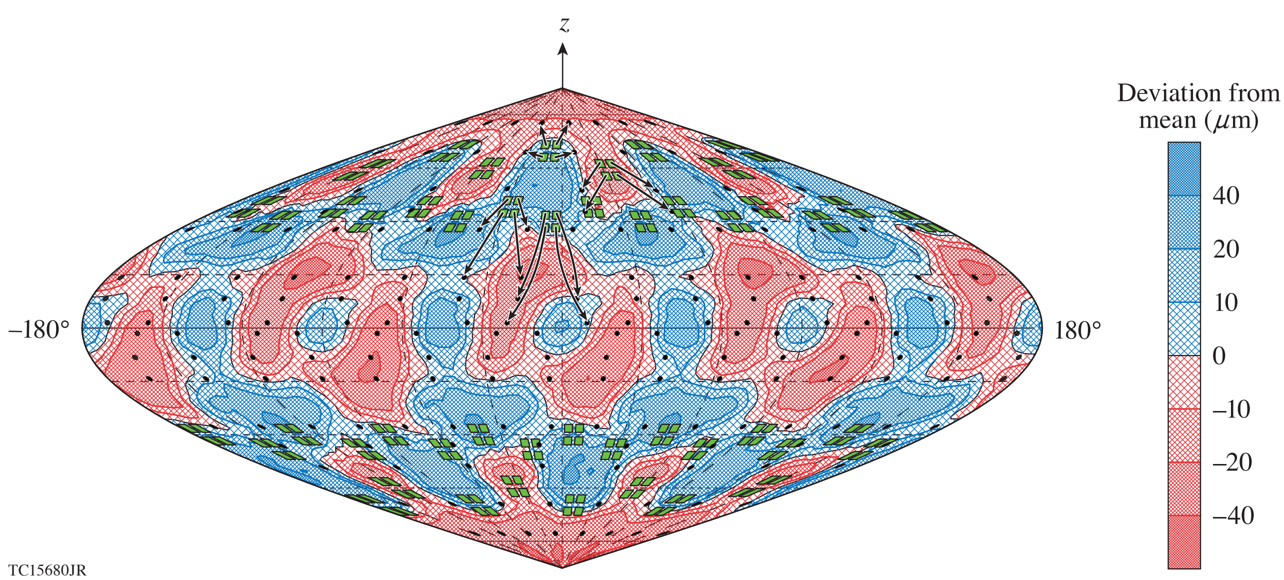


Figure 2
Contour plot, relative to the spherical coordinate angles ($\theta$,$\varphi$), of the deviation from the mean of the center-of-mass radius of a 4-mm-diam plastic target after implosion through 923 $\mu$m, predicted using the code *SAGE*. The plot shows that the average velocity variation over the sphere is 2.22% rms, the quadrature sum of 1.23% in the $\theta$ direction and 1.85% in the $\varphi$ direction. The green squares indicate the 192 NIF beams, the black circles their aim points, and the arrows the beam repointings in $\theta$ and $\varphi$.

Experimental results for the neutron yield are shown in Fig. 3. Neutron images viewing in the polar and equatorial directions are given in Figs. 3(a) and 3(b), respectively, for Little Guy. The images are approximately round, indicating very acceptable uniformity. Figure 3(c) gives a compilation of the yields obtained on a large number of shots, including direct-drive shots using 3-mm- and 4-mm-diam CH shells and some (at lower energy) using ~2-mm-diam $SiO_2$ shells. The highest yields come from indirect-drive cryogenic targets close to the nominal 1.8-MJ NIF energy. However, the direct-drive targets provide significantly higher neutron fluxes: test objects can be placed much closer to the source because of the decrease in debris load from the much smaller target vaporized mass.[8] In addition, the direct-drive targets are non-cryogenic and therefore much simpler to field.

Basic parameters and yield results are given in Table I for the three particularly noteworthy shots highlighted in Fig. 3. Little Guy, a 3-mm target, produced $4.81 \times 10^{15}$ neutrons at an energy of 585 kJ that was low enough to incur no damage to NIF optics. "Orange," an optimized 4-mm target driven by 1.1 MJ, produced $1.11 \times 10^{16}$ neutrons with an efficiency (fusion energy divided by incident laser energy) of 2.85%, the yield scaling with energy from OMEGA experiments according to the predictions of

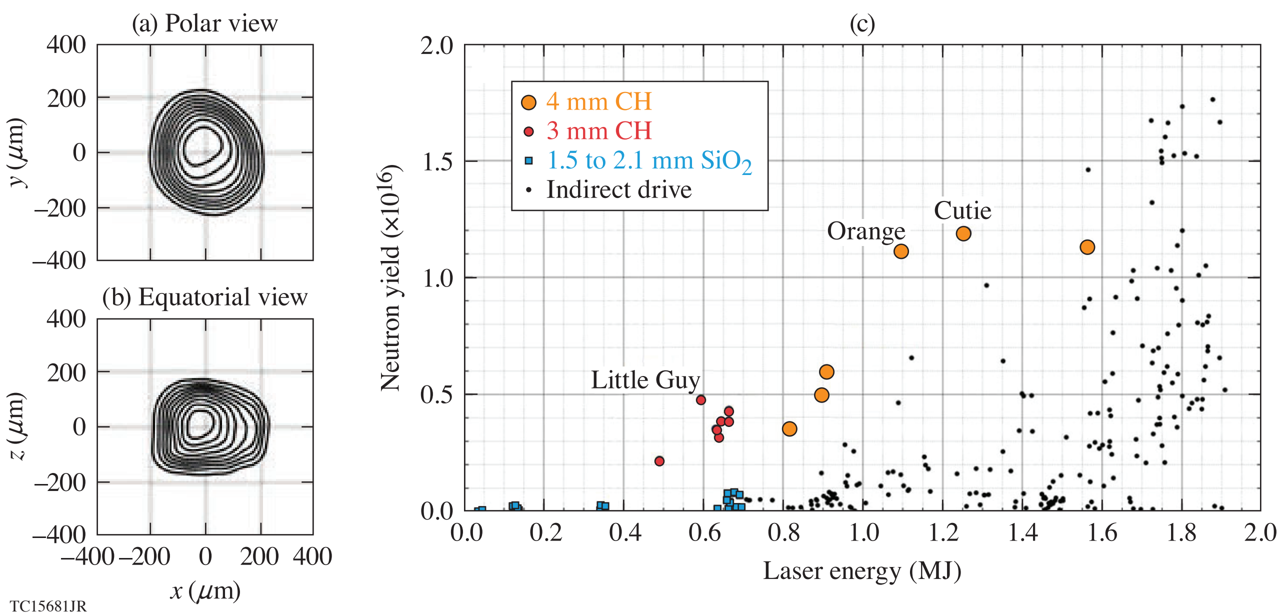


Figure 3
[(a),(b)] Experimental time-integrated neutron images at 10-$\mu$m resolution of the 3-mm Little Guy target, with contours in units of 10% of the peak intensity. (c) Yield from a variety of NIF neutron sources (through October 2020) as a function of target energy. Details of the three labeled shots are given in Table I.

Table I: Selected parameters of three NIF shots of particular interest. Each target is filled with 8 atm of DT (~64% D).

| | | Little Guy | Orange | Cutie |
|---|---|---|---|---|
| | NIF shot | N190707-001 | N190227-001 | N191027-003 |
| Capsule | Outer radius ($\mu$m) | 1480 | 1971 | 1978 |
| | Thickness ($\mu$m) | 18.4 | 25 | 22.7 |
| Laser | Laser energy (kJ) | 585 | 1097 | 1256 |
| | Peak power (TW) | 328 | 390 | 425 |
| Results | Yield (#DT neutrons) | $4.81 \times 10^{15}$ | $1.11 \times 10^{16}$ | $1.19 \times 10^{16}$ |
| | Fusion conversion efficiency $G_L$ | 2.28% | 2.85% | 2.67% |
| | Ion temperature (keV) | 11.14 | 8.94 | 10.22 |

Ref. 7. "Cutie," a little thinner than Orange and irradiated with a higher peak power, was somewhat overdriven and produced a slightly higher yield with lower efficiency. All three targets produced high ion temperatures of ~10 keV, measured by four neutron time-of-flight detectors with different viewing angles.[9] Further information on this work can be found in Ref. 10. Work on the modeling of these targets is in progress and will be reported elsewhere.

This platform is being routinely used for neutron effects experiments. Further work on platform development is focused on optimizing designs that deliver the full NIF energy to larger targets subject to the maximum power constraints of the NIF.

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