NIF laser fails to meet the minimum specifications required for their ignition target designs

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Summary

LLNL has now published several scientific articles on the performance of the first National Ignition Facility (NIF) laser beams. According to their own data, the laser beams did not meet the minimum requirements needed to test their ignition target design. Their claims that the laser has met its specifications are not correct. They have recently changed their target design, apparently to try to match the poor performance of their NIF laser. This latest ignition target design is also very unlikely to be consistent with the real laser performance.

1.8 MJ Specifications and Performance

The NIF laser energy and performance specifications, and its costs, were based upon an ignition target design that used 1.8 MJ of laser energy. There was no other reason to build a laser of that size and cost, other than to test their ignition design. The laser's performance can be evaluated by comparing it with the specifications in a 2004 ignition target design review article, written by the NIF target designers:

That 2004 ignition point design specified[1], among other things:

1. 1.8 MJ of third-harmonic laser energy delivered to the target.
2. A focal spot size of 0.5 x 1.0 mm. (*Modified from the original contract spec of 0.5 x 0.5 mm*).
3. A package of optical smoothing techniques that included SSD phase plates, 270 GHz of bandwidth at third harmonic, and polarization rotation.

Not mentioned in this review article, but from the original contractual documents:

4. Less than 2% of the laser energy outside a spot size of 0.6 x 1.1 mm. (*The original requirement was that it be 1 mm larger than the focal spot size in #2.*)
5. With the package of beam smoothing techniques, the laser intensity fluctuations at the fusion target should not exceed 25%, when averaged over a 30 micron diameter circle.

In a 2007 article in Applied Optics[2], the NIF scientists provided their results. With 120 GHz bandwidth, the measured focal spot size with beam smoothing was 1.16 x 1.3 mm. In a follow-up letter[3] they listed results with 270 GHz bandwidth; the spot size was an even larger 1.64 x 1.91 mm (*See page 7 of this analysis for a copy of the relevant table.*) Both measured spot sizes are far outside the design requirement of 0.5 x 1.0 mm. Their table incorrectly lists required spot size much larger that 0.5 x 1.0 mm, but that claim is inconsistent with their own published target designs. (The spot sizes, incidentally, were measured at the half-intensity diameter. There is no information yet available on the focal spot size, with beam smoothing, that contained 98% of the laser energy.)

With those large focal spots, the laser beams would likely either hit the hohlraum entrance holes, or directly hit the spherical capsule. Either would lead to a dramatic failure of the ignition test. That is why the original focal spot specification existed. The laser performance at 1.8 MJ is a clear failure. How NIF scientists can call that data a success, as they did in journal articles and in a recent JASON review, I don't understand.

In a more recent 2008 article[4], they did find one way to resolve the inconsistency. A table in that article claims that the focal spot size and laser bandwidth were never specified! So instead of magically increasing the requirement on the spot size, they simply claimed that there was no spec. Well, that makes life easier. I don't know what is in the latest iteration of the contract between DOE and LLNL; so perhaps that is how they could make their claim. However, in my view, their physics requirements should have trumped their legal requirements. (*See page 8 for the excerpt from that 2008 article.*)

A Gimmick Shot at 1.8 MJ?

In a January 2009 presentation to a JASON committee, the NIF team showed a laser shot, dated September 1, 2008, that comes closer to meeting the first three of the above requirements. A cluster of beams had an energy equivalent to 1.8 MJ for the entire laser, a bandwidth of 210 GHz, and a focal spot size of about 1 x 1 mm. Still too large a spot compared to the 0.5 x 1.0 mm specification, but a lot closer.

Has there been a recent significant advance in NIF focusability? There is not enough detail in their presentation to evaluate this laser shot, so it is possibly an improvement. However there is another, simpler explanation. In a conversation a few years ago, the head of the NIF program pointed out to me that it was actually quite easy to meet the focal spot requirements, if that is all one wanted to do. Beam smoothing works by trading off the focal spot size for improvements in beam uniformity. Larger spot size, less intensity modulations. Smaller spot size, more intensity modulations. So all they had to do was to use a phase plate that divided the laser beam into larger segments. The focal spot size would then be reduced. But one would lose the whole purpose of beam smoothing: to smooth the beam and minimize the risk of laser-plasma instabilities. In other words, this latest shot is probably just a gimmick.

There are several reasons to take this more pessimistic interpretation.

- Other parts of the same presentation use the older data shots with larger spot sizes, including the table that compared the status and the requirements. (*See page 9 below for an excerpt from their presentation*.)
- They did not provide any explanation of what they did to improve the focusing.
- They have now given up on the 1.8 MJ target design. The new point design uses 1.221 MJ of laser energy.

Questions that could have been asked of the NIF scientists about that recent laser shot: What was the detailed structure of the phase plate, and how did it differ from previous laser shots which produced a larger focal spot size? What were the nonuniformities in the laser intensity in the focal spot, and how does that compare with previous shots? What was the diameter that contained 98% of the laser energy? Were other changes made to the laser to produce this smaller focal spot?

A Suggested Interpretation of the NIF Data

The 2007 publication also provided data at a beam energy corresponding to 1.0 MJ. The focal spot size at this energy was 0.5 x 1.0 mm, just what they needed. The table on page 7 shows that the focal spot size increased when they increased the laser energy or increased the bandwidth, or both.

The available data base on focal spot sizes is incomplete. Also, it is not a clean measure of inherent laser beam quality, since it is modified by the phase plates that they chose for each shot. However a reasonable interpretation is that the NIF works just fine at 1.0 MJ, but that there is some type of nonlinear optical problem that is dependent on both laser energy and laser bandwidth, and it destroys the laser beam quality above 1.0 MJ.

If I am correct, then one would notice that their program is attempting to redesign for both the lowest possible laser energy and the lowest possible laser bandwidth. That is exactly what they have been trying to do.

The Evolution of NIF Target Designs

In 2005, the NIF management proposed to postpone experiments at 1.8 MJ, and instead start NIF ignition experiments at just 1.0 MJ. They had a new modified target design that they thought could produce ignition at this lower laser energy. They even very confidently claimed that the entire set of target experiments to reach ignition could be accomplished in one year. A JASON review of that proposal was critical of their hyper schedule, and noted the delicacy of the 1.0 MJ ignition target.

In a 2007 scientific article[5], the NIF target designers finally agreed, stating, "at 1.0 MJ we do not have very much margin remaining", and "Some issues remain, but resolution of all of them is completely feasible, especially given the option to increase the laser energy to approximately 1.3 MJ." However their NIF data showed that laser operation at 1.3 MJ had too large of a focal spot size.

The target designs at 1.0 and 1.3 MJ were called Rev1 and Rev2. At the 2009 JASON review, LLNL presented a new ignition target point design for the NIF, called Rev3.1. The laser energy is now specified as 1.221 MJ. The third-harmonic bandwidth has been reduced from 270 GHz to 180 GHz. The required focal spot size is 0.7 x 1.0 mm, just a little more relaxed than the 2004 design. Good. At least on this design we can now all agree on the required focal spot size, although I wonder if the change from 0.5 to 0.7 mm was driven by the physics, or by the laser limitations. (*See page 9 of this report for the relevant excerpt from the NIF presentation*.)

And, most interestingly, some of the NIF laser-plasma scientists suggested at the review that the laser--plasma instabilities might be controllable at much lower bandwidths. That would be nice.

So they have a new point design, called target design Rev3.1, with a bit more energy than the earlier proposal of 1.0 MJ. They are apparently hoping, with no data to back them up, that the laser beams will focus properly at this energy, if they reduce the bandwidth to ⅔ or less of their previous spec. And there is obvious pressure on the plasma physicists to see if they can get away with even less bandwidth. There is of course no experimental data on the NIF performance near 1.2 MJ, at any bandwidth. Those experiments are not scheduled until the year 2010.

Amazing. Simply amazing.

I agree that they should try every possible way to salvage their program after having spent so many billions of dollars. But apparently the NIF laser beam has some type of nonlinear optical problem, (in addition to the severe optical damage problem), such that when they try to increase the laser energy above 1.0 MJ, the beam smoothing mechanism destroys the transverse near-field phase quality. Therein lies their current quandary, and their floundering around, starting with 1.8 MJ, then switching to 1.0 MJ, thinking about 1.3 MJ, and now just fantasizing about 1.221 MJ. (LLNL's specification of the laser energy to four significant digits is, by the way, ridiculous precision.)

Some Comments

How did a world-class laser laboratory get into this mess? There are lots of fundamental reasons, but let's examine here the laser engineering. Going back to the early 1990s, they wanted to sell a new laser implosion facility, their third, for their third attempt at ignition. Their existing laser at that time had a completed cost, including everything, of about $6000/joule ($180M and 30 kJ). Extrapolating that laser design to 1.8 MJ would have led to a total cost way too high to be accepted by Washington.

So they came up with a completely new laser design that had a greater laser energy extraction efficiency, and a greater laser energy flux. They claimed that by increasing the energy packing they could reduce the total cost to about $1000/joule. They built a prototype of the new laser design, called Beamlet, but then they announced success, shutting Beamlet down and disassembling it, before completing the testing. With no solid basis from integrated tests using their prototype[6], they nonetheless rushed ahead with the full NIF to meet their previously determined schedule. Specifically because of their basic design choice of a higher energy packing, they now have a laser that has severe and costly optical damage when fired at or above 0.6 MJ, and whose focal quality falls apart above 1.0 MJ. They also had an unfortunate cost over-run and time delay. Interestingly, the final unit cost of the NIF is now about the same as the older laser. $5B and 1 MJ equals $5000/joule. At their operating point without severe optical damage, 0.5 MJ, the total cost comes to $10,000/joule.

When the decision was made to end new nuclear weapons design and testing, and to concentrate upon maintenance of our existing weapons, the political decision was made to also maintain a weapons design capability, in case it was needed at some future time. This led to the NIF, and other large projects, which would be used to attract, train, and evaluate the next generation of weapons designers. However there is a conflict in the type of scientists and engineers needed for weapons maintenance and the type that would do weapons design. For maintenance, one wants conservative, cautious people who would be skeptical about making any changes to the weapons. Laser fusion has attracted the exact opposite personality type: entrepreneurs, who are optimistic and want to advance their careers by doing something. There is also now the need to justify the large expenditure for the NIF, which could lead to unnecessary changes in our stockpile.

LLNL apparently remains hopeful that they will eventually solve the problems with the NIF laser, or find an ignition target that matches, or find some other application for the facility. This is the laboratory that also wants to design Reliable Replacement Warheads without testing. No risk they say. But what if there is some unexpected problem, such that their new warhead designs have a significant chance of failure? Would they know it? Would they admit it, to themselves and others? Would they cancel their replacement program? If the laboratory won't even admit to itself that there is a big problem with the NIF laser, and always exudes optimism, how can they be trusted with designing reliable replacement warheads? Can they even be trusted to maintain the existing stockpile?

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[1] J. D. Lindl et al, Phys. Plasmas, **11**, 339-491 (2004). See Table II-1 on pg. 348, and accompanying text on that page. Note that a bandwidth of 3 Å at 1ω is the same as 270 GHz at 3ω.

[2] C. A. Haynam et al, Appl. Optics **46**, 3276-3303 (2007).

[3] My Comment associated with Ref. 2: S. E. Bodner, Appl. Optics **47**, 1387-1388 (2008);
The NIF Reply: C. A. Haynam et al Appl. Optics 47, 1384-1386 (2008)

[4] C. A. Haynam et al, J. Physics, Conf. Series **112**, (2008). See Table 2.

[5] S. W. Haan et al, Fusion Science & Tech. **51**, 509-513 (2007)

[6] Exchange of letters between S. Bodner and E. Moses, Physics Today, (July, 2001)

From the NIF Reply, footnote #3:

Response to comment on "The National Ignition Facility laser performance status"

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We appreciate Stephen Bodner's continuing interest in the performance of the NIF laser system. However, we find it necessary to disagree with the conclusions he reached in his comments [Appl. Opt. **47**, XXX (2008)] on "National Ignition Facility Laser Performance Status" [Appl. Opt. **46**, 3276 (2007)]. In fact, repeated and ongoing tests of the NIF beamlines have demonstrated that NIF can be expected not only to meet or exceed its requirements as established in the mid-1990s in the document National Ignition Facility Functional Requirements and Primary Criteria [Revision 1.3, Report NIF-LLNL-93–058 (1994)], but also to have the flexibility that provides for successfully meeting an ever expanding range of mission goals, including those of ignition.

OCIS codes: 140.0140, 140.3610, 140.3070.

Table 2. Comparison of a Number of Requested and Demonstrated Spot Size and Laser Bandwidths for Ignition Experiments[a]

Campaign Description			Beam Energy and Power			Beam Smoothing		
Campaign	Pulse Shape	Pulse Length (ns)	3ω Energy per Beam (J)	3ω Energy Full NIF (MJ)	Peak Power (TW/beam)	CPP (mm, FWHM)	Polarization Rotation	SSD (GHz 3ω)
2006 Baseline 1.0 MJ (Rev. 1) Ignition Design	Ignition	15.4	5208	1.00	1.85	.95 × .5	1/2 of beams	270
Demonstrated: 1.0 MJ Shot N060302–001	Ignition	15.4	5316	1.02	1.9	.95 × .5	Yes	270
2006 Conceptual 1.8 MJ Ignition Design	Ignition	20.4	9375	1.80	2.6	1.3 × 1.16	1/2 of beams	90
Demonstrated: 1.8 MJ Shot N060324–001	Ignition	20.4	9438	1.81	2.6	1.3 × 1.16	Yes	120
2007 Baseline (Rev. 2) 1.3 MJ Ignition Design	Ignition	15.1	7050	1.35	1.99	1.48 × 1.27	1/2 of beams	210
Demonstrated: 1.3 MJ Shot N070607–001	Ignition	15.1	7600	1.46	2.06	1.91 × 1.64	Yes	220
2007 Conceptual 1.8 MJ Ignition Design	Ignition	17.2	9375	1.80	2.6	1.91 × 1.64	1/2 of beams	270
Demonstrated: 1.8 MJ Shot N070809–002	Ignition	17.2	10600	2.00	2.67	1.91 × 1.64	No	270

[a]Each demonstrated shot has all parameters shown occurring simultaneously on that shot.

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Although their abstract claims success, none of the Demonstrated laser shots in their table simultaneously satisfied all of the specifications in the 2004 NIF target design review article. See the column "CPP" which gives the focal spot sizes in mm. Only the 1.0 MJ shot has the necessary focal spot size.

From footnote #4:

The National Ignition Facility 2007 Laser Performance Status

C. A. Haynam, R. A. Sacks, P. J. Wegner, M.W. Bowers, S. N. Dixit, G. V. Erbert, G. M. Heestand, M. A. Henesian, M. R. Hermann, K. S. Jancaitis, K. R. Manes, C. D. Marshall, N. C. Mehta, J. Menapace, M. C. Nostrand, C. D. Orth, M. J. Shaw, S. B. Sutton, W. H. Williams, C. C. Widmayer, R. K. White, S. T. Yang, and B. M. Van Wonterghem

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Requirement (Full NIF Equivalent)	NIF Primary Criteria	Current Point Design	Demonstrated to date
Pulse Energy (MJ)	1.8	1.3	2.0
Peak Power (TW)	500	383	>550
Temporal dynamic range	50:1	80:1	150:1
Temporal pulse shape	shaped	Rev2 shape	Rev2 shape
Focal spot size (μm) (unconditioned 80% enclosed energy diameter)	275	275	250 for 1.8 MJ ignition pulse
Beam conditioning (focal spot/SSD bandwidth)	Not specified	1.9mm X 1.6mm 70 GHz	1.9mm X 1.6mm 90 GHz
RMS focal spot position (μm)	50	80	80
Pre-pulse (W/cm^2)	$<10^8$ (96 beams)	$<10^8$ (96 beams)	$<<10^8$ (96 beams)
Power Balance (RMS 2ns average)	<8%	Variable: foot 15% peak 3%	Consistent with Rev2 requirements
Shot-to-shot power reproducibility (2 ns average)	Not specified	3% (192 beam total)	Consistent with Rev2 requirements
Cycle time (between full system shots)	≤ 8 h	≤ 8 h	≤ 3 h

Table 2. Summary table showing NIF laser performance requirements as specified in the 1994 NIF primary criteria and the current National Ignition Campaign (NIC) Rev2 Point design. The last column shows the performance achieved to date.

Note the "Beam conditioning" row. It claims that the NIF Primary Criteria for focal spot size and SSD bandwidth were not originally specified. They were actually specified in both the original NIF contract and in the 2004 target design article. The 1.3 MJ point design has a huge spot size of 1.6 x 1.9 mm. No such target design actually existed.

Copied from the NIF presentation to the JASON committee, January 16, 2009:

NIC Point design — The fusion ignition mission imposes stringent performance requirements

NIC
The National Ignition Campaign

Requirement (Full NIF Equivalent)	NIF FR&PC	Rev3.1 Be Point Design	Demonstrated to date	
Pulse Energy (MJ)	1.8	1.221	2.0	✓
Peak Power (TW)	500	361	540	✓
Temporal dynamic range	50:1	60:1	150:1	✓
Temporal pulse shape	shaped	Rev3.1 Be shape	Rev3.1 shape	✓
Focal spot size	600µm	80% energy of unconditioned beam in ≤275µm	250µm for 1.8 MJ ignition pulse shape	✓
Beam conditioning (focal spot/SSD bandwidth)	Shall have spatial & temporal capability	0.978mmX0.693mm 60 GHz	1.9mm X 1.6mm 90 GHz	✓

<u>Finally</u>, they admit that the focal spot requirement is not larger than 1 mm, although they still won't admit that there is a spec the original contract. They now accept a requirement of about 0.7 x 1.0 mm, at a laser energy of 1.221 MJ. Should we forget about those other recent NIF laser publications that listed much larger spot sizes?

No reason is given as to why, after all these years, the minor diameter has now been increased from 0.5 mm to 0.7 mm. One can however easily guess.

(*Their bandwidth of 60 GHz is specified at the fundamental laser frequency. After frequency tripling, their bandwidth converts to 180 GHz*.)

The last column shows no experimental data at 1.221 MJ. But they can dream and hope.

And of course, their specification of the laser energy to four significant digits (1.221), and the focal spot size to three significant digits (0.978 mm and 0.693 mm), is just silly. How does this survive at the management level in a DOE nuclear weapons laboratory? Do they think this phony over-precision will impress people?