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The National Ignition Facility 2007 Laser Performance Status

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Abstract. The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory contains a 192-beam 3.6 MJ neodymium glass laser that is frequency converted to 351nm light. It has been designed to support high energy density science (HEDS), including the demonstration of fusion ignition through Inertial Confinement. To meet this goal, laser design criteria include the ability to generate pulses of up to 1.8-MJ total energy at 351nm, with peak power of 500 TW and precisely-controlled temporal pulse shapes spanning two orders of magnitude. The focal spot fluence distribution of these pulses is conditioned, through a combination of special optics in the 1ω (1053 nm) portion of the laser (continuous phase plates), smoothing by spectral dispersion (SSD), and the overlapping of multiple beams with orthogonal polarization (polarization smoothing).

In 2006 and 2007, a series of measurements were performed on the NIF laser, at both 1ω and 3ω (351 nm). When scaled to full 192-beam operation, these results lend confidence to the claim that NIF will meet its laser performance design criteria and that it will be able to simultaneously deliver the temporal pulse shaping, focal spot conditioning, peak power, shot-to-shot reproducibility, and power balance requirements of indirect-drive fusion ignition campaigns. We discuss the plans and status of NIF’s commissioning, and the nature and results of these measurement campaigns.

1. Overview
The National Ignition Facility (NIF) is by far the world’s largest and most complex optical system. Its 192 beamlines occupy a building with a volume of about 350,000 m³, all of which is climate controlled to within a fraction of a degree C and a few percent relative humidity. It is designed to deliver as much as 1.8 MJ of UV light at peak power of 500 TW, with a precise high-contrast temporal pulse shape, and beam placement accurate to better than 100 μm. The conditions created in the targets will allow a wide variety of high-energy-density investigations, including laboratory-scale thermo-nuclear ignition and burn. The NIF laser design and operation have been extensively described by Haynam et. al. [1]
2. Commissioning Status
The NIF laser has been designed around the concept of line replaceable units (LRUs): segments of the laser that can be assembled in the optics assembly building, cleanly transported to the laser bays, and inserted by mechanical handlers. The entire NIF facility is composed of more than 6200 LRUs. As is detailed in Table 1, as of August 16, 2007 about 70% of these LRUs have been assembled, installed in the laser bay, and installation qualified (IQ – a check of each system to certify that it is properly installed and functional). All of Laser Bay 2 has been activated and performance qualified (PQ – a complete check that the system performs up to its design specification), giving NIF a current capacity to produce up to 2.4 MJ of IR light with well-controlled pulse shapes and beam quality. Hardware installation in Laser Bay 1 is nearing completion, and we are beginning now to install the switchyard and target bay.

Figure 1 compares the achieved LRU installation total with the pace that is planned in order to support initiation of an ignition campaign in 2010. Commissioning is slightly ahead of the scheduled pace.

3. Operational Status
The remainder of this paper is devoted to the assessments available of NIF performance as compared both to the NIF Primary Criteria and to the current point design specifications for executing an ignition campaign.

| LRU Installations | Installed | Total | Percent Complete |
|-------------------|-----------|-------|-----------------|
| Laser Bay 1       | 2066      | 2289  | 90              |
| Laser Bay 2       | 2289      | 2289  | 100             |
| Switchyard        | 43        | 178   | 24              |
| Target Bay        | 29        | 1450  | 2               |
| Overall           | 4427      | 6206  | 71              |

| Beamlines Activated (1w PQ): | 97/192 |
| Overall 1w Commissioning: | 82%   |
| Overall Project Completion: | 93%   |
| Total 1w Energy Capability: | 2.4 MJ |

Table 1. NIF installation and commissioning status as of August 16, 2007. Altogether, 4366 LRUs, or 70% of the total required, have been installed and qualified for commissioning.

3.1. Precision Diagnostic System Tests
In addition to the 1ω and 3ω diagnostics that are integrated into every beamline, NIF has a separate precision diagnostics system (PDS) that can perform detailed analysis of the performance of one selected beam. A single beam of NIF is deflected by a mirror inserted just downstream of the transport spatial filter (TSF), and is directed to a final optics assembly (FOA) that is the prototype for those that will be assembled on the target chamber. A large suite of diagnostics is available at the PDS to give detailed information about energy and power, nearfield and farfield...
fluence profiles, and spectrum at both 1ω and 3ω. We have carried out extended PDS campaigns in 2006 and 2007, using two different NIF beams, to assess how well NIF will meet its design criteria, and to help optimize the design and the operational plans.

![Cumulative LRU activation chart](chart.png)

**Figure 1.** The planned (line) and actual (data markers) cumulative total LRUs activated vs. time. This schedule supports the start of 192-beam operations in mid-2009 and the initiation of a full-scale ignition campaign in 2010.

Table 2 is an overall summary of the results of those campaigns. Eleven primary requirements are listed, along with the NIF primary criteria and the specification now determined to be required for the current ignition point design (Rev2). In some cases, these requirements have become more challenging (temporal dynamic range, beam conditioning, power balance at the peak of the pulse); in others they are somewhat more relaxed (total energy, peak power, focal spot positioning). In all cases but 3, we have exceeded the more difficult of the requirements. The precision of focal spot positioning, as inferred from repeated shots to the NIF target chamber with 2 beams, meets the point design specification. Measurements in 2008 will evaluate pointing precision for multiple beams.

Power balance for 192-beams and shot-to-shot total power reproducibility will be measured when we are able to diagnose multiple beams at 3ω. In PDS we have carried out three sequences of nominally-identical shots – using single beam reproducibility as a surrogate for both of these quantities – and find results that are consistent with the Rev2 requirements. In one of the more striking accomplishments shown in this table, we have been able to fire full system shots at less than 3 hour intervals with little or no degradation in beam quality.

3.1.1. Precision Diagnostic System 2007 tests

The PDS layout and the 2006 PDS experimental campaign are both described in Reference 1. Here, we discuss new results from the 2007 PDS campaign. PDS07 had a number of goals including to test and validate the new production FOA design and to explore pulse-shaping effectiveness, repeatability, and tunability.

3.1.2. FOA Performance Qualification

The production prototype FOA deployed on PDS is shown in Figure 2. A fused silica window separates the converter crystals, which are housed in an atmosphere of 10 Torr of dry air, from the beam tube which holds atmospheric-pressure Argon. The continuous phase plate (CPP) may be
located either before this window or between the converter crystals. The \( \omega \) position allows the CPP to be rotated out of the beam path for optics inspection and for alignment. The \( 2\omega \) slot minimizes the effect of large phase gradients on conversion efficiency. To implement polarization smoothing, there will be a polarization rotator in two beam lines of every group of four (quad), along with correspondingly rotated crystals. Following the conversion crystals, one sees the off-axis wedged focus lens, a combined sampling grating/debris shield, which acts also as a barrier between the 10 Torr atmosphere and the vacuum in the target chamber, and a cassette of 1 to 3 mm thick disposable debris shields. This design was modified as a result of lessons learned during the 2006 PDS campaign. Early shots in 2007 were devoted to validating that it functioned as anticipated.

| 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 (\( \mu m \)) (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 (\( \mu m \)) | 50 | 80 | 80 |
| Pre-pulse (W/cm²) | \(<10^8 \) (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) | \( \leq 8 \) h | \( \leq 8 \) h | \( \leq 3 \) 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.

Early tests in PDS07 verified the strengths of this modified FOA design. The off-axis lens successfully moved a first-order focusing ghost beam to a benign position outside the beam paths. The separated-crystal converter design simplified insertion, extraction, and alignment of the crystals for optimal conversion efficiency. No adverse effects of ghost beams within the FOA were found.
3.1.3. Mission Baseline Performance Verification (MBPV)

The MBPV portion of PDS07 concentrated on assessing and honing our ability to reliably and reproducibly produce precise pulse shapes for the ignition campaign. Figure 3 displays the results of a series of 16 shots during which the requested nano-Joule injected pulse shape was held constant. The desired 1.3 MJ Rev 2 pulse shape is shown, along with the time-dependent power balance specification and the time-dependent rms variation actually achieved among the 16 shots. Treating the variation among multiple shots of a single beamline as a surrogate for the variation among multiple beamlines on a single shot, this test indicates that NIF will meet its power-balance specifications. Further, assuming that shot-to-shot power variations are correlated within a quad, but uncorrelated between quads, we would expect the maximum shot-to-shot variation for the full NIF to be \(-9%/\sqrt{48} = 1.3\%\), comfortably less than the 3% Rev 2 requirement.

Figure 2. Suite of optics comprising the NIF FOA design. The FOA employed in PDS07 was the production prototype of this design. FOA optics from the PDS07 will be deployed on the NIF target chamber.

Beyond producing the same pulse shape shot after shot and quad-to-quad, the NIF laser must be able to precisely tune the pulse shape to achieve proper shock and implosion timing. Figure 4 addresses the precision with which that can be accomplished. The second and third shock portions of the Rev2 3ω pulse are shown. The solid curve is an average of sixteen shots which had been first tuned to match that request and then repeated. A new requested input shape from the master oscillator was then generated, using numerical tools only (no experimental tuning) that would shift the second shock up by 10% and the third shock later by 100 ps. Averaging 12 shots taken with this requested input yields the dashed curve.

In PDS06 we verified that the NIF design supports the ability to generate 1.8 MJ ignition-shape pulses at 500 TW peak power with polarization smoothing, \(\sim 1.2\) mm diameter smooth focal spot, and smoothing by spectral dispersion (SSD) at 40 GHz. A similar but more demanding integrated test was performed in PDS07. Figure 5(a) shows the power trace of a shot fired on the evening of August 9.
Figure 3. The time-dependent rms variation among a set of 16 nominally-identical shots (red), compared to the Rev 2 power-balance requirement (green), with the temporal pulse shape for reference (blue).

Figure 4. The PDS07 campaign validated our ability to make small, precise adjustments to the pulse shape without repeating the pulse-shaping loop used to obtain the initial shape.

The peak power of 2.6 TW corresponds to a 192-beam full NIF equivalent of 500 TW. Total measured energy, 9.91 kJ, scales to 1.9 MJ. In Figure 5(b), we see a smoothed histogram of the nearfield fluence, along with an inset of the nearfield fluence profile. The fluence is very smooth, with an absence of high-fluence hot spots, indicating good control of nonlinear-index-induced self-focusing effects. The three small holes, with a combined area less than 2% of the total beam area, are created intentionally by positioning masks in the low power front end to remove small portions of the near field. This is an important element in our operational plans to improve laser maintainability. The farfield fluence profile in Figure 5(c) reveals a spot that has been conditioned by a CPP to 1.9 mm × 1.6 mm. For this shot, high conversion efficiency was maintained despite the large angular distribution in the beam by utilizing the 2ω slot for the CPP. The smooth profile seen is a result of smoothing the CPP-induced speckle pattern with SSD. As shown in Figure 5(d),
the measured $3\omega$ bandwidth on this shot was $\sim 270$ GHz, consistent with the 90 GHz imposed on the $1\omega$ beam.

Figure 5. Power history, nearfield, farfield, and SSD spectrum of a 1.8 MJ ignition shot. The farfield spot of 1.9 mm diameter is smoothed by application of SSD with 270 GHz bandwidth. Peak power and total energy correspond to full-NIF equivalents of 500 TW and 1.9 MJ.

4. Conclusion/Summary
Installation and commissioning of the National Ignition Facility is proceeding on, or slightly ahead of, schedule for the planned start of full 192-beam operations in 2009, and the first ignition campaign in 2010. Two experimental campaigns utilizing the precision diagnostics system have been instrumental in both optimizing and verifying the laser’s performance. These tests verify that NIF will meet its design criteria and the requirements for the ignition campaign.

References
[1] C. A. Haynam et al, App Opt 46, 3276-3303 (2007)

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