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The National Ignition Facility Performance Status

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Abstract. The National Ignition Facility (NIF) laser has been designed to support high energy density science (HEDS), including the demonstration of fusion ignition through Inertial Confinement. NIF operated a single “quad” of 4 beams from December 2002 through October 2004 in order to gain laser operations experience, support target experiments, and demonstrate laser performance consistent with NIF’s design requirement. During this two-year period, over 400 Main Laser shots were delivered at 1ω to calorimeters for diagnostic calibration purposes, at 3ω to the Target Chamber, and at 1ω , 2ω , and 3ω to the Precision Diagnostics System (PDS). The PDS includes its own independent single beam transport system, NIF design frequency conversion hardware and optics, and laser sampling optics that deliver light to a broad range of laser diagnostics. Highlights of NIF laser performance will be discussed including the results of high energy 2ω and 3ω experiments, the use of multiple focal spot beam conditioning techniques, the reproducibility of laser performance on multiple shots, the generation on a single beam of a 3ω temporally shaped ignition pulse at full energy and power, and recent results on full bundle (8 beamline) performance. NIF’s first quad laser performance meets or exceeds NIF’s design requirements.

1. Introduction

The National Ignition Facility (NIF) is designed to deliver 192 lasers beams, with carefully controlled energy, temporal, wavefront, and timing requirements, to a set of precisely positioned targets located near the center of a ten meter diameter target chamber. The extreme temperatures and pressures created by this array of lasers will be used to perform inertial confinement fusion and high energy density experiments. This facility is now being commissioned at the Lawrence Livermore National Laboratory, and upon scheduled completion in 2009, the NIF will be capable of delivering up to 1.8MJ of 3ω (351nm) energy. Pulse lengths will be adjustable between 0.2 and 32ns. The design of NIF is the culmination of over 25 years of laser development and operation, and is designed to exceed the energy of currently operating Nd:Glass lasers by a factor of 50. NIF’s 192 beamlines are divided into 24 bundles, with 8 beamlines per bundle that are spatially arranged in a rectangular array with two beams wide by four beams high (2x4). A bundle is further divided into an upper and lower quad, each with 4 beamlines (2x2).

In April 2001, the NIF project began an effort titled NIF Early Light (NEL) to install and commission the first four beamlines, or first Quad, of the NIF. The location of these lasers is shown in Fig. 1. This first quad was operated through October 2004. The integrated operations demonstrated prototype and first article diagnostics and control systems, as well as a full cluster of beampath infrastructure, support systems, and utilities in the laser bay and switchyard.

Figure 1. NIF Early Light (NEL) utilized four beamlines, with light originating with a nanojoule level pulse in the Master Oscillator Room (MOR) and amplified to the Joule level in the Injection Laser System (ILS), to the tens of kJ level in the main laser, and finally directed to the Final Optics System (FOS). The FOS uses two crystals, a 14mm KDP second harmonic generation (SHG) crystal and 10mm dKDP third harmonic generation (THG) crystal configured for Type I-Type II harmonic generation. A 7.7m wedged focus lens is used to separate the three wavelengths in the chamber and form the focus of the 3 ω laser within +50mm of the target chamber center (TCC). A target positioner is used to position various targets to within an accuracy of tens of microns at this location.

In just under two years of operations, over 400 system shots were taken. A list of the major shot campaigns taken during this period is shown in Fig. 2. Shots to operationally qualify the 1 ω main laser were completed late in 2002. Operational qualification of the 3 ω FOS was completed early in 2003. The sequence of qualification activities involved have been documented elsewhere [1]. After operational qualification of the 1 ω and 3 ω sections was complete, a number of performance campaigns were conducted to characterize NIF energetics and beam quality. This paper will focus on the highlights of these performance campaigns. In addition to these performance campaigns, several NEL campaigns supported target physics experiments. Results of two initial experiments have been published, the first measuring long scale length laser plasma interactions and a second to study the 3D Hydrodynamics of Jets at high mach numbers [2],[3].

Figure 2. Over 400 system shots have been taken on NIF's first four beamlines. NIF has demonstrated 2 ω and 3 ω performance over much of its operational range. Triangles indicate 3 ω shots and diamonds indicate 2 ω shots.

These performance campaigns have also served to demonstrate much of NIF's operation space in terms of both power and energy. The plot of power vs. energy in Fig.2 shows a series of constant pulse duration shots as straight lines. All series are square pulses with the duration as labeled, with the exception of the 3 ω shaped Haan ignition pulse and the 2 ω shaped Suter ignition pulse. Two series (5ns and Suter) were accomplished with a single beamline delivered to our Precision Diagnostic System (PDS). The 2 ω shots were accomplished by removing the THG and using a single 11mm

The energetics of each NIF beamline vary due to slight differences in beamline gain and transmission. In order to achieve precisely specified energies over a wide range of temporal shapes and pulse lengths, a computation model has been developed and utilized on every NIF shot. This Laser Performance Operations Model (LPOM) maintains a description of each beamline (i.e. optical losses, gain variations, amplifier and frequency conversion configurations). LPOM includes a 4 dimensional (3 spatial and 1 temporal) laser model that calculates energy extraction by solving the Frantz-Nodvik equation, and propagates the laser using a diffractive optics FFT code [5]. The LPOM uses feedback from NIF's standard diagnostics to specify and optimize laser setup (Fig.3). The LPOM model calculates the pulse shape required in each of the 48 PAMs to achieve the desired 3ω pulse shape and provides this to the MOR. Similarly, it calculates and specifies the energy required to be injected into each of the beamlines. It also performs an equipment protection function, by confirming that the laser has been set up as specified by analyzing the low energy ILS shots taken prior to each system shot.

Diagnostic Setpoints

Laser Setpoints

Input Sensor

Output Sensor

Target Chamber Diagnostics

Shot Settings

LPOM

Shot Goals

Diagnostic Feedback

Target Chamber Data (3 σ)

1 σ PD diagnostics

3 σ PD

Injection Data (1 σ)

Input Data (1 σ)

Output Data (1 σ)

Energy Attenuators

PABTS Splits

PAM

MOR

96% Mirror

B316

Roving Mirror

FOA

1m Diagnostics

2m/3m Diagnostics

Frequency converters

Multiple wavelength primary mirror

Target plane

Beam dump

NIF IOM

7.7m

Energy balance (1,2,3 σ)

Pulse shape (1,2,3 σ)

Alignment (1 σ)

Near-field imaging (3 σ : resolution <100 μ m)

WFOV calorimetry (3 σ)

Far-field imaging (3 σ : FOV: 4.4 mm @ focal plane)

Apertured calorimetry (3 σ)

The PDS 300 optics provide an attenuated high quality beam sample to NF, FF, energy and temporal diagnostics

Figure 3. NIF standard diagnostics are shown on the left. The PDS diagnostic hardware is shown on the right

Figure 4. NIF has generated 152 kJ of 1 ω light in a 10ns flat in time pulse with excellent fluence uniformity.

1.1 Full bundle (8 beamline) recent results

Starting in October 2004, NIF initiated the installation of the remaining optics into the NIF beampath, an activity that is scheduled for completion in 2009. In August of 2005 we completed the operational qualification of the first full 8 beamline bundle of NIF (Fig.4). We operated the full bundle with energies up to 152kJ at 1ω using a 10ns flat in time pulse. A single bundle of NIF (4% of the full system) exceeds the demonstrated 1ω drive energy of any presently operating fusion class laser.

2. NIF Laser Performance and Repeatability

The NEL 400-shot series demonstrated the performance level goals set for the ignition campaigns planned to start in 2010. Energies per beamline have exceeded goals with 26kJ demonstrated at 1ω , 11.4kJ at 2ω , and 10.4 kJ at 3ω (Full NIF equivalents of 5MJ, 2.2MJ, and 2MJ respectively). Near field beam uniformity is shown in Fig.5, with the standard deviation of the normalized fluence

Figure 5. Fluence distributions for 1ω shots (left), 2ω and 3ω shots (center). 1ω output beamline energies are plotted against injected energies (right). Results show variations in gains between inner and outer apertures.

distribution varying from 6.5% at 1ω to 17% at 3ω . Also shown are the recent 8 beamline results for a series of increasing energy 1ω shots used to commission Bundle 31 and calibrate LPOM. Using the lower energy shots for calibration, the LPOM balanced the high energy shots to within 1%, significantly exceeding the 3% energy balance goal. The LPOM model has automated NIF's ability to achieve a broad variety of pulse shapes. As an example for a flat pulse the LPOM specified the highly shaped pulse at the oscillator as shown in Fig.6. Saturation in PAM and the main laser result in a flat in time output into the Final optics. Pulse shapes after frequency conversion are shown for the 3ω and 2ω ignition pulses, and two shapes used in target experiments. The deviations between the measured shape and the goal were readily minimized, with a single iteration required to obtain a 3% RMS deviation in the 3ω ignition pulse shape.

Figure 6. LPOM automates pulse shaping and shot setup. A wide range of pulse shapes have been produced.

Target campaigns have been used to characterize the NIF laser. Laser quad synchronization was accomplished by arranging the focus of four 200 ps 200 J 3ω pulses in a line onto a Au coated silica disk. An x-ray streak camera (SXD) was used to record the relative pulse timing (Fig.7). The results from a first shot were used to adjust the mechanical length of a timing trombone in the PABTS, and a second shot to confirm the lasers were timed to within 6ps. The hydrodynamic jet campaign [2] required 17 identical energy shots. A histogram of a single beamline's energy in Fig.7 shows the energy repeatability is better than 2%, well within the 3% energy balance allocation. The same hydro test demonstrated a pointing stability of $<50\mu\text{m}$ RMS. A single focal spot profile obtained from a PDS measurement is convoluted with the pointing variation observed during this test. Analysis indicates the FWHM of the 17 shot average FF spot increases only 1% relative that of single beam.

Figure 7. NIF energy repeatability and beam synchronization. NIF pointing requirement ($<50\mu\text{m}$ RMS) was demonstrated in June 2004 Hydro Campaign. The single and average shot far field profiles are shown (left).

3. Beam Conditioning on NIF

Two of the three beam conditioning methods used on NIF are shown in Fig.8. Continuous phase plates (CPPs) are placed in the 1ω laser to create a controlled set of phase aberrations. The unconditioned NIF focal spot is about 200 microns at its 50% enclosed energy diameter. By controlling the magnitude of these aberrations, focal spots have been created that varied in their full width at half maximum (FWHM) from between $250\mu\text{m}$ to $800\mu\text{m}$ at the center of the target chamber. Smoothing by spectral dispersion (SSD) has also been accomplished by phase modulating the NIF oscillator at 17GHz and angularly dispersing the beam during amplification with a grating located in the ILS. Bandwidths of up to 150GHz have been demonstrated at 1ω and up to 270 GHz at 3ω . The focal spot profile of six identical shots with an $800\mu\text{m}$ CPP were taken on the PDS diagnostic (Fig.8). The resulting encircled energy fractions for all six shots are coincident on this plot. This level of repeatability was valuable to analysis of NEL target experiments and will facilitate ignition experiments.

Figure 8. Beam conditioning is used to modify the spatial uniformity of the laser focal spot. Encircled energy fractions match model predictions and are nearly identical for 6 shots.

Campaign	Date	Peak Power (TW)	CPP μm (FWHM)	Polarization on Smoothing	SSD (GHz 1σ)	Location
Initial CPP, SSD characterization	Aug-03	1.6	250	—	—	PDS
VISAR commissioning	Apr-04	0.3	800	—	—	TCC/PDS
90 GHz SSD demonstration	Apr-04	2.4	—	—	90	PDS
Hydrodynamic Evolution of Jets	Jun-04	2.0	800	—	—	TCC/PDS
Full Power 3σ Ignition (1.8 kJ full NIF equivalent)	Sep-04	2.6	—	Yes	—	PDS
High Temperature Hohlraum	Oct-04	2.5	250	Yes	—	TCC
LPI - Gas Pipes	Sep-04	1.2	350	Yes	90	TCC
D1 Point design	Oct-10	2.3	1000	Yes	90	—

- The LPI target campaign simultaneously demonstrated CPPs, SSD, and PS at half the NIF ignition power
- PS, CPPs, and SSD have all been demonstrated independently at full power

Specification	Beamline Requirement	Measured 3σ Performance	Current Beamline Status
Pulse energy	9.375 KJ	10.4 KJ	✓
Peak power	2.6 TW	2.6 TW (Haan)	✓
Focal spot size	600 μm	600 μm (80% energy enclosed in $< 275\mu\text{m}$)	✓
Temporal pulse dynamic	$\geq 50:1$	$>100:1$	✓
Temporal shape	Output Haan Pulse	Output Haan Pulse	✓
RMS deviation in power between beams	$\leq 8\%$ RMS deviation from specified power averaged over 2ns	Components consistent with requirement (energy balance and repeatability, 3σ temporal shape, beam synchronization, PAM stability, diagnostic accuracy/repeatability)	✓
Pulse length	21 ns	21 ns	✓
RMS focal spot position	$\leq 50 \mu\text{m}$ RMS	$\leq 50 \mu\text{m}$ RMS	✓
Prepulse	$<10^8 \text{ W/cm}^2$ (96 beams)	$<10^8 \text{ W/cm}^2$ (96 beams) (PAM measurement, modeled 1σ gain and 3σ conversion)	✓
Cycle time	$\leq 8 \text{ h}$ between full system shots	$\leq 3 \text{ h}$	✓

Figure 9. Beam conditioning demonstrations on NIF meet or exceed ignition requirements. NIF has demonstrated the performance levels required to support ignition experiment.

NIF's third beam conditioning technique, polarization smoothing, is described elsewhere in these proceedings [6]. A summary of NEL's beam conditioning campaigns is shown in Fig.9. These campaigns used the three techniques individually, or in combinations of two or all three as required to meet the objectives of target experiments or PDS tests.

4. Summary

The laser beam quality, alignment, timing, and pulse shaping requirements specified to achieve ignition are demanding. These specifications, shown in Fig.9 have all been demonstrated, on a beamline basis, during the NEL shot series. Commissioning results in 2005, demonstrating 150kJ/bundle, continue to support our expectation that NIF's laser will support ignition tests in 2010.

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