Performance Enhancements for the National Ignition Facility and Contributions to Inertial Fusion Energy

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Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is the National Nuclear Security Administration (NNSA) Stockpile Stewardship Program's (SSP) premier tool for High Energy Density (HED) Physics science, delivering data at levels of precision, pressure and temperature unparalleled in the world [1,2] and recently fusion experiments on the threshold of ignition [3]. With continued upgrades and plans for modest changes that would produce significant performance enhancements, the NIF will likely be the leading ICF facility for studying fusion ignition at full scale for at least another decade. Additionally, there are multiple areas of Inertial Fusion Energy (IFE) development where NIF can play an important role, ranging from testing of high gain advanced ignition schemes, to target chamber dynamics experiments, to materials damage, to Equation of State (EOS) studies of IFE-relevant materials (for target ablators or chamber walls) at extreme conditions, to data for the further development of code predictive capability. Furthermore, lessons from NIF in construction, operations, systems integration, and large facility architecture will provide a very useful steppingstone to any follow-on dedicated IFE facility.

An essential component of the NIF is its Mega-Joule (MJ) class solid-state laser driver– currently the world's largest and most energetic, and at time of completion was a 60x increase in energy from previous ICF lasers. The laser operates on target in the ultra-violet (UV) at the third-harmonic (3ω) of the $^4F_{3/2}$ to $^4I_{11/2}$ transition in Nd:glass. Since the completion of NIF construction in 2009 and its transition to a User Facility in 2013, the NIF laser has steadily continued to improve in performance and is now operating at its highest levels of energy, power, and precision. This trend – unique among past and current ICF lasers – is a result of sustained NNSA investments in optics and laser technology, coupled to a laser architecture designed to readily incorporate and leverage those investments.

Laser Precision

Motivated by mission need for increased rate of learning from experiments and a demand for higher energy and power to address stewardship issues, investments to date have focused mainly on lowering the damage rates and related operating costs for the UV section of the laser, and increasing the fidelity and reproducibility of the laser pulses delivered on target – i.e. higher shot rates at higher precision.

While the laser has been meeting its power balance and accuracy requirements ~90% of the time, improvement beyond this performance remained challenging without hardware upgrades, particularly in the low-power picket where inaccuracies produced in the laser front-end are effectively doubled in the 1ω amplifier and harmonic converter [1]. Imbalance or inaccuracies in the picket of the ignition pulse seed early-time low-mode asymmetries in the implosions, motivating tightening of tolerances on power balance and accuracy. Analysis has shown that these tighter tolerances could be achieved by updating the Master Oscillator Room (MOR) to currently available, state-of-the-art technologies and reducing gain uncertainty in the preamplifier section. This program was launched two years ago and has recently enabled higher-quality implosions.

The first modernization phase of the MOR pre-shaped pulse generation system was successfully concluded in the summer of 2021 with the replacement of most of the fiber-based components, acousto-optic

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modulators, dual optical amplifiers, etc... spanning from the oscillator output to the input of the pulse shaping system. This new architecture demonstrated 2-3x shot-to-shot stability improvements of the pulse train before shaping while also providing more flexibility with a fourth color for NIF, allowing the 50° cone to have a wavelength different from the 44.5° one.

In parallel, an aggressive refurbishment campaign of our Multi-pass Power Amplifier (MPA) –the last amplification stage (Joule-level) in the laser front-end [4]– was conducted. The shot-to-shot gain stability of this amplifier employing a flashlamp-pumped LHG-8 Hoya Nd:glass rod amplifier of 32 mm in diameter was improved from 5% rms to better than 3% rms. Additional improvements are possible with a diode-pumped preamplifier, proposed for deployment in FY28.

Finally, during its last phase in early FY23, the pulse shaping system will be modernized to a High-Fidelity Pulse Shaping (HiFiPS) system, reaching the full potential enabled by the previous MOR modernization. The combination of these two upgrades was shown on a prototype system to provide about 4x performance improvements especially for the short-term stability of the picket for a high-contrast ignition pulse [5].

Power and Energy

In response to growing interest in understanding the ultimate limits of the current NIF architecture for ICF, other stewardship applications, and IFE, we have assessed the laser performance that can be achieved with modest enhancements from the current operating point at 1.9 MJ, 500 TW, already beyond the initial NIF design requirements. This assessment relies on experience gained during various laser performance campaigns conducted over the past years with a limited number of beamlines and experiments. Those experimental results, along with progress in terms of laser performance modeling and laser codes give us confidence that NIF can potentially be operated in a sustainable way at elevated energies and powers.

Mostly, we are relying on the learnings of the Performance Quad Campaign [6] exercising a single quad of NIF (Q45T) at elevated energy ignition-relevant hydro-scaled versions of CH “high-foot” pulses [7] with energy up to 13.5 kJ / 2.5 TW at 3ω per beamline, equivalent to 2.6 MJ / 480 TW for full-NIF operations. This ~45% energy increase from baseline is enabled by: 1/ actively flattening the beam near field using the Programmable Spatial Shaper [8] 2/ reducing the passive losses by replacing polarization rotators Potassium Dihydrogen Phosphate (KDP) crystals with deuterated ones and uncoated grating debris shields for beam sampling with anti-reflection coated ones 3/ increasing damage resistance with Advanced Mitigation Process version 3 [9-11] 4/ using fused silica debris screen (FSDS) [12] and finally managing the debris making their way around the disposable debris shields. Follow-up edge-filamentation mitigation and debris mitigation experiments have showed encouraging results and give us confidence NIF energy can be safely increased in the short-term to 2.2 MJ, 450-500 TW, followed by a second mid-term phase delivering 2.6 MJ, 500TW after some NIF deferred-maintenance and sustainment activities are completed.

Towards higher peak power, the capability for present HDC-type pulses can be pushed upward to the range of 2.6 MJ, 600 TW – mostly limited by B-integral– with modest changes affecting few of the NIF components, among which: re-optimizing the final optics configuration for power, restoring the power amplifier section to its as-built small-signal gain capability, and operating the flashlamps at 23% explosion fraction –within safe limits of the existing pulsed power system.

Toward higher energy, the capability for longer CH-type pulses can be extended to 3 MJ, 450 TW –mostly limited by UV optics damage–with similarly modest enhancements also including fielding additional amplifier slabs in existing available slots of the NIF Main Amplifiers.

For all the upgrades above the current operating point, laser-plasma mitigation techniques are investigated.

Ignition and High Gain

While the NIF is a scientific exploration facility, and very different from what would be needed for an IFE power plant, the NIF provides a uniquely opportunity to experiment at “fusion scale.” Experiments are ongoing to demonstrate full ignition (via the NAS 1997 definition of “Fusion Energy/Laser Energy >1”) with the current NIF capabilities. Further enhancements to the facility will therefore provide additional laser power and laser energy margin to experiment with novel target designs for higher gain. Reactor-scale gain will require comprehensive understanding of laser-plasma interaction physics, hohlraum physics (for

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indirect-drive designs), ablation physics, instabilities and mix, symmetry control, real-world fabrication and alignment tolerances, and temperature control, all of which NIF provides a unique full-scale capability with which to experiment. Studies of burn physics, implosion characteristics, sensitivity studies, performance cliffs can also be carried out. Specifically, in the laser indirect drive scheme, experiments will be needed to explore the robustness of IFE target physics to laser delivery, illumination geometry, radiation asymmetries, engineering features, capsule fabrication surface finish, cryogenic layering quality, etc. With some (non-trivial) modification to the facility, 2ω implosions and implosions in the polar-direct drive configuration are also an option.

An ongoing effort is the benchmarking and improvement of our simulation codes and theoretical models for ICF. This is a core component of the NIF's SSP mission, and as there is much overlapping physics, will be very beneficial to IFE. The enhanced NIF will allow for testing and validation of these models at even more extreme plasma conditions, and continued improvements to the laser will allow for more precise laser delivery to further enhance the fidelity of experiments.

Chamber dynamics

Chamber dynamics includes issues of (1) IFE target emissions such as radiation and debris, (2) first wall materials response to debris and radiation, (3) gas dynamics covering chamber clearing and beam propagation. Targeted experiments, potentially requiring the use of specialized diagnostics (such as RadChem) can be conducted to collect debris, or witness plates can provide information on the responses of candidate wall materials to x-ray or neutron irradiation. The impact of ablation impulse on wall stresses or material erosion can be studied in single-shot mode.

Materials damage

A full-scale IFE plant would suffer from repeated pulsed high doses of neutrons. While the NIF cannot emulate the full dose rate due to its limited shot rate, a single NIF implosion can provide useful information of the basic physics of radiation effects in materials. From Tobin et al. [13], this includes "(a) cascades (morphology, size, fraction of free and clustered defects, impurities), (b) microstructural evaluation, (c) electrical properties, (d) optical properties (fiber optics, coatings) and (e) molecular cross-linking. The repetitive regimes of mechanical, thermal, and radiation loads will require experimentation and study, particularly in the context of continuous erosion, re-deposition, and continuous exposure to particles, radiation and plasma.

The impact of pulsed irradiation on the mechanical properties of materials is currently a gap in our knowledge base.

Materials Properties and EOS of IFE-relevant materials

Novel materials will need to be developed for fusion energy, for next-generation targets and diagnostics, drivers, and chamber walls and blankets. At the high temperature, high density, high pressure (10-100 Mbar) conditions common to IFE, there are significant uncertainties in phase transition rates, the equation of state, the conditions at which phase boundaries occur, and the response of materials to gradients and rapidly evolving temperature and electromagnetic fields. These materials and their properties will have enormous implications on the design of the reactor, its economics, and the physics of the high gain target (e.g., IFE targets initially start at ambient conditions then make transitions through the warm dense state to hot dense plasma, with fundamental changes in atomic and electronic structures under compression and heating). The NIF provides an unprecedented capability to carry out these investigations, with the high precision of pulse shaping and laser delivery, and state-of-the-art diagnostics.

Continued upgrades, improvements, and innovations to the NIF facility are planned over the next few years, including a potential extension of the NIF laser energy to 2.6 MJ. These improvements will ensure that the NIF remains one of the premier tools for HED and ICF science. As such, NIF's capabilities and the experiments undertaken there can uniquely contribute to answering key questions for IFE, and the NIF will play an important role as a steppingstone facility toward an IFE power plant.

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