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INERTIAL CONFINEMENT FUSION

ICF Quarterly Report

January–March 1995
Volume 5, Number 2

*The Role of the National
Ignition Facility in the
Development of Inertial
Fusion Energy*

*Laser–Plasma Interactions
in Large Gas-Filled
Hohlraums*

*Evolution of Solid-State
Induction Modulators
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*Terminal-Level
Relaxation in Nd-Doped
Laser Material*

*Testing a New Multipass
Laser Architecture on
Beamlet*

*Four-Color Laser Irradiation System
for Laser–Plasma Interaction Experiments*

The ICF Quarterly Report is published four times each fiscal year by the Inertial Confinement Fusion Program at the Lawrence Livermore National Laboratory. The journal reports selected current research within the ICF Program. Major areas of investigation presented here include fusion target theory and design, target fabrication, target experiments, and laser and optical science and technology. Questions and comments relating to the technical content of the journal should be addressed to the ICF Program Office, Lawrence Livermore National Laboratory, P.O. Box 5508, Livermore, CA 94551.

The Cover: The 3 ω far-field images of a Nova beamline show the potential improvements in uniformity with the beam-smoothing techniques planned for the National Ignition Facility (NIF). From top to bottom, the three smaller images show (1) the original Nova far-field image without beam smoothing; (2) the effects of a random phase plate (RPP); and (3) the superposition of four different-frequency beams each with an RPP. The center image shows the addition of smoothing-by-spectral-dispersion to each beam with the RPP. The article "Four-Color Laser Irradiation System for Laser-Plasma Interaction Experiments," p. 130, describes the implementation of these smoothing techniques on Nova. The article "Laser-Plasma Interactions in Large Gas-Filled Hohlräume," p. 97, presents the effect of beam smoothing on targets with plasma conditions similar to those for the NIF.

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INERTIAL CONFINEMENT FUSION

Quarterly Report

January–March 1995
Volume 5, Number 2

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The Role of the National Ignition Facility in the Development of Inertial Fusion Energy 87

As part of its national security mission to demonstrate inertial fusion ignition, the National Ignition Facility (NIF) has the potential to contribute to the development of inertial fusion energy (IFE). As a national users' facility, it could be used for weapons physics and effects testing, IFE experiments, and science applications. We also find that the NIF could provide important data for (a) target physics experiments useful to a variety of IFE driver and target options, (b) generic IFE target-chamber phenomena and materials responses to target emissions, (c) experiments on prototypical IFE fusion power technologies, and (d) tests of prototypical IFE targets for low-cost manufacture and their associated injection and tracking methodologies.

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We are developing an accelerator power source that is switched entirely by field effect transistors (FETs). This transistorized approach to accelerator power is motivated by our interest in a heavy-ion recirculator, which requires agile pulses that vary at a high repetition rate. The ability to explore our interests in an all solid-state accelerator is made possible by recent advancements in FET power devices. As a result, we have built several prototype sources that are fast, compact, and powerful.

The National Ignition Facility Project 110

The Department of Energy's (DOE's) proposed National Ignition Facility (NIF) is a critical element of the Defense Programs' Stockpile Stewardship and Management Program. It is the scientific cornerstone in maintaining confidence in America's nuclear deterrent capability in light of arms control agreements and absence of underground nuclear testing. The NIF laser would also provide significant research advances in fusion energy and other scientific and technological fields. Those participating in the Project will include Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, and the Laboratory for Laser Energetics at the University of Rochester.

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This article offers a comprehensive evaluation of the magnitudes and impact of the terminal-level lifetime in various Nd-laser systems. Although the reduction in extraction efficiency is >30% for some Q-switched Nd:YLF oscillators, it is confirmed to have a very minor influence on the performance of Nd:glass-based fusion lasers.

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Four-Color Laser Irradiation System for Laser-Plasma Interaction Experiments 130

This article discusses the laser science and performance of a Nova beamline modified to simulate the focal geometry and beam-smoothing design proposed for the NIF. This system is used to study the scaling of parametric instabilities in NIF-like plasmas.

Testing a New Multipass Laser Architecture on Beamlet 142

We completed proof-of-principle tests on Beamlet for a variation on the multipass laser architecture that uses a device we call the Reverser. The Reverser is used in the baseline design for the French Megajoule laser and in a backup design for the U.S. National Ignition Facility. Our Beamlet experiments in 1994 demonstrated the basic viability of the concept, but they also identified a vulnerability to damage by back-reflected light. However, a modified design provides much greater tolerance to back-reflections that we plan to test in FY 1996.

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FOREWORD

This issue of the *ICF Quarterly* has seven articles conveying a variety of developments in the Inertial Confinement Fusion (ICF) program at Lawrence Livermore National Laboratory (LLNL). These developments include plans for the National Ignition Facility (NIF); experimental work in support of NIF, using existing LLNL facilities; advanced planning for an ICF application—inertial fusion energy (IFE); and a laser-science topic relevant to a wide range of laser research, including lasers for ICF.

Two articles discuss advancements toward ICF as an energy source for commercial power. In "The Role of the National Ignition Facility in the Development of Inertial Fusion Energy," the author outlines those research and development tasks needed for inertial fusion energy (IFE) that could be addressed by the NIF. In "Evolution of Solid-State Induction Modulators for a Heavy-Ion Recirculator," the authors describe developmental progress on high-powered modulators for heavy-ion accelerators, which are a promising driver candidate for an IFE reactor.

Indirect-drive targets for NIF will likely use low-density, low-Z gasses inside the hohlraums to maintain irradiation symmetry by reducing the expansion of the interior wall of the hohlraum. However, stimulated Brillouin scattering (SBS) in these gasses potentially reflects large amounts of the incident laser pulses. Two articles describe experimental efforts which resolve this issue. In "Laser-Plasma Interactions in Large Gas-Filled Hohlraums," the authors discuss Nova experiments to measure SBS reflectivity for NIF-relevant conditions. In "Four-Color Laser Irradiation System for Laser-Plasma Interaction Experiments," the authors describe the modifications to Nova that were necessary to create the NIF-relevant conditions.

Two of the articles are directly related to planning for the NIF. "The National Ignition Facility Project" presents the design criteria, the laser system design, target area design, project schedule, and costs; and "Testing a New Multipass Laser Architecture on Beamlet" introduces a potential variation to the NIF laser multipass architecture and describes proof-of-principle tests on the Beamlet laser facility.

The lifetime of the terminal level in 4-level laser systems affects extraction efficiency and is therefore one of the parameters used to select potential solid-state laser host materials. In "Terminal-Level Relaxation in Nd-Doped Laser Materials," the authors present and compare three independent methods for measuring this lifetime.

James E. Murray
Scientific Editor

THE ROLE OF THE NATIONAL IGNITION FACILITY IN THE DEVELOPMENT OF INERTIAL FUSION ENERGY

B. G. Logan

Introduction

We have completed a conceptual design¹ for a 1.8-MJ, 500-TW, 0.35- μm solid-state laser system for the National Ignition Facility (NIF), which will demonstrate inertial fusion ignition and gain for national security, energy, and science applications. Figure 1 shows the size and

scale of the facility, which is the minimum size required to achieve inertial fusion ignition. The technical goal of the U.S. Inertial Confinement Fusion (ICF) Program as stated in the current ICF Five-Year Program Plan² is "to produce pure fusion ignition and burn in the laboratory, with fusion yields of 200 to 1000 MJ, in support

FIGURE 1. The 192-beam National Ignition Facility will demonstrate inertial fusion ignition for defense, energy, and science missions.

(40-00-0294-0498Zpb02)

of three missions: (1) to play an essential role in accessing physics regimes of interest in nuclear weapon design...; (2) to provide an above-ground simulation capability for nuclear weapon effects...; and (3) to develop inertial fusion energy for civilian power production." This article addresses the third goal—the development of inertial fusion energy (IFE).

The NIF plays an important role in IFE development. In October 1994, U.S. Department of Energy (DOE) Secretary O'Leary made the official decision (Key Decision 1, or KD1) to proceed with the NIF. The achievement of inertial fusion ignition, NIF's primary near-term goal, is a key to developing IFE. In addition, the NIF will provide the means of optimizing the conditions for minimum driver energy, power, pulse shape, and symmetry required to get ignition and gain in a cryogenic deuterium-tritium (DT) capsule. This is the most difficult and important test of the feasibility of IFE with any driver. In fact, the 1990 National Academy of Sciences (NAS) review³ of the ICF Program recommended glass lasers, as used in the NIF, as the only driver sufficiently mature to proceed with an ignition demonstration facility (i.e., the NIF). The review also noted that ignition in the NIF would be a prerequisite to any future inertial fusion facility, even with other, future drivers.

The development of IFE requires both the NIF and a parallel development program in efficient, high-pulse-rate drivers. The NIF, due to its defense mission, is not required to provide laser pulses more frequently than several hours apart; to produce IFE in future power plants, about 5 pulses per second will be required. In addition to a higher pulse rate, an IFE power plant driver must be more efficient than the glass laser driver selected for the NIF. Thus, the NAS has also recommended continued development of other driver technology for defense and energy applications beyond the NIF. As an example, the DOE recently approved KD1 for the first half of the Induction Linac Systems Experiments (ILSE)⁴ to demonstrate the feasibility of heavy-ion accelerators as a candidate IFE driver.

This article reports a variety of potential contributions the NIF could make to the development of IFE, drawn from a nationally attended workshop⁵ held at the University of California (UC) at Berkeley in February 1994. In addition to demonstrating fusion ignition as a fundamental basis for IFE, the findings of the workshop, summarized later in this article, are that the NIF could also provide important data for target physics and fabrication technology, for IFE target chamber phenomena such as materials responses to target emissions, and for fusion power technology-relevant tests. The NIF's contributions to IFE in all

these areas will help define the corresponding design requirements for an integrated IFE technology test facility to follow the NIF, referred to by the Fusion Policy Advisory Committee as the Engineering Test Facility (ETF).⁶ In particular, tests of both direct- and indirect-drive targets on the NIF will be critical to the selection of the ETF driver and of the targets that would be compatible for the chosen ETF driver. Figure 2 shows that the NIF plays a central role in decisions for any follow-on ICF facility, including the ETF, the Laboratory Microfusion Facility (LMF),^{2,7} and a possible combined ETF/LMF sharing a common driver.⁸ This is true even for other driver technology options for the ETF shown in Fig. 2, since the NAS review³ noted that the most critical target physics issues (capsule symmetry, hydrodynamic stability, and fuel mix) that would be addressed in the NIF are common to all ICF and IFE target options.

Summary of the 1994 NIF-IFE Workshop

Scope of the Workshop

Sixty-one participants from 17 U.S. organizations attended the NIF-IFE workshop convened at UC Berkeley on February 22–24, 1994. The participants were briefed on the NIF laser and target area experimental capabilities, and then were asked to identify possible experimental approaches for the NIF to address critical IFE issues apart from driver development (since drivers other than the glass laser type used by the NIF will be developed for IFE). Nondriver-specific IFE issues in the areas of target physics, fusion chambers, fusion power technology, and target technology were drawn from recent power plant studies.^{9–11} Rather than test specific IFE power plant designs, the NIF experiments will be used to provide data to improve understanding of generic target and fusion chamber physics and technologies relevant to IFE. Then, by experimentally benchmarking various design codes using the NIF data, those codes could be applied to many specific designs for future IFE power plants and for defining corresponding tests in the ETF following the NIF.

The workshop participants considered possible NIF contributions in four IFE areas: target physics, target chamber dynamics, fusion power technology, and target systems. Examples in each of these areas will be discussed in the following sections. The participants considered experiments that were generally consistent with the flexibility of the NIF conceptual design.¹ However, recognizing the preliminary nature of the proposed IFE experiments, the participants recommended more

detailed designs of these experiments to adapt them to the NIF target chamber design, and to define IFE development needs prior to the possible fielding of such experiments in the NIF.

IFE Target Physics Experiments

Many of the most important target physics issues for IFE will be addressed by the planned experiments on the NIF for ICF ignition and defense sciences, using the flexibility of the NIF laser system. Each of the 192 beamlets amplify independent light input pulses, allowing significant flexibility to produce variable pulse shapes up to 20 ns and in different illumination geometries, including both direct- and indirect-drive capabilities. Figures 3 and 4 show two possible configurations of the NIF target area for indirect- and direct-drive experiments, along with some schematic examples of targets that might be tested in each beam configuration. For example, in Fig. 3, the indirect-drive target is relevant to heavy-ion IFE concepts,¹¹ and in Fig. 4, the direct-drive target shown is relevant to Fast Ignitor¹² and Diode-Pumped Solid State Laser¹³ IFE options. Figure 4 also shows another target using the direct-drive NIF laser beam configuration that could simulate indirect-drive light-ion-type targets. The NIF ignition target physics program will explore a range of target yields

and gain, studying capsule implosion characteristics and symmetry requirements, and capsule ignition and burn physics. In parallel with this effort, there will be development and benchmarking of ICF theoretical models and simulation codes also needed for the understanding of target physics requirements for IFE with laser as well as other drivers, and for direct-drive as well as indirect-drive targets.

Beyond the target physics experiments planned for the initial ignition campaign for ICF and defense applications, NIF can also perform experiments to explore target physics issues specific to IFE. Table 1 lists IFE target physics issues for generic ion and laser drivers, and for direct- and indirect-drive illumination geometries. The spaces marked with an "X" in Table 1 list those target physics issues that could be largely resolved using the NIF capabilities; the NIF can resolve most IFE target physics issues. The Omega Upgrade, PBFA II, and other ICF facilities around the world will be able to address the remaining issues. The completion of these experiments will provide the target physics basis to proceed with an ETF.

Figure 5(a) shows a typical indirect-drive target for IFE using heavy-ion drivers, compared with a typical target planned for the NIF ignition tests shown in Fig. 5(b). The heavy-ion IFE target in Fig. 5(a) is based on the work of Ho and Tabak.¹⁴ The driver energies, target

FIGURE 2. The national ICF/IFE program strategy. The NIF provides data critical to driver and target decisions for the ETF facility options, providing integrated IFE technology development. Development of a suitable chamber technology in the ETF, by upgrading one of the ETF chambers to accommodate a higher average fusion power, can lead to a demonstration power plant by 2025. Gray lines indicate an optional path. (05-00-0295-0387pb01)

fusion yields, capsule convergence ratios, in-flight aspect ratios, capsule implosion speed, maximum compressed fuel density, and maximum hohlraum temperatures for each case are compared in the table immediately below the target cross sections [Fig. 5(a)]. The comparison shows that the NIF targets will achieve target parameters either comparable to, or more challenging than, those required for the IFE target.

Target Chamber Dynamics Experiments

Three of the basic target chamber dynamics issues of IFE identified from past IFE power plant conceptual design studies⁹⁻¹¹ that can be addressed on the NIF are (1) characterization of IFE target soft x-ray and debris emissions, (2) the response of first-wall materials and protective wall fluids to those target emissions, and (3) the subsequent gas dynamics of the vapor blow-off in chamber clearing, vapor condensation, and vacuum recovery. The NIF has a larger laser energy than the existing Nova laser at LLNL, so that tests of the above three issues are possible on material samples large enough to exhibit temporal and spatial scales more relevant to IFE, and at energy fluxes representative of a power plant. A typical NIF target output at a full target yield of 20 MJ will put $\sim 48 \text{ J/cm}^2$ of soft x rays and target debris plasma on surfaces $\sim 1 \text{ m}$ away from the target, similar to the deposition from 350-MJ yields on walls $\sim 4 \text{ m}$ away in an IFE power plant target chamber. Thus,

the NIF can provide a reduced-scale test chamber environment representative of an IFE power plant for a limited number of shots. There are also a number of one- and two-dimensional (1- and 2-D) hydrodynamics and radiation-hydrodynamics codes that could be calibrated and improved with NIF chamber dynamics data, including CONRAD,¹⁵ HYADES,¹⁶ SRIPUFF,¹⁷ L2D,¹⁸ PHD-4,¹⁹ and TSUNAMI.¹⁹ To acquire the data needed for these codes, NIF chamber dynamics experiments will need new diagnostics to measure the ion velocities (energies), species, and flux originating from targets, and modest improvements of existing instruments to measure gas dynamics and condensation phenomena (such as fast-response pressure transducer arrays).

Figure 6 shows an example of a possible NIF experiment designed to test the predictions of a chamber dynamics code such as TSUNAMI. The test assembly consists of a conical chamber in which a test material at the back surface is ablated by x rays that are admitted through a hole in the larger front plate. The conical shape will provide a better test of the 2-D modeling capability of the codes than would a cylindrical chamber. The high fluences attainable on the NIF will permit the use of a relatively long chamber (for longer time-scale gas dynamics) while still providing a large amount of ablated vapor from the rear surface.

The table in Fig. 6 immediately below the drawing shows how this NIF experiment is a relevant test to IFE first-wall designs (OSIRIS, HYLIFE-II and CASCADE),

FIGURE 3. The 192 beams of the NIF configured for indirect-drive are distributed around two pairs of cones with a vertical axis of symmetry. Examples of indirect-drive targets are shown on the right. (40-00-0894-3299pb01)

NIF indirect-drive laser target

Heavy-ion-relevant simulation target

Doped gas or foam

in the areas of x-ray fluence, ablation depth, and time scale for the ablation of material. Passage of the expanding vapor is recorded by pressure transducers placed along the length of the cone. This information will enable the confirmation of model predictions of velocities and shock reflection strengths (from the plate at the large end of the cone). The experiment will also allow estimates of condensation rates to be obtained from the reduction in pressures at later times. Distribution of condensed material will be determined from post-shot analysis of the cone's inner surface.

Examination of the ablated disk after the shot will determine the amount of material ablated, an important input parameter for the gas dynamics calculations.

Fusion Power Technology Experiments

Fusion power technology (FPT) in an IFE power plant includes components whose primary functions are energy conversion, tritium production and processing, and radiation shielding. The dominant issues for FPT in IFE power plants involve the nuclear and material

NIF direct-drive laser target

Light-ion-relevant simulation target

FIGURE 4. By moving 24 final beam optics assemblies to the equatorial plane and repointing each beam, direct-drive experiments with beam clusters illuminating the capsule on 48 spherically symmetric points can be performed. The light-ion simulation target is a potential indirect-drive target using a doped-foam soft-x-ray converter, but uses the NIF direct-drive-illumination configuration for symmetry reasons. (40-00-0894-3299pb02)

TABLE 1. IFE target physics issues for ion and laser drivers, direct and indirect drive. An "X" indicates issues that can be largely resolved with the NIF capabilities.

	Ion drivers		Laser drivers	
	Indirect	Direct	Indirect	Direct
Usability of a variety of pulse shapes	X	X	X	X
Radiation flow, illumination geometry, and internal pulse shaping	X		X	X
Sensitivity of capsules to radiation asymmetry	X		X	X
Materials issues (capsule, hohlraum, ablator)	X	X	X	X
Fabrication surface finish and precision	X	X	X	X
Capsule mounting and injection	X		X	X
Power vs energy trade-offs	X		X	X
Output spectra and shielding	X	X	X	X
Reduced tritium	X	X	X	X
Advanced targets	X	X	X	X

performance of components so as to achieve economic competitiveness and to realize safety and environmental advantages. The NIF will provide valuable information to IFE FPT, both with the demonstrated performance and operation of the basic facility itself and with data obtained from experiments designed specifically to test

	Heavy-ion fusion target	NIF target
Driver energy (MJ)	4 to 6	1.8
Yield (MJ)	300 to 450	15
Convergence ratio	27	36
In-flight aspect ratio	40	45
Imploded speed (cm/ μ s)	32	41
Max density ρ (kg/m ³)	6.5×10^5	1.2×10^6
Max hohlraum temp (eV)	260	300

FIGURE 5. Key target parameters compared between (a) a heavy-ion target design for an IFE power plant, shown in schematic views, and (b) a typical NIF ignition target. (70-37-0894-3150pb04)

FPT issues. The NIF's relevance to FPT is in its prototypical size and configuration and its prototypical radiation field (neutrons, x rays, debris) spectra and intensity per shot. The most important limitation of the NIF for FPT experiments is the low repetition rate (low neutron fluence). The most important contributions of NIF to FPT development for IFE are the following:

1. Fusion ignition.
2. Design, construction, and operation of the NIF (integration of many prototypical IFE subsystems).
3. Viability of first-wall protection schemes.
4. Dose rate effects on radiation damage in materials.
5. Data on tritium burnup fractions in the target, some important tritium inventory and flow rate parameters, and data on achievable tritium breeding rate in samples.
6. Neutronics data on radioactivity, nuclear heating and radiation shielding.

Figure 7 depicts an example of a possible NIF experiment addressing item 3: a NIF experiment to study the recovery of a protective liquid metal film flow following the effects of pulsed heating by the target output of soft x rays, target plasma debris, and neutrons, analogous to the first-wall protective film invoked in the Prometheus study.¹⁰ In addition to soft x rays and target debris, the NIF target would generate 10^{19} 14-MeV neutrons/shot, sufficient to test liquid jet breakup at 25 to 50 cm distance due to isochoric neutron heating representative of the liquid-wall HYLIFE-II IFE concept.¹²

	NIF experiment	IFE first wall		
		OSIRIS	HYLIFE-II	CASCADE
X-ray fluence at radius	200 J/cm ² 0.4 m	60 J/cm ² 3.5 m	2000 J/cm ² 0.5 m	60 J/cm ² 3.1 m
Ablation	20 μ m	20 μ m	200 μ m	3 μ m
Time scale	40 μ s	100 μ s	50 μ s	90 μ s

FIGURE 6. An experiment on the NIF to calibrate gas dynamic codes. The x-ray fluence, ablation depths, and time scales for the NIF experiment shown are comparable to many cases of interest in IFE first-wall concepts. Where the parameters differ, the NIF experiments can still be useful to calibrate the computational model. (05-00-0894-3048pb02)

One of the more unique features the NIF can provide is a very high dose rate in each shot that can be equivalent to 10–1000 displacements per atom per second. Even with single shot operation, the NIF will be useful for basic physics of radiation effects in materials. Examples include cascades (morphology, size, fraction of free and clustered defects, impurities), microstructural evaluation, electrical properties, optical properties (fiber optics, coatings), and molecular cross linking. In some low-activation materials like SiC, we predict that such a large number of damage sites can be produced in each pulse that the collection of interstitial atoms produced from one damage site can combine with the vacancies created not only at that site, but also from nearby sites. This would lead to higher recombination rates of interstitial atoms with vacancies than the steady-state situation. The very high neutron dose rates provided by the NIF allow these dose rate effects to be tested.

One predictive technique that can calculate and interpret material responses to NIF neutron damage is called Molecular Dynamic Simulation (MDS).²⁰ MDS calculates responses at an atomic level by quantifying the response of a 3-D matrix of atoms to so-called “knock-on” atoms that impinge on the matrix from a range of angles and with a range of energies, as would result from an incident neutron flux. Potentially, MDS capabilities include predicting for a material the number of vacancies and interstitials that will result from a neutron irradiation pulse, the cluster fraction of defects, atomic mixing and solute precipitation, and phase transformations.

IFE Target Systems

The workshop separated IFE target systems topics into three broad areas: IFE target fabrication, IFE target transport, and IFE target systems. The following subsections discuss each of these areas, including some of the issues that must be resolved to successfully develop an IFE power plant, and examples of experiments that could be done in the NIF to help resolve these issues.

IFE Target Fabrication

IFE target fabrication includes target materials and configuration selection, capsule production, hohlraum production, target assembly, characterization, fill, and layering. The targets that fuel an inertial fusion power plant based upon the indirect-drive approach will be similar to the ignition and high-gain targets developed for the NIF. There are differences, however. The IFE fuel capsules will be two to three times larger in diameter. For a laser driver, hohlraums will scale similarly, but ion targets will require substantially different hohlraums and x-ray converters. As with NIF high-gain targets, IFE targets will be cryogenic. The major issues associated with developing these targets, broadly stated, are (1) assuring the target component quality specifications as sizes increase and fabrication techniques change; (2) assuring a fast enough fuel fill rate to be able to maintain the plant’s tritium inventory at acceptable levels; and (3) developing fabrication and inspection techniques that produce high-quality, economically viable targets. A fourth issue, dealt with in the section below on target transport, is providing targets that can

FIGURE 7. Example of a protective liquid metal film flow experiment on the NIF (not drawn to scale). The debris window might be removed to study effects of soft x rays and debris separately. (05-00-0295-0386pb01)

withstand the accelerations attending chamber injection and that can withstand the chamber environment once injected.

Table 2 lists more fine-grained issues that must ultimately be addressed to produce and use IFE targets, and an assessment of the importance of the NIF in developing solutions. Those that require full scaling to IFE sizes, such as the effect of cryogenic layer quality on gain, cannot be completely tested to ignition on the NIF. Those that do not require such scaling, such as materials choices and automated cryogenic assembly techniques, should be tested on the NIF. The NIF would be a unique test bed, since the relevant test of success is ignition.

IFE Target Transport

Under the category of target transport, we include both transport from the target fabrication facility to the target injector and the injection of the target to the point of ignition. Completed targets will be stored in a cryogenic storage system prior to transport to the injector and must be kept at constant temperature throughout the entire transport and injection process. Even after the target leaves the injector and enters the chamber environment, the allowed temperature rise of the cryogenic fuel is very low, estimated to be less than 0.2 K. Targets must also survive the acceleration process. The

target transport issues for IFE are listed in Table 2. As indicated, the NIF will be useful for addressing many of these issues.

IFE Target Systems

Target fabrication and injection systems for IFE will require developments listed in Table 3. For each target development activity, Table 3 indicates whether the development is needed for the ICF ignition campaign as well as for IFE ("Needed for NIF"), needed specifically for IFE and able to be tested in the NIF ("Needed for NIF-IFE experiments"), or needed specifically for IFE beyond that which is to be tested in the NIF ("Needed for IFE"). The last column on the right in Table 3 indicates, where applicable, in which ongoing ICF program each target development activity would be included. The label "B—target fabrication development activity" indicates that the activity would be included as part of the present ICF base program for development on noncryogenic targets, and the label "D—National Cryogenic Target (R&D) Research and Development Program" indicates the activity would be part of the ICF Program to develop smooth DT cryolayer targets, initially for the Omega Upgrade direct-drive tests and later for the NIF. Some of the target fabrication issues must be faced early to field ignition targets on the NIF and will require continuation and expansion of current

TABLE 2. IFE target fabrication and target transport issues.

	NIF usefulness*	NIF uniqueness**
Target Fabrication		
Low-cost mass-production techniques for capsules and their effect on quality, materials choice and gain	2	3
Low-cost mass production techniques for laser driver hohlraums	2	3
The effect of cryogenic layer quality on gain	2	3
Automated cryogenic assembly techniques	3	3
Fast fill techniques for low tritium inventory	2	3
High-throughput quality inspection techniques	2	3
Target Transport		
Injection techniques for high-rep-rate cryogenic operation	0	1
Time and space accuracy and sensing	0	1
Integration	2	1-2
Target survival under acceleration	2	3
Thermal protection and temperature control	2	2
Chamber environment effects on trajectory	1-2	3
Demonstration of high-rep-rate operation	2	3

* Usefulness: 3 = complete resolution; 2 = partial resolution; 1 = useful information; 0 = no use.

**Uniqueness: 3 = NIF unique and required; 2 = NIF not unique but could be used; 1 = issues addressed better or cheaper in new facility; 0 = issues addressed better or cheaper in existing facility.

target development activities. The proposed testing in the NIF of IFE-relevant targets will require that those targets first be developed. Relatively little has been done in that area to date, and the workshop recommended a program of target design and fabrication R&D to have prototypical IFE targets ready for testing on the NIF. This testing will come after the NIF primary mission of ignition has been achieved, which is about 5 yr after the startup of the NIF.

Cryogenic ignition experiments on the NIF will require cryogenic target transport systems. Development of these systems will benefit greatly from work on similar systems being developed for OMEGA Upgrade. IFE will require sophisticated target injection and tracking systems that have yet to be seriously studied. IFE target experiments on the NIF will require that a portion of the development needed on these systems be done. The workshop recommended that IFE tracking and pointing studies be done now to define the systems that could be tested on the NIF, followed by development of the required hardware for these experiments. These experiments would logically follow the static tests of IFE prototype targets described above.

The NIF can provide integrated performance tests of candidate IFE targets as a function of reduced precision and manufacture cost. A series of non-ignited model targets could be injected in a 5-Hz burst, by stagger-firing 2–4 groups of laser chains ~100 ms apart, to test the repeatability of beam-target engagement accuracy in a multishot chamber environment. Since each of the 192 beamlets of the NIF can be fired separately, this type of experiment should be possible. It would also be useful to conduct experiments where uniform illumination of a target could be obtained using only a fraction (e.g., 1/4 or 3/4) of the beams.

Conclusions

The role of the NIF can uniquely cover a large and essential portion of needed IFE development in four areas.

1. IFE target physics and design/performance optimization. NIF target physics experiments with both direct and indirect drive will give us the data needed to predict the minimum driver energy, power, pulse shape and symmetry requirements for a variety of potential IFE drivers and targets.

TABLE 3. IFE target systems R&D needs.

Development Item	Needed for:			Current R&D activity*
	NIF	NIF-IFE experiments	IFE	
Target Fabrication				
Targets for Ignition				
Ignition target design	X			A
1–3-mm capsules	X	X	X	B
High-pressure DT fill and condensation	X	X	X	C
Cryogenic layering	X	X	X	D
Cryogenic characterization	X	X	X	D
Cryogenic assembly	X	X	X	—
Targets for IFE				
IFE target design	X	X	—	
IFE target fabrication		X	X	—
Cost-effective fabrication			X	—
Target Transport				
Transport Systems				
Transport to reaction chamber	X	X	X	C
High through-put transport			X	—
Injection and Tracking				
Stationary mounting system	X	X		C
Free-fall injection	X		—	
High-speed injection		X	X	—
High-rep-rate, rad-hardened injection			X	—
Target tracking	X	X	—	
Hardened target tracking			X	—

*A = NIF design activity; B = target fabrication development activity; C = OMEGA Upgrade design; D = National Cryogenic Target Research and Development Program.

2. IFE fusion chamber dynamics and first-wall response. Using the output of ignited targets, NIF experiments will be able to characterize radiation, shock, and debris effects on various first-wall candidates and on driver/reactor interface systems, providing the data necessary to design multiple pulse and high-rep-rate experiments for the ETF.
3. IFE fusion power technology, materials science and safety. NIF experiments will be essential for calibrating and improving the predictive capabilities of x-ray, debris, and neutron emissions and their effects on tritium handling, nuclear heating, materials, and safety and the environment. The NIF facility will be prototypical of future IFE power plants in these areas.
4. IFE target systems tests of precision and performance of mass-fabricated IFE targets and high-rep-rate target-injection systems. NIF experiments can study the target manufacturing tolerances required for mass production and the positioning requirements of the injection, tracking, and beam pointing systems.

In conclusion, the NIF will be a centrally important experimental facility to support a broad range of research on the IFE development path.

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LASER-PLASMA INTERACTIONS IN LARGE GAS-FILLED HOHLRAUMS

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Introduction

Indirect-drive targets planned for the National Ignition Facility (NIF) laser consist of spherical fuel capsules enclosed in cylindrical Au hohlraums. Laser beams, arranged in cylindrical rings, heat the inside of the Au wall to produce x rays that in turn heat and implode the capsule to produce fusion conditions in the fuel. Detailed calculations show that adequate implosion symmetry can be maintained by filling the hohlraum interior with low-density, low-Z gases.¹ The plasma produced from the heated gas provides sufficient pressure to keep the radiating Au surface from expanding excessively.

As the laser heats this gas, the gas becomes a relatively uniform plasma with small gradients in velocity and density. Such long-scale-length plasmas can be ideal mediums for stimulated Brillouin Scattering (SBS). SBS can reflect a large fraction of the incident laser light before it is absorbed by the hohlraum; therefore, it is undesirable in an inertial confinement fusion (ICF) target. To examine the importance of SBS in NIF targets, we used Nova to measure SBS from hohlraums with plasma conditions similar to those predicted for high-gain NIF targets. The plasmas differ from the more familiar exploding foil or solid targets as follows: they are hot (3 keV); they have high electron densities ($n_e = 10^{21} \text{cm}^{-3}$); and they are nearly stationary, confined within an Au cylinder, and uniform over large distances ($>2 \text{ mm}$). These hohlraums have $<3\%$ peak SBS backscatter for an interaction beam with intensities of $1\text{--}4 \times 10^{15} \text{ W/cm}^2$, a laser wavelength of $0.351 \mu\text{m}$, $f/4$ or $f/8$ focusing optics, and a variety of beam smoothing implementations. Based on these conditions, we conclude that SBS does not appear to be a problem for NIF targets.

Theory

In the NIF targets, the laser beams will propagate through several millimeters of plasma ($n_e \sim 10^{21} \text{cm}^{-3}$) before depositing energy in the hohlraum wall. In this case, $n_e/n_c \sim 0.1$ for $0.351\text{-}\mu\text{m}$ light, where n_c is the critical density or the maximum density through which light of a given wavelength can propagate. The fraction of the laser energy that is collisionally absorbed in the low-Z (low atomic number) gas fill is modest ($\sim 10\%$ at the peak of the laser pulse). However, estimates based on simple linear gain theory generate concern that SBS reflectivities could exceed acceptable levels for the large-scale-length plasmas in these targets.

SBS is one of several parametric instabilities that can occur in a plasma. In the case of SBS, the laser light reflects off of an ion-acoustic wave in the plasma. A chain of events occur if certain resonance conditions are met: the size of the ion-acoustic wave increases, which causes the scattered light to increase, which causes the ion-acoustic wave to increase, etc., until nonlinear effects limit the process. SBS reflectivity $>10\%$ may unacceptably degrade target performance by reducing the energy available for radiation heating and/or by disrupting symmetry.

In the NIF plasmas, density and velocity gradients are weak (although they limited the growth region for SBS in previous experiments); however, damping of the SBS-produced ion waves by light ions in the gas fill is efficient² and limits the SBS gain coefficient. Predicted gain coefficients for NIF plasmas, using linear theory, are >20 , whereas gains of <15 are required to insure reflectivities of 10% or less. For such large gains, theoretical estimates³ indicate that nonlinear mechanisms will limit the scattering to lower levels. Because nonlinear damping is difficult to calculate, we must do experiments to verify these estimates. Previous SBS

experiments are insufficient, since the plasma conditions in past studies⁴ differ significantly from expected NIF conditions. For those exploding foil or solid targets, where scale lengths <1 mm and electron temperatures $T_e \sim 0.5$ – 2 keV were typical, SBS is limited by detuning (loss of phase matching conditions), due to gradients in the flow velocity. The lack of quantitative theoretical understanding of those experiments discourages extrapolation to NIF conditions. There is little data on the effect of various beam-smoothing techniques, or increased laser bandwidth, interacting with NIF-type plasmas.

Random phase plates (RPP)⁵ and temporal smoothing methods such as smoothing by spectral dispersion (SSD)⁶ are commonly used in laser-plasma interaction experiments to increase the time-averaged beam uniformity at the target plane. The idea is to avoid having higher-than-average intensities in the interaction region, since high intensities more easily drive SBS. Localized regions of higher intensity can occur because of imperfections in the laser beam. They can also occur when there is filamentation of the beam in the plasma. The filamentation instability has thresholds very similar to those for SBS, and can be initially seeded by imperfections in the laser beam. The smoothing techniques reduce the intensity variations in the beam but on a time scale that is often comparable to the SBS growth time. The interactions among SBS, filamentation, and the short-time-scale smoothed beam are complicated and not completely understood. One goal of these experiments is to test the f -number and temporal smoothing scale of SBS.

Instability growth in an RPP intensity distribution⁷ can vary with the size of the speckles. The role of speckles in determining instability levels is important for NIF because the underdense plasma size is large compared with the speckle length of the proposed $f/8$ beam focusing. In simulations,^{8,9} $f/8$ beams filament more than $f/4$ beams. Three-dimensional simulations¹⁰ show that SBS reflectivity, unlike filamentation, is not directly limited by the speckle length. In these simulations, SBS grows over the entire resonant region, which is several speckles long, with a total gain greater than that calculated for the average intensity. However, even if the bandwidth is less than the SBS growth rate, temporal smoothing reduces SBS by partially destroying the cooperative scattering among hot spots. Modification of the RPP intensity distribution by filamentation could also affect SBS. For the plasma parameters of these experiments and laser intensity $I \sim 2 \times 10^{15}$ W/cm², simulations indicate that $f/4$ speckles are stable to filament but $f/8$ speckles are unstable.⁹ Temporal smoothing makes filamentation more difficult because the filament must form rapidly, before the hot spot moves to a different location.

Experiment

We use the Nova laser to produce plasmas with conditions similar to those predicted for NIF hohlraum targets and to measure SBS from these plasmas. In these experiments, the targets are cylindrical Au hohlraums with a length and diameter of 2.5 mm.¹¹ The hohlraums do not contain capsules, but are filled with neopentane (C₅H₁₂) gas at a pressure of 1 atm ($n_e = 10^{21}$ cm⁻³ when fully ionized). For some targets, a trace of Ar is also added for diagnostic purposes. As shown in Fig. 1, the gas is contained by two polyimide (C₂₂H₁₀N₂O₅) windows ~ 6500 Å thick. Nine of Nova's beams are used to heat the gas with ~ 30 kJ of 0.351- μ m light in a 1.4-ns shaped pulse. The tenth beam is a probe, or interaction, beam whose intensity, pulse shape, f -number, and "smoothness" are varied. The SBS backscatter intensity and spectrum from the interaction beam are measured with temporal resolution of 100 ps and spectral resolution of 1 Å. The interaction beam has a trapezoidal pulse with a ~ 600 -ps flat top and a ~ 300 -ps rise and fall time. The interaction beam is typically delayed ~ 600 ps relative to starting the heating beams and is smoothed spatially with an RPP, providing peak average intensities in the range of 1 – 4×10^{15} W/cm². Temporal smoothing is done either by SSD with FM bandwidth⁶ or by four colors. (See "Four-Color Irradiation System for Laser-Plasma Interaction Experiments," p. 130 of this *Quarterly* for a discussion of four-color systems.) The four-color scheme propagates four different frequencies through four quadrants of the laser. The focusing lens overlaps the frequencies at the focal plane. The line separation is $\delta\lambda = 4.4$ Å at 1.053 μ m for a total line width of 13.2 Å for these experiments (four-color bandwidth with $\delta\lambda \approx 10$ Å is proposed for the NIF).

To produce a uniformly hot plasma inside the Nova hohlraum, a substantial fraction of Nova's energy (~ 12 kJ) must be coupled to the gas. Because the

FIGURE 1. Schematic diagram of the target geometry. Shaded regions show the focusing and pointing of the heater beams (light shading) and interaction beam (dark shading). (10-01-0395-0652pb01)

absorption length exceeds the target size for the temperatures of interest (>5 mm for $0.351\text{-}\mu\text{m}$ light at $T_e = 3$ keV), the energy absorbed in the gas is determined by the laser-path length. The heater beam geometry (shown in Fig. 1) has the long path length necessary to maximize the absorption in the gas and to produce the desired plasma temperature. We also use a ramped pulse for the heater beams, which keeps the initial intensities low, to minimize scattering from the solid window material or the initially cold fill gas.

The detailed plasma conditions for the Nova gas-filled hohlraums and NIF targets are obtained from two-dimensional LASNEX¹² simulations. The simulations are cylindrically symmetric about the hohlraum axis and include the Au hohlraum wall, the gas fill (including dopants in the Nova targets), the membrane over the laser entrance hole (LEH) which confines the gas, and (in the case of the NIF target) the capsule. Standard LASNEX models are used for Lagrangian hydrodynamics, laser absorption, electron and radiation transport, and nonequilibrium atomic physics. The simulations predict that a uniform plasma (~ 2 mm long) with $n_e \sim 10^{21}\text{cm}^{-3}$, $T_e \sim 3$ keV, and flow velocity $< 10^7\text{cm/s}$ is maintained for longer than 0.5 ns during the peak of the interaction pulse. Under these conditions, the small signal intensity gain coefficient for SBS is

$$G_{\text{SBS}} = \pi \times 10^{-16} \left(\frac{I \lambda^2}{T_e} \right) \left(\frac{n_e}{n_c} \right) \left(\frac{\omega_a}{v_i} \right) \left(\frac{L}{\lambda} \right), \quad (1)$$

where λ is the laser wavelength and L is the plasma length, both in micrometers; T_e is in keV; ω_a and v_i are the ion-acoustic-wave frequency and amplitude damping rate, respectively; and I is in W/cm^2 .

To illustrate the similarity between plasma conditions in NIF target designs and these Nova gas-filled hohlraums, Table 1 summarizes the SBS gain and the calculated values of the plasma parameters in the underdense plasma that determine the gain.

The Nova plasma parameters are within $\sim 50\%$ of the NIF values except for the T_i/T_e ratio (where T_i is the ion temperature), which is lower in the Nova targets

due to the shorter time available for electron-ion equilibration to occur. This difference leads to larger ion acoustic wave damping v_i in NIF than in Nova targets.² However, the difference in path length compensates to give similar gain coefficients for NIF and Nova targets at the same intensity ($I \approx 2 \times 10^{15} \text{ W/cm}^2$). Hence, these Nova targets access conditions that are very similar to NIF designs both in SBS linear gain and in the individual plasma parameters that determine the scattering characteristics. Calculated gain coefficients for the highest-intensity Nova experiments ($I \approx 5 \times 10^{15} \text{ W/cm}^2$) exceed the NIF value by more than a factor of two.

We performed extensive characterization to assure that predicted plasma conditions were achieved in the underdense plasma. The T_e is inferred from both single-element and isoelectronic line ratios¹³ using Ti/Cr or K/Cl spectra from thin foils placed in the path of the interaction beam. In the isoelectronic technique, one looks at x rays emitted from different ions, which contain the same number of electrons (e.g., x rays from Ti and Cr ions that each contain one electron "H-like"). The ratio of the x-ray intensity from these differing ions is temperature dependent, but is nearly independent of other parameters, such as density.¹³ This makes the analysis and interpretation of the data more straightforward. Detailed analysis of the isoelectronic spectra confirms that $T_e > 3$ keV during the interaction pulse.¹⁴ Time-resolved measurements without the interaction beam verify that electron conduction provides good temperature uniformity. Several diagnostics characterize the propagation of the heating beams through the (initially) cold gas. A streaked x-ray spectrometer records the temporal history of Au M-band x rays emitted through the LEH. This measures the time at which the laser beam begins to heat the Au wall of the hohlraum; from this data, we can deduce the average beam propagation speed through the gas. Time-gated (≈ 100 ps) x-ray images, dominated by emission from 1% Ar dopant in the gas, provide evidence that the beams propagate without significant breakup or refraction. These experimental observations, which are in good agreement with LASNEX predictions, support important aspects of our modeling of NIF targets.

SBS Data and Discussion

Backscattered light near the laser frequency is collected by the interaction beam focusing lens and is measured with a grating spectrometer-streak camera combination to provide spectrally and temporally resolved data. The resolutions are 0.1 nm (spectral) and 100 ps (temporal). We also use time-integrating

TABLE 1. Comparison of selected plasma parameters for Nova gas-filled hohlraums and NIF targets.

	Nova	NIF
Interaction length	~ 2 mm	~ 3 mm
Line density $\int (n_e/n_c) dl$	~ 0.2 mm	~ 0.3 mm
T_e	3 keV	5 keV
T_i/T_e ratio	0.1–0.2	0.4
Gain coefficient G_{SBS} ($2 \times 10^{15} \text{ W/cm}^2$)	22	21

calorimeters to provide an absolute calibration. Figure 2 shows a typical spectrum. Just after time zero, before the interaction (or “probe”) beam is turned on, weak sidescattered light is observed from the “heater” beams as they interact with the polyimide window. At 0.6 ns, the “probe” beam is turned on; its reflection from the expanding polyimide window at the LEH produces the unshifted feature observed to start at 0.6 ns. A stimulated Raman scattering diagnostic (not shown) observes $\omega/2$ scattered light (700 nm) at this time; since half-harmonic light is generated at the $n_c/4$, this confirms the LASNEX prediction that the expanding window plasma density is still over $n_c/4$ when the probe beam is first turned on. However, it quickly drops below the gas density of $0.1 n_c$, and red-shifted SBS is then observed. This SBS backscatter (shown in Fig. 2) peaks soon after the interaction beam reaches peak intensity and decreases before the intensity drops. We calculate that the decrease is due to an increase in the ion acoustic wave damping rate, as the ratio of T_i/T_e increases. The time dependence of this ratio is due to the relatively slow heating of the ions; the ion heating depends on electron-ion collisions, which are relatively weak for low-Z plasmas. At the time of peak scattering, the wavelength of the peak emission is red-shifted $\sim 3\text{--}7 \text{ \AA}$. In the fluid limit, the frequency shift of SBS-scattered light $\Delta\omega = 2 k_0 (V_{||} - C_s)$, where k_0 is the laser wavenumber, C_s is the ion sound speed, and $V_{||}$ is the flow velocity parallel to the scattering vector; hence the observed red-shift is evidence that the SBS

spectrum is dominated by scattering from regions of plasma where $V_{||} < C_s$, as predicted by linear gain analysis. In contrast, SBS spectra from lower-temperature, expanding targets⁴ are routinely blue-shifted.

Figure 3 shows the peak SBS backscatter into the lens as a function of intensity for $f/4$ and $f/8$ interaction beams (using an RPP smoothed interaction beam). Peak SBS reflectivities with $f/8$ interaction beams, which closely match the NIF beam configuration, are $<3\%$ for C_5H_{12} -filled targets. Time-integrated reflectivities are $<1\%$. The scattering levels for all intensities are well below the $>30\%$ reflectivities predicted by linear theory. Reflectivity levels are not changed when four-color bandwidth is added. This insensitivity to bandwidth agrees with simulations¹⁰ only if ad hoc nonlinear damping rates are imposed to match the measured SBS reflectivity. At higher interaction intensities ($>2 \times 10^{15} \text{ W/cm}^2$), the simulations indicate that filaments form and scatter significant light outside the lens cone. Experiments are planned to investigate the angular distribution of the reflected light.

Peak scattering levels from $f/4$ interaction beams are comparable to the $f/8$ beams (1–2%). With SSD bandwidth of $3.5 \text{ \AA}$, scattering from the interaction beam is below the detection threshold of $\sim 0.1\%$. The apparent efficiency of SSD in suppressing SBS may be related to the details of the speckle motion: with SSD, the hot spots move in an effectively random way, whereas with four-color smoothing the hot spot pattern exactly recurs in a time $2\pi/\delta\omega$, where $\delta\omega$ is the line separation.

FIGURE 2. Streaked spectrum of backscattered light from the $f/8$ interaction beam. The plot shows temporal lineouts of the frequency-integrated reflectivity (black line) and the interaction beam intensity (gray line). The peak reflectivity is 0.015 and the peak intensity is $I = 1.7 \times 10^{15} \text{ W/cm}^2$. (10-01-0395-0653pb01)

FIGURE 3. Peak SBS reflectivity into the focusing lens for $f/4$ and $f/8$ interaction beams, for an RPP-smoothed interaction beam. Filled squares show $f/8$ shots, adding four-color bandwidth with $4.4\text{-\AA}$ line separation. Reflectivities from $f/4$ shots with $3.5\text{-\AA}$ SSD bandwidth (filled circles) were below the detection threshold. (10-01-0395-0654pb01)

The observation of similar reflectivities from single-color $f/4$ and $f/8$ interaction beams at comparable intensities is somewhat at odds with gain scaling calculations. For these large plasmas, beam divergence produces a significant drop in intensity (a factor of ~ 2 for $f/8$ and ~ 4 for $f/4$) across the scattering region. This difference leads to larger calculated gain for $f/8$ ($G_{\text{SBS}} = 22$) than for $f/4$ ($G_{\text{SBS}} = 15$) for the same intensity at best focus. Several possible explanations for these findings are under investigation, theoretically and experimentally. For example, for the large gains calculated for these targets, nonlinear saturation mechanisms may limit the amplitude of the ion waves driven by SBS.³

High Levels of SBS

We observed only low levels of SBS when approximately duplicating the expected NIF conditions. We used several Nova shots with $f/4$ focusing to see if truly significant levels of energy could be scattered at more extreme conditions. We found that, with the maximum Nova power, we could generate a high level of SBS by removing all beam smoothing, and simultaneously removing H ions from the target. With no beam-smoothing techniques employed, the interaction intensity is difficult to define, making comparison with theory difficult. The spot size continually increases as the beam propagates from best focus, through the LEH, through the gas, to the Au wall. Furthermore, the unsmoothed Nova beams contain a substantial fraction of their energy in localized regions of high intensity.

Ions of H are particularly adept at damping the ion-acoustic waves. Their low mass means that, at a given temperature, their thermal velocities are higher than those of more massive ions, and thus they are more closely matched to the ion-acoustic wave's phase velocity. This enables them to draw energy away from the wave, effectively damping it. To remove H from the target, we used deuterated C_5D_{12} gas.

Figure 4 shows the resulting time-resolved SBS spectrum from this shot. Its features illustrate brief,

FIGURE 4. Streaked spectrum of backscattered light from the $f/4$ interaction beam with no smoothing and from the fully deuterated C_5D_{12} gas target. In contrast to Fig. 2, the reflectivity is nearly 20% and persists throughout the interaction pulse. (10-01-0395-0655pb01)

nearly unshifted scatter from the window-plasma when the probe beam turns on followed by red-shifted SBS. Unlike the data shown in Fig. 2, taken with smoothed beams, the SBS persists throughout the probe pulse. This shows that the (non-H) ions, in this case, are ineffective at damping the acoustic wave. Also unlike the smoothed beam data, the scattering level is high. In this case, 18% of the probe energy was scattered back into the $f/4$ lens.

Partially as a result of these experiments, the NIF target design now includes a small amount of H gas in the hohlraum to add an increased safety margin to the suppression of SBS.

Summary

We demonstrated low SBS reflectivity in NIF-relevant gas-filled hohlraum experiments on Nova. These targets approximately produced the calculated plasma conditions and SBS gain coefficients for NIF targets. The interaction beam mimics the NIF laser beam intensity, focusing, and beam smoothing. The maximum time-dependent SBS reflectivity is less than 3% for NIF-relevant conditions.

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EVOLUTION OF SOLID-STATE INDUCTION MODULATORS FOR A HEAVY-ION RECIRCULATOR

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Background

The Laser Program at Lawrence Livermore National Laboratory (LLNL) pioneered the use of large-scale glass lasers to heat inertial-fusion targets. Today, that same exploratory spirit applies to our latest laser-fusion effort—the National Ignition Facility (NIF). The NIF has the potential to pave the way to commercial power extraction from inertial fusion, as long as the generating system is affordable and it operates repetitively. These fundamental issues of cost and repetition rate have stimulated a search for alternative fusion-target drivers to replace large, single-shot lasers. We are developing an ion approach whereby converging beams of heavy ions act as the driver. Like lasers, the ions impart their energy to the target and produce fusion temperatures. The difference lies in the ability of particle accelerators to generate repetitive bursts of ions with a higher efficiency at a lower cost.

Several accelerator concepts are being investigated for Inertial Fusion Energy (IFE).¹ The challenge is to identify an accelerator configuration that meets the technical requirements for heavy-ion fusion (HIF) and competes economically with existing and alternate energy sources. To meet the challenge, the LLNL HIF project is investigating a circular induction accelerator called a recirculator,² as shown in Fig. 1. The recirculator is economically attractive because the beam acceleration sequence uses the most expensive accelerator components multiple times. However, the recirculator concept presents some unique technical challenges, because the sub-relativistic ion completes a circulation in a short time and is constantly gaining speed with each lap. Consequently, the pulsed modulators that accelerate and shape the beam must produce uniquely tailored pulses at repetition rates that are continuously variable and that can exceed 100 kHz. Therefore, our role in the HIF project is to investigate and to develop agile induction modulators that use the latest in solid-state power technologies.

Development Overview

Our efforts to develop agile induction modulators are guided by the future experimental needs of the HIF project. In close collaboration with Lawrence Berkeley Laboratory (LBL), we are developing a short-term and a longer-range experimental capability that will be shared between the two laboratories. The short-term experiment is a small-scale recirculator (4.5-m-diam ring), presently being built at LLNL, that will be the first demonstration of the recirculator concept. The longer-range experiment is a much larger scale recirculator (30-m-diam ring) that will be built using the proposed Induction Linac Systems Experiments (ILSE) accelerator at LBL as the heavy-ion source. Both of these experimental activities require significant advancements in the technology for induction-accelerator modulators.

FIGURE 1. The recirculator uses a multipass acceleration concept to reduce system costs. (30-00-0295-0486pb01)

For our initial experiments, we selected a full-scale demonstration of solid-state power management based on the long-range requirements of the proposed LBL recirculator. A prototype modulator was built and tested that achieved the nominal parameters of 5-kV, 200-A pulses that vary in format from 1 μ s to 400 ns and repeat at a 50- to 150-kHz repetition rate.

In addition to pulse-width and repetition-rate agility, the induction cell modulators for a recirculator will ultimately incorporate a much more sophisticated power-management scheme. The amplitude and shape of each individual acceleration pulse must be tailored to accurately match the continually changing velocity and shape of the ion beam. This will require the implementation of feedback control capabilities to the basic modulator technology. At LLNL, we are presently developing an induction modulator for our short-term experimental needs on the small-scale recirculator. This new modulator will generate precisely programmed waveshapes in addition to pulse-width and repetition-rate agility. While the total peak power requirements are much smaller in this second developmental modulator (600-V, 100-A pulses), it must still operate in excess of 100 kHz while delivering a sequence of pulses that have a precisely controlled shape and amplitude.

This article describes the requirements, designs, and results from our initial work, which focused on the larger modulator technology for the LBL recirculator experiment, followed by our present efforts to develop a "smarter" modulator technology. We also summarize spin-off applications of the HIF induction technology currently being developed.

Solid-State Induction Technology

Induction machines accelerate the beam through electrical cavities that apply the accelerating voltage to the beam. These cavities contain toroids of ferromagnetic material that encircle the beam axis and enable the applied accelerating voltage to be impressed along the beam while the outer cavity surfaces remain at ground potential.³ Figure 2 illustrates the differences between a linear induction accelerator and a recirculating induction accelerator. Figure 2(a) shows a linear arrangement of induction cells, where each cell receives fixed duration pulses of a relatively low pulse repetition frequency (prf).⁴ Figure 2(b) is a circular arrangement of the induction cells, but the pulse parameters for these cells differ greatly from their linear accelerator counterpart:

- Recirculators operate in a rapid burst of multiple pulses, corresponding to the number of beam circulations in the ring.
- The pulse separation changes during the burst because the ion beam gains speed from each preceding pulse.

- The pulse width changes during the burst because the beam is spatially compressed as it gains speed.
- The prf within the burst is very high (10–150 kHz) because the beam accelerates on each lap around the ring.

The need for complex pulse agility led us to examine solid-state switching components that have an on/off capability. The intrinsic speed of solid-state switching satisfies our high prf requirements, while the on/off switching action of some semiconductor devices enables us to select an arbitrary pulse width. Eventually, we selected field effect transistors (FETs) as the preferred switching elements because they have fast rise and fall times, low gate-drive power, low on-state impedance, and a capacity for high-prf operation.

The basic concept of our solid-state modulator is simple—close the FET switches to connect a large capacitor bank to the accelerator induction cell and open the switches when the pulse is long enough. However,

(a) Linear induction accelerator

(b) Recirculating induction accelerator

FIGURE 2. Ferromagnetic cores are used in induction cells to accelerate the beams. (99-74-0491-0659pb01)

this action becomes considerably more complicated due to the inductive nature and magnetic properties of the accelerator core: (1) The inductance of the accelerator cell is energized by the applied pulse. When the FET switches are commanded to open, the cell inductance generates a very large voltage in an attempt to maintain a constant current. (2) The applied pulse also magnetizes the core material and leaves it in a different state of polarization following the pulse. The difficulty lies in resetting the core to its former magnetic state in the short time between pulses. We resolved these difficulties by applying the circuit architecture shown in Fig. 3.

When the switch S1 is closed, the energy storage capacitor C1 is connected directly across the induction

cell L1. The voltage VC1 accelerates the ion beam, but it also drives a steadily increasing magnetization current in the cell [Fig. 3(b)]. Once the acceleration pulse has ended, S1 opens and the cell current begins to decrease. The sudden change in cell current results in a rapid voltage reversal on L1, which continues in the positive direction until the diode D1 is forward biased. At that time, the cell current is fully diverted from the switch branch to the reset capacitor C2. The reset capacitor is precharged to the voltage VC2, which dictates the rate of cell current decay and helps to restore the magnetic flux density back to its original value. When the cell current reaches zero, D1 turns off and the pulse is ended; however, the core reset action is still incomplete. Additional reset is provided by reversing the flow of cell current. Energy for the current reversal is stored in the FET snubber capacitors (not shown) and reinforced by current from the external charging system. The diversion of cell current to C2 causes VC2 to increase with each pulse and results in a net accumulation of voltage during an acceleration sequence. However, the capacitance value of C2 is equal to or greater than C1, so the net voltage increase is very small. The regulator element in Fig. 3(a) maintains VC2 at a steady-state value by returning the recovered energy back to C1 at the end of each acceleration sequence. Note that C1 contains far more energy than the ion beam and core material need per pulse, so C1 does not require recharging during a burst.

FIGURE 3. (a) Circuit that provides core drive and reset functions for a single induction cell. (b) Waveforms that illustrate the operation of the circuit shown in (a). In (b), t = time. (30-00-0295-0487pb01)

ILSE-Scale Induction Modulator

Our first attempt to implement the circuit architecture of Fig. 3 resulted in a 4-kV modulator and cell switched by a total of 24 FETs.⁵ Our latest HIF machine features a larger switching system, containing a total of 128 FETs. Figure 4 shows the physical layout of four parallel 1-kV

FIGURE 4. Photograph of a circuit board containing FET switches and optically controlled drive circuitry. (30-00-0295-0489pb01)

power FETs on each of 32 circuit boards along with the two isolated gate-drive circuits that control them. The on/off commands to each gate drive are delivered through a single optical fiber. Isolated control power is supplied from a dc/dc converter for each circuit board. The 32 circuit boards are divided into four modules each containing a stack of eight series-connected boards. The four modules and their capacitor banks surround a single induction cell, as shown in Fig. 5.

FIGURE 5. Photograph illustrating the close integration between the FET switching modules and the induction core. (30-00-0295-0490pb01)

Space is available to expand this modulator to a total of 8 modules, doubling its peak power capability from 4 MW to 8 MW.

Figures 6 and 7 contain preliminary performance data for 3-kV operation. Figure 6(a) shows cell voltage and the switch voltage on module 4 for a 1- μ s pulse. Figure 6(b) shows currents from modules 3 and 4, indicating a good current balance between them. Each module has two current probes so that eight probe signals are needed to show the total machine current. The general ramp-like shape of the current waveform is characteristic of an inductive load with a constant applied voltage. The narrow pulse at the start of the

FIGURE 7. Five-pulse burst at 3 kV showing a 150-kHz pulse rate. (30-00-0295-0492pb01)

FIGURE 6. (a) Cell and switch voltages for a 3-kV charge voltage and a 400-V reset voltage. Waveforms are the acceleration portion of the whole voltage waveform. (b) Switch currents from modules three and four showing a 15-A peak current at the end of a 1- μ s ramp. Peak cell current is the sum of all module currents ($= 120$ A in this case). (30-00-0295-0491pb02)

current signal is due to the discharge of external cable capacitance. Figure 7 shows the cell and switch voltage of module 4 during a 5-pulse burst at a 150-kHz rate. The machine has achieved full voltage operation at 5 kV, but much work still remains in modeling the system and understanding the behavior of the magnetic core during the burst.

Small-Scale Induction Modulator

The small LLNL recirculator, currently under construction, consists of 32 accelerator stations spaced around a 4.5-m-diam ring. Each accelerator station houses a 600-V induction modulator and cell. When a stream of low-energy ions are injected into the ring, they are steered into a circular path by an arrangement of electrostatic dipoles. As the singly charged ion stream passes by each induction cell, the particles undergo a nominal 500-eV gain in energy. The ions complete 15 revolutions in the recirculator before being extracted.

The transport scenario described is further complicated by the large space charge of the ion bunch. To inhibit ion scattering, the recirculator must provide confinement forces that bind the beam in the radial and axial directions. The electrostatic quadrupoles provide the radial restoration, but the axial spread is controlled by shaping the acceleration pulse so that the space charge forces are balanced by the accelerating voltages. Basically, the ions in the lead receive less acceleration (lower mean voltage) than the trailing ions that receive additional acceleration (higher mean voltage). In practice, the pulse shape is generated by adding a 500-V rectangular pulse with two triangle-shaped "ear" pulses at the leading and trailing edges. The leading-edge ears have a negative polarity to decelerate the head of the beam, while the trailing-edge ears have a positive

polarity to speed up the tail. There are several possible combinations of pulses that form an "acceleration schedule" that may be used to accelerate the ion beam. Figure 8(a) shows one example, which details the schedule of acceleration pulses, and Fig. 8(b) shows the ear-pulse schedule. As the ion beam is bunched together, the acceleration pulses grow narrower and the ears become taller to restrain a spatially compressed beam. Figure 9 shows the ensemble of net accelerating voltages from start to finish.

FIGURE 9. This voltage waveform, which appears in the accelerating gap, is the summation of the accelerator and ear pulses shown in Fig. 8. (30-00-0295-0494pb01)

FIGURE 8. (a) Accelerator pulses vary from a 4- μ s rise-time ramp to a 1- μ s rectangular pulse. Interpulse spacing starts at 17 μ s and reduces to 10 μ s. (b) These ear pulses are added to the acceleration pulses to provide longitudinal confinement of the ion beam. (30-00-0295-0493pb02)

Generating the pulse format shown in Fig. 9 is the responsibility of our "smart" induction modulator. In this case, FETs are still used to connect a precharged capacitor bank to an induction cell, but the smart feature of this new modulator lies in the use of the FETs as amplifier elements instead of on/off switches. In addition, our new modulator and cell use two separate induction cores, one for the main accelerator pulse and one for the ear pulses, to generate the net voltages of Fig. 9. Figure 10 is a block diagram that illustrates the nesting of two cores and two modulator circuits. Fast feedback amplifiers are used to control two power FET arrays so that each core voltage is a scaled version of an applied input waveform. A computer system is used to command two programmable waveform generators to produce a properly shaped pulse train. The ear core in Fig. 10 is made from PE-11B ferrite while the main accelerator cores are an assembly of three 2605S-3A Metglas⁶ cores.

The modulator and core assembly are still in the design phase, but comprehensive modeling of the electronic portion of the design is presently underway. We are using the Micro-Cap IV⁷ circuit analysis program to model the cell and power amplification circuits. Figure 11 is a typical simulation showing an input waveform compared with the output voltage at the accelerator cell.

Spin-Off Technologies

The various power-control technologies being developed for HIF are also applicable in other programs. For example, the Advanced Radiographic Machine (ARM), a multipulse electron-beam accelerator for dense-target

tomography, derives its power system from the HIF work, but requires a peak power and repetition rate far beyond those needed for heavy-ion recirculators. The ARM induction modulator is designed to generate 15-kV pulses that vary in width from 200 ns to 1 μ s at repetition rates up to 1 MHz.⁸

We also applied our HIF knowledge to two other projects. During FY 1992, we built and tested a miniature induction modulator as a power source for pulsed plasma processing.⁹ This work was based on the proposition that plasma processing is a dynamic electrochemical reaction that also requires an agile power source to help maintain an optimal process efficiency. During FY 1994, we applied our FET switching experience to the design and construction of a compact power source for a solid state laser array.^{10,11} In this case, the work focused on enhancing the industrial and medical uses of the laser array by reducing the size and cost of the power system.

FIGURE 10. The gap voltage is generated by two separate core and modulator circuits. (30-00-0295-0495pb02)

FIGURE 11. Circuit simulation showing two examples of (a) input voltage waveforms and (b) amplified voltages at the cell. The negative bias on the amplified voltage signal is the result of the applied reset voltage. These simulations contain detailed amplifier models that are used to guide our design. (30-00-0295-0496pb01)

Summary

Induction accelerators are typically powered by energy stored in a pulse-forming network that delivers an accelerating pulse of a fixed duration and amplitude. This type of accelerator system is limited in prf to a few kilohertz and treats the dynamic beam as a simple time-invariant load. Our research has merged the growing capability of solid-state power control with induction accelerator technology to produce a new accelerator system that is fast, flexible, and interactive with the beam. As a result, the beam may receive variations in pulse shape, amplitude, width, and prf to suit a specific objective in beam quality or accelerator performance. The solid-state powered accelerator delivers intelligent beam power that is actively directed in the right proportions at the right time. The recirculator is only one example of how smart power management can improve the capability of well-established technologies.

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THE NATIONAL IGNITION FACILITY PROJECT

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Introduction

The Secretary of the U.S. Department of Energy (DOE) commissioned a Conceptual Design Report (CDR) for the National Ignition Facility (NIF) in January 1993 as part of a Key Decision Zero (KD0), Justification of Mission Need. Motivated by the progress to date by the Inertial Confinement Fusion (ICF) program in meeting the Nova Technical Contract¹ goals established by the National Academy of Sciences in 1989, the Secretary requested a design using a solid-state laser driver operating at the third harmonic (0.35 μm) of neodymium (Nd) glass. The participating ICF laboratories signed a Memorandum of Agreement in August 1993, and established a Project organization, including a technical team from the Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and the Laboratory for Laser Energetics at the University of Rochester. Since then, we completed the NIF conceptual design, based on standard construction at a generic DOE Defense Program's site, and issued a 7,000-page, 27-volume CDR in May 1994.² Over the course of the conceptual design study, several other key documents were generated, including a Facilities Requirements Document, a Conceptual Design Scope and Plan, a Target Physics Design Document, a Laser Design Cost Basis Document, a Functional Requirements Document, an Experimental Plan for Indirect Drive Ignition, and a Preliminary Hazards Analysis (PHA) Document. DOE used the PHA to categorize the NIF as a low-hazard, non-nuclear facility.

Figure 1 shows the NIF conceptual design, which was exhaustively reviewed during the past year. A

subcommittee of the Inertial Confinement Fusion Advisory Committee (ICFAC) reviewed and endorsed the laser performance of the 40-cm aperture, 192-beam multipass architecture in April 1994. The full ICFAC reviewed target design and ignition scaling in May 1994 and recommended DOE approval of the preliminary design phase of the Project. Subcontractors to DOE Defense Programs scrutinized the engineering design during the design period, while an Independent Cost Estimator team commissioned by DOE Field Management intensively reviewed and validated the cost and schedule in March and April 1994. The performance, cost, and schedule represented in the CDR were formally submitted in June 1994 in a Project Data Sheet for inclusion in the FY 1996 DOE funding cycle.

On October 21, 1994 the Secretary of Energy issued a Key Decision One (KD1) for the NIF, which approved the Project and authorized DOE to request Office of Management and Budget approval for congressional line-item FY 1996 NIF funding for preliminary engineering design and for National Environmental Policy Act activities. In addition, the Secretary declared Livermore as the preferred site for constructing the NIF. In February 1995, the NIF Project was formally submitted to Congress as part of the President's FY 1996 budget. If funded as planned, the Project will cost approximately \$1.1 billion and will be completed at the end of FY 2002.

This article presents an overview of the NIF Project.

NIF Design Criteria

The identified laser power and energy operating regimes for indirect-drive fusion ignition targets are displayed in Fig. 2 and are the basis for the primary

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design criteria for the facility (Table 1). Each point on the operating map corresponds to a different temporal pulse shape, typically one with a relatively long foot-pulse (10–20 ns), followed by a short peak-pulse (2–8 ns) having a high contrast ratio (25–100:1). In the high-power, short-temporal-pulse region, performance is limited by laser–plasma instabilities, while in the low-power, long-temporal-pulse region, performance is limited by hydrodynamic instabilities.

The baseline target, shown in Fig. 3, requires a laser system that routinely delivers 500 TW/1.8 MJ at 0.35 μm in a 50:1 contrast ratio pulse through a 500- μm spot at the laser entrance hole of the target hohlraum with a positioning accuracy of 50 μm . Each beam must achieve a power balance of approximately 8% rms (over any 2-ns interval) with respect to a reference value. As summarized by the design rules in Table 2, symmetrical implosion of the capsule requires two-sided target irradiation with two cones per side, each having an outer cone:inner cone laser power ratio of 2:1, and at least

eight-fold azimuthal irradiation symmetry. The cone angles, nominally at 53° (outer) and 27° (inner), and laser power ratio are chosen to maintain time-dependent symmetry of the x-ray drive seen by the imploding capsule.

To avoid laser–plasma instabilities, such as filamentation and stimulated scattering, the baseline indirect-drive target hohlraum requires laser spatial beam smoothing using phase plates and laser temporal smoothing with a combination of four beams at different center wavelengths, each separated by 3.3 $\text{\AA}$ ($3.3 \times 10^{-4} \mu\text{m}$). This separation is set by a beam-smoothing requirement on the motion of the kinoform-induced speckle pattern at the target focus.

As a consequence of these symmetry design rules, the laser system must deliver at least 192 beams to the target chamber. A laser system designed to meet these criteria has a power and energy safety margin of approximately two for achieving ignition, as indicated in Fig. 2. These laser system requirements, optimized

FIGURE 1. The NIF overview. The NIF will be a low-hazard, non-nuclear facility. (40-00-0294-0498Zpb03)

for indirect-drive ignition targets, are consistent with those proposed for direct-drive ignition targets.

The primary criteria for the NIF systems given in Table 1 represent a small subset of the functional requirements for the facility, which include other mission-related and lifecycle requirements for the laser, experimental area, radiation-confinement systems, building and structural systems, safety systems, environmental protection systems, and safeguard and security systems. The NIF was designed for a generic site and is consistent with all relevant orders, codes, and standards. The U-shaped building configuration satisfies a key functional requirement: providing for the

FIGURE 2. The indirect-drive target operating regime in laser power-energy space at $0.35\ \mu\text{m}$. The operating regime is constrained by laser-plasma instabilities and hydrodynamic instabilities. Each point on the plane corresponds to a unique two-step temporal pulse. The baseline design at $500\ \text{TW}/1.8\ \text{MJ}$ has approximately a factor of two safety margin for ignition. This energy and power safety margin above threshold provides room to trade off asymmetry, laser-plasma instabilities, and other uncertainties. (50-05-0494-1803pb02)

TABLE 1. Primary criteria for the National Ignition Facility.

Laser pulse energy	1.8 MJ
Laser pulse peak power	500 TW
Laser pulse wavelength	$0.35\ \mu\text{m}$
Beamlet power balance	<8% rms over 2 ns
Beamlet pointing accuracy	<50 μm
ICF target compatibility	Cryogenic and non-cryogenic
Annual number of shots with fusion yield	100 with yield 1 kJ–100 kJ 35 with yield 100 kJ–5 MJ 10 with yield 5 MJ–20 MJ
Maximum credible DT fusion yield	45 MJ
Classification level of experiments	Classified and unclassified

future addition of a second large target chamber to accommodate special requirements of other communities, such as for weapons effect tests, with minimal interruptions to system operations. Preliminary analysis

FIGURE 3. A baseline NIF target was used to establish design criteria for the facility. The outer cones enter at 57° and 48° , with a $500\text{-}\mu\text{m}$ best focus at the entrance hole ($f/8$). The inner cones enter at 23° and 32° , with a $500\text{-}\mu\text{m}$ best focus $\sim 3\ \text{mm}$ inside the hohlraum ($f/8$). (40-00-0294-0596Apb01)

TABLE 2. Minimum number of 192 beams delivered to ignition target is determined by implosion symmetry requirements.

Symmetry	Beam multiplier	Notes
Time dependent hydrodynamic	3	Outer cone at $\sim 53^\circ$ at $2\times$ energy/power Inner cone at $\sim 27^\circ$ at $1\times$ energy/power
Azimuthal	≥ 8 (or 8, 9, 10...)	Number of inner-cone laser spots on hohlraum wall
Reflection	2	
Beam smoothing	4	Smoothing by multiple apertures/colors
Required number of beams	≥ 192 (or 192, 216, 240...)	

has shown that a modest upgrade of the currently designed NIF target area and target chamber system would accommodate direct-drive ignition target experiments without impacting the indirect-drive mission.

Laser System Design

The Nd:glass laser system must provide at least 632 TW/3.3 MJ in a 5.1-ns pulse at 1.053 μm to account for modest beam transport losses, and energy and power conversion efficiencies of 60% and 85%, respectively. Figure 4 shows a schematic of one NIF beamline. It uses a four-pass architecture with a large-aperture optical switch consisting of a plasma-electrode Pockels cell and polarizer combination.

The laser chain in this beamline was designed using the CHAINOP family of numerical codes that model the performance and cost of high-power solid-state ICF laser systems. These codes vary a number of design parameters to maximize laser output per unit cost, while remaining within a set of constraints. The constraints include fluence maxima, nonlinear effects, and pulse distortion. CHAINOP contains several analytical models that simulate the optical pumping process, the propagation of the laser beam through the system (including gain, loss, diffraction, and nonlinear optical effects), frequency conversion, and cost. This design procedure is excellent for cost scaling and system trade-off studies, but does not suffice for predicting detailed performance, which requires analysis with a suite of nonlinear physical optics codes, or determining project costs, which are estimated using a detailed engineering design and a rigorous item by item or "bottom-up" costing described later in this article.

The laser chain used in the CDR as the baseline for estimating NIF system cost and performance has a hard aperture of $40 \times 40 \text{ cm}^2$. The amplifiers contain 19 Nd-doped glass laser slabs arranged in a 9-5-5 configuration as shown in Fig. 4. Each Brewster-angled slab is 3.4 cm thick. Figure 5 shows the 1.053- μm performance of this

laser chain. At the 5.1-ns design point each laser chain should generate 3.9 TW/20.5 kJ. Because only 162 beams are required to achieve the performance criteria, a 192-beam system has a design margin of greater than 15%. A prototype beamline, called Beamlet, is undergoing tests at LLNL to demonstrate NIF performance projections using the large-aperture optical switch. Variations of a NIF design with reduced-aperture switches have comparable performance projections when optimized.

The NIF design incorporates 4-high $\times$ 12-wide arrays of laser beams as shown in Figure 1. The design is more compact than previous laser fusion systems, increasing

FIGURE 5. The 1.05- μm power/energy performance as a function of pulse length for the 9-5-5 configuration (shown in Fig. 4). The gray line shows the baseline performance (nominal-gain and -loss case). The black line illustrates the performance with line-center gain and with improved optical transmission of the laser glass and optical switch. For a 5.1-ns effective pulse length, determined by the NIF temporal pulse shape, the maximum gray-line performance of 20 kJ sets the number of required beams at 162. This would produce 3.3 MJ of 1.05 μm light and would deliver 1.8 MJ of 0.35- μm light to the laser entrance hole of the target hohlraum. Changing the system total from 162 to 192 (240) beams would provide an 18% (48%) laser design margin to meet the target hohlraum requirements. (40-00-0394-1378pb01)

FIGURE 4. A schematic of one beamline of the NIF laser from pulse injection to final focus on target. (40-00-0394-0789Apb02)

overall electrical and optical efficiency while simultaneously reducing system size and cost. The optical-pulse generation system provides individually controlled input pulses from one of four tunable fiber oscillators and an integrated optics network located in the master oscillator room (MOR). The outputs from the MOR are delivered on single-mode polarization preserving fibers to each of 192 preamplifiers. These stand-alone packages, located beneath the transport spatial filters, provide individual power balance capability for each of the 192 beams. The output beams from the preamplifiers are injected into the far-field pinholes of the transport spatial filters, passed through the boost-amplifier stages, the optical switch assemblies, and then captured inside the multipass cavities. The flash lamps located in the amplifier enclosures that uniformly pump the glass laser slabs are energized with approximately 260 MJ of electrical energy from a modular bank of thin film, metallized dielectric capacitors. After four passes through the cavity amplifiers, the pulses are switched out of the multipass cavity, further amplified by the boost stage, and then transported to the target chamber. The laser arrangement allows for top and bottom access to the amplifiers and the optical switch arrays. The pulsed power is transmitted to the amplifiers overhead with large, 30-cm-diam, coaxial conductors. The space below the amplifiers

allows access for assembly and maintenance of any four-high amplifier column.

Wavefront aberrations resulting from the long-term thermal cooling of the glass laser slabs ultimately limit the shot rate of the laser system. The NIF is currently designed to achieve about 700 full-system performance shots/year. A novel feature of the current design is the use of deformable mirrors in place of the end cavity mirrors (see Fig. 4) to correct for static and pump-induced short-term wavefront aberrations, which will allow for higher shot rates. It is expected that through continued engineering design of the wavefront-correction and cooling systems, the laser shot rate will increase substantially. This is consistent with engineering improvements on all previous ICF glass laser systems, including Nova, which has had its shot rate increase by a factor of six since operations began in 1985.

Target Area Design

Figure 6 shows a cutaway view of the switchyard and target area. The 192 laser beams are optically relayed via the transport spatial filters in 48×2 groupings to the final optics assemblies. The beams are constrained to only *s*- and *p*-polarized reflections in the optical switchyard and target areas so that they maintain linear

FIGURE 6. A cutaway view of the NIF target area showing major subsystems.
(40-00-0394-1030pb01)

polarization and radial symmetry with respect to the cylindrical axis on the hohlraum. Consequently, there is complete azimuthal symmetry. The 48 final optics assemblies (Fig. 7) are positioned on the 53° outer cones (16 assemblies) and 27° inner cones (8 assemblies) at the top and on the bottom of the target chamber. At the chamber each 2×2 grouping is converted to $0.35 \mu\text{m}$ by a Type I (potassium dihydrogen phosphate, or KDP)/Type II (deuterated KDP, or KD*P) crystal array in the final optics assembly. The final optics assemblies mount to the exterior of the chamber, and also provide 2×2 lens arrays for focusing the light onto the target and 2×2 debris shield arrays for protecting the lenses from target shrapnel. (The debris shields also contain the kinoform phase plates.) Each beam in every 2×2 grouping can be operated at a different center wavelength to provide the requisite laser temporal beam

smoothing. The final optics assemblies are offset from the nominal cone angles by $\pm 4^\circ$ to provide isolation between opposing beamlines.

The target chamber is housed in a reinforced-concrete building with three separate operational areas (see Fig. 6). The upper and lower pole regions of the target chamber house the final optics and turning mirrors in a class 1000 clean room. Personnel access to these areas will be limited to preserve cleanliness levels. The cantilevered floor sections of the building provide a separation of the clean-room enclosures at the polar regions from the equatorial target diagnostics area. This horizontal, planar architecture simplifies the design of the access structures required to service the optical components and target diagnostics.

The NIF baseline target chamber is a 10-cm-thick by 10-m internal-diam spherical Al shell designed to

FIGURE 7. The final optics assembly has multiple functions: Frequency conversion, focusing, spatial smoothing, optics protection, $1\omega/2\omega$ dispersion, 3ω calorimetry, and vacuum interface. (40-00-0294-0600Bpb01)

accommodate the suite of x-ray and neutron diagnostics required to measure the performance of targets that can achieve ignition. The Al wall provides the vacuum barrier and mounting surfaces for the first-wall panels, which protect the Al from soft x rays and shrapnel. The unconverted laser light hitting the opposite wall is absorbed by other panels offset from the opposing beam

port. The exterior of the chamber is encased in 40 cm of concrete to provide neutron shielding. The chamber is supported vertically by a hollow concrete pedestal and horizontally by radial joints connected to the cantilevered floor. The target area building, chamber, and auxiliary systems are designed to handle 145 shots/year of yields up to 20 MJ as shown in Table 1.

Recent engineering analyses and target physics calculations show that the baseline design can be easily modified, as illustrated in Fig. 8, to incorporate a direct-drive ignition capability, further broadening the utility of the facility.

FIGURE 8. Implementation of direct drive requires that 24 of the 48 beams be repositioned. This can be accomplished easily using the NIF optical system design. Compare to Fig. 6. (40-00-0694-2750pb01)

NIF Project Schedule

The summary schedule shown in Fig. 9 illustrates the sequence of events leading to NIF operations in October 2002. This overall schedule assumes the NIF Project is initiated by line-item funding in FY 1996 consistent with a KD1. A more detailed integrated Project schedule (not shown) reveals the critical path that affects the Project duration. The major NIF critical path consists of design, site selection, design and construction of the laser and target areas building, laser and other special equipment installation, completion of the acceptance test procedures, and start-up. Construction completion, equipment installation, and start-up are overlapped to shorten the critical path within limits of a practical funding profile. The release of design, construction, procurement, and operating funds is constrained by the DOE Key Decision (KD1 through KD4) process.

FIGURE 9. NIF Project schedule (hash marks and solid triangles indicate completion). (40-00-0195-0269Hpb01)

NIF Project Cost

The NIF Total Project Cost (TPC) is the sum of the Total Estimated Cost (TEC) and the Other Project Cost (OPC). The TEC is funded by Plant and Capital Equipment (PACE) funds and the OPC is funded by Operating Expense (OPEX) funds. Division of costs

TABLE 3. Summary of NIF costs for 192-beam system, in millions of dollars.

	Base costs (\$M FY94)	Contingency (\$M FY94)	Total (\$M FY94)	Total (\$M escalated)
TEC	586	121	707	842
OPC	199	N/A	199	231
TPC	785	121	906	1073
Annual operating costs	57	N/A	57	N/A

between TEC and OPC is provided in DOE guidelines. TEC activities include, for example, Title I and II design, and Title III engineering; building construction; procurement; assembly and installation of all special equipment; and sufficient spares to pass the acceptance test procedures. OPC activities include, for example, conceptual design; advanced conceptual design; NEPA documentation; vendor facilitization and pilot production; vendor component qualification/reliability/lifetime testing; operational readiness reviews; startup costs; and operational spares.

The costs shown in Table 3 were derived from a bottom-up estimate based on a detailed work breakdown structure (WBS) that is summarized at WBS Level 3 in Fig. 10. The Project adopted the Martin Marietta Energy Systems, Inc. Automated Estimating System (AES) as its cost management tool. The AES is consistent with DOE Order 5700.2d, "Cost Estimating Analysis and Standardization," and has been used in many other DOE projects in the past. The labor rates,

FIGURE 10. NIF Project WBS elements to Level 3. (1.4.0893.2859Mpb01)

overhead costs, allowances for incidental costs not directly estimated, and other indirect costs were applied to the database using the AES. Contingency information provided by each estimator for every Level 3 item was used in a separate probabilistic contingency analysis performed by Bechtel Corporation using their MICRORAC code. The results of that analysis were entered into the AES. Integrated project schedule data were combined with the cost information in the AES to estimate escalation and calculate the Budget Authority and Budget Outlay profiles required in the Project submission to DOE. The annual operating costs for the facility, shown in Table 3, were estimated by identifying all the NIF unit operations based on Nova experience. It does not include, per DOE guidance, the annual ICF Program costs (currently at approximately \$175 million/yr).

Figure 11 gives a second-level breakout of TEC and a third-level breakout of OPC (without contingency or escalation). The engineering design was sufficiently

detailed to generate costs, typically, at Level 5, and, in some cases, at Level 6 or 7. Approximately 70% of the costs (in dollars) were derived from catalog prices, vendor estimates, or engineering drawings. The costs in Table 2 have been validated by the DOE and by an Independent Cost Estimator team commissioned by DOE.

Summary

The NIF design is the product of the efforts of a multilaboratory team, representing more than 20 years of experience at the LLNL, LANL, SNL, and the Laboratory for Laser Energetics at the University of Rochester. Using the world's most powerful laser to ignite and burn ICF targets, the NIF will produce conditions in matter similar to those found at the center of the Sun and other stars. New, well characterized, high-energy-density regimes will be routinely accessible in the laboratory for the first time. The NIF will impact and extend scientific and technical fields such as controlled thermonuclear fusion, astrophysics and space science, plasma physics, hydrodynamics, atomic and radiation physics, material science, nonlinear optics, advanced coherent and incoherent x-ray sources, and computational physics. The importance and uniqueness of the NIF to these wide-ranging fields of science and technology have been recently reviewed in a series of workshops.³ If authorized in FY 1996, the NIF could begin operations in FY 2003.

Notes and References

1. Committee for a Second Review of DOE's ICF Program, *Final Report—Second Review of the Department of Energy's Inertial Confinement Fusion Program*, National Academy of Sciences, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, National Academy Press, Washington, D.C. (September 1990).
2. J. A. Paisner, *National Ignition Facility Conceptual Design Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-117093 (1994).
3. J. A. Paisner, *Utility of the National Ignition Facility*, Lawrence Livermore National Laboratory, Livermore, CA, NIF-LLNL-94-240, UCRL-117384 (1994).

FIGURE 11. Cost breakouts for (a) TEC without contingency in unescalated dollars, broken down to Level 2 and for (b) OPC in unescalated dollars, broken down to Level 3. (40-00-0494-1720Apb01)

TERMINAL-LEVEL RELAXATION IN ND-DOPED LASER MATERIALS

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Introduction

During the energy extraction of a 1- μm pulse in a Nd-doped laser material, the Nd-ion population is transferred from the metastable $^4F_{3/2}$ level into the terminal $^4I_{11/2}$ level, as shown in Fig. 1. The *terminal-level lifetime*, $\tau_{11/2}$, is defined in this case as the time it takes the Nd-ion population to decay from the $^4I_{11/2}$ level

into the $^4I_{9/2}$ ground state. Several experimental and theoretical approaches over the last three decades have been made to measure the terminal-level lifetime. However, an agreement in the results among the different approaches for a large sampling of laser materials has never been demonstrated.

This article presents three independent methods (pump-probe, emission, and energy extraction) for measuring the terminal-level lifetime in Nd:phosphate glass LG-750. We find remarkable agreement among the data and determine the $\tau_{11/2}$ lifetime to be 253 ± 50 ps. We extend our studies to show that the results of the pump-probe and emission methods agree to within a factor of two for additional Nd-doped glasses and crystals investigated, thus offering validation for the emission method, which is a simpler, indirect approach.

FIGURE 1. A Nd³⁺ energy level diagram that shows the 1- μm laser transition from the $^4F_{3/2}$ metastable level into the $^4I_{11/2}$ terminal level. During this transition, the input extraction pulse is amplified to produce a more energetic output pulse. The nonradiative relaxation from the $^4I_{11/2}$ level into the $^4I_{9/2}$ ground state is known as the terminal-level lifetime ($\tau_{11/2}$). (70-15-0993-3196pb01)

Background

As explained, $\tau_{11/2}$ is the time it takes the Nd-ion population to decay from the $^4I_{11/2}$ level into the $^4I_{9/2}$ ground state during the energy extraction of a 1- μm pulse. If the decay time is infinitely fast compared with the length of the extraction pulse ($\tau_{11/2} \ll t_p$) then the $^4I_{11/2}$ level will appear to be virtually unpopulated for the duration of the extraction pulse. Since the small signal gain coefficient (g_0) is directly proportional to the population inversion (ΔN) between the upper $^4F_{3/2}$ level and the lower $^4I_{11/2}$ level, the incoming laser pulse will extract more of the stored energy if the $^4I_{11/2}$ level remains unpopulated. Conversely, if the length of the extracting pulse is much less than the terminal-level lifetime ($t_p \ll \tau_{11/2}$) then the population in the $^4I_{11/2}$ level will remain populated or bottlenecked. As a consequence, the extraction process will be less efficient

since stimulated emission and absorption processes can become competitive and thus cause the re-excitation of the Nd-ion population in the $^4I_{11/2}$ level back into the $^4F_{3/2}$ level during extraction.

Figure 2 is a plot of the ideal extraction efficiency for Nd:phosphate glass as a function of the ratio $R = t_p/\tau_{11/2}$. For comparison, a few additional data are shown, including the oxide crystals Nd:YAG and Nd:YALO and the fluoride crystal Nd:YLF. The data points for these materials do not lie exactly on the phosphate curve due to differences in the spacing of the energy levels that affect the degeneracies of the upper and lower laser levels and thus the values for the extraction efficiency. The pulse lengths are assumed to be square in shape with a length of 3 ns, with the exception of the National Ignition Facility (NIF) data point, where t_p is 8 ns. The proposed design of the NIF will use a Nd-doped phosphate glass similar to LG-750 and will require longer pulse lengths. We discuss a derivation of this curve in a later section, but for now it illustrates that the extraction efficiencies for a Nd:phosphate glass laser are only moderately impacted by the short terminal lifetime (< 1 ns), whereas for Nd:YLF the long terminal lifetime (~ 10 ns) can become a limiting factor.

FIGURE 2. The ideal extraction efficiency plotted as a function of the ratio of the pulse length t_p to the terminal-level lifetime $\tau_{11/2}$ for Nd:phosphate glass. For comparison, additional data are shown (solid squares). The plots illustrate that the relatively short terminal lifetimes (< 1 ns) of the phosphate glass used in the Nova laser and of the glass used in the design of the NIF are not a limiting factor in obtaining the highest possible extraction efficiency. In comparison, the long lifetime (~ 10 ns) of the fluoride crystal, Nd:YLF, can be a limiting factor. (70-00-0295-0392pb01)

Given the importance of the terminal-level lifetime for phosphate glass, we employ three different methods for measuring its value. We first describe a novel and more accurate direct approach that employs a pump-probe technique.¹ We also explore an indirect emission method, which is based on the "energy-gap law,"^{2,3} since this method continues to be the preferred method due to its simple and straightforward approach. However, it is a method that presupposes that the lifetime of a different nonradiative transition ($^4G_{7/2} \rightarrow ^4G_{5/2}$, $^2G_{7/2}$), whose energy gap coincidentally matches that of the relevant transition ($^4I_{11/2} \rightarrow ^4I_{9/2}$), provides a reasonable assessment of the actual terminal-level lifetime. Based on the validity of the energy gap law, the two lifetimes are expected to be equal. Finally, we model data taken from a previous set of experiments and show that the terminal lifetime for phosphate glass derived from the best fit to the data is in agreement with the values derived from the pump-probe and indirect emission experiments.

In addition, we found in the process of modeling the extraction data that it would be useful if an approximate solution of the energy transport and kinetic differential equations existed that explicitly include the terminal lifetime and the pulse length. The motivation for finding an empirical solution was to be able to use a simple expression within the existing models that would include the effects of the terminal-level lifetime without having to tediously integrate the energy transport and kinetic differential equations. To date, the only analytic solutions that exist are for the two extreme cases of $t_p/\tau_{11/2} \ll 1$ and $t_p/\tau_{11/2} \gg 1$, that is, very short or long pulse lengths relative to the terminal lifetime.⁴ We formulated an empirical solution of the saturation fluence that explicitly includes the ratio $t_p/\tau_{11/2}$ and is therefore valid in the intermediate region of $t_p/\tau_{11/2} \approx 1$ as well. Our empirical solution of the saturation fluence can be substituted within the well known Frantz-Nodvik⁴ analytic solution to model the energy extracted from an amplifier. We present a modified expression for the saturation fluence and describe how we used it to model the energy extraction data for Nd:phosphate glass.

We first describe the direct (pump-probe) method followed by the indirect (fluorescence) method and discuss the lifetime results for LG-750. Next, we model the extraction data previously taken by Yarema and Milam⁵ and discuss our model. We show concurrence among the three methods with an averaged lifetime of $\tau_{11/2} = 253$ ps with an rms error of ± 50 ps. In the final section we compare the results from the direct and indirect methods for 13 materials and show that the simpler, indirect method can be used to determine the terminal lifetimes with an uncertainty of less than a factor of two in most circumstances.

Direct Method: Experiment and Results

To directly measure the population decay time between two electronic levels of interest, we must first find a way to selectively populate the upper level and then be able to detect and accurately measure the population decay. The total decay rate of the emission signal is a sum of the radiative and nonradiative decay rates. In most Nd-doped hosts, the small energy gap ($<1500\text{ cm}^{-1}$) of the $^4I_{11/2} \rightarrow ^4I_{9/2}$ transition and high phonon frequencies (up to 1300 cm^{-1}) enable the nonradiative rate to be much faster than the radiative rate. This causes the photon emission signal from the $^4I_{11/2}$ level to be very weak, thus making an accurate measurement of the nonradiative lifetime inherently difficult. Until recently, many of the direct measurements employed either an energy-extraction or gain-recovery method coupled with a numerical model.^{6,7}

We designed a unique pump-probe experimental technique to directly measure the nonradiative lifetime for the $^4I_{11/2} \rightarrow ^4I_{9/2}$ transition in various Nd-doped glasses and crystals. Figure 3 shows a series of energy level diagrams describing the sequence of events for the experiment: (1) A $2.41\text{-}\mu\text{m}$ pump beam excites a fraction of the ground state Nd ions into the $^4I_{13/2}$ level, after which the Nd ions will nonradiatively decay into the $^4I_{11/2}$ level. (2) After an incremental time delay, a $1.06\text{-}\mu\text{m}$ probe beam excites a fraction of the $^4I_{11/2}$ population into the $^4F_{3/2}$ level. (3) The $^4F_{3/2}$ population can decay into several of the lower 4I_J levels, but we chose to record the $0.88\text{-}\mu\text{m}$ emission signal corresponding to the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition. The time-integrated $0.88\text{-}\mu\text{m}$ signal is proportional to the $^4I_{11/2}$ population. This sequence of events is repeated for each increased time delay between the pump and probe pulses. Therefore, as the time delay between the pump and probe pulses increases, the value of the integrated $0.88\text{-}\mu\text{m}$ emission signal diminishes since most of the $^4I_{11/2}$ population

will eventually return into the ground state. A plot of the *time-integrated* $0.88\text{-}\mu\text{m}$ emission values vs time delay (τ_d) will construct the temporal evolution of the $^4I_{11/2}$ population. In passing we note that directly populating the $^4I_{11/2}$ level can be difficult due to the increased intrinsic absorption of the host medium at $5\text{ }\mu\text{m}$.

Figure 4 shows a simplified experimental diagram. The $1.06\text{-}\mu\text{m}$ output of a mode-locked laser operating at a repetition rate of 76 MHz is injected into a regenerative amplifier. The output pulses emerge from the amplifier at a 10-Hz repetition rate with an energy of 55 mJ per pulse. Two nonlinear frequency conversion processes are required to generate the $2.41\text{-}\mu\text{m}$ pump beam: a Raman process to generate $1.91\text{-}\mu\text{m}$ output and a difference frequency generator to produce the $2.41\text{-}\mu\text{m}$ output. The $1.06\text{-}\mu\text{m}$ pulse is split with a beam splitter that allows 80% of the $1.06\text{-}\mu\text{m}$ energy to pass through a high-pressure (55-atm) Raman cell filled with H_2 . The $1.06\text{-}\mu\text{m}$ beam excites several vibrational modes of the H_2 molecules, allowing the output beam to emerge with several different Stokes- and anti-Stokes-shifted frequencies. We chose a difference frequency mixing scheme with a lithium niobate (LiNbO_3) crystal that requires the collinear mixing of a $1.91\text{-}\mu\text{m}$ and a $1.06\text{-}\mu\text{m}$ beam. Therefore, the first Stokes-shifted $1.91\text{-}\mu\text{m}$ output from the Raman cell is mixed with the other $1.06\text{-}\mu\text{m}$ beam in the LiNbO_3 crystal to produce the $2.41\text{-}\mu\text{m}$ pump beam. The residual $1.06\text{-}\mu\text{m}$ beam from the conversion process is used as the probe beam and is sent into a variable time delay that consists of a reflective corner cube mounted onto a computer-controlled translation stage. The delay stage allows for precise incremental time delays between the pump and probe beams. The pump and probe beams are independently focused into the sample, and the $0.88\text{-}\mu\text{m}$ emission signal is recorded with a photomultiplier tube placed at the side of the sample. Two independent reference detectors are used to account for fluctuations in the laser output. All three signals from the detectors are

FIGURE 3. The pump-probe experiment. A $2.41\text{-}\mu\text{m}$ pump pulse excites a fraction of the ground state population into the $^4I_{13/2}$ level. After a time delay (τ_d), the $1.06\text{-}\mu\text{m}$ probe pulse excites the Nd ions from the $^4I_{11/2}$ level into the upper $^4F_{3/2}$ level. The $0.88\text{-}\mu\text{m}$ emission corresponding to the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition is time integrated and recorded. This sequence of events is repeated for longer time delays. (70-15-0194-0202pb02)

sent into electronic boxcars that integrate the waveforms. A hardware interface allows a computer to store the integrated signals. After the data are stored, the computer translates the delay stage and records a new set of data.

Figure 5 shows an example of the data taken with this setup. The data are illustrated with circles; the line is the numerical model. Details of the numerical model have been described elsewhere.¹ In brief, the model of the data includes information about the $^4I_{13/2} \rightarrow ^4I_{11/2}$ and $^4I_{11/2} \rightarrow ^4I_{9/2}$ nonradiative transitions. Three adjustable physical parameters fit the data to the model. We calculated a lower bound of the terminal lifetime by correcting the effective lifetime for the $\sim 200 \text{ cm}^{-1}$ smaller gap in the $^4I_{11/2} \rightarrow ^4I_{9/2}$ transition compared with the $^4I_{13/2} \rightarrow ^4I_{11/2}$ transition. The terminal lifetime (lower-bound) was found to be 250 ps with an error of ± 100 ps.

Indirect Method: Experiment and Results

Before discussing the indirect method, we first briefly explain the energy gap law. The nonradiative rate for the transition of a rare-earth ion such as Nd

within a glass or crystalline host medium can be written as

$$W_{nr} = A \exp(-\alpha p) \quad , \quad (1)$$

where A and α are host-dependent parameters and p is the normalized energy gap of the transition, $\Delta E_{\text{gap}}/h\nu_{\text{eff}}$.

FIGURE 5. The analysis of the data yielded a terminal lifetime of $\tau_{11/2} = 250$ ps with an error of ± 100 ps. (70-15-0194-0202pb04)

FIGURE 4. A simplified experimental diagram for the pump-probe experiment. The $1.06\text{-}\mu\text{m}$ output of the laser is mixed with the $1.91\text{-}\mu\text{m}$ Stokes-shifted output from an H_2 Raman cell to produce a $2.41\text{-}\mu\text{m}$ pump beam. The residual $1.06\text{-}\mu\text{m}$ beam is delayed and used as the probe beam. Three individual detectors and boxcars record and integrate the signals, which are stored on the computer for subsequent data analysis. (70-15-0194-0202pb03)

This expression assumes that for transitions involving approximately two or more phonons, only the highest frequency of vibration (ν_{eff}) in the host plays a significant role in enabling the nonradiative transition. Therefore the smallest number of high-frequency phonons needed to bridge the energy gap (ΔE_{gap}) tends to dominate the nonradiative decay. In addition, the theory assumes

FIGURE 6. An energy level diagram for the emission experiment. A 532-nm pump beam transfers a fraction of the ground state population into the $^4G_{7/2}$ level. The resulting emission at 600 nm from the $^4G_{7/2}$ level is recorded. Since the nonradiative decay for the $^4G_{7/2} \rightarrow ^4G_{5/2}, ^2G_{7/2}$ transition will be much faster than the radiative decay rate, the 600-nm emission signal will be a direct measure of the $\tau_{7/2}$ lifetime. (70-00-0295-0391pb01)

that only the size of the gap is important and not the specific details of the initial and final electronic states over which the transition takes place—hence the reason for the name “energy gap law.”

For most Nd-doped materials, the upper $^4G_{7/2} \rightarrow ^4G_{5/2}, ^2G_{7/2}$ transition and the lower $^4I_{11/2} \rightarrow ^4I_{9/2}$ transition have a similar-size energy gap. Figure 6 shows the energy level diagram for the pumping and emission processes. If the energy gap theory is assumed valid, then the values of the $\tau_{7/2}$ and $\tau_{11/2}$ lifetimes should also be quite similar. Since the Nd ions are easily excited from the ground state to the $^4G_{7/2}$ level with the frequency-doubled output of a 1.06- μm laser, one must only monitor emission signals from the $^4G_{7/2}$ level for a direct measure of the $\tau_{7/2}$ lifetime. This is because the rate of decay of the emission signal will be largely dominated by the $^4G_{7/2} \rightarrow ^4G_{5/2}, ^2G_{7/2}$ nonradiative rate. After exciting the ground-state Nd ions with the 532-nm pump, the 600-nm emission signal corresponding to the $^4G_{7/2}$ population decay is recorded. A technique suitable for measuring time-resolved fluorescence emission spectra characterized by weak signal levels and/or picosecond lifetimes is called “time-correlated single photon counting.”

Figure 7 illustrates an experimental scheme for measuring the $\tau_{7/2}$ lifetime that employs a photon counting system. The frequency-doubled output of a mode-locked Nd:YAG laser produces 1 W of 532-nm light with a 90-ps pulse length at a rate of 76 MHz. The 532-nm light is split into two paths. In path 1, the sample is illuminated and the fluorescence is collected and focused into the monochromator. A multichannel plate photomultiplier tube (MCP-PMT) is placed at the output of the monochromator and detects the 600-nm

FIGURE 7. An experimental scheme for the emission experiment using a time-correlated single-photon counting technique. The 532-nm pulse is split into two beams. In path 1, a beam illuminates the sample, and the resulting 600-nm emission is detected with a multichannel plate detector. The beam from path 2 is time delayed and focused onto a silicon detector. The photon counting electronics (constant fraction discriminator, time-to-amplitude converter, multichannel buffer) condition the electronic pulses from the two detectors. After multiple excitation pulses, the 600-nm emission waveform is reconstructed. (70-00-0295-0391pb02)

emission signal. The photon counting method assumes that the probability distribution for the emission of the first photon after excitation is also the intensity vs time distribution of the photons emitted as a result of the excitation. Therefore, by measuring the time at which the first photon is emitted for a large number of excitation events, the experiment eventually constructs the full probability distribution.⁸ This method uses the high repetition rate of the laser system to build up the emission signal after many excitation pulses.

The sequence of electronic events, as shown in Fig. 7, is as follows: The MCP-PMT monitors the arrival of the first 600-nm photon emitted after the sample has been excited. From the single photon event, the MCP-PMT is able to generate an electronic signal known as the start pulse. The constant fraction discriminator (CFD) conditions the electronic signal from the detectors so that the signals going into the time-to-amplitude converter (TAC) have a precisely timed leading edge independent of the amplitude fluctuations. The pulses entering the TAC initiate the charging of a capacitor. In path 2, the 532-nm pulse is time delayed and sent into a silicon photodetector, which outputs an electronic pulse to stop the charging of the capacitor. The amount of charge stored on the capacitor is proportional to the time interval (Δt) between the start and stop pulses. The TAC outputs an electronic pulse with an amplitude (A) that is directly proportional to the stored charge on the capacitor. A multichannel buffer (MCB) stores the value of the pulse amplitude.

FIGURE 8. A plot of the 600-nm emission as a function of time. The $\tau_{7/2}$ lifetime derived from the data analysis is 228 ± 50 ps. (70-00-0295-0391pb03)

The sequence is repeated until enough single-photon events have been sampled to accurately reconstruct the emission signal. Figure 8 shows the data and model for LG-750. The $\tau_{11/2}$ lifetime inferred from the kinetic analysis is found to be $\tau_{11/2} \equiv \tau_{7/2} = 228 \pm 50$ ps on the basis of the ${}^4G_{7/2} \rightarrow {}^4G_{5/2}$, ${}^2G_{7/2}$ relaxation time.

Energy Extraction Experiments and Modeling

In 1982, Yarema and Milam⁷ performed a series of energy extraction experiments for several Nd-doped glasses, including LG-750. Figure 9 shows a plot of the fluence out vs fluence into an LG-750 amplifier for 1-ns and 20-ns pulse durations. The data show that at higher input fluences, the 20-ns pulses begin to extract the stored energy more efficiently. Based on the experimental values of the terminal lifetime derived from the two experiments previously discussed, we would expect the 20-ns data to extract the energy more efficiently since there is virtually no bottlenecking of the terminal level. This is because the 20-ns pulses are 80 times longer than the terminal lifetime, as opposed to the 1-ns pulses, which are only 4 times longer. The difference in the two data curves can be accounted for by including the terminal-level lifetime in the solution to the coupled population rate and transport differential equations. However, as mentioned earlier, no analytic solution exists, and therefore the equations must be integrated for each new value of the pulse length t_p or the terminal

FIGURE 9. A plot of the extraction data taken by Yarema and Milam for 1- and 20-ns square pulses in the phosphate glass composition LG-750. A model that includes the ratio of the pulse width to the terminal-level lifetime is shown as the two solid lines. The terminal-level lifetime was left as a variable fitting parameter within the model. A best fit to the data yielded $\tau_{11/2} = 280 \pm 100$ ps. (70-00-1194-3749pb02)

lifetime $\tau_{11/2}$. We have found an empirical formula for the saturation fluence F'_{sat} that explicitly includes t_p and $\tau_{11/2}$:

$$F'_{\text{sat}} = \left[\frac{h\nu / \sigma_{\text{em}}}{1 + \frac{g_2}{g_1} B(R)} \right], \quad (2)$$

where $B(R)$ is a function of $R = t_p / \tau_{11/2}$, σ_{em} is the emission cross section, and g_2/g_1 is the ratio of upper to lower level degeneracies of the laser transition. The derivation of the function $B(R)$ will be discussed in the next section. The empirical formula for the saturation fluence can be substituted within the Frantz–Nodvik⁶ solution for energy extraction to model both the 1-ns and 20-ns data. The Frantz–Nodvik solution is written as

$$F_{\text{out}} = F'_{\text{sat}} \ln \left[1 + G_0 \left[\exp(F_{\text{in}} / F'_{\text{sat}}) - 1 \right] \right], \quad (3)$$

where G_0 is the small signal gain and F_{in} is the input fluence. The model is shown as the curves in Fig. 9. The terminal-level lifetime was left as a fitting parameter within Eq. (3). The best fit to the data yielded a terminal lifetime of $\tau_{11/2} = 280 \text{ ps} \pm 100 \text{ ps}$. This result is within the experimental error of the lifetimes derived from the previous sections. The average terminal lifetime and estimated error from all three experiments is 253 ps with an rms error of $\pm 50 \text{ ps}$.

Derivation of the Modified Saturation Fluence

There are six steps involved in finding the functional form of $B(R)$ in Eq. (2).

1. Transform the coupled rate and transport equations that include the terminal-level lifetime ($\tau_{11/2}$) to a coordinate system that moves within the frame of the pulse.
2. Simplify the equations by integrating over the spatial dimension so that only a set of coupled ordinary differential equations in time remain.
3. Integrate the coupled equations for a range of R values.
4. Substitute the modified saturation fluence defined in Eq. (2) into the Frantz–Nodvik solution, Eq. (3), fit each of the empirical output-vs-input fluence solutions to the exact numerical solutions found in step 3, and determine $B(R)$.
5. Find an analytic form for $B(R)$.
6. Determine the range of input parameters over which the modified saturation fluence F'_{sat} can be used.

We begin by assuming that the upper laser level has a population $N_2(0)$ created by a previous pumping process when the input pulse arrives. The coupled rate

and energy transport equations for a lossless system can be written as

$$\frac{\partial N_2(t)}{\partial t} = -\frac{I(z,t)}{h\nu} [\sigma_{\text{em}} N_2(t) - \sigma_{\text{abs}} N_1(t)], \quad (4a)$$

$$\frac{\partial N_1(t)}{\partial t} = \frac{I(z,t)}{h\nu} [\sigma_{\text{em}} N_2(t) - \sigma_{\text{abs}} N_1(t)] - \frac{N_1(t)}{\tau_{11/2}}, \quad (4b)$$

and

$$\frac{\partial I(z,t)}{\partial z} + \frac{n}{c} \frac{\partial I(z,t)}{\partial t} = I(z,t) [\sigma_{\text{em}} N_2(t) - \sigma_{\text{abs}} N_1(t)], \quad (4c)$$

where $N_2(t)$ and $N_1(t)$ represent the upper (${}^4F_{3/2}$) and lower (${}^4I_{11/2}$) level populations, σ_{em} is the single-ion stimulated emission cross section for the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition, and σ_{abs} is the single-ion absorption cross section for the ${}^4I_{11/2} \rightarrow {}^4F_{3/2}$ transition. The intensity of the laser pulse is denoted by $I(z,t)$. In a glass, σ_{em} , σ_{abs} , and $\tau_{11/2}$ are supposed to be site-averaged or ensemble values.

Eqs. (4a)–(4c) can be simplified by transforming them to a moving coordinate system that travels at the velocity of the pulse by making the following transformation of variables: $T = t - (zn/c)$ and $Z = z$. Using the prescription of Trenholme et al.⁹ we also define $\beta = N_2 \sigma_{\text{em}}$ to be the gain coefficient of the upper level ions and $\alpha = N_1 \sigma_{\text{abs}}$ to be the absorption coefficient of the lower level ions. The ratio of degeneracies is defined to be the constant $K = \sigma_{\text{abs}} / \sigma_{\text{em}}$. The result is

$$\frac{\partial \beta}{\partial T} = -\frac{I}{h\nu / \sigma_{\text{em}}} [\beta - \alpha], \quad (5a)$$

$$\frac{\partial \alpha}{\partial T} = \frac{IK}{h\nu / \sigma_{\text{em}}} [\beta - \alpha] - \frac{\alpha}{\tau_{11/2}}, \quad (5b)$$

and

$$\frac{\partial I}{\partial Z} = I[\beta - \alpha]. \quad (5c)$$

Eqs. (5a)–(5c) can be further simplified by observing that integration over their spatial dimension is possible, leaving a set of ordinary differential equations in time to be solved. Continuing to follow Trenholme, the quantities $U(t)$ and $L(t)$ are defined as

$$U(t) = \int_0^{\ell} \beta(z,t) dz \quad (6a)$$

and

$$L(t) = \int_0^t \alpha(z, t) dz \quad (6b)$$

Integrating Eqs. (5a)–(5c) along the length of the amplifier, we find that the problem now reduces to solving the following set of coupled differential equations of Trenholme⁹:

$$\frac{dU}{dt} = -\frac{I_{in}(e^{U-L} - 1)}{h\nu / \sigma_{em}} \quad (7)$$

$$\frac{dL}{dt} = \frac{I_{in}K(e^{U-L} - 1)}{h\nu / \sigma_{em}} - \frac{L}{\tau_{11/2}} \quad (8)$$

and

$$\frac{dF_{out}}{dt} = I_{out} = I_{in}e^{U-L} \quad (9)$$

where the known initial conditions $U(0)$, $L(0)$, and $I_{in}(t)$ are used to integrate Eqs. (7)–(9) forward in time. The integrated output intensity yields the output fluence

$$F_{out}(\text{numerical}) = \int_0^\infty I_{out}(t) dt = \int_0^\infty I_{in}(t) e^{U-L} dt \quad (10)$$

where $F_{out}(\text{numerical})$ is the exact solution to the lossless coupled rate and energy transport equations that includes effects of the terminal-level lifetime ($\tau_{11/2}$). The

numerical solutions of Eq. (10) for square pulses with $R = t_p/\tau_{11/2} = 0.01, 2$, and 100 are plotted in Fig. 10(a). For each numerical solution shown, a best fit of the empirical solution, Eq. (3), was found by adjusting the value of $B(R)$ to minimize the χ^2 fitting error. The empirical solutions are also shown in Fig. 10(a) along with the corresponding $B(R)$ and χ^2 values where we define

$$\chi^2 = \sqrt{\sum_{i=1}^{N=100} [F_{out}^{num}(i) - F_{out}^{emp}(i)]^2 \frac{1}{N-1}} \quad (11)$$

In Fig. 10(a), only three different values of $B(R)$ were determined. To find a functional form for $B(R)$, additional values were needed. In Fig. 10(b), over 1000 fits are shown to produce a nearly continuous curve for $B(R)$ (solid line). As required, $B(R)$ converges to the asymptotes of 1 and 0 for $t_p/\tau_{11/2} \ll 1$ and $t_p/\tau_{11/2} \gg 1$, respectively. The $B(R)$ curve shown in Fig. 10(b) was fit to three exponentials (open circles). This allowed for an improved fit to the $B(R)$ curve compared with the single exponential form originally proposed by Trenholme.¹⁰ The exponential sum is written as

$$B(R) = a_1 \exp(-R/b_1) + a_2 \exp(-R/b_2) + a_3 \exp(-R/b_3) \quad (12)$$

where the coefficients are

$$a_1 = 0.59735, a_2 = 0.34025, a_3 = 0.0605 \quad (13a)$$

FIGURE 10. (a) A plot of the numerical solution of the coupled differential equations, Eq. (10), is shown as the solid line. The open circles represent the empirical solution, Eq. (3). The value for $B(R)$ and the χ^2 fitting error are also shown. (b) Over a thousand fits, such as those shown in (a), were made to form a nearly continuous curve for $B(R)$. A best fit to the curve for a sum of three exponentials is shown by the open circles. (70-00-0295-0393pb01)

and

$$b_1 = 1.29348, b_2 = 4.14937, b_3 = 30.38384 \quad (13b)$$

To match the experimental data, Eq. (12) was evaluated for the following input parameter values:

$$g_2 / g_1 = 0.35 \quad (14a)$$

$$G_0 = 6.9 \quad (14b)$$

and

$$I_{in}(t) = I_0 \exp\left[-(t/w)^{30}\right] \quad (14c)$$

$I_{in}(t)$ being a square pulse approximated by a super-Gaussian of power 30. In addition, the relevant range of input fluences are defined with

$$\frac{F_{in}}{h\nu/\sigma_{em}} < 3.5 \quad (14d)$$

The empirical expression for the saturation fluence, Eq. (3), with $B(R)$ defined in Eq. (12), can be used to calculate the output energy with an error of less than 1.5%. Our choices for the value of the parameters— g_2/g_1 , G_0 , and $I_{in}(t)$ —and therefore $B(R)$ are specific to Yarema and Milam's extraction experiment. Equation (12) has some applicability for alternative ranges of input parameters.¹¹

In a recent publication by Beach et al.,¹² an approximate form for $B(R)$ was derived and shown to be

$$B(R)' = \frac{1 - \exp(-R)}{R} \quad (15)$$

However, Eq. (15) proved to be useful only for input fluences less than the saturation fluence of the medium ($F_{in} < h\nu/\sigma_{em}$). We have nonetheless found that an adequate fit to $B(R)$ can be achieved over a larger F_{in} range if an additional phenomenological parameter is introduced by taking the entire expression to the 1.13 power (i.e., $[B(R)']^{1.13}$). By substituting this alternative form of $B(R)$ into Eq. (2), we can determine the output energy with an error of less than 1.5% for the input parameters in Eqs. (14a)–(14c).

Comparison of the Direct and Indirect Methods for Several Nd-Doped Materials

We have discussed three possible experiments for measuring the terminal lifetime for Nd:phosphate glass. It would be convenient if the simplest method were shown to be sufficiently accurate for measuring the terminal lifetime of any Nd-doped laser material. Table 1 lists lifetime data for 13 different Nd-doped laser materials taken from the pump-probe and emission experiments previously discussed. In Fig. 11, the lifetime from the direct data ($\tau_{11/2}$) is plotted against the lifetime from the indirect method ($\tau_{7/2}$). The figure shows a line representing the best fit to the data of the form $y = mx$. Ideally, if both methods yielded the same results, then the slope m would be equal to one. However, the best fit produced a slope of 1.15, which suggests that the simpler, indirect method can be used to determine the terminal-level lifetime for most Nd-doped materials within a factor of two provided that the excitation pulses are short enough and the detectors and electronics have the required sensitivity and resolution.

FIGURE 11. The terminal lifetimes from the direct and indirect measurements are plotted. A best fit to the data is shown as the solid line of the form $y = mx$. The slope is 1.15. We find that the indirect method can be used to measure the terminal lifetime to within a factor of 2 for most Nd-doped laser materials. (70-00-0295-0394pb01)

The rightmost column of Table 1 lists our best assessment of the terminal lifetime from the two approaches. In comparing the lifetimes of the various groups of materials, we find that the phosphate glasses have a factor-of-two shorter lifetime than the silicate glasses. This is primarily due to the high phonon frequencies of the network forming PO_4 complexes in the phosphate host as opposed to the relatively low-frequency SiO_4 complexes in the silicate glasses. The shortest lifetime measured was from the phosphate crystal Nd:C-FAP. This material has both high phonon frequencies and a small energy gap. Within the oxide crystals, we find that Nd:YAG has the shortest lifetime and correspondingly the smallest energy gap. And finally, as expected, we find that for the fluoride materials, including Nd:YLF, the relatively low $300\text{--}600\text{ cm}^{-1}$ phonon frequencies give rise to slower (nanosecond) lifetimes.

Conclusions

We measured the terminal-level lifetime of the Nd-doped phosphate glass LG-750 from three independent measurements and found the average value to be $\tau_{11/2} = 253\text{ ps}$ with an rms error of $\pm 50\text{ ps}$. In the process of modeling data from the energy extraction experiments, we developed an empirical formula for the saturation fluence that can be used to account for the bottlenecking effects of the $^4\text{I}_{11/2}$ level in the Frantz–Nodvik analytic solution for energy extraction. We determined that the indirect emission measurements yield lifetimes that are within a factor of two of the direct pump-probe measurements. This result gives us confidence in using the simpler indirect approach for estimating the terminal lifetime for new prospective Nd-doped laser materials.

TABLE 1. Results from the direct, pump-probe measurements and the indirect, emission measurements. The right column lists our best assessment of the terminal lifetimes.

Material	Lifetime $\tau_{11/2}$ (ps)	Lifetime $\tau_{7/2}$ (ps)	Best assessment of lower-level lifetime (ps)
Phosphate glasses			
LG-750	250	228	250 ^(a)
APG-1	192	215	192 ^(a)
APG-x	200	210	200 ^(a)
APG-y	158	150	158 ^(a)
Phosphate crystal			
C-FAP, $\text{Ca}_5(\text{PO}_4)_3\text{F}$	156	70	70 ^(b)
Silicate glasses			
LG-660	535	215	535 ^(c)
LG-650	510	210	510 ^(c)
SOL-GEL	247	245	247 ^(a)
Oxides			
YAG, $\text{Y}_3\text{Al}_5\text{O}_{12}$	115	200	200 ^(b)
YALO, YAlO_3	896	1090	1090 ^(b)
GSGG, $\text{Gd}_3\text{Sc}_2\text{Ga}_3\text{O}_{12}$	401	715	715 ^(b)
Vanadate			
YVO_4	531	190	531 ^(d)
Fluorides			
YLF, LiYF_4	10,500	9100	9100 ^(b)
SrF_2	>5000	7000	7000 ^(b)
Fluoride glass			
ZBLAN, $\text{ZrF}_4\text{--BaF}_2\text{--AlF}_3\text{--LaF}_3\text{--NaF}$	>5000	18,000	18,000 ^(b)

^(a) Lower limit of the lifetime from the direct method agrees with the lifetime measured from the indirect method.

^(b) Indirect method is preferred since data is more accurate.

^(c) Energy gap relevant to $^4\text{I}_{11/2}$ and $^4\text{G}_{7/2}$ states are anomalously different so the $\tau_{11/2}$ and $\tau_{7/2}$ lifetimes do not agree.

^(d) Basis for difference between the $\tau_{11/2}$ and $\tau_{7/2}$ lifetimes is uncertain.

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FOUR-COLOR LASER IRRADIATION SYSTEM FOR LASER-PLASMA INTERACTION EXPERIMENTS

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Introduction

Since 1986, optical smoothing of the laser irradiance on targets for Inertial Confinement Fusion (ICF) has gained increasing attention.¹⁻⁵ Optical smoothing can significantly reduce wavefront aberrations that produce nonuniformities in the energy distribution of the focal spot. Hot spots in the laser irradiance can induce local self focusing of the light, producing filamentation of the plasma. Filamentation can have detrimental consequences on the hydrodynamics of an ICF plasma, and can affect the growth of parametric instabilities, as well as add to the complexity of the study of such instabilities as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).⁶⁻¹⁰ As experiments approach and exceed breakeven (i.e., where driver energy = fusion yield), the likelihood of significant excitation of these processes increases. As a result, we are including a scheme for implementing optical-beam smoothing for target experiments in the baseline design for the proposed next-generation ICF facility—the National Ignition Facility (NIF).¹¹

To verify the efficacy of this design for the suppression of parametric instabilities in NIF-like indirect-drive targets, we successfully modified a Nova beamline to simulate the proposed NIF conditions. In this article, we discuss the laser science¹² associated with a four-color target campaign on Nova to test the effect of f -number (ratio of focal length to beam diameter) and temporal smoothing on the scaling of SBS with a four-segment interaction beam using NIF-like parameters. The results of the target series associated with the four-color configuration are discussed in "Laser-Plasma Interactions in Large Gas-Filled Hohlräume," p. 97 of this *Quarterly* and elsewhere.¹³⁻¹⁵

The NIF¹¹ design has four beamlets per beamline, which overlap to form an effective $f/8$ beam focus. Each beamlet is smoothed by a random phase plate (RPP).

RPPs consist of many randomly distributed on/off phase elements deposited on a fused-silica substrate.^{16,17} The focal-plane intensity distribution resulting from focusing light through a bilevel RPP consists of an overall envelope, modulated by fine-scale spatial structure within that envelope. The envelope is produced by diffraction from a single-phase element, and the fine-scale structure, or speckle, is due to the superposition of the diffraction patterns from each of the phase elements. The speckle size corresponds to the diffraction limit of the full-aperture beam incident on the RPP. Because speckle size increases with f -number, an $f/8$ beam should filament more than the $f/4.3$ beams on Nova.^{18,19} Simulations indicate that SBS reflectivity increases due to filamentation, with a total gain greater than calculated for a uniform laser intensity. SBS reflectivities $>10\%$ may unacceptably degrade target performance by disrupting symmetry or reducing the energy available for radiation heating. The introduction of temporal and spatial incoherence over the face of the beam using techniques such as smoothing by spectral dispersion (SSD)¹ or induced spatial incoherence (ISI)⁵ reduce the rms-intensity variations in the laser irradiance when averaged over a finite time interval, providing temporal smoothing. Temporal smoothing makes filamentation less likely because the filament must form before the hot spot moves to a different location.

Figure 1 is a schematic of the SSD technique. Broadband light, produced in this case by electro-optic phase modulation (FM), is spectrally dispersed by a grating, and then amplified, frequency converted, and focused through an RPP on to a target. Each distinct frequency component produces a speckle pattern, resulting in a superposition of many speckle patterns. Since each frequency propagates at a different angle through the phase plate, the speckle patterns spatially shift as a function of frequency. As the frequencies change throughout the length of the pulse, the rapidly

fluctuating interference of the displaced speckle fields for the different spectral components causes the irradiance to appear smooth on a time-averaged basis. The most effective beam smoothing is obtained when the speckle field for each spectral component is spatially shifted at the target plane by at least one-half speckle diameter, $d_{1/2} = 1.22\lambda f/D$, where D is the beam diameter on the phase plate, λ is the third harmonic (3ω , 351 nm) wavelength, and f is the focal length of the lens.⁴ This level is achieved when the 3ω dispersion at the output aperture is fixed at $d\theta/d\nu = d_{1/2}/f\delta\nu$ in rad/Hz, for a specified spacing between spectral components, $\delta\nu$, and speckle size, $d_{1/2}$.

The time-integrated smoothness, σ/I , is defined as the spatial rms-intensity variance normalized to the average at the target plane. The smoothness is equal to $1/\sqrt{N}$, where N is the number of decorrelated speckle fields superimposed at each point on the target. The effective time-integrated smoothing level for spectrally dispersed beams can be approximated by

$$\sigma/I = \sqrt{\tau \delta\nu} = \left[\frac{1.22\lambda\tau}{D} \left(\frac{d\theta}{d\nu} \right)^{-1} \right]^{\frac{1}{2}} \quad (1)$$

where $\delta\nu$ is the effective separation between independent spectral components in Hz, τ is the coherence time in seconds (inverse of the frequency-converted bandwidth), and $d\theta/d\nu$ is the spectral dispersion at 3ω in rad/Hz. For optimal dispersion, N is the total number of spectral components in the beam and $\delta\nu$ is the modulation frequency of the electro-optic phase modulator. Instantaneously, $\sigma/I \cong 1$ due to basic Rayleigh speckle statistics, but this value decreases rapidly as the irradiance variations are averaged over time. The initial smoothing occurs on a time scale proportional to $1/\tau$, reaching the asymptotic level given by Eq. (1) in a time determined by $1/\delta\nu$. The initial onset of smoothing is delayed due to the spatially varying time delay across the beam imposed by the grating (i.e., a delay of λ/c per illuminated grating line). This time delay δt is proportional to $1/\delta\nu$, and therefore N is proportional to $\delta t/\tau$.

In the case of m beamlines, each with a different central frequency and n decorrelated FM components per beamline, $\sigma/I = 1/\sqrt{N}$, where $N = nm = \Delta\nu/\delta\nu$. The value of D in Eq. (1) becomes the individual beamlet diameter, and the coherence time τ is proportional to $1/\Delta\nu$, where $\Delta\nu$ is the total bandwidth of the four FM-modulated central frequencies. With a four-color segmented beam, as used in the current Nova experiments, the superposition of the four narrowband speckle fields should produce a smoothing level of 50% ($\sigma/I = 0.5$) at the target plane. Since all four colors are present simultaneously throughout the pulse, the asymptotic level is achieved within a few picoseconds. The smoothing rate is proportional to the number of beamlines and is unaffected by the grating time delay, δt . The resulting pattern fluctuates with a periodicity determined by the narrowest frequency separation. The addition of FM bandwidth to the four-color beam allows additional temporal smoothing by creating many additional decorrelated speckle fields. This smoothes very rapidly due to the wide overall bandwidth. The rate of four-color beam smoothing with FM bandwidth and spectral dispersion is four times faster than one-color FM smoothing, assuming the same bandwidth per beamline, reaching a 50% lower σ/I at the same f -number per beamlet.

One of the primary limitations on previously used beam-smoothing techniques is the reduced frequency conversion efficiency to the third harmonic due to bandwidth.²⁰ High-efficiency frequency tripling can be achieved only over a narrow spread in wavelength for a given crystal phase matching condition; thus to remain within 10% of the maximum conversion efficiency, the input bandwidth should be limited to ~ 0.2 nm, or ~ 60 GHz. However, while beam smoothness is strongly dependent on both the amount of dispersion and spectral bandwidth used, the larger the bandwidth (i.e., the shorter the coherence time), the more rapidly the structure changes, and the more rapidly the time-averaged intensity smoothes.

The NIF design can simultaneously achieve high third-harmonic conversion efficiency with broad

FIGURE 1. Schematic illustration of the smoothing by spectral dispersion (SSD) technique.
(70-00-0395-0824pb01)

bandwidth for rapid smoothing. The NIF is proposed to have four beamlets focused to a single spot per beamline, each with a different frequency and separated by 1 nm.¹¹ Each individual beamlet will have a bandwidth of only 0.25 nm, allowing high-efficiency frequency tripling. The superposition of four beamlets with different frequencies will produce the wide overall-spectral width required for good temporal smoothing.

To simulate this configuration, a Nova beam was modified to have an $f/8$ geometry, with a segmented four-quadrant beam. We developed a multifrequency bandwidth source that is spatially separated into four quadrants, each containing a different central frequency separated by up to 0.88 nm. Each quadrant is independently converted to the third harmonic in a four-segment Type I/Type II potassium dihydrogen phosphate (KDP) crystal array with independent phase matching in each quadrant for efficient frequency conversion of the four frequencies. In addition, a limited amount of bandwidth (~ 0.2 nm) can be added to each frequency component to more closely approach a continuous broadband spectrum. We compared the results obtained with this

method with those previously obtained on Nova with a continuous bandwidth source and a single-frequency conversion array.²⁰ Using this method, we obtained a factor of four increase in 3ω output energy with comparable overall bandwidth.

Four-Color Implementation on Nova

Significant modifications to the oscillators, mid-chain optics, SSD table, frequency-conversion arrays, laser diagnostics, target diagnostics, and final focus lens allowed implementation of four-color capability on Nova, as shown in Fig. 2. To perform target experiments, the four-color input spectrum must be stable to $\pm 10\%$ in energy, with frequency jitter $< 0.0019\%$ and be reproducible from shot to shot. Energy balance between the four quadrants must be better than $\pm 10\%$ at 1ω and $\pm 20\%$ at 3ω . The composite beam is required to have $> 2 \times 10^{15}$ W/cm² at the third harmonic in a 500- μ m-diam focal spot. This section describes the modifications

FIGURE 2. Layout of Nova's four-color system. Areas modified to accommodate the four-color system are shaded. (70-00-0395-0792pb01)

required to meet these conditions and the overall laser performance of the four-color system.

Four-Color Bandwidth Source

Four-color target experiments required the development of a four-color laser source with a bandwidth capability similar to that planned for the NIF. The technique chosen to provide the four discrete frequencies is based on the nonlinear mixing of two frequencies in an optical fiber. Two photons at the pump frequencies are annihilated to create two photons at frequencies shifted toward the blue and red sides.^{21,22} These newly created spectral components result in self-phase modulation (SPM)-induced broadening of the pulse. The phase shift incurred by propagation through the fiber is proportional to the fiber length L and the pulse intensity I , and the number of sidebands generated is linearly proportional to this phase shift. The number of lines generated is controlled by changing the pump intensity into the fiber, while the separation between frequencies

is varied by tuning the frequencies of the oscillators. This technique produces a broad comb of discrete single-mode frequencies (up to ~ 40 lines), which can be spectrally separated to provide a tunable single-frequency source.

We produce the two-frequency input to the fiber by etalon-tuning two single longitudinal mode, Q-switched Nd-doped yttrium lithium fluoride (Nd:YLF) oscillators²³ to 1053.23 nm and 1052.79 nm, respectively. The measured frequency variation of each oscillator is $<0.0016\%$. The output beams are temporally and spatially overlapped, and shortened to a 15-ns nominally square pulse and coupled into a single-mode polarization preserving fiber. The spectrally integrated beam energy is recorded at the input and output of the fiber. The time-integrated and time-resolved output spectra and spectrally integrated pulse shape are also recorded.

Time-integrated spectral measurements, like the example shown in Fig. 3(a), indicate that the energy content of the central spectral lines remains constant to within $\pm 10\%$ as the input energy increases and the spec-

FIGURE 3. Multifrequency spectrum generated by self-phase modulation of two frequencies separated by 0.44 nm in an optical fiber. (a) Shows a representative time-integrated spectrum for an intensity-length product, $IL = 1.2 \text{ TW/cm}$. (b) Shows the temporal evolution of the same spectrum. The number of spectral lines increases and decreases linearly with the 4-ns rise and fall of the pulse. (70-00-0395-0793pb02)

trum broadens. The amplitude between lines varies $< \pm 10\%$, while the output energy of the integrated spectrum varies $< \pm 3\%$ from shot to shot. A maximum spectral width of 14-nm full-width at half maximum (FWHM) is obtained by this technique. The temporal buildup of the SPM spectrum, shown in Fig. 3(b), reflects the change in pulse intensity caused by the 4-ns rise and fall time of the input pulse. The central 3–5-ns section of the 15-ns pulse is nominally flat in time across the generated spectrum. A temporally uniform 1-ns slice is selected from the center of that section by the main pulse shaping system in the Master Oscillator Room (MOR), then shaped to precompensate for square-pulse distortion later in the laser chain.^{24,25} The time-resolved spectra shown in Fig. 4 demonstrate that each spectral component is stable on the time scale required for four-color experiments for low- and high-energy input to the fiber.

To produce the main pulse for the other nine Nova beams, we split off a percentage of the energy in one of the frequencies before it enters the fiber, as shown in Fig. 2. The split-off pulse is then re-injected into the main beam path before it enters the temporal pulse shaping system. Following spectral and temporal shaping, the beam propagates through a double-pass electro-optic phase modulator, which allows the addition of 0.2 nm of FM bandwidth to each frequency component to provide SSD. The time-resolved spectrum of the FM-modulated pulse is shown in Fig. 4(c). Since both the multifrequency and single-frequency

beams share this beam path, FM bandwidth is present on all 10 Nova beamlines when the modulator is active.

Grating Separator

The multifrequency beam from the MOR is amplified in the preamplifier section of Nova, where its energy increases to several Joules before being routed to the appropriate beamline. The time-multiplexed multifrequency and single-frequency beams are separated into different beamlines by a Pockels cell/polarizer combination in the preamplifier section. The multifrequency pulse is directed to beamline 7 (BL7), which contains the wavelength separation optics, while the single-frequency pulse is sent to the other nine beamlines via beam splitting and delay optics. The four-color separation optics in BL7 introduce sufficient delay, relative to the other arms, to allow all pulses to arrive simultaneously at the target.

We modified the existing SSD table² in BL7 to accommodate the four-color separation optics. These optics, shown schematically in Fig. 5, convert the single multifrequency beam into a four-quadrant beam with one frequency per quadrant. The system is equivalent to four monochrometers sharing a common output slit; as a result, the four output beams are coincident and parallel. This "multichromometer" consists of a four-segment grating array followed by a 1:1 relay with the slit at the focal plane. The image of the grating array is relayed to the output plane where the wavelength of

FIGURE 4. The time-resolved spectra of the amplified 1-ns sliced pulse demonstrate that each component of the multifrequency spectrum is stable on the time scale required for four-color experiments. The separation between each color is 0.44 nm. (a) Low-energy input to the fiber, $IL = 0.2$ TW/cm. (b) High-energy input to the fiber, $IL = 1.3$ TW/cm. (c) High-energy input into the fiber with 0.2 nm of FM bandwidth per component, $IL = 1.3$ TW/cm. (70-00-0594-2299pb01)

each segment is selected by independently angle tuning each grating. The unwanted frequencies in each segment are blocked by the slit. A charge-coupled device (CCD) camera imaging the slit monitors the unselected frequency components, allowing alignment of the grating components before each shot. A spectrometer after the slit provides a record of the four-color output spectrum.

The gratings separate each of the four main frequency components with up to 0.3 nm of FM bandwidth per frequency, by more than the focal spot size, allowing passage through the slit without interference from adjacent frequency-modulated bandwidth components. In addition, sufficient dispersion is used to separate each frequency-modulated bandwidth component at the target by at least one-half speckle diameter to achieve optimal beam smoothing. We chose 1800 grooves/mm gratings with a dispersion of 5.64×10^{-3} rad/nm at 1053 nm to meet these constraints. The gratings used in the array were fabricated in-house to obtain the highest possible diffraction efficiency and damage threshold.²⁶ To reduce the temporal delay of the pulse

front across the beam, the gratings are arranged in a "V" configuration. This reduces the temporal skew from 600 to 300 ps, producing a chevron-shaped temporal distortion across the face of the beam, symmetric about the horizontal midline. The non-Littrow grating configuration produces a geometric distortion that is corrected with a four-quadrant heart-shaped apodizer, as shown schematically in Fig. 5. This preforms the beam into a heart-shaped design before the grating array, which then diffracts into a circular beam.

To compensate for unequal SPM sideband amplitudes, the line shape of the amplifier gain, and other spectral inhomogeneities, we independently adjust the energy in each segment to achieve an equal distribution of energy at the target. To balance the quadrant energies, a four-quadrant array of absorbing filters, adjustable in 5% increments, is placed before the grating. Rod shots, in which only the preamplifier section fires, are used to balance the energies between the quadrants. Using this method, better than $\pm 6\%$ energy balance at 1 ω and $\pm 17\%$ at 3 ω is routinely achieved.

FIGURE 5. Schematic of the special optics installed in the four-color beamline to convert the single multifrequency beam into a four-quadrant beam with one frequency per quadrant. In the output plane, the wavelength of each segment is selected by independently angle-tuning each grating. The unwanted frequencies are blocked by a slit at the focal plane. The beam shape is preformed into a heart-shaped design before the grating array, which then diffracts into a circular beam due to the grating configuration. (70-50-0993-3246pb01)

Frequency Converter

The full-aperture 2×2 frequency conversion array, shown in Fig. 6, converts the four-color beam to the third harmonic. Each quadrant contains a 12-mm-thick Type I doubler and a 10-mm-thick Type II tripler, using 27-cm Nova KDP crystals. We use the Type I/Type II frequency tripling scheme because of increased performance previously demonstrated on Nova,^{20,27} and its adaptability to angle tuning. The four crystal segments are mechanically offset in angle and independently tunable, to allow placement of any of the four wavelengths in each quadrant. The array allows independent tuning of all eight crystals, although the bandwidth of the doublers is sufficient to accommodate the frequency span of the four colors with a single angular orientation. Although the area provided by the four 27-cm crystals is smaller than the full Nova aperture ($\sim 80\%$), the expected energy on target is sufficient for four-color

FIGURE 6. Photograph of the Type I/Type II four-color frequency conversion array. (70-10-0494-2032pb01)

target experiments. We chose the crystal separation to maximize the beam area ($\sim 2600 \text{ cm}^2$), compatible with the beam apodization on the grating separation table. Once installed and aligned, a rocking curve was performed to tune the array for maximum performance. This four-color array design achieves up to 65% 3ω conversion efficiency, providing up to 2.3 kJ on target.

Four-Color System Performance

1ω Propagation Experiments

We performed a series of 1ω propagation tests to assess various issues associated with the propagation of a multifrequency beam through the Nova preamplifier section. The energy and near-field image of the unsegmented multifrequency beam are recorded midway through the Nova preamplifier section. The characteristics of the 1ω segmented four-color beam are recorded in the input sensor immediately following separation, and again in the output sensor package before conversion to the third harmonic. The output sensor diagnostics include near-field photography of the spatially separated four-color beam, measurement of the integrated beam energy via calorimetry and diode measurements, and measurement of the integrated pulse shape of the full beam. The energy in each frequency is determined by integrating the fluence in each quadrant of the output sensor near-field camera. A 1-m spectrometer provides a time-integrated spectrum of the full beam. In addition, an array of four photodiodes records the pulse shape of the individual frequencies.

We observe substantial spectral gain narrowing of the SPM spectrum in the Nova chain. Amplification (gain $\sim 10^{21}$) reduces the unamplified SPM spectrum shown in Fig. 3(a) from $\sim 9.8 \text{ nm}$ FWHM to the $\sim 2.1 \text{ nm}$ FWHM spectrum shown in Fig. 7(a). This results from spectral gain narrowing produced by the 2.15-nm

FIGURE 7. (a) Significant gain narrowing of the input spectrum occurs after full amplification in the Nova chain (gain $\sim 10^{21}$). A frequency spacing of 0.88 nm can be obtained with this spectrum by selecting alternate lines. (b) The central four lines of a low-power SPM spectrum produce a 0.44-nm separation for the first set of four-color target experiments. (c) A series of lines offset from the center of the spectrum are selected for the second four-color target series. The four colors selected by the grating array are indicated by 1, 2, 3, and 4, while 5 is the heater beam frequency. (70-00-0395-0794pb02)

FWHM fluorescence line width of Nd:glass²⁸ and bandwidth limiting components in the laser chain. As the extraction frequency moves off the peak of the laser glass fluorescence spectrum, the gain coefficient decreases. Thus, to maintain a constant output fluence from the amplifier chain, the input energy must increase to compensate for the reduction in gain off the peak. Experimental measurements show that although the gain and saturation fluence differ for each wavelength as expected, the differences in square pulse distortion are minimal. We performed small-signal gain measurements for the multifrequency spectrum by propagating low-power shots through the laser chain without firing the disk amplifier section. These measurements indicate that the maximum bandwidth that can be supported by the Nova chain is ~ 3 nm. At maximum bandwidth, it is necessary to keep the energy in the preamplifier section below the fluence threshold for self-focusing and other nonlinear interactions.

For the first four-color target series, we chose a 0.44-nm separation between the four selected frequencies. The intensity propagated through the optical fiber was reduced to allow the generation of only six lines,

FIGURE 8. Comparison of the temporal pulse shape for each of the four colors (a) at the source and (b) at the output of the laser chain for a 0.44-nm separation. (70-00-0395-0795pb01)

as shown in Fig. 7(b). The four lines selected on the grating table are centered on the peak of the Nd:glass gain curve to maximize the gain in the amplifier chain, producing 6 kJ at 1ω in 1 ns. Figure 7(c) shows the 8-line spectrum propagated to the grating array for subsequent target experiments. For these experiments, the four-color gratings were tuned to select four colors shifted off the peak of the gain curve. Four colors with a maximum separation of 0.88 nm can be obtained by selecting alternate lines in the SPM spectrum shown in Fig. 7(a), with sufficient 3ω energy to perform target experiments simulating the NIF frequency separation.

Figure 8 compares the pulse shape of each frequency at the source and the output of the laser chain for a 0.44-nm separation between the four colors. The pulse shapes of each frequency at the source, shown in Fig. 8(a), are comparable to within the diagnostic background noise. In Fig. 8(b), the four-quadrant output-diode traces show that three of the pulses lie on top of each other, while the fourth shows a slight difference in contrast ratio, consistent with the higher output fluence in this quadrant. At this fluence and line separation, it is possible to balance the 1ω energy between the four quadrants to better than $\pm 6\%$, with temporally smooth pulses to within the diagnostic resolution. Figure 9 shows a representative near-field image of the 1ω beam taken with the output sensor diagnostic CCD camera.

FIGURE 9. Representative near-field image of the 1ω beam taken with the output sensor diagnostic CCD camera. The 1ω energy in each of the four quadrants is balanced to better than $\pm 6\%$. (70-00-0495-0924pb01)

Four-Color Beam Smoothing

The two-beam laser diagnostic station (TBLDS)²⁹ was used to characterize the beam smoothing properties of the four-color irradiance. We used a 3.3-mm-diam, square element phase plate with the standard Nova $f/4.3$ focal geometry to produce approximately the same size focal spot (550 μm) as the $f/8$ geometry in the 10-beam chamber. The near-field, far-field, and expanded far-field images; temporal profile, energy, and spectra were recorded in the TBLDS following frequency conversion to the third harmonic. Figure 10 shows the effect of beam smoothing at 3ω in the equivalent target plane images for (a) an unsmoothed Nova beam; (b) a single-frequency beam with an RPP; (c) a four-color beam with 0.44 nm, or 122 GHz, separation between colors at 1ω and an RPP; and (d) a four-color beam with 0.2 nm or 5.4 GHz of FM bandwidth per component at 1ω and an RPP. All four images have equivalent magnification. The nonuniformities in the unsmoothed irradiance shown in Fig. 10(a) demonstrate the need for beam smoothing. The far-field image

FIGURE 10. (a) Nonuniformities in the equivalent target plane image of the 3ω beam at best focus demonstrate the need for beam smoothing. The effect of beam smoothing at 3ω can be seen in the equivalent target plane images for (b) a single-frequency beam with an RPP, (c) a four-color beam with a 0.44-nm separation and RPP, and (d) a four-color beam with a 0.44-nm separation, 0.2 nm of FM bandwidth per color, and RPP. The normalized rms intensity variance, σ/I , for these images is (b) ~ 0.79 , (c) ~ 0.25 , and (d) ~ 0.16 . (70-00-0395-0796pb01)

of a single-frequency beam with the RPP in Fig. 10(b) shows that the intensity structure is broken up into a homogeneous well-controlled speckle pattern. This pattern remains static throughout the pulse length. The normalized rms variance of the focal irradiance, σ/I , is ~ 0.79 for this image. This is less than the theoretical predicted value of one for a single speckle pattern, but consistent with previous measurements on Nova and elsewhere.^{20,30} This may be an indication that some polarization smoothing is occurring due to birefringence in the focus lenses. In Fig. 10(c), the pattern produced by the four-color beam shows the smoothing obtained by superposition of four independent speckle patterns, with the significant residual speckle structure expected from the limited number of static patterns. The four-color beam produces a time-integrated smoothing level of $\sigma/I \sim 0.25$, in contrast to the theoretically predicted value of $\sigma/I = 0.50$. The reduced σ/I may be associated with the effects seen in Fig. 10(b). Also note that the intensity-length product for these experiments exceeds the threshold for stimulated rotational Raman scattering in air by $\sim 25\%$,^{31,32} as observed experimentally. The chromatic dispersion of this additional bandwidth by the additional optics used to direct the beam to the TBLDS may also contribute slightly to the lower σ/I measured on this shot. Figure 10(d) clearly shows that SSD with four colors and FM bandwidth produces a much smoother focal spot than the previous three images. Discrete speckles are no longer observable and the irradiance is smooth and uniform. The vertical streaks in the image are formed by the one-dimensional nature of the dispersion. This image has a $\sigma/I \sim 0.16$. This is less smooth than theoretically predicted, but is consistent with previous measurements of smoothing with FM bandwidth on Nova.²⁰

Theoretical modeling of the temporal dynamics of beam smoothing demonstrates that the multiple-aperture SSD technique described here can give very rapid and effective beam smoothing at the target plane. Simulations of the power spectra and the smoothing capability for (a) one-color SSD with 108 GHz of bandwidth at 1ω , (b) four colors with 136 GHz separation at 1ω and no FM bandwidth, and (c) four colors with 136 GHz separation and 54 GHz of bandwidth at 1ω are shown in Figs. 11 and 12. Figure 11(a) shows the spectrum for a one-color beam with 108 GHz of FM bandwidth at 1ω , 324 GHz at 3ω . There is sufficient dispersion to decorrelate each FM component of this spectrum at the target plane (0.21 $\mu\text{rad}/\text{GHz}$ at 3ω). These values represent the maximum bandwidth/dispersion that can be propagated through the Nova chain with decorrelated spectral components without clipping in the spatial filter pinholes. The smoothing rate, $(d\sigma/dt)/\sigma$, reaches a peak rate of 0.11 ps^{-1} in 2–3 ps, comparable to the inverse of the total bandwidth. The intensity cross-correlation between the speckle field at

a given time and the initial speckle field drops from 1.0 to a value near zero in the same 2–3 ps. The normalized smoothing level, σ , drops from near unity to 0.707 in the first 2–3 ps, and to 0.5 in 8–10 ps, as shown in Fig. 12(a). It reaches an asymptotic level of ~ 0.15 after

1 ns, consistent with time-integrated smoothing levels previously measured on Nova under these conditions.²⁰

Figure 11(b) shows the 3ω output spectrum for a four-color beam with frequencies separated by 136 GHz at 1ω or 405 GHz at 3ω . Figure 11(c) shows the same four-color spectrum, but with 54 GHz of 1ω FM bandwidth (162 GHz at 3ω) added to each of the four colors. We use a spectral dispersion of $0.29 \mu\text{rad}/\text{GHz}$ at 3ω in the simulations, corresponding to the value used in the four-color experiments on Nova. The initial smoothing rate for four-colors alone is five times faster than for the single-color FM bandwidth case. A peak rate of 5 ps^{-1} is achieved in less than 1 ps, corresponding to the inverse of the total frequency spread of 1.2 THz, reaching $\sigma = 0.5$ within 2.5 ps. The speckle field initially decorrelates in <1 ps, but the cross-correlation returns to unity at every beat period of the closest frequency spacing (405 GHz), and the field repeats every 2.47 ps. Thus even though the initial smoothing rate is very high, once σ reaches 0.5, as expected for the sum of four independent speckle fields, no further smoothing is obtained, as shown in Fig. 12(b). With the addition of FM bandwidth to each of the four colors, the initial high smoothing rate is still achieved, but the integrated smoothing level continues to decrease rapidly, reaching an asymptotic value of 0.08 in a few tens of picoseconds [Fig. 12(c)]. Since the overall spectrum is not continuous, the intensity cross-correlation shows secondary and tertiary peaks at times related to the beat frequencies of the principal four colors; however, these peaks are significantly damped within 8–10 ps, reducing in magnitude over one FM period when all frequency components are available for smoothing. The combination of four colors with FM bandwidth provides both a rapid initial smoothing level and effective time-averaged beam smoothing at the target plane.

FIGURE 11. Power spectrum of a beam with (a) 324 GHz of FM bandwidth at 3ω , (b) four colors with 405 GHz separation at 3ω , and (c) four colors with 405 GHz separation and 162 GHz of FM bandwidth on each color. (70-00-0395-0797pb01)

3ω Four-Color Performance

To simulate the $f/8$ geometry proposed for the NIF, we retrofitted the four-color beamline to accommodate an $f/8$ target chamber lens on the 10-beam chamber. The incident beam diagnostic (IBD) is used to diagnose the 3ω performance of the four-color system.³³ The IBD records the spatially integrated 3ω energy, the near-field image, and the temporal pulse shape integrated over all four quadrants. Figure 13 shows a representative near-field image of the 3ω beam taken with the IBD CCD camera. The energy in the four quadrants is balanced to better than $\pm 17\%$.

After installation on the 10-beam chamber, the four-color KDP array was rocked $\pm 500 \mu\text{rad}$ to establish the best tuning coordinates, achieving a 3ω array efficiency

of up to 65%. This delivers up to 2.3 kJ at 3ω in 1 ns to the target. In addition, since the standard master oscillator is tuned 0.22 nm off Nd:YLF line center to produce the four-color beam, the pulse to the other nine arms is also shifted in frequency. Thus, the KDP arrays on the other nine arms of Nova are appropriately tuned to

FIGURE 12. Calculated rms intensity variance, σ/I , of the focal irradiance plotted as a function of integration time for (a) 324 GHz of FM bandwidth at 3ω , (b) four colors with 405 GHz separation at 3ω , and (c) four colors with 405 GHz separation and 162 GHz of FM bandwidth on each color. (70-00-0395-0798pb01)

compensate for this shift. Conversion efficiencies on the other nine arms with the Nova Type II/Type II arrays at the shifted wavelength are within 10% of their nominal conversion efficiencies on YLF line center. The addition of 0.2 nm of FM bandwidth to the four-color beam and the other nine arms reduces the 3ω conversion efficiency by <5%.

Pointing experiments performed with the $f/8$ lens after the four-color array activation show the expected beam symmetry and size at best focus, with all four quadrants within 50 μm of their expected positions. The arrival of the four-color beam at target chamber center relative to the other nine arms is synchronized to within 20 ps using techniques developed for the Precision Nova project.³⁴ A 5.8-mm-diam, square element phase plate inserted in the four-color beamline after the $f/8$ lens, produces a 570- μm focal spot diameter with a peak intensity of $2 \times 10^{15} \text{ W/cm}^2$ for target experiments. To determine the effectiveness of the four-color system in controlling instabilities in NIF-like plasmas, the Full-Aperture Backscatter Station was used to measure the spatial distribution of the backwards propagating SBS from a target in each of the four beam quadrants, as well as the wavelength-resolved temporal evolution of the SBS in each quadrant. Measurements show that the four-color system produces <1% SBS backscatter at $>2 \times 10^{15} \text{ W/cm}^2$ when used to

FIGURE 13. Representative near-field image of the 3ω beam taken with the incident beam diagnostic CCD camera in the 10-beam chamber area. The 3ω energy in each of the four quadrants balances to better than $\pm 17\%$. (70-00-0495-0924pb02)

probe NIF-like plasmas. Further details of the plasma physics experiments performed using the four-color system are described in "Laser-Plasma Interactions in Large Gas-Filled Hohlräume," p. 97 of this *Quarterly* and elsewhere.¹³⁻¹⁵

Summary

We successfully deployed a four-color bandwidth system with optical characteristics similar to that of the proposed NIF on Nova for laser experiments. A multi-frequency bandwidth source is spatially separated into four quadrants, each containing a different central frequency, providing a total bandwidth of 1.32 nm at 1 ω . The four colors are spatially separated into four quadrants using a novel grating multichrometer design. Each quadrant is independently converted to the third harmonic in a four-quadrant frequency conversion array with independent phase-matching, providing up to 2.3 TW at the third harmonic. The measured far-field irradiance shows ~25% rms intensity variation with four colors alone, reaching this level within 3 ps. The addition of 0.2 nm of FM bandwidth to each frequency component reduces the rms intensity variation level to ~16% without significant impact on the conversion efficiency.

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TESTING A NEW MULTIPASS LASER ARCHITECTURE ON BEAMLET

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Introduction

We completed proof-of-principle tests on Beamlet for a new multipass laser architecture that is the base-line design for the French Megajoule laser and a backup concept for the U.S. National Ignition Facility (NIF) laser. These proposed laser facilities for Inertial Confinement Fusion (ICF) research are described in their respective *Conceptual Design Reports*.^{1,2} The lasers are designed to deliver 1.8 MJ and 500 TW of 0.35- μm light onto a fusion target using 240 independent beams for the Megajoule laser and 192 beams for the NIF laser. Both lasers use flash-lamp pumped glass amplifiers and have approximately 38-cm square output beams. However, there are significant differences in their architecture.

Figure 1 shows the NIF baseline architecture. A single beam consists of three amplifier modules with a total of 19 laser slabs, cavity and transport spatial filters, two cavity mirrors to form a multipass cavity, and a full-aperture Pockels cell and polarizer to switch the beam out of the cavity after four passes. During a shot, a beam from the optical pulse generator is injected into the transport spatial filter. The beam passes through the booster amplifier, makes four passes through the

cavity amplifier, exits the cavity, and again passes through the booster amplifier and out of the laser towards the target. The Pockels cell and polarizer are required to switch the beam out of the cavity. After pass 1, the Pockels cell is turned "on" to rotate the beam polarization 90°, making passes 2 and 3 the correct polarization to pass through the polarizer and stay in the cavity. The Pockels cell is turned "off" at the end of pass 3, so pass 4 reflects off the polarizer to leave the cavity. Because the beam is reflected out of the cavity, the booster amplifier is at a different level than the cavity amplifier.

In contrast, the Megajoule laser and the NIF backup designs do not use a full-aperture Pockels cell and polarizer to switch the beam out of the cavity. Instead, they use a relatively small set of optics, called a Reverser, located in the center section of the transport spatial filter to steer the beam from pass 2 to pass 3 (Fig. 2). This steering is possible because the beam is intentionally pointed off-axis through the amplifiers for both architectures so that each pass focuses at a separate location at the center of the spatial filter. (Beams are focused through a small hole at the center

FIGURE 1. A single beam of the proposed National Ignition Facility (NIF) laser. (70-50-0495-1005pb01)

of the spatial filter to remove high spatial-frequency noise from the beam.) Separation of the passes permits the Reverser to extract the beam on pass 2, manipulate it, and re-inject it on pass 3. This same feature permits beam injection into the laser using a small mirror near the pinholes as shown in Figs. 1 and 2. The energy of the beam after pass 2 is low enough that a mirror only a few centimeters square can survive without being damaged. Consequently, the beam can be turned around with small optics rather than a large Pockels cell and polarizer.

The Reverser

In its simplest form, the Reverser consists of a small pick-off mirror that directs the pass 2 beam to a collimating lens and a retro-mirror. The retro-mirror points the beam back through the same collimating lens and along the beamline of pass 3. Practical considerations lead to at least one additional turning mirror between the pick-off mirror and lens, as shown in Fig. 2, and an isolation unit to protect against back reflections. The size of the beam in the collimated section is determined by the desired fluence on the Reverser component with the lowest damage threshold. The pick-off mirrors are sized to withstand the amount of energy expected at the end of pass 2. The size of the pick-off mirrors determines the pinhole spacing, and the pinhole spacing

determines the off-axis angle of the beam through the laser. This angle causes the beam position to shift slightly in the amplifier aperture from pass to pass and reduces the maximum beam size that can pass through a given amplifier aperture. Since a smaller beam size means less energy on target, this loss, called vignetting loss, should be minimized. For NIF, a pick-off mirror about $5 \times 5 \text{ cm}^2$ is large enough to avoid damage, but small enough to cause about the same vignetting loss as the NIF baseline.

The French and U.S. Reverser designs are the same in principle, but are implemented differently—the French version is the L-turn and the U.S. version is the U-turn. The L-turn is simpler, with only seven components required (see Fig. 3). After the pick-off mirror, a second mirror directs the beam through a collimating lens to the cavity mirror, which is oriented to reflect pass 2 back along pass 3. The isolation system, a Pockels cell between crossed polarizers, blocks forward and backward transmission, except during a 50-ns window to allow passage of the shot pulse. The insertable half-wave plate is used for alignment, but not for a shot. Both passes 2 and 3 go through each of the L-turn components. This requires component apertures slightly larger than for the beam by itself, due to vignetting. Also, if the pulse length is long enough to overlap in time on an L-turn optic, interference increases the fluence on that optic substantially.

FIGURE 2. The generic Reverser in a four-pass laser architecture. (70-50-0495-1006pb01)

FIGURE 3. The French version of the Reverser, called L-turn. (70-50-0495-1003pb01)

In the U-turn, the pulse passes through each component only once, as shown in Fig. 4. Consequently, it has about twice as many components (13 vs 7), which are slightly smaller because there is no vignetting. The isolation system uses a half-wave plate to properly orient the polarization of the output pulse. With these exceptions, the corresponding components function the same as in the L-turn. The added complexity required to separate passes 2 and 3 in the U-turn provides design flexibility. For example, the cavity mirror of the L-turn can be replaced by a corner cube as shown in Fig. 4, which potentially improves the output pointing stability of the laser. The corner cube inverts the beam profile horizontally and vertically, so that any odd-order aberration that accumulates on passes 1 and 2, such as a drift in pointing, is canceled on passes 3 and 4.

Separation of passes 2 and 3 also makes it possible to change the beam size between passes 2 and 3. If passes 1 and 2 have a beam area about half that of passes 3 and 4, vignetting loss is determined by passes 3 and 4 only, not all four passes, which reduces vignetting loss by about 50%. This scheme also reduces aberrations, because the first two passes are through the center of the amplifiers, avoiding the more aberrated edges of the amplifier slabs. However, this scheme requires a change to the pinhole configuration that we did not attempt in these tests.

The L- and U-turn Reverser architectures have potential advantages over the NIF baseline architecture. They replace the large Pockels cell and polarizer with much smaller ones (10×10 vs 40×40 cm² apertures). Smaller components are lower in cost, easier to fabricate, and generally have better quality. They allow a straight, more compact layout with all the amplifier slabs in two modules to improve amplifier efficiency by reducing end losses. They eliminate the elbow mirror and one of the full-aperture cavity mirrors and allow the beam to pass through all the amplifier slabs four

times. The beam passes through the booster amplifier only twice in the NIF baseline. This increases the total system amplification and allows a smaller output energy from the front end. Nevertheless, a full-size, proof-of-concept device had never been built before and was needed to establish the viability of the Reverser concept.

Joint French/U. S. Testing of the L- and U-Turn Designs

In March 1994, a team from Lawrence Livermore National Laboratory (LLNL) visited the French Centre d'Études de Limeil-Valenton (CEL-V) to discuss a joint venture to build and test a Reverser on LLNL's Beamlet laser. CEL-V had previously expressed its desire to test the L-turn on Beamlet, and U-turn tests were scheduled for early FY 1995. It was impractical to test each design independently, because of the limited time available on Beamlet (October–December 1994). Therefore, both teams hoped to jointly decide on one design.

The goal was to prove the feasibility of the basic concept. In both cases the device would be installed into the transport spatial filter of Beamlet. The requirements for isolation components and alignment and diagnostic sensors were the same. However, it was important to test the unique features of each design. Therefore, rather than decide on either the L- or U-turn, the teams jointly agreed to share responsibility for building a Reverser that could be reconfigured to test both designs by changing only a few components. The objectives were to (1) compare performance of L-turn, U-turn, and baseline concepts; (2) evaluate L- and U-turn alignment; (3) learn about control of parasitic beams caused by back reflections and amplified spontaneous emission; and (4) determine vulnerability of Reverser optics to pinhole debris.

FIGURE 4. The U.S. version of the Reverser, called U-turn.
(70-50-0495-1002pb01)

Since our primary goal was to prove viability of the Reverser concept, we did not modify the Beamlet layout for optimum Reverser performance. We added the Reverser hardware and removed the large Pockels cell and the harmonic generators, which were not needed. Figure 5 shows the baseline Beamlet layout, indicating the location of the Reverser hardware in the center of the transport spatial filter. All the Reverser components fit within the existing transport spatial filter's 24-in.-diam vacuum tube, and existing ports on the tube were used for access. Figure 6 shows the U-turn corner cube mounted in the mid-section of the Beamlet transport spatial filter.

Figure 3 illustrates the configuration of the L-turn that was tested on Beamlet. The beam enters through the pass 2 pinhole on the lower right, makes two passes through all the L-turn optics, and exits through the pass 3 pinhole. The alignment and diagnostic system includes a calorimeter for determining the energy of the pulsed beam, and a near-field camera that can image any of the components during alignment or at shot time. A motorized cavity mirror provides pointing adjustments during routine alignment. The half-wave plate was inserted during alignment to allow transmission of the system alignment laser. As shown, other components were also motorized to allow adjustment under vacuum, but they were only needed for the initial setup.

Figure 4 illustrates the U-turn layout, which we tested. It has similar optics to simplify conversion between the two layouts. Only the corner cube mirrors and the two pick-off mirrors replace corresponding components of the L-turn. The pass-2 lens was present for the L-turn, but not used. When reconfiguring from

the L-turn, polarizer 2 had to be rotated 90° and the half-wave plate was inserted during shot time and removed for alignment.

For both L- and U-turn tests, the temporal and spatial profiles of the injected beam from the front end were the same as they had been for previous tests with the baseline configuration.³ The injected beam had a parabolic spatial profile, higher at the edges than the center by about a factor of two, to compensate for gain roll-off toward the edges of the amplifiers. The input pulse was shaped temporally to compensate for gain saturation and to give an approximately square pulse

FIGURE 6. The middle section of the Beamlet transport spatial filter (end section removed). The corner-cube assembly of the U-turn is shown inside the 2-ft-diam tube. (70-50-0595-1191pb01)

FIGURE 5. The Reverser's position in the transport spatial filter of the Beamlet laser. (70-50-0495-1001pb01)

at the output. The main beam was 32.5 cm square at its 10^{-2} intensity boundary with corners rounded at a radius of 5 cm and a fill factor of 84% (defined as the ratio of the beam energy to the energy if the entire 32.5×32.5 cm² beam were filled at the fluence of the central area of the beam).

The focal length of the lenses in the L- and U-turn optics was 110 cm to give a 4.0-cm square beam at the 10^{-2} intensity point in the collimated sections. The corresponding beam size on the first pick-off mirror was 2.2 cm square. For the L-turn, the angle between passes 2 and 3 was 27.3 mrad. The Pockels cell was a cylindrical-ring-electrode type with a 95% deuterated potassium dihydrogen phosphate (KD*P) crystal, an aperture of 7.3 cm in diam, and a length of 9.2 cm. The polarizers transmitted $\geq 97\%$ of the *p*-polarized light and rejected up to 99.8% of the *s*-polarized light. The measured damage threshold of the polarizers was ≥ 10 J/cm² at 1.5 ns. In the L-turn configuration, the pulse length was limited to 2.3 ns to avoid beam overlap on polarizer 2.

L-Turn Tests

We arbitrarily chose to test the L-turn configuration first. In its original configuration, we used only polarizer 1 in the isolation unit. The Pockels cell was oriented such that it gave a quarter-wave retardation for a single pass with no applied voltage. The resulting isolation was 8×10^{-4} , good for a Pockels cell and polarizer of that aperture, but not enough to protect the front end against back reflections from lenses in the transport spatial filter. To increase the isolation, we added polarizer 2, as shown in Fig. 3, and oriented the Pockels cell for zero retardation with no applied voltage. Then, back-reflected energy made two complete passes through the isolation unit to reach the front end, and the isolation improved to 1.5×10^{-5} . This reduced the back-reflected energy at the front end to that of the injected energy, a level for which the front end was adequately isolated. The transmission through the L-turn was 53%.

Figure 7 shows the output fluences (energy per unit area) for the L-turn and baseline architectures as functions of input energy. Output fluence was used for the comparison rather than output energy, because the beam size for the L-turn was slightly smaller, 32.5 vs 34 cm square, to avoid clipping on the turning mirrors. (The turning mirror mounts were designed to clear only one pass, as required for the baseline. In the Reverser configuration, the beam reflects three times off the turning mirrors at offset positions. Since the mounts were not big enough to clear the three offset positions, we reduced the beam size slightly.) The maximum output energies

for the L-turn at 2.3 ns and the baseline at 3 ns were 11.0 and 12.5 kJ, respectively. Note that the L-turn input energy required for a given output was 10 times less than for the baseline, because of the two extra passes through the booster amplifier. Clearly, the L-turn architecture gives comparable energy performance to the Beamlet baseline.

Figure 8 shows output irradiance (power per area) relative to output fluence (energy per area) for Beamlet. The Beamlet baseline architecture was originally optimized to provide maximum performance at 3 ns, but tests were also conducted at other pulse lengths, as shown. Outputs were limited by potential optical damage due to self-focusing at pulse lengths below 3 ns, and by the damage threshold of the polarizer above 3 ns. The shaded area in Fig. 8 indicates the maximum expected output at varying pulse lengths. The 11-kJ L-turn shot is the maximum irradiance attempted on Beamlet to date.

Because the large Pockels cell was removed for the Reverser tests, the amount of glass in the beamline was less, lowering the potential for nonlinear growth of output modulations. However, the two additional beam passes through the booster amplifier and the two

FIGURE 7. Injected energy vs output fluence for the Beamlet baseline and with the L-turn. The L-turn input energy required for a given output was 10 times less than for the baseline due to the two extra passes through the booster amplifier. (70-50-0495-1096pb01)

FIGURE 8. Irradiance vs fluence for Beamlet baseline and L-turn shots. (05-00-0494-2167pb01)

passes through the L-turn optics added aberrations. Consequently, the output modulation for the L-turn was slightly worse than for the baseline. For example, Fig. 9(a) shows the near-field image of the L-turn output at 4.3 GW/cm^2 , which is equivalent to the highest irradiance baseline shot at 4.2 GW/cm^2 . This image is a cumulative intensity distribution for the flat-top area of the output beam. There are 400×400 pixels, with each pixel corresponding to a beam area of $0.7 \times 0.7 \text{ mm}$. Figure 9(b) shows horizontal and vertical lineouts. The peak-to-average fluence modulation in the image was 1.4:1. The comparable baseline modulation at this irradiance was 1.3:1.

Figure 10 shows near-field image data from L-turn shots at three values of peak irradiance. The number of

FIGURE 9. Near-field (a) image of the output beam with the L-turn at 4.3 GW/cm^2 and (b) horizontal and vertical lineouts through the image. (70-50-0595-1265pb01)

pixels at each fluence (normalized to the maximum) is plotted vs that fluence (normalized to average fluence). There is virtually no difference between the modulation at 1.53 and 4.25 GW/cm^2 . However, at 5.4 GW/cm^2 , the modulation jumps from 1.4 to 1.5, implying the onset of nonlinear growth. To avoid risking optical damage, this regime of nonlinear growth is generally avoided, limiting the performance of the laser. This type of increase in modulation has also been observed in the baseline configuration.³

U-Turn Tests

In the U-turn configuration tests, the isolation provided by one pass through the polarizers and Pockels cell was 1×10^{-4} (see Fig. 4), which was barely acceptable for protection against back reflections. Note that the L-turn isolation was higher because the beam made two passes through the polarizer and Pockels cell. Conversely, the 70% U-turn transmission was better, because one pass through the isolation unit had less loss than the two passes with the L-turn.

Before the first U-turn tests, it was necessary to turn the L3 lens around so that the surface previously in vacuum was in air. Two damage spots on the vacuum side of L3 were created during tests before the L-turn experiments, and they increased to 6 and 8 mm at the lens surface during the L-turn shots. Since the vacuum side of the lens was in tension, these damage spots could have lead to crack propagation and lens failure, so the lens was turned around before the U-turn experiments began. This put the damage spots on the air

FIGURE 10. Near-field image data for output with the L-turn at three irradiances, showing nonlinear modulation growth at 5.3 GW/cm^2 . (70-50-0595-1266pb01)

surface where they were in compression and not a threat to the lens integrity.

Attempting to duplicate the L-turn shots, the first U-turn shot delivered 780 J, but caused damage to several of the U-turn and front-end optics. In the front end, the injection mirror had a 1-mm portion of the coating removed, and small pits formed on the injection window and injection lens. In the U-turn, the pass 3 lens, both polarizers, and the Pockels cell had 1-mm damage, although none of the mirrors was damaged. In the Pockels cell, there were two damage tracks through the KD*P crystal.

The damaged components were replaced or repositioned, and low-energy shots allowed a detailed investigation of what caused the damage. Near-field images of the beam showed numerous pencil beams and ghost foci, but the most prominent was the one generated by L3's air surface. Reflectivity tests on the spatial filter lenses indicated that the antireflection coating (sol-gel) on that surface had deteriorated, from the typical value of about 0.1% to 3.2%. The measured reflectivities of the L3 vacuum surface and both L4 surfaces were normal. The cause of the coating deterioration is not known.

It became clear that turning the L3 lens around caused the U-turn to damage, whereas in L3's earlier orientation the L-turn was protected. This was because the deteriorated coating was on the vacuum-side during the L-turn tests. The vacuum side of the lens is concave with respect to pass 4, causing the reflection from that surface to focus in the air between the lens and booster amplifier. This focus causes the air to break down and absorb or deflect most of the energy in the reflection. Consequently, the unusually high energy of this reflection was greatly decreased by air breakdown, and the L-turn components were protected. However, when the lens was turned around at the start of U-turn tests, the defective coating went to the air surface of the lens, which is convex with respect to pass 4. The reflection from the convex surface did not focus, and consequently, there was no air breakdown to protect the U-turn optics.

We believe the optical damage was caused by parasitic pencil beams originating from the reflection off

the air surface of L3. Figure 11 shows how the pass-4 output beam generates pencil beams from L3. (All beam passes through the lenses create reflections, but the final pass reflection is the most dangerous because it has the most energy.) Both reflections (one from each surface) pass through the booster amplifier and focus near the pinhole plane in the cavity spatial filter. Most of the light is blocked by the cavity pinhole plate, but some light passes through the pinholes forming three beams. (There are four pinholes, but the injection mirror blocks light from going through pinhole 1.) These beams are diffraction limited, and they remain small throughout the laser, from a couple of millimeters to about 1 cm, thus, the name "pencil beams." Because these pencil beams propagate parallel to the shot beam, they pass through the amplifiers and increase in fluence.

The pencil beam that caused damage in the U-turn was formed by cavity pinhole 4. That pencil beam continued backwards through the system to pass through the main amplifier twice, through cavity pinhole 3, through the booster amplifier, through pinhole 3 in the transport spatial filter, and into the U-turn. With a calculated fluence of around 270 J/cm^2 , this pencil beam was more than sufficient to damage optics. Five factors contributed to this pencil beam's high fluence. (1) It had 15 to 30 times more energy than typical, because the coating reflected 3.2% rather than the typical 0.1 to 0.2%. (2) It propagated through both amplifiers twice, experiencing a gain of about $1200\times$ before entering the Reverser. (3) It was down collimated into the Reverser (in this case 32.5- to 4-cm^2), which magnified the fluence of the pencil beam by a factor of 66. (4) It focused near the U-turn Pockels cell, which further increased its fluence by about $2\times$. (5) It was generated during a low-output-energy shot, 780 J, that was close to the most dangerous output with respect to back reflections. (As laser output energy is increased, gain saturation reduces the amount of energy left to amplify back reflections. Therefore, the highest-energy back reflections do not occur at maximum output but at about 2-kJ output.) Note that factors 1, 2, and 5 are system factors, and only factors 3 and 4 relate to the Reverser.

FIGURE 11. Reflections from the input lens to the transport spatial filter lens, L3, are formed into pencil beams by the pinholes in the cavity spatial filter. (70-50-0495-1004pb01)

Some energy from this same pencil beam passed through the U-turn as it damaged the Pockels cell and continued in reverse direction along passes 2 and 1. This energy was amplified by another pass through the booster amplifier and two more passes through the main amplifier, resulting in enough fluence to damage the injection mirror. The source of the damage to the injection lens and window was traced to a different pencil beam from the same L3 air surface. This pencil beam was formed by pinhole 2 in the cavity spatial filter, passed twice through the main amplifier (backwards along passes 2 and 1), and focused enough to damage the injection window and injection lens. It is important to emphasize that this damage had nothing to do with the U-turn and would have occurred in the baseline configuration if L3's air surface reflectivity had been 3%.

Two attempts were made to eliminate the L3 pencil beams—tilting L3 and inserting a beam block on the cavity mirror. Tilting L3 far enough eliminates the pencil beams by preventing its reflections from illuminating the pinholes in the cavity spatial filter. However, this required a tilt of more than 2° , which caused unacceptable output aberrations. The goal of the second scheme was to absorb the pencil beams with a 1-cm disk of absorbing glass fixed on the cavity mirror. The beams were blocked, but diffraction around the edges of the glass caused an unacceptable 20% increase in output beam modulation.

A more ambitious solution would have been to reduce the energy of the pencil beams at the Reverser by taking the Pockels cell and polarizer out of the Reverser and locating them at full-aperture near the cavity mirror, as shown in Fig. 12. In this configuration, the Pockels cell would cause half-wave retardation with applied voltage and zero retardation with no applied voltage. Unlike the NIF baseline, this Reverser architecture uses the Pockels cell and polarizer only for isolation and not to switch the beam from the cavity. Consequently, this isolation unit can be located anywhere in the beamline. By being located at the start of pass 4 (near the cavity mirror), the Pockels cell and polarizer reject the back reflections at full aperture and after only one pass through the amplifiers. This lowers

the fluence of the pencil beams entering the Reverser by a factor of more than 10,000. This change would also be effective in eliminating other types of back reflections such as from pinholes or targets. It does, however, require a full-aperture Pockels cell and polarizer, which would eliminate some of the initial appeal for the Reverser concept, but the other benefits remain. This change is of interest for future Beamlet tests, but moving the large Pockels cell and polarizer would have taken longer than the remaining time available for these Reverser experiments. As a result, we did not risk damage by taking any more high energy shots.

Summary

These experiments demonstrated the basic viability of the Reverser concept. They showed that the concept of turning pass 2 into pass 3 with small mirrors and lenses in the transport spatial filter is valid. The Reverser output compares well with the results for the baseline architecture, and it achieved the highest irradiance output to date on Beamlet of 5.3 GW/cm^2 . We encountered no problems with ASE or degradation to optics due to pinhole blowoff or vacuum conditions. Also, routine alignment of both L- and U-turn architectures was straightforward.

These experiments also exposed a serious weakness. They identified the inadequacy of a small-aperture isolation unit to protect the laser against back reflections. Although the damage to the front end from the L3 pencil beams would have occurred even with the baseline architecture, the severity of the damage to the Reverser optics resulted from two features of this Reverser design. (1) Back reflections make two complete passes through the amplifiers before entering the Reverser. (2) Back reflections are down collimated into the Reverser, magnifying their fluence by a large factor.

A change to the Reverser design would provide much greater tolerance to back reflections. Moving the isolation unit so that it attenuates the back reflections sooner along their backwards path through the laser substantially reduces their maximum fluence. With the Reverser, the Pockels cell and polarizer are not used to

FIGURE 12. Locating a full-aperture Pockels cell near the cavity mirror would provide better isolation. (70-50-0595-1187pb01)

switch the beam from the cavity, so they can be located anywhere. One attractive location is near the start of pass 4, where the fluence of the out-going pulse is lower than in its baseline position, and where it attenuates reflections from final optics after only one backwards pass. This location for the isolation unit provides significantly better tolerance to back reflections. Therefore, we are considering a large Pockels cell and polarizer at this location for future Reverser tests on Beamlet.

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FACILITY REPORT

JANUARY–MARCH 1995

G. Hermes

Nova Operations Group

Nova Experiments Group

Laser Science Group

During this quarter, Nova Operations fired a total of 242 system shots resulting in 299 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser experiments, Laser Sciences, and facility maintenance shots.

To support continued experiments in FY 1995, the Nova target chamber, Master Oscillator Room (MOR), and beamline 7 (BL7) were reconfigured to conduct $f/8$ and four-color operations. Several scattered light diagnostics were also installed and activated in the target chamber. At the completion of these experiments, the system was again reconfigured for normal $f/4$ single-color operations.

Work began to convert the old Nova safety interlock system to a new Programmable Logic Controller (PLC) system with expanded capability to support the 100 TW project: Phase I supports the 100 TW project and is scheduled for completion in early May; Phase II completes the system conversion in FY 1995.

A digital oscilloscope (SCD 5000) and a fast diode replaced the MOR Fiducial Diagnostic (MFD) streak camera. After the system is validated by the MOR personnel, it will be integrated into the Laser Diagnostics controls software.

All major optics procurements have been awarded for the 100 TW project, with delivery expected by mid-April. We completed the installation of the 100 TW capacitor bank, and high-voltage cabling between the bank and the 9.4-cm amplifier will be installed early in the third quarter FY 1995. We received the 100 TW compressor chamber from EG&G, Inc. on March 21, 1995 and installed it in the two-beam area the following week.

In support of precision alignment operations, we performed two 2ω alignment shots to determine the consistency between the 2ω and 3ω transverse offsets. The data show that it is probably reasonable to use the 3ω offsets for the 2ω precision pointing series. However, the z (focus) offsets were quite different, as expected. Therefore, it might be necessary to perform 2ω alignment shots periodically to update the z offsets.

A series of shots verified beam timing—nine of the ten beams were within the Precision Nova specification of ± 10 ps (BL7 was approximately 30 ps early). As a result, five timing adjustments were made and confirmed using the 1ω streak camera data.

The BL7 potassium dihydrogen phosphate array was replaced with a refurbished unit, increasing the conversion efficiency by $\sim 20\%$.

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