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INERTIAL CONFINEMENT FUSION

ICF Quarterly Report

*October–December 1994
Volume 5, Number 1*

*System Description and
Initial Performance
Results*

*Design and Performance
of the Amplifiers*

*Design and Performance
of the Optical Switch*

*Pulse-Generation and
Wavefront-Control
System*

*Large-Aperture, High-
Damage-Threshold Optics*

Pulsed-Power System

Laser Diagnostics

*Modeling Beam
Propagation and
Frequency Conversion*

**Special Issue:
Beamlet Laser
Project**

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 photograph is of Beamlet, the lower image (darkest central spot) highlights Beamlet's far-field (focus) spot. Beamlet is a prototype of one of the 192 beamlines of the National Ignition Facility laser and operates in a regime never before achieved by ICF lasers. Its unique multipass design is 20 times more compact than the Nova laser and it operates at output energy fluences nearly four times greater. The far-field spot size is less than twice the diffraction limit and attests to the excellent beam quality achieved by using a state-of-the-art adaptive optics system. This adaptive optics system represents just one of the many novel technologies successfully demonstrated on Beamlet that have never been used on other ICF lasers. For details, see "System Description and Initial Performance Results for Beamlet," p. 1.

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INERTIAL CONFINEMENT FUSION

Quarterly Report

October–December 1994
Volume 5, Number 1

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FOREWORD

This issue of the *ICF Quarterly* is dedicated to the Beamlet Laser project. Beamlet is a scientific prototype of one of the 192 identical laser chains that form the National Ignition Facility's (NIF's) laser driver. The eight articles that follow describe the Beamlet laser system, its major components, and the experimental and modeling results from initial performance tests.

The first article, entitled "System Description and Initial Performance Results for Beamlet," describes the layout of the laser and results from initial performance tests at 1054 and 351 nm. Beamlet uses a multipass amplifier cavity and active switch to generate output energies up to 12.5 kJ at 1054 nm (1 ω) in a square beam (34 $\times$ 34 cm²). The average fluence is equivalent to that for the NIF when operated at 3 ns. The initial results at the third harmonic (351 nm) exceed the fluences required on the NIF and show a peak conversion efficiency of near 80%. In addition, the outstanding beam quality achieved with Beamlet's adaptive optic system produces a far-field image that is less than two times diffraction limited.

The design and performance of the Beamlet flash-lamp pumped multisegment amplifiers are described in the second article, "Design and Performance of the Beamlet Amplifiers." These amplifiers demonstrate a much higher pump efficiency and better pump uniformity than achieved on Nova. The gain and gain distribution in the amplifiers are quantified, and a simple model is used to explain the gain distribution for amplifiers in different cavity locations (i.e., ends vs interior). Pump-induced beam steering results are also presented.

The full-aperture Pockels cell, used to switch the beam in and out of the cavity, is discussed in "Design and Performance of the Beamlet Optical Switch." Our measurements show that the full-aperture Pockels cell has a switching efficiency of 99.5% or greater, which exceeds our goal of 95% with a switching time of less than 200 ns.

The high output energies, good conversion efficiencies, and excellent beam quality achieved on Beamlet are a direct result of our unique beam-shaping capabilities as described in "Beamlet Pulse-Generation and Wavefront-Control System." These capabilities are installed on the front end and allow us to shape the temporal, spatial, intensity, and phase-front profiles of the beam. This range of capabilities has never before been fielded on ICF lasers.

After several years of intense effort, we have developed new, damage-resistant, large-aperture optics for use on Beamlet and the NIF. Many of these optics are two times larger than those used on Nova and have damage thresholds two to four times greater. The damage threshold and other properties of these optics are discussed in "Large-Aperture, High-Damage-Threshold Optics for Beamlet."

Beamlet's pulsed-power and beam diagnostic systems are discussed separately in the articles entitled "Beamlet Pulsed-Power System" and "Beamlet Laser Diagnostics." Beamlet uses four separate diagnostic stations on the main laser cavity. These diagnostic stations fully characterize the laser pulse as it multipasses back and forth through the main cavity and at its input to, and output from, the frequency converter. Some of the key data obtained are output energy, near- and far-field intensity profiles, temporal pulse shape, and phase-front measurements. The Beamlet pulsed-power system uses a new capacitor design that has four times the stored energy density of the older, Nova-style capacitors. In addition, the capacitors do not fail catastrophically, and they have longer lifetimes.

During the course of the experimental campaign, we compared our results with predictions generated using Lawrence Livermore National Laboratory propagation and frequency conversion computer codes. A brief description of these codes and several sample comparisons with Beamlet experimental data are given in the final article, "Modeling Beam Propagation and Frequency Conversion for the Beamlet Laser."

Jack Campbell
Scientific Editor

DEDICATION

Beamlet is the result of the dedicated and tireless efforts of a large number of people, many of whom are shown in this photograph (taken the date we achieved our 3 ω performance milestone). We also thank representatives of numerous companies who provided the high-quality materials and components from which Beamlet was built.

In appreciation of those who participated on the Beamlet project, this issue of the *ICF Quarterly* is dedicated to you.

SYSTEM DESCRIPTION AND INITIAL PERFORMANCE RESULTS FOR BEAMLET

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Introduction

The Department of Energy has proposed to design and construct a National Ignition Facility (NIF) for Inertial Confinement Fusion (ICF) research. This facility will contain a frequency-tripled, Nd:Glass laser system capable of irradiating fusion targets at an energy and power of 1.8 MJ and 500 TW. The laser output pulse contains most of the energy, where the low-intensity leading foot is 15–20 ns long and the final high-intensity pulse is 3–4 ns long. The laser will have 192 independent “beamlets,” each having a final square clear aperture of $40 \times 40 \text{ cm}^2$ and an output beam area slightly smaller than the clear aperture. A Conceptual Design Report (CDR),¹ prepared in May 1994, discusses the laser and facility design in detail.

We have constructed and are now testing a scientific prototype of a single beamlet of the proposed NIF laser (Fig. 1). The purpose of these tests is to show that the novel features proposed for the NIF laser design will perform as projected and that the laser is ready for final engineering design. The final dimensions and component arrangements for NIF will differ somewhat from our scientific prototype, but the differences are sufficiently small that tests on the prototype can be used to demonstrate performance essentially equivalent to a NIF beamlet.

The project to build a scientific prototype beamlet (hereafter referred to as “Beamlet”) was begun in 1991 and consisted of three main efforts: (1) development of laser components, (2) design and construction of the main laser system, and (3) activation. Previous *Quarterlies* present the results of the component development activities^{2–5} and the laser design.⁶ This article presents an overview of the constructed Beamlet laser system, and the results from the first integrated tests performed near the end of laser activation. These integrated tests culminated in a third-harmonic milestone shot on

(a) Beamlet laser

(b) Fully assembled system

FIGURE 1. (a) Artist's rendering of the Beamlet laser showing the main subsystems. (b) A photograph of the fully assembled system. (70-50-0195-0181pb01)

September 8, 1994 that produced an average output 3 ω fluence of 8.7 J/cm² in a 29.6 $\times$ 29.6 cm² beam and a 3-ns square pulse. Table 1 summarizes the key energy and fluence performance results recently achieved on Beamlet at 1 ω and 3 ω . The fluence levels listed in Table 1 (and discussed later in this article) are higher than the fluences projected for the NIF design.¹

Subsequent articles in this *Quarterly* present detailed design and test results for many of the major components on Beamlet. The final article compares the results of the performance of Beamlet with recent model calculations.

The NIF Laser Design Compared with Current ICF Lasers

Figure 2 shows the singlepass master oscillator/power amplifier (MOPA) architecture; Fig. 3 shows the multipass architecture proposed for the NIF laser and contrasts that with the prototype Beamlet design.¹

Current ICF Laser Design—A Singlepass Architecture

Most large glass lasers designed for inertial fusion experiments have the singlepass MOPA architecture: the Nova laser⁷ at Lawrence Livermore National Laboratory (LLNL), USA; the Omega laser⁸ at the

Laboratory for Laser Energetics, University of Rochester, USA; the Gekko XII laser⁹ at the Institute of Laser Engineering, University of Osaka, Japan; the Phébus laser¹⁰ at the Commissariat à l'Énergie Atomique, Centre d'Études de Limeil-Valenton, France; and the Helen laser at the Atomic Weapons Research Establishment, England.

A master oscillator generates a few-nanosecond pulse of several millijoules that is then spatially and temporally shaped at about a 1-cm aperture and split into parallel chains of singlepass rod and Brewster's-angle slab amplifiers of increasing size. Gain isolation is provided at small aperture (<~10 cm) by ring-electrode Pockels cells and thin-film polarizers. Faraday rotators, driven by pulsed electromagnets, are used at large apertures to isolate pulses from propagating backward down the laser chain. Single-beam amplifiers with round apertures up to about 32 cm are used in all of these facilities. In addition, Nova and Phébus lasers have amplifiers with apertures of 46 cm using glass slabs that are split into two independent pieces.

The singlepass MOPA is a familiar and well-proven design that can be assembled and tested in stages, so performance risk is low. Cost and complexity are high, however, because of the very large number and variety of components required for a MOPA design. The Nova laser, for example, contains one rod amplifier

FIGURE 2. Singlepass master-oscillator, power-amplifier (MOPA) laser architecture commonly used by existing ICF lasers. (40-00-0294-0375pb01)

TABLE 1. Initial performance results for the NIF prototype beamlet at 1054 and 351 nm.

Wavelength (nm)	Zero-intensity beam dimensions (cm ²)	Output ^a pulse length (ns)	Fluence (J/cm ²)	Total energy (kJ)	Spatial intensity modulation (pk-avg) ^b
1054	34 $\times$ 34	3	12.5	12.1	1.45:1
		5	14.3	13.9	1.25:1
		8	16	15.5	1.25:1
351	29.6 $\times$ 29.6	3	8.7	6.4	1.35:1

^aTemporally square output pulse.

^bPeak-to-average ratio.

and five sizes of elliptically shaped slab amplifiers (a total of 41 slabs) in each of ten laser chains. There are also eight additional rod amplifiers of several sizes between the oscillator and the chains. In addition, there are relay telescopes and isolators between all of these amplifier stages.

The existing ICF MOPA lasers were all designed for maximum effective operation at pulse lengths near 1 ns. Fusion targets for the NIF, however, require effective pulse lengths typically in the range of 3–5 ns. If the

laser design pulse length increases above 1 ns then the corresponding increase in component damage thresholds allows the laser to operate at higher fluences. This significantly increases the efficiency of energy extraction from the laser glass. In the case of the MOPA design, however, these high extraction fluences produce significant gain saturation in the large amplifiers. This, in turn, requires that the successive MOPA amplifiers have increasingly larger apertures so they do not gain-saturate, since gain-saturation effects produce

(a) NIF laser design

(b) Prototype Beamlet

FIGURE 3. (a) Schematic drawing of the multipass NIF laser design. (b) Prototype Beamlet design. (40-00-0394-0789pb02)

severe temporal pulse distortion. (See "Beamlet Pulsed-Power System," p. 62). In contrast, a multipass amplifier uses the full aperture of the main amplifier as a preamplifier on early passes, such that the fluence increases monotonically during propagation, reaching a maximum of several times the saturation fluence in the last slab of the booster amplifier. Temporal pulse distortion is minimized in this configuration.

NIF/Beamlet—A Large-Aperture, Multipass Laser Design

In the NIF design [Fig. 3(a)], the pulse-forming system uses a low-power oscillator to drive an array of single-mode optical fibers, one for each beamlet of the system (the prototype Beamlet oscillator drives only a single fiber). The output from each fiber is input to waveguide-amplitude modulators to temporally shape the pulse and then fed to phase modulators to add the required bandwidth (bandwidth is required to suppress stimulated Brillouin scattering, or SBS, in the output optics when driven at high intensities). These integrated optical modulators are derived from the low-voltage designs used in high-speed fiber communications networks, and ultimately could be operated under direct computer

control, although Beamlet has not yet implemented this option. The pulse output from the modulator is then fed to a single-mode, regenerative amplifier that amplifies the pulse to ~ 10 mJ.³ A beam-shaping section forms the appropriate spatial intensity profile that is injected into the preamplifier section of the laser amplifier chain. A four-pass, single-rod preamplifier amplifies the pulse to about 1 J and injects it into the main four-pass slab amplifier, where it reaches approximately 10 kJ. The four-pass configuration permits us to make the preamplifier section small enough that the cost savings from any further reduction would be negligible. The prototype Beamlet uses 16 rectangular slabs in the final amplifier stage that have a pumped aperture of 39 cm. The pulse that exits the laser amplifier section proceeds to a frequency converter and, in the case of the NIF, to the target chamber.

A multipass amplifier requires a method for separating input and output beams in the amplifier, which is not necessary in a singlepass system. There are three generic techniques for accomplishing this: (1) a polarization rotator can be used to separate beams at a polarizer [Fig. 4(a)]; (2) the beams can be separated in angle in the near field [Fig. 4(b)]; or (3) they can be separated in angle in the far field near a focal plane [Fig. 4(c)]. Near-field angle separation has been used with large laser systems.¹¹ It requires either a very long propagation distance, leading to difficulties with diffraction, or a beam size much smaller than the amplifier aperture to accommodate the beam motion, leading to poor utilization of the amplifier volume. Therefore, near-field separation has not been considered for the NIF design.

Far-field angle separation has several desirable features for this application. There is no closed path in the laser cavity, so parasitic oscillations are less of an issue than for a configuration in which there are closed resonant feedback paths. Each pass through the focal plane goes through a separate aperture in that plane, so the propagation of later passes is not affected by plasma generated in the aperture by earlier passes. Any leakage out of the cavity on early passes is at an angle to the final output beam, so it is easily occluded in a transport spatial filter and cannot disturb the laser target. Finally, far-field angular separation gives a convenient location for injecting a low-energy input pulse near the focal plane without requiring additional full-aperture optical components.

The Beamlet test series presented here uses a combination of far-field angle plus polarization separation. Polarization separation is achieved using a full-aperture Pockels cell plus a polarizer in the large final amplifier stage. The far-field angle separation gives the advantages

FIGURE 4. Three generic schemes for separating the input and output beams for a multipass laser architecture: (a) polarization rotator and polarizer, (b) near-field angle separation, and (c) far-field angle separation. NIF and the prototype Beamlet use a combination of far-field angle separation and polarization rotator. (70-50-0195-0020pb01)

just mentioned, while the Pockels cell gives gain isolation and isolation from back reflections. The full-aperture Pockels cell also allows the off-axis angle in the far-field to be very small since, at that point, the energy handled on the injection optics is only about 1 J. The small angle allows efficient use of the amplifier aperture with a relatively short laser cavity. It is possible to configure the system to do separation using a far-field angle only, using a smaller Pockels cell for isolation purposes only. This alternate configuration requires handling the beam near the far field and at energies up to 100 J, but avoids the cost of the full-aperture Pockels cell and polarizer. Both configurations will be tested on Beamlet.

The NIF laser design groups beamlet amplifiers into large arrays stacked four high and twelve wide to minimize the number of components and flash lamps (see Fig. 1 in "Design and Performance of the Beamlet Amplifiers," p. 18). The individual beamlets are optically independent, though supported by common mechanical hardware and pumped by common flash lamps. This full array of 48 apertures is too large and expensive to test in a small scientific prototyping effort. Therefore, on Beamlet we constructed the amplifier as an array of four apertures stacked two high and two wide to study many of the major issues of this type of amplifier assembly. (See "Design and Performance of the Beamlet Amplifiers," p. 18.) Only one of the four beamlet apertures contains high-quality laser glass and is used for the tests discussed here. The amplifiers are constrained to have an odd number of slabs, since this cancels asymmetric gain gradients in the two end slabs.

A state-of-the-art adaptive wavefront control system is used on Beamlet to correct for static and dynamic optical aberrations. The Beamlet adaptive optic system

consists of a deformable mirror (DFM), two Hartmann wavefront sensors, and a closed-loop controller. This adaptive optic technology was developed and demonstrated on the large dye laser systems that are part of the LLNL Uranium-Isotope Separation project.¹² The Beamlet adaptive optics system is discussed further in "Beamlet Pulse-Generation and Wavefront-Control System," p. 42.

The amplifier stages are separated by relay telescopes or spatial filters that reimage a beam-forming aperture at several places through the amplifier chain. This reimaging reduces the diffractive growth of spatial intensity noise and provides Fourier transform planes at the focal planes in the telescopes where high-spatial-frequency intensity noise can be reset to zero. The noise level needs to be kept low because nonlinear propagation effects cause it to grow exponentially at high intensity.¹

Beamlet Test Configuration

Figure 5 is a plan view of Beamlet as configured for the test series presented here. We use a prototype³ of the pulse generation and preamplifier system proposed for NIF to produce an approximately 1-J pulse that is injected into the main four-pass laser cavity. The injected pulse is temporally shaped to compensate for gain saturation effects and is designed to produce a 3-ns square pulse output. To compensate for gain roll-off near the edges of the amplifier slabs, the intensity profile is shaped using a transmission filter with a parabolic transmission profile (see "Beamlet Pulse-Generation and Wavefront-Control System," p. 42). Also, all laser experiments reported here use input pulses that are phase-modulated

FIGURE 5. Plan view of Beamlet as configured for the tests described in this article. (02-30-1091-3760Epb01)

by the front end at a single modulation frequency of 5 GHz to provide a total bandwidth of about 30 GHz. This additional bandwidth reduces the net SBS gain, thus eliminating the damage threat posed by transverse SBS. The output pulse from the front end is injected using a small $2 \times 2 \text{ cm}^2$ 45° mirror, and the pulse comes to a focus at an aperture in the focal plane of a vacuum spatial filter. The pulse expands past focus to fill a recollimating lens and a multisegment amplifier² containing eleven Brewster's-angle slabs. (See the article "Design and Performance of Beamlet Amplifiers," p. 18.) It then reflects from a cavity end mirror M_1 , and makes a second pass through the multipass amplifier, emerging with an energy of about 100 J.

At the other end of the laser cavity is an optical switch, consisting of a plasma-electrode Pockels cell (PEPC) and a polarizer. (See Ref. 4 and "Design and Performance of the Beamlet Optical Switch," p. 29 for a discussion of optical switches; see "Large-Aperture, High-Damage Threshold Optics for Beamlet," p. 52 for a discussion of polarizers.) As the pulse is injected for its first two passes through the multipass amplifier, the Pockels cell is switched on to rotate the polarization so that the pulse passes through the polarizer and strikes a second mirror, M_2 . It then returns to the multipass amplifier for a third and fourth pass, emerging with an energy near 6 kJ. By the time it returns to the Pockels cell, the cell has switched off, so the pulse then reflects from the polarizer and makes a single pass through a second so-called "booster" amplifier containing five Brewster's-angle slabs. A transport spatial filter relays the pulse to the frequency converter. At this point, the 1ω energy is 12–15 kJ, as shown in Table 1.

FIGURE 6. Pinhole array layout at the focal plane of the Beamlet multipass cavity. (70-50-0393-0724Bpb01)

Figure 6 is a schematic of the array of pinhole apertures at the focal plane of the cavity spatial filter. Mirror M_1 is positioned such that the pulse injected at pinhole 1 returns to a position at pinhole 2. Similarly, mirror M_2 is aligned so that the return pulse from M_2 is at pinhole position 3. The return from the second pass then automatically lies at pinhole 4. Any energy not switched out of the cavity strikes mirror M_2 and returns to the focal plane at position 5 where it is intercepted by an absorbing glass beam dump. For this series of experiments, we used 3.6-mm-diam pinhole apertures, giving a spatial frequency cutoff wavelength of 7.2 mm in the near field, or an angular acceptance of $\pm 200 \mu\text{rad}$ in the far field. The separation between pinhole apertures is 3 cm.

The clear aperture of the potassium dihydrogen phosphate (KDP) crystal installed in the Pockels cell for the 1ω tests is 37 cm, which sets a beam hard aperture of about 35 cm. The beam must be smaller than the smallest clear aperture because of the vignetting allowance for beam motion due to off-axis propagation plus an allowance for full-beam alignment. The edge of the beam is apodized to suppress edge diffraction, as discussed later. The 39-cm amplifier aperture is not completely filled under these conditions, and could support slightly larger beam dimensions.

The cavity spatial filter lenses have a focal length of 9 m. The separation between M_1 and M_2 is 36 m and these mirrors lie at relay image planes of the system.

The beam is reflected out of the multipass cavity by the switch polarizer and then routed to the booster amplifier using three turning mirrors. After passing through a second spatial filter identical to the one in the multipass cavity, the beam then passes through an uncoated fused silica beamsplitter. The beamsplitter reflects a small portion of the $1\text{-}\mu\text{m}$ output beam to a diagnostics package. This package captures near- and far-field images on charge-coupled device (CCD) cameras, determines the energy using a calorimeter, and measures the temporal pulse shape using a vacuum photodiode with a transient digitizer or a streak camera. It also includes a 77-element CCD-based Hartmann sensor to measure wavefront distortion and to control the figure of the 39-actuator DFM.

The 1ω output beam enters a dual crystal frequency converter. The frequency converter uses a Type I/II third-harmonic generation scheme (Fig. 7), consisting of a 1.05-cm-thick KDP doubler crystal and a 0.95-cm-thick KD*P tripler crystal. In the experiments described here, $32 \times 32 \text{ cm}^2$ crystals were used and the KD*P was 80% deuterated. The $32 \times 32 \text{ cm}^2$ crystals will support about a 30-cm beam size. Crystals $37 \times 37 \text{ cm}^2$ are currently being manufactured and will be used in future experiments. (Due to the long time required to grow the $37 \times 37 \text{ cm}^2$ crystal boules, these larger crystals

were not available during our initial frequency conversion tests.) Finally, the output beam is absorbed by a $74 \times 74 \text{ cm}^2$ calorimeter/beam dump after first passing through a biconcave expansion lens to reduce the fluence onto the calorimeter below the damage threshold of the absorbing glass in the calorimeter.

Measurement of Laser Performance at $1.05 \mu\text{m}$

Optical Transmission with Unpumped Amplifiers

Optical losses reduce the laser output, particularly with long pulses where the laser amplifier gain is highly saturated. It is important to quantify these losses to match the measured laser output to theoretical models. We measured transmission through the system with unpumped amplifiers from pinhole to pinhole of the spatial filters, and also measured individual components to determine what these optical losses are for the Beamlet.

The transmission for a double pass through the eleven-slab-long cavity amplifier section is 84%, which consists of 22 laser slabs having an average transmission of 99.3%, one mirror with 99.6% reflection, and two lens transmissions at 99% each. The 0.5% loss per lens surface is typical of sol-gel antireflection coatings applied to fused silica, although coatings as good as 99.8% transmission have been prepared. The loss in laser slab transmission is dominated by absorption from the Boltzman population in the lower Nd:Glass

laser level, and illustrates that bulk and surface losses due to contamination or defects in the laser glass are extremely small.

The double-pass transmission through the Pockels cell (in its "on" position) plus the polarizer is 71%. The crystal in the Pockels cell is 1-cm-thick undeuterated KDP (KH_2PO_4), so it has an absorption of $6\%/ \text{cm}$ at $1.053 \mu\text{m}$, giving a double-pass transmission of 88%. The polarizer singlepass transmission for p -polarized light is 97.3%. This includes 1.1% loss due to the 9-cm-thick BK-7 substrate and 1.5% loss in the coating. If we assume 1% loss per surface for 16 antireflection coated surfaces (a lens, two windows, and a KDP crystal) and a mirror reflection of 0.995, the net transmission would be 71%, which is consistent with the measured value. (See "Design and Performance of the Beamlet Optical Switch," p. 29 for a more detailed discussion of the optical performance of the Pockels cell.)

The transmission of amplifier slabs in the booster and lenses in the output spatial filter are consistent with the measurements for the cavity amplifier and spatial filter discussed earlier. The polarizer reflects 99.6% of the s -polarized light that strikes it when the Pockels cell is switched to its "off" configuration. At an output energy of $\sim 12 \text{ kJ}$ after the booster amplifier, the polarizer reflects 6 kJ out of the multipass cavity and the energy transmitted through the polarizer is less than 30 J (polarizer s -polarized leakage plus any light rotated to p -polarization by birefringence in the system).

Gain Compensation

Figure 8 shows the singlepass, small-signal gain profile of a five-slab-long Beamlet amplifier pumped to

FIGURE 7. Type I/II frequency conversion scheme used on Beamlet. (70-10-0494-1827pb01)

FIGURE 8. Gain profile for a five-slab-long amplifier. Amplified spontaneous emission causes the gain to roll off near the edges in the horizontal direction of the slabs. (02-30-1093-3495pb01)

its nominal operating point, 20% of the flash-lamp explosion energy. The gain peaks in the center of the aperture and is about 15% lower in the extreme corners of the aperture. Most of the gain roll-off is in the horizontal direction, which is the long dimension of the Brewster's-angle slab. Amplified spontaneous emission trapped by total internal reflection within the slab depletes the stored energy in the glass and causes this gain roll-off. (See "Design and Performance of the Beamlet Amplifiers," p. 18.)

To produce a flat intensity profile at the output of the laser requires that the input intensity profile to the multipass amplifier stage be shaped to compensate for the nonuniform gain profile in the horizontal direction (the effect of the vertical gain profile is insignificant). The input intensity profile used for the results presented here is parabolic in the horizontal direction with the edges of the aperture twice as intense as the center. Figure 9 shows the output intensity profile in the horizontal direction from the multipass stage only (without the booster amplifier) showing the effect of the gain compensation on the horizontal intensity profile. Note that without compensation for the gain distribution, the intensity near the edges of the beam rolls off

FIGURE 9. Effect of gain compensation on the horizontal intensity profile after four passes through the main multipass cavity. By compensating for the horizontal gain roll-off in the amplifier, the extracted energy increases 30%, and the output has the desired flat-top shape. (70-50-0494-2115pb02)

dramatically. However, with gain compensation, a nearly flat, top-hat-shaped intensity profile is obtained. This is very important because the performance is limited by the peak laser fluence on the optical components. Therefore a flat beam profile allows a higher output energy at equal peak fluence: the gain-compensated profile has nearly 30% greater energy extraction for the same peak fluence.

Edge Apodization and Fill Factor

It is important to fill the beam aperture as fully as possible to maximize the flat-top portion of the beam area and hence the laser output energy. A 1-cm margin around the edge of a nominal $34 \times 34 \text{ cm}^2$ beam contains 11% of the beam area, so changes of only a few millimeters in beam dimensions can have a noticeable impact on the output energy of the system. Edge diffraction from sharp beam edges causes intensity peaks on the beam, however, so the beam intensity at the edge must be apodized. (That is, the intensity must decrease smoothly to zero over a region occupying at least a few Fresnel zones over the propagation distances for which these intensity peaks are not acceptable.)

The edge apodization used in the 1ω tests is an inverted Gaussian profile with the 10^{-2} intensity point at a square aperture of $34 \times 34 \text{ cm}^2$.¹³ (For the 3ω tests, we used a smaller square beam size of $29.6 \times 29.6 \text{ cm}^2$.) The 10^{-2} intensity point is considered the "zero intensity" level and is the maximum intensity allowed to strike the edges of the clear aperture of optical components. The corners of the beam are rounded with a radius of 5 cm to suppress diffraction from these regions; this subtracts 20 cm^2 from the beam area.

The 1ω output beam with a zero intensity width of 34 cm has a half-power width of 31.5 cm when the laser is operated under heavily saturated conditions. The flat-top, high-intensity region in the center is 30.6 cm wide. The experimental data show no growth of diffractive intensity peaks around the edge of the beam, though simulations suggest that there is some growth under high-fluence and high-B conditions near the end of the pulse. We project, from simulations, that it should be possible to steepen the edge profile and reduce the edge apodization region by approximately half a centimeter with acceptable diffractive intensity growth. (This will be tested during future experiments on Beamlet.) The effective beam area at half power is 971 cm^2 after allowing for the 20 cm^2 loss in the corners, and we use that value to calculate fluence and intensity in the flat-top portion of the beam. The "fill factor" is 84% (defined as the ratio of the beam energy to the energy if the entire $34 \times 34 \text{ cm}^2$ hard aperture were filled at the fluence of the flat central area of the beam).

Energy Performance

Figure 10 shows the Beamlet 1ω output energy that goes to the frequency converter as a function of energy injected into the main four-pass amplifier cavity. The solid line is the calculated performance from a model that includes measured gains and optical transmissions of the system. The maximum 1ω energy and fluence demonstrated at 3, 5, and 8 ns are listed in Table 1.

The gain-performance curve shown in Fig. 10 does not depend on the temporal pulse shape. However, for this shot series, the input pulses were temporally shaped to give nearly square output pulses. Figure 11 shows an example of input and output temporal pulse shapes under highly saturated conditions with an output of 15.5 kJ in an 8-ns pulse. Under these conditions, the intensity of the leading edge of the input pulse is shaped to be 12.5 times the intensity of the trailing edge to maintain a square output pulse shape.

Near-Field Beam Features

All large glass lasers have intensity noise in the near field as a result of diffraction from small obscurations and flaws in the many optical components through which the beam passes. The operating limit of ICF glass lasers is often set by the peak of the near-field intensity noise because of the threat for optical damage. However, the output power of the laser is determined by the average intensity. Therefore it is desirable to have a peak-to-average intensity ratio as near to unity as possible.

FIGURE 10. Measured 1ω output energy vs energy injected into the large multipass cavity. These tests were carried out with eleven amplifier slabs in the four-pass cavity and five in the singlepass booster amplifier (with a flash-lamp pump explosion fraction of 0.2). (70-50-1094-3626pb01)

Figure 12 shows the 1ω near-field image of the Beamlet output at 8 kJ and 3 ns. This represents the quality of the beam that is sent toward the frequency converter. The peak-to-average fluence modulation, due to diffractive noise sources, is about 1.3 to 1. For comparison, the Nova laser, when operated at high fluence, typically has a peak-to-average fluence modulation of about 1.5 to 1.

Some of the prominent patterns shown in the near-field image (Fig. 12) originate from identified sources. For example, the small obscurations near the center of the image are originally from optical breakdown in air paths caused by ghost reflections. Ghost reflections refer to the small reflections from antireflection (AR) coated optics. Because AR coatings are not perfect, some very small portion of the incident light is reflected. If these reflections originate from curved surfaces such as lenses, they will either diverge or come to a focus. The focused ghosts can be intense enough to cause optical breakdown in the air path of the beam or even optical damage if the focus occurs at or near an optical component. Ghost reflections from the Beamlet cavity spatial filter lenses come to a focus in air between the lens and the amplifier or Pockels cell where they cause small air breakdown plasmas to form. When the laser pulse returns through that region on a later pass, these ghost foci appear as small obscurations on the beam. The obscurations are much less apparent after the booster amplifier since they fill in due to unsaturated gain in that amplifier stage. Other features faintly visible in the

FIGURE 11. Comparison of 1ω input and output temporal profiles for a full-system shot (eleven- and five-amplifier slab configuration). The input energy is 1.2 J and the contrast ratio (ratio of the leading to trailing edge intensities) is about 12.5 to 1. The output energy is 15.5 kJ at 8 ns. (70-50-0195-0024pb01)

near-field image (Fig. 12) include multiple Airy patterns caused by small opaque defects. Nearly all of these originate from tiny particulates on some of the small optics of the diagnostic camera system.

Figure 13 shows the cumulative intensity distributions for image pixels within the flat-top area of the Beamlet output beam under several different conditions, illustrating the effects of saturation and modulation growth due to the nonlinear index of refraction in the optical components. Each pixel corresponds to a beam area of $1.4 \times 1.4 \text{ mm}^2$. The 8-ns pulse at 15.5 J/cm^2 or 1.94 GW/cm^2 has a steeper distribution function than the other shots plotted, particularly in the high-intensity regions. This shows the effect of gain saturation for high-intensity peaks, coupled with the absence of any significant nonlinear effects at this long pulse length and low intensity. The 3-ns pulse at 12 J/cm^2 or

4.0 GW/cm^2 shows some growth of intensity peaks due to nonlinear index; at high intensities, this nonlinear effect tends to amplify light scattered at small angles by defects in the optics.

Nonlinear Effects at High Intensity

At very high intensities, the intensity-dependent part of the refractive index becomes important. This nonlinear effect causes growth of noise (small angle scattering) by energy transfer from the main beam through a second-order wave mixing process.¹⁴ The gain of noise growth depends on its spacial frequency. This process limits the laser performance, because excessive growth of noise components can lead to damage of laser components. In Beamlet, beam breakup (due to small-scale self-focusing of noise spikes) limits the performance at and below 3 ns. Quantifying this effect on Beamlet is very important to confirm the theory and modeling, which also have been applied to establish the NIF performance.

These studies are hazardous for the laser components, however, because the intensity modulation can grow very quickly to damaging levels. To minimize the risk to the laser, we chose to study the growth of intensity modulation with short pulses (200 ps) and with the booster amplifier unpumped. Note that by using short pulses, we can propagate high-intensity beams at fluences far below the damage thresholds of the optical components. For these shots, the unpumped booster amplifier served as merely an array of nonlinear components in which we could study the growth of beam modulation.

The onset of significant small-scale self-focusing usually occurs when the intensity-driven, nonlinear

FIGURE 12. (a) Near-field image of the 1ω output from Beamlet for a 5.9-kJ shot at 3 ns; (b) Horizontal and vertical lineouts through the image. (70-50-0494-2124pb01)

FIGURE 13. Cumulative 1ω intensity distributions determined from near-field image profiles for Beamlet shots at various pulse lengths and mean fluences. (a) 0.53 GW/cm^2 , (b) 1.94 GW/cm^2 , (c) 5.5 GW/cm^2 , and (d) 4.0 GW/cm^2 . (70-50-0195-0017pb01)

phase shift reaches about 2 rad. There is a noticeable growth of the intensity modulation in the $4.0\text{-GW}/\text{cm}^2$ image, and serious beam breakup has begun at $5.5\text{ GW}/\text{cm}^2$. Figure 14 shows the near-field appearance of the output beam at this intensity. The nonlinear phase shift through the Pockels cell and booster amplifier amounts to 3 rad for this shot. These shots were taken using the original KDP Pockels cell crystal that had a poor-diamond-turned surface and imposed a 6.4-mm period modulation on the beam. (See "Large-Aperture, High-Damage Threshold Optics for Beamlet," p. 52 for a detailed discussion.) It is clear that this modulation serves as the noise source that seeds the nonlinear intensity growth and beam breakup.

1 ω Far-Field Beam Quality

The nominal NIF ignition target design requires a 0.5-mm-diam spot at the focus of a 7-m focal length lens.¹ Energy lying much outside this $\pm 35\text{-}\mu\text{rad}$ angle is not useful and can be harmful if it strikes the wrong area of certain targets. Some experiments planned for NIF require smaller spots, so a smaller beam divergence is desired. The diffraction limit of a normal 35-cm beam is $\pm 5\text{ }\mu\text{rad}$, so a NIF beamlet should be roughly 3 to 7 times the diffraction limit, as usually defined, at the fundamental $1.053\text{-}\mu\text{m}$ wavelength (this divergence is preserved when the beam is converted to the third harmonic). Efficient frequency conversion also sets a beam divergence specification,⁵ but it is less stringent than this spot size requirement for NIF ($\pm 35\text{ }\mu\text{rad}$).

FIGURE 14. Near-field image of the 1ω output beam for a $5.5\text{-GW}/\text{cm}^2$ shot at a 200-ps pulse width. The white dots are hot spots with an intensity nearly twice the average intensity. Figure 13(c) shows the cumulative intensity distribution for this shot. (70-50-0195-0023pb01)

As mentioned earlier, a DFM is used on Beamlet to correct for low-order static and dynamic wavefront aberrations. (See "Beamlet Pulse-Generation and Wavefront-Control System," p. 42.) Figure 15 shows a recent Beamlet 1ω far-field profile obtained using pre-correction for static and pump-induced aberrations on a 4.5-kJ 3-ns shot. The rms wavefront aberration is reduced to 0.17 waves, which leads to a calculated Strehl ratio of 0.4. The central spot is diffraction limited and approximately $10\text{-}\mu\text{rad}$ wide. Most of the energy is contained well within the NIF requirement of $\pm 25\text{-}\mu\text{rad}$ divergence angle. The booster amplifiers were not yet installed at the time this shot was taken. For comparison, the beam without wavefront correction by the DFM would almost fill the entire image plane shown in Fig. 15.

FIGURE 15. (a) 1ω far-field image and (b) horizontal and vertical lineouts of a 4.5-kJ 3-ns Beamlet shot. The wavefront of the $35 \times 35\text{ cm}^2$ beam was fully precorrected for static and pump-induced aberrations using a 39-element DFM. (70-50-0195-0022pb01)

Table 2 summarizes preliminary results obtained using the Beamlet Hartmann wavefront sensor and adaptive optics control system. The DFM corrects for the static aberration in the beamline, such that the output wavefront is nearly flat before a shot. The pump-induced wavefront aberration during a shot is largest near the edges of the beam and amounts to 1.65 waves peak-to-valley (p-V) for a 34-cm beam size.

Preliminary attempts to precorrect the injected wavefront for this dynamic distortion showed a reduction of the output aberration by a factor of two. The large and slowly decaying thermally induced aberration in the amplifier slabs after a shot can again be corrected in real time. These results clearly demonstrate the value of the adaptive optics system to increase the brightness of ICF lasers.

Harmonic Generation Experiments

Beamlet Frequency Conversion System

Third-harmonic generation on Beamlet was achieved by the sequential application of collinear sum-frequency mixing in two nonlinear crystals. A beam at the fundamental laser frequency is incident upon the first nonlinear crystal in which second-harmonic generation takes place via degenerate sum-frequency mixing ($\omega_2 = 2\omega_1$). Two copropagating beams, one at the fundamental and the other at the second harmonic, emerge from this "doubling" crystal. They are incident upon the second nonlinear crystal in which the fundamental and the second harmonic again interact through sum-frequency mixing to create a wave at the third harmonic. To efficiently transfer power from the incident waves to the higher harmonic requires that both waves traverse the crystal in phase. Two methods of phase matching are

possible—Type I phase matching, where the two input waves have the same polarization; and Type II phase matching, where the two input waves are orthogonally polarized. Details of the harmonic generation process are described elsewhere.^{15,16}

The Type I KDP second-harmonic generation crystal converts a large fraction of the 1054-nm light to the second harmonic at 532 nm. The Type II KD*P "tripling" crystal then converts this residual fundamental and the second-harmonic beam to the third harmonic at 351 nm. The efficiency with which the third harmonic is generated is very sensitive to the ratio of the intensities of the fundamental and the second-harmonic beams incident on the tripler. This mix ratio is controlled by the length of the doubling crystal and a slight mismatch between the propagation direction of the beam inside the doubling crystal and the perfect phase matching direction.

The Beamlet frequency conversion system is designed to hold two different sizes of square crystal plates (32 and 37 cm). These crystals can accommodate maximum beam sizes up to about 30 and 34.5 cm, respectively. We activated the frequency converter with 32-cm crystals, although 37-cm crystals will be installed and tested in early 1995. The smaller crystals were used in our initial tests because they became available about 6 months before the larger ones. This is simply due to the longer time needed to grow the 500-kg single-crystal boules from which the 37-cm plates were cut. (See "Large-Aperture, High-Damage Threshold Optics for Beamlet," p. 52 for more details on the crystals.) The crystals are installed in two 61-cm-diam optical mounts that allow x and y translation, rotation about the axis of beam propagation, and tilt about two orthogonal axes in the plane of the crystal (Fig. 16). The crystals and their mounts are contained within an insulated housing that maintains the temperature to within ± 0.1 K and $\pm 10\%$ relative humidity.

TABLE 2. Measured 1 ω static and dynamic beam aberration on Beamlet.

Measurement Condition ^a	30-cm beam		34-cm beam	
	p-V ^b	rms	p-V	rms
Static aberration (cold cavity)	1.4	0.2	2.6	0.4
Dynamic aberrations starting with a corrected wavefront in a cold cavity				
• Preshot (~10 min)	0.11	0.03	0.13	0.04
• Shot without correction	0.69	0.22	1.65	0.39
• Shot with partial correction	0.50	0.17	0.72	0.20
• Post shot (~+10 min)	2.4	0.85	3.6	1.3

^aMeasured distortion (in waves at 1.05 μm).

^bPeak-to-valley.

The input and output surfaces of the conversion crystals were coated with a single-layer, quarter-wave-thick, SiO_2 sol-gel AR coating. To simplify the crystal AR-coating process, both the input and output faces of the doubler have an AR coating with optimum transmission at 700 nm. This provides a very good compromise for optimal transmission at both 1054 and 527 nm when using a single-layer AR coating. The output face of the tripler has an AR coating optimized at 351 nm, whereas the input face has an extra coating layer applied to produce the $1\omega/2\omega$ compromise coating thickness.

The tripling crystal was deuterated to reduce the potential for damage from stimulated Raman scattering (SRS). The intense spontaneous Raman band that occurs in KDP near 915 cm^{-1} (and seeds the SRS growth) is split into two weaker bands in KD^*P .¹⁷ In addition to

using KD^*P , we also beveled and AR-coated the edges of the crystal to prevent parasitic oscillations from SRS within the plane of the crystal and orthogonal to the beam propagation vector.

Second-Harmonic Generation

The frequency conversion system was activated in two stages. The $32 \times 32\text{-cm}^2 \times 1.05\text{-cm}$ -thick Type I doubling crystal was installed and the second-harmonic conversion efficiency was measured as a function of input intensity at the phase matching angle ($\Delta k = 0$). Experiments were carried out with increasing 1ω input intensities up to about 5.3 GW/cm^2 using 1-ns square pulses. The second-harmonic conversion efficiency increased monotonically with drive intensity, reaching a maximum value of 83%. These results

FIGURE 16. Layout of the third-harmonic frequency-conversion system showing the location of the crystals in the optical mounts. The crystals can be independently moved in and out of the beamline. (70-50-0494-1913pb01)

(Fig. 17) were compared with plane-wave model calculations and were found to be in excellent agreement. This attests to the nearly flat wavefront quality (i.e., low distortion) of the Beamlet 1ω drive beam.

The plane-wave model assumes a 1% loss at each AR-coated surface of the crystals and 6%/cm absorption at 1054 nm by the bulk KDP. As noted earlier in this section, the second-harmonic generation crystal is slightly "detuned" from the phase-matching angle to achieve the proper mix ratio of the fundamental and second-harmonic beam that drives the tripler. Theory predicts that a detuning angle of ± 250 μ rad from the phase matching direction in the crystal will give the correct mix ratio to achieve maximum 3ω conversion at incident fundamental intensities between 3 and 3.5 GW/cm².

During the course of the doubling experiments, we also measured the conversion efficiency at detuning angles of ± 250 and 350 μ rad and compared the results

FIGURE 17. Second-harmonic conversion efficiency vs 1ω drive intensity using a $32 \times 32 \times 1.1$ cm³ KDP Type I doubling crystal. The conversion efficiency agrees well with the plane-wave model at 0, ± 250 , and ± 350 μ rad detuning angles. (70-50-1094-3625pb01)

with the plane-wave model (Fig. 17). Again, the agreement between the model and experiment was very good. To do these conversion tests, the doubling crystal was first tilted (detuned) to one side and the conversion efficiency measured. This experiment was then repeated with the crystal tilted an equivalent amount in the opposite direction. Thus, the two points shown in Fig. 17 at each of the detuning angles represent two separate experiments where the crystal was detuned by either "plus" or "minus" the respective angle.

Third-Harmonic Generation

Table 3 summarizes the results from third-harmonic generation experiments carried out with a 3-ns square pulse shape. These results are compared with both the NIF requirements and the Beamlet performance goal established at the beginning of the project at the recommendation by the National Academy of Sciences (NAS).

Beamlet is judged against three key third-harmonic performance criteria: (1) fluence, (2) beam quality, and (3) conversion efficiency. For all three criteria, Beamlet either exceeds or meets the goals of the NIF (see Table 3). The difference in total output energy proposed for a NIF beamlet vs that achieved on the prototype Beamlet is due to the difference in aperture size. The prototype Beamlet aperture was set at the beginning of the project in 1991 and supports a maximum beam size of 35 cm. On the other hand, the somewhat larger NIF aperture reflects the more recent thinking that apertures near 40 cm, rather than 30 cm, are a better compromise between performance and cost.

Perhaps the most critical performance criteria is the 3ω fluence, because of the lower optical-damage limits at shorter wavelengths. Specifically, the optical material most at risk is the tripling crystal, because the laser output is set to be near the damage threshold of this material. Beamlet has operated at a 3ω fluence that exceeds the NIF performance requirement by about 10%. During these initial tests, we carried out 17 shots

TABLE 3. Comparison of Beamlet 3ω performance with NIF and the NAS technical contract specifications.

Parameters	Beamlet Phase I ^a	NIF	NAS technical contract
Mean 3ω fluence J/cm ²	8.7	8.0 ^b	6.4–7.6
Quality:			
• Beam size (cm ²)	29.6 $\times$ 29.6	38 $\times$ 36	30 $\times$ 30
• Effective beam area (cm ²)	736	1280	784
• 3ω energy (kJ)	6.4	10.2	5–6
• Beam divergence (μ rad)	$\leq \pm 25$	$\leq \pm 35$	$\leq \pm 50$
• Bandwidth (GHz)	90	90	90
Conversion efficiency:			
3ω peak conversion efficiency	80%	80%	70%

^aSee Ref. 18.

^bat 3.6 ns.

in excess of 7.5 J/cm^2 at 3 ns without sustaining any damage to the K*DP tripling crystal.

The third-harmonic converter was activated by first "laser conditioning" the KD*P tripling crystal at 3ω . Laser conditioning refers to the process of increasing the damage threshold of an optical material by exposing it to a series of laser shots with monotonically increasing fluence. (See "Large-Aperture, High-Damage Threshold Optics for Beamlet," p. 52 for a detailed discussion of laser conditioning of Beamlet optics.) Following conditioning, a series of experiments was conducted to characterize the 3ω conversion performance. One of our major goals was to demonstrate $>70\%$ conversion efficiency at high peak power ($2.5\text{--}3.5 \text{ GW/cm}^2$). These experiments were carried out using temporally square, 3-ns pulses. Figure 18 shows the results where the third-harmonic conversion efficiency is plotted vs the 1ω input intensity delivered to the harmonic converter system. At the highest drive intensities ($>3.25 \text{ GW/cm}^2$) conversion efficiencies of 80% were achieved. The results were in good agreement with plane-wave model predictions. The model calculations include the effects of the 30-GHz bandwidth (90-GHz at the 3ω output) that we add to the drive pulse to suppress SBS in the output optics. The added bandwidth reduces the conversion efficiency about 3% at the highest drive intensities. The model calculation shown in Fig. 18 does not include the effects of the spatial and temporal edges of the real beam, but instead assumes a perfect top-hat-shaped profile. Including these effects would tend to slightly reduce the

FIGURE 18. Third-harmonic conversion efficiency vs 1ω drive intensity achieved with 3-ns square pulses with 30-GHz 1ω (90-GHz at 3ω) bandwidth. The Type II tripling crystal was 80% deuterated KD*P $32 \times 32 \times 0.95 \text{ cm}^3$ with 0 μrad detuning. The doubling crystal was detuned at $\sim 250 \mu\text{rad}$ to achieve optimum 3ω conversion. (70-50-1094-3624pb01)

conversion efficiency, giving even closer agreement with the experiments.

The maximum average 3ω output fluence achieved during this series of shots was 8.7 J/cm^2 , about 10% greater than the NIF performance goal of 8.0 J/cm^2 . At the Beamlet beam aperture area of 736 cm^2 , this gave 6.4 kJ 3ω output and corresponds to over 11 kJ at the NIF beam area of 1280 cm^2 (Table 3).

The input beam quality and fill factor were maintained during the 3ω conversion process as shown by the 3ω near-field image and lineout in Fig. 19. These data were taken during a 3-ns shot at 2.56 GW/cm^2 producing 7.7 J/cm^2 (5.6 kJ) output at 3ω . The peak-to-mean intensity modulation is about 1.4 to 1 at 3ω compared to about 1.3 to 1 at 1ω .

(a) Near-field image

(b) Horizontal and vertical lineouts

FIGURE 19. (a) Near-field image and (b) horizontal and vertical intensity lineouts of that image for a 3ω output pulse from the Beamlet harmonic generator. The peak-to-mean intensity modulation is about 1.35 to 1. (70-50-0195-0021pb01)

Figure 20 further illustrates the similarity in the fluence modulation observed for the 1 and 3ω near-field images at high drive intensities. Plotted is the normalized probability distribution of fluences observed at 1 and 3ω for a 3-ns shot. The average pulse intensities are 3.3 GW/cm^2 and 2.65 GW/cm^2 at 1 and 3ω , respectively. The wings of the two curves compare the p-V intensity distribution for the 1 and 3ω pulses. The data clearly show that there is no significant growth in near-field fluence modulation during the conversion process.

During the course of our 3ω tests, we also demonstrated frequency conversion for shaped pulses roughly similar to NIF ignition target drive pulses. The proposed NIF ignition target pulse shape consists of a low-intensity "foot" about 15 ns long followed by a higher intensity, 3–3.5-ns, main drive pulse. The harmonic conversion process depends strongly on the product of the beam intensity and crystal thickness and therefore has a limited intensity range over which it is fully optimized. This is illustrated by the data in Fig. 18, where the conversion efficiency is shown to drop-off dramatically at low-drive intensity; in this case, the crystals are optimized for intensities in the range of $2\text{--}5 \text{ GW/cm}^2$. In both the NIF and prototype-Beamlet design, the conversion efficiency of the foot will be lower than the main pulse. The NIF requirement is 60% conversion efficiency for the nominal ignition pulse shape. Because the Beamlet preamplifier section was designed to handle a maximum pulse length of 10 ns, we simulated a complex pulse shape (similar to what might be used on NIF) using a 7-ns foot and a 3-ns main pulse. The 1ω input to the harmonic converter had a foot-to-main pulse contrast ratio of 9:1, giving the desired 30:1 contrast ratio for the 3ω output pulse (Fig. 21). The 1ω beam had an equivalent pulse length of 3.9 ns and a mean fluence of 12.4 J/cm^2 compared with 3.2 ns and 8.2 J/cm^2 for the output 3ω pulse. The measured foot

FIGURE 20. Comparison of normalized probability distribution of intensities for the 1ω drive pulse and corresponding 3ω output observed during a 3-ns shot at a 1ω input drive intensity of 3.3 GW/cm^2 . (70-50-0195-0019pb01)

and peak pulse conversion efficiencies were 23 and 77%, respectively. The average 3ω conversion efficiency was 64%, which compares quite favorably with our model predictions.

The above 3ω experiments also gave us the added opportunity to more fully test the capability of the integrated optical-pulse forming and preamplifier section of our front end. To create the desired 9:1 1ω NIF-like pulse shape that was used to drive the harmonic converter requires nearly a 75:1 intensity contrast for the shaped pulse at the injection to the main laser cavity [Fig. 21(b)]. The injected pulse was shaped to compensate

FIGURE 21. (a) Shows a "NIF-like" 3ω pulse shape with a 30:1 contrast ratio generated using a 9:1 1ω drive pulse to the harmonic converter. (b) An injected pulse with a 75:1 contrast and a complex temporal shape was generated using the new front-end architecture to achieve the desired 1ω drive-pulse shape. (70-50-1094-3622pb01)

for effects of gain saturation in the main laser cavity and booster amplifiers. This pulse shape was easily synthesized using the low-voltage waveguide modulators in the pulse generation system.

Summary

We recently completed construction and preliminary testing of the NIF prototype Beamlet laser, a large-aperture flash-lamp-pumped Nd:Glass laser. The laser uses a multipass architecture that represents the first attempt to employ such a design at this scale. The main laser cavity is unique in that it uses a full-aperture plasma-electrode Pockels cell and an angular multiplexing scheme to execute four passes through a group of eleven large phosphate glass amplifiers contained in the cavity. The output from the main laser cavity then makes a single pass through a booster amplifier section comprised of five more amplifiers. The 1054-nm output from the laser is converted to the third harmonic (351 nm) using a Type I/II KDP/KD*P frequency conversion scheme.

We have successfully demonstrated Beamlet's 1 ω and 3 ω performance at its 3-ns design point. Good beam quality is maintained as defined by the low peak-to-average fluence modulation and small wavefront aberration. We demonstrated several new pre-compensation techniques in the preamplifier that allow control over fill factor, wavefront, and temporal shape of the output beam. Key 1 ω performance parameters have been investigated at high 1 ω fluence (15.5 J/cm²), and high intensity (5.5 GW/cm²). Similarly, at 3 ω we demonstrated damage-free operation at fluences in excess of those required for NIF and third-harmonic conversion efficiencies >80% for 3-ns pulses and 64% for NIF-like pulse shapes. The conversion efficiencies mentioned exceed NIF requirements. The results from current and future Beamlet performance tests will be used to validate the NIF laser design.

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23. Eastman Kodak Company, Department 177, Building 601, Rochester, NY, 14650-0803.
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DESIGN AND PERFORMANCE OF THE BEAMLET AMPLIFIERS

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Introduction

In future laser systems, such as the National Ignition Facility (NIF), multi-segment amplifiers (MSAs) will be used to amplify the laser beam to the required levels. As a prototype of such a laser architecture, we have designed, built, and tested flash-lamp-pumped, Nd:Glass, Brewster-angle slab MSAs for the Beamlet project.

In this article, we review the fundamentals of Nd:Glass amplifiers, describe the MSA geometry, discuss parameters that are important in amplifier design, and present our results on the characterization of the Beamlet MSAs. In particular, gain and beam steering measurements show that the Beamlet amplifiers meet all optical performance specifications and perform close to model predictions.

The Beamlet amplifiers also demonstrate advances in MSA mechanical design: hermetically sealed blast shields to protect the laser slabs from contamination generated by the flash lamps; hermetically sealed flash-lamp cassettes to protect the lamp envelopes from outside sources of contamination; modular slab cassettes to reduce the size of the amplifier parts that need to be handled; and flash-lamp cassettes that can be installed and removed without disturbing the laser slabs. These features will be included in the amplifiers for the NIF.

Background

The Amplifier Pumping Process

Many energy transfer steps occur during the amplifier pumping process,¹ which begins when the switch

in the flash-lamp discharge circuit is closed and current begins to flow through the flash lamps. Typically, circuits transfer 70–90% of the bank energy to the flash lamps, with the remainder lost as heat to the circuit elements. Flash-lamp plasmas convert about 80% of the delivered electrical energy to photons, with approximately half the optical output energy falling in the 400–1000-nm region of Nd³⁺ pumping bands. As these photons circulate in the pump cavity, some are reabsorbed by the flash-lamp plasma, which in turn re-emits a fraction of this reabsorbed energy; some are absorbed by the metal reflectors or slab holders; and some are lost through the ends of the amplifiers. The remaining photons (about 10% of those emitted by the plasma) are absorbed by the laser slabs.

The photons absorbed by the laser slabs produce stored energy in the form of excited Nd³⁺ ions. However, due to quantum defects between the absorbed photons and the upper laser level, about half of the absorbed energy is immediately converted to heat, depending on the spectral distribution of the flash-lamp light. Energy transfer from excited ions to ground-state ions (concentration quenching) produces additional heating.

Pump-induced beam steering and wavefront distortion arise from two main sources: (1) The laser slabs are warped when pump light deposits more heat on one side than the other. This warping causes beam steering and wavefront distortion that is distributed over the entire aperture. (2) Amplified spontaneous emission (ASE) heats the absorbing edge claddings that are used to prevent parasitics. The resulting thermal expansion produces significant wavefront distortion within approximately one slab thickness of the edge claddings. This edge distortion can be avoided by setting the beam aperture appropriately.

Parameters Governing Amplifier Performance

In Brewster-angle slab amplifiers, the three most important parameters for describing laser performance are α , the average gain coefficient; g , the small signal gain per slab; and a , the hard aperture area. Both α and g are related to the stored energy density, ρ , by the relations

$$\alpha = \sigma \rho / h\nu \quad (1)$$

and

$$g = \exp \left[\alpha (n^2 + 1)^{1/2} (t/n) \right], \quad (2)$$

where σ is the stimulated emission cross section for excited Nd ions, $h\nu$ is the laser photon energy, n is the refractive index of the laser glass, and t is the caliper thickness of the laser glass. The term $(n^2+1)^{1/2}(t/n)$ is the beam path length through the Brewster-angle laser slab.

Generally, high values of α , g , and a are desired: as α increases, the desired beam fluence is achieved with less laser glass and, as a result, with smaller nonlinear phase shifts; as g increases, the desired fluence is achieved with fewer slabs; and as a increases, the desired laser energy can be achieved with fewer beamlets. However, it is difficult to attain the desired values for all three key amplifier performance parameters simultaneously. For example, increased ASE causes both α and g to decrease as a is increased. The gain per slab can be increased by making slabs thicker, but, as a result, α falls because flash-lamp light is preferentially absorbed near the slab surfaces. The sophisticated amplifier model² that Lawrence Livermore National Laboratory (LLNL) has developed to predict α and g is essential for characterizing tradeoffs between parameters and for arriving at cost-effective fusion laser designs.

Other important amplifier parameters are gain uniformity across the aperture, pump-induced wavefront distortion, and storage efficiency. A measure of gain uniformity is the parameter U , defined as the peak-to-average ratio of the gain coefficient evaluated over the beam aperture. Good gain uniformity, i.e., U close to unity, is desired because gain variations produce fluence variations in the output beam, thereby reducing the damage-limited output energy. Low pump-induced wavefront distortion is desired for good beam focusability and high harmonic-conversion efficiency. To some degree, both gain variations and pump-induced wavefront distortion can be compensated for, albeit at additional cost and complexity to the system. For example, the Beamlet preamplifier section uses a variable transmission filter to tailor the fluence distribution and a deformable mirror to precorrect the wavefront. To evaluate pump cavity designs, models for predicting

gain distributions³ and pump-induced wavefront distortion⁴ are being developed at LLNL and at the CEA Laboratory in Limeil, France.

Storage efficiency, η , is defined as the total extractable energy stored in the laser slabs divided by the total electrical energy delivered to the flash lamps. High storage efficiency is desired to reduce the size and therefore cost of the pulsed power system.

Multisegment Amplifier (MSA) Development

Prior to Beamlet, all flash-lamp-pumped Nd:Glass fusion lasers have used one-beam-per-box amplifiers. MSAs, in which several beams are contained in the same amplifier box, were first proposed in 1978 as a way to reduce the cost of flash-lamp-pumped, Nd:Glass fusion laser systems.⁵ MSAs cost less than the one-beam-per-box amplifiers in three ways: (1) by making amplifiers more compact, thereby reducing the size and cost of the building; (2) by increasing pumping efficiency, thereby reducing the size and cost of the pulsed power system; and (3) by reducing the number of internal amplifier parts.

Figure 1 shows the MSA design currently envisioned for the NIF. Optical gain at the 1.05- μm wavelength is provided by Nd-doped, phosphate glass, rectangular laser slabs oriented at Brewster's angle with respect to the beam to eliminate reflection losses. The amplifier hard apertures are 40 $\times$ 40 cm². The slabs are stacked four-high in holders that are arranged in 12 columns.

FIGURE 1. The MSA design currently envisioned for the NIF uses 48 apertures arranged in a 4-slab-high $\times$ 12-slab-wide matrix. (40-00-0294-0535pb01)

The columns of slabs are separated by arrays of central flash lamps that emit radiation to both sides. The outermost columns are also illuminated by arrays of side flash lamps that have large silver reflectors to redirect the flash-lamp radiation toward the slabs. In this respect, the side flash-lamp arrays are similar to the arrays used in one-beam-per-box amplifiers on Nova and other previous fusion lasers. Glass blast shields, placed between the flash lamps and the laser slabs, serve two purposes: (1) They prevent acoustic waves generated by the flash lamps from propagating into the beam path and causing wavefront distortion; and (2) they provide a contamination barrier between the flash-lamp cavity and the critical slab cavity. The blast shields also form a channel that could potentially be used for flowing cooling gas around the flash lamps. To simplify assembly and maintenance, the NIF MSAs would be assembled from one-slab-long, one-slab-wide, four-slab-high modules. In addition, the flash lamps would be mounted in 6- or 8-lamp removable cassettes.

Since 1989, LLNL has built and tested three MSA designs: MSA-1⁽²⁾, MSA-2⁽⁶⁾, and the Beamlet amplifiers. Although MSA-1 and MSA-2 contained only four apertures, in a one-slab-long, 2×2 array, they were large enough to permit us to study important MSA performance issues. In particular, we discovered that central flash-lamp arrays pump more efficiently than side flash-lamp arrays. In side arrays, the large reflectors return a portion of the flash-lamp radiation to the lamps, where it is absorbed by the plasma. Furthermore, the reflectors themselves absorb a significant fraction of the flash-lamp radiation. In contrast, central flash-lamp arrays allow the lamps to radiate freely in both directions, and the only reflectors are small diamond-shaped reflectors between the lamps that effectively reduce the transfer of radiation from lamp to lamp. Although MSA-1 had high storage efficiency (about 3.5%) and high average gain coefficient (5.5%/cm) at the normal operating point (lamps fired at 20% of the single-shot explosion energy), gain varied significantly across its aperture. MSA-1 was not versatile enough to permit us to explore solutions to the gain uniformity problem or to study how MSA performance is affected by changes in pump cavity design.

MSA-2, also called the Beamlet prototype amplifier, was used to develop pump cavity designs for the Beamlet amplifiers. MSA-2 had a flexible pump cavity that enabled us to study the effect of different designs on gain uniformity and cavity transfer efficiency. Gain gradients in the vertical direction were reduced by installing reflectors at the tops and bottoms of the flash-lamp cassettes to reduce the loss of pump radiation through the gaps between the flash lamps, and by installing dimpled silver reflectors with raised surfaces on the slab holders so that the reflected light illuminated the facing slabs more uniformly. Gain gradients in the horizontal direction were reduced by replacing

the cylindrical silver reflectors in the side lamp arrays with flat reflectors. These changes lead to an extremely uniform gain distribution, with a gain uniformity parameter $U = 1.025 \pm 0.004$. Pumping was balanced between the 12-lamp central array and the less efficient side arrays by increasing the number of lamps in the side arrays from six to eight. Balanced pumping is desired to reduce wavefront distortions caused by slab warping due to preferential heating of one side of the laser slab by pump radiation.

Beamlet Amplifiers

Although testing MSA-1 and MSA-2 greatly enhanced our understanding of MSA performance, their 29×29 cm² apertures had only about 50% of the area of the 40×40 cm² apertures proposed for the NIF, and serious concerns remained regarding the feasibility of manufacturing large laser slabs and the effect of increased ASE on efficiency and gain uniformity. In addition, it remained to be demonstrated that MSAs could be cleanly assembled and operated. These issues were addressed by designing, building, and testing the Beamlet amplifiers.

Amplifier Description

The Beamlet amplifiers use the MSA architecture in which four apertures are arranged in a 2×2 matrix. Figure 2(a) shows an assembled Beamlet amplifier, with one end open. Beamlet contains two large amplifiers: a four-pass, eleven-slab-long cavity amplifier and a singlepass, five-slab-long booster amplifier. The positions of these amplifiers in the laser chain are discussed in "System Description and Initial Performance Results for Beamlet," p 1. The hard apertures of the Beamlet amplifiers are 39.5×39.5 cm², larger than the apertures used for any previous Nd:Glass amplifiers and approximately the same size as the amplifiers envisioned for the NIF.

The measurements described below show that at the standard operating point, for which the lamps are driven at 20% of their single-shot explosion energy (in air), the amplifiers have the following characteristics: the average gain coefficient is 5%/cm, the storage efficiency is 3%, and pump-induced wavefront distortion is <1.5 waves at 1.053 μ m for the entire system. The ratio of peak gain coefficient to average gain coefficient, evaluated over the central 95% of the amplifier hard aperture, is 1.06:1. The gain distribution is influenced by ASE, which preferentially depumps the edges of the aperture.

The Beamlet amplifiers were designed modular, which facilitates assembly and maintenance. The basic amplifier assembly units (BAUs) are one slab long, one slab wide, and two slabs high. Each BAU consists of an aluminum frame, blast shields mounted on the sides, and a slab

holder mounted internally, as shown in Fig. 2(b). The aluminum frame is nickel-plated, for cleanliness. The BAUs are assembled in a class-100 clean room, bagged, and transported to the laser bay. In the laser bay, a crane lifts the BAUs onto rails, which allows the BAUs to be easily positioned along the direction of the laser beam. The BAUs are installed in pairs and bolted together side by side to form one-slab-long 2×2 units. The flash-lamp cassettes are slid into place from the top, using the crane. All

amplifier assembly is performed under portable class-100 clean rooms.

The laser slabs are made of Schott glass (composition LG-750), doped at a Nd ion concentration of 3.5×10^{20} ions/cm³. The finished slab dimensions are $4 \times 42.4 \times 76.4$ cm³, excluding the 1.2-cm-thick edge claddings glued onto the perimeter to absorb ASE. The edge claddings are made of Cu-doped LG-750, which has an absorption coefficient of 2.8/cm at the peak gain wavelength of 1.053 μ m. The volume of the Beamlet laser slabs is 12 L, nearly twice the volume of the largest laser slabs fabricated previously. Further details about the laser slabs are contained in the article "Large-Aperture, High-Damage-Threshold Optics for Beamlet," p. 52.

To reduce costs, only one of the four Beamlet apertures has real laser slabs. The other three apertures have dummy slabs consisting of two panes of Greylight-14, a relatively inexpensive architectural glass. These dummy slabs are indistinguishable from the real laser slabs in the degree to which they absorb flash-lamp light. The pumped regions of the slabs measure 39.5×75.6 cm². The vertical separation between the hard apertures is 5.5 cm. Like MSA-2, the slab masks use dimpled, silver reflectors, to improve gain uniformity.

Figure 3 shows a plan view of the pump cavity, the design of which is based on the MSA-2 results. The bore diameter of the flash lamps is 2.5 cm and the arc length is 91.4 cm. The flash lamps are made of UV-absorbing Ce-doped quartz to protect the pump

FIGURE 2. (a) Photograph of assembled 2×2 Beamlet amplifiers with 39.5×39.5 cm², hard-edged apertures (this supports about a 35×35 cm² beam size). (b) Schematic drawing showing key elements of the design: the shaded square represents the active beam aperture. (02-30-1093-3491Apb01)

FIGURE 3. Plan view of the Beamlet pump cavity showing flash-lamp and slab locations for two one-slab-long, one-slab-wide modules joined side by side. (02-30-1093-3490Apb01)

cavity from solarization, and are filled with 200 Torr of Xe gas. The flash lamps were manufactured by EG&G, Inc. The 16 flash lamps in each central flash-lamp array are spaced 3.94 cm apart, corresponding to a lamp packing fraction (defined for central arrays as the bore diameter divided by the center-to-center distance) of 0.64. Like MSA-1 and MSA-2, silver diamond-shaped reflectors are placed between the lamps to increase efficiency.

The ten lamps in each side array are spaced 6.29 cm apart, corresponding to a lamp packing fraction (defined for side arrays as half the bore diameter divided by the center-to-center distance) of 0.79. As in MSA-2, a higher lamp packing fraction is used in the side arrays than in the central arrays to better balance pumping on the two sides of the laser slabs.

To further reduce costs, especially for the pulsed power system, only six flash lamps are installed in the side arrays on the inactive side (the side opposite the real Nd:Glass laser slabs) of the amplifiers. Experiments previously performed on MSA-1 showed that very little of the pump light produced by the flash lamps on the far side is transmitted by the central flash-lamp array under normal operating conditions.

Inspections show that after nearly one year of operation the Beamlet flash lamps remain essentially free of the C "brown spots" that commonly appear on Nova lamps. The improved cleanliness is partly attributed to the use of O-ring seals on the lamp bases that protect the lamp envelopes from outside sources of contamination.

During the amplifier activation tests, which were conducted when the Beamlet cavity amplifier was one, two, and five slabs long, the ends of the amplifiers were covered with hard-anodized panels. These panels kept the amplifiers clean and absorbed flash-lamp light. The panels had adjustable slits permitting gain measurements at any location in the amplifier aperture. To reduce the risk of contaminating the laser slabs, either with particles from the laser bay or particles that might have been generated when the panels were moved, each end panel was separated from the amplifier by an empty BAU.

Pulsed Power Description

The Beamlet pulsed-power system is described more fully in "Beamlet Pulsed-Power System" on p. 62 of this *Quarterly*. In brief, we use single-mesh LC circuits (circuits with inductance and capacitance) to drive pairs of flash lamps connected together in series. Each circuit has a 208- μ F capacitor and a 140- μ H inductor, and the $3(LC)^{1/2}$ pulse length is 500 μ s. The measured capacitor-to-lamp transfer efficiency is 71%. To improve pumping

efficiency, the flash lamps are preionized with 0.2-J/cm² pulses (electrical energy per unit of bore area) delivered 200 μ s before the main pulses.^{7,8}

The flash-lamp pulse energies, expressed in explosion fraction units, range from 0.075 to 0.30. Flash-lamp explosion fraction, f_x , is defined as the total electrical energy delivered to a flash lamp divided by the electrical energy required to explode the flash lamp on a single shot. Using the standard formula,⁹ the single-shot explosion energy for the Beamlet flash lamps is 60.0 kJ per lamp.

Amplifier Gain Characterization Method

An important parameter in amplifier design is the gain of the amplifier. In this section, we describe the experimental layout to characterize gain, and how the gain measured on a one-slab-long amplifier may be used to obtain the gain for a chain of amplifiers.

13-Beam Gain Probe

To measure gain distributions over the entire aperture width on a single shot, we generated thirteen 5-mm-diam probe beams using beam splitters, rattle optics, and an 8-W continuous-wave (cw) Nd:YLF laser. The probe beams, which measure gain distribution by tracking changes in their own intensity, were centered in the aperture horizontally. The beam-to-beam spacing was 3 cm except for the two probe beams nearest the middle, where the spacing was 6 cm. To measure gain distributions over the entire aperture, the probe beams were moved to different vertical locations using a motor-driven stage to translate a turning mirror.

After passing through the amplifier, the probe beams struck an array of 13 PIN-44 photodiodes. To reduce the sensitivity of the gain measurements to lateral translations of the probe beam, we illuminated the photodiodes indirectly, using cavities made of diffusely reflecting material. Background flash-lamp radiation was reduced by the use of narrow-band interference filters and by placing the photodiodes 4–5 m away from the amplifiers. Neutral-density filters protected the photodiodes from saturation. The remaining flash-lamp contributions were eliminated by subtracting the signal produced by a 14th diode, which was physically close to the other diodes but had no incident probe beam. Scale factors for the subtracted signals, which were different for each channel, were obtained by firing the amplifiers with the probe beams turned off.

The photodiode signals were digitized at 0.5 MHz with 10-bit resolution. The shot-to-shot variations in the measured gain coefficients were about $\pm 1\%$.

Predicting Amplifier Performance

The symmetry of the Beamlet (and NIF) amplifiers leads to a simplified method for predicting their performance. Figure 4 illustrates this method schematically. Here an amplifier N slabs long (in this case $N = 7$) is displayed in plan view [Fig. 4(a)]. Because of the system symmetry it can be shown⁶ that the gain for an N -slab-long amplifier is a linear combination of three simple amplifier pump configurations: "X," "V" and "diamond" [Fig. 4(b)]. This observation greatly simplifies the testing needed to predict the performance of a Beamlet or NIF MSA consisting of an arbitrary number of slabs. Rather than having to build the complete N -slab-long amplifier, we can simply test one- and two-slab-long modules and extrapolate the performance of the N -slab-long unit. Note that if a mirror is placed on one end of a V configuration module, a diamond is formed, and if the mirror is placed on the other end of a V configuration module, an X is formed [see Fig. 4(b)]. Thus, by using a flat silver reflector at the end of the one-slab long module, one can also simulate the diamond and X pump configurations without having to build separate two-slab-long test modules [Fig. 4(b)]. This is the approach we have used successfully on Beamlet and will also use for the NIF amplifier development.

The basic assumption in this method is that the main pumping contributions are additive.⁶ This assumption leads to an expression for α_i , the gain coefficient for an internal slab that is a function of gain measured in the three test configurations:

$$\alpha_i = \alpha_d + \alpha_x - \alpha_v \quad (3)$$

where α_d , α_x , and α_v are the gain coefficients measured in the diamond, X and V configurations, respectively. Similarly, α_N , the average gain coefficient for an amplifier N slabs long (where N is odd), is given by

$$\alpha_N = \frac{[\alpha_x + \alpha_d + (N-2)\alpha_i]}{N} \quad (4)$$

Generally, an odd N is desired to achieve good gain uniformity. This is because of gain gradients in the two end slabs. These gradients can be rather large and are caused by the loss of pump light out the ends of the cavity. By using an odd number of slabs, the gradients can be made to run in opposite directions and therefore tend to cancel each other out.

To test the above extrapolation technique for predicting amplifier performance, we compared measured and predicted gain distributions for a five-slab-long Beamlet amplifier. The gain measurements were made

FIGURE 4. (a) Schematic drawing of an N -slab-long amplifier. (b) The three simple amplifier modules (X, V, and diamond) that were tested and used to predict the performance of the N -slab-long amplifier. (70-50-1294-3979pb01)

horizontally across the aperture and at the vertical middle using five different lamp explosion fractions ranging from 0.075–0.25. Figure 5(a) shows the horizontal gain distributions measured at $f_x = 0.2$ for the diamond, X, and V test configurations. From these measurements, we predicted the gain performance of a five-slab-long Beamlet amplifier and then compared it with actual measurements, shown in Fig. 5(b). The predicted and measured gain distributions for the five-slab-long amplifier have about the same shape, but the predicted value is about 5% higher. This discrepancy is because the predicted gain—Eq. (3)—does not take into account the nonlinear effect ASE has on the gain distribution. The slabs interior to the amplifier have higher gain coefficients, and therefore higher ASE decay rates, than the slabs in the X, V, and diamond configurations. For the NIF amplifier development, these and other results taken at different lamp explosion fractions will be used to validate an improved technique for predicting amplifier performance that takes ASE into account.

FIGURE 5. Horizontal gain distributions for (a) the V, diamond and X amplifier test configurations, and (b) the five-slab-long Beamlet amplifiers at $f_x = 0.20$. For comparison the predicted “extrapolated” performance for the five-slab-long Beamlet amplifier is also shown. (70-50-1294-3978pb01)

The gain coefficient profiles in Fig. 5(a) illustrate two other points about the amplifiers. First, note that the slopes in the gain distributions of the two slabs in the X and diamond configurations do not cancel out, because they have an even number of slabs (i.e., 2). Second, the one-slab-long amplifier (V) has a gain distribution similar to that of the five-slab-long amplifier (because N is odd), but the gain for the V is much lower due to large end-loss effects. The end losses also cause the two-slab-long amplifiers to have a lower average gain than the five-slab-long case.

Beamlet Amplifier Characterization Measurements

In addition to the gain, the storage efficiency and pump balance are important amplifier parameters. In this section, we discuss the results of our gain measurements and how they may be used to compute storage efficiency and pump balance.

Horizontal Gain Distributions vs f_x

Figure 6 shows horizontal gain distributions for the five-slab-long amplifier, which were measured at six different values of f_x . These gain distributions are relatively flat at low f_x and become more peaked as f_x increases. We attribute the higher gain at the center of the aperture to two effects: (1) ASE, which preferentially depumps the edges of the aperture and becomes more important as the average gain coefficient in the slab is increased; and (2) changes in the pump distribution as

FIGURE 6. Horizontal gain distributions measured on the five-slab-long Beamlet amplifier at six different flash-lamp explosion fractions. (70-50-0494-2129pb01)

energy to the flash lamps is changed. It appears that ASE is the stronger of the two effects, based on MSA-2 experiments that showed that pump distributions produced by similar flash-lamp arrays varied only slightly with changes in how hard the lamps are driven (i.e., f_x).

Temporal Variations in the Horizontal Gain Distributions

Figure 7(a) shows the horizontal gain distributions that were measured on the five-slab-long amplifier at different times after initiation of the main pump pulse. In the figure, time increases from bottom to top for the rising edge of the pulse, and from top to bottom for the

FIGURE 7. (a) Horizontal gain distributions of the five-slab-long Beamlet amplifier at different times during the main flash-lamp pulse, shown vs time in (b). (70-50-1294-3977pb01)

falling edge. The times were chosen to facilitate comparisons between gain distributions measured on the rise and fall of the gain, at comparable values of the average gain coefficient, as may be seen in Fig. 7(b). The gain distributions measured at the peak and on the fall of the pump pulse show the gain-peaking near the middle of the aperture that is attributed to ASE. The gain distributions measured on the rise lack this peaking effect, but show other types of variations that are attributed to nonuniform pumping. It appears that the pump distribution is not as uniform early in the pulse as it is later, after the arcs in the flash lamps have become better developed. These curves are indicative of the complexity that must be included in ray-trace codes to accurately predict gain distributions, as well as the wealth of Beamlet amplifier data now available for rigorous validation of such codes.

Full-Aperture Gain Distributions

Knowledge of the gain distribution over the full aperture is also required for rigorous validation of amplifier performance models. Full-aperture gain distributions were measured for the diamond, X, and five-slab-long amplifiers, at flash-lamp explosion fractions of 0.15 and 0.20. Figure 8 shows a contour plot of the full-aperture gain distribution measured on the five-slab-long amplifier at $f_x = 0.20$. Except for regions near the top and bottom of the aperture where the slab is partially shadowed by its mask, the gain gradients were larger in the horizontal direction than in the vertical direction because of ASE. For this gain distribution, in the central 95% of the aperture, the

FIGURE 8. Gain distribution across the aperture of the five-slab-long Beamlet amplifier. (02-30-1093-3495pb01)

peak-to-average ratio of the gain coefficient (U) was 1.06 ± 0.004 . In comparison, the MSA-2 amplifier, which had a similar pump cavity design, attained a U value of 1.025 ± 0.004 . We attribute most of this difference to the higher ASE rates because of the Beamlet amplifier's larger pumped aperture ($39.5 \times 39.5 \text{ cm}^2$ compared to $29 \times 29 \text{ cm}^2$ for MSA-2).

Storage Efficiency

Figure 9 shows storage efficiency vs gain per slab for the five-slab-long Beamlet amplifier and the Nova 31.5- and 46-cm amplifiers. At $f_x = 0.20$, the normal operating point for all three amplifiers, the Beamlet amplifier has a storage efficiency of 3.0%, compared to 1.8% for the Nova amplifiers. The principal factors causing the Beamlet amplifiers to attain higher storage efficiency are lower lamp packing fraction, shorter flash-lamp pulse length, and the use of more efficient central flash-lamp arrays in the 2×2 MSA architecture. Because of the large size of the Beamlet slabs and higher ASE decay rates, the efficiency curve for the Beamlet amplifier decreases faster than for the Nova amplifiers as gain per slab increases.

Pump Balance

Balanced pumping helps to reduce pump-induced beam steering. To determine how well balanced the pumping is between the central and side flash-lamp arrays, we measured horizontal gain distributions in the two-slab-long amplifiers while firing the central

and side flash-lamp arrays separately. End losses were minimized by firing the central flash-lamp array in the diamond configuration and by firing the side flash-lamp array in the X configuration. Figure 10 shows the average gain coefficient plotted vs flash-lamp explosion fraction, for both central- and side-array pumping. We calculated average gain coefficients by integrating the measured horizontal gain distribution across the aperture. We found that over the entire explosion fraction range, from $f_x = 0.075$ –0.25, pumping by the two flash-lamp arrays was balanced to within 5%, with the central array achieving slightly higher average gain coefficients than the side array.

Pump-Induced Wavefront Distortion

In the MSA geometry, the front and back of the laser slab gets heated unequally by the pump radiation. As a result, thermal stresses build up and cause the slab to deform. This deformation results in wavefront distortion of an initially plane beam. In this section, we describe our work in measuring pump-induced wavefront distortion.

Local Beam-Steering Probe

During the Beamlet amplifier activation, we characterized pump-induced wavefront distortion in the Beamlet amplifiers by measuring local pump-induced beam-steering angles using three 5-mm probe beams, generated with the cw Nd:YLF laser described earlier.

FIGURE 9. Storage efficiency vs the small signal gain per slab (and stored fluence per slab) for the five-slab-long Beamlet amplifier and the Nova 31.5-cm and 46-cm amplifiers. (70-50-0494-19589pb01)

FIGURE 10. Average gain coefficient vs flash-lamp explosion fraction for two cases: (1) only the central array was fired (in the diamond configuration); and (2) only one of the side arrays was fired (in the X configuration). Central and side pumping were balanced over a wide range of explosion fractions. (70-50-1294-4015pb01)

The wavefront distortion in waves, Φ , is related to the local beam-steering angle, $\Delta\Theta$, by

$$\Phi(x) = \frac{1}{\lambda_0} \int_0^x \Delta\Theta(x') dx' , \quad (5)$$

where x and x' are positions in the aperture and λ_0 is the wavelength. The three probe beams were arranged in a column, with a 9-cm vertical separation between adjacent probe beams. A motor-driven stage was used to move the three probe beams to different aperture positions.

The method for measuring local beam-steering angles has been described previously.¹⁰ After passing through the amplifier, each probe beam was split, with one part directed to a lateral-effect photodiode and the other part to a conventional photodiode. Lateral-effect photodiodes produce output voltages proportional to the product of the beam power and the displacement of the beam centroid from the center of the detector. Each lateral-effect photodiode was placed at the focus of a 2-m-focal-length lens to ensure that the output voltages were proportional to changes in the propagation direction of the probe beam, and were insensitive to lateral translations of the probe beams. The lateral-effect photodiodes produced two beam-steering signals, one for the horizontal direction and one for the vertical direction. The effects of variations in probe beam power were removed by dividing the output voltages from each lateral-effect photodiode by the output voltage from the corresponding conventional photodiode. Integrating spheres ensured that the conventional photodiode signals were insensitive to lateral beam translations. The apparatus was calibrated absolutely by placing in each probe beam a rotating wedge with

208 μ radian of angular deflection. Beam-steering and gain signals were digitized at a 200-kHz rate with 10-bit resolution.

The effects of static and quasi-static distortions were removed by subtracting the beam-steering angle measured during the pump pulse from the beam-steering angle measured 50–100 μ s prior to the flash-lamp preionization pulse. The shot-to-shot variations in the beam-steering angles measured at the time of peak gain were approximately ± 0.25 μ radian. This reproducibility was achieved by placing the laser, amplifiers, and diagnostics under a class-100 HEPA filter hood to shield the beam paths from air turbulence. The blowers in the hood and the N_2 gas flow in the amplifiers were turned off during shots.

Results from Pump-Induced Distortion Measurements

We measured pump-induced beam-steering angles $\Delta\Theta_d$, $\Delta\Theta_x$, $\Delta\Theta_5$ on the diamond, X, and five-slab-long amplifiers, respectively. Using the formulas

$$\Delta\Theta_i = \frac{[\Delta\Theta_5 - (\Delta\Theta_d + \Delta\Theta_x)/2]}{3} \quad (6)$$

and

$$\Delta\Theta_{\text{cav}} = 4[9\Delta\Theta_i + (\Delta\Theta_d + \Delta\Theta_x)/2] , \quad (7)$$

we obtained the pump-induced beam steering angles $\Delta\Theta_i$ for an interior slab and $\Delta\Theta_{\text{cav}}$ for a four-pass eleven-slab-long cavity amplifier, respectively. Figure 11 shows the pump-induced horizontal beam-steering angle vs horizontal position in the aperture for the four-pass eleven-slab-long amplifier, with the flash lamp fired at $f_x = 0.2$. Shown with our data are pump-induced beam-steering angles measured directly on the four-pass eleven-slab-long amplifier with a Hartmann sensor, as described in "Beamlet Pulse-Generation and Wavefront-Control System," p. 42. The beam-steering angles measured with the two techniques are in good agreement, with pump-induced beam-steering angles falling within ± 15 μ radian over most of the aperture. Negative angles correspond to beam steering toward the central flash-lamp arrays while positive angles correspond to beam steering toward the side flash-lamp arrays.

The pump-induced phase variation across the aperture, calculated using Eq. (5), was < 2 waves at 1.053 μ m. With active wavefront correction using a deformable mirror, the phase variation was reduced to approximately 0.7 waves, well within Beamlet focusing and harmonic conversion requirements.

FIGURE 11. Pump-induced horizontal beam-steering angle vs horizontal position in the aperture for the four-pass 11-slab-long amplifier at $f_x = 0.2$. Values extrapolated from the diamond, X, and 5-slab-long amplifier data are in good agreement with values measured directly using a Hartmann sensor. (70-50-1294-3976pb01)

The major conclusions drawn from our beam-steering measurements are that in the central region of the slab more than one-half slab thickness from the edge claddings, pump-induced wavefront distortion is only weakly dependent on the vertical location in the aperture; pump-induced beam steering is much greater in the horizontal direction than in the vertical direction; and pump-induced beam steering is much greater in the end slabs than in the interior slabs. These results are consistent with previous pump-induced beam-steering measurements conducted at LLNL and with our understanding of pump-induced wavefront distortion. They are important because they confirm our understanding of the process and they establish confidence in our design of the NIF amplifiers.

Summary

We have completed detailed gain and pump-induced beam-steering measurements on the Beamlet amplifiers. The measurement results will be used to rigorously validate new and improved models for predicting amplifier performance, and will be of great value in the development of the NIF amplifiers. For the first time, MSA performance has been demonstrated at approximately the same aperture dimensions that are anticipated for the NIF.

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DESIGN AND PERFORMANCE OF THE BEAMLET OPTICAL SWITCH

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Introduction

High-energy lasers for Inertial Confinement Fusion (ICF) experiments are typically designed with large apertures (>30 cm) to keep the fluence below the damage threshold of the various optical components. Until recently, no optical switch technology could be scaled to the aperture size, aperture shape (square), and switching speed required for the next generation of ICF drivers. This step is critical: The Beamlet multipass amplifier cavity uses a full-aperture optical switch to trap the laser pulse within the cavity and to divert the pulse out of the cavity when it reaches the required energy.¹ By rotating the polarization of the beam, a Pockels cell in the switch controls whether the beam is transmitted through, or reflected from, the polarizer.

In conventional Pockels cells, a longitudinal electric field is applied to an electro-optic crystal via external ring-electrodes.² To achieve a reasonably uniform field distribution in the crystal, the crystal's aspect ratio (diameter:length) must be no greater than 1:1 (1:2 is preferable). Since the required aperture in high-energy ICF drivers is in the range 30 to 40 cm, the crystal would have excessive optical absorption, strain depolarization, and cost. One alternative Pockels cell design approach, which allows for thin crystals, employs transparent, conductive thin films applied to the crystal surfaces as electrodes.³ Unfortunately, such films exhibit insufficient conductivity to meet our switching speed requirements and do not have a high enough optical damage threshold.

In this article, we describe an optical switch technology that does scale to the required aperture size and shape for Beamlet and the proposed National Ignition Facility (NIF) laser, and can employ a thin crystal. This switch consists of a thin-film polarizer and a plasma-electrode Pockels cell (PEPC), the latter originally invented at Lawrence Livermore National Laboratory (LLNL) in the 1980s⁴ and under further development

since 1991. After discussing the PEPC concept, we present the design and optical performance of a 32×32 cm² prototype PEPC, including discussions of the crystals, the PEPC assembly, the vacuum and gas system, and the high-voltage pulsers. Then we describe the performance of the 37×37 cm² PEPC constructed specifically for the Beamlet laser. Finally, we discuss important technology issues that arose during PEPC development: cathode sputtering, cathode heating, nonuniformities in the switching profile, switch-pulse leakage current, and an estimate of the plasma density and temperature produced during PEPC operation.

The Plasma-Electrode Pockels Cell Concept

Figure 1 shows a top view cross-section of a PEPC and a simplified schematic of the required external electronic circuit. Vacuum regions on each side of the crystal are filled with working gas (He + 1% O₂) at an optimized operating pressure (30–40 mTorr). The plasma pulsers ionize this gas with a high-current pulse, forming the plasma-electrodes. Voltage from the switch pulser is applied across the crystal via these plasma-electrodes. As in a conventional Pockels cell, if the potential difference across the crystal is V_π , the half-wave voltage, the polarization of an incoming linearly polarized beam is rotated by 90°. For the crystals considered here, potassium dihydrogen phosphate (KDP) and potassium dideuterium phosphate (KD*P), V_π is 16.4 kV and 6.5 kV (at 1.06 μ m optical wavelength) respectively.⁵

Requirements on the plasma and switch pulsers are set by the switching speed requirement placed on the PEPC, which depends on the particular application. In the Beamlet laser, the optical pulse propagates through

the amplifier cavity for two round trips, leading to four passes through the amplifier. The PEPC and the polarizer function together as an optical switch that controls the state of the cavity. If the cavity is closed, the optical pulse and any amplified stimulated emission are trapped within the cavity. If the cavity is open, the optical pulse is switched out of the cavity. The polarizer is arranged so that the cavity is open when no voltage is applied to the PEPC crystal and closed when the crystal is charged to V_π . To switch the optical pulse out of the cavity, the PEPC must change state in less than the cavity round-trip transit time, which is approximately 240 ns for Beamlet. We chose 100 ns as the nominal switching speed to allow extra time for voltage equilibration across the crystal aperture. The time constant by which the voltage on the crystal changes is given by $\tau = Z_{sw} C_{KDP}$, where Z_{sw} is the effective impedance of the switch pulser (parallel combination of the pulser output impedance and the terminating resistance) and C_{KDP} is the capacitance of the crystal. The Beamlet crystal is $37 \times 37 \text{ cm}^2$ and 1 cm thick and consists of ordinary KDP with a relative dielectric

constant $\epsilon_r = 20$. We calculate the crystal capacitance by assuming a simple parallel-plate geometry and obtain $C_{KDP} = 2500 \text{ pF}$. It takes four time constants to charge the crystal to 98% of V_π , so τ must be one-fourth of our desired switching speed, or 25 ns. This implies that Z_{sw} must be 10Ω , and this determines the peak current I_{sw} that must be delivered by the switch pulser: $I_{sw} = V_\pi / Z_{sw} = 1.7 \text{ kA}$. If a KD*P crystal is used, the capacitance is higher because $\epsilon_r = 50$. An impedance of 4.0Ω is required to achieve the same 25-ns time constant. The peak current requirement is about the same (2.0 kA) because of the lower V_π for KD*P.

The plasma current I_p at the time the switch pulse is fired must be greater than I_{sw} ; otherwise the current from the switch pulser charging the crystal clamps at I_p , which increases the time required to fully charge the crystal.⁶ This effect is due to the diode-like nature of the plasma discharge. Figure 1 depicts the discharge current and the KDP charging current. On side 2, the plasma and switch-pulse currents are in the same direction; on side 1 they are in opposite directions, so they cancel. If the peak switch-pulse current is greater than the plasma current, the current at the side 1 anode must go negative, which means that it is emitting electrons. This cannot happen on the time scale of the switch pulse.

A circuit model, shown in Fig. 2, was used to determine the relation between peak switch-pulse current and the plasma current. We model each plasma with a $0.1\text{-}\Omega$ resistor in series with a diode, and we model the crystal capacitance with a 2500-pF capacitor. We set the value of the resistors to be on the order of the plasma collisional resistivity (see below), which is much smaller than Z_{sw} . We model the plasma currents with a pair of

FIGURE 1. A top-view cross-section of the PEPC and its associated electronic circuit. The plasma pulsers produce the plasma electrodes by high-current discharge in He; the switch pulser then applies the switching voltage across the KDP crystal. (70-50-1294-3986pb01)

FIGURE 2. Circuit model of the PEPC used to determine the relation between peak switch-pulse current and plasma current (results shown in Fig. 3). (70-50-1294-3980pb01)

current sources; the switch-pulse voltage is applied by a 20-kV rectangular pulse source with a 10- Ω series resistor to model Z_{sw} . Using PSPICE⁷ to calculate the circuit response, we find the peak charging current for this case is 2 kA, so the plasma current must be greater than 2 kA if it is not to limit the crystal charging time. Figures 3(a) and 3(b) show the model results for the crystal charging current and voltage, respectively, for cases when the plasma current is 2.0 and 0.5 kA. For the 2-kA case, the current in the crystal peaks at slightly <2 kA (because of the plasma resistance), and the crystal charges with the expected time constant. For the 0.5-kA plasma current case, the charging current clamps at 0.5 kA, extending the charging time. The voltage rise time is longer for the 0.5-kA case.

The preceding analysis puts a lower limit on the required plasma current. In practice, however, we find that optimum performance is achieved at somewhat higher current. This is because the plasma resistance must be small compared to the Z_{sw} assumed in our circuit model, and because the plasma must be sufficiently uniform across the full aperture. Two processes contribute to the plasma resistance: electron scattering by collisions with neutrals and coulomb scattering of electrons by the plasma ions.

FIGURE 3. (a) Current (based on circuit in Fig. 2) in the crystal capacitance for plasma currents of 2 kA and 0.5 kA. For currents <2 kA, the charging current clamps at the plasma current, extending the charging time. (b) Corresponding voltage waveforms. The voltage rise time is longer for the 0.5-kA plasma current.

(70-50-1294-3981pb01)

The plasma resistivity η_{en} due to electron-neutral collisions is given in $\Omega\text{-cm}$ by

$$\eta_{en} = 8.93 \times 10^{11} \frac{n_n}{n_e} \left(\frac{m_e \sigma_{en}}{q^2} \sqrt{\frac{kT_e}{m_e}} \right), \quad (1)$$

where n_n is the neutral density, n_e is the electron density, m_e is the electron mass, σ_{en} is the electron-neutral collision cross-section, which we take to be $5.3 \times 10^{-16} \text{ cm}^2$ for He,⁸ kT_e is the electron thermal energy, and q is the electron charge. All quantities are in cgs units.

The resistivity due to coulomb scattering is given by⁹

$$\eta_{ei} = 5.2 \times 10^{-3} \frac{Z \ln \Lambda}{T_{ev}^2}, \quad (2)$$

where Z is the average ion charge state, and T_{ev} is the electron temperature in electron-Volts. The Coulomb logarithm $\ln \Lambda$ (≈ 10) is a correction term for small-angle scattering.

The relative contribution to plasma resistance from these two processes depends on the operating conditions. Using a method described later, we estimate $n_e = 1.6 \times 10^{12} \text{ cm}^{-3}$ for $T_{ev} = 5 \text{ eV}$. With an operating pressure of 35 mTorr, the plasma resistivity is dominated by electron-neutral collisions, and the total plasma resistance is 0.04 Ω , which is much less than the switch-pulser impedance.

Design of the 32-cm Prototype PEPC

In this section, we describe design details for the PEPC and its associated subsystems, including the crystals, the PEPC assembly, the vacuum and gas supply system, the discharge electrodes, the plasma generation system, and the switch pulser.

Crystals

The original design for the Beamlet PEPC called for a KD*P crystal with a high deuterium concentration (>90%). KD*P is desirable because at 90% deuteration, optical absorption for 1.05- μm light traveling parallel to the crystal z-axis is 0.49%/cm compared to 5.8%/cm for KDP.¹⁰ However, when we began this development work it was not known whether KD*P crystals of sufficient size and quality could be grown for use in the Beamlet PEPC. We constructed a prototype PEPC based on the largest KD*P crystal available at that time ($32 \times 32 \text{ cm}^2$) and tested it with both KDP and KD*P crystals. Before testing in the PEPC, we measured the strain depolarization of both crystals using an experimental setup described elsewhere.¹¹ This apparatus

measures the extinction ratio (ER) point by point across the surface of the crystal under test. From the array of data points, we construct a strain image of the crystal. For consistency, we convert all ER s to effective switching efficiency, S_{eff} , which is given by

$$S_{eff} = 1 - \frac{1}{ER} \quad (3)$$

An ER of 100 corresponds to an efficiency of 99% while an ER of 1000 corresponds to an efficiency of 99.9%.

Figure 4 shows the resulting strain images for the KD*P and KDP crystals. The KD*P crystal exhibits more strain structure than the KDP crystal: growth sector boundaries are clearly visible, for example. However, for these particular crystals, the KD*P has slightly higher average efficiency than the KDP (99.987% vs 99.952%) and higher worst-spot efficiency (99.78% vs 99.65%).

FIGURE 4. Strain map for a 32×32 cm² KD*P crystal shown in terms of the switching efficiency (see text for definition). Regions of lower efficiency denote loss due to strain-induced depolarization. (70-50-1294-3982pb01)

PEPC Assembly

Figure 5 shows the PEPC assembly. The crystal is potted into a ceramic frame with silicone elastomer. This frame mounts between two housings, which are in turn sandwiched between two 4-cm-thick fused silica windows. The housings, made from ultrahigh-molecular-weight polyethylene, define the vacuum regions on each side of the crystal. The housings also hold the discharge electrodes in place and interface to the vacuum pumping system. The windows seal the vacuum regions on the outside and allow transmission of the optical pulse. The windows and the KDP crystal are antireflection coated with sol-gel silica particles.¹² The total transmission through the cell was 99.1% with the KD*P crystal and 93.9% with the KDP crystal.

The housing assembly rests on a support structure that provides motorized x and y translation and manual adjustment of tip, tilt, and twist so that we can align the PEPC to our test beam. The support structure also holds the vacuum pumping system.

Vacuum and Gas System

The vacuum and gas system provides the required environment inside the PEPC for optimum formation of the plasma electrodes. A two-stage turbomolecular pump evacuates the PEPC interior to less than 5×10^{-5} Torr. This base pressure ensures that the concentration of impurity species in the plasma is low enough that it does not degrade the discharge uniformity. The gas system injects the working gas (a mixture of He plus 1% O₂) into the cell and maintains the gas pressure at 35 mTorr with active feedback control. The feedback system uses a capacitance manometer to monitor the cell pressure and drives a servo loop actuating a gas metering valve. The operating pressure is maintained by flowing gas while the turbopump continuously evacuates the cell. We discuss the purpose of the oxygen below.

Discharge Electrodes

The plasma electrodes are formed by driving current between pairs of anodes and cathodes. The anodes are simple bars of stainless steel. The cathodes are planar magnetron structures (Fig. 6).¹³ Planar magnetrons are commonly used in direct current and radio frequency discharges as sputtering sources, but to our knowledge this is the first application as a cathode for a high-current pulse discharge.

Permanent magnets beneath the cathode surface provide a closed $E \times B$ path for electron flow on the cathode surface, leading to increased plasma density near the cathode. The magnetron cathodes result in lower operating pressure and lower discharge voltage

across the anode-cathode gap than with unmagnetized cold cathodes. The lower operating pressure leads to lower plasma resistivity, as explained in "The Plasma-Electrode Pockels Cell Concept" earlier. Lower discharge voltage leads to less cathode sputtering, less cathode heating, and lower potential differences between the side 1 and side 2 plasmas (higher potential differences are more likely to cause partial optical switching before application of the switch pulse).

During the discharge, He ions from the plasma are accelerated by the discharge potential and bombard the cathode, producing electrons by secondary emission. This electron emission sustains the discharge. However, the ion bombardment also leads to sputtering of the cathode material, which can deposit on the crystal and window surfaces, reducing their optical damage threshold. To eliminate this deposition, the cathode surfaces are made from high-purity graphite, so the sputtered material is C. The sputtered C reacts with the 1% O_2 in the plasma to form CO and CO_2 , which are pumped away by the vacuum system. We describe experimental tests of this process later in this article.

FIGURE 6. (a) Cutaway side view and (b) top view of the magnet layout for the planar magnetron cathodes used in the PEPC. The magnetron cathodes provide a uniform discharge without thermionic emission. (40-00-0494-1608pb01)

FIGURE 5. Exploded view of the PEPC assembly, showing the sandwich-like structure. (02-30-0391-1444pb01)

Plasma Generation System

The plasma is created in a two-stage process: a low-current preionization (simmer) discharge and a high-current pulsed discharge. The simmer discharge is initiated by a high-voltage, low-current power supply that provides enough voltage to break down the gas (about 1.5 kV) and then provides a constant discharge current of 30 mA. The voltage required to maintain the simmer discharge is about 300 V. The high-current pulse is produced by discharging a 5- μ F capacitor charged to 4 to 7 kV depending on the required peak current. We call the capacitor and low-current power supply the *plasma pulser*. Figure 7 shows a typical plasma current waveform and the relative timing of the switch pulse, which we typically time to fire just after the peak in the plasma current.

FIGURE 7. Plasma current for a 2-kA pulse, and relative timing of the switch pulse. (70-50-0594-2403pb01)

FIGURE 8. Voltage across the PEPC during normal operation, and when the optical pulse traverses the cell—twice when the voltage is on (pass 2 and pass 3) and once after the cell is discharged (switch out). (70-50-0594-2402pb01)

Switch Pulser

The switch-pulse generator¹⁴ produces a nominally rectangular pulse applied across the crystal via the plasma electrodes. The switch pulser satisfies several important requirements: shot-to-shot jitter is <2 ns, a voltage flat-top at least 50 ns long is within $\pm 2\%$ of V_{π} , and the voltage returns to zero ($\pm 2\%$ of V_{π}) after the pulse, so that the optical pulse is efficiently switched out of the cavity. The pulse is produced by sections of coaxial cable used as a pulse-forming network (PFN). A high-voltage power supply charges the PFN to twice the required output voltage, and a thyatron switches the charged PFN into the output line, which is also made up of coaxial cable sections. Multiple PFN and output lines are connected in parallel to achieve the switch-pulser impedance required to charge and discharge the crystal in less than the round-trip transit time of an optical pulse in the Beamlet laser-amplifier cavity. The output pulse duration depends on the length of the PFN cables. The output cables are long enough that electrical reflections due to impedance mismatches at the cell do not return to cause voltage ripples until after the required switch-out time.

We can configure the switch pulser for operation with KDP or KD*P. For KDP, we use four 50- Ω PFNs and output lines in parallel to achieve a pulser impedance of 12.5 Ω . For KD*P, we use eight cables in parallel for an impedance of 6.25 Ω . Figure 8 shows a typical voltage waveform produced by the Beamlet switch-pulse generator. Also shown is the relative timing of the optical pulse on the multiple passes through the cell when used in the Beamlet multipass cavity. The laser pulse traverses the cell three times: twice when the voltage is on and once when the voltage is off.

Prototype PEPC Optical Switching Performance

We evaluated the switching performance of the prototype PEPC with both KD*P and KDP crystals. A Q-switched, pulsed laser (10-ns nominal pulse duration at 1.06 μ m) was used as the illumination source. A beam splitter diverted a small portion of the beam into a reference detector. After traversing a polarizer, the beam was expanded with a negative lens and collimated through the PEPC with a 30-cm-diam lens. After traversing the PEPC, a second 30-cm-diam lens focused the beam through an analyzing polarizer. A small-aperture positive lens imaged the plane of the PEPC crystal on the detector. We used two types of detectors: a photodiode to look at average performance across the whole aperture and a charge-coupled device (CCD) video camera to produce images of the

performance in two dimensions. With these optics, we could not illuminate the full $32 \times 32 \text{ cm}^2$ aperture at once; we used the x - y translation capability of our support structure to diagnose the cell in four quadrants.

We define several different ER s to help describe the switching performance. The system extinction, ER_{sys} , is the ratio of the detected intensity with the polarizers aligned to the intensity with the polarizers crossed without activating the PEPC. ER_{sys} is a measure of depolarization errors in the various optical components. With the beam at small aperture (only the polarizers in the beamline with no expansion optics), we find $ER_{\text{sys}} > 1 \times 10^5$. Adding the expansion, collimating, and imaging lenses reduces ER_{sys} to about 3000. Adding the PEPC into the beamline further reduces ER_{sys} to about 1500 because of strain in the windows and crystal.

During PEPC operation, we measure ER_{on} , the ER when the voltage is on, and ER_{off} , the ER in the switch-pulse tail at the time of switch-out (about 200 ns after the end of the switch pulse). ER_{on} is the ratio of light intensity incident on the PEPC to the light intensity that remains unrotated with the PEPC at V_π . We measure ER_{on} with the polarizers aligned and take the ratio of the detector signal with no voltage on the PEPC to the signal with V_π on the PEPC. Although the switch pulser does a good job of discharging the crystal, some residual charge remains on the crystal at the critical switch-out time, leading to an ER_{off} lower than ER_{sys} . We measure ER_{off} by taking the ratio of the detector signal with the polarizers aligned and no voltage on the switch to the detector signal with the polarizers crossed, 200 ns after the trailing edge of the switch pulse as already defined.

As before, we express the data in terms of efficiency. S_{off} represents the percentage of light that would be switched out of the cavity on pass 4, while S_{on} is the percentage of light that stays in the cavity for gain passes 2 and 3. The goals for S_{on} and S_{off} , set at the beginning of the development program, were $>99\%$ ($ER=100$) average across the aperture and no spots worse than 98% ($ER=50$). These efficiencies include only losses due to depolarization of the beam and do not include losses due to surface reflections and absorption.

Figure 9 shows a typical S_{on} image of the prototype PEPC with a KDP crystal. In this example, S_{on} in the worst spot is 99.64%. Table 1 summarizes switching performance with our 30-cm-diam imaging aperture centered on the PEPC for KDP and KD*P. The performance exceeds the required performance for both KD*P and KDP. The shot-to-shot reproducibility is indicated by the standard deviations of the average efficiencies. We obtained the average efficiencies by averaging 10 or more consecutive photodiode signals (with the system operating at a consistent 0.25 Hz). We obtained the worst-spot results by scanning images acquired with our CCD video system for each condition.

FIGURE 9. Typical S_{on} efficiency image from the prototype PEPC with a $32 \times 32 \text{ cm}^2$ KDP crystal. A 30-cm-diam central view is shown. (70-50-1294-3983pb01)

TABLE 1. Switching performance of prototype PEPC with KD*P and KDP crystals. Goals were average efficiencies greater than 99% and no spots worse than 98%.

Crystal type	During switch pulse, S_{on}		After switch pulse, S_{off}	
	Average ($\pm 1 \sigma$)	Worst spot	Average ($\pm 1 \sigma$)	Worst spot
KD*P	$99.90 \pm 0.02\%$	99.60	$99.85 \pm 0.02\%$	99.39
KDP	$99.91 \pm 0.01\%$	99.49	$99.91 \pm 0.02\%$	99.64

Design and Optical Performance of the Beamlet PEPC

Based on our experience with the prototype PEPC, we designed and built a PEPC for use in the Beamlet laser. Figure 10(a) shows the Beamlet PEPC fully assembled, and Fig. 10(b) shows it integrated into the Beamlet laser. It is essentially the same as the prototype PEPC, except that it is large enough to accommodate a

$37 \times 37 \text{ cm}^2$ crystal, the cathodes are set back from the edge of the crystal by 6 cm in a reentrant cavity, and the outer windows are 3 cm thick (they were 4 cm thick in the prototype).

Operation of the Beamlet PEPC as part of the Beamlet laser began in February 1994. Before operation at high optical fluence, we evaluated the switching performance at low fluence using a $32 \times 32 \text{ cm}^2$ KDP crystal. We performed these tests with the PEPC installed into the Beamlet laser cavity and used the Beamlet diagnostic system. Figure 11 shows the experimental setup we used to test the switching performance at low fluence. At the beginning of a Beamlet shot, an optical pulse from the front-end laser is injected into the spatial filter. A small injection mirror (not shown) reflects the pulse toward cavity mirror M_1 through the cavity amplifier (which was not energized for the low-fluence tests). The pulse reflects from M_1 and passes back through the amplifier and spatial filter before it illuminates the PEPC at full aperture (35 cm). After traversing the PEPC, the beam reflects from the polarizer if the PEPC is off and passes through the polarizer if the PEPC is on (as shown in Fig. 11). A portion of the light transmitted by the polarizer passes through the partially transmitting cavity mirror M_2 into the diagnostic system. The sampled pulse is down-collimated by lens L_3 and other small-aperture optics (not shown) that image the crystal plane of the PEPC onto a high-resolution CCD video camera.

We ratio the switch-on and switch-off images to produce a switching efficiency image as shown in Fig. 12. As before, the switching efficiency data includes only losses due to beam depolarization and not losses from surface reflections or absorption. In this low-fluence test, we observed an average switching efficiency across the aperture of 99.5%; the minimum efficiency was 97.5% in the upper left-hand corner. The regions of lower switching efficiency in the corners are caused by strain-induced depolarization in the fused silica windows arising from vacuum loading.

During a full system shot, the cavity amplifier is energized. The voltage pulse applied to the switch starts at about the same time the optical pulse hits the injection mirror. Voltage across the crystal equilibrates while the optical pulse propagates towards mirror M_1 in Fig. 11 and makes its first two gain passes through the amplifier. While passing through the PEPC, the optical pulse polarization rotates by 90° and thus passes through the polarizer. The optical pulse reflects from mirror M_2 and passes through the polarizer and PEPC (rotating another 90°) before it propagates back toward the amplifier for two more gain passes. During this 240-ns interval, the voltage across the PEPC drops to zero. When the optical pulse returns again, the polarization is not rotated by the PEPC, so the pulse

(a)

(b)

FIGURE 10. (a) Beamlet PEPC before installation into the Beamlet laser. (b) Beamlet PEPC integrated into the Beamlet laser. (70-50-0494-1845pb01)

reflects off the polarizer and out of the cavity. While details of the Beamlet laser performance¹⁵ are not within the scope of this paper, we report that the main Beamlet cavity has produced up to 6 kJ of 1.06- μm light in a 3-ns pulse with switched, four-pass operation. During these tests, the Beamlet PEPC operated reliably and reproducibly, exhibiting high-fluence (average of 5 J/cm²) switching efficiency >99.5% for both cavity-closed and cavity-open states.

PEPC Technology Issues

In this section, we discuss important technology issues that surfaced during our developmental work, including sputtering of cathode material, indirect crystal heating by the cathode, magnetically induced regions of nonuniform switching (bright spots), and switch-pulse leakage current to the vacuum system.

Although we have no direct measurement of the plasma parameters (density and temperature) except for the low-current simmer plasma, we also present in this section a method for estimating the plasma density based on the observed difference between the known V_π for KDP and the applied voltage required to achieve optimum switching. These plasma parameters are required for estimating the plasma resistance.

Sputtered Cathode Material

As mentioned in "Discharge Electrodes" earlier, the gaseous discharges that form the plasma electrodes sputter the cathode material. In an early cathode design, we used Mo for the cathode surface because of its relatively high secondary-electron emission coefficient under He-ion bombardment. After several thousand shots with this cathode, we illuminated the prototype PEPC with a partially focused beam to test operation at high fluence. Our setup allowed us to vary the fluence to over 25 J/cm². During this test, we imaged the crystal with a telescope and watched for

optical damage as we increased the fluence. We observed a significant reduction in damage threshold near the cathode, while the threshold for other parts of the crystal remained unchanged. We found that this reduction in damage threshold was due to deposition of Mo on the crystal, which was highest near the cathode and decreased with distance from the cathode.

FIGURE 12. Switching efficiency across the 35 $\times$ 35 cm² aperture of the Beamlet PEPC. Lower switching efficiency in the corners is due to strain-induced birefringence in the silica windows arising from vacuum loading. (70-50-1294-3984pb01)

FIGURE 11. Simplified diagram of the experimental setup used to evaluate the switching performance of the PEPC in the Beamlet laser at low fluence. An optical pulse from the Beamlet front-end laser propagates through the PEPC and polarizer. A high-resolution CCD video camera images the light transmitted by the PEPC-polarizer combination. (70-50-1294-3985pb01)

To confirm this sputter coating of the crystal, we exposed witness plates to several thousand shots and detected Mo on the plates with standard analysis techniques, including electron spectroscopy chemical analysis and inductively coupled plasma mass spectroscopy.

We solved this sputtering problem by replacing the Mo cathode covers with high-purity graphite and adding 1% O₂ to the He working gas as described in "Discharge Electrodes." We confirmed the effectiveness of this technique with three experiments: direct measurement of sputter deposition using a quartz crystal microbalance, observation of CO and CO₂ gas production using residual gas analysis, and optical damage tests performed on witness plates exposed to the plasma.

To monitor the deposition of sputtered material directly, we inserted a quartz crystal microbalance into the prototype PEPC, placing the face of the microbalance 4 cm from the cathode surface. The quartz crystal is coated with a thin Au film and is part of a resonant circuit whose frequency depends on the temperature of the crystal and the mass of material on the crystal face. The sensor frequency is also affected by changes in the ambient pressure, which affects the mass of adsorbed gas on the crystal face. As long as temperature and pressure are held constant, changes in the resonant frequency are due to changes in mass arising from deposition.

The results of an experiment in which we initially ran the discharge with a pure He plasma showed C sputtered from the cathode depositing on the nearby sensor head. Without stopping the discharge, we changed the working gas to a mixture of He plus 1% O₂. Initially, the sensor responded with an apparent step increase in film thickness when the gas was changed. However, the sensor response is actually due to a change in the mass of adsorbed gas. After the sensor reached a new equilibrium, the effective film thickness decreased monotonically as the previously deposited C reacted with the O₂ to form CO and CO₂.

For the second test, we directly measured with a residual gas analyzer the formation of CO and CO₂ during the discharge. We estimated the sputtered flux of C to be 1.1×10^{16} atoms/s for a 23-mA discharge current and a sputtering coefficient of 0.1 for He bombarding graphite.¹⁶ We compared this with the throughput of CO and CO₂, which we estimated from the partial pressures of these species and the speed of our pumping system. Within the accuracy of this measurement, we found that 100% of the sputtered C was converted to gaseous species and pumped away.

As a final test of this new cathode design, we placed a high-quality fused-silica substrate (witness plate) as close as possible to the cathode and exposed it to 80,000 consecutive PEPC shots. We compared the optical damage threshold before and after exposure to PEPC discharges and found that it was not significantly changed (we actually observed a slight increase in damage threshold after plasma exposure). During five months of operation in Beamlet, we have subjected the Beamlet PEPC to 50 to 60 high-fluence shots and 10,000 to 15,000 low-fluence alignment shots. We have not observed any reduction in damage threshold from plasma-related effects, proving the effectiveness of the C conversion process in actual use.

Crystal Heating

Most of the electrical energy used to drive the plasma discharges ends up as thermal energy deposited in the cathode surface by ion bombardment. The heated cathode heats the crystal, leading to a thermal gradient in the crystal. This causes strain in the crystal, which increases the depolarization of a beam traversing the PEPC. To quantify this depolarization, we removed the expansion optics from our polarimeter and illuminated a small spot on the crystal near the cathode side.

The results showed how the *ER* in this spot (normalized by the *ER* at the start of the test) decreases as the crystal heats. In one case, the simmer discharge was run continuously and dissipated 9 W at the cathode. The pulsed discharge, running at 0.25 Hz, adds another 3 W of average power. Under these conditions, the *ER* dropped to about 15% of its original value in only 30 minutes of continuous operation. In a second case, we reduced the average power dissipated by gating the simmer discharge on for only 100 ms for each shot. This reduces the average power due to the simmer discharge by a factor of 40. The average power from the pulsed discharge is unchanged, so the total average power for this case is 3 W. With the simmer discharge gated rather than running continuously, the *ER* only decreased to about 50 to 60% of its original value in a 30-minute operating period.

We measured heating in the PEPC by installing thermistors at five locations: center of the cathode, center of the E × B path (racetrack region) on the cathode, cathode edge of the crystal, anode edge of the crystal, and surface of the anode. Table 2 summarizes the temperature change at these locations after 100 minutes of operation. As expected, we observe maximum heating in the racetrack region, where the ion flux to the cathode is maximum. Heat conducts through the graphite to the rest of the cathode. The cathode edge of the crystal

exhibits more heating and depolarization than the anode edge. By gating the simmer, we reduced the temperature increase at the cathode edge of the crystal by a factor of 10.

As mentioned above, to further reduce crystal heating in the Beamlet PEPC, we increased the distance from the cathode to the crystal edge by mounting the cathode in a reentrant cavity. This design change, in combination with gating the simmer discharge, permits continuous operation of the Beamlet PEPC without significant thermal degradation of its switching performance.

Magnetic Bright Spots

During experiments with the prototype PEPC, we observed regions of nonuniform polarization rotation at various locations across the crystal. These regions show up as "bright spots" of light in the rejected polarization when imaging the PEPC in our polarimeter. In the PEPC, as originally constructed, we observed these bright spots along the bottom edge of the crystal, particularly in the lower corner near the anode. The bright spots were quite variable from shot to shot, indicating that they were due to a plasma-related effect and not a static optical effect.

We found that these bright spots are caused by the magnetic field surrounding wires carrying the discharge current external to the plasma. The discharge pulse is transmitted to the PEPC from the pulse generator via a pair of coaxial cables. The shields of these cables terminate at the anodes and the center conductors must connect to the cathodes. A magnetic field surrounds the unshielded sections of wire that traverse the PEPC. Figure 13 shows this magnetic field in a cross-sectional side view of the PEPC. The flux density from the current pulse is ≈ 60 G along the crystal edge near the wires. We verified that this was the cause of the bright spots by moving these wires from the bottom of the cell to the top. When we did this, the bright spots moved from the bottom anode corner to the top anode corner. We found that we could minimize bright spot formation by feeding the discharge current from opposite sides of the PEPC.

Our first explanation of the bright spots was as follows: Electrons carrying the switch-pulse current that charges and discharges the crystal must cross the magnetic field from the discharge wires, which is roughly perpendicular to the crystal surface; since plasma conductivity is lower across a magnetic field, charging and discharging is impeded. If this were a complete explanation, however, we would expect to see a bright spot across the full bottom edge of the image and not just in one corner. This simplistic model also does not explain why feeding current from opposite sides minimizes the bright spots. A better explanation for bright-spot formation will be a focus of future work.

FIGURE 13. Cutaway end-view of the PEPC showing how the magnetic field from wires carrying the discharge current interferes with electron transport, and can therefore cause nonuniform switching. (70-50-0494-1852pb02)

TABLE 2. Heating (increases in °C) due to plasma discharge at five locations inside the prototype PEPC, measured with thermistors.

	Cathode racetrack	Cathode center	Crystal (cathode edge)	Crystal (anode edge)	Anode
Continuous wave simmer	9.0	7.5	4.0	0.3	0.3
Gated simmer	0.7	0.5	0.4	0.25	0.25

Control of Switch-Pulse Leakage Current

The two sides of the PEPC are evacuated by a common vacuum system, most of which consists of metallic pipe sections held at ground potential. During the high-voltage switch pulse, leakage current can flow from the plasmas into the vacuum pipes. This effect is observable as droop in the switch pulse. We implemented two modifications to the original prototype design to control this leakage current (see Fig. 13): DC breaks and Metglass inductive isolators. The DC breaks are simply sections of vacuum line made of insulating material. The Metglass inductive isolators are toroids of tape-wound magnetic material that increase the inductance of the vacuum line for short pulses. During initial prototype experiments, we observed no switch-pulse droop, so we assumed that the leakage current was effectively controlled.

However, when we moved the discharge wires to the top of the cell, we observed a significant droop in the switch pulse. When the wires were on the bottom, the magnetic field surrounding them magnetized the DC breaks. The field in the breaks impeded electron flow, so we observed no leakage current. With the wires moved to the top of the cell, there was no field in the breaks. The leakage current was partially limited by the Metglass cores, but the droop was not acceptable.

One way to reduce the droop would have been to increase the inductance by increasing the cross-sectional area of Metglass. We used a more effective and less expensive solution: We mounted a pair of baffles inside the vacuum port and in the region of the DC break. This increases the effective path length through the DC breaks. The baffles also block the line of sight for electron flow and increase the wall area on which plasma can be neutralized. The resulting increase in isolation is enough to eliminate the switch-pulse leakage current.

The baffles also reduce the vacuum conductance through the DC breaks, which increases the base pressure but reduces the required flow of working gas to maintain the operating pressure. The increase in base pressure with one pair of baffles did not reduce switching performance, but the increase with two pairs of baffles on each side was high enough to reduce performance noticeably.

Estimation of Plasma Density

Plasma density and temperature produced during PEPC operation are required to compute the plasma resistance. Our estimation of these parameters is based

on the observation that the switch-pulse voltage required to induce 90° of polarization rotation is consistently higher than the known half-wave voltages for KDP and KD*P. We also observe that if we increase the discharge current, lower applied switch-pulse voltage is required, and vice versa. This indicates that the voltage appearing across the crystal depends on plasma density. Since the current in the switch-pulse circuit drops to zero after initial charging, there can be no resistive voltage drops. Voltage not appearing across the crystal must be appearing across other capacitive elements that form a capacitive voltage divider. In this case, the extra capacitance comes from the plasma sheaths that form at the interface between the plasma and the crystal. The voltage divider expression is

$$V_{\pi} = V_{sw} \frac{C_{sheath}}{C_{KDP} + C_{sheath}} \quad , \quad (4)$$

where $V_{\pi} = 16.4$ kV and is the clamped half-wave voltage for KDP,⁶ $V_{sw} = 18.1$ kV and is the switch-pulse voltage required for 90° rotation, $C_{KDP} = 1.81$ nF and is the capacitance of the $32 \times 32 \times 1$ cm³ KDP crystal, and C_{sheath} is the sheath capacitance. Solving for C_{sheath} and inserting numerical values, we find $C_{sheath} = 17.5$ nF. If we assume that similar sheaths form on each side of the crystal, then the capacitance for each sheath is 35 nF.

To relate the sheath capacitance to the plasma density and temperature, we start with an expression for the potential, $\phi(x)$, in an infinite, planar sheath:

$$\phi(x) = \phi_0 e^{-x/\lambda_D} \quad , \quad (5)$$

where λ_D is the Debye length given by

$$\lambda_D = 740 \sqrt{\frac{T_{eV}}{n_e}} \quad . \quad (6)$$

The electric field in the sheath is then given by

$$E = \frac{d\phi}{dx} = -\frac{\phi_0}{\lambda_D} e^{-x/\lambda_D} \quad . \quad (7)$$

The energy W stored in the electric field is then

$$W = \frac{\epsilon_0}{2} \int E^2 dv = \frac{A\epsilon_0}{2} \frac{\phi_0^2}{\lambda_D^2} \int_0^{\infty} e^{-2x/\lambda_D} dx = \frac{A\epsilon_0\phi_0^2}{4\lambda_D} \quad , \quad (8)$$

where A is the area of the crystal and the sheaths and ϵ_0 is the dielectric constant of vacuum. The stored electrostatic energy can also be expressed in terms of capacitance C_{sheath} by

$$W = \frac{1}{2} C_{sheath} \phi_0^2 \quad . \quad (9)$$

Equating the expressions for W and solving for C , we obtain

$$C_{\text{sheath}} = \frac{A\epsilon_0}{2\lambda_D}, \quad (10)$$

which is the expression for the capacitance of a parallel-plate capacitor of area A and separation $2\lambda_D$. Note that we use the dielectric constant for vacuum in the above expressions. Although a region filled with plasma has a modified dielectric constant, most of the sheath electric field is in the region closest to the crystal, where the electron density is very low, so the use of ϵ_0 is a good approximation. We substitute Eq. (6) for the Debye length in Eq. (10) and solve for the electron density, obtaining

$$n_e = 3.3 \times 10^{11} T_e. \quad (11)$$

For the expected range of electron temperature (1 to 10 eV), the plasma density is then in the range 3.3×10^{11} to 3.3×10^{12} .

Conclusion

In the technology of PEPCs, plasma discharges facilitate uniform application of voltage to large-aperture, thin, electro-optic KDP crystals. PEPC technology makes possible the construction of large-aperture optical switches for use in high-energy ICF laser drivers. After building and testing a 32×32 cm² prototype PEPC with KDP and KD*P crystals, we built a 37×37 cm² PEPC with a KDP crystal for use in the Beamlet laser. The Beamlet PEPC routinely switches a 5- to 6-kJ, 3-ns optical pulse out of the amplifier cavity after four gain passes. The Beamlet PEPC has demonstrated switching efficiency >99.5% and has operated reliably during Beamlet experiments.

We also discuss PEPC technology issues, including cathode sputtering, cathode heating, and magnetic

bright spots. We control deposition of sputtered cathode material by using graphite cathodes and adding oxygen to the plasma; the oxygen reacts with sputtered carbon to form gaseous species. We control cathode heating by reducing the average discharge power with a gated simmer discharge and by moving the cathode further from the crystal. Magnetic fields from the discharge current can cause spatial nonuniformities in the switching profile. We control this effect by feeding the side 1 and side 2 discharge currents from opposite sides to reduce stray magnetic fields. Finally, we show that we can estimate the plasma density from the extra capacitance caused by sheath formation between the plasma and the crystal.

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BEAMLET PULSE-GENERATION AND WAVEFRONT-CONTROL SYSTEM

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Introduction

The Beamlet pulse-generation system (or "front end") refers to the laser hardware that generates the spatially and temporally shaped pulse that is injected into the main laser cavity. All large ICF lasers have pulse-generation systems that typically consist of a narrow-band oscillator, electro-optic modulators for temporal and bandwidth shaping, and one or more preamplifiers. Temporal shaping is used to provide the desired laser output pulse shape and also to compensate for gain saturation effects in the large-aperture amplifiers. Bandwidth is applied to fulfill specific target irradiation requirements and to avoid stimulated Brillouin scattering (SBS) in large-aperture laser components. Usually the sharp edge of the beam's spatial intensity profile is apodized before injection in the main amplifier beam line. This prevents large-amplitude ripples on the intensity profile.

Beamlet's pulse-generation system provides the same functions as stated, but uses entirely new technology. For example, compact diode-pumped oscillators and integrated optical-waveguide modulators, in combination with a high-gain multipass preamplifier, replace typical room-sized systems, such as used on Nova^{1,2} and other ICF lasers. In addition, the Beamlet front end provides a new feature of extensive precompensation for gain nonuniformity in the cavity and booster amplifiers. It also corrects for static and dynamic (pump-induced) phase aberrations in the entire laser chain.

The newly developed Beamlet front end significantly increases the quality of the output beam of a large-amplifier chain and is essential to the National Ignition Facility's (NIF's) conceptual design. (See "System Description and Initial Performance Results

for Beamlet," p. 1.) Compensation for optical phase aberrations increases the frequency conversion efficiency and the brightness, and hence the 3 ω peak power at the focus of the target chamber. Correction for spatial amplifier gain variations improves the output beam intensity uniformity and thereby increases the aperture fill-factor and the total output energy per beam line. The compact integrated optics approach to temporal shaping allows precise control over individual pulse shapes, which improves control of power balance and irradiation uniformity in a multiple-beam target irradiation scheme such as NIF.

Beamlet's pulse-generation system has proven to be very flexible and reliable in operation with minimal operator intervention; Table 1 summarizes the current performance limits and nominal operating points for this system.

Many aspects of the Beamlet front end are described in other publications.^{1,2} In this article, we briefly review the front-end design and discuss improvements to the oscillator and modulator systems. Our main focus, however, is to describe Beamlet's novel beam-shaping and wavefront-control systems that have recently been fully activated and tested.

TABLE 1. Beamlet's front-end performance limits and nominal operating points.

	Maximum	Typical
Energy (3 ns pulse duration)	12 J	1 J
Pulse duration	0.2–10* ns	3 ns
Temporal shaping contrast	100:1	5:1
Bandwidth	100 GHz	32 GHz
Center-to-edge intensity profile ratio	0.2	0.3
Wavefront shaping	$\pm 4\lambda$	$> 3\lambda$ peak to valley

*Limited by length of regenerative amplifier cavity.

Beamlet Front-End Description

Figure 1 shows the detailed layout of the Beamlet front-end oscillator and preamplifier. A single-mode oscillator generates high-rep-rate pulses, which are coupled into a single-mode polarization preserving fiber. The fiber couples the light into an integrated high-speed amplitude and phase modulator. Control signals are generated by low-voltage electronic pulse generators. The resulting shaped pulse is transported

to the preamplifier section in the laser high-bay using a 60-m-long fiber. A ring regenerative amplifier provides a gain of 10^9 to elevate the energy to the millijoule level. At this point, the Gaussian spatial intensity is flattened and shaped into a one-dimensional (1-D) parabolic intensity profile. A square serrated aperture creates the desired spatial edge shape for injection in the main amplifier. A second four-pass rod amplifier boosts the energy to the joule-level and two 10-cm-aperture Faraday rotators provide isolation against

FIGURE 1. Schematic overview of Beamlet's front-end subsystems and how they interface. MOR means that this equipment is housed in the master oscillator room whereas all other front-end components are mounted on a spaceframe in the main laser bay. (70-50-0194-0033pb01)

back reflections from the main laser amplifier cavity. Then, the beam is incident on a 39-actuator deformable mirror (DFM) and relayed to the injection optics of the Beamlet cavity spatial filter.

Master Oscillator, Temporal Shaping, and Phase Modulation System Upgrades

Several upgrades and improvements have been implemented to the Beamlet master oscillator and modulator system since its initial description by Wilcox et al.² The original Nd:YLF microchip oscillator-amplifier system has been replaced by a very stable, compact, and powerful single-mode unidirectional ring oscillator.³ A diode-pumped Nd:YLF crystal is used as a gain medium, while an acousto-optic Q-switch creates high-peak-power pulses and also serves as a direction-selective element for the three-mirror ring cavity [Fig. 2(a)]. The ring oscillator's higher peak power allows for

optimization of the diagnostics and fail-safe systems. Figure 2(b) illustrates the complete oscillator, including the diagnostics and fiber couplers. Specifically, pulse shape and Fizeau bandwidth spectra can be monitored on a continuous basis. Additional fail-safe switches monitor the occurrence of beat modes and the magnitude of the bandwidth modulation created in the waveguide modulators.

The original LiNbO₃ amplitude modulator circuit continues to provide Beamlet with pulse widths ranging from 200 ps to 10 ns, and shapes as simple as Gaussian or as complex as the ignition pulse shapes required for NIF. (See "System Description and Initial Performance Results for Beamlet," p. 1.) The performance of the amplitude modulators has been significantly improved by a modification of the modulator bias control system. In the original system,² a DC bias voltage was used to optimize extinction of the amplitude modulators, but charge migration effects in the LiNbO₃ substrate resulted in a continuous drift of the desired bias point. The present system of short-pulse bias voltages results

FIGURE 2. (a) Layout and (b) photograph of the new Beamlet unidirectional, single-frequency ring oscillator. The physical dimensions of the complete unit, including the pump-diode laser and diagnostics, are 30 cm × 60 cm; the size is six times smaller than the original oscillator, with a ten-fold increase in peak output power. (70-50-0494-1946pb01)

in optimum performance for extended periods of time without adjustments. The LiNbO_3 phase modulators easily provide Beamlet bandwidth requirements of 30 GHz at 1 ω by using a single radio-frequency (RF) generator (with 3–6 GHz variable frequency output) and a power amplifier. Complex high-density sideband spectra have been demonstrated by driving the phase modulator with the sum of two different RF signals.

Stability requirements for the pulse-generation system are very demanding and several major stability problems have been recently solved. Using an all-fiber-optic polarization compensating device,⁴ we reduced long-term fluctuations in the power delivered from the modulators to the regenerative amplifier in the preamplifier section by optimizing the polarization coupling in the long transport fiber. Another major source for shot-to-shot fluctuations is the gain instability of the flash-lamp-pumped amplifier heads in the ring regenerative amplifier. The instability of the output energy E_{out} is given by

$$\frac{\delta E_{\text{out}}}{E_{\text{out}}} \approx \frac{\delta E_{\text{pump}}}{E_{\text{pump}}} (\ln G) \quad (1)$$

where G is the total small signal gain ($\sim 10^9$) and E_{pump} is the energy delivered by the flash lamps. It is clear from Eq. (1) that an unreasonably high pump stability of $\pm 0.2\%$ is required to maintain the output energy stable to within the required $\pm 5\%$. To solve this stability problem, we implemented a new and elegant feed-forward stabilization scheme.⁵ This scheme uses the existing pulse-slicer Pockels cell as a variable transmission element, controlled by a photoconductive Si switch. Light leaking through one of the regenerative amplifier cavity mirrors is used to

control the conductance of the switch (Fig. 3). This scheme increased the shot-to-shot stability of the pulse-generation system to well within the operational requirements for Beamlet.

Spatial Intensity Profile Shaping

Beamlet's front-end spatial intensity shaping optics create the 2-dimensional (2-D) beam profile required for injection in the main cavity amplifier. First, the basic scheme uses a set of birefringent filters to flatten the Gaussian regenerative amplifier beam profile (Fig. 4). Next, the beam passes through a square serrated aperture with rounded corners; this generates a well-defined square edge profile of the beam.⁶ The serrated edges of the aperture need to smoothly reduce the beam intensity from its peak to near zero to avoid diffraction ripples on the transmitted beam. However, the width of the serrated edge needs to be sufficiently narrow to guarantee a high fill factor of the beam. Fill factor is defined as the ratio of the power in the actual beam to the power of an equivalent beam that completely fills (100%) the same area. (Note that to completely fill the area the intensity profile at the edge of the beam is discontinuous, i.e., infinitely steep.) Beamlet uses an inverted Gaussian serrated edge profile with a width equal to 10% of the beam size. A new type of serrated aperture, produced by a photolithographic process, resulted in a significant improvement of quality and uniformity of the beam edge profile as shown in Fig. 5. Using this procedure, the shape of the serrations can be controlled to within a precision of 2 μm . The resulting fill factor of the Beamlet output beam exceeds 84% when integrated between the 1% intensity points at the edge of the beam profile.

FIGURE 3. The existing pulse slicer behind the regenerative amplifier was modified to a feed-forward energy stabilization system. Light leaking through one of the regenerative amplifier cavity mirrors illuminates a Si photoconductive switch in the Pockels cell driver line, providing negative feed-forward control of the pulse slicer Pockels cell's energy transmission. (70-50-0295-0400pb01)

A major improvement in Beamlet performance is achieved by shaping the spatial intensity profile of the pulse generated by the front end to compensate for spatial gain variations in the main Beamlet multisegment amplifiers. Spatial variations in the gain of the amplifiers result from amplified spontaneous emission within the laser slabs. Briefly, amplified spontaneous emission trapped within the laser slab by total internal reflection depletes the stored energy in the glass, particularly near the edges of the slabs. This depletion in stored energy produces a corresponding roll-off in the gain, largely in the horizontal direction. (See "Design and Performance of the Beamlet Amplifiers," p. 18.) The resulting small signal gain for the combined 44 slabs that the beam traverses during a Beamlet shot resembles a parabola with center-to-edge gain ratio in the horizontal direction exceeding 3.5. Therefore, if a beam with a

flat-top intensity profile is injected into the main laser cavity, then the output beam profile will roll off at the edges in the same way as the overall gain profile. This greatly reduces the fill factor. For a system designed to run at beam fluences near the damage threshold of its optical components, a reduction of fill factor reduces the maximum output energy available. Gain saturation at very high output fluences ($>10 \text{ J/cm}^2$) tends to reduce this effect. However, the system fluence limit can be located at nonsaturated points in the amplifier, such as the Beamlet cavity polarizer (its limiting fluence is 11 J/cm^2). Precompensating the lower gain near the edges by increasing the intensity of the injected profile counteracts this effect, as shown in Table 2, where we compare the total modeled output energy at fixed peak fluence with, and without, precompensation for the gain nonuniformity.

Four birefringent quartz lenses produce a radial intensity filter

FIGURE 4. The spatial profile of the Beamlet injection pulse is generated in a three-step process in the beam-shaping section: (1) The beam is converted from Gaussian to a flat-topped round beam; (2) the beam is converted to a square footprint using a serrated aperture; and (3) a parabolic profile is created using a special transmission filter. The beam shaping section is located between the regenerative amplifier and the four-pass rod amplifier. (02-07-0892-2883pb01)

(a) Details at the beam's edge

(b) Full-aperture display

FIGURE 5. A smooth yet rapid roll-off in the intensity profile at the edge of the beam is created using precisely shaped serrations in a photolithographically created pattern. The low-pass spatially filtered image of this aperture is relayed through the main amplifier onto the frequency-conversion crystals. (70-10-1193-3899pb01)

Various methods exist to shape a beam's intensity profile, ranging from simple spatially varying neutral density filters to afocal refractive optical systems and complex high-resolution programmable spatial light modulators. We use the first method on Beamlet. Figure 6(a) compares an actual profile with the specified transmission profile for a shaped neutral density filter.

(b) Resulting beam profile

FIGURE 6. (a) Experimental transmission scan of a parabolic 1-D transmission filter compared with the specified transmission curve. The relevant beam size dimensions are overlaid. (b) A 2-D plot of the resulting beam profile measured at the 1ω output diagnostics station for an unpumped amplifier cavity. (70-50-0295-0401pb01)

TABLE 2. Shaping the intensity profile of the injected beam improves the output energy.^a

Output fluence (Beamlet 11-5)	Output energy flat profile	Output energy shaped profile	Improvement with shaped profile
8 J/cm ²	6.8 kJ	8.2 kJ	21%
10 J/cm ²	8.7 kJ	10.2 kJ	17%
12 J/cm ²	10.8 kJ	12.3 kJ	13.6%

^aBeamlet baseline, 11-5 configuration, 0.20 explosion fraction, f_x , 34 cm $\times$ 34 cm² beam.

The filters are created using variable-speed computer-controlled e-beam deposition of Cr on a BK-7 glass substrate. The filter's parabolic transmission profile is slightly wider than the actual beam size, allowing the profile of the transmitted beam to be adjusted to match the slightly skewed Beamlet amplifier gain profile. Figure 6(b) shows the near-field intensity profile of the beam transmitted through this filter and then propagated through the entire *unpumped* amplifier chain and measured at the 1ω output diagnostic station. Figure 7 shows the output near-field profile using the same parabolic transmission filter *pumping* the amplifiers; note the desired flat-top output profile that is achieved. These results are discussed further in the "System Description and Initial Performance Results for Beamlet," p. 1.

Compensation for gain nonuniformity in the amplifiers has a second advantage—it decreases any spatially dependent pulse-shape distortion produced by the main amplifiers. The temporal pulse shape distortion, caused by gain saturation at high fluences during the last pass through the cavity and the booster amplifier, is homogenous because of the fluence uniformity. If the beam is not corrected for spatial gain variations, then it will have lower fluences near the beam edges, and hence will undergo different temporal pulse distortions near the edges than near the center of the beam. The result is that the output temporal profile will be different at the edges of the beam than at the center. Therefore, by correcting for spatial gain variations in the main amplifiers we also produce a uniform-pulse temporal profile across the full aperture.

Wavefront Shaping Using the Adaptive Optics System

The wavefront of a laser beam governs how well the beam propagates. Since rays of light always travel perpendicular to the local wavefront, the wavefront determines whether the laser beam is diverging, converging, collimated, or is generally deforming in shape and size and breaking up. In Beamlet, the wavefront determines the size of the beam's focus and how the energy is distributed at the focus. In addition, the

wavefront determines how much of the light is within the acceptance angle for conversion to shorter wavelengths, which impacts the conversion efficiency of the light from the fundamental wavelength at 1054 nm to the third-harmonic wavelength at 351 nm. The Beamlet Type I/Type II frequency converter requires 95% of the 1ω energy be within a divergence angle of $\pm 50 \mu\text{rad}$. The beam divergence requirement needed to meet the NIF focusability requirement is much more stringent: 95% of the 3ω energy needs to be within a $\pm 35\text{-}\mu\text{rad}$ divergence angle. Beam divergence is caused by the static aberration of the individual optics surfaces, pump-induced spatially varying beam steering in the amplifiers during a shot, thermal aberrations in hot amplifier slabs, and turbulence in the heated amplifier cavity. Table 3 provides an overview of the various aberrations, the associated time scale on which they occur, and the spatial scale length. The correctability constraints are imposed by the choice of actuator density and control system speed. Both factors can be increased significantly beyond the performance of the system used on Beamlet.

1ω output near field

FIGURE 7. Example of the approximately flat-topped near-field intensity profile achieved at the output of the Beamlet amplifier chain using the parabolic gain compensation filter described in the text and shown in Fig. 6(b). (70-50-0295-0594pb01)

TABLE 3. Factors affecting Beamlet's wavefront quality, and the ability to correct for these factors using the 39-element DFM.

Factor	Magnitude of aberration (waves)	Temporal dependence	Aberration spatial scale ^a	Correctability ^b
Optics figure errors	2.5	Static	$d/4$	Excellent
Pump induced	2.5–3	50 μs	$d/4$	Good
Thermal effects in slabs	2.5–6	4 hr	$d/3$	Excellent
Turbulence in amps ^c	0.5–1	Seconds	$d/10$	Marginal
Small scale errors	0.01–0.2	Static	$<d/10$	Not possible ^d

^a d represents the beam size.

^bUsing the present Beamlet DFM hardware.

^cTurbulence due to thermally driven convection currents.

^dLimited by the choice of actuator density.

The Beamlet adaptive optics system is designed to correct the wavefront of the laser beam to be nearly "flat," i.e., to as near a plane wave as possible. As mentioned earlier, this maximizes the conversion efficiency of the fundamental IR beam to the UV and minimizes the size of the focus spot, thus maximizing the power density at the target. The adaptive optics system, shown schematically in Fig. 8, consists of a DFM, a wavefront sensor, and a controller. The design is based on an adaptive optics system developed by Salmon et al.⁷ for laser isotope separation. The DFM is located in front of the injection spatial filter for the main multipass amplifier. The light is sampled by the wavefront sensor after the DFM, and the controller analyzes the wavefront from the wavefront sensor and drives the DFM until the sensor reads the desired wavefront, which is flat for Beamlet. The DFM is comprised of a single thin-glass substrate with 39 magnetostrictive actuators bonded to its back side. The mirror substrate is $70 \times 70 \text{ mm}^2$ wide and 4 mm thick. Its front surface is coated with a low-stress $\text{HfO}_2/\text{SiO}_2$ high-damage-threshold and high-reflectivity multilayer coating (Fig. 9). The arrangement of actuators divides the mirror surface into grids of sub-apertures, each subaperture being the smallest area

FIGURE 9. The Beamlet DFM has 39 actuators mounted to the back of a $70 \times 70 \times 4 \text{ mm}^3$ coated substrate. The range of motion of individual actuators is approximately $10 \mu\text{m}$. (70-50-0494-2093pb01)

FIGURE 8. Beamlet adaptive optics system layout: a DFM located in the injection beam path is operated by a control system. This system operates in closed loop to a Hartmann wavefront sensor in the injection path (flat injection wavefront), or in the 1ω -output diagnostics of the Beamlet amplifier (flat output wavefront). An additional higher spatial resolution Hartmann sensor is located in the output diagnostics. (70-50-0295-0402pb01)

that is enclosed by a group of adjacent actuators. Each actuator expands when a voltage is applied and produces a local bulge in the front surface opposite the actuator, while the neighboring actuators hold the mirror surface in place. This movement causes the mirror surface to tilt across the subapertures, adjacent to the moving actuator. The wavefront change, induced by the movement of a single actuator, is called the influence function. The influence function is usually Gaussian shaped, with its $1/e$ point located at the neighboring actuator.

The wavefront sensor is a Hartmann sensor, which has a series of lenses that collectively "view" the entire surface of the DFM. Figure 10 shows the relationship between the DFM actuator positions and the Hartmann sensor lenslets. Each lenslet spans a subaperture of the DFM and is configured as a local pointing sensor for that subaperture, i.e., the detector for each lenslet is in the focal plane of that lenslet. As the tilt in the wavefront of light entering the Hartmann lenslet changes, the focus spot on the detector moves laterally from its nominal position on the detector. Moving any actuator will cause the Hartmann spots to move from their nominal positions. Knowing how the spots move when each actuator is moved, the controller can drive the DFM until the displacement of the Hartmann spots is minimized, thus minimizing the wavefront error sensed by the Hartmann sensor.

FIGURE 10. Layout of the 39 actuators and the 77 Hartmann sensor lenslets mapped onto the DFM surface. (70-50-0295-0403pb01)

The system uses two Hartmann sensors—one to sample the light immediately after the DFM (input Hartmann sensor) and the other on the 1 ω diagnostics table (output Hartmann sensor). Afocal telescopes relay the image of the DFM to each Hartmann sensor, and each Hartmann sensor is calibrated by a wavefront reference source. The wavefront calibration effectively removes any aberration introduced by either the afocal relay telescope or the beam sampler. The wavefront controller is designed to control the wavefront using either of the two Hartmann sensors. The bandwidth for the closed-loop system is about 1/2 Hz for continuous wave (cw) light and about 1/50 Hz for regenerative amplifier pulses. A third Hartmann sensor is installed in the output diagnostic station. It is used for wavefront characterization measurements and provides a higher resolution than the control system sensors. It has a larger density of lenslets over the beam aperture (17 $\times$ 29).

As presently configured, the adaptive optics system can correct the wavefront using either cw light from the alignment laser or a 0.2-Hz pulsed beam from the regenerative amplifier. Precorrection of the injected wavefront to compensate for pump-induced aberration in the amplifier proceeds as follows: (1) The wavefront is flattened before a shot by running the control system closed loop to the output Hartmann sensor using the alignment laser. (2) The Hartmann sensor images are grabbed during the laser shot, and the resulting aberrated wavefront is reconstructed offline. (3) Before the next shot, this wavefront is entered in the control system that subsequently sets the mirror in closed loop such that the output wavefront is the conjugate of the shot wavefront error. The wavefront aberration of the shot should be corrected for pump-induced aberrations. Figure 11 shows recent wavefront data to illustrate this process. Two situations are depicted: the wavefront of a shot with static precorrection only, and a shot where full precorrection is applied. The wavefront shape is typical of the pump-induced wavefront aberration by the Beamlet amplifier slabs added to a focus error in the front-end rod amplifier. Its shape and magnitude agree closely with model predictions and offline beam-steering characterization data. (See "Design and Performance of the Beamlet Amplifiers," p. 18.) The second wavefront is the result of a shot where full precorrection for the errors shown in Fig. 11(a) is applied. The rms value of the resulting aberration is <0.2 waves, leading to a Strehl ratio (ratio of actual peak intensity of the focal spot to the diffraction limited peak intensity) of 0.3. The correction capabilities are presently limited by turbulence-induced wavefront variations between the time of prefiguring the DFM and the actual shot. This effect is small in a cold cavity, but becomes substantial after firing subsequent shots at the nominal 2-hr Beamlet shot rate.

(a) Uncorrected shot wavefront

(b) Shot wavefront with full wavefront precorrection

FIGURE 11. Experimental output high-resolution Hartmann sensor wavefronts obtained during 4.5-kJ 3-ns Beamlet shots ($34 \text{ cm} \times 34 \text{ cm}^2$ beam). (a) The typical pump-induced wavefront aberration in the Beamlet amplifiers. (b) The output wavefront of a shot with full precorrection of the injected wavefront for static and dynamic aberrations in the Beamlet amplifier. The resulting 0.18 waves rms aberration correspond to a calculated Strehl ratio of 0.3. (70-50-0295-0404pb01)

Summary

We added the capability to control the spatial intensity profile and wavefront of the pulse produced by the Beamlet pulse-generation system (i.e., front end). We also demonstrated how these capabilities can be used to control and increase the beam quality and performance of Beamlet's large-aperture multipass Nd:Glass amplifier—a technology critical to the design of the proposed NIF laser system.

In addition, we have also modified and improved the front-end oscillator and modulator systems to increase the stability and reliability of their performance.

Notes and References

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LARGE-APERTURE, HIGH-DAMAGE-THRESHOLD OPTICS FOR BEAMLET

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Introduction

Beamlet serves as a test bed for the proposed National Ignition Facility (NIF) laser design and components. Therefore, its optics are similar in size and quality to those proposed for the NIF. In general, the optics in the main laser cavity and transport section of Beamlet are larger and have higher damage thresholds than the optics manufactured for any of our previous laser systems. In addition, the quality of the Beamlet optical materials is higher, leading to better wavefront quality, higher optical transmission, and lower-intensity modulation of the output laser beam than, for example, that typically achieved on Nova. In this article, we discuss the properties and characteristics of the large-aperture optics used on Beamlet.

The damage threshold is perhaps the most critical property of the optical materials, because the cost of the laser system is driven largely by the amount of laser energy that can be delivered in a given aperture size. The higher the transmitted energy density (fluence), the fewer the number of laser beams needed to meet the output energy requirement and, therefore, the

lower the overall system cost. Consequently, Beamlet (and NIF) are designed to operate near the damage threshold limit for the optical materials.

Table 1 summarizes the damage threshold requirements at 1.0 and 0.35 μm for the large optics on Beamlet for a nominal operating pulse length of 3 ns and lists the measured damage thresholds for comparison. Note that the measured thresholds represent the absolute maximum operating laser fluence possible for that specific optic. To provide a safety margin for our designed operating limit, we multiply the measured thresholds by a "de-rating" factor that accounts for measurement uncertainties. The product of the measured damage threshold times the de-rating factor is called the "safe operating limit" and represents the fluence limit for that specific optic. Beamlet is designed to never exceed the safe operating limits.

Figure 1 compares the peak designed laser fluence at key optical materials on Beamlet with the safe operating threshold. These peak fluences are reached during the final pass through the laser and are based on model calculations. Note that the peak fluence

TABLE 1. Beamlet's damage threshold requirements and measured values at 3 ns for various optical materials.

	Optics	Measured damage threshold (J/cm^2)	Safe operating limit (J/cm^2)	Beamlet peak fluence (J/cm^2)
1 ω	Laser glass	34	28	20
	HfO ₂ /SiO ₂ HR	26	18	8
	HfO ₂ /SiO ₂ polarizer	18	13	8
	SiO ₂ sol-gel AR	34	29	21
	KDP doubler	43	30	20
	KDP (Pockels cell)	43	30	8
3 ω	KD*P tripler	20	14	11
	SiO ₂ sol-gel AR	19	16	11

HR=high reflectivity; AR=antireflection

determines the damage limit of the laser, whereas the average fluence determines the energy output. Therefore on the Beamlet, we have worked hard to keep the peak-to-mean intensity variation within the laser pulse as low as possible to maximize the energy out and to minimize the risk of optical damage. Because laser optical materials do not all have the same damage thresholds, one or two materials generally limit the performance of the system. In the case of Beamlet, the optical material at most risk is the $\text{HfO}_2/\text{SiO}_2$ multilayer thin film polarizer (at 1ω) and the deuterated potassium dihydrogen phosphate (KD*P) tripling crystal (at 3ω).

Optical Materials

The optical materials on Beamlet can be divided into four main types: laser glass, potassium dihydrogen phosphate (KDP)/KD*P, dielectric coatings, and lenses and diagnostic beam splitters. This section briefly describes each of these materials and their key properties.

Laser Glass

The energy storage medium for the Beamlet flashlamp-pumped amplifiers is a commercial phosphate laser glass (composition LG-750) manufactured by Schott Glass Technologies Inc. It has an Nd^{3+} doping concentration of $3.4 \times 10^{20}/\text{cm}^3$ and consists of a metaphosphate glass composition. Although the details of the composition are proprietary, it contains the major oxides P_2O_5 , Al_2O_3 , K_2O , BaO , Nd_2O_3 , and a number of other miscellaneous components.

For Beamlet (and NIF) the laser glass is in the form of large rectangular plates $78.8 \times 44.8 \times 4 \text{ cm}^3$ (Fig. 2). The volume of these glass plates or "slabs" is about 14 L. For comparison, the largest pieces of Nova laser glass are elliptically shaped disks and have a volume

of about 7 L. Thus, the size and shape of Beamlet's slabs required a significant advancement in the prior laser glass manufacturing process. A total of 20 slabs were manufactured for the Beamlet laser—16 are installed on the system, and 4 are reserved as spares.

The size of the Beamlet laser slabs is driven by four main factors: (1) The maximum beam size, which is 35 cm for Beamlet. In addition, the laser slab is mounted in the amplifier cavity at Brewster's angle, requiring that the slab be lengthened to account for both the angle and the refractive "walk-off" of the beam as it travels through the glass. (2) The vignetting effect, allowing for the beam to propagate back and forth four times through the main laser cavity slightly off-axis to pass through the four different pinholes. (See "System Description and Initial Performance Results for Beamlet," p. 1.) The contribution of the vignette to the slab size is dependent on the length of the cavity amplifier section, the focal length of the spatial filter lens, and the pinhole spacing. (3) The alignment allowance which, within the main laser cavity, is set at 2% of the maximum beam size. (4) The stand-off distance from the edge cladding, required to avoid wavefront distortion of the beam caused by amplified spontaneous emission (ASE) heating the cladding. When the cladding is heated, it expands and distorts the region near the edge of the slab. Based on experiments,¹ the stand-off distance from the edge cladding bond line needs to be at least $t/2$, where t is the slab thickness. Since Beamlet slabs are 4 cm thick, the minimum stand-off distance is 2 cm around the border of the entire slab.

FIGURE 1. Comparison of the peak laser fluence during the final pass through the laser system with the "safe operating limits" of the material. The data are for a nominal square output pulse of 3 ns. (70-50-0693-2242pb01)

FIGURE 2. Beamlet's $78.8 \times 44.8 \times 4 \text{ cm}^3$ laser slab containing $3.4 \times 10^{20} \text{ Nd}^{3+}/\text{cm}^3$; the edges of the laser slab are clad with a Cu:Doped phosphate glass designed to absorb ASE at 1054 nm. (70-50-0393-0716pb01)

The laser slabs are clad with Cu:Doped phosphate glass having an absorption coefficient at $1.05\ \mu\text{m}$ of $0.28/\text{mm}$. The base composition of the cladding glass is the same as LG-750 (without the Nd^{3+}) and is bonded to the laser slabs using an epoxy adhesive specially formulated to match the index of the laser glass. Details for the cladding process are described elsewhere.² The laser slabs were clad and finished by Zygo Corporation and Eastman Kodak Company.

FIGURE 3. Summary of three key properties of the laser slabs produced for Beamlet compared with the design specifications: (a) absorption loss at 1054 nm, (b) -OH absorption at 3000 nm, and (c) fluorescence lifetime. The lifetime measurements were performed on samples $5 \times 5 \times 0.5\ \text{cm}^3$. (70-50-0295-0397pb01)

Laser glasses are specially formulated to give the desired laser, optical, thermal-mechanical, and physical-chemical properties needed for a specific application. Most of these properties are controlled by the base composition of the glass. However, some critical properties are also impacted by the manufacturing process. These include the optical absorption at 1054 nm, optical homogeneity, Nd^{3+} fluorescence lifetime, and the Pt inclusion content. Because of Beamlet's larger slabs, we were concerned whether these critical properties could be maintained throughout the process. Figure 3(a) shows the variation in optical absorption at 1054 nm for all the slabs produced. Optical absorption arises from either impurities in the raw materials and/or contaminants that enter during the processing (e.g., contaminants added by dissolution of the melter refractory walls).³ The absorption offsets the laser gain of the material, thereby requiring either more amplifiers or harder pumping. The data in Fig. 3(a) show that the Beamlet slabs have very low absorption loss and meet the necessary absorption specification. In fact, about 30% of the absorption loss (i.e., $4.5 \times 10^{-4}\ \text{cm}^{-1}$) is due to absorption by the thermal population of Nd^{3+} in the lower laser level ($^4I_{11/2}$).

The Nd^{3+} fluorescence lifetime is mainly a function of the glass composition. To efficiently store energy in the amplifiers requires long fluorescence lifetimes. Two features of the manufacturing process can affect the lifetime— Nd^{3+} doping concentration and H_2O absorbed in the glass. The Nd^{3+} content affects the lifetime at high concentrations through the well-known concentration quenching mechanism.⁴ Therefore, to avoid melt-to-melt variability in fluorescence lifetime, careful control of glass volatility during the melt cycle and precise addition of Nd^{3+} are necessary. Absorbed H_2O of only a few ppm can also affect the lifetime; therefore, very dry conditions must be maintained during melting. The hygroscopic nature of molten-phosphate laser glass makes it particularly vulnerable to H_2O uptake. The H_2O content of the laser glass is quantified by measuring the -OH absorption at 3300 nm; Fig. 3(b) shows the results from the Beamlet melt. Although there is some variability, all slabs are quite dry having H_2O absorptions between ≈ 0.2 – $0.6\ \text{cm}^{-1}$ at $3.3\ \mu\text{m}$. This absorption corresponds to about 6–18 ppm of H_2O . Because of the good control of the Nd^{3+} doping concentration ($3.4 \pm 0.1 \times 10^{20}/\text{cm}^3$) and the H_2O content, all laser glass slabs exceed the Nd^{3+} fluorescence lifetime specification shown in Fig. 3(c). The Nd^{3+} lifetime specification for Beamlet laser glass is

$$\tau_L \geq 340 - 150 \left(\left[\text{Nd}^{3+} \right] - 3.4 \right) \quad (1)$$

where $[\text{Nd}^{3+}]$ is the Nd-ion concentration in units of $10^{20}/\text{cm}^3$ and τ_L is the minimum acceptable lifetime (in microseconds). In arriving at this specification, we also included the effects of radiation trapping by the $5.0 \times 5.0 \times 0.5 \text{ cm}^3$ standard sample size used by vendors for routine fluorescence lifetime measurements. The specification also includes the effects of concentration quenching at high Nd-dopings, derived from work by Jancaitis.⁵

The Beamlet melts have very low residual H_2O content so there is little effect of $-\text{OH}$ quenching on the lifetime. At low levels of H_2O contamination, the effect of $-\text{OH}$ in reducing the lifetime can be estimated from the expression⁶

$$\Delta\tau = -7.62(\alpha_{3.3\mu\text{m}}), \quad (2)$$

where $\alpha_{3.3\mu\text{m}}$ is the measured $-\text{OH}$ absorption at $3.3 \mu\text{m}$ and $\Delta\tau$ is the lifetime reduction relative to a sample with zero residual H_2O . For Beamlet's laser glass, the residual H_2O contributed less than a 4- μs reduction in lifetime.

We maintained good optical homogeneity during the manufacturing process with all the laser slabs meeting the homogeneity specifications. Because of the rectangular shape of the glass, there was some concern whether the homogeneity could be maintained in the corners of the slabs. All finished Beamlet laser slabs had <0.1 wave (at $1.054 \mu\text{m}$) transmitted wavefront distortion across the clear aperture.

The damage threshold of the laser glass is controlled by the quality of the surface and the presence of absorbing impurities. The typical high-quality "super" polish used to finish laser glass gives a damage threshold in excess of $30 \text{ J}/\text{cm}^2$ at 3 ns (1054 nm) and, therefore, exceeds the requirements for Beamlet (Table 1). More important is the presence of absorbing particles within the glass, particularly Pt inclusions. Pt inclusions originate from the Pt containers used to melt the laser glass and can cause optical damage at fluences of $2\text{--}3 \text{ J}/\text{cm}^2$ at 3 ns, far below the Beamlet operating fluence. In addition, damage from large inclusions can grow with successive shots, eventually rendering the slab useless. Using new glass-melting processes,^{7,8} we were able to maintain inclusion levels well below our manufacturing goal of <15 in any given slab and an average for all 20 Beamlet slabs of <3 inclusions per slab. In fact, 50% of the laser slabs had no inclusions at all and 90% had 3 or less.

KDP/KD*P

Large plates of single-crystal KDP are used in the Beamlet Pockels cell and frequency converter. The Pockels cell and second-harmonic generation crystals

are undeuterated, whereas the harmonic tripling crystal is deuterated to a level of about 80%. (KD*P is the commonly used representation of the deuterated material.) The KDP and KD*P crystals are arguably the most difficult optics to manufacture and require the greatest production time. In addition, they represent a marked increase in size and quality over the crystals that were manufactured for Nova. For example, the crystal plates used on Beamlet are $37 \times 37 \text{ cm}^2$ compared with $27 \times 27 \text{ cm}^2$ on Nova. In addition, the Beamlet damage threshold requirement exceeds that required for Nova by about a factor of three.

The use of deuterated material for the third-harmonic crystal is driven by the need to suppress stimulated Raman scattering (SRS) at 3ω . At high drive intensities (such as those used on Beamlet) the spontaneous Raman-scattered light is amplified as it traverses the crystal face. The SRS gain coefficient in KDP has been measured to be approximately $0.23 \text{ cm}/\text{GW}^{9,10}$ at 3ω for a Type II tripling crystal. The scattered Raman Stokes intensity I_s grows as it travels a distance l across the crystal, according to the relationship

$$I_s(l) = I_s(0) \exp(gI_p l) \quad (3)$$

where I_p is the pump intensity (GW/cm^2) and g is the gain coefficient. Because of the large aperture used on Beamlet, there is a significant gain-path length for the SRS light. Therefore, at high operating intensity ($>3.0 \text{ GW}/\text{cm}^2$), the potential exists for the transversely propagating SRS light to reach intensities high enough to damage the KD*P.

The magnitude of the SRS gain coefficient for a particular Stokes Raman band is proportional to the scattering cross section. Therefore, because the spontaneous Raman band at 915 cm^{-1} is the most intense in KDP, it presents the greatest threat of unacceptable SRS. In KD*P, the mode at 915 cm^{-1} is split into two peaks and the magnitude of each band is dependent on the deuterium concentration (Fig. 4). At high deuteration levels, the Raman scattering cross sections for the two bands are about a factor of two lower than that for the single band of the undeuterated KDP. Therefore, deuteration of the KDP greatly reduces the SRS threat to the tripling crystal.

The Beamlet crystal plates were cut from large single-crystal boules of KDP and KD*P, grown from aqueous solution by Cleveland Crystals, Inc. The KDP and KD*P boules produced for Beamlet weigh as much as 500 kg and take up to 2 years to grow (Fig. 5). This is about a factor of three increase in boule volume over those grown for Nova. The crystals required for the Pockels cell and harmonic converter system are

FIGURE 4. Measured spontaneous Raman scattering intensity profile for the 915 cm^{-1} mode at different deuteration levels. (70-35-0195-0316pb01)

FIGURE 5. Photograph of a large KDP single crystal grown for Beamlet (note the meter stick shown for scale). The Beamlet crystals each weigh about 500 kg and are the largest ever produced. The smaller crystal on the right is the size grown for Nova. (70-39-1093-3487pb01)

then cut from these boules in an orientation shown schematically in Fig. 6. The Pockels cell uses a crystal cut normal to the z-axis of the boule, whereas the frequency-conversion crystals are cut at the phase matching angles required for the specific harmonic generation scheme. Beamlet uses a Type I/II third-harmonic generation method. (The harmonic generation system is described in detail elsewhere.¹¹)

We chose to grow 80% deuterated material (vs 95%) because the level of stress-induced birefringence was expected to be lower and the time to grow the boules was expected to be shorter. Deuterated water (D_2O), having a deuteration level of 99.7%, was obtained from the Department of Energy's national stockpile. In general, the growth rate for fully deuterated material is as much as 10 times slower than for undeuterated KDP.

Apart from size and deuteration level, the quality of the KDP and KD^*P crystals is also of critical importance. Specifically, stresses within the crystal can lead to stress-induced index variations and birefringence that in turn can produce distortions in the optical wavefront and beam depolarization.¹²⁻¹⁴ Wavefront distortion and depolarization degrade the performance of the laser. For example, in the case of the Pockels cell, any depolarization in the beam results in a direct transmission loss at the polarizer. Likewise, wavefront distortions can reduce the conversion efficiency of the harmonic generator, produce downstream modulation, and degrade focusability. Our operating goal for the Pockels cell was to produce <1% depolarization loss for any given pass and to keep the transmitted wavefront distortion and wavefront gradients for the finished crystal to $<\lambda/4$ and $\lambda/4/\text{cm}$, respectively.

(a) Type I doubler

(b) Type II tripler

(c) Pockels cell z-plate

FIGURE 6. Schematic diagram showing the orientation in which the crystal plates used on Beamlet are cut from large KDP and KD^*P single-crystal boules. (a) Type I doubler, (b) Type II tripler, and (c) Pockels cell z-plate. In general, several crystals of a given type can be cut from one boule. (70-35-0195-0317pb01)

The birefringence (δn) in a Pockels cell plate, cut normal to the z-axis of the crystal, is dominated by the shear strain and is given by¹⁰

$$\delta n = n^3 p_{66} \varepsilon_{xy} , \quad (4)$$

where n is the refractive index, ε_{xy} is the shear strain, and p_{66} is the elasto-optic tensor element appropriate for this geometry; p_{66} has the value of 0.028 for KDP and 0.025 for K*DP. The depolarization loss (L), due to this birefringence, is given by¹²

$$L = \sin^2 \left[\left(\frac{\pi}{\lambda} \right) \delta n t \right] , \quad (5)$$

where t is the crystal thickness and λ is the laser wavelength. Equation (5) is valid for the "on" and "off" states of the Pockels cell (i.e., when the voltage applied across the crystal is either $V\pi$ or 0, respectively). The shear strain can be directly related to the shear stress, τ_{xy} :

$$\tau_{xy} = C_{66} \varepsilon_{xy} , \quad (6)$$

where C_{66} is the elastic constant and has the value of 6.24 and 5.94 GPa for KDP and KD*P, respectively. To achieve a depolarization loss of 1% or less requires a shear stress $<10^6$ Pa.

Distortions in the beam phase front transmitted through the Pockels cell z-plate are controlled by the residual normal strains in the crystal:¹²

$$\Delta n = \left(\frac{n^3}{2} \right) \left[\frac{1}{2} (p_{11} + p_{12}) (\varepsilon_x + \varepsilon_y) + p_{13} \varepsilon_z \right] , \quad (7)$$

where Δn is the index shift, the p_{ij} 's are elasto-optic coefficients, and ε_x , ε_y , and ε_z are the normal strains in the crystal. These strains can be related to residual normal stresses using the relationships developed by DeYoreo and Woods.¹⁴ The index shift produces a spatial variation in the transmitted phase given by

$$\phi = \left(\frac{2\pi}{\lambda} \right) \Delta n t . \quad (8)$$

To meet the transmitted wavefront distortion specification of $<\lambda/4$ for the Pockels cell KDP crystal, requires a minimum residual normal stress field of $\approx 10^5$ Pa. Also, to meet the transmitted wavefront gradient specification for the crystal requires that the stress gradient be $<10^5$ Pa/cm.

The birefringence and wavefront distortions of the crystals used on Beamlet are characterized using the method described by DeYoreo and Woods.¹³ Figure 7 presents the measured polarization efficiency (i.e., 100%—% depolarization loss) for a 32×32 cm²

(a) Polarization efficiency—KD*P crystal

(b) Polarization efficiency—KDP crystal

FIGURE 7. Polarization efficiency of z-cut (a) KD*P and (b) KDP plates expressed as the percent of the output energy in the correct polarization state, i.e., 100%—% depolarization loss. The crystal plate dimensions are $32 \times 32 \times 1$ cm³. (70-50-1294-3982pb02)

KDP crystal. The data show a maximum loss of 0.4% through any point in the crystal with an aperture loss averaging 0.05%. The data show that the maximum residual shear stress in the crystal is $<1.5 \times 10^5$ Pa. Similarly, interferometry measurements show phase-front distortions from the bulk material of less than an eighth of a wave at 1054 nm, again suggesting very low residual normal stresses in the crystal.

The KDP crystal plates are finished by diamond turning instead of polishing. In this process, a crystal blank is mounted on a carriage that translates the crystal blank parallel to the cutting plane. The cutting plane is defined by the single-point diamond tool mounted at a fixed radius in a high-speed spindle. This is commonly referred to as a fly-cutting mode of operation, and the cutting direction can be more closely aligned with a preferred axis on the crystal. By rotating the tool, rather than the crystal, the cutting rate remains the same across the whole face of the crystal. During the final finishing steps, the distance between subsequent tool cuts is usually only a few micrometers. Using this method, surface finishes of about 30 Å (rms) are typical.

One recurring problem we have encountered during finishing of large KDP crystals is a small-scale waviness in the transmitted wavefront. Our initial tests on Beamlet showed this same waviness in the output 1 ω near-field image [Fig. 8(a)]. This waviness originated from the diamond-turned surface of the Pockels cell crystal and had a spatial scale length of about 6.3 mm. The measured amplitude of the phase ripple suggests a surface with a 100-Å peak-to-valley (p-V) periodic variation at that scale length. We investigated ways to reduce the surface waviness, because at high laser intensities the phase ripple from the diamond turning process may seed small-scale beam breakup due to self-focusing.¹⁵ The source of the waviness was traced to a problem with the carriage system that translates the crystal. Specifically, we found that the flexure coupling that connects the drive-lead screw to the carriage was not properly aligned. Therefore, the flexure coupling was unable to adequately remove the natural once-per-revolution "wobble" motion of the lead screw. In this condition, the increased transmission of the lead-screw wobble into the carriage caused the crystal blank to move excessively in and out of the cutting plane in a sinusoidal fashion. After adjusting the flexure coupling, we found that the surface waviness was greatly reduced. Transmitted wavefront measurements on crystals finished before and after this repair showed that for scale lengths of ≈ 6 mm, the p-V surface waviness on the crystals was reduced from ≈ 60 Å to ≈ 10 Å above the background roughness near that spatial frequency. Figure 8 compares the near-field image of the Beamlet output beam before and after this corrective measure. Note that the circular arcs due to the spatial ripple are nearly absent in the "after" near-field image [Fig. 8(b)].

The damage threshold of some optical materials can be improved by "laser conditioning." KDP and KD*P are two such materials. During the process of laser conditioning, the optical material is exposed to a series of laser shots with monotonically increasing fluence. The wavelength of the conditioning laser shots is the same as the wavelength at which the optic is intended to be used. At the end of this sequence of exposures, the optical damage threshold is typically increased

FIGURE 8. Near-field images of the 1 ω output on Beamlet showing (a) the intensity modulation caused by diamond turning "ripples" on the Pockels cell KDP crystal, and (b) dramatic reduction of the ripples after the diamond turning machine is properly adjusted. (70-50-0295-0593pb01)

by a factor of two or more over the unconditioned (i.e., single-shot) threshold. As a general rule of thumb, at least five shots are needed to condition the optic to $\approx 85\%$ of the maximum conditioned threshold. Furthermore, the first shot in the conditioning sequence should be at a fluence of about one-half the unconditioned damage threshold.

Table 2 summarizes the unconditioned and conditioned damage thresholds of KDP and KD*P at 1ω and 3ω , respectively.

Dielectric Coatings

Two main types of optical coatings are used on Beamlet: (1) multilayer $\text{HfO}_2/\text{SiO}_2$ high-reflectivity (HR) and polarizer coatings and (2) single-layer SiO_2 sol-gel antireflection (AR) coatings. Figure 9 shows the Beamlet polarizer and two of the mirrors. The sol-gel AR coating design, coating process, optical performance, and damage threshold have been well documented¹⁶⁻¹⁸ and will not be discussed here. We note only that these coatings are routinely applied to all Beamlet and Nova transmissive optics (large and small) and have excellent transmission ($>99.5\%$ per surface) and high damage thresholds at 1ω and 3ω (Table 1).

Beamlet uses $\text{HfO}_2/\text{SiO}_2$ multilayer coatings because of their demonstrated damage threshold improvement with laser conditioning,^{19,20} good optical properties, and relative ease in application over large apertures by electron beam (e-beam) evaporation.²¹ All the multi-

layer coatings on large-aperture Beamlet optics were applied by conventional e-beam processing.

There are three reasons the polarizer is the most difficult optical coating to make: (1) The size of the polarizer is $75 \times 39 \times 9 \text{ cm}^3$ and is more than twice the size of anything previously manufactured. (2) The damage threshold of the polarizer required for Beamlet represents a three-fold improvement over those used on Nova. (3) The coating layers need to be uniformly and precisely deposited over the entire substrate surface.

The polarizer coating was deposited on a BK-7 silicate glass substrate. BK-7 is significantly lower in cost than SiO_2 , although it has the disadvantage of having a low bulk damage threshold due to Pt inclusions in the glass. However, because the polarizers used on Beamlet are used in reflection at high intensity, the BK-7 substrate is never exposed to damaging fluences.

Table 3 summarizes the transmission properties of the four polarizers manufactured for Beamlet by

FIGURE 9. Photograph of the large-aperture $\text{HfO}_2/\text{SiO}_2$ thin-film polarizer used with the PEPCs on Beamlet to switch the beam out of the multipass cavity. The polarizer is used in a transmissive mode at low fluence (p-polarized incident light) during the first and second pass. On the final pass, the light is s-polarized and reflected off the polarizer coating and out of the cavity. The peak fluence is about 11 J/cm^2 at 3 ns (1054 nm). (70-50-0594-2486p01)

TABLE 2. Summary of damage threshold for KDP and KD*P crystal plates used on Beamlet. The accuracy of the measurement is $\pm 15\%$ and $\pm 30\%$ for unconditioned and conditioned values.

Optic	Material	Wavelength (nm)	Damage threshold at 3 ns (J/cm^2)	
			Unconditioned	Conditioned
Pockels cell z-plate	KDP	1054	34	43
Type I doubler	KDP	1054	34	43
Type II tripler	KD*P	1054	16	25
		351	10	20

TABLE 3. Summary of transmission, extinction ratio, reflected wavefront distortion, and conditioned damage threshold for the four $79 \times 39 \times 9 \text{ cm}^3$ $\text{HfO}_2/\text{SiO}_2$ thin film polarizers manufactured for Beamlet (measured in dry N_2). Damage threshold is accurate to $\pm 30\%$.

Polarizer designation	Optimum use angle	Transmission (%)		Extinction ratio T_p/T_s	Reflected wavefront distortion (in waves at $1.05 \mu\text{m}$)	Conditioned damage threshold at $1.054 \mu\text{m}$ and 3 ns (J/cm^2) ^a	
		p-polarized T_p	s-polarized T_s			p-polarized	s-polarized
1	55.5°	98.2	0.60	163	0.4	18	23
2	54.5°	98.1	0.10	981	0.25	20	26
3	56°	98.0	0.25	392	0.28	13	18
4	54.5°	98.2	0.14	701	0.38	20	35

^aDamage measurements on witness samples from the production run.

Spectra-Physics. The optimum-use angle is between 54.5 and 56° and the polarizer can be “tuned” to the maximum extinction ratio by rotating the optical mount that holds the polarizer over the specified use range. We manufactured four polarizers: two are used on the system and two are spares. The polarizers were prepared in two separate coating production runs (with two polarizers in each run); the reproducibility between the two runs was quite good. Three of the polarizers had extinction coefficients >390, supporting the excellent control of the deposition process. The reflected wavefront distortion is between ≈0.25 and 0.4 waves and is largely due to spherical aberration that can be easily corrected by other optical elements in the system.

HfO₂/SiO₂ e-beam coatings can be laser conditioned to improve their damage threshold. (The conditioning process is similar to that described previously for KDP.) The conditioned damage thresholds of the polarizers all exceeded the Beamlet safe operating limit of 8 J/cm² at 3 ns (Table 3). The polarizers were conditioned off-line using the output from a pulsed Nd:YAG laser, operating at 10 Hz, to scan the full aperture of the optic in incremental fluence steps.²² The conditioning effect has been associated with the gentle removal of nodular-shaped defects, which are known to limit the damage threshold of these multilayer coatings.²³ Based on measurements, the damage threshold of the polarizers scales with the pulse length as $\tau^{0.35}$.

The HfO₂/SiO₂ thin-film mirrors on Beamlet all had measured damage thresholds exceeding 25 J/cm² and reflectivities >99%. Damage thresholds of mirror coatings are typically higher than those of similar polarizer coatings.

Lenses and Diagnostic Beam Splitters

The lenses and diagnostic beam splitters used on Beamlet were all fabricated from fused silica, manufactured by Corning. The fused silica is prepared by flame-hydrolysis of SiCl₄ and is inclusion free. As a consequence, the damage threshold is limited by the surface finish and AR coating on the optic, not the bulk material. Extensive front-surface damage measurements at 1.0 and 0.35 μm and over a range of pulse lengths

give a simple empirical relationship governing the safe operating limit for bare surface fused silica of

$$D = 22 t_p^{0.4} \text{ (at 1.0 } \mu\text{m)}$$

and

$$D = 9.2 t_p^{0.5} \text{ (at 0.35 } \mu\text{m)},$$

where t_p is the pulse length (ns) and D is the damage threshold (J/cm²). When a sol-gel AR coating is applied to the fused silica surface, the safe operating limit is slightly higher than that measured for the bare surface material, specifically²⁴

$$D = 24.6 t_p^{0.4} \text{ (at 1.0 } \mu\text{m)}$$

and

$$D = 13.7 t_p^{0.5} \text{ (at 0.35 } \mu\text{m)}.$$

Summary

Nearly all of the large optics used on Beamlet represent a dramatic increase in size and optical quality over those used on previous ICF lasers. Specifically the laser slabs, KDP/KD*P crystals, and polarizers are more than a factor of two larger than those used on Nova. In addition, the damage thresholds and quality of the Beamlet optical materials are also improved by two- to three-fold over those used on Nova. The sizes and quality of optics used in Beamlet closely match those expected to be used in the proposed NIF.

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BEAMLET PULSED-POWER SYSTEM

D. Larson

Introduction

The 13-MJ Beamlet pulsed-power system provides power to the 512 flash lamps in the cavity and booster amplifiers. Since the flash lamps pump all of the apertures in the 2×2 amplifier array, the capacitor bank provides roughly four times the energy required to pump the single active beam line. Figure 1 is a block diagram illustrating the main pulsed-power subsystems. During the 40 s prior to the shot, the capacitors are charged by constant-current power supplies. Ignitron switches transfer the capacitor energy to the flash lamps via coaxial cables. A preionization system triggers the flash lamps and delivers roughly 1% of the capacitor energy 200 μ s prior to the main discharge. This is the first time flash-lamp preionization has been used in a large facility. Preionization improves the amplifier

efficiency by roughly 5% and increases the lifetime of the flash lamps. Figure 2 shows a typical Beamlet current pulse. LabVIEW¹ control panels provide an operator interface with the modular controls and diagnostics. Figure 3 shows one of the four aisles of capacitor circuits and the wall of equipment racks containing the controllers, triggers, and charging supplies.

Table 1 shows the primary pulsed-power requirements. The system is assembled from 32 independent modules, each capable of driving 16 flash lamps to 30% of their explosion limit. The circuit architecture (Fig. 4) is similar to Nova's, but the Beamlet system demonstrates several features of the proposed National Ignition Facility (NIF) pulsed-power design. To improve the reliability of the system, high-energy-density, self-healing, metallized dielectric capacitors are used.

FIGURE 1. Block diagram of the Beamlet pulsed-power system. (40-00-0591-1686pb01)

High-frequency, voltage-regulated switching power supplies are integrated into each module on Beamlet, allowing greater independence among the modules and improved charge voltage accuracy, flexibility, and repeatability. On Nova, by contrast, many modules are charged with a single large unregulated power supply with high-voltage diodes to provide isolation. Failure of these diodes allows very large amounts of energy to be released in a single fault.

FIGURE 2. Typical flash-lamp current and voltage waveforms during the firing of the Beamlet pulsed-power system. (70-50-1294-4019pb01)

Capacitor Circuits

The Beamlet capacitor bank contains 256 capacitor circuits, each of which stores 52 kJ at 22 kV (Fig. 5). An additional 32 preionization circuits each store 3.6 kJ. The main capacitor circuits include: a single high-energy-density capacitor, a manual disconnect switch, a high-voltage fuse, a pulse-shaping inductor, a charge resistor, and a spark-gap. The capacitor-inductor combination forms the 500- μ s current pulse that drives the flash lamps. The manual disconnect switch disconnects the capacitor circuit from the remainder of the module and shorts the capacitor terminals. The high-voltage fuse, rated to carry 45,000 A²s and open at 180,000 A²s, is designed to protect the flash lamps from a failure that could exceed their explosion energy rating. This failure mode could occur in the event of a capacitor short circuit prior to triggering the switches. The spark-gap limits the magnitude of the voltage transient generated by the inductor when the fuse clears.

The energy storage capacitors, developed for Beamlet, use the metallized dielectric electrode technology. This technology gives the capacitors improved energy density and reliability in ICF applications and is included in the conceptual design for the proposed NIF pulsed-power system. Figure 5 is a photograph illustrating the evolution of capacitor technology for ICF pulsed-power systems over the past 20 years. The Beamlet capacitor stores 4 times the energy of the Nova capacitor, and 15 times that of Shiva, in roughly the same volume. The Beamlet capacitors have a different construction and failure mechanism compared to conventional

Control panel and charging supplies

Ignitron switches

50-kJ capacitors

FIGURE 3. Photograph of the pulsed-power control panel and one of the four aisles that contain the ignition switches and 50-kJ capacitors. The total bank's stored energy is 12.8 MJ at 20 kV. (70-50-0294-0465pb01)

foil-electrode capacitors. The improvements in the Beamlet metallized electrode result primarily from the self-healing characteristic of the dielectric system. The electrode is a thin (20-nm) layer of Al deposited onto the dielectric. If the dielectric is punctured, the resulting current flow vaporizes the electrode in the vicinity of the fault so that the short is cleared, or "healed," resulting in a small reduction in capacitance. In a conventional capacitor, the punctured dielectric would result in a short circuit and catastrophic capacitor failure. Thousands of healing events may occur before the capacitance is significantly reduced. Failure is typically defined as a 5% reduction in capacitance from the nominal value for metallized dielectric capacitors. Energy density is improved, since the capacitors may be operated near the intrinsic dielectric strength of the material, rather than derated to account for material or manufacturing flaws. System reliability is improved by the "soft" failure mode of the metallized capacitors. The capacitors suffer a gradual capacitance loss, rather than a catastrophic short-circuit. This effect can be monitored directly by periodically measuring the capacitance, or inferred by recording the peak current on each shot and detecting a reduction resulting

from reduced capacitance. The second method is implemented on Beamlet. This information allows the operator to monitor the status of the capacitors during normal operation, and to replace aging capacitors during scheduled maintenance times.

Qualification and acceptance tests were performed on the Beamlet capacitors to validate their performance. Qualification testing consisted of a life test at simulated Beamlet operating conditions (22 kV, 13 kA), including 25 fault-mode shots (22 kV, 24 kA, 70% reversal). Acceptance tests were performed on 7 lots of approximately 40 capacitors per lot. Each capacitor received a 25-shot functional test at nominal Beamlet operating conditions, and a DC high-voltage test of the bushing-to-case insulation. Three capacitors from each lot received an additional 1000 shots, and one of those an additional 9000 shots. No failures were observed in any of the tests, although due to a manufacturing defect, one of the capacitors dropped 4% from nominal during the 10,000-shot test. Periodic capacitance measurements were conducted to monitor the capacitor status. Figure 6 shows the results of a typical life test. A Weibull statistical analysis of the qualification and acceptance test data was used to predict the reliability

FIGURE 4. Simplified schematic of a Beamlet capacitor-bank module. (40-00-0591-1684pb01)

TABLE 1. Major requirements of the Beamlet pulsed-power system.

Item	Requirement	Purpose
Maximum delivered energy	9.1 MJ	Operates 512 Beamlet flash lamps at $f_x = 0.3$
Explosion fraction range	$0.2 \leq f_x \leq 0.3$	Operating flexibility
Preionization energy	0.3 J/cm ² of lamp bore	215 J/lamp, 90 μs pulse
Main pulse length	500 μs	3 (LC) ^{0.5}
Maximum repetition rate	3 shots/hr	Amplifier characterization shot rate
Bank lifetime	>10 ³ shots at $f_x = 0.3$, or >10 ⁴ shots at $f_x = 0.2$	Capacitors are limiting component. End of life determined by 5% capacitance reduction
Number of capacitor modules	32	Allows separate drive energies of inner and outer flash-lamp arrays
Charge voltage repeatability	±0.5%	Minimize shot-to-shot gain fluctuation

f_x = explosion fraction = lamp energy/theoretical limit.

LC = (L) circuit inductance, (C) circuit capacitance.

of the capacitors.² The analysis showed that we can expect a mean-time-between-failures (MTBF) of 2000 shots over the expected 5000-shot life of the Beamlet. If the same capacitors were used in the larger NIF system, a capacitor would require replacement roughly every 100 shots over the same period.

Switches

The Beamlet switch assembly is an evolution of the Nova design. Two size "D" ignitrons, in series, switch the 8 circuits of each module in parallel. The switches operate at 22 kV, 100 kA, and transfer 35 C per shot. A size "A" ignitron is added to the assembly to discharge the preionization circuit. The single tube is operated at up to 22 kV, 11 kA peak current.

FIGURE 5. Photograph comparing Shiva, Nova, and Beamlet capacitors. The capacitor energy storage density has increased 15-fold in the 20 years since Shiva was built and 4-fold since Nova was built. (70-50-0594-2523pb01)

Charging Supplies

The Beamlet design maximizes system modularity by embedding the charging supplies within each module. In this way, the "copper" connections between modules are limited to common AC power and grounds. This approach is especially important in large systems such as the proposed NIF, in which it is desirable to build a system from 200 independent 1.6-MJ capacitor banks, rather than a single 320-MJ capacitor bank.

This approach has been made practical by the development of efficient, reliable, high-frequency switching power supplies over the past decade. These supplies use advanced insulated-gate bipolar-transistor-power semiconductor devices and reliable architectures such as the series-resonant-inverter. The high operating frequency enables the use of efficient ferrite magnetics, resulting in small size and weight. The Beamlet charging supplies are approximately 30 times smaller than the equivalent supplies used on Nova.

The main capacitors in each module are charged by a supply with an average charge rate of 10 kJ/s, which delivers up to 20 kW at the end of the charge cycle. The output current is a constant 900 mA until the supply reaches its regulation point. It then holds the capacitors at a constant voltage until they are discharged.

Additional circuitry is needed to protect the supplies in the event of a bank fault that results in reversal of the capacitor voltage. Voltage reversal tends to drive large values of current through the small diodes in the output rectifier of the charging supply, resulting in failure of the diodes. The circuit shown in Fig. 7 protects the supplies from bank faults. The diode stack diverts the fault current, while the 50- Ω resistor limits the fault current to a safe level for the diodes. The fuse limits the energy deposited in the charging supply in the event of a short circuit in the supply itself.

FIGURE 6. Results from lifetime tests on two Beamlet 50-kJ dielectric capacitors. The data show the slow decay in capacitance with the number of shots. (70-50-1294-4018pb01)

The preionization capacitors are charged by a small, 200-J/s power supply similar in design to the large supplies. A 50,000- Ω resistor is placed in series with the output to protect the supply from capacitor voltage reversal. A series of equipment racks contain the charging supplies, triggers, and controls for the system. Each rack bay contains the controls, chargers, and triggers for two capacitor modules.

Power Transmission

Coaxial cables are used to deliver the capacitor energy from the bank to junction blocks near the amplifiers. The length of the cables varies from 25 to 70 m. We chose a 50- Ω , high-voltage coaxial cable (RG-217) since it was used on Nova and Shiva, and many excess fittings and terminators were available for use on Beamlet. This cable, however, resulted in high resistive losses at the elevated Beamlet operating currents. As much as 30% of the capacitor energy is lost in the cables at the highest explosion fractions and longest cable lengths.

The coaxial cables terminate in junction blocks in the Beamlet center tray near the amplifiers. The junction blocks affect the transition from the coaxial cable to the flexible twisted-pair cable, which delivers the energy the last several meters to the flash-lamp cassettes in the amplifier. A custom twisted-pair cable was developed for Beamlet, since the magnetic forces due to increased current caused failures in the Nova-type cables during prototype tests. The cable is made from flexible, silicone-insulated wires that are twisted and covered with a layer of mylar and a strong nylon braid to contain the magnetic forces. A PVC jacket covers the assembly.

Controls and Diagnostics

As shown schematically in Fig. 8, a hierarchical computer system controls the Beamlet pulsed-power system. A central control computer, located in the Beamlet control room, provides a graphical LabVIEW operator interface, data archiving, timing control, and coordination of pulsed-power system operation with other Beamlet subsystems. In the capacitor bank, single-board computers receive high-level commands from the central computer and control bank operation through the control-interface chassis. The single-board computers, their fiber-optic communications system,

FIGURE 7. A combination of resistors and diodes protects the charging supply in the event of capacitor bank faults. (70-50-1294-4017pb01)

and the control interface chassis were assembled from industrial process control components to achieve a robust and inexpensive system. Conceptually, this design is very similar to the design of the power conditioning system controls for the proposed NIF.

The principal diagnostic for the Beamlet pulsed-power system is measurement of peak current in each flash-lamp string. The current in each flash-lamp pair is detected by a current transformer. The current-peak-detector chassis in each pulsed-power module provides analog peak-detection measurements that are digitized by the control interface chassis and transferred to the central control computer.

The current-peak-detector chassis also performs a fault protection function. In the event that a capacitor should short while charged, the other capacitors in that module would discharge through it into its lamp string. If the fuse fails to open properly, this fault may result in the explosion of the lamp and serious damage to nearby optics. This failure mode has occurred on Nova and is responsible for nearly all of its flash-lamp explosions to date. To prevent this on Beamlet, the current-peak detector sends an indication of the onset of current flow to the trigger-distribution chassis. If current flow is detected before the system triggers have been generated,

FIGURE 8. Schematic diagram of the pulsed-power control system. (70-50-1294-4016pb01)

the trigger-distribution chassis fires the main bank ignitrons. This diverts the current flow from the failed circuit to the ignitron, thereby preventing the flash-lamp explosion energy from being reached.

The single-board computers also perform a fault protection function by monitoring the value of the voltage on the preionization power supply. If significant charge were left on the preionization capacitors by, for example, an aborted shot, and then the main bank were charged, the output of the preionization supply would be subjected to the sum of the voltages, which could exceed the maximum voltage design rating of the supply. If the single-board computers detect excessive preionization voltage, they automatically shut off the main bank charging supply to protect the system.

The Beamlet timing controls are based on commercial delay generators. A master radio-frequency clock and the 0.2-Hz regenerative amplifier trigger are distributed building-wide on a system of transformer-isolated coaxial cables. A fiber-optic extended GPIB network connects all the delay generators to the Beamlet pulsed-power system's central control computer. The resulting system meets a specification of 250 ps peak-to-peak jitter.

Summary

To date, the reliability of the Beamlet pulsed-power system has been very good. During the first 700 system shots, no failures occurred in the high-current circuitry. The ignitron pre-fire rate was high during the first 100 shots until the weak tubes were culled from the system. A design defect in the preionization supplies resulted in a high initial failure rate. The addition of external components solved that problem. No measurable reduction in capacitance has been detected in any of the metallized dielectric capacitors.

Notes and References

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BEAMLET LASER DIAGNOSTICS

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Introduction

Beamlet is instrumented extensively to monitor the performance of the overall laser system and many of its subsystems. Beam diagnostics, installed in key locations, are used to fully characterize the beam during its propagation through the multipass cavity and the laser's output section (Fig. 1). This article describes the diagnostics stations located on Beamlet and discusses the design, calibration, and performance of the Beamlet calorimeters. We used Nova's diagnostics packages to develop the Beamlet design to determine beam energy, spatial profile, temporal profile, and other beam parameters.^{1,2} Technologic improvements within the last several years in controls, charge-coupled device (CCD) cameras, and fast oscilloscopes have allowed us to obtain more accurate measurements on the Beamlet laser system. We briefly cover some of these techniques, including a description of our LabVIEW³ based data acquisition system.

Diagnostics Systems

The first diagnostics station in the main laser is at the east end of the cavity where the beam is sampled after the first pass through the amplifier (Fig. 1). The cavity mirrors are designed to leak approximately 0.5% of the incident $1.053\text{-}\mu\text{m}$ (1ω) light, which is down-collimated to a near-field camera, an energy diode, a temporal pulse-shape diode, and an absorbing glass calorimeter. The beam is diagnosed in a similar manner at the west end of the cavity following the second pass through the laser. The third and fourth passes are also sampled and diagnosed to a limited extent, since the imaging and energy diagnostics can only view one pass for any particular shot. In addition, only the depolarized portion of the fourth pass is transmitted through the polarizer to the west cavity diagnostics.

At the output of the 1ω section of the laser, the beam is again sampled using the reflection off an uncoated

FIGURE 1. View of the Beamlet laser and the diagnostics systems. Dedicated diagnostics are located at both ends of the main cavity and at the output section prior to, and after, the frequency conversion crystals. An instrumented beam-dump calorimeter absorbs all of the remaining beam. (70-50-0395-0662pb01)

fused-silica beamsplitter (Fig. 1). This 1ω output package contains an extensive suite of diagnostics including energy, temporal pulse shape (diode and streak camera), low- and high-resolution near- and far-field imaging, phase front (Hartmann array and a radial-shear interferometer), and beam bandwidth (Fabry-Perot). Another large set of diagnostics are present in the $2\omega/3\omega$ diagnostics station that follows the frequency conversion section. This diagnostics package also includes a beam energy balance system that measures the absolute energy in each of the primary (1ω), doubled (2ω), and tripled (3ω) beams. The last diagnostics station consists solely of a single, large-aperture, 74-cm absorbing glass calorimeter that quantifies the combined output beam energy (minus, of course, the small amount of energy that is deflected to the previous diagnostics systems). This calorimeter also serves as a "beam dump."

Cavity Diagnostics

Cavity diagnostics are located at both ends of the main amplifier cavity, with the diagnostic transport shown in Fig. 2 for the east cavity diagnostics. For

diagnostic purposes, the cavity mirrors leak a nominal 0.4–1% of the incident beam and the transmitted beam passes through the uncoated backside and the antireflective (AR) coated 7.6-m focusing lens. The converging beam is folded twice by the upper and lower turning mirrors; attenuated by one or two 99.3% mirrors (Fig. 3); and split to the far-field camera, the near-field camera, and to an integrating sphere/photodiode energy diagnostic. The rejected beam from the first attenuator mirror is directed to a calorimeter and a temporal pulse-shape vacuum photodiode diagnostic. The cameras and integrating sphere are discussed here; the calorimeter and temporal diagnostics are discussed in subsequent sections. Figure 2 shows the east cavity diagnostics, including extensive baffling. This baffling prevents the intense off-axis flashlamp light, transmitted through the cavity mirror, from reaching the diagnostics.

The near-field camera (a Cohu 6400 series) images the cavity mirror directly onto the CCD camera through an attenuating protective window mounted on the camera's face. To achieve the right intensity, the beam is transmitted through filter-wheel-mounted neutral-density filters. These filters consist of AR-coated

FIGURE 2. Side view of the cavity diagnostic beam transport optics. The 0.5% leakage through the cavity end mirror is focused and folded down to the diagnostic package. The east and west end diagnostic transport optics are identical, but the east diagnostics are substantially baffled to prevent the light of the adjacent cavity amplifier flash lamps from saturating the diagnostics. (70-50-0494-1667pb01)

FIGURE 3. Top view showing the east cavity diagnostics. Attenuating filters, beam blocks, and pinholes strip off ghost images, select the desired cavity pass, and set the energy levels to each diagnostic. (70-50-0494-1666pb01)

31-mm-diam glass (NG-1, NG-3, NG-4, NG-5, NG-9, and NG-11). The image is viewed on the alignment display through the Beamlet video switching system for beam centering, with the attenuator mirrors replaced by identical AR-coated blanks. To capture the near-field image during a shot, the attenuator mirrors and filters are set to calculated values, and the 16-channel framegrabbing system is triggered to capture the image field at shot time. The near-field camera is quite useful for centering operations and for shots; however, automation of the attenuator mirror insertion is needed as Beamlet's shot rate increases. The camera images either pass 1 or pass 3 (pass 2 or pass 4 for the west cavity diagnostics) with automated selection between the passes. A stepper-motor-mounted pinhole array at the focus selects pass 1, pass 3, or both passes simultaneously, and strips off the unwanted image from the uncoated back surface of the cavity mirror.

The far-field camera has a complicated design to perform both the diagnostic and pointing functions. The compromised design limited its performance in diagnostic mode, and the pointing function was superseded by a telescope mounted at the cavity pinhole plane. The camera had two fields of view of the cavity spatial filter pinhole plane. The first field (a 4×4 cm image) viewed all four cavity spatial filter pinholes simultaneously for pointing purposes. The other field (a higher resolution 8×8 mm image) required manual replacement of several lenses, and viewed one pinhole at a time. To achieve the wide field of view required a fast lens mounted directly in front of the camera imaging surface. To do this, we glued the lens onto a faceplate ring that replaced the CCD protective cover. In addition, several oversized lenses were required to perform high-quality off-axis far-field imaging. We designed the far-field camera to perform Beamlet pointing in the wide field of view mode, an operation now routinely performed by the Questar telescope. For a time, the camera was used in shot mode, but the angular resolution was too small to be of much use. Thus, the camera was removed as Beamlet activation proceeded to, and beyond, the four-pass experiments.

During the activation stage, the integrating sphere energy diagnostic proved to be exceedingly useful and was instrumental in determining the plasma electrode Pockels cell performance in the west cavity diagnostics. The system consists of a Labsphere 4-in.-spectralon integrating sphere with an EG&G FND-100 Si photodiode reverse biased to 40 V and recorded by a Tektronix TDS-320 digitizing oscilloscope. The bias voltage is

coupled in by a Picosecond Pulse Lab bias tee, and the signal is terminated in $50\ \Omega$ at the oscilloscope. During initial activation, especially continuous-wave (cw) tests, a slower, more sensitive PIN-8 diode replaced the FND-100 photodiode. The PIN-8 diode was battery biased with the bias tee removed to transmit the 350- μ s gain test signal, and the signal was recorded by the TDS-320 in high-impedance mode. In later, more routine, system operations, the integrating sphere signals were recorded but were used largely in a qualitative sense. Software was developed to calculate the charge delivered by the photodiode from the recorded voltage waveform and to infer the energy from the calibrated sensitivity and system transmission. However, with our extensive use of inexpensive and very accurate calorimeters, the integrating sphere energy diagnostic was used only as a relative comparison between the passes and as a post-mortem for shots which did not perform as expected.

1 ω Output Diagnostics

A portion of the fully amplified Beamlet beam is sampled by a 61-cm beamsplitter and relay imaged to the 1 ω diagnostic station (Fig. 4). The beam sample is approximately 3% of the main beam from the 12° angle of incidence "P" reflection of the uncoated silica splitter. The sampled beam is propagated through an AR-coated, 920-cm, focal-length lens, and folded by three more in-plane reflections off a bare surface BK-7 splitter, and two high-reflectivity mirrors. A minimum of several joules of 1 ω light were required for high-resolution near-field imaging onto film in the original 1 ω diagnostics design. This design necessitated the incorporation of a vacuum cell at the transport focus. The vacuum cell was designed with a tilted, wedged input window to protect the folding mirrors and to eliminate fringing, and had a collimating lens at its output. It was extremely important to have a well-collimated, representative sample of the beam for the wavefront correction system (Hartmann sensor) and for the 1 ω far-field camera. To accomplish this, all flat optics leading to the collimating lens were mounted and interferometrically tested prior to installation. Mounting problems were corrected on several of the large splitters, which allowed us to achieve low-aberration transport to the diagnostic table.

The diagnostics transport enclosure contains the output 1 ω calorimeter as shown in Fig. 4, after three uncoated reflections to keep the calorimeter energy below 1 J. Calculating the Fresnel reflection from all three surfaces determines the transmission coefficient from the main beamline to the calorimeter.

Measurements were made to confirm these values. We changed the 12° angle of incidence for the large splitters to 12.2° due to a 14-cm shift of the 61-cm splitter midway through the frequency converter activation. This mitigated a collimated ghost reflection from the frequency converting crystals, which was reflected and focused by the spatial filter lens onto the splitter, causing damage. The increased angle changed the calculated transmission value by 0.4%. All the splitters were wedged to keep unwanted direct backside reflections and double bounce reflections from the three large splitters outside of the calorimeter aperture. The final uncoated splitter had a 2° wedge and a 0.1% AR coating on the backside, with the estimated overlap between the AR surface reflection and the calorimeter aperture of $<25\%$. The additional energy due to the reflection is $<0.7\%$. No unwanted energy from any of the other splitters fell within the calorimeter aperture.

Figure 5 shows the 1ω diagnostics that are located in a separate enclosure from the diagnostics transport optics to prevent scattered light from entering any of the sensitive diagnostics. After the beam enters the table, 10% of the beam is split off and directed to the wavefront control Hartmann sensor (located on the lower part of Fig. 5), and relayed to the Hartmann lenslet array and

camera. The rest of the beam passes through a path-compensating splitter, a 50% splitter, and a 1:1 vacuum relay. Several pointing and centering mirrors direct the beam from the 50% splitter to the 1ω far-field camera. Due to pointing problems, it was difficult to implement the far-field camera and it was also difficult to obtain attenuating filters with good optical quality. Most of the optical filters could be placed directly in front of the far-field camera, but enough attenuation had to be placed in the near-field filters to prevent damage to those in the far field. We selected Schott KG glass filters placed in front of the focusing lens, filters which could be checked for wavefront quality at 633 nm, yet are optically dense at $1.053\ \mu\text{m}$. These are the same filter types as used in the Hartmann sensor.

The far-field camera was used for some time at $f/100$, but was changed to the rattle pair configuration [Fig. 6(a)]. The rattle pair, based on a photographic film design originally prepared for Nova,² was adapted for use with the Beamlet high-resolution CCD cameras. The Beamlet design uses two pairs of wedged mirrors to create an array of far-field spots variable in both intensity and focus at the camera image plane [Fig. 6(b)]. The first pair of mirrors on the left side are 3-in.-diam partially (50%) reflecting mirrors, tilted to generate an array of

FIGURE 4. The main beam is relayed to the 1ω output diagnostics through a series of uncoated and high-reflector flat optics and is focused by a 9.2-m focal length lens. Up to 10 J is sent through focus in the vacuum cell and collimated. The system 1ω output calorimeter operates directly from three uncoated reflections. (70-50-0494-1682pb01)

spots at the image plane graded in intensity. The focusing lens has a focal length of 1800 mm and is followed by two more wedged mirrors, which have a 90% reflection from their facing surfaces. This second pair of reflectors acts to offset the focus in both angle and longitudinal dimension to take images of the far field through several focal planes. The spacing of the focal planes is adjusted by the spacing between the second pair of mirrors. All rattle pair elements were wedged by 2.4 mrad to mitigate the ghost images from the AR-coated transmission surfaces and were mounted in precision mirror mounts to facilitate system setup. The reflected wavefront quality is important since the beam is reflected numerous times from the same surfaces. To help maintain the wavefront quality, the beam size was kept small on the mirrors (18 mm square), and the mirror reflected wavefront was specified to $\lambda/11$ at $1.05 \mu\text{m}$, with a gradient $<\lambda/24/\text{cm}$. Excellent results were obtained from this system as described in "System Description and Initial Performance Results for Beamlet," p. 11. Using the rattle pair camera, we diagnosed dynamic focal plane shifts during a shot. This was a significant aid in correctly applying wavefront pre-correction for dynamic aberrations using the Beamlet Adaptive Optics System.

After the main beam passes through the 1:1 vacuum relay (Fig. 5), the recollimated beam is folded twice and directed back through a holographic beamsplitter (HBS)—designed to transmit most of the beam, while diffracting a small amount to either side for diagnostic purposes. The units transmit 10% of the beam energy

into the first order, 1% into the second, etc. This approach was chosen because multiple splitters would have steered the beam and caused unwanted reflections. Initial alignment was difficult, but the HBS performed well for all of the Beamlet activation sequence. Figure 5 shows a first-order beam from the first HBS directed to a vacuum photodiode temporal diagnostic. The photodiode signal is recorded by a Tektronix SCD-5000 transient digitizer for a combined rise time of 110 ps. In addition, the leakage through the second turning mirror, just ahead of the first holographic beamsplitter, is routed out of the diagnostics enclosure to a streak camera for higher-resolution temporal diagnosis. The zero order from the first splitter, which constitutes nearly 78% of the incident beam, is reflected off of a 97% splitter to the radial-shear interferometer and the Fabry-Perot bandwidth diagnostics. Originally, the near-field film camera for high-resolution imaging was to be at this location, but the performance obtained from the high-resolution CCD camera made the film camera unnecessary. The 14-bit dynamic range, 1024×1024 pixel, cooled scientific-grade CCD camera is over 10^6 more sensitive than film and has none of the inherent problems or delays associated with film densitometry. The remainder of the zero-order beam after the 97% splitter is passed through an AR-coated compensating splitter to the second HBS element. The zero order from the second element is relayed into the high-resolution near-field CCD camera, and a first-order beam is relayed to a standard-resolution near-field camera.

FIGURE 5. Beamlet 1ω output diagnostics include near- and far-field imaging, temporal pulse shape, wavefront, and beam bandwidth. The wavefront control system output sensor (Hartmann sensor) is also located on this table. (See Fig. 4 for the 1ω energy measurement.) (70-50-0395-0666pb01)

2 ω /3 ω Output Diagnostics

The 2 ω /3 ω diagnostic transport optics demagnify and relay all three wavelengths to the specific diagnostics as shown in Figs. 7 and 8. The transport optics use a bare-surface silica splitter identical to the 1 ω splitter, except the back surface has a 3 ω sol-gel AR coating. The splitter is oriented with a 25° angle of incidence, "P" polarized, with the diagnostic beam directed through a 900-cm focal length (at 1 ω) Beamlet spatial filter lens. The converging beam is passed through a 40-cm wedged silica splitter (the calorimeter splitter) with the uncoated front surface reflection sent to the energy balance calorimetry station (described below). The beam transmitted through the calorimeter splitter, which is AR coated on the back side with a compromise 2 ω /3 ω coating, is reflected in plane by a combination bare surface silica splitter and a 1 ω /3 ω high reflector in the lower vertical fold location. The converging 1 ω /2 ω /3 ω beams are then sent through the 3 ω splitter, with a sample of the beams split off by the uncoated front surface, folded by 1 ω /3 ω high reflectors, and sent to the 3 ω diagnostics. The beams are similarly folded to the 2 ω diagnostics with that splitter being a high reflector at 2 ω , and the folding mirrors being at least 95% reflective at both 1 ω and 2 ω to relay the 1 ω alignment beam to the 2 ω diagnostics. The remaining beam, transmitted through the 2 ω splitter, is relayed to a Cohu CCD camera and is used for system alignment.

The 3 ω beam was thoroughly diagnosed, with two near-field cameras, a far-field camera, a vacuum photodiode temporal diagnostic, and a streak camera temporal diagnostic. The energies were measured in the energy balance diagnostic station. The 2 ω beam near-field profile was also diagnosed on a regular basis. Schott filters [UG-5, KG-10, and VG-11 (a nonfluorescing filter glass

(a) Rattle pair arrangement

(b) Focal spots

FIGURE 6. Two mirrors arranged as "rattle pairs" and a focusing lens (a) project an array of focal spots onto the high-resolution CCD camera. These focal spots (b) are graded by intensity in one dimension and are different focal planes in the other dimension. (70-50-0395-0667pb01)

FIGURE 7. The doubled and tripled beam is focused and folded using uncoated and dichroic reflectors, and collimated after focus. The 1 ω light is transported to all locations for alignment purposes. A vacuum cell is not required, as the beams are attenuated sufficiently before focus. (70-50-0395-0668pb01)

for blocking 3ω)] were used to perform color separation of each diagnostic. We set the energy levels at each diagnostic using attenuating mirrors located just beyond the folding mirrors and by manually inserting neutral density filters.

The $2\omega/3\omega$ diagnostics station transport optics use the 1ω alignment beam to perform pointing and centering for 2ω and 3ω diagnostic paths. We employed dichroic transport mirrors to transmit sufficient 1ω light intensity, an achromatic relay system, and a manually insertable collimation lens (Fig. 8). The design worked well for alignment, but did not determine the near-field camera image planes. The depth of focus at the aperture size of the Cohu 6400 series camera is very small, so calculated locations could not be practically used. A temporary alignment beam, a tripled Nd:YAG, injected into the output spatial filter solved this problem. We located the tripler array image plane on each camera at its design wavelength. Another complication was that the pointing for the three wavelengths was slightly different after passing through the wedged optics, including the large calorimeter splitter. For high angular resolution far-field imaging, we offset the alignment focal spot so that the shot focus would fall within the camera's field of view.

Energy Balance Diagnostics

An accurate energy balance is extremely important to understanding Beamlet operation. A good measure of the absolute energy in each of the three wavelengths, following frequency conversion, impacts decisions and conclusions on frequency converting crystal orientation, 1ω beam divergence, conversion efficiency, and a host

of other laser and frequency conversion parameters. Figure 9 shows the energy balance calorimetry station. The beam from the main $2\omega/3\omega$ uncoated silica splitter is directed to the dispersing prisms after passing through the focusing lens and reflecting from the uncoated silica calorimeter splitter. We used two uncoated silica prisms, each with a 40° apex angle, to achieve a total deviation of 38.9° , 39.9° , and 41.4° for the $1\omega/2\omega/3\omega$ beams, respectively. We use two prisms instead of one because of the thickness limitations of commercially available silica blanks. The pair of prisms are located at a distance

FIGURE 9. The Beamlet energy balance diagnostic relies solely upon uncoated surface reflections to attenuate the beam below 1 J into the calorimeters. Chromatic dispersion is accomplished with two 40° uncoated fused silica prisms, with the total path attenuation calculated from the measured beam incident angles. The sum of the calorimeter energies is routinely within $\pm 2\%$ of the 1ω output calorimeter. (70-50-0395-0670pb01)

FIGURE 8. Beamlet 3ω diagnostics consist of near- and far-field imaging and temporal pulse-shaping, as well as housing the system alignment camera. (70-50-0395-0669pb01)

from the focusing lens where the beam size allows them to be reasonably small, yet far enough from the calorimeters such that the beams become sufficiently separated. The prisms are mounted on rotation stages with 1 min of resolution, and are aligned to a 30° angle of incidence from the input beam. The dispersed, converging beams are then propagated to a series of uncoated silica 20° wedges that direct the beams into a calorimeter for each of the three wavelengths. We chose the final wedges to ensure that only the first surface reflection would be reflected into the calorimeter.

Altogether, the converging beams undergo three uncoated reflections and are attenuated by about 2×10^{-5} to avoid the possibility of damage to the calorimeter absorbing surface. Using the 1ω alignment beam, all three calorimeters were aligned by rotating the dispersive prisms by a prescribed amount to deviate the 1ω beam along the 2ω path or 3ω path, respectively. The distance used from the main focusing lens is a calculated value. We used exposed polaroid film in a plastic cover taped over the calorimeter input apertures to confirm the beam size and alignment on a shot. The beam size and locations were exactly what we specified. On the system shots, the sum of the energy balance calorimeters and the other two output calorimeters agreed to well within $\pm 5\%$ (described in the calorimetry section).

Beam-Dump Calorimetry

Figure 10 shows the beam-dump calorimeter—the final diagnostic on the Beamlet beam that absorbs all the remaining 1ω , 2ω , and 3ω light. After the main Beamlet beam goes through the $2\omega/3\omega$ splitter, it passes through a silica beam expander lens and on to the beam-dump calorimeter. The unit has a 74-cm square aperture, and uses Schott NG-4 glass to absorb all three wavelengths without being damaged by the maximum fluence of any of the wavelengths during the various phases of Beamlet operation.

FIGURE 10. Diverging silica lens directs the remaining $1\omega/2\omega/3\omega$ beam onto the absorbing glass of the beam-dump calorimeter. It is a 74×74 cm² design capable of absorbing and diagnosing the full Beamlet output energy at any combination of wavelengths. (70-50-0395-0671pb01)

Calorimetry and Imaging Components

The following sections describe the design, calibration, and performance of the calorimeter components and the imaging components, respectively.

Calorimetry

All of the absolute energy diagnostics on Beamlet consist of absorbing glass calorimeters. A temperature change, due to absorbed laser energy, is measured by thermocouples and is read out by precision nanovoltmeters at a 2-Hz rate. To avoid relying on one model or algorithm, we used three different calorimeter models to measure absolute energy output: (1) The Scientech model 38-0111 (a surplus from Nova) obtained from the Optical Sciences Laboratory; (2) the Scientech model 38-0101 with NG-1 and NG-4 glass to use at all three wavelengths after the frequency converters; and (3) the beam dump calorimeter to absorb the full Beamlet output at all three wavelengths, installed in the main beamline following the fused silica expansion lens.

1ω Output Calorimeter

The calorimeters in the cavity diagnostics and the 1ω output diagnostic stations are 1-in.-aperture Scientech model 38-0111 that have a $1/e$ decay time of 160 s. The voltage from these devices is of the order of a few to several hundred microvolts, with a sample voltage waveform shown in Fig. 11. To determine the incident energy, the step voltage as determined by the difference between two linear fits (see Fig. 11) was multiplied by an experimentally determined calibration factor. The preshot baseline fit was performed over a

FIGURE 11. Calorimeter waveform for an 8.85-kJ shot. The voltage step is determined between two least-square line fits before and after shot time. The voltage difference is calculated when the rising edge is at the 50% level. Shot energy is then inferred from the calorimeter calibration and optical transport attenuation. (70-50-0395-0672pb01)

60-s interval prior to shot time, and the post-shot fit over a 90-s interval starting 7 s after the shot. This gave the energy on the calorimeter, and the energy in the main beam was inferred from the calculated and measured transmission coefficients of the transport optics.

We used two methods to calibrate the model 38-0111 calorimeter: (1) Using the electronic heater in the calorimeter head for electronic calibration, and (2) by comparison to an optical calorimeter transfer standard from the National Institute of Standards and Technology (NIST). To perform the electronic calibration, we measured the internal heater resistance using the 4-wire technique, then injected a known current over a precise time interval. The amount of injected energy was simply

$$E = I^2 R \Delta t, \quad (1)$$

where I is the injected current, R is the heater resistance, and Δt is the current pulse width. The voltage waveform was captured in the voltmeter measurement buffer (512 measurements long) and analyzed using the Macintosh/LabVIEW systems. The analysis program automatically finds the shot time by searching for the step change and calculating the preshot and post-shot linear fits using predetermined intervals prior to, and after, shot time. Voltmeter resolution was 100 nV, which corresponded to approximately 150- μ J energy resolution. After compensation for the Fresnel loss of the calorimeter's uncoated NG-1 absorber, we calculated an equivalent optical calibration factor K in microvolts/joule.

To perform optical calibration we reflected a short pulse from a Nd:YAG laser off an approximately 50% transmission beam-splitter onto the NIST transfer standard calorimeter and transmitted the remaining 50% of the beam to the calorimeter under test. The fraction of energy split to each of the calorimeters is given by

$$E_{\text{ref}} = \beta E \quad (2)$$

and

$$E_{\text{cal}} = \alpha E = KV \quad (3)$$

where α and β are unknown, E_{ref} is the energy incident upon the NIST calorimeter, E_{cal} is the energy incident

upon the calorimeter under test, K is the undetermined calibration factor, and V is the voltage step for a particular shot. Manipulating these equations, a constant C_1 can be defined as

$$C_1 = K \frac{\beta}{\alpha} = \frac{E_{\text{ref}}}{V}. \quad (4)$$

A series of measurements of E_{ref}/V determined C_1 . Then, the NIST calorimeter and the calorimeter under test were exchanged such that the NIST calorimeter was on the αE split and the calorimeter under test was installed in the βE split. Another series of measurements of E_{ref}/V determined constant C_2 , which was similarly defined as

$$C_2 = K \frac{\alpha}{\beta} = \frac{E_{\text{ref}}}{V}. \quad (5)$$

The calibration constant for the calorimeter under test was then determined from

$$K = \sqrt{C_1 C_2}. \quad (6)$$

Note that this calibration technique is entirely independent of the shot-to-shot repeatability of the laser source, does not require knowledge of the splitter ratio, and does not require that the splitter and transport paths be lossless ($\alpha + \beta$ does not have to equal 1). The optical and electrical calibrations are in excellent agreement between the two techniques ($\pm 1.5\%$).

Energy Balance Calorimeters

The Energy Balance Calorimetry station uses the 1-in. Scientech model 38-0101. It has a $1/e$ time constant of 16 s, which is too fast to use the linear extrapolation method previously described. For these calorimeters, the main problem with backward linear extrapolation is the extreme sensitivity to shot time determination. Therefore, we used an alternative method, where we integrate the area under the curve—the volt-seconds of the voltage waveform. As before, we use an edge-detection algorithm to find shot time and then integrate over a 70-s interval starting at shot time (the same used for calibration). An issue with these calorimeters is the baseline drift, due to temperature fluctuations within the laser bay, similar to the slower model 38-0111 calorimeters. The baseline drift is quantified using an algorithm to interpolate between the baseline value

measured before and after the laser shot. The incident energy is then calculated from the total integrated calorimeter signal voltage (minus the correction for baseline), and the integrated signal is related to the laser energy using a calibration constant.

Because of the excellent agreement between electrical and optical calibration demonstrated on the model 38-0111 calorimeters, only electrical calibration was performed on the model 38-0101 calorimeters. While the electrical calibration values were not as repeatable as the slow-decay-time model 38-0111 calorimeters, they still provided results well within the requirements for the Beamlet diagnostics.

Beam-Dump Calorimeter

The beam-dump calorimeter, designed and fabricated using Nova's 74-cm calorimeter as a guide, absorbs the full Beamlet energy at all three wavelengths. The main absorbing element is a 76-cm-square, 0.25-in.-thick Al plate, tiled with 4-mm-thick, 6-in.-square panes of NG-4 absorbing glass. The glass thickness was selected to attenuate incident 1ω energy to $<25 \text{ mJ/cm}^2$, which is 10% of the level at which damage to the glue holding the absorbing glass has been known to occur. For this reason, we chose 4-mm-thick NG-4, which is just sufficient for full energy 1ω shots, yet has enough absorption depth at 2ω and 3ω full-energy shots to avoid surface damage. The sensing elements are type K thermocouples glued in a 7×7 array on the back side of the Al plate, wired to reference thermocouples attached to a dummy plate located in the back of the calorimeter body. The thermocouples are standard types from Omega, and are glued to the Al using a high-thermal-conductivity epoxy and are electrically wired in series using similar-metal terminal blocks. The only unwanted thermocouple junctions are where the output connector copper wires connect to the first and last thermocouple leads on one of the terminal blocks. Those connections are adjacent to minimize temperature differences. The entire absorbing plate assembly is mounted using insulating spacers to a support structure, designed to provide protection from air currents.

We use NIST traceable standards and a high-power laser to perform full-scale optical calibration in the Nova calorimeter calibration facility. To achieve reasonable signal levels, approximately 500 J in 1 s was directed onto the calorimeter in a round beam (unlike the square Beamlet beam). This was sufficient to obtain about $70 \mu\text{V}$ for calibration, and resulted in a calibration factor of $0.1417 \mu\text{V/J}$. This calibration factor was about 2% higher than that determined using standard Nova waveform analysis methods, a difference due to how the voltage waveforms are interpreted. In Nova, the voltage step is calculated by the difference between the peak of the voltage waveform and the extrapolated baseline. For Beamlet, the voltage step is calculated by the difference

between the linear least-square fit of the baseline before the shot, and the linear fit of a waveform segment after the shot. This difference is calculated at the time when the voltage waveform is half of its peak value. The Beamlet analysis technique has the advantage of averaging many measurements during the voltage waveform decay.

Calorimeter Performance

The performance of the calorimeter system was repeatable to better than $\pm 2\%$ for the model 38-0101 calorimeters and approached $\pm 1\%$ for the model 38-0111 calorimeters during calibration. To test this, we compared their performance during system operation using calculated and measured transmission values to propagate the energy results back to "standard" beam-line locations. Comparison between the 1ω output calorimeter and the energy balance calorimeters was done at the first surface of the $2\omega/3\omega$ calorimeter splitter. Comparison between the energy balance calorimeters and the beam dump calorimeter was made at the surface of the beam dump calorimeter.

Figure 12 compares the calorimeters for a series of shots taken in August and September, 1994. We met our original specification for the Beamlet calorimetry system, which was to achieve better than $\pm 5\%$ absolute accuracy. The most remarkable observation about the agreement is that three totally independent calorimeter systems, two separate analysis algorithms, and three separate calibration systems were used to achieve this level of accuracy. Because of this agreement, the Beamlet project scientists can report on laser and frequency converter performance with a high degree of confidence.

FIGURE 12. Comparison between the three output calorimeter systems for a sequential series of Beamlet shots in August and September 1994. Shown are the ratios of the measured energies between the 1ω output calorimeter, sum of the energy balance calorimeters, and the beam-dump calorimeter. In all cases, the sum of the energy balance calorimeters agrees with the other two systems to better than 5%. (70-50-0395-0673pb01)

Imaging Diagnostics

Imaging of the laser beam is done extensively on Beamlet. This is of great importance for diagnosing the beam during the four passes in the main cavity and out through the booster amplifier. In the cavity diagnostics, near-field imaging of the beam at the cavity mirrors is useful for preshot beam centering, for measuring the spatial beam profile in the various passes, and for measuring the extinction of the plasma-electrode Pockels cell during the fourth pass. In the output 1 ω diagnostics, the near-field image at the frequency converter crystals is vital for ensuring that the beam intensity profile converts efficiently and that damaging intensity modulation is not present in the beam. Imaging of the beam at focus is also done in the 1 ω output diagnostics to understand the quality of the beam phase-front before conversion. After frequency conversion, both near-field and far-field images of the beam at 2 ω and 3 ω are taken, and prove to be very useful to understanding the performance of the laser system and the frequency converter crystals. All of the images use CCD cameras/framegrabbers or dedicated high-resolution scientific-grade CCD cameras.

The standard-resolution cameras we use in all the diagnostic packages are Cohu 6400 remote head CCD cameras, which have a $6.4 \times 4.8 \text{ mm}^2$ active area, and have 739 wide $\times$ 484 high picture elements. The model 6400 is a frame transfer camera, where the charge storage cell is shared between adjacent horizontal lines. Because of this, only 242 horizontal lines have shot data available for analysis from the framegrabber system. We investigated the use of the interline transfer camera, which is a microlensed CCD chip incorporated into certain models of Cohu and Pulnix cameras. The camera can be configured to integrate over 1/30 s and has the complete image frame in consecutive field transfers that can be merged in software. Another camera type from Cohu, which has a frame transfer CCD chip with dual charge storage cells, also outputs two consecutive fields (a full frame) with image data from a shot. However, it would have required development work by the manufacturer of the framegrabber/analysis system. We therefore stayed with the standard system that produces images with a spatial resolution of 240×240 pixels, digitized 8 bits deep (identical to the Nova framegrabbing system). Higher spatial resolution is somewhat of a liability because of the increased storage space requirements and slower image analysis.

We perform high-resolution imaging using a Macintosh-controlled scientific-grade CCD camera. The camera has 1024×1024 pixels digitized 14 bits deep, and is Peltier cooled to -55°C for low noise integration and readout. It is especially useful in replacing the original film-based camera systems in the 1 ω diagnostics, because film has poor sensitivity at $1.054 \mu\text{m}$. An additional advantage of the high-resolution

camera is that the results are immediately available for analysis. It was also used for high-resolution surveys of Beamlet using the alignment beam, where the high dynamic range proved extremely valuable. Because of our positive experience with these cameras, we purchased an additional camera, 512×512 pixels, which has a full 16-bit dynamic range.

Data Acquisition System

The Beamlet data acquisition system consists of a SUN Sparc Station operating LabVIEW software to control all the laser diagnostics. There are six types of diagnostic devices interfaced to this system: the Tektronix TDS-320 oscilloscope and SCD-5000 transient digitizer, HP 34401A and HP 3478A voltmeters, IO-Tech digital IO box, and Kiethley 220 current source. The streak camera and high-resolution camera are operated in standalone mode, although the streak camera is initiated by the system trigger, and the high-resolution camera uses a software trigger through the IO-Tech box over the GPIB network.

The National Instruments LabVIEW control system is used to provide setup, control, data acquisition, and analysis. Before a shot, each diagnostic has to be specifically activated and in some cases software-triggered. After everything is set up, the diagnostics operator selects a particular menu item to inform shot control that the diagnostics are configured and ready for the shot. Upon initiation of the main capacitor bank charge, the diagnostics control software interprets the shot state and takes background data on all the calorimeter channels; the shot either occurs before the voltmeters run out of buffer space or else is aborted. Following the shot, the acquisition system pauses until the calorimeter voltmeters have completed acquisition and then polls the diagnostics for data. The system acquires all the data from the remote devices, stores it to disk, then retrieves it for analysis. Thus if there is a storage problem, it is discovered immediately and steps can be taken to retrieve the data again from the instruments. Data analysis is limited to basic waveform analysis of the energy diagnostics, calculation of the round-trip cavity system gain, and display of the oscilloscope traces.

Imaging diagnostics, other than the high-resolution camera, is operated by the Coherent Big-Sky system,⁴ which performs framegrabbing on 16 channels, simultaneously. All of the cameras in the diagnostics system are routed to the 30×30 video switcher, which supplies the video signals to the Big-Sky system. The Big-Sky system receives a system trigger to select which frame to grab. After the shot, the diagnostic operator manually saves the results on the Big-Sky computer and transfers the video files to the SUN system for storage and archiving.

Summary

We developed a comprehensive set of diagnostics for the Beamlet laser system to provide all of the information necessary for determining the laser performance. Optical transport systems for demagnifying laser beam samples in four separate diagnostics stations demonstrate low-aberration performance, which is key to obtaining far-field images of the 1ω beam at the output section. The primary energy diagnostics, absorbing glass calorimeters, are installed throughout the system and demonstrate outstanding accuracy and reliability. Calibration repeatability is well within $\pm 1\%$. New acquisition methods, such as using voltmeters to replace the Nova calorimeter amplifiers and analysis techniques adapted from the Optical Sciences Laser, enable us to achieve agreement between multiple calorimeters of much better than $\pm 5\%$. The imaging diagnostics make wide-scale use of CCD cameras, with nearly half the number of installed cameras as the Nova system. Beamlet is also the pioneer in using high spatial-resolution and high dynamic-range, scientific-grade CCD cameras to replace film for beam profiling and far-field imaging. The diagnostics were activated on time and were key to achieving the Beamlet performance goals.

Acknowledgments

We thank the optical engineers D. Aikens, K. Moore, and W. Whistler, who designed and procured the large number and variety of optical elements required by Beamlet diagnostics. We give special thanks to R. Speck for his excellent analysis, where he compared the different system calorimeters and obtained the outstanding results shown in Fig. 12.

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MODELING BEAM PROPAGATION AND FREQUENCY CONVERSION FOR THE BEAMLET LASER

J. M. Auerbach

Introduction

The development of the Beamlet laser has involved extensive and detailed modeling of laser performance and beam propagation to: (1) predict the performance limits of the laser, (2) select system configurations with higher performance, (3) analyze experiments and provide guidance for subsequent laser shots, and (4) design optical components and establish component manufacturing specifications.

In contrast to modeling efforts of previous laser systems such as Nova,¹ those for Beamlet include as much measured optical characterization data as possible. This article concentrates on modeling of beam propagation in the Beamlet laser system, including the frequency converter, and compares modeling predictions with experimental results for several Beamlet shots. It briefly describes the workstation-based propagation and frequency conversion codes used to accomplish modeling of the Beamlet.

Propagation Modeling

PROP92 is the new family of single-wavelength propagation codes. It includes PROP1, a code for one-dimensional geometries; PROP2, a code for two-dimensional geometries; and HANK (derived from the HANKEL transforms), a code for circularly symmetric geometries. Multi-wavelength processes, such as frequency conversion, are modeled using other codes. Phase retardation, due to the nonlinear index of refraction, is the only nonlinear process modeled in the PROP92 set of codes. The linear processes that are modeled include bulk and reflective losses and the refractive index effects on propagation length. Amplifier gain is modeled by treating laser slabs as Frantz-Nodvick saturable amplifiers. The codes can thus model spatially varying gain, depletion of gain due to energy extraction, and saturation effects at high extraction.

The "chain editor" is a powerful feature of the PROP92 codes, which allows a complex laser system to be described using a compact, simple input format. By using simple path definitions, the laser beam can be propagated in a multitude of different paths. This is especially useful for Beamlet, which consists of a multipass amplifier cavity that uses a Pockels cell and polarizer to switch the beam out of the cavity.

A useful feature of the PROP1 and PROP2 codes is their capability to assign measured spatial distributions of gain, transmission, or phase to each optical component, which is crucial to accurate modeling of laser systems. Spatial gain distribution measurements of the interior and end slabs of the Beamlet amplifier are discussed in detail in "Design and Performance of the Beamlet Amplifiers," p. 18. (Specifically, Fig. 4 of that article illustrates the diamond, interior, and X slab configuration.) This data is stored in three files—one corresponding to the interior slab and one for each end slab configuration. In a PROP1 or PROP2 input file, each file is assigned to the corresponding amplifier slab defined in the system configuration file.

The phase aberration data consists of two main parts: (1) dynamic or "pump induced" aberrations that are a result of thermally induced distortions produced by flash-lamp pumping of the laser slabs, and (2) static distortions that arise from optical inhomogeneities in the bulk optical material or surface imperfections caused by the finishing process. Beam-steering measurements have been performed to determine the pump-induced aberrations in each amplifier slab configuration as discussed in "Design and Performance of the Beamlet Amplifiers," p. 18. The static aberrations of amplifier slabs, potassium dihydrogen phosphate optical switch and converter crystals, and other optical components have been measured using phase shift interferometry. The phase map data are stored in files and can be

arbitrarily assigned as an aberration to an optical component. These phase maps range in size from 40 cm $\times$ 40 cm to 3 cm $\times$ 3 cm. The larger maps contain phase data with ripple scale lengths resolved to a few millimeters. The smaller phase maps contain phase data with ripple scale lengths resolved to less than a millimeter.

Transmission masks can also be used by the codes to simulate the effects of various apertures in the propagation path. The most important application for a transmission mask is to model a beam apodizer. For example, the input apodizer for Beamlet is a serrated aperture. The Beamlet input list references a file that holds a transmission mask for a serrated aperture.² This mask file was created using a code specifically designed to create serrated aperture transmission patterns.

The PROP1, PROP2, and HANK codes are also capable of including spatial filter/optical relay information. The spatial filter is the optical component used to reduce or eliminate optical component noise. It consists of a set of confocal lenses and a pinhole. The pinhole can be circular or rectangular in shape. The parameters for defining the filter in the model are the focal length of the input lens, the magnification, and the size and shape of the pinhole.

In Beamlet's front end, there is an additional beam-shaping component, called a gain compensator mask, that compensates for the amplifier slab gain roll-off due to amplified spontaneous emission. In the following examples, the gain compensator produces a spatially flat intensity distribution in the output beam. Figure 1(a) shows a calculated beam profile after it has passed through a compensator mask transmission profile, which is parabolic in the x -direction and uniform in the y -direction. The minimum transmission of the mask is 0.3 and the spatial separation between the 0.3 transmission point and the near unity peak transmission is 1.5 mm. Figure 1(b) shows the measured profile of a continuous-wave laser beam after it has passed through one of the actual masks used in Beamlet.

To illustrate the capability of the PROP92 codes, we modeled the 1.053- μ m propagation through Beamlet using PROP2. The simulation corresponds to an actual experiment in which Beamlet produced 6.6 kJ of energy at 1.053 μ m in a temporally flat pulse of 3 ns duration. Figure 2 shows a schematic of the laser system. The simulation starts at the serrated apodizer and ends at the input to the frequency converter. An output fluence of ~ 9 J/cm² is specified for a temporally flat pulse shape. PROP2 automatically calculates the input fluence and the temporal shape of the input pulse required for these output conditions.

In the PROP2 simulation of Beamlet, the following "real" optical component characteristics were used:

- Small signal gain profiles for the amplifier slabs,
- Pump-induced aberrations for the amplifier slabs,
- Static, large-scale ($L > 1$ cm) aberrations for the amplifier slabs, and
- Static aberrations ($L > 2$ mm) for the optical switch.

FIGURE 1. Comparison of (a) the modeled and (b) the measured transmission profiles of a continuous-wave laser beam through the gain compensation mask in the front end of Beamlet. (70-35-0195-0319pb01)

In the actual Beamlet, the amplifier slabs also have minor small-scale phase aberrations ($\sim\lambda/100$ peak-to-valley) that cannot be included in the modeling because of grid size limitations. Hence, we expect to see *less* small-scale modulation on calculated beam distributions as compared with actual beam distributions. In addition, PROP2 does not account for small obscurations that result from dust, scratches, or other minor imperfections in, or on, the optical components. These imperfections can lead to spikes in the fluence distribution.

Figure 3(a) shows the PROP2 calculated 1ω fluence central spatial x-profile at the laser system output, which is at the input plane of the frequency converter. The modulation at the top of the profile consists of both small- and large-scale phase aberrations. The small-scale modulation is due to the small-scale aberrations associated with the optical switch. The large-scale modulation is associated with pump-induced aberrations and large-scale static aberrations assigned to the amplifier slabs. Figure 3(b) shows the corresponding measured near-field fluence profile. Note that the measured small-scale modulation is larger than predicted with the model (not all the small-scale noise sources are included in the model). Large-scale modulation for both

the measured and calculated profiles are comparable.

To further illustrate Beamlet's modeling performance, we present the calculated and measured output fluence distributions of a Beamlet high-energy shot. In this case, the output pulse has an energy of approximately 12 kJ and a 3.0-ns flat temporal shape. Figure 4 shows the calculated and measured central vertical profiles of fluence. The measured profile has more small-scale modulation than the model results since all small-scale phase noise sources could not be included in the calculation. Figure 5 shows the histogram based on calculated fluence data and the histogram based on measured fluence data at the input to the frequency converter. Note that the measured histogram has a higher peak abscissa value than the calculated histogram. We attribute the difference in the histograms to the fact that the phase noise source for the model does not contain all the noise sources that exist in Beamlet.

Frequency Conversion Modeling

To complement the PROP92 propagation codes, we have developed a family of codes to model frequency tripling in a dual-crystal scheme. The results have been

FIGURE 2. Schematic of the propagation path through the Beamlet laser system showing all the components from the serrated aperture in the front end to the frequency tripling system. This diagram shows optical components traversed by the beam during each pass. (70-35-0494-1900pb01)

in excellent agreement with the experiment. These codes have the following modeling capabilities for two-crystal conversion schemes:

- Frequency tripling of plane-wave, steady-state electric fields;
- Frequency tripling of plane-wave, time-varying electric fields—to model beams with applied bandwidth; and
- Frequency tripling of spatially varying (two transverse dimensions) steady-state electric fields—to model tripling of 1ω field distributions calculated by the PROP2 propagation code.

The codes account for the following physical processes and parameters: (1) Three-wave mixing (frequency doubling and frequency tripling), (2) nonlinear index phase retardation (B-integral), (3) paraxial diffraction and walkoff (spatially varying fields), (4) dispersion (temporally varying fields), (5) crystal bulk losses and surface reflections, and (6) crystal surface roughness (spatially varying fields). Item 6 is extremely important in modeling of 3ω beam transport after the converters. Small-scale phase ripples on the 3ω beam convert into intensity ripples by diffraction and nonlinear processes in 3ω transport optics. These intensity ripples and the associated nonlinear growth can lead to optical damage or poor focusability of the beam, or both.

FIGURE 3. Comparison of (a) the modeled prediction and (b) the measured horizontal intensity profile at the input to the frequency converter. The predicted mean output fluence is approximately 9 J/cm² at a pulse width of 3.0 ns and energy of 6.8 kJ. This compares with the measured energy of 6.6 kJ at a pulse width of 3.0 ns. (70-35-0195-0320pb01)

FIGURE 4. Comparison of (a) the modeled and (b) the measured horizontal intensity profile at the input to the frequency converter. The predicted mean output fluence is approximately 12 J/cm². The output pulse is temporally flat with a width of 3.0 ns and an energy of 12.6 kJ. This compares with the measured pulse of 12.0 kJ at a pulse width of 3.0 ns. (70-35-0195-0318pb01)

The time-dependent plane-wave code was used to model Beamlet's 3ω output for a 1ω temporally flat input beam that is phase modulated at 30 GHz bandwidth and has a 1ω intensity range of 2–4 GW/cm². Figure 6 shows the calculated 3ω conversion efficiency as a function of 1ω intensity for the case of no-added bandwidth and 30-GHz bandwidth phase modulation. It also shows the measured 3ω conversion efficiency values. The departure at high intensities between calculated and measured values is attributed to spatial intensity and phase variations in the actual beam compared with the ideal plane wave assumed in the model. Also, at high intensities, conversion efficiencies are more

sensitive to crystal detuning errors. In the model, we assume a fixed set of detuning angles designed to give the maximum conversion efficiency. However, experimentally the crystal detuning angle is varied to try to achieve an optimum mix-ratio and conversion efficiency. The precision with which the crystal detuning angles can be set experimentally is limited by the accuracy of the crystal mounts and the accuracy with which the exact phase matching angle of the crystal can be determined.

We have also used the frequency conversion code that allows transverse spatial variation in the electric field to model the near-field 3ω intensity profile at the output of the Beamlet tripler. Figure 7 shows these results compared with the actual measured output. In this case, the mean input drive intensity is approximately 3 GW/cm² in a 3-ns square pulse and the measured conversion efficiency is about 80%. On average, the two profiles have the same amount of modulation, but their shapes are different since the calculation of the model input 1ω beam does not include all the optical component phase and noise sources that exist in the actual Beamlet laser system.

FIGURE 5. Comparison of (a) the modeled and (b) the measured fluence histograms for the Beamlet performance with a 3.0-ns temporally flat pulse with an energy of approximately 12 kJ. The histogram for the measured data has a higher peak abscissa value since the model does not include all noise sources. (70-35-0195-0321pb01)

FIGURE 6. Calculated and measured values of 3ω conversion efficiency as a function of input 1ω intensity with 30 GHz of bandwidth applied to the 1ω input beam. (70-50-1094-3624pb02)

FIGURE 7. Comparison of (a) the modeled prediction and (b) the measured conversion efficiency for the 3ω fluence profiles at the output of the tripler crystal. (70-35-0195-0323pb01)

Summary

A new family of propagation and frequency conversion codes has been used to model Beamlet's performance. These codes incorporate many of the actual measured characteristics of the optical components. In general, the results of the model calculations are in good agreement with the measured Beamlet performance. The models have also proven to be a reliable tool for planning and guiding the experimental program.

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FACILITY REPORT

OCTOBER–DECEMBER 1994

G. L. Tietbohl

Nova Operations Group

Nova Experiments Group

Laser Science Group

During this quarter, Nova Operations fired a total of 252 system shots resulting in 308 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser experiments, Laser Sciences, and facility maintenance shots. Only four of these experiments were classified.

The fail-safe chirp system was successfully demonstrated. The system produces a small frequency "chirp" on the laser pulse that spoils stimulated Brillouin scattering (SBS) induced in the large-aperture chamber optics when operating with long pulses of high energy at 3ω . High levels of SBS can damage the final focus lenses and therefore limits the amount of energy we can direct into the chamber for use in target experiments. The fail-safe chirp system will allow us to increase the current energy limit by about 33% at a 3-ns pulse length.

Effort continued in support of the Petawatt Laser Project, which involves the modification of a Nova beamline and development of the necessary technology to produce a short-pulse beam on-target in the 10-beam chamber of ~ 1000 J at 1 ps. Beam transport experiments to the 2-beam target area were performed using the Petawatt laser front end as the pulse source with amplification through the Nova laser chain. The purpose of these experiments was to measure the spectral, temporal, and spatial modification of a broadband, linearly chirped pulse as a function of laser energy. Beamline 6 (BL-6) of Nova was configured according to the Petawatt design to produce a high-spatial-quality 40-cm-diam

beam at the output of the laser chain. This included removal of the 46-cm amplifiers and spatial filter #6 on this beamline.

The Petawatt configuration of BL-6 significantly improved the beam quality relative to conventional Nova operation. Preliminary analysis indicates a far-field spatial distribution at the 2-beam chamber of approximately three times diffraction limited for the first shot of the day. Convection currents induced by temperature gradients in the disk amplifiers severely degraded the beam quality on subsequent laser shots.

Significant spectral and temporal reduction of the pulse was observed on propagation through Nova. This bandwidth limitation arises due to passive components in the Nova chain. Gain narrowing of the spectrum was also observed with increasing pulse energy at the predicted level. The impact of convective currents on the Petawatt beam quality should be minimized in an alternative configuration of Nova with spatial filter #6 left in place. This concept will be tested on an upcoming Nova/Petawatt shot series.

Engineering effort continued on the Petawatt project. A component design review was held on the vacuum compressor vessel, an aluminum chamber ~ 2.7 m across $\times$ ~ 12.8 m long. This vessel will house large-diam (94-cm) gratings for use in pulse compression. We plan to have the chamber installed in the 10-beam bay and demonstrate Petawatt capability by the end of FY 1995. Modifications to the 10-beam chamber to use the Petawatt beam in target experiments will be done in FY 1996.

A final design review was held on the 100-TW system for use on the 2-beam target chamber. This system will use a pulse from the Petawatt master oscillator with some non-Nova amplification to produce a beam on-target of ~36 J at 400 fs (or ~30 J at 300 fs using mixed glass in the amplifiers). The system will be used for investigation of ignitor concepts and compressed-pulse issues prior to installation of the Petawatt system on the 10-beam chamber. Fabrication of the large vacuum vessel began, all the major optics were ordered or bid, and many other off-the-shelf items were ordered. Completion is scheduled for the 3rd quarter of FY 1995.

Effort continued on converting x-ray pinhole cameras from film to CCD data recording. One system has been installed on the Nova target chamber and has recorded many images on a variety of target shots. Software has also been developed to process the raw data and more quickly determine beam offsets for use in precision pointing. The system lacks only a communication link

to the open lab net to become a routine instrument on Nova. A second camera is planned to be installed on the chamber in the 3rd quarter of FY 1995 and will have the ability to change filtering as well as magnification without venting the target chamber. The first camera will then be retrofitted to incorporate this same capability.

We are working on improving the resolution of our gated microchannel plate detectors used in many of our x-ray diagnostics. The armed forces have shown an interest in this technology, as it is also applicable to night vision goggle detectors.

Most of the Nova operations personnel attended Total Quality Leadership classes sponsored by Allied Signal Corporation (the Nova facility contractor). These classes are intended to aid in team interactions, help understand performance measures, and improve overall Nova productivity.

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