#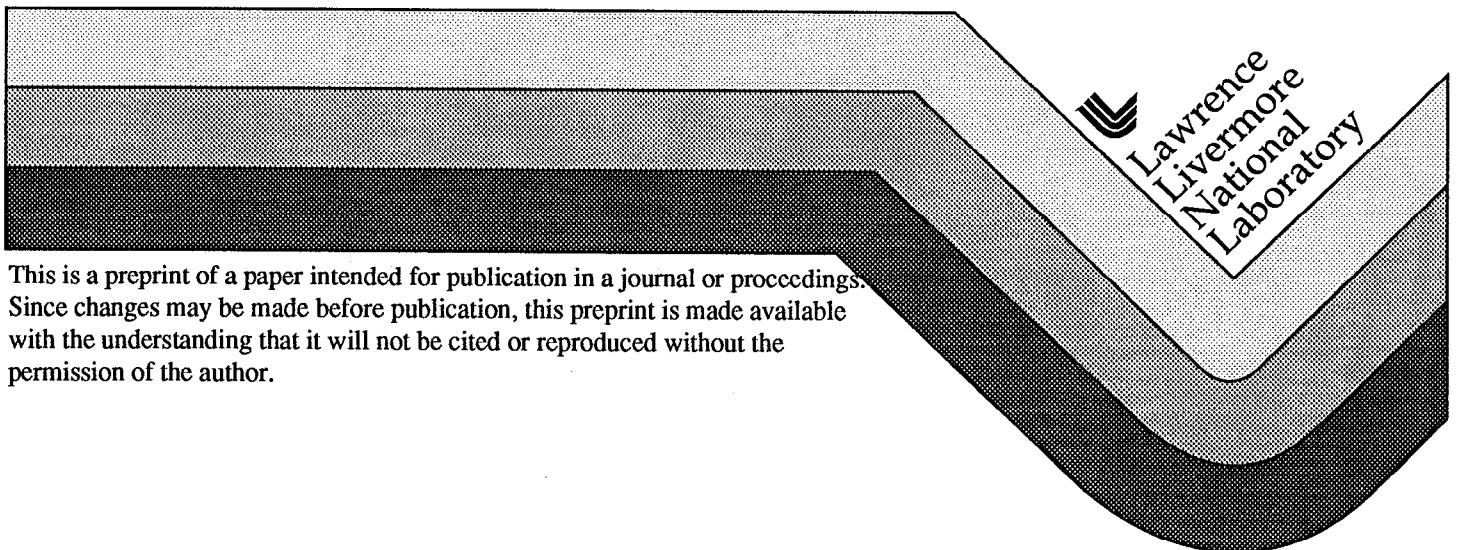 Performance Results of the High Gain, Nd: Glass, Engineering Prototype Preamplifier Module (PAM) for the National Ignition Facility (NIF)

M. D. Martinez, K. M. Skulina, F. J. Deadrick, J. K. Crane,
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This paper was prepared for submittal to
Photonics West 99 Symposium
San Jose, CA
January 23-29, 1999

February 9, 1999

DISCLAIMER

Performance results of the high gain, Nd:Glass, engineering prototype preamplifier module (PAM) for the National Ignition Facility (NIF)

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ABSTRACT

We describe recent, energetics performance results on the engineering preamplifier module (PAM) prototype located in the front end of the 1.8MJ National Ignition Facility (NIF) laser system. Three vertically mounted subsystem located in the PAM provide laser gain as well as spatial beam shaping. The first subsystem in the PAM prototype is a diode pumped, Nd:glass, linear, TEM_{00}, 4.5m long regenerative amplifier cavity. With a single diode pumped head, we amplify a 1nJ, mode matched, temporally shaped ($\approx$ 20ns) seed pulse by a factor of approximately 10^7 to 20mJ. The second subsystem in the PAM is the beam shaping module, which magnifies the gaussian output beam of the regenerative amplifier to provide a 30mm X 30mm square beam that is spatially shaped in two dimensions to pre-compensate for radial gain profiles in the main amplifiers. The final subsystem in the PAM is the 4-pass amplifier which relay images the 1mJ output of the beam shaper through four gain passes in a ϕ5cm X 48cm flashlamp pumped rod amplifier, amplifying the energy to 17J. The system gain of the PAM is 10^{10}. Each PAM provides 3J of injected energy to four separate main amplifier chains which in turn delivers 1.8MJ in 192 frequency converted laser beams to the target for a broad range of laser fusion experiments.

Keywords: NIF, Nd:Glass, diode pumped, pre-amplifier, SSD

1. INTRODUCTION

The National Ignition Facility (NIF) is a high energy laser system being developed, designed and constructed for the United States Department of Energy at Lawrence Livermore National Laboratory (LLNL) in Livermore California. This solid state, Nd:Glass laser system will be used for a wide range of Inertial Confinement Fusion (ICF) experiments as well as high temperature and high density physics research[1]. NIF will continue and expand physics research performed by its predecessor the NOVA laser system here at LLNL. The NOVA laser culminated from 9 years of solid state laser development and in 1984 was the first laser to be used for ICF experiments using ultraviolet, frequency converted light. The NIF laser system will deliver 1.8MJ/500TW of ultraviolet light to target in 192 separate beamlines. This is a twenty fold increase in energy from the 10 beam NOVA laser system. The figure below shows what the NIF site will look like after full system activation in 2003.
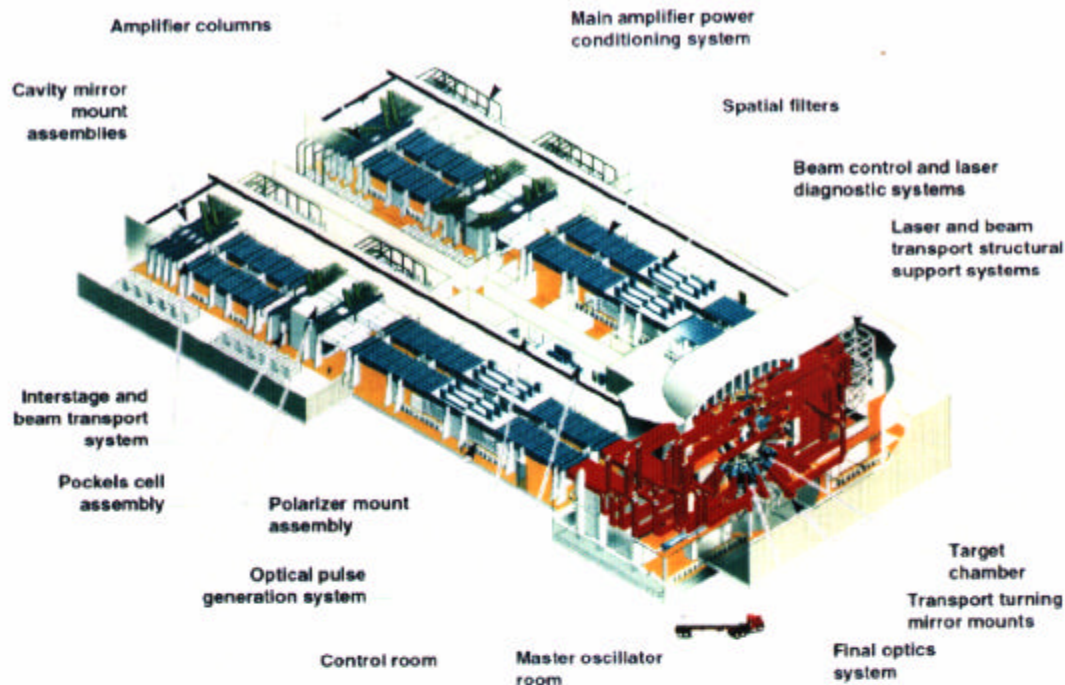
Figure 1. Diagram of what the NIF site will look like.

The NIF laser also incorporates a fundamentally different architecture than NOVA's single pass amplifier scheme. With the increase in beamlines, optical components and the shear size of the laser building, NIF had to be designed with cost and packaging in mind. To reduce costs and size, the NIF laser will utilize multi-passing 40cmX40cm^2 Brewster slab amplifiers which reduces the number of optical components as well as improves saturation of the amplifiers.

The NIF Front End or OPG consists of an all fiber-based master oscillator[2] that generates an optical pulse which is subsequently phase modulated and temporally shaped with a pulse duration of up to 21ns. This specially tailored pulse is then propagated via polariz ing (P Z) fiber to a series of optical splitters and amplifiers. The splitters generate 48 amplified pulses of 1 nJ which are injected into 48 separate PAM's via PM fiber. Each PAM output is then split into four separate beams in the Preamplifier Beam Transport System (PABTS) and injected into the 192 main amplifier chains. The NIF subsystems: Master Oscillator Room (MOR), PAM and PABTS are combined into a system called the NIF Front End or Optical Pulse Generation(OPG) system. Below is a block diagram describing the OPG system.
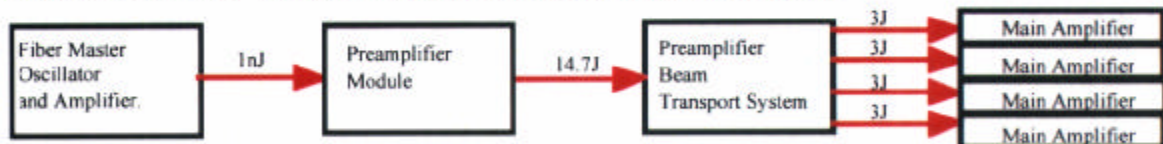
Figure 2. Block diagram of subsystems located in NIF front end or OPG.

Each PAM consists of a diode-pumped, Nd:glass regenerative amplifier[3], a spatial- beam-shaping subsystem, and a flashlamp pumped, multi-pass amplifier[4]. The PAMs produce the largest optical gain of the entire NIF laser system, boosting the 1nJ master oscillator pulse to 16.9J. The total gain of each preamplifier is 2 x 10^{10}. All PAM laser subsystems are mounted on a double-sided, vertical, optical table housed in the optical support structure (OSS) which rolls on precision rails for rapid on-line installment. The regenerative amplifier and beam shaper are mounted on one side and feed light through a clearance hole to inject the 4-pass amplifier on the other side of the optical table. Figure 3 is a schematic diagram of a PAM showing its component subsystems: fiber injection, diode-pumped regenerative amplifier, spatial beam shaping, SSD, and the 4-pass amplifier.
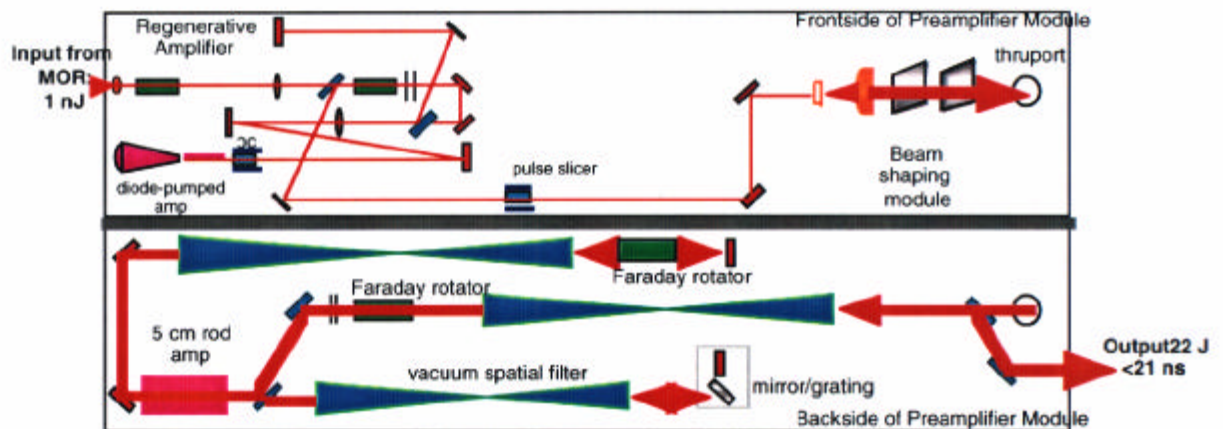
Figure 9.3 Schematic diagram of subsystems in all 48 PAM's.

The NIF front end or OPG consists of an all fiber-based master oscillator that generates an optical pulse which is subsequently phase modulated and temporally shaped with a pulse duration of 21ns. This specially tailored pulse is then propagated via polarization maintaining (PM) fiber to a series of optical splitters and amplifiers. The splitters generate 48 amplified pulses of 1 nJ which are injected into 48 separate PAM's via PM fiber. Each PAM output is then split into four separate beams in the Preamplifier Beam Transport System (PABTS) and injected into the 192 main amplifier chains. The NIF subsystems: Master Oscillator Room (MOR), PAM and PABTS are combined into a system called the NIF front end or Optical Pulse Generation(OPG) system. Each of the 192 amplifiers, receives a 3J injected pulse from the OPG.

Each PAM consists of a diode pumped, solid state, Nd:glass regenerative amplifier[5], a spatial beam shaping subsystem, and a flashlamp pumped, multi-pass amplifier. The system gain of each preamplifier is 2×10^{10} amplifying the 1nJ master oscillator pulse to 16.9J at the output of each PAM.

All PAM laser subsystems are mounted on a double sided vertical optical table housed in the optical support structure (OSS) which rolls on precision rails for rapid on-line installment. The regenerative amplifier and beam shaper are mounted on one side and feed light through a clearance hole to inject the 4-pass amplifier on the other side of the optical table.

All PAM controls and diagnostics hardware occupy a separate area from the OSS in order to maintain optical cleanliness and thermal control. The electronics bay (e-bay) houses a VME based front end control system containing an embedded processor, general purpose analog and digital I/O, stepper motor control, and timing modules used to control PAM operation. Controlled hardware includes the pulser for the diode pumped solid state laser in the regenerative amplifier, 16 channels of stepper motor drive, electrical power and signal conditioning, ion pump controllers, and thermal heat exchangers for temperature control. A 30 kJ capacitor bank (PCU) is used to drive the flashlamps in the 4-pass amplifier is housed in a separate unit. Particular care has been devoted to electro-magnetic interference (EMI) and electrical isolation in the PAM and PCU. Below is a block diagram of the OPG subsystems.

The OPG requirements are listed below and come from a flow down of the main laser requirements.

Optical Pulse Generation Requirements	
Injected energy into main amps:	3.0 J
-Preamp output energy (flattop beam)	22 J
-Preamp power energy (shaped beam)	16.9 J
Peak power at injection	1.2 GW
Wavelength	1053 nm

Pulse duration	20 ns
Power balance (in 2 ns window)	<3%
Power dynamic range	>125:1
Square-pulse-distortion	<2.3
Prepulse contrast	>2X10^6
Number of preamplifier modules	48

Table 1. General requirements for the OPG[7].

2.0 DESCRIPTION

2.1 Regenerative amplifier

The regenerative amplifier is the first stage of amplification in the PAM and represents the largest gain component in the NIF laser system.
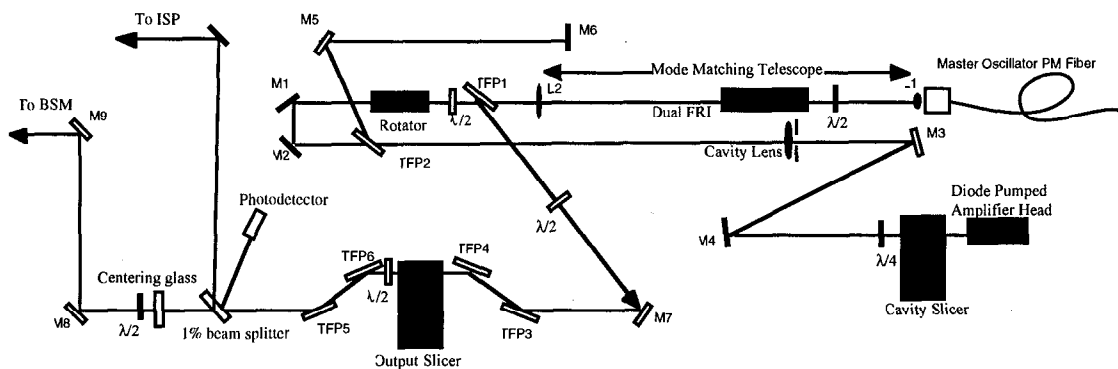

Figure 4. Optical layout of the regenerative amplifier used in the pre-amplifier module of the NIF. A single solid state amplifier is end pumped by a laser diode array and provides the required single pass gain of 1.6 per pass An injected beam is captured in the cavity for 27 passes, amplifying the beam energy from 1 nJ to a 23 mJ output. The beam is coupled out by means of polarization switching.

This regenerative amplifier is comprised of a folded, linear, 4.5m, TEM_{00} cavity using a diode-pumped, phosphate glass rod in an end-pumped configuration. A master oscillator pulse, is injected into the regenerative amplifier at the fiber launch. Refer to Figure 4 for the optical layout of the regenerative amplifier. Using both the fiber launch lens (L1) and a second lens (L2) we form a telescope that matches the spatial mode of the seed beam to the eigenmode of the TEM_{00} cavity. The seed also propagates through a dual stage Faraday isolator that protects the fiber from the much higher energy output leakage which propagates in the reverse direction. After the telescope, the beam propagates through a thin film polarizer (TFP1) which functions as the output coupler of the amplifier. The seed then propagates through a Faraday rotator and half wave plate that act as a directional coupler, separating the injected input from the regen output pulse Mirrors M1 and M2 are used to point and center the injected pulse into the cavity. The p-polarized seed is injected into the cavity through the thin film polarizer TFP2, goes through a 3m focal length cavity lens and mode limiting aperture. By adjusting the size of this aperture we force the cavity to operate in a single TEM_{00} spatial mode. Within the cavity the seed makes a Z-fold via mirrors M3 and M4, passes through the quarter waveplate the Q-switch Pockels cell (QS-PC) and into the amplifier head. It then reflects off the high reflectivity coating end of the rod reversing direction back through the cavity. With the QS-PC turned off, the polarization of the seed rotates 90 degrees from P to S due to double passing the quarter-waveplate and propagates back along its original path through the lens, aperture and reflects off of TFP2, propagating to mirror M5 and mirror M6. The mirrored end of the diode pumped amplifier rod and mirror M6 form the end mirrors of a linear cavity. Energizing the QS-PC traps the pulse in the cavity for 20-40 round trips. When the pulse is amplified to the desired energy , the QS-PC is switched off and the pulse is ejected from the cavity and reflects off of TFP1 and travels to the output

slicer. The slicer PC is turned on long enough to pass the desired output pulse while eliminating unwanted prepulses that leak out of the regen. Following the output slicer, part of the beam is monitored with a photodiode. A motorized centering glass is then used to recover any alignment errors and mirrors M8 and M9 direct light to the beam shaping module (BSM).

2.2 Beam shaping module

The beam shaping module, located after the regenerative amplifier (regen), provides several functions. First, the 20X telescope, magnifies the Gaussian-shaped regen beam to over fill the shaping filters and apodizers that provide the desired shape injected into the 4-pass. Second, pixelated, chrome-on-glass filters spatially shape the beam to pre-compensate for the radial gain profiles of the main amplifiers, to provide a spatially flat-topped beam at target. Third, a serrated apodizer shapes the edge of the beam to minimize diffraction ringing and limit laser damage as the beam propagates through the rest of the system [6] Fourth, motorized stages provide rapid *in situ* placement of two different serrated apertures for different ICF missions. The output of the beam shaper is then folded to the other side of the table to be injected into the 4-pass amplifier. See Figure 5 below for a schematic of the BSM.
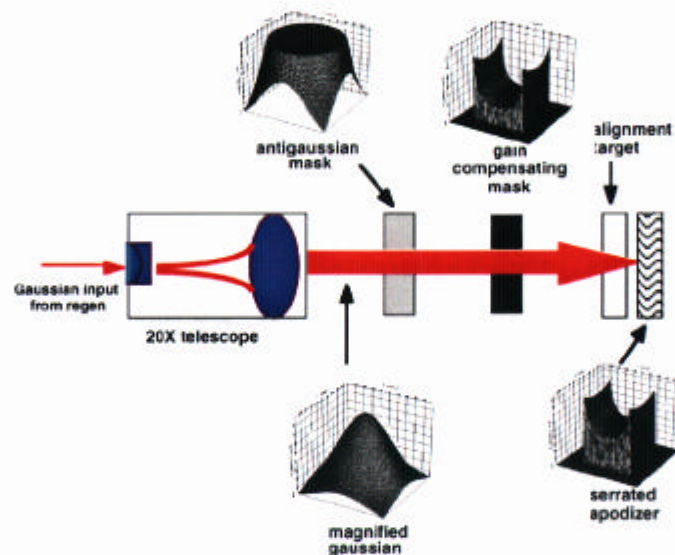
Figure 5. Diagram of beam shaping module used in NIF to expand, shape and provide 30mm X 30mm beam to be injected into the 4-pass amplifier.

2.3 4-pass amplifier/1D SSD

The 4-pass amplifier is the second gain component in the PAM. This relay imaged, linear amplifier provides a gain of about 10^4 as well as a user selectable, inter-cavity diffraction grating at Littrow for one dimensional smoothing by spectral dispersion (1D SSD).

Figure 6. Optical layout of flashlamp pumped 4-pass amplifier 16.9 J is extracted in four passes giving a net gain of 10^3.

The 4-pass amplifier is a passively switched linear amplifier which uses a 45 degree Faraday rotator, polarizers and a half waveplate to couple light into and out of the amplifier cavity providing four gain passes through the rod amplifier. A ϕ5cm x 48cm phosphate glass rod is pumped by 6 series flashlamps to provide the gain in the system. Three vacuum relay telescopes provide gain hold off, spatial filtering of high frequency components as well as relay imaging of the serrated aperture to prescribed locations in the cavity. The telescope, RT1, relays the serrated aperture to the center of the rod amplifier. The amplifier cavity is formed by the combination of mirrors, M4,M3, M2, M5, and telescopes RT2 and RT3. The image of the serrated aperture relayed to the center of the rod, is subsequently relayed to the cavity end mirrors, M4 and M5, using the cavity telescopes RT2 and RT3. The quarter waveplate controls the polarization so the amplified pulse makes four passes through the rod, then out of the cavity via the two thin-film polarizers. The cavity Faraday rotator, FR2, compensates for thermal and stress-induced birefringence from the rod and vacuum spatial filters by rotating the noncircular polarization components by 90 degrees[5].

In all of the relay telescopes, each gain pass is separated by a field angle that helps isolate these passes to aid in holding off the gain which can cause parasitic oscillations. Following is a diagram of the pinhole configuration in the 4-pass telescopes.

Figure 7. Pinhole configuration with field angle in the 4-pass cavity which helps with parasitic gain hold off.

3.0 RESULTS

3.1.1. Regenerative amplifier

Given the requirements for the entire OPG, we flow down these system requirements to the individual subsystems. Following is a list of requirements for the regenerative amplifier.

Output Energy	20mJ
Square Pulse Distortion	<1.45
Energy Stability	<3%
Pre-pulse contrast	10^{-6}
Injected Energy	<1nJ

Table 2. NIF regenerative amplifier performance requirements.

The first energetics measurement made on the regenerative amplifier in the PAM was to evaluate the single pass gain of the diode pumped head. This will tell us if the regenerative amplifier has the gain and stored energy to meet the NIF requirements.

Using a cw Nd:YLF laser as a probe, we measured the double-pass gain of the end pumped rod amplifier as a function of pump diode driver current. The results are shown below along with a photo of the diode pumped head.
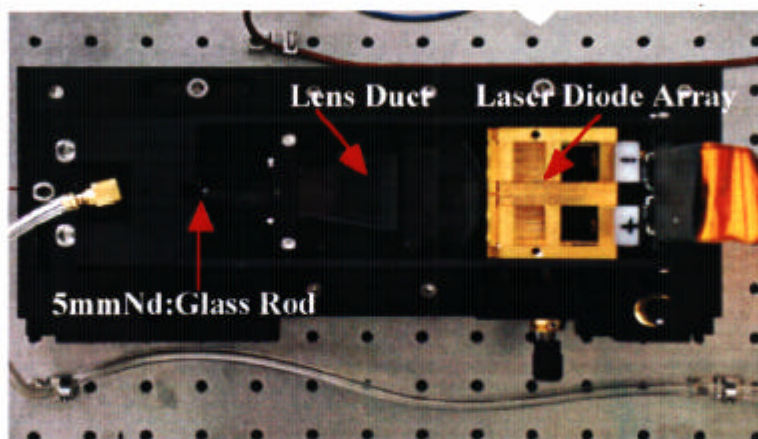
Figure 8. Photograph of diode pumped rod amplifier including: laser rod, laser diodes and lens duct.
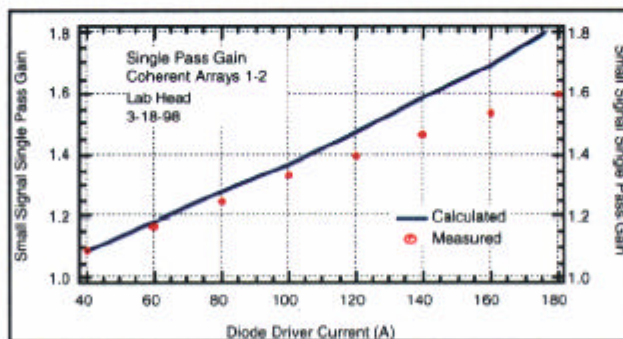
Figure 9. Experimental results show a single pass gain of 1.6 for the diode pumped head.

A simple model agrees with the data at the lower gains. At high gain the data rolls off due to ASE depleting the gain. The barrel of the diode pumped head is polished to support the TIR propagation of the pump light in the rod, but also supports the propagation of ASE which can itself extract energy from the rod.

One of the performance specifications of the NIF, is a precisely controlled temporal pulse shape at the target. A measure of temporal fidelity is square-pulse-distortion (SPD), which is the ratio of the gain at the leading edge of a square pulse to the gain at the end of the pulse, SPD=G(0)/ G(T). We measured SPD in

To determine the SPD of the regen, we use a high bandwidth (6Ghz) photoreceiver to measure the injected pulse and a second high bandwidth detector to temporally resolve the regen output pulse. These input and output pulses are converted to optical power and divided to show gain versus pulse length. The

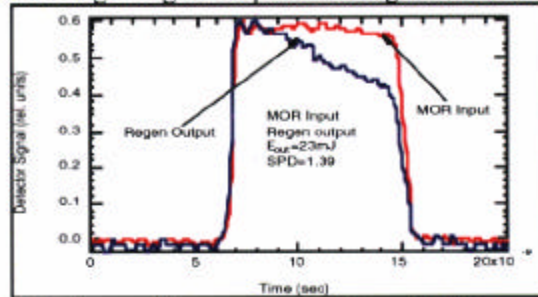SPD is the ratio of the gain at the beginning of the pulse to the gain at the end of the pulse.

Figure 10. Results of SPD at a specific measurement shows PAM regen exceeds NIF requirements.

The plot above shows that the PAM regen exceeds NIF requirements given in Table 2. By injecting <1nJ from the master oscillator we extracted 23mJ out of the regen with an SPD of 1.39. Following is a picture of the regenerative amplifier.
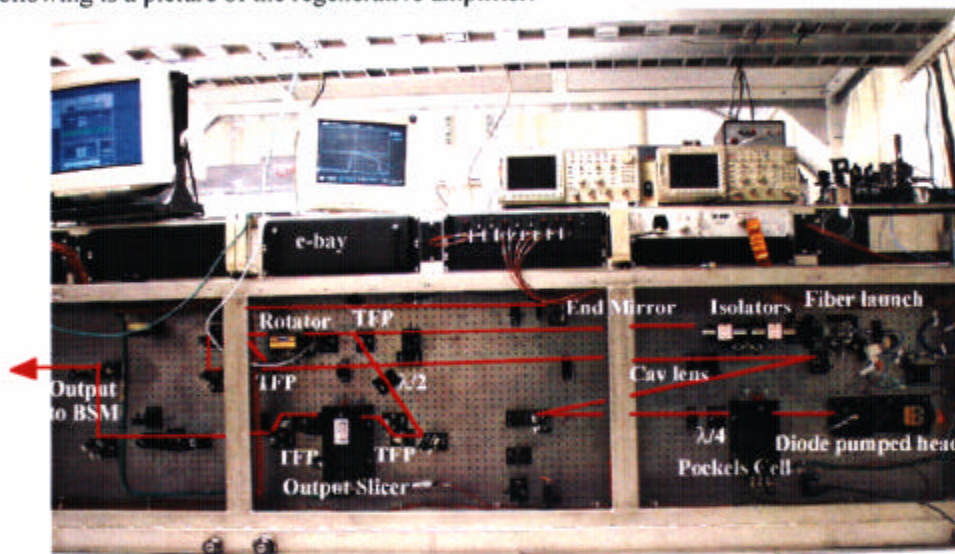

Figure 11. Photograph of regenerative amplifier shows critical components mounted on vertical laser table.

3.1.2 Beam shaping module

The beam shaping module (BSM) was designed and built by an outside contractor. As described above, this BSM mounted a 20X expanding telescope, two beam shaping masks, an alignment target and a serrated aperture. The BSM converts the Gaussian output of the regenerative amplifier into a 30mm X 30mm square, apodized beam that is shaped to compensate for the spatial gain profiles of all the downstream amplifiers.. The serrated apertures and alignment masks are mounted on motorized stages to provide remote selection.. Below is a picture of the BSM mounted on the vertical table with camera images of the small Gaussian input and spatially shaped output, measured at the four-pass output.
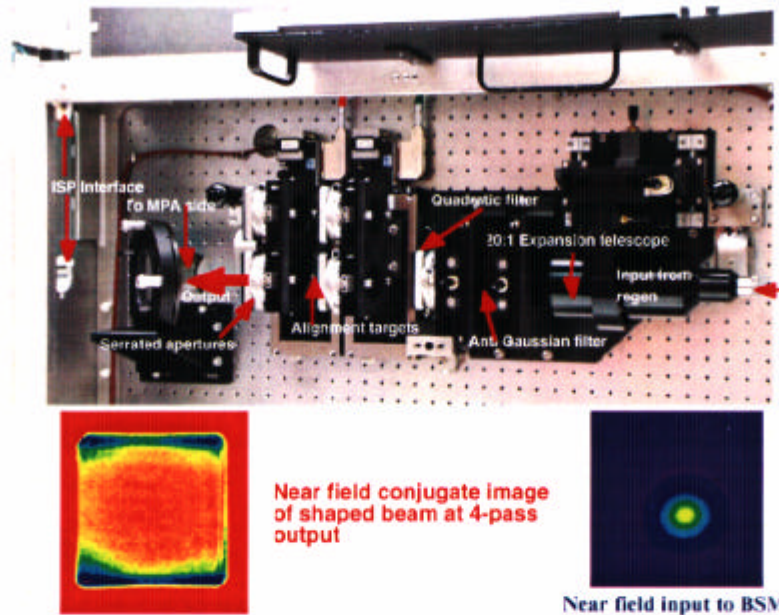
Near field conjugate image of shaped beam at 4-pass output

Near field input to BSM

Figure 12. Beam shaping module provides a pre-shaped, 30mm square beam from the regen, to be injected into the 4-pass pass amplifier.

3.1.3 4-pass amplifier

The last stage of amplification in the PAM is the 4-pass amplifier. A 30mmX30mm beam is injected into the relay imaged cavity and passed four times through a ϕ5cm X 48cm phosphate glass amplifier rod. Below is list of requirements for the 4-pass amplifier.

Output Energy	22J (Flat-topped beam)
	14.5J (Spatially Shaped)
Peak Power	8.8GW
SPD (PAM/4-pass)	<2.3 / <1.6
Injection Energy	1mJ

Table 3. Energetics requirements list for the 4-pass amplifier.

In order to ensure the PAM would meet the energetics requirements, we characterized the ϕ5cm rod amplifier for small signal gain and radial gain profile. With the small signal gain and cavity transmission, we can predict the amount of energy to be extracted for a given injected energy. The spatial profile of the gain media is needed to design the spatial beam shaping masks that produce the required shape injected into the main amplifiers.

With a ϕ10mm probe beam, we measured the centerline gain of the amplifier head using two calorimeters. Below is a plot of the small signal gain versus delivered electrical energy and explosion fraction of the flashlamps.
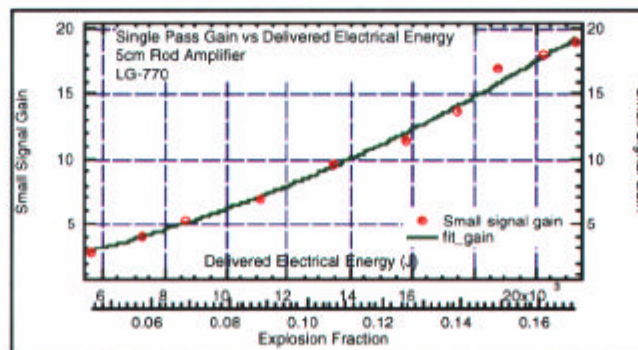

Figure 13. Results of measurements show a peak gain of 19.

With a delivered electrical energy of 22kJ, we measure a single pass gain of 19 with an explosion fraction of 0.17. This gain is sufficient to produce the energy requirements listed in table 3.

We measured the radial gain profile by imaging the center of the rod at full aperture. The regenerative amplifier was used as the probe source and a reference image and gain image of the center of the rod were taken to determine the spatially dependent gain. Figure 14 shows the flat gain profile that we measured.
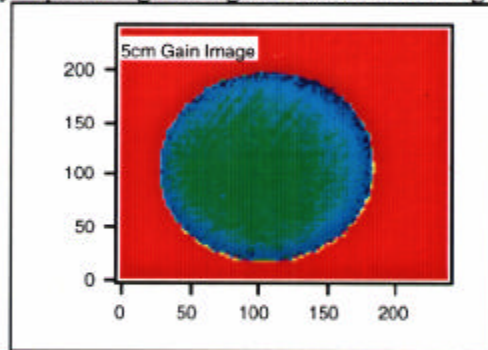

Figure 14. Radial gain profile measurement shows a relatively flat spatial gain profile.

Using the regenerative amplifier as an alignment source, the 4-pass amplifier was installed and aligned as shown in Figure 4. Figure 15 is a picture of the amplifier mounted on the OSS.
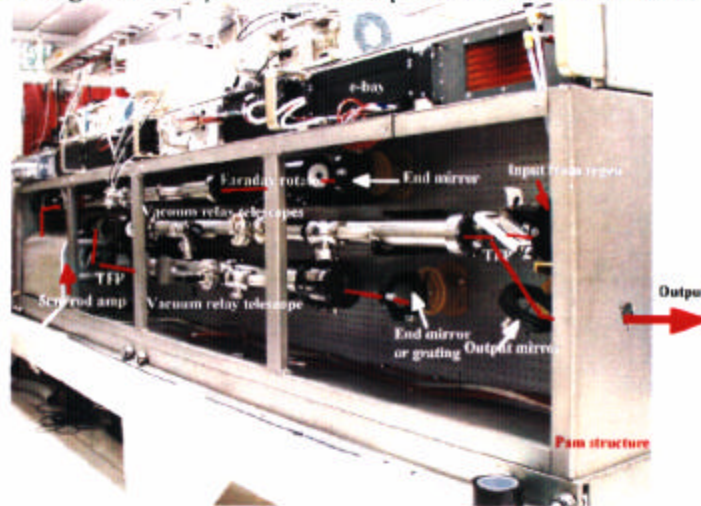

Figure 15. 4-pass amplifier is housed on one side of the optical support structure.

Once the 4-pass amplifier was installed and aligned, energy extraction measurements were conducted. Operating the ϕ5cm amplifier at peak gain, we varied the energy injected into the 4-pass amplifier and measured the output energy. The plot in Figure 14 shows energy extracted from the four-pass versus input energy. The solid line shows predicted energy based on a Frantz-Nodvik model[7].
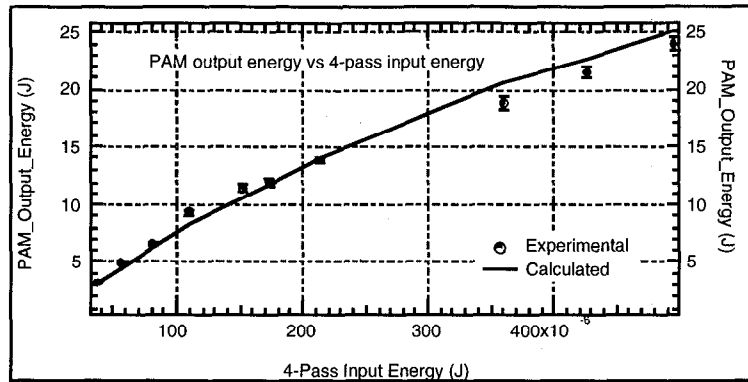
Figure 16. Results of energy extraction from 4-pass amplifier show the PAM exceeds the
NIF OPG requirement of 22J unshaped.

For an input energy of 488µJ into the 4-pass cavity, we extracted 24J. This exceeds the 22J
requirement listed in Table 3 for an unshaped beam.

4.0 CONCLUSION

We have completed the construction and alignment of the high gain, Nd:glass NIF prototype pre-
amplifier module. Using the general laser design developed on a physics testbed [1,2] to meet NIF laser
requirements, we have packaged the amplifier system in the optical support structure (OSS). This
support structure is designed as a line replaceable unit(LRU). This LRU design provides rapid installment
and removal to meet NIF shot rate requirements. Also, an electronics bay housed on the OSS provides
controls and diagnostics. The PAM will remotely provide alignment for the laser system as well as define
the level of energy injected into the main amplifiers which in turn defines energy delivered to target.

We have successfully demonstrated a fully integrated PAM prototype that exceeds NIF performance
specifications for output energy, power and temporal pulse distortion. We continue to work to demonstrate
the full performance requirements of the preamplifier-prototype before integrating with the OPG systems,
MOR and PABTS, to demonstrate performance of the entire front end.

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