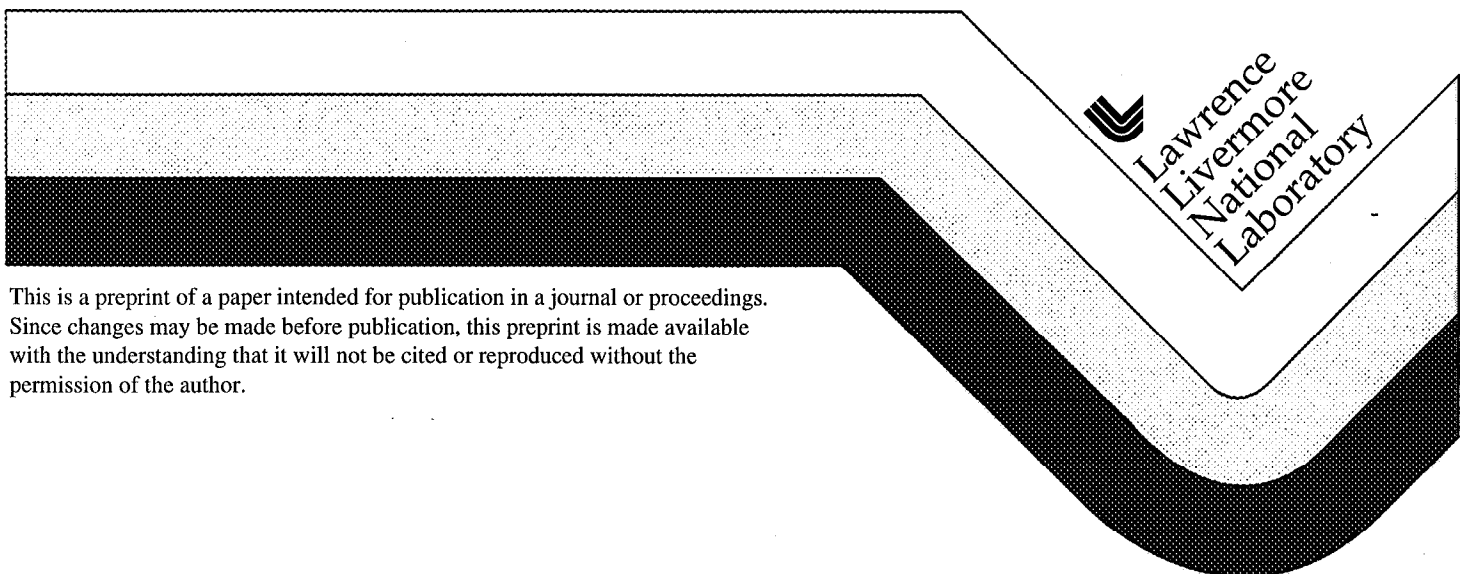# Optimized, Diode Pumped, Nd:glass, Prototype Regenerative Amplifier for the National Ignition Facility (NIF)

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DISCLAIMER

Optimized, diode pumped, Nd:glass, prototype regenerative amplifier for the National Ignition Facility(NIF)

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ABSTRACT

The National Ignition Facility (NIF) will house a 2 MJ Nd:glass laser system to be used for a broad range of inertial confinement fusion experiments. This record high energy laser output will be initiated by a single low energy, fiber-based master oscillator which will be appropriately shaped in time and frequency prior to being split into 48 beams for intermediate amplification. These 48 intermediate energy beams will feed the 192 main amplifier chains. We report on the baseline design and test results for an amplifier subsystem in the intermediate amplifiers. The subsystem is based on a diode pumped, Nd:glass regenerative amplifier. The amplifier is comprised fo a linear, folded, TEM_{00}, 4.5m long cavity and represents the highest gain (approximately 10^7) component in the NIF laser system.[1] Two fundamentally important requirements for this amplifier include output energy of 20 mJ and square pulse distortion of less than 1.45. With a single 48 bar 4.5kW peak power diode array and lens duct assembly we pump a 5 mm diameter X 50 mm long Nd-doped, phosphate glass rod, and amplify the mode matched, temporally shaped (approximately 20ns in duration)oscillator seed pulse to 25 mJof output energy with a very acceptable square pulse distortion of 1.44. This most recent design of the regenerative amplifier has increased the performance and reduced the cost, enabling it to become a solid baseline for the NIF laser system.

Keywords: regenerative amplifier, National Ignition Facility(NIF), diode pumped

1. INTRODUCTION

The National Ignition Facility is a large Inertial Confinement Fusion (ICF) laser system being developed and constructed at Lawrence Livermore National Laboratory. This large Nd:Glass laser system consists of 192 separate beamlines that provide approximately 20kJ of energy in each beamline at a wavelength of 1.05µm or a total energy of around 2MJ.. The laser output originates in a fiber based master oscillator, is split into 48 beams for intermediate amplification and is then further split into 192 beams prior to power amplification. The 192 infrared beams are frequency tripled prior to focused delivery to the target.

More specifically, the all fiber-based master oscillator generates an optical pulse that 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 energy that are injected into 48 separate preamplifier modules (PAM's) via PM fiber. Each PAM consists of a diode pumped, solid state, regenerative amplifier, 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 22J at the output of each PAM. The output of each PAM is then split into four separate beams in the Preamplifier Beam Transport System (PABTS) and injected into the main amplifiers. The NIF subsystems: master oscillator, PAM and PABTS are combined into a unit called the NIF front end or Optical Pulse Generation(OPG) System. Each of the 192 amplifiers, receives a 3J injected pulse from one of the 48 OPGs and amplifies that pulse to 20kJ and after frequency conversion to the UV, a total energy of 2 MJ can be delivered to the target.
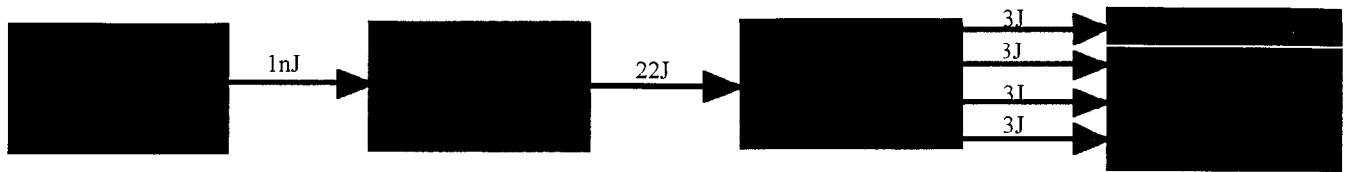
Figure 1. Block Diagram of 1 of the 48 NIF master oscillator/preamplifier beamlines

In this paper we report on a simplified design for the regenerative amplifier located in the PAM section of the front end for the NIF laser system. We have shown this to meet the critical NIF design requirements as listed in Table I below Additionally important, this design provides reduced cost for building and operating this regenerative amplifier The NIF requirements for the regenerative amplifier result from demanding target system needs as well as requirements of the power amplifier The output energy of 20 mJ matches into the available gain in the main amplifiers so as to allow 2 MJ system output The square pulse distortion value (the deviation from true square pulse output when an equivalent square pulse is injected) is required to maintain the critical prepulse and main-pulse shapes necessary for specific target activation The energy stability requirement results from the need for precise energy balance to achieve uniform and stable target compression from the 192 beams Finally, the injected energy requirements is derived from the available injection energy from the master oscillator

Table I
NIF Regenerative Amplifier Performance Requirements

Output Energy	20mJ
Square Pulse Distortion	<1.45
Energy Stability	<3%
Injected Energy	<1nJ

2. DISCUSSION

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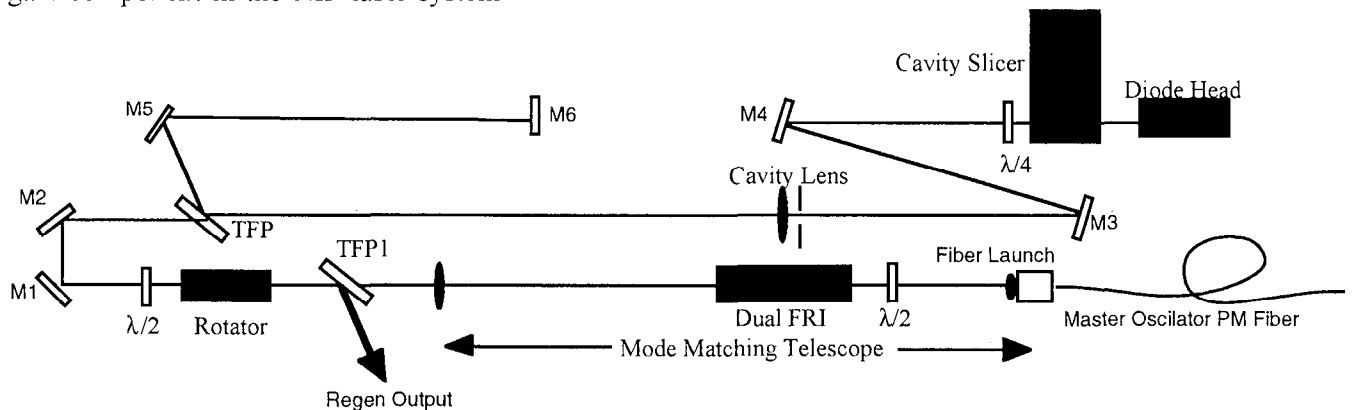

Figure 2
Optical layout of the regenerative amplifier used in the pre-amplifier module of the NIF A single solid state amplifier is end pumped by a diode array and provides the required gain of ?? per pass. An injected beam is captured in the cavity for ?? passes, amplifying the beam energy from 1 nJ to a 25 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 endpumped configuration. A master oscillator pulse specially tailored for specific NIF pulse formats, is injected into the regen at the fiber launch. Using both the fiber launch lens and a second lens we form a mode matching telescope that matches the spatial mode of the seed beam to the eigenmode of the TEM_{00} cavity. Within this telescope the seed also propagates through a dual stage Faraday isolator that protects the fiber from the much higher energy regenerative output leakage which naturally propagates in the reverse direction. After the telescope, the beam propagates through a thin film polarizer (TFP1) which functions the eventual output coupler of the amplifier. The seed then propagates through a Faraday rotator and half wave plate. This rotator-waveplate combination will form the directionally sensitive polarization optical switch for switching the amplified output out of the amplifier cavity. Mirrors M1 and M2 are used to overlap the mode matched seed mode onto the eigen mode of the cavity. The seed is then 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 and position of this aperture we force the cavity to amplify a single TEM_{00} cavity mode. Within the cavity the seed makes a Z-fold via mirrors M3 and M4, passes through the quarter waveplate and the cavity slicer and into the amplifier head. It then reflects off the high reflectivity coating end of the rod reversing direction back into the cavity. With the cavity slicer turned off, the polarization of the seed rotates 90 degrees from P to S due to double passing the 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 stable cavity. With a cavity now formed specific control of the polarization can cause the beam to amplify by means of multiple passes through the diode pumped head. The Pockels cell cavity slicer provides the polarization control and switching. It is energized when the seed beam first returns from M6 to the amplifier head. Energyzing the cavity slicer effectively traps the seed in the cavity as long as the slicer is energized. During the multiple (we should say how many passes) passes of the amplification, the seed beam transforms into a spatial mode of the amplifier cavity, but maintains most of its injected frequency and temporal characteristics. When the cavity mode is amplified to a desired energy , the slicer is turned off and the quarter waveplate rotates the polarization back to P such that the beam transmits through TFP2 and retraces its path back to through the injection leg where the combination half waveplate, rotator and TFP1 couple the energy off of TFP1 and out of the cavity.

The expected value of output energy can be estimated by the following equation;

$$E_{OUT} = E_{IN}(G_{DP} * T)^k \qquad (1)$$

where E_{IN} is the input energy, G_{DP} is the double pass, small signal gain, T is the round trip transmission of the cavity and k is the number of round trips in the cavity.

One of the fundamentally important design requirements of the NIF is a precisely controlled pulse shape at the target. Since the pulse shape is generated at the oscillator and saturation in the amplifiers tends to distort this shape, the shape requirement flows down into specific requirement for the regenerative amplifier of a low square pulse distortion. Square pulse distortion results from the leading edge of a pulse extracting energy before the tail of the pulse enters the gain medium. Due to saturation, the tail of the pulse, then sees a reduced gain and consequently a lower amount of extractable energy. If a simple, temporally square pulse were injected, the leading edge of the output pulse would be higher in magnitude than the trailing edge. This effectively changes the desired shape of the pulse. The square pulse distortion can be approximated by equation 2 below.

$$SPD \approx e^{(F_{ext}/J_{sat})} \qquad (2)$$

Where F_{ext} is the extracted fluence in J/cm^2 and J_{sat} is the saturation fluence in J/cm^2 of the glass rod.

Since the SPD varies exponentially as the extracted fluence, the extractable energy is is strongly dependent on the allowable SPD. Also, the end-pumped design of the amplifier head accelerates the SPD because the seed pulse is overlapped on itself in the head. The leading edge of the pulse thus sees a double pass of gain before the tail of the pulse arrives at the gain medium. This pulse overlap increases the onset of SPD.

Our original design for the regenerative amplifiercontained dual amplifier heads to achieve a high single pass gain. In this design there were going to be 192 regenerative amplifiers. However, for cost reasons the NIF design requirementschanged to requiring only 48 amplifiers and consequently required increased output energy. It became clear that the original baseline design would not meet the energy requirements. We decided to improve the regenerative amplifier design in two specific ways:, one was to reduce the losses of the cavity and the second was to increase the volume of rod accessed for energy extraction. Reducing the losses clearly directly adds to the output energy. As can be realized from equation 1, a reduction in loss (equivalently an increase in transmission) will increase the net gain (G*T), and thus increase the amount of energy that can be extracted at low SPD from the regenerative amplifier. Increasing the volume of rod accessed by the extraction beam provides more energy without requiring additional pumping and adds output energy with less saturation effects. Equations 3 show the relationship between stored energy and mode area.

$$G = e^{(E_{ST}/(A*J_{SAT}))} \qquad \text{3(a)}$$
$$\text{or}$$
$$E_{ST} = \ln(G)*A*J_{SAT} \qquad \text{3(b)}$$

E_{ST} is the stored energy, G is the single pass, small signal gain, A is the total pumped area of the area of the rod, and J_{SAT} is the saturation fluence of the glass rod. A second important area to consider is the area of the rod from which the seed beam extracts energy. Clearly the larger this extraction area, the greater energy extracted withtout a reduction in gain or consequent increase in SPD.

2.1 Cavity transmission

By making relatively straight forward changes to the layout of the regenerative amplifier we were able to increase the transmission of the cavity.The original baseline design incorporated a nearly confocal cavity with a diode pumped amplifier head at either end of the cavity. This design injected the seed into the cavity by reflecting off of a thin film polarizer , double passing one head and waveplate and transmitting through two TFPs and into another diode pumped head.. There were two Pockels cells, one trapped the seed in the cavity and the other switched the seed out of the cavity via the second thin film polarizer. The new design it much more efficient; It couples light into the cavity though a single TFP and a single Pockels cell both traps and switches the seed out of the cavity. Since thin film polarizers operate more efficiently in reflection the cavity loss is reduced by using one thin film polarizer in reflection instead of two in transmission. (Mikewhat was the message in the last two sentences?) The new cavity design also allowed the removal of a Pockels cell, thus additionally reducing the amount of optical surfaces in the cavity. With these two changes, the transmission of the cavity increased from ??? to ???.

2.2 Increased mode size

By changing the design of the cavity from a nearly confocal cavity to an asymmetric cavity we were able to increase the modal area on the rod. This increased the stored energy available for extraction from around 20mJ to 40 mJ. From Equation 2 one can see that the SPD decreases exponentially as the extracted fluence

decreases. Therefore, for a larger extracted volume the SPD at a given output energy is lower. As a result of making these straight forward changes to the cavity, we are able to extract the energy required with a single diode pumped head instead of two diode pumped heads as shown in the original design. Diode pumping is very expensive. With this change we were able to reduce the cost of diodes in the regen from 100K$ to 50K$ for each PAM or from 4.8M$ to 2.4M$ for the NIF laser system.

3. RESULTS

3.1 Cavity Transmission

In order to evaluate the transmission of the cavity a ring down measurement was made. In this measurement, the seed is first injected into and out of the cavity with the diode pumped head off. We then measured the amplitude of the un-amplified seed pulse as a function of the number of roundtrips. With no gain term Equation 1 reduces to :

$$S_{OUT} = S_{In}(T)^k \qquad (4)$$

Where S_{OUT} is the seed signal at the output, S_{IN} is the input seed signal, T is the cavity transmission and k is the number of roundtrips. To find the cavity transmission, we measure the seed amplitude as a function of round trip and then fit the data to Equation 4 to find T. Below is a schematic of the experimental setup.
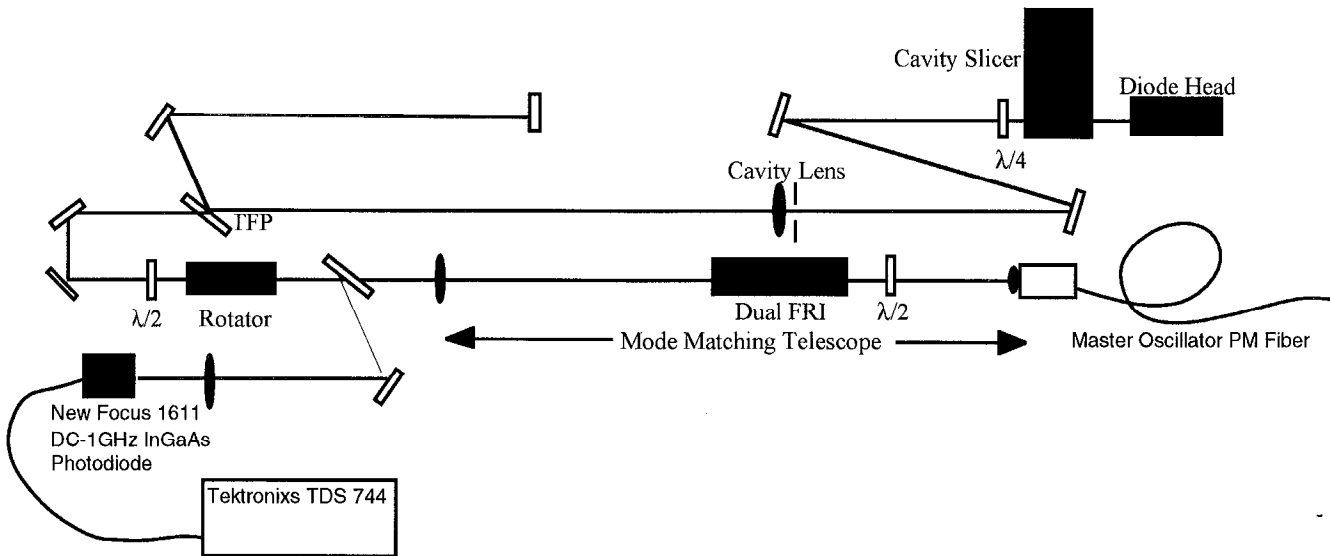
Figure 3. Experimental setup to measure cavity transmission.
This ring down measurement was made on both regen designs and can be seen below in Figure 4. (Discuss here also in more detail what the data looks like and how you reduce it to the graph below.)
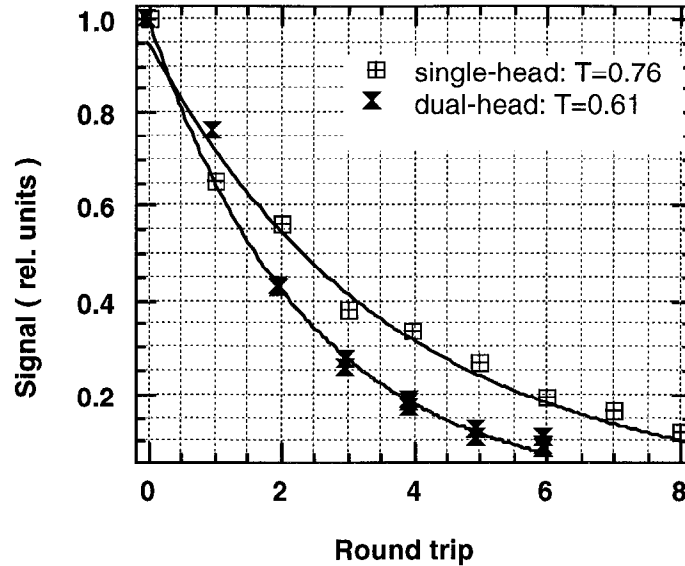
Figure 4. Cavity transmission measurement results.

This plot shows the ring down results. The most recent design of the regenerative amplifier shows a cavity transmission that improved from 61% to 76%. This corresponds to a 15% increase in the cavity transmission.

3.2 Increased mode size

By changing the cavity design from nearly confocal to asymmetric, we are able to increase the area of the mode in the rod. This allows us to extract more energy from the rod by increasing the fill factor. The increase in modal area also decreases the fluence for a given output energy. From Equation 2 the SPD decreases exponentially as the extracted fluence decreases. As the 3m cavity lens in Figure 2. moves closer to the diode head, the mode size increases. In order to get a measure of the mode size on the rod, the face of the rod was imaged onto a CCD detector through a cavity mirror. Using a beam profiling system the image on the CCD camera was calibrated and a direct measurement of the mode size was made. Below is a schematic of the experimental setup used to measure the mode size.
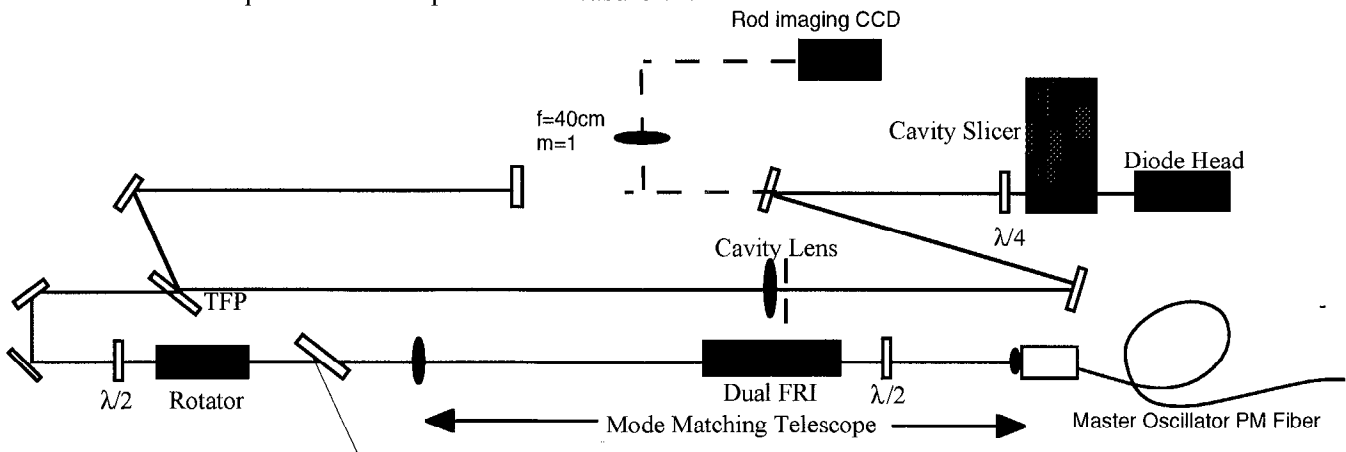
Figure 5. Experimental setup to measure mode size on the rod.

The CCD camera images the face of the rod through the cavity mirror, quarter waveplate and slicer. The regen is then turned on a the mode size is measured in the rod. Below are some results and comparisons of the mode size on the rod.
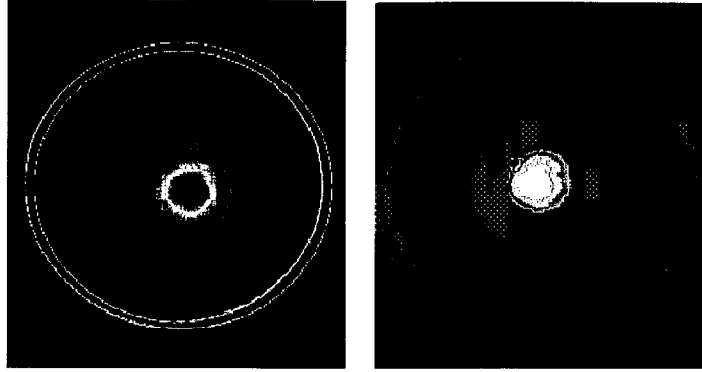
Figure 6. Mode size measurement results.

The image on the left is the mode size with respect to the edge of the rod of the original design and has a $1/e^2$ diameter of 1.72 mm. The image on the right is the most recent mode size diameter measurement of 2.5 mm. (Discuss here that the energy extracted scales as the area which goes as the ratio of the diameters squared. Give the actual number for the ratio of $(2.5/1.72)^2$.

An energetics measurement was made on both designs that compared the amount of energy that could be coupled out running the cavity longpulse (define long-pulse better) and single mode. The experimental setup looks identical to Figure 3 only the fast detector and lens were replaced with a calorimter and negative lens. The output energy of both designs was measured as a function of diode driver currents. Below are the results - Take the reader through your results in words.

Diode Drive Current (Amps)
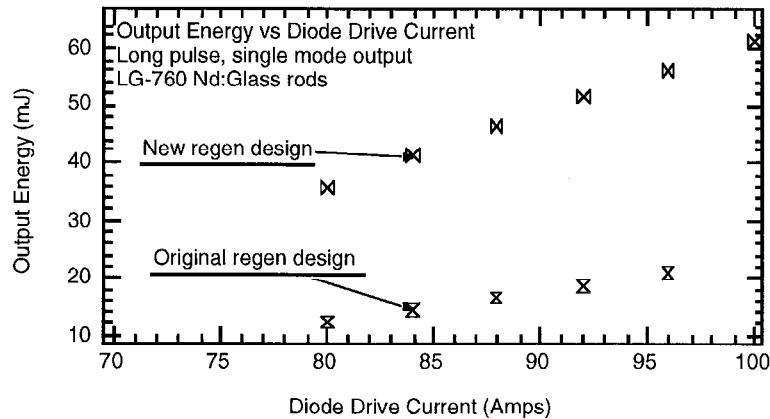
Figure 7. Results of output energy vs diode current for two designs.

As shown above the new regenerative amplifier surpasses the original design in output energy. This increase in performance was achieved with a single diode pumped amplifier head as opposed to the previous dual head design. At a diode driver current of 88 amps, the output energy increased from 16mJ to 46mJ.

Given the mode size increase on the rod and Equation 2, the SPD for a given output energy will decrease. A measurement of SPD vs output energy was made. Refer to Figure 5 for a layout (layout of what - try saying it). Using a vacuum photodiode at the output and a fast InGaAs photodiode at the fiber injection launch, we measured the input and output pulse as a function of output energy and diode driver current. These results are plotted below along with a simple Frantz-Nodvic (need reference and explaination of this concept) computer model to predict the results.
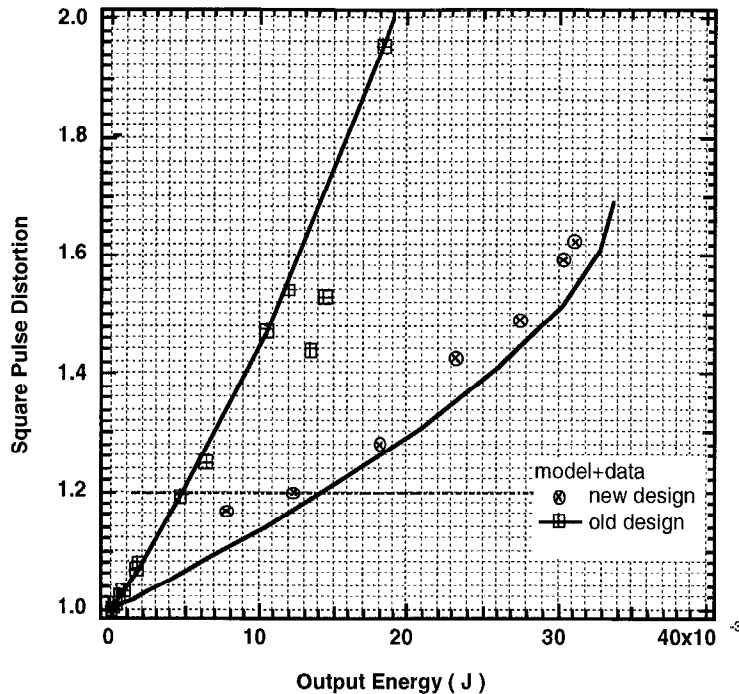
Figure 8. Results of SPD vs output energy for different diode driver currents

This plot shows how the SPD builds up as a function of output energy for both design cases. With a required limit of SPD at <1.45, the new regenerative amplifier design can extract 25mJ from the single diode pumped configuration. The dual head configuration would extract only 10mJ. This 25mJ output surpasses the NIF requirement and the 10mJ does not meet the requirement. The solid lines are the Frantz-Nodvic models and appear to agree very well with the data.

4. CONCLUSION

Making some simple design changes, we have increased the performance and reduced the cost of the current NIF regenerative amplifier design. By changing the cavity layout to use a single Pockels cell, diode pumped amplifier head and thin film polarizer in reflection we have increased the cavity transmission from 61% to 76%. This corresponds to a output energy increase of 15%.

The mode size on the rod has also been increased from 1.72 mm in diameter to 2.5?? mm. This increased mode size came from changing the cavity design from nearly con-focal with two diode pumped heads to a linear, asymmetric cavity. This increased extraction efficiency provided three times the output energy when the cavity was running long-pulse (again definelong-pulse) single mode. At 88 amps the energy increase from 16mJ to 46mJ. With the increases mode volume, the SPD for a given energy decreased as predicted. At an output energy of 10mJ, the dual head regenerative amplifier had an SPD of 1.45 and the single head design had an SPD of 1.14.

The most recent design for the regnerative amplifier located in the pre-amplifier module in the NIF laser system meets the critical design requirements with a reduction in cost and is now the baseline design for the NIF laser system.

5. ACKNOWLEDGMENTS

6. REFERENCES1. J. Crane, *et al.* CLEO paper CW03, Anaheim, Ca (1996).

2. R. Beach, *et al.* Optics Letters **18,** 1329, (1993)