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OPTICAL PULSE GENERATION SYSTEM FOR THE NATIONAL IGNITION FACILITY (NIF)

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ABSTRACT

We describe the Optical Pulse Generation (OPG) system for the National Ignition Facility (NIF). The OPG system begins with the Master Oscillator Room (MOR) where the initial, seed pulse for the entire laser system is produced and properly formatted to enhance ignition in the target. The formatting consists of temporally shaping the pulse and adding additional bandwidth to increase the coupling of the laser generated x-rays to the high density target plasma. The pulse produced in the MOR fans out to 48 identical preamplifier modules where it is amplified by a factor of ten billion and spatially shaped for injection into the 192 main amplifier chains.

I. INTRODUCTION

The Optical Pulse Generation (OPG) system or Front-End is the portion of the National Ignition Facility (NIF) laser system where a single pulse is produced, modulated and shaped, then amplified and multiplexed to feed the 192 main amplifier chains in the NIF. The OPG system is comprised of three major subsystems: the master oscillator room (MOR), the preamplifier modules (PAMs) and the preamplifier beam transport system (PABTS). The MOR is responsible for generating the single pulse that seeds the entire NIF laser system. In the MOR this single pulse is phase modulated to add bandwidth then multiplexed into 48 separate beam lines on single-mode, polarizing fiber. Before leaving the MOR the pulses are temporally sculpted into high contrast shaped pulses designed to produce ignition of the D-T targets. Forty-eight single-mode fibers from the MOR serve as inputs to the 48 PAMs that are the second major subsystem in the OPG. The PAMs provide the largest amount of amplification in the laser system, >100 dB. In addition to amplification the PAMs spatially shape the Gaussian beam that emerges from the single mode fiber to form a square beam that is shaped to compensate for the spatial gain profiles of the main slab amplifiers. A third function performed in the PAMs is spectral dispersion of the phase modulated light produced initially in the MOR. This dispersion is part of a scheme, called smoothing by spectral dispersion, or SSD, that reduces the spatial coherence of the laser light irradiating the target. The 48, 15 J outputs from the PAMs enter the final subsystem of the OPG system, the PABTS. In the PABTS the 48 beams from the 48 PAMs are split into 192 separate beams that feed the main amplifier chains. After the 4-way split of the beams each leg has an optical trombone section for precisely adjusting the timing so that all 192 beams converge on target simultaneously. Figure 1 shows a schematic block diagram of the OPG and its constituent systems.

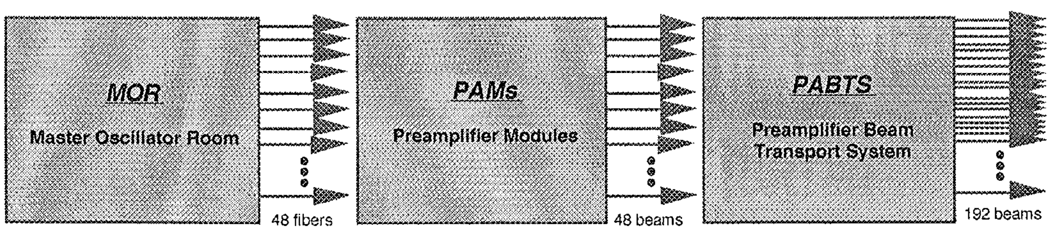

Figure 1. Block diagram of the Optical Pulse Generation System (OPG).

The requirements for the OPG system flowdown from the overall laser system requirements at the target. Table I lists the overall system requirements at the target and the resulting parameters for the OPG system determined from the flowdown.

NIF System Requirements [1]	
Output energy	1.8 MJ
Peak power	500 TW
Wavelength	352 nm
Pulse duration	20 ns
Power balance	8% in 2 ns window
Pointing accuracy @ target	6 microrad
Power dynamic range	> 50:1
Prepulse in 20 ns window	< 10^8 W/cm^2
Number of beamlets	192

Optical Pulse Generation Requirements	
Injected energy into main amps	3.0 J
Peak power at injection	1.2 GW
Preamp output energy (flattop beam)	22 J
Preamp power energy (shaped beam)	14.7 J
Wavelength	1053 nm
Pulse duration	20 ns
Output pulse rate	1/20 minutes
Prepulse contrast	>2X10^6
Square pulse distortion	<2.3
Bandwidth	81 GHz
Critically dispersed (SSD)	
Spatially shaped for gain compensation	
Number of preamplifier modules	48

Table I. System requirements for the laser at the target and the requirements at the output of the OPG determined from a flowdown of the system requirements back to the Front End.

In the next section we will give detailed descriptions of the components of the three major subsystems within the OPG system. In many cases the subsystems have been developed and are in an engineering prototype phase in which we work with outside vendors to produce working hardware. We have also connected the MOR and Preamplifier Development Labs to perform integrated performance measurements on a combined system.

II. DESCRIPTION

A. Master Oscillator Room (MOR)

In this section we describe the subsystems that comprise the MOR. Most of these subsystems are complete and some, such as the fiber amplifiers and arbitrary waveform generator (AWG), are in the next stage of development-engineering prototyping. A simplified version of the MOR architecture is shown in Figure 2.

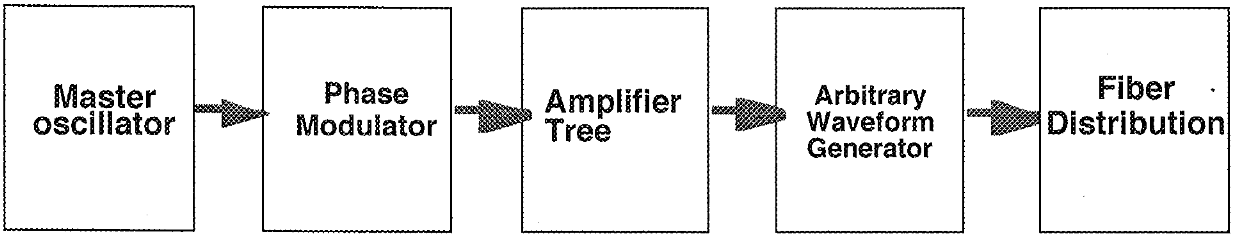

Figure 2 Layout of Master Oscillator Room (MOR).

The 192 pulses that converge on the target with a combined energy of nearly 2 million Joules originate as a single pulse in the MOR's master oscillator. The master oscillator is a small, Yb-doped silica fiber, Q-switched, ring oscillator that produces 300 ns long pulses at 960 Hz. The output pulse has a power at its peak of about 130 mW. The Yb-doped gain fiber is optically pumped with a 980 nm diode laser. The laser is made to operate single mode by including two narrow band fiber gratings in the ring cavity. These fiber gratings operate as filters that pass the desired mode and attenuate any additional modes that are outside the frequency band of the filter. Figure 3 shows a schematic of the fiber master oscillator.

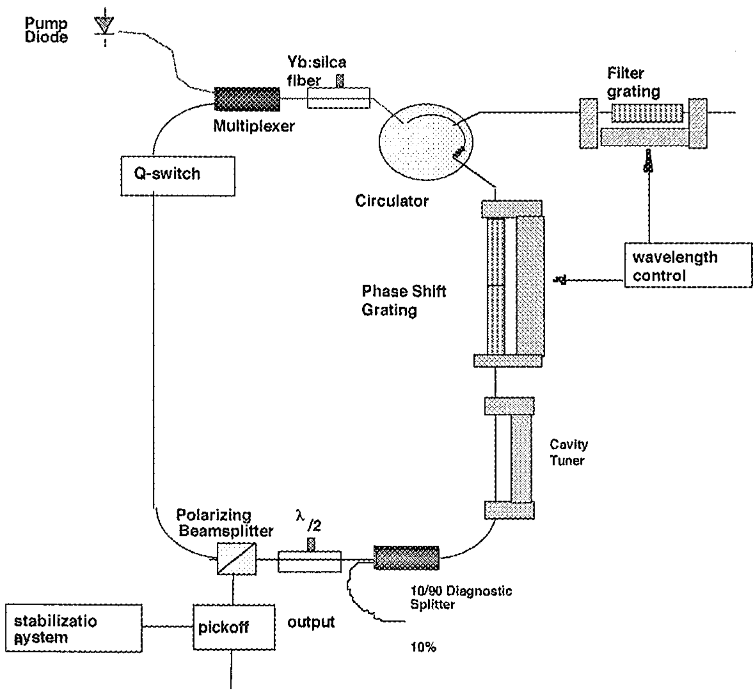

Figure 3. Fiber master oscillator.

Frequency stability in the master oscillator is maintained by enclosing the laser in a temperature and vibrationally isolated box. For the NIF laser an active control loop will maintain continuous, single mode operation of the master oscillator; for our experiments we relied upon the stability provided by the isolated enclosure.

The 300 ns output pulse from the master oscillator is temporally shaped in three stages. The first stage is an acousto-optic modulator that chops off the pre-lase interval leaving the 300 ns output pulse. The second stage is an electro-optic modulator that chops a 30 ns pulse from the center of the 300 ns master oscillator pulse. By chopping out a 30 ns square pulse we reduce the pulse energy while maintaining the peak power so we can amplify the pulse to the desired power level and not be limited by gain saturation in the fiber amplifiers. The 30 ns pulse that is cut from the 300 ns oscillator output is phase modulated in two stages to add sinusoidal, FM bandwidth to the laser pulse. A lower frequency, 1.5-3.0 GHz modulator, adds 27 GHz of bandwidth to suppress stimulated Brillouin scattering (SBS), which can generate an accoustic wave powerful enough to destroy the large optics in the main amplifier chains. A second, higher frequency modulator (~ 17 GHz) adds more sinusoidal, FM, as part of the scheme to smooth the beam by spectral dispersion (SSD). The modulators are small, integrated optic devices made out of lithium niobate that can be combined with their associated radio frequency hardware in small, rack-mounted chassis. In the NIF laser system the phase modulation is done before the amplifier tree so that a single set of phase modulators is required.

The next subsystem in the MOR chain after phase modulation is the amplifier tree. In the NIF laser system the amplifier tree consists of a series of 4-way fiber splitters with fiber amplifiers. The single initial fiber line is first amplified, then split in four. One of the four lines in the first split is sent to a diagnostics package leaving three lines to be amplified for the laser system. These three lines are each split four-ways to produce 12 lines that are each amplified by a set of twelve fiber amplifiers. A final set of four-way splitters produces 3X4X4=48 separate laser lines exiting the amplifier tree section. The amplifiers themselves are two-stage fiber amplifiers as shown in Figure 4. The first stage is a small core, Yb-doped gain fiber, G=12, followed by an amplified spontaneous emission (ASE) filter to eliminate light that is outside the bandwidth of the laser. A second, power amplifier stage is made of larger core fiber and has a gain of 3 giving a total gain of 36 for each fiber amplifier. The fiber amplifier is one of the OPG subsystems that is already in an engineering prototype phase where we are collaborating with a commercial manufacturing company to develop production hardware for the final laser system.

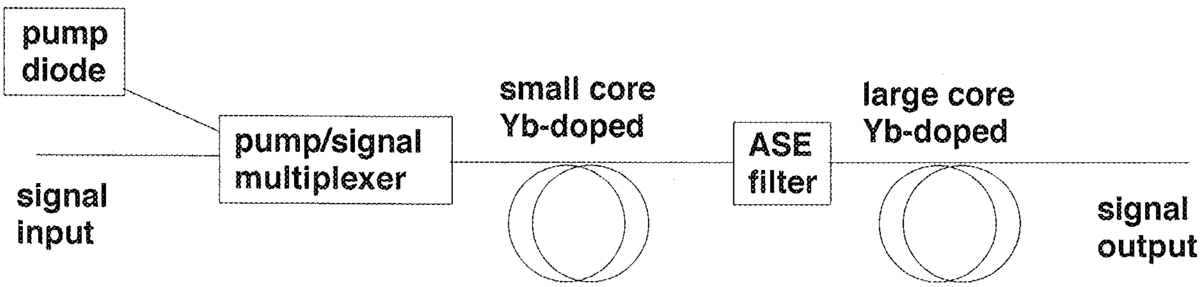

Figure 4. Two-stage fiber amplifier is part of the amplifier tree that converts a single output into 48 parallel outputs.

The final temporal pulse shape is sculpted from the 30 ns square pulse after the laser has fanned out to 48 parallel fiber lines. We developed a high-bandwidth, programmable, arbitrary waveform generator (AWG) to produce the high-temporal-contrast pulses that are needed for fusion ignition[2]. The AWG is made from 96 individual, 250 psec, GaAs FETs that sequentially switch the voltage on a transmission line to form the desired pulse shape. The electronic waveform generator supplies the shaped voltage pulse to an integrated optic, lithium niobate, amplitude modulator. The electronic waveform generator and optical modulator are combined in a single chassis that is also being prototyped by an outside manufacturer. There will be 48 individual chassis in the final NIF laser system. Figure 5 shows a typical, high-temporal-contrast pulse generated by the AWG. In addition to shaping the 48 laser pulses, the AWG is triggered by the Precision Timing System, and so precise timing among the 48 parallel beam lines is set here.

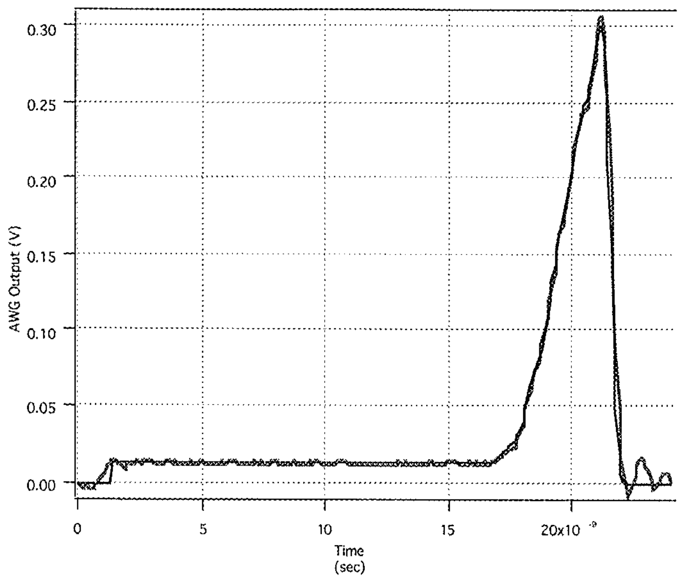

Figure 5. High-temporal-contrast voltage waveform produced by the AWG.

After final temporal shaping the 48 parallel fiber lines are routed through a central distribution rack where they are sent to the 48 Preamplifier Modules (PAMs). The central fiber distribution is carefully designed to ensure that the individual lines produce the correct timing delay to each PAM. We can also add or subtract fiber jumpers to discretely vary the delay of each beamline for needed adjustment, or to satisfy the requirements of special experiments. In addition to the laser itself the MOR contains auxiliary systems for controls, fail-safe protection and precision timing.

B. Preamplifier Modules (PAMs)

Each of the 48 fibers from the MOR distribution rack feeds one of the 48 PAMs in the NIF laser system. The PAM is a high gain (>100 dB) preamplifier that also spatially shapes the beam for the main amplifier chain. There are three major subsystems within the PAM: a high-gain, diode-laser-pumped, Nd:glass regenerative amplifier; a spatial shaping module, and a four-pass amplifier.

The regenerative amplifier is the highest gain amplifier in the entire NIF laser chain[3]. The optical layout for the regenerative amplifier, or "regen" for short is shown in Figure 6. The input section to the regen consists of a fiber launch, where the pulse from the MOR is launched from single-mode fiber into free-space via a precision fiber positioner and a short focal length lens. Next, two Faraday isolators in series protect the single-mode fiber from a high intensity pulse propagating back from the regen output. A second lens in conjunction with the short focal length lens in the fiber launch, forms a telescope to match the beam size at the fiber output to the laser cavity mode for efficient coupling of energy into the regen. A Faraday rotator, a half-wave plate (WP), and a thin-film-polarizer (TFP) form a unidirectional coupler to separate the counter-propagating input and output laser pulses. The input laser pulse from the MOR is injected into the regen cavity through a second TFP. The regen cavity is a long, asymmetric cavity with a single, diode-laser-pumped, Nd:glass amplifier located at one end. The amplifier has a single pass gain of G=1.6 in a 5mm diameter X 50mm rod that is end-pumped by a 4 kW diode array. The cavity transmission is T=0.76, and so the net gain per round trip of the regen is $G_{net}=G^2 \cdot T=1.95$. The total gain of the regenerative amplifier is the net gain raised to the power of the number of round trips that the pulse makes in the cavity before being switched out. For example, if the number of round trips in the regen cavity is k=25, then the total regen gain is

$$G_{total}=(G_{net})^k=(1.95)^{25}=1.8X10^7 \qquad (1)$$

Eventually the amount of extracted energy depletes the available stored energy in the amplifier (amplifier saturation) and the net gain drops below unity and the output energy per round trip starts to decrease. In typical operation we extract 20 mJ from the regen for 0.8 nJ input for a total gain of 74 dB.

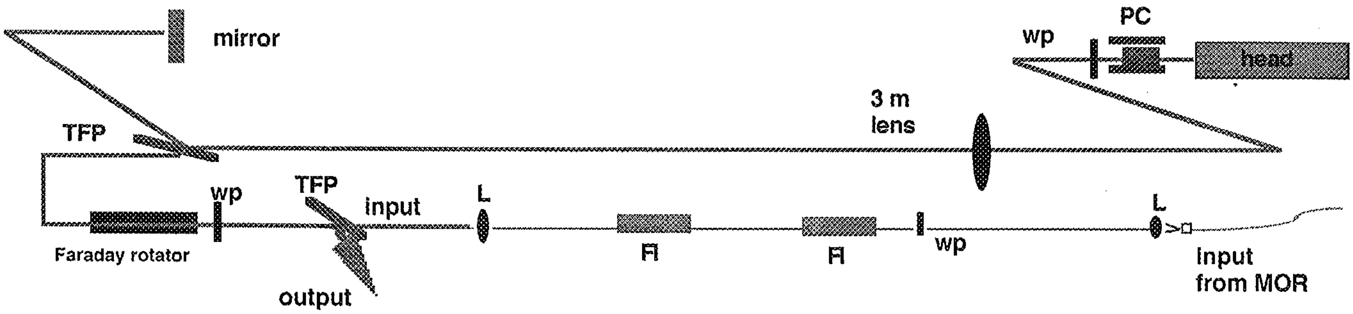

Figure 6. The diode-laser-pumped, Nd:glass regenerative amplifier has a gain >70 dB. Components: L-lens; FI-Faraday isolator; TFP-thin film polarizer; wp-wave plate; PC-Pockels cell.

The output beam shape from the regen is a 3.5 mm diameter circular Gaussian cross-section. The next subsystem in the PAM is the spatial shaping module where the round Gaussian beam is converted to a square-shaped beam that is sculpted in a well defined manner to precompensate for the spatial gain profile of the main amplifiers. The goal is to produce a spatially flattop beam at the NIF target chamber. First the round beam is magnified by a 20X telescope. The expanded Gaussian beam is shaped by an antiGaussian filter that flattens the top of the beam. This flattop beam is further shaped by a gain compensating mask that carves out the center of the beam to produce the final shape. We determine this final shape based on a complex diffraction code that models an entire beamline, including the spatial gain profiles of the main amplifiers. The final mask in the beamshaping module apodizes the beam so that it will propagate over a long distance in a well-behaved manner. All of the beam shaping masks in the module are made by depositing chrome on glass in a standard photolithographic method.

The final amplifier in the PAM is laid out in a four pass configuration as shown in Figure 7. The laser pulse leaving the beamshaping module is reduced in energy to about 600 microJoules from the 20 mJ output of the regen. This input beam is spatially filtered by a vacuum relay telescope with a pinhole that blocks the higher spatial frequencies produced by the final apodizing mask. The filtered input beam passes through a combination of Faraday rotator, half-wave plate, and thin-film-polarizer that acts as a directional coupler to separate the input beam from the counter-propagating output beam exiting from the 4-pass cavity. The 4-pass cavity contains a large, 5 cm, flashlamp-pumped rod amplifier at the cavity center. This amplifier can operate with a single pass gain of 25. Due to the high, single-pass gain of the 5 cm amplifier the cavity is especially susceptible to unwanted, parasitic oscillation. Parasitic oscillation can occur in a high-gain amplifier if there is sufficient gain and feedback to cause oscillation. This oscillation is uncontrolled and chaotic and produces a background of intense light that can propagate into the main amplifier chain along with the amplified and formatted pulse from the MOR. We take several steps to successfully eliminate unwanted oscillation in the 4-pass cavity by carefully controlling the polarization of the light using the Faraday rotator and the quarter-wave plate, and offsetting the beam slightly from the optical axis as it propagates through the cavity so light is never reflected directly back on itself[4]. We have operated the 4-pass amplifier to obtain > 27 J output in a spatially unshaped beam or 15 J in a beam that has been shaped as described in the previous paragraph- these values exceed the requirements for the PAM as noted in Table I.

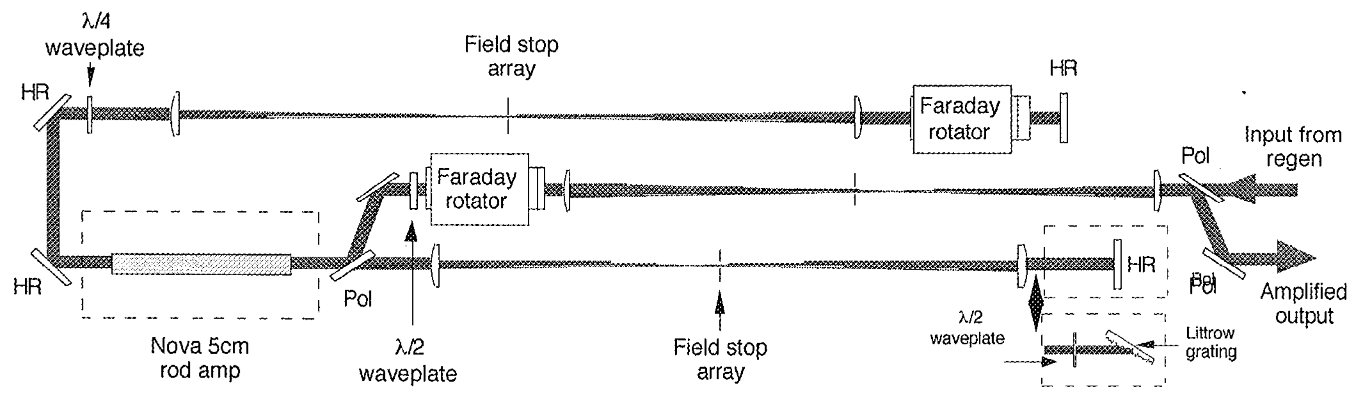

Figure 7. This layout shows the 4-pass amplifier and the grating at Littrow angle that can be substituted for the cavity end mirror to provide angular dispersion of the FM light as part of SSD.

A second function of the 4-pass amplifier optical layout is to provide angular dispersion of the light that has been frequency modulated in the MOR. To achieve this we replace one of the end mirrors in the 4-pass cavity with a diffraction grating positioned at the Littrow angle so the first diffraction order is reflected back in the same direction as the incoming beam. If the 4-pass output is viewed in the farfield (i.e. at the focus of a lens) the focal spot is dithered in one dimension at the sinusoidal frequency of the rf driver to the modulator (e.g. 17 GHz). The angularly deflected light from the 4-pass propagates through the rest of the amplifier chain to the target chamber and final optics assembly where it passes through a special phase plate. The combination of the rapid dithering of the FM light due to dispersion from the grating and the smearing of the focal spot produced by the random phase plate reduces the inhomogeneity (or speckle pattern) normally associated with coherent light and increases the uniformity of the target illumination.

The regen, beam shaping module, and 4-pass amplifier have been built and tested in the Preamplifier Development Lab. Currently we are assembling the first PAM prototype, which consists of the three major subsystems described in this section mounted on a vertical breadboard housed within an enclosed, mechanical structure. Several electronic instruments, including power supplies, and a computer control system are housed on top of the mechanical structure. The PAMs are designed to be line-replaceable-units (LRUs) that can be easily added or removed from their locations in the laser bay for repair or replacement. An additional system, called the input sensor package (ISP) is mounted with each PAM to diagnose the laser at various locations in the PAM, and provide this information to the laser operators.

C. Preamplifier Beam Transport System (PABTS)

The final system in the OPG or Front End of the NIF laser is the PABTS, shown in Figure 8. The 14.7 J output from a PAM/ISP passes through an Isolation Module that contains a large aperture Faraday rotator, half-wave plate, plus polarizers to isolate and protect the Front End from a high energy pulse traveling backwards from the main amplifier chain. From the Isolation Module, the beam enters the 1:4 Split Assembly, where the single beam is split into four beams that will seed four separate main amplifier chains. The four-way split and balancing of power among the four legs is accomplished using thin-film-polarizers and half-wave plates. Each of the beams passes through a five element Vacuum Relay Telescope that relays the beam to the input relay plane of the Transport Spatial Filter. This five element zoom telescope has variable magnification from 0.95-1.02 and can be used to adjust the size of the beam in each of the four legs to accomodate changes in the Main Amplifiers optics. Next a Timing Section allows for adjustment of the timing in each leg by changing the optical path length via mirror, M3. A pair of turning mirrors directs the beam either into the Transport Spatial Filter (TSF), or a final telescope prior to the TSF depending upon the side of the laser space frame in relation to the Main Amplifiers. Detailed mechanical and optical designs of the PABTS are complete and hardware prototyping is underway. One quad of a PABTS beamline will be built in 1999.

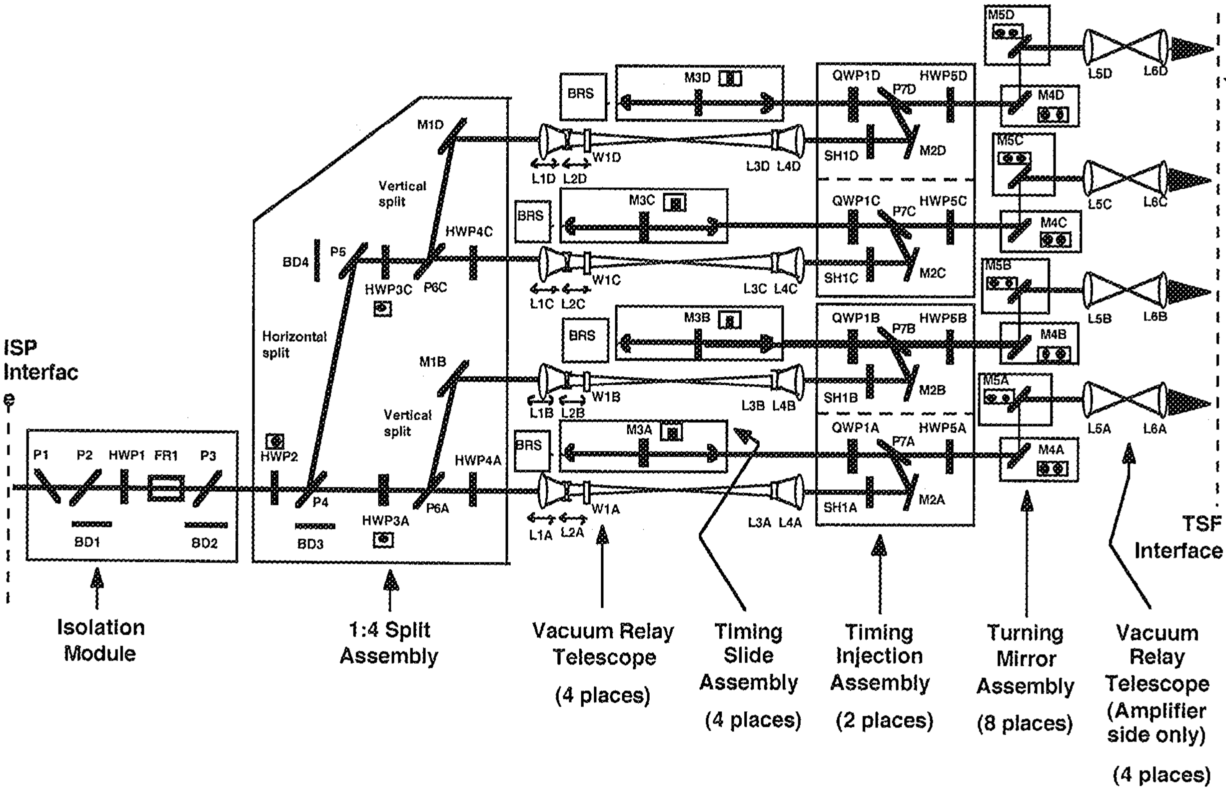

Figure 8. Layout of the Preamplifier Beam Transport System

III. RESULTS

We combined subsystems in the MOR and Preamplifier Development Labs into an Integrated OPG Testbed to demonstrate the performance specifications listed in Table I. The fiber oscillator, amplitude modulator, three fiber amplifiers in series, and a 3 GHz phase modulator were combined to form the MOR system. The Preamp system included the regenerative amplifier, beam shaping module, and 4-pass amplifier with the SSD grating. We linked the two labs together using single-mode polarizing fiber with additional signal cables. We performed several experiments using this Integrated OPG Testbed in order to verify the output energy and power capabilities of the combined system, demonstrate steady-state operation at output levels exceeding the specified requirements, and to demonstrate the functionality of subsystems such as beam shaping and SSD. In addition we developed energetics and propagation models that successfully simulated the behavior of the combined system. Figure 9 shows some highlights from this series of experiments. Figure 9a shows an image of a 15 J shaped beam at the output of the PAM, which equals the energy requirement for a shaped beam listed in Table I. Figure 9b shows a camera image taken in the farfield of the PAM output. The series of spots are produced from the angular dispersion of the frequency modulated light. The plot below the image shows a lineout from the image along with the predicted FM spectra for 81 GHz of bandwidth, which is the requirement (see Table I). Figure 9c shows output energy from the PAM vs energy injected into the 4-pass. In this experiment the mirror replaces the grating in the 4-pass cavity and a square aperture replaces the shaping masks, producing a square flattop beam at the PAM output. We exceeded the 22J specification, extracting 27J from the 4-pass amplifier and PAM.

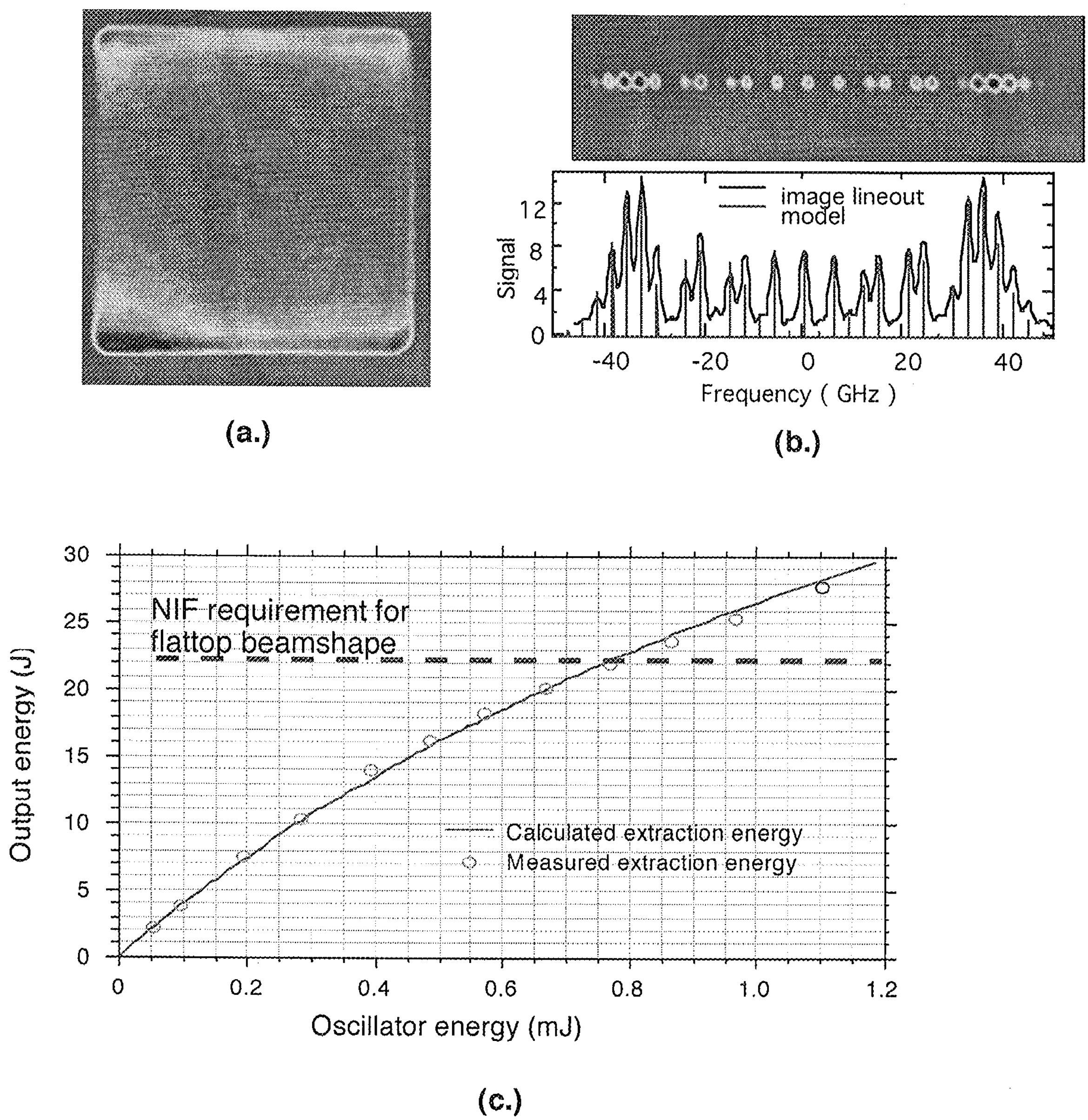

Figure 9 (a). Near-field image of 15 J shaped beam at the PAM output; (b.) Far-field image at PAM output showing FM laser angularly dispersed by diffraction grating in 4-pass amplifier; (c.) PAM output energy vs 4-pass input energy for a square flattop beam.

IV. SUMMARY

The OPG System or Front End of the NIF laser system is nearing the end of its development phase. In the past year we performed a series of experiments that demonstrated or exceeded the performance specifications listed in Table I for the combined MOR and Preamplifier Development Systems. Many of the subsystems described in this paper and demonstrated in our development laboratories are currently being built as engineering prototypes.

ACKNOWLEDGMENTS

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