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Front-End Laser System**

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The National Ignition Facility Front-End Laser System

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ABSTRACT

The proposed National Ignition Facility is a 192 beam Nd:glass laser system capable of driving targets to fusion ignition by the year 2005. A key factor in the flexibility and performance of the laser is a front-end system which provides a precisely formatted beam to each beamline. Each of the injected beams has individually controlled energy, temporal pulseshape, and spatial shape to accommodate beamline-to-beamline variations in gain and saturation. This flexibility also gives target designers the options for precisely controlling the drive to different areas of the target. The design of the Front-End laser is described, and initial results are discussed.

1. OVERVIEW

The National Ignition Facility (NIF) consists of a 192 beam high-energy glass laser system and target chamber, intended for inertial confinement fusion research. Each beam originates from the Front-End as a nominal 1.7 J, 20 ns pulse. This temporally and spatially modulated pulse is injected into the main laser amplifier, boosted to 17.2 kJ, frequency tripled, and directed onto the fusion target. Advances in fiber oscillators and amplifiers, temporal modulation, diode and flashlamp-pumped rod amplifiers, and spatial beam shaping are required to successfully generate the laser pulse for NIF.

In Fig. 1 we show the block diagram of the Front-End laser. We use four oscillators to provide four separate wavelengths separated by 10 Å, a specification derived from target beam-smoothing requirements. Each output from the Q-switched oscillators is phase modulated, amplified, and split in three stages to 48 individual beams plus spares for diagnostic purposes. Finally, each of the 4 X 48 beams is amplitude modulated to a specified temporal pulseshape and is sent via fiber to the preamplifier module (PAM) which is located in the main laser bay next to the large beamlines.

The main amplification stages for the Front-End laser are located in the PAM as shown in Fig. 1. A fiber for each beam from the oscillator and modulator subsystem provides the highly formatted 500 pJ pulse to each PAM, where the energy is boosted to 10 mJ in a regenerative amplifier, and then to as much as 10 J in a four-pass flashlamp-pumped rod amplifier. The regenerative amplifier is designed to operate under minimal saturation to preserve the temporal pulse shape, and amplify the pulse by 10^7 with better than $\pm 2\%$ pulse to pulse repeatability. A pair of diode-pumped rods was chosen to

accomplish this, in a regenerative amplifier configuration which minimizes the amplifier footprint while maximizing the rod gain. The Gaussian beam from the regenerative amplifier is apertured to a square beam and spatially shaped to compensate for spatial gain variations in the main laser cavity. The final amplification stage is a four-pass flashlamp-pumped rod amplifier.

Fig. 1. Block diagram of the National Ignition Facility Front-End laser.

2. OSCILLATOR AND MODULATOR SUBSYSTEM

System considerations. The oscillator and electrooptic modulator systems are housed in the Master Oscillator Room (MOR), where all optical signals are transported in fiber. In the MOR¹, four oscillators of different wavelengths feed amplifier/splitter arrays which deliver light to the amplitude modulators. The output signals leave the room via fiber, to be amplified in the preamplifier modules. The oscillator and amplifier/splitter system for one wavelength is shown in Fig. 2.

Fig. 2. Master oscillator, phase modulator, and fiber distribution system diagram.

Due to the peak power requirements for the output pulses that arrive at the preamplifier, these fiber amplifiers must produce about one microjoule of energy. Of the several fiber amplifier materials we have considered, Ytterbium-doped silica has the most desirable spectral properties, and the silica host allows for high doping concentrations as well as being mechanically robust. Also, silica can be fusion spliced with other fibers, making possible low loss connections between dissimilar fiber types. For these reasons, we have concentrated on Yb:Silica in these experiments.

Oscillator development. To perform tests on an amplifier, we needed a tunable source with enough output energy in a short pulse to drive the amplifier into saturation. Initial tests with a Yb:Silica fiber pumped at 860nm indicated that the gain peak at 975nm was suppressed by absorption at the same wavelength, due to the quasi-three-level nature of this transition. Small signal gain tests were performed with a Nd:YLF laser at 1053nm, demonstrating high gain in a fiber pumped at 860nm. We therefore constructed a Q-switched, tunable oscillator, using a simple linear cavity scheme, shown in Fig. 3. A diffraction grating is the tunable element, resulting in lasing on only about five modes of the 135 MHz cavity, despite the large gain bandwidth. The resulting 20-50ns pulse is temporally noisy, but stable in energy and timing with respect to the Q-switch trigger, and therefore adequate for our experiments. The pulse contains about 60nJ of energy, about 30% of which is coupled into the fiber that feeds the amplifier experiment. We were able to tune the oscillator over a broad range, as shown in Fig. 4.

Figure 3. A multi-longitudinal mode oscillator for amplifier tests.

Figure 4. Wavelength tuning curve of the test oscillator.

We are currently working on development of a single longitudinal mode, Q-switched ring oscillator using mainly fiber components. Single mode lasers are highly sensitive to perturbations of the opto-mechanical system, resulting in optical instability. A fiber cavity will be more stable and offer lower loss than a bulk optic version.

Amplifier experiments. The pumping scheme for the amplifier is similar to that for the oscillator, except a 980nm pump diode is used. This wavelength is more highly absorbed, has a higher quantum efficiency, and is available as a standard commercial pump source for erbium-doped fiber amplifiers. We introduced the oscillator signal into the pumped Yb-doped fiber through a free-space optical isolator, and observed the output pulse on energy, temporal, and spectral diagnostics. Data for output energy versus input energy at the four selected wavelengths are shown in Fig. 5.

Figure 5. Output versus input energy for four wavelengths.

The small signal gain was 90, but dropped to about 60 with 900 microJoules extracted. A Franz-Nodvik saturation model was fit to the data, so that we could predict performance in a multistage amplifier system. Since the NIF fiber amplifier system needs to minimize pulse amplitude rolloff in order to provide for maximum shaped pulse contrast, we have designed an amplifier with larger core size and higher saturation energy. As with communication amplifiers, this amplifier design will be housed in a compact module, allowing convenient interconnection and servicing of the amplifier system.

As expected, small signal gain was about three times higher at 1023nm than the 1054nm operating wavelength. In the NIF system, narrowband filters will reject ASE and introduce loss around 1023nm to prevent oscillation.

Temporal pulseshaping is performed using a system similar to that shown in Fig. 6. The optical fiber from the splitting system is connected to a Mach-Zehnder interferometer driven by an arbitrary electrical waveform generator (AWG). The desired temporal pulseshape is generated under closed loop computer control by measuring the 1 kHz repetition-rate optical waveform, and modifying the AWG waveform so as to minimize the error between the desired and measured waveforms. The heart of the system is a microwave GaAs-FET based waveform generator. This system is based upon the summation of temporally delayed and scaled impulses which form the desired pulse with a resolution of 4 GS/sec. The waveform generator is followed by a pulse-biased GaAs-FET amplifier in order to generate the ~5V signals required by the modulator.

Fig. 6. Computer controlled pulseshaping has been demonstrated using GaAs-FET circuitry at 4 GS/s under closed loop.

An example of results obtained to date is shown in Fig. 7. We used a 14-element AWG followed by a commercially available DC to 1 GHz amplifier driving the electrooptic modulator. The large errors before the desired pulse rising and falling edges are not relevant, since both edges are chopped by an optical gate. What is relevant, however, is the inability to conform to the precise pulseshape near the peak of the pulse. This is due to the limited bandwidth of the amplifier, which will be fixed when our pulse-biased GaAs-FET amplifier is used. In addition we will soon have a wide-bandwidth commercially available modulator driver for these higher-bandwidth applications.

3. PREAMPLIFIER MODULE

The preamplifier module schematic is shown in Fig. 8. The laser input via fiber is coupled into the regenerative amplifier²⁻⁴ in the top of the figure, where it is trapped in the amplifier for approximately 13 round trips and amplified to approximately 10 mJ. This amplifier is intended to perform linear amplification of the shaped input pulse, thus it is designed to gain saturate no more than 20% for the 10 mJ output. We are using two diode-pumped glass rod amplifier heads in the regenerative amplifier, glass to

The graph plots Pulse Intensity (arb. units) on the y-axis (0 to 0.06) against Time (ns) on the x-axis (0 to 6). The 'Desired optical pulse' is a narrow peak reaching ~0.055 at 4.2 ns. The 'Measured optical pulse' is broader, reaching the same peak intensity but with a long tail extending to 5 ns.

Time (ns)	Desired optical pulse (arb. units)	Measured optical pulse (arb. units)
0.0	0.000	0.000
1.0	0.000	0.005
2.0	0.000	0.005
3.0	0.000	0.018
4.0	0.000	0.048
4.2	0.055	0.055
4.5	0.000	0.020
5.0	0.000	0.003

The diagram illustrates the FEL injection system, divided into two main sections: the electron beam path and the optical pulse generation system.

Electron Beam Path:

- Input:** Input fiber in from MOR.
- Pre-amplifier module:** Contains a fiber coupler and a diode pumped rod amp (2 PLC's).
- Regenerative amplifier:** A long tube with a 30 ns roundtrip time, featuring an aperture and a Faraday isolator.
- Beam Shaping:** Includes a flat-top Gaussian transmission filter, beam orient mask (align only), serrated aperture (RPO), and a quadratic Y-B transmission filter.
- Beam Transport:** Consists of a beam expander, insert, centering ref, and a beam transport section.
- Output:** Output to amplifier cavity.

Optical Pulse Generation System:

- Beam transport:** A section for transporting the beam.
- Optical Pulse Generation System:** Includes a beam transport section, a Galilean telescope, a vacuum spatial filter with pinhole, and a shutter.
- Transport spatial filter:** A section for filtering the beam.
- Output:** Output to amplifier cavity.

Other Components:

- RP1, RP2, RP3, RP4, RP5:** Various optical components and mirrors.
- Faraday rotator:** A component used to rotate the polarization of the beam.
- PC:** A component, possibly a polarizing component.
- Shutter:** A component used to control the beam's path.

Fig. 8. The NIF Preamplifier module.

To meet this beam uniformity goal, we set the gain stability at

$$\frac{\Delta E_{in}}{E_{in}} \leq 2\%, \quad \frac{\Delta E_{out}}{E_{out}} \leq 3\% \quad \text{Peak to peak}$$

where ΔE_{in} and ΔE_{out} are the p-p error in the input energy and output energy respectively. Assuming that the input and output error are uncorrelated, the allowable variation of stored energy in each of the two glass rods is

$$\frac{\Delta E_{stored}}{E_{stored}} = 0.18\%$$

which can only be achieved using diode pumping. Experience on the LLNL Beamlet laser showed that we could only achieve an overall gain stability of 5% in the short term and 10% as aging occurred in a flashlamp-pumped glass regenerative amplifier design.

The design of the diode-pumped head is shown in Fig. 9. We chose an end-pumped design⁵ over side pumping for several reasons. First, the pumping efficiency is extremely high - 86% of the raw laser diode power is delivered to rod. The rod is designed with a polished barrel, and the doping is such that three e-foldings occur over the 5 cm length. In addition, an anti-reflective coating at the pump wavelength and a high-reflective coating at the laser wavelength is applied at the pump end, with a conjugate coating being put on the laser beam entrance end of the rod. The pump light experiences six e-foldings of absorption before exiting at the pump end while at the same time pumping uniformly due to total internal reflection from the walls of the rod. We were worried about parasitics due to the polished barrel, but this has not proved to be a problem. The primary downside to this design is alignment, which is made difficult since the pump end of the rod must be simultaneously pointed and centered correctly. Another issue unique to this design is preconditioning of the laser diode output. The laser diode divergence in the fast axis is too large for the lens duct⁶ to handle, the $1/e$ half-width must be reduced below 40 milliradians to obtain greater than 90% transfer efficiency from the diodes to the lens duct exit face.

Fig. 9. Regenerative amplifier glass rod, pumped by laser diode stack through a lensing duct.

This is accomplished by attaching cylindrical lenses as close as possible to the laser diode facets. Our prototype diode array utilized large glass fibers to perform the lensing, later designs will use custom plano-convex cylindrical lenses designed using variational methods, and manufactured by grinding the figure into a fiber preform. However, even with the round fiber micro-lensing on our prototype heads we obtained the transfer efficiencies shown in Fig. 10.

Fig. 10. Micro-lens conditioning and lensing duct transfer efficiency.

The original regenerative amplifier design shown in Fig. 8 has been modified somewhat, such that now it is a linear cavity with two Pockels cells, one to switch the beam in, and another to switch the beam out. Making it linear simplified cavity design enormously, and using two Pockels cells allowed the use of much less expensive, single-transition, electrical drivers.

The beam from the regenerative amplifier has a Gaussian spatial profile, which must be transformed to a square beam in order to match the square aperture of the main cavity amplifier. The ideal beam profile at the main laser output is square with a flat profile and minimal modulation. Spatial shaping is performed after the regenerative amplifier as shown in Fig. 11, utilizing three separate elements. An azimuthally symmetric filter compensates for the regenerative amplifier beam profile, and compensates for the final rod amplifier radial gain variation. This is followed by a filter which precompensates for any gain variation in the main amplifier in the horizontal direction, and finally a square aperture with a serrated apodization followed by a spatial filter pinhole is used to create the square beam. The square aperture also defines the relay plane image which is subsequently re-imaged throughout the main laser amplifier

Fig. 11. The NIF spatial shaper utilized two partially reflective spatial filters followed by a serrated square aperture and spatial filter pinhole.

The final gain in the preamplifier module comes from a 4.5 cm by 50 cm rod amplifier pumped by flashlamps in a diffuse cavity design. It is arranged in a four-pass architecture as shown in Fig. 8, utilizing a Faraday rotator, waveplate, and polarizer to obtain the four passes. We are currently prototyping such an amplifier in the laboratory, and have just begun testing. Initial results utilizing a 3%/wt doped LG-750 rod yielded a centerline gain of 6.5, close to the predicted gain of 8.0. We suspect the reflector to be the cause of this gain deficit, the sintered Al_2O_3 tube used in the prototype appeared to be less reflective than other alumina tubes used previously, a decrease in reflectivity to 85% would account for the measured gain.

4. CONCLUSIONS

We are developing a sophisticated front-end laser system which can provide a $>10\text{J}$ beam with temporal, spatial, and spectral modulation required for high performance operation of the National Ignition Facility. Significant progress has been made this year in all the components, in fact all have been prototyped with at least some initial testing completed on each one. We have demonstrated the basic concepts for a entirely fiber-based oscillator subsystem and computer-controlled temporal pulseshaping. We developed a highly-efficient diode-pumped glass amplifier and regenerative amplifier cavity, and a diffuse cavity flashlamp-pumped 4.5 cm diameter rod amplifier. In the next year, these components will be integrated, and tested as a system. In addition, we will be seeking strong industry participation to perform final design and production on the large quantity items.

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