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Abstract: Operation of the Mercury laser with two amplifiers activated has yielded 30 Joules at 1 Hz and 12 Joules at 10 Hz and over $8x10^4$ shots on the system. Static distortions in the Yb:S-FAP amplifiers were corrected by magneto rheological finishing technique.

OCIS codes: (140.3580) Solid State Lasers; (140.3280) Laser Amplifiers

1. Introduction

The Mercury laser was initially commissioned with a single amplifier to test the basic architecture and assess performance of the component technologies: high power diode arrays, Yb:S-FAP crystals, gas cooling, and a high average power Pockels cell. We report the first integrated operation of the two amplifier system in the upgraded Mercury laser laboratory (see Fig. 1a). In addition to increased energy and average power operation, active wavefront control and average power frequency conversion will be added as capabilities in the coming year to meet our requirements for a scalable inertial fusion driver. The Mercury laser project is part of a national inertial fusion energy program in which four driver technologies are being considered including solid-state lasers, krypton fluoride gas lasers, Z-Pinch and heavy ions. These drivers will be evaluated on several important criteria including: scalability, efficiency, reliability, cost, and beam quality. Mercury's operational goals of 100 J, 10 Hz, 10% efficiency in a 5 time diffraction limited spot will demonstrate the critical technologies before scaling the system to the multi-kilojoule level.

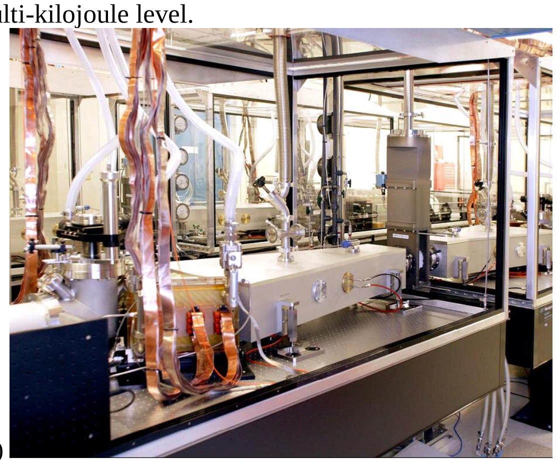
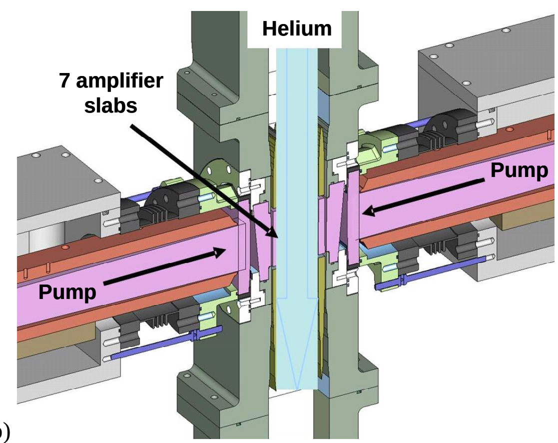
a)  b) 

Figure 1. a) A picture of the Mercury laboratory showing dual amplifiers and Class 1000 clean room enclosures which minimize air turbulence and decrease optical damage due to contaminants. b) Amplifier module showing gas-cooled vane structure

II. Crystals and gas cooling

Before downselecting to the optimum gain medium, we explored numerous gain materials and architectural options to best fit the design space of a fusion energy class laser. Yb^{3+}:$Sr_5(PO_4)_3F$ or Yb:S-FAP was chosen as the gain media based on its long energy storage lifetime, suitable absorption and emission cross sections, and good thermal conductivity. The primary challenge has been in the fabrication of full aperture Yb:S-FAP slabs of 4x6x0.75 cm^3. Growth techniques have advanced such that the boules being regularly provided by Nortrop Grumman Inc. are 6.5 cm diameter by 10 cm long from which 2 full size amplifier slabs can be fabricated. However, the techniques employed to eliminate or reduce crystalline defects have produced boules that are difficult to cut without fracture due to the high residual stress from the growth process. Water jet cutting of the material is gentle compared to other cutting techniques, and has been used to successfully cut the large boules. The boule halves slabs are then shaped and polished. If the transmitted wavefront does not meet the $\lambda/10$ peak-to-valley or $\lambda/90$ cm^{-1} gradient specification, then the slab is polished by magneto rheological finishing (MRF) which is a method of deterministically removing material from the surface. The MRF technique is capable of removing features down to the 1 mm scale and to several waves in amplitude. An example of a slab polished by MRF technique is shown in Fig. 2 where the stress induced distortion is removed from the bonding process to two smaller slabs to form one full size slab. In addition to wavefront distortion, we are also concerned with the optical lifetime of the slabs. Employing established polishing technology adapted to the Yb:S-FAP material, subsurface damage is removed and the surface microroughness can be reduced to less than 3. Measured damage threshold at 1047 nm of conventionally or MRF polished Yb:S-FAP substrates has increased to 18 J/cm^2 at 10 ns. The slabs are then mounted with a compliant urethane compound into aerodynamic aluminum structures called "vanes" (Fig. 1b). The faces of the two crystals are separated by 1 mm in helium gas cooling channels where typical gas velocity exceeds Mach 0.1 at 4 atmospheres helium pressure.

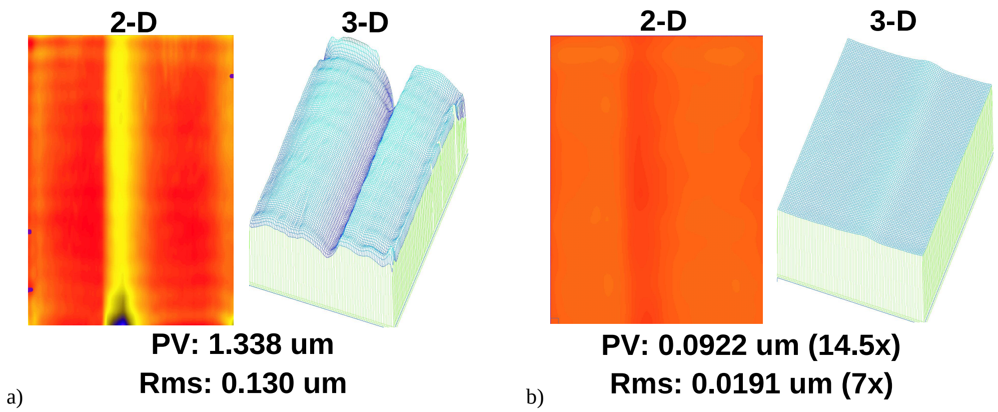


Figure 2a) Initial phase of bonded slab showing 1.338 micron wavefront distortion, and b) final phase of amplifier slab after MRF treatment showing 0.0922 micron wavefront distortion.

III. Laser diodes and architecture

The laser diodes emit at 900 nm to overlap the 4.6 nm wide Yb:S-FAP absorption line. The diodes are precision mounted onto etched silicon heatsinks with microlenses to increase brightness to 1.0 MW/cm2-Sr, then secured onto large copper cooling blocks [1]. Each amplifier assembly is pumped by four 80 kW diode arrays. The diode arrays are separated to allow for the passage of the 1047 nm extraction beam through the center. The diode array light is guided to the amplifier through multiple reflections within a hollow highly reflective metal lens duct and parallel plate homogenizing structure.

The overall architecture employs an off-axis, four-pass beam layout. Image relaying of the laser beam with telescopes between the amplifiers helps to greatly reduce the intensity modulation at the crystalline amplifiers. An average-power, birefringence-compensated Pockels cell [2] is inserted after two passes at low fluence (< 1 J/cm^2) to help suppress the buildup of parasitic beam energy.

The laser system, diode laser power conditioning, and utilities are all computer controlled. A full suite of sensor packages has been fielded to diagnose the beam after each pass. The most important diagnostic is the dark field, which allows rapid detection of damage in the amplifier relay plane at up to 10 Hz. When the computer software algorithm detects damage in the dark field image, a signal is sent to the control system to the shut down the laser. The algorithm can detect damage features as small as 100 μm.

IV. Laser experiments

The first set of laser experiments utilized seven Yb:S-FAP slabs in a single amplifier, 4-pass architecture. These tests were performed before MRF had been validated on Yb:S-FAP. In the interim, a static conjugate silica phase plate, fabricated by MRF, was tested and shown to correct for the non-thermal distortion when placed in an image relay location. We measured a factor of three improvement in the energy within a diffraction-limited spot (Fig. 3a). The energetics data curve for the single amplifier system was mapped by holding the front-end energy constant and increasing the diode pump pulsewidth to increase the gain. The data shows reasonable overlap with our energetics model with no adjustable parameters (Fig. 3b). Utilizing 360 mJ of front energy, and pumping for up to 1 millisecond, we were able to extract up to 33.4 joules of energy at 1047 nm, which corresponds to a 4.6% electrical to optical efficiency. Increasing the pump repetition rate to 5 Hz, 114 W of average power was achieved with < 0.5 % rms energy fluctuation (Fig. 3c) for 20 minutes. The single amplifier activation campaign had an accumulation of greater than 3.8 x 10^4 shots. The beam quality or M^2 of the output beam was captured at this highest power level and was found to be 2.8 x 6.3 times diffraction limited, with the larger divergence associated with the bond distortion.

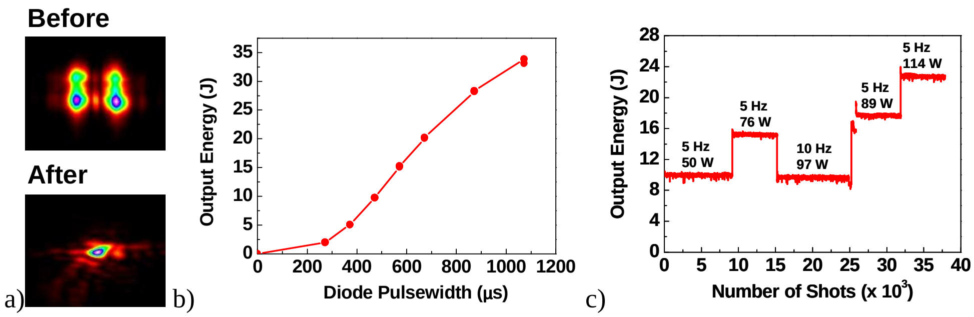


Fig. 6. a) far field image of the amplifier head ~ 15 times diffraction limited, and with the additional wavefront corrector ~ 5 times diffraction limited, b) Single shot energetics showing peak energies of 33.5 J, e) Mercury energetics operation for several repetition rates up to 114 W, 23.5 J at 5 Hz

The second set of laser experiments utilized two amplifiers in the upgraded laser facility (Fig. 1). Four Yb:S-FAP slabs were mounted in each amplifier. Four of these S-FAP slabshave an MRF correction for transmitted wavefront, and were placed in the final higher fluence amplifier. One of our primary design tools for this system has been the MIRÓ beam propagation software developed by CEA in France, which allows prediction of beam modulation, beam clipping and diffractive effects, B-integral or non-linear beam breakup, two-dimentional energetics and temporal pulse distortion. For example, our designs require reliability and long optical lifetime for the system. A histogram of the modeled average and peak fluence through the system is plotted relative to the optical damage threshold of these optics (Fig. 4a), showing us which optics are under the highest risk. Energetics of the 8 slab system was performed with peak energies of 40 J (Fig. 4b). The output near field shows < 1.33 peak to average modulation (Fig. 4c) and the output far field (Fig. 4d).

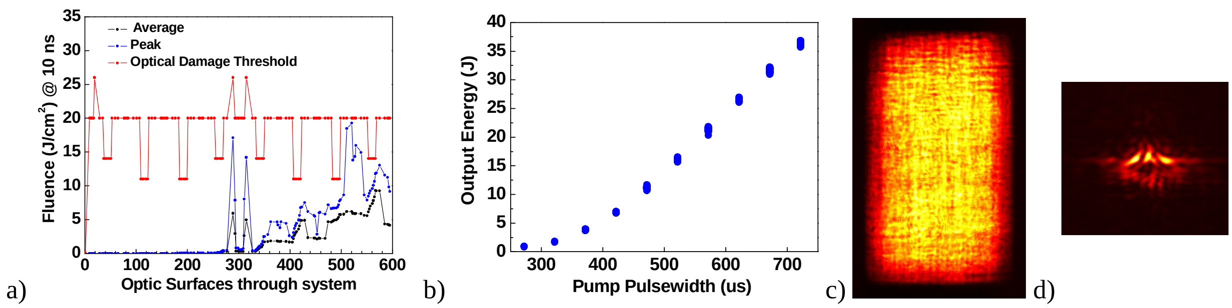


Fig. 4 a) Histogram of fluence throughout the Mercury laser system for a 100 J output simulation compared to the damage threshold of optics, b) Energetics of 8 slab, two amplifier full system, c) Output near field, d) Output far field.

In the coming months two more slabs will be installed in the system, increasing the extracted energy to greater than 50J. The system will be operated at 10 Hz and long term hour long operations demonstrated. In addition, an average power frequency conversion module will be commisioned. Predicted output of the harmonic converter should exceed 20 J or greater than 40% conversion efficiency. A temporal pulse shaping upgrade to the front end will allow generation of shorter pulses which will further enhance performance and bring us closer to our system milestones.

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