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Thermal recovery measurements on multi-segment amplifiers

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ABSTRACT

We present the results of a series of experiments to measure the thermal recovery times of a flashlamp-pumped, Nd:Glass multi-segment laser amplifier. In particular, we investigated the thermal recovery times under the following cooling options: 1) passive cooling, 2) active cooling of the flashlamp cassettes, and 3) active cooling of the flashlamp cassettes and gas flow in the pump cavity.

Keywords: flashlamp-pumped Nd:Glass laser amplifiers, thermal recovery, inertial confinement fusion

1. INTRODUCTION

As presently envisioned, multi-segment amplifiers (MSAs) will be used in megajoule-class Nd:glass laser drivers for inertial confinement fusion experiments.¹ When the flashlamps are fired in a these Nd:Glass amplifiers, the various components in the amplifier become heated by the absorption of the radiant energy from the flashlamp. After the shot, temperature gradients in the laser slab cause the slab to warp, thereby distorting the beam's wavefront. In addition, the release of heat from the amplifier module may set up convection currents either in the amplifier module itself or in the connecting beam tubes. These convection currents may persist for quite a long time after the slab itself has come to equilibrium, again distorting the wavefront of the beam.

It is therefore important to understand the cool-down times of the amplifier module so that trade-offs can be made regarding shot rate and the complexity of the cooling system. To this end, we have measured the thermal recovery time of a 2x2 multi-segment amplifier under various cooling configurations. This paper will present the results from those measurements. To our knowledge, this is the first time such detailed experiments have been carried out on an MSA.

2. EXPERIMENTAL LAYOUT

A. Amplifier and thermocouple configurations

We used two one-slab-wide by two-slabs-high Beamlet Basic Assembly Units (BAUs)² for our temperature recovery measurements, arranged in a two-by-two configuration. In one BAU (the instrumented side), we placed two slabs of LG-750 laser glass. The other (non-instrumented) side contained dummy slabs of Graylite architectural glass to simulate the laser glass. We used a full complement of flashlamps for the experiment: two side arrays and one central array containing 10 lamps and 16 lamps in each array respectively.

In order to obtain as complete a data set as possible, we identified approximately ninety locations in and on the amplifier at which we were to take temperature measurements. In addition, we measured the temperature at various locations in the room. As an example, the thermocouple distribution on the laser slab is shown in Fig. 1. As can be seen, information about horizontal and vertical temperature gradients, as well as temperatures near the edge cladding may be determined.

Fig. 1 Thermocouple distribution on laser slab, showing location of thermocouples on the edge claddings.

B. Thermocouple mounting considerations

We used type K thermocouples with various mounting configurations to obtain the temperature readings. The flashlamp radiation in the amplifier is sufficiently intense so that any organic compounds in the direct path of flashlamp radiation will burn. Consequently, for these measurement locations we used special bare-wire thermocouples. The wires for these thermocouples were butt-welded so as to make the leads come out at an angle of 180° from the active region. The wire size was 0.010" and the welded region had a diameter of approximately 0.030". Self-adhesive thermocouples or thermocouples secured with thermally conductive epoxy were used for measurement locations not in the path of flashlamp radiation.

The actual mounting of the thermocouples is very important if one wants to measure what one thinks they are measuring. Simply pressing the thermocouple against the surface to be measured is poor technique as there is always a doubt as to whether the surface temperature or the air temperature is being measured. To obtain accurate measurements of the temperature in the laser slab, we drilled millimeter-sized holes through the slab and inserted the thermocouple inside this cavity. The thermocouple wires passed through feed-throughs in the top of the amplifier to the quick-disconnect plug. We used a similar method for mounting the thermocouples to the blastshields. For temperature measurements on the flashlamps, we wrapped the thermocouple around the envelope.

The nature of the bare-wire thermocouple requires that the two leads not short against each other. For especially long lead runs (*e.g.* to the bottom of a flashlamp), we used two-hole ceramic tubes to isolate the leads from each other. Likewise, we used ceramic feed-throughs when the thermocouple leads had to pass through a metal bulkhead. For those thermocouples whose leads were too far apart to pass through a single ceramic feed-through (*e.g.* slab thermocouples), we used specially-modified Cajon fittings which screwed into the top plate of the amplifier.

C. Cooling options

One of the goals of the experiment was to measure the thermal recovery time of the amplifier under various cooling scenarios. To this end, we investigated three cooling options: 1) Passive Cooling, 2) Forced air flow through the flashlamp cassettes, and 3) Nitrogen (N_2) flow in the pump cavity plus air flow through the flashlamp cassettes. There are two options for passive cooling. In the first option, the tops of the flashlamp cassettes are blocked so there is no airflow past the flashlamps. In the second option, the tops of the flashlamp cassettes are open so natural convection can occur in the cassette. For the case of active cooling, we used half-horsepower air pumps to pull the air past the flashlamps. We were able to vary the air flow from 10 CFM/lamp to 2 CFM/lamp.

The jets used to flow N_2 into the pump cavity are shown in Fig. 2. These jets were centrally located on the top and bottom reflectors on both sides of the amplifier. For most of the tests, we used the smallest hole diameter (1 mm) as we found little difference in cooling rates from one hole size to another. The N_2 flow rate was adjustable from 1.8 CFM/jet down to 0.5 CFM/jet. A thermocouple in the N_2 line at the inlet to the amplifier monitored the N_2 temperature. By running long feed lines from the N_2 outlet in the room to the amplifier, we were able to match the N_2 temperature closely to that of the ambient room temperature.

NOTES
UNLESS OTHERWISE SPECIFIED:

1. ALL DIMENSIONS ARE IN INCHES.
2. DIMENSIONING AND TOLERANCING PER
ANSI Y14.5M-1982.
3. SURFACE TEXTURE PER ANSI B46.1-1978.
4. 125 ☒ ALL MACHINED SURFACES.
5. BREAK SHARP EDGES .010-.030 R
OR CHAMFER.

				ALUM 6061-T6					
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		DWN Rick McCrecken	2-7	CLASSIFICATION THIS DOCUMENT IS THE PROPERTY OF THE UNIVERSITY OF CALIFORNIA LAWRENCE LIVERMORE NATIONAL LABORATORY. REPRODUCTION PROHIBITED OFFICIAL USE WITH OUT PERMISSION OF THE		MAJOR UNIT NIF			
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Fig. 2 Detail of Nitrogen jets.

In an amplifier chain such as that envisioned for NIF, a given amplifier module (or Frame Assembly Unit) will find itself surrounded by at least three other FAUs, which can act as sources of heat for the FAU in question. Consequently, the thermal recovery times we measured on our lone 2x2 MSA under conditions of natural convection will not be representative of the thermal recovery time for an amplifier module immersed in a "sea" of similar modules; our measurements will probably be optimistic as regards to the time it takes to reach thermal equilibrium. In the case of forced-air cooling, this argument probably isn't valid as the heat is rapidly removed from all amplifiers. In order to try and simulate the behavior of such an interior module, we placed 2-inch-thick blankets of a thermally insulating material known as "Fiberfrax" on four sides of the amplifier, as well as placing silvered plates on the ends of the amplifier. We chose Fiberfrax because not only does it have excellent insulating properties, but it is a totally inorganic material, and thus would not burn when subjected to flashlamp radiation.

D. Data acquisition and analysis

We acquired the thermocouple data with a computerized scanning system. We scanned all the thermocouples at 5 sec intervals for the first hour, so that any short-time-constant thermal effects would be certain to be captured, and at 2 min. intervals for times greater than one hour. Most of the data shown in this memo is relative to a 10-min. baseline acquired before each shot (except in the case of repetitive shots). The uncertainty in our measurements is $\pm 0.1^\circ\text{C}$.

Because some of the thermocouples were mounted on metal plates, there was concern that electromagnetic transients induced by the firing of the flashlamps would generate large voltages in the thermocouple. These voltages could then damage the input electronics of the acquisition system. To prevent this, all thermocouple leads were brought together and terminated in four MS-style multi-pin connectors. Similarly, all leads from the acquisition system were brought together to four mates for the above connectors. The pins in these connectors were made of the same metals as those used for the thermocouples. The connectors were uncoupled at the time the flashlamps were fired, and then mated as soon as possible after firing. As a result, the earliest time we could acquire data after we fired the flashlamps was somewhere between 30 seconds and one minute.

3. RESULTS

As regards to the thermal recovery of the laser slab, we have found there are two significant time scales. The first one has to do with the rate at which temperature gradients in the slab disappear (so-called self-equilibration time). We obtained this time scale by plotting the maximum temperature difference in the slab as a function of time. The second time scale has to do with the rate at which the laser slab returns to its pre-shot temperature (slab equilibration time). We obtained this time scale by plotting the average temperature in the slab as a function of time. Typically, the slab equilibration time is a factor of 2-4 times longer than the self-equilibration time. For reasons mentioned in the introduction, both time constants must be taken into consideration when determining when it is possible to propagate a beam through the system.

The source for all heat in the amplifier is the flashlamps. When fired, the envelope temperature rises 20-25 $^\circ\text{C}$ above ambient, and if nothing is done, this heat gets slowly transferred to the blast shield, which continues to radiate for quite some time. Thus, the rate at which the amplifier cools down is a direct function of how quickly the heat can be removed from the flashlamp cassette. Once the heat is removed from the cassettes, further air flow really doesn't help; the blowers do not have to be on the whole time between shots.

A summary of the experimental results is shown in the following table.

EXPERIMENT	SELF-EQUILIBRIUM TIME (hrs.)	AMPLIFIER EQUILIBRIUM TIME (hrs.)
No external cooling		
Cassette blocked	3-4	>12
Natural convection	3-4	10-12
Forced-air cooling		
10 CFM/lamp	1-1.5	≈3
2 CFM/lamp	1-1.5	≈6
10 CFM/lamp+ 1.8 CFM/jet N ₂	≈1	≈2
2 CFM/lamp+ 0.5 CFM/jet N ₂	1-1.5	≈6

A. Natural convection and inhibited natural convection in the lamp cassette

As mentioned previously, the tops of the flashlamp cassettes can either be blocked or open. This section describes the temperature histories for these two cases. We show in Fig. 3 the temperature of a flashlamp as a function of time for various positions along the flashlamp for the case of natural convection. Since the top of the cassette is open to the air, the top of the flashlamp cools quite a bit faster than the rest of the lamp. After four hours, the top has returned to its pre-shot value, whereas the middle and bottom of the lamp are still about half a degree above their pre-shot value. As can be seen, the initial temperature rise in the envelope is quite high - on the order of 25 °C. This gradient is also impressed on the blastshield, as shown in Fig. 4. We clearly see in this figure the delay in reaching the maximum temperature in the blastshield and the following slow decay of heat. It is this rise and decay that drives the recovery times in the laser slab. It should be pointed out that the horizontal gradient is much smaller than the vertical gradient, both for the flashlamps in the cassette and for the blastshield.

In Fig. 5, we show the average temperature rise in the slab as a function of time. As may be seen, it takes 10-12 hours for the slab to reach its pre-shot temperature, and much longer than that if the cassette is blocked. As expected, an uninsulated single module cools down faster than an insulated, double module. It is interesting to note that after an initial cooling period, the average temperature in the slab rises before it begins its final cooling. This feature does not occur during forced-air cooling, and suggests that the temperature rise is due to continued heat input from the blastshield.

In Fig. 6, we show the temperature difference in the slab as a function of time. Even though there was quite a difference in the average temperature histories, we see that blocking or unblocking the top of the lamp cassette has a very small affect on the slab self-equilibration time. In either case, temperature gradients in the slab disappear after three to four hours.

Fig. 3 Temperature history of a flashlamp under natural convection conditions, taken at three different vertical positions.

Fig. 4 Temperature history of a blast shield under natural convection conditions, taken at three different vertical positions.

Fig. 5 Average temperature in the slab, comparing natural convection with inhibited natural convection. Also shown on the graph is the case of one BAU and no insulation.

Fig. 6 Maximum temperature difference in the slab, comparing natural convection with inhibited natural convection.

B. Forced-air cooling of flashlamps

As might be expected, if the heat is removed from the flashlamp cassettes more quickly than natural convection, then the amplifier cool-down time should decrease. This is the premise behind the sequence of experiments where we flowed air past the flashlamps. We describe the results of those experiments in this section.

In Fig. 7 we show the average temperature in the slab as a function of time for different levels of cooling. As expected, the greater the amount of air flow past the lamps, the more rapid the recovery rate of the amplifier. Under the conditions of maximum air flow, the amplifier equilibration time is on the order of three hours, and this time extends to six hours at the minimum air flow. For comparison is the temperature history under natural convection conditions. We also note that under forced air cooling, the rise in slab average temperature following the initial decline is missing (cf. Fig. 5), and the slab cools monotonically. This is because we have eliminated the long-time radiation of heat by the blast shield that was present under passive cooling.

Fig. 7 Average temperature in the slab, comparing the case of maximum air flow (10 CFM/lamp) to that of minimum air flow (2 CFM/lamp). Also shown for comparison is the natural convection case.

In Fig. 8 we show the temperature difference in the slab as a function of time for minimum and maximum air flow past the flashlamps. Even though varying the air flow past the flashlamps had a large effect on the amplifier equilibration time, we see that the slab self-equilibration time is very insensitive to the degree of air flow past the lamps, for these flow rates. In both cases, the slab comes to equilibrium in about 1.5 hours.

Effect of air flow on temp. difference

Fig. 8 Maximum temperature difference in the slab, comparing maximum air flow in lamp cassette with minimum air flow.

C. Forced-air cooling of flashlamps/ N_2 flow in cavity

It has been suggested³ that flowing N_2 in the pump cavity can accelerate the thermal recovery time of the amplifiers. To test this hypothesis, we installed a total of four jets centrally located in the two top and two bottom reflectors of the amplifier module. This section describes the results of those tests.

We found that under conditions of maximum cooling (10 CFM/lamp air + 1.8 CFM/jet N_2), the slab self-equilibration time was on the order of one hour and the amplifier equilibration time was on the order of two hours. Decreasing the air flow to 2 CFM/lamp and the N_2 flow to 0.5 CFM/jet resulted in approximately the same slab self-equilibration time, but lengthened the amplifier equilibration time to about six hours.

Based on these experiments, flowing N_2 in the pump cavity is beneficial if the absolute minimum time between shots is desired. However, if this option is chosen, care must be taken to prevent particulate contamination of the laser slab. This contamination can come from the gas itself, or from particles in the pump cavity. The latter may be attracted to the laser slab via static charges set up on the laser slab by the flowing gas.

D. The behavior of the amplifier under repetitive firings

The data presented so far describes the temperature recovery of an amplifier under single-shot conditions. It is instructive to examine, however, the temperature history of an amplifier under repetitive firings. This data is presented in Figs. 9 and 10.

Fig. 9 Average temperature rise and maximum temperature difference in the slab under natural convection conditions and repeatedly firing the amplifier every two hours. The gradual increase in average temperature is clearly visible. A steady state is reached after approximately five shots.

Fig. 10 Average temperature rise in the slab under maximum cooling conditions and repeatedly firing the amplifier every hour.

In Fig. 9, we show the slab temperature (average and difference) for repetitive firings every two hours under conditions of natural convection. The two hour time between shots is just shy of the slab self-equilibration time, and well short of the amplifier equilibration time. Whereas the slab temperature difference returns to approximately the same value after the two hour interval, the slab average temperature "ratchets up" in value and reaches steady-state after about five firings.

In Figs. 10 and 11, we present the repetitive firing data under conditions of maximum cooling. The one hour fire time was chosen to be approximately the same as the slab self-equilibration time (see Fig. 10); but is about an hour shorter than the amplifier equilibration time. As can be seen in Fig. 11, there is only a small increase in average temperature even after eight shots; the final temperature in this case is about one fifth that for natural convection (cf. Fig. 9). In this case, too, a steady-state is reached after about five shots. This data clearly shows the advantages of actively cooling the flashlamp cassettes.

Fig. 11 Same as Fig. 10 but showing the maximum temperature difference in the slab.

4. CONCLUSIONS

Based on our experiments, we have found that under conditions of passive cooling, the slab will come to equilibrium in 3-4 hours, and the amplifier itself will come to equilibrium in a minimum of 10 hours. Furthermore, without active cooling, the laser slabs will ratchet up in temperature over time and substantial slab-to-slab and chain-to-chain temperature differences will develop. The equilibration times can be significantly shortened (by at least a factor of three) by actively cooling the flashlamp cassettes. Flowing gas in the pump cavity will shorten the recovery times even more.

5. ACKNOWLEDGMENTS

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