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Large Aperture Diagnostic System for Gain and Wavefront Measurements on NIF/LMJ amplifiers

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INTRODUCTION

We are in the midst of constructing an amplifier laboratory (Amplab) that will be the physics and engineering proving ground for full sized segmented glass amplifiers of designs that will outfit the National Ignition Facility (NIF) and Laser Megajoule (LMJ) projects. Amplab will demonstrate the cornerstone mechanical, electrical and optical concepts that support the NIF and LMJ amplifier schemes. Here we address the optical diagnostics that will be used to characterize optical performance of the amplifiers. We describe, the apparatus that will be used in pulsed measurements of gain distribution and wave-front distortions. The large aperture diagnostic system or LADS, is now being built through a collaborative effort between CEL-V and LLNL. The LADS will provide measurements of gain and wave front distortions over the full extracting aperture of the NIF and LMJ prototype amplifiers. The LADS will be able to address each of eight apertures via motorized stages and following semi-automated alignment, take data on the aperture of interest. The LADS should be operational in mid-'97 at LLNL and will be used to characterize the optical performance of the very first full scale prototype 4 x 2 NIF and LMJ amplifiers. It will be transported to Bordeaux, France to make similar measurements during activation of the first 8-aperture LMJ-like facility (LIL) that is planned to start in the near future.

The gain measurement will map the gain distribution of each of eight 40 by 40 cm apertures. Small signal gain of 5 %-per-cm is the nominal operating point (lamps fired at 20% of their explosion energy). It is desired to measure the small signal gain of the amplifier with a resolution of 0.1% ($\pm$ 0.005 %-per-cm) at the center of the aperture, 0.5% at the corners, or better. The amplifier pump distribution is tailored in order to counteract the effects of amplified spontaneous emission that tends to deplete gain in areas near the edges. This diagnostic will be useful in amplifier optimization experiments. Subtle effects of shaping reflector surfaces, the tarnishing of silver or the damage to reflector coatings could be found correlated to the gain data and thus, will be readily monitored.

To be useful, the wavefront measurement must resolve features that calculations and Beamlet data show will have fourth order components with peak to valley excursions of about one twentieth wave per amplifier pass (λ =1.053 µm). Even smaller effects are expected from gas stratification/motion inside beam tubes. To chart these subtle wavefront distortions with fidelity it will be necessary to resolve the measured wavefront to λ /100.

The wavefront and gain measurements will be performed simultaneously. A Twyman-Green interferometer set up will present reference and sample beams to a pulsed, phase shifting interferometer for wavefront analysis. A wavefront map of the quiescent state will be acquired 66 milliseconds before the flashlamps fire. In the quiescent state the wavefront data contains the static distortions and will be used as the reference wavefront from which the dynamic distortions will be differentially obtained. Both prompt and delayed maps of wavefront distortions accompanying a shot will be stored. The prompt effects of the firing of the lamps are important at extraction time. Sampling delayed interferograms at say 1 to 5 minute intervals, will be used to monitor the evolution of waste heat and to monitor the effects of cooling flashlamps, edge claddings, convection in the different sections of the beam transport...etc.

The main components for the LADS are the optical relay telescopes, the probe laser, the alignment system, the gain diagnostics cameras and the pulsed, phase shifting interferometer.

OPTICAL ARCHITECTURE

The probe laser is a critical item in the LADS. It will deliver near perfect light pulses that will interrogate the optical state of the amplifier and intervening gas and glass filled space within the optical cavity. Performance specifications include 10 μrad pointing stability, stable single frequency operation at 15 Hz delivering ~100 mJ in each transform limited ~20 ns pulse. The energy required is derived from the need to overcome flashlamp and amplified spontaneous emission background. The single frequency is necessary to obtain coherence length, a useful commodity when balancing interferometer arms ~ 30 m in length. The probe laser has already been built to specifications by Quantel in France and is now in transit to LLNL.

The gain measurement will be performed by expanding the probe laser beam until it fills the 40 cm x 40 cm amplifier aperture. The relayed beam expansion will be done with three afocal telescopes. Referring to figure 1, after passing through the Brewster amplifiers, the beam will be retro-reflected at an image plane (M1 in figure 1) passing through the amplifier(s) once again and back through two of the three beam expansion telescopes. A beam-splitter (W2) will divert a sample of the probe laser beam (**I_o**) towards a high performance ~1024x1024 CCD camera where it will be mapped. The same beam splitter will sample the returning test beam containing the gain signal (**$I = G \cdot I_o$**) plus the background (**B**) diverting it towards a second high performance CCD. A second beam-splitter (W1) provides the reference and test beams to the phase shifting interferometer. Strict one to one mapping will be necessary for all the cameras. Registration of a common target onto cameras will be accomplished mechanically and by software post-processing as necessary. The T2 telescope will be mounted on a linear stage that will make it possible to precisely place the image plane at the back mirror M1. The back mirror location will have two possible locations so that the effects of beam transport tubes can be experimentally obtained. Mirrors M2 and M3 are also mounted on translation stages so that each of the 8 apertures will be addressable. Cameras located behind the large mirrors will be used for alignment of the system. A reference arm, necessary for the wavefront measurement, will also be incorporated. The lenses will be anti-reflection coated. Because of limited space in the laboratory, there are several aspheres in the system. The largest telescope T3 is a Galilean to avoid the large vacuum vessel; telescope T2 is a vacuum telescope fitted with a set of pinholes that will block out the amplified spontaneous emission and flashlamp background that will accompany the signal. Shot noise in the CCD's pixels will be the dominant source of uncertainty in the measurement of test and reference beam intensities.

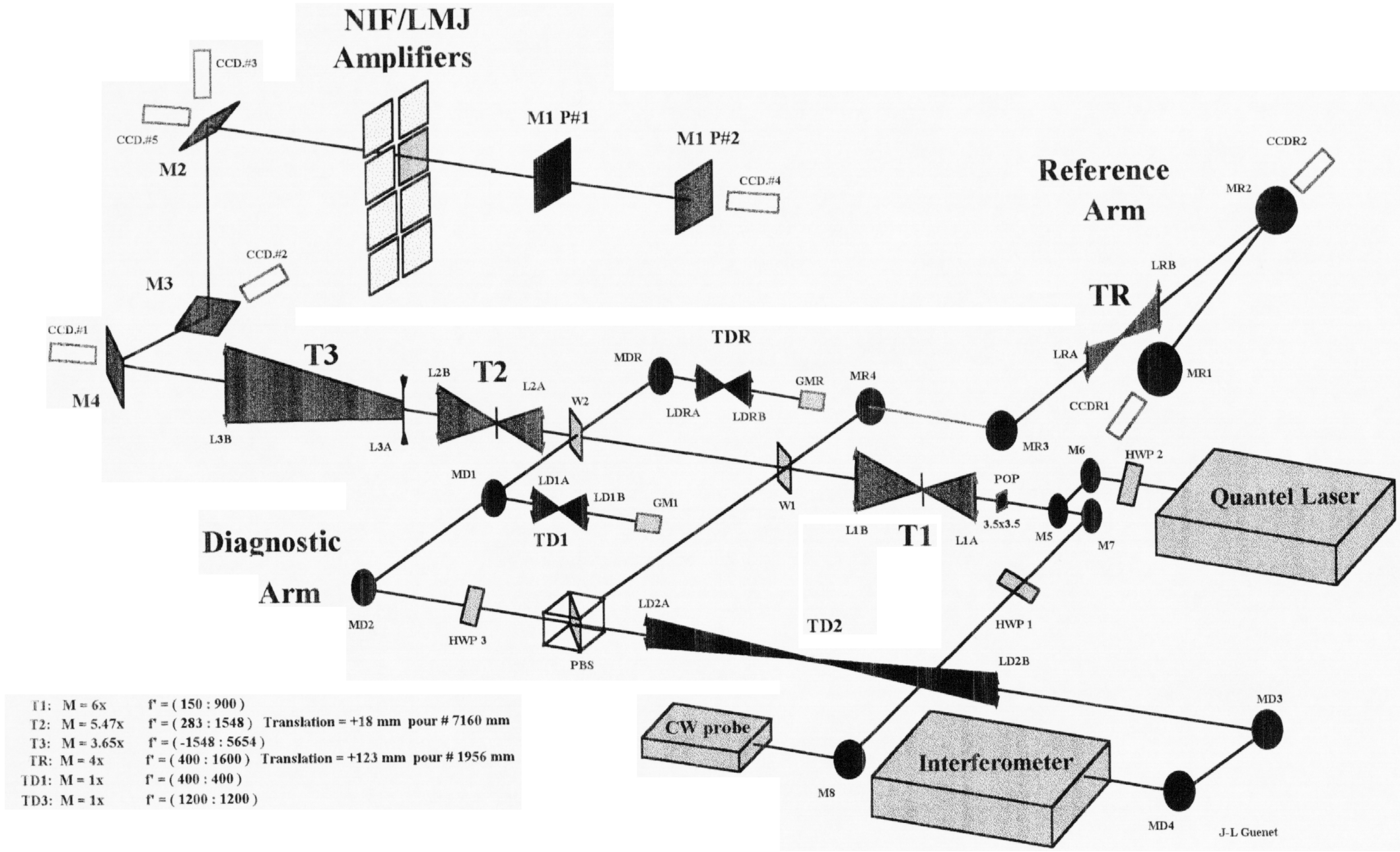

Figure 1.- Large aperture diagnostic system schematic.

Quantities to be measured and associated errors

The light intensity signals to be measured will be the reference beam **Io**, the test beam **I+B** and the background **B**. The error in the high light level measurements of **Io** and **I+B** are dominated by photoelectron statistics or shot noise. The standard deviation is given by the square root of the number of photoelectrons generated. If we assume that the CCD pixel full well capacity will be filled by the intense signal (brought to the appropriate level with neutral density filters) and, that we are able to "bin" 1, 4, 16 etceteras, pixels then, the standard deviation relative to the signals **Io** or **I+B** is given by

$$\delta = \pm\,(\mathbf{Ne}\cdot\mathbf{Nbin})^{-0.5} \qquad (1),$$

where the photo-electron well capacity is **Ne**, and we are able to "bin" **Nbin** pixels.

The strategy for collecting the data, will be to adjust the neutral density filters in front of the cameras to fill the pixel wells for both the measurements of **Io** and **I + B**. These measurements will have an error of $\delta\mathbf{Io} = \pm\,\delta\cdot\mathbf{Io}$ and $\delta\mathbf{m} = \pm\,\delta\cdot(\mathbf{I}+\mathbf{B})$ respectively. With the probe laser turned off, the measurement of the optical background $\mathbf{B}\pm\delta\cdot\mathbf{B}$ will be performed. Should the background measurement produce less than 1000 photoelectrons per pixel, the CCD readout noise of 10-20 electrons per pixel will be added to the measurement error for it will then be comparable to the shot noise. This limiting error level is not accounted for in what follows. The background subtraction will then proceed. The value for **I** obtained will have an error that will depend on the ratio $\mathbf{x} = \mathbf{I}/\mathbf{B}$ as $\delta\mathbf{I} = \delta\mathbf{m}\cdot\sqrt{\{(x+2)/(x+1)\}}$. This error gravitates between $\delta\mathbf{m}$ and $\sqrt{2}\cdot\delta\mathbf{m}$ depending on **x**.

At this point we will have $\mathbf{Io}\pm\delta\mathbf{Io}$ and $\mathbf{I}\pm\delta\mathbf{I}$. The measured amplification of the doubly passed amplifier(s) will be simply $\mathbf{G} = \mathbf{I}/\mathbf{Io}\pm\gamma$ where by using partial differentials we obtain the propagation of the independent errors into the error γ as,

$$\gamma := \sqrt{\left(\frac{\delta\mathbf{I}}{\mathbf{I}}\right)^2 + \left(\frac{\delta\mathbf{Io}}{\mathbf{Io}}\right)^2} \qquad (2).$$

To obtain the small signal gain we perform the operation $\mathbf{go} = \ln(\mathbf{I}/\mathbf{Io})$. Once again the propagation of the errors $\delta\mathbf{I}$ and $\delta\mathbf{Io}$ can be estimated by using the partial differentials on **go** as,

$$\varepsilon := \frac{1}{\ln(\mathbf{G})}\cdot\sqrt{\left(\frac{\delta\mathbf{I}}{\mathbf{I}}\right)^2 + \left(\frac{\delta\mathbf{Io}}{\mathbf{Io}}\right)^2} \qquad (3).$$

Measurement accuracy estimates

The relative errors γ and ε in (2) and (3) can be studied if the background **B** can be estimated from basic physics. The optical background (integrated over one flashlamp pulse and spread evenly upon the image area) has two sources: amplified spontaneous emission ($\mathbf{P_{ASE}}$) and lamp black body radiation ($\mathbf{P_{BB}}$). Thermodynamics dictates the amount of electromagnetic power per spatial mode in a blackbody enclosure. The blackbody power depends on the lamp temperature **Tp** and the frequency **ν** of observation and band pass **Δν** in front of the camera as

$$P_{BB} = \frac{h \cdot \nu \cdot \Delta\nu}{1 - \exp\left(\frac{-h \cdot \nu}{k \cdot Tp}\right)} \qquad (4).$$

The ASE phenomenon can also be described from basic principles. It is similar to blackbody radiation if one applies the concept of negative temperature and gain[1]. We can calculate the ASE contributions to the background if we know the fluorescence bandwidth $\Delta\nu_f$ of the laser transition **ν** and the amplifier gain **G**. It is given approximately by,

$$P_{ASE} \simeq G \cdot h \cdot \nu \cdot \Delta\nu_f \qquad (5).$$

The shape of our enclosure includes a telescopic arm that is akin to an antenna in the radio spectrum. The number of free space modes in the enclosure that filter through the telescope (T2 in figure 1) depends on the size of the pinhole and can be selected. In the estimates below, we assume that a pinhole ~ 100 times the diffraction limit is used. This also sets the spatial resolution to about 40 cm / 100 or 4 mm. Because the aperture will image onto a ~1000 x 1000 grid of pixels, a bin arrangement of 100 x 100 pixels can be used when collecting data without loss of spatial resolution.

A generalized expression can be obtained that provides some insight into the processes at play and can be written as,

$$\varepsilon \approx \frac{\delta}{\ln(G)} \cdot \sqrt{\frac{x+2}{x+1}\left(1 + \frac{P_{ASE}}{Io} + \frac{P_{BB}}{G \cdot Io}\right)^2 + 1} \qquad (6).$$

In the above expression we can see that if the probe laser is significantly above the background components, the most important contributions to the relative error will derive from the instrumental error δ and the small gain $g_o = \ln(G)$ being measured.

In figure 2 the accuracy in the value of g_o (i. e., ε^{-1}) is plotted on the y-axis as a function of the single pass gain G of a single amplifier. The amplifier is considered double passed and the probe beam energy of 10 mJ is distributed in a gaussian beam that is clipped at the one-half intensity at the edges of the aperture (1/16 at the corner). There are two curves that show the accuracy at the center of the aperture and the corner of the aperture for each of three "bin" arrangements that bear on the instrumental resolution achieved by the CCD cameras expressed in equation 1. The probe beam intensity at the center of the aperture is intense enough to reach the limiting instrumental resolution that only depends on the collection of photoelectrons and the propagation of errors due to the operations carried on the signals measured. The probe beam intensity at the corners is 1/16 that at the center and the limiting instrumental resolution is not realized. The probe beam energy of 80 mJ or greater is necessary to achieve equal resolution at

[1] A basic reference on the subject can be found in Siegman's "An Introduction to Lasers and Masers", chapter 11, McGraw-Hill (1973).

the center and corners of the aperture (the lower curves in figure 2 move up to meet the aperture center curves).

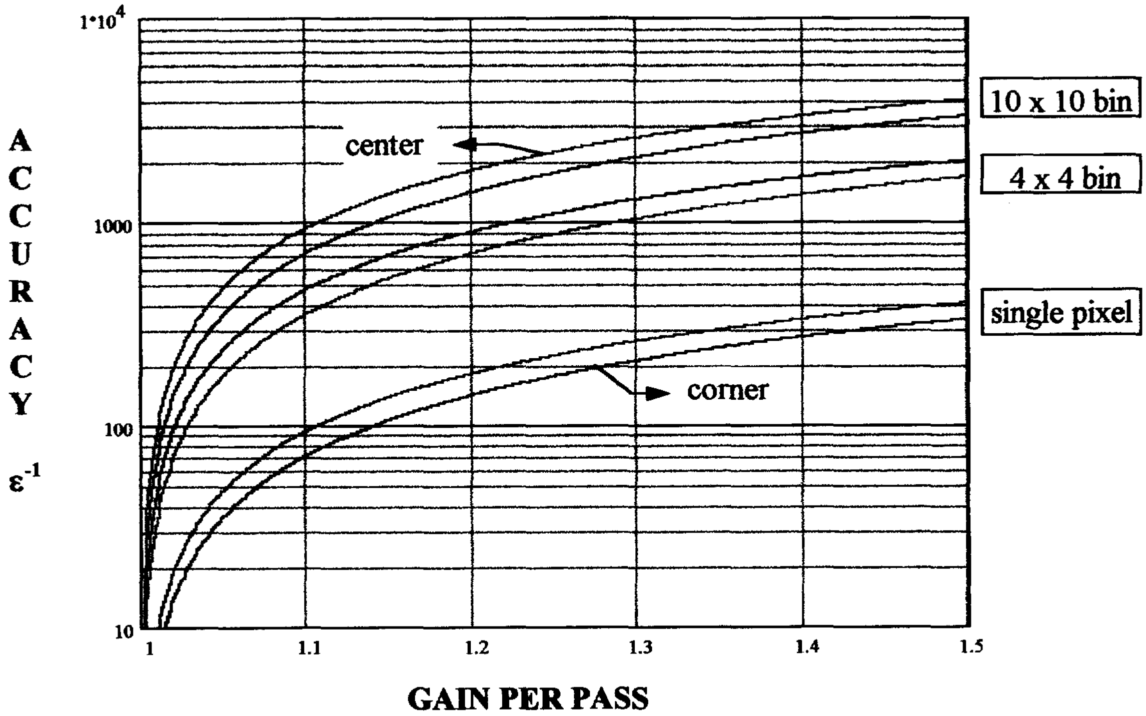

Figure 2.- The gaussian probe laser beam contains 10 mJ before it impinges on the square aperture. The gaussian parameter is set so that the intensity in the center is 16 times that at the corners. The 10 x 10 bin arrangement yields an accuracy of one part in 1900 in the center of the aperture at the nominal operating point (G=1.2/pass) and, one part in 1400 at the corner. The probe laser energy of 80 mJ (or greater) improves the accuracy at the corners to equal that at the center.

Phase Shifting Interferometer

The phase shifting interferometer is the instrument of choice in recent years for wave front measurements that offer high accuracy (~λ/100) and repeatability. A minimum of three phase shifted interferograms are needed to convert the data to wave front shape information. The phase shifted interferograms are reduced on a pixel by pixel basis using trigonometric identities and algebra. The phase shifting is normally accomplished by moving the reference arm back mirror by means of a PZT. The advantage of acquiring the phase shifted interferograms simultaneously has many advantages for the testing of optical surfaces plagued by a vibration environment. In the case of the LAD wavefront measurements, pulsed, simultaneous phase shifting interferometry is the only kind of interferometry that will provide the resolution required. To achieve phase shifting, waveplates are used in the three to four separate interferograms that are recorded each achieving an integral number of quarter waves between the reference and test beams.

The CEL-V has graciously taken the responsibility of providing this costly instrument and at present, the negotiations continue with the few companies that can provide it namely, Phase Shift Technologies of Tucson Arizona and CILAS of Paris, France.

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