An Optical Measurement System for Characterizing Cryogenic Fusion Targets

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Abstract:

The Laboratory for Laser Energetics (LLE) houses the OMEGA 60-beam, 30kJ laser capable of generating shaped optical pulses that are used for high-energy physics and inertial confinement fusion (ICF) research. OMEGA is seeded by an optical pulse that is repeatedly amplified and split to produce 60 individual ultraviolet beams (UV wavelength 352 nm).

LLE has developed extensive facilities and expertise for fielding cryogenic deuterium-filled targets. During a cryogenic implosion experiment, all 60 beams are focused onto a 1mm diameter plastic shell filled with a cryogenic (~18K) layer of deuterium ice. This target is heated and compressed by the lasers to initiate fusion. Some cryogenic targets do not achieve their expected performance due to vibrations that cause the target to be decentered relative to the laser beam foci. The causes of vibration are complex. However, they can be exacerbated by inconsistent target fabrication.

This report presents a new quality control instrument that has been built to ensure proper target construction. The instrument consists of an electrodynamic shaker (EDS) and a calibrated optical measurement system (OMS). As the EDS excites the target with known input, the OMS is used to measure the target's response. The EDS/OMS also can be used to test new target designs as well as new imaging equipment before implementation on OMEGA.

Introduction:

Fusion is a virtually inexhaustible energy source that holds great potential in replacing other means of power production. Fusion has almost no environmental impact in comparison to coal and oil, which produce large amounts of carbon dioxide. Fusion is a very safe alternative for power production because it produces no harmful emissions and can be safely contained without the possibility of a “meltdown”.[1] Fusion has been very difficult to harness as an energy source because it needs very high pressures and temperatures to cause hydrogen atoms to fuse and produce helium and energy.

The Laboratory for Laser Energetics was established in 1970 as a center for the investigation of the interaction of intense radiation with matter, and has the five-fold mission: [2]

- Conduct implosion experiments and basic physics experiments in support of the National Inertial Confinement Fusion (ICF) program;
- Develop new laser materials and technologies;
- Provide graduate and undergraduate education in electro-optics, high-power lasers, high-energy-density physics, plasma physics, and nuclear fusion technology;
- Operate the National Laser User’s Facility; and
- Conduct research and development in advanced technology related to high-energy-density phenomena.

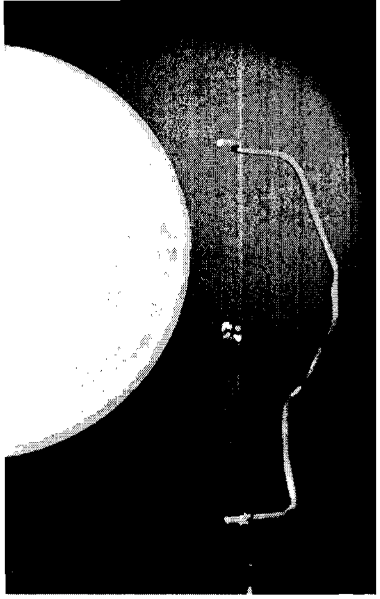

Figure 1. Target compared to a penny

Many experiments conducted at LLE use cryogenic fusion targets. These targets are comprised of a spherical plastic shell typically 3um thick and 860um in diameter (1 um = 0.001mm). These targets are suspended in a C-mount frame (similar to a staple) by four spider silk threads (figure 1). These targets are pressurized with deuterium and tritium gas, and then cooled to a temperature of 18K to form an ice layer on the inside of the target.

These targets are then placed into the OMEGA target chamber and irradiated by the OMEGA laser. Cryogenic targets require a very complex apparatus (moving cryostat (MC)) (Figure 2) to position the target at the convergence of the beam foci (=target chamber center= TCC). This apparatus also must maintain a precisely controlled thermal environment around the target prior to an experiment.

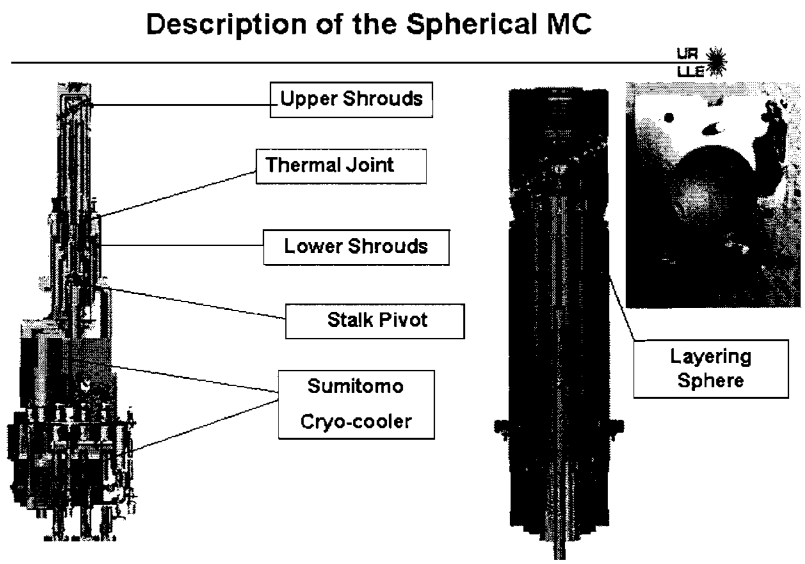

Figure 2. Pieces of a Moving Cryostat

Many improvements have been made to increase the stability of the MC but target construction has remained relatively unchanged. The stability of targets varies because each individual target is different. In order to obtain optimal performance (as measured by neutron yield or another measure of fusion efficiency), the target must be centered within +10um of the beam foci. Both static and dynamic (e.g. vibration) position errors contribute to the total error budget. Sources that cause target vibration include vacuum pumps that are attached to the target chamber and refrigeration equipment in the moving cryostat transfer cart. A target's position in the chamber is measured using images from two cameras. These images are analyzed to determine the exact center of the target. Static position errors can result from viewing the target through windows in the MC shrouds.

The EDS/OMS will be used as a quality control device to ensure good target manufacturing by testing the stability of the target (by measuring its resonant frequencies) before use in the OMEGA system. The EDS/OMS will incorporate interchangeable parts so that new target structures and mounting interfaces can be evaluated. The EDS/OMS will be able to evaluate new high-speed video cameras as well as new target detection systems.

This report concentrates on the development and calibration of the OMS. Integration of the OMS with the EDS was completed later than anticipated due to delays in procuring the EDS. Photographs were taken after the integration was completed.

Overview:

A commercially available EDS unit [3] capable of exciting frequencies from DC to 4500 Hz is integrated with an Optical Measuring System (Figure 3). The Optical Measuring System is mounted onto the EDS. The OMS is constructed with two achromat doublets with 50mm and 20mm focal lengths[4]. Figure 3 shows the system layout.

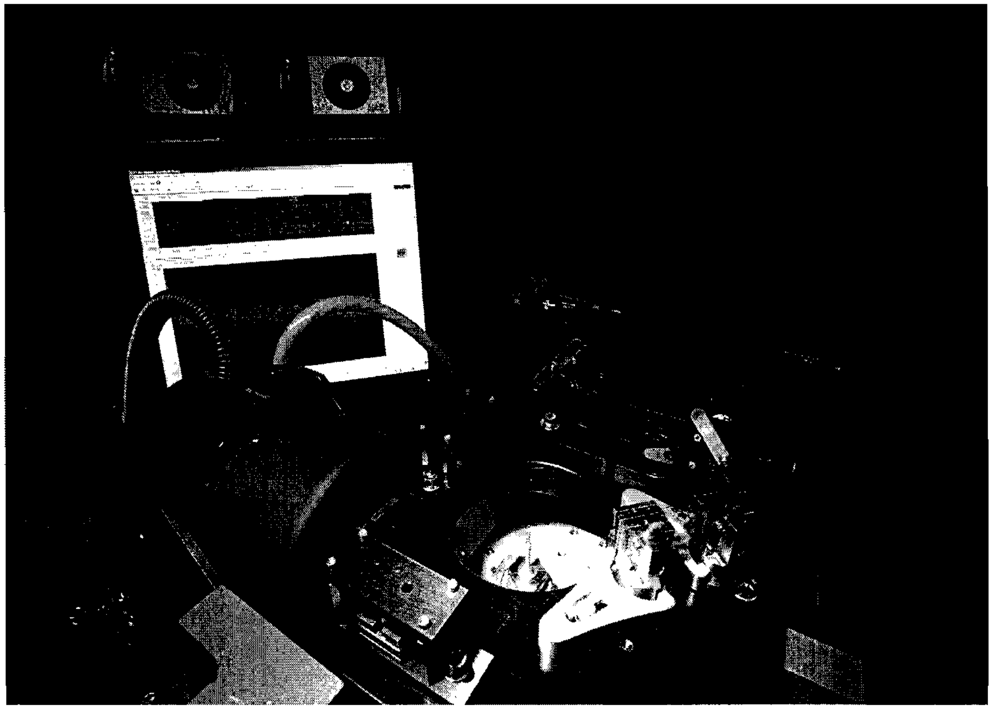

Figure 3. Completed EDS and OMS with target in place and histogram displayed on computer monitor

The optical modeling software Oslo™ [5] is used to optimize the position of the lenses inside the optical tubes of the OMS for a given working distance and magnification. The target is backlit with a red diode laser beam. The illuminated target image is focused simultaneously onto a charge-coupled device (CCD) camera and a four-quadrant photodiode (quad cell, Figure 4) [6] via a beam splitter cube, so that the camera and detector "see" the same image plane. The CCD is used to ensure that the target is aligned onto the center of the OMS viewing axis.

The quad cell contains four photodiodes in a 2x2 array; each produces a voltage (or current) proportional to the amount of light that strikes it. Since the target casts a "shadow" on the quad cell, the voltage is also proportional to target displacement.

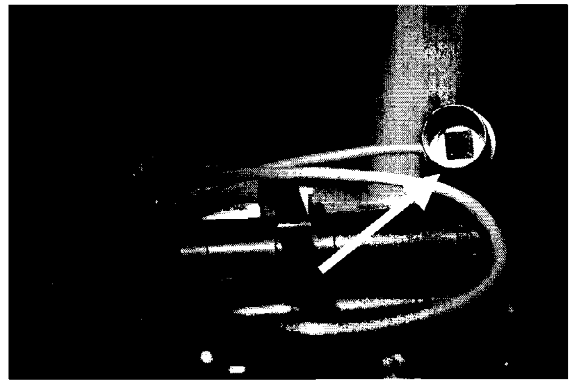

Figure 4. Mounted Quad Cell (upper right corner)

As the target image is projected onto the center of the quad cell it produces voltages on all four quadrants, which are sent to the signal conditioner. The signal conditioner amplifies the quad cell voltages. The voltage sum from the right column is subtracted from the sum from the left column to produce a signal proportional to the horizontal target displacement. Voltage signals from the top and bottom rows are combined in a similar manner to produce a signal proportional to the vertical displacement. These signals are then feed into a spectrum analyzer that constructs a histogram of signal strength vs. frequency of excitation.

The spectrum analyzer [7] is a four-channel measurement system and a signal generator. It provides the EDS with the excitation signal source and measures the output voltages from the signal conditioner. The measured data can be analyzed and displayed in several formats including a time-history or frequency spectrum. The frequency spectrum is a mathematical representation of the data broken into discrete frequencies, with each frequency having different amplitudes, like a histogram. Spectra are computed in real time, making analysis very efficient.

Calibration of the Optical Measuring System:

The OMS needs to be aligned and calibrated in order to obtain accurate data. Proper magnification, working distance, and image quality are all important. The gain of each amplifier in the signal conditioner is adjusted to match the sensitivity of the individual quad cells. After adjustment of the amplifier gain, the quad cell is installed and optically aligned with a knife-edge fixture. The spectrum analyzer then sends the information received from the electronic signal conditioners to the computer for analysis.

The first step in calibrating the optical measuring system is to align the optics. The optical system is comprised of one, two, and three-inch optical tubes, and various accessories which can be screwed together. The optical layout is determined by using the OSLO program. The optics are secured in the optical tubes with lens rings. To check the placement of the optics, a caliper is used to measure the depth of the optics in relation to the individual tubes. After the optics are placed in the tubes the system is placed together on prefabricated boards.

After the system is assembled it is necessary to determine the magnification of the optical system (to ensure that all the optics are in the right locations). This is done by placing a target with a known diameter (d) in the view of the optical system and measuring the diameter of the target as it appears on the screen (s), the screen height (h), and the height of the CCD (c). Noting that the magnification from the CCD detector to the display screen is h/c, the magnification of the optical system is (s/d)(c/h). If this magnification is correct it is then necessary to determine if the working distance is correct for both of the optical axes. To find the focal distance of the two axes it is necessary to measure the distance from the front element of the optical system to the center of the target that is placed in the view of optical system. The working distance of the primary axis should be 4″ and that of the secondary axis should be 4.5″. Correct focus is determined when the contrast and definition are greatest between the backlight and the target edge. If the focal distance is not correct it is necessary to move the front optic forwards and backwards until correct focus is obtained at the specified focal distance.

After the correct magnification and focal distances are achieved it is necessary to align the optical system and laser backlight source for even illumination of the target. To make sure the alignment is correct it is necessary to remove the quad cell and replace it with a circular, semi-translucent piece of glass with a calibrated center mark on it. The laser alignment is adjusted until the laser beam center coincides with the calibrated center mark.

Finally, it is necessary to determine the rotational alignment of the quad cells themselves. This is achieved by using a

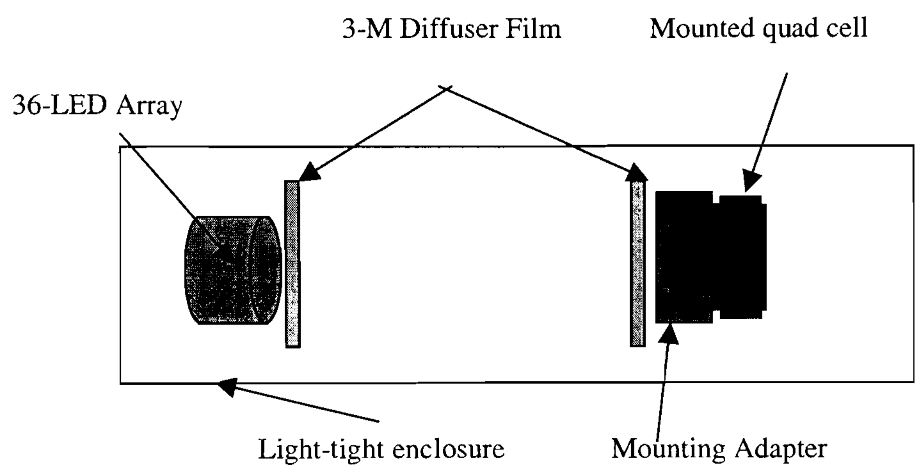

Figure 5. Illumination Source used for calibrating the quad cell

knife-edge fixture (see Figure 7 below).

Calibration of the Electronics:

The electrical signal conditioning circuit consists of four operational amplifiers that amplify the signals from each of the four quadrants of the detector. The optical sensitivity of each quadrant differs slightly, so detectors are uniquely matched to a signal conditioning circuit before any calibration is preformed. Electrical gain is adjusted with identical illumination on all four quadrants. This is achieved using a flat field calibration fixture that consists of a light source, and optical diffuser film[8] between the source and detectors (figure 5) to achieve a diffuse even light source on the detectors. In this case, the illuminator is an array[9] of 36 green LEDs driven with a square wave at approximately 1 kHz (figure 6). A light–tight shroud with a black, diffuse scattering interior surface surrounds the source and detector, to ensure that no outside light will interfere with the sensor. A 4-channel oscilloscope is triggered by the pulsed light source, and the square-wave output

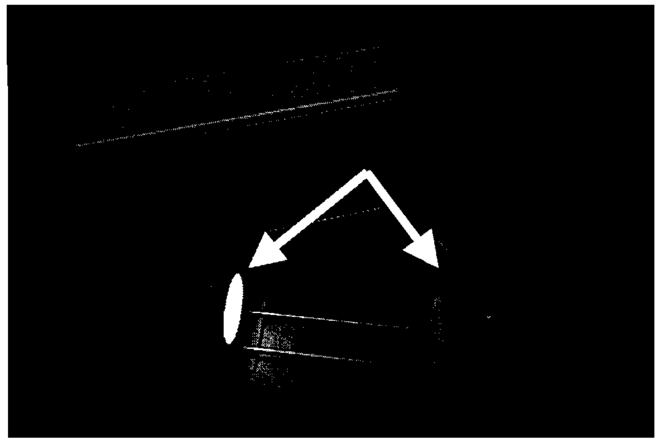

Figure 6. LED illuminator with a diffuser and quad cell attached

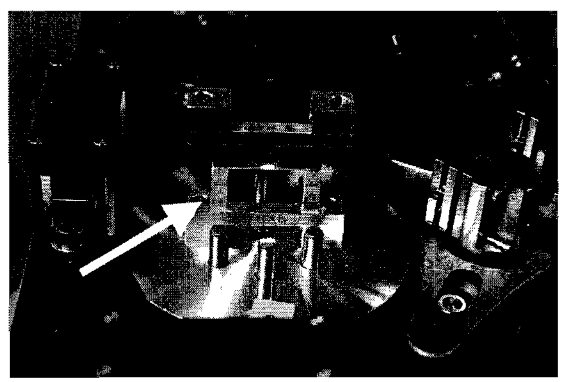

Figure 7. Knife-Edge Alignment Fixture

voltages from each quadrant are simultaneously adjusted until the peak-to-peak voltage from each quadrant is equal.

A knife-edge alignment fixture (Figure 7) was designed to serve as an alignment tool and consistent focal reference for each measurement axis. The fixture is used to calibrate one axis of the optical system at a time. When it is installed and the system is fully aligned, the edge of a razor blade is at the center of the optical system, half of the detector is shadowed, and half is illuminated. Calibration marks on the fixture can be viewed on each video display, allowing magnification to be determined.

The fixture is installed so that the knife-edge is vertical, and the quad cell is replaced by a diffuser film that serves as a screen on which the image is projected. This film is mounted on an SM1[10] focus ring that has a centerline reference mark that can be rotated vertically or horizontally. Starting with lenses in the positions determined by the optical model, the knife-edge calibration marks are imaged and displayed on the video monitor. The imaging system is moved longitudinally and the focus ring is adjusted until the desired magnification and focus are achieved. An iris on the input lens is closed down, and the shadow of the knife-edge is aligned with the vertical center of the iris. With the lens-end of the imager bolted in place to avoid changing the longitudinal position of the imager, the detector-end of the imager is rotated until the knife-edge image is aligned with the vertical centerline reference on the diffuser. The process is iteratively repeated until the knife-edge image is centered on both the entrance iris and the diffuser. Once completed, the side cover is removed from the mounting cube, and the beam splitter cube is rotated until the knife-edge is centered on the video display.

In order to accurately resolve target motion, each detector must be rotated until the horizontal axis of the detector coincides with the horizontal direction of shaker motion. This is done by installing the alignment fixture so that the knife-edge is horizontal (bottom or top quadrants are shadowed). The detector is installed and rotated until the signal voltage from the exposed quadrants is equal, after which the detector is clamped in place. With the fixture in any other orientation, the voltage from a different pair of quadrants will be near zero, and another pair will be maximized. The entire calibration and alignment procedure is performed on both axes.

The final step is to measure the output voltage generated when the target is moved by a known displacement. The alignment fixture is removed, and a stalk-mounted target is installed on the EDS. With the shaker power off, the shaker position is adjusted until the target is centered on both video displays. The target diameter displayed on the video screen is measured. The EDS is set up to generate a low frequency output (e.g. 9-13 Hz), and the drive amplitude is adjusted until the target image is blurred to approximately 120% of its original size. The video image is re-measured, and the "Transverse" signal output voltage is measured (in the time-domain) using either an oscilloscope or the spectrometer. Knowing the static diameter (D_s), the blurred diameter (D_b), and the output voltage (V_o), the sensitivity is calculated as (V_o/ D_b-D_s). This calibration constant is entered into the RT-Pro software[11], and is used by the software when plotting measurement data.

Summary:

A new inspection instrument has been described that will be used to fully characterize the mechanical stability of targets used for cryogenic ICF research. The instrument consists of an Electrodynamic Shaker (EDS) and Optical Measurement system (OMS) that are used to stimulate a target and measure its response. The EDS and OMS have been fully integrated, and the system is now being used to characterize production targets. Initial plans are to acquire data on many targets prior to conducting implosion experiments. This data will be correlated with the target's stability during an implosion experiment to establish acceptance and rejection criteria.

Acknowledgments:

I would like to thank Dr. Douglas Jacobs-Perkins for his help and the time he spent with me on this project. Without his help and persistence, this project would not have been possible. I would also like to thank Dr. Craxton for allowing me the pleasure to work in the 2004 High School Summer Research program and everyone in the lab for being there when I needed help.

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[10] Thor Labs http://www.thorlabs.com/NewGroupPage4.cfm?Guide=4&Category_ID=25&ObjectGroup_ID=55

[11] RT-Pro software is a product of LDS-Dactron, Inc.