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Abstract

Off-line conditioning of full-size optics for the National Ignition Facility required a beam delivery system to allow conditioning lasers to rapidly raster scan samples while achieving several technical goals. The main purpose of the optical system designed was to reconstruct at the sample plane the flat beam profile found at the laser aperture with significant reductions in beam wander to improve scan times. Another design goal was the ability to vary the beam size at the sample to scan at different fluences while utilizing all of the laser power and minimizing processing time.

An optical solution was developed using commercial off-the-shelf lenses. The system incorporates a six meter relay telescope and two sets of focusing optics. The spacing of the focusing optics is changed to allow the fluence on the sample to vary from 2 to 14 Joules per square centimeter in discrete steps. More importantly, these optics use the special properties of image relaying to image the aperture plane onto the sample to form a pupil relay with a beam profile corresponding almost exactly to the flat profile found at the aperture. A flat beam profile speeds scanning by providing a uniform intensity across a larger area on the sample. The relayed pupil plane is more stable with regards to jitter and beam wander. Image relaying also reduces other perturbations from diffraction, scatter, and focus conditions. Image relaying, laser conditioning, and the optical system designed to accomplish the stated goals are discussed.

Introduction

Off-line conditioning of full-size optics for the National Ignition Facility (NIF) use lasers to scan the large optics deployed on NIF. These large optical components are scanned to condition the optic and initiate small damage sites that could grow when exposed to the extreme fluences of the NIF, the world's most powerful laser. These small damage sites are then repaired so that they will not initiate or grow when subjected to the high NIF fluences. Conditioning requires that the test sample be scanned with lasers at various fluences. Laser conditioning is discussed further in the next section.

One of the laser systems used for the development of laser conditioning is a Nd:YAG in the Lawrence Livermore National Laboratory (LLNL) Phoenix lab operating at 355 nm. A requirement of the scanning system was for all of the area of the sample to receive within 5% of the same fluence during a particular scan. Two problems were encountered: The system was experiencing unacceptable amounts of beam wander on the test sample which necessitated considerable overlapping the scan. A second difficulty was the beam profile at the sample, which was nearly Gaussian, requiring scans to further overlap. These two characteristics of the beam delivery system required substantial overlap of the scans in order to achieve specifications which made scanning of large samples prohibitively slow.

A third factor reducing scan time was the method of varying fluence levels on the sample. The samples are examined at a number of fluence levels ranging from 2-14 J/cm^2. The method at the time was to use a variable attenuator, which functioned well. However, it was realized that if the fluence level were lowered by increasing the beam size on the sample without sacrificing beam quality, the system could be scanned much faster at lower fluences.

LLNL's Optical Design Group developed an optical system that would significantly improve the sample scan times. In order to achieve this, two primary goals were given. The first was to reduce the amount of beam wander and jitter since a more stable beam requires less scan overlap. The second goal was to produce a beam profile with greater spatial uniformity, which would also significantly reduce the amount of overlap required in beam scans. A third goal was the ability to change the beam size on the sample without sacrificing uniformity to increase scan times at lower fluence levels. It was realized that these goals could best be utilized if image relaying (see below) was incorporated into the design.

This paper will discuss the basic concepts of laser conditioning to aid in understanding the problem being solved. The technique of image relaying will then be discussed to provide a basis for understanding the optical solution developed. The optical design to solve the stated problem will be explained in some detailed, and analytical results of the beam profile will be shown.

Laser Conditioning

Laser conditioning is a process that has been developed to prevent optical components from experiencing catastrophic damage at very high fluence levels. Small damage sites on optics can grow with successive high power laser shots. Initiating and correcting these damage sites can significantly increase the usable life of the optical components in a high power laser system. Conditioning raises the damage threshold of a material by irradiating the material at sub-threshold fluences. Two damage mechanisms are used to explain bulk damage in optical materials exposed to high fluence. The first is breakdown of defect-free materials. The second is the contribution of chemical, structural, and/or mechanical defects to the initiation and growth of laser damage. Experiments have shown that bulk damage thresholds of various optical materials can be significantly increased through laser conditioning.[1]

There are various schemes of illumination for laser conditioning, from single shots, to many shots at increasing fluences. Laser conditioning can stop the initiation of damage sites in the material at moderate fluences. The conditioning process often initiates damage on sites, which can be readily mitigated when the site is small. The mitigating laser beam locally melts and evaporates the optical surface, producing Gaussian-shaped pits. These pits do not damage at higher fluence levels, protecting the component. The conditioning process raises the threshold at which damage can occur in the material, as well as lessening the severity of damage at high fluences by up to a factor of four.[2, 3]

For the NIF program's Phoenix lab for laser conditioning, a large translation stage moves the optic in a raster pattern through a stationary sampling beam. At the time of this experiment the sampling beam was from a Nd:YAG laser at 355 nm with a 3.7 ns pulse width at 300 mJ. The laser pulses overlap in the scans to produce uniform conditioning over the entire crystal.[1, 2]

Image Relaying

Vacuum spatial filters were developed by LLNL in the mid 1970's.[4] Soon afterward the imaging properties of these optical systems were better understood and exploited to produce high quality propagation of laser light.[5] This propagation of light acts as a light relay and was called "image relaying".[6] In primary usage, the aperture stop is relayed, or imaged, onto subsequent pupils through the system, and the object and image pupils are called relay planes. While LLNL often uses relay imaging in conjunction with spatial filters, relay systems do not have to employ spatial filtering.

The advantages afforded by image relaying, and the implications of these advantages, are numerous. In normal beam propagation, diffraction and nonlinear phase distortion work together to degrade the beam profile. By controlling near field imaging properties relay systems minimize diffraction effects in propagation, greatly reducing small-scale spatial irregularities on a pulse which cause beam breakup, and minimizing self-induced phase-front distortion on the spatial envelop which leads to whole beam self-focusing. The implication of this is an increase in focusable power in the propagated beam. Relaying also has the effect of reducing propagation errors due to irregularities in intermediate transmissive elements. When used in conjunction with spatial filters, small scale intensity perturbations can also be eliminated.

During free space propagation, a non-relayed laser beam will develop a pronounced shoulder near the edge of the beam and a ripple pattern throughout the beam profile as it propagates, while the ratio of peak to average intensity increases. In a relayed system, the residual modulation is quite small, which implies smaller intensity gradients and lower local intensities for a given fluence level. This maintains a smooth beam profile at the relay planes. The beam profile at the image pupil is a smooth, reasonably close facsimile of the incident beam profile at the object plane, and the profile remains well defined for some distance beyond the image plane, depending on the aperture size and beam divergence at the aperture. With proper selection of lenses, the relayed image can also be magnified or minified to produce a facsimile of the beam profile of a different size.[5,6]

A final advantage of relay imaging is the stability of beam profile. Just as the imaged beam profile is fairly immune to small irregularities in intermediate transmissive elements; it is also robust with regard to factors such as air turbulence and vibrations of the optical table. One can almost visualize the optical relay system as a rope held between two fixed points. The rope can oscillate in a variety of modes along its length, yet the two points remain constant. While the analogy should not be taken to extremes, it gives a fitting mental picture for the ability of the optical relay system to reform the image of the object pupil between the relay planes.

Two advantages of relay planes that were exploited for this task were the marked reduction in beam jitter and the ability to reconstruct the beam profile from one pupil to another to near perfection.

Optical Design Solution

The first two goals of the optical design were to reduce the amount of beam wander, and to provide a beam profile on the sample similar to that at the laser aperture. For this reason it was determined that the optical system should provide relay imaging to exploit the special features of such systems. To meet the third goal of being able to vary the fluence on the sample, the plan was to zoom the focusing optical element positions to change beam size on the sample while holding the image relay close to the sample.

The parameters and restraints for the optical design are shown in Table 1. The optical system design was required to relay the laser aperture onto or near the conditioning sample. The beam size at the sample determined the fluence level on the sample. Another constraint on the design was that the beam could not focus too soon after the relay plane as this would cause fluence levels inside the sample to be too high. The lenses chosen needed to be fused silica to accommodate the fluence levels of the conditioning system. To reduce costs, it was desirable to use off the shelf lenses.

Table 1. Optical Design Requirements

Laser aperture (diam)	9.0 mm
Divergence	±1.0 mrad
Laser power	≈ 300 mJ
Wavelength	351 nm
Beam size (square) @sample for 14 J/cm^2	1.26 x 1.26 mm
Beam size (square) @sample for 2 J/cm^2	3.17 x 3.17 mm
Lens material	Fused Silica
Beam path	≤ 8 m
Focus separation from sample	≥ 80 mm
Relay plane location	Close to sample
Beam profile @sample	“flat-top”
Beam jitter, wander	≈ 0

It was recognized that a relay telescope was needed to relay the aperture onto the sample. However, the need to focus the beam down to smaller sizes reduces the distance over which the relay plane can be imaged. A 1:1 telescope over 6 meters in length was chosen to project the aperture as far forward as possible. The telescope was built with two identical lenses, L_1 and L_2. A set of two lenses were selected to image the beam to the proper size at the relay plane for the 14 J/cm^2 case. The two imaging lenses, L_3 and L_4, are moved to attain the proper beam size for the 12, 10, and 8 J/cm^2 runs. All lenses used are plano-convex fused silica from a commercial vendor.

A summary of the optical design used for 8 to 14 J/cm^2 is given in Table 2. In the table t_{01} is the spacing from the laser aperture to the first lens, L_1. The spacing from the L_4 to the sample is t_{4s}, and t_{sf} is the distance from the sample to beam focus. The value represented by δ_{rs} is the distance from the relay plane to the sample face. Lenses are described by their effective focal length at 351 nm. It can be seen in Figure 1 that L_3 and L_4 are moved as a group to obtain the different fluence levels.

Table 2. Optical System for 14, 12, and 10 Joules/cm^2

J/cm^2	**t_{01}**	**L_1 efl**	**t_{12}**	**L_2 efl**	**t_{23}**	**L_3 efl**	**t_{34}**	**L_4 efl**	**t_{4s}**	**t_{sf}**	**δ_{rs}**
14	1000	3245	6484	3245	20	4327	79.4	1082	739.0	123	0.0
12	"	"	"	"	29.9	"	"	"	729.1	132.7	9.7
10	"	"	"	"	42.6	"	"	"	716.4	145.1	22.1
8	"	"	"	"	60.1	"	"	"	698.9	163.2	39.3

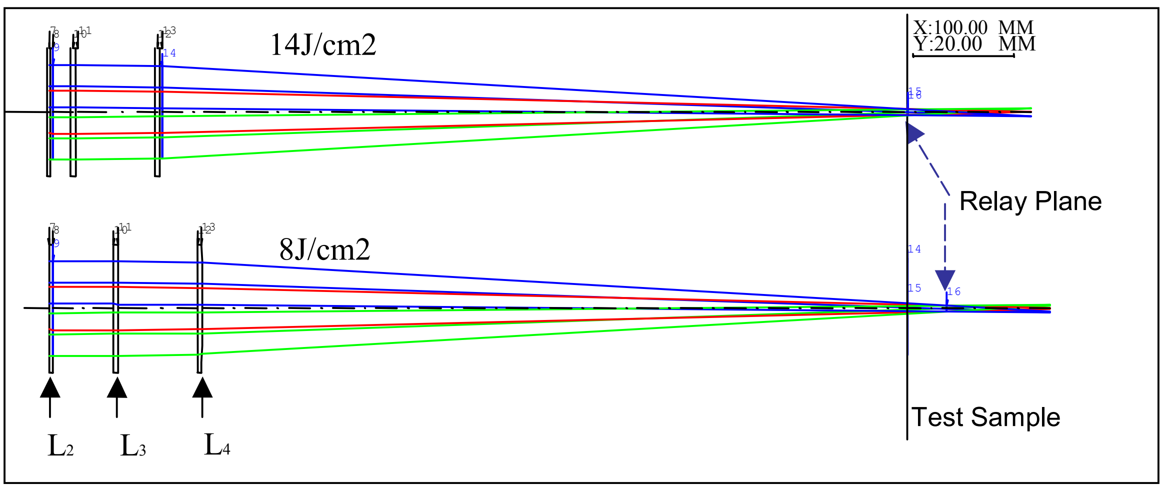

Figure 1. L_3 and L_4 Move to Vary Fluence On Test Sample.

It can be seen in Table 2 and Figure 1 that the relay plane had moved 39.3 mm from the sample for the 8 J/cm^2 case. Due to the divergence and aperture of the laser, the beam profile at the relay remained fairly constant over distances up to 30 mm, but as the separation approached 40 mm the beam profile was beginning to exhibit a shoulder in the beam profile (refer to Figure 5 below). It was decided to use this lens system only for fluences between 10 and 14 J/cm^2. For the operations at 2 to 8 J/cm^2 a different lens set was required.

Ideally the optical system for the lower fluences is similar to the one used at the higher fluences to minimize the time required to change settings. The beam size required on the sample in the lower fluence cases is larger. Therefore the telescope was changed by using a different lens 1 (designated L_1') at a different location to produce a 1.5x magnifying telescope. A different lens 3 (L_3') was also used in this configuration, and no fourth lens was required. The different fluence levels are achieved by moving L_3'. Again, all lenses are commercially available plano-convex fused silica. A summary of the optical design used for 2 to 8 J/cm^2 is given in Table 3. In the table the labels are as described in Table 2. The movement of L_3' to achieve various fluence levels is seen in Figure 2.

Table 3. Optical System for 8, 6, 4, and 2 Joules/cm^2

J/cm^2	**t_{01}**	**L_1' efl**	**t_{12}**	**L_2 efl**	**t_{23}**	**L_3' efl**	**t_{3s}**	**t_{sf}**	**δ_{rs}**
8	2081	2164	5404	3245	276	649	566.4	80.2	-30.6
6	"	"	"	"	288.4	"	554.0	92.5	-18.6
4	"	"	"	"	309.2	"	533.2	113.4	1.6
2	"	"	"	"	356.0	"	486.4	160.2	47.0

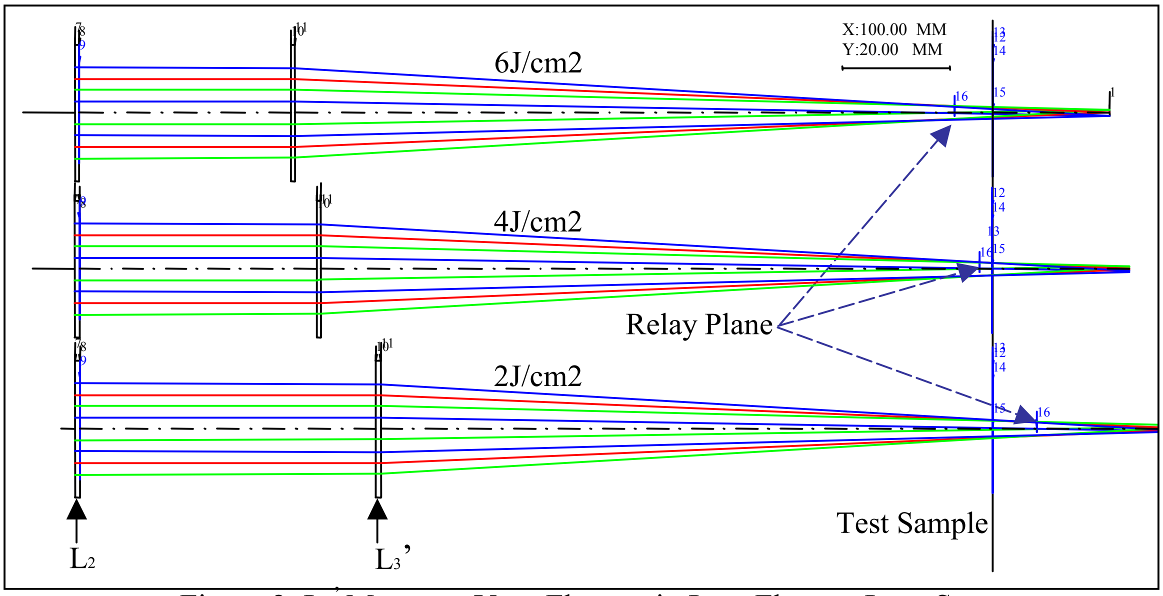

Figure 2. L_3' Moves to Vary Fluence in Low Fluence Lens Set.

The two lens sets have a similar form, but L_2 is the only element common to both. However the overall distances between the laser, L_2, and the test sample never change, so configuring the experimental setup to accommodate the two designs is straightforward using translation stages. The difference in beam path between the 2 and 14 J/cm^2 fluences is illustrated in the Y-Ybar diagrams in Figure 3, where Y-bar represents the marginal ray height and Y is the chief ray height. Aperture stops and relay planes are those where the chief ray (Y-bar) is at zero height, and beam focus occurs for marginal ray height (Y) of zero. Slope changes in the curves are caused by elements with optical power.[7]

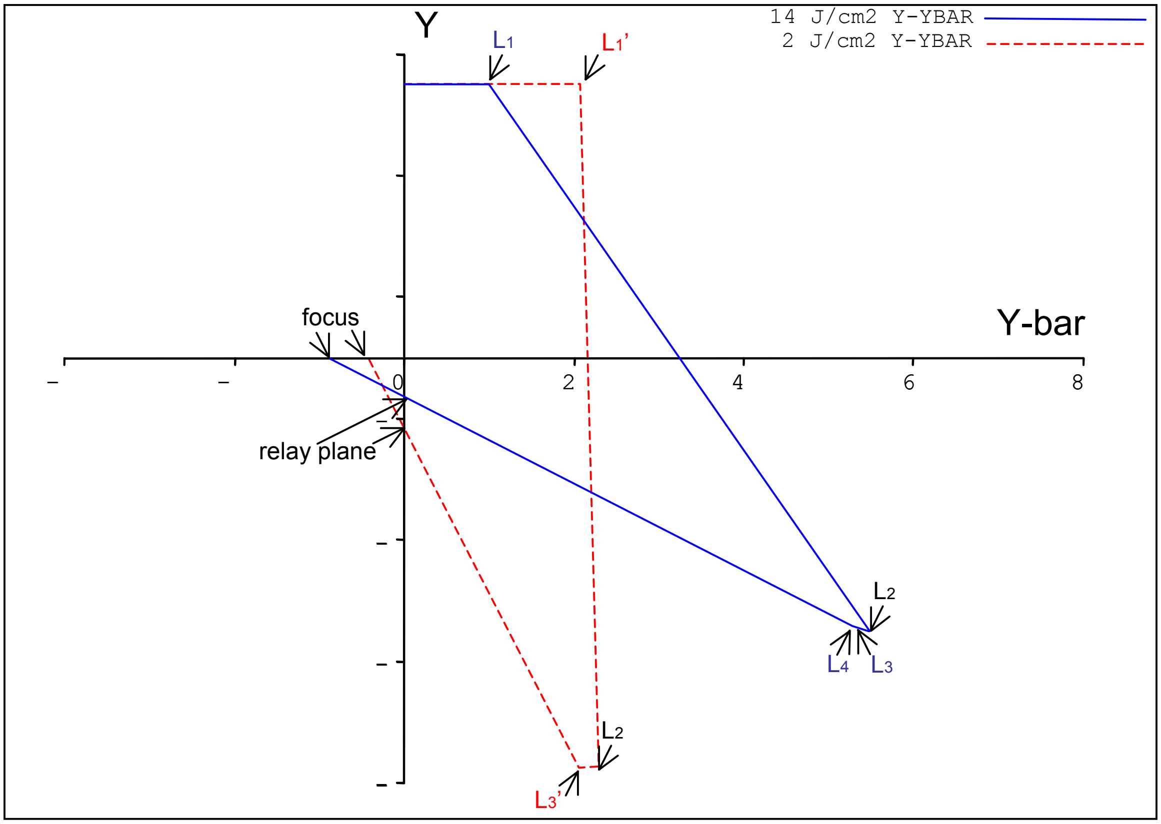

Figure 3. Y-Ybar Diagram of 2 and 14 J/cm^2 Optics Positions

Analytical Results

To test the beam profile at the test sample, the optical systems were modeled in the ASAP software package.[8] The laser aperture was modeled as a "top-hat" as shown in Figure 4. The beam was propagated to the test sample and the profile examined to ensure that the "top-hat" form remained.

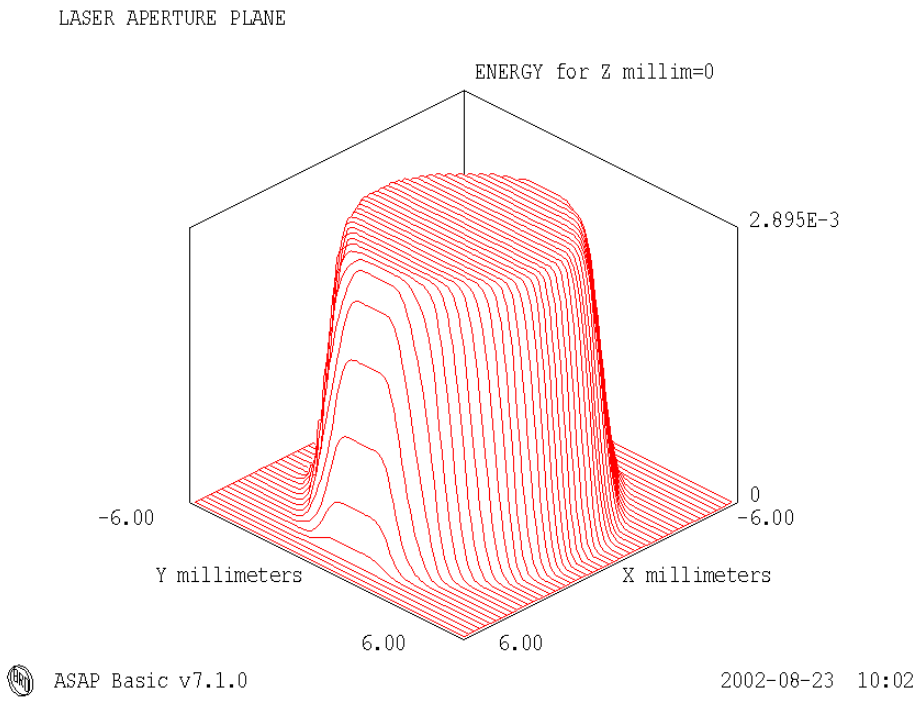

Figure 4. Beam Profile at Laser Aperture

Figure 5 shows the beam profile 100 mm before the relay plane. Figure 6 shows the beam profile at the test sample for the 14 J/cm^2 case, in which the relay plane is coincident with the test sample. It can be seen that the beam profile at the sample is very well preserved. Figure 7 shows the beam profile 100 mm after the relay plane. These figures provide a good demonstration of the utility and power of image relaying in maintaining beam profile through propagation. It shows how the profile far from the relay plane can be severely degraded and still reconstruct itself at the relay plane.

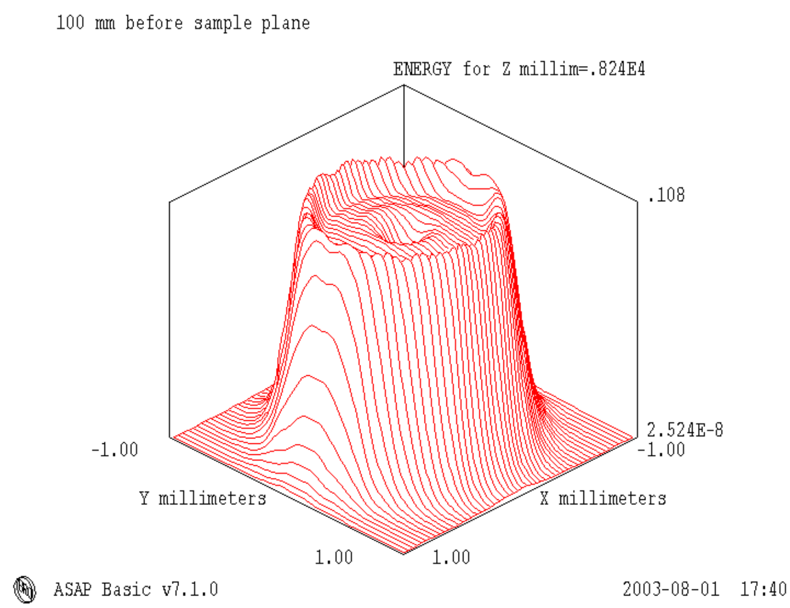

Figure 5. Beam Profile 100 mm Before Relay Plane.

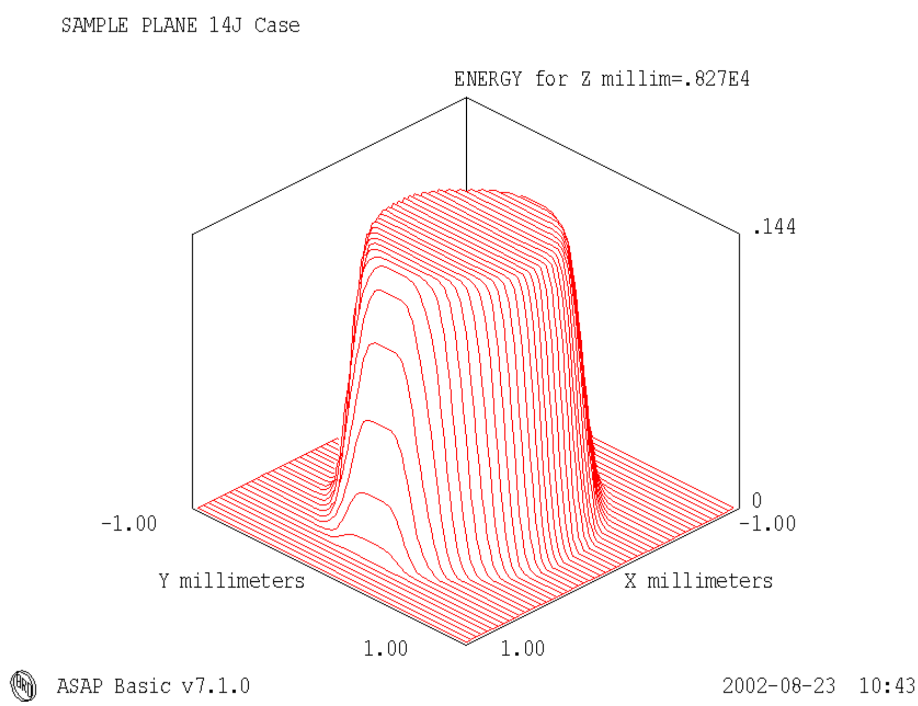

Figure 6. Beam Profile at Test Sample for 14 J/cm^2 Fluence Setting.

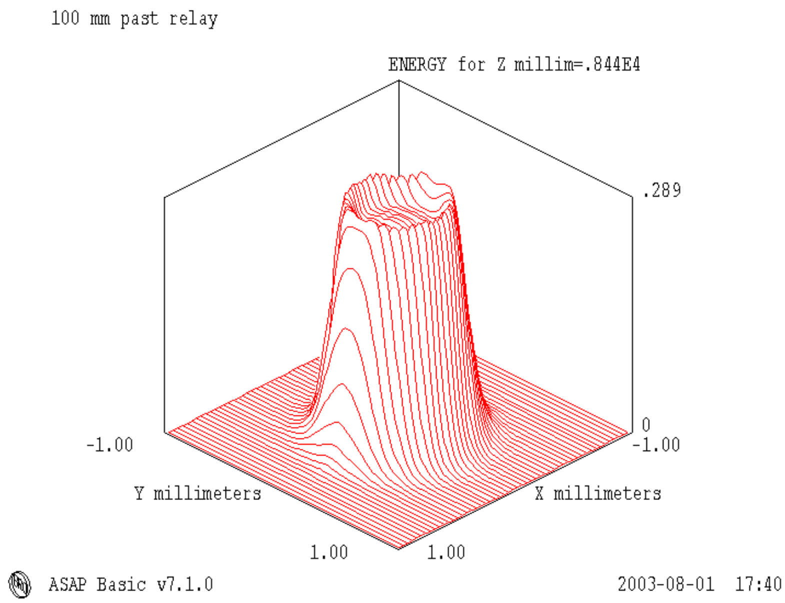

Figure 7. Beam Profile 100 mm after Relay Plane

Laboratory Results

The optical system specified was procured and assembled in the Phoenix lab at LLNL and worked as expected. This was a prototype design and the laser conditioning system has moved on to a different laser system requiring a different optical system for relay imaging and beam size adjustment.

Conclusion

An optical system was designed and described for relaying the beam profile at the laser aperture onto a distant test sample without degradation of the beam profile. The system also greatly reduces beam wander on the sample. The system was also capable of adjusting the beam size on the sample without sacrificing the beam profile by moving lenses as described. The system described functioned as expected in the Phoenix lab.

Image relaying has been in use at Lawrence Livermore National Laboratory for nearly three decades as of this writing. The advantages with respect to beam profile and image stability have been demonstrated in various experiments and are relied on in big science projects such as the National Ignition Facility. The analysis above provides analytical verification of the effect of image relaying and demonstrates that such systems are able to restore the aperture profile at the sample plane.

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