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Spot Size and Effective Focal Length Measurements for a Fast Axial Flow CO2 Laser

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Robert J. Steele
Naval Air Warfare Center
China Lake, California 93555-6100

Phillip W. Fuerschbach
Danny O. MacCallum
Sandia National Laboratories
Albuquerque, New Mexico, 87185-0367

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Abstract

An evaluation of the variation in focal plane position and spot size for a 1650 W fast axial flow CO_2 laser was performed. Multiple measurements of the focused beam were taken at stepped intervals along the beam axis to create a composite representation of the focus region. Measurements were made at several power levels from low to full power for each of five nominally identical lenses. It was found that as laser output power increases, the minimum focused spot radius increases, and the position of minimum focus shifts toward the laser resonator. These effects were attributed to observed variations in the diameter of the beam entering the focusing lens. For the ZnSe (f = 127 mm) lenses examined, variations in spot radius and focal plane position were seen. Lenses with high rated absorption had a larger variation in spot size and effective focal length than those with low absorption. Lenses that had previously been degraded by welding had the greatest variation.

Introduction

Accurate knowledge of the characteristics of a focused laser beam is critical for process control of laser beam welding and cutting. These characteristics include focused spot size, focal plane axial position, and depth of focus. In a job shop or laboratory environment, processing requirements can lead to frequent changes in laser set up conditions (such as output power or lens focal length) which, in turn, may lead to changes in the focus characteristics. In order to build process models, accurate values of spot size and focal position are required.

Other laser system related conditions are thought to have an effect on focusing as well. Heating of the output coupler from the resonator cavity is reported to cause distortion of the optic and affect the output laser beam. What effect does the surface condition of the lens have on the focusing characteristics? Focus lens condition is thought to be critical to the stability and repeatability of focus. Lens damage from weld vaporization and spatter, for example, may have an effect on the focused spot size. In addition to causing refractive effects, this damage may lead to lens heating and lens distortion.

This study is an evaluation of the focusing characteristics of several 127 mm focal length, plano convex, ZnSe lenses. Due to manufacturing tolerances, focusing lenses are produced with different values of absorption. A variation in focusing characteristics due to absorption might be expected. The repeatability of focusing characteristics for multiple nominally identical focusing lenses was also of interest.

Experimental

The laser used for this experimentation was a Rofin Sinar 1200SM fast axial flow CO_2 capable of producing up to 1650 W. The output coupler had been in the laser for less than 2 years and had less than 100 hours use time. Focus lenses were evaluated at 7 power levels from 200 to 1600 W.

DISCLAIMER

All power levels were measured with a calorimeter type power probe after the focus lens. The data in Table 1 describes each of the lenses tested. The table includes the manufacturer supplied power absorption value for the lens. Lenses B thru E were manufactured by Laser Power Optics. Lens A was of uncertain manufacture.

Table 1 – Lenses Evaluated

Lens Designation	Lens Type	Focal Length (mm)	Edge Thickness (mm)	Rated Absorption (%)	Condition at Testing
A	Plano Convex	127	4.0	Unknown	Used
B	Plano Convex	127	2.0	0.13	New
C	Plano Convex	127	4.0	0.18	New
D	Plano Convex	127	4.0	0.23	Used
E	Plano Convex	127	4.0	0.23	New

Focus measurements were made with a Prometec UFF 100 Laserscope. For each power level the focused beam was scanned at, above, and below optimum focus over a range of approximately 6.3 mm. Each scan was incremented in 0.64 mm steps. At least 10 scans were made for each power level.

The Laserscope uses a hollow needle on a rotating drum to scan the laser intensity. A small hole in the needle permits laser radiation to enter. The radiation entering the needle is guided to a detector. Figure 1 shows the set up for the Laserscope. To complete a measurement, the needle is rotated and indexed through the beam to permit the cross sectional area of the beam to be sensed. Figure 2 shows a typical output from a single scan. Figure 3 shows a composite representation of all scans made for a specific power level and lens.

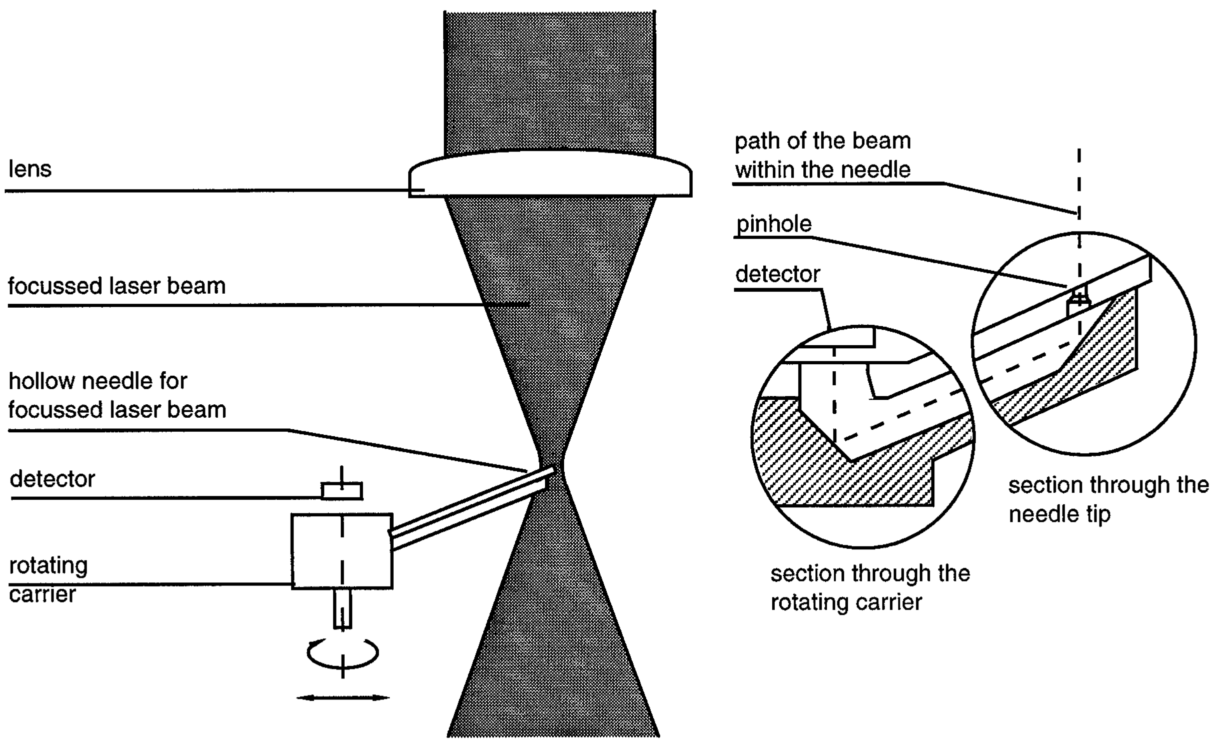

Fig. 1 – Laserscope scanning aperture system

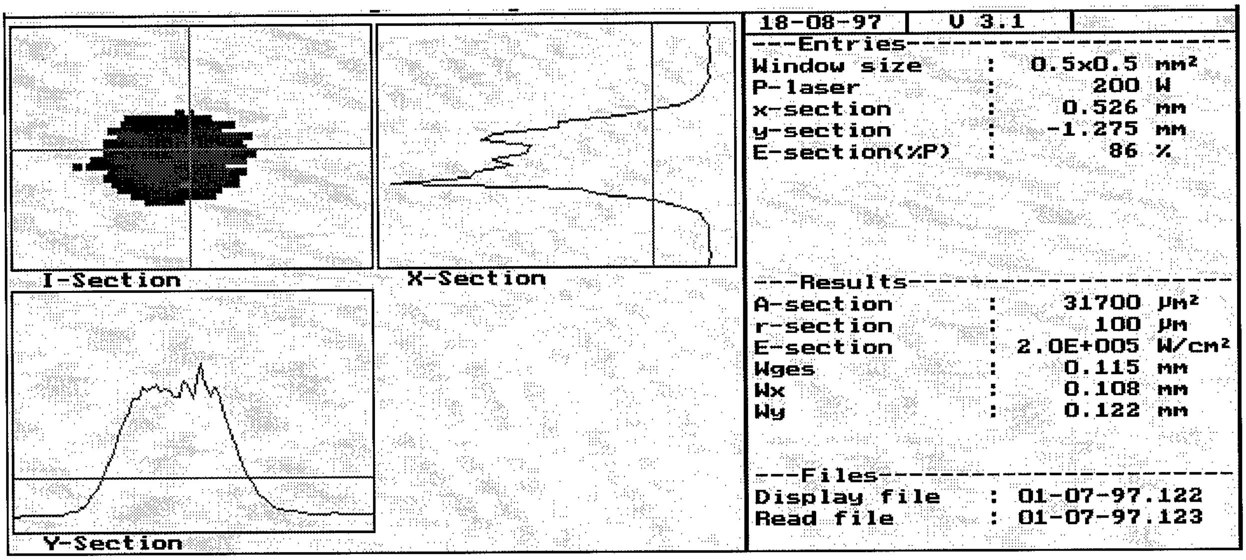

Fig. 2 – Laserscope single scan results

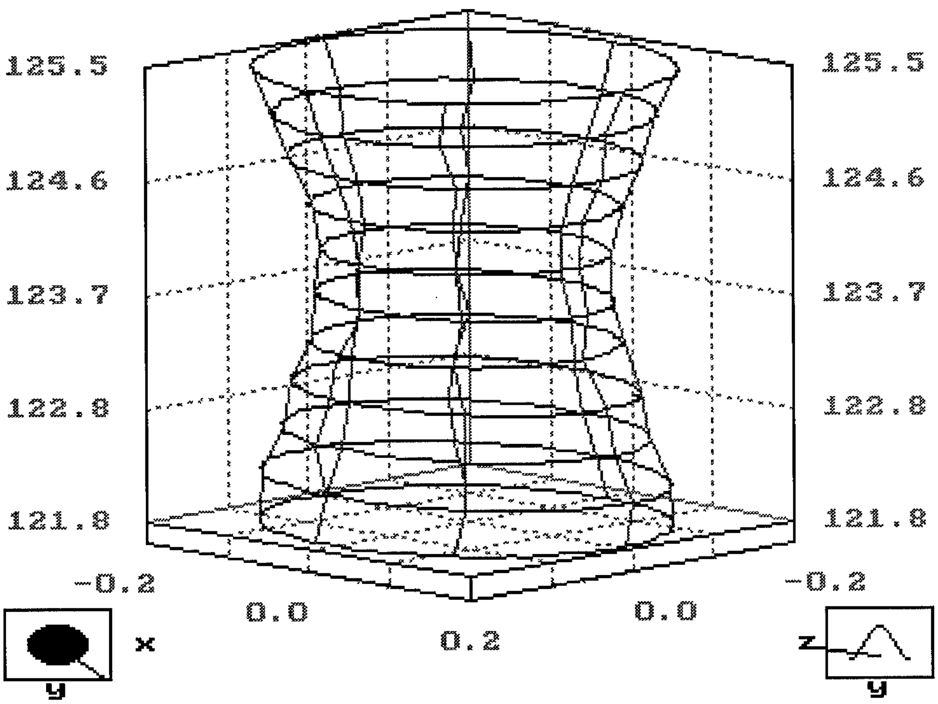

Fig. 3 – Laserscope composite of multiple scans

The Laserscope can also be used to measure unfocused beam size. Measurements of unfocused beam size were made at a position just outside the output coupler and at the focus lens position (with the lens removed). The distance between the two points is 3 meters. The unfocused beam was measured over the full power range in 200 W increments.

The spot size and position data collected from the Laserscope for each lens were plotted and a nonlinear curve-fitting algorithm was used to analyze the data (Ref. 1). The curve fit provided three important parameters including minimum beam radius, position of the minimum waist (effective focal length), and M^2. For these measurements, effective focal length is determined from the front (mounting) face of the lens.

Results and Discussion

Spot Size

Figure 4 shows the measured spot size and its position for Lens A at different power levels. This lens had been used for production and had some minor spatter on the lens face. Apparent in this graph is the increasing minimum spot size as power increases. At 200 W the spot radius is 0.105 mm. At 1600 W however, the spot radius has increased to 0.125 mm, a 0.02 mm increase in radius.

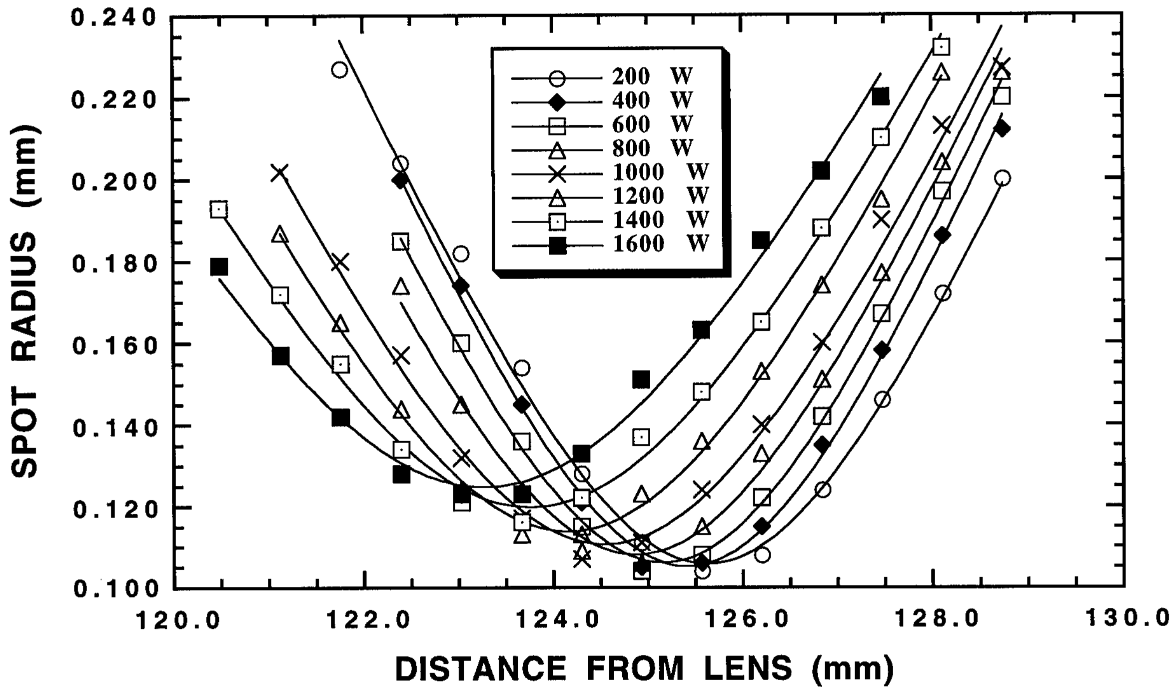

Fig. 4 – Change in spot radius and shift in effective focal length at several power levels for a 127 mm plano convex lens.

The variations in spot size with power seen in Fig. 4 were thought to be caused primarily by a change in unfocused beam size. Because thermal lensing of the output coupler is known to affect spot size, (Ref. 2) determination of the unfocused beam size throughout the power range was undertaken to help explain the variation. Figure 5 shows the results of unfocused beam measurements taken at 2 positions in the beam path. For the measurements at the exit of the output coupler, the small increase in beam size with power is suspected to be due to system performance variation related to better filling of the laser resonator at increasing power. The measurements taken at the lens position show a more dramatic change in beam size. This is attributed to thermal lensing of the output coupler. Work by Klein (Ref. 3) described and evaluated the thermal lensing phenomena that occurs as a result of the absorption of laser light in solid windows. Ifflander and Weber (Ref. 4) showed that the effect of thermal lensing could be compensated for by special optics. However, many laser systems, including the laser used in this study, do not have provisions for thermal lensing compensation and therefore, the effects must be compensated for during material processing in order to optimize the process. As seen in Figure 5, for laser power up to approximately 1500 W the beam becomes less divergent and above 1500 W, the beam is converging. The transition from a diverging to a converging beam occurs in Figure 5 where the two curves cross.

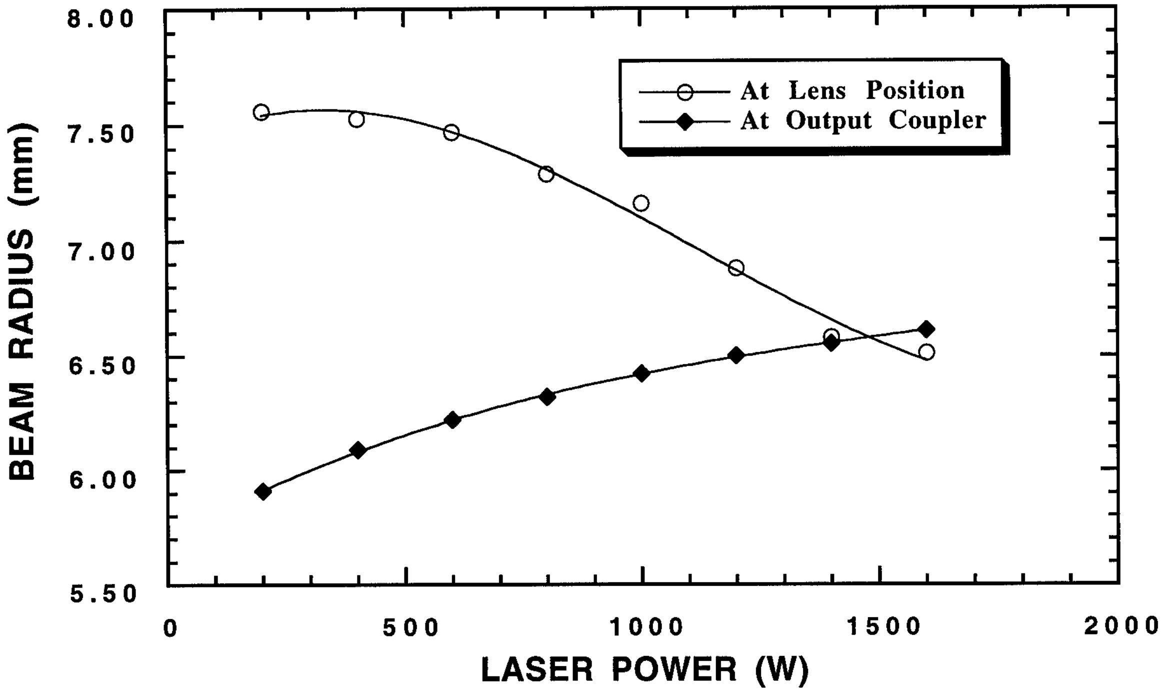

Fig. 5 – Variation in beam radius with laser power at 2 locations in beam path.

The variation in unfocused beam radius at the focus lens position shown in Figure 5 will significantly change the optic *F#*, which is the ratio of the lens focal length *(f)* to the unfocused beam diameter *(D)* as described by:

$$F\# = \frac{f}{D} \tag{1}$$

A prediction for the focused beam radius (w_0) can be made with the following equation:

$$w_0 = \frac{2M^2 F\# \lambda}{\pi} \tag{2}$$

where M^2 is the beam quality and λ is the wavelength of the laser radiation. (Ref. 2) One can see from (2) that the spot radius is directly related to the F#. If f = 127 mm and unfocused beam values for F# and M^2 are substituted into Equation 2, the effect on spot radius can be evaluated. For Lens A, at 200 W, a spot radius of 0.103 mm is predicted. The measured value was 0.105 mm. At 1600 W, the predicted spot radius is 0.119 mm and the actual was 0.124 mm.

Thermal distortion of the lens at higher power can explain the additional spot size increase above that predicted by equation (2). The lens is heated by the laser beam on the surface near its center; cooling is provided from the edges. The result is a thermal gradient that distorts the shape and an increase in spot radius. Since Lens A had been previously damaged with spatter, the absorption should be greater than for a new lens.

To verify this assumption, an unused f = 127 mm plano convex lens (Lens B) was evaluated, it has a lower rated absorption than Lens A, and a smaller edge thickness (see Table 1). Table 2 shows the predicted and actual values for spot size radius for Lens A and B. The results for Lens B are exactly the predicted values indicating no thermally induced distortion of the lens.

Table 2 - Predicted and Measured Spot Radius Values for Low and High Power

Power (watts)	Predicted Radius (mm)	Measure Radius (Lens A) (mm)	Measured Radius (Lens B) (mm)
200	0.103	0.105	0.103
1600	0.119	0.124	0.119

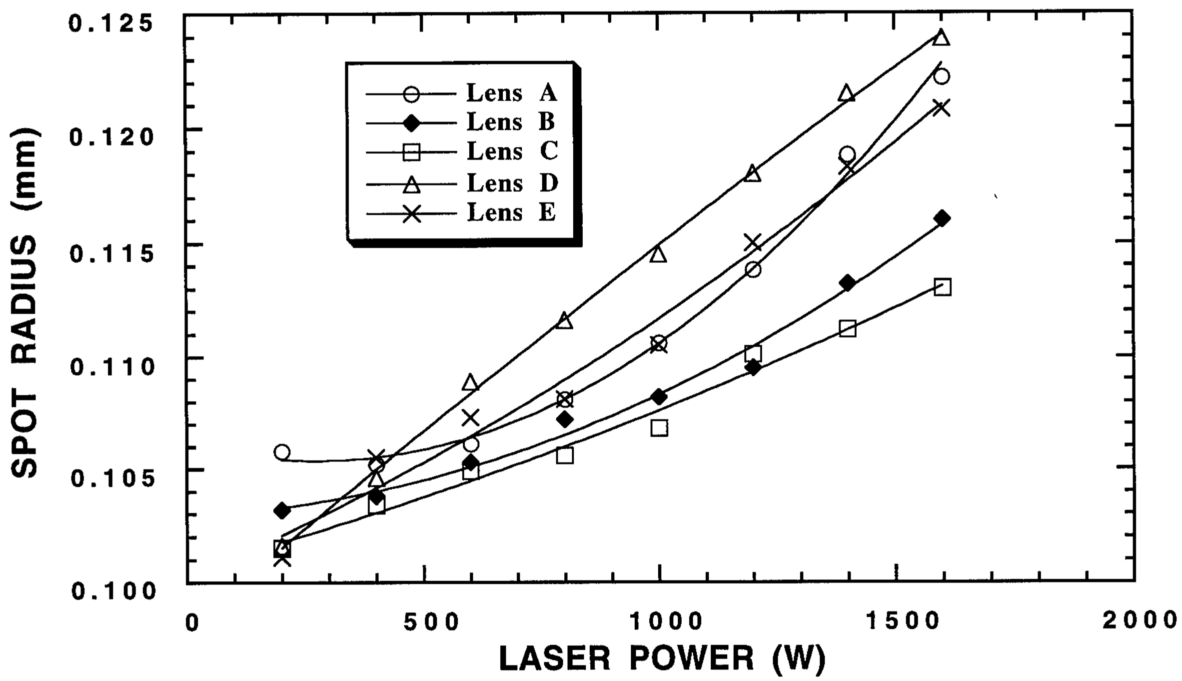

Fig. 6 – Variation in spot radius with power for 5 nominally identical 127 mm plano convex ZnSe lenses.

Additional f = 127 mm plano convex lenses were also evaluated to determine if the variability in spot size seen with Lens A and B would occur for other lenses. Figure 6 shows the variation in spot radius with power for the five lenses tested. All lenses show a similar dependence of spot size on power. It is significant that at 1600 W, there is a variation of 28% in spot radius among the lenses that are nominally identical. Lenses A and D show the largest spot size at high power. Lens D had also been used in production welding and exhibited some minor spatter on the surface. This lens was the highest in rated absorption (0.23%) of all lenses tested. Lens E, also with high rated absorption (0.23%), but unused at the time of evaluation, had slightly less spot size increase. The lenses with smallest spot radius, B and C, were low in rated absorption and had not been used for welding when evaluated.

Effective Focal Length

The focal plane position shift with power shown in Figure 4 is a serious concern for process control. A noticeable variation in effective focal length is seen. At 200 W the effective focal length is 125.6 mm and at 1600 W is 123.3 mm — a shift of 2.3 mm. Observed is the position of minimum focus shifted toward the lens as power is increased (a decrease in effective focal length). Figure 7 shows a summary of all lenses tested comparing the change in effective focal length of each lens with power. As the power increases, the distortion of the output coupler causes a change in the wavefront characteristics of the propagating beam. The result is a decrease in beam divergence (Fig. 5) and a change in the focal plane position (Ref. 5). For this laser, the beam becomes convergent at 1500 W. The trend of reduced effective focal length is seen with all lenses in Figure 7 and can be attributed as for increased spot radius to the distortion of the output coupler.

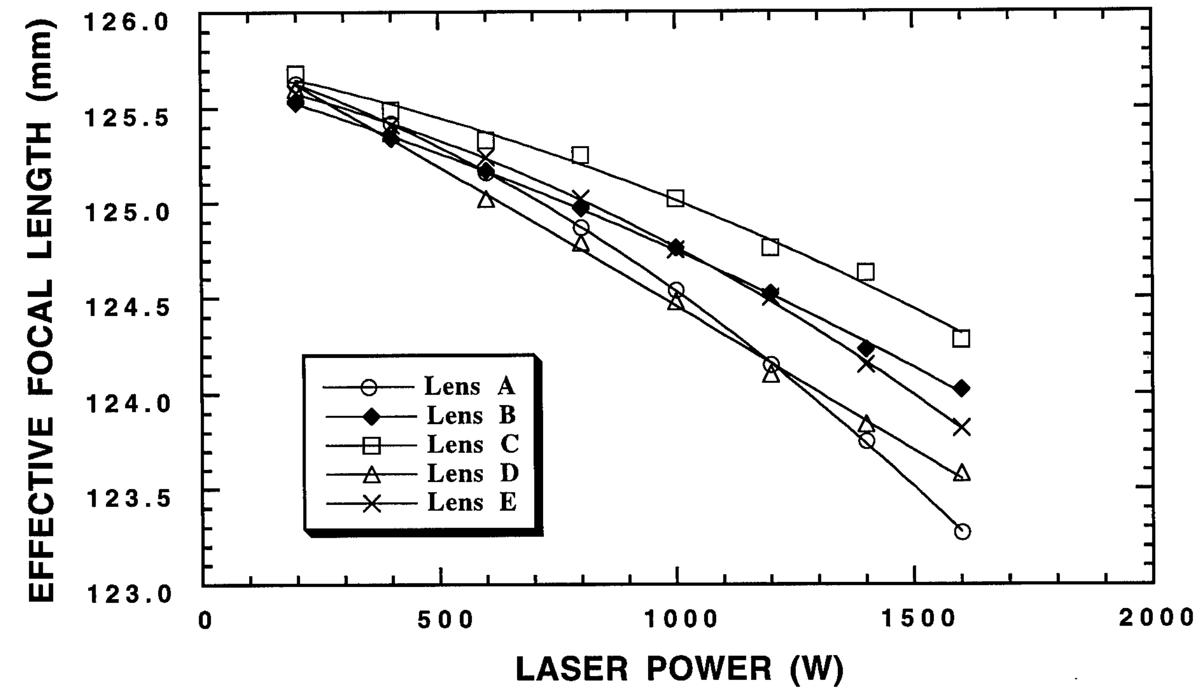

Fig. 7 – Variation in effective focal length with power for 5 nominally identical 127 mm plano convex ZnSe lenses.

The variation between lenses in Fig. 7 however, must be explained. As was seen with the variation in spot radius, individual lens characteristics can have a contributive effect. Sufficient absorption of the laser beam by the lens can cause a change in the curvature and therefore, alter the focal plane position. The lenses with the greatest shift in effective focal length were A and D. These lenses were damaged with minor spatter and, in the case of Lens D, had the highest relative rated absorption. Lens C, high rated absorption, but unused, was next in relative variation. Finally, unused and low in rated absorption, Lenses B and C had the smallest change in effective focal length.

Depth of Focus

Consistent beam irradiance is fundamental to reproducibility of laser welds. Irradiance (I) is defined by

$$I = \frac{P}{\pi r^2} \tag{3}$$

where P is the measured laser power and r the measured spot radius. To evaluate the variation in beam irradiance with power, the data for the f = 127 mm lenses was plotted (Figure 8). The variation in irradiance is considerable — as much as a 25% variation is seen.

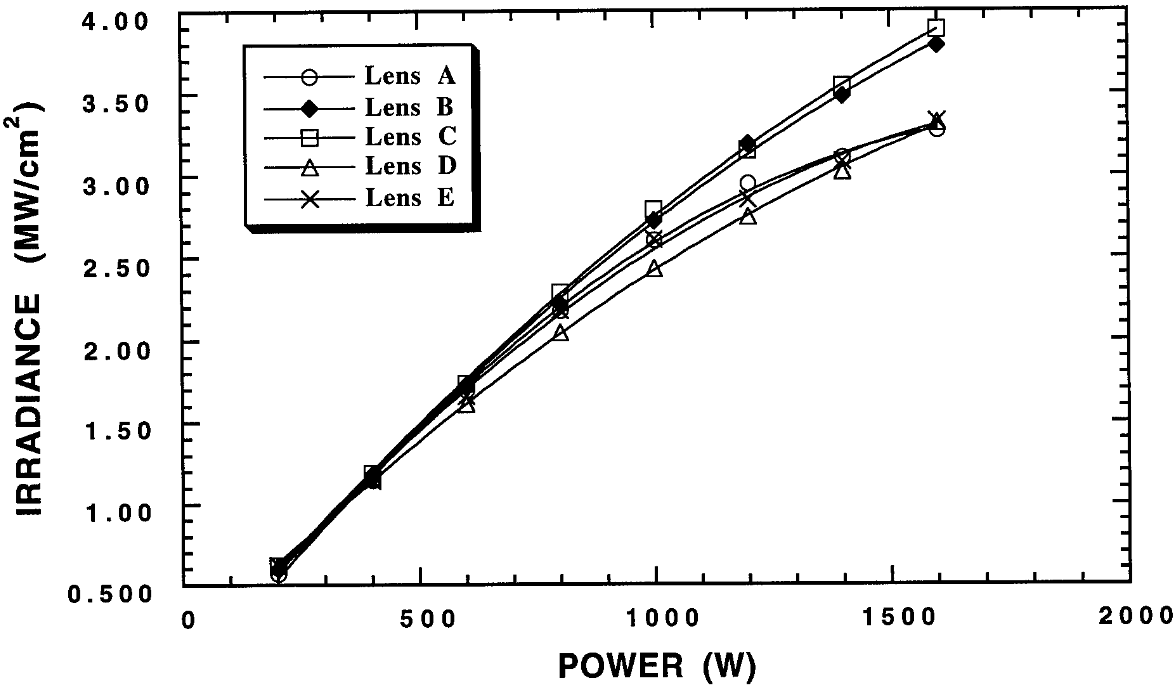

Fig. 8 – Variation in beam irradiance with power for 5 nominally identical 127 mm plano convex ZnSe lenses.

The average depth of focus as a function of power for all the lenses is shown in Figure 9. Depth of focus (d) was calculated using the equation (Ref. 1)

$$\delta = \frac{2\pi w_0^2}{3M^2\lambda} \tag{4}$$

where w_0 is the minimum spot radius. Evident in Fig. 9 is a minimum depth of focus of 1.2 mm increasing to near 1.8 mm at full power. Clearly, this is a result of the increasing spot size at higher power. If we compare the shift in effective focal length in Fig. 7 (as much as 2.0 mm) to the maximum amount of depth of focus in Fig. 9 (1.8 mm), it is apparent that there is insufficient depth of focus to compensate for the shift in effective focal length. This could present a problem in a welding set up for which the optimum focus for a weld was determined at a low power and then a significantly higher power was used to weld. The result would be an out of focus condition.

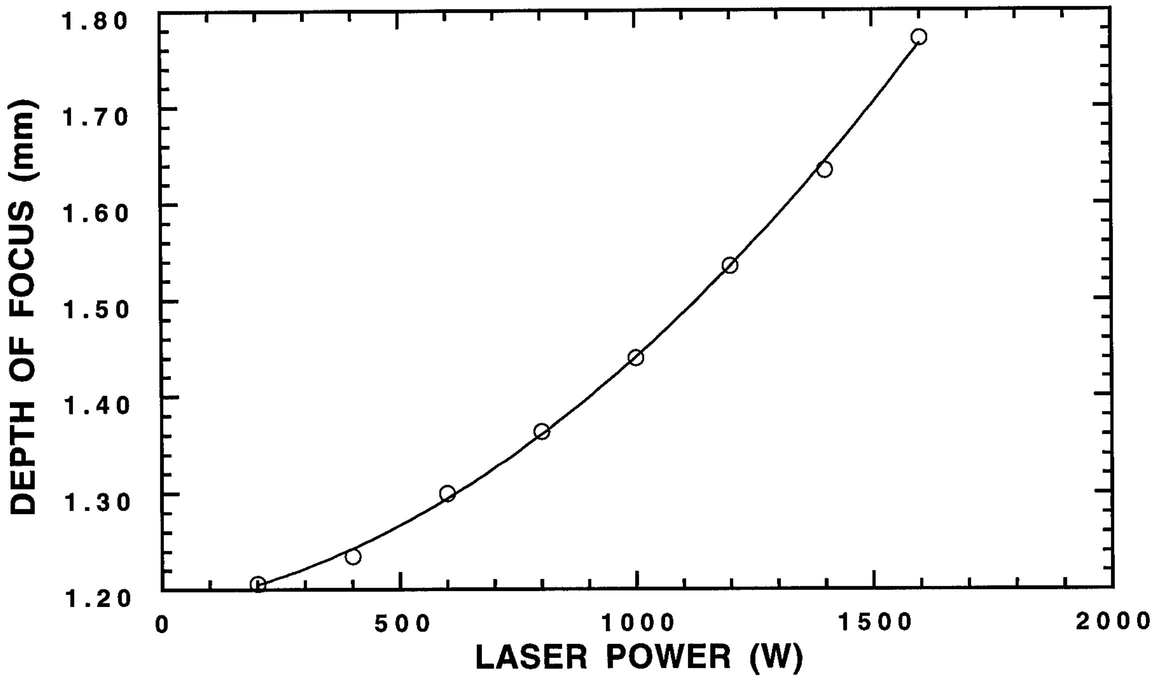

Fig. 9 – Average depth of focus for 127 mm plano convex ZnSe lenses.

Conclusions

1. Five nominally identical focusing lenses were evaluated for focusing characteristics on a fast axial flow CO_2 laser. A Prometec Laserscope was used to measure spot size and effective focal length for each lens at several laser power settings.
2. The minimum spot size was found to increase with increasing laser power. This effect was attributed primarily to the change in size of the unfocused beam due to thermal lensing of the output coupler.
3. The effective focal length of each lens was found to be shorter with increasing laser power. Changes in divergence and laser wavefront characteristics were consisdered the primary reasons for this effect.
4. Significant variation in minimum spot size and effective focal length was observed for the five nominally identical lenses. Lenses with high relative rated absorption had a larger variation in spot size and effective focal length than those with low absorption. Minor damage to the focusing lens from spatter increased the observed effects.
5. Beam irradiance was found to vary by as much as 25% for nominally identical lenses. This can have a significant impact on materials processing applications.
6. Depth of focus was found to increase with increasing laser power but not sufficiently to compensate for the observed changes in effective focal length with power.

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Meet the Authors

Robert Steele is a welding engineer with the Weapons Prototype Branch at the Naval Air Warfare Center. He has a B.S. Degree in Welding from Utah State University and 14 years experience in high energy density and conventional welding processes. He is a member of the Laser Institute of America (LIA) and the American Welding Society (AWS) and is chairman of the AWS C7C Committee for Laser Beam Welding and Cutting. He holds two patents in Laser Beam Welding.

Phillip Fuerschbach is a Senior Member of the Technical Staff at Sandia National Laboratories. Mr. Fuerschbach received his B.S. degree in Mechanical Engineering from the University of New Mexico. Since 1978, he has worked in the welding research laboratory at Sandia, principally with the advanced joining processes. His main areas of research have been in fusion welding process control for the high power density welding processes: laser beam welding, pulsed gas tungsten arc, pulsed plasma arc, and variable polarity plasma arc welding.

Danny MacCallum is a PTNG at Sandia National Laboratories Joining Metallurgy department. He has a B. Sc. Degree in Applied Mathematics and Physics from the University of New Mexico and nine years experience in data acquistion, analysis and numerical computing. He is a member of the LIA (Laser Institure of America) and AWS (American Welding Society).

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